Direct measurements of parton shower modification in hot QCD medium using vector boson-tagged jets

by

Kaya Tatar

B.S., Computer Engineering (2014)
B.S., Physics (2014)
Boğaziçi University

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Physics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2020

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Abstract

Measurements for jets and charged particles tagged with vector bosons (Z bosons or photons) in pp and PbPb collisions are presented, using data collected with the CMS detector at the LHC at a nucleon-nucleon center-of-mass energy of 5.02 TeV. The measurements study how energetic partons interact with a hot QCD medium that forms in PbPb collisions, but lacks in pp collisions. Jet deflection and jet energy loss are studied using angle and momentum correlations between a Z boson and the recoiling jet. The results suggest that jets lose energy in PbPb collisions compared to pp collisions, but jet angles in PbPb collisions are not significantly deflected. Medium induced parton shower modification as well as the medium’s response to the jet propagation is studied for partons recoiling from a Z boson or an isolated photon. In particular, momentum spectra are obtained for the recoiling charged particles. Additionally, jet fragmentation functions and jet shapes are constructed using charged particles falling within a cone around the jet axis. When compared to pp collisions, jets in PbPb collisions are observed to have more low energy and less high energy particles. At the same time, a larger fraction of the jet energy is carried at larger angles from the jet axis. Studies of particle production indicate an excess of charged particles in PbPb collisions over all azimuthal angles with respect to the Z boson, suggesting the presence of medium response effects at large angles from the parton shower. These measurements, for the first time, demonstrate medium induced modifications of parton showers whose initial kinematics are constrained with vector bosons, and constitute new, well-controlled references for the understanding of QCD medium.

Thesis Supervisor: Yen-Jie Lee
Title: Associate Professor of Physics
Acknowledgments

My doctorate in the MIT heavy ion group has been an intense, transforming, and rewarding experience.

First, I would like to thank my supervisor Yen-Jie Lee who gave me the opportunity to do the physics studies that resulted in this thesis. He was both a knowledgeable supervisor, who taught me a lot, and an intimate colleague as we learned things together. A lot of times I was amazed by his curiosity, energy, experimental skills, and ability to achieve multiple things at a time. Through him I observed how great scientific progress can be made if one correctly identifies the important items. I hope I have learned from him.

I was fortunate to have worked with Gunther Roland, our group leader, who demonstrated how to do scientific analysis, to consider broader aspects of a situation, and to plan something with a vision in mind. I witnessed how instrumental a good management is to accomplish projects efficiently. I thank Bolek Wyslouch, who was director of the LNS during most of my time in the group, for ensuring that students can remain focused on what they do without being concerned by external factors. It was delightful to talk to Wit Busza with whom I had invaluable and memorable chats on science and life. I was lucky to have interacted with Krishna Rajagopal, he followed our measurements over the years and improved our understanding of the underlying physics by sharing his interpretation of our results. As a member of my thesis committee, his constructive feedbacks from the perspective of a theorist made this thesis much more refined and clear.

I had the chance to work with many talented senior colleagues. I thank Ivan Cali for all the efforts that resulted in successfully recorded CMS heavy ion data, Christof Roland for coordinating the data taking efforts and guidance on analysis methods, Yi Chen for coordinating the trigger operation and his impressively fast analysis workflows, and George Stephans for coordinating the simulation, language editing our papers, and the physics discussions. Even if we mostly worked on different projects, Gian Michele Innocenti and I shared many enjoyable and also nervous experiences in
various locations: at MIT, CERN, and conferences around the world. I thank him for the moments together and for his mentorship over years. Camelia Mironov’s help with editorial works accelerated the publication of all papers presented in this thesis. I am grateful for her companionship as well as her mentorship, especially on how to collaborate and communicate with people.

In my first year, other students helped me get up to speed. Alex Barbieri introduced me to the CMS technicalities as well as the reconstruction and analysis software. Dragos Velicanu passed his knowledge on the computing clusters. Doğa Gülhan described the heavy ion physics and what to do to understand it better.

I am grateful to my fellow students, Ran Bi for all the assistance and knowledge he provided in software, analysis, and detector works; and Chris McGinn for all the works in jet reconstruction, guidance on trigger development, and serving as the High-$p_T$ physics group coordinator. They have a substantial contribution to the works presented in this thesis and helped moving things forward even in hard and stressful times, it was a pleasure to work with them. I thank Austin Baty for his contributions in track reconstruction, and also for memories in CMS center during various data takings. It was a nice experience to share my office with Jing Wang and Ta-wei Wang who were ready to help calmly. I saw the onboarding of new students: Zhaozhong, Michael, Gwang-jun, Molly, Tzu-An, and our former undergrad Anthony. I hope they will keep things interesting or make even better.

I appreciate the assistance from my senior colleagues in CMS heavy ion group including Yetkin, Matt, Marta, Inna, Émilien, and Maxime. I consulted their expertise in various items of the experiment.

I enjoyed fruitful discussions with theorists in the field, especially during conferences and workshops. In particular, exchanges with Yang-Ting, Dani, and Xin-Nian clarified to me a lot of things about theoretical models.

I thank my friends, their presence made the whole process a bit smoother.

Above all, there is no need to express my gratitude for my parents who were always there and always supported me in doing what I find valuable.
Preface

The work in this thesis aims to extract hot QCD medium properties by comparing measurements of high energy parton showers in PbPb collisions to those in pp collisions. High energy partons are tagged with vector bosons (Z bosons and photons) which traverse QCD medium unmodified, providing event samples with no selection bias. Therefore, interactions between partons and QCD medium can be measured directly by using vector boson tags. The measurements covered in this thesis are

- Jet quenching using Z-tagged jets, published in Ref. [1] and presented in Ch. 6
- Modification of jet fragmentation functions using photon-tagged jets, published in Ref. [2] and presented in Ch. 7
- Modification of jet radial momentum density profile using photon-tagged jets, published in Ref. [3] and presented in Ch. 8
- Studies of parton-medium interactions using Z+hadron correlations, preliminary results in Ref. [4] (journal publication to follow the submission of this thesis) and presented in Ch. 9

All measurements used data recorded by the CMS experiment at a nucleon-nucleon center-of-mass energy of \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \) during the LHC Run 2 at CERN. Apart from the measurements, the author’s contribution to the CMS experiment include the development of photon triggers for PbPb collisions (see Sec. 4.2.1) and the modification of photon reconstruction for PbPb data (see Sec. 5.3.2). In addition to the experimental work, nucleus collisions were studied using event generators. A subset of those studies can be found in Ref. [5] and some of the results are presented in Sec. 10.1.
An overview of the thesis is as follows.

Ch. 1 introduces the strong interaction, gives a brief history of its theory, the Quantum chromodynamics (QCD). Sec. 1.2 moves on to systems governed by the strong interaction, i.e. QCD matter, and introduces its phases. Collisions of heavy nuclei (heavy ion collisions) are proposed as an experimental method to create and study a hot QCD medium, in particular the quark-gluon plasma (QGP), a system of deconfined quarks and gluons. Sec. 1.3 describes configuration, geometry and kinematics in heavy ion collisions. Sec. 1.4 and 1.5 review the results from previous RHIC and LHC experiments. The chapter closes with Sec. 1.6 listing the goals of this thesis, specifically what questions it will address and how it will contribute to the understanding of hot QCD medium.

Ch. 2 overviews theory of the processes relevant to this thesis, such as jets and parton-medium interactions. Sec. 2.1 introduces jets (a spray of particles originating from parton showers), Sec. 2.2 lists properties of photon+jet and Z+jet processes and introduces the observables measured in this thesis. Sec. 2.3 reviews the theoretical modelling of parton showers in QCD medium.

Ch. 3 introduces the experiment apparatus, the CMS detector at the LHC, CERN. It briefly describes the subdetectors utilized in this thesis.

Ch. 4 explains how collision events are selected for analysis, in particular how the trigger systems work and how events are classified. Later on, Sec. 4.6 describes the simulation software that is employed to test the analysis methods.

Ch. 5 describes the reconstruction of physics objects, in particular photons, Z bosons as lepton pairs, jets, and charged particles.

Ch. 6, Ch. 7, Ch. 8, and Ch. 9 present the measurements performed in this thesis. Specifically, those chapters first introduce the analyzed samples and the observables. Then they describe, evaluate and validate the experimental analysis methods, and examine the uncertainties. Finally, the chapters present and discuss the results, compare them to theoretical models, and conclude with a summary of the learnings.

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Chapter 1

Introduction

There are four known, fundamental interactions in the universe: gravity, electromagnetism, the weak interaction, and the strong interaction.

Most of the earthly processes, be they natural or artificial, are governed by the electromagnetic interaction and gravity. All electronic and mechanical devices harness electromagnetism. Motion of our muscles are generated by electromagnetic interactions. All chemical and biological processes are actually reconfigurations of electromagnetic bound states between atoms.

The strong interaction is the underlying mechanism for the formation of atomic nuclei. It is responsible for some radioactive decays and plays a role in nuclear power production and nuclear weapons where weak interactions modify states bound by the strong interactions. Although the strong interaction does not appear in such a multitude of earthly processes as electromagnetic interaction does, the sunlight that powers life on Earth is produced at the Sun’s core via nuclear fusion, a process involving electromagnetic, weak, strong interactions resulting in modification of states bound by the strong interaction. Besides, most of the atomic nuclei on Earth also were created via fusion, as lighter nuclei at the core of stars merge under extreme conditions realized by the high gravitational pressure of the surrounding matter.

Interactions between elementary particles are described by the quantum field theory (QFT) framework developed in the 20th century [6][7]. Quantum electrodynamics (QED) is the theory of electromagnetism describing the interactions between fermions
and photons. The dynamic part of the QED Lagrangian is given by

\[ \mathcal{L}_{\text{QED}} = g \bar{\psi} (\gamma^\mu A_\mu) \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]  (1.1)

where the first term describes the interaction between fermions and photons, and the second term contains the electromagnetic field dynamics. The only direct interaction (coupling) is between fermions and QED gauge fields, i.e. photons, whose diagram is shown in Fig. 1-1.

Quantum chromodynamics (QCD) is the theory of strong interaction. Quarks and gluons are the elementary particles that undergo strong interaction and the interaction is formulated using the QCD Lagrangian

\[ \mathcal{L}_{\text{QCD}} = \frac{g_s}{2} \bar{\psi} (\gamma^\mu A_\mu) \lambda \psi - \frac{1}{4} G^\rho_{\mu\nu} G^\mu\nu \]  (1.2)

where the first term describes couplings between quarks and gluons, and the second term describes the self-coupling of gluon fields. Feynman diagrams for quark-gluon coupling and gluon self-coupling are shown in Fig. 1-2. Fundamental interactions in QCD are more complex compared to QED in the sense that gluons (QCD gauge fields) couple to themselves while there is no self-coupling for photons. The self-coupling of gluons is a result of QCD being a gauge theory with symmetry group SU(3) [8].
1.1 Brief history of QCD

Historically, the discovery of the fundamental electromagnetic interactions preceded that of the associated particles. Already in ancient times, humans were able to observe electromagnetic interaction via naturally magnetized materials. However, it was not until the 19th century that electricity and magnetism were combined in Maxwell’s equations [9] that fully described the electromagnetic interaction. Later on it was understood that light, i.e. the photon, was the propagator of the electromagnetism [10] and although charge carriers were proposed previously to explain the attraction and repulsion between rubbed objects, it was at the end of the century that electron was unquestionably discovered [11].

In the case of the strong interaction, discoveries happened in the opposite order compared to electromagnetism. The theory of the strong interaction followed the discovery of particles interacting via the strong force. In 1911, Rutherford pointed out that most of the mass of an atom was concentrated at its center and that center had a large positive charge [12]. Experiments within the following decade revealed that heavier nuclei contained several hydrogen nuclei, naming the hydrogen nucleus as proton, believed to be a fundamental particle at the time. The discovery of the neutron in 1932 [13] removed the puzzle about the nucleus composition, but opened up new questions about the mechanism that binds the neutrons and protons inside the nucleus by overcoming the electromagnetic repulsion between positively charged protons.
In 1935, Yukawa formulated an interaction which turned to be quite successful to describe the “strong nuclear” force between protons and neutrons \[14\]. The strength of that interaction would be proportional to the inverse of distance, as in electromagnetism, however it would also decay exponentially with the distance such that the force would be effective only at the length scales of atomic nucleus. This exponential modulation was requiring that the interaction between protons and neutrons is mediated by the exchange of a boson with a mass on the order of 100 MeV/c². This middle-weight particle called “meson” was discovered \[15\] about a decade later, and today it is known as the pion.

A multitude of other strongly interaction particles, called hadrons, were observed in 1950s and 1960s. It did not seem convincing that all of these particles are fundamental. In addition, it looked like some group of particles were very similar in some properties, than another group of particles. For example, all three pion species had a mass around 135 MeV/c² and all four kaon species had a mass around 490 MeV/c². Besides these particles were much lighter than protons and neutrons whose masses are very close and approximately 1 GeV/c². In 1961, Gell-Mann and Ne’eman proposed a model that organizes hadrons into unitary groups \[16, 17\], the eightfold way as Gell-Mann called it. The model’s success was established when one of its predictions, a hadron with strangeness magnitude 3, the Ω baryon was discovered in 1964 \[18\].

Another important development in 1964 happened when quarks were proposed as mathematical devices to model the strong interaction \[19, 20, 21\]. In the mid 20th century, QCD developed as efforts to interpret the unexpectedly large number of observed hadrons and understand their underlying structure. As of today, hadrons are understood as composite objects made of partons, i.e. quarks and gluons.

Existence of quarks and that protons actually have structure were verified in 1969 by deep inelastic scattering (DIS) experiments \[22, 23\]. About a decade later, three-jet events in $e^+e^-$ collisions provided the first evidence for existence of gluons \[24\]. Meanwhile, 1970s was the period of crucial developments about the formulation of strong interaction and its nature. Each quark and gluon had an associated “color charge”, however the color confinement property \[25\] stated that an isolated parti-
cle with a net color charge cannot exist and no violation of this property has been observed. Asymptotic freedom [26, 27] showed that the strong interaction become weaker (coupling strength become smaller) as the transferred momentum becomes larger and this was verified by cross section measurements [28]. Strong coupling constant $\alpha_s$ has been measured in various experiments operating at different momentum transfers and its evolution as function of momentum transfer $Q$ is shown in Fig. 1-3 verifying the interactions’ asymptotically free nature.

![Figure 1-3: Measurements of strong coupling constant $\alpha_s$ as function of energy scale $Q$. Figure taken from Ref. [29].](image)

1.2 Macroscopic QCD systems

Experimental results have confirmed the QCD’s description of strong interaction between elementary particles. On the other hand, a precise understanding of fundamental interactions is not necessarily sufficient for a precise description of a
macroscopic system. Calculations describing the system get more complicated as the number of particles increase. The dynamics of hydrogen atom, a system of an electron and a proton, is governed by QED and can be calculated analytically, but analytic calculations become increasingly difficult for systems with more than one electron.

Atomic matter is a system of atoms (or molecules) and can be regarded as “QED matter” since atoms predominantly interact via electromagnetic force. Today, properties of atomic matter are studied in a wide range of disciplines. There are many phenomena whose mathematical description might be so complex or simply not self-evident that their existence was not inferred from fundamental interactions and can be recognized only after experimental observations. For example, superconductivity was observed experimentally in 1910s, but explained about four decades later [30]. Thus, experiments are crucial for the understanding of atomic and molecular phenomena arising from fundamental electromagnetic interactions. Presumably, experimental studies are much more vital to understand the systems governed by strong force where fundamental interactions are much more difficult to calculate than in electromagnetic force.

QCD matter is a system of particles whose interactions are governed by the strong force. QCD matter has different phases as shown in Fig. 1-4. Ordinary QCD matter is made of hadrons, i.e. a hadronic phase. An extreme phase is quark-gluon plasma (QGP), a system of deconfined quarks and gluons [31, 32, 33]. Due to color confinement and asymptotic freedom features, quarks can be liberated from hadrons only under extreme conditions, e.g. very high temperatures or very high particle densities, and thus form a QGP. Lattice QCD (LQCD) calculations predict that temperatures of $T \sim 150 \text{ MeV} \ (\sim 1.7 \times 10^{12} \text{ Kelvin})$ are needed for a phase transition into QGP [34, 35, 36]. It is thought that these extreme conditions arise naturally only rarely in the universe, even the temperatures at the core of supernovae are not high enough. Sufficiently high temperatures for QGP were prevalent everywhere in the universe for its first microsecond [37, 38, 39]. Concerning the observable universe, the high gravitational pressure at the core of neutron stars can give rise to densities high enough (corresponding to chemical potential of $\mu_B \gtrsim 1 \text{ GeV}$) to form
a cold dense quark matter \cite{37, 40, 41}. Recent observation of binary neutron star mergers \cite{42} prompted ideas to extract cold dense quark matter properties from gravitational wave detections \cite{43}. On the other hand, experimental studies of hot QGP phase of QCD matter are, as of today, performed in hadron colliders.

![Figure 1-4: Phases of QCD](image)

Figure 1-4: Phases of QCD is illustrated as functions of temperature and baryon chemical potential. Figure taken from Ref. \cite{44}.

### 1.2.1 Understanding QCD matter

The structure in the universe is dictated by the scale of fundamental interactions and their balance. At the largest length scale, the systems of galaxies, stars, and planets are governed by gravity where interaction strength scales with the mass. The structure we see around us on the meter to kilometer scale is governed by an
interplay between gravity and the electromagnetic interaction, e.g. Earth is held together by gravity, segmented into layers with varying density, and life (from cells to plants and animals) evolves on Earth’s surface, made of biological processes which are essentially electromagnetic interactions. The next largest structure not governed by gravity would be atoms and molecules, states bound by the electromagnetic force. Finally, the smallest structure (as far as we know today) would be hadrons made up of quarks and gluons. The weak force (assuming that it is not considered as part of electroweak interaction) does not have an associated structure as weakly interacting particles are not observed to have a bound state. Furthermore, it is the competition between fundamental interactions that give rise to phenomena with large impact on the universe’s structure, e.g. it is the balance between the strong force and gravity that makes a star shine, and imbalance makes it explode or collapse into a black hole.

Given the role of the strong interaction in the universe, understanding QCD matter is foremost a quest driven by curiosity about nature. Moreover, mankind’s technology is built upon knowledge obtained by studies of nature, e.g. all electronics devices harness an understanding of electromagnetism. Information obtained from QCD matter studies can also serve technology applications of the future when they are advanced enough to exploit the knowledge about QCD matter. Finally, while the complexity of its fundamental interactions poses challenges for the description of QCD matter, experimental studies will reveal the phenomena arising in such matter. Consequently, QCD matter observations can be unique training ground to understand or predict the phenomena arising in other real or hypothetical systems governed by complex interactions.

1.2.2 Hot QCD matter

In late 1970s, it was proposed that the matter emerging from a collision of heavy nuclei would have very high energy densities and be composed of deconfined quarks and gluons, a QGP \[31, 32, 33\]. With the current technology, the heavy ion (HI) collisions are in fact the only tool to liberate quarks from hadrons and create QGP. Through the 1970s, 1980s and 1990s, QGP was assumed to be a gas-like plasma
consisting of well-defined quark and gluon quasiparticles travelling between discrete scattering events at which they bump into each other \cite{13}. This picture of QGP did not agree with what was seen later in the RHIC experiments (see Sec. 1.4).

First research program involving HI collisions was conducted at the Bevalac facility at the Lawrence Berkeley National Laboratory (LBL) in the 1970s. This was followed by programs in the Alternating Gradient Synchrotron (AGS) located at the Brookhaven National Laboratory (BNL) and Super Proton Synchrotron (SPS) at CERN which operated from 1987 until late 1990s \cite{16}. Collisions in these accelerator facilities were achieved by smashing nuclei on a static target, dubbed as “fixed-target collisions”, and nucleon-nucleon center-of-mass energies, $\sqrt{s_{NN}}$, ranged from 2 GeV at the Bevalac to 17 GeV at the SPS. In 2000s, the Relativistic Heavy Ion Collider (RHIC) \cite{17} at BNL provided order of magnitude higher collision energies ($\sqrt{s_{NN}} = 130$ GeV and $\sqrt{s_{NN}} = 200$ GeV). Later on, the Large Hadron Collider (LHC) \cite{18} at CERN delivered HI collisions at even higher energies ($\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV), creating higher temperature QCD matter. It was the RHIC experiments whose results provided the first compelling evidence for the creation of deconfined phase of QCD matter (see Sec. 1.4). The LHC experiments observed the same phenomena as in RHIC, and quantified the matter’s properties with an improved precision (see Sec. 1.5).

\subsection*{1.2.3 How to study QGP}

HI collisions are currently the method to create QGP, as noted in the preceding section (Sec. 1.2.2). One approach to study matter is to send a probe with well-known properties and measure the probe after its interaction with the matter. A common example is spectroscopy from condensed matter studies where properties of a matter is inferred by exposing it to light and studying how it modifies the incident light. Another example is diffraction of X-rays revealing a material’s crystal structure. This approach could in principle be carried to QCD matter where one would send a well-controlled particle, e.g. a proton, to the matter and see how it is modified. This is very challenging as the matter created in HI collisions disappears very quickly,
at time scales of $\sim 10 \text{ fm/c}$, and unfortunately, today’s technology is not precise enough to synchronize the probes within such short time scales. On the other hand, hard scattering processes occasionally occur in HI collisions producing high energy particles, e.g. partons, which can serve as probes. These “hard” probes penetrate through and interact with the QCD matter produced in HI collisions, i.e. “QCD medium”, and their modification provides information about the dynamics of QCD medium.

One distinct prospect of hard probes (high energy particles) is that they can explore short length scales and reveal microscopic structure of QCD medium, in analogy to Rutherford experiments where high energy alpha particles revealed the structure of atom [12] or DIS experiments where high energy electrons demonstrated that protons have internal structure [22, 23].

This thesis is composed of measurements which aim to reveal the dynamics of QCD medium by measuring its interactions with high energy partons.

\section*{1.3 Heavy ion collisions}

\subsection*{1.3.1 Collision geometry and kinematic variables}

Understanding the configuration of HI collisions is instructive for the discussion in subsequent sections. The geometry of a HI collision is illustrated in Fig. 1-5. Incident nuclei travel along the $z$-axis (beam axis) and pass through each other at the origin of the coordinate system. The $x-y$ plane is transverse to the collision axis. The radial coordinate $r$ is the distance from the $z$-axis. The azimuthal angle $\phi$ is measured starting from the $x$-axis in the $x-y$ plane. The polar angle $\theta$ is measured starting from the $z$-axis.

Kinematic variables for a particle emerging from the collision can be listed as follows. The momentum vector is $\vec{p} = (p_x, p_y, p_z)$ where $p_x, p_y$ and $p_z$ are the momentum in the $x, y$ and $z$ directions, respectively. Magnitude of the momentum is $p = |\vec{p}| = \sqrt{p_x^2 + p_y^2 + p_z^2}$. The transverse momentum $p_T = \sqrt{p_x^2 + p_y^2}$.
is the component of the momentum in the $x - y$ plane. The four-momentum is $\mathbf{P} = (E/c, p_x, p_y, p_z)$ where $E$ is the energy of the particle and $c$ is the speed of light, respectively. The mass $m$ of the particle is related to its energy and momentum via $E^2 = m^2c^4 + p^2c^2$. The particle momentum can be related to its angular coordinates as follows. The polar angle is given as $\theta = \cos^{-1}(p_z/p)$ and the azimuthal angle is $\phi = \tan^{-1}(p_y/p_x)$. Furthermore, rapidity is defined as $y = \frac{1}{2} \ln \left( \frac{E+c p_z}{E-c p_z} \right)$ and pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. The rapidity of a massless particle is the same as its pseudorapidity. Unless specified otherwise, the subsequent discussion will use the coordinate system and kinematic variables introduced above.

Figure 1-5: Geometry of a HI collision in the plane orthogonal to the particle beams. Nuclei travel and collide along the $z$-axis. The reaction plane angle $\psi_R$ is the azimuthal angle $\phi$ for the impact parameter vector $b$ which connects the nuclei centers in the $x - y$ plane. Figure taken from Ref. [49].

The shape of the collision region can be azimuthally anisotropic and several quantities are defined to characterize the initial configuration of a collision. The impact parameter $b$ is the distance between the centers of the nuclei in the $x - y$ plane. The number of participants, $N_{\text{part}}$, is the number of nucleons that collide with at
least another nucleon. The number of binary collisions, $N_{\text{coll}}$, is the total number of colliding nucleon pairs. If there are 3 nucleons from the right-going nucleus and 5 nucleons from the left-going nucleus that undergo a collision, then $N_{\text{part}} = 8$ and $5 \leq N_{\text{coll}} \leq 15$. While there is no direct way to experimentally measure $N_{\text{part}}$ and $N_{\text{coll}}$, they can be related to the impact parameter $b$ and inelastic nucleon-nucleon cross section via a Glauber model \[50, 51\].

A collision is "central" if the impact parameter is small (a large overlap region), or "peripheral", if the impact parameter is large (a small overlap region). On the other hand, impact parameter is not directly accessible in collider experiments. The "centrality" of a collision can be inferred using the total energy of the produced particles following the assumption that the total produced energy increases monotonically with decreasing impact parameter. The 5% most central collisions are those collisions which make up the 5th percentile of the total energy per event distribution (see Sec. 4.5 for centrality determination in the CMS experiment). In AA collisions ("A" means nucleus larger than hydrogen), the increase of $N_{\text{coll}}$ with centrality is much faster than that of $N_{\text{part}}$.

1.3.2 Collision evolution

Typical $\sqrt{s_{NN}}$ are 200 GeV at RHIC and 5.02 TeV at LHC. Given that nucleon mass is about 1 GeV, the Lorentz contraction factor $\gamma$ along the collision axis are typically $\gamma_{\text{RHIC}} \approx 100$ and $\gamma_{\text{LHC}} \approx 2500$ for RHIC and LHC, respectively. Hence, in the lab frame, a colliding nucleus is so much contracted that it looks like a disc, instead of a sphere. Typical nucleus species are $^{196}\text{Au}$ (gold) at RHIC and $^{208}\text{Pb}$ (lead) at the LHC, they are "heavy" as they have a large number of nucleons and they are "ions" as they are made by removing all the electrons from the corresponding atoms. From the empirical formula of $R \approx 1.2 \ A^{1/3} \ \text{fm}$ one gets that the radius of the colliding "disks" are $R_{\text{RHIC}} \approx 7 \ \text{fm}$ and $R_{\text{LHC}} \approx 7.1 \ \text{fm}$.

The collision of two nuclei, can be pictured as a set of interactions, happening around $t = 0$, the time in the lab frame when the nuclei coincided at $z = 0$. Most interactions are small momentum transfer processes with small angle scatterings and
the nuclei pass through each other without falling apart creating a debris of color fields between them. Interactions with larger momentum transfers (hard scattering processes as they will be introduced in Sec. 1.4.2) proceed in shorter time scales, but occur much less frequently. A “debris” of fields and particles emerges in the space between the nuclei and this debris expands along the $z$-axis filling the space between receding nuclei. Assuming that QCD medium can form only after the nuclei pass through each other, one gets a lower bound on the formation time as $c \tau_{\text{form}} > c \tau_{\text{overlap}} = 2R/\gamma$ \cite{52}.

The energy density in the rest frame of one nucleus is $\epsilon_{\text{rest}} = \frac{m^2 c^2}{(4/3\pi R^3)} \approx 0.14 \text{ GeV/fm}^3$. Energy density in the lab frame at $t = 0$ will be $\epsilon_0 = 2 \gamma^2 \epsilon_{\text{rest}}$ where the factor of 2 counts the two nuclei in the same position and the factor of $\gamma^2$ accounts for energy in the lab frame and the Lorentz contraction along $z$-axis. Using the typical $\gamma$ values at RHIC and LHC gives $\epsilon_{0,\text{RHIC}} \approx 2800 \text{ GeV/fm}^3$ and $\epsilon_{0,\text{LHC}} \approx 1.75 \times 10^6 \text{ GeV/fm}^3$. These are extremely high energy densities values, they will last no longer than $2R/(\gamma c)$, the time for nuclei to cross each other. These energy densities during the overlap of nuclei are not of interest as they are not directly related to the matter produced in the collision. The energy density of the matter produced in the collision will be much smaller, as energy is released over a longer time interval, thus over a larger volume.

The energy density $\epsilon$ of the produced matter can be related to its formation time $\tau_{\text{form}}$ and the total measured energy as described in Ref. \cite{52}

$$\epsilon = \frac{1}{A \tau_{\text{form}}} \frac{dE_T}{dy} \quad (1.3)$$

where $A$ is the area of overlap and $E_T$ is the transverse energy. The most central PbPb collisions at the LHC show that $\epsilon \tau_{\text{form}} \sim 10 \text{ GeV/fm}^2 c$ \cite{53, 54}, where $\tau_{\text{form}}$ is a model dependent quantity and as of today cannot be measured experimentally.
1.3.3 Picture before experiments

Before the RHIC experiments, some properties of the matter produced in such high energy HI collisions were predicted. For example, this matter would be composed of deconfined quarks and gluons, have very high energy densities and temperature, as these properties are directly related to the colliding system and its energy. On the other hand, the dynamics of the matter was not clear.

Theoretical calculations attempted to infer the matter’s dynamics using a thermodynamic description. The Stefan-Boltzmann limit relates the pressure $p_{SB}$ and temperature $T$ for a gas of non-interacting gluons and massless quarks at zero net quark density and in thermal equilibrium [55]

$$\frac{p_{SB}}{T^4} = \left[ 2 (N_c^2 - 1) + \frac{7}{2} N_c N_f \right] \frac{\pi^2}{90} \quad (1.4)$$

where $N_c$ ($N_f$) is the color (quark flavor) degrees of freedom and $\hbar = c = 1$. Fig. 1-6 shows LQCD calculations for the temperature dependence of pressure, energy density, and entropy density and compares them to the Stefan-Boltzmann limit. A rapid but continuous increase in pressure and energy density sets on as temperature reaches and goes above $T_c$ indicating that a crossover happens around $T_c$ and a phase with quark and gluon degrees of freedom emerges.

LQCD calculations showed that at temperatures several times larger than the transition temperature, the energy density of the system saturates at about 80% that of a non-interacting gas [56]. So it was predicted that the system of deconfined quarks and gluons would be interacting, however, it was not clear whether interactions would be weak or strong. A widely shared prediction was that the matter at RHIC would be weakly coupled as its equation of state (EoS), i.e. its energy/momentum relation, was calculated to deviate from the ideal gas behavior by a not large (10–20%) fraction [57]. Ultimately, RHIC results showed that the matter is strongly interacting even if its EoS deviates from the ideal gas only by a small fraction.
1.4 The RHIC experiments

RHIC experiments started in 2000, delivering nucleus collisions with $\sqrt{s_{NN}}$ up to 200 GeV. A multitude of measurements explored the properties of the matter produced in AuAu collisions and searched for the signatures of a QCD phase transition. Specifically, macroscopic properties such as energy and number density, thermalization, critical behavior, and phase transition, as well as QCD phenomena such as hadronization processes and signs of deconfinement were investigated. Moreover, the higher collision energies at RHIC opened up the phase space for high energy particles (see Sec. 1.4.2) making them accessible for HI collision studies. Secs. 1.4 and 1.5 provide an overview of results from RHIC and LHC experiments, respectively, and what is learned from those experiments.

The experimental results during the first four years of running [58, 45, 59, 60] show that the matter produced at RHIC

- has large energy densities
• is strongly coupled
• behaves hydrodynamically and flows like a liquid
• reaches local thermalization very quickly
• follows a crossover instead of a first order phase transition
• is hard to describe with hadron degrees of freedom
• consistent with a system of deconfined quarks and gluons

Perhaps, the most fundamental finding at RHIC was that the produced matter is very dense and strongly coupled. There were two important observations that supported this finding:

1. Elliptic flow

2. Suppression of high energy particles

1.4.1 Elliptic flow

Relativistic hydrodynamics has been one of the frameworks used to describe the matter produced in HI collisions. A hydrodynamic description, by definition, requires that the system is in local equilibrium and equilibrium state is reached following the interaction of particles. Flow, a collective motion of particles, is a phenomenon arising from particle interactions. Therefore, observation of flow in HI collisions is evidence for interacting matter. Random thermal motion would result in isotropic transverse momentum distributions. If collision geometry is azimuthally anisotropic, and if the system behaves hydrodynamically, then pressure gradients turn the azimuthal anisotropy into anisotropies in transverse momentum distributions. Anisotropy has been proposed as a signature of flow $[61]$ via its relation to the transverse ($\phi$-direction) component of flow. Besides, transverse flow is a more precise tool for theoretical studies than the longitudinal ($z$-direction) flow as the latter is very sensitive to initial conditions $[62]$. 
The azimuthal angle distribution of particles can be expressed as

\[
\frac{dN}{d\phi} \propto \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos [n(\phi - \Psi)] \right)
\]

(1.5)

where \(\Psi\) is the experimentally determined azimuthal angle of maximum particle density and \(v_n\) is the \(n^{th}\) Fourier coefficient \[49\]. The magnitude of \(v_2\) is referred to as the “elliptic” flow.

The geometry of a collision can be azimuthally anisotropic, as illustrated in Fig. 1-5. However, this does not necessarily mean that the produced particles will follow a similar anisotropy. The spatial anisotropy will fade away as the system expands irrespective of whether the system behaves hydrodynamically or not, whereas the spatial anisotropy converts into momentum anisotropy if the system behaves hydrodynamically.

The elliptic flow at RHIC \[63, 64, 65, 66, 67\] was found to be so large that its description requires a strongly coupled system, in particular a system that behaves like a relativistic fluid \[68\]. The proportionality of the elliptic flow to eccentricity (a measure of spatial anisotropy in collision geometry) \[64\] provided direct evidence that flow signal is related to spatial anisotropy. Fig. 1-7 compares the elliptic flow measurements at RHIC with a hydrodynamic calculation. Calculations \[69, 70, 71, 72\] showed that elliptic flow arises from azimuthally anisotropic pressure gradients. Furthermore, the elliptic flow signal will be smaller if interactions start later in the system evolution \[73\]. The large signal in data indicates that local thermalization must be reached very quickly, at times earlier than \(t \sim R/c\), the time scale over which the initial spatial anisotropy would disappear if particles stream freely in random directions without any interaction. Most hydrodynamics models extracted thermalization times of \(\tau_{\text{thermal}} \approx 0.6 - 1 \text{ fm}/c\) \[74, 72, 71, 70\] from RHIC data.

The shear viscosity \(\eta\) dissipates spatial gradients into heat, random thermal motion, reducing momentum anisotropy \[39\]. Viscous hydrodynamics fits to data yielded very small values for the ratio of shear viscosity over entropy density \((\eta/s \gtrsim 1/4\pi)\) suggesting an almost perfect fluid where momentum anisotropies persisted \[75\]. The
elliptic flow in data was consistent with, or at least very close to, the hydrodynamics
description of an ideal relativistic fluid, implying that interactions in the early stages
have very short mean free paths, thus a very dense system was formed in the early
stages.

Figure 1-7: The $v_2$ versus $p_T$ for inclusive and identified hadrons in PHENIX and
STAR experiments are compared to a hydrodynamic calculation. Figure taken from
Ref [65].

1.4.2 Suppression of high energy particles

The majority of high energy particles produced in hadron collisions are remnants
of processes where partons from different hadrons scatter off each other imparting
large momentums to outgoing particles. Since these “hard” processes involve large
momentum transfers, they can be calculated via perturbative QCD (pQCD).

One advantage of the high collision energies at RHIC was to give access to hard
scattering processes that produce high energy particles. For $\sqrt{s_{NN}} \sim 100$ GeV, most
particles with $p_T > 2$ GeV/c in mid-rapidity region originate from hard scattering
processes [60]. High energy partons produced in hard scattering processes can probe
the complete evolution of QGP, as they form earlier than low energy partons which
make up most of QGP.
A multitude of models had predicted that high energy partons would lose energy as they traverse the QCD medium, the first such prediction was given in Ref. \cite{76}. Radiative energy loss (illustrated in Fig. 2-25) and collisional energy loss (illustrated in Fig. 2-26) were the most common energy loss mechanisms \cite{77, 78, 79, 80, 81, 82, 83, 84} where radiative processes are generally found to cause larger energy loss than collisional processes \cite{83}. Later on, energy loss in strongly coupled plasma was also studied via gauge/gravity duality as described in Refs. \cite{86, 87, 88, 89, 90}.

Nuclear modification factor, $R_{AB}$, is a common observable to quantify how the particle spectrum in collisions of nuclei A and B are modified with respect to the pp collisions. The $R_{AB}$ is defined as

$$R_{AB} = \frac{dN_{AB}}{\langle T_{AB} \rangle d\sigma_{pp}} = \frac{dN_{AB}}{\langle N_{coll} \rangle dN_{pp}}$$

(1.6)

where $N_{AB}$ ($N_{pp}$) are the number of particles produced in AB (pp) collisions and $\sigma_{pp}$ is the cross section in pp collisions. The average number of binary collisions in the AB system, $\langle N_{coll} \rangle$, scales the $N_{AB}$ down to the number of particles produced per nucleon-nucleon collision. The $T_{AB} = \langle N_{coll} \rangle / \sigma_{pp}$ is the nuclear overlap function that can be calculated from Glauber model \cite{51}. The observable notation can change to adopt to nucleus species, e.g. $R_{AA}$ for AA collisions, $R_{pA}$ for proton+A (pA), or $R_{dA}$ for deuteron+A (dA) collisions.

The $R_{AA}$ results at RHIC demonstrated, for the first time, a large suppression ($R_{AA}$ smaller than 1) of high energy particles at collisions energies of $\sqrt{s_{NN}} \sim 100$ GeV (Refs. \cite{91, 92, 93} for $\sqrt{s_{NN}} = 130$ GeV and Refs. \cite{94, 95, 96, 97} for $\sqrt{s_{NN}} = 200$ GeV). No significant parton energy loss effects were seen before at SPS for collision energies of $\sqrt{s_{NN}} \approx 17$ GeV \cite{98, 99}, and later results from RHIC Beam Energy Scan (BES) showed that suppression of high energy particles disappears for $\sqrt{s_{NN}} \lesssim 40$ GeV \cite{100}. This modification could originate from QGP effects as well as from effects independent of QGP formation.

Effects causing differences between pp and HI collisions independent of QGP formation are broadly referred to as cold nuclear matter (CNM) effects which are present
before QGP formation, i.e. at the “initial state” of the collision. First of all, parton distribution functions (PDFs) for free nucleons are different than nuclear PDFs (nPDFs), i.e. PDFs for nucleons in nuclei. Thus, hard scattering processes in pp and HI collisions are not initiated with identical parton distributions. Second, different than in pp collisions, partons in HI collisions penetrate multiple nuclei, thus they can suffer energy loss or undergo multiple scattering before initiating hard scattering processes. These effects can cause differences between the production of high energy particles in pp and HI collisions. Details about CNM effects can be found in Sec. 2.5.

No (or very small) QCD medium is expected to form in collisions of light and heavy nuclei, e.g. p+A or d+A collisions. Though, CNM effects in those collisions are expected to be very similar to those in collisions of heavy nuclei, e.g. AA collisions. The lack of a significant modification for high energy particles in dA collisions [101, 102, 103, 104] clearly showed that the suppression seen in AA collisions is largely due to QCD medium effects, not CNM effects.

Another test of QCD medium effects came from measurements of photons that do not arise from decays of hadrons, i.e. “direct” photons. Since photons pass through QCD medium undisturbed, direct photons can provide constraining information about the contribution of CNM and QCD medium effects to the suppression of high energy particles. While low energy photons have contributions from “thermal” photons, i.e. photons radiated by QCD medium, high energy photons at RHIC are produced dominantly via hard scattering processes, particularly the QCD Compton scattering process (see Fig. 2-7). RHIC experiments measured [105, 106] direct photons with $p_T \gtrsim 5$ GeV, a range where the thermal photon contribution is very small, showing that the photon $R_{AA}$ is consistent with 1 modulo $\sim 10\%$ deviations that can be attributed to CNM effects. In addition, as will be discussed in Sec. 1.5, LHC experiments measured production of photons as well as Z bosons and W bosons finding no significant modification in PbPb collisions beyond what is expected from CNM effects. These provided additional evidence that the observed suppression of high energy hadrons is dominantly a QCD medium effect.

Fig. 1-8 shows the $R_{AA}$ for charged hadrons, the $R_{dA}$ for charged hadrons and
neutral pions at $\sqrt{s_{NN}} = 200$ GeV. Charged hadrons in dA collisions are suppressed for $p_T \lesssim 2$ GeV/$c$ and enhanced ($R_{dA}$ larger than 1) for $p_T \gtrsim 2$ GeV/$c$. This modification is interpreted to originate from a CNM effect, the “Cronin effect” [107], where particle production is modified, because partons from the lighter nucleus undergo multiple scatterings with the heavy nucleus before initiating a hard scattering. The $R_{dA}$ for neutral pions with $p_T \gtrsim 2$ GeV/$c$ is not as large as that for charged hadrons, this could be due that different hadron species are affected differently by the Cronin effect. More about the Cronin effect can be found in Sec. 2.5.2. The $R_{AA}$ for charged particles in central collisions is suppressed (smaller than 1) for the whole ($p_T \gtrsim 0.4$ GeV/$c$) range and the $R_{AA}$ for $p_T > 5$ GeV/$c$ can be as small as 0.2 (a suppression factor of 5). These observations in $p_T$ spectrum was interpreted [108, 109] as parton energy loss in dense QCD medium. Models can describe the high $p_T$ suppression using a QCD medium with large gluon densities [58]. For instance, the GLV model [108] extracted a gluon density of $dN_g/dy \sim 1000$. An interesting feature of the RHIC results is that the $R_{AA}$, is almost constant at $\sim 0.2$ for $p_T \gtrsim 5$ GeV/$c$. A very simplistic energy loss model is presented in Sec. 2.3.3, where one of the assumptions is that the $R_{AA}$ is constant as function of $p_T$.

Another approach to study parton energy loss was to analyze the correlation of particles originating from the same hard scattering. Hard scattering processes usually produce a pair of partons that propagate back to back in azimuthal coordinates, i.e. the difference of their azimuthal angles, $\Delta \phi$, is usually $\pi$. Both of the partons and their subsequent showers are expected to lose energy in QCD medium, but one of the parton showers will lose relatively more energy than the other (see Ch. 2 for parton showers). Thus, back-to-back parton showers would be more imbalanced in QCD medium than in vacuum. Fig. 1-9 shows one of the two-particle azimuthal angle correlation measurements at RHIC. A large suppression was observed for particles recoiling from the trigger particle (highest energy particle) in AuAu collisions [110, 111], on the other hand no such suppression was seen in d+Au collisions [103]. These measurements provided another evidence for parton energy loss. Besides, the peak of the angular correlations at $\Delta \phi \sim 0$ show that many other particles are produced
in association with a high energy particle. This is a confirmation that high energy particles in HI collisions are indeed produced via hard scattering processes and then undergo fragmentation, as in pp collisions \[29\].

Other studies showed that high energy trigger particles in AA collisions tend to be associated with more lower energy particles and less higher energy particles compared to those in pp collisions \[112\]. This was one of the early evidences for the softening of the parton shower in QCD medium. Besides, a broadening in two-particle angle correlations were seen \[113\], indicative of particles being radiated to larger angles or a widening of jet radial density.

The magnitude of the high $p_T$ particle suppression at RHIC was suggestive of
deconfined partonic matter, nevertheless it could not completely rule out the case for a hadronic matter, since parton energy loss can happen in hadronic matter as well, even if enormously high hadron densities are needed to produce the suppression in data.

Parton energy loss studies could make a definitive statement about deconfinement if measurements could be done at lower collision energies, where energy densities are not high enough and QCD medium is most likely hadronic. An absence of parton energy loss at lower $\sqrt{s_{NN}} \lesssim 10$ GeV would support that parton energy loss at $\sqrt{s_{NN}} \sim 100$ GeV happens in deconfined matter. On the other hand, collision energies of $\sqrt{s_{NN}} \lesssim 10$ GeV are so low that there is almost no phase space available for high $p_T$ particle production which makes the experiments extremely challenging. Therefore, parton energy loss could not be tested as a signature of deconfinement.
1.4.3 Other findings

Bulk properties

Integrated transverse energy measurements show that energy density is well above the 1 GeV/fm$^3$ range for deconfined matter [114, 115]. In fact, as seen in eq. 1.3, there is no way to extract the energy density without knowing the formation time which is a model-dependent quantity. Therefore, measurements report energy densities assuming a specific formation time (or simply as product of the two). Assuming a formation time of $\tau_{\text{form}} = 1$ fm/c, an energy density of $\epsilon \approx 5$ GeV/fm$^3$ was extracted for most central collisions at $\sqrt{s_{NN}} \sim 100$ GeV [116]. At LHC, an energy density of $\epsilon \approx 14$ GeV/fm$^3$ was extracted for the same $\tau_{\text{form}}$ value [53].

Typical values for formation time and energy density can be estimated using RHIC data. The average $E_T$ divided by average number of charged particles was found to be $\sim 0.85$ GeV [116]. Assuming that there is one neutral particle for every two charged particles gives an average particle energy of $\langle E_T \rangle \sim 0.57$ GeV [60]. Via uncertainty principle, one gets a formation time of $\tau_{\text{form}} \sim 0.35$ fm/c at RHIC, translating to an energy density of $\epsilon \sim 15$ GeV/fm$^3$, much larger than in hadronic matter. The thermalization times of $\tau_{\text{termal}} \approx 0.6 - 1$ fm/c, cited before, can serve as an upper bound for the formation time. Using $\tau_{\text{form}} < \tau_{\text{termal}} \lesssim 1$ fm/c gives $\epsilon \gtrsim 5$ GeV/fm$^3$ as a lower bound for energy density.

Phase transition

In its very early stages, the universe had very high energy densities where quarks were deconfined, as noted before in Sec. 1.2. Then it underwent a phase transition from a deconfined QCD medium to hadronic matter as energy densities decreased during its expansion. Later theoretical work investigated the impact of a QCD phase transition (PT) on the evolution of the universe [117, 118]. An interesting aspect was the order of PT. Specifically, during a first order PT, bubbles of low temperature hadronic matter would form and expand into a region surrounded by high temperature partonic matter [117, 39]. Such a PT would have enormous effect on the evolution of
universe, in particular on the nuclear matter distribution. One proposed outcome of a first order PT was distortions in synthesis of light nuclei, in particular an increased abundance of deuterium [118].

The current knowledge about the QCD PT is based on LQCD calculations. The PT order depends on the number of quarks and their masses. The PT is first order for a theory with gluons only, it becomes second order if there are 2 or 3 massless quarks. The PT changes from a second order to a smooth crossover if quarks have small, but non-zero mass [119]. Since 1990s, calculations have favored a crossover type PT rather than first order PT [120, 121, 119, 122, 123], predicted to occur at temperatures of \( T_c \sim 170\text{MeV} \) [56].

As mentioned above, energy densities extracted from RHIC data are well above the values required for deconfinement. Thus, there is evidence that energy density conditions for a PT were met at \( \sqrt{s_{NN}} \sim 100 \text{GeV} \).

For a grand canonical ensemble (a system with thermal equilibrium), particle densities can be related to the temperature and chemical potential [124, 125]. Fits performed to the ratios of identified hadrons yield a temperature of \( T_{\text{chem}} \approx 155\text{MeV} \) [126] at the “chemical freeze-out”, the point after which number of hadrons and their composition do not change. The experimentally extracted chemical freeze-out temperature, \( T_{\text{chem}} \), is close to the critical temperature, \( T_c \), obtained from LQCD calculations mentioned above. This evokes the picture that during its expansion, QCD medium cools down to temperatures around \( T_{\text{chem}} \) where it undergoes a crossover from partonic matter back to hadronic matter. Furthermore, the extracted baryon chemical potential was \( \mu_B \approx 20 \text{MeV} \) [126], a value as low as where the PT was predicted to be of crossover type (see Fig. 1-4). Nevertheless, caution must be taken for the interpretation of extracted chemical freeze-out values as the ensemble model does not account for QCD medium evolution, i.e. its expansion.

Features of a QCD PT have been explored in different studies. Imprints of the PT order could be seen in the event-by-event (EbE) fluctuations of multiplicity (number of charged particles in an event), charge densities, and momentum.

The net charge \( Q = N_+ - N_- \) over all the particles in an event is conserved to be
a constant where \( N_+ \) \( (N_-) \) are the total charge of particles with positive (negative) charge (Most charged particles have net charge of +1 or -1). Same conservation follows simply for the net charge’s variation \( \text{Var}(Q) = \text{Var}(N_+) - \text{Var}(N_-) \) over events, as shown in Ref. [60]. These identities follow simply because the \( N_+ \) and \( N_- \) have the same distribution. However, variation of the net charge in some smaller part of the phase space (e.g. a portion of angular space) is not necessarily constant. Ultimately, it is found that the net charge fluctuation data [127] does not differ significantly from the stochastic modeling of particle interactions [128].

The EbE fluctuation of the average \( p_T \) in an event was found to be consistent with what is expected from hard scattering events [129]. Besides, the suppression of high \( p_T \) hadrons was a smooth function of centrality [95], without any abrupt changes.

The RHIC results pointed to signatures of a deconfined QCD medium, that was not observed in previous experiments which operated at much smaller collision energies. On the other hand, no dramatic difference was seen in the shapes of distributions between the RHIC and previous experiments. Moreover, no abrupt changes in the measurements were seen as function of collision energy [60]. All in all, these observations do not favor a sharp PT in HI collisions and are consistent with, but does not necessarily imply that the PT is of crossover type.

The RHIC BES Phase-I increased the baryon chemical potential from \( \mu_B \sim 20 \text{ MeV} \) to \( \mu_B \sim 400 \text{ MeV} \) by lowering the collision energy \( \sqrt{s_{NN}} = 200 \text{ GeV} \) to \( \sqrt{s_{NN}} = 7.7 \text{ GeV} \) [130, 131] and looked for the fluctuations which are expected if the PT goes from crossover to first order at a second order critical point. No nonmonotonic behavior signifying a first order PT was seen in the moments of net charge multiplicity measured as a function of collision energy [132, 133]. At the same time, results from proton “directed” flow \( (v_1) \) [134] and moments of net proton multiplicity [135] indicate a nonmonotonic behavior for \( \sqrt{s_{NN}} \leq 27 \text{ GeV} \), however the current statistical precision for the \( \sqrt{s_{NN}} \lesssim 20 \text{ GeV} \) region precludes conclusive statements and needs to be improved using data from BES Phase-II.
Particle production

Identifying the dominant mechanisms in particle production is theoretically challenging. One popular idea before RHIC experiments was that the dominant mechanism would be the scatterings of incoming partons that produce low and intermediate energy particles, via “mini-jet” production in HIJING model \cite{136, 137, 138}. According to this model, multiplicity should increase rapidly with centrality (since number of scatterings scale with $N_{\text{col}}$) and $\sqrt{s_{NN}}$ (since scattering cross section increases with $\sqrt{s_{NN}}$). However, the multiplicities measured at RHIC \cite{139, 140, 114, 141} (one of them being shown Fig. 1-10) were much lower than the mini-jet expectations.

![Figure 1-10: The charged particle multiplicity for $|\eta| < 1$ per participant pair, $dN_{ch}/d\eta/\langle N_{\text{part}}/2 \rangle$, as function of $\langle N_{\text{part}} \rangle$ for Au+Au collisions in PHOBOS experiment at RHIC. Open and closed markers correspond to different analysis techniques. Figure taken from Ref. \cite{141}.](image)

A centrality dependent gluon shadowing was inserted to HIJING model to sup-
press the rapid increase of multiplicity with centrality [142]. Other models have been successful in describing the multiplicity in data [142, 143, 144, 116] after accounting for parton saturation, saturation of low-\(x\) states (\(x\) is fraction of the nucleon’s momentum carried by a parton) as a result of competing effects between the splitting of higher-\(x\) states (\(g \rightarrow g + g\)) and fusion of two low-\(x\) states (\(g + g \rightarrow g\)) [145].

Multiplicity density was found to be roughly proportional to the number of participant pairs, \(N_{\text{part}}/2\), as seen in Fig. 1-10 and in Refs. [139, 140, 146, 141]. Another scaling behavior was first observed in \(\pi + A\) collisions for total multiplicity [147] and is known as “participant scaling”. Participant scaling shows that particle production has a centrality dependence that is much weaker than what would be expected from a parton scattering production, i.e. mini-jet processes, where number of scatterings are proportional to \(N_{\text{coll}}\). The underlying mechanism for participant scaling is not well understood, a review of current understanding can be found in Ref.[39].

The direct photon production mentioned above in Sec. 1.4.2 was also a test for high \(p_T\) particle production. The high \(p_T\) photon \(R_{AA}\) being consistent with 1 [105, 106] also reveals that production of high \(p_T\) processes in AA collisions is the same as in pp scaled by \(N_{\text{coll}}\) modulo small CNM effects.

**Recombination**

Quark recombination is a model of hadron production where constituents quarks of a hadron do not originate from the same process. Recombination was first proposed to explain the hadron production in “forward”, i.e. large \(|\eta|\), region of pp collisions [148, 149, 150, 151]. For example, a meson would be “recombined” if one of its constituents (say the anti-quark) was emitted in the fragmentation of an energetic parton and the other constituent (say the quark) originated in some other CNM process. A meson is not considered recombined if both of its constituent quarks can be traced to the same scattering process.

In HI collisions, recombination can happen via the coalescence of quarks originating from different nucleon-nucleon collisions or via the coalescence of one quark in QCD medium with another quark produced in a hard scattering [152, 153].
The application of recombination for HI collisions implicitly requires the QCD medium to have quark degrees of freedom. This has several implications for particle spectrum. First, baryons at intermediate $p_T$ would be relatively enhanced compared to mesons at the same $p_T$ region, since a baryon carries total momentum of three quarks, a meson carries that of two quarks. Basically, information of a quark with transverse momentum $p_T^{\text{quark}}$ will show itself in hadrons with higher momentum $p_T^h \approx 2 - 3 \, p_T^{\text{quark}}$. Thermal and hydrodynamic properties will appear at hadron $p_T$ scales that are significantly higher than the $p_T$ scales where they actually play a role. Likewise, the dominant hadron production mechanism at intermediate $p_T$ could actually be recombination, not hard scattering \[152\]. Lastly, hadron flow should be proportional to the number of constituent quarks, as it must be quarks that flow, not hadrons. These features were detailed in Refs. \[154, 152, 155, 156, 157, 158\] and can, at the very least qualitatively, describe the identified particle flow at RHIC \[159, 160\]. Especially, the scaling of hadron flow with the number of constituent quarks is a very strong evidence for a QCD medium with quark degrees of freedom.

In addition to studies at RHIC, recombination also has significant implications for $J/\psi$ meson yield at LHC, which are reviewed in Sec. 1.5.

### 1.4.4 Summary of the first RHIC results

As discussed above, the observation of flow phenomena (Sec. 1.4.1) and suppression of high energy particles (Sec. 1.4.2) in the first RHIC runs are the most compelling evidences for the formation of a dense and strongly coupled system.

The results also support that a transition into a phase with quark degrees of freedom has occurred. The energy densities were well above the boundary for a PT. Furthermore, the success of recombination models in describing the hadron spectra and flow made a convincing case for deconfined phase. Measurements of particle yields and spectrum were observed to have a smooth evolution as function of centrality and collision energy. No abrupt changes were seen that could hint at a first order PT.

Evidence for deconfinement was found not only in RHIC experiments. LHC results, reviewed in Sec. 1.5, showed strong evidence for deconfinement from the overpro-
duction of $J/\psi$ mesons due to recombination and from the suppression of $\Upsilon$ mesons.

1.5 The LHC experiments

Starting from 2010, the LHC delivered PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV. The collision data were recorded by general purpose detectors and analyzed by the collaborations of the corresponding detectors, namely the ALICE (A Large Ion Collider Experiment) [161], the ATLAS (A Toroidal LHC Apparatus) [162], the CMS (Compact Muon Solenoid) [163], and the LHCb (LHC beauty) [164] experiments.

Flow phenomena was observed at the LHC, where the results point to the same conclusion that was drawn from the RHIC results, that is formation of a dense and strongly coupled system in PbPb collisions. In particular, elliptic flow was quantified with unprecedented precision [49, 165, 166, 167, 168] and supplemented with measurements of higher order flow coefficients [169, 170, 171, 172, 173, 174] imposing further constraints on the bulk properties of QCD medium. Besides, initial state of HI collisions were explored via measurements of EbE flow fluctuations [175, 176, 177, 178]. Hadron formation was studied via anisotropic flow of identified particles [179, 180, 181, 182] where flow coefficients were found to scale approximately with the number of constituent quarks, similar to the observation at RHIC, and in agreement with the quark recombination model of hadron formation. Flow measurements have expanded the reach for high energy particles, extending up to particles with $p_T \sim 100$ GeV/c, and found a small but nonzero azimuthal anisotropy for those particles [183, 184, 172], providing input for relations between the energy loss of partons and the distance they travelled in QCD medium.

In addition to complementing the observations at RHIC, the LHC experiments revealed striking collectivity features in small systems. Unexpectedly high number of charged particle pairs were found to have large differences in pseudorapidity, i.e. large $\Delta\eta$ (long-range correlation), and be very close in azimuthal angles, i.e. $\Delta\phi \approx 0$ (near-side correlation), in pPb [185, 186, 187, 188] and in high multiplicity pp
collisions [189, 190, 191], as shown in the left panel in Fig. 1-11. The long-range near-side correlations were followed with measurements of flow coefficients in pPb and pp collisions [192, 193, 194] that were found to be smaller than in PbPb collisions, but still nonzero, as shown in the right panel in Fig. 1-11. These results challenged the understanding of origin of collective behavior in HI collisions and raised the question of whether a QCD medium, albeit small, is produced in small systems. Searches in even smaller collision systems such as ep (electron+proton) [195] and e+e− (electron+positron) [196] are being scrutinized and no significant signal for collective behavior was found so far.

Figure 1-11: Left: The Δφ versus Δη correlations between charged particle pairs with 1 < p_T < 3 GeV/c in pPb collisions. High-multiplicity events are selected by requiring the number of reconstructed charged particle tracks, N_{trk}^{\text{offline}} , to be at least 110. Right: The v_2 (upper) and v_3 (lower) versus N_{trk}^{\text{offline}} in pp, pPb, and PbPb collisions. Figures taken from Refs. [185, 194].

The higher collision energies at LHC extended the phase space for hard probes to higher p_T. Moreover, using their trigger system, the CMS and ATLAS experiments were able to record data for hard scattering processes efficiently and developed algorithms to record rare probes, such as Z bosons, high p_T photons, and mesons...
made up from heavy quarks (B, D, J/ψ, Υ mesons) that were much more difficult to access before. Hadron suppression measurements from all LHC experiments covered a wide $p_T$ range from $p_T \approx 0.1$ GeV/$c$ up to $p_T \approx 400$ GeV/$c$ finding no significant difference between the suppressions at $\sqrt{s_{NN}} = 2.76$ TeV [197, 198, 199] and $\sqrt{s_{NN}} = 5.02$ TeV [200, 201]. Fig. 1-12 shows the charged particle $R_{AA}$ measurements in various collision systems and energies, where CMS measurement [200] covers the $0.7 < p_T < 400$ GeV/$c$ interval that is even wider than the collision energies at RHIC. No significant suppression was seen for high energy particles in pPb collisions [200], similar to the RHIC results discussed in Sec. 1.4.2.

![Figure 1-12: The charged particle $R_{AA}$ measured as function of $p_T$ in various collision systems and energies. Figure taken from Ref. [200].](image)

The full reconstruction of heavy quark mesons allowed a direct study of their production. Thanks to its trigger developments, CMS experiment was able to extend the D meson studies up to $p_T \approx 100$ GeV/$c$ [202], surpassing the limits of $p_T \approx 20$ GeV/$c$ in ALICE measurements [203, 204], and finding that charm quark suppression is slightly smaller compared to that of light quarks in the $p_T \lesssim 10$ GeV/$c$ range. The beauty quark production was measured using reconstructed B mesons [205].
pressions for all light, charm, and beauty quarks were consistent with each other in the $p_T \gtrsim 10$ GeV/c range. The heavy quark production was studied via $J/\psi$ mesons (bound states of charm quark and its antiquark) \cite{206,207,208,209,210,211} and $\Upsilon$ mesons (bound states of bottom quark and its antiquark) \cite{212,213,214,215} as well. In particular, at forward-rapidity (large $|y|$), the suppression for $J/\psi$ with low $p_T$ was found to be significantly smaller than for $J/\psi$ with higher $p_T$ \cite{208,209}, suggesting that production of low $p_T$ $J/\psi$ has a contribution originating from recombination. Furthermore, suppression of $\Upsilon$ was found to be “sequential” \cite{215}, i.e. the suppression was larger for states with lower binding energies. These results for $J/\psi$ and $\Upsilon$ mesons provided strong evidence for deconfinement and formation of QGP in HI collisions.

Thanks to their superior calorimeters, CMS and ATLAS experiments studied parton energy loss in QCD medium using fully reconstructed jets (see Sec. 2.1.2 for jet definition and Sec. 5.5 for jet reconstruction in the experiment). Jet energy loss in HI collisions, “jet quenching”, at the LHC was observed for the first time in studies of “dijets”, pair of jets that recoil off each other \cite{216,217}. Dijets in PbPb were found to have a worse $p_T$ balance (less balanced in $p_T$) compared to dijets in pp, which is interpreted as that jets lose energy in PbPb collisions and one jet in the dijet pair loses more energy relative to the other jet, thus worsening the $p_T$ balance. The first observation of jet quenching using dijets was later followed with studies more differential in $p_T$ and collision centrality \cite{218,219,220}. No significant collision energy dependence was seen between the jet suppression at $\sqrt{s_{NN}} = 2.76$ TeV \cite{221,222,223,224,225} and $\sqrt{s_{NN}} = 5.02$ TeV \cite{226,227,228}. Furthermore, the jet $R_{AA}$ was seen to increase slowly with $p_T$, as seen in Fig. 1-13 which shows the ATLAS jet $R_{AA}$ measurement \cite{220} for jets with $40 < p_T < 1000$ GeV/c.

Electroweak (EW) bosons opened up new prospects for QCD medium studies. Production of isolated photons (see Sec. 5.3.3 for isolation) in PbPb collisions was not modified more than what is expected from CNM effects \cite{229,230,231}, experimentally confirming that photons do not interact with QCD medium. $Z$ bosons were observed in PbPb collisions for the first time \cite{232,233,234} and their pro-
duction was consistent with that in pp collisions \cite{235,236,237,238} within CNM effects. Similarly, modification of W boson production in PbPb collisions relative to that in pp collisions \cite{239} was not more different than the modification in pPb collisions \cite{240,241}. The absolute quantification of jet quenching was performed for the first time via isolated photon-tagged jets \cite{242} using the $\sqrt{s_{NN}} = 2.76$ TeV data. Later on, jets tagged with isolated photons were studied using the larger data sample at $\sqrt{s_{NN}} = 5.02$ TeV \cite{243,244}, measuring the parton energy loss directly with improved precision. Fig. 1-14 shows the evolution of the isolated photon+jet momentum imbalance, i.e. distributions of the $x_{j\gamma}$ defined in eq. 2.14, with the collision centrality.

In addition to jet quenching measurements, LHC experiments analyzed jet structure to learn more about the underlying mechanisms of parton-medium interactions. Particularly, the studies measured

- how the energy of a parton shower is redistributed in the angular space \cite{245,246,247,248}
- how the jet fragmentation pattern is modified \cite{249,250,251}

Fig. 1-15 shows the modifications of the jet fragmentation functions (introduced
Figure 1-14: The isolated photon+jet momentum imbalance, $x_{j\gamma} = p_{Tj}^γ / p_{T\gamma}$, (defined in eq. 2.14) distributions in various centrality intervals for pp (open circles) and PbPb (closed circles) data. Figure taken from Ref. [243].

Figure 1-15: The modification of jet fragmentation functions in central PbPb collisions is studied via $R_D (p_T)$, the PbPb over pp ratio of yields of charged particles within a jet cone as a function of the charged particle $p_T$. Figure taken from Ref. [251].

in Sec. 2.2.2 in PbPb collisions where PbPb jets are modified relative to pp jets to have more particles with low energies ($p_T \lesssim 4$ GeV/c) and very high energies ($p_T \gtrsim 40$ GeV/c), but less particles with intermediate energies ($4 \lesssim p_T \lesssim 40$ GeV/c). Fig. 1-16 shows the modifications of the differential jet shapes as a function of
$r$, the distance from the jet axis (this observable is introduced in Sec. 2.2.2). In central PbPb collisions, a larger fraction of the jet energy is carried at large distances ($r \approx 0.3$) and a smaller fraction is carried at intermediate distances ($r \approx 0.1$).

### 1.6 Questions addressed in this thesis

Most measurements for medium induced parton shower modifications analyzed “inclusive” jets, i.e. all jets that satisfy a criteria for kinematic variables, or dijets. Event samples in these measurements were selected using detected jets, thus sample selection is based on the “final” jet properties, i.e. properties after the event evolution has completed. For instance, results in Figs. 1-15 and 1-16 are obtained from samples selected using the final $p_T^{\text{jet}}$. This means that jets in PbPb data were selected based on their properties after they have suffered energy loss in QCD medium, not based on their “initial” properties, i.e. properties when they were initiated which happens before their interaction with QCD medium. Therefore, dijet and inclusive jet measurements compared PbPb and pp jets whose initial properties were not the same. This can complicate the interpretation of the results because the comparison...
is already biased by the phenomena that it aims to measure.

First, the pp and PbPb samples do not share the same initial jet energy distribution for reasons listed above. Second, fractions of jets initiated by quarks (or gluons), i.e. quark/gluon \((q/g)\) fractions, are not necessarily the same between the pp and PbPb samples. This can be understood from Fig. 2-10 which demonstrates that \(q/g\) fractions changes with jet energy. It is expected that \(q/g\) fractions are different between the pp and PbPb samples (unless jet quenching happens in a magical way that \(q/g\) fractions of quenched jets in PbPb end up the same as fractions in unquenched pp jets). At the same time, jet structure

1. is different for quark and gluon initiated jets, as seen in Fig. 2-21.

2. evolves with jet energy, as seen in Fig. 2-22.

These points show that the observables can be sensitive to biases introduced by the sample selection. As a result, interpretation of the PbPb-to-pp comparisons becomes ambiguous for jet structure measurements obtained in dijet or inclusive jet samples. Differences between the pp and PbPb results could arise due to the fact that jet structure is indeed modified in QCD medium as a result of parton-medium interactions as well as due to differences introduced in the sample selection. Ideally, one wants to study only those effects that arise from parton-medium interactions.

Ambiguities in the PbPb-to-pp jet structure comparisons can be eliminated by selecting samples using EW bosons, which are not modified in PbPb collisions. This ensures that the pp and PbPb jets are selected based on their initial properties. Besides, the fraction of quarks recoiling from EW bosons is larger compared to quark fraction in dijets, as seen in Fig. 2-10. Thus, EW bosons provide higher purity samples to probe modification of jets initiated by quarks. In short, the main advantages of EW bosons for jet modification studies are in that they constrain the following properties of an energetic parton

- Energy before its interaction with QCD medium
- Flavor, i.e. whether it is a quark or gluon
Having said that, EW bosons are produced much less frequently compared to dijets (see Sec. 2.2), thus earlier jet measurements were performed using dijets or inclusive jets exploiting their much higher abundance. Thanks to the CMS trigger system and the high rates of collisions delivered by the LHC in Run 2, the CMS experiment was able to record pp and PbPb data large enough to study parton shower modifications in events selected by isolated photons or Z bosons.

The questions addressed in this thesis work can be listed as follows.

1.6.1 Quantification of jet quenching

Jet energy loss was first quantified directly in Ref. [242] using the $p_T$ correlations between an isolated photon and recoiling jets. Yet, Z-tagged jets are even “cleaner” than photon-tagged jets since experimentally selected photons contain an irreducible contamination from the jet fragmentation (see Sec. 5.3.3) and there is no such contamination for Z bosons. On the contrary, Z+jet events are much rarer than photon+jet events, thus the study of Z-tagged jet quenching became feasible first in 2015 when sufficiently large data were collected during the LHC Run 2.

The study of Z-tagged jets is crucial for several reasons. First, it provides a direct quantification of jet quenching as in photon-tagged jets. Second, there are inherent differences between photon+jet and Z+jet processes (see Sec. 2.2), e.g. the initial energy spectrum of partons recoiling from photons and Z bosons are different, as seen in Fig 2-11. A comparison between the photon-tagged and Z-tagged jet results would reveal to what extent the differences between those processes, e.g. difference in the initial energy spectrum, affects the observed jet quenching. In addition to scientific output, the first Z-tagged jet measurement would lay out the experimental “know-how” for similar studies in future. The study of jet quenching using Z-tagged jets is presented in Ch. [3]
1.6.2 Observation of parton shower modification

High energy partons probe the microscopic structure of QCD medium, as noted in Sec. 1.2.3. The inner workings of QCD medium would manifest itself via a modification of parton showers in PbPb collisions with respect to those in pp collisions. For reasons listed above, direct measurements of parton shower modification can be performed in samples tagged with EW bosons. In this regard, parton shower modifications are studied for photon-tagged jets via measurements of the jet fragmentation functions and the jet shapes, presented in Ch. 7 and Ch. 8 respectively.

1.6.3 Angular distribution of medium response

Just as parton showers are modified as a result of parton-medium interactions, QCD medium itself is also modified. Partons forming the QCD medium, i.e. the “medium partons”, can recoil against the energetic partons that pass through, i.e. QCD medium “responds” to the jet’s passage. In analogy to a real life example, parton energy loss resembles the drag of a bullet penetrating a fluid and the medium response (or the medium recoil) can be thought as the fluid’s excitation induced by the bullet.

The medium response is thought to manifest predominantly in form of low energy particles radiated at large angles [252, 253, 254, 255, 256] (see Sec. 2.4 for medium response). Hence, photon-tagged jet structure studies (mentioned above in Sec. 1.6.2) can serve to test the understanding of medium response. Though, those studies are confined to a relatively smaller range of angles, whose size is set by the jet distance parameter (see Sec. 2.1.2 for jet definition).

Effects of parton-medium interactions in angular space beyond that defined by jets were studied in the past in Refs. [246, 247, 248]. However, these studies are performed using dijets and inclusive jets, thus suffer the sample selection biases outlined above. Apart from that, analysis of medium response at large angles from a jet is complicated in dijet or inclusive jet samples, because the medium is excited by at least two jets, not by one jet.
A selection based on EW boson would not only provide unbiased samples, but also ensure that there is (to leading order) only one jet that excites the medium. RHIC experiments had measured particles at large angles from parton showers using photon-tagged samples \[257\], however the analysis method causes the measurement to ignore some of the particles of interest \[258\], preventing an accurate measurement of particle production. In that regard, the $Z+$hadron correlations analysis presented in Ch. 9 investigates the parton-medium interactions using Z-tagged parton showers and measures the particle production accurately. Particularly, the analysis quantifies the parton shower modification, but more importantly scans medium response effects over all azimuthal angles, including the angles opposite the direction of the jet propagation for which interesting effects, e.g. a medium depletion (see Sec. 2.4), were predicted.
Chapter 2

Theory of jets in vacuum and in QGP

High energy partons (quarks or gluons) are useful probes to study QCD medium. In hadron collisions, high energy partons are produced in scattering processes with large momentum transfer, i.e. “hard” scattering processes. Partons carry color, and due to color confinement, are not stable as isolated particles and undergo a series of processes that result in hadrons which are color singlets. The whole process that starts with free partons and ends with a state of hadrons can be split into two processes, parton showering and hadronization. A parton knocked out in a hadron collision cannot form new hadrons alone, it connects to other knocked-out partons via gluon fields making “color connections”, and new partons can be created during the evolution of showering. Creation of new partons during the propagation of high energy partons is known as “fragmentation” and the set of produced partons is called a parton shower. Fig. 2-1 shows an example parton shower arising from the fragmentation of a high energy quark. Observe that a quark can radiate a photon as well and such “fragmentation” photons contribute the isolated photon sample discussed in Sec. 2.2. Showering is followed by hadronization where partons combine into hadrons.

The strong coupling constant $\alpha_s$ in QCD becomes smaller for processes with large momentum transfer $Q$ allowing the usage of perturbation theory in QCD calculations, a framework known as perturbative QCD (pQCD). An important success of pQCD was its accurate description of hadron production in $e^+e^-$ collisions [29].

It is instructive to first consider the energetic partons in vacuum, i.e. in absence
of QCD medium, this is discussed in Sec. 2.1. Following that, Sec. 2.2 introduces the Z+jet and photon+jet processes and relevant observables whose measurements are presented in Chapters 6, 7, 8, and 9. Theories for hard processes in QCD medium are discussed after that, in Sec. 2.3.

2.1 Jets in vacuum

Consider the collision of two hadrons $h_1$ and $h_2$ whose partons $i$ and $j$, respectively, interact to yield a final state $k$. The cross section for this process can be expressed as

$$
\sigma (i + j \to k) = \sum_{n=0}^{\infty} \alpha_s^n (Q^2) \sum_{i,j} \int dx_1 dx_2 f_i^1 (x_1, Q^2) f_j^2 (x_2, Q^2) \times \hat{\sigma}^n (i + j \to k) \quad (2.1)
$$

where $x$ is the fraction of hadron’s longitudinal momentum carried by an incoming parton and $f (x, Q^2)$ is the parton distribution function (PDF) for an incoming parton with momentum fraction $x$ to undergo a process with momentum transfer $Q$. Factorization theorem for hard scattering cross section [259] allows to treat the $f_i^1 \cdot f_j^2$ and $\hat{\sigma}$ terms separately where the former represents the probability of incoming partons $i$ and $j$ having an interaction and the latter represents the probability that the inter-

Figure 2-1: Diagram corresponding to a possible parton shower initiated by a quark.
action of partons $i$ and $j$ will result in state $k$. For example, the $f_i^1 \cdot f_j^2$ term could correspond to the production cross section for $Z+\text{jet}$ pairs and the $\hat{\sigma}$ could correspond to the evolution of the $Z$ boson and partons to a state of leptons and hadrons. Using factorization theorem, the $Z+\text{jet}$ pair production and its evolution can be treated separately.

### 2.1.1 Fragmentation

Partons created in hard scattering build color connections and fragment, a process that ultimately creates hadrons. The fragmentation function (FF) $D^h_a(x, \mu_F^2)$ is a measure of the probability that the fragmentation of parton $a$ results in hadron $h$ where $x$ is the fraction of parton’s momentum transferred to the hadron and $\mu_F$ is the factorization scale [29]. $D^h_a$ is constrained by the probability sum rule

$$\sum_h \int_0^1 dx \, x \, D^h_a(x, \mu_F^2) = 1$$

(2.2)

which holds for any parton $a$ and the sum runs over all hadron species. FFs are related to the $\mu_F$ via the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations [260, 261, 262]

$$\frac{\partial}{\partial \ln \mu_F^2} \, D^h_i(x, \mu_F^2) = \sum_j \int_x^1 \frac{dz}{z} \, P_{ji}(z, \alpha_s(\mu_F^2)) \, D^h_j\left(\frac{x}{z}, \mu_F^2\right)$$

(2.3)

where the splitting function $P_{ij}(z, \alpha_s)$ represents the probability for parton $i$ to split and the resulting parton $j$ to carry momentum fraction $z$ of parton $i$. The $P_{ij}(z, \alpha_s)$ can be expressed as a perturbative expansion [29]

$$P_{ij}(z, \alpha_s) = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^{n+1} P_{ij}^{(n)}(z)$$

(2.4)
Figure 2-2: Diagrams for \( q \rightarrow q + g \) (left), \( g \rightarrow g + g \) (middle), and \( g \rightarrow q + \bar{q} \) (right) splittings listed in eqs. 2.5, 2.6, and 2.7 respectively.

The leading order (LO) functions \( P_{ij}^{(0)}(z) \), i.e. splitting kernels, are given by

\[
P_{q,q}(z) = C_F \frac{1 + z^2}{1 - z} \tag{2.5}
\]
\[
P_{g,g}(z) = C_A \frac{(1 - z)(1 - z)}{z(1 - z)} \tag{2.6}
\]
\[
P_{g,q}(z) = \frac{1}{2} \left( z^2 + (1 - z)^2 \right) \tag{2.7}
\]

where \( C_F = 4/3 \) and \( C_A = 3 \). The Feynman diagrams for those splitting processes are shown in Fig. 2-2. Ignoring the dependence on \( z \), then kernels for the gluon splitting \( (P_{g,g} + P_{g,q}) \) are larger than that for quark splitting \( P_{q,q} \), meaning that gluons have a larger splitting probability than quarks.

In the remaining of this chapter, the Pythia 8 package is employed as an instructive tool for parton evolution in vacuum. This choice is driven by Pythia 8’s reasonably good description of the photon-tagged jet structure in pp data, in particular its description of the jet FFs (see Fig. 7-19) and shapes (see Fig. 8-14).

First, parton showers are studied via “hard” partons, i.e. those that initiate the fragmentation, and “final” partons , i.e. those at the end of parton evolution. To illustrate in Fig. 2-1, the quark in the very left would be the hard parton and partons in the very right would be final partons. Technically, parton \( i \) is an “ancestor” of parton \( j \) if the creation of parton \( j \) can be traced back to the splitting of parton \( i \). The hard parton is ancestor of all final partons.
The QCD scattering events with momentum transfer $Q > 80$ GeV are created and studied using PYTHIA 8. The left panel in Fig. 2-3 shows the number of final partons per hard parton as a function of the angular distance, $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$, between the hard and final parton. The distribution is wider for hard gluons than for hard quarks. The right panel in Fig. 2-3 shows the number of final partons per hard parton within a radius of $\Delta R$. The hard gluons have more associated final partons compared to hard quarks, implying that gluon showers undergo more splittings and evolve into showers with higher multiplicity. Within a radius of $\Delta R = 1.5$, gluon initiated showers have $\sim 50\%$ more partons compared to quark initiated showers.

The left panel in Fig. 2-4 shows the fraction of the energy of the hard parton carried by final partons as function of $\Delta R$. The fractional energy distribution is wider for hard gluons than for hard quarks. The right panel in Fig. 2-4 shows the fraction of the energy of the hard parton carried within a radius of $\Delta R$. While a hard parton’s energy recovery continues up to $\Delta R \approx 1.5$, recovery “saturates” mostly at $\Delta R \sim 0.8$ as the energy fraction remaining outside this radius is $\sim 5\%$ and it is recovered slowly with increasing $\Delta R$. Note that the energy fraction within $\Delta R \approx 1.5$ is seen to be larger than 1, this is because other partons in the PYTHIA event can impart momentum to final partons or their ancestors, hence the total energy of final partons do not necessarily add up exactly to the hard parton energy. Compared to hard gluons, a larger fraction of the hard quark’s energy is contained within the same $\Delta R$. A fraction of $\sim 80$ ($\sim 70\%$) of a hard quark’s (gluon’s) energy is carried by final partons within a radius of $\Delta R \approx 0.3$.

2.1.2 Jets

A number of particles are created as a result of the fragmentation of the parton produced in hard scatterings. Final set of particles are clustered into physics objects known as “jets”. There are a number of algorithms to cluster particles into jets, widely known algorithms are the $k_T$ [264, 265, 266], Cambridge/Aachen (C/A) [267, 268], SISCone [269], and anti-$k_T$ [270] algorithms which allow direct comparisons between theoretical calculations and experiments.
Figure 2-3: **Pythia 8** events for pp collisions with at least one scattering with momentum transfer $Q > 80$ GeV. Left: The distribution of the number of final partons per hard parton, as a function of the $\Delta R$ between the hard and final parton. Right: The distribution on the left integrated over $\Delta R$, giving its cumulative distribution function (CDF), i.e. the number of final partons per hard parton within a radius of $\Delta R$. Hard quarks and gluons are indicated by black and blue markers, respectively.

Due to the splitting function and “color coherence”, the destructive interference of the color wavefunctions that suppresses of low energy gluon radiation [271, 272, 29], particles originating from the same hard parton tend to be close to each other in angular position. Distances between particles (both in angle and momentum space) are useful information to identify jets. General distance measures between entities (particles or pseudojets) $i$ and $j$, and between entity $i$ and the beam $B$ are given in Ref. [270] as

$$d_{ij} = \min \left( k_{T_i}^{2n}, k_{T_j}^{2n} \right) \frac{\Delta_{ij}^2}{R^2} \tag{2.8}$$

$$d_{iB} = k_{T_i}^{2n} \tag{2.9}$$

where $\Delta_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$ and $k_{T_j}$, $y_j$, and $\phi_j$ are the transverse momentum, rapidity, and azimuthal angle of the entity $j$, respectively. The distance parameter $R$ defines a scale such that if two entities are separated by less than $R$
Figure 2-4: **PYTHIA 8 events for pp collisions with at least one scattering with momentum transfer \(Q > 80\text{ GeV}\).** Left: The distribution of the hard parton’s energy fraction carried by final partons as a function of the \(\Delta R\) between the hard and final parton. Right: The distribution on the left integrated over \(\Delta R\), giving its cumulative distribution function (CDF), i.e. the hard parton’s energy fraction carried by final partons within a radius of \(\Delta R\). Hard quarks and gluons are indicated by black and blue markers, respectively.

They tend to get grouped together into a single jet. This means that \(R\) is not necessarily a jet size, as for a given \(R\), constituents of a jet may turn out to have angular separations smaller than \(R\), i.e. jet is narrower than \(R\). But, there will not be two jets that are separated by less than \(R\). The parameter \(n\) sets the sensitivity to momentum.

Jets in an event are found as follows. Jet clustering starts by making an entity for each particle and iterates over the list of entities by calculating all distances. If the smallest distance is \(d_{ij}\), then entities \(i\) and \(j\) are recombined, if it is \(d_{iB}\), then entity \(i\) is defined as a jet and removed from the list. The jet finding completes when no entity is left in the list.

The case for \(n = 1\) and \(n = 0\) reproduce the \(k_T\) and C/A algorithms, respectively. The \(n = -1\) case is the anti-\(k_T\) algorithm. Fig. 2-5 shows a sample event where jets are clustered using the \(k_T\) and anti-\(k_T\) algorithms. The anti-\(k_T\) algorithm produces jets with more circular and regular shapes than the \(k_T\) algorithm. The anti-\(k_T\) algorithm makes a better case for experimental jet reconstruction as the jet energy correction
Partons in a sample event clustered using the $k_T$ (left) and anti-$k_T$ (right) algorithms. Jets are indicated with colored regions. Figure taken from Ref. [270].

(see Sec. 5.5) performs better for jets with regular shapes.

When entities $i$ and $j$ are recombined, the momentum of the new entity is assigned according to a recombination scheme. The default recombination scheme for LHC experiments is the “E-scheme” where momentum of the new entity is assigned by simply adding up the 4-momentums for $i$ and $j$. A more general recombination scheme is listed in Ref. [273] where momentum of the new entity $r$ is assigned as

$$p_{T,r} = p_{T,i} + p_{T,j}$$  \hspace{1cm} (2.10)
$$y_r = (w_i y_i + w_j y_j) / (w_i + w_j)$$  \hspace{1cm} (2.11)
$$\phi_r = (w_i \phi_i + w_j \phi_j) / (w_i + w_j)$$  \hspace{1cm} (2.12)

where $w_i$ is weight of the entity. The $w_i = p_{T,i}$ case is called the $p_T$ (or the $E_T$) scheme. The cases for $p_T$ based weighting can be generalized to $w_i = p_{T,i}^n$ giving $p_T^n$ scheme and the extreme case of $n \to \infty$ gives the “winner-takes-all” (WTA) scheme where $(y_r, \phi_r)$ is simply the $(y, \phi)$ of the entity with higher $p_T$ [274, 275]. A use case of the WTA scheme for future jet measurements in HI collisions is presented in Sec. 10.1.

Unless specified otherwise, jets in this thesis are clustered, i.e. found, with the anti-$k_T$ algorithm using a distance parameter of $R = 0.3$ and recombined with E-scheme.
Figure 2-6: Mean value of $p_{T}^{\text{jet}}/p_{T}^{\text{parton}}$ ratio as function of $p_{T}^{\text{parton}}$ in Pythia 8 events where jet is the highest $p_{T}$ jet that is associated to the hard scattering parton. Distance parameters are $R = 0.3$ (black) and $R = 0.8$ (blue).

The recovery of a hard parton’s energy using jets is tested in Pythia 8. All particles coming out of a simulated pp interaction are used in jet clustering, i.e. particles from parton level processes other than the hard scattering (e.g. the multiparton interactions) are not excluded. Fig. 2-6 shows average of the $p_{T}^{\text{jet}}/p_{T}^{\text{parton}}$ ratio. On average, $\approx 85\%$ of the hard parton’s energy can be recovered with jets using a distance parameter of $R = 0.3$, an almost full recovery can be achieved for jets with $R = 0.8$.

2.2 V+jet processes

At the LHC energies, the cross section for isolated photons with $p_{T} \sim 60$ GeV/c is $\sim 1000$ times smaller than for jets at the same $p_{T}$ and the cross section for Z bosons (decaying into muon and electron pairs) are $\sim 100$ times smaller than for isolated photons [276].

Several tree level processes are dominant in the production of photon+jet events.
These are

- $q + g \rightarrow q + \gamma$ process, namely QCD Compton scattering, illustrated in Fig. 2-7.
- $q + \bar{q} \rightarrow g + \gamma$ process, namely quark-antiquark annihilation, illustrated in Fig. 2-8.

There is also a contribution from gluon-gluon interactions (see the left panel in Fig. 2-9), but this involves a loop diagram and has a subdominant contribution compared to tree level processes mentioned above. Moreover, rarer processes such as two photon production via the $q + \bar{q} \rightarrow \gamma + \gamma$ process contribute to the high energy photons, however these processes are ignored for purposes of this thesis as these are much (about 1000 times) rarer compared to photon+jet events.

![Diagram of $q + g \rightarrow q + \gamma$ process](image1)

Figure 2-7: $q + g \rightarrow q + \gamma$ process

![Diagram of $q + \bar{q} \rightarrow g + \gamma$ process](image2)

Figure 2-8: $q + \bar{q} \rightarrow g + \gamma$ process

Photons in the processes listed above are produced directly in the hard scattering (giving “direct” photons). However, high energy photons can be produced also via the
Figure 2-9: Left: $g + g \rightarrow g + \gamma$ process. Right: Quark radiating a photon (Bremsstrahlung)

parton fragmentation or bremsstrahlung as shown in Fig. 2-3 (or simply in the right panel in Fig. 2-9). The measured isolated photons have an irreducible contribution from fragmentation processes. Details about the experimental definition of the photon signal are discussed in Sec. 5.3.3.

Dominant processes for $Z+$jet events are basically the same as those in photon+jet events. Corresponding processes can be obtained by simply replacing the photon with a $Z$ boson. In principle, there can be $Z$ bosons radiated in a fragmentation process as well, but this is extremely unlikely due to the large $Z$ boson mass, hence all $Z$ bosons are practically produced in the hard scattering.

Fig. 2-10 shows the fraction of partons recoiling from photons, $Z$ bosons, and another parton in case of dijet processes. Most jets with $p_T \sim 100$ GeV/$c$ in dijet events are initiated by gluons and the gluon fraction decreases with increasing $p_T$. On the other hand, the parton recoiling from the photon or $Z$ boson is most likely a quark. There are some differences in the quark fractions between photon+jet and $Z+$jet processes especially around the $p_T$ values close to the $Z$ boson mass ($M_Z \approx 91$ GeV/$c^2$) where the contribution from the $q + g \rightarrow q + Z$ process (see Fig. 2-7) increases. The large mass of $Z$ boson causes differences in the $p_T$ spectrum as well. Fig. 2-11 compares the $p_T$ distributions of $Z$ bosons and photons recoiling from jets in PYTHIA events. The $Z$ boson mass flattens the $p_T$ distribution in $Z+$jet events.

Another feature seen in Fig. 2-10 is that the fraction of recoiling quarks decreases monotonically with increasing $p_T$, the fraction is $\sim 90\%$ for $p_T \sim 50$ GeV/$c$ and de-
Figure 2-10: Prompt photon+jet (upper left), Z+jet (upper right), and dijet (lower) events are generated using Pythia 8. Fraction of events for which the recoiling parton is a gluon, a light quark \((u, d, s)\), or a heavy quark \((c, b)\) is indicated with blue, gray, and red areas, respectively.
Figure 2-11: Upper: The $p_T$ distributions of Z bosons (black) and photons (blue) recoiling from a jet in *Pythia* 8 events. Lower: The $p_T^Z$ over $p_T^\gamma$ ratio of the distributions.
creases to $\sim 80\%$ for $p_T^\gamma \sim 600$ GeV/c. This change can be understood by considering how the probed PDFs regions evolve with momentum transfer $Q$.

Fig. 2-12 shows the parton densities $x \cdot f (x, Q^2)$ probed in PYTHIA 8 photon+jet events as function of momentum fraction $x$. The higher is the momentum transfer $Q$ the more is the contribution from large $x$. Fig. 2-13 shows the same densities separately for events with recoiling quarks and gluons. While incoming gluons contribute significantly to events with a recoiling quark, they do not contribute much to events with a recoiling gluon (Recall that the major source of recoiling gluons is quark+antiquark annihilation). In addition, gluon density decreases faster with $x$ than quark densities. Thus, the relative contribution from incoming gluons decreases with increasing momentum transfer $Q$, so does the fraction of events with a recoiling quark.

![Figure 2-12: Parton densities $x \cdot f (x, Q^2)$ probed in PYTHIA 8 photon+jet events as function of momentum fraction $x$ for $Q > 40$ GeV (left) and $Q > 300$ GeV (right). Partons corresponding to each density is marked with red text.](image)

2.2.1 Bulk observables

Jet modification in QCD medium are studied using observables where jet quantities are measured with respect to the EW boson (photon or Z boson in this thesis) that
Figure 2-13: Partron densities $x \cdot f(x, Q^2)$ probed in PYTHIA 8 photon+jet events as function of momentum fraction $x$ where the recoiling parton is a quark (left) or gluon (right). Partons corresponding to each density is marked with red text.

passes through QCD medium unmodified. The azimuthal angle difference between a EW boson and jet is defined as

$$\Delta \phi_{jV} = |\phi_{\text{jet}} - \phi_{V}|$$  \hspace{1cm} (2.13)

where the $V$ symbol is to be replaced with $Z (\gamma)$ if the EW boson is a Z boson (photon). The $\Delta \phi_{jV}$ distributions are studied to search for medium induced jet deflection effects in HI collisions. The transverse momentum imbalance between a EW boson and jet is defined as

$$x_{jV} = \frac{p_{T}^{\text{jet}}}{p_{T}^{V}}$$  \hspace{1cm} (2.14)

where, in order to increase the fraction of jets associated with the EW boson, the $V+\text{jet}$ pairs are required to satisfy the azimuthal separation of $\Delta \phi_{jV} > 7\pi/8$. The $x_{jV}$ distributions are used to quantify the jet energy loss in QCD medium. In this thesis, the $\Delta \phi_{jV}$ and $x_{jV}$ distributions are measured in Ch. C in $Z+\text{jet}$ events.

The hard scattering EW boson and the parton are to first order back-to-back
in azimuth and balanced in $p_T$. Thus, one would expect the $x_{j\gamma}$ distribution to be centered at 1 and spread around it due to detector effects and the spread would be leaned towards lower $x_{j\gamma}$, since a jet finding algorithm does not recover all of the hard parton energy (as seen in Fig. 2-6). However, the measured distributions in pp data (the upper panel in Fig. 6-10 and the left panel in Fig. 6-13) has a non-negligible number of V+jet pairs at values as large as $x_{j\gamma} \gtrsim 1.5$ meaning that $p_T^{\text{jet}}$ is at least 50% larger than $p_T^{\gamma}$. Given the $p_T$ selections of $p_T^{\gamma} > 60 \text{ GeV/c}$ and $p_T^{\text{jet}} > 30 \text{ GeV/c}$ in these measurements, it is very unlikely that detector resolution is responsible for this effect. Large $x_{j\gamma}$ can be understood via V+jet events generated using Pythia 8.

In order to understand the entries in large $x_{j\gamma}$ region, photon+jet events are generated using Pythia 8 at $\sqrt{s} = 5.02 \text{ TeV}$ (collision energy at the LHC). A set of parton level processes, specifically the multiparton interactions (MPI), initial-state radiation (ISR), and final-state radiation (FSR) [263], are simulated and their effect on the $\Delta \phi_{j\gamma}$ and $x_{j\gamma}$ distributions are studied in four settings that differ by the simulation of these processes being switched on or off. The first setting is the default setting in Pythia 8 which simulates all of the MPI, ISR, and FSR. Remaining settings switch off only one process in the first setting and keep the rest on. In particular, the second setting switches off the MPI, the third switches off the ISR, and the fourth switches off the FSR. Photons and jets are selected to have $p_T^{\gamma} > 60 \text{ GeV/c}$ and $p_T^{\text{jet}} > 30 \text{ GeV/c}$, respectively, the same kinematic selections as in the measurements [1, 243].

Fig. 2-14 shows the $\Delta \phi_{j\gamma}$ and $x_{j\gamma}$ distributions for the settings listed above. Both the $\Delta \phi_{j\gamma}$ and $x_{j\gamma}$ distributions are much sharper for the “ISR off” setting that switches the ISR off, specifically the $\Delta \phi_{j\gamma}$ is sharply peaked at $\Delta \phi_{j\gamma} \sim \pi$ falling more steeply with decreasing $\Delta \phi_{j\gamma}$ and the $x_{j\gamma}$ distribution vanishes for $x_{j\gamma} \gtrsim 1.2$. Hence, the wide distributions in V+jet correlations are predominantly due to the ISR.

The ISR effects on photon+jet observables are smaller for smaller collision energies. The left panel in Fig. 2-13 shows the $\Delta \phi_{j\gamma}$ distributions for the four settings at RHIC energies. The kinematic selections are $p_T^{\gamma} > 40 \text{ GeV/c}$ and $p_T^{\text{jet}} > 20 \text{ GeV/c}$, typical thresholds at the RHIC are slightly lower than at the LHC. Similar to the case at LHC energies, ISR is the dominant source for the widening of $\Delta \phi_{j\gamma}$ at RHIC.
Figure 2-14: Upper: The $\Delta \phi_{j\gamma}$ (left) and $x_{j\gamma}$ (right) distributions in photon+jet events generated using Pythia 8 where different physics processes are switched off one by one. Default setting simulates all of the MPI, ISR, FSR (black) and is compared to settings where MPI (blue), ISR(green), and FSR (violet) are turned off. Lower: Ratios of the distributions to the default setting.

Lower-left panels in Fig. 2-14 and Fig. 2-15 show ratios of the $\Delta \phi_{j\gamma}$ from the last three settings to the one from the default setting. At LHC (RHIC) energies, the “ISR off” setting and default settings differ by $\sim 100\%$ ($\sim 20\%$) at $\Delta \phi_{j\gamma} \approx \pi$, thus modification in the $\Delta \phi_{j\gamma}$ distributions due to ISR are larger at the LHC than at RHIC. The right panel of Fig. 2-15 compares the $\Delta \phi_{j\gamma}$ between the $\sqrt{s} = 5.02$ TeV (LHC) and $\sqrt{s} = 200$ GeV (RHIC) collision energies where same kinematic selections are applied for photon+jet pairs. The distribution is much sharper for the RHIC case because of the smaller ISR effects. Relatively smaller ISR effects at RHIC energies is due to the fact that the collision energy at RHIC is lower than at LHC, thus the phase space available for ISR is smaller at RHIC.
Figure 2-15: Upper left: The $\Delta \phi_{j\gamma}$ distributions in photon+jet events generated using Pythia 8 at $\sqrt{s} = 200$ GeV. Events are simulated separately for the four scenarios described in the text. Lower left: Ratios of the distributions to the default setting. Upper right: The $\Delta \phi_{j\gamma}$ distributions in Pythia 8 for $\sqrt{s} = 5.02$ TeV (black) and $\sqrt{s} = 200$ GeV (red) where same kinematic selections are used for both distributions. Default setting is used for parton level processes. Lower right: The $\sqrt{s} = 200$ GeV to $\sqrt{s} = 5.02$ TeV ratio of the distributions.

2.2.2 Jet structure observables

Fragmentation functions

The modification of parton showers in HI collisions can be studied using the jet structure observables. Fragmentation functions (FFs) represent the distribution of momentum fraction inside the parton shower and are sensitive to QCD medium effects [277, 278, 109, 279, 280, 281, 282, 283].

Jet FFs can be analyzed as distributions of the $\xi_{\text{jet}}$ variable [249] defined as

$$\xi_{\text{jet}} = \ln \frac{|p_{\text{jet}}^\parallel|^2}{p_{\text{trk}} \cdot p_{\text{jet}}} \quad (2.15)$$
where \( \mathbf{p}^{\text{jet}} \) and \( \mathbf{p}^{\text{trk}} \) are the 3-momenta of the jet and charged particle, respectively. Particles are required to fall within a cone of radius \( R \) around the jet direction where \( R \) is the jet distance parameter. For a particle satisfying this requirement does not necessarily mean that the particle is a constituent of the jet. Though, most particles satisfying the requirement happen to be constituents of the jet. For jets recoiling from an EW boson, one can study the distribution of an additional variable, \( \xi_T^V \), \[283\]

\[
\xi_T^V = \ln \frac{-|\mathbf{p}_T^V|^2}{\mathbf{p}_T^{\text{trk}} \cdot \mathbf{p}_T^V}
\] (2.16)

where \( \mathbf{p}_T^V \) and \( \mathbf{p}_T^{\text{trk}} \) are the \( p_T \) with respect to the beam direction of the EW boson and charged particle, respectively. Technically, \( \mathbf{p}_T \) is obtained from \( \mathbf{p} \) by setting the \( \eta \)-coordinate to 0. The \( \mathbf{p}_T^V \) is used instead of \( \mathbf{p}_T^V \), because the recoiling EW boson and parton have the same \( |p_T| \) at LO, but not necessarily the same magnitude of longitudinal momentum. Both the \( \xi^{\text{jet}} \) and \( \xi_T^V \) distributions are normalized by the number of jets, hence the distribution integral gives the average number of charged particles per jet. For jets recoiling from a Z boson (photon), the \( \xi_T^V \) symbol is replaced with \( \xi_T^Z \) (\( \xi_T^\gamma \)).

It can be seen from the definitions in eqns. \[2.13\] and \[2.16\] that large \( \xi^{\text{jet}} \) (\( \xi_T^V \)) regions are populated with low \( p_T \) charged particles or high \( p_T \) jets (EW bosons). Figs. \[2-16\] \[2-17\] \[2-18\] \[2-17\] depict the relation between \( \xi^{\text{jet}} \) and \( \xi_T^V \) for various photon, jet, and charged particle kinematics.

The left panel in Fig. \[2-21\] shows the \( \xi^{\text{jet}} \) distribution in PYTHIA photon+jet events. The distributions exhibit the hump backed plateau \[29\] of FFs, as the distributions do not peak at the largest \( \xi^{\text{jet}} \) (smallest value of \( p_T^{\text{trk}}/p_T^{\text{jet}} \)), but instead inside the \( 2.5 < \xi^{\text{jet}} < 3.0 \) region. The gluon initiated parton showers fragment into more soft (low-energy) particles than quark initiated jets, i.e. gluon jets have softer fragmentation than quark jets. There are on average \( \approx 5.0 \) (6.8) charged particles inside the jet cone for quark (gluon) jets, thus gluon initiated parton showers have more particles (as seen Fig. \[2-3\]).
Figure 2-16: Left: $p_T^{\text{jet}}$ calculated as a function of $\xi^{\text{jet}}$ for different $p_T^{\text{trk}}$ selections. Right: $p_T^{\text{trk}}$ calculated as a function of $\xi^{\text{jet}}$ for different $p_T^{\text{jet}}$ selections. The $\Delta R$ between the track and the jet is 0. Figure taken from Ref. [2].

Figure 2-17: Left: $p_T^{\text{jet}}$ calculated as a function of $\xi^{\text{jet}}$ for $p_T^{\text{trk}} = 1 \text{ GeV}/c$ in different $\eta^{\text{jet}}$ and $|\eta^{\text{trk}}| - |\eta^{\text{jet}}|$ selections. Right: $p_T^{\text{trk}}$ calculated as a function of $\xi^{\text{jet}}$ for $p_T^{\text{jet}} = 30 \text{ GeV}/c$ in different $\eta^{\text{jet}}$ and $|\eta^{\text{trk}}| - |\eta^{\text{jet}}|$ selections. The $\Delta \phi$ between the track and the jet is 0. Figure taken from Ref. [2].
Figure 2-18: Left: $p_T^\gamma$ calculated as a function of $\xi_T^\gamma$ for different $p_{T,\text{trk}}$ selections. Right: $p_T^\gamma$ calculated as a function of $\xi_T^\gamma$ for different $p_T^\gamma$ selections. The $\Delta\phi$ between the track and the photon is $\pi$. Figure taken from Ref. [2].

Figure 2-19: Left: $p_T^\gamma$ calculated as a function of $\xi_T^\gamma$ for $p_{T,\text{trk}} = 1$ GeV/c and different selections of the $\Delta\phi$ between the track and the photon. Right: $p_T^\gamma$ calculated as a function of $\xi_T^\gamma$ for $p_T^\gamma = 60$ GeV/c and different selections of the $\Delta\phi$ between the track and the photon. Figure taken from Ref. [2].
Jet shapes

FFs give information about the momentum distribution inside a parton shower along the longitudinal direction (parallel to the jet propagation). The jet structure in the transverse direction can be studied using a “jet shape” observable which is a measurement of the energy distribution along the axis transverse to the direction of jet propagation. Therefore, jet shapes are also proposed to be useful tools for parton shower modifications in QCD medium \[284, 285, 286\]. The differential jet shape \(\rho (r)\) is defined as

\[
\rho (r) = 1 \frac{\sum_{\text{jets}} \sum_{r_a < r < r_b} (p_T^\text{trk} / p_T^\text{jet})}{\delta r \sum_{\text{jets}} \sum_{0 < r < r_f} (p_T^\text{trk} / p_T^\text{jet})},
\]

where \(\delta r = r_b - r_a\) is the width of the annulus of inner and outer radii \(r_a\) and \(r_b\) with respect to the jet axis, respectively. The \(p_T^\text{trk}\) is the \(p_T\) of charged particles falling within each annulus of the jet with \(p_T^\text{jet}\), and \(r = \sqrt{(\eta^\text{jet} - \eta^\text{trk})^2 + (\phi^\text{jet} - \phi^\text{trk})^2}\) is the angular distance between the particle and the jet axis. The distribution is normalized such that the integral inside the range \(0 < r < r_f\) is unity where \(r_f = R = 0.3\). Hence, \(\rho (r)\) gives a measure of how the \(p_T\) of a jet is distributed (over charged particles) in a direction transverse to the jet axis. Fig. 2-20 illustrates the geometry for \(\rho (r)\) calculation.

The right panel in Fig. 2-21 shows the \(\rho (r)\) distribution in PYTHIA photon+jet events. The \(\rho (r)\) distribution is a steeply falling function of \(r\). This is also seen in measurements \[287, 245\]. The more steeply falling with \(r\), the sharper is the jet shape. Gluon jet shapes are wider than quark jet shapes, i.e. for gluon jets the fraction of the energy radiated to large angles is larger than for quark jets (as seen in Fig. 2-4). In the inclusive photon+jet sample, \(~80\%\) of the energy is carried by particles in the \(r < 0.1\) region, the energy fraction carried in the \(0.25 < r < 0.3\) region is \(~2\%) much smaller.

The jet structure evolves with the jet energy. Fig. 2-22 compares the \(\zeta^\text{jet}\) and \(\rho (r)\) distributions between jets with two different \(p_T\) requirements. The \(\zeta^\text{jet}\) distributions
show that higher $p_T$ jets have more particles where the additional particles are mostly low energy particles. The $\rho (r)$ distributions show that higher $p_T$ jets have narrower shapes, i.e. a larger fraction of the jet energy is radiated at small distances.

The sensitivity to the hadronization process is studied for the jet structure observables. Fig. 2-23 shows the $\xi^{\text{jet}}$ and $\rho (r)$ distributions constructed separately using charged particles, i.e. particles in hadronic state, and using partons. There are sizable differences between particle-level (hadronic) and parton-level distributions, implying both observables are sensitive to the hadronization process (Differences actually persist for jets with $p_T^{\text{jet}} \gtrsim 90$ GeV/c). The differences for the $\rho (r)$ distribution ranges from 20\% to 40\%. On the other hand, the differences for the $\xi^{\text{jet}}$ distribution is larger than 100 (50)\% for the $\xi^{\text{jet}} < 0.5$ ($\xi^{\text{jet}} > 3$) region. Differences between partons and hadrons are larger for FFs, i.e. the momentum and multiplicity distribution in the longitudinal direction, than for jet shapes, i.e. the radial momentum density profile.
Figure 2-21: The $\xi^\text{jet}$ (left) and $\rho(r)$ (right) distributions for jets from particle level PYTHIA 8 simulation of prompt photon+jet events. Photons have $p_T^{\gamma} > 60$ GeV/c and jets are selected to satisfy $p_T^{\text{jet}} > 30$ GeV/c and $\Delta\phi_{\gamma\text{jet}} > 7\pi/8$. The distributions are constructed using charged particles with $p_T > 1$ GeV/c, for jets from all parton flavors (black) and for jets initiated by quarks (blue) and gluons (red).

### 2.3 Jets in heavy ion collisions

Particles produced in hard scattering processes in AA collisions are useful probes to study the properties of QCD medium. Hard probes are formed in time scales of $\tau \sim 1/Q$, shorter than QCD medium formation (as mentioned before in Sec. 1.4.2), thus explore the complete evolution of QCD medium. Besides, production of hard probes can be calculated using the pQCD framework.

Energy loss of high energy partons was the first proposed phenomenon where hard probes could reveal the formation of QCD medium [76]. Partons would interact with the QCD medium as they penetrate through and lose energy in these interactions. The analogy of this phenomenon for QED matter would be the passage of electrically charged particles through atomic matter where the Bethe equation [29] relates the mean energy loss of a particle to the particle’s kinematics as well as matter’s properties such as charge density and atomic mass. Similarly, the amount of parton energy loss depends both on the properties of the parton itself and QCD medium, and could be
Figure 2-22: The $\xi^\text{jet}$ (left) and $\rho (r)$ (right) distributions for jets from particle level PYTHIA 8 simulation of prompt photon+jet events. Photons have $p_T^\gamma > 60 \text{ GeV/c}$ and jets are selected to satisfy $\Delta \phi_{j\gamma} > 7\pi/8$. The distributions are constructed using charged particles with $p_T > 1 \text{ GeV/c}$, for jets with $p_T^{\text{jet}} > 30 \text{ GeV/c}$ (black squares) and $p_T^{\text{jet}} > 90 \text{ GeV/c}$ (green circles).

expressed as

$$\Delta E_{\text{parton}} = f (E_{\text{parton, color}}, \alpha, L, \rho, T)$$

where $\alpha$, $L$, $\rho$, and $T$ are the parton-medium coupling, the medium length traversed, the medium density and temperature, respectively. Note that the actual energy loss function $\Delta E_{\text{parton}}$ can (and does very likely) depend on more variables than listed in eq. (2.18). Fig. 2-24 shows the average energy loss for electrically charged projectiles in copper (a dense QED matter) as function of the projectile’s momentum. Effect of different energy loss mechanisms differ with the projectile momentum. For intermediate projectile momentum ($0.1 \lesssim \beta \gamma \lesssim 1000$), the energy loss proceeds predominantly via ionization, i.e. elastic scatterings. At higher momentum ($\beta \gamma \gtrsim 1000$), radiation effects emerge and the energy loss rises rapidly with the projectile momentum. In principle, the parton energy loss in QCD medium can also be modelled separately as collision and radiation processes.
Figure 2-23: The $\zeta_{\text{jet}}$ (left) and $\rho(r)$ (right) distributions for PYTHIA 8 simulation of prompt photon+jet events. Photons have $p_T^\gamma > 60$ GeV/c and jets are selected to satisfy $p_T^{\text{jet}} > 30$ GeV/c and $\Delta\phi_{j\gamma} > 7\pi/8$. The distributions are constructed first using partons with $p_T > 1$ GeV/c for jets clustered using partons (violet squares), then using charged particles with $p_T > 1$ GeV/c for jets clustered using particles in hadronic state (black circles).

### 2.3.1 Parton energy loss

A parton loses energy in QCD medium either by radiating a gluon (illustrated in Fig. 2-25) and or colliding with other partons in the medium (illustrated in Fig. 2-26). Thus, energy loss can be expressed as a sum of the “radiative” and “collisional” energy losses

$$\Delta E_{\text{parton}} = \Delta E_{\text{rad}} + \Delta E_{\text{coll}}$$  (2.19)
Collisional energy loss

The first parton energy loss calculation \cite{76} was based on collisions, i.e. elastic scatterings, between the incident parton and another parton in the medium. Other early works included Refs. \cite{288,289}. Calculations were improved later by including various effects such as running coupling constant, quark mass, medium size and evolution \cite{290,291,292,293}.

The amount of collisional energy loss should be proportional to the medium density \( \rho \) and the elastic scattering cross section \( \sigma^{\text{coll}} \)

\[
\Delta E_{\text{coll}} \propto \rho \sigma^{\text{coll}} \tag{2.20}
\]

The differential cross section for elastic scattering with small momentum transfer
\[
\frac{d\sigma^{\text{coll}}}{dt} = C \frac{2\pi \alpha_s^2(t)}{t^2}
\] (2.21)

where the proportionality constant \( C \) depends on the flavors of partons involved in the scattering. The energy loss per length is given as

\[
-\frac{dE^{\text{coll}}}{dx} \propto \int d^3k \, \rho(k) \int_{t_{\text{min}}}^{t_{\text{max}}} dt \, \frac{d\sigma^{\text{coll}}}{dt} \, t
\] (2.22)

where \( J = 1/(2k) \) is a flux factor [294]. The value for the boundary \( t_{\text{min}} \) is dictated by the Debye screening mass squared \( m_D^2 \sim \alpha_s T^2 \). The value for \( t_{\text{max}} \) is dictated by the incident parton energy and the medium parton energy, thus \( E \cdot T \), where \( T \) is the medium temperature [294, 295] which is proportional to the average energy of medium.
partons. The collisional energy loss reduces to the following form \cite{76, 294, 295}

\[- \frac{dE_{\text{coll}}}{dx} \propto \alpha_s^2 T^2 \ln \left( \frac{E}{T} \right) \] (2.23)

proportional to the medium temperature squared.

**Radiative energy loss**

Partons lose energy not only via collisions, but also via gluon radiation induced by the QCD medium. Early works for radiative energy loss include Refs. \cite{77, 296, 79, 80}. The radiative energy loss is generally calculated as integral of the radiated gluon energy spectrum \( \omega \frac{dI}{d\omega} \) \cite{294, 295, 297, 298}

\[ \Delta E_{\text{rad}} = \int_0^{\infty} d\omega \; \omega \frac{dI}{d\omega} \] (2.24)

where \( \omega \) is the radiated gluon energy. Different approximations were followed to calculate eq. 2.24, common examples are the multiple soft scattering approximation \cite{299} and the opacity expansion \cite{300}. Fig. 2-27 shows an example of the \( \omega \frac{dI}{d\omega} \) distribution in multiple soft scattering approximation. Details of the radiation spectrum depends on models (see Sec. 2.3.2).

A well-known calculation is provided in the Baier-Dokshitzer-Mueller-Peigné-Schiff (BDMPS) framework \cite{81}. The calculation considers an energetic parton traversing a finite size medium of length \( L \), filled with heavy (almost static) scattering centers. Multiple scattering of the parton in the medium induces gluon radiation. The mean free path \( \lambda \) is related to the medium density \( \rho \) and interaction cross section \( \sigma \)

\[ \lambda = \frac{1}{\rho \; \sigma} \] (2.25)

The Debye screening length \( m_D^{-1} \) is assumed to be much smaller than the mean free path \( \lambda \) so that successive scatterings can be treated independent

\[ \frac{1}{m_D} \ll \lambda \] (2.26)
Figure 2-27: The radiated gluon energy spectrum $\omega \frac{dI}{d\omega}$ in the multiple soft scattering approximation for different values of the kinematic constraint $R = \omega_c L$, where $\omega_c$ is the “characteristic gluon frequency”, an upper bound for the radiated energy, and $L$ is the QCD medium length. Figure taken from Ref. [301].

It is also assumed that the medium is much longer than the mean free path to allow multiple scatterings

$$\lambda \ll L \quad (2.27)$$

Lastly, it is assumed that the incident parton energy $E_{\text{parton}}$ is much larger than the radiated gluon energy $\omega$

$$E_{\text{parton}} \gg \omega \quad (2.28)$$

Following these assumption, the radiative energy loss in the BDMPS framework [81] is found as

$$-\frac{dE_{\text{rad}}}{dx} \propto \alpha_s \hat{q} L \quad (2.29)$$

giving a total radiative energy loss that is proportional to the distance travelled.
squared

\[ \Delta E_{\text{rad}} \propto \alpha_s \, \hat{q} \, L^2 \]  \hspace{1cm} (2.30)

where the transport coefficient \( \hat{q} \) is a measure of the medium “scattering power” \[302\].

\[ \hat{q} \propto \frac{m_D^2}{\lambda} = m_D^2 \rho \sigma \]  \hspace{1cm} (2.31)

a quantity that combines the medium bulk properties and parton-medium interaction rates. The radiative energy loss formula in eq. 2.29 was for a static medium, later on it was generalized to an expanding medium in Ref. [82].

2.3.2 Calculations and models

BDMPS

The BDMPS calculations [81, 82] treat the radiative energy loss as multiple soft gluon scatterings. Same results were derived independently in Refs. [299, 303] and their equivalence to BDPMS results was shown in Ref. [304].

An important calculation from the BDMPS was broadening of the \( p_{\perp} \), momentum distribution in the plane transverse to the parton propagation \[305\]. The \( p_{\perp} \)-broadening effect relates the energy loss to the \( p_{\perp W}^2 \), the characteristic width of the \( p_{\perp} \) via

\[- \frac{dE_{\text{rad}}}{dx} \propto p_{\perp W}^2 \]  \hspace{1cm} (2.32)

The energy loss per unit length would be proportional to the broadening of the parton shower in the direction transverse to its propagation. The \( p_{\perp} \)-broadening would imply a widening of the azimuthal correlations (e.g. the \( \Delta \phi_{V} \) distributions in \( V+\text{jet} \) events) in AA collisions, an effect that was not observed at the LHC [217, 216, 218, 242, 243, 306, 220, 1]. The lack of a widening in the azimuthal correlations at the LHC can be due to large vacuum radiation effects that smear the correlations.
(e.g. the ISR effects shown in Fig. 2-14) and as a result wash out the $p_\perp$-broadening effects $[307, 308]$. Angular correlations measured at RHIC could provide a more accurate test of the broadening effects since the smearing effects are smaller at RHIC energies (see Fig. 2-15).

ASW

The Armesto-Salgado-Wiedemann (ASW) approach $[301, 309]$ introduced the “quenching weights” $P_E(\epsilon, \hat{q})$ to represent the probability for a parton to lose a fraction $\epsilon$ of its energy and later on implemented the quenching weights in a Monte Carlo program, the Parton-Quenching-Model (PQM) $[310]$.

GLV

The Gyulassy-Lévai-Vitev (GLV) approach $[311, 312]$ poses the same assumptions about the medium as in BDMPS mentioned in Sec. 2.3.1, i.e. a medium with heavy scattering centers. Instead of the multiple soft scatterings in BDMPS, the GLV model formulates the energy loss as one hard radiation and addresses the multiple scatterings via opacity expansion $[84, 83, 300]$. Calculations based on GLV for Z-tagged jet energy loss are compared to the measured results in Sec. 6.3.1.

The BDMPS, ASW, and GLV frameworks mentioned above have one common assumption that the radiated gluon’s energy $\omega$ is much smaller than the parton energy $E_{\text{parton}}$ and the gluon’s transverse momentum $k_\perp$ is much smaller than its energy $[297]$

$$E_{\text{parton}} \gg \omega \gg k_\perp \quad (2.33)$$

HT

The higher twist (HT) model $[278, 313]$ treats multiple scattering of partons as power corrections to the leading twist cross section. This approach was originally used in deep inelastic scattering calculations to account for the rescattering of a nucleus parton struck by an incoming lepton. The HT model incorporates the interference
between the vacuum and medium induced radiations, thus can directly calculate the medium induced modifications of the FFs. On the other hand it is more applicable for short medium lengths.

**AMY**

The Arnold-Moore-Yaffe (AMY) approach \cite{AMY1,AMY2,AMY3} calculates the parton energy loss by assuming the temperature $T$ of the QCD medium is much larger than the running strong coupling constant $g_s(T)$. Energetic partons scatter off in the medium with momentum transfers of $\mathcal{O}(g_s(T) T)$ resulting in gluon radiation. The AMY approach is a model-independent formulation of the medium induced radiation, however its applicability is limited to a thermalized medium.

**SCET$_G$**

The SCET$_G$ \cite{SCETG1,SCETG2} is a version of the soft collinear effective theory (SCET) \cite{SCET1,SCET2,SCET3} combined with Glauber gluon interactions in QCD medium. SCET describes the dynamics of energetic partons. In SCET$_G$, energetic partons interact with the medium via Glauber gluons, i.e. fields created by partons in the medium.

The photon-tagged jet FF and jet shape calculations based on SCET$_G$ are compared to the measurements in Secs. 7.4.1 and 8.3.1 respectively. In addition, calculations for Z-tagged FFs and recoil charged particle spectrum are compared to the measurements in Sec. 9.4.1.

**Hybrid**

The Hybrid model \cite{Hybrid1,Hybrid2} is a phenomenological approach where processes at different energy scales are treated differently. The weakly coupled processes of parton shower evolution from the formation of hard scatterers up to the start of hadronization are treated via pQCD. The strongly coupled processes between the high energy partons and QCD medium are treated with a gauge/gravity duality description of the medium dynamics.
Energy loss of a high energy quark in a strongly coupled plasma has the form \[^{283}\]

\[-\frac{dE_{SC}}{dx} \propto E_{in} \frac{x^2}{x_{stop}^2} \frac{1}{\sqrt{x_{stop}^2 - x^2}} \tag{2.34}\]

\[x_{stop} = \frac{1}{2 \kappa_{SC}} \frac{E_{in}^{1/3}}{T^{4/3}} \tag{2.35}\]

where \(E_{in}\) is the quark’s energy before entering the plasma, and \(x_{stop}\) is the stopping distance, the shortest distance along which the quark loses all its energy. The dimensionless “strong coupling” constant \(\kappa_{SC}\) is given in terms of the ’t Hooft coupling \(\lambda\) \[^{87}\] as \(\kappa_{SC} = 1.05 \lambda^{1/6} \) \[^{321, 283}\].

In addition to the strong coupling, the Hybrid model implemented collisional and radiative energy losses given by

\[-\frac{dE_{rad}}{dx} = \kappa_{rad} T^3 x \tag{2.36}\]

\[-\frac{dE_{coll}}{dx} = \kappa_{coll} T^2 \tag{2.37}\]

where the values for constants \(\kappa_{rad}\) and \(\kappa_{coll}\) are fit from the experiment data \[^{283}\].

Sec. 6.3.1 compares Hybrid model’s predictions for energy loss of Z-tagged jets to the measured results. Secs. 7.4.1, 8.3.1, and 9.4.1 compare the measurements for photon-tagged jet structure and Z+hadron correlations to Hybrid model’s predictions.

**LBT**

The linear Boltzmann transport (LBT) model \[^{322}\] combines the parton propagation with the hydrodynamics description of the medium evolution. The propagation of parton \(a\) in the medium is described by linear Boltzmann equations for elastic
\[ -p_1 \partial f_a (p_1) = \int \frac{dp_2^3}{(2\pi)^3} \frac{dp_3^3}{2E_2} \int \frac{dp_4^3}{(2\pi)^3} \frac{dp_4^4}{2E_3} \int \frac{dp_4^4}{(2\pi)^3} \frac{dp_4^4}{2E_4} \]
\[ \sum_{b,(c,d)} g_b \left[ f_a (p_1) f_b (p_2) - f_c (p_3) f_d (p_4) \right] |M_{ab\rightarrow cd}|^2 \]
\[ \times S_2 (s, t, u) (2\pi)^4 \delta^4 (p_1 + p_2 - p_3 - p_4) \]  

where the sum is over all medium partons \( b \) and all possible partons \( (c, d) \) that leave the scattering. Scattering matrix elements are given by \( |M_{ab\rightarrow cd}|^2 \) and \( s, t, u \) are Mandelstam variables \([29]\). The model can keep track of the medium partons that recoil from the incident energetic partons \([322]\). Later work coupled LBT with the 3+1 dimensional hydrodynamic description of QCD medium, giving the CoLBT-hydro framework \([255]\).

The photon-tagged jet FF and \( Z + \)hadron correlations calculations based on CoLBT-hydro are compared to the measurements in Sec. 7.4.1 and Sec. 9.4.1 respectively. The LBT calculations for the photon-tagged jet shapes are compared to the measurements in Sec. 8.3.1.

### 2.3.3 Very simplistic model for energy loss

Particles produced in hadron collisions have a steeply falling \( p_T \) spectrum in the high \( p_T \) region which can be characterized empirically with a power law

\[ \frac{dN}{dp_T} \propto p_T^{-n} \]  

where \( n > 0 \).

In the following, a simplistic model to extract the amount of energy loss is presented. The assumptions of this model are

- \( R_{AA} \) is constant as function of \( p_T \)
- The \( p_T \) spectrum follows a power law, as in eq. 2.39
• Energy loss is a function of $p_T$ only and proportional to the $p_T$, as in eq. 2.47

The last assumption is faulty as there are likely many other factors playing a role in the energy loss, such as medium density, length, and temperature that are ignored in this model. Assuming that energy loss is a one-to-one function of $p_T$ only, then the $p_T$ after energy loss, $p_T^{AA}$, and the $p_T$ in vacuum, $p_T^{vac}$ can be mapped via

$$p_T^{AA} = g_{AA}(p_T^{vac})$$

$$\rightarrow p_T^{vac} = g_{Vac}(p_T^{AA}) = g_{AA}^{-1}(p_T^{AA})$$

where $g_{AA}$ is a function that maps the $p_T$ in vacuum, i.e. no energy loss, to the $p_T$ after energy loss, and $g_{Vac}$ is the inverse of $g_{AA}$. In that case the density of particles in HI collisions around $p_T^{AA}$ would be the same as density in pp collisions around $p_T^{vac}$

$$\frac{dN^{AA}}{dp_T^{AA}} dp_T^{AA} = \frac{dN^{pp}}{dp_T^{vac}} dp_T^{vac}$$

(2.42)

The number of particles in HI collisions around $p_T^{AA}$ can be related to the one in pp collisions via

$$dN^{AA}(p_T^{AA}) = dN^{pp}(p_T^{vac}) \left| \frac{dp_T^{vac}}{dp_T^{AA}} \right|$$

$$= dN^{pp}(g_{Vac}(p_T^{AA})) \left| \frac{dp_T^{vac}}{dp_T^{AA}} \right|$$

(2.43)

(2.44)

Plugging this relation in the $R_{AA}$ formula (eq. 1.6) gives

$$R_{AA}(p_T^{AA}) = \frac{dN^{pp}(g_{Vac}(p_T^{AA}))}{dN^{pp}(p_T^{AA})} \left| \frac{dp_T^{vac}}{dp_T^{AA}} \right|$$

(2.45)

where the $\langle N_{coll} \rangle$ was assumed to be accounted in $N^{AA}$ and omitted for simplicity.

Adding the assumption of $p_T$ spectrum follows power law, eq. 2.39 gives

$$R_{AA}(p_T^{AA}) = \left( \frac{g_{Vac}(p_T^{AA})}{p_T^{AA}} \right)^{-n} \left| \frac{dp_T^{vac}}{dp_T^{AA}} \right|$$

(2.46)
Now, assume an energy loss that is proportional to the $p_T$

$$p_{T\AA}^{AA} = g_{AA} (p_{T\text{vac}}^{AA}) = (1 - C_{E-\text{loss}}) p_{T\text{vac}}^{AA}$$  \hspace{1cm} (2.47)

$$\implies p_{T\text{vac}}^{AA} = g_{\text{Vac}} (p_{T\AA}^{AA}) = \frac{p_{T\AA}^{AA}}{1 - C_{E-\text{loss}}} \hspace{1cm} (2.48)$$

where $C_{E-\text{loss}}$ would be the energy loss proportionality factor. Then the $R_{AA}$ expression in eq. 2.46 becomes

$$R_{AA} (p_{T\AA}^{AA}) = (1 - C_{E-\text{loss}})^{n-1} \hspace{1cm} (2.49)$$

Note that $R_{AA}$ becomes independent of $p_T$ if the spectrum follows power law (eq. 2.39) and if the energy loss is proportional to $p_T$ (eq. 2.47).

Fractional energy loss in this simplistic model can be expressed as function of $R_{AA}$ as

$$C_{E-\text{loss}} = 1 - R_{AA}^{1/(n-1)} \hspace{1cm} (2.50)$$

Similar derivations can be found in Refs. [323, 60]. Fig. 2-28 shows $C_{E-\text{loss}}$ for different values of $n$.

This simplistic formula can be applied to data. The power law fit to the $p_T$ spectrum at $\sqrt{s_{NN}} = 200$ GeV yields $n \approx 8$ for $p_T > 3$ GeV/c [60]. Observing that $R_{AA}$ in central collisions is almost constant at 0.2 (see Fig. 1-8) will point to a fractional energy loss of $\approx 20\%$ at RHIC energies. The power law fit to the $p_{T\text{jet}}$ spectrum at LHC energies yields $n \approx 5 - 6$ for $p_{T\text{jet}} \gtrsim 50$ GeV/c [323]. The jet $R_{AA}$ in central collisions at the LHC evolves slowly with the $p_{T\text{jet}}$, from around 0.45 at $p_{T\text{jet}} \sim 100$ GeV/c to around 0.6 at $p_{T\text{jet}} \sim 300$ GeV/c (see Fig. 1-13), pointing to a fractional energy loss between 10% and 20% at the LHC.

It is crucial to state that application of this simplistic model to jets is built entirely upon treating a jet as a single parton and this is not at all a realistic assumption. The model ignores the jet-by-jet fluctuations of energy loss, i.e. not all jets with the same $p_T$ lose the same amount of energy since energy loss depends on the jet structure as
Energetic partons are modified by a QCD medium, simultaneously the medium is modified by the passage of energetic partons, an effect referred to as “medium response” or “medium recoil”. Theoretical studies of jet induced medium modifications materialized later than the jet modifications studies. Early works focused on the “conical flow” or the “Mach cones” that the jet would induce in the medium along its direction of propagation [324, 325, 86, 326, 327, 328, 329].

Effects of medium response on jet observables were calculated by a number of
models, e.g. the Hybrid model \cite{253}, JEWEL \cite{254}, and LBT \cite{252, 330, 322, 255, 331, 332, 333, 334}. A common feature of the medium response between various models is that it produces low energy particles that are found at large angles with respect to the parton shower. The left panel in Fig. 2-29 shows a prediction for the modification of photon-tagged jet shapes in PbPb collisions where the effect of medium response is to increase the fraction of jet energy carried at large distances from the jet axis (The photon-tagged jet shape measurements in this thesis are compared to model calculations in Sec. 8.3.1).

Calculations investigated the medium response in different angles with respect to the jet direction. Most models predict the medium to be enhanced along the jet direction \cite{253, 254, 322, 255}. Interestingly, a medium depletion was predicted “behind” the jet, i.e. along the direction opposite the jet direction of propagation \cite{255}. The right panel in Fig. 2-29 shows a medium simulation in the presence of a jet recoiling from a photon. While the medium is excited along the jet direction (the red, hot region), a depletion is calculated behind the jet (the blue, cold region). (The Z+hadron correlations measurements in this thesis explore the medium response as function of angle with respect to the jet direction and results are compared to model calculations in Sec. 9.4.1).

2.5 Cold nuclear matter effects

Differences between pp and HI collisions do not originate only due to QCD medium formation, as pointed out previously in Sec. 1.4.2 Differences can also arise from cold nuclear matter (CNM) effects which occur before and thus independent of QCD medium formation.

Although the high $p_T$ particle suppression at RHIC \cite{91, 92, 93, 94, 95, 96, 97} was thought to be primarily due to QCD medium (final state) effects, an inarguable evidence for this interpretation was lacking and there were models which proposed that the modifications could be due to CNM effects \cite{333}. Collisions between light nuclei (protons or deuterons) and heavy nuclei were used to investigate the role of
Figure 2-29: Left: Calculations for the PbPb-to-pp ratio of photon-tagged jet shapes (defined in eq. 2.17) are performed with (red curve) and without (blue curve) including the contributions from medium response. Figure taken from Ref. [333]. Right: Simulation of a jet (straight lines) recoiling from a photon (wavy line) in QCD medium. The upper (lower) panel corresponds to early (late) times. The left and right panel show the energy density in units of GeV/fm$^3$ for the modified parton shower and the excited medium relative to the medium without excitation, respectively. Figure taken from Ref. [255].

CNM effects in high energy spectrum modification. These are pA and dA collisions, where QCD medium effects are very small, but CNM effects are very similar to those in AA collisions.

The high energy spectrum in dA collisions at RHIC turned out to be much more similar to the one in pp [101, 102, 103, 104] (the $R_{pA}$ did not deviate from 1 as much as the $R_{AA}$ did), providing the inarguable evidence that the modification for high energy particles were due to final state effects.

Below are some of the CNM effects playing a role in high energy particle production in HI collisions.
2.5.1 Nuclear parton distribution functions

The nuclear structure function of large nuclei is not a simple superposition of proton and neutron structure functions. That is, nPDFs (PDFs for nucleons in nuclei) are not the same as PDFs (for free nucleons).

The first evidence for nPDFs being different than PDFs came from the European Muon Collaboration (EMC) [336]. The EMC effect, observation was named after the collaboration, was that the $x \gtrsim 0.2$ region was suppressed in nPDFs compared to PDFs. Later studies showed a suppression for the $x \lesssim 0.01$ region, labelled “shadowing”, [337] and an enhancement in the $0.01 \lesssim x \lesssim 0.1$ region, labelled “anti-shadowing”, [338].

While deep inelastic scattering experiments explored the quark nPDF [339], stronger constraints for the gluon nPDF came from the LHC experiments, e.g. from the dijet measurements in pPb collisions [340, 341]. The modification of parton distributions in Pb nucleus compared to free protons is calculated in Ref. [342] using constraints from earlier LHC data in Ref. [340] and is shown in Fig. 2-30. The shadowing, anti-shadowing, and EMC effects can be recognized in the calculations. Precision for the gluon nPDF is worse than that for the quark nPDF and is expected to improve after using the latest LHC results in Ref. [341].
2.5.2 Cronin effect

As proton collides with a heavier nucleus, it undergoes multiple scattering before its final collision, leading to the “Cronin effect” in the low to intermediate $p_T$ region of particle spectrum [343, 344, 107]. Production of low $p_T$ particles are suppressed proportional to $A^{2/3}$ where $A$ is the number of nucleons in the nuclei. On the other hand, multiple scattering smears the spectrum to larger $p_T$, enhancing the larger $p_T$ region. The multiple scattering effects diminish at larger $p_T$ and particle production reverts to binary scaling.

Cronin effect can be seen in the RHIC $R_{dA}$ (see Fig. 1-8) which is suppressed for $p_T \lesssim 2$ GeV/c and enhanced for $p_T \gtrsim 2$ GeV/c.
Chapter 3

Experiment apparatus

Experiment apparatus is the Compact Muon Solenoid (CMS) detector at the LHC, CERN. The CMS detector has a cylinder shape and the beam axis, along which particle interactions happen, is at the center of that cylinder. The interactions are symmetric under rotations in azimuthal angle $\phi$, hence a cylinder shape is a well-suited detector geometry for this experiment.

The CMS coordinate system follows the same definition provided in Sec. 1.3.1. Specifically, the $x$-axis points to the center of the LHC ring, the $y$-axis points vertically upwards, and $z$-axis points along the beam direction.

Several subdetectors are used to detect and reconstruct the physics objects that were analyzed in the measurements presented in this thesis. The tracker is the subdetector closest to beam axis, and is used in the reconstruction of charged particles. Electromagnetic and hadronic calorimeters surround the tracker and they measure the energy deposited from electromagnetically interacting particles and hadrons, respectively. A superconducting solenoid surrounds the calorimeters in the barrel region and provides a magnetic field of 3.8 T directed along the $z$-axis. The outermost layer is the muon system which employs gas-ionization detectors to track trajectories of muons which penetrate the calorimeters without being stopped. The subdetectors fully cover the azimuthal angle space ($2\pi$ coverage), leaving no acceptance deficiency in that space. Fig. 3-1 shows the layout of the CMS detector.

Geometry of the subdetectors varies depending on their position along the beam
axis with respect to the nominal collision point, i.e. the rapidity. For small $|\eta|$, the detectors have the shape of a cylinder or a hollow cylinder packed into each other, this region of a subdetector is referred to as the “barrel”. For large $|\eta|$, the detectors look more like disks placed back to back, and these regions are referred to as the “endcaps”.

The CASTOR calorimeter and Zero Degree Calorimeters are placed at very large $|\eta|$, designed to serve programmes in diffractive $pp$ collisions and very forward region physics in heavy ion collisions. These subdetector are not used for the work in this thesis.

Detailed information about the CMS detector can be found in Ref. [163].
3.1 Tracker

The CMS inner tracking system, the “tracker”, is used in measuring the position of interaction vertex and in the reconstruction of charged particles, covering the $|\eta| < 2.5$ range in $\eta$-coordinates. It consists of silicon pixel modules which surround the beam axis and silicon strip modules which surround the pixel modules. Pixel modules surround the beam axis and provide a fine angular resolution in a small volume thanks to the densely packing of its pixels each of which having a surface area of $150 \times 100 \mu m^2$. Strip modules surround the pixel modules, extending the outer radius of the tracker up to $r = 120$ cm which increases the trajectory coverage to a larger length and improves the momentum resolution of measured charged particles. The width of strips vary between 80 and 180 $\mu m$.

Pixel modules went through an upgrade between 2016 and 2017 where the configuration with three pixel module layers was replaced with a four layer configuration [345]. The improvements provided by this upgrade were utilized in the charged particle reconstruction for the $Z+$hadron correlations measurement presented in Ch. [9].

Fig. 3-2 shows the track momentum resolution. The momentum resolution is better than $3\%$ for charged pions with $|\eta| < 1$ and $p_T$ up to 100 GeV/c. The resolution deteriorates with increasing $|\eta|$, e.g. at $|\eta| = 2.5$ it reaches up to 4% for $p_T < 10$ GeV/c and becomes worse than 10% for $p_T = 100$ GeV/c.

The tracker has a good spatial resolution thanks to its fine granularity silicon modules and a good momentum resolution thanks to its multiple layers of pixel and strip modules. But this material density comes with the cost that neutral particles (e.g. photons, neutral hadrons) will be more likely to interact with tracker material and scatter their energy around before reaching the calorimeters. As a result, for neutral particles which interacted with tracker material the energy deposit in the calorimeter will have a larger angular spread. This effect is important for photon reconstruction as will be seen in Sec. [5.3]. The effect becomes larger at larger $|\eta|$ since the tracker material that a particle goes through increases with $|\eta|$. Fig. 3-3 shows how the thickness of tracker material changes as a function of $\eta$. The material that a
particle with $\eta = 1$ travels through is more than twice thicker than that of a particle with $\eta = 0$.

### 3.2 Electromagnetic calorimeter

The electromagnetic calorimeter (ECAL) is a homogeneous calorimeter used to measure the energy of particles that predominantly interact electromagnetically, such as photons and electrons. It plays a significant role for the measurements presented in this thesis. First of all, photons are reconstructed using the ECAL primarily. Second, reconstruction of both electrons and jets employs information from multiple subdetectors, one of them being the ECAL.

The ECAL is made of PbWO$_4$ scintillating crystals which have a trapezoidal shape [347]. It is composed of a barrel and two endcaps with pseudorapidity coverages of $|\eta| \leq 1.479$ and $1.479 \leq |\eta| \leq 3.0$, respectively. The inner surface of the ECAL barrel is located at $r = 129$ cm and the ECAL endcaps are located at $z = \pm 315.4$...
Figure 3-3: Simulated thickness $t$ of tracker material in units of radiation length $X_0$, as a function of $\eta$. Stacked histograms show contributions from different components of the tracker [346].

cm. Fig. 3-4 shows ECAL’s geometrical configuration.

The ECAL barrel contains 61200 crystals. The front-face (surface of a crystal facing the beam axis) of one crystal has an area of $22 \times 22 \text{ mm}^2$, corresponding to an angular granularity of $0.0174 \times 0.0174 \text{ in } \eta \times \phi$ space. Length of a crystal is 230 mm. This corresponds to a radiation length of 25.6 $X_0$ which is long enough to completely stop the electrons and photons produced in the experiment whose energies are strictly below $\sim 10$ TeV. Fig. 3-5 is a picture of PbWO$_4$ crystals used in the ECAL. Crystals are connected to supermodules, each covering 1700 crystals. There are two supermodules along $\eta$, separated at $\eta = 0$ and one supermodule covers 20 degrees in $\phi$. This gives a total of 36 supermodules in the ECAL barrel. Each supermodule is segmented into four modules along $\eta$. There are small voids at the boundaries between (super)modules, making the energy resolution slightly worse at those locations. The voids happen at $|\eta| = 0, 0.435, 0.783, 1.131$ and at every 20 degrees in $\phi$. 
The ECAL barrel energy resolution is parametrized as

$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E \text{(GeV)}}} \oplus \frac{N}{E \text{(GeV)}} \oplus C$$  \hfill (3.1)

where the $S$, $N$, $C$ are the stochastic, noise, and constant terms, respectively \cite{350}. Energies of electron beams are measured in a $3 \times 3$ matrix of crystals, the parameters are extracted to be $S = 0.028 \sqrt{\text{GeV}}$, $N = 0.12 \text{ GeV}$, and $C = 0.003$ \cite{350}.

The ECAL endcaps contain 14648 crystals and the front-face of a crystal is $28.62 \times 28.62 \text{ mm}^2$. Length of a crystal is 220 mm, corresponding to 24.7 $X_0$. The crystals are organized in $5 \times 5$ arrays. A preshower detector consisting of two planes of silicon sensors interleaved with lead (thickness of 3 $X_0$) is placed in front of the ECAL endcaps, and covers $1.653 \leq |\eta| \leq 2.6$. This is to help the angular separation of particles, e.g. photon pairs from neutral meson decays, in that region where the angular separation using only crystals is worse than in the barrel.

The scintillation light emitted by crystals are collected by photodetectors attached to them. Silicon avalanche photodiodes (APDs) and vacuum phototriodes (VPTs) are used as photodetector in the barrel and endcaps, respectively. This choice was at least partly driven by the need of a photodetector that could work fast, amplify the low
light yield feeding from the crystals, cope with the high radiation environment and the magnetic field configuration. Apart from processing the light yield from crystals, APDs can give rise to an anomalous signal when charged particles ionize the silicon as they pass through. The cleaning of anomalous signals is addressed in Sec. 5.3.3.

3.3 Hadronic calorimeter

The hadronic calorimeter (HCAL) is a sampling calorimeter used to measure the energy of hadrons. The HCAL is positioned after the ECAL with respect to the beam axis. This results in that charged hadrons deposit part of their energy in the ECAL before arriving at the HCAL. Therefore, information from the ECAL and HCAL are combined to measure the energy of charged hadrons. On average, hadrons carry a larger fraction of a jet’s energy than photons and leptons do, therefore the HCAL is very crucial for jet measurements.

The HCAL consists of layers of brass absorber, where particles are slowed down, and scintillator, where energy from penetrating particles are collected. It consists of a barrel covering $|\eta| < 1.3$ and two endcap disks covering $1.3 < |\eta| < 3.0$. The HCAL barrel is installed between the outer extent of the ECAL barrel ($r = 177$ cm) and the

![Figure 3-5: PbWO$_4$ scintillating crystal used in the CMS ECAL subdetector]
inner extent of the solenoid magnet coil \( r = 295 \text{ cm} \). A tail catcher is placed just outside the solenoid coil to serve the HCAL barrel as an additional absorber material. The thickness of the absorber corresponds to about 6 interaction lengths, \( \lambda_I \), at \( \eta = 0 \) where particles enter at normal incidence and can go up to as large as 11 \( \lambda_I \) at larger \( |\eta| \) regions of the HCAL barrel.

The HCAL is read out in towers whose angular granularity is \( 0.087 \times 0.087 \) in \( \eta \times \phi \) for \( |\eta| < 1.6 \) (the same granularity of a \( 5 \times 5 \) matrix of ECAL barrel crystals). For \( |\eta| < 1.48 \), a calorimeter tower is formed by combining an HCAL tower with a \( 5 \times 5 \) array of ECAL crystals overlapping in \( \eta - \phi \) plane. The energy of calorimeter tower is the sum of HCAL tower and ECAL array and is used in measuring jet energy and direction. The granularity is \( 0.17 \times 0.17 \) in \( \eta \times \phi \) for larger \( |\eta| \), becoming coarser.

### 3.4 Forward hadron calorimeter

The forward hadron (HF) calorimeter covers \( 3.0 < |\eta| < 5.0 \), complementing the HCAL at large pseudorapidities, and is placed at \( z = \pm 11 \text{ m} \). It consists of grooved steel plates as absorber material and radiation-hard quartz fibers inserted into the grooves as active material which are then read out by photomultipliers. The active material choice in the HF was driven by the huge incident energy flux (and thus the huge radiation damage) at large \( |\eta| \). The quartz fibers are combined to give HF towers with granularity of \( 0.175 \times 0.175 \) in \( \eta \times \phi \).

The HF is not suitable for measuring particles, for reasons such as its coarse angular resolution, very high density of incident particles, and lack of useful information from other subdetectors which do not cover the same \( |\eta| \) range. However, it is very important for characterizing events. It is used in triggering to obtain an event sample with the least possible selection bias (minimum-bias events), in rejecting non-collision events, and in determining the centrality class of PbPb collisions.
3.5 Muon system

The muon system is composed of several large scale, gaseous detectors that surround the magnet coil and are interleaved into muon chambers by layers of steel which serve as yoke to return the coil's magnetic field. The drift tubes (DTs), cathode strip chambers (CSCs), and resistive plate chambers (RPCs) are the types of gas ionization chambers making up the muon system. The DTs and CSCs cover $|\eta| < 1.2$ and $0.9 < |\eta| < 2.4$, respectively. These are completed by RPCs covering $|\eta| < 1.6$.

The DTs are composed of drift cells, where muon position is estimated using the drift time of the ionized gas to an anode wire. The CSCs are composed of multi-wire proportional counters and cathode strip readouts that precisely measure the position of an incident muon. The RPCs are double-gap chambers which provide a poor spatial resolution, but a good time resolution which is useful for the timing of muon triggers. Detailed information about the muon system can be found in Refs. [351, 352].

Muons undergo multiple scattering inside the calorimeters and magnet coil before entering the muon system, this would distort the momentum measurement obtained from muon system alone. Therefore, muon trajectories are determined using both the muon system and the tracker in order to improve the momentum resolution.
Chapter 4

Event selection and simulation

4.1 Event selection

Events studied in this thesis are selected online via dedicated triggers for photons, muons, and electrons. In addition, minimum-bias (MB) events are used to estimate and subtract the underlying event (UE) background in PbPb analysis, where MB events are triggered if there is an energy deposit in HF above certain threshold (see Ref. [217] for a description of MB events). The threshold is optimized such that it is low enough not to introduce any bias in selecting the inelastic collisions, and high enough that noncollision events are rejected.

Events selected with triggers are cleaned offline to remove noncollision events, such as beam-gas collisions, cosmic ray muons. Events are required to have at least one reconstructed primary vertex and at least two tracks associated with it. In PbPb collisions, this requirement removes non-inelastic collisions with large energy deposits in the HF but very few reconstructed particles. In pp collisions, at least 25% of the tracks should pass the tight track quality criteria (detailed in Sec. 5.6). In PbPb, clusters in the pixel detector are required to be compatible with particles produced in a collision [200]. In PbPb data recorded in 2015 (2018), both sides of the HF must have at least 2 (3) HF towers each with energy deposit of at least 3 (4) GeV. Finally, the $z$-position of the reconstructed vertex cannot be more than 15 cm away from the detector origin.
4.2 Trigger

Events are selected using a two-level trigger system, as detailed in Ref. [353]. The first level (L1) is a hardware system which is designed to make a fast decision about whether to record the event or not. This level processes information without delving into details and can accept events at a rate of 100 kHz. It uses signal from the calorimeters and muon system, but not from the tracker. If the L1 trigger (L1T) decides to accept an event, then the event is passed to the second level, high-level trigger (HLT). The HLT is a software based system that uses information from the whole detector and performs an event reconstruction that is very similar to the one used in offline event reconstruction. If the HLT decides to accept an event, then the event is recorded for offline reconstruction. The HLT can accept events up to rates of $\sim 400$ Hz.

Events analyzed in this thesis require either a high energy photon, a pair of muons, or a pair of electrons. These events occur very rarely, therefore catching and recording those events with minimized loss, i.e. a high trigger efficiency, is crucial for the measurement’s statistical precision. On the other hand, an inefficient trigger will not necessarily require corrections for these analyses. This is because the measured distributions are normalized by the number of events, and no absolute yield measurements, i.e. production cross section, are performed in this thesis. Unless the trigger efficiency has a kinematic dependence or introduces a bias in sample selection, the impact of a not fully efficient trigger will be to worsen the statistical precision of the measurement, but not affecting the measured value itself.

4.2.1 Level-1 trigger

The L1T system has undergone the “Phase 1” upgrade during the shutdown between LHC Run 1 and Run 2, as described in Ref. [354]. This upgrade completely changed the L1T hardware and software in order to keep up to the data recording goals in Run 2.

The L1T can be split into two independently working triggers: calorimeter trig-
gers and muon triggers. The global trigger system combines input from these two subdetector triggers. Fig. 4-1 sketches the overview of the upgraded L1 calorimeter trigger system and its connection to the global trigger system.

**Photons and electrons in the level-1 trigger**

The calorimeter triggers process the information in two layers. The energy deposits in the calorimeter are processed into trigger primitives (TPs) which contain 8-bit information about the energy and its topology in a matrix of crystals. The first layer, Layer-1, calibrates and sorts the TPs. The second layer, Layer-2, reconstructs physics objects using TPs. Information from all detector regions are distributed to processing boards such that a board processes the whole event for a given bunch crossing. A demultiplexer (demux) orders the output from processing boards and sends them to the global trigger system [353].

There is no difference between photons and electrons in the L1 calorimeter system since tracker information is not used in the L1T. Therefore, electrons and photons are identified as the same calorimeter object, the L1 $e/\gamma$ (EG).

![Figure 4-1: Overview of dataflow in the upgraded L1 calorimeter trigger. L1 trigger system is composed of calorimeter and muon triggers. Content of the L1 muon trigger is omitted for simplicity. Details can be found in Ref. [354].](image-url)
A L1 EG object is a cluster of trigger towers (TTs). In the ECAL barrel, a TT is composed of a $5 \times 5$ matrix of crystals, covering the same angular granularity as one HCAL tower. In the ECAL endcaps, on the other hand, the number of crystals in a TT varies with $\eta$ in order to match the angular coverage of HCAL towers at the same position. The EG reconstruction starts with identifying the “seed” TTs which have the maximum local energy and a transverse energy $E_T$ above 2 GeV/c. L1 EGs are clustered around the seed TTs, by adding TTs with $E_T > 1$ GeV/c to a cluster if the TT is adjacent to another TT already in the cluster. A cluster can have a maximum of 8 TTs to minimize the contribution of the energy not associated with the electron or photon. Fig. 4-2 illustrates the L1 EG clustering algorithm.

The position of L1 EG is the energy weighted position of TTs in the cluster. To reduce the fraction of L1 “fakes”, i.e. L1 EGs not corresponding to genuine electrons or photons, several identification criteria are imposed based on

- A “fine grain” (FG) bit marking whether the shape of the electromagnetic shower in crystals of the seed the TT is compatible with a genuine electron or photon
- The $H/E$, the ratio of energy in HCAL and ECAL TTs.
- Isolation requirement based on the energy in a $6 \times 9$ (in $\eta \times \phi$) matrix of TTs around the cluster.

The PbPb UE can distort the shape and isolation of a ECAL shower for genuine electrons and photons. Therefore, in order to increase the efficiency, the L1 EG identification criteria based on the FG bit, $H/E$, and isolation were loosened for the PbPb data recorded in 2018. On the other hand, the L1 EGs were restricted to $|\eta| < 2.1$ range for the 2018 PbPb data, as the EGs at larger rapidities are contaminated by fakes arising from the large PbPb UE in forward region which could increase the trigger accept rates unnecessarily and waste hardware bandwidth.

Fig. 4-3 shows the efficiency of L1 EG algorithms in the 2018 PbPb data as a function of the reconstructed photon $p_T$. The “turn-on” of efficiency is not sharp since the L1 EG algorithm and offline photon reconstruction algorithm are different,
and they can obtain different energies for the same signal. However, the L1T efficiency reaches 100% efficiency for photons whose $p_T$ is at least 10 GeV larger than the L1 EG threshold.

4.2.2 High-level trigger

The HLT reconstructs physics objects using algorithms that are similar to the offline reconstruction algorithms, but the HLT reconstruction is on average less complex than offline reconstruction, as the decision to accept an event needs to be made faster than the time it takes for a full event reconstruction. Therefore, compared to the offline reconstruction, the HLT algorithms can trade precision off for faster execution.

Photons and electrons in the high-level trigger

The HLT algorithms for photon and electron reconstruction are similar to those in offline reconstruction presented in Secs. 5.3.1 and 5.4.2 but different in the “precision
Figure 4-3: The event selection efficiency of the L1T in the 2018 PbPb data as a function of photon $p_T$ for L1 EG algorithms with $E_T$ thresholds of 15 GeV (blue) and 21 GeV (red). Vertical lines indicate the $E_T$ thresholds applied in the algorithms.

vs speed” aspect mentioned above. The HLT algorithms are different than the offline algorithms in the following points:

- The ECAL clustering in the HLT is regional, i.e. the ECAL crystal energies are clustered only in a window of ($\eta, \phi$) around the L1 EG object.

- The search for electron track is driven by the ECAL, i.e. the algorithm finds an energy cluster in the ECAL and then searches for a matching track in the pixel detector.

- The ECAL energy calibration is less accurate than in the offline reconstruction.

- The momentum and angle of physics objects are calculated with respect to the origin of CMS, not with respect to the primary collision vertex.

- The requirements on the H/E and isolation are looser than in the offline reconstruction.
4.3 Triggering photon events

Events in the photon-tagged jet measurements presented in Ch. 7 and Ch. 8 are selected using photon triggers. The pp (PbPb) events are required to have one L1 EG with $E_T > 20$ (21) GeV. Next, the HLT photons in those events are required to be in the ECAL barrel and have $E_T > 40$ GeV. These trigger requirements are more than 99% efficient in selecting events containing an isolated photon with $p_T > 60$ GeV/c in the ECAL barrel.

4.4 Triggering Z boson events

Z bosons in this thesis are reconstructed using muon pairs and electron pairs. Therefore, events containing muons or electrons are selected using the trigger system. The electron and muon triggers are more than 99% efficient in selecting the Z bosons specified in Sec. 5.4 which provides the details of Z boson reconstruction.

4.4.1 Muon pairs

The L1T identifies muons using the muon system only. All three subdetectors in the muon system (DT, CSC, and RPC) are utilized in L1 muon triggers [353]. Trajectories are obtained by combining hits in the muon system. Trajectories whose bending and extrapolated position are compatible with a particle coming from interaction region yield the L1 muons.

The tracker is used for muons in the HLT. The HLT muon algorithm is split into two levels: Level-2 (L2) where muon tracks are reconstructed using only the muon system running Kalman filter [356] for track finding, and level-3 (L3) where muon tracks in L2 seed a track reconstruction that utilizes the tracker information. The L3 muon reconstruction is regional, the processed tracker information is limited to a region around the angular coordinates of the L2 muon.

A combination of several L1T and HLT muon algorithms are used to select $Z \rightarrow \mu\mu$ events. The algorithms differ only in the minimum $p_T$ requirement for the trigger.
muons, and in the minimum number of trigger muons in an event. For the $Z$+jet correlations measurement presented in Ch. 6, events were required to have at least one L1 muon with $p_T > 12 \text{ GeV}/c$, and one HLT muon with $p_T > 15 \text{ GeV}/c$ or two HLT muons with $p_T > 10 \text{ GeV}/c$. For the $Z$+hadron correlations measurement presented in Ch. 9, events were required to have at least one L1 muon with $p_T > 3 \text{ GeV}/c$, and one HLT muon with $p_T > 12 \text{ GeV}/c$.

### 4.4.2 Electron pairs

The L1T selects events with electron pairs using high energy L1 EG objects, as described in Sec. 4.2.1.

For the $Z$+jet correlations measurement presented in Ch. 6, events were required to have one L1 EG with $E_T > 21 \text{ GeV}$ and two photons reconstructed in the HLT, each with $p_T > 15 \text{ GeV}/c$. Furthermore, the invariant mass of the HLT photon pair was required to be above $50 \text{ GeV}/c^2$ in order to reduce the large combinatorial background from lower invariant mass region.

The $Z$+hadron correlations measurement presented in Ch. 9 used pp reference (PbPb) data recorded in 2017 (2018) where the $Z \rightarrow ee$ events were selected using high energy electron objects reconstructed in the HLT. Events are required to have one L1 EG with $E_T > 15 \text{ GeV}$ and one HLT electron with $p_T > 20 \text{ GeV}/c$.

### 4.5 Centrality and event plane

As discussed in Sec. 1.3.1, the number of interacting nucleons in AA collisions can vary with the impact parameter of the collision. The degree of overlap of the two colliding nuclei, the “centrality”, is determined experimentally using the total energy deposited in the HF subdetectors. Fig. 4-4 shows the distribution of the total HF energy deposited per event. The distribution is binned into percentiles and the events in the 10% percentile, i.e. the 10% of events with the largest HF energy, corresponds to 0–10% centrality. Details of centrality determination can be found in Ref. [217].
The event plane is defined as the $\phi$ angle of maximum particle density and determined using the HF as described in Ref. [183].

Figure 4-4: Distribution of the total HF energy for MB collisions (black histogram). The 10% of events with the largest HF energy are the event in 0–10% centrality class. Figure taken from Ref. [217].

4.6 Simulation

The analysis methods are validated using nucleus collision events that are first generated via a Monte Carlo (MC) software and then propagated through the detector simulation.

MC events for pp are generated by the Pythia 8 package [263] and by using a next-to-leading order (NLO) generator, MadGraph5_aMC@NLO [357]. Tune CP5 [358] is used for Pythia 8 events. The partonic processes and hadronization in MadGraph5_aMC@NLO events are executed using Pythia 8. MC events for PbPb are obtained by embedding Pythia 8 or MadGraph5_aMC@NLO events into MB
events generated by the Hydjet [359], these events are referred to as “embedded events” or “embedded samples”. Generated events are propagated through the CMS detector using the Geant4 package [360] to simulate the detector response.

All the simulation samples employed in the measurements were produced centrally by the CMS software group. In the subsequent discussion, the words “MC” and “simulation” will refer to the same thing, the simulated response of the detector to MC events.

Table 4.1 summarizes what physics processes are simulated for what purpose in this thesis.

<table>
<thead>
<tr>
<th>Process / MC generator</th>
<th>Purpose</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to ee$ + jet, $Z \to \mu\mu$ + jet</td>
<td>$Z$+jet and $Z$+hadron analysis method, Jet reconstruction</td>
<td>Refs. [1, 4]</td>
</tr>
<tr>
<td>$X + \gamma$</td>
<td>$\gamma$+jet FF and JS analysis method, Photon reconstruction, Jet reconstruction</td>
<td>Refs. [2, 3]</td>
</tr>
<tr>
<td>$X + \pi^0$, $\pi^0 \to \gamma\gamma$</td>
<td>Background photon contribution</td>
<td>Refs. [2, 3]</td>
</tr>
<tr>
<td>$f + \bar{f} \to Z$, $Z \to ee/\mu\mu$</td>
<td>$Z$ boson reconstruction</td>
<td>Refs. [1, 4]</td>
</tr>
<tr>
<td>$W$+jet, $t + \bar{t}$, QCD dijets</td>
<td>Background for $Z$ boson signal</td>
<td>Refs. [1, 4]</td>
</tr>
<tr>
<td>Pythia + Hydjet, MadGraph + Hydjet, Hydjet</td>
<td>PbPb UE subtraction method</td>
<td>Refs. [1, 2, 3, 4]</td>
</tr>
<tr>
<td>Pythia, MadGraph5_aMC@NLO</td>
<td>Comparison to pp data</td>
<td>Refs. [1, 3]</td>
</tr>
</tbody>
</table>

Table 4.1: The simulated processes and the MC generators used for various purposes in the measurements.
4.6.1 Underlying event in data and simulation

The UE in PbPb data and simulation are compared to verify if the simulation gives a workable description of the UE in data.

The level of UE is estimated using the $\rho$ variable, the median of the ratio of $p_T^{\text{jet}}$ to jet area, where jets are clustered using the $k_t$ algorithm [361, 362, 363]

$$\rho = \text{median} \left\{ \frac{p_T^i}{A_i} \right\}$$ (4.1)

where $i$ is the $i^{\text{th}}$ $k_t$ clustered jet in the event.

Fig. 4-5 compares the $\rho$ in MB PbPb data recorded in 2015 and the simulation for that data as a function of centrality. The simulation provides a good description and agrees with the data within 2% in central collisions, agreement becomes worse in peripheral collisions with differences increasing up to 5% in the most peripheral centrality bin. Effect of these differences on jet reconstruction is negligible.

4.6.2 Hard scattering and minimum-bias events

An embedded event (e.g., a Pythia + Hydjet event) has contributions from both hard scattering (Pythia) and MB (Hydjet) events, and therefore has more particles and a larger energy density than the underlying MB event (e.g. the Hydjet event). This results in that the energy deposit in the HF for embedded events is on average larger than for MB events, thus an embedded event is on average reconstructed to be more central than the underlying MB event. The left panel in Fig. 4-6 shows the average centrality as a function of the number of participants, $N_{\text{part}}$, in simulation and compares them between MB and embedded events ($N_{\text{part}}$ value is calculated for Hydjet events only, does not include Pythia events). The embedded (Pythia + Hydjet) events tend to be reconstructed more central than the MB (Hydjet) events which have the same $N_{\text{part}}$ as the underlying MB event of the embedded event. Another aspect of this effect is given in the right panel in Fig. 4-6 which shows the average $N_{\text{part}}$ as function of the reconstructed centrality. Embedded events tend to have a smaller $N_{\text{part}}$, therefore a smaller underlying MB event, than MB events with
Figure 4-5: Upper: Average value of $\rho$ as function of centrality in MB PbPb data (black) and in simulation (blue) where $\rho$ is calculated over the same $\eta$ range as the jets. Lower: The Data / MC ratio of the functions.
Figure 4-6: Upper: Average centrality as function of $N_{\text{part}}$ (left) and average $N_{\text{part}}$ as function of centrality (right) in PbPb simulation. MB events are simulated using Hydjet events (blue) and compared to hard scattering events simulated using Pythia+Hydjet events (black). $N_{\text{part}}$ is calculated in Hydjet events only, does not include contributions from Pythia events. Lower: The difference between the functions for Pythia+Hydjet and Hydjet events.

the same reconstructed centrality.

In order to address the effect of these differences between embedded and MB events, the combinatorial backgrounds estimated from MB events are scaled with a residual factor in photon+jet FF (see Sec. 7) and JS (see Sec. 8) measurements.
Chapter 5

Physics object reconstruction and identification

Physics objects used in this thesis are photons, Z bosons, jets, and charged particle tracks (for charged particle detection). The particle-flow (PF) algorithm (see Sec. 5.2) has been used to reconstruct some of the physics objects in this thesis, as noted in relevant sections. The reconstruction method for a collision system can differ between different data taking years, either due to improvements over a previous method or due to updates to incorporate the current detector conditions. The subsequent sections describe the reconstruction and identification of physics objects used in the measurements presented in this thesis.

Notes about terminology   Below is the terminology related to the reconstruction and detector response along with their clarifications. This terminology is used for sake of brevity in the subsequent text.

- “generator-level”, “generated”, “gen”, “truth”, “true” : Anything that comes from a MC event generator, before being propagated through detector simulation.

- “reconstructed” or “reco” : Anything that is obtained from reconstruction. Example : A “reco” photon is an output of the photon reconstruction algorithm that processes information from the ECAL and other subdetectors.
• “genuine” or “real”: Any reconstructed object that corresponds to a real particle, whether it is desired or not. Example: A photon originating from a neutral meson decay is genuine, although many analyses would prefer to avoid it.

• “misidentified” or “fake”: Any reconstructed object that is misidentified, i.e. the corresponding object does not exist in reality. Example: A reco electron is fake if it was actually a charged hadron that gave rise to the ECAL signal and the reconstruction algorithm identified the charged hadron as an electron.

• “nonprimary” or “secondary”: A final-state particle formed not during the hadronization stage, but via the decay of a long lifetime hadron with a proper lifetime less than 1 cm/c. Example: A kaon from the Omega baryon decay, $\Omega^- \rightarrow \Lambda K^-$. 

• “closure”: A test for the performance of an analysis or reconstruction method.

• “non-closure”: A number to quantify the deviation of an analysis or reconstruction method from the ideal case. Example: 5% non-closure in energy scale means that the reco $p_T$ is on average 5% different from the true $p_T$.

5.1 Performance evaluation

In order to perform an accurate and precise measurement one needs to understand the reconstruction performance and if needed account for the imperfections. Several metrics are used in evaluating the reconstruction performance. These are

• The energy scale and resolution

• The reconstruction and selection efficiency

• The misidentification (fake) rate
5.1.1 Energy scale and resolution

The energy measurement performance of the reconstruction algorithm is evaluated using the energy scale (average offset from the true energy) and the energy resolution (a measure of deviations from the true energy).

The energy response can be defined as the ratio of $p_{T}^{\text{reco}}$ (reconstructed $p_T$) over $p_{T}^{\text{gen}}$ (true $p_T$)

$$R(p_T) = \frac{p_{T}^{\text{reco}}}{p_{T}^{\text{gen}}}$$  \hspace{1cm} (5.1)

Hence, energy response is a measure of the offset from true energy. The energy scale is a measure for the average response

$$\mu(p_T) = f(R(p_T))$$  \hspace{1cm} (5.2)

There is no single way to evaluate the energy scale. Possible quantifications for energy scale are

- The arithmetic mean of the energy response distribution
- The expected value of a Gaussian distribution ($\mu$) fitted to the energy response distribution

The energy resolution is a measure for the variance of response

$$\sigma(p_T) = f(R(p_T))$$  \hspace{1cm} (5.3)

Possible quantifications for energy resolution are

- The standard deviation of the energy response distribution
- The deviation of a Gaussian distribution ($\sigma$) fitted to the energy response distribution
Effective width: Shortest range of energy response over which the integral of the distribution is 68.3% of the total. For a Gaussian distribution, the effective width is the same as the Gaussian’s deviation $\sigma$.

5.1.2 Efficiency

The reconstruction efficiency is defined as the fraction of true particles or physics objects for which a physics object has been reconstructed. When identification (selection) criteria are imposed on reco objects, then the efficiency becomes reconstruction and identification efficiency. Generally, simply efficiency is used as a shorthand to denote fraction of gen objects that were reconstructed and then selected.

5.1.3 Misidentification rate

The misidentification rate or fake rate, is defined as the fraction of reconstructed and selected objects for which there is no matching gen object.

Ideally, one would want to have a reconstruction with maximum efficiency and minimum fake rate. On the other hand, reconstruction and the subsequent identification criteria comes with a trade-off between efficiency and fake rate. To maximize efficiency, one could set the reconstruction algorithm in such a way that physics objects are reconstructed from any non-zero signal in the detector. Unfortunately, this will shoot up fake rate as well, and equivalently the data size, a fraction of which will be wasted with reco objects with no physics use. Depending on the measurement needs one devises a reconstruction algorithm and a “working point” for identification criteria.

5.2 Particle-flow reconstruction

The CMS subdetectors are discussed in Ch. 3. The CMS collaboration has introduced the particle-flow (PF) algorithm [364] which reconstructs physics objects by utilizing the information from all subdetectors, making a global event description
(GED) possible. The PF algorithm first aims to identify the PF candidates, i.e., final-state particles which are either photons, charged hadrons, neutral hadrons, electrons, or muons. Then, it uses the PF candidates to reconstruct more sophisticated physics objects, e.g., jets, taus, and missing transverse energy.

Fig. 5-1 shows a sketch of the CMS detector along with the subdetectors used in the reconstruction of PF candidates. PF muons are identified as charged particle tracks in the tracker system consistent with hits in the muon system. Among the remaining tracks, those that can be extrapolated to ECAL clusters are identified as PF electrons if their momentum is consistent with energy in the ECAL. Tracks that are neither PF muons nor PF electrons are identified as PF charged hadrons. ECAL clusters not associated with any track are identified as PF photons. Finally, PF neutral hadrons are either HCAL clusters not linked to any charged hadron or remaining energy in ECAL and HCAL clusters after subtracting the expected energy deposit of PF charged hadrons.

Information obtained from the PF algorithm is used in the reconstruction of GED photons (Sec. 5.3.1), electrons (Sec. 5.4.2), jets (Sec. 5.5), and tracks (Sec. 5.6).

5.3 Photons

Photons are identified as ECAL clusters, groups of ECAL crystals. A photon hitting the ECAL typically interacts with only one ECAL crystal until it is completely stopped. However, the deposited energy is spread over multiple ECAL crystals. A $3 \times 3$ matrix (centered around the crystal with the highest energy) of ECAL crystals contain about 95% of the energy of a high energy photon that reaches the ECAL, and a $5 \times 5$ matrix contains about 98% of the photon energy.

A photon might interact with detector material, in particular the tracker, before reaching the ECAL. In such cases, a photon “converts” to an electron–positron ($e^+e^-$) pair. Magnetic field inside the tracker will bend the trajectory of $e^+$ and $e^-$, each electron might emit photons via bremsstrahlung and these photons might convert again. At the end, a set of photons and electrons, will reach the ECAL, the energy of
Figure 5-1: The CMS detector sketched on a plane transverse to collision axis along with the response of its subdetectors to various particles. Figure taken from Ref. [364].
the original photon is spread to angular spaces larger than the size of a ECAL crystal, and the spread is larger along the $\phi$ direction along which $e^+$ and $e^-$ trajectories are bent into opposite $\phi$.

Fig. 5-2 shows the average fraction of photon energy contained in $3 \times 3$ and $5 \times 5$ matrices of ECAL crystals. The fractions increase with $p_T$ as the energy spread is relatively smaller for higher energy photons. The matrices can on average contain at least 90% of the true photon energy for not converted photons. The energy fractions contained in $3 \times 3$ ($5 \times 5$) matrices can range from $\sim 65\%$ to $\sim 85\%$ ($\sim 74\%$ to $\sim 95\%$) for converted photons.

Figure 5-2: Average fraction of a photon's energy inside $3 \times 3$ (blue) and $5 \times 5$ (red) matrix of ECAL crystals as a function of the true photon $p_T$. The simulation does not include physics events, but only a pair of photons with $|\eta| < 0.5$ emerging from the origin. Horizontal dashed lines are drawn at $y = 98\%$ and $y = 95\%$. The left panel includes photons not interacting with the tracker, whereas the right panel includes photons that convert in the tracker.

Given the possibility of conversion in the tracker, the ECAL clustering should consider groups larger than $5 \times 5$ matrices in order to recover the original photon energy. On the other hand, the cluster should not grow more than necessary, otherwise it will include energy from other particles not originating from the photon. These factors dictate that fixed size clusters are not ideal for photon reconstruction. Instead,
the ECAL clustering should be **dynamic**, the cluster size should be optimized to recover the true photon energy and avoid the unrelated energy.

ECAL clustering in CMS proceeds in two fundamental steps

1. **Basic clusters** (BCs) or simply **clusters** are constructed by grouping crystals around a “seed-crystal”, i.e. a crystal whose energy is larger than its “adjacent” crystals. Crystals are adjacent if they have an edge in common.

2. **Superclusters** (SCs) are constructed by grouping BCs around a “seed-cluster”, a BC whose energy is larger than other BCs.

### 5.3.1 Reconstruction algorithms

A photon is reconstructed from a SC. The energy of a SC is energy sum of all crystals in the SC. The position of a SC is the average position of its crystals weighted by crystal energy. Thus, a SC’s position tends to be close to that of its highest energy crystal.

Several ECAL clustering algorithms have been employed in CMS. The “hybrid” and “multi-5 × 5” algorithms were used in Run 1 pp data for clustering in the ECAL barrel and endcaps, respectively [365].

The hybrid algorithm starts by building 5 × 1 crystal arrays (5 crystals along \( \eta \)-direction and 1 crystal along \( \phi \)-direction) whose central crystal is the seed-crystal whose transverse energy must be above a threshold \( E_{T, \text{seed}}^{\min} \). The clustering performs a search inside a \( 5 \times (2 \times N_{\text{steps}}^{\text{hybrid}} + 1) \) crystal region whose center is the array containing the seed-crystal. The \( 2 \times N_{\text{steps}}^{\text{hybrid}} \) many arrays inside the region are checked for energy. Adjacent arrays (arrays having a common edge) whose individual energy are above some threshold \( E_{\text{array}}^{\min} \) are clustered to yield a BC. The BCs which have an array with energy above \( E_{\text{BC,seed}}^{\min} \) are grouped into a SC. The \( N_{\text{steps}}^{\text{hybrid}} \) is set large enough to capture the energy spread in \( \phi \). The energy thresholds \( E_{\text{array}}^{\min} \) and \( E_{\text{BC,seed}}^{\min} \) are imposed in order to suppress the contribution from unrelated particles. The values of thresholds can be found in Ref. [365]. Note that, \( E_{T, \text{seed}}^{\min} \) is larger than other thresholds ensuring that the seed-crystal will always end up in a SC.
The BCs in multi-5 × 5 algorithm are 5 × 5 crystal matrices whose center is the seed-crystal whose energy is larger than any of the adjacent crystals and a specific threshold. BCs with $E_T$ above $E_{T,\text{min,cluster,EE}}$ are grouped into a SC if they are within a specific $(\eta, \phi)$ range. The values of thresholds and ranges can be found in Ref. [365].

**Island algorithm**

The Island algorithm is primarily used for photon reconstruction in PbPb data recorded in 2015. The Island algorithm proceeds in the following steps

- Crystals are identified as seed-crystals if their energy satisfies $E_T > 0.5 \text{ GeV}$
- Seed-crystals are sorted by their energy. Starting with the highest energy seed-crystal, a BC is built from each seed-crystal as follows
  - $\phi$-scan: Moving in $\pm \phi$ direction, crystals are added to the BC until the next crystal satisfies one of the following:
    * has zero energy, i.e. an energy “hole”
    * has energy larger than that of the adjacent crystal already in the BC, i.e. an energy “rise”
    * is already in another BC
  - $\eta$-scan: The algorithm goes back to the crystal where the $\phi$-scan step had started and moves one step in $\pm \eta$. If the crystal is not an energy “hole” or “rise”, then the crystal is added and a new $\phi$-scan step is started.
- A BC is completed when the $\eta$-scan step finishes.
- BCs with $E_T > 1 \text{ GeV}$ are identified as seed-clusters. Starting from the highest energy seed-cluster, a SC is built by grouping together all BCs in the ECAL barrel (endcaps) that
  - are within windows of $\Delta \eta = 0.07$ ($\Delta \eta = 0.14$) and $\Delta \phi = 0.8$ ($\Delta \phi = 0.6$) whose center is the seed-cluster, and
  - are not already in another SC
Fig. 5-3 shows an illustration of the Island algorithm in the ECAL. Basically, the algorithm expands a cluster by searching first in the $\phi$, then in the $\eta$ direction. The expansion continues until the search hits an energy “hole” or “rise”. The rejection of energy rises reduces sensitivity to background energy fluctuations, such as the UE fluctuations in HI collisions.

Further information about the Island algorithm can be found in Refs. [229, 366]. Photons used in the measurements presented in Ch. 7 and Ch. 8 are reconstructed using the Island algorithm.

Figure 5-3: Illustration of the Island clustering algorithm in the ECAL. Figure taken from Ref. [366].

Global Event Description algorithm

A dedicated ECAL clustering algorithm was developed as part of the PF reconstruction (see Sec. 5.2). Photons reconstructed using this ECAL clustering algorithm are called “GED” algorithm photons.

The GED algorithm proceeds in the following steps in the ECAL barrel (endcaps)

- Crystals are identified as seed-crystals if their energy satisfies $E > 0.230 \pm 0.6$ GeV
• Topological clusters are built around seed-crystals by adding crystals with \( E > 0.08 \) (0.3) GeV and having at least one common corner with a crystal already in the BC.

• Topological clusters with \( N \) seed-crystals are split into \( N \) BCs using a “Gaussian mixture model” (detailed in Ref. [364]) which postulates that the energy in each crystal can be shared between multiple BCs and the energy profile of each BC is Gaussian.

• The BCs with \( E_T > 1 \) GeV are identified as seed-clusters. Starting from the highest energy seed-cluster, a SC is built following the “mustache” procedure where BCs are added into the SC if they pass requirements based on their energy and position with respect to the seed-cluster.

The Gaussian mixture model aims to separate the energy from different particles which are incident on the ECAL in nearby positions. This implies that energy of a crystal can be shared between multiple clusters, a crystal is not necessarily dedicated to one cluster. Details of the GED algorithm can be found in Ref. [364].

The GED algorithm was optimized for pp collisions, however its performance in PbPb collisions is worse compared to that of the Island algorithm. This is because, in PbPb collisions the GED algorithm tends to produce SCs which are contaminated by ECAL signal not associated with a photon. The GED algorithm was modified for the PbPb collision data recorded in 2018. Details of the performance studies and the algorithm modification can be found in Sec. 5.3.2.

5.3.2 Performance of the Island and GED algorithms in PbPb

Isolated photon analyses in the 2011 and 2015 PbPb data have employed the Island algorithm to reconstruct photons. The use case of the GED algorithm for photon reconstruction in future PbPb data has been investigated by comparing performances of the GED and Island algorithms. The comparisons focus on the ECAL barrel, performance for the ECAL endcaps is left for future studies.
It is instructive to compare the clustering algorithms via an example. Fig. 5-4 shows an example of ECAL clustering for a photon in a simulated PbPb event. The seed-clusters for the Island and GED algorithms have different shapes. For example, the top (bottom) crystal in the rightmost column of the GED seed-cluster ($N^\phi = 3.5$) has energy $E = 0.14$ (0.09) GeV and is not included in the Island seed-cluster. This is because the Island algorithm rejects energy rises (as described in Sec. 5.3.1) and these crystals are energy rises with respect to the preceding crystals in the $\phi$-scan step ($N^\phi = 2.5$), e.g. preceding crystal for the top (bottom) crystal has $E = 0.10$ (0.07) GeV, a smaller energy. Likewise, the two crystals at $N^\phi = -0.5$ and $N^\eta = -1.5$, $-2.5$ (both have energy of $E = 0.11$ GeV) are included in the GED cluster, but not in the Island cluster as they are energy rises with respect to the crystals at $N^\phi = 0.5$ and the same $N^\eta$ (which have energies of $E = 0.08$, 0.06 GeV). Similarly, at a given $N^\phi$, the Island cluster is continuous, i.e. no crystal is excluded between the first and last $N^\eta$, this is a result of that the $\eta$-scan stops when it sees an energy rise or energy hole. On the other hand, GED clusters can have discontinuity at a given $N^\phi$, e.g. the crystal at $(N^\eta, N^\phi) = (1.5, 3.5)$ is excluded, although the ones at the same $N^\phi$ and $N^\eta = 0.5$ and $N^\eta = 2.5$ are included. Whether a crystal is included in a GED cluster is determined by the Gaussian mixture model (see Sec. 5.3.1).

The GED algorithm was optimized for pp collisions, however its performance in PbPb collisions is worse compared to the Island algorithm as will be shown in the following discussion. In order to improve its performance in PbPb collisions, the GED algorithm is modified such that when clustering BCs into SCs the $\Delta \phi$ between a BC and the seed-cluster is required to be less than 0.2. This modification has been applied for the PbPb data recorded in 2018. Fig. 5-5 shows the same simulation as in Fig. 5-4 in a wider $\phi$ range. The Island algorithm gives a SC consisting of a single BC. The GED algorithm optimized for pp data, the “default” GED, gives a SC consisting of many BCs spanning a wide $\phi$ range. The SC produced by the “modified” GED algorithm has fewer BCs spanning a smaller $\phi$ range. BCs are more likely to be created along the $\phi$-direction because photon energy tends to spread more along the $\phi$-direction as a result of the photon conversion and bending of associated charged...
Figure 5-4: Reconstruction of a photon in a simulated central PbPb collision. The true photon energy is 31.4 GeV. Upper: Energy response in the ECAL barrel centred around the crystal hit by the simulated photon. Each bar along x-axis (y-axis) represents an ECAL crystal in \( \phi \) (\( \eta \)) direction and the height of a bar is the energy reconstructed for the crystal. The numbers \( N^\eta \) and \( N^\phi \) are to index the crystals, their values are not the same as kinematic variables \( \eta \) and \( \phi \). Lower: The photon is reconstructed using the Island (left) and default GED (right) algorithms which cluster crystals in the ECAL. The number inside a bin is the crystal’s energy. The seed-crystal is at the center, \( (N^\eta, N^\phi) = (0.5, 0.5) \) and has energy \( E = 21.75 \) GeV. All crystals surrounded by red lines belong to the SC where seed-cluster is the region enclosed with dashed red lines and remaining clusters are enclosed with solid red lines.

particles in the magnetic field (see Sec. 5.3 for details).
Figure 5-5: The same simulation as shown in Fig. 5-4 is depicted in a wider $\phi$ range. The true photon energy is 31.4 GeV. The number inside a bin is the crystal’s energy. The seed-crystal is at the center, $(N^y, N^\phi) = (0.5, 0.5)$ and has energy $E = 21.75$ GeV. All crystals surrounded by red lines belong to the SC where seed-cluster is the region enclosed with dashed red lines and remaining clusters are enclosed with solid red lines. The photon is reconstructed using the Island (upper row), default GED (middle row), and modified GED (lower row) algorithms.

Fig. 5-6 shows the distribution of the number of BCs in a photon SC for different collision centralities. In central collisions, the number of the ECAL barrel BCs for the default GED algorithm is noticeably larger than for the Island and modified GED algorithms. In peripheral collisions, the number of BCs are less different between the default GED and other algorithms. The number of BCs for the modified GED
Performance of the different algorithms in PbPb simulation is compared using energy resolution, misidentification (fake) rate, and reconstruction efficiency. In this section, the energy resolution performance is evaluated via the width of \( \frac{E_{\text{SC}}^{\text{raw}}}{E_{\text{gen}}^{\text{gen}}} \) distribution (see Sec. 5.1.1 for energy resolution quantifications) where \( E_{\text{SC}}^{\text{raw}} \) is the uncorrected SC energy and \( E_{\text{gen}}^{\text{gen}} \) is the true photon energy. Fig. 5-7 compares the \( E_{\text{SC}}^{\text{raw}}/E_{\text{gen}}^{\text{gen}} \) distributions in the ECAL barrel and the energy resolutions (quantified using the effective width defined in Sec. 5.1.1) as function of the \( p_{T}^{\text{gen}} \). The \( E_{\text{SC}}^{\text{raw}}/E_{\text{gen}}^{\text{gen}} \) distributions are narrower in peripheral collisions, consequently the energy resolutions are better in peripheral collisions than in central collisions. The algorithms have comparable energy resolution in peripheral collisions, on the other hand, in central collisions the energy resolution for the modified GED is at least as good as the Island and significantly better than the default GED.

Fig. 5-8 compares the misidentification rates. In peripheral collisions, the misidentification rates are smaller than in central collisions and similar between the algorithms. In central collisions, the misidentification rate for the modified GED is substantially smaller compared to the default GED and more similar to the one for the Island algorithm.

Fig. 5-9 compares the reconstruction efficiencies which do not seem to be affected by the collision centrality. The reconstruction efficiencies are very similar between different algorithms except the Island algorithm being \( \sim 1\% \) more efficient than the others.

These comparisons can be understood as follows. The default GED is optimized for pp data where the clustering is allowed to span a wide \( \phi \) range in order to recover the photon energy spread across the ECAL. However, this strategy is not necessarily optimal for PbPb data where the UE can give rise to ECAL signals not associated with the photon. A search performed in a wide \( \phi \) range can end up including ECAL clusters arising from the UE particles and, as a result, worsen the energy resolution and increase the fake rate in central collisions. By restricting the \( \phi \) range in the clustering, the modified GED algorithm reduces its sensitivity to the PbPb UE, thus improves
Figure 5-6: Number of basic clusters (BCs) versus $\eta$ for photons reconstructed using the Island (upper), default GED (middle), and modified GED (lower) algorithms in simulated PbPb events. The panels in the left (right) columns are for 30–100% (0–30%) collision centralities. Vertical dashed lines indicate the transition region between the ECAL barrel and endcaps.
Figure 5-7: Photons are reconstructed in the ECAL barrel using the Island (black square), default GED (blue circle), and modified GED (red crosses) algorithms in simulated PbPb events. Upper: The $E_{\text{SC}}^{\text{raw}}/E_{\text{gen}}$ distributions. Lower: Effective width of the $E_{\text{SC}}^{\text{raw}}/E_{\text{gen}}$ distribution as function of the $p_T^{\text{gen}}$. The left (right) columns are for 30–100% (0–30%) collision centralities.
Figure 5-8: The misidentification rate as a function of $p_T$ for photons reconstructed in the ECAL barrel using the Island (black square), default GED (blue circle), and modified GED (red crosses) algorithms in simulated PbPb events. The left (right) columns are for 30–100% (0–30%) collision centralities.

Figure 5-9: The reconstruction efficiency in the ECAL barrel as a function of $p_T^{\text{true}}$ for the Island (black square), default GED (blue circle), and modified GED (red crosses) algorithms in simulated PbPb events. The left (right) columns are for 30–100% (0–30%) collision centralities.
the reconstruction performance to a level comparable to the Island algorithm.

Different versions of the modified GED algorithm were investigated by varying
the value of $\Delta \phi_{BC, \text{seed-cluster}}$, the maximum $\Delta \phi$ between a BC and the seed-cluster,
before deciding on the value whose performance is presented above. It was found that
the $\Delta \phi_{BC, \text{seed-cluster}} = 0.2$ case was an optimum and therefore chosen for the modified
GED algorithm. Improvements in misidentification rate and energy resolution are not
better for larger values of $\Delta \phi_{BC, \text{seed-cluster}}$. On the opposite side, misidentification rate
actually becomes better for even smaller values of $\Delta \phi_{BC, \text{seed-cluster}}$, however the energy
resolution starts to worsen again, as the $\phi$ range becomes too narrow to recover the
photon energy without losses.

5.3.3 Signal and background

Signal definition

Photons of interest in this thesis are “prompt” photons, i.e. photons that are
produced via $N + N \rightarrow \gamma + X$ where $N$ is nucleon. A photon is prompt if it is
produced by one of the following

- directly in the hard scattering process (“direct” photon)
- fragmentation of a parton shower (“fragmentation” photon)

Most of the direct photons are from photon+jet events with the dominant pro-
cesses being the QCD Compton scattering and quark-antiquark annihilation intro-
duced in Sec. 2.2.

Most of the fragmentation photons are from dijet events where a high energy
parton in the shower emits a photon (such as the photon shown in Fig. 2-1).

Ideally, for parton energy loss studies in HI collisions, one would prefer to ana-
lyze only direct photon events as these photons are the precise tags for the recoiling
parton. However, at the LHC energies, a non-negligible fraction of photons with
$p_T \sim 50 \text{ GeV/c}$ are fragmentation photons. Fig. 5-10 illustrates the physics processes
that contribute to direct and fragmentation photons. A high energy photon with
Figure 5-10: Physics processes that contribute to prompt photons. Left: Photons can be produced directly in photon+jet processes such as QCD Compton scattering or $q\bar{q}$ annihilation (introduced in Sec. 2.2). Right: Photons can be produced indirectly via Bremsstrahlung or fragmentation of partons in other hard scattering processes. An isolated photon is produced either directly (left panel) or indirectly (right panel) where the parton shower energy around its position is relatively small.

very little energy around its position in the detector is considered “isolated”. Being isolated does not necessarily mean that the photon is direct, it can be also be a fragmentation photon carrying a large fraction of its parent parton’s energy. Fraction of fragmentation photons in a sample can be reduced by applying an isolation criteria. In this thesis, isolated prompt photons are considered as “signal” photons.

Fig. 5-11 shows the simulated contributions of direct photons and fragmentation photons to isolated photons used in the photon-tagged jet measurements presented in Ch. 7 and Ch 8. Fraction of fragmentation photons decreases with increasing $p_T^\gamma$ and can be about $\sim 30\%$ for $p_T^\gamma \sim 60$ GeV/c.

Background definition

Photons can be produced not only in parton-level processes happening before hadronization, but also via decays of hadrons. Photons originating from hadron decays are not prompt and therefore not signal, they are considered background
Figure 5-11: Relative contributions of fragmentation (red), photon+quark jet (grey), and photon+gluon jet (blue) processes to the production of isolated photons in PYTHIA events. Isolation requires that the total transverse energy of generated particles inside a cone of radius $\Delta R = 0.4$ around the photon is less than 5 GeV. Figure taken from Ref. [3].

and avoided as much as possible in photon+jet measurements. The majority of the background photons are the ones from neutral meson decays. Neutral mesons such as $\pi^0$ and $\eta$ decay into a pair of photons well before reaching the detector and photons from these decays, “decay photons”, constitute the majority of background for prompt photons. At the LHC energies, the angle between the two photons originating from a meson decay, the “opening angle”, tend to be so small that the two decay photons are usually reconstructed as a single photon. On the other hand, energy of these reconstructed photons tend to have a spread over the calorimeter wider than for signal photons and this can be exploited in photon identification (see Sec. 5.3.4).

Fig. 5-12 shows the distribution of opening angle for a $\pi^0$ decaying to a pair of photons. The angle tends to be smaller for higher energy $\pi^0$'s. If the angle is smaller
than the angular width of an ECAL crystal, then it is practically impossible to detect these photons separately. For a $\pi^0$ with $p_T = 30$ GeV/c and $\eta = 0$, the fraction of decays with an opening angle smaller than the size of an ECAL crystal is $\approx 86\%$. This fraction increases to $\approx 95\%$ for $\pi^0$ with $p_T = 50$ GeV/c. The fraction is even larger for $\pi^0$ with the same $p_T$, but larger $|\eta|$. For $p_T \gtrsim 40$ GeV/c and $|\eta^{\pi^0}| = 1.44$, the “decay” photons usually cannot be resolved and they are reconstructed as a single photon object.

5.3.4 Identification

Photons described in Sec. 5.3.3 correspond to genuine photons. However, the reconstruction algorithm can also produce misidentified (fake) photons which represent neither a signal nor a background photon. Selections are applied to remove fake photons from the sample to be left with a sample of genuine photons.

Fake removal

**Spike rejection** Early LHC data showed unexpectedly many high energy photons in the ECAL barrel with most of the energy being deposited in a single crystal. Investigation of the ECAL subdetector showed that these anomalous signals were produced when a charged particle goes through the APDs and ionizes the silicon creating a large signal [367]. Photons reconstructed from these signals have a spiky energy profile in the ECAL, where the seed crystal carries a much larger than expected fraction of the cluster energy. The “spike” photons are rejected by applying the following requirements

- **Swiss cross** defined as $1 - E_4/E_1$, where $E_1$ is the seed crystal energy and $E_4$ is the total energy of the four crystals adjacent to the seed crystal, must be less than 0.90
- The $\sigma_{\eta\eta}$, defined in eq. 5.4, must be greater than 0.002.
- **Signal time** for the seed crystal to be less than 3 ns away from the average
Figure 5-12: Opening angle distribution between the two photons originating from the decay of a neutral pion ($\pi^0$) with $\eta = 0$ (upper panel) and $\eta = 1.44$ (lower panel) for different $p_T$ values. Vertical dashed lines indicate the angular width of an ECAL crystal ($1 \times 1$ matrix) and a $3 \times 3$ matrix of ECAL crystals.
time an ECAL shower is reconstructed \[368\]. Due to different mechanism of the signal generation, spike signals have different pulse shapes than genuine ECAL signals where signal is collected from scintillation light. This results in spike signals having much shorter timing than genuine signals.

Fig. 5-13 shows the correlation between the swiss cross variable and signal time for seed crystal for reconstructed photons in the 2015 PbPb data. Signal from the ECAL crystals are concentrated around a signal time of 0 ns. The above listed criteria remove almost all spikes and a negligible fraction of genuine photons \[367\].

Figure 5-13: Distribution of the swiss cross variable vs signal time for seed crystal for photons in the ECAL barrel region in the 2015 PbPb data. Photons are reconstructed using the Island algorithm. Spikes are removed by requiring the swiss cross to be less than 0.9 and signal time to be inside the \((-3, 3)\) ns interval.

**Electron rejection** A genuine electron can be reconstructed as a photon. Although such a photon is fake, it is useful for studying the photon energy response in data by selecting photons reconstructed from electron SCs in \(Z \rightarrow ee\) events. For physics analysis, on the other hand, electrons reconstructed as photons are avoided. This
is done by removing photons which are within $\Delta \eta = 0.02$ and $\Delta \phi = 0.15$ from a reconstructed electron with track $p_T > 10$ GeV/c.

Identification variables are employed to select signal photons and reject background photons. Identification variables are

- **Fraction of hadronic energy**: The ratio of HCAL energy over the photon SC energy

- **Shower shape**: A measure of how energy is spread in the ECAL. See Sec. 5.3.4 for details.

- **Isolation**: A measure of the energy deposited around the photon’s location in the detector

**Fraction of hadronic energy**

Background photons are produced via decay of neutral mesons which usually form via hadronization of parton showers, hence the fraction of hadronic energy around the position of a background photon is generally larger than for a signal photon. An identification variable is defined as the ratio of HCAL over ECAL energy inside a cone of radius $\Delta R = 0.15$ around the photon SC position, denoted as $H/E$.

The left panel in Fig. 5-14 compares the $H/E$ distribution for signal and background photons in simulation. As expected, background photons tend to have larger $H/E$ values than signal photons.

**Shower shape**

Shape of ECAL shower is quantified via energy weighted covariances defined on a $5 \times 5$ matrix. Three types of covariances can be defined depending on the direction
in the $\eta - \phi$ space

\[
\sigma^2_{\eta\eta} = \frac{\sum_{i}^{5\times5} w_i (\eta_i - \eta_{5\times5})^2}{\sum_{i}^{5\times5} w_i} \quad (5.4)
\]

\[
\sigma^2_{\phi\phi} = \frac{\sum_{i}^{5\times5} w_i (\phi_i - \phi_{5\times5})^2}{\sum_{i}^{5\times5} w_i} \quad (5.5)
\]

\[
\sigma^2_{\eta\phi} = \frac{\sum_{i}^{5\times5} w_i (\eta_i - \eta_{5\times5})(\phi_i - \phi_{5\times5})}{\sum_{i}^{5\times5} w_i} \quad (5.6)
\]

where $w_i = \max(0, c + \ln \frac{E_i}{E_{5\times5}})$ \quad (5.7)

where $E_i$ and $\eta_i$ ($\phi_i$) are the energy and pseudorapidity (azimuthal angle) of the $i$th crystal within the $5 \times 5$ matrix. The $E_{5\times5}$ is energy of the $5 \times 5$ matrix. The $\eta_{5\times5}$ ($\phi_{5\times5}$) is the energy averaged $\eta$ ($\phi$) for that matrix. The value of $c$ is a constant which was set to 4.7 in the previous CMS studies and is effectively a cutoff on the crystal energy to be considered in the calculation. The $\sigma_{\eta\eta}$ is basically an energy weighted width of the ECAL energy in $\eta$-direction.

The right panel in Fig. 5-14 compares the $\sigma_{\eta\eta}$ distribution for signal and background photons in simulation. Compared to background photons, signal photons have smaller $\sigma_{\eta\eta}$ values, concentrated in the $0.007 \lesssim \sigma_{\eta\eta} \lesssim 0.012$ region. Background photons tend to have a larger $\sigma_{\eta\eta}$ as the two photons produced in a neutral meson decay are reconstructed as a single photon (see Sec. 5.3.3).

Background photons would be expected to have relatively larger $\sigma_{\phi\phi}$ as well. However, the $\sigma_{\phi\phi}$ is not as useful for identification. A signal photon can convert in the tracker widening its SC in $\phi$-direction (as explained in Sec. 5.3), resulting in a relatively larger $\sigma_{\phi\phi}$. Therefore, a large $\sigma_{\phi\phi}$ (or $|\sigma_{\eta\phi}|$) is not an as strong indicator for a background photon.

**Isolation**

There tends to be a larger amount of energy around the position of background photons as they originate from neutral mesons which are produced after hadronization of parton showers, in an environment with a relatively high energy density. “Isolation
Figure 5-14: Distribution of the $H/E$ (left) and $\sigma_\eta$ (right) variables in PbPb simulation for signal (solid red histogram) and background (dashed green histogram) photons with $p_T > 40$ GeV/c reconstructed in the ECAL barrel.

-cones” are cones with radius $\Delta R$ that are centered at the photon SC position. The light gray circular region in Fig. 5-15 illustrates the isolation cone. “Isolation variables” give a measure of the energy that is inside the isolation cone but not associated to the photon.

A detector-based isolation has been used in analysis of the 2015 pp reference and PbPb data where the isolation variables are the

- total ECAL energy
- total HCAL energy
- $p_T$ sum of tracks

inside the isolation cone.

There can be particles that fall inside the isolation cone, but are uncorrelated to the nucleon-nucleon interaction that produce the photon. In pp events, these particles can originate from different pp interactions in the same bunch crossing. In PbPb events, they can originate from different nucleon-nucleon interactions in the
same PbPb collision. It is hard to identify the particles that are uncorrelated to
the interaction that produce the photon object of interest (In fact, identification of
uncorrelated particles can be achieved only for charged particles in pp collisions,
thanks to the association of charged particles to the interaction vertex). Therefore,
contribution of uncorrelated particles (or UE particles in this context) to an isolation
variable must be estimated and subtracted.

The UE contribution to an isolation variable is estimated as follows: the to-
tal energy is calculated inside a region that covers the rectangle defined by $\eta \in
(\eta^{SC} - \Delta R, \eta^{SC} + \Delta R)$ and $\phi \in (0, 2\pi)$ but not including the isolation cone. This
region is essentially the dark gray region in Fig. 5-15. The total energy in the region
is divided by the area over which it was calculated, giving the estimated density of
UE energy, then multiplied by the area of isolation cone, giving the estimated UE
energy inside the isolation cone.

For a given photon candidate, the local environment in a cone of $\Delta R$ with respect
to the centroid of the supercluster is inspected for hadronic, electromagnetic, and

Figure 5-15: Isolation variables estimate the amount of energy deposited inside a
cone of radius $\Delta R$ (light gray region) centred at the photon supercluster position.
The contribution from different nucleon-nucleon interactions (UE contribution) to an
isolation variable is estimated by calculating the energy deposited into the dark gray
region as explained in the text.

\[ \Delta \eta \]
\[ +\Delta R \]
\[ -\Delta R \]
\[ \pi \]
\[ \Delta \phi \]
\[ -\pi \]
track activity. Tracks with $p_T^{\text{trk}} > 2 \text{ GeV/c}$ are included in track isolation calculation. The UE-subtracted detector-based isolation variables for cone radius of $\Delta R = i/10$ are defined as follows

$$iso_{i, \text{UEsub}}^{\text{ECAL}} = iso_{i}^{\text{ECAL}} - iso_{i}^{\text{ECAL,UE}}$$  \hspace{1cm} (5.8)$$

$$iso_{i, \text{UEsub}}^{\text{HCAL}} = iso_{i}^{\text{HCAL}} - iso_{i}^{\text{HCAL,UE}}$$  \hspace{1cm} (5.9)$$

$$iso_{i, \text{UEsub}}^{\text{TRK}} = iso_{i}^{\text{TRK}} - iso_{i}^{\text{TRK,UE}}$$  \hspace{1cm} (5.10)$$

The first terms on the right side of the equations denote energies inside the isolation cone (light gray region in Fig. 5-15). The second terms denote the contribution of the particles emerging from other nucleon-nucleon interactions (UE particles), estimated using energies inside the UE strips (dark gray region in Fig. 5-15).

$$iso_{i}^{\text{ECAL}} = -E_{T}^{\text{SC}} + \sum_{\Delta R<i/10} E_{T}^{\text{BC}},$$  \hspace{1cm} (5.11)$$

$$iso_{i}^{\text{ECAL,UE}} = c_{R} \cdot \sum_{(\eta, \phi) \in \text{UE strip}} E_{T}^{\text{BC}}$$  \hspace{1cm} (5.12)$$

$$iso_{i}^{\text{HCAL}} = \sum_{\Delta R<i/10} E_{T}^{\text{HCAL}},$$  \hspace{1cm} (5.13)$$

$$iso_{i}^{\text{HCAL,UE}} = c_{R} \cdot \sum_{(\eta, \phi) \in \text{UE strip}} E_{T}^{\text{HCAL}}$$  \hspace{1cm} (5.14)$$

$$iso_{i}^{\text{TRK}} = \sum_{\Delta R<i/10, p_T^{\text{trk}}>2 \text{ GeV/c}} p_T^{\text{trk}},$$  \hspace{1cm} (5.15)$$

$$iso_{i}^{\text{TRK,UE}} = c_{R} \cdot \sum_{(\eta, \phi) \in \text{UE strip, } p_T^{\text{trk}}>2 \text{ GeV/c}} p_T^{\text{trk}}$$  \hspace{1cm} (5.16)$$

where $E_{T}^{\text{SC}}$ is the $E_T$ of photon supercluster, $E_{T}^{\text{BC}}$ is the $E_T$ of an ECAL basic cluster, $E_{T}^{\text{HCAL}}$ is the $E_T$ of an HCAL crystal. The “UE strip” is defined by

$$\eta \in (\eta^{\text{SC}} - \Delta R, \eta^{\text{SC}} + \Delta R), \phi \in (0, 2\pi), \text{ and } \Delta R > i/10$$  \hspace{1cm} (5.17)$$

The isolation cone and UE strip cover different cross-sectional areas. The $c_{R}$ factor
scales the energy density in an UE strip to the one in an isolation cone

\[
c_R = \frac{\pi \Delta R^2}{2\Delta R \cdot 2\pi - \pi \Delta R^2}
\]

\[
= \frac{\Delta R}{4 - \Delta R}
\]

The electromagnetic (ECAL), hadronic (HCAL), and track isolation variables can be added up to give a combined isolation variable

\[
is_{\text{i}} \text{iso}^{\text{ECAL,UEsub}} + is_{\text{i}} \text{iso}^{\text{HCAL,UEsub}} + is_{\text{i}} \text{iso}^{\text{TRK,UEsub}}
\]

The variable defined in eq. (5.20) is usually referred to as the “summed” isolation and can be labelled shortly as SumIso$^{\text{UE-sub}}$.

Isolation variables for the photon-tagged jet measurements presented in Ch. 7 and Ch. 8 are calculated inside a cone of radius $\Delta R = 0.4$ and photons were selected using a SumIso$^{\text{UE-sub}} < 1$ GeV/c requirement. Fig. 5-16 shows the summed isolation distributions for signal and background photon events simulated for analysis of the 2015 PbPb data.

Details about the application of photon identification variables for the measurements in this thesis can be found Sec. 7.1.1. Specifically, Table 7.1 lists the value requirements for variables.

### 5.4 Z bosons

Z bosons in this thesis are reconstructed in the $\mu^+\mu^-$ and $e^+e^-$ decay channels. CMS detector is able to trigger and reconstruct Z bosons in HI collisions as shown previously in Ref. [235]. Triggering for Z bosons is described in Sec. 4.4.

#### 5.4.1 Muons

Muons are reconstructed by combining information from the inner tracker (see Sec. 3.1) and the muon system (see Sec. 3.5). Details of the muon reconstruction can
Figure 5-16: Distribution of the sum of photon isolation variables in PbPb simulation for signal (red histogram) and background (green histogram) photons. Isolation is calculated inside a cone of $\Delta R = 0.4$. Figure taken from Ref. [2].

Muons in this thesis are identified using a restrictive selection criteria, a “tight” identification, in order to suppress hadrons that punch through the calorimeters and muons from hadron decays. This criteria requires a reco muon to have

- at least 1 hit in the muon system
- a good-quality fit ($\chi^2$/dof < 10) when connecting the track from the muon system to inner tracker
- segments in at least 2 muon stations
- at least 1 hit in the pixel and 6 hits in the strip layers
• a distance from the primary vertex of at most 5 and 2 mm in the longitudinal (z) direction and in the transverse (xy) plane, respectively

5.4.2 Electrons

Electrons are reconstructed by combining the ECAL SCs with tracks that are matched in position and energy. The SCs are reconstructed using the GED algorithm and electron energies are corrected using regression analysis in TMVA [369].

Electrons are identified by imposing criteria on the information collected from the calorimeters and the tracker. Mainly, the identification is based on energy and position compatibility between the associated ECAL SC and track, the ECAL cluster shape, and relation of energies in the ECAL and HCAL. The specific variables used in the identification are,

• \(|\Delta \eta_{SC, seed}| = |\eta_{SC} - \eta_{trk_{extrap}}|\) : The \(\eta\) difference between the associated SC and track extrapolated from the inner most track position

• \(|\Delta \phi_{SC, seed}| = |\phi_{SC} - \phi_{trk_{extrap}}|\) : The \(\phi\) difference between the associated SC and track extrapolated from the inner most track position

• \(\text{H/E} \) : The HCAL over ECAL energy ratio (described in Sec. 5.3.4)

• \(\sigma_{\eta} \) : Same as the one defined in eq. 5.3.4

• \(|1/E^{SC} - 1/p|\) : Compatibility between the SC energy \((E^{SC})\) and track momentum \((p)\) at the point of closest approach to the vertex

• \(|d_0|\) : Distance between the track and interaction vertex in transverse (xy) plane

• \(|d_z|\) : Distance between the track and interaction vertex in longitudinal (z) direction

• \(N^{\text{miss, hit}}\) : “Missing hits”, Number of the inner tracker layers where the track has no hits
Small values of $|\Delta \eta^{SC,seed}|$, $|\Delta \phi^{SC,seed}|$, and $|1/E^{SC} - 1/p|$ are required to ensure that position and energy measurements from the calorimeter and the tracker are consistent. The $H/E$ and $\sigma_{\eta}$ are required to have small values in order to enhance the fraction of genuine electrons in the selected sample and suppress the contribution from charged hadrons misidentified as electrons. Small values of $|d_0|$ and $|d_z|$ are imposed to select electrons originating from the very early processes, e.g. the $Z$ boson decay. A photon undergoing conversion in the upper layers of the tracker can produce electron-positron pairs (see Sec. 5.3). Track of an electron originating from a conversion will miss a number of hits in the inner tracker layers. A low $N_{\text{miss},\text{hit}}$ is required to reject electrons produced in a conversion.

Further details about the electron identification in CMS can be found in Ref. [365]. Table 5.1 lists the electron identification variables and their value requirements applied in the $Z+\text{jet}$ correlations measurement (presented in Ch. 6) which used the 2015 data. The values used in pp is recommended by the electron object group in CMS and correspond to a working point that provides medium ($\sim 80\%$) efficiency. Performance of the $Z \to ee$ reconstruction and identification can be found in Ref. [?]. The identification criteria for the 2015 PbPb data have been optimized separately to account for the PbPb UE.

<table>
<thead>
<tr>
<th>Variable</th>
<th>2015 pp</th>
<th>2015 PbPb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta \eta^{SC,seed}</td>
<td>&lt;$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi^{SC,seed}</td>
<td>&lt;$</td>
</tr>
<tr>
<td>$H/E &lt;$</td>
<td>0.088</td>
<td>0.0958</td>
</tr>
<tr>
<td>$\sigma_{\eta} &lt;$</td>
<td>0.010</td>
<td>0.0111</td>
</tr>
<tr>
<td>$</td>
<td>1/E^{SC} - 1/p</td>
<td>&lt;$</td>
</tr>
<tr>
<td>$</td>
<td>d_0</td>
<td>&lt;$</td>
</tr>
<tr>
<td>$</td>
<td>d_z</td>
<td>&lt;$</td>
</tr>
<tr>
<td>$N_{\text{miss},\text{hit}} \leq$</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.1: Identification variables and their upper values applied for electrons in the analysis of pp reference and PbPb data recorded in 2015. B (E) denotes the ECAL barrel (endcaps) regions.

Table 5.2 (5.3) lists the electron identification variables and their value require-
ments applied in the Z+hadron correlations measurement in Ch. 9 which used the pp (PbPb) data taken in 2017 (2018). Several variables had minor definition changes compared to the 2015 data as these changes improved identification performance, albeit slightly. The $|\Delta \eta|$ in 2015 has been replaced with $|\Delta \eta^{\text{SC,seed}}|$ which uses seed ECAL cluster $\eta$, instead of the ECAL SC $\eta$. The $d_0$ and $d_z$ in 2015 have been replaced with $d_{0z}$ which calculates the distance between track and interaction vertex in three dimensions, instead of one or two. For the 2018 data, the H/E has been replaced with $H^\text{low}/E$ where the involved HCAL energy is that of a single tower instead of all towers within a cone.

| Variable | $|\Delta \eta^{\text{SC,seed}}| <$ | $|\Delta \phi^{\text{SC,seed}}| <$ | H/E | $\sigma_\eta <$ | $|1/E^{\text{SC}} - 1/p| <$ | $d_{0z} <$ | $N^{\text{miss,hit}} <$ |
|----------|-----------------|-----------------|------|-------------|-----------------|--------|-----------------|
|          | 0.0048          | 0.0625          | 0.0607 | 0.0103      | 0.1327          | 0.03   | 2               |
|          | 0.0066          | 0.0881          | 0.0452 | 0.0306      | 0.9066          | 0.03   | 1               |

Table 5.2: Identification variables and their upper values applied for electrons in the analysis of pp reference data recorded in 2017. B (E) denotes the ECAL barrel (endcaps) regions.

| Variable | $|\Delta \eta^{\text{SC,seed}}| <$ | $|\Delta \phi^{\text{SC,seed}}| <$ | H/E | $H^\text{low}/E <$ | $\sigma_\eta <$ | $|1/E^{\text{SC}} - 1/p| <$ | $d_{0z} <$ | $N^{\text{miss,hit}} <$ |
|----------|-----------------|-----------------|------|-----------------|-------------|-----------------|--------|-----------------|
| Cent:30–100% | 0.0037 | 0.128 | 0.181 | 0.0113 | 0.106 | 0.03 | 3 |
| Cent:0–30%   | 0.0074 | 0.209 | 0.114 | 0.0376 | 0.024 | 0.03 | 3 |
| B          | 0.0041 | 0.085 | 0.273 | 0.0147 | 0.037 | 0.03 | 3 |
| E          | 0.0097 | 0.235 | 0.190 | 0.0480 | 0.030 | 0.03 | 3 |

Table 5.3: Identification variables and their upper values applied for electrons in the analysis of PbPb data recorded in 2018. B (E) denotes the ECAL barrel (endcaps) regions.
5.5 Jets

Jets are reconstructed by clustering the particles identified by the PF algorithm using the anti-$k_t$ jet finding algorithm in the FastJet framework \cite{270,273} (see Sec. 5.2 for the PF identification and Sec. 2.1.2 for jet algorithms). A rather small distance parameter of $R = 0.3$ is chosen in order to minimize the effects of HI UE fluctuations. All jets used in this thesis are selected to have $p_T^{\text{jet}} > 30$ GeV/c and $|\eta^{\text{jet}}| < 1.6$. Furthermore, there is no attempt to select the jet with the highest $p_T$ (leading jet) or the second highest $p_T$ (subleading jet). All jets that satisfy a kinematic requirement are selected, that is the jet selection is “inclusive”.

An iterative algorithm \cite{370} is employed to subtract the UE background from jets in PbPb. The implementation of the subtraction in CMS has been provided in Ref. \cite{217}. This subtraction method is described in Sec. 5.5.1. No UE subtraction has been applied for jets in pp reference where effects of the UE are negligible.

5.5.1 Background subtraction in heavy ion collisions

The HI UE is subtracted EbE, using an algorithm that is a variant of an iterative “noise/pedestal subtraction” technique \cite{370}.

The mean value of cell energy, $\langle E_{\text{cell}} \rangle$, and the dispersion of cell energy $\sigma (E_{\text{cell}})$, are calculated separately for each $\eta$-ring, a set of cells at the same $\eta$-coordinate. In this context, a cell is a calorimeter crystal. In earlier CMS measurements jets were found by clustering the calorimeter energy. Jets in this thesis are found by clustering the PF candidates, therefore the cells in this case are obtained by converting the PF candidates into “pseudo” calorimeter clusters by adjusting their position to the calorimeter spatial resolution. Then, for each $\eta$-ring, the $\langle E_{\text{cell}} \rangle + \sigma (E_{\text{cell}})$ value is subtracted from the energy of each cell. If energy of a cell is negative after the subtraction, then its energy is set to zero. The purpose of the subtracted value being $\langle E_{\text{cell}} \rangle + \sigma (E_{\text{cell}})$ instead of simply the $\langle E_{\text{cell}} \rangle$ is to minimize the bias introduced by the zeroing of cell energies that became negative after the subtraction.

Next, jets are clustered using the cells with positive energies. In a second iteration,
the \( \langle E_{\text{cell}} \rangle + \sigma (E_{\text{cell}}) \) value is calculated again for each \( \eta \)-ring, but this time using only the cells whose position lie outside the area covered by the high energy jets, e.g. \( p_{\text{jet}}^{T} > 15 \text{ GeV}/c \). The subtraction and zeroing step is repeated for all cells using the \( \langle E_{\text{cell}} \rangle + \sigma (E_{\text{cell}}) \) value for each \( \eta \)-ring. Then cells are clustered again giving the final jet collection.

This subtraction algorithm is generally referred to as the "Pileup (PU) subtraction".

### 5.5.2 Jet energy correction

The jet energy obtained after the clustering and the iterative subtraction procedure is uncorrected and its \( p_{T} \) is denoted as \( p_{T}^{\text{raw}} \). Jet energy is corrected via a multiplicative factor derived in multiple steps as described in Ref. [371]. The steps in jet energy correction (JEC) in order of application are listed as

- **Pileup offset corrections** remove the additional PU contribution from the jet energy.
- **Simulated response corrections** remove the offset between the simulated, reconstructed \( p_{\text{jet}}^{T} \) and the true \( p_{\text{jet}}^{T} \).
- **Residual corrections for data** remove the residual discrepancy between the detector response in data and simulation.

Correction factors in each step are derived as a function of \( p_{T} \) and \( \eta \). The reco \( p_{T} \) used as input in each step has the corrections from previous steps applied. The final \( p_{T}^{\text{reco}} \) is the corrected jet \( p_{T} \) and can be related to the \( p_{T}^{\text{raw}} \) via

\[
p_{T}^{\text{reco}} = C \cdot p_{T}^{\text{raw}} \quad (5.21)
\]

\[
C = C_{\text{PU}} \cdot C_{\text{Sim}} \cdot C_{\text{Res}} \quad (5.22)
\]

where the final correction factor \( C \) is the multiplication of correction factors from each step.
Note that the pileup offset corrections in PbPb are already taken care of via the subtraction described in Sec. 5.5.1, thus only the last two steps are applied to correct jet energy in PbPb. Besides, the average number of primary vertices in pp reference, \( \langle N_{PV} \rangle \), is between 1 and 3. This is a much lower pileup than the one in standard pp collisions at \( \sqrt{s} = 13 \text{ TeV} \). So pileup offset corrections for the pp reference were smaller than the average corrections for the \( \sqrt{s} = 13 \text{ TeV} \) pp collisions.

### 5.5.3 Jet energy scale

The jet energy scale (JES) is extracted as the mean value of Gaussian distributions fitted to the energy response distribution given in eq. 5.1.

The JEC for Z+jet and photon+jet measurements are derived as function of \( p_T \) in bins of \( \eta \) and rapidity. Fig. 5-17 and 5-18 show the JES in PbPb simulation samples as function of \( p_T^{\text{gen}} \) and \( \eta \), respectively, after the application of JEC. Note the difference in the fragmentation pattern of quark jets and gluon jets translate to difference in detector response, resulting in a flavor dependent of JES. The JES for the whole Z+jet simulation (black markers in Figs. 5-17 and 5-18) contains a mixture of contributions from the quark and gluon jets, lying somewhere between the quark JES (blue markers) and gluon JES (red markers). Quark jets tend to have relatively fewer but more energetic particles than gluon jets with the same energy, as shown in Sec. 2.1. The effect of this in jet reconstruction is that the detector response to quark jets is relatively larger. The JES non-closures, i.e. the deviations of JES from 1, are accounted for in the systematics uncertainties.

#### Uncertainty in jet energy scale

The are several sources contributing to the JES uncertainty for the measurements in this thesis. First, simulation shows that the JES has a non-closure of 2%. Second, there is 2% uncertainty arising from the difference between data and simulation. Third, there is an uncertainty arising from the fact that the JES depends on fragmentation pattern, or equivalently the parton flavor, and there is no precise understanding...
of the parton flavor mixture in PbPb data. Hence, JES uncertainties can be listed as

1. Non-closure in simulation

2. Difference between data and simulation

3. Lack of knowledge about the parton flavor mixture or fragmentation pattern in PbPb data

The first two uncertainty sources apply to both pp and PbPb data. The third source is unique for PbPb and arises from the fact that jets are modified in QCD medium in an unknown way (which is actually a motivation for this thesis). The total JES uncertainty for pp (PbPb) is calculated assuming that the first two (all three) sources are uncorrelated. Thus, the total JES uncertainty for a measurement in pp (PbPb) is obtained by adding the uncertainty due to two (three) sources in quadrature. Details of the evaluation and impact of these uncertainties on the measurements are discussed in the relevant chapters.

Figure 5-17: The jet energy scale vs $p_T$ after the application of energy corrections derived using Pythia + Hydjet samples where the inclusive jets (black) represent the mixture of quark (blue) and gluon (red) jets expected in Z+jet process. Left (right) panel corresponds to 10–30% (0–10%) event centrality.
5.5.4 Jet energy and angle resolution

The jet energy resolution (JER) is extracted as the deviation of Gaussian distributions fitted to the jet energy response distribution given in eq. 5.1. Similarly, the jet $\phi$ (jet angular) resolution is extracted as the deviation of Gaussian distributions fitted to $|\phi_{\text{reco}} - \phi_{\text{gen}}|$ where $\phi_{\text{reco}}$ and $\phi_{\text{gen}}$ are the reconstructed (detector-level) and generated (true) jet $\phi$, respectively. The jet energy and jet $\phi$ resolutions as function of $p_T$ can be parametrized via the $CSN$ formula as given in eq. 5.23 and eq. 5.24 respectively (the same parametrization as for the ECAL energy resolution given in eq. 3.1). The parameters describe the various effects on the resolution: the $S$ (stochastic) parameter describes the $p_T$ dependence, the $C$ (constant) represents the high $p_T$ limit, and the $N$ (noise) reflects the effect of UE fluctuations. The parameter values for jets in pp (PbPb) are determined in the PYTHIA (PYTHIA + HYDJET) sample. One exception is the $C$ parameter whose value is determined only in the PYTHIA sample, and is the same for pp and PbPb. This approach follows from the assumption that pp and PbPb resolutions would converge to the same value in the $p_T^{\text{jet}} \to \infty$ limit.
Due to the large UE fluctuations, the PbPb jet energy and angle resolutions can be significantly worse than the pp counterparts. For all PbPb-to-pp comparisons in the Z+jet (see Ch. 6) and photon+jet FF (see Ch. 7) measurements, resolutions of the measured jet energy and azimuthal angle in pp are smeared to match those in PbPb. The energy (angle) smearing for pp jets is performed by calculating the relative resolution $\sigma_{\text{rel}}$ given in eq. 5.25 and multiplying the $p_T^{\text{jet}}$ with a random Gaussian variable with mean 1 and variance $\sigma_{\text{rel},p_T}^2$ (adding to $\phi^{\text{jet}}$ a random Gaussian variable with mean 0 and variance $\sigma_{\text{rel},\phi}^2$). It was found that the effect of jet angle smearing was negligible compared to the energy smearing.

Fig. 5-19 shows the JER in PbPb simulations for Z-tagged jets and the CSN formula fitted to it. The values of $C$, $S$, and $N$ parameters extracted for the JER in Z+jet measurement are listed in Table 5.4 as well as in Ref. [1], and the JER corresponding to this set of parameter values is shown in Fig. 5-20. The extracted JER at $p_T^{\text{jet}} = 30 \text{ GeV}/c$ are $\approx 18\%$ ($\approx 35\%$) for pp (0-30% centrality PbPb). The values used in photon+jet FF measurement are provided in Ref. [243]. Theoretical calculations can make a proper comparison to these measurements by smearing the generator-level jet $p_T$ using the parameter values pointed above.

\[ \sigma \left( \frac{p_T^{\text{reco}}}{p_T^{\text{gen}}} \right) = \sqrt{C^2 + \frac{S^2}{p_T^{\text{gen}}} + \frac{N^2}{(p_T^{\text{gen}})^2}} \]  
\[ \sigma (|\phi^{\text{reco}} - \phi^{\text{gen}}|) = \sqrt{C_\phi^2 + \frac{S_\phi^2}{p_T^{\text{gen}}} + \frac{N_\phi^2}{(p_T^{\text{gen}})^2}} \]  
\[ \sigma_{\text{rel}} = \sqrt{\sigma_{\text{PbPb}}^2 - \sigma_{\text{pp}}^2} \]  

<table>
<thead>
<tr>
<th>System</th>
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<th>$S$ [$\text{GeV}/c$]</th>
<th>$N$ [$\text{GeV}/c$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbPb (Cent:0-30%)</td>
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<td>2.14</td>
<td>8.08</td>
</tr>
<tr>
<td>pp</td>
<td>0.061</td>
<td>0.95</td>
<td>0.001</td>
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</tbody>
</table>

Table 5.4: The JER is parametrized via eq. 5.23. Values of $C$, $S$, and $N$ parameters extracted for the Z+jet correlations measurement [1].

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Figure 5-19: The jet energy resolution vs $p_T$ in Pythia + Hydjet samples (marker) are fit via the CSN formula in eq 5.23.

**Uncertainty in jet energy resolution**

Comparison between data and simulation shows that the JER can be 15% worse in data [371]. This number is used in evaluating the JER uncertainty for the jet measurements presented in the following chapters.

### 5.6 Tracks

The magnetic field along the $z$-axis forces a charged particle into a circular motion in the transverse ($xy$) plane and the particle’s ultimate trajectory becomes very close to a helix. Charged particles passing through the inner tracker layers give rise to signals in the silicon detectors, which are then reconstructed as “hits”. A trajectory is fit through the hits to obtain a “track” from which the momentum and position of a charged particle can be extracted. The task of finding trajectories of all particles can become a very computation intensive operation, as the number of possible trajectories
increase with the number of particles. Assuming that all charged particles create a hit in each layer (without a miss) and a trajectory contains a hit from exactly one layer, then the number of possible trajectories for $M$ charged particles going through $N$ tracker layers is $M^N$. Certainly this complexity can be chopped down dramatically via assumptions on particle directions (e.g., helical trajectories) and proximity of hits. Nevertheless this simple complexity scaling was given here to illustrate the challenges in CMS track reconstruction, as the inner tracker has $\sim 10$ layers and $\sim 10$ charged particles are produced in a typical pp collision with a hard scattering. It is more of a challenge for HI collisions where $\sim 1000$ charged particles are produced.

In order to avoid the excessive computation times, tracks are reconstructed over a number of iterations, an “iterative tracking” procedure. In each iteration, the pro-
procedure attempts to find track segments that are easiest to identify using the hits that are not yet assigned to a trajectory. After each iteration, there are less unassigned hits than the previous iteration, decreasing the computation complexity after each step.

Each iteration starts with the seeding step where 2-4 hits are combined to produce a “seed” which is then used to estimate the whole trajectory of a charged particle going through those hits. Next, the track finding step extrapolates seeds and searches if new hits can be added to the trajectory. Kalman filter [356, 372, 373] is used in track finding and to estimate the trajectory parameters. A track is labelled with its quality and removed if it does not meet a certain quality criteria.

Details of the track reconstruction in pp and PbPb collisions are given in Refs [346] and [200], respectively.

Selections are applied on the track quality variables in order to increase the fraction of tracks corresponding to genuine charged particles and suppress the fraction of misidentified tracks. The specific variables used in the track identification are,

- Track quality assigned based on number of layers, hits, the fit quality in each iteration. The criteria from the loosest to most stringent are named “loose”, “tight”, “high purity”. In general, physics measurements require high-purity quality for a track. Details about track quality can be found in Ref. [346].

- $\sigma_{p_{T}^{trk}}/p_{T}^{trk}$: The uncertainty in $p_{T}^{trk}$

- $N_{hit}$: Number of hits in the tracker layers

- $\chi^2$/dof/$N_{layer}$: A fit quality, the fitted $\chi^2$ divided by the number of degrees of freedom and the number of tracker layers hit

- $|d_0|/\sigma_{d_0}$: Significance of distance to the interaction vertex in the transverse $(xy)$ plane

- $|d_z|/\sigma_{d_z}$: Significance of distance to the interaction vertex in the longitudinal $(z)$ direction
• A calorimeter energy deposit compatible with the track’s momentum.

Tracks are required to have a small $p_T^{\text{trk}}$ uncertainty, a minimum number of hits, as well as a good quality fit. A small significance of distance from the interaction vertex is required to suppress the tracks corresponding to nonprimary particles (Fig. 5-21 shows the average path of hadrons before their decays in the CMS detector). Misidentified tracks with a high $p_T^{\text{trk}}$ are rejected by requiring the energy deposit in calorimeters to be compatible with the track momentum. Calorimeter energy deposits are associated with tracks via the PF algorithm (see Sec. 5.2).

Table 5.5 lists the track selection variables and their value requirements. The values used are derived recommended by the Track physics object group in CMS.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality</td>
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<td>high purity</td>
</tr>
<tr>
<td>$\sigma_{p_T^{\text{trk}}}/p_T^{\text{trk}} &lt;$</td>
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<td>0.1</td>
</tr>
<tr>
<td>$\chi^2/\text{dof}/N^{\text{layer}} &lt;$</td>
<td>–</td>
<td>0.15 (0.18)</td>
</tr>
<tr>
<td>$</td>
<td>d_0</td>
<td>/\sigma_{d_0} &lt;$</td>
</tr>
<tr>
<td>$</td>
<td>d_z</td>
<td>/\sigma_{d_z} &lt;$</td>
</tr>
<tr>
<td>$N^{\text{hit}} &gt;=$</td>
<td>–</td>
<td>11</td>
</tr>
<tr>
<td>(if $p_T^{\text{trk}} &gt; 20$ GeV) $E^{\text{calo}}/p_T^{\text{trk}} &gt;$</td>
<td>0.5 (–)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 5.5: Selection variables and their value requirements applied for tracks in the analysis of pp reference and PbPb data. The values for a collision system different than the previous data taking period are indicated in parenthesis.

Fig. 5-22 shows the ratio of track spectrum to that of the gen charged particles in simulation for the 2018 PbPb data. The ratio for uncorrected tracks corresponds to values slightly above tracking efficiency as track spectrum contains misidentified tracks as well. On the other hand, fake track rate in the $p_T^{\text{trk}} > 1$ GeV/c range is order of magnitude smaller than tracking efficiency. Therefore, the ratio for uncorrected tracks can be taken as a proxy for tracking efficiency. The extraction of actual tracking efficiency and misidentification rate is beyond the scope of the work in this thesis and can be found in Ref. [374]. The ratio is $\sim 0.6$ for the 0–10% centrality range and goes up to $\sim 0.7$ for 50–90% centrality collisions.

The track and gen particle spectrum agree much better after tracking corrections
Figure 5-21: Mean transverse path \( c \tau \) of hadrons as function of \( p_T \). Distances of the CMS subdetectors from interaction point are indicated with dashed bold horizontal lines.

(see the right panel in Fig. 5-22). For most part of the spectrum, corrected tracks agree with gen particles within 5%. However, there is no perfect agreement for several reasons. First, the corrections are parametrized in bins of track kinematics \( (p_T, \eta, \text{ or } \phi) \) and event centrality which is not a perfect modelling of tracking efficiency. Second, the particle spectrum and species composition are not identical between the samples used in deriving and testing the corrections. Specifically, corrections for misidentified particles are derived from HYDJET and efficiency corrections are derived from PYTHIA + HYDJET, and the final correction is a combination of the two and is tested on a single sample, the effect of this is more important for disagreements at high \( p_T \). Third, correction factors are derived from particle densities averaged over events, however
particle density is not necessarily uniform over different events and a limited number of events is used in simulation.

Details about the tracking efficiency, misidentification rate, and the correction procedure for pp reference and PbPb data can be found in Refs. [374, 200].

Figure 5-22: The ratio of reconstructed tracks over generated charged particle $p_T$ distributions in PbPb simulation for various collision centralities. The left (right) panel includes tracks that are uncorrected (corrected) for efficiency.
Chapter 6

Jet quenching using Z+jet correlations

This chapter is dedicated to the Z+jet correlations measurement in Ref. [1], the first characterization of parton energy loss through angular and $p_T$ correlations between a Z boson and the associated jets. As pointed out in Sec. [1.6.1] due to the accuracy and high purity of Z boson reconstruction, this is the first study of the “most precise probe” of QGP. The analysis exploits PbPb and pp data samples recorded in 2015 at $\sqrt{s_{NN}} = 5.02$ TeV, corresponding to integrated luminosities of 404 $\mu$b$^{-1}$ and 27.4 pb$^{-1}$, respectively.

The possible angular deflection or momentum broadening effects in QCD medium are studied via the azimuthal angle difference of the Z+jet pair

$$\Delta \phi_{jZ} = |\phi_{\text{jet}} - \phi_{Z}|$$  \hspace{1cm} (6.1)

Jet energy loss is primarily quantified via the momentum imbalance of the Z+jet pair

$$x_{jZ} = \frac{p_{Tj}}{p_{TZ}}$$  \hspace{1cm} (6.2)

These observables were already introduced in eqs. [2.13] and [2.14] in theory discus-
sion of jets tagged with EW bosons. The $\Delta \phi_{jZ}$ and $x_{jZ}$ are analyzed as distributions normalized by the number of $Z$ events, $N_Z$. Further studies of parton energy loss are performed via the mean value of the momentum imbalance, $\langle x_{jZ} \rangle$, and the average number of associated jets per $Z$, $R_{jZ}$.

Events are selected as described in Sec. 4.4. Reconstruction and identification of muons (electrons) are provided in Sec. 5.4.1 (Sec. 5.4.2). In addition, leptons are required to be within the detector acceptance, hence muons must fall in the acceptance of muon detectors, $|\eta^{\mu}| < 2.4$, and electron SCs must be within the tracker acceptance, $|\eta^{SC}| < 2.5$, and outside the transition region between the ECAL barrel and endcaps (electron SCs with $1.44 < |\eta^{SC}| < 1.57$ are excluded). In order to suppress the contamination from muons produced in hadron decays in the same event, muons are required to have $p_T > 10$ GeV/$c$. Electrons must have $p_T > 20$ GeV/$c$ for the same reason as muons as well as to be above the trigger threshold.

The $p_T$ thresholds for leptons do not cause a large reduction in sample size. Unlike most charged particles, leptons from $Z$ boson decays have a $p_T$ spectrum different than a steeply falling one. Fig. 6-1 shows the $p_T$ spectrum of muons from $Z$ decays in generated events. The spectrum for the leading lepton (the one with higher $p_T$) peaks at $p_T \approx 45$ GeV/$c$ (half the $Z$ mass) for $Z$s at rest, and the peak shifts to higher values with increasing $p_T^Z$.

The $Z$ bosons candidates are made from oppositely charged muon or electron pairs, required to have an invariant mass $M^{ll}$ satisfying $70 < M^{ll} < 110$ GeV/$c^2$ and $p_T^Z$ above 40 GeV/$c$. $Z$ bosons are corrected for reconstruction efficiency following the procedure described in Sec. 9.1.1.

In PbPb collisions, the analysis focuses on 30% most central collisions, the region of physics interest, which has stronger QCD medium effects and statistically significant number of events in the data set. This centrality region contains 78% of the $Z$ candidates defined above. Fig. 6-2 shows the invariant mass distributions of all the lepton pairs used in the PbPb analysis, a total of 536 events with a $Z$ candidate were analyzed in PbPb data.
Figure 6-1: True $p_T^\mu$ distributions of muons in Pythia $Z \rightarrow \mu\mu$ events satisfying different thresholds for $Z$ boson $p_T$, $p_T^Z > 10$ (blue), $p_T^Z > 30$ (black), $p_T^Z > 40$ (red) GeV/c. The left (right) panel corresponds to the higher (lower) $p_T$ muon in the pair.

### 6.1 Analysis method

Each $Z$ candidate is paired with all the jets in the same event that satisfy the $p_T^{\text{jet}} > 30$ GeV/c and $|\eta^{\text{jet}}| < 1.6$ requirement. In addition jets found within $\Delta R < 0.4$ from a lepton are rejected in order to eliminate the energy contamination by leptons from $Z$ boson decays. Jet energies are corrected as described in Sec. 5.5.2.

The jet selection is inclusive, as mentioned in Sec. 5.5, all jets that satisfy kinematic requirements are included. In PbPb collisions, this type of selection gives rise to a “combinatorial” background in $Z$+jet correlations, as there can be “background” jets arising from nucleon-nucleon interactions different from the one that produced the $Z$. The “background” jet contributions can be due to one of the following:

- fake jets reconstructed from the PbPb UE fluctuations
- hard scattering processes in nucleon-nucleon interactions other than the one producing the $Z$ boson.

The background jet contributions are estimated using MB events. For each $Z$+jet event, the $Z$ boson is correlated with jets in a set of 40 MB events that have the same
Figure 6-2: Invariant mass distributions of the selected muon pairs (left) and electron pairs (right) used in the PbPb analysis, compared to PYTHIA + HYDJET $Z(\ell\ell) + \text{jet}$ events. The simulation histogram is normalized to the number of events in the data. Figure taken from Ref. [1].

centrality as the $Z + \text{jet}$ event and an interaction vertex whose $z$-coordinate, $v_z$, is not separated by more 10 cm than the one in $Z + \text{jet}$ event. The number of MB events per $Z + \text{jet}$ event is chosen to be high enough to provide the desired precision for the background estimation.

Fig. 6-3 shows a simple illustration of the procedure. The original correlation in the $Z + \text{jet}$ event can be labelled as "raw", as it is not modified yet. The background contamination in the raw correlation is estimated using MB events, and then subtracted from the raw correlation to reveal the signal correlation. This method to subtract combinatorial background is generally referred to as "event mixing" or "mixed-event" method.

Fig. 6-4 demonstrates how the background jet contributions for $\Delta \phi_{\ell Z}$ observable are estimated and subtracted using the event mixing method. No subtraction is applied for the pp data, where the pileup, i.e. contribution from other nucleon-nucleon collisions, was negligible.
6.2 Systematic uncertainties

General procedure for systematic uncertainty calculation is as follows. For a given uncertainty source, a varied result is obtained by varying the analysis with the source’s uncertainty. For example, if JES uncertainty is $x\%$, then the varied result is obtained by shifting the jet $p_T$ by $\pm x\%$. A ratio of the varied result to the nominal (actual) result is taken for each measurement bin and the deviation of the ratio from 1 is quoted as systematic uncertainty. If the variation is in both upwards and downwards directions (e.g. JES shift by $+x\%$ and $-x\%$), then the larger deviation is taken as uncertainty.

The total systematic uncertainty is calculated by adding the uncertainties from each source in quadrature.

Systematic uncertainties for this analysis can be split into uncertainties related to

- Z boson reconstruction
- Jet reconstruction

Uncertainties related to Z boson are dominantly from electron pairs, uncertainties from muon pairs are very small or negligible. Comparison of the invariant mass of electron pairs in simulation shows that the reco electron $p_T$ can deviate from the
true $p_T$ up to 0.5%. Systematic uncertainty is calculated for electron energy scale by shifting the electron $p_T$ up and down by this deviation. The Z bosons from electron pairs in central PbPb collisions have a $p_T^{Z}$ resolution up to 5% and an uncertainty is calculated in PbPb simulation by smearing the $p_T^{Z}$ by the amount of resolution. Electrons and muons are corrected for their reconstruction and selection efficiency. A systematics uncertainty is assigned for the efficiency correction by comparing the results with and without corrections applied.

Sources of JES uncertainty were discussed in Sec. 5.5.3. Effect of the first two sources are evaluated by shifting the jet $p_T$ by ±2%. Effect of the third source
is evaluated by shifting the jet $p_T$ by the amount of JES for a parton flavor with assumption of the extreme case that the fragmentation of jets in PbPb data could be represented with a single flavor. That is, assuming that all jets in PbPb fragment like quark (gluon) jets, the jet $p_T$ is shifted down (up) by the 4 (6)%, to bring the quark (gluon) jet response to unity. Effect of the JER uncertainty in PbPb is evaluated by smearing the jet $p_T$ by 15% in simulation. As discussed in Sec. 5.5.4, jets in pp are smeared to match the resolution in PbPb. The jet $p_T$ and angle resolution uncertainty for smeared jets in pp are evaluated by varying the relative resolution $\sigma_{rel}$ (see eq. 5.25) by ±15%.

Tables 6.1, 6.2, 6.3, and 6.4 list the systematic uncertainties for the $\Delta\phi_{jZ}$, $x_{jZ}$, $\langle x_{jZ} \rangle$, and $R_{jZ}$ observables, respectively. The tables provide ranges for uncertainties if they vary across the bins. This applies to total uncertainty as well, i.e. a range for total uncertainty cover the total uncertainties across bins, not the total of range boundaries listed for the individual sources.

Table 6.1: Systematics uncertainties for the $\Delta\phi_{jZ}$ distributions listed separately for each source. Numbers are in percentage. Uncertainties are provided in ranges if they vary across the bins in $2.5 < \Delta\phi_{jZ} < \pi$ interval.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>PbPb (Cent:0–30%)</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>0.1-1.5</td>
</tr>
<tr>
<td>Z energy resolution</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Z reconstruction efficiency</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>JES</td>
<td>2.1-2.5</td>
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<tr>
<td>JER</td>
<td>0.1-1.1</td>
</tr>
<tr>
<td>Jet angle smearing</td>
<td>0.1-0.8</td>
</tr>
<tr>
<td>Total</td>
<td>2.2-3.1</td>
</tr>
</tbody>
</table>

### 6.3 Results

Fig. 6-5 shows the $\Delta\phi_{jZ}$ distribution of $Z$+jet pairs where Z bosons are required to have $p_T^Z > 60$ GeV/c in order to reduce the fraction of events where jets associated
Table 6.2: Systematics uncertainties for the $x_{jZ}$ distributions listed separately for each source. Numbers are in percentage. Uncertainties are provided in ranges when they vary across the bins in $0.6 < x_{jZ} < 1.2$ interval.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pp</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>1.1-2.1</td>
</tr>
<tr>
<td>Z energy resolution</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Z reconstruction efficiency</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>JES</td>
<td>2.6-6.8</td>
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<tr>
<td>JER</td>
<td>0.3-2.6</td>
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<tr>
<td>Jet angle smearing</td>
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<tr>
<td>Total</td>
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Table 6.3: Systematics uncertainties for $\langle x_{jZ} \rangle$ listed separately for each source. Numbers are in percentage. Uncertainties are provided in ranges when they vary across the observable bins.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pp</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>0.1-0.6</td>
</tr>
<tr>
<td>Z energy resolution</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Z reconstruction efficiency</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>JES</td>
<td>2.3-2.6</td>
</tr>
<tr>
<td>JER</td>
<td>0.2-0.9</td>
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<tr>
<td>Jet angle smearing</td>
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</tr>
<tr>
<td>Total</td>
<td>2.5-2.7</td>
</tr>
</tbody>
</table>

with the Z lose energy in QCD medium and fall below the $p_T^{jet} > 30$ GeV/c threshold. The results hint at a narrowing of azimuthal angle correlations in PbPb collisions, a feature that is more expected in dijet azimuthal angle correlations [253] where the selection bias (explained in Sec. 1.6) increases the fraction of narrower jets in PbPb that contain fewer partons and have narrower azimuthal angle correlations to each other. Next, the shape differences between pp and PbPb $\Delta \phi_{jZ}$ were quantified using a Kolmogorov-Smirnov (KS) test which draws random data from the same distribution. The probability to obtain a KS test value, p-value, larger than the one observed in the data is greater than 0.4, even if systematics uncertainties are not included. This
Table 6.4: Systematics uncertainties for $R_{ijZ}$ listed separately for each source. Numbers are in percentage. Uncertainties are provided in ranges when they vary across the observable bins.

<table>
<thead>
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<th>Source</th>
<th>Uncertainty [%]</th>
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<th>PbPb (Cent:0–30%)</th>
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</tr>
<tr>
<td>Z energy resolution</td>
<td>&lt; 0.1</td>
<td>0.8-1.1</td>
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<tr>
<td>Z reconstruction efficiency</td>
<td>&lt; 0.1</td>
<td>5.8-8.5</td>
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</tr>
<tr>
<td>JES</td>
<td>1.9-3.3</td>
<td>3.1-11.6</td>
<td></td>
</tr>
<tr>
<td>JER</td>
<td>0.4-0.5</td>
<td>2.9-7.7</td>
<td></td>
</tr>
<tr>
<td>Jet angle smearing</td>
<td>0.1-0.3</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2.1-3.6</td>
<td>8.3-15.6</td>
<td></td>
</tr>
</tbody>
</table>

deems pp and PbPb $\Delta \phi_{ijZ}$ as not significantly different.

A minimum azimuthal separation of $\Delta \phi_{ijZ} > 7\pi/8$ is imposed in $x_{ijZ}$ and $R_{ijZ}$ results to increase the fraction of back-to-back $Z$+jet pairs. 63 (73)% of the $Z$+jet events in pp (PbPb) are left after the azimuthal separation requirement. Fig. 6-6 shows the $x_{ijZ}$ distributions. The PbPb $x_{ijZ}$ is shifted to lower $x_{ijZ}$ values compared to the pp indicating jet energy loss in PbPb. Average values of the distributions are $\approx 0.80$ and $\approx 0.70$ in pp and PbPb data, respectively, indicating the jets in PbPb that ultimately ended up with $p_T$ above 30 GeV/c had lost about 12–13% of their energy compared to jets in pp.

The amount of shift from pp to PbPb $x_{ijZ}$ is quantified via the mean of $x_{ijZ}$ distributions, $\langle x_{ijZ} \rangle$, as a function of $p_T^Z$ as shown in Fig. 6-7. The $\langle x_{ijZ} \rangle$ decreases with increasing $p_T^Z$ for both pp and PbPb. This is because the minimum $p_T^{jet}$ requirement imposes a minimum value for $x_{ijZ}$ and this minimum value becomes smaller with increasing $p_T^Z$, shifting the distribution to lower $x_{ijZ}$. The $\langle x_{ijZ} \rangle$ in PbPb is lower than in pp for all $p_T^Z$ ranges by $\sim 10\%$, which can be used as the scale of fractional energy loss for jets with $p_T^{jet} \sim 60$ GeV/c at the LHC energies. Having said that, the $\langle x_{ijZ} \rangle$ comparison does not include the complete the jet spectrum, but only those with final $p_T$ above 30 GeV/c.

Fig. 6-8 shows $R_{ijZ}$ as function of $p_T^Z$. Jets tend to have higher $p_T^{jet}$ for higher $p_T^Z$,
making them more likely to survive the minimum $p_T^{jet}$ requirement. Therefore, $R_{ijz}$ increases with $p_T^Z$ for both pp and PbPb, as expected, e.g. the pp $R_{ijz}$ is $\approx 0.32$ for $40 < p_T^Z < 50$ GeV/c, and goes up to $\approx 0.76$ for $80 < p_T^Z < 120$ GeV/c. The PbPb $R_{ijz}$ is smaller than pp $R_{ijz}$ for all $p_T^Z$ ranges and the relative difference becomes smaller with increasing $p_T^Z$. This is expected, because for jets produced at higher $p_T$, a fewer fraction of them will lose as much energy as to fail the minimum $p_T^{jet}$ requirement. The PbPb $R_{ijz}$ is smaller than pp by $\sim 45\%$ for $40 < p_T^Z < 50$ GeV/c, and by $\sim 15\%$ for $80 < p_T^Z < 120$ GeV/c.

### 6.3.1 Comparison to theory

The results are compared to several theoretical calculations. The pp data shown in Fig. 6-9 through 6-12 are not smeared to match the resolution in PbPb, as they
Figure 6-6: Distributions of the transverse momentum ratio, \( x_{jZ} \), between the jet and the Z boson with \( \Delta \phi_{jZ} > 7\pi/8 \). The distributions are normalized by the number of Z events, \( N_Z \). Vertical lines (bands) indicate statistical (systematic) uncertainties [1].

are compared to theoretical calculations, not the PbPb results.

The PbPb results are to the following jet quenching models:

- An extension of JEWEL [375] for boson-jet processes. JEWEL is a dynamical, perturbative framework for jet evolution in dense QCD medium, which has been extended to simulate boson-jet events.

- The Hybrid model is introduced earlier in Sec. 2.3.2. The model provided three separate calculations. The “Strong coupling” calculation combines the weakly coupled and strongly coupled physics. The other calculations implement weakly coupled physics where the “collisional energy loss” has a quadratic temperature dependence and “radiative energy loss” has a cubic temperature dependence.

- The GLV model is introduced in Sec. 2.3.2 and Z+jet correlations are calcu-
Figure 6-7: The mean value of the $x_{jZ}$ distribution, as a function of $p_T^Z$. Vertical lines (bands) indicate statistical (systematic) uncertainties [1].

In addition to jet quenching calculations, the models also provided calculations for their pp baseline, which are obtained from different tunes of PYTHIA event generator. All calculations incorporate the jet resolution effects (see Sec. 5.5.4) for the relevant collision system. Finally, as part of the measurement work, Z+jet events including LO and NLO Z+multijet processes were generated using MadGraph5_aMC@NLO, and simulated through the CMS detector.

Figs. 6-9, 6-10, 6-11, and 6-12 compare the $\Delta\phi_{jZ}$, $x_{jZ}$, $\langle x_{jZ} \rangle$, and $R_{ijZ}$ results, respectively, to calculations.
Figure 6-8: The average number of jet partners per Z boson $R_{jZ}$, as a function of $p_T^Z$. Vertical lines (bands) indicate statistical (systematic) uncertainties [1].

The MadGraph5_aMC@NLO simulation provides the best description of pp data, especially the agreement to the $\Delta\phi_{jZ}$ and $x_{jZ}$ distributions are very good. Hybrid model describes the pp $\Delta\phi_{jZ}$, $x_{jZ}$, and $R_{jZ}$ reasonable well, while its $\Delta\phi_{jZ}$ and $x_{jZ}$ calculations are just slightly sharper than data. The pp $x_{jZ}$ description from GLV model is as good as the one from Hybrid model. The $\Delta\phi_{jZ}$ and $x_{jZ}$ baseline from JEWEL tend to be sharper than data, e.g. overshooting the data for $\Delta\phi_{jZ} \sim \pi$ and $0.6 \lesssim x_{jZ} \lesssim 1$, and undershooting for $\Delta\phi_{jZ} \lesssim 2\pi/3$ and $x_{jZ} \lesssim 0.5$. The $\langle x_{jZ}\rangle$ and $R_{jZ}$ from JEWEL capture the trend in pp data, albeit with fluctuations. On the other hand, the JEWEL baseline suffers relatively larger uncertainties than other models.

All three calculations from the Hybrid model are compatible with the PbPb $\Delta\phi_{jZ}$, $x_{jZ}$, and $R_{jZ}$ within the experimental uncertainties. The strong coupling and weak coupling scenarios do not differ significantly for $\Delta\phi_{jZ}$ calculations, however they seem to split in $x_{jZ}$ and $R_{jZ}$ calculations. The strong coupling scenario suggests larger
jet quenching effects than the weakly coupled scenarios, as its \( x_{jZ} \) and \( R_{jZ} \) values are relatively smaller, and closer to the measured values. The JEWEL calculations for the PbPb \( \Delta \phi_{jZ} \), \( x_{jZ} \), \( \langle x_{jZ} \rangle \), and \( R_{jZ} \) are also compatible with data given the uncertainties, however the \( \Delta \phi_{jZ} \) calculation seems to be slightly sharper than data and the \( R_{jZ} \) calculation is consistently smaller than the data, by \( \sim 1\sigma \). The GLV model calculations for the PbPb \( x_{jZ} \) agree with data for both values of the model’s jet-medium coupling strength, however the data seems to favor \( g = 2.2 \) as the coupling strength value.

Figure 6-9: Comparison of the measured pp (left) and PbPb (right) \( \Delta \phi_{jZ} \) distributions \[1\] with several theoretical models, smeared by the respective jet energy resolution: JEWEL \[375\] and Hybrid \[283\]. The curve labeled MG5aMC@NLO represents the MadGraph5_aMC@NLO calculation \[357\].
Figure 6-10: Upper panel: Comparison of the measured pp $x_{jZ}$ distributions [1] with several theoretical models, smeared by the jet energy resolution in pp: JEWEL [375], Hybrid [283], and GLV [376]. The curve labeled MG5aMC@NLO represents the MadGraph5_aMC@NLO calculation [357]. Lower panel: Comparison of the measured PbPb $x_{jZ}$ distributions [1] with several theoretical models, smeared by the jet energy resolution in PbPb: JEWEL [375], Hybrid [283], and GLV [376].
Figure 6-11: The mean value of the $x_{jZ}$ distribution as a function of $p_T^Z$ in pp (left) and PbPb (right) collisions compared to predictions from JEWEL [375] smeared by the respective jet energy resolution. The curve labeled MG5aMC@NLO represents the MadGraph5_aMC@NLO calculation [357].

Figure 6-12: The average number of jet partners per Z boson $R_{jZ}$, as a function of $p_T^Z$ in pp (left) and PbPb (right) collisions compared to several theoretical models, smeared by the respective jet energy resolution: JEWEL [375] and Hybrid [283]. The curve labeled MG5aMC@NLO represents the MadGraph5_aMC@NLO calculation [357].
6.3.2 Comparison to photon+jet correlation measurements

The results are compared to the isolated photon+jet [243] measurements and overlaid in Figs. 6-13, 6-14, and 6-15 separately for each collision system. The distributions of transverse momentum ratio, $x_{jV}$, from Z+jet and photon+jet correlations are very similar both in pp and central PbPb collisions. Mean values of these distributions, $\langle x_{jV} \rangle$, and average number of jet partners per boson, $R_{jV}$, are also in agreement. The energy spectrum of jets recoiling from Z bosons and photons are different, as can be seen in Fig. 2-11. These comparisons indicate that, within the current experimental uncertainties, the difference of recoil jet spectra is not as large to introduce a difference in the measured jet energy loss.

6.4 Summary

This chapter presented the studies of jet quenching using Z+jet pairs in pp and PbPb collisions at the LHC. Correlations of a Z boson with $p_T^{Z} > 40$ GeV/c with $p_T^{jet} > 30$ GeV/c jets have been measured. Distributions of the azimuthal angle

Figure 6-13: Distributions of the transverse momentum ratio, $x_{jV}$, from the Z+jet and isolated photon+jet [243] correlation measurements in pp (left) and PbPb (right) collisions.
Figure 6-14: The mean value of the transverse momentum ratio distributions, $\langle x_{jV} \rangle$, from the Z+jet [1] and isolated photon+jet [243] correlation measurements in pp (left) and PbPb (right) collisions.

Figure 6-15: The average number of jet partners per boson, $R_{jV}$, from the Z+jet [1] and isolated photon+jet [243] correlation measurements in pp (left) and PbPb (right) collisions.
difference, $\Delta \phi_{jZ}$, seem to be narrower in central PbPb collisions compared to the pp, however, the distributions were not found to be significantly different between the two collision systems after accounting for the experimental uncertainties. The $p_T$ ratio between the jets and the Z boson, $x_{jZ}$, is measured to be lower in PbPb than in pp, and the average value of the $p_T$ ratios, $\langle x_{jZ} \rangle$, is lower in PbPb than in pp for all $p_T^Z$ intervals. The average number of jets associated with a Z, $R_{jZ}$, is lower in PbPb than in pp collisions, for all $p_T^Z$ intervals, implying that in PbPb a larger fraction of associated jets end up with a $p_T$ below the 30 GeV/c $p_T$ threshold as they lose energy in QCD medium.

Experimental results were compared to theoretical models. Calculations including both LO as well as NLO processes, e.g. Z+multijet using MadGraph5_aMC@NLO, describe the pp reference data better than calculations including LO processes only, e.g. Z+jet using Pythia. Thus, for an accurate description of the pp reference it is crucial for models to account for the higher order processes in their baseline calculations. Calculations from several jet quenching models are found compatible with the PbPb results. Besides, despite the relatively worse experimental precision, the PbPb results can impose constraints on calculations as they can favor one model parameter value over the other.

These measurements quantify jet quenching using a sample with well-defined flavor and initial kinematics, thereby provide new constraints for the parton energy loss models.
Chapter 7

Fragmentation modification of photon-tagged jets

This chapter is dedicated to the photon-tagged jet fragmentation functions (FFs) measurement in Ref. [2], the first unambiguous (due to the use of photons, hard process taggers not modified in QCD medium, as explained in Sec. 1.6) quantification of parton shower modification in QCD medium. The analysis exploited pp and PbPb data recorded in 2015 at $\sqrt{s_{NN}} = 5.02$ TeV.

This work measures QCD medium effects on parton shower via two different FF observables. The first one is the distribution of $\xi^\text{jet}$ defined as

$$ \xi^\text{jet} = \ln \frac{|p^\text{jet}|^2}{p^\text{trk} \cdot p^\text{jet}} $$

(7.1)

where $p^\text{jet}$ and $p^\text{trk}$ are the 3-momenta of the jet and charged particle. The second observable is the distribution of $\xi_T^\gamma$,

$$ \xi_T^\gamma = \ln \frac{|p_T^\gamma|^2}{p_T^{\text{trk}} \cdot p_T^\gamma} $$

(7.2)

where $p_T^\gamma$ and $p_T^{\text{trk}}$ are the $p_T$ with respect to the beam direction of the photon and charged particle, respectively. These observables were already introduced in eqs. 2.15 and 2.16 in theory discussion. The $\xi^\text{jet}$ and $\xi_T^\gamma$ are analyzed as distributions normalized
by the number of jets, $N_{\text{jet}}$.

Events are selected as described in Sec. 4.3. Photon reconstruction in pp (PbPb) data has been performed via the GED (Island) algorithms described in Sec. 5.3.1 (5.3.1). Photons are required to be within the ECAL barrel acceptance, $|\eta| < 1.44$ and selected to have a $p_T$ above 60 GeV/c.

FFs are analyzed for jets with $p_T^{\text{jet}} > 30$ GeV/c and $|\eta^{\text{jet}}| < 1.6$. In addition, an azimuthal angle separation of $\Delta \phi_{j\gamma} > 7\pi/8$ is imposed to increase the fraction of jets associated with the photon. For each jet passing these requirements, FFs are measured using tracks which have $p_T^{\text{trk}} > 1$ GeV/c and fall within a cone of radius $\Delta R = 0.3$ around the jet direction.

In order to probe the evolution of QCD medium effects, the PbPb data has been analyzed in four centrality intervals: 0–10%, 10–30%, 30–50%, and 50–100%.

7.1 Reconstruction and identification

7.1.1 Photons

After the selection of events and kinematic requirements, misidentified photons are removed as described in Sec. 5.3.4. Photon energy is corrected as described in Ref. [243].

Fraction of isolated photons in the sample are enhanced by imposing requirements on the identification variables introduced in Sec. 5.3.4. Photons are selected to satisfy $H/E < 0.1$, a low hadronic energy compared to electromagnetic energy, and $\text{SumIso}^{\text{UE-sub}} < 1$ GeV inside an isolation cone of $\Delta R = 0.4$, a small amount of energy from particles around the photon.

Application of the identification criteria listed above gives a photon sample where the isolated prompt photon fraction is enhanced and the fraction of background photons from meson decays is suppressed. Fraction of the background photons in the sample is estimated via a two-component template fit method.

The distribution of the shower shape variable $\sigma_{\eta\eta}$, defined in eq. 5.4, is fit
with signal and background templates. The signal template is obtained from isolated prompt photons in simulation. The background template is obtained from photons with $10 < \text{SumIso}^{\text{UE-sub}} < 20$ GeV, a non-isolated region in data. Fig. 7-1 shows the signal and background templates for PbPb data as well as the application of template fit. The fit results show that the $\sigma_\eta < 0.01$ region in data is enriched with signal and the $\sigma_\eta \gtrsim 0.01$ region is dominated with background.

Photons in the sideband region, $0.011 < \sigma_\eta < 0.017$, are used to estimate how events with background photons impact the measurement, i.e. the shape of measured distributions. On the other hand, photons in the signal region, $\sigma_\eta < 0.01$, are composed of both signal and background photons.

The measurement for signal photon events is obtained by selecting the photons in signal region, $\sigma_\eta < 0.01$, and subtracting the contribution of background photons where the background fraction is extracted from the template fit and the effect of background photons to the shape of measured distributions is estimated by selecting photons in the sideband region, $0.011 < \sigma_\eta < 0.017$. Specifically, the measurement of some quantity $F$ that is subtracted for background photons, can be expressed as

$$F = \frac{1}{\text{purity}} \times [F_{\text{signal region}} - (1 - \text{purity}) \times F_{\text{sideband region}}]$$  \hspace{1cm} (7.3)

where purity is the fraction of signal photons in the signal region, $\sigma_\eta < 0.01$, obtained from the template fit method. Hence, $(1 - \text{purity})$ is the fraction of background photons in the signal region. Purity ranges from $\sim 80\%$ (peripheral collisions) to $\sim 70\%$ (central collisions) as indicated in Fig. 7-1. Details of the photon template method is described in Ref. [243]. Application of the background photon subtraction is further described in Sec. 7.2.1.

The photon identification is completed with the last step, the shower shape selection. As explained above, this step is split into two different selections where the “sideband” selection is used to estimate the photon background measurement which is then subtracted from the measurement obtained from the “signal” selection. Table 7.1 lists the various selection steps executed to identify photons in the measurement.
Figure 7-1: The distribution of the shower shape variable $\sigma_{\eta\eta}$ in PbPb data for different collision centralities. The distribution in data (black points) are fit with a signal template obtained from simulation (red histogram) and a background template obtained from non-isolated region in data (green histogram). Figure taken from Ref. [243].

<table>
<thead>
<tr>
<th>Step</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise rejection</td>
<td>swiss cross $&lt; 0.9$</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\eta\eta} &gt; 0.002$</td>
</tr>
<tr>
<td>Kinematics</td>
<td>$p_T^\gamma &gt; 60$ GeV/c, $</td>
</tr>
<tr>
<td>In case there is more than one photon candidate,</td>
<td></td>
</tr>
<tr>
<td>then select the one with largest $p_T$.</td>
<td></td>
</tr>
<tr>
<td>Electron rejection</td>
<td>If there is an electron with $p_T^{\text{elec}} &gt; 10$ GeV/c</td>
</tr>
<tr>
<td></td>
<td>then $</td>
</tr>
<tr>
<td>Low hadronic energy</td>
<td>$H/E &lt; 0.1$</td>
</tr>
<tr>
<td>Isolation</td>
<td>$\text{SumIso}^{\text{UE-sub}} &lt; 1$ GeV for $\Delta R = 0.4$</td>
</tr>
<tr>
<td>Shower shape</td>
<td>Signal: $\sigma_{\eta\eta} &lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>Sideband: $0.011 &lt; \sigma_{\eta\eta} &lt; 0.017$</td>
</tr>
</tbody>
</table>

Table 7.1: Steps taken to identify photons in photon+jet measurements using the pp reference and PbPb data taken in 2015. Selection steps and variables are described in Sec. 5.3.4.
Figure 7-2: Reconstruction and selection efficiency for photons in pp (left) and PbPb (right) simulated events.

Efficiency of the identification criteria in selecting the isolated photons has been studied in simulation. Fig. [7-2] shows the photon reconstruction and selection efficiency as a function of $p_T$. While the efficiency has a weak $p_T$ dependence in pp sample and in peripheral PbPb simulation, there is a stronger $p_T$ dependence in central collisions. Inefficiencies are removed by reweighting events with the inverse of efficiency.

The photon reconstruction, identification and corrections in this measurement are the same as in the photon+jet correlations measurement in Ref. [243].

7.1.2 Jets

Jet energies are corrected as described in Sec. 5.5.2. Jets in pp are smeared to the resolution in PbPb, using the procedure described in Sec. 5.5.4 and the resolution parameters provided in Ref. [243].
7.1.3 Tracks

Momentum and position of charged particles are obtained using tracks. Track reconstruction is described in Sec. 5.6 and identification criteria is provided in Table 5.5.

7.2 Analysis method

The analysis constructs distributions by processing a set of jets for each photon and then a set of tracks for each jet. Jets and tracks are selected inclusively which results in the inclusion of a combinatorial background, introduced in Sec. 6.1. Different from the case in Z+jet measurement, combinatorial background in this measurement arises not only for jets, but also for tracks. The source of background jets are the same as in Z+jet correlations (see Sec. 6.1). Similarly, background for tracks arises from nucleon-nucleon interactions other than the one producing the photon+jet process.

7.2.1 Background subtraction

Combinatorial background

The “signal” this analysis aims to measure is particles which originate from the same nucleon-nucleon interaction that produced the isolated photon. On the other hand, combinatorial backgrounds emerge in PbPb where there are additional nucleon-nucleon interactions in the same event (The combinatorial background in pp reference is found to be negligible, as the pileup was negligible).

The backgrounds for jets and tracks in PbPb are estimated and subtracted using the event mixing method introduced in Sec. 6.1. MB events with similar event characteristics as the photon+jet event are used to estimate the background contributions. Specifically, for each photon+jet event, a set of MB events is chosen where each MB event satisfies the following compared to the photon+jet event

- to have a centrality not different by more than 0.5%
• to have the $z$-coordinate of the interaction vertex, $v_z$, not different by more than 1 cm

• to have an event plane angle not different by more than $\pi/16$

The background subtraction proceeds in two steps. First, the contribution of background tracks are subtracted for each jet. Then, the contribution of background jets are subtracted from all jets. Note that all selected jets, be it a jet in photon+jet event or MB event, need to be subtracted for background tracks. This implies that for each MB event (say event $A_{MB}$) that is used for background jet estimation, a set of other MB events (say events $B_{MB}$, $C_{MB}$, $D_{MB}$, ...) are used to estimate the background tracks for jets in event $A_{MB}$. The background track and jet subtraction steps are illustrated in Fig. 7-3 and 7-4.

The application of the track and jet subtraction for the measured $\xi^\text{jet}$ distributions are shown in Fig. 7-5 and Fig. 7-6 respectively. In general, the combinatorial background from tracks is relatively larger than the one from jets. The fraction of background tracks compared to subtracted distributions is very small in low $\xi^\text{jet}$ regions (less than 5% for $\xi^\text{jet} < 2$) and larger in large $\xi^\text{jet}$ regions which are populated with lower $p_T^{\text{trk}}$ particles. The signal to background ratio is $\sim 70\%$ for $2.5 < \xi^\text{jet} < 3$, drops to $\sim 30\%$ for $3 < \xi^\text{jet} < 3.5$, and ultimately down to $\sim 15\%$ for $4 < \xi^\text{jet} < 4.5$.

**Photon background subtraction**

Following the subtraction of combinatorial backgrounds, the contribution from background photons needs to subtracted to obtain the final distributions. Fraction of background photons among the photon candidates is estimated as explained in Sec. 7.1.1. First, distributions are constructed using events with photons in the signal and sideband regions, then the distribution in sideband region is subtracted from the one in signal region as expressed in eq. 7.3. In this measurement, the quantity $F$ in eq. 7.3 are $\xi^\text{jet}$ and $\xi^\gamma$. The background photon subtraction step is illustrated in Fig. 7-7.
Figure 7-3: Illustration of analysis step for subtraction of background tracks. The background tracks are subtracted from jets both in the photon+jet event (left column) and in MB events (right column). This step gives jets subtracted for tracks.

Figure 7-4: Illustration of analysis step for subtraction of background jets. The jets were already subtracted for tracks in the previous step shown in Fig. 7-3. Jets in MB events (right column) are subtracted from jets in the photon+jet event (left column). This step gives photon+jet pairs subtracted for background jets and tracks.
Figure 7-5: Subtraction of the background tracks (red crosses) from the $\xi_{\text{jet}}$ distribution for jets associated with an isolated photon (black squares) for 0–10% centrality PbPb collisions. The distribution after background track subtraction (blue circles) is further subtracted for background jets (corresponding to orange squares in Fig. 7-6). Figure taken from Ref. [2].
Figure 7-6: Subtraction of the background jets (violet crosses) from the $\xi_{jet}$ distribution for background track subtracted jets associated with an isolated photon (orange squares) for 0–10% centrality PbPb collisions. The subtraction gives the distribution subtracted for background track and background jet (green circles). Figure taken from Ref. [2].

Figure 7-7: Illustration of analysis step for photon background subtraction. The track and jets were already subtracted for in the previous steps as illustrated in Fig. 7-3 and 7-4. The contribution of background photons, i.e. photon sideband, (right) are subtracted from the signal photon region, i.e. photon candidate, (left).
Summary

The analysis works with three different physics objects: photons, jets, and tracks. Selection of each object introduces a non-negligible background for the analysis. The background contributions are subtracted as described in the preceding sections. Statistical uncertainties for subtracted quantities are calculated assuming subtrahend and minuend are independent. Below is a summary of the three background contributions and their subtraction in order of application

1. Tracks, subtracted via MB event mixing method, procedure illustrated in Fig. 7-3

2. Jets, subtracted via MB event mixing method, procedure illustrated in Fig. 7-4

3. Photons from meson decays, subtracted via purity extracted from a template fit, procedure illustrated in Fig. 7-7

7.2.2 Validation

The analysis method described above is tested in simulation. The tests involve comparisons of the observables constructed using analysis methods to the reference observables obtained from truth objects. Pythia and Pythia + Hydjet events are reconstructed in pp (PbPb) simulation. Reference observables are constructed using truth objects in Pythia event.

First, the event mixing method to subtract jets and tracks will be tested using generated particles. Reco particles are not included in this test in order not to fold in the detector effects.

Next, reconstruction effects are studied by comparing observables constructed using reco objects (jets, tracks) to the “smeared” reference observables, i.e. reference for which truth jets are smeared to reflect the detector resolution.
Background subtraction method

The background subtraction method is applied to generator level objects in PbPb simulation, i.e. Pythia + Hydjet events. The estimated combinatorial background is normalized by the number of Hydjet events used. As seen in simulation studies in Sec. 4.6.2, the average UE density is slightly different between a MB (Hydjet) event and an event containing a hard scattering (Pythia + Hydjet), even when the two have the same collision centrality. Therefore, estimated backgrounds are further scaled with residual factors to account for this effect.

The obtained $\xi_{\text{jet}}$ ($\xi_T$) distributions are compared to the truth distributions in Fig. 7-8 (7-9). In general, the agreement is better than 2% in the $\xi < 3$ region where the background contamination is relatively smaller. There are deviations of $\sim 5\%$ in the $\xi > 3$ region, however distributions are compatible within statistical uncertainties.

Detector effects

Fig. 7-10 compares the $\zeta$ distributions between reco and truth objects in pp simulation. The distributions generally agree within 2%, though for some $\xi_T$ regions,
Figure 7-9: Upper: The $\xi_\gamma$ distributions obtained from generated charged particles and jets in PbPb simulation for various centralities. Distributions constructed using signal gen particles (histogram) are compared to the ones obtained after event mixing technique (green markers). Lower: Ratio of the distributions.

The differences can increase up to 4%. These differences are mostly due to imperfect tracking corrections, as described in Sec. [5.6] and accounted for in the systematic uncertainties.

Fig. 7-11 (7-12) compares the $\xi_{\text{jet}}$ ($\xi_\gamma$) distributions between reco and truth objects in PbPb simulation. Distributions agree better than 10% in regions with $1 < \xi < 3.5$. Differences arise from the imperfect tracking corrections and statistical fluctuation in background subtraction. Larger than 10% differences can show up in the $\xi < 1$ and $\xi > 3.5$ regions which originate from differences in jet energy response due to variances in the fragmentation patterns. Systematic uncertainties are quoted to account for the observed differences.

The simulation tests show that the analysis method works sufficiently enough, if not perfectly. The observed disagreements, i.e. non-closures in this context, stem from detector effects arising mostly from jet energy response and tracking corrections which are studied as part of systematic uncertainties.
Figure 7-10: Upper: The $\xi_{\text{jet}}$ (left) and $\xi_{T}$ (right) distributions obtained from tracks and jets (red markers) are compared to the ones obtained from truth jets and charged particles (histogram) in pp simulation. Truth jets are smeared to reflect the detector resolution. Lower: The reco / gen ratio of the distributions.
Figure 7-11: Upper: The $\xi_{\text{jet}}$ distributions obtained from reco tracks and jets (red markers) are compared to the ones obtained from truth jets and charged particles (histogram) in PbPb simulation for various centralities. Truth jets are smeared to reflect the detector resolution in the corresponding centrality. Lower: The reco / gen ratio of the distributions.

Figure 7-12: Upper: The $\xi_{\gamma}$ distributions obtained from reco tracks and jets (red markers) are compared to the ones obtained from truth jets and charged particles (histogram) in PbPb simulation for various centralities. Truth jets are smeared to reflect the detector resolution in the corresponding centrality. Lower: The reco / gen ratio of the distributions.
7.3 Systematic uncertainties

Systematic uncertainties arise from the uncertainties related to analysis method, object reconstruction, and corrections. The uncertainty calculation procedure is the same as in Sec. 6.2.

Uncertainties arising from photon reconstruction and identification are described as follows. The non-isolated regions used in background templates in data are varied to obtain the uncertainty in purity estimation. The extracted photon purity can vary by 5 (10)% in pp (PbPb) \cite{243} and this variation is propagated to the results. The uncertainty due to photon isolation is evaluated in simulation by comparing the observables between the ones obtained with detector and generator-level isolation variables. The photon energy scale uncertainty is obtained after varying the $p_T$ by the scale difference between data and simulation. The uncertainty arising from electron rejection is evaluated by obtaining results without applying the electron rejection criteria which yield results with the maximum possible electron contamination. The difference from nominal results is scaled down by the remaining electron contamination after the application of electron rejection and quoted as uncertainty. The uncertainty in photon efficiency corrections is evaluated by varying the selection criteria and applying the corresponding efficiency correction.

The JES uncertainty sources are listed in Sec. 5.5.3. Uncertainties due to first two sources are obtained by shifting the jet $p_T$ by ±2%. For the third source, the distributions in PbPb data are fit with templates for quark and gluon jet distributions in simulation \cite{243}. The quark jet template fits a larger fraction of the data distributions ranging from $\sim 70\%$ up to $\sim 100\%$. Based on that, the uncertainty for the third source is evaluated by varying the jet $p_T$ with the difference between the JES for quark jet and inclusive jet samples. The JER uncertainty has two independent components. The first one is the 15% relative difference between resolutions in data and simulation \cite{5.5.4}. The second component is due to the uncertainty and modeling of the energy response distributions, amounting to 7%. The uncertainty due to JER is evaluated by smearing the jet $p_T$ to obtain a resolution which differs from the
nominal resolution by the amount of uncertainties quoted above.

The uncertainty arising from tracking efficiency is extracted from the efficiency difference between data and simulation [200], and assigned as 4 (5)% in pp (PbPb) data for all track $p_T$ and event centralities. The effect of long range $\eta$ correlations [378] is assigned as systematic uncertainty and estimated by constructing the observables using tracks that are in the same $\phi$ range as the jet, but separated by a pseudorapidity interval of $1.5 < \Delta \eta < 2.4$.

The uncertainty in background subtraction has two different components. First, effect of the background subtraction method is evaluated using an alternative method, the $\eta$-reflection method [249], which estimates the background tracks at a given $\eta$-coordinate using the tracks at $-\eta$ in the same event. Jets and tracks with $|\eta| < 0.3$ are excluded from analysis when this method is used, in order to avoid the overlap of phase spaces for unsubtracted distributions and background estimation. Second, the uncertainty arising from the residual scaling of background distribution (see Sec. 7.2.2) is evaluated by not applying the scaling.

The dependence of jet energy response on FFs can result in differences between reconstructed and generator-level distributions, i.e. non-closures, as seen in Sec. 7.2.2, especially in small and large $\xi$ regions. The differences are quoted as systematic uncertainty.

For the PbPb/pp ratio results, correlations between PbPb and pp uncertainties are treated as follows. If a systematics source in one collision system has no correlation with a source in the other collision system, then its uncertainty goes directly to PbPb/pp ratio. For example, the uncertainty for background subtraction is only for PbPb, and there is no counterpart in pp, therefore the background subtraction uncertainty in the PbPb/pp ratio is the same as background subtraction uncertainty in the PbPb result. The photon related systematics are assumed to be correlated between PbPb and pp. The uncertainties are calculated by comparing (varied PbPb)/(varied pp) to (nominal PbPb)/(nominal pp). For example, for upwards variation of purity the varied PbPb/pp ratio is (PbPb with purity up)/(pp with purity up). Partial correlation has been assumed for the JES uncertainty. Out of the three sources of
the JES uncertainty for PbPb (see Sec. 5.5.3), the first two are applied as a constant JES shift and are assumed to be correlated with the same source in pp. For example, \((\text{PbPb with JES shifted up by 2\%})/(\text{pp with JES shifted up by 2\%})\) is compared to nominal PbPb/pp. The third source is specific for PbPb, hence no correlation is possible. For tracking efficiency systematics a partial cancellation is assumed in the PbPb/pp ratio as described in Ref. [200] where the uncertainty in the PbPb/pp ratio is computed via a variation of tracking corrections as function of event centrality and \(p_{\text{trk}}\).

Table 7.2 lists the systematic uncertainties averaged over \(\xi\) for the 0–10\% centrality (most central) collisions.

Figs. 7-13 and 7-14 show the uncertainties arising from various systematic sources and the combined, i.e. total, systematic uncertainties as a function of \(\xi\) for pp and PbPb data respectively. Note that uncertainties due to tracking efficiency and background subtraction methods are constant across \(\xi\), they are not shown in the figures for a less crowded view. The bin-by-bin maximum of JES up and jet energy scale down variations contributes to the total systematics. The same is true for photon purity up and photon purity down variations.
Table 7.2: Systematics uncertainties averaged over $\xi$ for 0–10% centrality events. Numbers are in percentage.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
<th>$\xi_{\text{jet}}$</th>
<th>$\xi_{T}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy scale</td>
<td>1.2 &lt;0.1 1.2</td>
<td>1.2 &lt;0.1 1.1</td>
<td></td>
</tr>
<tr>
<td>Photon isolation</td>
<td>1.7 0.9 1.0</td>
<td>1.1 0.7 0.7</td>
<td></td>
</tr>
<tr>
<td>Photon purity</td>
<td>2.8 0.4 2.4</td>
<td>5.4 0.4 4.9</td>
<td></td>
</tr>
<tr>
<td>Electron contamination</td>
<td>0.6 &lt;0.1 0.6</td>
<td>0.5 0.1 0.3</td>
<td></td>
</tr>
<tr>
<td>Photon efficiency</td>
<td>0.1 &lt;0.1 0.1</td>
<td>0.5 &lt;0.1 0.6</td>
<td></td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>7.3 2.4 4.3</td>
<td>6.5 0.6 6.0</td>
<td></td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>2.8 0.7 3.7</td>
<td>1.7 0.5 2.0</td>
<td></td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>5.0 4.0 6.2</td>
<td>5.0 4.0 6.3</td>
<td></td>
</tr>
<tr>
<td>Long range contribution</td>
<td>4.1 1.7 2.3</td>
<td>3.3 1.5 1.8</td>
<td></td>
</tr>
<tr>
<td>Background subtraction</td>
<td>3.6 -- 3.6</td>
<td>3.5 -- 3.5</td>
<td></td>
</tr>
<tr>
<td>Non-closure in $\xi$</td>
<td>3.5 -- 3.5</td>
<td>3.5 -- 3.5</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>11.9 5.1 10.5</td>
<td>11.7 4.4 11.6</td>
<td></td>
</tr>
</tbody>
</table>
Figure 7-13: The uncertainties arising from various systematic sources and the combined (total) systematic uncertainties for pp data as a function of $\xi^\text{jet}$ ($\xi^\gamma$) are shown in the upper (lower) row. Columns on the left (right) correspond to pp data smeared for peripheral (central) collisions.
Figure 7-14: The uncertainties arising from various systematic sources and the combined (total) systematic uncertainties for PbPb data as a function of $\xi^{\text{jet}}$ ($\xi^{\gamma}$) are shown in the upper (lower) row. Columns on the left (right) correspond to peripheral (central) collisions.
7.4 Results

Fig. 7-15 shows the distributions of $\zeta_{\text{jet}}$ in pp and PbPb collisions, and the PbPb to pp ratio of the distributions. While the pp $\zeta_{\text{jet}}$ distributions represent unquenched jets, the distributions in PbPb stand for the fragmentation pattern of jets that lose energy as a result of their interactions with QCD medium. Therefore, populations of detected jets in PbPb and pp collisions do not necessarily have the same $p_T$ spectrum. The hump backed plateau [29] of the distributions can be seen in pp collisions where the maximum particle yield per jet happens in the $2.5 < \zeta_{\text{jet}} < 3.0$ region. The $\zeta_{\text{jet}}$ distributions for 50–100% centrality PbPb collisions are consistent with those in pp. The distributions in more central PbPb collisions have differences with respect to the ones in pp. There is an enhancement in $\zeta_{\text{jet}} > 2.5$ (corresponding to $p_T^{\text{trk}} < 2.5$ GeV/c for $p_T^{\text{jet}} = 30$ GeV/c and $\Delta R = 0$ between the track and the jet, see Fig. 2-16 for reference), indicating an excess of low energy particles in the parton shower. Furthermore, there is a slight suppression in the $0.5 < \zeta_{\text{jet}} < 2.5$ region (corresponding to $2.5 < p_T^{\text{trk}} < 18$ GeV/c for $p_T^{\text{jet}} = 30$ GeV/c and $\Delta R = 0$ between the track and the jet, see Fig. 2-16 for reference).

Fig. 7-16 shows the distributions of $\zeta_{\gamma T}$ in pp and PbPb collisions, and the PbPb to pp ratio of the distributions. The $\zeta_{\gamma T}$ distributions are shifted to larger $\zeta$ compared to the $\zeta_{\text{jet}}$ distributions in both pp and PbPb collisions. This is because the photon energy is generally larger than the jet energy in both collision systems. Similar to the $\zeta_{\text{jet}}$ case, the $\zeta_{\gamma T}$ distributions in most peripheral PbPb is consistent with those in pp data. The distributions in central PbPb collisions are more different than those in pp, specifically, the PbPb distributions is enhanced relative to pp in the $\zeta_{\gamma T} > 3$ region (corresponding to $p_T^{\text{trk}} < 3$ GeV/c for $p_T^{\gamma} = 60$ GeV/c and $\Delta \phi = \pi$ between the track and the photon, see Fig. 2-18), and the enhancement becomes larger as the PbPb collisions become more central. The PbPb distributions are suppressed relative to pp in the $0.5 < \zeta_{\gamma T} < 3$ region (corresponding to $3 < p_T^{\text{trk}} < 36$ GeV/c for $p_T^{\gamma} = 60$ GeV/c and $\Delta \phi = \pi$, see Fig. 2-18).

The differences between the $\zeta_{\gamma T}$ distributions in pp and PbPb data are more sig-
Figure 7-15: Upper: The centrality dependence of the $\xi^{\text{jet}}$ distribution for jets associated with an isolated photon for PbPb (full markers) and pp (open markers) collisions. The pp results are smeared for each PbPb centrality bin. Lower: The ratios of the PbPb over smeared pp distributions. The vertical bars through the points represent statistical uncertainties, while the colored boxes indicate systematic uncertainties.
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ p_{T}^{h} > 1 \text{ GeV/c}, \text{anti-}k_{T} \text{, jet } R = 0.3, p_{T}^{\gamma} > 30 \text{ GeV/c}, |\eta^{\gamma}| < 1.6 \]
\[ p_{T}^{j} > 60 \text{ GeV/c}, |\eta^{j}| < 1.44, \Delta_{R} > \frac{7\pi}{8} \]

PbPb 404 \unit{\mu b}^{-1}, pp 27.4 \unit{pb}^{-1}

Figure 7-16: Upper: The centrality dependence of the \( \xi_{T}^{\gamma} \) distribution for jets associated with an isolated photon for PbPb (full markers) and pp (open markers) collisions. The pp results are smeared for each PbPb centrality bin. Lower: The ratios of the PbPb over smeared pp distributions. The vertical bars through the points represent statistical uncertainties, while the colored boxes indicate systematic uncertainties \cite{2}.
nificant than the differences for $\xi_{\text{jet}}$ distributions, especially in the $\xi \gtrsim 3$ region. This is partly because the $\xi_{\text{jet}}$ in PbPb is shifted to smaller $\xi_{\text{jet}}$ due to the relatively lower $p_T$ of quenched jets, thereby making the enhancement effects look smaller at larger $\xi_{\text{jet}}$. Differences between the pp and PbPb distributions are quantified by comparing the two distributions using a $\chi^2$ test, yielding $p$-values of $10^{-3}$ ($10^{-20}$) for the $\xi_{\text{jet}}$ ($\xi_T^\gamma$) distribution in most central collisions.

The suppression and enhancement features seen in the fragmentation functions is unambiguous evidence for parton shower modification where high energy partons lose energy as they go through the QCD medium created in HI collisions. The suppression at small $\xi$ and enhancement at large $\xi$ point out that the parton showers interacting with the QCD medium contain less higher energy and more lower energy particles. The decrease in the number of higher energy particles arise primarily from the high energy partons losing energy. On the other hand, the increase in number of lower energy particles can originate directly from the same source, i.e. energy loss of high energy partons, as well as from the medium response, the recoil of the medium as a parton passes through (see Sec 2.4). Comparison to theoretical calculations (Sec. 7.4.1) reveals that the data is useful to identify the role of medium response effects in parton shower evolution.

Figs. 7-17 and 7-18 show the $\xi_{\text{jet}}$ and $\xi_T^\gamma$ distributions, respectively, by combining the data from adjacent centrality intervals shown in Fig. 7-15 and 7-16 and thereby revealing the modification in $\xi$ distributions with an improved statistical precision. As the $\xi$ distributions are normalized by the number of jets, integral of the distributions give the average number of charged particles inside the jet cone. There are on average $\approx 2.6$ (3.8) particles in the $3 < \xi_T^\gamma < 4.5$ region in pp (0–30% centrality PbPb) collisions, suggesting an excess of $\approx 1.2$ low energy particles per jet in central PbPb collisions. To the contrary, an average of $\approx 2.8$ (2.5) particles in the $0.5 < \xi_T^\gamma < 3$ region in pp (0–30% centrality PbPb) collisions, indicating a depletion of $\approx 0.3$ high energy particles per jet.
Figure 7-17: Upper: The $\xi_{\text{jet}}$ distribution from two event centralities for jets associated with an isolated photon for PbPb (full markers) and pp (open markers) collisions. The pp results are smeared for each PbPb centrality bin. Lower: The ratios of the PbPb over smeared pp distributions. The vertical bars through the points represent statistical uncertainties, while the colored boxes indicate systematic uncertainties [2].
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

- \( p_T^{\text{jet}} > 1 \text{ GeV/c}, \) anti-\( k_t \) jet R = 0.3
- \( p_T^{\gamma} > 60 \text{ GeV/c}, |\eta^{\gamma}| < 1.6 \)
- \( p_T^{\gamma} > 1 \text{ GeV/c}, |\eta^{\gamma}| < 1.6, \Delta\phi^{\gamma l} > \frac{7\pi}{8} \)

**CMS Supplementary**

**Cent. 30 - 100%**

**Cent. 0 - 30%**

\[ \frac{dN^{\text{jet}}}{d\xi_T} \]

Figure 7-18: Upper: The \( \xi_T^{\gamma} \) distribution from two event centralities for jets associated with an isolated photon for PbPb (full markers) and pp (open markers) collisions. The pp results are smeared for each PbPb centrality bin. Lower: The ratios of the PbPb over smeared pp distributions. The vertical bars through the points represent statistical uncertainties, while the colored boxes indicate systematic uncertainties [2].

\[ \text{PbPb / pp} \]

\[ 1 \quad 2 \quad 3 \quad 4 \]

\[ \xi_T^{\gamma} \]

\[ 1 \quad 2 \quad 3 \quad 4 \]

\[ \xi_T^{\gamma} \]
7.4.1 Comparison to theory

Figs. 7-19, 7-20, and 7-21 compare the results to several theoretical calculations, listed below:

- SCET_G model introduced earlier in Sec. 2.3.2

- CoLBT-hydro model [255] which couples the linear Boltzmann transport model [252, 330] (introduced in Sec. 2.3.2) for jet propagation with the 3+1 dimensional hydrodynamics of QCD medium, describing jet-medium interactions by combining the pQCD approach with a hydrodynamic simulation of QCD medium where the quenched jet energy feeds into the hydrodynamic evolution.

- The Hybrid model introduced earlier in Sec. 2.3.2. The calculations implement two different scenarios. These are the “with” and “without” back reaction scenarios which do and do not include, respectively, the medium response effects.

The pp baseline for CoLBT-hydro and Hybrid models are obtained from PYTHIA 8 where the detector resolution effects (see Sec. 5.5.4) are incorporated. Fig. 7-19 compares the model’s calculations for smeared pp $\xi_{\text{jet}}$ and $\xi^\gamma_T$ distributions to the data, calculations describe the data very well.

Figs. 7-20 and 7-21 compare the PbPb/pp ratio of $\xi_{\text{jet}}$ and $\xi^\gamma_T$ results, respectively, to calculations. The SCET_G model finds a suppression in the small $\xi_{\text{jet}}$ region that overlaps well with the data. While it describes the rising trend with $\xi_{\text{jet}}$, it undershoots the $2.5 \lesssim \xi_{\text{jet}} \lesssim 3.5$ region and predicts that enhancement of the particles will be observed for $\xi_{\text{jet}}$ values larger than the ones in data. The CoLBT-hydro model can describe the data qualitatively, i.e. the $\xi_{\text{jet}}$ and $\xi^\gamma_T$ regions where the PbPb/pp ratio is below or above 1. Although the CoLBT-hydro calculations for the PbPb/pp ratios tend to be lower than those in data, the model calculates a large enhancement in the large $\xi$ region which is a better description than the ones from other models. None of the two scenarios in the Hybrid model can capture the suppression and enhancement trend in the $\xi_{\text{jet}}$ results. Both scenarios seem to be agree with the suppression in $\xi^\gamma_T$ results, albeit the predicted values being slightly larger than the data for most central
collisions. The “with” back reaction scenario shows an enhancement in the large $\xi_T^\gamma$ region that is missed by the “without” scenario, though none of them showing an enhancement as large as the one in data.

The Hybrid model’s “with” and “without” back reaction scenarios have similar predictions for small $\xi$ regions, however they split in large $\xi$ regions where the “with” back reaction scenario, including the medium response effects, predicts more particles inside the jet cone. It is worthwhile to add that CoLBT-hydro model incorporates the medium response effects. Thus, for some models, integration for the medium response is crucial to describe the enhancement in large $\xi$ region.

7.5 Summary

This chapter presented the first measurement of the fragmentation functions for jets associated with isolated photons in pp and PbPb collisions at the LHC. Fragmentation patterns are constructed as distributions of $\xi_{\text{jet}}$ defined in eq. [7.1] and of $\xi_T^\gamma$ defined in eq. [7.2] using charged particles with $p^\text{trk}_T > 1$ GeV/c and jets with $p^\text{jet}_T > 30$ GeV/c associated with isolated photons with $p_T > 60$ GeV/c. The selection of the jets via an association to an isolated photon ensures that the initial parton $p_T$ spectra are the same in pp and PbPb data, providing a testing ground to theoretical models for the parton-medium interactions. When compared to the pp results, the $\xi_{\text{jet}}$ and $\xi_T^\gamma$ distributions in the central PbPb collisions show an excess of low energy particles and a depletion of high energy particles inside the jet cone. This feature is more pronounced in the $\xi_T^\gamma$ distributions where the fragmentation function variable is calculated with respect to the photon energy, a proxy for the initial parton energy before energy loss. The measurement is the first direct demonstration of parton shower modification induced by QCD medium, establishing a new well-defined reference for understanding of the parton propagation inside QCD medium.
Figure 7-19: Comparison of the $\xi_{\text{jet}}$ (upper) and $\xi_T^\gamma$ (lower) distributions in pp smeared for 10–30% (left) and 0–10% (right) centrality intervals, with several theoretical models: CoLBT-hydro [255], and Hybrid [321, 283, 253, 379]. Calculations are obtained from PYTHIA 8 and smeared for the detector resolution [2].
Figure 7-20: Comparison of the ratios of PbPb over smeared pp $\xi^{\text{jet}}$ distributions, for 10–30% (left) and 0–10% (right) centrality intervals, with several theoretical models: SCET$_G$ [380], CoLBT-hydro [255], and Hybrid [321, 283, 253, 379]. The SCET$_G$ band represents the variation of coupling strength between the jet and the QCD medium. The Hybrid band represents the variation of the dimensionless constant $\kappa$ in the model [2].
Figure 7-21: Comparison of the ratios of PbPb over smeared pp $\xi_T^\gamma$ distributions, for 10–30% (left) and 0–10% (right) centrality intervals, with several theoretical models: CoLBT-hydro [255] and Hybrid [321, 283, 253, 379]. The Hybrid band represents the variation of the dimensionless constant $\kappa$ in the model [2].

$\sqrt{s_{NN}} = 5.02$ TeV
PbPb 404 $\mu$b$^{-1}$
pp 27.4 $\mu$b$^{-1}$

$R_{\text{jet}} > 1$ GeV/$c$, anti-$k_T$ jet $R = 0.3$
$p_T^{\text{jet}} > 30$ GeV/$c$, $|\eta^{\text{jet}}| < 1.6$
$p_T^{\gamma} > 60$ GeV/$c$, $|\eta^{\gamma}| < 1.44$, $\Delta\phi^{\gamma} > \frac{7\pi}{8}$
Chapter 8

Radial profile modification of photon-tagged jets

This chapter is dedicated to the measurement of jet shapes for photon-tagged jets in Ref. [3], another first measurement of the parton shower modification in QCD medium. The analysis is performed in pp and PbPb data at $\sqrt{s_{NN}} = 5.02$ TeV recorded in 2015, the same data set as in FF measurements presented in Ch. 7.

This work measures the differential jet shapes, $\rho(r)$, defined in eq. 2.17, for jets associated with an isolated photon, probing how the jet radial momentum density profile is modified in QCD medium. The shape for a jet is calculated using charged particle tracks, i.e. the $\rho(r)$ is function of the $r = \sqrt{(\eta^{\text{jet}} - \eta^{\text{trk}})^2 + (\phi^{\text{jet}} - \phi^{\text{trk}})^2}$, the distance between the track and the jet axis in $\eta - \phi$ plane. The $\rho(r)$ is measured up to $r_t = 0.3$.

Event selection is as described in Sec. 4.3, set of events are the same as in the FF analysis in Ch. 7. The PbPb data has been analyzed in four centrality intervals: 0–10%, 10–30%, 30–50%, and 50–100%. Physics object reconstruction and selection are the same as in FF analysis (see Sec. 7.1), i.e. selected physics objects are photons with $p_T^\gamma > 60$ GeV/c and $|\eta^\gamma| < 1.44$, jets with $p_T^{\text{jet}} > 30$ GeV/c and $|\eta^{\text{jet}}| < 1.6$, and charged particle tracks with $p_T^{\text{trk}} > 1$ GeV/c. Different than in the $Z+$jet correlations and photon $+$jet FF analysis presented before, jets in pp will not be smeared to match the resolution in PbPb. This is because the analysis applies corrections for jet shapes
To see Sec. 8.1.3.

8.1 Analysis method

The analysis measures the $\rho(r)$ distribution (eq. 2.17) which is normalized to unity. Unity normalization can reduce the sensitivity to several systematic effects, e.g., total yield or the cross section. On the other hand it becomes harder to trace the source of a systematic effect for a given bin after unity normalization, as the bin content is affected by the content of all other bins as well, hence by the systematic effecting other bins. In order to follow the systematic effects for analysis bins without introducing the effects from other bins, the distributions studied in this section will be $r$ distributions before any normalization, defined as

$$h(r) = \frac{1}{\delta r} \sum_{\text{jets}} \sum_{r_a < r < r_b} \left( \frac{p_{\text{trk}}^T}{p_{\text{jet}}^T} \right)$$

Thus, the $\rho(r)$ is obtained after normalizing the $h(r)$ such that the integral over the range $0 < r < r_f$ is unity

$$\rho(r) = \frac{h(r)}{\sum_{\text{jets}} \sum_{0 < r < r_f} \left( \frac{p_{\text{trk}}^T}{p_{\text{jet}}^T} \right)}$$

Although the analysis aims to measure the $\rho(r)$ up to $r_f = R = 0.3$, the $r$ range analyzed in this section might extend beyond $r = 0.3$ in order to keep an eye on possible jet clustering or detector effects in the $r > R$ region that can have correlations with the $r < R$ region.

8.1.1 Background subtraction

The signal definition and background sources as well as the background subtraction method for this analysis are the same as in FF analysis detailed in Sec. 7.2.1. Jets and tracks are subtracted for combinatorial backgrounds, and photons are subtracted for background stemming from neutral meson decays. The estimated backgrounds
Figure 8-1: Upper: The $h(r)$ for gen jets constructed using generated charged particles in PbPb simulation for various centralities. Distributions constructed using signal gen particles (histogram) are compared to the ones obtained after event mixing technique (green markers) Lower: Ratio of the distributions.

for tracks and jets are scaled with residual factors to account for the UE density difference between the HYDJET and PYTHIA + HYDJET samples (this is done for FF analysis as well, see Sec. 7.2.2 for details).

The background subtraction method is tested using generator level objects in PbPb simulation, as was done in the FF analysis in Sec. 7.2.2.

The obtained $h(r)$ are compared to the true distributions in Fig. 8-1. The agreement is in general better than 2% in the $r < 0.3$ region. Note that these distributions show $p_T$ weighted yield as function of $r$, they are not normalized to unity, different than the $\rho(r)$ distributions. The normalization to unity is avoided in this test in order to identify any yield deficits or excesses in the subtraction method.

### 8.1.2 Angular resolution

The $\rho(r)$ distribution is a steeply falling function of $r$, as pointed out in Sec. 2.2.2. Therefore, jet shapes can be more sensitive to jet angular resolution than fragmentation functions. Furthermore, the $\rho(r)$ distribution has a sudden change of slope at $r = R$ where $R$ is the distance parameter in jet finding algorithm (see Sec. 2.1.2).
Figure 8-2: The distribution of $\rho(r)$ (left) and $\Delta\eta-\Delta\phi$ (right) for generated jets constructed using generated charged particles in pp simulation. Jets are defined with distance parameter $R = 0.3$.

... for details). This is an effect of the jet finding algorithm which tends to place the jet axis at the center of a particle cluster with radius $R$. The effect can be seen in Fig. 8-2 where distributions are constructed using gen-level objects in pp simulation. The shape of the $\rho(r)$ distribution changes after $r = R$. A more detailed view is given in the $\Delta\eta-\Delta\phi$ correlation between jets and charged particles where $\Delta\eta = |\eta^{\text{jet}} - \eta^{\text{trk}}|$ and $\Delta\phi = |\phi^{\text{jet}} - \phi^{\text{trk}}|$. Entries are weighted by $p_T^{\text{trk}}/p_T^{\text{jet}}$. The density is maximum at $\sqrt{\Delta\eta^2 + \Delta\phi^2} = r = 0$ and drops to a minimum at $r \approx R$, then increases again after $r > R$.

In the following discussion, the $h(r)$ or $\rho(r)$ distributions in figures show regions with $r > R$ in order to study the effects of the abrupt change, i.e. the “jump”, at $r = R$.

Effect of the jump on reco jets are studied by comparing the $h(r)$ between reco jets and gen jets. The upper panel in Fig. 8-3 compares the $h(r)$ for reco jets and gen jets in pp simulation, constructed using generated charged particles. The largest disagreement is $\sim 4\%$ happening at $r = 0.3$, a sudden increase in disagreement compared to adjacent bins. Larger disagreements are seen when the study is repeated...
The disagreement between signal reco jets and gen jets are larger for more central events, the largest disagreement is $\sim 50\%$ happening at $r = 0.3$ (second largest disagreement is $\sim 20\%$ happening at $r = 0$). As $r$ is angular distance from the jet axis, these disagreements could arise from the worsening of jet angle resolution in presence of large UE.

The $p_T$ and angle of gen jets are smeared to the detector resolution as an attempt to reproduce the distributions for reco jets. The $p_T$ smearing has been performed as described in Sec. 5.5.4. The angle smearing has been performed via two different methods:

1. By convolving the jet angle with a Gaussian variable whose variance is given by the $CSN$ formula in eq. 5.24, following the procedure in Sec. 5.5.4.

2. By randomly sampling a $(\Delta \eta^{r,g}, \Delta \phi^{r,g})$ pair from the two-dimensional distribution of $\Delta \eta^{r,g} = \eta^{rec} - \eta^{gen}$ vs $\Delta \phi^{r,g} = \phi^{rec} - \phi^{gen}$ and adding it to the gen jet $(\eta, \phi)$. A subset of $(\Delta \eta^{r,g}, \Delta \phi^{r,g})$ distributions are shown in Fig. 8-4. This method makes sure that the outlier pairs, i.e. the ones with large $\Delta \eta^{r,g}$ or $\Delta \phi^{r,g}$, are included in the worsening of angle resolution, a contribution that is underestimated by the Gaussian variable convolution of the previous method.

Fig. 8-5 compares the distribution for signal reco jets (the same one as in Fig. 8-3) to the one for signal gen jets which are smeared for detector resolution using the two methods described above. Both smearing methods fail to reproduce the distributions for reco jets.

The disagreement between the $h(r)$ for reco and gen jets are investigated via the correlation of jets with particles from the background event, i.e. the UE. In embedded $\text{PYTHIA} + \text{HYDJET}$ events, the $h(r)$ for signal reco jets and gen jets, i.e. jets from the $\text{PYTHIA}$ event, are constructed using generated charged particles in the background.
Figure 8-3: The $h(r)$ in pp (upper block) and PbPb (lower block) simulation for reconstructed jets (blue circles) and gen jets (histogram) constructed using generated charged particles. The gen jets and charged particles are required to be from the signal (PYTHIA) process and reco jets are required to match the gen jets in angle. The reco jet to gen jet ratio of the distributions are shown in the lower panels.
Figure 8-4: Distributions of $\Delta \eta^{r,g} = \eta^{\text{reco}} - \eta^{\text{gen}}$ vs $\Delta \phi^{r,g} = \phi^{\text{reco}} - \phi^{\text{gen}}$ in pp (left) and in 0–10% centrality PbPb (right) simulation. Gen jets are selected from the $p_T$ intervals of $30 < p_T^{\text{gen}} < 40$ GeV/c (upper) and $60 < p_T^{\text{gen}} < 80$ GeV/c (lower).
Figure 8-5: The $h(r)$ in pp (upper block) and PbPb (lower block) simulation for reconstructed jets (blue circles) and gen jets smeared by Gaussian convolution of CSN formula (red histogram) and by random sampling of $(\Delta \eta, \Delta \phi)$ pairs (green histogram). Distributions are constructed using generated charged particles. The gen jets and charged particles are required to be from the signal (PYTHIA) process and reco jets are required to match the gen jets in angle. The reco jet to gen jet ratio of the distributions are shown in the lower panels.
event, i.e. the HYDJET event. These distributions are compared in upper block of Fig. 8-6. Generated particles in PYTHIA and HYDJET events are independent, thus the distributions for signal gen jets does not portray any correlation. The yield increases with $r$, not due to a physics correlation, but purely due to the growth of phase space with $r$ (the area of the annulus increases with $r$ as shown in Fig. 2-20). However, the distributions for signal reco jets seem to differ from the ones for gen jets. Especially, the yield for reco jet distributions are relatively larger for smaller $r$. For example, in 0–10% centrality simulated events, the yield for reco jets at $r = 0$ (0.3) is $\sim 25\%$ ($\sim 4\%$) larger than the yield for gen jets. This effect is augmented for distributions constructed using higher energy particles, e.g. particles with $p_T > 5$ GeV/$c$ as shown in lower block of Fig. 8-6. In this case, differences between distributions for reco and gen jets are more obvious. The yield for reco jets at $r = 0$ is a factor of $\sim 3$ larger than for gen jets when particles have $p_T > 5$ GeV/$c$. This implies that assignment of reconstructed jet coordinates is biased such that reco jet coordinate tends to be closer to that of UE particles. The effect becomes larger with energy of the UE particles and can be thought of as UE particles “pulling” the jet axis to themselves.

The $h(r)$ for reco jets arise from an effect where the reconstructed jet axis is correlated with the position of UE particles, and this effect cannot be reproduced via a random distortion of the jet angle. Given the failure of resolution smearing, the distributions for reco jets are corrected to true distributions as described in Sec. 8.1.3.

### 8.1.3 Jet shape corrections

Bin-by-bin corrections are applied to correct the $h(r)$ for reco jets to the one for gen jets. Previous jet shape measurements by CMS [245, 378] did not apply such corrections. This is because the jet sample in those measurements covered higher $p_T$ than in this analysis where angular distortion effects become low enough to perform the analysis without dedicated corrections.

The correction steps are listed in the following where $A \rightarrow B$ means that $A$ (input) is corrected to $B$ (output)
Charged particles with $p_T > 1$ GeV/c.

Figure 8-6: Upper panels: The $h(r)$ in PbPb simulation for reconstructed jets (blue circles) and gen jets (histogram) constructed using generated charged particles. The reco jets and gen jets are from signal (PYTHIA) process. The charged particles are required to be from the background (HYDJET) event. Lower panels: The reco jet to gen jet ratio of the distributions. The charged particles in upper (lower) blocks have $p_T$ above 1 (5) GeV/c.

Charged particles with $p_T > 5$ GeV/c.

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1. reco jet, reco tracks → reco jet, gen particles:

The $h(r)$ distribution for reco jets constructed using tracks is corrected to the one constructed using gen particles.

2. reco jet, gen particles → reco jet, signal gen particles:

The $h(r)$ distribution for reco jets constructed using gen particles is corrected to the one constructed using subtracted gen particles from signal (PYTHIA) process.

3. reco jet, signal gen particles → gen jet, signal gen particles:

The $h(r)$ distribution for reco jets constructed using signal gen particles is corrected to the one for gen jets.

The output of each step is the input for next step. The second step is specific for PbPb simulation and it has no effect for pp simulation where all the gen particles are from the signal (PYTHIA) process.

The correction factors are derived as follows. At each step, the $h(r)$ are constructed for the one that is to be corrected and for the one to which we want to correct. The distributions are split into bins of jet $p_T$, jet $\eta$, track $p_T$. For PbPb, the distributions are also split into centrality intervals. The ratio of the distributions as a function of $r$ becomes the correction factor for that step. The bins used for corrections are

- Jet $p_T$ bins: $[30, 60)$, $[60, 120)$, and $[120, \infty)$ GeV/c
- Jet $|\eta|$ bins: $[0, 1.0)$ and $[1.0, 1.6)$
- Charged particle $p_T$ bins: $[1, 2)$, $[2, 3)$, $[3, 4)$, $[4, 8)$, and $[8, \infty)$ GeV/c
- Centrality bins: 50–100%, 30–50%, 10–30%, and 0–10%

**Step 1**

Jet reconstruction is effected by track reconstruction. This is because jets are reconstructed by clustering PF candidates (see Sec. 5.5), and tracks constitute a
subset of PF candidates. Therefore, a jet is less likely to be reconstructed if tracks for associated charged particles are not reconstructed, similarly a jet is more likely to be reconstructed in a region where track reconstruction efficiency is higher. This results in that the $h(r)$ for reco jets constructed using tracks have relatively smaller yield at large $r$ compared to distributions constructed using gen particles.

The first correction step accounts for this effect, i.e. the jets being reconstructed in regions with relatively higher track reconstruction efficiency, or equivalently reconstructed jet axis being away from regions with relatively lower track reco efficiency. Fig. 8-7 compares the distributions for reco jets constructed using tracks and gen particles. The lower panels give the relative yield of tracks compared to gen particles. While the ratio is mostly flat for small $r$, there is a drop around $r \approx 0.3$. Corrections are applied for the differences as function of $r$.

Step 2

The second correction step is to account for the correlations between reco jet and particles from the PbPb UE which results in that reco jet axis is pulled by the UE particles, as shown in Sec. 8.1.2.

Fig. 8-8 compares the distributions for reco jets constructed using gen particles from signal (PYTHIA) process and using gen particles obtained after background subtraction. The differences can be as large as $\sim 20\%$ at $r \approx 0.3$. Corrections are applied for the relative yields as function of $r$.

Step 3

The third and last step of the corrections account for the difference between the $h(r)$ for reco jets and gen jets. In particular, this step corrects for the differences that were shown in Fig. 8-3 and discussed in Sec. 8.1.2. Corrections are applied for the differences between the reco and gen jet shapes.

The corrections do not take the parton flavor into account. In order to confirm that the corrections work in the expected direction for both flavors, they are applied separately for quark and gluon jets. Fig. 8-9 (8-10) shows the $h(r)$ for reconstructed
Figure 8-7: The $h(r)$ in pp (upper block) and PbPb (lower block) simulation for reco jets constructed using tracks (black circles) and generated charged particles (blue squares). Background contributions for tracks and gen particles are subtracted in PbPb simulation. The track to gen particle ratio of the distributions are shown in the lower panels.
Figure 8-8: Upper: The $h(r)$ in PbPb simulation for reco jets constructed using generated charged particles subtracted for background (black circles) and particles from signal (PYTHIA) process (blue squares). Lower: The background subtracted to signal ratio of distributions.

Quark (gluon) jets before and after the application of corrections and compares them to distributions for gen quark (gluon) jets. The corrections improve the closure for both quark and gluon jets. Besides, the closure for gluon jets are worse compared to quark jets. This is because majority of jets associated with isolated photons are quark initiated (as shown in Fig. 5-11), thus the corrections are based more on quark jets because of their relatively higher abundance. Specifically quark jets make up a larger fraction of the $h(r)$ than gluon jets, as shown in Fig. 8-11 which compares the $r$-distributions for quark and gluon initiated jets and their contribution to the distribution for inclusive jets.

8.2 Systematic uncertainties

A number of systematic uncertainties for this measurement are common with the ones in the FF measurement listed in Sec. 7.3. Following uncertainties are computed using the same procedure as in Sec. 7.3:

- Uncertainties related to photon reconstruction
Figure 8-9: The $h(r)$ in pp (upper block) and PbPb (lower block) simulation for quark initiated jets constructed using generated charged particles. The reconstructed jets before (blue circles) and after (red squared) the jet shape corrections are compared to gen jets (histogram). The gen jets and charged particles are required to be from the signal (Pythia) process and reco jets are required to match the gen jets in angle. The reco jet to gen jet ratio of the distributions are shown in lower panels.
Figure 8-10: The $h(r)$ in pp (upper block) and PbPb (lower block) simulation for gluon initiated jets constructed using generated charged particles. The reconstructed jets before (blue circles) and after (red squares) the jet shape corrections are compared to gen jets (histogram). The gen jets and charged particles are required to be from the signal (PYTHIA) process and reco jets are required to match the gen jets in angle. The reco jet to gen jet ratio of the distributions are shown in lower panels.
Figure 8-11: Upper: The $h(r)$ for gen jets constructed using generated charged particles in Pythia. The contribution to inclusive jets (open squares) are split as quark (red squares) and gluon (green circles). Lower: Fractional contribution from the quark (red squares) and gluon (green circles) jets to the inclusive distributions.
Specifically, these are the uncertainties due to photon energy scale, efficiency, isolation criteria, purity estimation, and electron rejection.

- Uncertainties due to the JES and JER
- Uncertainty due to background subtraction

The uncertainty due to tracking efficiency is evaluated via a $p_T^{\text{trk}}$-dependent variation of the tracking corrections (The $\rho(r)$ observable is normalized to unity, thus the uncertainty for the observable cannot be extracted via a $p_T^{\text{trk}}$-independent variation whose results will not differ from the nominal one). The tracking efficiency difference between data and simulation is obtained as a function of $p_T^{\text{trk}}$ via $D^*$ meson studies [381] and the uncertainty is evaluated by varying the tracking corrections by this difference.

Systematic uncertainties are quoted for the jet shape correction procedure in Sec. 8.1.3. First, the $h(r)$ in PbPb simulation after the first step corrections has a remaining disagreement of 2% at $r \approx 0.3$. The effect on the results is evaluated by varying the $h(r)$ in data by the disagreement amount, then obtaining the $\rho(r)$ after this variation and comparing it to the nominal result. Second, model dependence of the corrections is studied by fitting the $\rho(r)$ distributions in data using the simulated distributions for quark and gluon jets as templates. The templates are varied by the fit uncertainty and their difference from the nominal templates is quoted as uncertainty.

The uncertainty in PbPb/pp ratio results are evaluated following the same treatment and assumptions as in the FF analysis (see Sec. 7.3).

Table 8.1 lists the systematic uncertainties averaged over $r$ for pp and 0–10% centrality PbPb data.

Fig. 8-12 shows the uncertainties arising from various systematic sources and the combined, i.e. total, systematic uncertainties as a function of $r$ for pp and PbPb data. Fig. 8-13 shows the same functions for the PbPb/pp ratio.
Figure 8-12: The uncertainties arising from various systematic sources and the combined (total) systematic uncertainties for pp (upper block) and PbPb (lower block) data as a function of $r$. Columns on the left (right) correspond to peripheral (central) collisions.
Table 8.1: Systematics uncertainties averaged over \( r \) for the \( \rho(r) \) distributions in pp, 0–10% centrality PbPb data, and the PbPb/pp ratio. Numbers are in percentage.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>PbPb</td>
</tr>
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<tr>
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<tr>
<td>Photon purity</td>
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<tr>
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</tr>
<tr>
<td>Total</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Figure 8-13: The uncertainties arising from various systematic sources and the combined (total) systematic uncertainties for the PbPb/pp ratio as a function of \( r \). Columns on the left (right) correspond to peripheral (central) collisions.
Figure 8-14: Upper: The differential jet shape, $\rho(r)$, for jets associated with an isolated photon for pp (solid circles) collisions compared to PYTHIA simulation (histogram). Lower: The MC over pp data ratio of the distributions. The vertical lines through the points represent statistical uncertainties, while the shaded colored boxes indicate the total systematic uncertainties in data [3].

8.3 Results

Fig. 8-14 shows the differential jet shape $\rho(r)$ for pp collisions and PYTHIA simulation. The simulated $\rho(r)$ is higher than the pp data at large $r$, but describes the pp data within 10% in each bin, allowing its use to derive the jet shape corrections.

Fig. 8-15 shows the $\rho(r)$ distributions for pp and PbPb collisions in four centrality intervals and Fig. 8-16 shows the same distributions by merging the adjacent centrality intervals, improving the statistical precision. The PbPb to pp ratio of distributions are shown in the lower panels. The results from 50–100% centrality PbPb collisions
is consistent with that in pp. The distributions in most central PbPb collisions are observed to be enhanced at $r \approx 0.3$ with respect to the distributions in pp. The differences between the pp and 0–10% (0–30%) centrality PbPb results are quantified via a $\chi^2$ test that accounts for all statistical and systematic uncertainties. The test yields $p$ value of 0.029 (0.017), lower than the general cutoff of 0.05, implying that the pp and most central PbPb results are incompatible. Integrating the distributions over the $r$ intervals shows that the $r > 0.2$ region carries $\sim 5\%$ and $\sim 9\%$ ($\sim 8\%$) of the jet energy in pp and 0–10% (0–30%) centrality PbPb data, respectively. Thus, in PbPb data a larger fraction of the jet energy is carried at large distances from the jet axis, a modification that is in qualitative agreement with the inclusive jet shape results in Refs. [245, 248] and results from dijet pairs in Ref. [378]. On the other hand, no significant depletion is seen in central collisions for intermediate $r$, in contrast to what was observed in the aforementioned results from inclusive jets and leading jets of dijet pairs. This different observation could be due to quark jet fraction in the isolated photon-tagged sample being larger than in the inclusive jet sample or due to the lower $p_T^{\text{jet}}$ threshold which increases the fraction of quenched jets, i.e. jets that suffered larger relative energy loss and became less collimated. Or it may be that the selection bias (described in Sec. 4.6) in the aforementioned measurements have worked in a way to select narrower jets in PbPb which cause a slight depletion at intermediate $r$ in those measurements. Note also that the $\rho (r)$ distributions decrease rapidly with $r$, with most of the jet energy being concentrated at small $r$, e.g. more than 70% of the energy is carried in the $r < 0.1$ region for both collision systems. In case of a shift in the $\rho (r)$, the fractional change at small $r$ will be smaller than at large $r$. Thus, a modification in the intermediate $r$ region, e.g. a depletion, does not appear as large as in the large $r$ region.

### 8.3.1 Comparison to theory

Fig. 8-17 compares the results to theoretical calculations, listed below:

- SCET$_G$ model introduced earlier in Sec. 2.3.2 Calculations are based on Refs. [377].
Figure 8-15: Upper: The differential jet shape, $\rho(r)$, for jets associated with an isolated photon for (from left to right) 50–100%, 30–50%, 10–30%, 0–10% PbPb (solid circles), and pp (open circles) collisions. Lower: The ratios of the PbPb and pp distributions. The vertical lines through the points represent statistical uncertainties, while the shaded colored boxes indicate the total systematic uncertainties in data [3].
Figure 8-16: Upper: The differential jet shape, $\rho(r)$, for jets associated with an isolated photon for (from left to right) 30–100%, 0–30% PbPb (solid circles), and pp (open circles) collisions. Lower: The ratios of the PbPb and pp distributions. The vertical lines through the points represent statistical uncertainties, while the shaded colored boxes indicate the total systematic uncertainties in data [3].
Figure 8-17: Comparison of the PbPb over pp ratio of the differential jet shape, \( \rho(r) \), for 0–10% centrality interval with SCET\(_G\) \cite{377,382,383} and LBT \cite{333} theoretical models. The SCET\(_G\) band represents the variation of physics scale \cite{3}.

- The linear Boltzmann transport, LBT, model introduced earlier in Sec. 2.3.2. Different than the CoLBT-hydro model (see Sec. 7.4.1), the LBT model is not coupled with hydrodynamics simulation of QCD medium. Calculations are based on Ref. \cite{333}.

Both SCET\(_G\) and LBT models can capture the trend in data, slightly overshooting the data in the 0.1 < \( r < 0.2 \) region and undershooting at \( r \approx 0.3 \), nevertheless both model calculations are consistent with the data given the experimental uncertainties.
8.4 Summary

This chapter presented the first measurement of the radial density profile for jets associated with isolated photons in pp and PbPb collisions at the LHC. The differential jet shapes are constructed using charged particles with $p^T_{\text{Trk}} > 1$ GeV/c, for jets with $p^T_{\text{jet}} > 30$ GeV/c associated with an isolated photon with $p^T_{\gamma} > 60$ GeV/c and measured as a function of $r$, the angular distance between the track and the jet axis. The result from the most peripheral (50–100%) PbPb data is consistent with that in pp. In more central collisions however, the jet shapes in PbPb collisions are enhanced at large angles from the jet axis, i.e. the 0–10% (10–30%) PbPb $\rho(r)$ is enhanced for $r \gtrsim 0.15$ (0.20) and no significant depletion is seen for $r \sim 0.1$. The results demonstrate that in PbPb collisions a larger fraction of jet energy is carried at larger angles, a modification also seen in previous measurements using inclusive jet samples. This first measurement of using jets tagged by an isolated photon unambiguously concluded that the observed phenomena arises as a result of the parton shower radiating its energy to larger angles.
Chapter 9

Parton-medium interactions using Z+hadron correlations

This chapter is dedicated to the measurement of angle and momentum correlations between Z bosons and charged particles in Ref. [4], a study that probes the parton-medium interactions over all azimuthal angles expanding the previous shower modification studies beyond the angular space covered by jets. The analysis exploited pp and PbPb data at $\sqrt{s_{NN}} = 5.02$ TeV recorded in 2017 and 2018, respectively. These pp and PbPb data sets had a factor of $\sim 11$ and $\sim 4$ more events than the corresponding data sets recorded in 2015, respectively, providing a crucial statistical improvement for studies involving rare probes such as Z bosons.

Angular correlations are measured to reveal the possible momentum broadening effects induced by QCD medium and to scan the medium response effects as a function of azimuthal angle. The FFs and momentum spectrum are measured for charged particles recoiling from the Z boson to study the momentum modification in parton shower.

The first measured quantity is the azimuthal angle difference between the Z boson and tracks in the event

$$\Delta \phi_{\text{trk},Z} = |\phi_{\text{trk}} - \phi_{Z}|$$  \hspace{1cm} (9.1)
Next, Z-tagged FF is measured as

$$\xi_{trk,Z}^T = \ln \frac{-|p_{trk}^Z|^2}{p_{T\ trk} \cdot p_{Z\ T}^Z} \quad (9.2)$$

where $p_{Z\ T}$ and $p_{trk}^T$ are the $p_T$ of the Z boson and charged particle, respectively, with respect to the beam direction (This is essentially the same observable as in eq. 2.16 with the EW boson being replaced with the Z boson).

Last measured quantity is the $p_{trk}^T$. In order to increase the fraction of particles recoiling from the Z boson, tracks used in the $\xi_{trk,Z}^T$ and $p_{trk}^T$ measurements are required to satisfy the azimuthal separation of $\Delta\phi_{trk,Z} > 7\pi/8$.

All three measured distributions are normalized by the number of Z bosons, thus the integrated distributions yield the number of tracks per Z boson.

Events are selected as described in Sec. 4.4. Reconstruction and identification of muons (electrons) are provided in Sec. 5.4.1 (Sec. 5.4.2). In addition, leptons are required to be within detector acceptance, hence muons must fall in the acceptance of muon detectors, $|\eta^\mu| < 2.4$, and electron SCs must be within the acceptance of the trigger, $|\eta| < 2.1$ and outside the transition region between the ECAL barrel and endcaps (that is electron SCs with $1.44 < |\eta^{SC}| < 1.57$ are excluded). For PbPb data, an additional region ($\eta < -1.39$ and $-1.6 < \phi < -0.9$) is excluded for electrons because of the corresponding calorimeter modules being inactive during data taking. In order to suppress the contamination from muons produced in hadron decays in the same event, muons are required to have $p_T > 20$ GeV/c. Electrons must have $p_T > 20$ GeV/c for the same reason as muons.

The Z boson candidates are defined as electron or muon pairs, with a reconstructed invariant mass $M_{ll}$ in the interval 60–120 GeV/$c^2$ and $p_T^Z > 30$ GeV/c. Results are obtained in events with oppositely charged lepton pairs and subtracted for the relative contribution from same charge pairs in order to minimize the residual contribution from processes other than Z boson events, as explained in Sec. 9.2.1.

Tracks for charged particles are reconstructed as described in Sec. 5.6 and identified using the criteria listed in Table 5.5. Tracks are selected to have $p_T > 1$ GeV/c
Figure 9-1: Invariant mass distributions of the selected muon pairs in pp (left) and PbPb (right) data compared to the Z boson events in simulation (histogram). The simulation result is normalized to the number of opposite charge pairs in data.

and be within the tracker acceptance, $|\eta| < 2.4$. To eliminate the contamination of leptons from Z decays, the $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ between a lepton from the Z decay and a track is required to be greater than 0.02.

The PbPb data has been analyzed in four centrality intervals: 0–30%, 30–50%, 50–70%, and 70–90%.

## 9.1 Z boson reconstruction

Figs. [9-1] and [9-2] show the invariant mass distribution of the Z bosons reconstructed from muon and electron pairs, respectively. The muon and electron momentums are corrected using the recipe provided by the corresponding physics object groups.

### 9.1.1 Z boson reconstruction efficiency

Efficiency of Z boson reconstruction using muon and electron pairs are studied in simulation with the requirements for denominators and numerators being:
Figure 9-2: Invariant mass distributions of the selected electron pairs in pp (left) and PbPb (right) data compared to the Z boson events in simulation (histogram). The simulation result is normalized to the number of opposite charge pairs in data.

- **Denominator**: Event has a generated Z boson with $60 < M_Z < 120$ GeV/c² and $|y^Z| < 2.4$ ($|y^Z| < 2.1$), and the Z decays into muon (electron) pairs each with $p_T > 20$ GeV/c and $|\eta| < 2.4$ ($|\eta| < 2.1$).

- **Numerator**: Event passes the denominator requirement and has a reconstructed Z boson with $60 < M_Z < 120$ GeV/c² made from reconstructed and selected lepton pairs.

The region with the inactive calorimeter modules is excluded when selecting reconstructed electrons in PbPb. Note that this region is not excluded for the denominator, therefore efficiency corrections recover the acceptance loss due to this exclusion.

Figs. 9-3 and 9-4 show the reconstruction and selection efficiency of Z bosons reconstructed using muon and electron pairs, respectively, in pp simulation. Figs. 9-5 and 9-6 are the corresponding figures for efficiency in PbPb simulation.

The Z bosons in this analysis are corrected for efficiency as function of $p_T^Z$ and $y^Z$. In addition, corrections for PbPb are split into four centrality intervals: 0–10%, 10–30%, 30–50%, 50–90%. Inverse of efficiency, $1/\text{eff}$, is applied as efficiency correction factor.
Figure 9-3: Efficiency of Z boson reconstruction and selection using muon pairs in pp simulation as function of the true $p_T^Z$ (left) and $y^Z$ (right).

Figure 9-4: Efficiency of Z boson reconstruction and selection using electron pairs in pp simulation as function of the true $p_T^Z$ (left) and $y^Z$ (right).
Figure 9-5: Efficiency of Z boson reconstruction and selection using muon pairs in PbPb simulation as function of the true $p_T^Z$ (left) and $y^Z$ (right) in four centrality intervals.

Figure 9-6: Efficiency of Z boson reconstruction and selection using electron pairs in PbPb simulation as function of the true $p_T^Z$ (left) and $y^Z$ (right) in four centrality intervals.
9.1.2 Z boson spectrum

The $p_T$ and rapidity distributions for Z bosons from muon and electron pairs are constructed after applying the corrections. Figs. 9-7 and 9-8 compare the $p_T^Z$ and $y^Z$ distributions in pp and PbPb data. Distributions are compatible ($\chi^2$ tests yield $p$ values of at least 0.2), verifying that partons recoiling from the Z boson have the same initial spectrum between pp and PbPb.

![Figure 9-7: The $p_T^Z$ distributions from muon (left) and electron (right) pairs in PbPb data (black) are compared to the same distribution in pp (red).](image)

9.2 Analysis method

9.2.1 Background subtraction

Several background sources are identified and their contribution is removed to obtain correlations of interest. First, physics processes other than Z boson events
are studied for their contribution to selected lepton pairs. Second, the combinatorial background in PbPb is analyzed.

**Physics processes**

Lepton pairs which do not directly originate from Z bosons are considered as background physics processes. These physics processes are W+jet, t\(t\bar{t}\), QCD jet events, and Z bosons which decay into \(\tau\) pairs which eventually decay into electrons or muons. The contribution from W+jet, t\(t\bar{t}\), and \(Z \rightarrow \tau\tau\) are estimated using simulation and the one from QCD events is estimated using same charge lepton pairs in data. Contribution of all these processes to lepton pair mass distribution is shown in Fig. 9. Distribution obtained from a simulation is normalized such that its integral becomes (cross section of the physics process calculated by the MC generator) \(\times\) (fraction of events that pass the lepton pair selection). Distribution from QCD same charge pairs is normalized such that its integral becomes (cross section of the \(Z \rightarrow \mu\mu\) or \(Z \rightarrow ee\) calculated by the MC generator) \(\times\) (fraction of same charge pairs with respect to opposite charge pairs in data).

The contribution from W+jet events and same charge pairs to electron pairs are 1.5% and 6%, respectively, all the remaining contributions are smaller than 1%. Possible contaminations from QCD processes are removed by obtaining the results using same charge lepton pairs and subtracting them from the results for opposite charge pairs.

**Background for tracks**

The “signal” for this analysis are particles originating from the same nucleon-nucleon interaction that produced the Z boson, the same definition as in the photon-tagged FF (Sec. 7.2.1) and JS analysis (Sec. 8.1.1). Similarly, the combinatorial background arises from the PbPb UE. These signal and background definitions are the same as in all previous measurements discussed in Secs. 6.1, 7.2.1 and 8.1.1.

Different than previous measurements, this analysis does not use jets, thus the combinatorial background arises and is subtracted only for tracks. It is crucial to
Figure 9-8: The $y^Z$ distributions from muon (left) and electron (right) pairs in PbPb data (black) are compared to the same distribution in pp (red).

Figure 9-9: Invariant mass distribution of opposite charge muon (left) and electron (right) pairs in simulated PbPb events. The contribution from $Z$+jet process is stacked over contributions from $t\bar{t}$, $W$+jet, $Z\rightarrow\tau\tau$, and QCD jet events.
note that this set of object selections results in a combinatorial background which is remarkably larger than the backgrounds in previous analysis. Fig. 9-10 shows the $\Delta\phi_{\text{trk},Z}$, $\xi_{T}^{\text{trk},Z}$, and $p_{T}^{\text{trk}}$ distributions for signal and background particles in PbPb simulation. Same distributions in PbPb data (obtained after the background subtraction explained in next sections) are shown in Fig. 9-11. The signal/background ratio (S/B) in central collisions can be as small as $\sim 1\%$ in parts of the distributions, e.g. for lowest $p_T$ particles ($1 < p_{T}^{\text{trk}} < 2$ GeV/c) or for the near-side region ($\Delta\phi_{\text{trk},Z} < \pi/2$). Such levels of S/B is considerably smaller than the ones in previous analyses where S/B is at least $\sim 10\%$. Looking at the $p_{T}^{\text{trk}}$ distributions in Fig. 9-11 one can see that the S/B increases to $\sim 5\%$ for $2 < p_{T}^{\text{trk}} < 3$ GeV/c and reaches $\sim 10\%$ level only for $p_{T}^{\text{trk}} > 3$ GeV/c. The reason for the larger background fraction in this analysis can be understood as follows. While the signal fraction is higher (or equivalently the background fraction is smaller) around coordinates where a jet is identified, the goal of the analysis is to measure all particles associated with the Z boson process not only those found by jets. Thus the analyzed angular space is not limited to jet coordinates but covers a much larger region (the whole azimuthal space and $|\eta| < 2.4$) and consequently the background fraction becomes larger.

The combinatorial background is estimated and subtracted using the event mixing method, as in the case for all previous works shown in Secs. 6.1, 7.2.1, and 8.1.1. However, the larger background fraction in the analysis necessitates a more precise estimation which is obtained as follows. For a Z boson event, the event mixing method selects MB events whose

- energy represents the UE energy in the Z boson event

- $z$-coordinate of the interaction vertex, $v_{z}$, is within 1 cm of the Z boson event

where the UE energy is estimated as follows. The total energy in the forward region, $E_{HF}$, is calculated as energy sum of the PF candidates with $3 < |\eta| < 5$ detected in
Figure 9-10: The $\Delta \phi_{\text{trk,Z}}$ (upper row), $\xi_{\Sigma T}$ (middle row), and $p_T^{\text{trk}}$ (lower row) distributions in PbPb simulation constructed using generated charged particles in 30–90% (left) and 0–30% (right) centrality intervals. The raw distributions (black) are subtracted for background which is estimated using gen particles in mixed events (blue). The “background subtracted” distribution (red) is compared to distributions constructed using signal gen particles (histogram).
Figure 9-11: The $\Delta \phi_{\text{trk},Z}$ (upper row), $\xi^\text{trk,Z}_T$ (middle row), and $p_T^\text{trk}$ (lower row) distributions in 0–30% centrality PbPb data. Estimated contribution from background tracks (blue crosses) are subtracted from the raw distribution (black squares) to obtain the distribution subtracted for background tracks (red circles).
the HF

\[ E^{HF} = \sum_{3<|\eta|<5} E^{PF} \]  

(9.3)

where \( E^{PF} \) is the energy of a PF candidate. Fig. 9-12 shows the average of \( E^{HF} \) as a function of \( N_{\text{part}} \) in PbPb simulation. The \( N_{\text{part}} \) in embedded (PYTHIA + HYDJET) events is the \( N_{\text{part}} \) of the underlying MB (HYDJET) event. The energy in embedded simulation is larger than the one in MB simulation due to the additional event activity from the Z+jet process. The difference is independent of \( N_{\text{part}} \), therefore a constant function is used to extract the energy difference.

\[ \Delta (E^{HF}) = E^{HF}(\text{embedded}) - E^{HF}(\text{MB}) \]  

(9.4)

The fit in simulation gives \( \Delta (E^{HF}) \approx 682 \text{ GeV} \) which is used in event mixing as follows. The \( E^{HF} \) is calculated for an embedded event and the event will be mixed with a MB event where the \( E^{HF}(\text{embedded}) - \Delta (E^{HF}) \) difference and \( E^{HF}(\text{HYDJET}) \) lie in the same interval. The width of an interval in simulation (data) is 187.5 (150) GeV. Therefore, the MB events are chosen such that their forward energy match the one in embedded event after removing the contribution from the Z boson process.

The \( \Delta (E^{HF}) \) in data is estimated from pp data by selecting Z boson events without additional pp interactions, that is Z boson events with exactly one interaction vertex. The requirement on the number of vertices ensures that the energy is coming only from the collision that produced the Z boson. Fig. 9-13 shows the average of \( E^{HF} \) as a function of \( p_T^Z \) in pp events with a single collision. There is no dependence on \( p_T^Z \), a constant function is fit to extract the \( E^{HF}(\text{pp}) \). The fit to pp data gives \( E^{HF}(\text{pp}) \approx 660 \text{ GeV} \) which is used as \( \Delta (E^{HF}) \) in analysis of the data.

### 9.2.2 Validation

The background subtraction method is tested in simulation using gen and reco particles.
Figure 9-12: Upper: Average of $E^{HF}$ as a function of $N_{part}$ in embedded (black) and MB (blue) PbPb simulation. Lower: The difference between the functions in embedded and MB event simulation.
Figure 9-13: The total energy in the forward rapidity region of $3 < |\eta| < 5$ is calculated in each pp event where a Z boson is identified and there is no extraneous collision. The per event average of the energy is calculated as function of the Z boson $p_T$.

**Generated particles**

The simulated distributions are constructed using all gen particles in the event and the combinatorial background is subtracted using the method explained above in Sec. 9.2.1. The background subtracted gen particle distributions are compared to the distributions for signal gen particles.

Figs. 9-14, 9-15, and 9-16 draw the comparison for the $\Delta \phi_{\text{trk},Z}$, $\xi_{T,\text{trk},Z}$ and $p_{T,\text{trk}}$ distributions, respectively. The distributions for background subtracted and signal particles are consistent, $\chi^2$ tests performed separately for each distribution and centrality interval yield $p$ values of at least 0.15. Despite the consistency tests, there can be disagreements between the signal particles and background subtracted gen particles depending on the specific $\Delta \phi_{\text{trk},Z}$, $\xi_{T,\text{trk},Z}$, $p_{T,\text{trk}}$ bin, or collision centrality. See Sec. 9.2.3 for an explanation of the various disagreements.
Figure 9-14: Distributions of $\Delta \phi_{\text{trk,Z}}$ in PbPb simulation constructed using generated charged particles for 50–90% (upper left), 30–50% (upper right), and 0-30% (lower) centrality intervals. Distributions for signal gen particles (histogram) are compared to the ones for background subtracted particles (green markers).
Figure 9-15: Distributions of $\xi_{\text{trk}, Z}$ in PbPb simulation constructed using generated charged particles for 50–90% (upper left), 30–50% (upper right), and 0-30% (lower) centrality intervals. Distributions for signal gen particles (histogram) are compared to the ones for background subtracted particles (green markers).
Figure 9-16: Distributions of $p_T^{trk}$ in PbPb simulation constructed using generated charged particles for 50–90% (upper left), 30–50% (upper right), and 0–30% (lower) centrality intervals. Distributions for signal gen particles (histogram) are compared to the ones for background subtracted particles (green markers).
A note about the background estimation

As noted in Sec. [9.2.1] the smaller S/B in this analysis required an improved background estimation. In previous works, the size of UE for an analyzed (photon or Z boson) event was estimated by using MB events that have the same reconstructed centrality as the analyzed event (shown in Secs. [6.1], [7.2.1] and [8.1.1]).

As an exercise, instead of the procedure described in Sec. [9.2.1] the subtraction is tested by estimating the background using MB events that have the same centrality as the Z boson event. As above, the background subtracted gen particle distributions are compared to the distributions for signal gen particles. Fig. 9-17 shows the comparison for the $\Delta \phi_{\text{trk,Z}}$ and $p_{T}^{\text{trk}}$ distributions. There are sizable disagreements which grow with decreasing $\Delta \phi_{\text{trk,Z}}$ and $p_{T}^{\text{trk}}$, i.e. the disagreements are larger in regions with lower S/B, e.g. the disagreement is more than 100% for $\Delta \phi_{\text{trk,Z}} < \pi/2$ and about 50% for $1 < p_{T}^{\text{trk}} < 2$ GeV/c.

The failure of “same centrality” requirement can be understood as follows. Let be $N_{\text{coll}}$ the number of binary nucleon-nucleon (N-N) collisions in a PbPb collision that produces a Z boson. The signal in this analysis is defined as the particles originating from the N-N collision that produces the Z boson. Thus, the remaining N-N collisions, $N_{\text{coll,UE}} = N_{\text{coll}} - 1$, constitute the UE (or the background) whose contribution is to be subtracted.

The procedure described in Sec. [9.2.1] assumes that the forward energy defined in eq [9.3] has contributions from the $N_{\text{coll}}$ binary collisions, i.e. the $N_{\text{coll,UE}}$ collisions plus the N-N collision producing the Z boson, and estimates the background using MB events whose forward energy is matched after subtracting the contribution from the N-N collision producing the Z boson, the $\Delta (E^{\text{HF}})$, ensuring that the matched MB events have on average $N_{\text{coll,UE}}$ binary collisions.

On the other hand, requiring the MB events to have the same centrality as the Z boson event, selects MB events that on average have $N_{\text{coll}}$ binary collisions, the same as in the Z boson event and one more than the desired $N_{\text{coll,UE}}$. Therefore, requiring the MB events to have the same centrality as the Z boson event tends to
overestimate the background whose effects are magnified in regions with low S/B, as seen in Fig. 9-17. Thanks to the larger S/B in previous works, the inaccuracy of the same centrality requirement did not have large effects that could invalidate the background subtraction method.

**Tracks**

The background subtraction method has been validated for gen particles. Next step is to construct the background subtracted distributions using tracks and compare them to signal gen particles in order to study how the analysis method is affected by reconstruction. This comparison is done after application of an additional track correction described below.

**Residual track corrections**

Corrections are applied for the residual tracking efficiency difference seen between the simulated embedded and MB events. These “residual” corrections are in addition to the standard track corrections described in Sec. 5.6.

Adding Z+jet process into a MB event gives an embedded event whose particle density is larger than the MB event. As a result the tracking efficiency in the embedded event is smaller than the one in the MB event (tracking efficiency generally decreases with increasing particle density). Although particle density and thus the tracking efficiency differences between the embedded and MB events are smaller than $\sim 1\%$, the effect of the efficiency difference can be augmented after background subtraction, especially in regions with small S/R.

Residual corrections are defined as the ratio of gen particle yields over track yields binned in track $p_T$, $\eta$, $\phi$, and event centrality. Corrections are derived separately for embedded and MB events.

The procedure is illustrated in several figures. Fig. 9-18 shows the $\phi$ vs $\eta$ distributions of gen particles and tracks before the application of residual corrections. While the distributions for gen particles are uniform across $\phi$, there is a $\phi$ dependence for the track distributions. This is due to a local inefficiency in the 2018 data and
Figure 9-17: Distributions of Δφ_{trk,Z} (upper) and p_{trk}^{#it{kin}} (lower) in PbPb simulation constructed using generated charged particles. Left and right panels correspond to 30–90% and 0-30% centrality intervals, respectively. Distributions for signal gen particles (histogram) are compared to the ones for background subtracted particles (green crosses) where the background is estimated using MB events that have the same centrality as the Z boson event.
standard corrections for that data are not differential in $\phi$, but averaged over $\phi$. The “gen / track” ratio of these distributions are applied as correction factors and as an example, one of them is shown in the left panel in Fig. 9-19. The right panel in Fig. 9-19 compares a slice of the ratios along $\phi$. The ratios are larger for embedded sample by $\sim 1\%$, meaning that the tracking efficiency in embedded sample is smaller by the same amount.

Figure 9-18: $\phi$ vs $\eta$ distributions of gen particles (left) and corrected tracks (right) in simulated PbPb MB events where $p_T$ and centrality bins are indicated in the title.

The background subtracted $\Delta\phi_{trk,Z}$, $\xi_T^{trk,Z}$, and $p_T^{trk}$ distributions are constructed using tracks and compared to signal gen particles in Figs. 9-20, 9-21, and 9-22 respectively. Distributions constructed using tracks are shown both before and after the application of residual corrections. While the agreement with the signal $\xi_T^{trk,Z}$ and $p_T^{trk}$ distributions are not much affected by the residual corrections, the agreement for $\Delta\phi_{trk,Z}$ in most central collisions (especially for $\Delta\phi_{trk,Z} < \pi/2$ where S/B is smaller) improves significantly after applying the residual corrections. A discussion of the various disagreements between the signal and track distributions is given in Sec. 9.2.3.
Figure 9-19: Left: The gen / track ratio of the $\phi$ vs $\eta$ distributions shown in Fig. 9-18. Right: The gen particle to track ratio as a function of $\phi$ in simulated MB and embedded PbPb events are shown in black squares and red circles, respectively.
Figure 9-20: The $\Delta \phi_{\text{trk},Z}$ distributions in PbPb simulation for 50–90% (upper left), 30–50% (upper right), and 0-30% (lower) centrality intervals. Distributions constructed using signal gen particles (histogram) are compared to the ones for background subtracted tracks. Track distributions are shown before (blue squares) and after (red circles) the application of residual corrections.
Figure 9-21: The $\xi_{T}^{\text{trk},Z}$ distributions in PbPb simulation for 50–90% (upper left), 30–50% (upper right), and 0-30% (lower) centrality intervals. Distributions constructed using signal gen particles (histogram) are compared to the ones for background subtracted tracks. Track distributions are shown before (blue squares) and after (red circles) the application of residual corrections.
Figure 9-22: The $p_T^{\text{trk}}$ distributions in PbPb simulation for 50–90% (upper left), 30–50% (upper right), and 0–30% (lower) centrality intervals. Distributions constructed using signal gen particles (histogram) are compared to the ones for background subtracted tracks. Track distributions are shown before (blue squares) and after (red circles) the application of residual corrections.
9.2.3 Event-by-event fluctuations

Fig. 9-23 shows the average and the standard deviation of number of particles per event as function of centrality in PbPb simulation. There are on average more charged particles in more central collisions and the standard deviation of the number of charged particles is larger in more central collisions. Furthermore, charged particles in a PbPb collision are not emitted uniformly over $\phi$. The density of charged particles varies strongly with the azimuthal angle with respect to event plane. Fig. 9-24 shows the distribution of the azimuthal angle difference between the event plane and charged particles yields in PbPb simulation. Particle densities can vary by $\sim 50\%$ as function of $\phi$.

Figure 9-23: The mean number of particles per event (left) and the standard deviation of number of particles per event (right) as function of centrality in PbPb simulation. Generated charged particles are selected.

Generated particles

The effect of particle density fluctuations on the simulated observables is studied. For each observable bin, the EbE deviation of the particle density is calculated as the standard deviation of number of “raw” (not subtracted for background) particles per event. Fig. 9-25 compares the deviations, labelled $\sigma(N_{\text{raw}})$, to the observables.
Figure 9-24: Distribution of $\Delta \phi_{EP, trk} = |\phi_{trk} - \phi_{EP}|$, the azimuthal angle difference between the event plane and charged particles in various collision centralities in PbPb simulation.

constructed using signal gen particles, labelled $N_{\text{sig}}$. Deviations are larger for more central collisions. The lower panels in Fig. 9-25 show $\sigma (N_{\text{raw}})/N_{\text{sig}}$, the ratio of deviations to the signal particles, revealing the sensitivity of observables to the EbE fluctuations. A large ratio implies a large sensitivity. The sensitivity is larger for small $\Delta \phi_{trk, Z}$, large $\xi_{T}^{trk, Z}$, and small $p_{T}^{trk}$ regions which are also regions where the non-closure (disagreements between signal and subtracted particles) are relatively larger, as seen in Sec. 9.2.2.

The background subtraction procedure subtracts particles separately for each event and the background is estimated based on the forward energy, $E^{HF}$, which is correlated with the average number of particles. That is, the background estimation accounts for the average particle density, but not necessarily the density fluctuations. Fluctuation effects would reach a minimum in the limit of infinite number of events. On the other hand, the simulation has a limited number of events. Larger non-closures can be observed for measurements where the EbE fluctuation of the particles before subtraction is larger compared to the signal, i.e. where the $\sigma (N_{\text{raw}})/N_{\text{sig}}$ is larger.
Tracks

Tracks are correlated with the gen particles in the same event. A comparison between observables constructed using background subtracted (“raw-bkg”) gen particles and tracks would give the non-closure due to tracking. Such a comparison is shown in Fig. 9-26 for the 0–30% centrality interval. Reasons for the lack of perfect agreement between gen particles and corrected tracks were provided in Sec. 5.6. Residual tracking corrections improve the agreement, however cannot make it perfect, as the residual corrections are not as differential enough as to capture the exact spectrum dependence (especially at high $p_T$). Furthermore, as mentioned above, the low S/R makes this analysis sensitive to particle density fluctuations and the tracking corrections are based on particle densities averaged over events, without accounting for density fluctuations. This can leave room for differences between the observables obtained using gen particles and tracks, especially in regions with large $\sigma (N_{\text{raw}}) / N_{\text{sig}}$. Differences between distributions for subtracted gen particles and tracks, i.e. those in Fig. 9-26 are quoted as non-closure uncertainty.

In summary, the disagreements between distributions for signal gen particles and corrected tracks (see Sec. 9.2.2) can be decomposed into two components. First, the EbE particle density fluctuations can appear as non-closure in simulations with finite number of events. Second, the tracking corrections are imperfect.
Figure 9-25: Distributions of $\Delta \phi_{\text{trk,Z}}$ (upper left), $\zeta_{T}^{\text{trk,Z}}$ (upper right), and $p_{T}^{\text{trk}}$ (lower) constructed using signal gen particles (labeled $y = N_{\text{sig}}$) are compared to the event-by-event deviations of number of gen particles before background subtraction (labeled $y = \sigma(N_{\text{raw}})$) for various collision centralities. The number of particles in each bin are divided by bin width.
Figure 9-26: The $\Delta \phi_{\text{trk,Z}}$ (upper left), $\xi_{\text{trk,Z}}$ (upper right), and $p_T^{\text{trk}}$ (lower) distributions in PbPb simulation for the 0–30% centrality interval. Distributions constructed using generated charged particles (green circles) are compared to the ones constructed using tracks (red squares). Both gen and reco distributions are subtracted for background. Residual corrections are applied for tracks.
9.2.4 Particles in pp

Tracks in pp are corrected for efficiency and fake rate. Distributions obtained using corrected tracks are compared to the ones obtained using signal gen particles. Fig. 9-27 shows the comparison for $\Delta\phi_{\text{trk},Z}$, $\xi_{T}^{\text{trk},Z}$, and $p_{T}^{\text{trk}}$ observables.

Generally, the agreement between tracks and signal gen particles is better than 2%, agreement is worse for small $\xi_{T}^{\text{trk},Z}$, becoming $\sim 8\%$ for $\xi_{T}^{\text{trk},Z} < 0.5$. Reasons for disagreements are listed in Sec. 5.6 Systematics uncertainties are quoted for these non-closures.

9.2.5 Pileup in pp

The effect of pileup (PU) in pp has been checked in simulation. Fig. 9-28 shows the $\Delta\phi_{\text{trk},Z}$, $\xi_{T}^{\text{trk},Z}$, and $p_{T}^{\text{trk}}$ distributions constructed using tracks and compares them between events with PU and without PU. The bin-by-bin differences between the two case are at most $\sim 2\%$, $\sim 4\%$, and $\sim 7\%$ for $\Delta\phi_{\text{trk},Z}$, $\xi_{T}^{\text{trk},Z}$, and $p_{T}^{\text{trk}}$, respectively. Integral of distributions agree better than 1% suggesting that the PU does not have a significant effect on the analysis.

The PU in pp Z boson events is illustrated in Fig. 9-29. The average number of primary vertices is 2.8 and 3.0 for pp simulation and data, respectively, validating that PU profile in data is simulated well for this analysis.

9.3 Uncertainties

9.3.1 Statistical uncertainties

In order to address the effect of EbE particle density fluctuations (see Sec. 9.2.3), statistical uncertainties for PbPb data are calculated using the bootstrapping method [384]. Events in PbPb data are resampled 400 times by using sample with replacement, i.e. same event can be sampled. For example, if the original PbPb data consisted of 5 events labelled as A,B,C,D,E, then a resample could be A,B,B,C,C or A,B,D,D,D,E.
Figure 9-27: The $\Delta \phi_{\text{trk},Z}$ (upper left), $\xi_{T}^{\text{trk},Z}$ (upper right), and $p_T^{\text{trk}}$ (lower) distributions in pp simulation. Distributions constructed using signal gen particles (histogram) are compared to the ones constructed using tracks (red markers).
Figure 9-28: The $\Delta \phi_{trk,Z}$ (upper left), $\xi_{T,Z}^{trk}$ (upper right), and $p_{T}^{trk}$ (lower) distributions in pp simulation constructed using tracks for events with at least two interaction vertices (violet circles) and exactly one interaction vertex (black crosses).
Each resample corresponds to one measurement. The standard deviation of measurements over all resamples is assigned as statistical uncertainty.

### 9.3.2 Systematic uncertainties

Systematic uncertainties are assigned to account for uncertainties related to the tracking efficiency and corrections, PU, background subtraction, lepton efficiency and energy scale, and disagreements seen between reco and gen particles. No significant differences are seen between the results from electron and muon pairs. Systematic uncertainties, except for lepton efficiency and energy scale, are not significantly different between electron and muon pairs.

The uncertainty related to the tracking efficiency is estimated as the difference in the track reconstruction efficiency between data and simulation [200]. It is 5 (2.4)% for PbPb (pp) data, for all of $\Delta\phi_{\text{trk,Z}}$, $\xi_{T,\text{trk,Z}}$, and $p_{T,\text{trk}}$. The uncertainty related to the residual track corrections is obtained by comparing the corrections obtained from embedded PYTHIA and MadGraph5_aMC@NLO samples. As pointed out in Sec. 9.2.3, the amount of disagreement seen in the comparison of observables constructed using corrected tracks and gen particles are quoted as non-closure uncer-
No corrections were applied to remove the residual PU effects in pp data. Nominal results (which do not have a requirement on PU) are compared to those from events without PU and differences are quoted as systematic uncertainty.

The UE energy was estimated from pp data as described in Sec. 9.2.1 using the energy deposited in the HF. The pp and PbPb data are recorded in different years, in 2017 and 2018, respectively. Possible changes in the HF energy scale between the two run data-taking periods are checked by comparing the $E_{\text{HF}}$ between the $\sqrt{s} = 13$ TeV pp data recorded in 2017, just before the pp reference data, and in 2018, just before the PbPb data. Fig. 9-30 shows the average of $E_{\text{HF}}$ as a function of number of vertices for Z boson events in the $\sqrt{s} = 13$ TeV pp data. For most data, the functions agree within 5%, indicating there is no significant shift in the HF energy scale. The PbPb background subtraction procedure was repeated by shifting the $E_{\text{HF}}$ by 5%, the maximum difference in the HF response between the pp and PbPb data-taking periods. Differences from the nominal results are quoted as systematic uncertainty.

Uncertainty in lepton efficiencies are calculated by varying the lepton corrections by the uncertainty in their data-to-MC differences. In addition, the uncertainty due to lepton energy scale is evaluated by shifting by the $p_T$ of leptons by their energy correction uncertainties.

The total systematic uncertainty was calculated by summing the quadratures of the uncertainties from each source (same as in previous works, Sec. 6.2, 7.3, and 8.2).

For results that combine the pp and PbPb data, i.e. the PbPb-pp differences or the PbPb/pp ratios, if a systemsatics source in collision system A has no correlation with a source in the other collision system B, then its uncertainty in system A becomes the uncertainty in the result that combines A and B. For example, background subtraction is a systemsatics source for PbPb only, therefore the background subtraction uncertainty in PbPb-to-pp comparisons is same as the one in the PbPb result. Similarly, PU effects is a systemsatics source only for pp, hence the PU uncertainty in PbPb-to-pp comparisons is same as the one in the pp result. The tracking efficiency and the non-closure uncertainties in the PbPb-to-pp comparisons are calculated assuming that the
Figure 9-30: Upper: Average of $E^{HF}$ as a function of number of vertices for Z boson events in 13 TeV pp data from 2017 (black squares) and 2018 (violet circles). Lower: The 2017 to 2018 ratio of the functions.
Table 9.1: Systematic uncertainties averaged over $\Delta \phi_{\text{trk},Z}$ in pp data, 0–30% centrality PbPb data, and the PbPb-pp difference. Numbers are in percentage.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
<th>$\Delta \phi_{\text{trk},Z}$</th>
<th>PbPb</th>
<th>pp</th>
<th>PbPb/pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background subtraction</td>
<td>3.0</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracking efficiency</td>
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<td>2.4</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pileup</td>
<td>--</td>
<td>1.3</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-closure</td>
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<td>0.7</td>
<td>8.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepton efficiency</td>
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<td>0.4</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepton energy scale</td>
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<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual corrections</td>
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<td>--</td>
<td>2.7</td>
<td></td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10.5</strong></td>
<td><strong>2.8</strong></td>
<td><strong>10.8</strong></td>
<td></td>
<td></td>
</tr>
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</table>

Table 9.2: Systematic uncertainties averaged over $\xi_{T}^{\text{trk},Z}$ in pp data, 0–30% centrality PbPb data, and the PbPb/pp ratio. Numbers are in percentage.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
<th>$\xi_{T}^{\text{trk},Z}$</th>
<th>PbPb</th>
<th>pp</th>
<th>PbPb/pp</th>
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<td>--</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracking efficiency</td>
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<td>2.4</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pileup</td>
<td>--</td>
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<td>1.9</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>2.3</td>
<td>5.9</td>
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</tr>
<tr>
<td>Lepton efficiency</td>
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<td>0.4</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepton energy scale</td>
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<td>0.4</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual corrections</td>
<td>2.7</td>
<td>--</td>
<td>2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
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<td><strong>3.8</strong></td>
<td><strong>9.3</strong></td>
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</tbody>
</table>

relevant uncertainties in PbPb and pp are independent.

Tables 9.1, 9.2 and 9.3 list the systematic uncertainties averaged over $\Delta \phi_{\text{trk},Z}$, $\xi_{T}^{\text{trk},Z}$, $p_{T}^{\text{trk}}$, respectively. In addition, Figs. 9-31, 9-32, and 9-33 show the total systematics and its breakdown into individual uncertainties as a function of $\Delta \phi_{\text{trk},Z}$, $\xi_{T}^{\text{trk},Z}$, $p_{T}^{\text{trk}}$, respectively.
Figure 9-31: Total systematics and its breakdown into individual uncertainties for the $\Delta\phi_{\text{trk},Z}$ distributions in pp data (top), PbPb data (middle), and in PbPb-pp difference (bottom) of the distributions. Left and right columns correspond to 30–50% and 0–30% centrality ranges, respectively.
Figure 9-32: Total systematics and its breakdown into individual uncertainties for the $\xi_{trk,Z}$ distributions in pp data (top), PbPb data (middle), and in PbPb/pp ratio (bottom) of the distributions. Left and right columns correspond to 30–50% and 0–30% centrality ranges, respectively.
Figure 9-33: Total systematics and its breakdown into individual uncertainties for the $p_T^{trk}$ distributions in pp data (top), PbPb data (middle), and in PbPb/pp ratio (bottom) of the distributions. Left and right columns correspond to 30–50% and 0–30% centrality ranges, respectively.
Table 9.3: Systematic uncertainties averaged over $p_T^{trk}$ in pp data, 0–30% centrality PbPb data, and the PbPb/pp ratio. Numbers are in percentage.

<table>
<thead>
<tr>
<th>Source</th>
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</tr>
</thead>
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<td>Tracking efficiency</td>
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<td>Pileup</td>
<td>--</td>
</tr>
<tr>
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</tr>
<tr>
<td>Total</td>
<td>7.1</td>
</tr>
</tbody>
</table>

9.4 Results

The $\Delta \phi_{trk,Z}$ distributions are shown in Fig. 9-34. This type of angular correlation function could reveal medium modification of the away-side ($\Delta \phi_{trk,Z} \sim \pi$) parton shower, and, on the same-side ($\Delta \phi_{trk,Z} < \pi/2$), effects of medium recoil and medium response predicted by some theoretical calculations [255]. The distributions are peaked at $\Delta \phi_{trk,Z} \sim \pi$, the signature of a parton recoiling from the Z boson back-to-back in azimuth. To quantify the medium modification of particle production, the difference between the PbPb and pp results is calculated as shown in Fig. 9-34. An enhancement of particle production is observed in 0–30%, 30–50%, and 50–70% central PbPb collisions with respect to the pp reference. This could be caused by medium response, or by the quenching of associated jets in Z+multi-jet events [251]. Finally, the enhanced production of associated particles disappears when looking in the most peripheral (i.e., the most pp-like) 70–90% centrality interval.

For the $\xi_T^{trk,Z}$ and $p_T^{trk}$ results, tracks are selected to be azimuthally separated from the Z boson, via the $\Delta \phi_{trk,Z} > 7\pi/8$ requirement. Fig. 9-35 shows the $\xi_T^{trk,Z}$ distributions measured in pp and PbPb data, where the low and high $\xi_T^{trk,Z}$ regions correspond to high and low energy particles, respectively. No significant modification is observed.
in the 70–90% centrality PbPb collisions. In more central collisions, charged particles in the $\xi_{T}^{\text{trk},Z} < 3$ interval are suppressed, whereas an enhancement is observed for $\xi_{T}^{\text{trk},Z} > 3$, a similar finding as observed in the photon+jet FF measurement presented in Sec. 7.4. The $\xi_{T}^{\text{trk},Z} \sim 3$ region corresponds to particles with $p_{T}^{\text{trk}} \sim 1.5\,(3)$ GeV/$c$ for $p_{T}^{Z} \sim 30\,(60)$ GeV/$c$, the mapping for other $\xi_{T}^{\text{trk},Z}$ regions can be read off from Fig. 2-16.

Fig. 9-36 shows the $p_{T}^{\text{trk}}$ distributions measured in pp and PbPb data, together with their ratio. In the most peripheral event class, there is no significant modification of the charged particle $p_{T}$ spectrum in PbPb collisions. In more central events, at high $p_{T}$, the particle production is suppressed in PbPb compared to the pp reference data. Meanwhile, an enhancement is observed at low $p_{T}$ ($1 < p_{T}^{\text{trk}} < 2$ GeV/$c$). Modifications of the $\xi_{T}^{\text{trk},Z}$ and $p_{T}^{\text{trk}}$ distributions are largest in the 0–30% centrality interval indicating the strongest medium effects.
Figure 9-35: Upper: The $\xi_{T,Z}$ distributions in pp collisions compared to PbPb collisions in 70–90% (left), 50–70%, 30–50%, and 0-30% (right) centrality intervals. Lower: Ratio of the PbPb and pp distributions. The vertical bars through the points represent statistical uncertainties, while the colored boxes indicate systematic uncertainties.

Figure 9-36: Upper: The $p_{T,\text{trk}}$ distributions in pp collisions compared to PbPb collisions in 70–90% (left) 50–70%, 30–50%, and 0-30% (right) centrality intervals. Lower: Ratio of the PbPb and pp distributions. The vertical bars through the points represent statistical uncertainties, while the colored boxes indicate systematic uncertainties.
9.4.1 Comparison to theory

Figs. 9-37, 9-38, and 9-39 compare the results to several theoretical calculations, listed below:

- SCET\textsubscript{G} model introduced earlier in Sec. 2.3.2. Calculations are based on Refs. [382, 385] and varied by different values of $g$, the coupling between the jet and QCD medium.

- The Hybrid model introduced earlier in Sec. 2.3.2. The calculations implement two different scenarios. The “w/o wake” scenario does not include medium response effects. The “w/ wake” scenario implements all medium response effects, including the diffusion wake, the medium excitation arising behind the jet as it boosts the medium.

- CoLBT-hydro introduced earlier in Sec. 2.3.2. Calculations are based on Ref. [386].

The overlay of theory on data in Fig. 9-37 shows that Hybrid model is completely off the data when not including the medium response. It can capture the trend in $\Delta \phi_{\text{trk},Z} \sim \pi$ region only after including medium response effects. On the other hand, the model seems to underestimate the enhancement in $\Delta \phi_{\text{trk},Z} < \pi/2$ region even when implementing medium response. Even more, it predicts a depletion in the $\Delta \phi_{\text{trk},Z} \sim 0$ region when medium response effects are included, an effect not seen in data. The CoLBT-hydro calculations, however, can get the general features in $\Delta \phi_{\text{trk},Z}$, including the excess of particle yields in the $\Delta \phi_{\text{trk},Z} \sim 0$ region. The failure of the Hybrid model to describe the $\Delta \phi_{\text{trk},Z} \sim 0$ region can be due to that the model’s simplistic implementation of the medium response is not accurate enough [253].

The calculation from the SCET\textsubscript{G} model is consistent with the suppression trends in $\xi_{T}^{\text{trk},Z} \lesssim 2.75$ and $p_{T}^{\text{trk}} > 4 \text{ GeV/c}$, as seen in Fig. 9-38 and Fig. 9-39, respectively. The Hybrid model calculations are consistent with the data for the $\xi_{T}^{\text{trk},Z} \lesssim 2.5$ and $p_{T}^{\text{trk}} \gtrsim 6 \text{ GeV/c}$ regions where including medium response makes no difference for the model’s calculations. However, it can catch the enhancement at low $p_{T}$ ($1 < p_{T}^{\text{trk}} < 2 \text{ GeV/c}$) only after including the medium response, but still undershoots the
yield at intermediate $p_T$ ($3 < p_T^{trk} < 5$ GeV/c) in most central collisions. Likewise, the CoLBT-hydro calculations are compatible with the features in the $\xi_T^{trk,Z}$ and $p_T^{trk}$ data, capturing the trends at low $p_T^{trk}$ (large $\xi_T^{trk,Z}$) and high $p_T^{trk}$ (small $\xi_T^{trk,Z}$). All of the SCET\textsubscript{G}, Hybrid (w/ wake), and CoLBT-hydro calculations show the expected weakening of medium effects from 0–30 to 30–50% PbPb event centralities, similar to the one in data.

9.5 Summary

This chapter presented the measurements of Z-tagged charged particle spectra using the pp (PbPb) data collected in 2017 (2018) at the LHC. Events with one Z boson with $p_T^Z > 30$ GeV/c are selected and distributions are measured for charged particles with $p_T^{trk} > 1$ GeV/c. The azimuthal angle distribution with respect to the Z boson, $\Delta \phi_{trk,Z}$, defined in eq. [9.1] indicates an enhanced particle production in most central PbPb collisions with respect to the pp extending to azimuthal angles close to the Z boson, an excess of particles at $\Delta \phi_{trk,Z} \sim 0$, i.e. a “near side” excess. There are several interpretations for this observation. One is that the jet recoiling from the Z induces a medium response that is large enough to enhance particle production at very large angles from its direction, i.e. at $\Delta \phi_{trk,Z} \sim 0$. The other is that in case of Z+multijet events (which are rarer compared to Z+1 jet), second or third jets from higher order processes are initiated at angles closer to that of the Z boson. Hence, the near side excess could also arise from the quenching of jets originating from higher order processes whose azimuthal angles are relatively closer to the Z boson angle.

The Z-tagged fragmentation function, $\xi_T^{trk,Z}$, defined in eq. [9.2] and $p_T^{trk}$ distributions reveal that the recoiling parton showers in QCD medium are modified to have more low energy and less high energy particles, an observation similar to that in photon-tagged jet FF in Sec. [7]. The measurement expands the parton-medium interaction studies to the complete azimuthal angle space, studies all charged particles associated with the Z boson for the first time and provides unique input for the understanding of QCD medium dynamics.
Figure 9-37: Upper: The $\Delta \phi_{\text{trk,Z}}$ distributions in pp collisions compared to PbPb collisions in 30–50% (left) and 0–30% (right) centrality intervals. Lower: Difference between the PbPb and pp distributions compared to calculations from the Hybrid [321] and CoLBT [386] theoretical models. The vertical bars through the data points represent statistical uncertainties, while the shaded boxes indicate systematic uncertainties.
Figure 9-38: Upper: The $\xi_{trk,Z}^{T}$ distributions in pp collisions compared to PbPb collisions in 30–50% (left) and 0–30% (right) centrality intervals. Lower: Ratio of the PbPb and pp distributions compared to calculations from the Hybrid [321], SCETG [382, 385] and CoLBT [386] theoretical models. The vertical bars through the data points represent statistical uncertainties, while the shaded boxes indicate systematic uncertainties.
Figure 9-39: Upper: The $p_T^{trk}$ distributions in pp collisions compared to PbPb collisions in 30–50% (left) and 0–30% (right) centrality intervals. Lower: Ratio of the PbPb and pp distributions compared to calculations from the Hybrid [321], SCET$_G$ [382, 385] and CoLBT [386] theoretical models. The vertical bars through the data points represent statistical uncertainties, while the shaded boxes indicate systematic uncertainties.
Chapter 10

Outlook

10.1 Improving jet angle resolution using a new recombination scheme

As pointed out in Sec. 2.1.2, jets in this thesis were recombined using the E-scheme, i.e. the jet axis is determined as the direction of the momentum sum of its constituents. Meanwhile, it is observed in the jet shape analysis that the jet axis is sensitive to the HI UE, i.e. UE particles pull the jet axis as described in Sec. 8.1.2.

The sensitivity to the HI UE can be reduced by determining the jet axis using the WTA recombination scheme described in Sec. 2.1.2. Details can be found in Ref. [5] which presents a subset of the event generator studies performed as part of this thesis. The HI UE effects on jet observables are studied via toy HI events. The study samples “toy HI” particles randomly from HYDJET events for the 10% most central PbPb collisions and embed those particles into PYTHIA events. Jets are defined separately for two cases, the first one uses only particles from PYTHIA events (labelled as “Pythia”), the second one uses both toy HI particles and particles from PYTHIA events (labelled as “Pythia+toy HI”). For the second case, the jet energy is corrected by subtracting the energy of toy HI particles. The jet finding is repeated for the E-scheme and WTA recombination schemes.

Fig. 10-1 compares the jet shapes (defined in eq. 2.17) between the “Pythia” and
“Pythia+toy HI” cases. When jets are recombined with the E-scheme, the jet shapes for the “Pythia+toy HI” case are significantly wider than those for the “Pythia” case. On the other hand, the “Pythia” and “Pythia+toy HI” cases agree much better when jets are recombined with the WTA scheme. This implies that jet axis determined using the WTA scheme is more robust against the HI UE.

The exercise with toy HI events has been repeated for $\sqrt{s} = 200$ GeV, the collision energy at RHIC. Fig. 10-2 compares the distributions of the photon+jet azimuthal angle difference, $\Delta \phi_{j\gamma}$ (defined in eq. 2.13) between the “Pythia” and “Pythia+toy HI” cases. Note that the distributions are shown for the $3\pi/4 < \Delta \phi_{j\gamma} < \pi$ range. The toy HI causes a deviation of roughly 5% at $\Delta \phi_{j\gamma} \approx \pi$ for jets recombined with the E-scheme, whereas the deviation at the same $\Delta \phi_{j\gamma}$ is smaller than 1% for jets.
recombined with the WTA scheme. Thus, distributions with and without the toy HI events agree better when using the WTA scheme.

In summary, the sensitivity of the jet axis to the HI UE can be reduced by recombining jets using the WTA scheme instead of the E-scheme, the current standard. Exercises in the Pythia and toy HI events suggest that the WTA recombination scheme can be particularly advantageous for angle dependent jet structure studies, i.e. jet shapes, and for the investigation of medium induced $p_T$ broadening via jet azimuthal angle correlations. The WTA recombination scheme is worthwhile to apply in analysis of LHC and future RHIC data, and is already applied in ongoing CMS measurements.

Figure 10-2: Distributions of the azimuthal angle difference $\Delta \phi_{j\gamma}$, between the photon and the jet in Pythia photon+jet events for pp collisions at $\sqrt{s} = 200$ GeV. Jets are defined using Pythia particles (black squares), and using both Pythia particles and toy HI particles (blue crosses). Jets are recombined with the E-scheme (left) and WTA (right) schemes. The lower panel shows the ratio of distributions. Figures are taken from Ref. [5].

In summary, the sensitivity of the jet axis to the HI UE can be reduced by recombining jets using the WTA scheme instead of the E-scheme, the current standard. Exercises in the Pythia and toy HI events suggest that the WTA recombination scheme can be particularly advantageous for angle dependent jet structure studies, i.e. jet shapes, and for the investigation of medium induced $p_T$ broadening via jet azimuthal angle correlations. The WTA recombination scheme is worthwhile to apply in analysis of LHC and future RHIC data, and is already applied in ongoing CMS measurements.
10.2 Energy loss extraction using data with improved statistical precision

The Z+jet results (see Sec. 6.3) and its comparison to the photon+jet results (see Sec. 6.3.2) suggested that the average energy loss for jets with $p_T^{\text{jet}} \sim 60 \text{ GeV}/c$ is about 10%. However, the results include only jets with $p_T^{\text{jet}} > 30 \text{ GeV}/c$, i.e. those which survive a $p_T$ threshold.

Integral of the $x_{jZ}$ distributions in Fig. 6-6 give the $R_{jZ}$, the number of jets per Z boson. The $R_{jZ}$ for $p_T^Z > 60 \text{ GeV}/c$ are about 0.63 and 0.53 in pp and PbPb collisions, respectively. Thus, compared to pp, an additional $\approx 16\%$ of the PbPb jets did not survive the $p_T^{\text{jet}} > 30 \text{ GeV}/c$ threshold.

The amount of energy loss for jets with $p_T \sim 30 \text{ GeV}/c$ can be estimated by assuming that energy loss is on average monotonic in $p_T$ (Jet energy loss depends on other jet properties as well, not just $p_T$ and varies between jets with the same $p_T$. Jets with more prongs, i.e. more fragments, lose more energy than those with the same $p_T$ but fewer prongs). If two jets have transverse momentum $p_T^A$ and $p_T^B$ before energy loss and $p_T^A < p_T^B$, then on average the order will be the same for the final $p_T$ after energy loss, that is $p_T^{A,\text{final}} < p_T^{B,\text{final}}$. See Ref. [387] for a study using this assumption.

Fig. 10-3 shows the $p_T^{\text{jet}}$ distribution for jets recoiling from a Z boson with $p_T^Z > 60 \text{ GeV}/c$ in PYTHIA simulation (PYTHIA describes the Z+jet results reasonably well as seen in Sec. 6.3.1). Integrating the distribution from $p_T^{\text{jet}} = 30 \text{ GeV}/c$ to higher $p_T^{\text{jet}}$, one reaches 16% of the jet population at $p_T^{\text{jet}} \sim 45 \text{ GeV}/c$. If jet energy loss is on average monotonic in $p_T$, then PbPb $R_{jZ}$ being $\approx 16\%$ smaller than the pp $R_{jZ}$ implies that PbPb jets initiated at $p_T^{\text{jet}} \sim 45 \text{ GeV}/c$ fall below the $p_T^{\text{jet}} > 30 \text{ GeV}/c$ threshold, corresponding to an energy loss of $\sim 30\%$, larger than the $\sim 10\%$ energy loss estimated for higher $p_T$ jets.

These estimations are useful to get an idea about the amount of energy loss and its evolution with $p_T$, however impact of experimental uncertainties are neglected here. More accurate statements can be made using future measurements where precision...
Figure 10-3: The $p_T^\text{jet}$ distribution for jets recoiling from Z bosons in events generated using PYTHIA 8. Jets are smeared to the detector resolution in pp following the procedure in Sec. 5.5.4.

will be improved. Besides, more data will be collected in future, improving the statistical precision for higher $p_T$ jets, e.g. those with $p_T^\text{jet} \sim 100$ GeV/c, whose energy loss extraction is less effected by the $p_T$ threshold since higher $p_T$ jets are less likely to fall below the threshold.
Chapter 11

Summary

The goal of this thesis was to contribute to the understanding of hot QCD medium by analyzing the particles produced in collisions of heavy nuclei. Specifically, interactions between energetic partons and QCD medium are explored in collisions that produce high energy particles. The effects of interactions are studied by comparing the measurements between the PbPb and pp collisions where a QCD medium is created in the former, but is absent (or very small) in the latter. The work analyzed data collected with the CMS detector at the CERN LHC at a collision energy of $\sqrt{s_{NN}} = 5.02$ TeV.

The parton-medium interactions are investigated in four different measurements, presented in Chapters 6, 7, 8, and 9. The kinematics and flavor of partons were constrained by tagging them with EW bosons (see Sec. 1.6 for details). The following paragraphs summarize the findings from those measurements, and if possible answer the questions posed in Sec. 1.6.

The jet quenching was studied using Z-tagged jets, the “cleanest” probe of jet quenching. This first study using Z-tagged jets established the proof of concept for the future measurements that will analyze more data with better precision. No significant jet angular deflection or jet momentum broadening were observed, actually the results hint at a narrower Z+jet azimuthal angle correlations in PbPb collisions, nevertheless differences are not deemed significant given the relatively large uncertainties. The energy loss for Z-tagged jets is consistent with that for photon-tagged
jets establishing the agreement between different EW boson tags. Despite the large statistical uncertainties, the results were able to favor some theoretical models over the other, showcasing a separation power. Comparison of the Z+jet pp data to MC calculations demonstrated that next-to-leading order processes are indeed important for description of the pp baseline, especially for the description of azimuthal angle correlations.

The medium induced parton shower modification is observed directly using photon-tagged jets and Z-tagged charged particles. In a QCD medium, parton showers are modified to have more low energy and less high energy particles, besides, a larger fraction of the jet energy is radiated at large angles. While similar modifications were found in previous measurements using jet triggered samples, the source of those modifications were not clear for reasons explained in Sec. 1.6. In this thesis, the EW boson tags provided well-controlled samples so that the analysis results can be interpreted unambiguously, concluding that the modifications are induced by a QCD medium.

Qualitatively, the observation of more low energy and less high energy particles in the modified parton showers can be understood as a result of that higher energy partons lose energy in QCD medium and end up as lower energy particles. The larger fractions of the jet energy being carried at larger angles demonstrate that the radiation to large angles is one of the effective energy loss mechanisms. Besides, comparisons with theoretical models suggest that the additional low energy particles can originate from medium response as well, recoil of the medium induced by a traversing parton (details in Sec. 2.4).

In the past, measurements using jet triggered samples indicated an onset of enhancement for very high energy particles and a depletion of jet radial density profile at intermediate angles (see Sec. 1.5). Those features are suggestive of narrower, harder fragmenting jets and are not (at least not as significantly) observed in the results presented in this thesis. The presence of those features in jet triggered samples can be interpreted as that the samples are biased in a way that increases the fraction of narrower, harder fragmenting jets which can be more likely to survive jet quenching.
Number of charged particles arising from the parton-medium interactions are measured for the first time over an almost complete sphere, i.e. over all azimuthal angles around the jet direction (The sphere is not complete, but almost complete, because large $\eta$ region is not accessible experimentally). More particles with $p_T > 1$ GeV/c are seen in QCD medium over all directions, including the direction opposite to the recoiling jet direction, i.e. “behind” the jet, where jets from higher order processes and medium response are expected to have a bigger role in particle production than a medium induced modification of the recoiling jet. These results provide important input for the understanding of jet induced medium response, especially given that some theoretical models predicted different results for particles behind the recoiling jet (details in Secs. 2.4 and 9.4.1).

Apart from the physics results, the effects observed during the validation of analysis methods provoked new approaches. The calorimeter energy clustering algorithm was modified to improve the performance of photon reconstruction in future HI data (see Sec. 5.3.2). The analysis of jet radial density profile revealed the sensitivity of the standard jet axis to the HI UE. This lead to the investigation of an alternative jet axis definition which was found to be more robust in HI environments (see Sec. 10.1). The low signal-to-background ratio in $Z+$hadron correlations analysis prompted the development of a more precise method to subtract the combinatorial background arising from the HI UE (see Sec. 9.2.1). The outlook in Ch. 10 demonstrated that the aforementioned alternative jet axis could improve the experimental precision for medium induced $p_T$ broadening searches at RHIC and presented an estimate for the fractional energy loss using the $Z+$jet results and how more data from future experiments could help extracting the jet energy loss in QCD medium.

Finally, this thesis measured parton-medium interactions in different aspects. While the results from different measurements are complementary to each other, they constrain theoretical models independently and consequently improve the understanding of QCD medium.
Appendix A

Acronyms

Physics terminology

CNM  Cold nuclear matter
DIS  Deep inelastic scattering
EoS  Equation of state
EW  Electroweak
LO  Leading order
LQCD  Lattice QCD
NLO  Next to leading order
nPDF  Nuclear PDF
PDF  Parton distribution function
pQCD  Perturbative QCD
QCD  Quantum chromodynamics
QED  Quantum electrodynamics
QFT  Quantum field theory
QGP Quark-gluon plasma

Collider physics

EbE Event-by-event

FF Fragmentation function

HI Heavy ion

JS Jet shape

N-N nucleon-nucleon

PU Pileup

UE Underlying event

WTA Winner-takes-all

Facilities

CERN Conseil Européen pour la Recherche Nucléaire (European Organization for Nuclear Research)

CMS Compact Muon Solenoid

LHC Large Hadron Collider

RHIC Relativistic Heavy Ion Collider
Detectors and experiment methods

BC  Basic cluster

EG  Electron gamma (\(e/\gamma\))

GED  Global event description

Gen  generated

HLT  High-level Trigger

L1T  Level-1 Trigger

MB  Minimum-bias

MC  Monte Carlo

PF  Particle-flow

Reco  reconstructed

S/B  Signal/background

SC  Supercluster

TIB  Tracker Inner Barrel

TOB  Tracker Outer Barrel
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