The Hottest, and Most Liquid, Liquid in the Universe

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Parádfürdő, Hungary, June, 2013

Liquid Quark-Gluon Plasma: Opportunities and Challenges

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Qualitative Lessons about Quark-Gluon Plasma and Heavy Ion Collisions from Holographic Calculations

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Gauge/String Duality, Hot QCD and Heavy Ion Collisions

Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann

A 500 page book. We finished the manuscript a few weeks ago. To appear in early 2014, Cambridge University Press.

95 page intro to heavy ion collisions and to hot QCD, including on the lattice. 70 page intro to string theory and gauge/string duality. Including a ‘duality toolkit’.

280 pages on holographic calculations that have yielded insights into strongly coupled plasma and heavy ion collisions. Hydrodynamics and transport coefficients. Thermodynamics and susceptibilities. Far-from-equilibrium dynamics and hydrodynamization. Jet quenching. Heavy quarks. Quarkonia. Some calculations done textbook style. In other cases just results. In all cases the focus is on qualitative lessons for heavy ion physics.

A Grand Opportunity

- By colliding “nuclear pancakes” (nuclei Lorentz contracted by $\gamma \sim 100$ and now $\gamma \sim 1400$), RHIC and now the LHC are making little droplets of “Big Bang matter”: the stuff that filled the whole universe microseconds after the Big Bang.

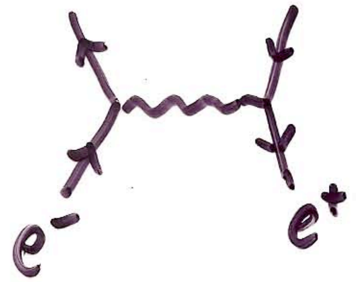
- Using five detectors (PHENIX & STAR @ RHIC; ALICE, ATLAS & CMS @ LHC) scientists are answering questions about the microseconds-old universe that cannot be addressed by any conceivable astronomical observations made with telescopes and satellites.

- And, the properties of the matter that filled the microsecond old universe turn out to be interesting. The Liquid Quark-Gluon Plasma shares common features with forms of matter that arise in condensed matter physics, atomic physics and black hole physics, and that pose challenges that are central to each of these fields.

WHAT IS QCD?

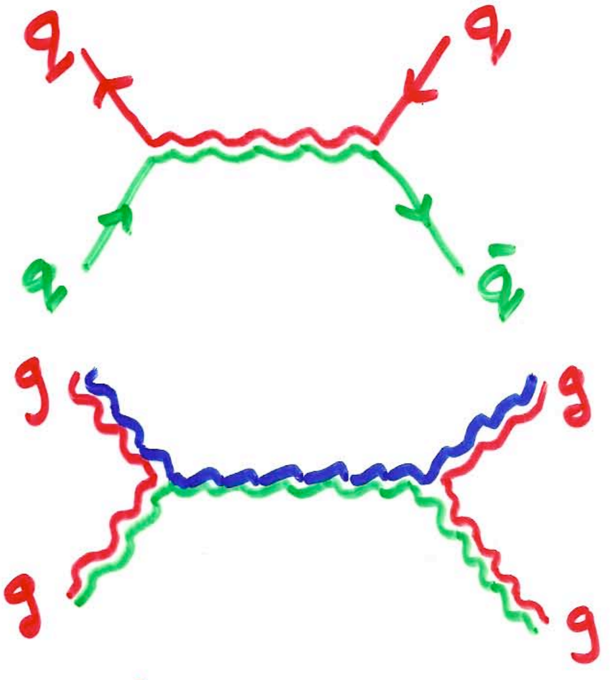
- A theory of quarks and gluons
- Its Lagrangian suggests it is not too different from QED, which is a theory of electrons and photons:

QED



e^-: charge -1
γ: neutral

QCD



q: charge r, g or b
gluons: also charged

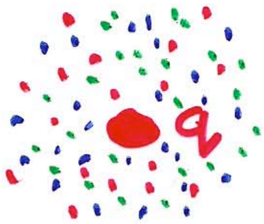
ASYMPTOTIC FREEDOM

Gross, Wilczek, Politzer (1973)

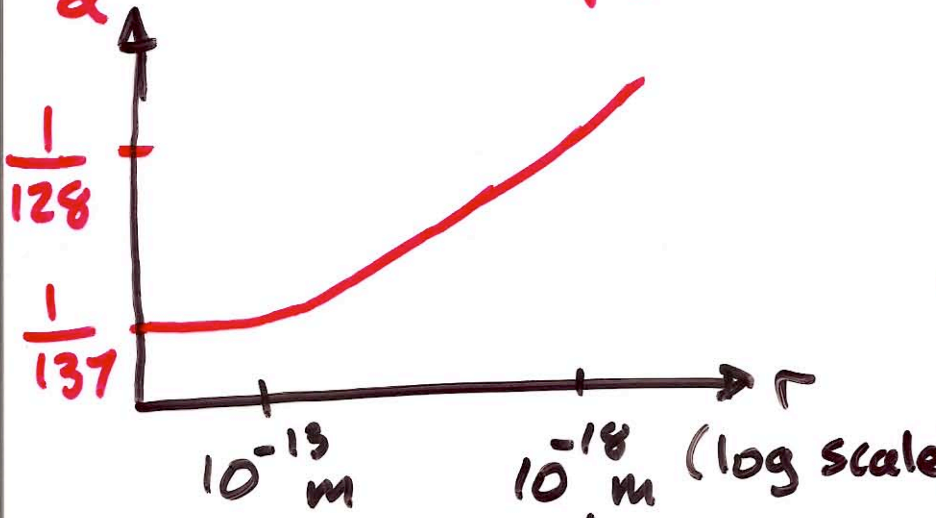
In quantum field theory, the vacuum is a medium which can screen charge.

QED

QCD

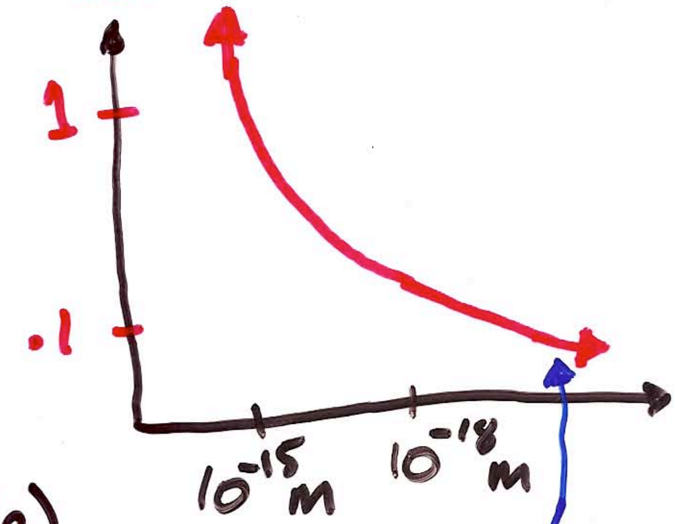


α: Force between electrons ~ $\frac{\alpha(r)}{r^2}$



experiments at CERN

α_{QCD}



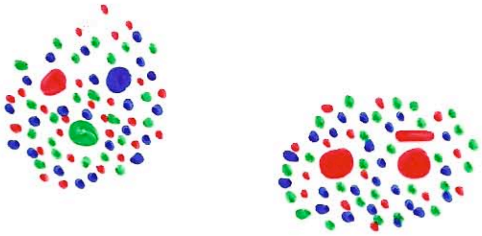
asymptotic freedom, or anti-screening. (That's why Friedman, Kendall, Taylor were able to see $_\wedge$ quarks.)
weakly interacting

Coupling "constants" not constant. Depend on scale at which you probe.

WHAT DOES QCD DESCRIBE?

It is an experimental fact that in the world around us quarks and gluons occur only in colorless, heavy packages:

protons, neutrons,...
pions, kaons,....



These hadrons are the quasiparticles of the QCD vacuum.

They, in turn, make up everything from nuclei to neutron stars, and thus most of the mass of you and me.

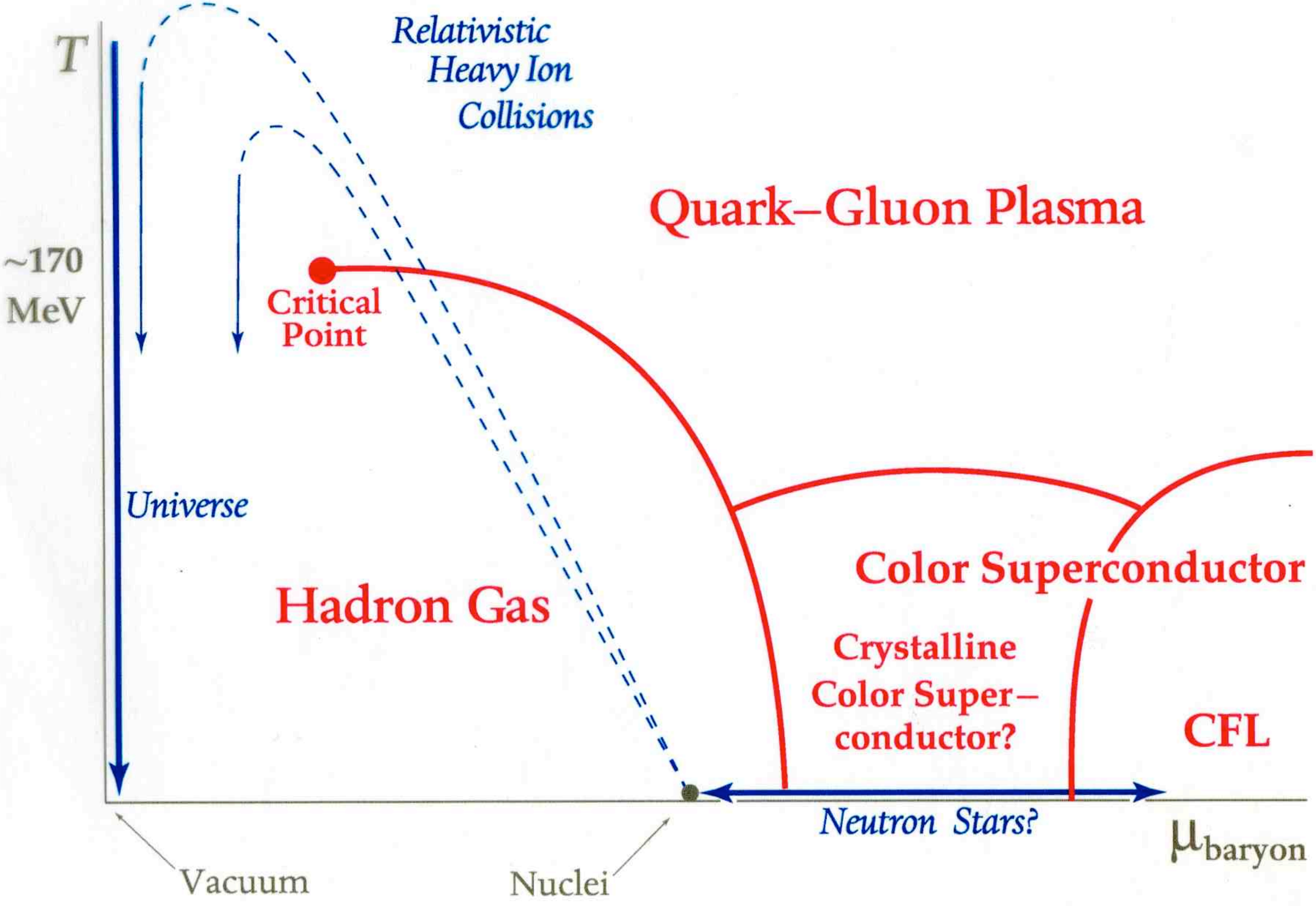
WHY STUDY QCD?
WHY IS IT A CHALLENGE?

- The only example we know of a strongly interacting gauge theory.
- We understand the theory at short distances
- The quasiparticles – the excitations of the vacuum – are hadrons, which do not look at all like the short distance quark and gluon degrees of freedom.

HOW DO WE RESPOND TO THE CHALLENGE?

- Study the spectrum, properties, and structure of the hadrons.
- Get away from the vacuum. Understand other phases of QCD, and their quasiparticles. Map the QCD phase diagram.

EXPLORING *the* PHASES *of* QCD



Quark-Gluon Plasma

- The $T \to \infty$ phase of QCD. Entropy wins over order; symmetries of this phase are those of the QCD Lagrangian.

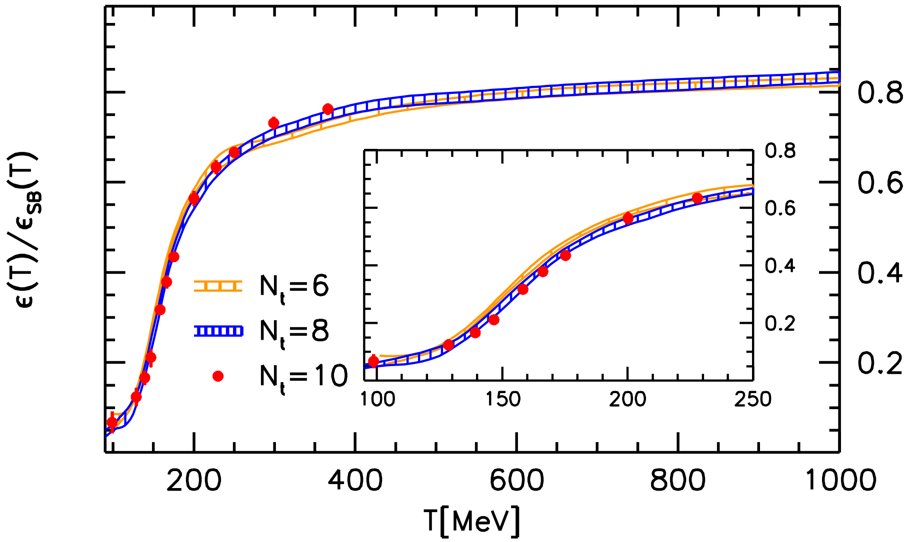
- Asymptotic freedom tells us that, for $T \to \infty$, QGP must be weakly coupled quark and gluon quasiparticles.

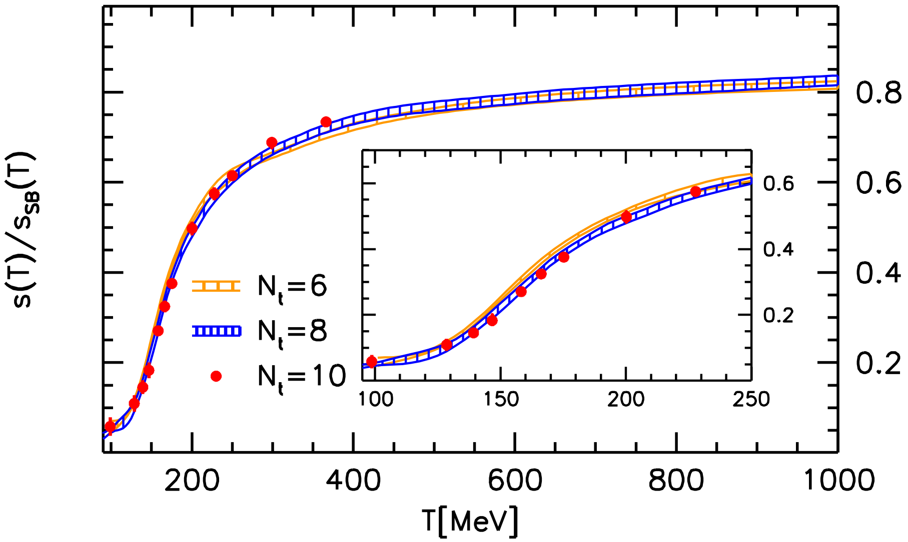
- Lattice calculations of QCD thermodynamics reveal a smooth crossover, like the ionization of a gas, occurring in a narrow range of temperatures centered at a $T_c \simeq 175$ MeV $\simeq$ 2 trillion °C $\sim$ 20 μs after big bang. At this temperature, the QGP that filled the universe broke apart into hadrons and the symmetry-breaking order that characterizes the QCD vacuum developed.

- Experiments now producing droplets of QGP at temperatures several times T_c, reproducing the stuff that filled the few-microseconds-old universe.

QGP Thermodynamics on the Lattice

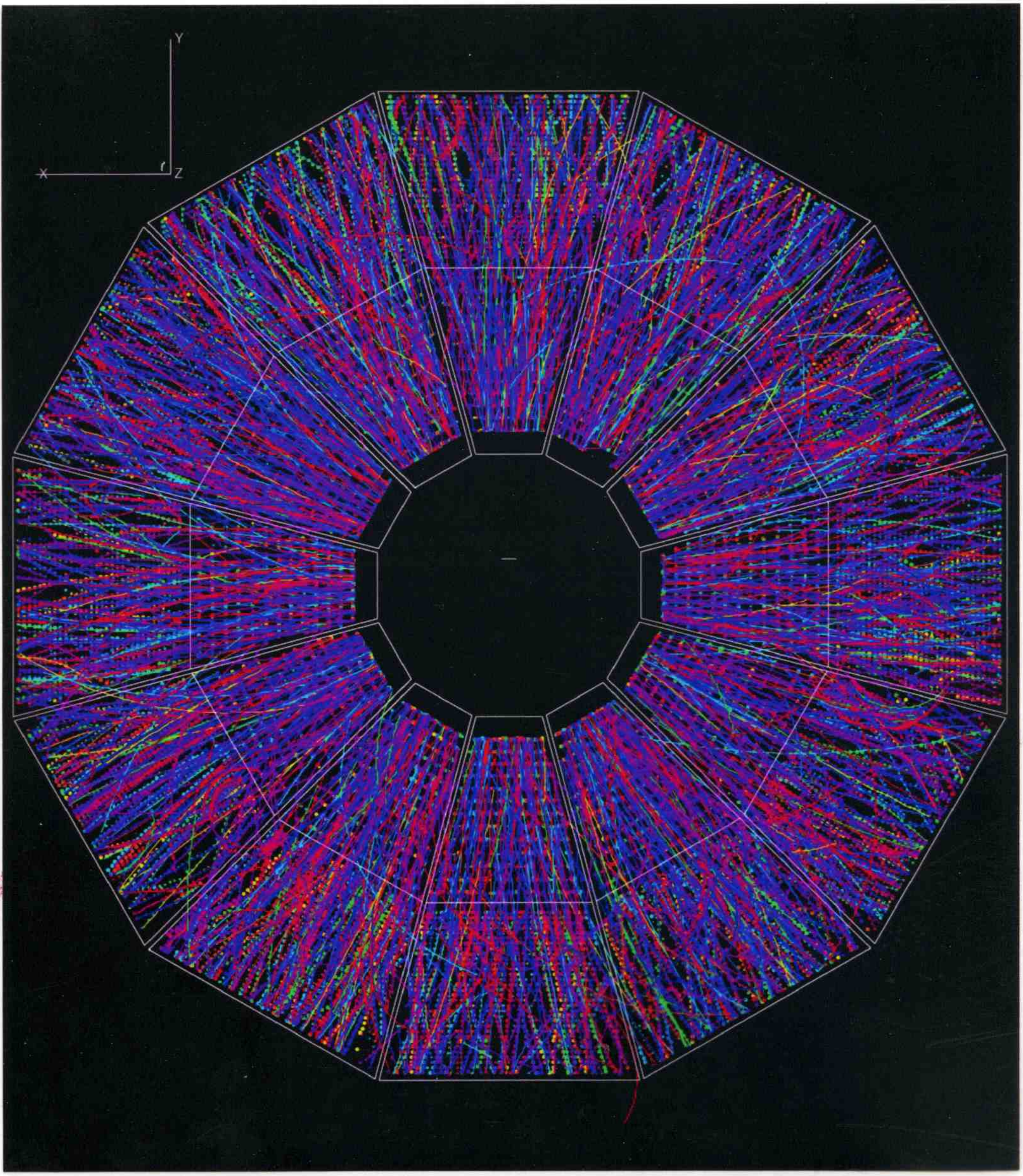
Endrodi et al. 2010





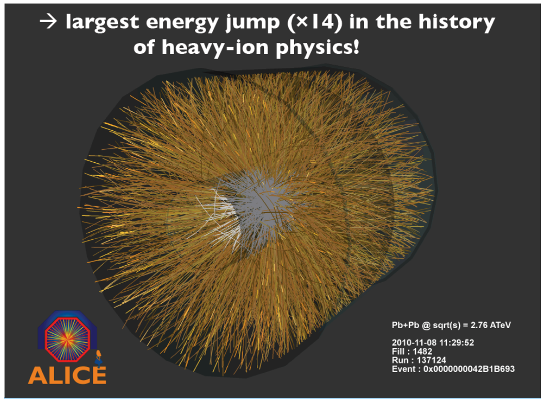
Above $T_{\text{crossover}} \sim$ 150-200 MeV, QCD = QGP. QGP static properties can be studied on the lattice.

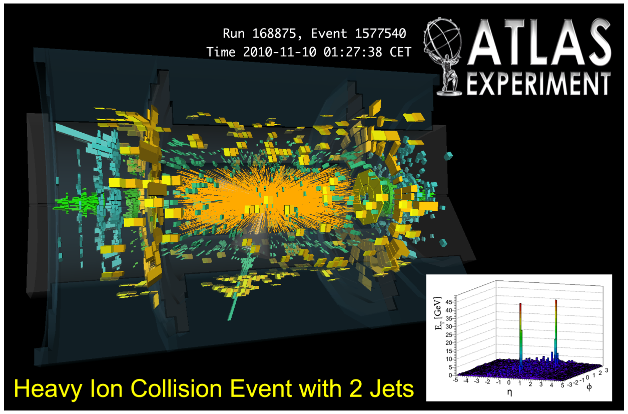
Lesson of the past decade: don't try to infer dynamic properties from static ones. Although its thermodynamics is almost that of ideal-noninteracting-gas-QGP, this stuff is very different in its dynamical properties. [Lesson from experiment+hydrodynamics. But, also from the large class of gauge theories with holographic duals whose plasmas have ε and s at infinite coupling 75% that at zero coupling.]

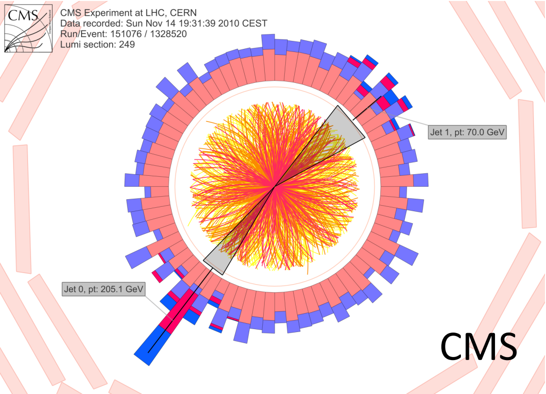


STAR

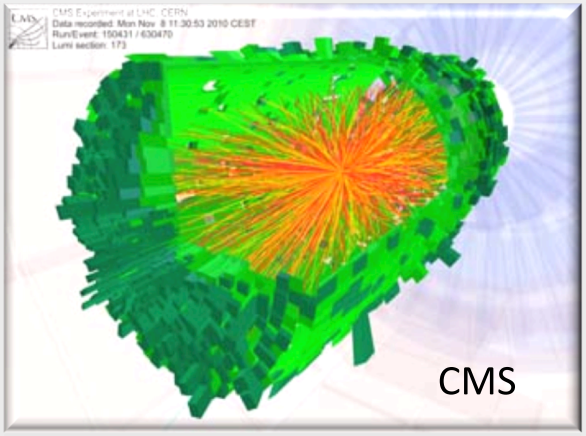
Nov 2010 first LHC Pb+Pb collisions


→ largest energy jump (×14) in the history of heavy-ion physics!





CMS



CMS

$\sqrt{s_{NN}}$ = 2760 GeV

Integrated
Luminosity = 10 μb^{-1}

Liquid Quark-Gluon Plasma

- Hydrodynamic analyses of RHIC data on how asymmetric blobs of Quark-Gluon Plasma expand (explode) have taught us that QGP is a strongly coupled liquid, with (η/s) — the dimensionless characterization of how much dissipation occurs as a liquid flows — much smaller than that of all other known liquids except one.

- The discovery that it is a strongly coupled liquid is what has made QGP interesting to a broad scientific community.

- Can we make quantitative statements, with reliable error bars, about η/s?

- Does the story change at the LHC?

Ultracold Fermionic Atom Fluid

- The one terrestrial fluid with η/s comparably small to that of QGP.

- NanoKelvin temperatures, instead of TeraKelvin.

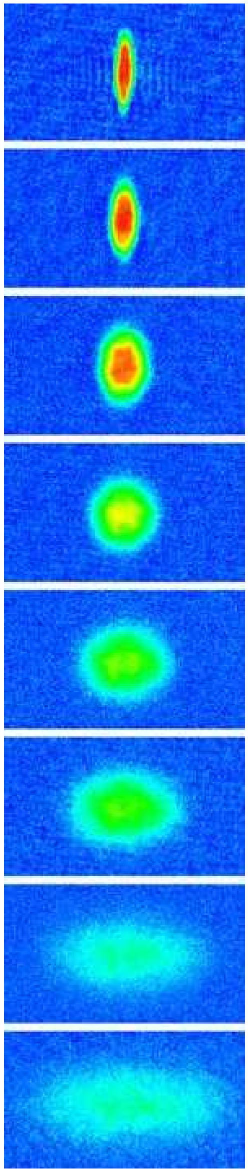
- Ultracold cloud of trapped fermionic atoms, with their two-body scattering cross-section tuned to be infinite. A strongly coupled liquid indeed. (Even though it's conventionally called the "unitary Fermi gas".)

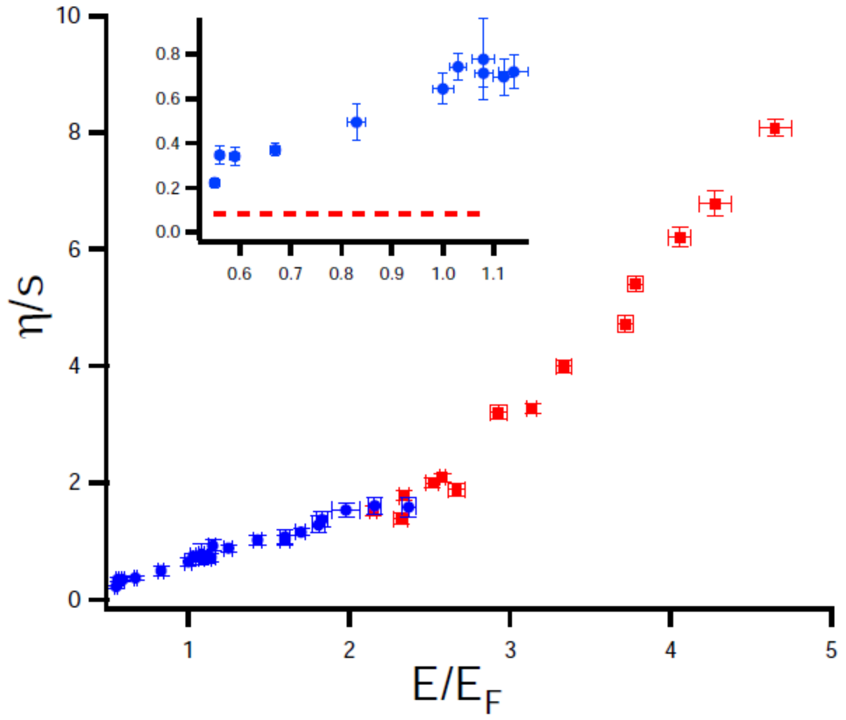
- Data on elliptic flow (and other hydrodynamic flow patterns that can be excited) used to extract η/s as a function of temperature...

Viscosity to entropy density ratio

consider both collective modes (low T)

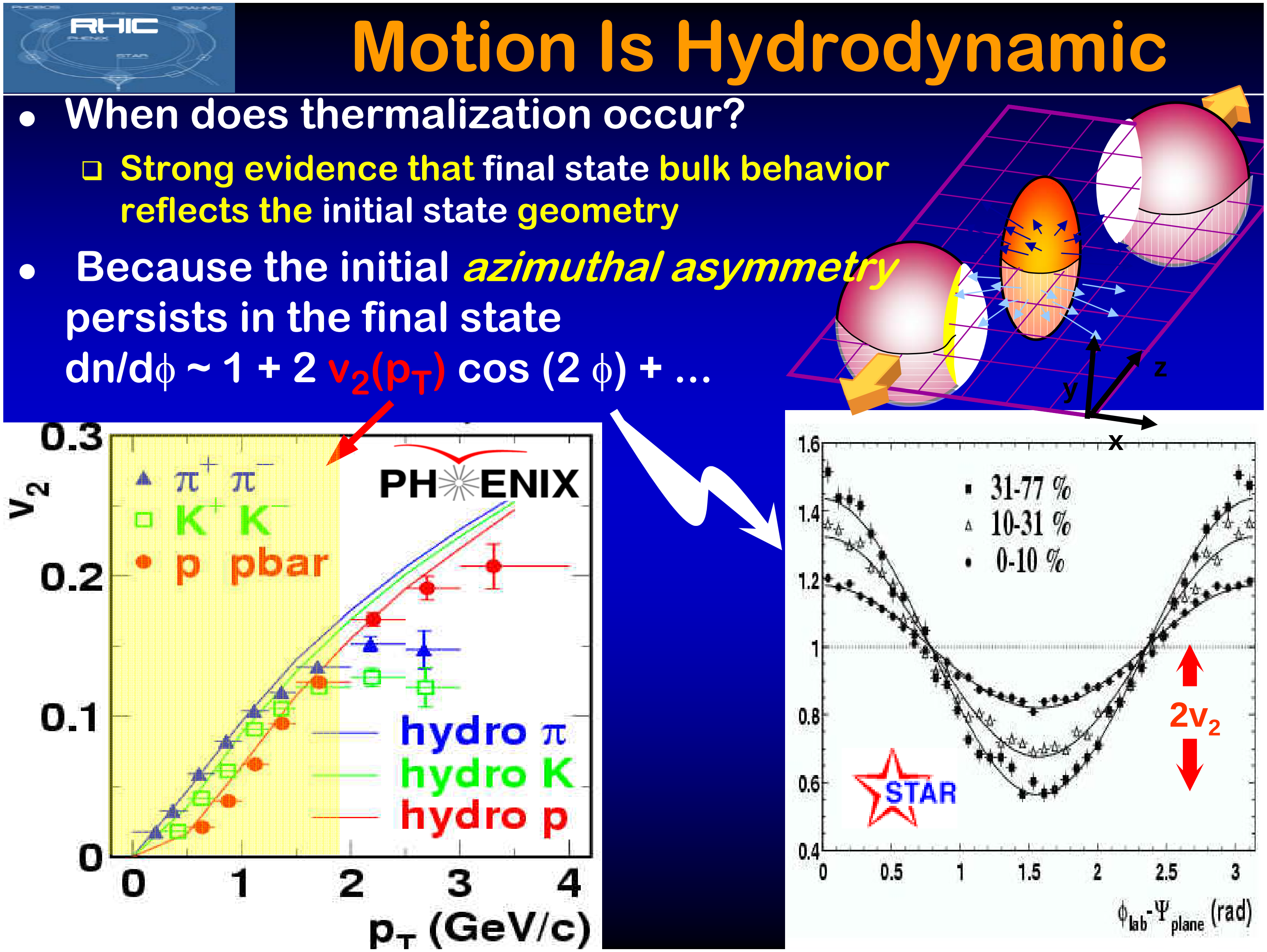
and elliptic flow (high T)





Cao et al., Science (2010)

$$\eta/s \leq 0.4$$



RHIC

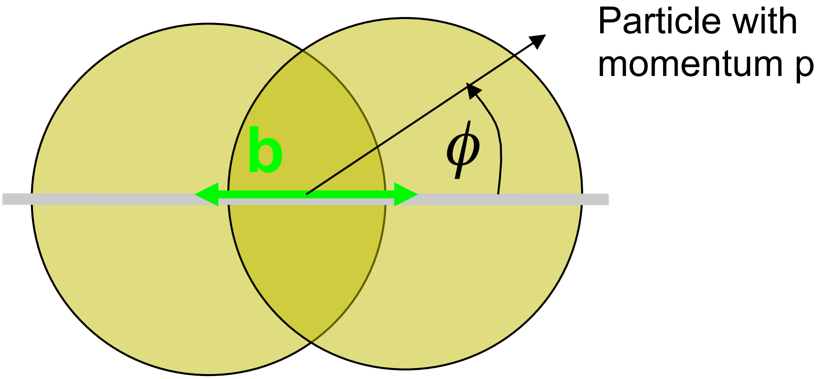
Motion Is Hydrodynamic

- When does thermalization occur?
  - Strong evidence that final state bulk behavior reflects the initial state geometry
- Because the initial *azimuthal asymmetry* persists in the final state
  $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

This old slide (Zajc, 2008) gives a sense of how data and hydrodynamic calculations of v_2 are compared, to extract η/s.

Particle production w.r.t. reaction plane

Consider single inclusive particle momentum spectrum



$$f(\vec{p}) \equiv dN/E\,d\vec{p}$$

$$\vec{p} = \begin{pmatrix} p_x = p_T \cos\phi \\ p_y = p_T \sin\phi \\ p_z = \sqrt{p_T^2 + m^2}\,\sinh Y \end{pmatrix}$$

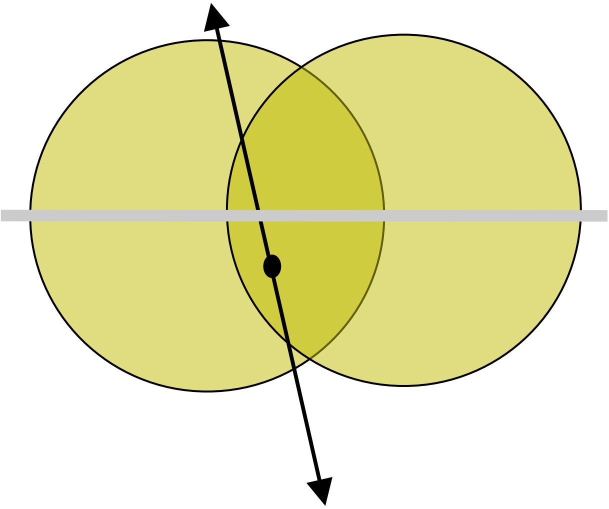
To characterize azimuthal asymmetry, measure n-th harmonic moment of f(p).

$$v_n \equiv \left\langle\left\langle e^{i n \phi} \right\rangle\right\rangle = \left\langle \frac{\int d\vec{p}\, e^{i n \phi} f(\vec{p})}{\int d\vec{p}\, f(\vec{p})} \right\rangle_{\substack{event \\ average}}$$

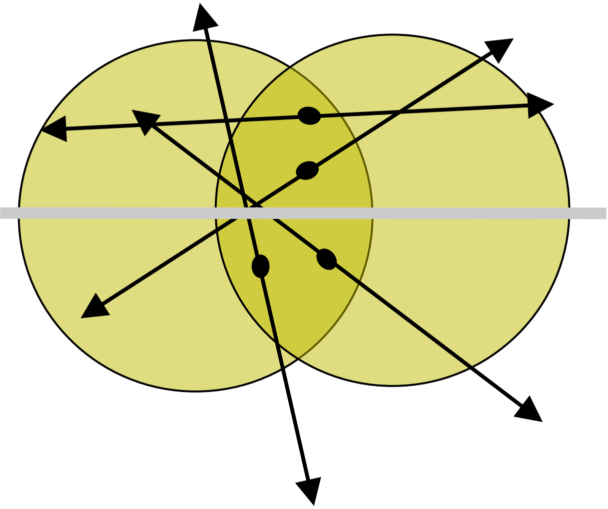
n-th order flow

<u>Problem</u>: This expression cannot be used for data analysis, since the orientation of the reaction plane is not known a priori.

How to measure flow?



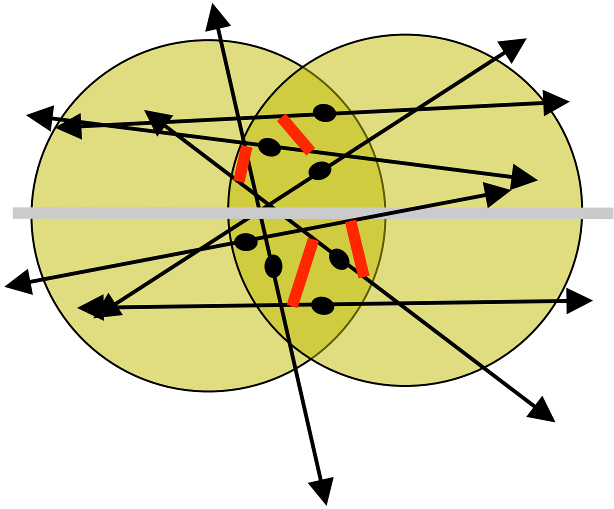
- “Dijet” process
- Maximal asymmetry
- NOT correlated to the reaction plane



- Many 2->2 or 2-> n processes
- Reduced asymmetry

  $\sim 1/\sqrt{N}$

- NOT correlated to the reaction plane

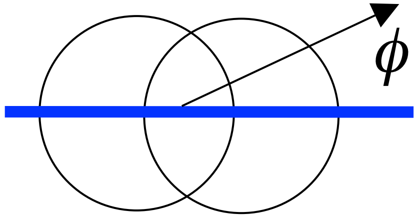


- final state interactions
- asymmetry caused not only by multiplicity fluctuations
- collective component is correlated to the reaction plane

The azimuthal asymmetry of particle production has a collective and a random component. Disentangling the two requires a statistical analysis of finite multiplicity fluctuations.

Measuring flow – one procedure

- Want to measure particle production as function of angle w.r.t. reaction plane



$$\boxed{v_n(D) = \left\langle e^{i n \phi} \right\rangle_D}$$

But reaction plane is unknown ...

- Have to measure particle correlations:

$$\left\langle e^{i n(\phi_1 - \phi_2)} \right\rangle_{D_1 \wedge D_2} = v_n(D_1)\, v_n(D_2) + \boxed{\left\langle e^{i n(\phi_1 - \phi_2)} \right\rangle^{corr}_{D_1 \wedge D_2}}$$

"Non-flow effects"

$$\boxed{\sim O(1/N)}$$

But this requires signals $v_n > \frac{1}{\sqrt{N}}$

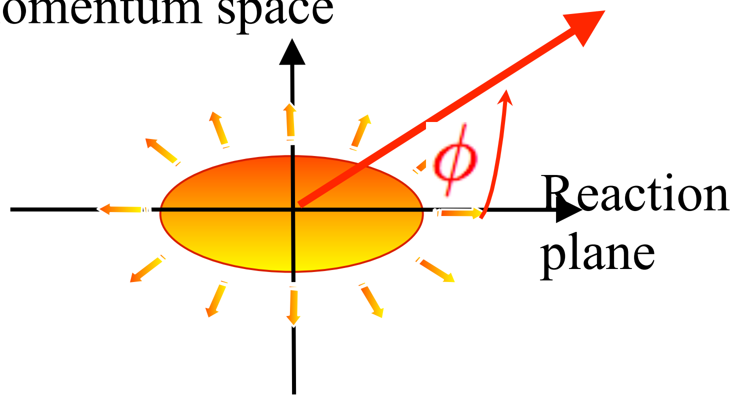
- Improve measurement with higher cumulants: Borghini, Dinh, Ollitrault, PRC (2001)

$$\left\langle e^{i n(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \right\rangle - \left\langle e^{i n(\phi_1 - \phi_3)} \right\rangle \left\langle e^{i n(\phi_2 - \phi_4)} \right\rangle - \left\langle e^{i n(\phi_1 - \phi_4)} \right\rangle \left\langle e^{i n(\phi_2 - \phi_3)} \right\rangle = -v_n^4 + O\left(1/N^3\right)$$

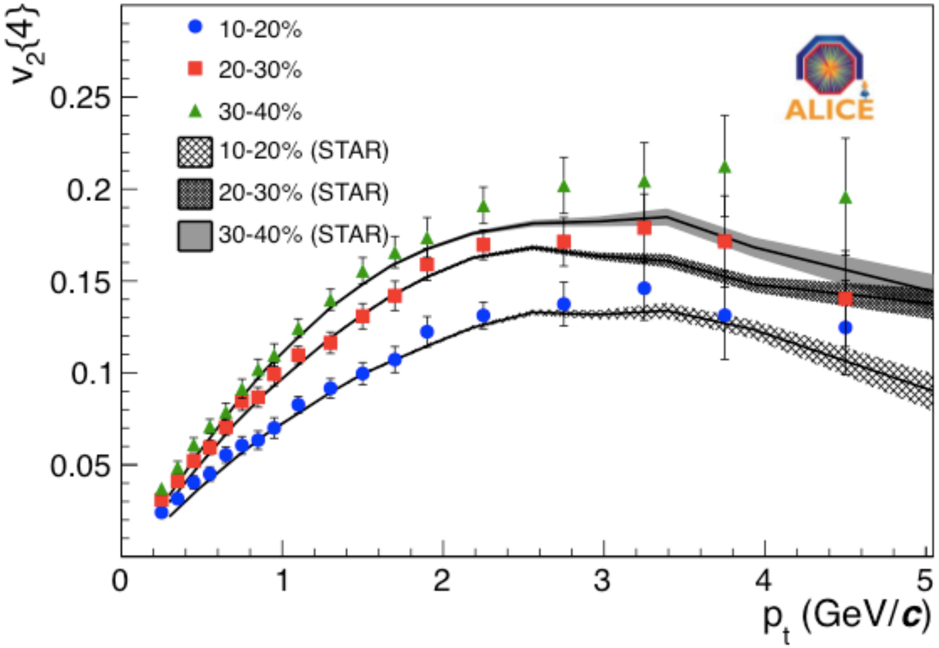
This requires signals $v_n > \frac{1}{N^{3/4}}$

v_2 @ LHC

- Momentum space



$$\frac{dN}{d\phi\, p_T dp_T} \propto \left[1+2v_2(p_T)\cos(2\phi)\right]$$



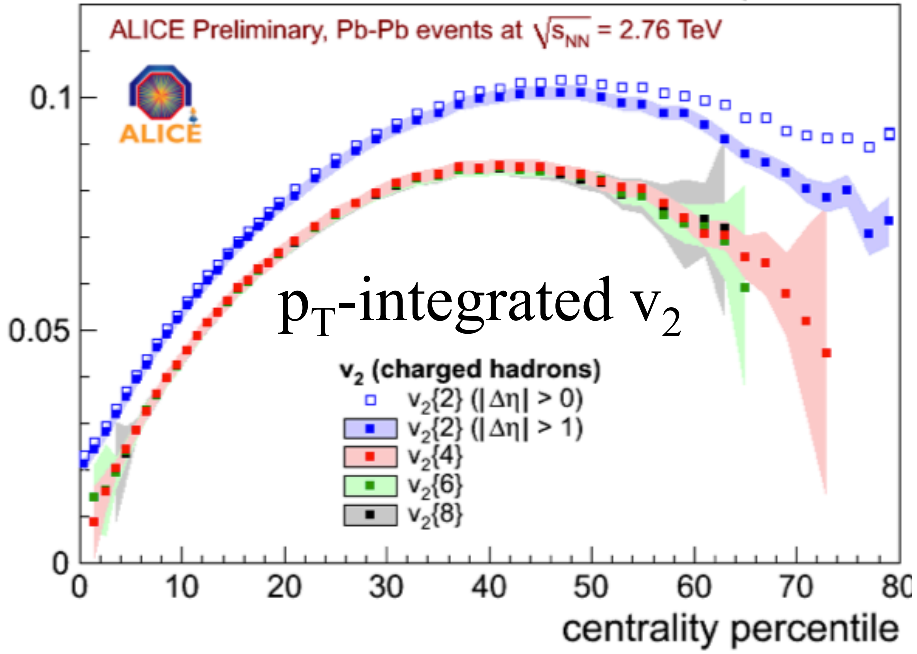
- Signal $v_2 \approx 0.2$ implies 2-1 asymmetry of particles production w.r.t. reaction plane.
- 'Non-flow' effect for 2nd order cumulants

$$N \sim 100-1000 \Rightarrow 1/\sqrt{N} \sim 0.1 \sim O(v_2)\,??$$

2nd order cumulants do not characterize solely collectivity.

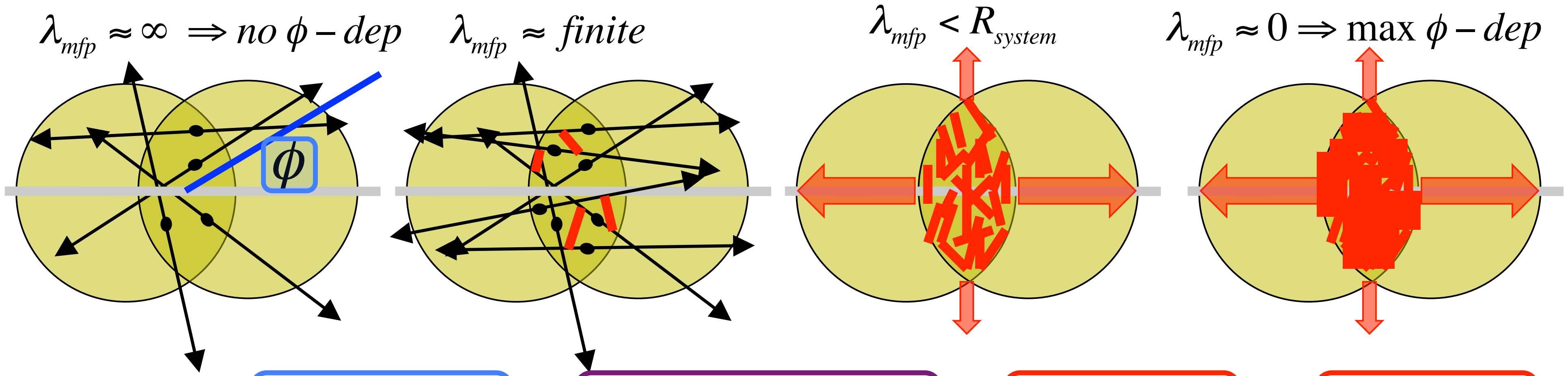
$$1/N^{3/4} \ \sim\le 0.03 \ll v_2$$

→ **Strong Collectivity !**



The appropriate dynamical framework

- depends on mean free path
  (more precisely: depends on applicability of a quasi-particle picture)



$\lambda_{mfp} \approx \infty \Rightarrow no\ \phi - dep$

$\lambda_{mfp} \approx finite$

$\lambda_{mfp} < R_{system}$

$\lambda_{mfp} \approx 0 \Rightarrow \max\ \phi - dep$

Theory
tools:

Free streaming → Particle cascade (QCD transport theory) → Dissipative fluid dynamics → Perfect fluid dynamics

System p+p ?? … pA …?? … AA … ??

Rapid Equilibration?

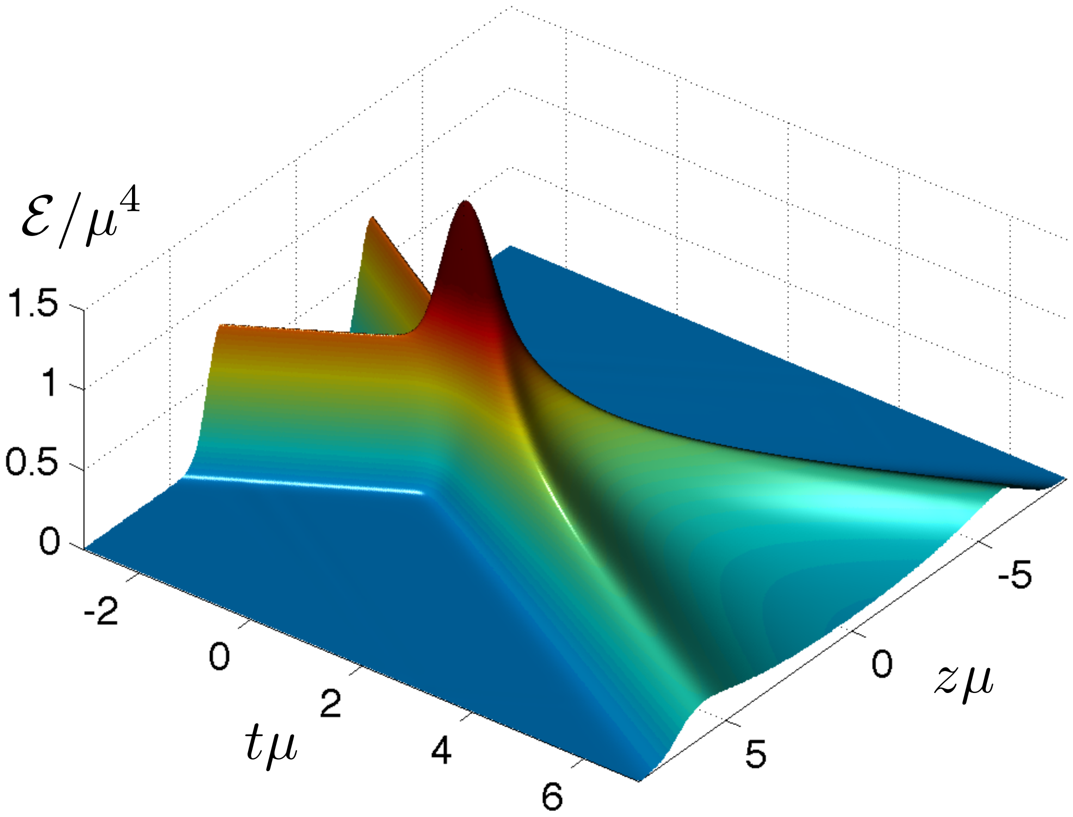
- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.

- Long-standing estimate is that a hydrodynamic description must already be valid only 1 fm after the collision.

- This has always been seen as *rapid equilibration*. Weak coupling estimates suggest equilbration times of 3-5 fm. And, 1 fm just sounds rapid.

- But, is it really? How rapidly does equilibration occur in a strongly coupled theory?

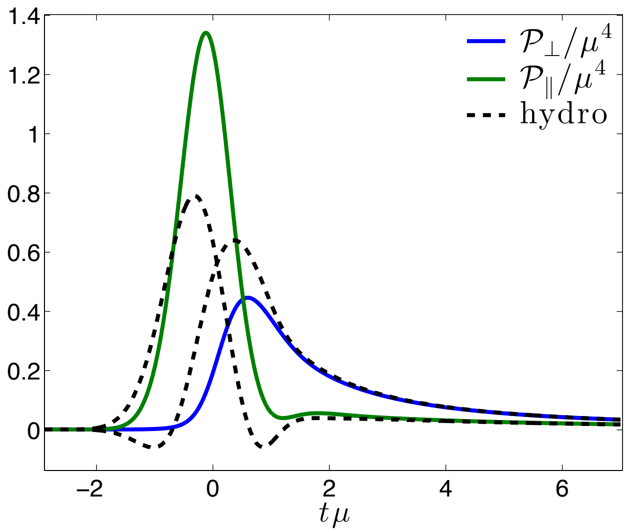
Colliding Strongly Coupled Sheets of Energy



Hydrodynamics valid ~ 3 **sheet thicknesses after the collision, i.e.** ~ 0.35 **fm after a RHIC collision. Equilibration after** ~ 1 **fm need not be thought of as rapid.** Chesler, Yaffe arXiv:1011.3562

Similarly 'rapid' hydrodynamization times ($\tau T \lesssim 0.7 - 1$) **found for** *many* **non-expanding or boost invariant initial conditions.** Heller et al, arXiv:1103.3452, 1202.0981, 1203.0755, 1304.5172

Anisotropic Viscous Hydrodynamics



Hydrodynamics valid so early that the hydrodynamic fluid is not yet isotropic. 'Hydrodynamization before isotropization.' An epoch when first order effects (spatial gradients, anisotropy, viscosity, dissipation) important. Hydrodynamics with entropy production.

This has now been seen in very many strongly coupled analyses of hydrodynamization. Janik et al., Chesler et al., Heller et al., ...

Could have been anticipated as a possibility without holography. But, it wasn't — because in a weakly coupled context isotropization happens first.

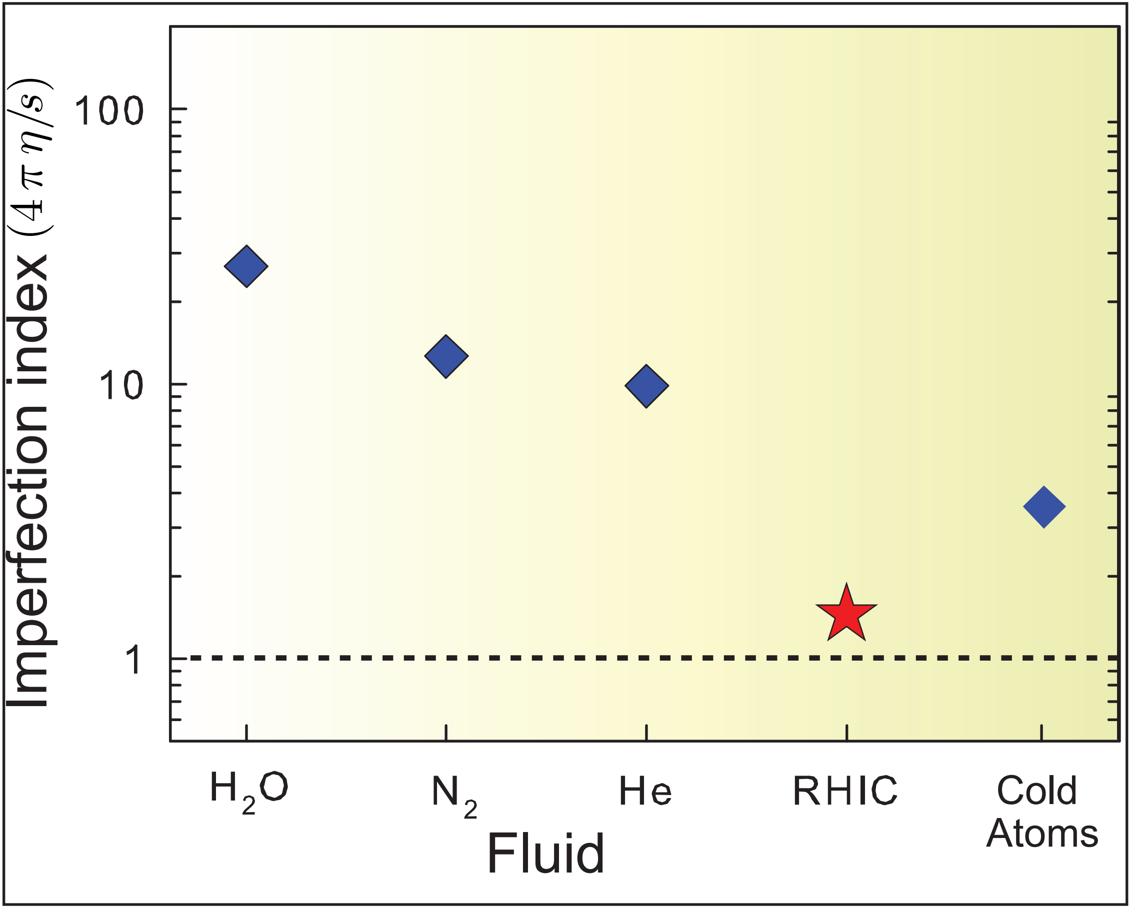
Determining η/s from RHIC data

- **Using relativistic viscous hydrodynamics to describe expanding QGP, microscopic transport to describe late-time hadronic rescattering, and using RHIC data on pion and proton spectra and v_2 as functions of p_T and impact parameter. . .**

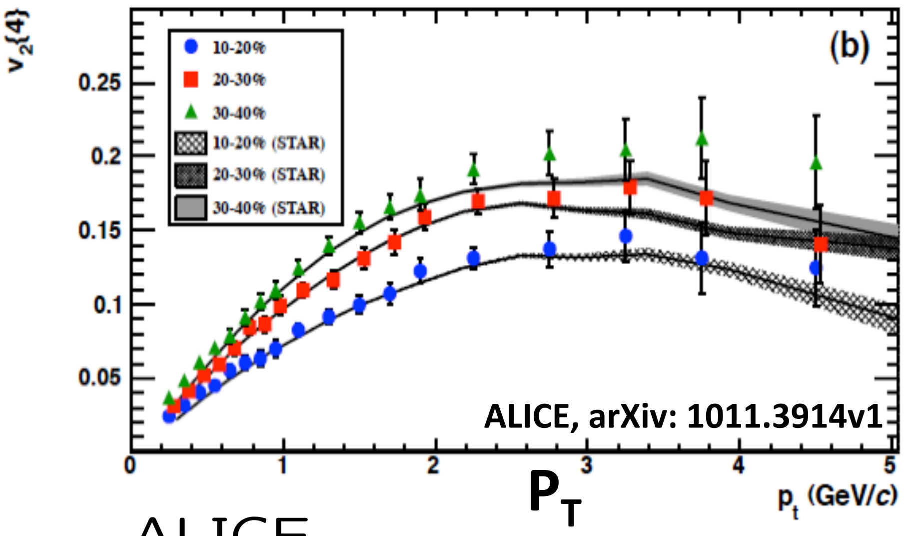
- **Circa 2010/2011: QGP@RHIC, with $T_c < T \lesssim 2T_c$, has $1 < 4\pi\eta/s < 2.5$. [Largest remaining uncertainty: assumed initial density profile across the "almond".]** Song, Bass, Heinz, Hirano, Shen arXiv:1101.4638

- **$4\pi\eta/s \sim 10^4$ for typical terrestrial gases, and 10 to 100 for all known terrestrial liquids except one. Hydrodynamics works much better for QGP@RHIC than for water.**

- **$4\pi\eta/s = 1$ for any (of the by now very many) known strongly coupled gauge theory plasmas that are the "hologram" of a (4+1)-dimensional gravitational theory "heated by" a (3+1)-dimensional black-hole horizon.**

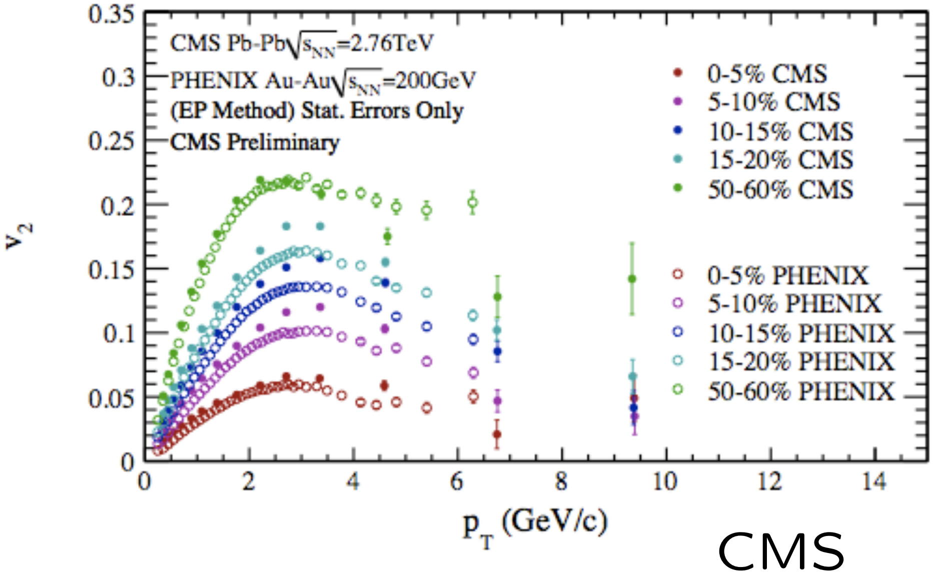

Imperfection index ($4\pi\eta/s$)
100
10
1
H_2O
N_2
He
RHIC
Cold Atoms
Fluid

What changes at the LHC?



ALICE, arXiv: 1011.3914v1

ALICE

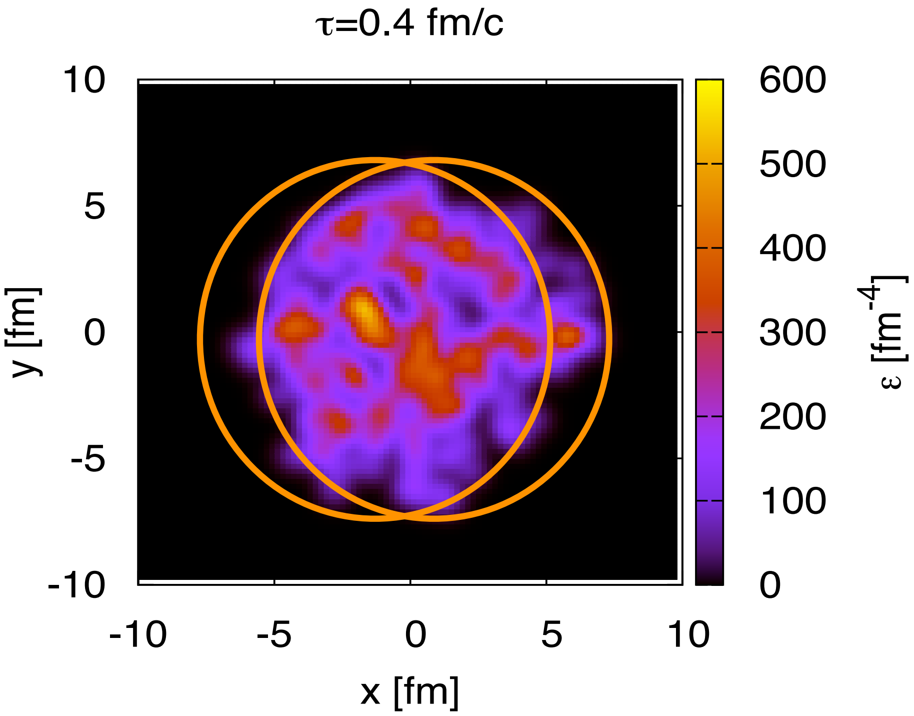


CMS

$v_2(p_T)$ for charged hadrons similar at LHC and RHIC. At zeroth order, no apparent evidence for any change in η/s. The hotter QGP at the LHC is still a strongly coupled liquid.

Quantifying this, i.e. constraining the (small) temperature dependence of η/s in going from RHIC to LHC, requires separating effects of η/s from effects of initial density profile across the almond.

Determining the Shear Viscosity of QGP: Using Fluctuations to Beat Down the Initial State Uncertainties



1. Characterize energy density with ellipse

   Elliptic Shape gives elliptic flow

$$v_2 = \langle \cos 2\phi_{\mathbf{p}} \rangle$$

2. Around almond shape are *fluctuations*

   Triangular Shape $\longrightarrow v_3$ Alver, Roland, 2010

$$v_3 = \langle \cos 3(\phi_{\mathbf{p}} - \Psi_3) \rangle$$

3. Hot-spots give *correlated* higher harmonics

$$v_n = \langle \cos n(\phi_{\mathbf{p}} - \Psi_n) \rangle$$

Different harmonics depend differently on hot-spot size, damped differently by viscosity, and depend differently on system size, momentum. Experimental data on magnitude and correlations of higher harmonics can vastly overconstrain hydrodynamic predictions for QGP, and hence determination of η/s. Maybe even $\eta/s(T)$. A *flood* of data in 2011 and 2012.

Slide adapted from Teaney; image from Schenke, Jeon, Gale.

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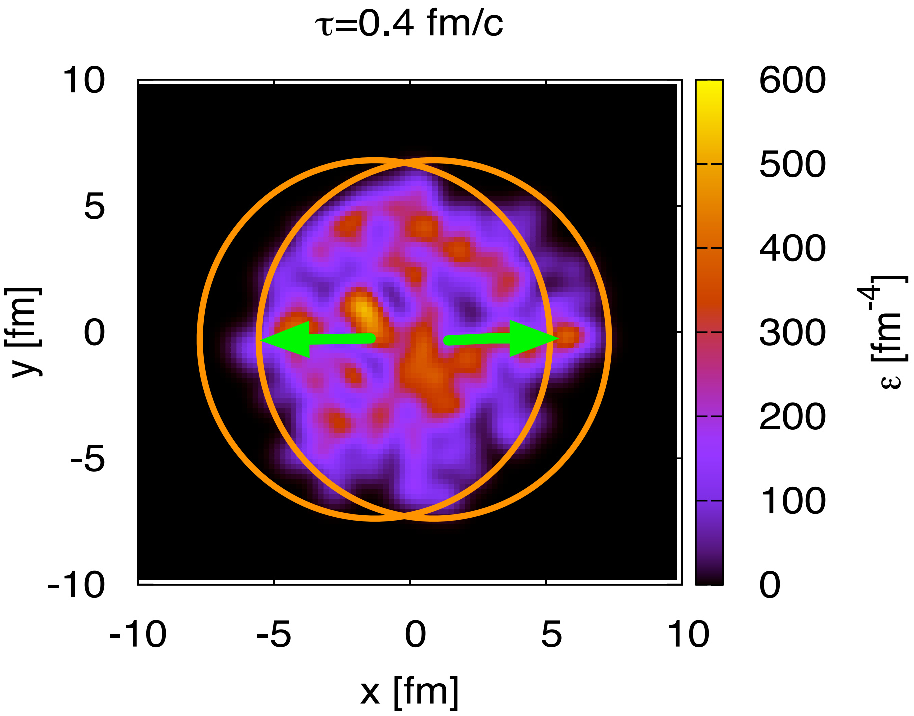

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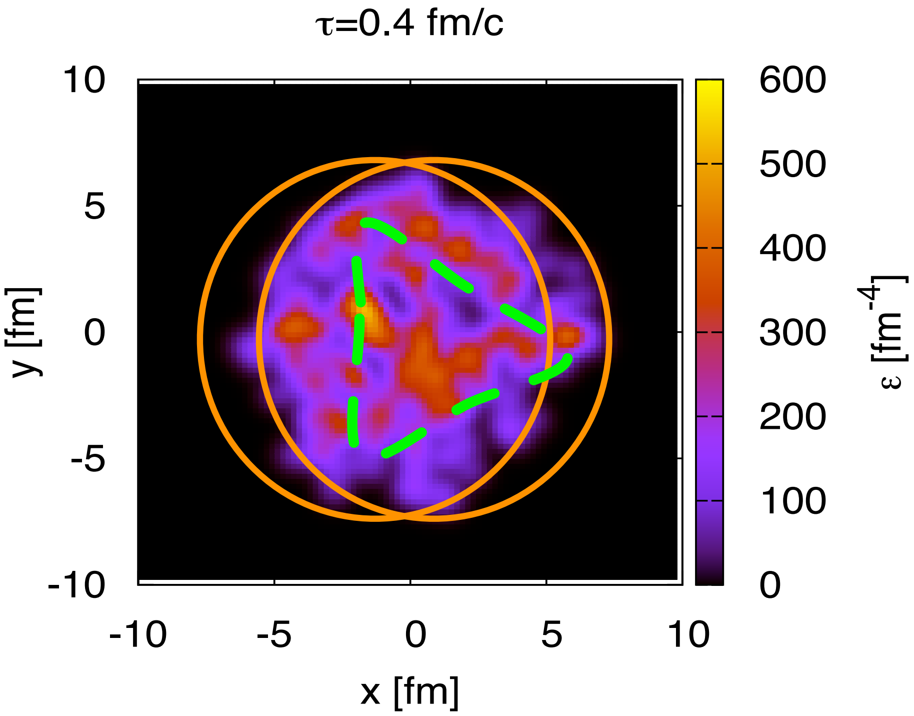

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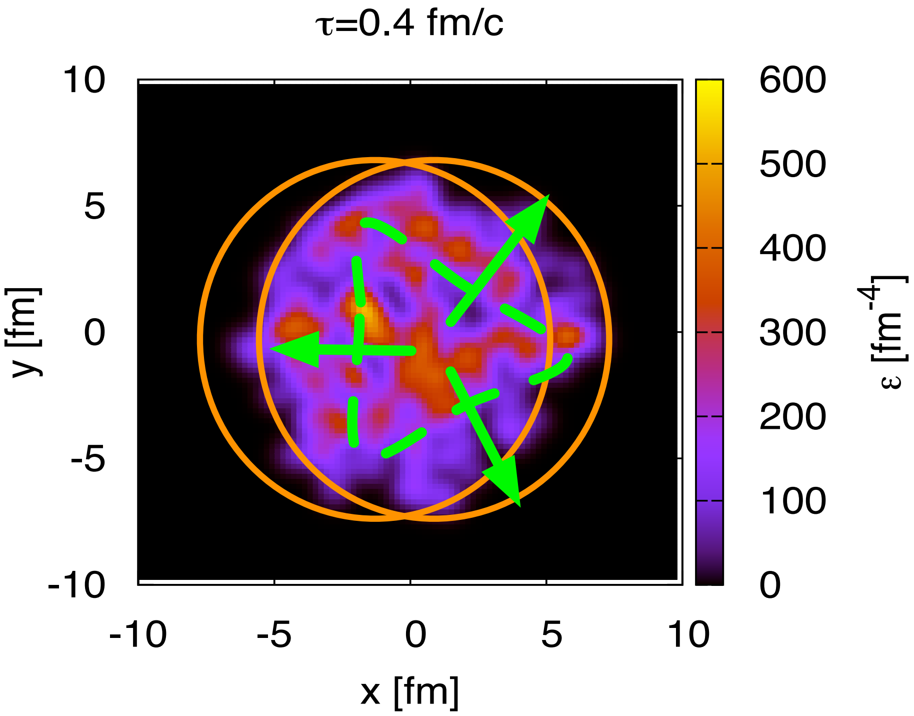
Determining the Shear Viscosity of QGP: Using Fluctuations to Beat Down the Initial State Uncertainties



1. Characterize energy density with ellipse

   Elliptic Shape gives elliptic flow

$$v_2 = \langle \cos 2\phi_{\mathbf{p}} \rangle$$

2. Around almond shape are *fluctuations*

   Triangular Shape $\longrightarrow v_3$ Alver, Roland, 2010

$$v_3 = \langle \cos 3(\phi_{\mathbf{p}} - \Psi_3) \rangle$$

3. Hot-spots give *correlated* higher harmonics

$$v_n = \langle \cos n(\phi_{\mathbf{p}} - \Psi_n) \rangle$$

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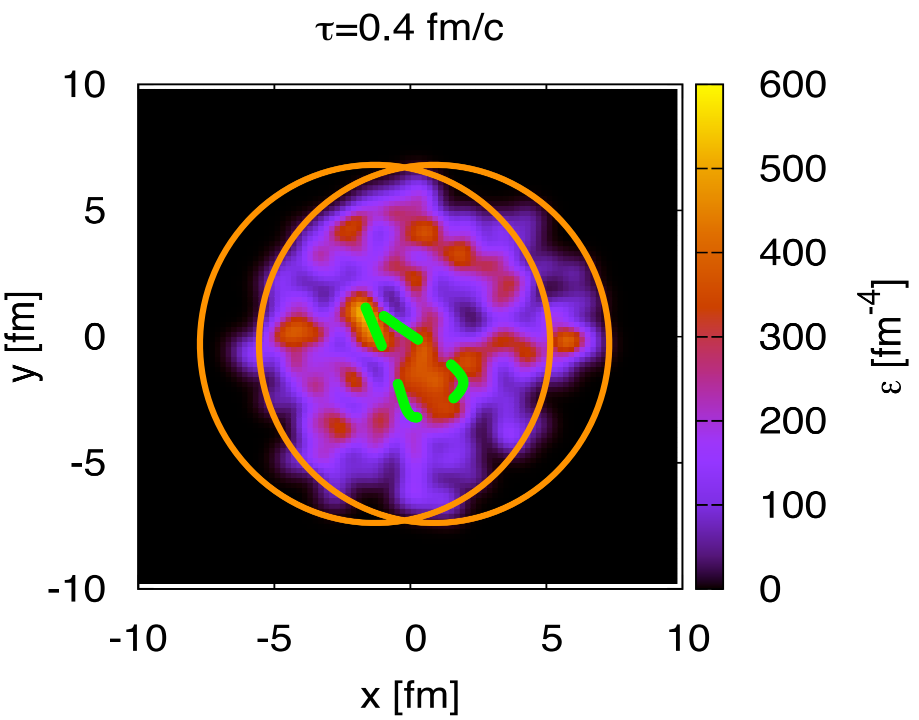

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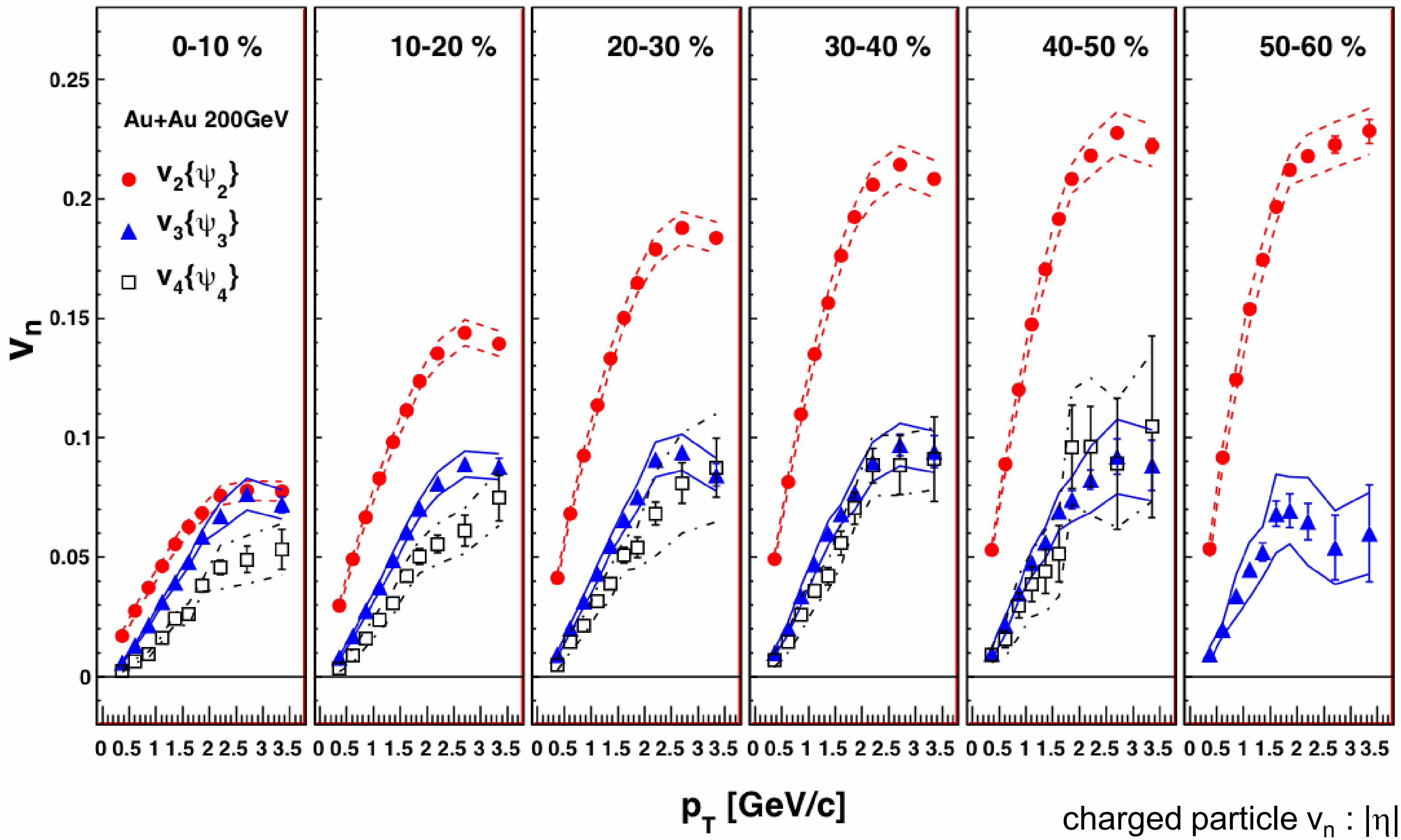
$v_2\{\Phi_2\}$, $v_3\{\Phi_3\}$, $v_4\{\Phi_4\}$ at 200GeV Au+Au

arXiv:1105.3928

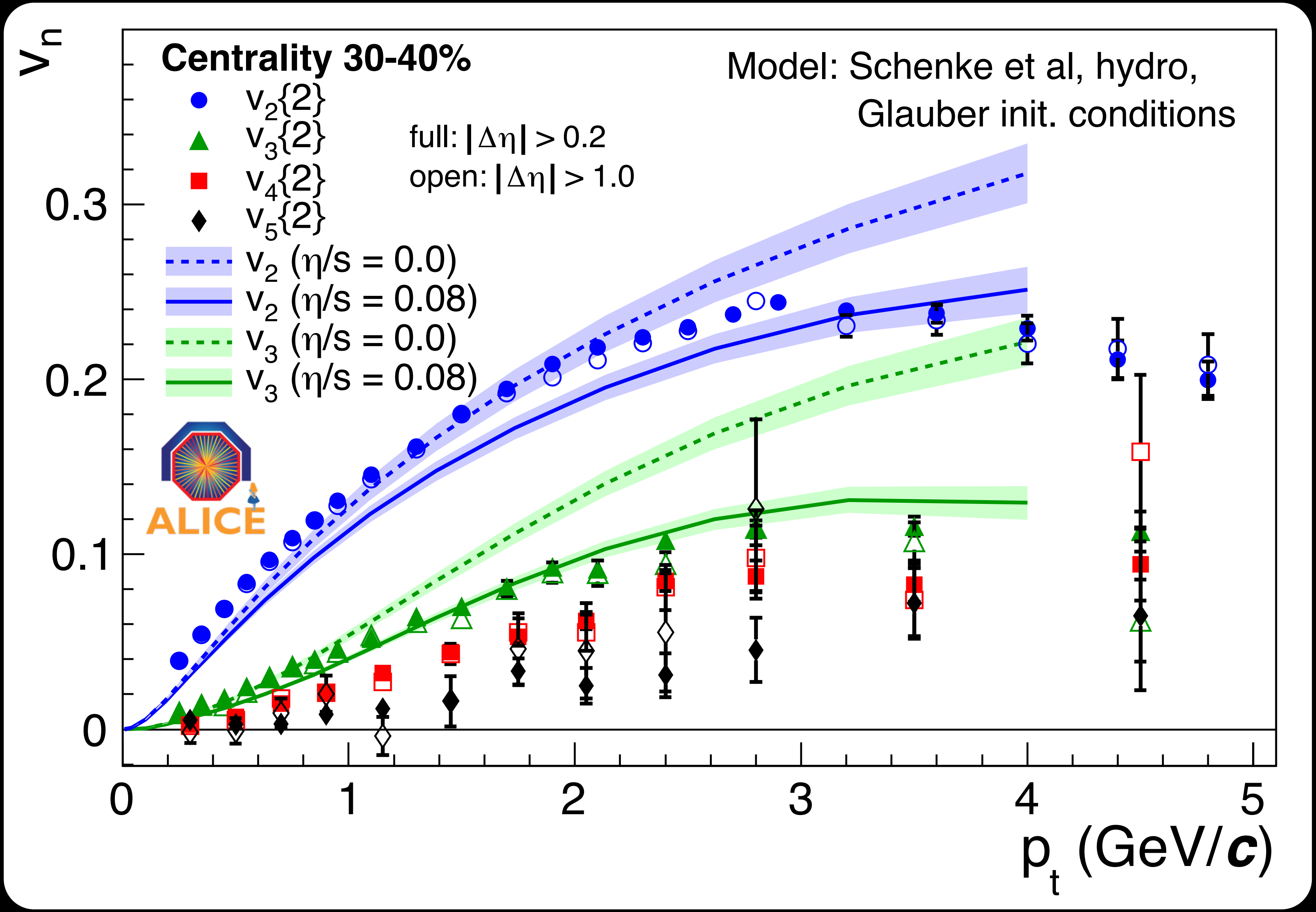


charged particle v_n : $|\eta|<0.35$
reaction plane Φ_n : $|\eta|=1.0\sim2.8$

(1) v_3 is comparable to v_2 at 0~10%
(2) weak centrality dependence on v_3
(3) $v_4\{\Phi_4\} \sim 2 \times v_4\{\Phi_2\}$

All of these are consistent with initial fluctuation.

Other Harmonics



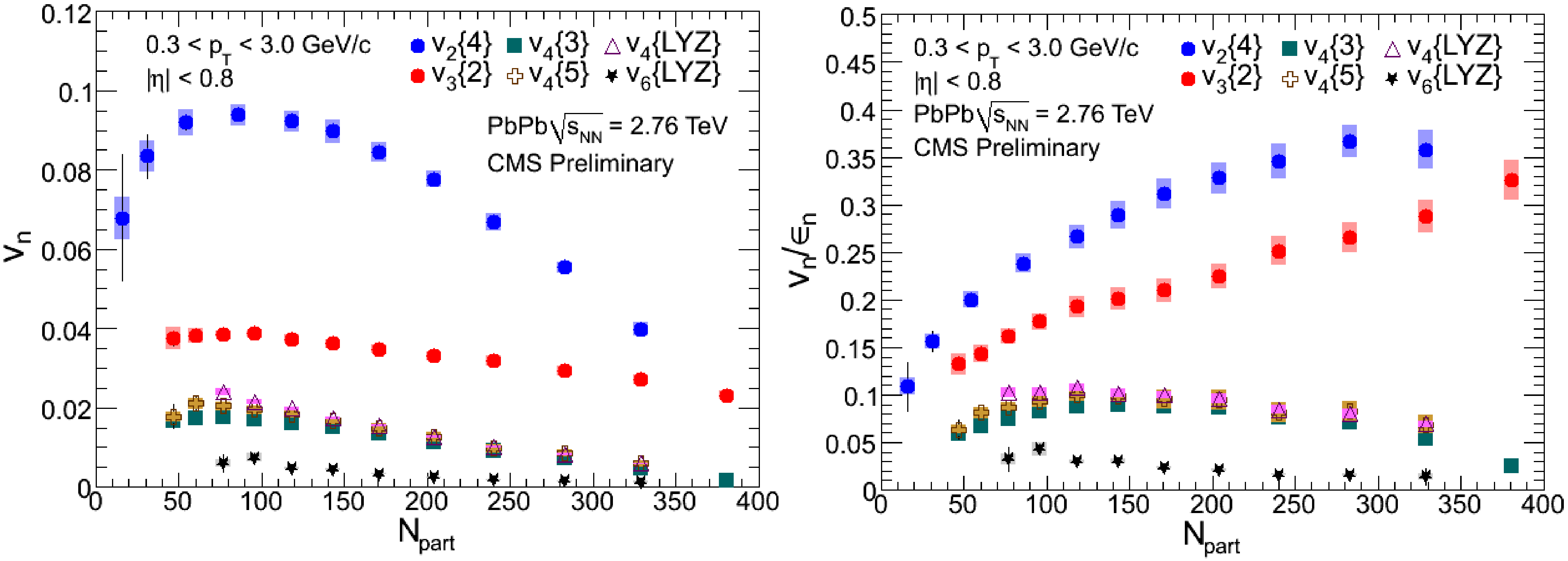
ALICE Collaboration, arXiv:1105.3865

see presentation A. Bilandzic

The overall dependence of v_2 and v_3 is described

However there is no simultaneous description with a single η/s of v_2 and v_3 for Glauber initial conditions

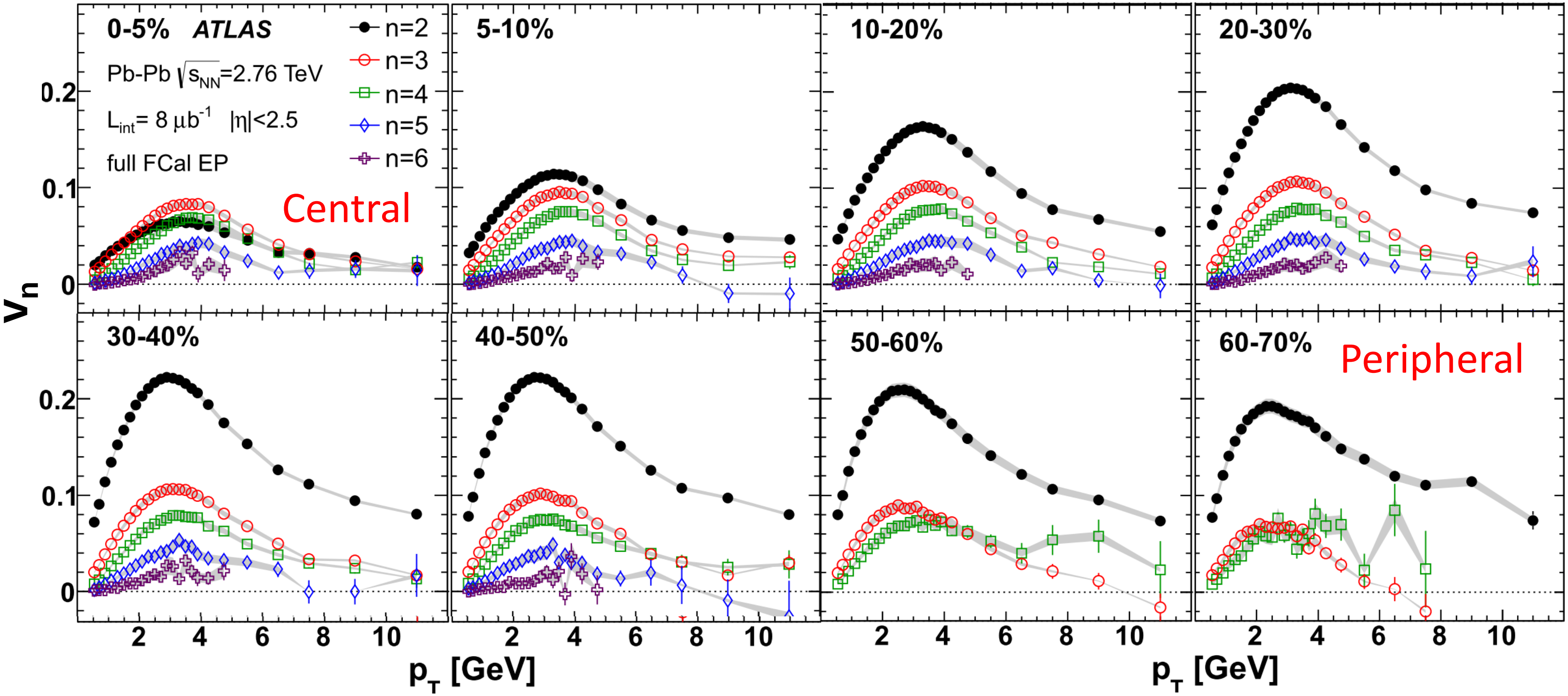
The full harmonic spectrum



- v_n vs N_{part} shows different trends:
  - even harmonics have similar centrality dependence:
    - decreasing → 0 with increasing N_{part}
  - v_3 has weak centrality dependence, finite for central collisions

Higher Order Flow Harmonics (v_2-v_6)

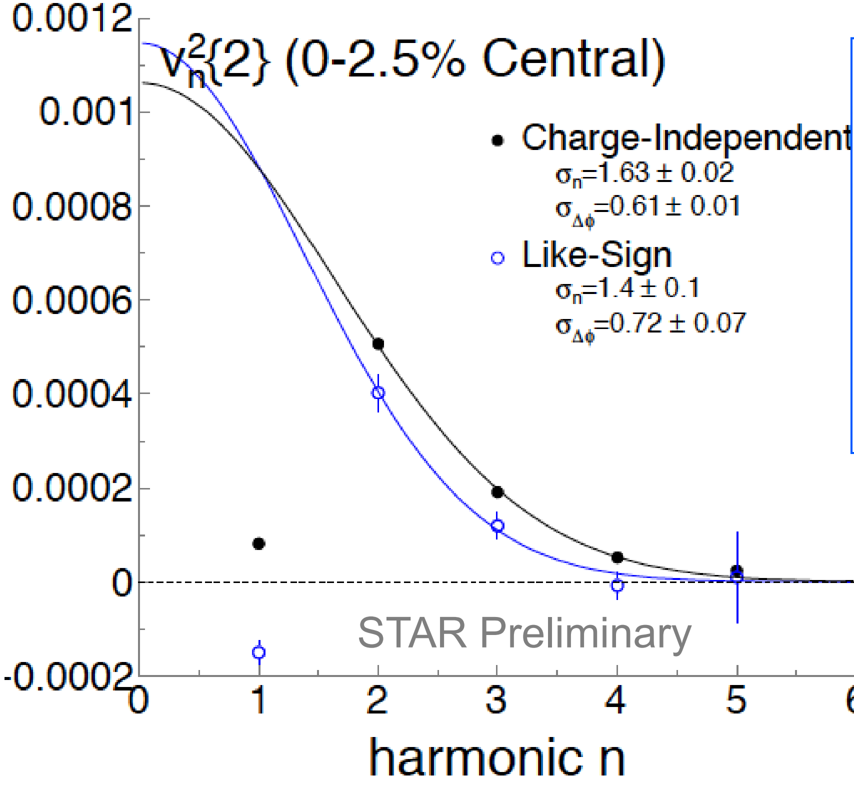
ATLAS, Phys. Rev. C 86, 014907 (2012)

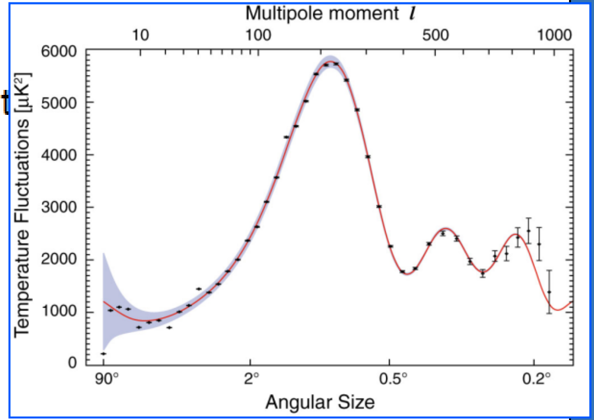


- Significant v_2 – v_6 are measured in broad range of p_T, η and centrality
- p_T dependence for all measured amplitudes show similar trend
- Stronger centrality dependence of v_2 than higher order harmonics
- In most central collisions (0-5%): v_3, v_4 can be larger than v_2

$v_n^2\{2\}$ vs n for 0-2.5% Central

This is the Power Spectrum of Heavy-Ion Collisions





|η|<1

$v_n\{4\}$ is zero for 0-2.5% central: look at $v_2^2\{2\}$ vs n to extract the power spectrum in nearly symmetric collisions

Fit by a Gaussian except for n=1. The width can be related to length scales like mean free path, acoustic horizon, 1/(2πT)…

P. Staig and E. Shuryak, arXiv:1008.3139 [nucl-th]
A. Mocsy, P. S., arXiv:1008.3381 [hep-ph]
A. Adare [PHENIX], arXiv:1105:3928

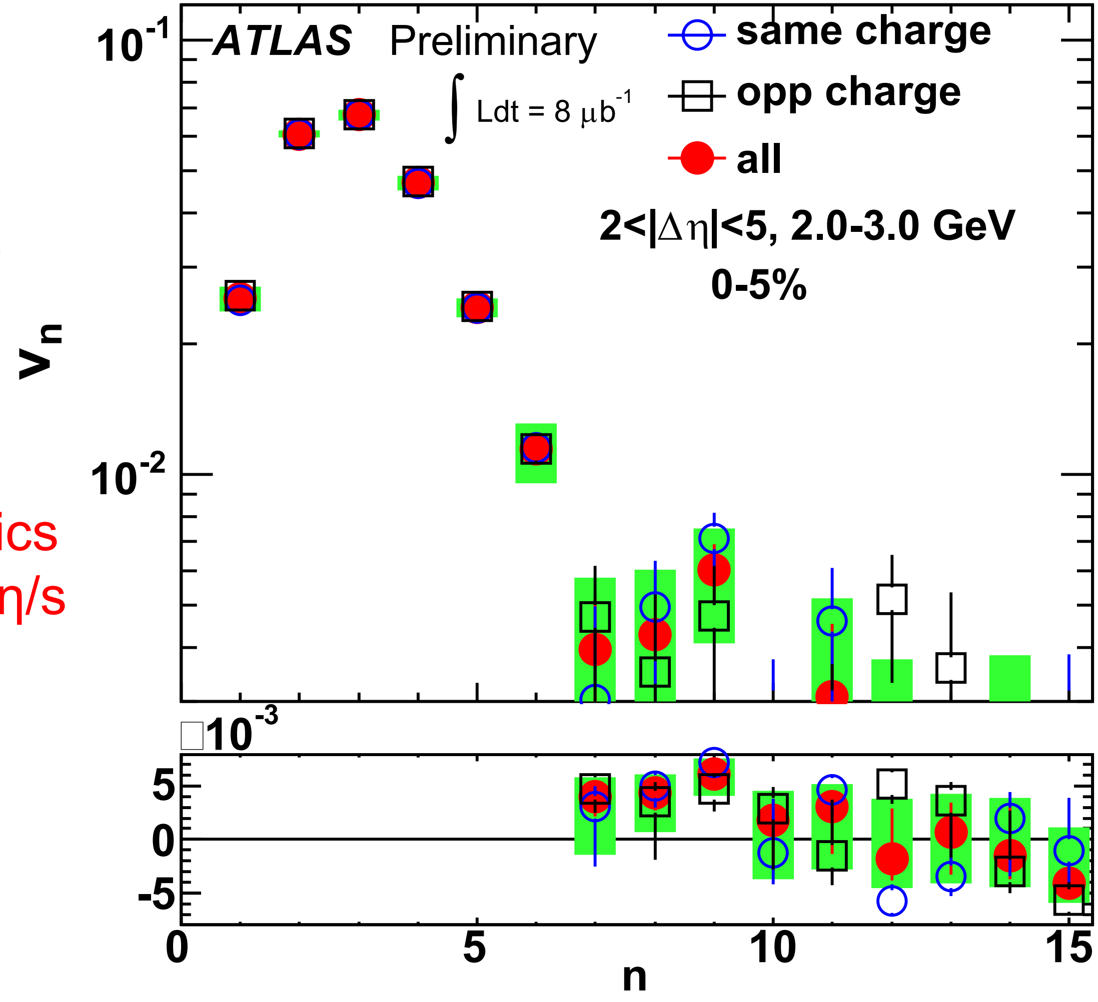
Integrates all Δη within acceptance: we can look more differentially to assess non-flow

Power spectra in azimuth angle

- v_n vs n for n=1-15 in 0-5% most central collisions and 2.0-3.0 GeV

Significant v_2-v_6 signal, higher order consistent with 0

Damping of higher order harmonics provides important constraint on η/s



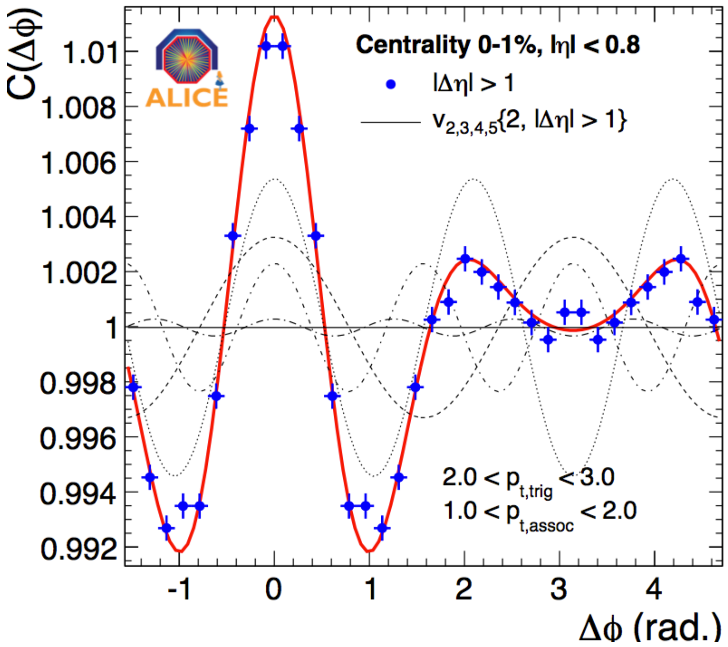
The error on $v_n=\sqrt{v_{n,n}}$ is highly non-Gaussian

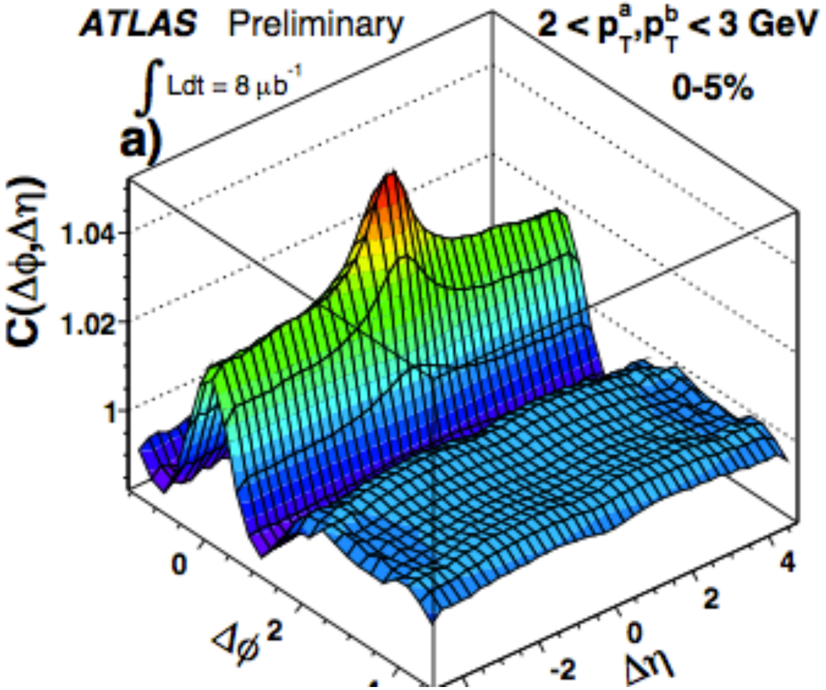
Odd harmonics dominate central collisions

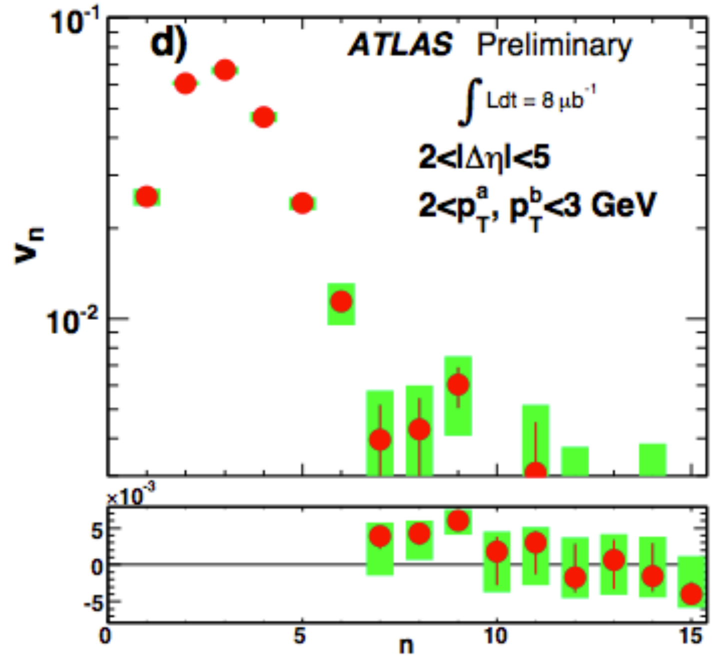
In the most central 0-5% events,

$$v_3 \geq v_2$$

Fluctuations in initial conditions dominate flow measurements





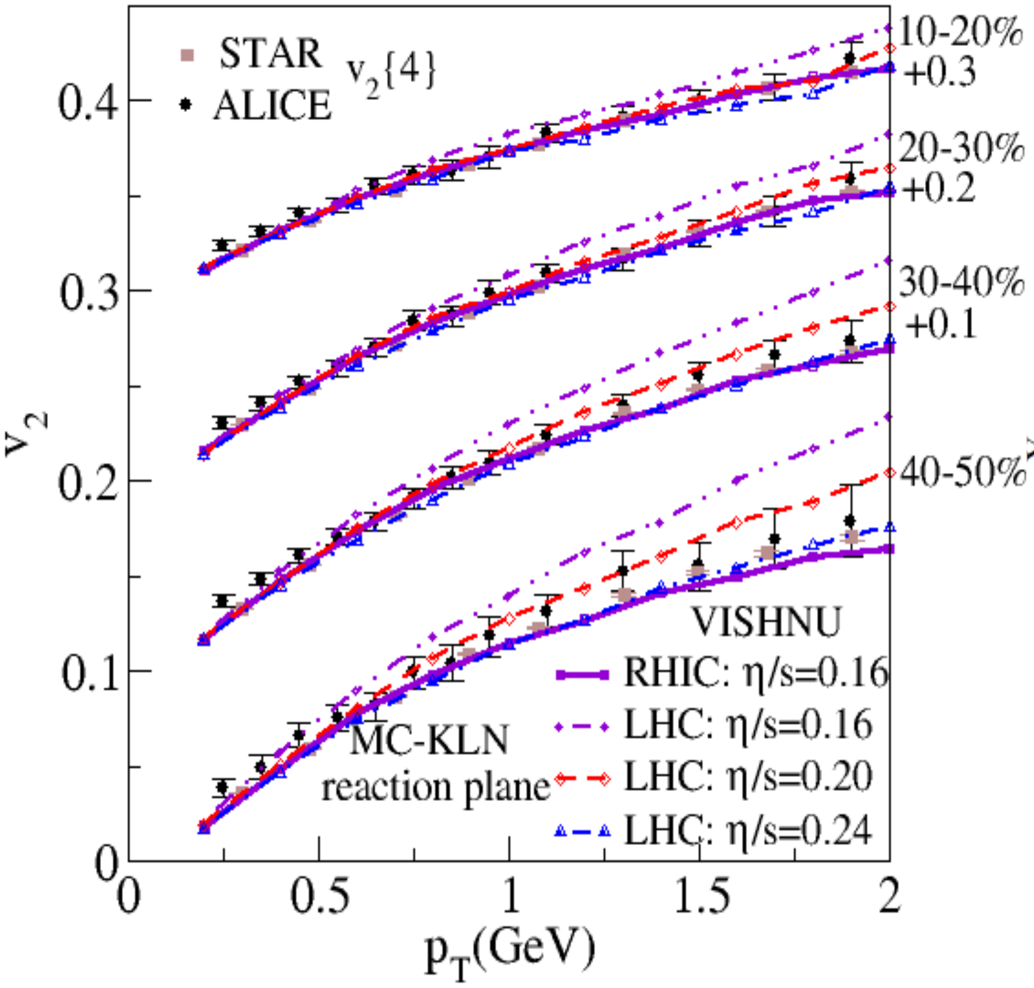


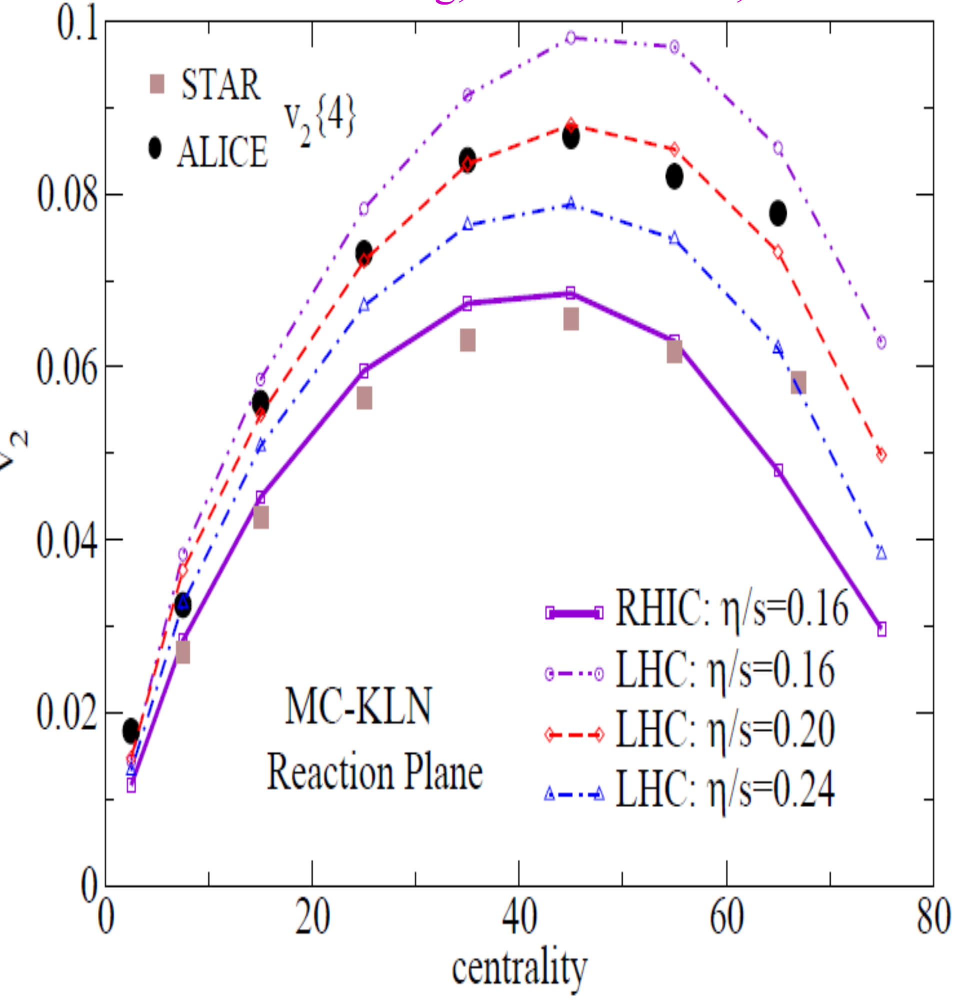
Early Responses to Flood of Data

- v_2 alone indicates η/s roughly same at LHC as at RHIC.
- Full-scale relativistic viscous hydrodynamics calculations, with systematic exploration of initial-state fluctuations, and treatment of the late-stage hadron gas are being done by many groups, but will take a little time. Early, partial, analyses indicate that flood of data on $v_{3\ldots6}$ will tighten the determination of η/s significantly. Eg. . .
- Measurements of v_3 and v_2 together allow separation of effects of η/s from effects of different shapes of the initial density profile.
- The higher v_n's are sensitive to the size of the density fluctuations, and to η/s.
- Systematic, state-of-the-art, analyses are coming, but take longer. The shape of things to come . . .

V_2 at RHIC and LHC

Song, Bass & Heinz, PRC 2011





The average QGP viscosity is roughly the same at RHIC and LHC

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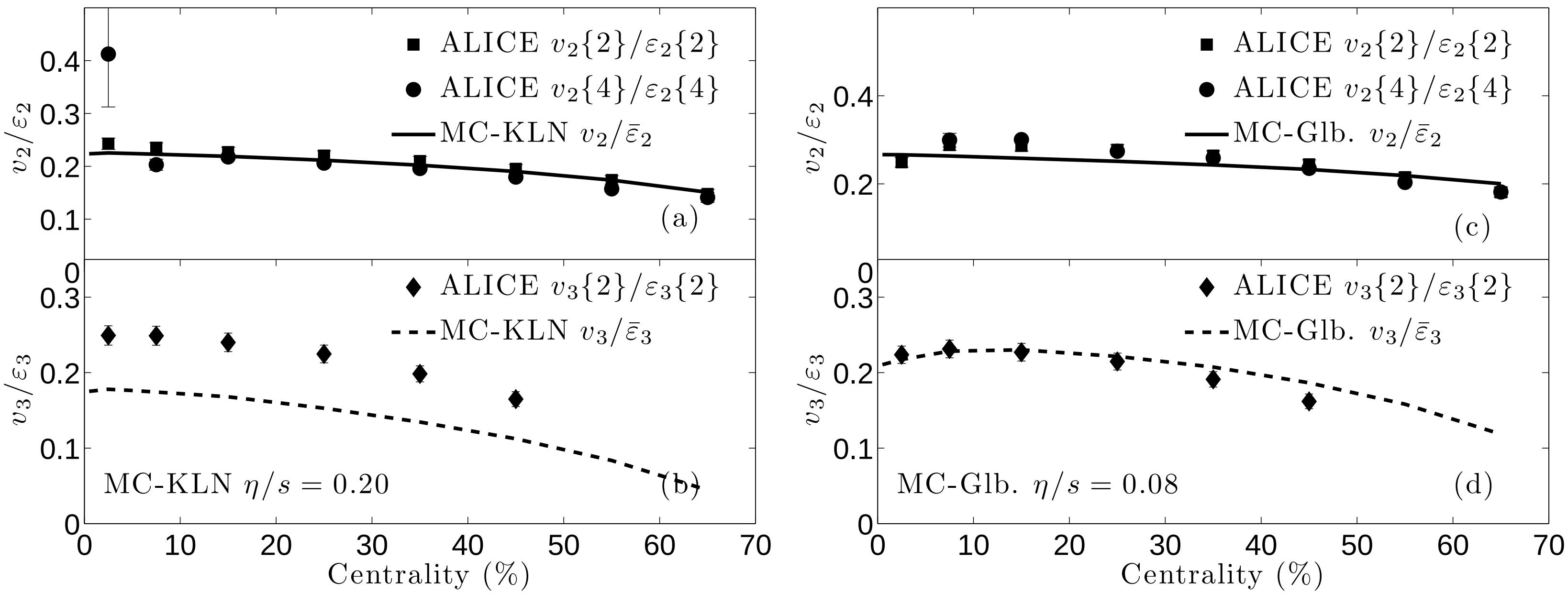
Using v_3 *and* v_2 to extract η/s



An example calculation showing LHC data on v_2 alone can be fit well with $\eta/s = .08$ and $.20$, by starting with different initial density profiles, both reasonable. But, v_3 breaks the "degeneracy". Qiu, Shen, Heinz 1110.3033

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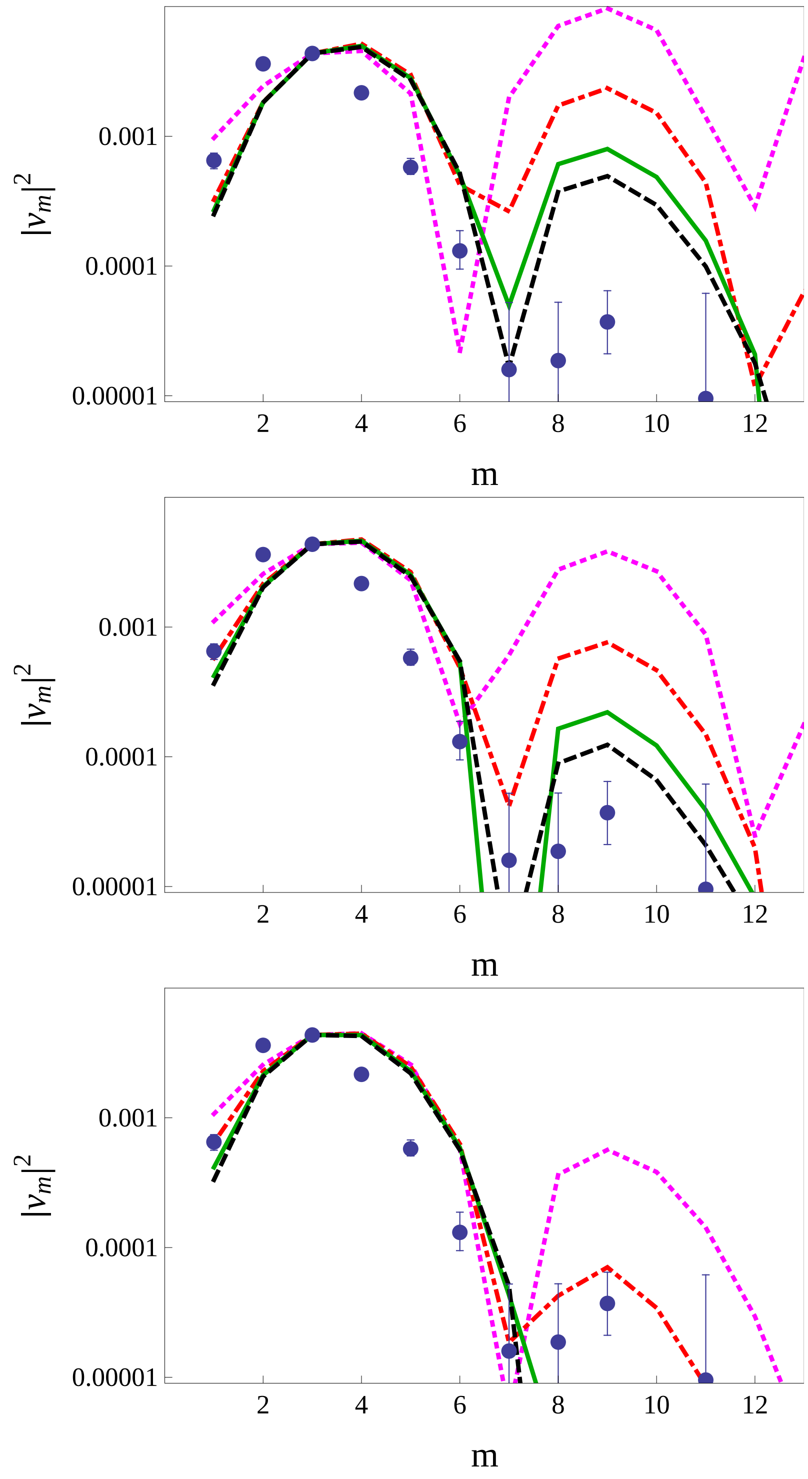
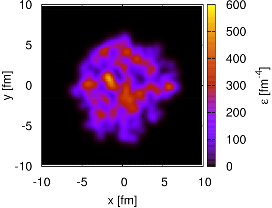


- **Analytic calculation of “shape” of v_n’s in a simplified geometry with small fluctuations of a single size.**
- **Panels, top to bottom, are for fluctuations with size 0.4, 0.7 and 1 fm.**
- **Colors show varying η/s, with magenta, red, green, black being η/s =0, 0.08, 0.134, 0.16.**
- **Evidently, higher harmonics will constrain size of fluctuations and η/s, which controls their damping.**

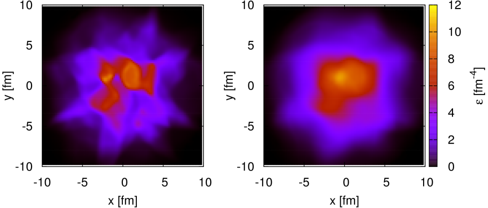
Staig, Shuryak, 1105.0676



initial

evolve to

$\tau = 6\,\mathrm{fm}/c$



ideal

$\eta/s = 0.16$

Flow analysis

B. Schenke, S. Jeon, C. Gale, Phys. Rev. C85, 024901 (2012)

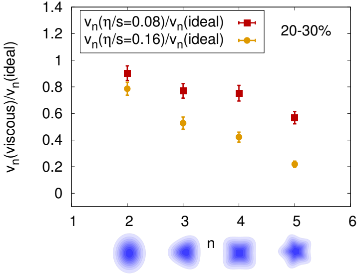
After Cooper-Frye freeze-out and resonance decays in each event we compute

$$v_n = \langle \cos[n(\phi - \psi_n)] \rangle$$

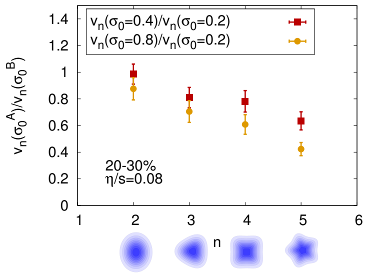
with the event-plane angle $\psi_n = \frac{1}{n} \arctan \frac{\langle \sin(n\phi) \rangle}{\langle \cos(n\phi) \rangle}$

Sensitivity of event averaged v_n on

viscosity



initial state granularity



Sensitivity to viscosity and initial state structure increases with n

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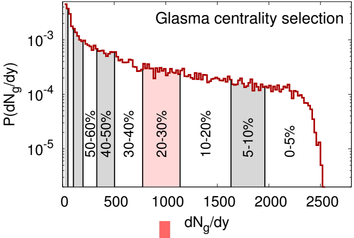
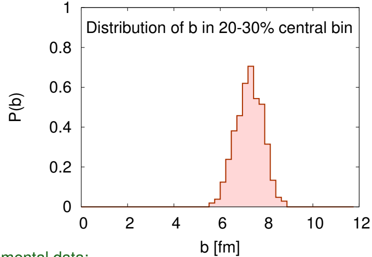
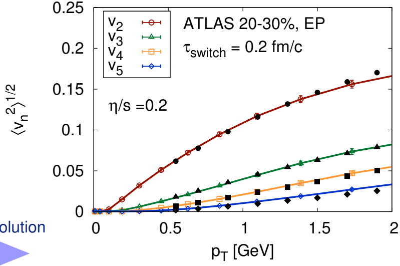
Centrality selection and flow

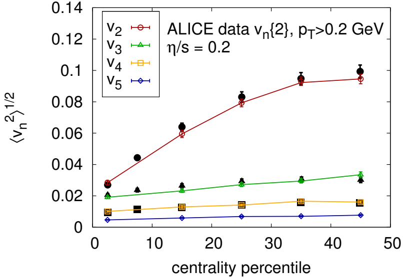




Hydro evolution

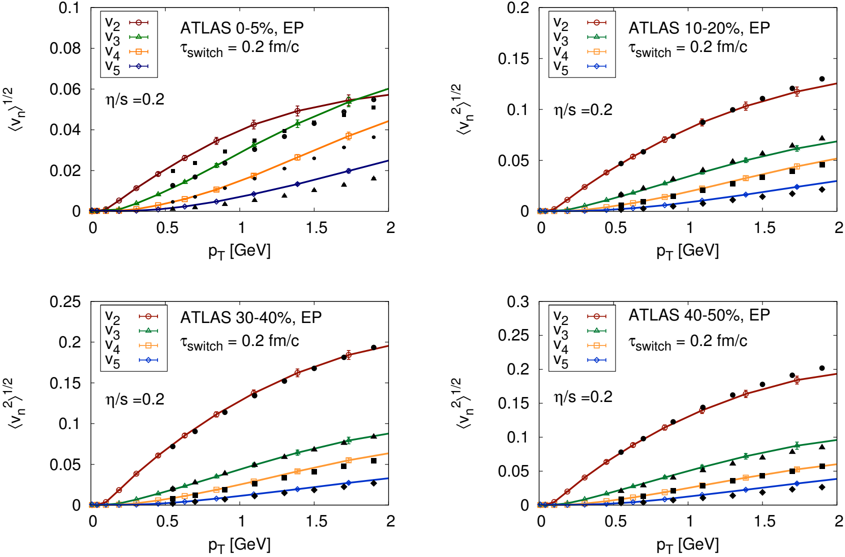
MUSIC



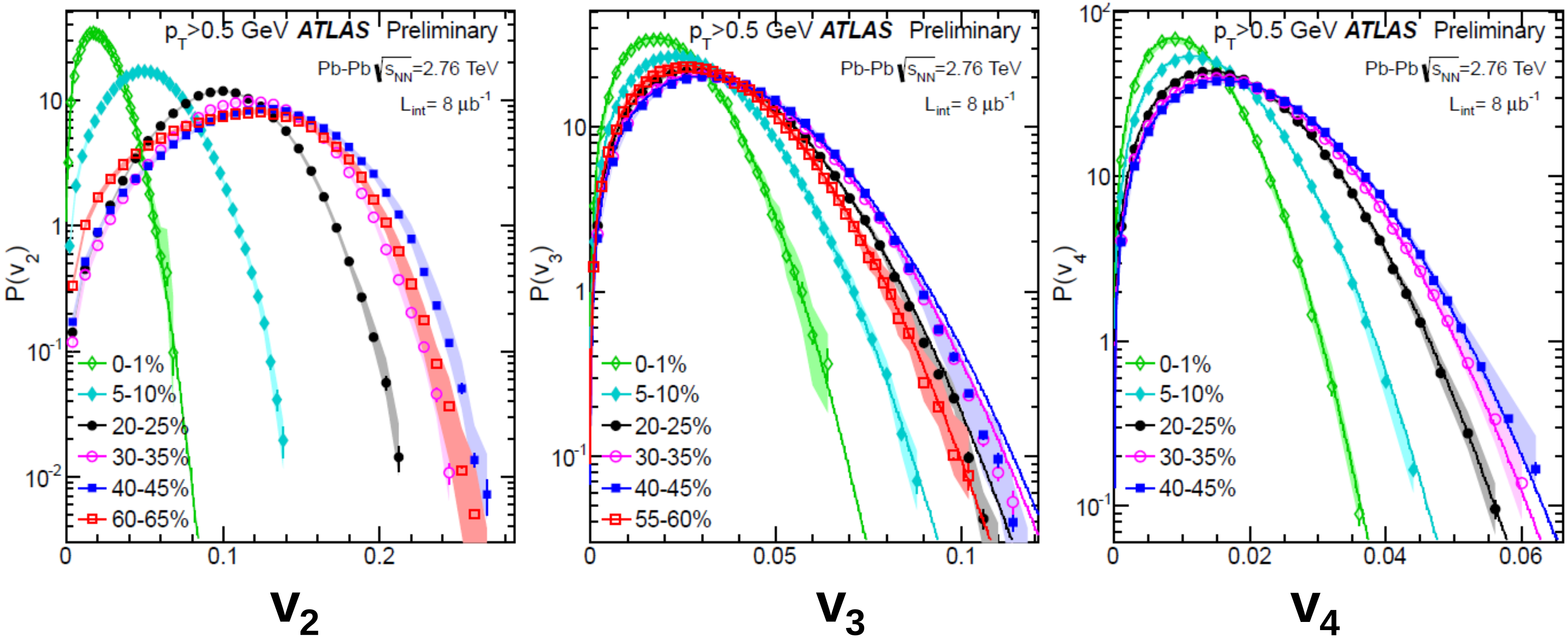


Experimental data:
ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)
ALICE collaboration, Phys. Rev. Lett. 107, 032301 (2011)

More centrality classes: IP-Glasma + MUSIC



Unfolded v_2, v_3 and v_4 Distributions



- v_n distributions normalized to unity for n = 2,3 and 4
- Lines represent radial projections of 2D Gaussians, rescaled to $\langle v_n \rangle$
    - for v_2 only in the 0-2% of most central collisions
    - for v_3 and v_4 over all centralities

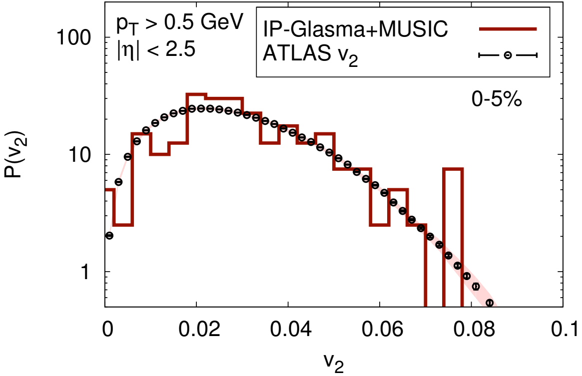
Direct measure of flow harmonics fluctuations

Event-by-event distributions of v_n

comparing to all new ATLAS data:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-114/

see talk by Jiangyong Jia in Session 4A, today, 11:20 am



Preliminary results: Statistics to be improved.

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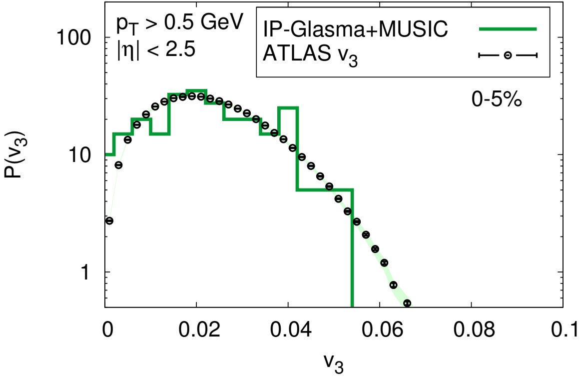

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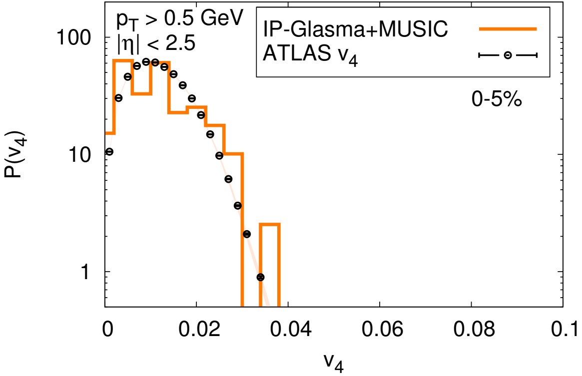

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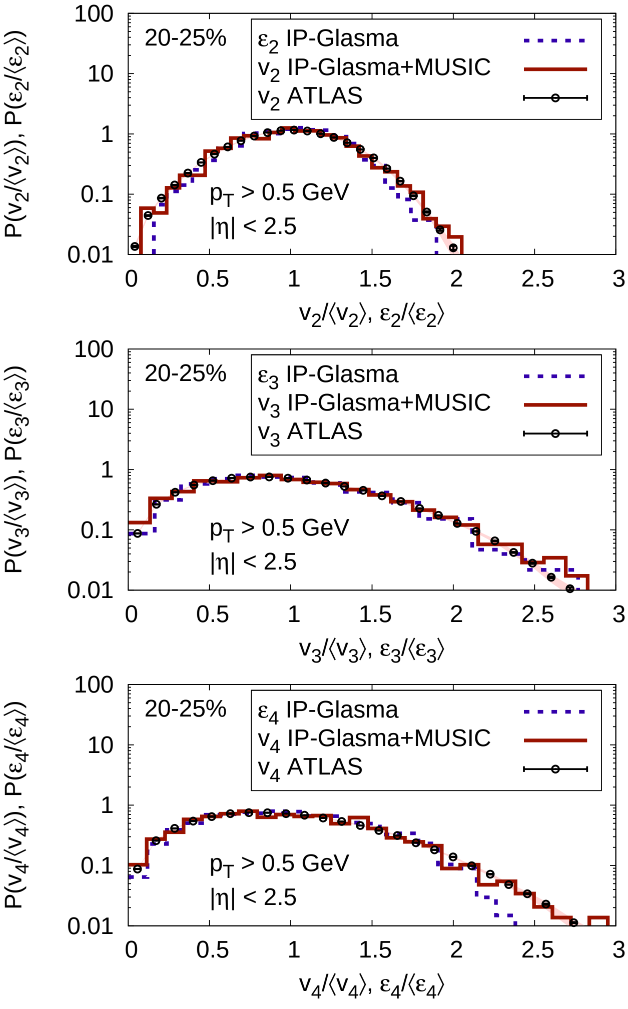
20-25%
ε_2 IP-Glasma
v_2 IP-Glasma+MUSIC
v_2 ATLAS
$p_T > 0.5$ GeV
$|\eta| < 2.5$
$P(v_2/\langle v_2\rangle)$, $P(\varepsilon_2/\langle\varepsilon_2\rangle)$
$v_2/\langle v_2\rangle$, $\varepsilon_2/\langle\varepsilon_2\rangle$
100
10
1
0.1
0.01
0
0.5
1
1.5
2
2.5
3
20-25%
ε_3 IP-Glasma
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$v_4/\langle v_4\rangle$, $\varepsilon_4/\langle\varepsilon_4\rangle$
100
10
1
0.1
0.01
0
0.5
1
1.5
2
2.5
3

QGP cf CMB

- In cosmology, initial-state quantum fluctuations, processed by hydrodynamics, appear in data as c_ℓ's. From the c_ℓ's, learn about initial fluctuations, and about the "fluid" — eg its baryon content.
- In heavy ion collisions, initial state quantum fluctuations, processed by hydrodynamics, appear in data as v_n's. From v_n's, learn about initial fluctuations, and about the QGP — eg its η/s, ultimately its $\eta/s(T)$ and ζ/s.
- Cosmologists have a huge advantage in resolution: c_ℓ's up to $\ell \sim$ thousands. But, they have only one "event"!
- Heavy ion collisions only up to v_6 at present. But they have billions of events. And, they can do controlled variations of the initial conditions, to understand systematics$\ldots$

New Experiments

- **In Au-Au collisions, varying impact parameter gives you one slice through the parameter space of shape and density. New experiments will bring us closer to independent control of shape and density.**

- **Uranium-Uranium collisions at RHIC. Uranium nuclei are prolate ellipsoids. When they collide "side-on-side", you get elliptic flow at zero impact parameter, ie at higher energy density.**

- **Copper-Gold collisions at RHIC. Littler sphere on bigger sphere. At nonzero impact parameter, get triangularity, and v_3, even in the mean. Not just from fluctuations.**

- **Both will provide new ways to understand systematics and disentangle effects of η/s.**

- **First runs of each a few months ago.**

η/s and Holography

- $4\pi\eta/s = 1$ for any (of the very many) known strongly coupled large-N_c gauge theory plasmas that are the "hologram" of a (4+1)-dimensional gravitational theory "heated by" a (3+1)-dimensional black-hole horizon.
- Geometric intuition for dynamical phenomena at strong coupling. Hydrodynamization = horizon formation. Nontrivial hydrodynamic flow pattern = nontrivial undulation of black-hole metric. Dissipation due to shear viscosity = gravitational waves falling into the horizon.
- Conformal examples show that hydrodynamics need not emerge from an underlying kinetic theory of particles. A liquid can just be a liquid.
- $1 < 4\pi\eta/s < 3$ for QGP at RHIC and LHC.
- Suggests a new kind of universality, not yet well understood, applying to dynamical aspects of strongly coupled liquids. To which liquids? Unitary Fermi 'gas'?

Why care about the value of η/s?

- Here is a theorist's answer...

- Any gauge theory with a holographic dual has $\eta/s = 1/4\pi$ in the large-N_c, strong coupling, limit. In that limit, the dual is a classical gravitational theory and η/s is related to the absorption cross section for stuff falling into a black hole. If QCD has a dual, since $N_c = 3$ it must be a string theory. Determining $(\eta/s) - (1/4\pi)$ would then be telling us about string corrections to black hole physics, in whatever the dual theory is.

- For fun, quantum corrections in dual of $\mathcal{N} = 4$ SYM give:

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + \frac{15\,\zeta(3)}{(g^2N_c)^{3/2}} + \frac{5}{16}\frac{(g^2N_c)^{1/2}}{N_c^2} + \ldots\right)$$

Myers, Paulos, Sinha

with $1/N_c^2$ and N_f/N_c corrections yet unknown. Plug in $N_c = 3$ and $\alpha = 1/3$, i.e. $g^2N_c = 12.6$, and get $\eta/s \sim 1.73/4\pi$. And, $s/s_{SB} \sim 0.81$, near QCD result at $T \sim 2 - 3T_c$.

- A more serious answer...

Beyond Quasiparticles

- QGP at RHIC & LHC, unitary Fermi "gas", gauge theory plasmas with holographic descriptions are all strongly coupled fluids with no apparent quasiparticles.
- In QGP, with η/s as small as it is, there can be no 'transport peak', meaning no self-consistent description in terms of quark- and gluon-quasiparticles. [Q.p. description self consistent if $\tau_{\rm qp} \sim (5\eta/s)(1/T) \gg 1/T$.]
- Other "fluids" with no quasiparticle description include: the "strange metals" (including high-T_c superconductors above T_c); quantum spin liquids; matter at quantum critical points;...
- Emerging hints of how to look at matter in which quasiparticles have disappeared and quantum entanglement is enhanced: "many-body physics through a gravitational lens." Black hole descriptions of liquid QGP and strange metals are continuously related! But, this lens is at present still somewhat cloudy...

A Grand Challenge

- How can we clarify the understanding of fluids without quasiparticles, whose nature is a central mystery in so many areas of science?
- We have two big advantages: (i) direct experimental access to the fluid of interest without extraneous degrees of freedom; (ii) weakly-coupled quark and gluon quasiparticles at short distances.
- We can quantify the properties and dynamics of Liquid QGP at it's natural length scales, where it has no quasiparticles.
- Can we probe, quantify and understand Liquid QGP at *short distance scales*, where it is made of quark and gluon quasiparticles? See *how* the strongly coupled fluid emerges from well-understood quasiparticles at short distances.
- The LHC and newly upgraded RHIC offer new probes and open new frontiers.