Long-range dihadron correlations in pp and PbPb from CMS

Wei Li

for the CMS Collaboration
Correlation measurements are powerful tools to:

- Study the mechanism of hadron production
- Probe the jet-medium interactions in AA
- Explore the initial conditions and medium properties

Intriguing ridge structure at RHIC

- STAR Au+Au 0-10%
- PHOBOS Au+Au 0-30%

Ridge in pp at LHC!

- CMS pp 7 TeV

With wider kinematics reach and better precision, LHC is ideally suited for correlation studies!
CMS experiment

EM Calorimeter (ECAL)

Hadron Calorimeter (HCAL)

Beam Scintillator Counters (BSC)

Forward Calorimeter (HF)

Tracker (Pixels and Strips)

Very large coverage (|Δη| up to 5.0)!
Dihadron correlations in CMS

**Signal pair distribution:**

\[
S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{same}}}{d\Delta \eta d\Delta \phi}
\]

**Background pair distribution:**

\[
B(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{mix}}}{d\Delta \eta d\Delta \phi}
\]

\[\Delta \eta = \eta^{\text{assoc}} - \eta^{\text{trig}}\]
\[\Delta \phi = \phi^{\text{assoc}} - \phi^{\text{trig}}\]

**Associated hadron yield per trigger:**

\[
\frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pair}}}{d\Delta \eta d\Delta \phi} = B(0,0) \times \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)}
\]

Significant ridge structure!

- 0-5% central PbPb 2.76 TeV
- \(p_T^{\text{trig}}\): 4 - 6 GeV/c
- \(p_T^{\text{assoc}}\): 2 - 4 GeV/c

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Dihadron correlations in CMS

PYTHIA8 pp simulation 2.76 TeV

0-5% central PbPb 2.76 TeV

Significant ridge structure!

\[ \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pair}}}{d\Delta \eta d\Delta \phi} \]

\[ p_T^{\text{trig}} : 4 - 6 \text{ GeV/c} \]
\[ p_T^{\text{assoc}} : 2 - 4 \text{ GeV/c} \]

arXiv:1105.2438
Ridge from higher-order flow harmonics

Long-range rapidity correlations ➔ early-time dynamics

Elliptic flow ($v_2$)

Fluctuating initial condition ➔ higher-order flow harmonics (e.g., triangular flow, $v_3$)

Add $V_{2\Delta}$ and $V_{3\Delta}$

"Shoulder"?

"Ridge"?

$\sim V_{2\Delta} \cos(2\Delta\phi)$

$\sim V_{3\Delta} \cos(3\Delta\phi)$

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Fourier analysis of $\Delta \phi$ correlations

Fourier decomposition:

$$\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} = \frac{N_{\text{assoc}}}{2\pi} \left( 1 + 2 \sum_{n=1}^{5} V_{n\Delta} \cos(n \Delta \phi) \right)$$

Short-range non-flow effects excluded!

Ridge structure exhausted by first 5 Fourier terms

For flow-driven correlations:

$$V_{n\Delta} = V_{n}^{\text{trig}} \times V_{n}^{\text{assoc}}$$
Fourier analysis of $\Delta \phi$ correlations

1-D $\Delta \phi$ projections at long-range ($2 < |\Delta \eta| < 4$)

$2 < p_T^{\text{assoc}} < 4 \text{ GeV/c}$

$2 < p_T^{\text{trig}} < 4 \text{ GeV/c}$

$4 < p_T^{\text{trig}} < 6 \text{ GeV/c}$

$6 < p_T^{\text{trig}} < 8 \text{ GeV/c}$

$8 < p_T^{\text{trig}} < 10 \text{ GeV/c}$

$10 < p_T^{\text{trig}} < 12 \text{ GeV/c}$

Ridge persists to high $p_T$ but decreases in magnitude
Fourier analysis of $\Delta \phi$ correlations

1-D $\Delta \phi$ projections at long-range ($2<|\Delta \eta|<4$)

$2 < p_T^{\text{assoc}} < 4 \text{ GeV/c}$

$p_T^{\text{trig}}$ projection for $2 < p_T^{\text{trig}} < 4 \text{ GeV/c}$

Ridge persists to high $p_T$ but decreases in magnitude

Extracted Fourier coefficients $V_{n\Delta}$
Centrality dependence in PbPb

$p_{T}^{\text{trig}} : 4 - 6 \text{ GeV/c}$

$p_{T}^{\text{assoc}} : 2 - 4 \text{ GeV/c}$

PbPb 2.76 TeV

CMS Preliminary

Centrality dependence in PbPb

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Flow harmonics ($v_n$) from the ridge

If assume factorization:

$$v_n^{\text{trig}} = \frac{V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}})}{\sqrt{V_{n\Delta}(p_T^{\text{assoc}}, p_T^{\text{assoc}})}}$$

Consistent results with other flow methods (EP, cumulant, LYZ)

Keep low $p_T^{\text{assoc}}$ (1-2 GeV/c) to minimize non-flow effects

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PbPb $\sqrt{s_{NN}} = 2.76$ TeV

$\int L \, dt = 3.1 \mu b^{-1}$

CMS PAS HIN-11-006
Flow harmonics \( (v_n) \) from the ridge

If assume factorization:

\[
v_n^{\text{trig}} = \frac{V_n \Delta (p_T^{\text{trig}}, p_T^{\text{assoc}})}{\sqrt{V_n \Delta (p_T^{\text{assoc}}, p_T^{\text{assoc}})}}
\]

Off-diagonal terms

Diagonal terms

Keep low \( p_T^{\text{assoc}} \) (1-2 GeV/c) to minimize non-flow effects

Consistent results with other flow methods (EP, cumulant, LYZ)
Ridge in high multiplicity pp

1 < \( p_T^{\text{trig}} \), \( p_T^{\text{assoc}} \) < 3 GeV/c

Unexpected “ridge-like” structure in pp

\[ R(\Delta \eta, \Delta \phi) = \left( \frac{N-1}{B(\Delta \eta, \Delta \phi)} \right)^n \]

High multiplicity pp (\( N \geq 110 \))

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Interpretations of the ridge in pp

Jet-induced ridge

Jet-Jet color connections
Jet-proton remnant color connections
Jet-string momentum kick

Persist up to high $p_T$ tracks or jets?

Ridge is aligned with jets in $\phi$

Glasma tube

Maximal for $p_T^{\text{trig}} = p_T^{\text{assoc}}$

Hydrodynamic flow

Ridge is random with jets in $\phi$

Ridge may go away at high $p_T$
Ridge in high multiplicity pp

Updated new results: (full 2010 dataset!)

CMS PAS HIN-11-006

100 billion (1.78 pb⁻¹) sampled minimum bias events

No ridge for higher $p_T$ particles!
Ridge in high multiplicity pp

Zero-Yield-At-Minimum (ZYAM)

Direct Fourier analysis is hard due to away-side jet peak

Ridge region (2<|Δη|<4)

Effect turns on at $N \sim 4 \times <N>_{\text{minbias}}$

Rise and fall of the ridge with $p_T^{\text{trig}}$

CMS PAS HIN-11-006

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$pp \sqrt{s} = 7 \text{ TeV}, N \geq 110$

$2 < |\Delta \eta| < 4$

$1 < p_T^{\text{assoc}} < 2 \text{ GeV/c}$

$2 < |\Delta \eta| < 4$

$2 < p_T^{\text{trig}} < 3 \text{ GeV/c}$

$1 < p_T^{\text{assoc}} < 2 \text{ GeV/c}$

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Summary

Unique capability of studying short-range and long-range correlations in pp and PbPb at CMS

Studies of dihadron correlations in PbPb

- Ridge can be described by higher-order flow ($v_n$)
- $v_n$ extracted from a Fourier analysis of long-range correlations as a function of $p_T$ and centrality
- Support a picture of fluctuating initial condition

Observation of the ridge in high multiplicity pp

- New phenomena in pp physics
- Intriguing similarity to the ridge in heavy-ion collisions
- Exciting new direction in high-density QCD physics!
Trigger on High Multiplicity pp

**CMS trigger and DAQ**

**Level-1:**
\[ \sum E_T > 60 \text{ GeV} \]
in calorimeters

**High-Level trigger:**
number of tracks with \( p_T > 0.4 \text{ GeV/c} \), \(|h|<2\) from a single vertex

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1-D projected $R(\Delta \phi)$ at large $\Delta \eta$

Increasing $p_T$

- $0.1 \text{GeV/c} < p_T < 1.0 \text{GeV/c}$
- $1.0 \text{GeV/c} < p_T < 2.0 \text{GeV/c}$
- $2.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c}$
- $3.0 \text{GeV/c} < p_T < 4.0 \text{GeV/c}$

Increasing multiplicity

$N < 35$

$35 < N < 90$

$90 < N < 110$

$N > 110$
Like-sign (++,--) and unlike-sign (+-) pair correlations:

No charge sign dependence of the ridge!
Comparing to various MC

(a) MinBias, $p_T > 0.1\text{GeV/c}$

(b) MinBias, $1.0\text{GeV/c} < p_T < 3.0\text{GeV/c}$

(c) $N > 110, p_T > 0.1\text{GeV/c}$

(d) $N > 110, 1.0\text{GeV/c} < p_T < 3.0\text{GeV/c}$

PYTHIA8, v8.135
More MC models

PYTHIA D6T MinBias, $N>70$

PYTHIA D6T, Dijet 80-120GeV

HERWIG++, $N>110$

Madgraph, Dijet 100-250GeV, $N>90$
Cross check: ECAL Photons

Charged hadron - photon correlations
(photons are mostly from $\pi^0$ decay)

$1.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c}$
for both hadrons and photons

Independent detector, independent reconstruction!
Cross check: ECAL Photons

**photon - photon correlations**

(photons are mostly from $\pi^0$ decay)

$1.0 \text{GeV}/c < p_T < 3.0 \text{GeV}/c$

Independent detector, independent reconstruction!
$\sqrt{s} = 7\text{ TeV}, N \geq 110$

$2 < p_T^{\text{trig}} < 3\text{ GeV/c}$
$1 < p_T^{\text{assoc}} < 2\text{ GeV/c}$

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$\frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pair}}}{d\Delta\eta \ d\Delta\phi}$

$N_{\text{trig}}$

$\Delta\phi$

$\Delta\eta$

$2$

$0$

$-2$

$-4$

$4$

$2$

$0$

$-2$

$-4$

$4$

$3.5$

$3.0$

$2.5$

$2.0$

$1.5$

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$5 < p_T^{\text{trig}} < 6\text{ GeV/c}$
$1 < p_T^{\text{assoc}} < 2\text{ GeV/c}$
Δφ projections in various p_T ranges

CMS pp 7 TeV, N ≥ 110

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High multiplicity pp collisions

See talk by Dragos Velicanu
(05/23, 3:00pm)

Very high particle density regime
Is there anything interesting happening?

~350K top multiplicity events (N>110) out of 50 billion collisions!

Dedicated triggers on high multiplicity events from a single collisions (not pileup!)

N_{\text{online}} > 85 trigger un-prescaled for full 980nb^{-1} data set

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Ridge in pp and PbPb

CMS pp 7 TeV, \( N \geq 110 \)

CMS PbPb 2.76 TeV, 0-5%

CMS \( \int L = 3.1 \mu b^{-1} \)
Flow harmonics \((v_n)\) from the ridge

Centrality dependence of \(v_n\) follows expectation from hydrodynamics (initial geometry and its fluctuation)

Further systematic tests of \(V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}})\) factorization

- Disentangle flow and non-flow correlations
- Study jet-medium interactions (after flow subtraction)