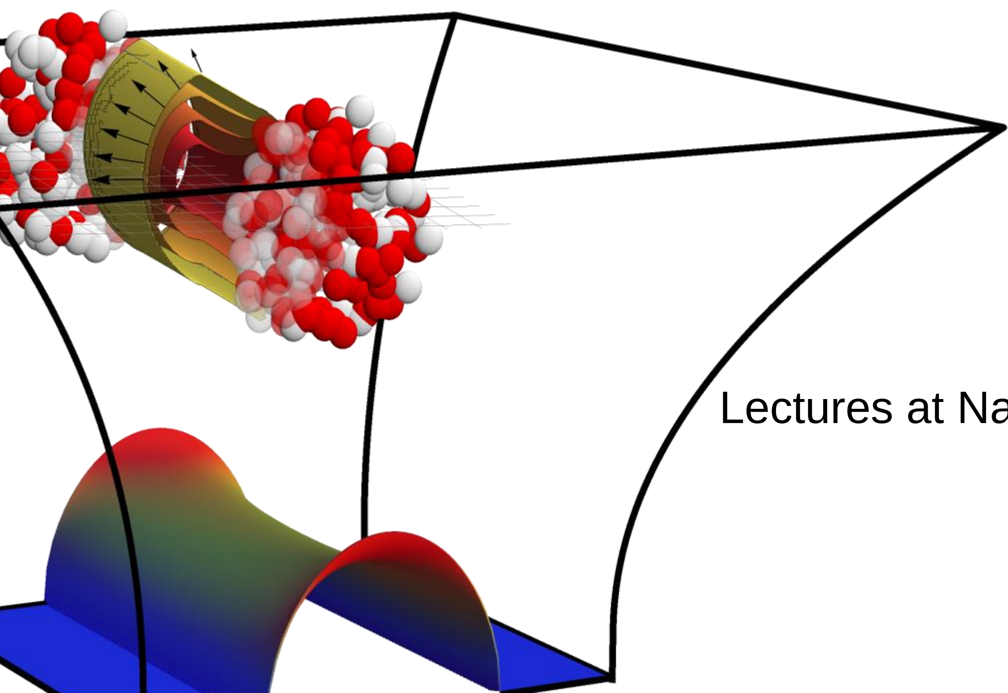
QUARK-GLUON PLASMA

HOT QCD, FLOWING PLASMA, JETS AND A TINY BIT OF STRING THEORY



Wilke van der Schee

Lectures at National Nuclear Physics Summer School,
MIT, 25 July 2016

OUTLINE

First lecture

- Heavy ion collisions, forming quark-gluon plasma
    - “the ridge” and particle spectra
- The standard model of heavy ion collisions
    - Initial dynamics (second)
    - Relativistic hydrodynamics (first)
    - Freeze-out / hadronic rescattering (not covered)

Second lecture

- Jets as probes of the medium
    - Internal jet structure
- The challenge: strong interactions, a bit of string theory

WHY DO WE STUDY QGP?

Quark gluon plasma in the early universe

- Heavy ion collisions, forming quark-gluon plasma
- Also: heavy ion collisions full of surprises ☺

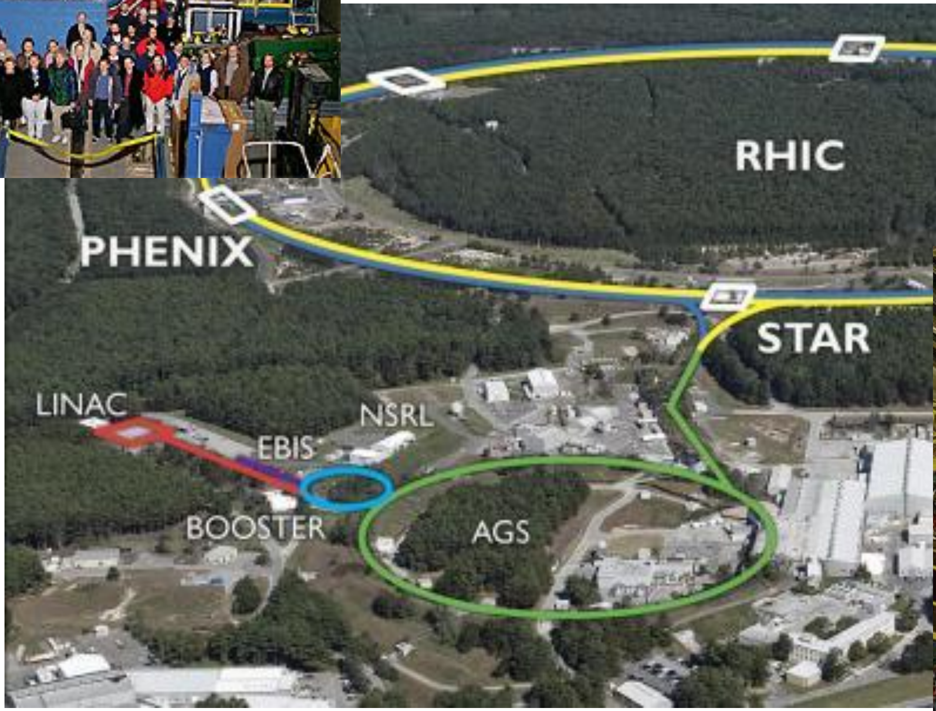
Strong force – Quantum Chromo Dynamics

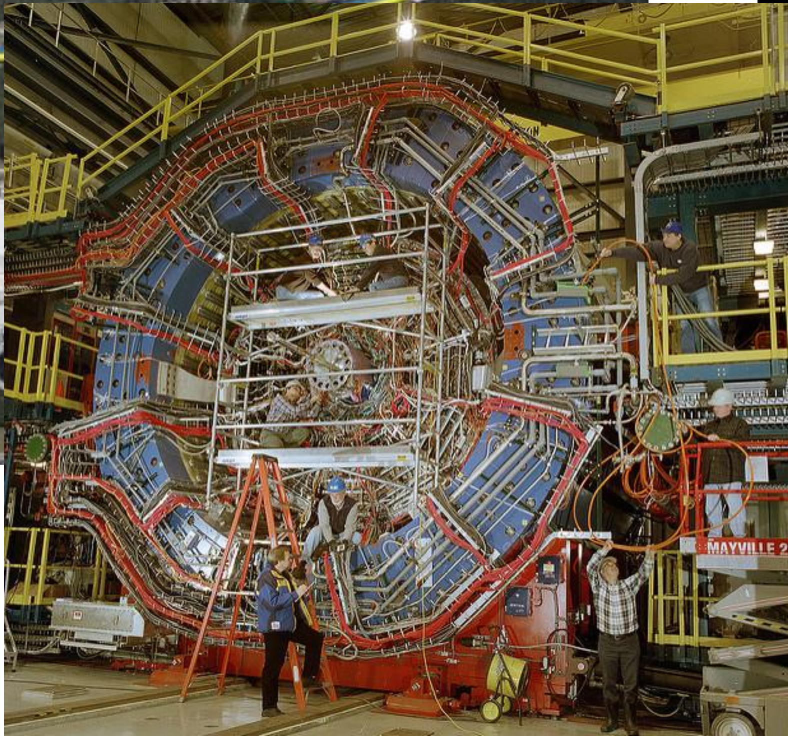
- No doubt about underlying Lagrangian and perturbative QCD
- But QCD non-perturbative and lattice is limited (Euclidean)
- Recent: perhaps insights in structure proton?

Strongly interacting quantum matter

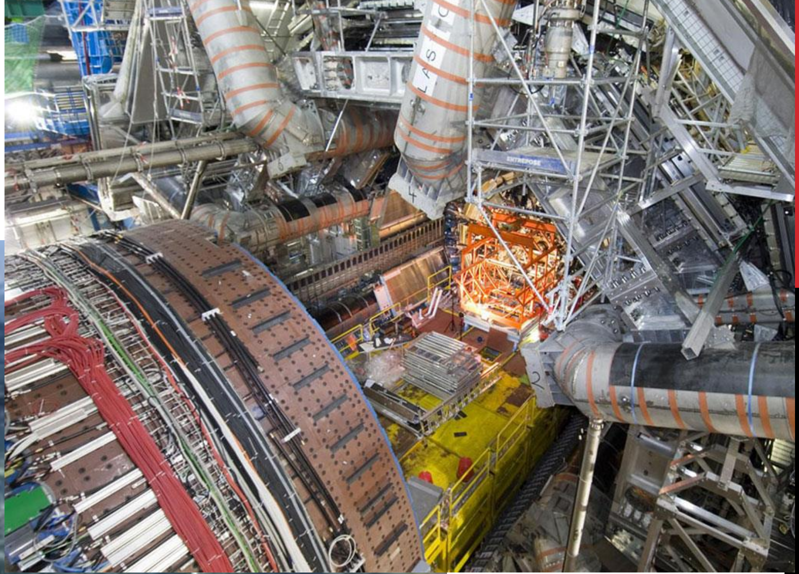
- QGP may be one of cleanest systems of quantum matter
- Interesting properties: low viscosity, fast thermalization
- Even connections to high temperature superconductors??

WHERE DO WE STUDY QGP? RHIC

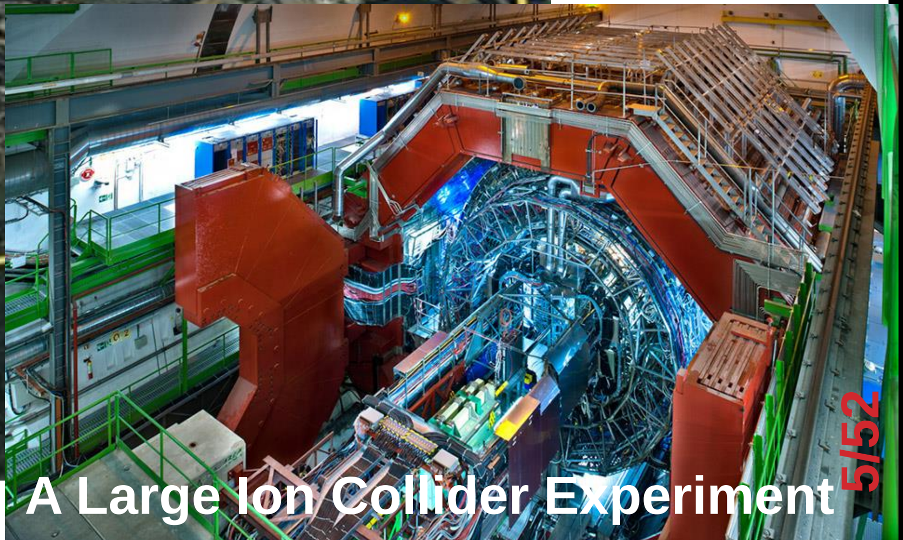




WHERE DO WE STUDY QGP? LHC



(1/12 months)



WHERE DO WE STUDY QGP?

Different energies

- RHIC: from 3.5 – 100 GeV per nucleon, i.e. top energy $\sqrt{s_{NN}}$ = 200 GeV
- LHC: $\sqrt{s_{NN}}$ 2.76 and 5.02 TeV for Pb-Pb and 5.02 TeV for p-Pb

Exercise: explain these numbers from pp collisions (7, 8 and 13 TeV)

Exercise: what is the transverse and longitudinal size? (Pb radius ~ 6.7 fm)

Different ions

- RHIC: wide variety, d^3, Cu^{64}, Au^{197}, also He^3, $Uranium^{238}$ (funny shapes)
- LHC: mostly Pb^{208}
- Also interesting: asymmetric collisions, i.e. d-Au or p-Pb

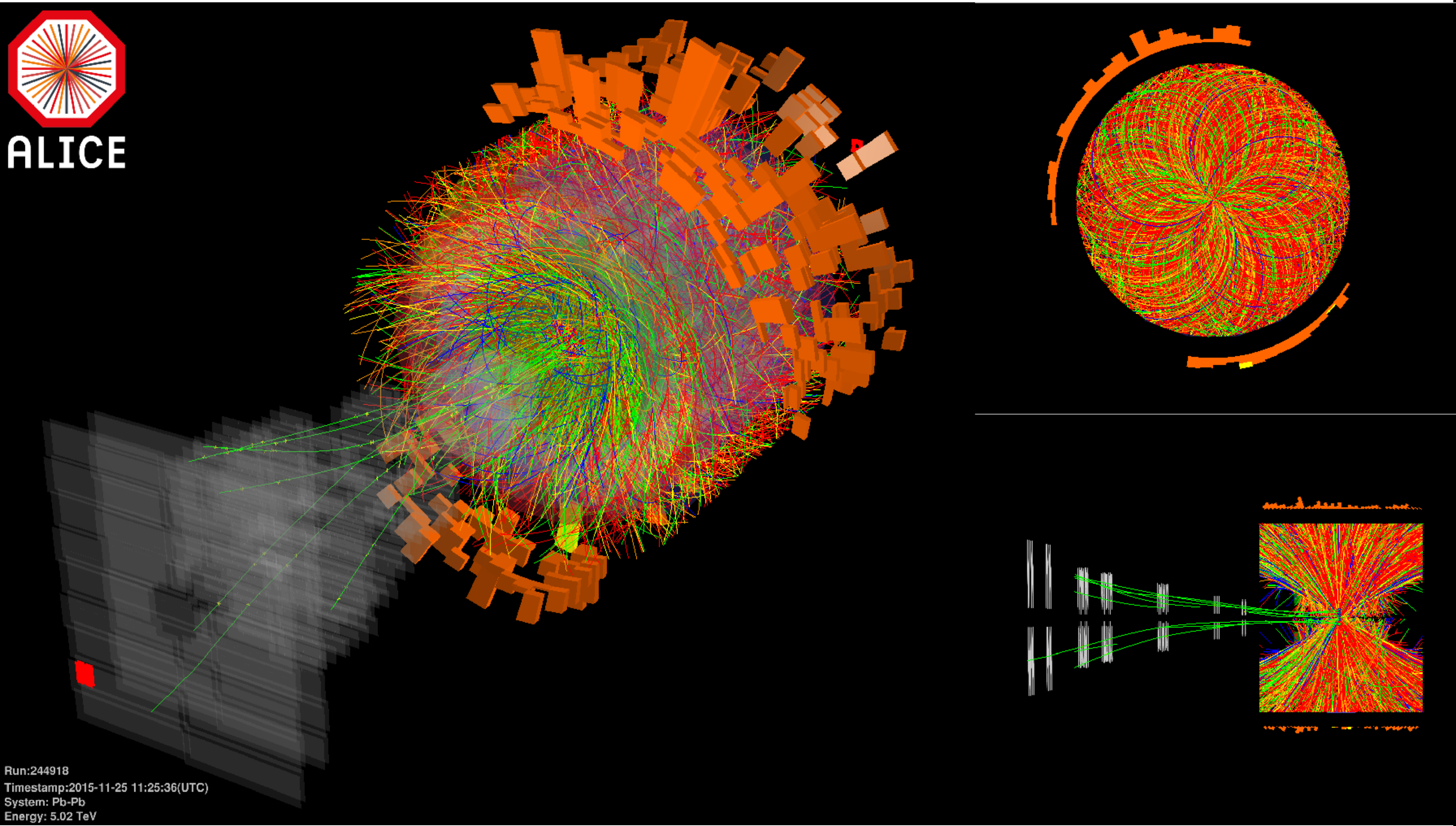
Different observables

- QGP maybe one of cleanest systems of quantum matter
- Interesting properties: low viscosity, fast thermalization
- Even connections to high temperature superconductors??

Wilke van der Schee, MIT

HOW DO WE STUDY QGP?

We only see resulting particles



QGP IS ALSO COOL! (OR HOT..)

As close to big bang as we can get (about a millisecond)

- Temperatures: $4x10^{12}$ ºK or $7x10^{12}$ ºF (100.000 hotter than interior sun)
- Lifetime: $7x10^{-23}$ s, size $20x10^{-15}$ m
- Accelerations: 10^{31} *g*

QGP may behave much like a black hole horizon

- A fluid-like horizon, in 4+1 dimensions, later more…

One unfortunate fact

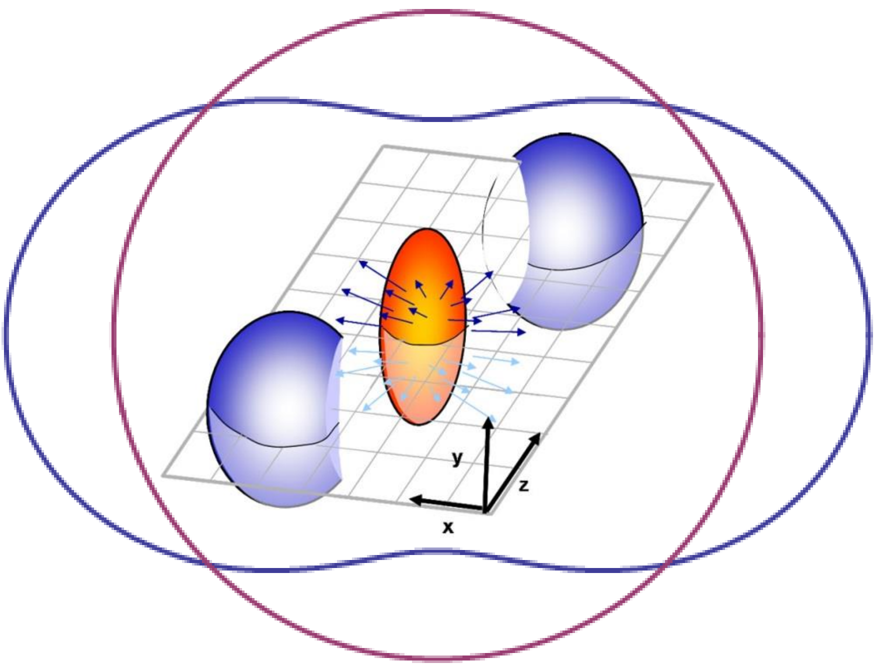
- QGP is hottest man-made plasma
- Unfortunately cosmic rays have higher $\sqrt{s_{NN}}$ and are hence even hotter

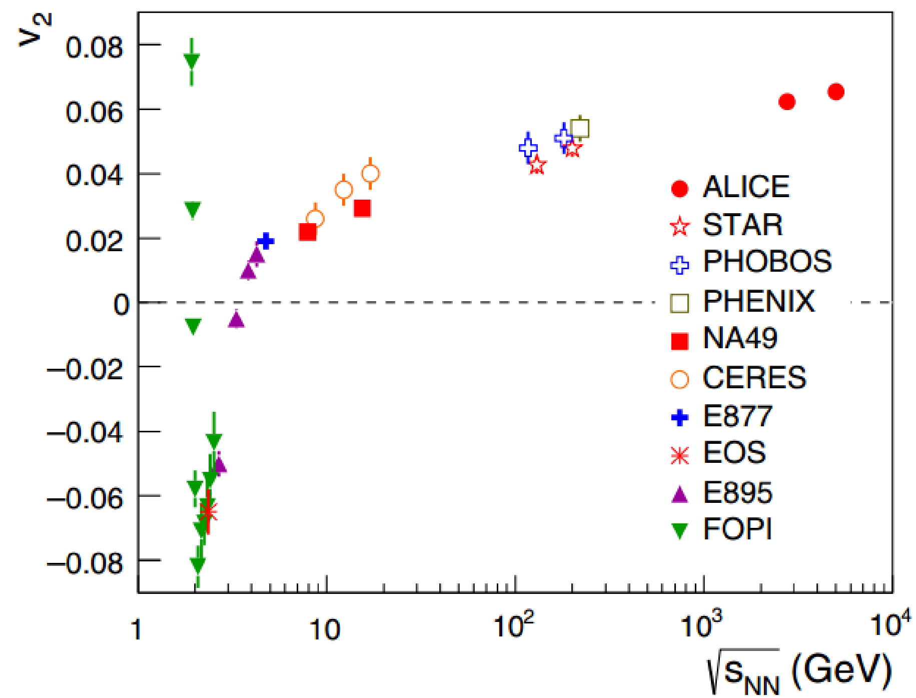
Figure ESA

ELLIPTIC FLOW: V_2, QGP IS INTERESTING

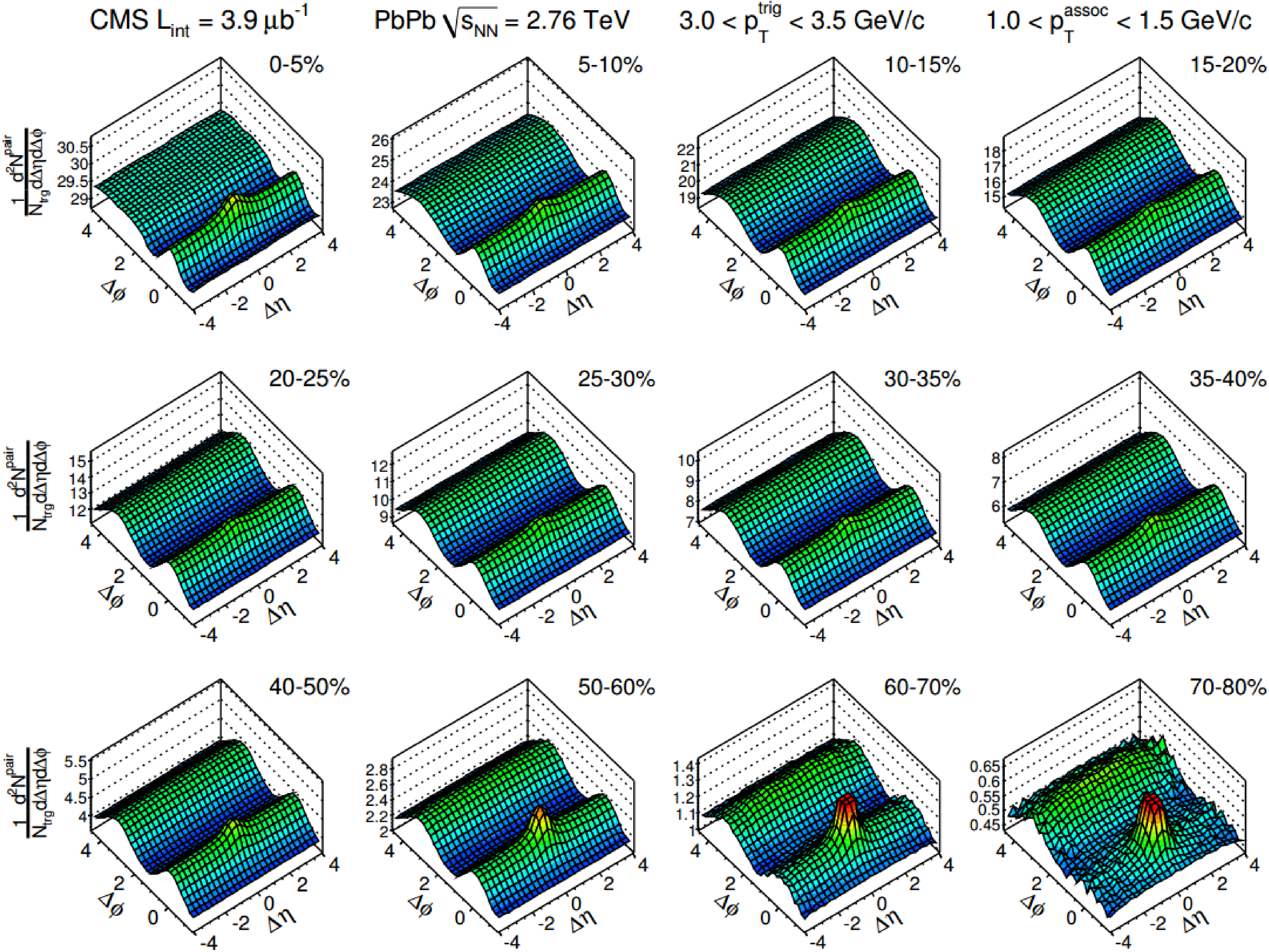
How anisotropic is the final state?

- Ideal gas/weak coupling
- Perfect fluid/strong coupling





K. Aamodt et al, Anisotropic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}}$=5.02 TeV (2016)



CMS L_{int} = 3.9 μb^{-1}
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
3.0 < p_T^{trig} < 3.5 GeV/c
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0-5%
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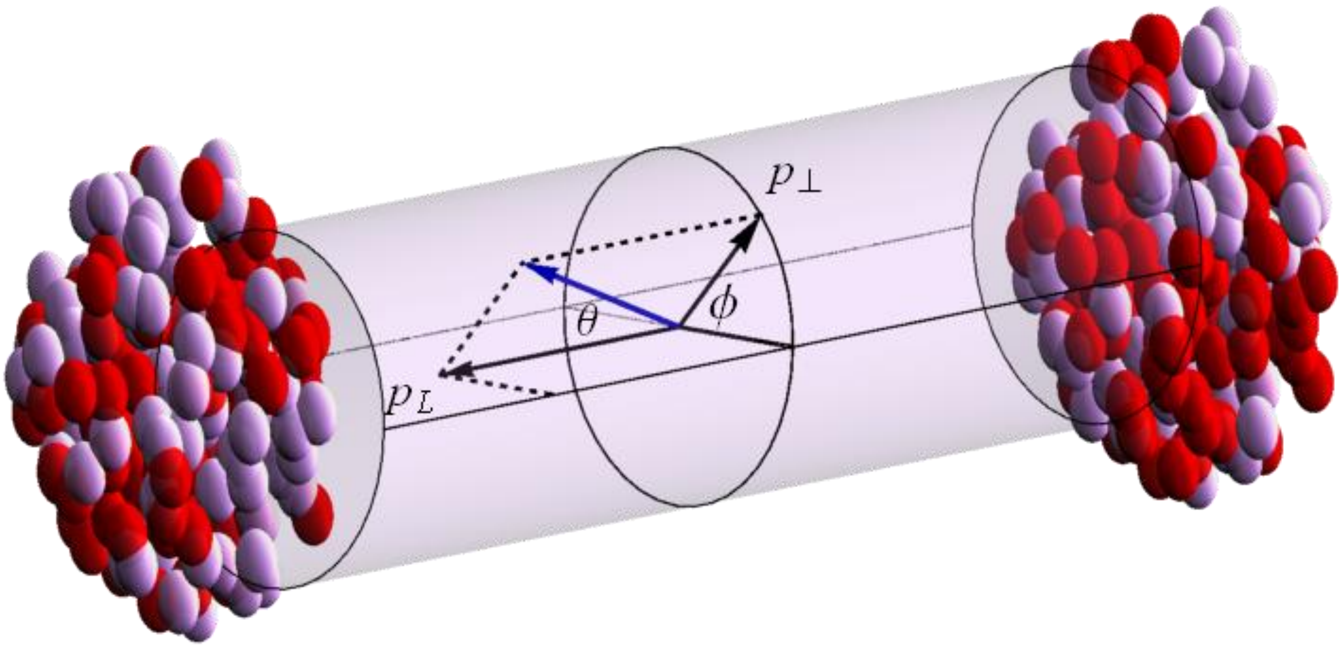
35-40%
40-50%
50-60%
60-70%
70-80%
$\frac{1}{N_{trg}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi}$
Δφ
Δη

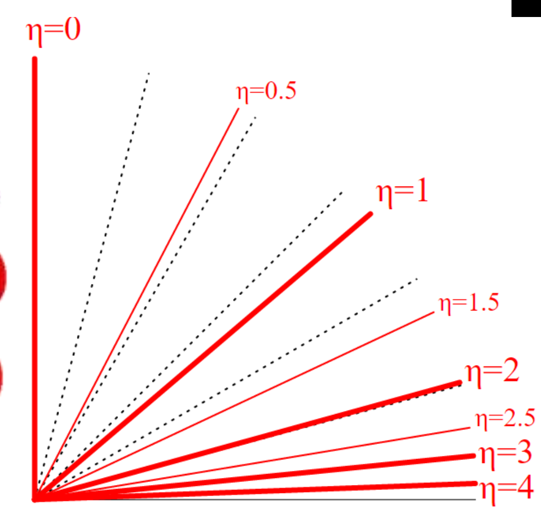
(PSEUDO)RAPIDITY

Transverse and longitudinal dynamics

- Note distinction between space and momentum rapidity
- Boost invariance: no y-dependence Bjorken symmetry, simplest model for expanding plasma

$$
\begin{aligned}
t &= \tau \cosh(y_s) \\
z &= \tau \sinh(y_s) \\
E &= m \cosh(y_p) = \gamma m \\
|\mathbf{p}| \text{ or } p_L &= m \sinh(y_p) = \gamma m v \\
y_p &= \tanh^{-1}\left(\frac{p_L}{E}\right) \\
\eta_p &= \tanh^{-1}\left(\frac{p_L}{|\mathbf{p}|}\right) \\
&= -\log(\tan(\theta/2))
\end{aligned}
$$



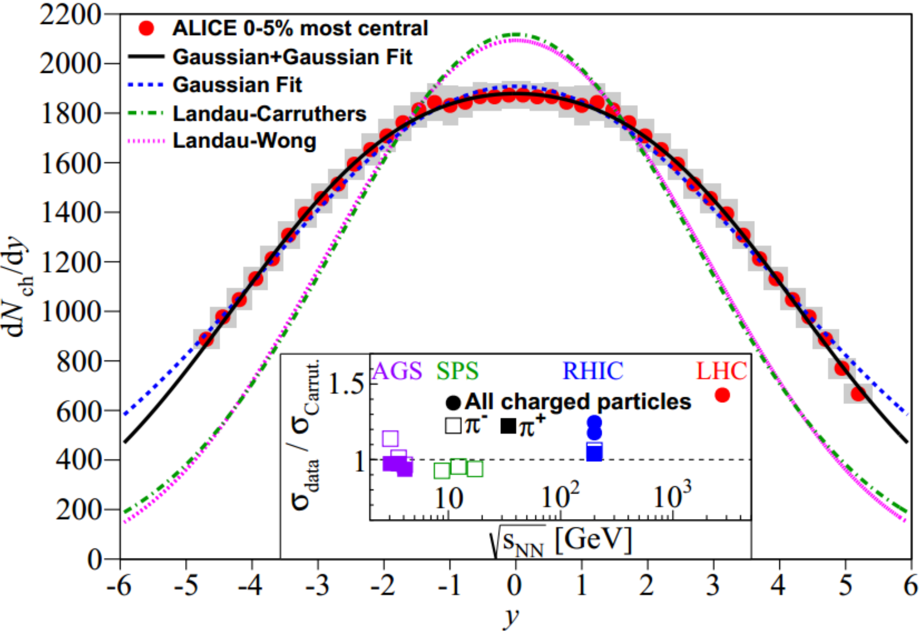


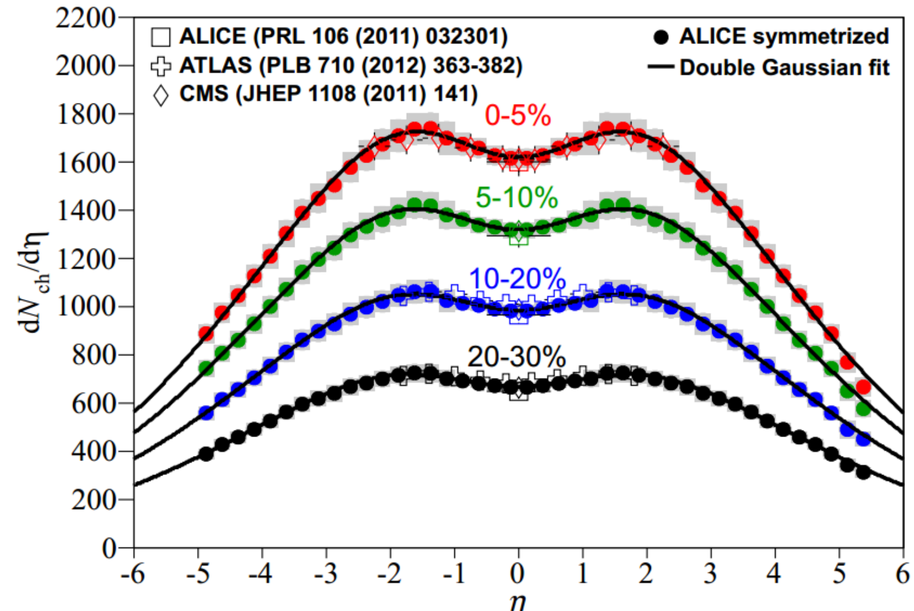
Exercise: ALICE measures up to η=5.1, 4cm from beam, how big is the detector?

RAPIDITY VERSUS PSEUDO-RAPIDITY

Longitudinal particle spectrum

- No real boost invariance: rapidity dependence Gaussian width (~ 2 at RHIC, ~3 at LHC), with Jacobian depending on mass
- Theorists prefer y, experimentalists η



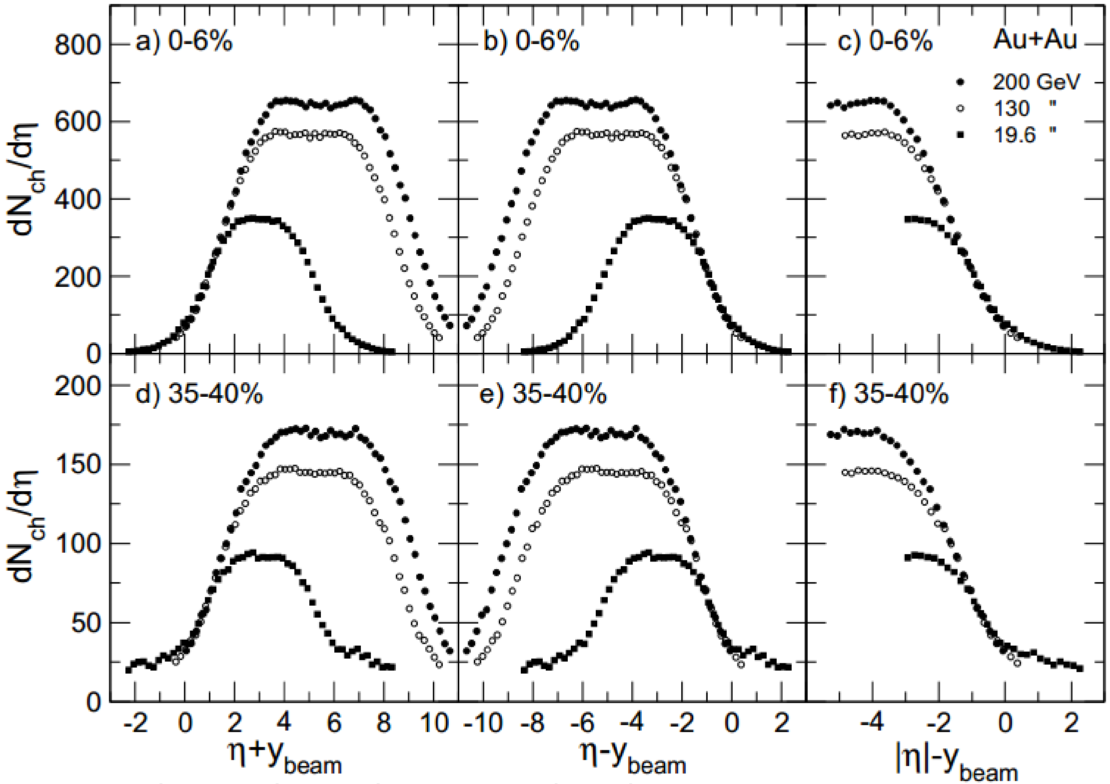


ALICE, Centrality dependence of the pseudorapidity distribution for charged particles in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (2013)

RAPIDITY SPECTRUM AT RHIC

Longitudinal particle spectrum at 19.6, 130 and 200 GeV

- Spectrum gets wider at higher energies
- Coincidence: pseudo-rapidity very flat at top RHIC energies
- Interesting: as a function of $\eta+y_{beam}$ they collapse (limiting fragmentation, related to saturation (?))



PHOBOS, The PHOBOS Perspective on Discoveries at RHIC (2004)

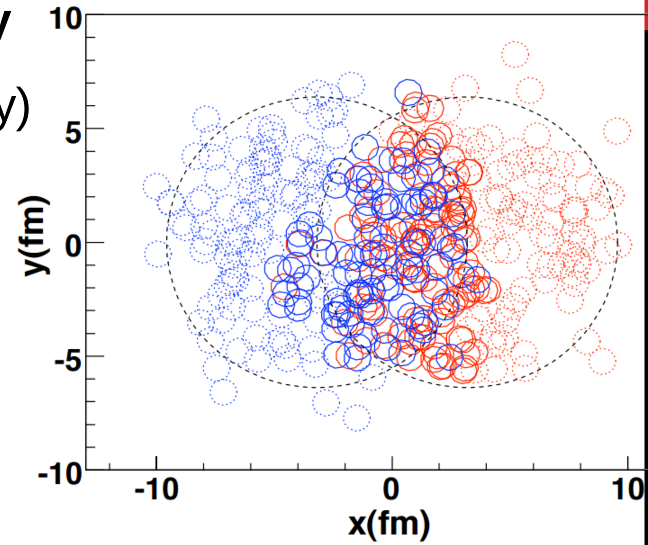
CENTRALITY

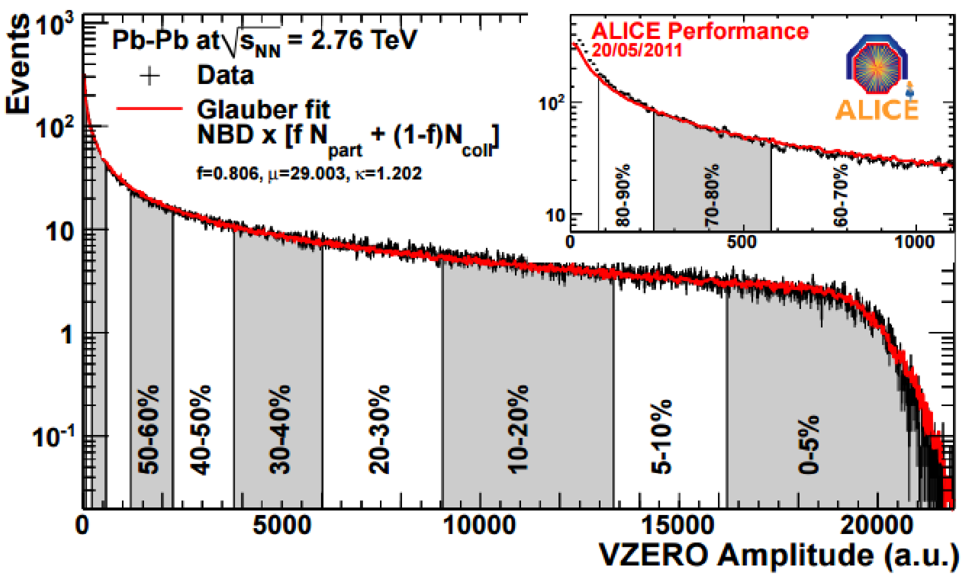
Ions collide with an impact parameter *b*: centrality

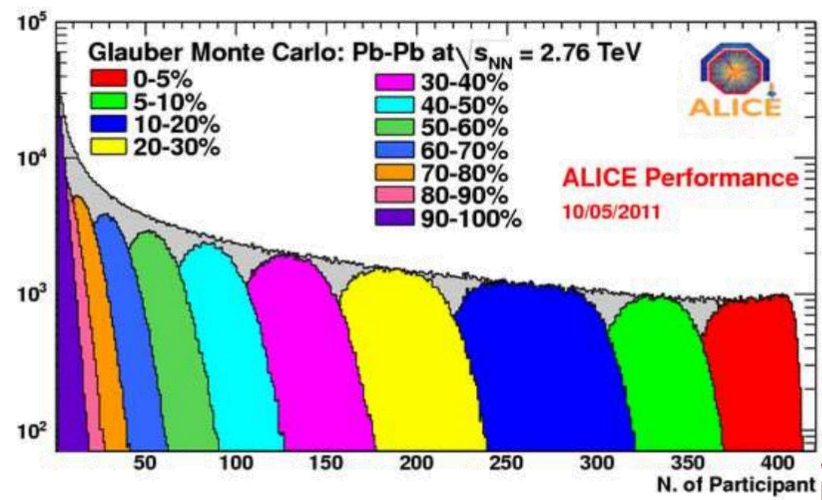
- 0% is head on: highest multiplicity (at mid-rapidity)
- >50% peripheral: skimming ions

Related to number of participants/spectators

- Estimate by Monte Carlo Glauber
- Subtleties defining centrality (especially in p-Pb)

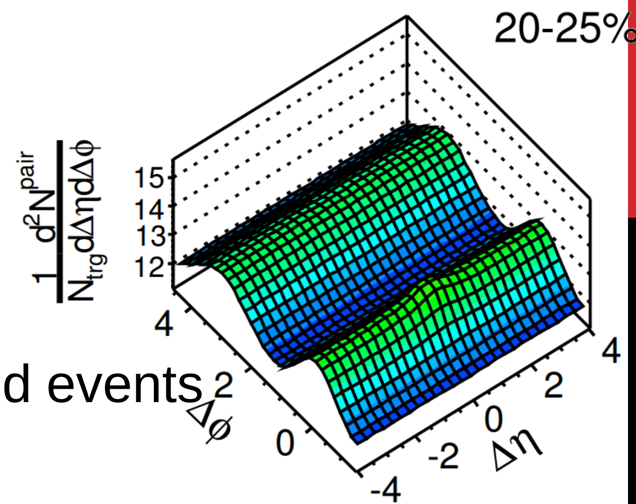






ALICE, Centrality determination of Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (2013)
B. Alver, M. Baker, C. Loizides and P. Steinberg, The PHOBOS Glauber Monte Carlo (2008)

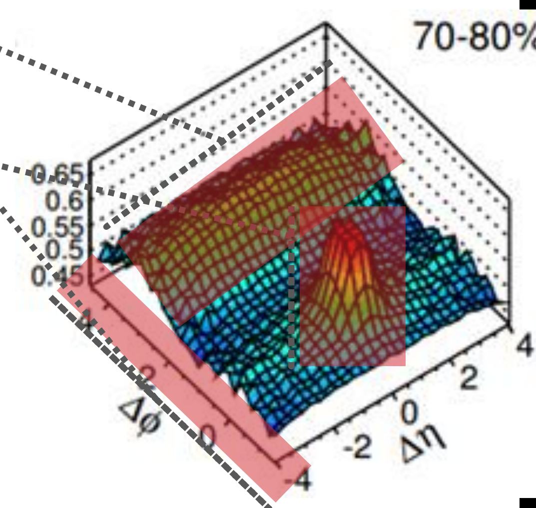
‘THE RIDGE’



Two particle correlator

- Trigger particle and response particle
- Compare particles in same event versus mixed events (to avoid detector effects)
- `jet’ contribution, transverse momentum conservation

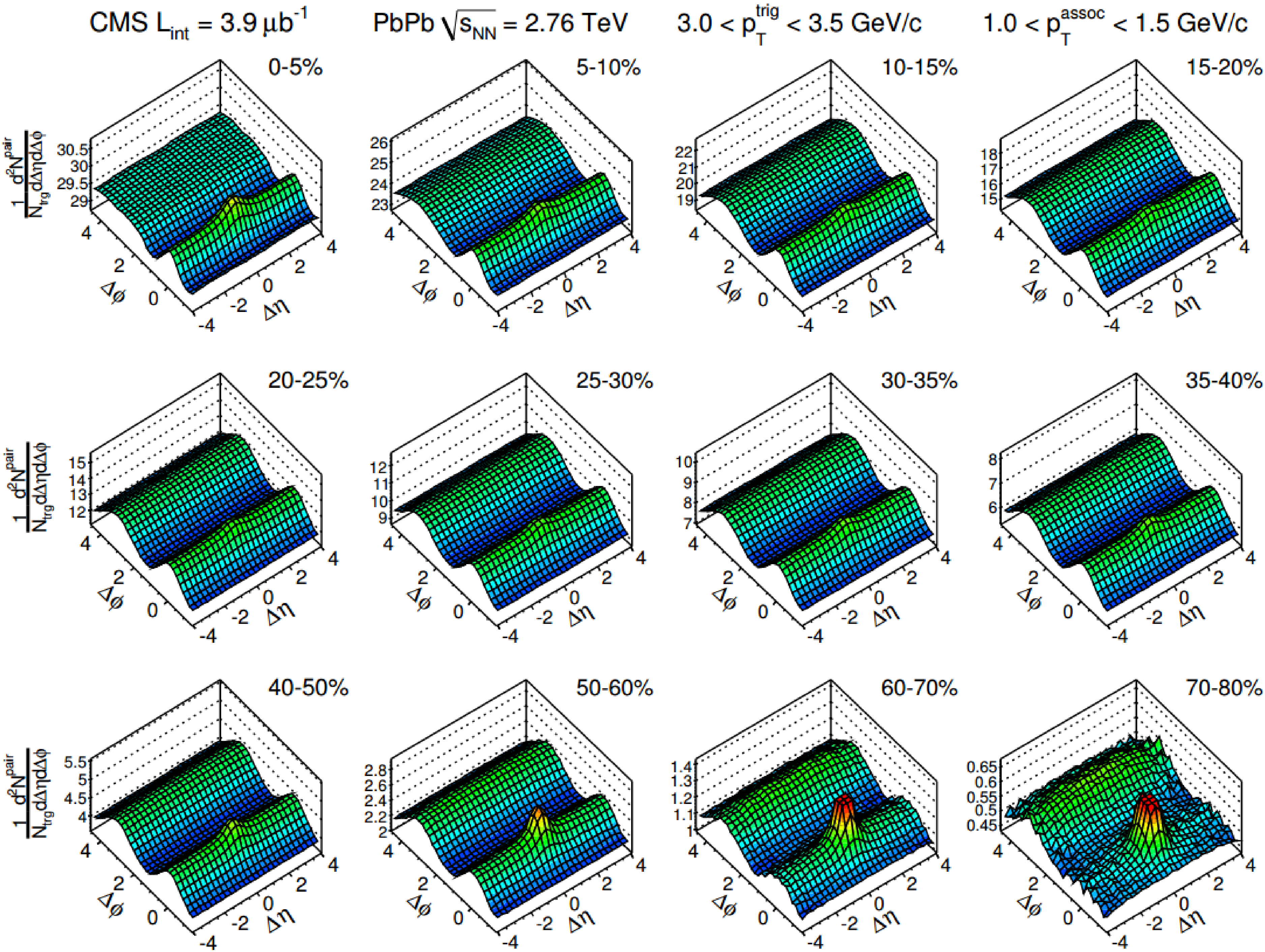
$$\frac{1}{N_{\rm trig}}\frac{{\rm d}^2N^{\rm pair}}{{\rm d}\Delta\eta\,{\rm d}\Delta\phi} = B(0,0)\times\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)},$$



$$S(\Delta\eta,\Delta\phi) = \frac{1}{N_{\rm trig}}\frac{{\rm d}^2N^{\rm same}}{{\rm d}\Delta\eta\,{\rm d}\Delta\phi}$$

$$B(\Delta\eta,\Delta\phi) = \frac{1}{N_{\rm trig}}\frac{{\rm d}^2N^{\rm mix}}{{\rm d}\Delta\eta\,{\rm d}\Delta\phi}$$

CMS, Centrality dependence of dihadron azimuthal anisotropy harmonics in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV



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Δφ
Δη

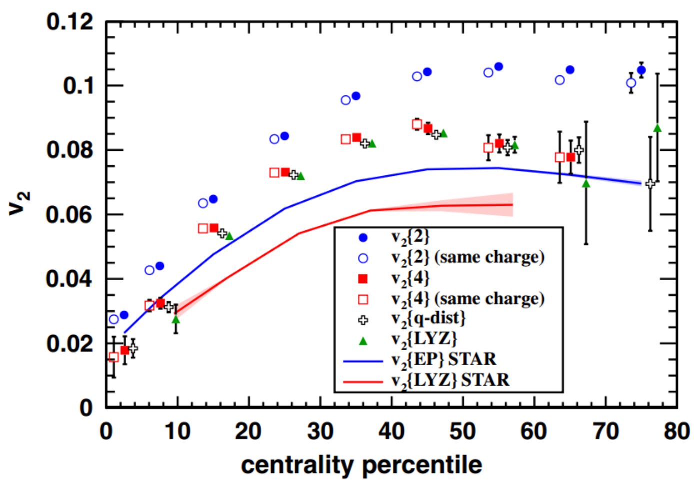
'THE RIDGE'

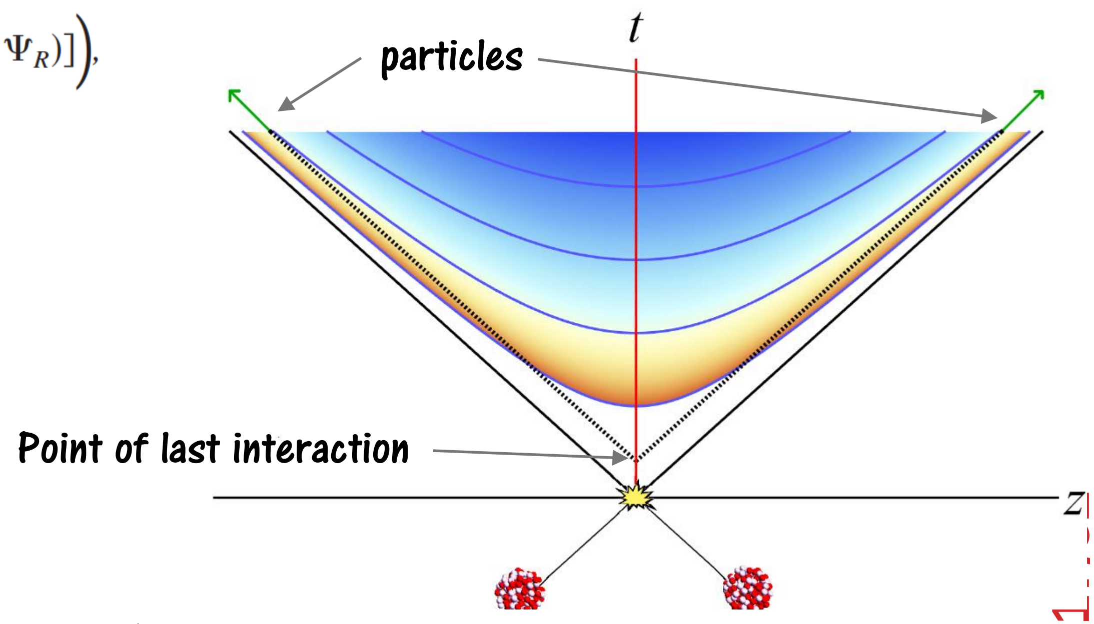
exclude short range `jet': $|\Delta\eta| > 2$

More fun: average over Δη to extract `flow'

- Quantifies response to initial correlations (causality)
  - Natural explanation is hydrodynamics (more later)
- Also causality in transverse plane
  - Centrality dependence of v_2 is convincing for hydrodynamics

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_R)]\right),$$





ALICE, Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}}$=2.76 TeV (2016)

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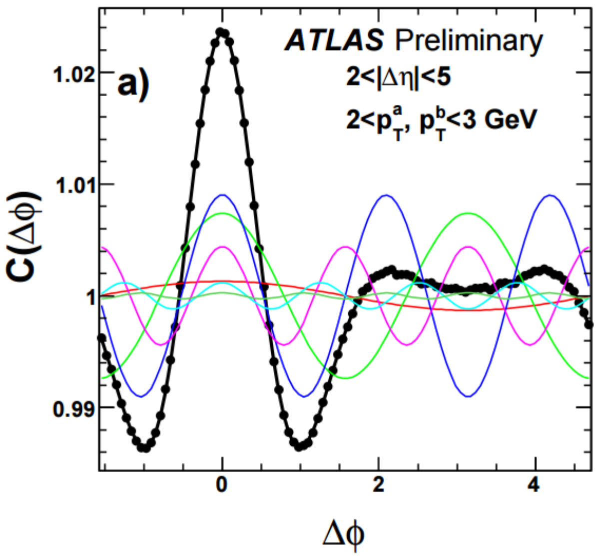
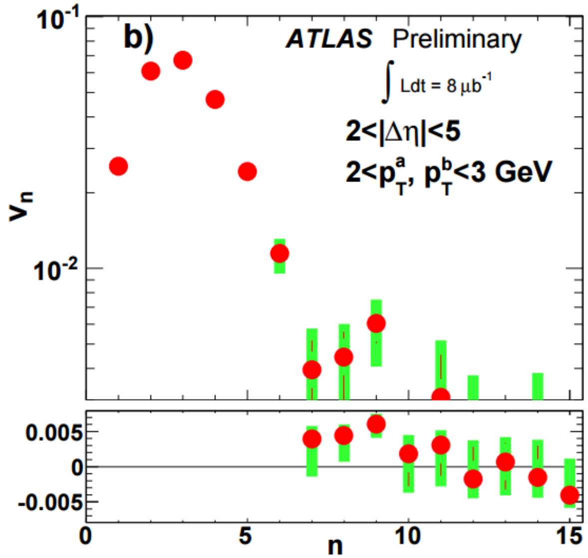




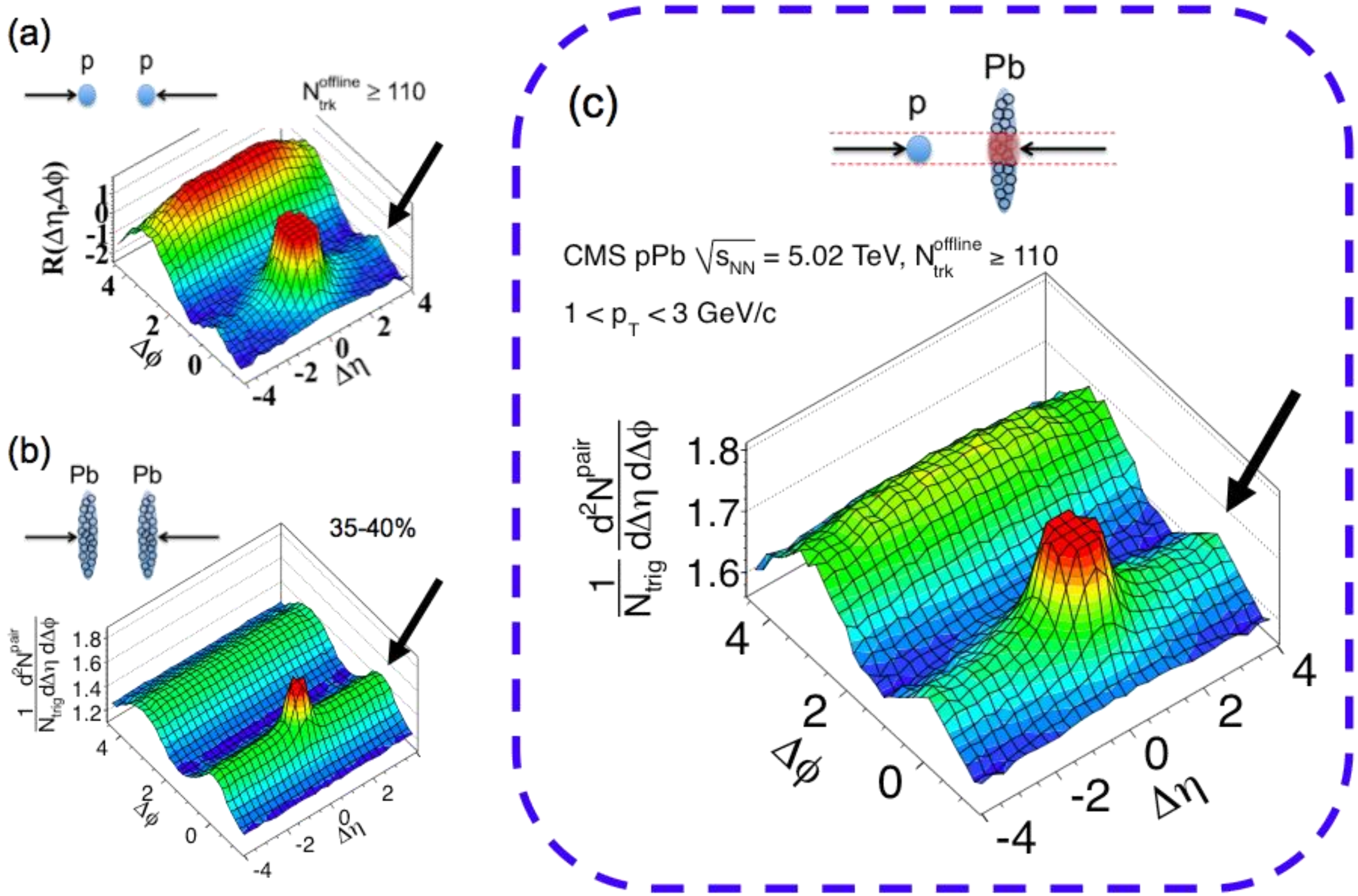
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_R)]\right),$$

ATLAS, Measurement of elliptic and higher order flow from ATLAS experiment at the LHC (2011)

'THE RIDGE'

Preview of small systems, recent excitement

- Ridge also seen in p-Pb *and* p-p (at high multiplicity? – spoiler)



CMS, Centrality dependence of dihadron azimuthal anisotropy harmonics in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

'THE RIDGE'

More fun: average over 4, 6 or 8 particle correlation to get `flow'

- Technique to remove short range correlation (i.e. momentum)
- Typical expectation weak coupling: weaker correlations
- Typical expectation hydro/strong coupling: `constant' correlations

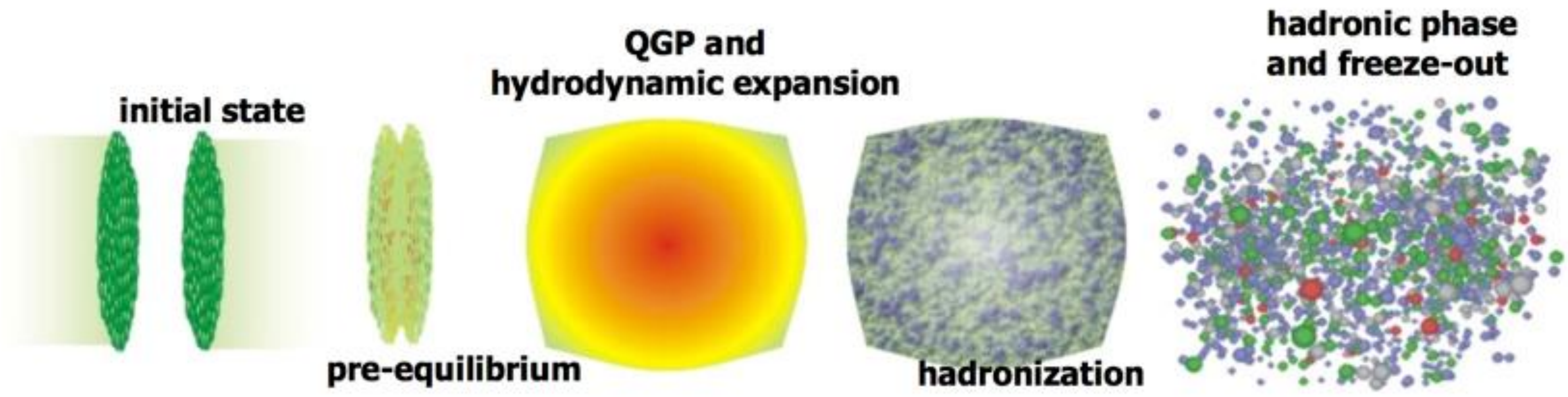
More non-trivial checks:

- Mass-ordering of pions/kaons/protons elliptic flow versus p_t
- Particles produced according to Boltzmann-distribution (more later)

THEORETICAL DESCRIPTION

Standard model of heavy ion collisions

- Will start with hydrodynamics
- Later: initial pre-equilibrium stage



RELATIVISTIC HYDRODYNAMICS

Hydrodynamics is a gradient expansion

- Start with homogeneous thermal state moving at constant v
- Promote temperature and velocity to field, assuming small variations

Evolution

- Equations of motion are conservation equations
- Extra input is equation of state and transport coefficients
- In real life: use 2nd order hydrodynamics (causal)

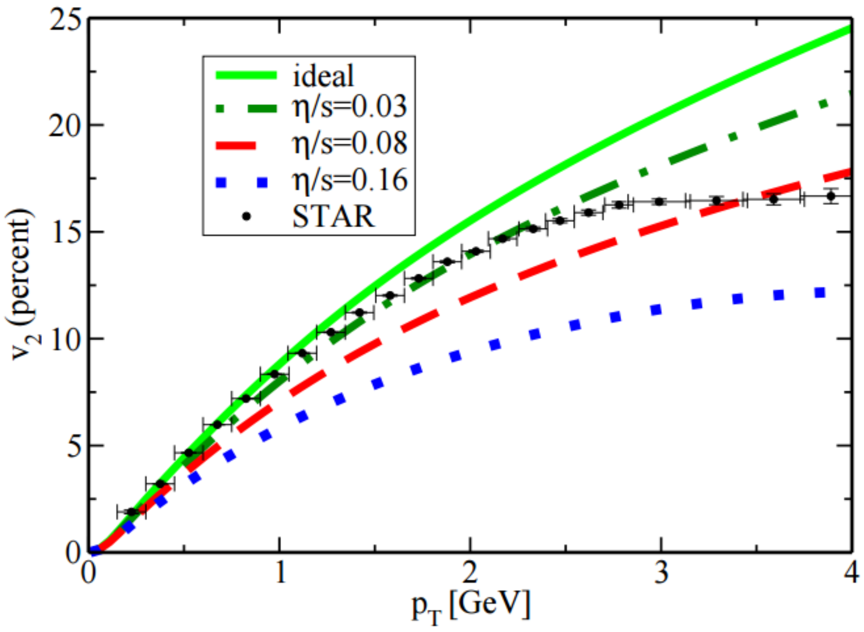
$$\begin{aligned}
T_{\mu\nu} &= e\, u_\mu u_\nu + p[e]\Delta_{\mu\nu} + \pi_{\mu\nu}, \ \text{where,} \\
\Delta_{\mu\nu} &= g_{\mu\nu} + u_\mu u_\nu \ \text{and} \\
\pi_{\mu\nu} &= -\eta[e]\,\sigma_{\mu\nu} - \zeta[e]\,\Delta_{\mu\nu}(\nabla\cdot u) + \mathcal{O}(\partial^2), \ \text{with} \\
\sigma_{\mu\nu} &= \Delta_{\mu\alpha}\Delta_{\nu\beta}(\nabla^\alpha u^\beta + \nabla^\beta u^\alpha) - \frac{2}{d-1}\Delta_{\mu\nu}\Delta_{\alpha\beta}\nabla^\alpha u^\beta,
\end{aligned}$$

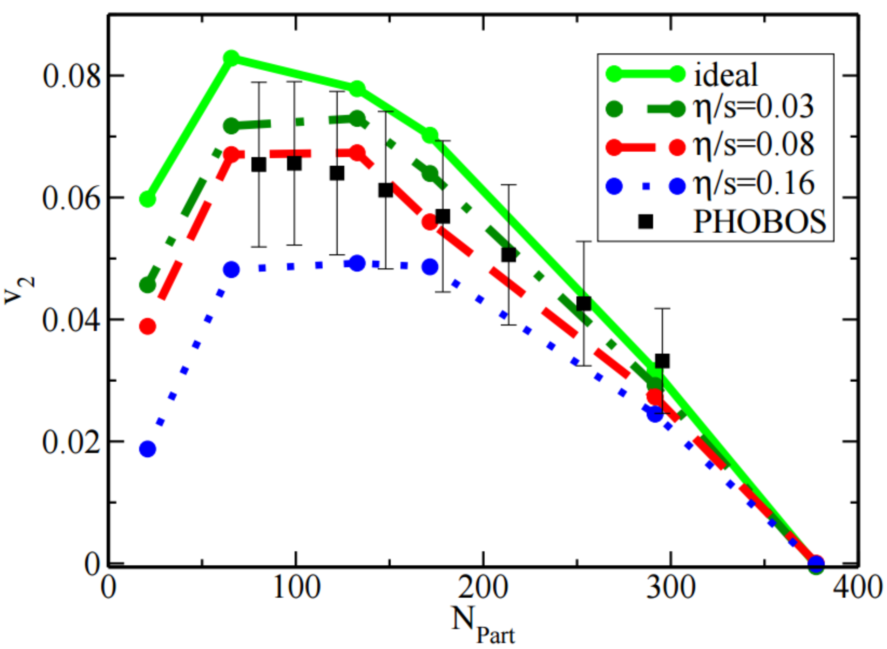
R. Baier, P. Romatschke and D. T. Son, A. Starinets and M. Stephanov, Relativistic viscous hydrodynamics, conformal invariance, and holography (2007)

RELATIVISTIC HYDRODYNAMICS

Hydrodynamic simulations

- Need initial conditions: simple Wood-Saxon shape of nucleus
- Has involved a lot of fitting in the past…



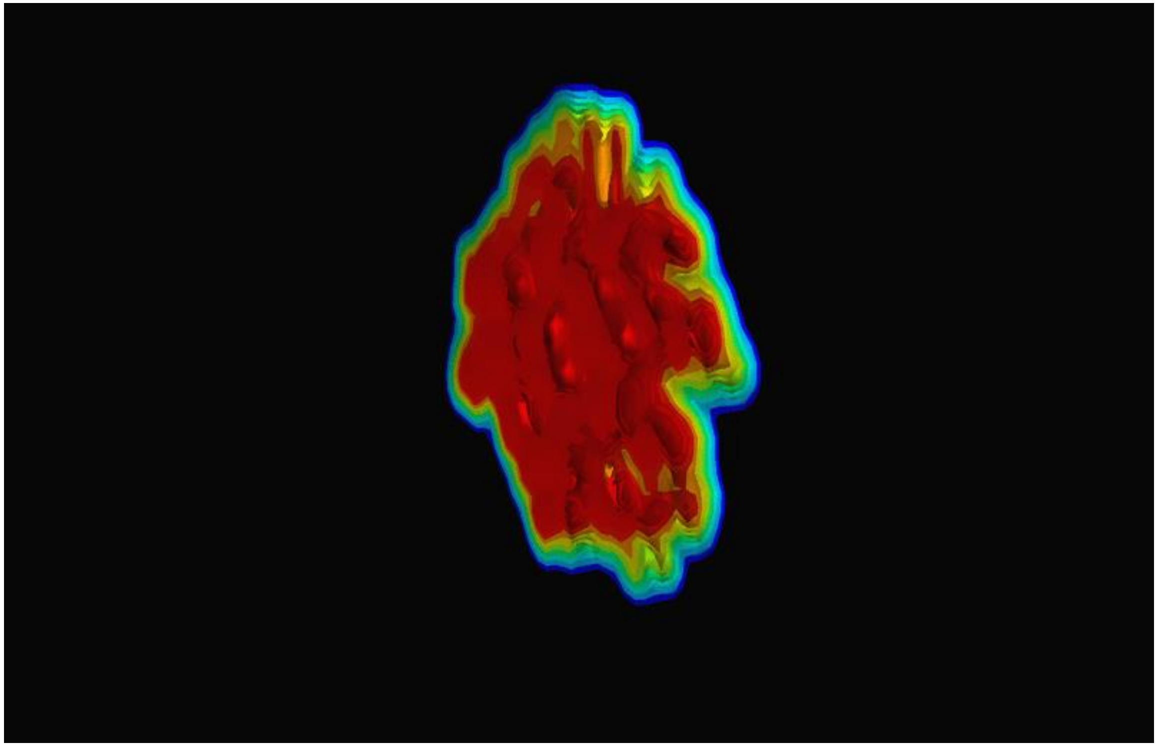


P. Romatschke and U. Romatschke, Viscosity Information from Relativistic Nuclear Collisions: How Perfect is the Fluid Observed at RHIC? (2007)

HEAVY ION STATE-OF-THE-ART (BJORN SCHENKE)

Start with energy density from Wood-Saxon profile

- Fluctuations may follow from glasma/saturation
- Profile in rapidity largely put in by hand (BI+cut-off)



PARTICLE MULTIPLICITY ≈ ENTROPY

Around temperature of 170 MeV QGP cross-over into hadron gas

- After few scatterings, and many resonance decays: free-streaming to detector (freeze-out)
- In local rest-frame particle distribution precisely known (Boltzmann): Cooper-Frye prescription (on constant temperature hypersurface)
- Direct link between entropy and multiplicity: $N_{ch} \approx S / 7.5$
- Also: entropy approx constant during hydrodynamic evolution
- Subtlety: when anisotropic also momentum distribution anisotropic

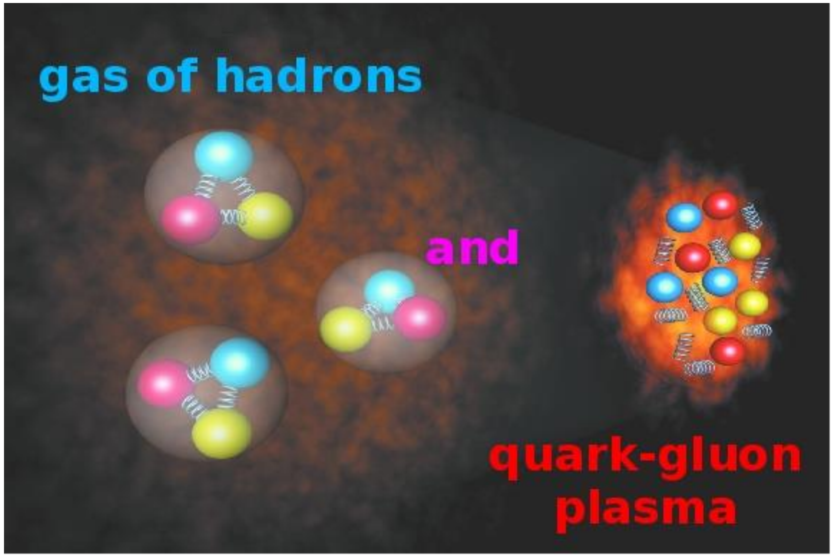
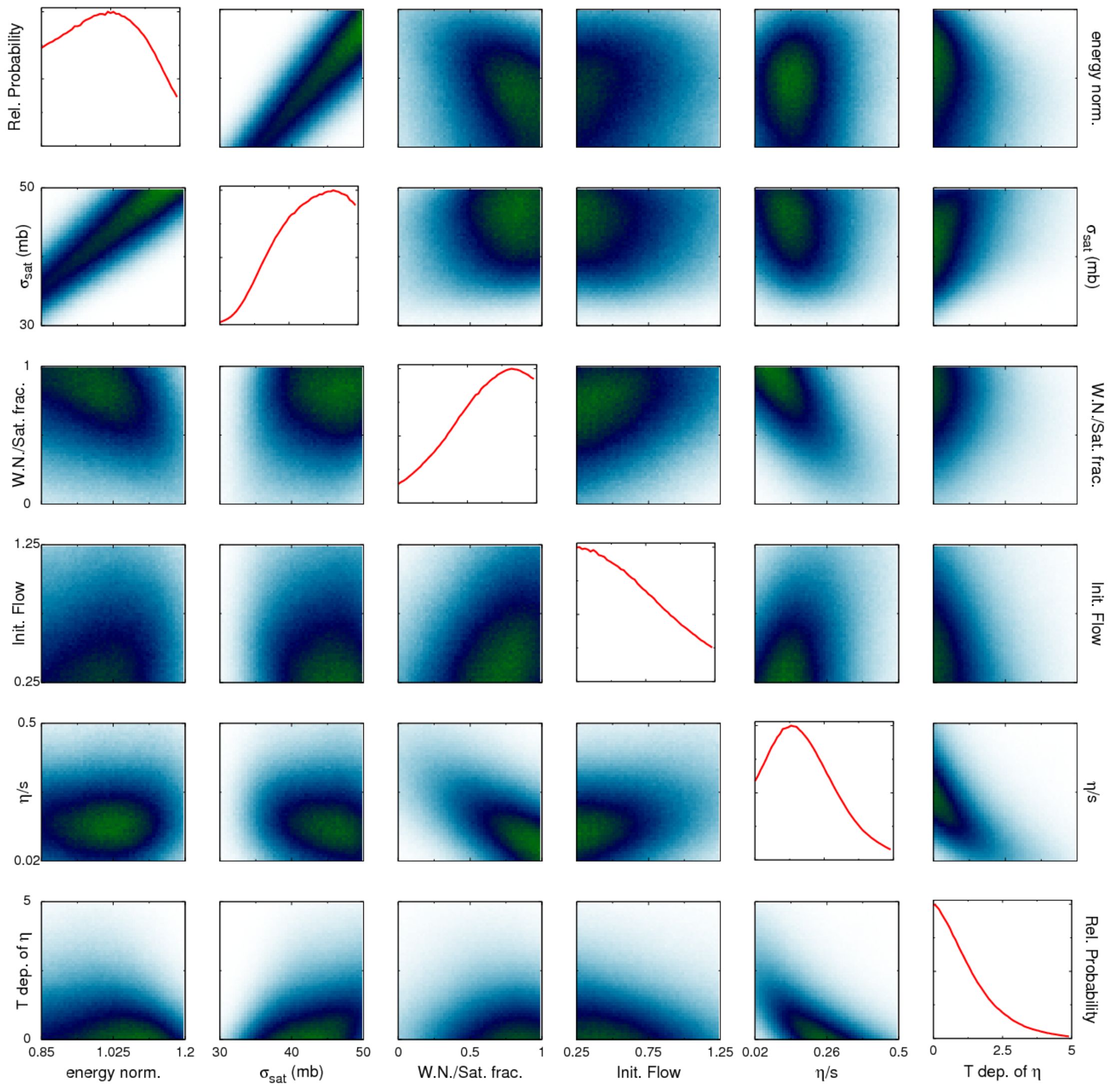


Figure NA61

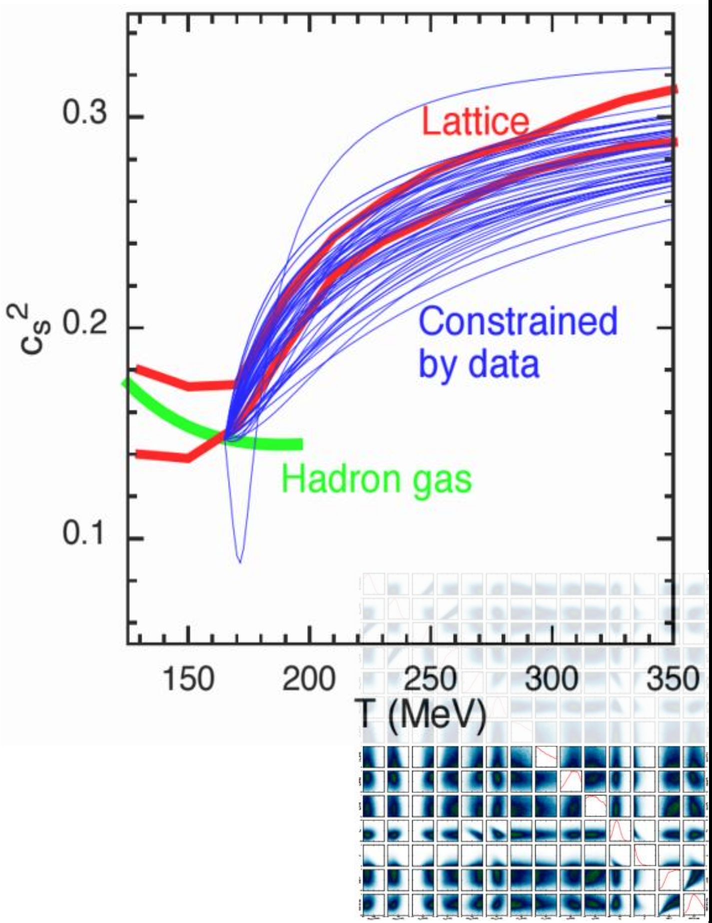
F. Cooper and G. Frye, Single-particle distribution in the hydrodynamic and statistical thermodynamic models of multiparticle production (1974)

EMULATOR + PRINCIPLE COMPONENT (PCA)



Likelihood of i.e. η/s, EOS

- Requires many models * events



J. Novak, K. Novak, S. Pratt, J. Vredevoogd, C. Coleman-Smith, R. Wolpert, Determining Fundamental Properties of Matter Created in Ultrarelativistic Heavy-Ion Collisions (2013)
S. Pratt, E. Sangaline, P. Sorensen and H. Wang, Constraining the Eq. of State of Super-Hadronic Matter from Heavy-Ion Collisions (2015)

SUMMARY FIRST LECTURE

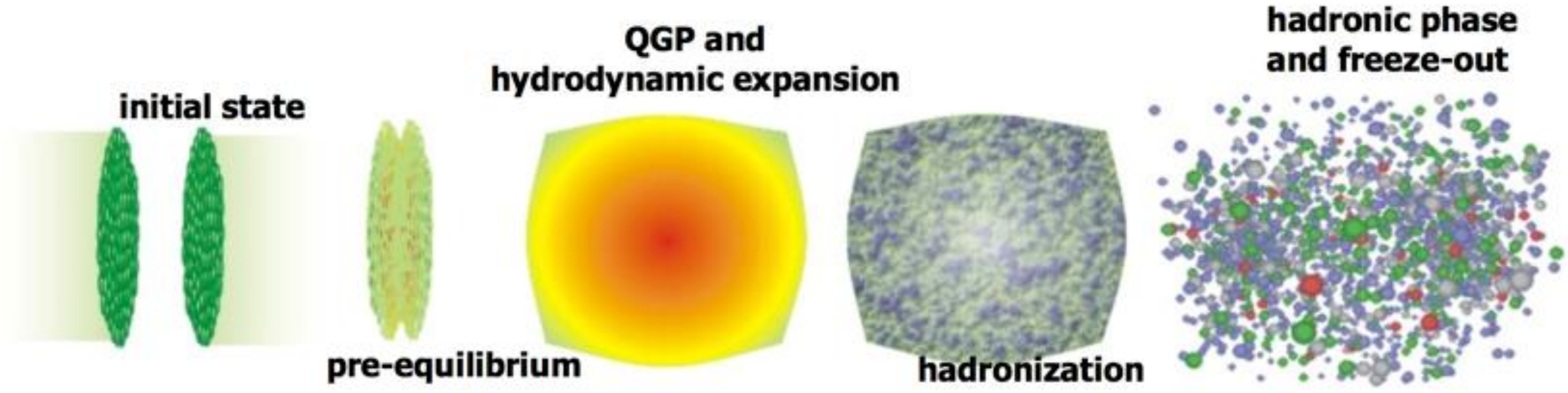
Heavy ion collisions are fun, interesting study of QGP

- Perhaps most striking: ridge
  - Suggests hydrodynamic flow
  - Non-trivial as function of rapidity and centrality
  - Can be used to estimate viscosity etc
- Still several puzzles
  - How to get initial conditions for hydrodynamics (Wednesday)
  - How to constrain physics more, such as viscosity versus temperature
  - Effect QGP on jets (Wednesday)
- Recent puzzles: is there QGP in proton-proton collisions?

THEORETICAL DESCRIPTION

Standard model of heavy ion collisions

- Now: initial pre-equilibrium stage



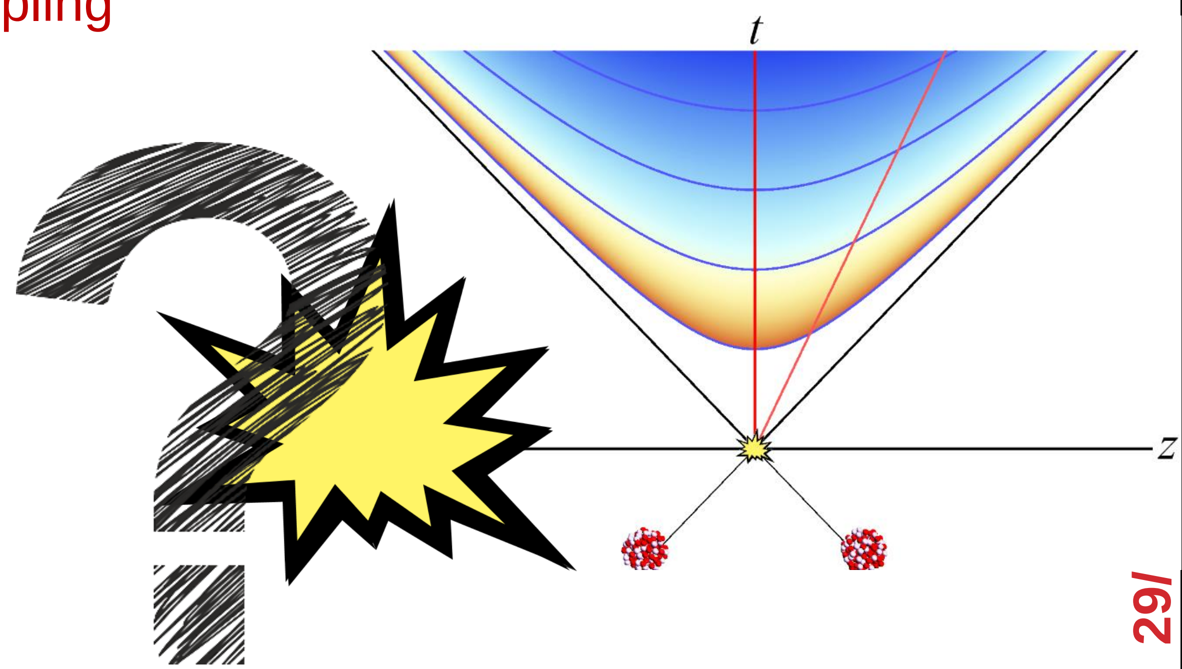
INITIAL STAGE

Hydrodynamics needs initial conditions

- Energy density, velocity, as function of space at initial time
- (Gradient tensors for 2nd order hydro)

QCD is well understood theory??

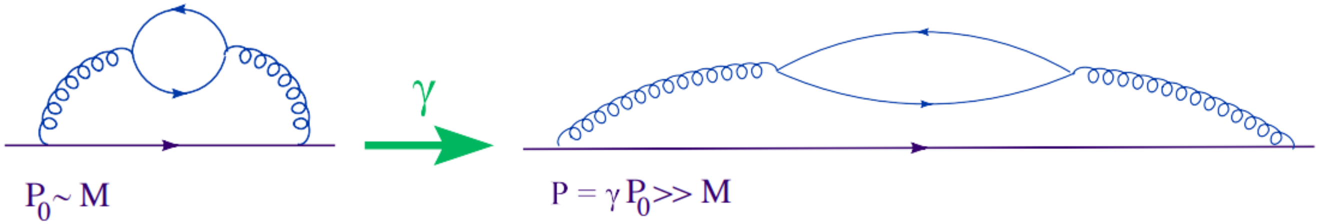
- Perhaps at weak coupling



INITIAL STAGE – PERTURBATIVE QCD

Many more gluons when probed at high energy

- Intuition: at short time scale vacuum fluctuations separated from loops
- Now we can treat (loop) gluons as partons, for purpose of scattering



Initial dynamics is governed by classical evolution of Yang-Mills charge

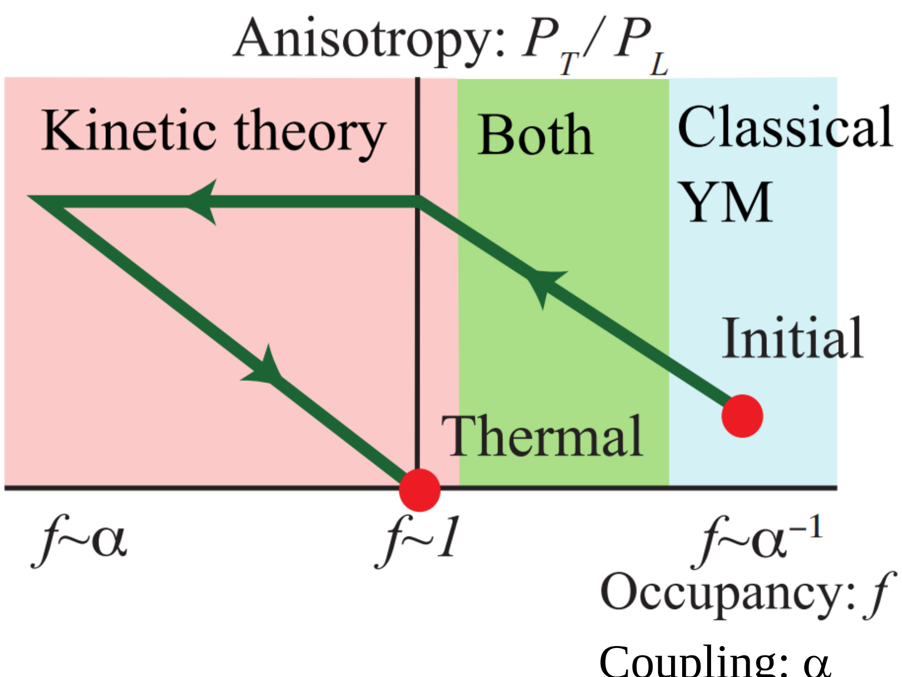
- Much like coherent photons together are described by Maxwell eqn
- System dilutes and at weak coupling becomes kinetic theory

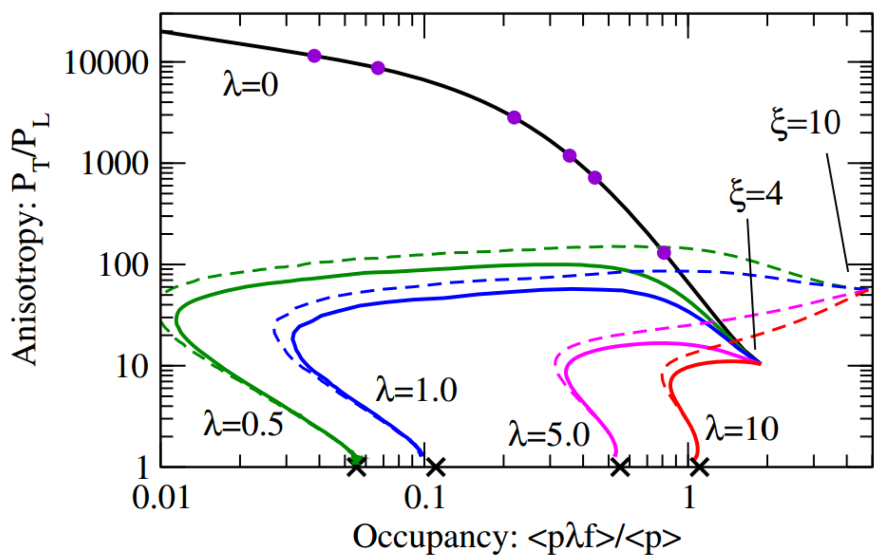
Edmond Iancu, QCD in heavy ion collisions (2012)

INITIAL STAGE – PERTURBATIVE QCD

Typical process of thermalization:

- Far-from-equilibrium universal scaling (Berges et al)
- Kinetic theory towards thermal equilibrium (time of order 1 fm/c)

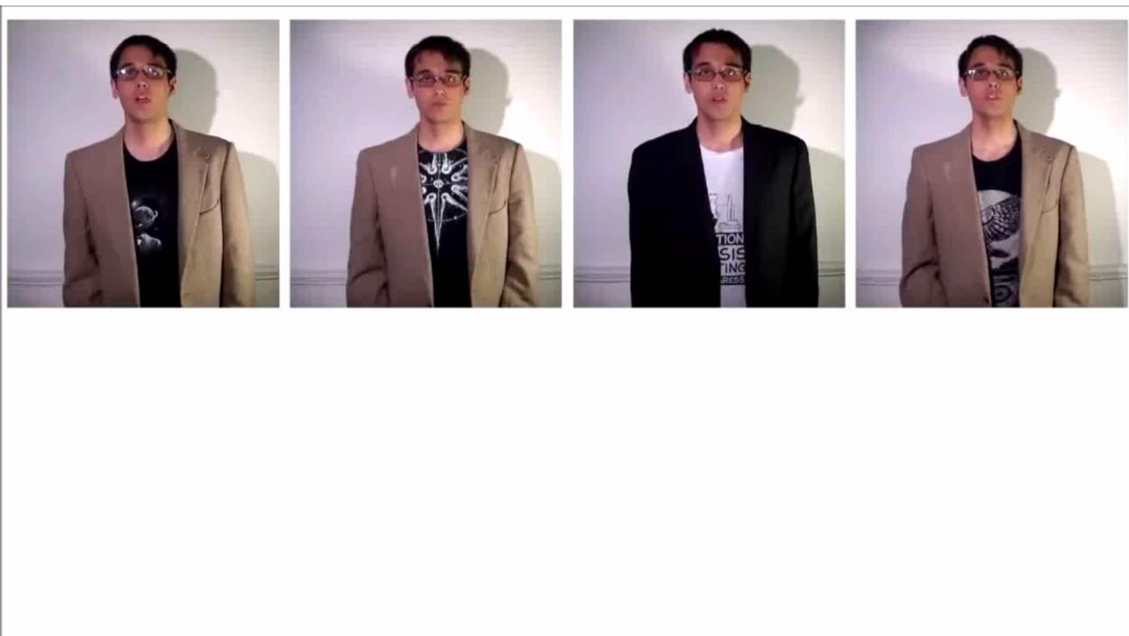




Aleksi Kurkela and Yan Zhu, Isotropization and Hydrodynamization in Weakly Coupled Heavy-Ion Collisions (2015)

INITIAL STAGE – STRING THEORY

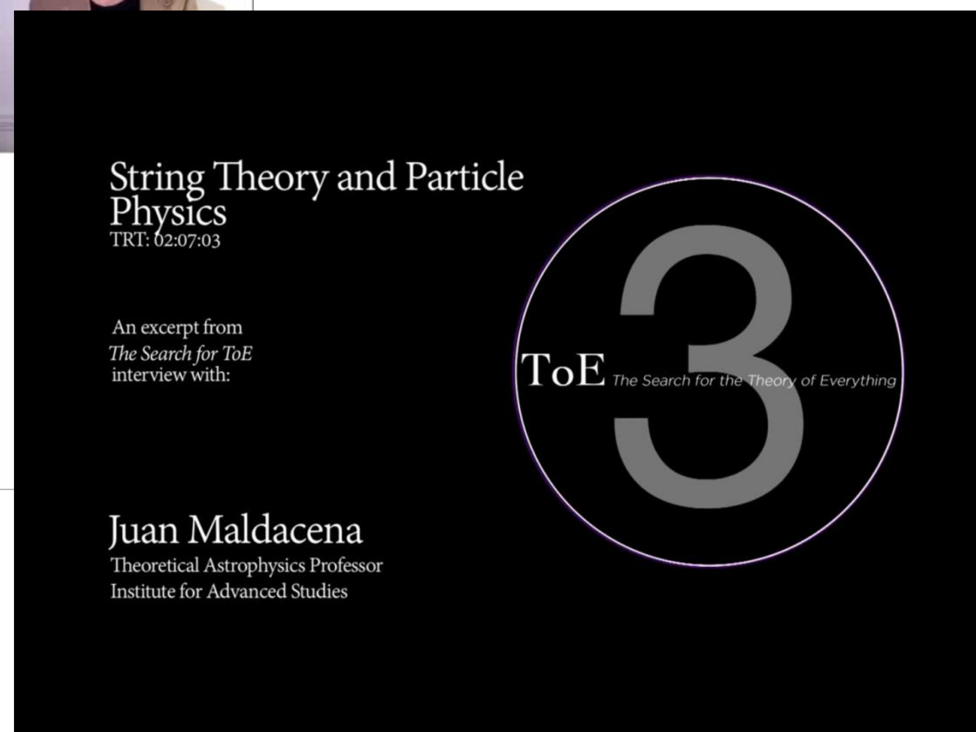
A theory of (more than?) everything?



A Capella Science - Bohemian Gravity! (2013)

STRING THEORY

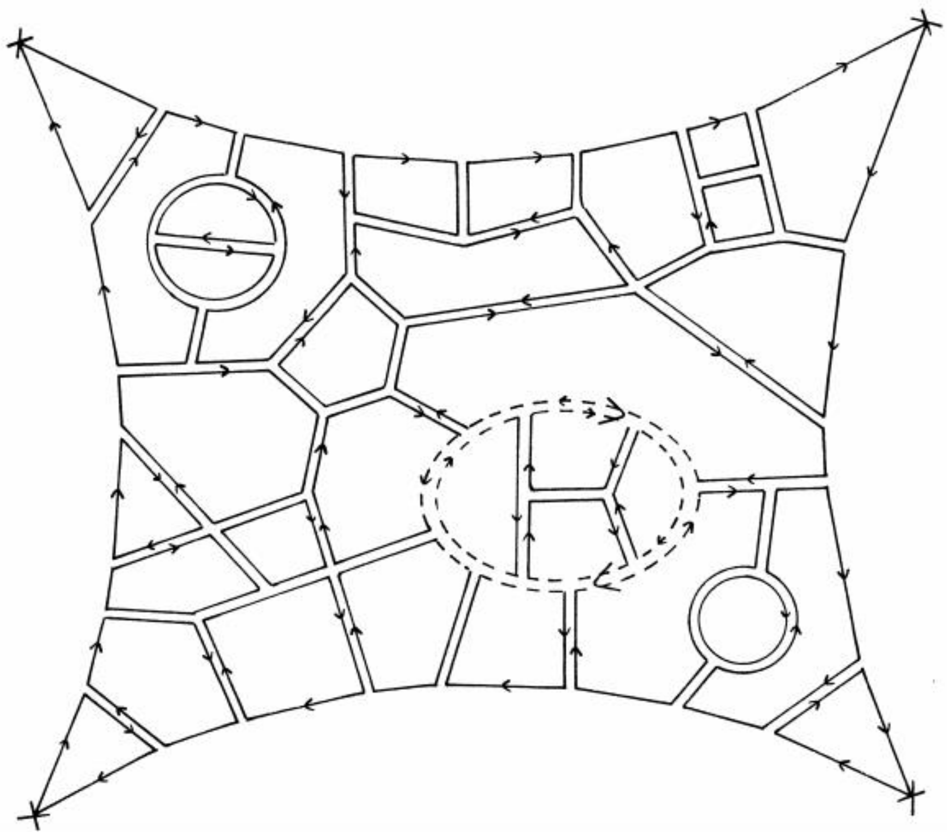
A theory of (more than?) everything?

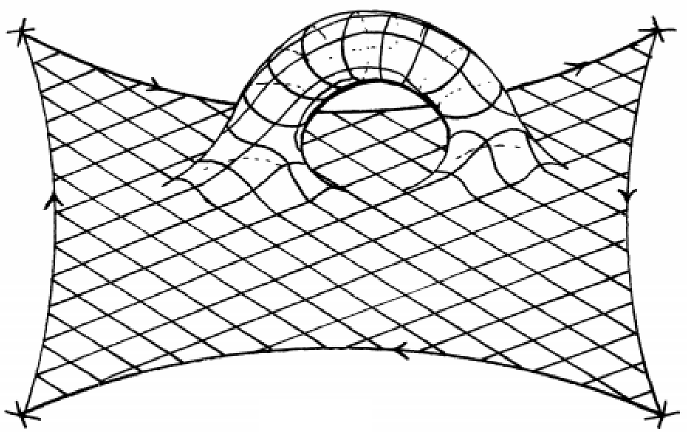


https://www.facebook.com/toemovie (The Search for the Theory of Everything)

LARGE N GAUGE THEORIES

At strong coupling we can get GR





Planar limit:

$\lambda = g^2 N$ fixed

$N \to \infty$

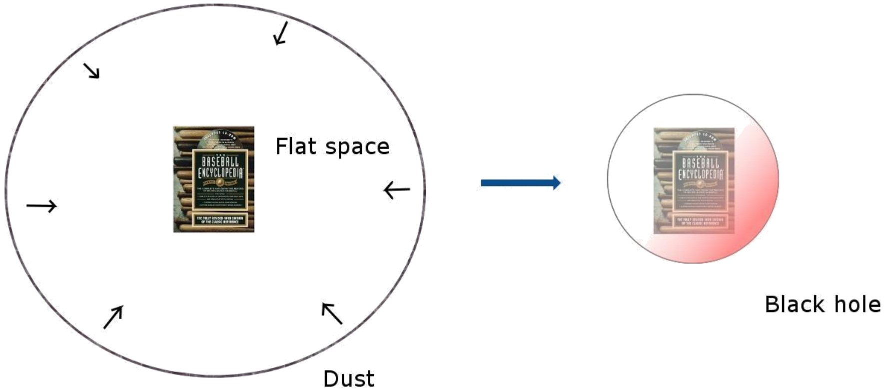
Gerard 't Hooft, A planar diagram theory for strong interactions (1974)

THE WORLD AS A HOLOGRAM

A very curious fact: black hole entropy proportional to area!

$$S_{BH} = A/4$$

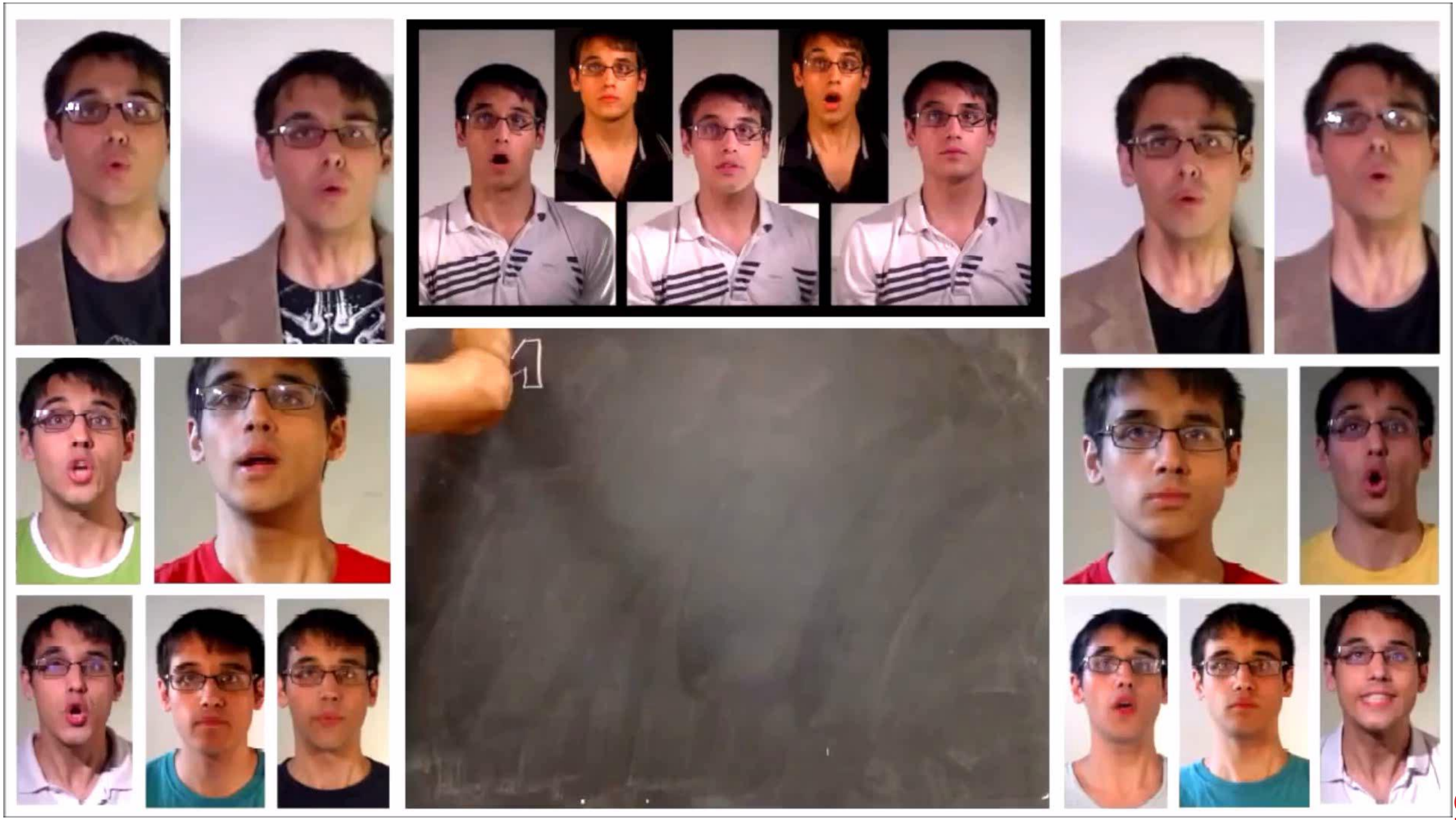
Thought experiment: collapse entropy to black hole



Intuition: gravity provides UV cut-off in space due to BH formation

Jacob Bekenstein, Black holes and entropy (1973)
Stephen Hawking, Particle creation by black holes (1975)
Gerard 't Hooft, Black hole quantization and a connection to string theory (1990)

ADS/CFT



A Capella Science - Bohemian Gravity! (2013)

QUICK GUIDE TO HOLOGRAPHY

Exact equivalence between string theory and quantum field theory

$$\mathcal{Z}_{bulk}\left[\phi(\vec{x},z)\big|_{z=0}=\phi_0(\vec{x})\right]=\langle e^{\int d^4x\,\phi_0(\vec{x})\mathcal{O}(\vec{x})}\rangle_{\text{Field Theory}}$$

$$\langle\mathcal{O}\rangle=-i\frac{\delta Z_{\text{bulk}}[\phi_{(0)}]}{\delta\phi_{(0)}}\overset{N\to\infty}{=}\frac{\delta S[\phi_{(0)}]}{\delta\phi_{(0)}}$$

Holography synonyms:
AdS/CFT, gauge/gravity duality, gauge/string duality

Dictionary:

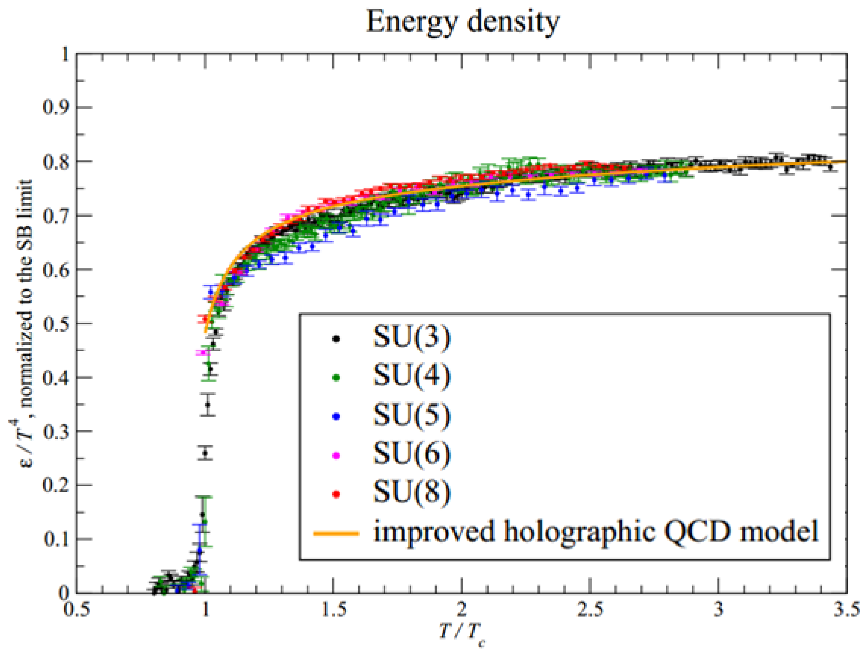
- Original: type IIB string theory $AdS_5\times S_5\sim\mathcal{N}=4\,\mathrm{SU}(N_c)$ SYM on $\mathbb{R}^4$
- Near-boundary metric of AdS ~ stress tensor
- Black hole ~ thermal state
- Fundamental string ~ Quark-antiquark pair

Most famous result: $\eta/s=\frac{1}{4\pi}$ **(from black hole horizon)**

Also: insights information paradox, fast thermalization, ... (14000+)

Juan Maldacena, The large-N limit of superconformal field theories and supergravity (1997)

ARE WE PERHAPS NOT CHEATING WITH $\mathcal{N}$=4 SYM?



SU(N): 3 ≈ ∞?

- Good for thermal

Quarks?

- Replaced by (dominant) gluons

Infinite coupling strength?

- But coupling runs only logarithmically…

Theories not the same:

$$\mathcal{E} = \frac{3N_c^2\pi^2}{8}T^4 \approx 33.3T^4(\mathcal{N}=4) \qquad \mathcal{E} \approx 11T^4(\mathrm{QCD})$$

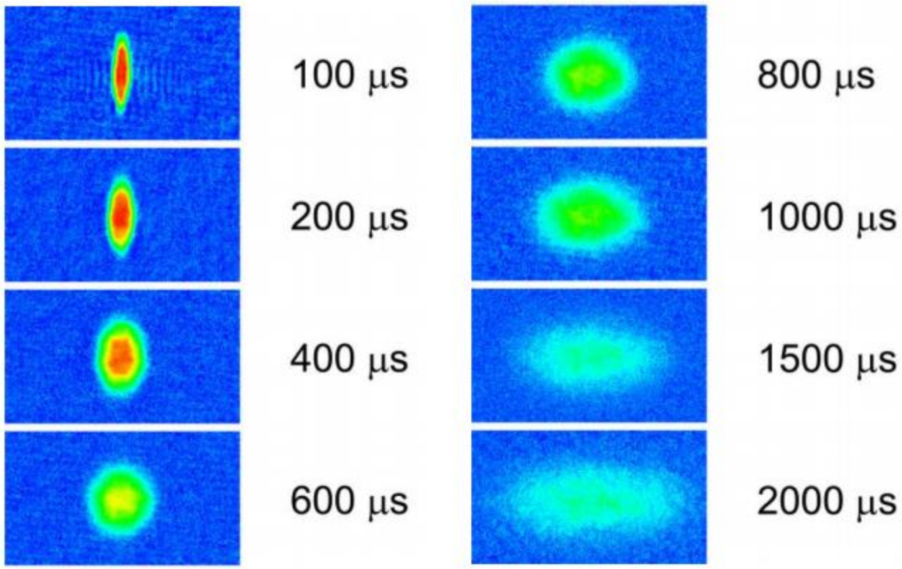
So maybe not too bad; and with room for improvement ☺

M. Panero, Thermodynamics of the QCD plasma and the large-N limit (2009)

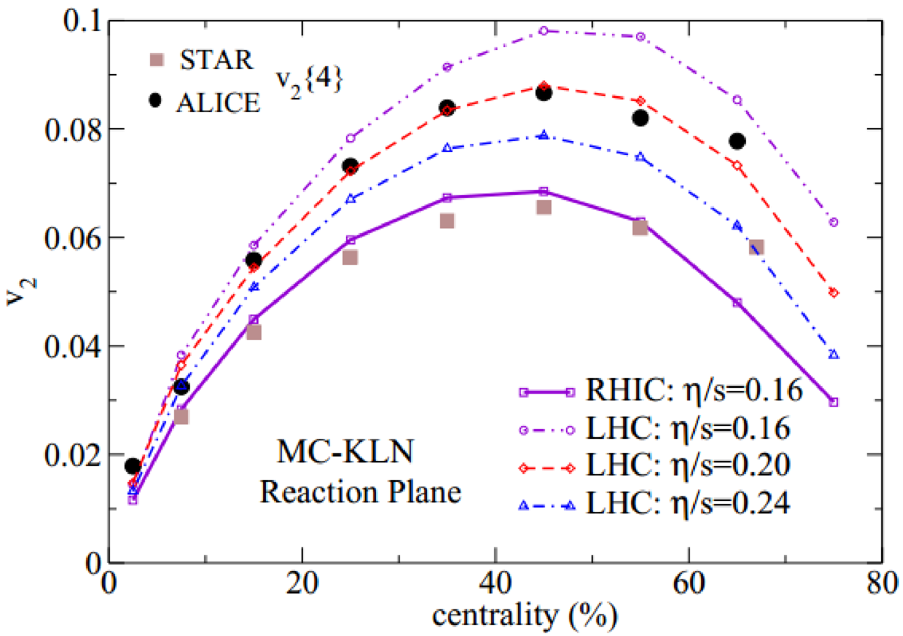
THE MOST PERFECT LIQUID?

Famous viscosity: $$\frac{\eta}{s} = \frac{1}{4\pi} \approx 0.08$$

Fermions at unitarity



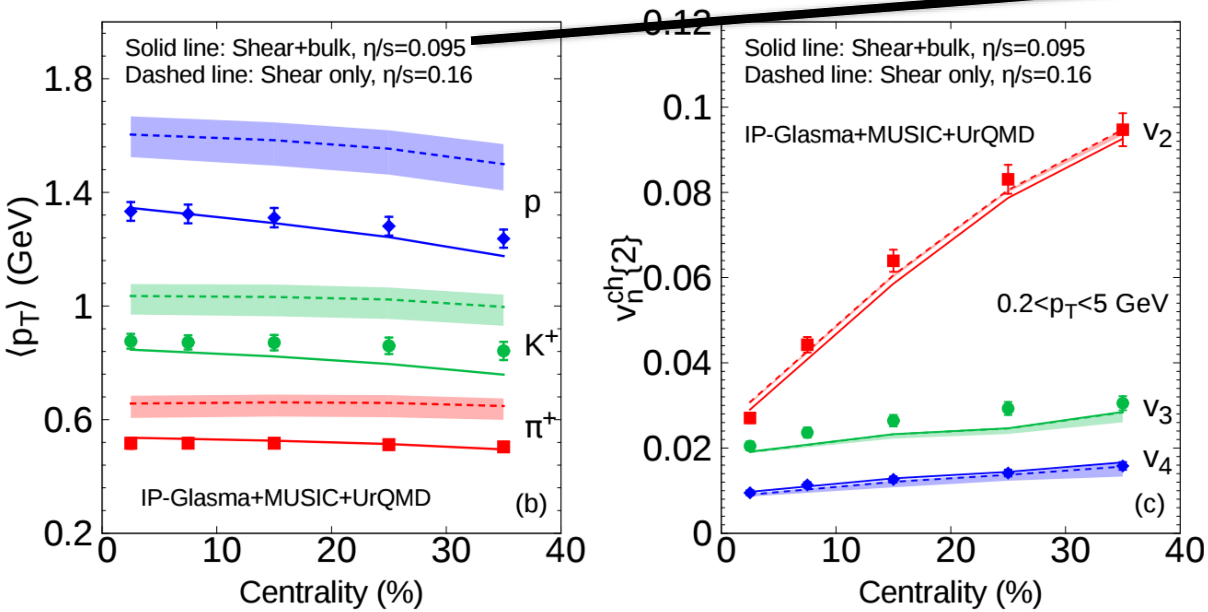
Quark-gluon plasma

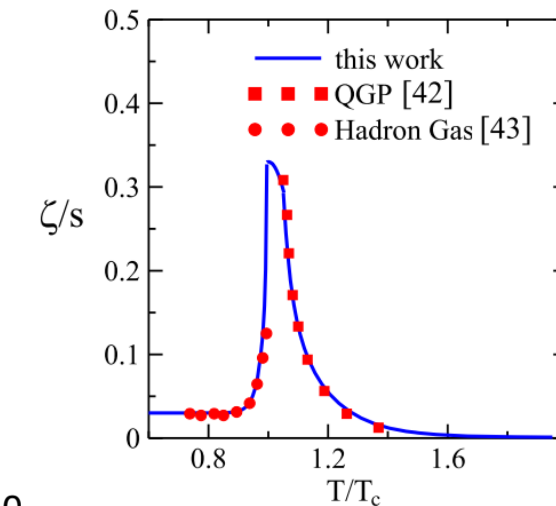


K. O'Hara, S. Hemmer, M. Gehm, S. Granade and J. Thomas, Observation of a Strongly-Interacting Degenerate Fermi Gas of Atoms, 2002
U. Heinz, C. Shen and H. Song, The Viscosity of Quark-Gluon Plasma at RHIC and the LHC, 2011

ADS/CFT VISCOSITY REVISITED?

New experimental estimate for shear viscosity QGP: η/s=0.095





Many caveats applying N=4 SYM to QCD:

- Infinite coupling limit (QCD = intermediate coupling?)
- SYM vs YM, no confinement, what to collide?, jet production?

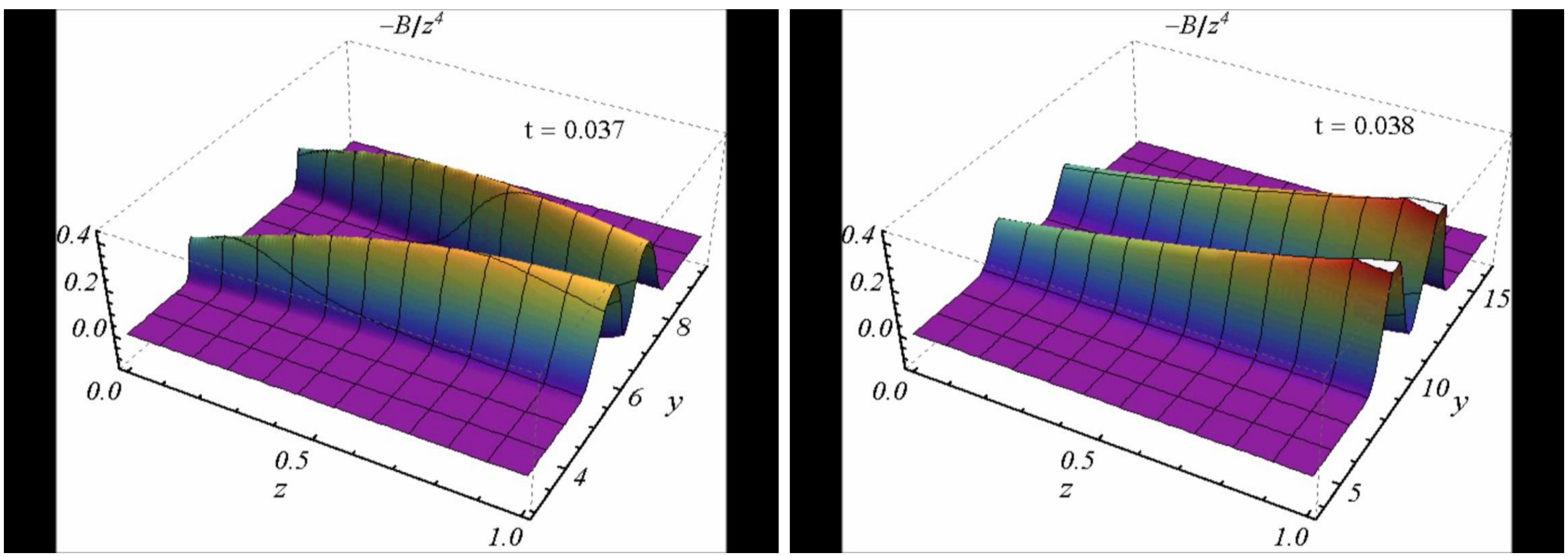
Idea: get strong coupling benchmark/intuition + improve model

S. Ryu, J.-F. Paquet, C. Shen, G. S. Denicol, B. Schenke, S. Jeon, C. Gale,
The importance of the bulk viscosity of QCD in ultrarelativistic heavy-ion collisions (2015)

STRONG COUPLING – INITIAL STAGE

Colliding lump of energy = gravitational shock waves!

- In one extra dimension, solve Einstein equations numerically
- Extract field theory stress-energy tensor
- Get resulting hydrodynamic fluid, both time and profile ☺



P.M. Chesler and L. Yaffe, Holography and Colliding Gravitational Shock Waves in Asymptotically AdS_5 Spacetime (2011)
J. Casalderrey-Solana, M.P. Heller, D. Mateos and WS, From full stopping to transparency in a holographic model of heavy ion collisions (2013)

A DYNAMICAL CROSS-OVER

Low energy:

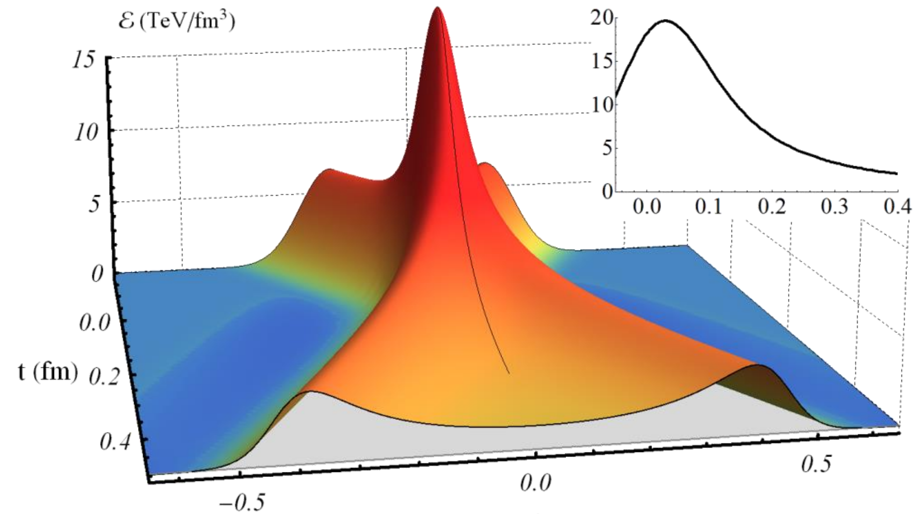
- Stopping, piling up of energy
- Expansion by hydro
- Compressed Landau model

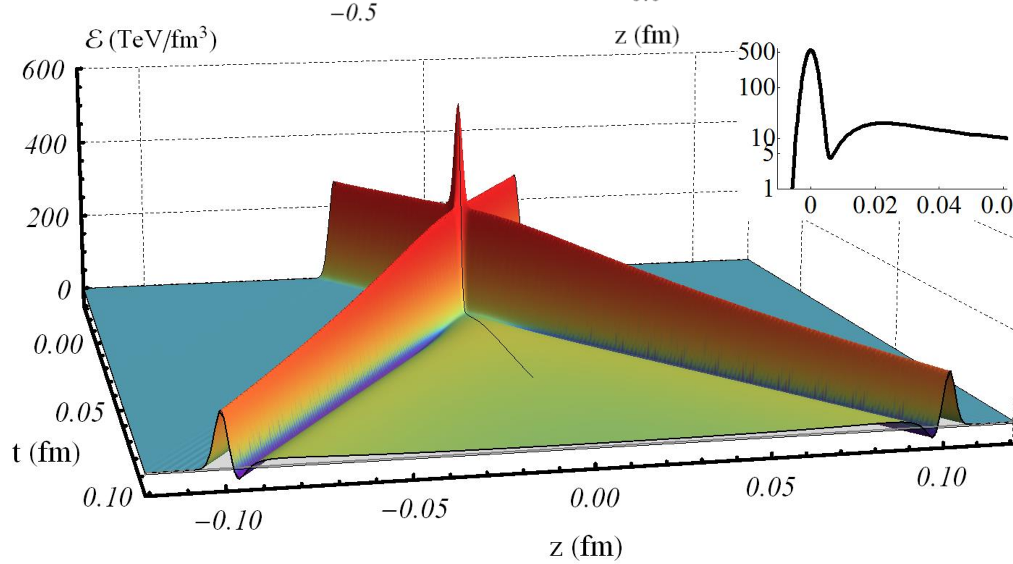
RHIC energy

- Landau model

High energy:

- no stopping
- plasma forms more slowly
- negative energy





J. Casalderrey-Solana, M.P. Heller, D. Mateos and WS, From full stopping to transparency in a holographic model of heavy ion collisions (2013)

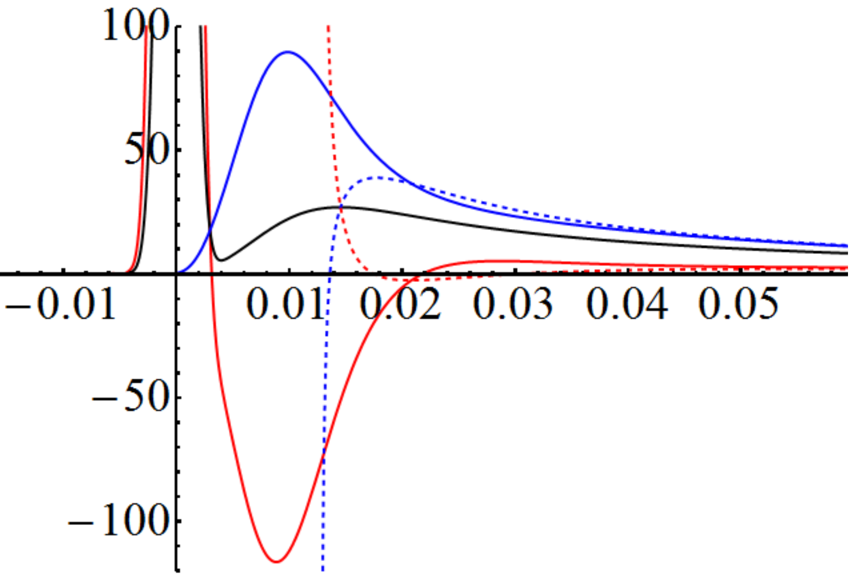
THERMALISATION/PRESSURES

Pressures, energy starts at zero, grows (unique to holography?)

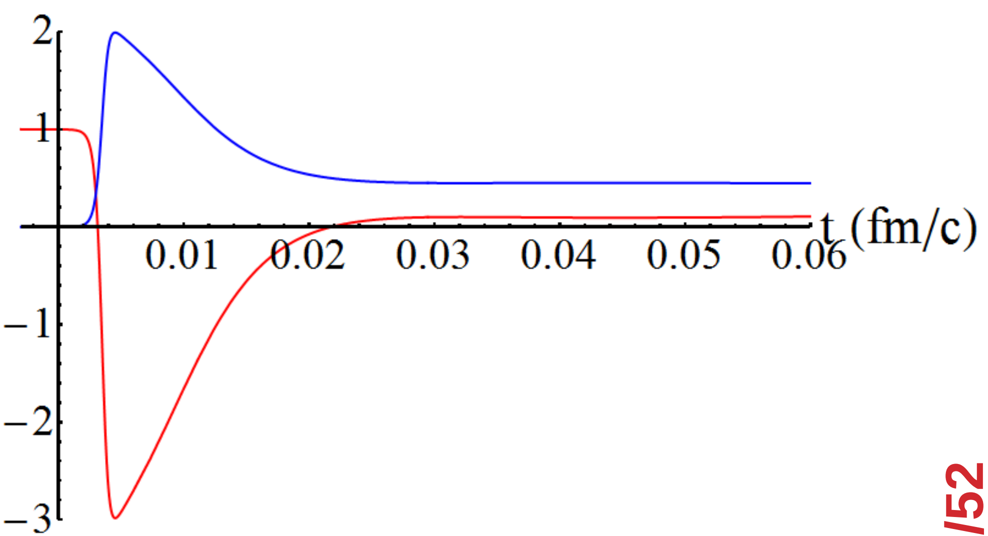
Thermalises very fast (hydro applies in perhaps 0.02 fm/c)

- Thermalisation = relaxation non-hydro modes
- Gradients + viscous corrections are big

$e/3$ (black), P_L (red), P_T (blue) at $z = 0$ fm

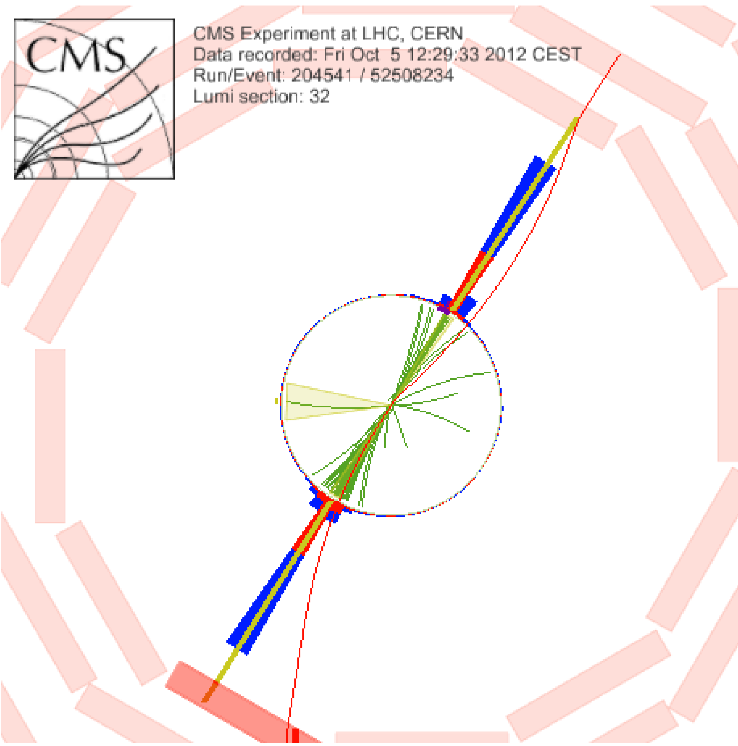


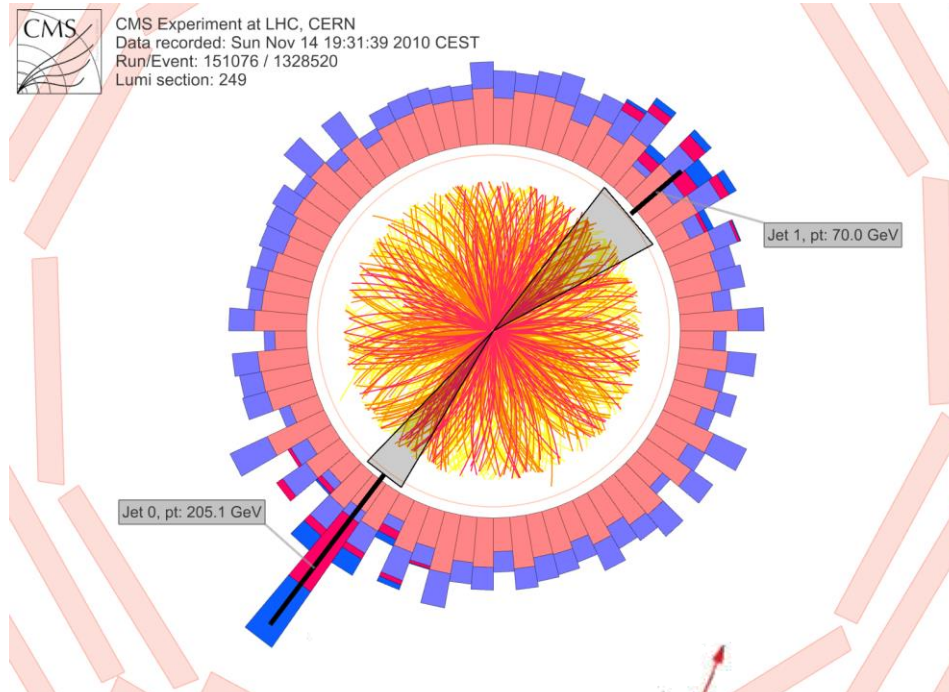
P_L/e (red) and P_T/e (blue), $z = 0$ fm

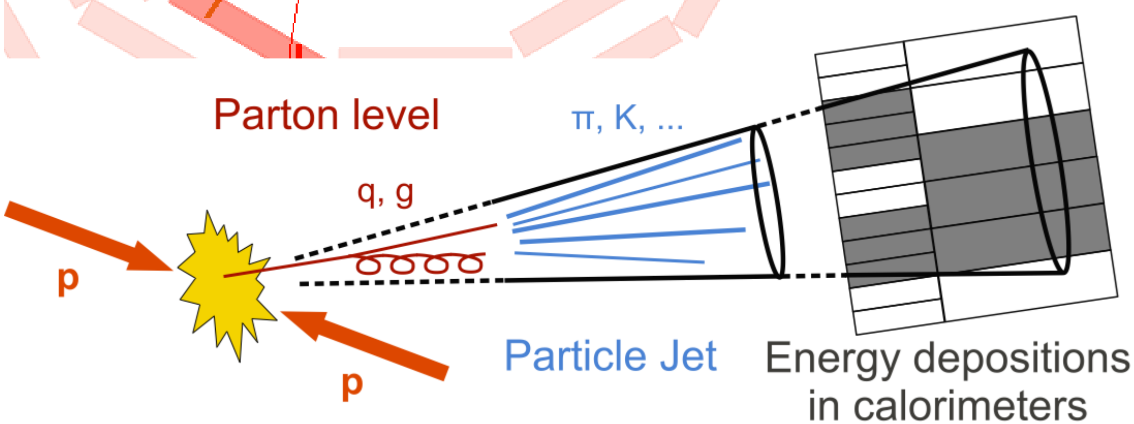


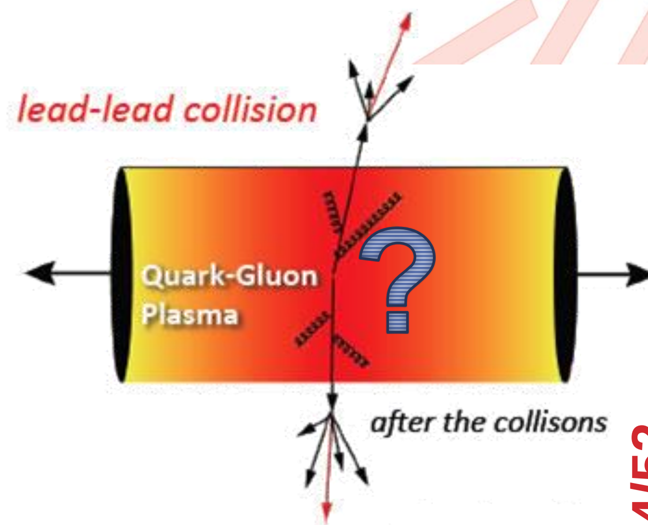
M.P. Heller, R.A. Janik and P. Witaszczyk, Hydrodynamic Gradient Expansion in Gauge Theory Plasmas (2013)

JETS IN QGP









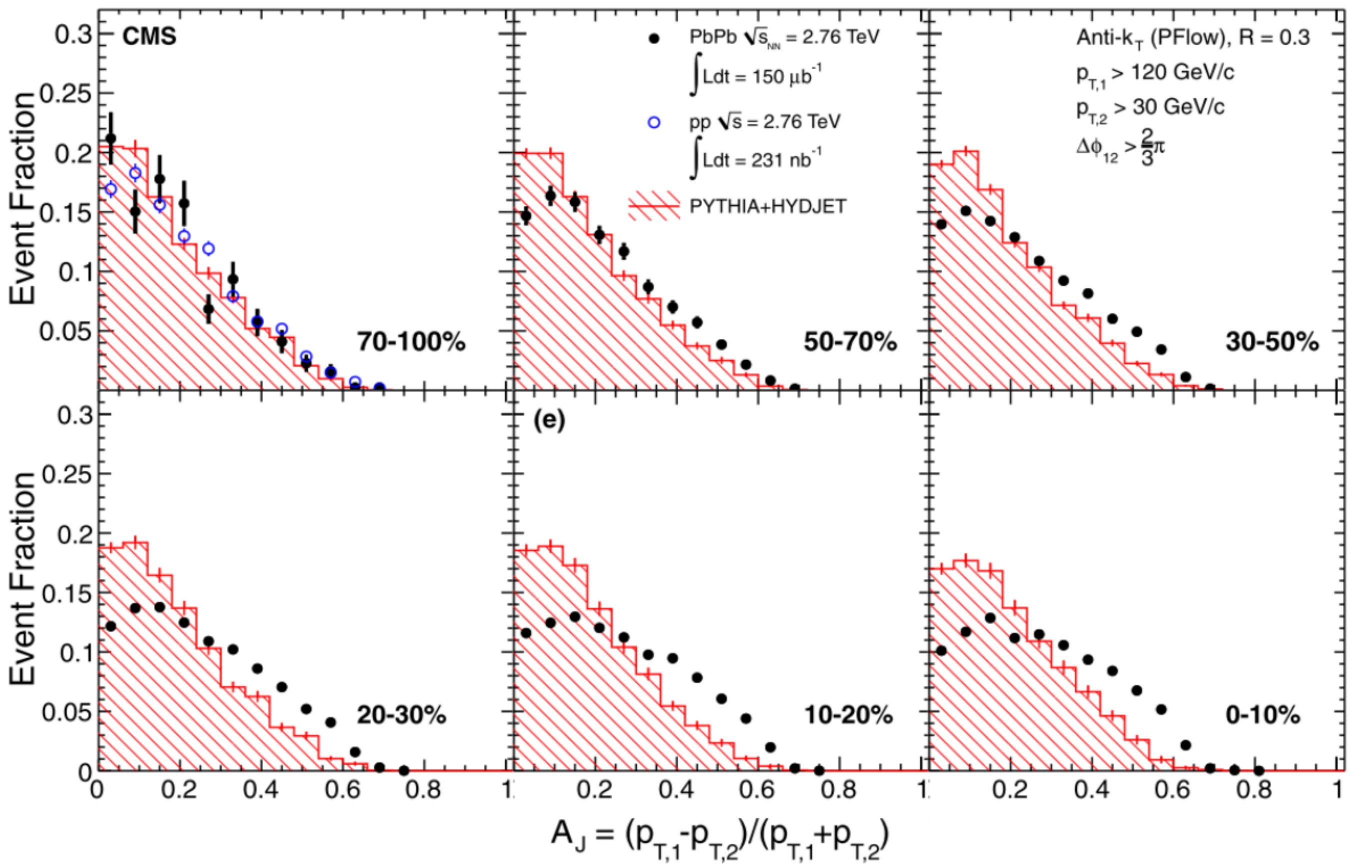
CMS PAPER EXO-12-059

JETS – DIJET ASYMMETRY

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

QGP affects fast moving quarks/gluons

- One jet loses more energy due to QGP
  - → Stronger asymmetry in jet energies
- Subtlety: compare with HYDJET/PYTHIA simulations

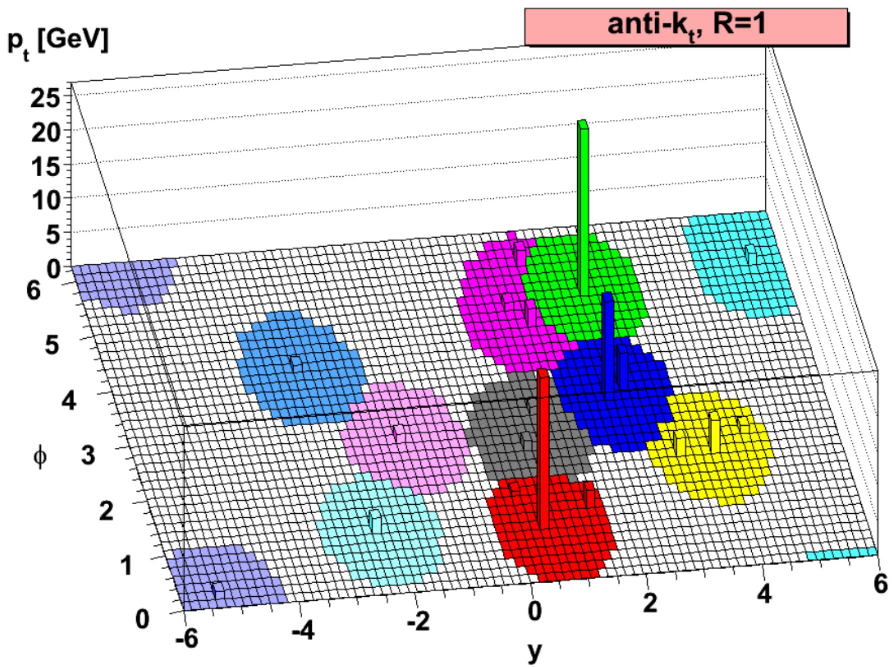


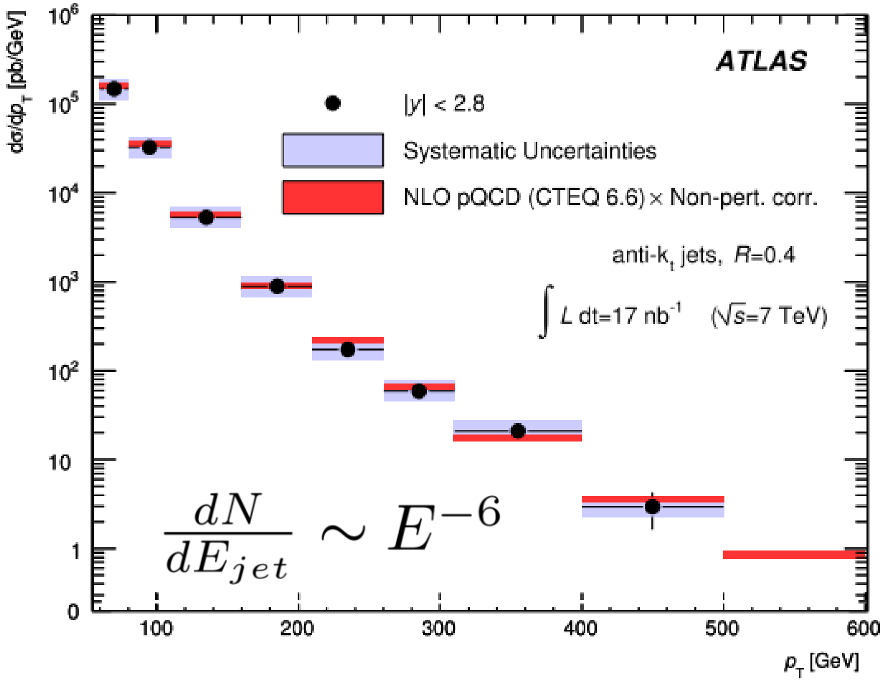
CMS, Jet momentum dependence of jet quenching in PbPb collisions at $\sqrt{s_{NN}}$=2.76 TeV (2012)

HOW TO DEFINE A JET?

Relatively recent consensus: anti-k$_T$

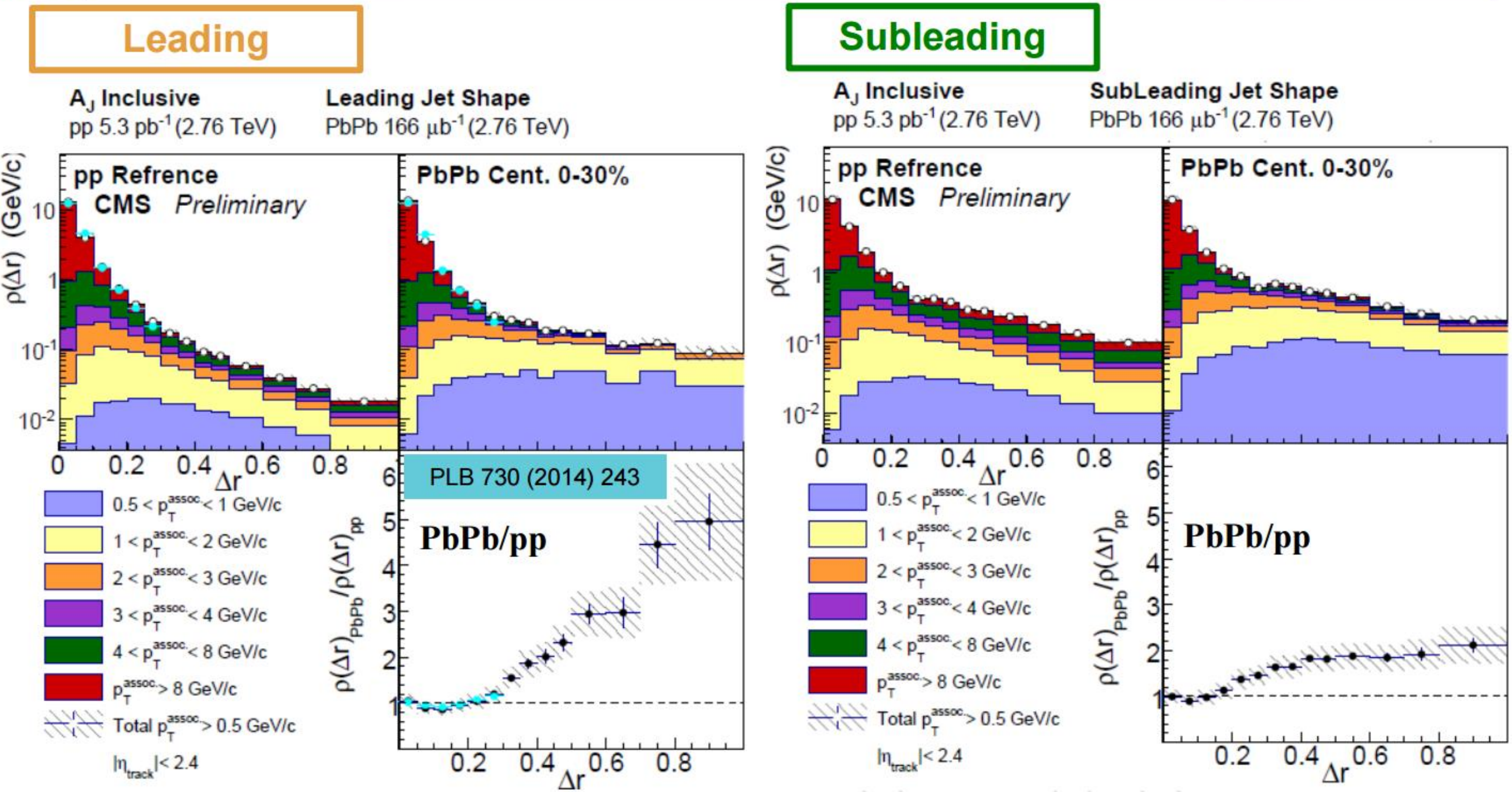
- Cluster around hard cores: $d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = \frac{1}{p_{ti}^2}$





Matteo Cacciari, Gavin P. Salam and Gregory Soyez, The anti-k$_t$ jet clustering algorithm (2008)

Jet Shape Modifications



- New measurement of jet shapes up to large radial distances

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\frac{\Sigma_{\text{tracks}\in(r_a,r_b)}\, p_T^{\text{track}}}{p_T^{\text{jet}}}$$

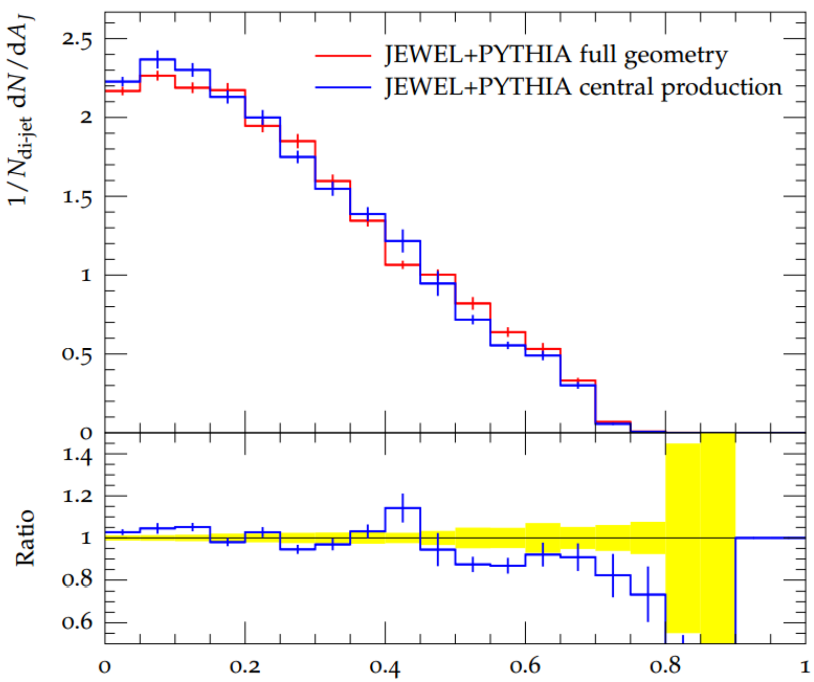
Olga Evdokimov, presentation Quark Matter 2015, CMS-PAS HIN-15-011

RECENT DEVELOPMENT: JET SHAPES

Look at distribution of particles/energy within a jet

- Using perturbative QCD, i.e. JEWEL + PYTHIA
- Compare path length dependence versus jet shape dependence

Di-jet asymmetry distribution



- Central production, i.e. artificially turned off path-length dependence
- \`Normal' binary collisions distribution over transverse plane
- Very little difference! I.e. most of energy loss asymmetry is caused by different jet shape, not by path length difference

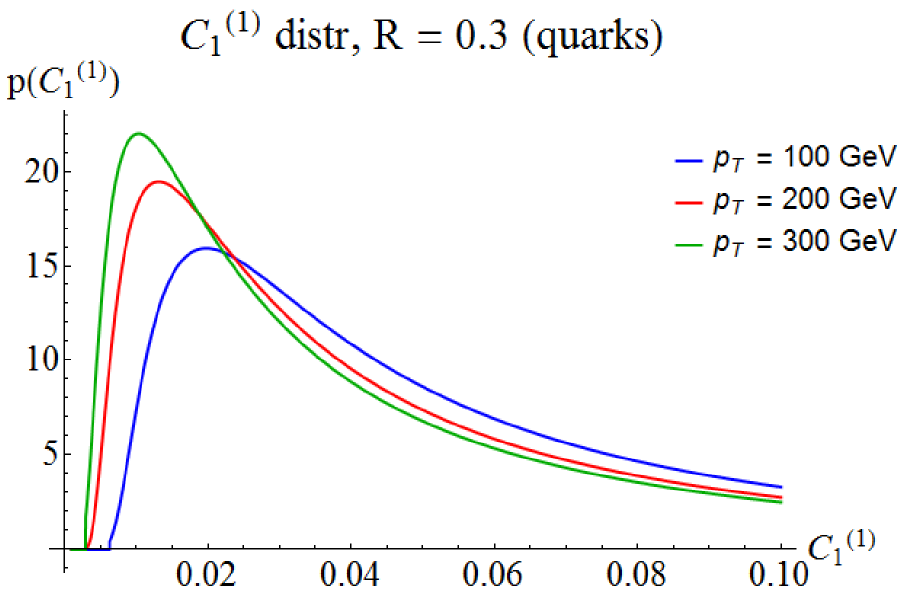
Guilherme Milhano and Korinna Zapp, Origins of the di-jet asymmetry in heavy ion collisions (2015)

JET SHAPES AT STRONG COUPLING

Jets in thermal plasma correspond to strings in black hole in AdS

Would like to mimic distribution of real QCD jets

- Motivation: how is distribution affected by QGP?
- Take from pQCD (compares well with PYTHIA)



$$C_1^{(\alpha)} \equiv \sum_{i,j} z_i z_j \left(\frac{|\theta_{ij}|}{R} \right)^{\alpha}$$

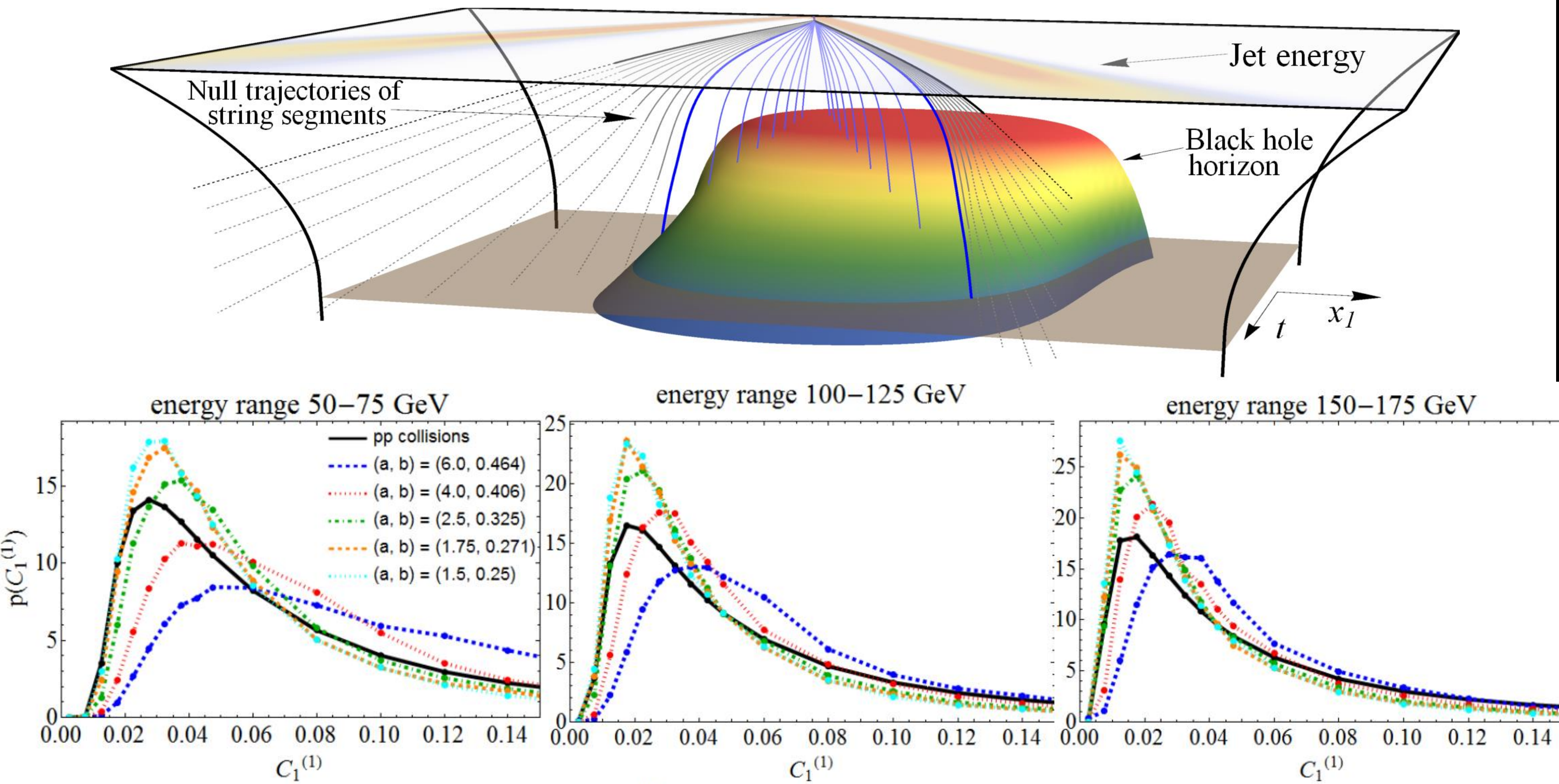
z_i: fraction of jet energy
θ_{ij}: angle between particle *i* and *j*
R: jet radius parameter

Link opening angle $C_1^{(1)}$ **to AdS angle:** $C_1^{(1)} = a\,\sigma_0$

A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft drop (2014)

FIRST EFFECT: JETS WIDEN

Change of probability distributions of jet opening angle

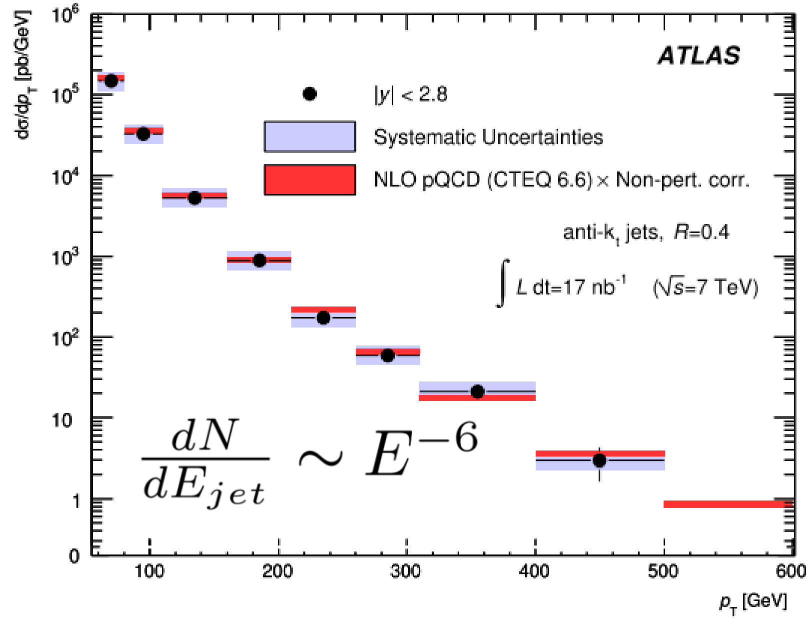


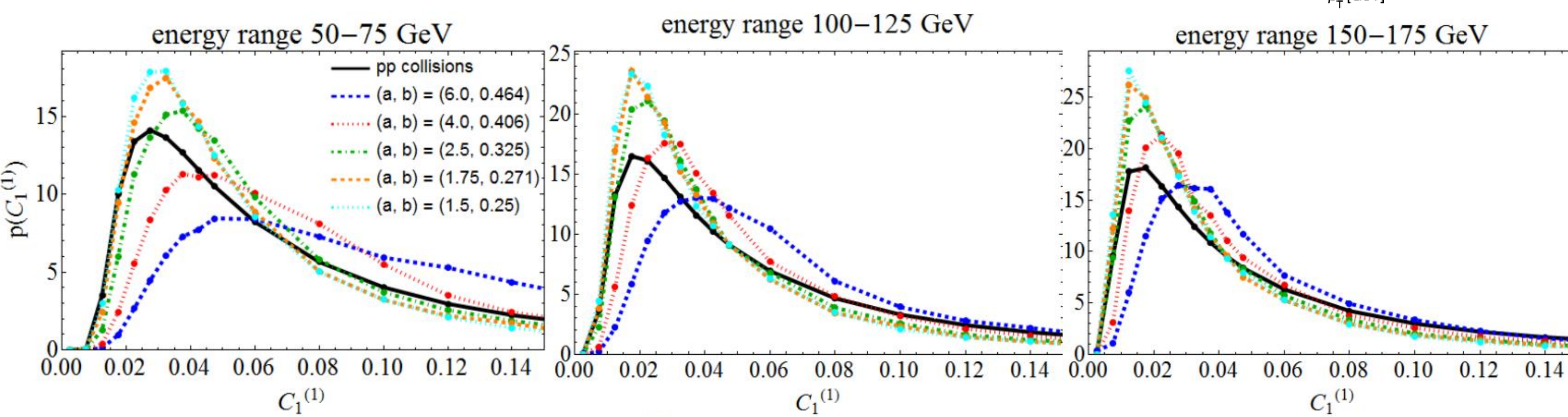
Has not been measured ☹ (could/should be possible)

Krishna Rajagopal, Andrey Sadofyev and WS, Evolution of the jet opening angle distribution in holographic plasma (2016)

SECOND EFFECT: NARROWER JETS

- **Energy distribution falls steeply (~E^-6)**
- **Wide jets lose (much) more energy**
- **→ selection bias on narrow jets**





ATLAS, Measurement of inclusive jet and dijet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy (2011)

DISCUSSION

Heavy ion physics is a lot of fun, full of surprises

- Plenty of pieces of the puzzle of QCD collisions, i.e.
  centrality dependence, pt dependence, geometry (p-Pb, d-Au, He3), even pp collisions (!), jet energy loss, jet shape evolution, event-by-event distributions
- Robust `standard model of heavy ion collisions', but many gaps, i.e.
  initial stage, transport coefficients (as function of T), hadronic freeze-out, medium effects to jets

Physics allows us to improve our understanding

- Quantitative tests of QCD framework, such as color glass
- Close to comparison with lattice QCD, such as viscosity or EOS

- May be one of cleanest ways to test AdS/CFT, at least at qualitative level
- Can have implications for other non-perturbative physics, i.e.
  unitary fermi gasses, high temperature superconductors, neutron stars …
- Insights into quantum gravity (??)