Liquid Quark-Gluon Plasma:

Opportunities and Challenges

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A Grand Opportunity

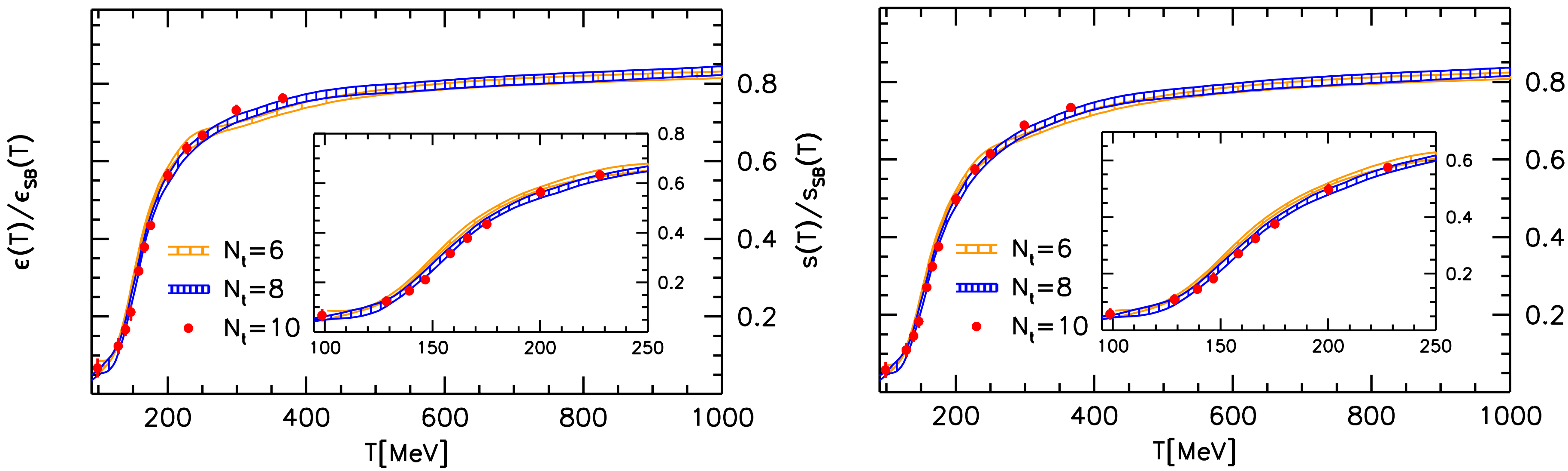
- By colliding "nuclear pancakes" (nuclei Lorentz contracted by $\gamma \sim 100$ and now $\gamma \sim 1400$), RHIC and now the LHC are making little droplets of "Big Bang matter": the stuff that filled the whole universe for the first few microseconds after the Big Bang.

- 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.

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.]

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?

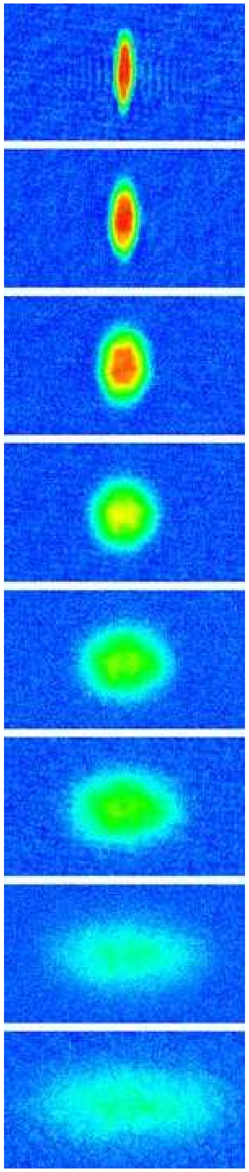
Ultracold Fermionic Atom Fluid

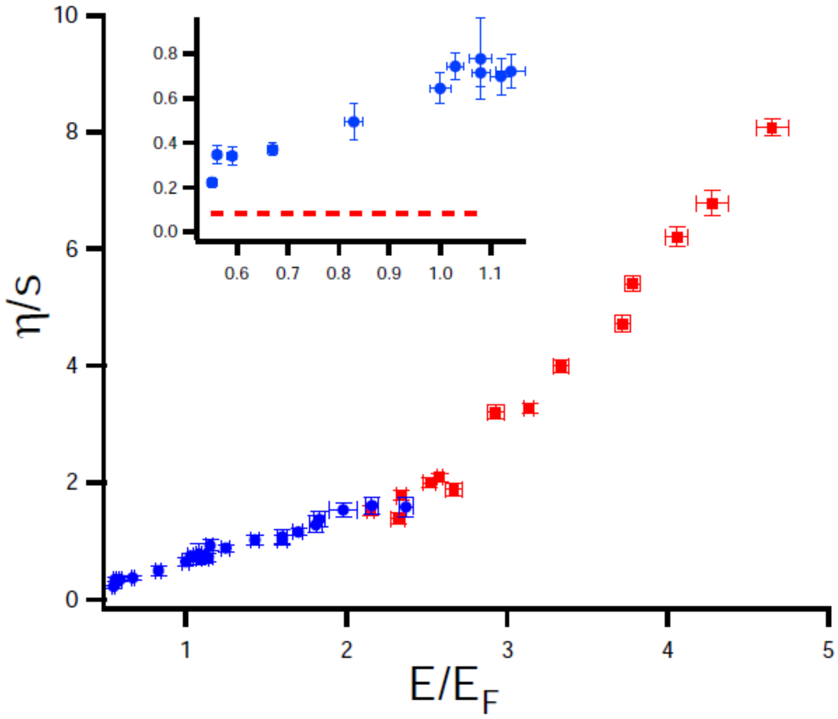
- The one terrestrial fluid with η/s comparably small to that of QGP.
- NanoKelvin temperatures, instead of TeraKelvin.
- Ultracold cloud of trapped fermionic atoms, with their two-body scattering cross-section tuned to be infinite. A strongly coupled liquid indeed. (Even though it's conventionally called 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)

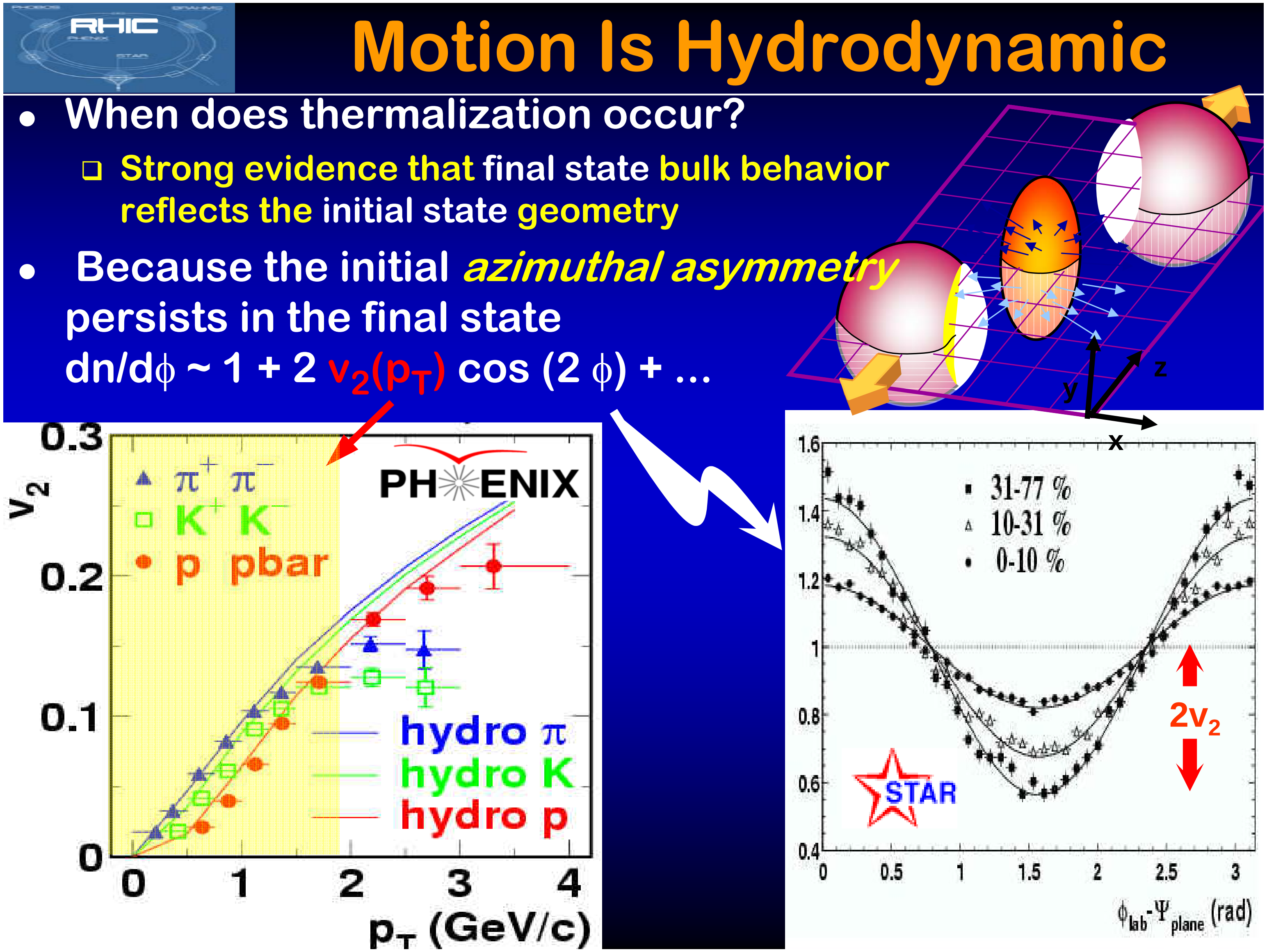
and elliptic flow (high T)





Cao et al., Science (2010)

$$\eta/s \leq 0.4$$



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

Rapid Equilibration?

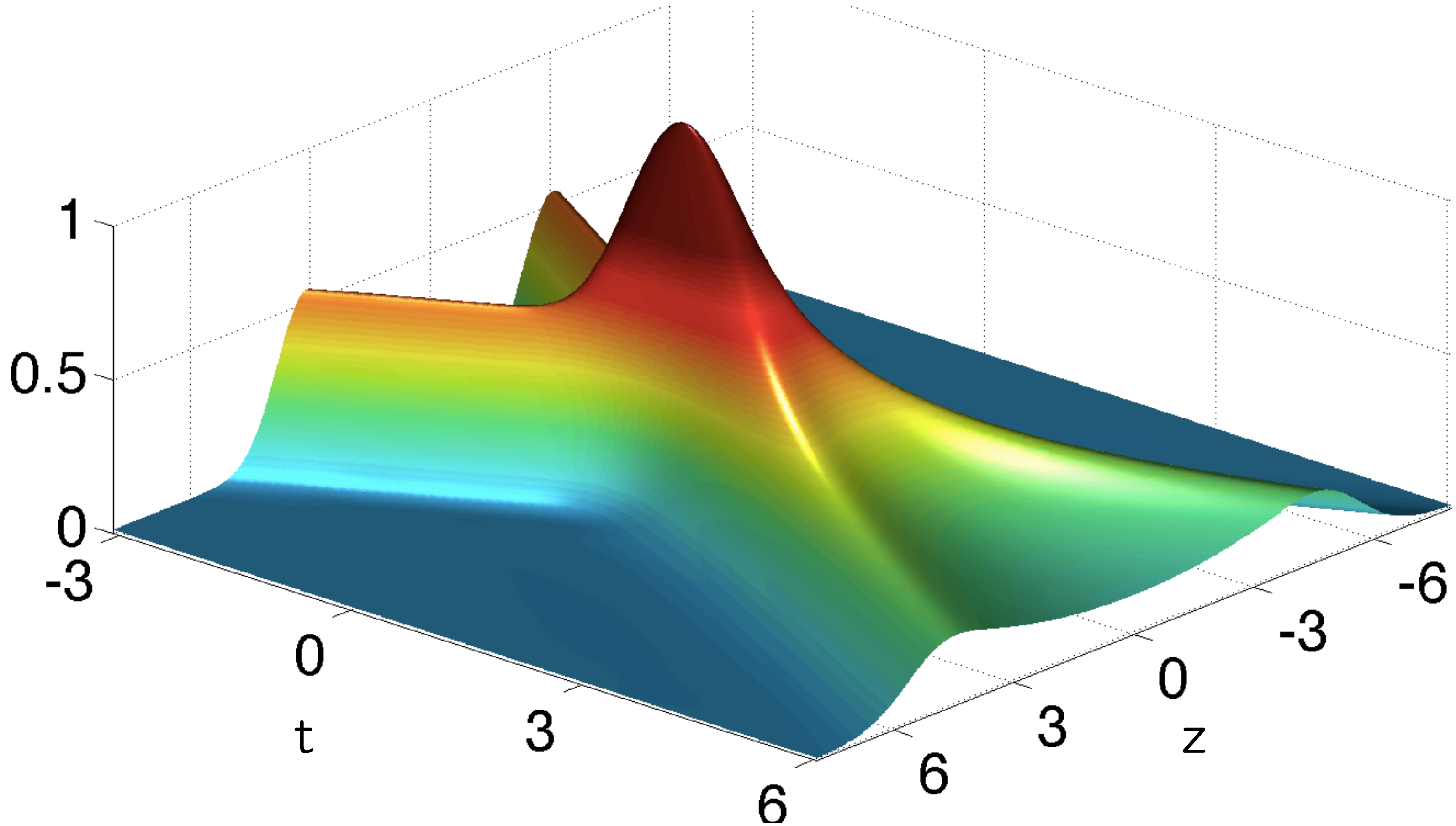
- **Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.**

- **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 Sheets of Energy in a Strongly Coupled Theory



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

Determining η/s from RHIC data

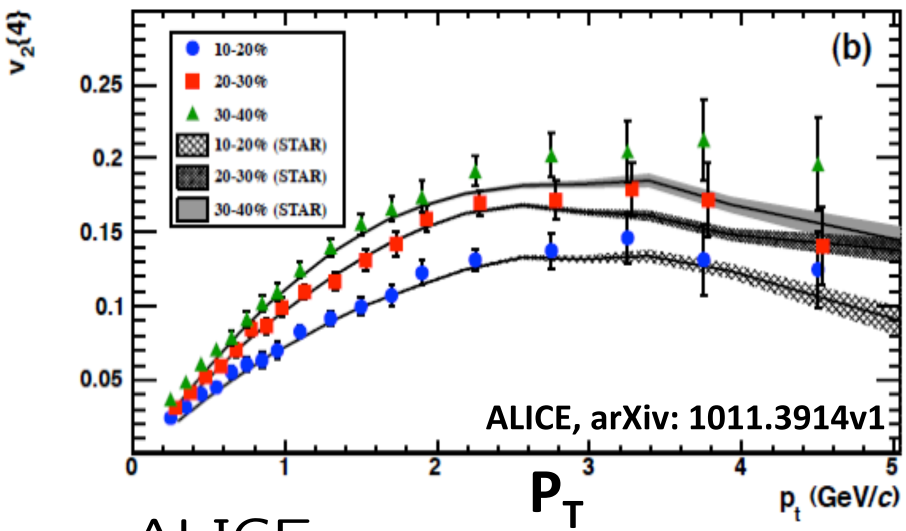
- **Using relativistic viscous hydrodynamics to describe expanding QGP, microscopic transport to describe late-time hadronic rescattering, and using RHIC data on pion and proton spectra and v_2 as functions of p_T and impact parameter...**

- **QGP@RHIC, with $T_c < T \lesssim 2T_c$, has $1 < 4\pi\eta/s < 2.5$. Uncertainty was more than twice as large in 2009. [Largest remaining uncertainty: assumed initial density profile across the "almond".]** Song, Bass, Heinz, Hirano, Shen arXiv:1101.4638

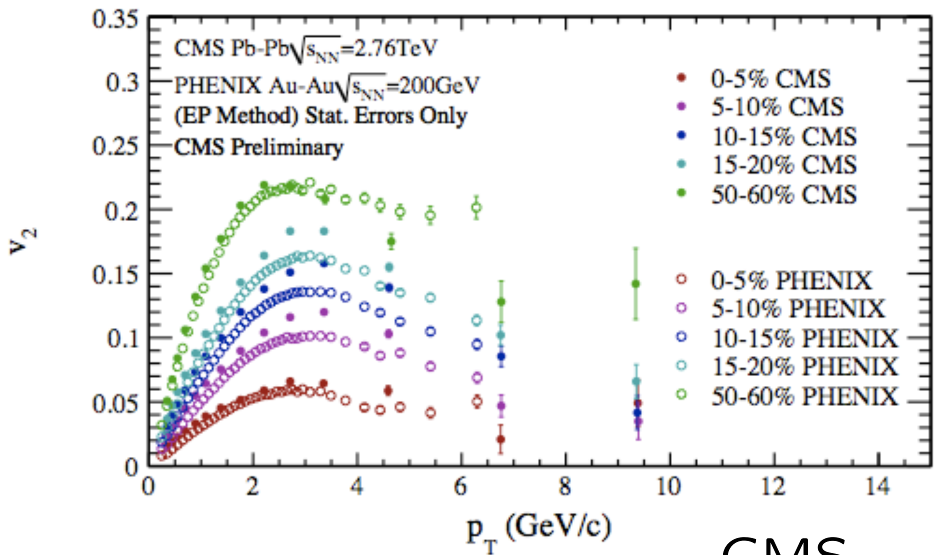
- $4\pi\eta/s \sim 10^4$ **for typical terrestrial gases, and** 10 **to** 100 **for all known terrestrial liquids except one. Hydrodynamics works much better for QGP@RHIC than for water.**

- $4\pi\eta/s = 1$ **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.**

What changes at the LHC?



ALICE



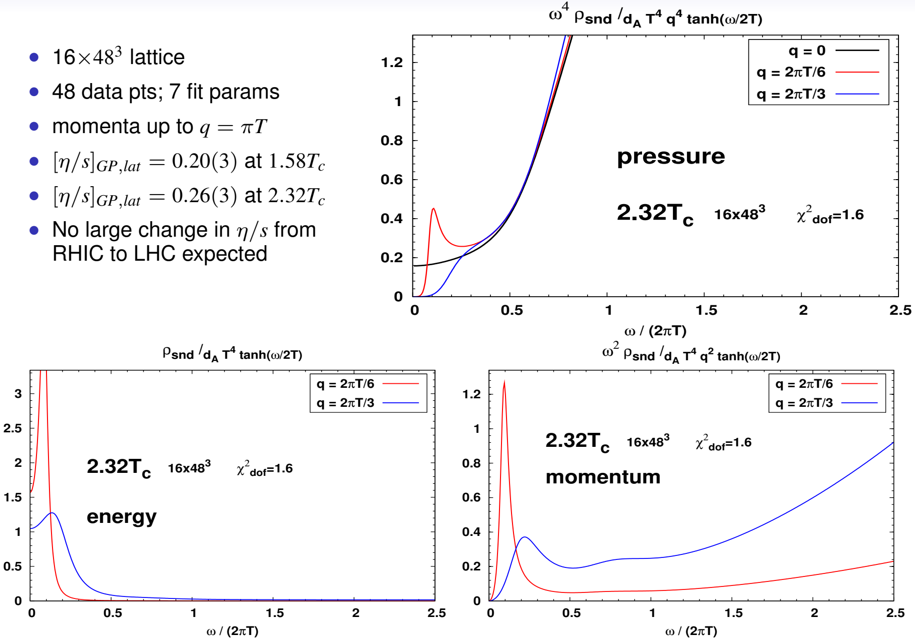
CMS

$v_2(p_T)$ 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.

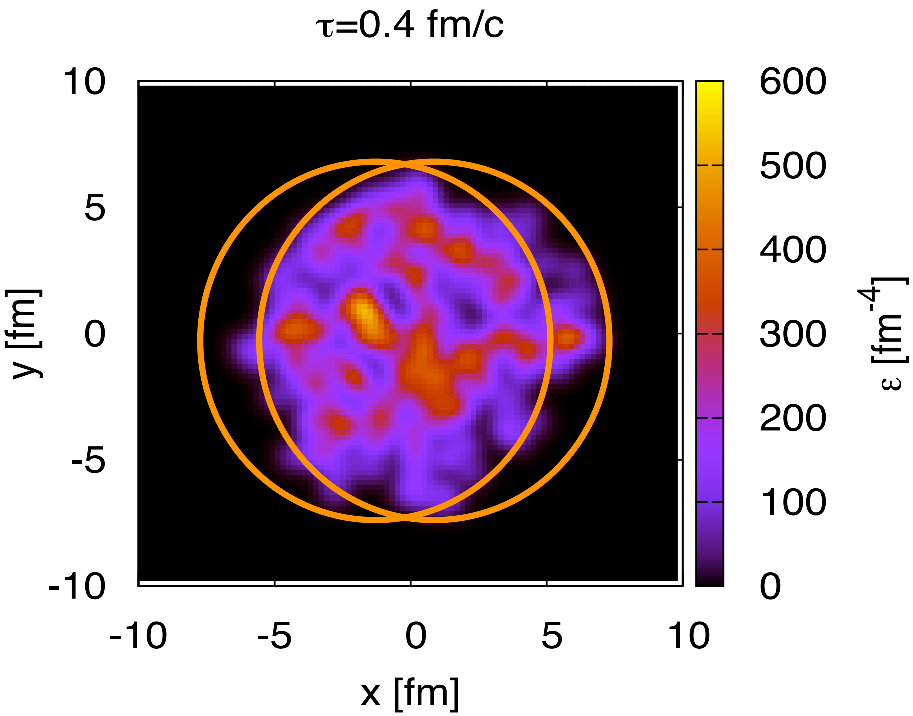
Quantifying this, i.e. constraining the (small) temperature dependence of η/s in going from RHIC to LHC, requires separating effects of η/s from effects of initial density profile across the almond.

Sound spectral functions for Gluon Plasma on lattice [H. Meyer, QM 09]

- 16×48^3 lattice
- 48 data pts; 7 fit params
- momenta up to $q = \pi T$
- $[\eta/s]_{GP,lat} = 0.20(3)$ at $1.58 T_c$
- $[\eta/s]_{GP,lat} = 0.26(3)$ at $2.32 T_c$
- No large change in η/s from RHIC to LHC expected



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 gives v_3 (Alver, Roland)

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

3. Hot-spots give *correlated* higher harmonics
   - Systematized and simulated

Different harmonics damped differently by viscosity, and depend differently on system size, momentum. Experimental data on 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 late May 2011. Many theory groups now working on this.

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

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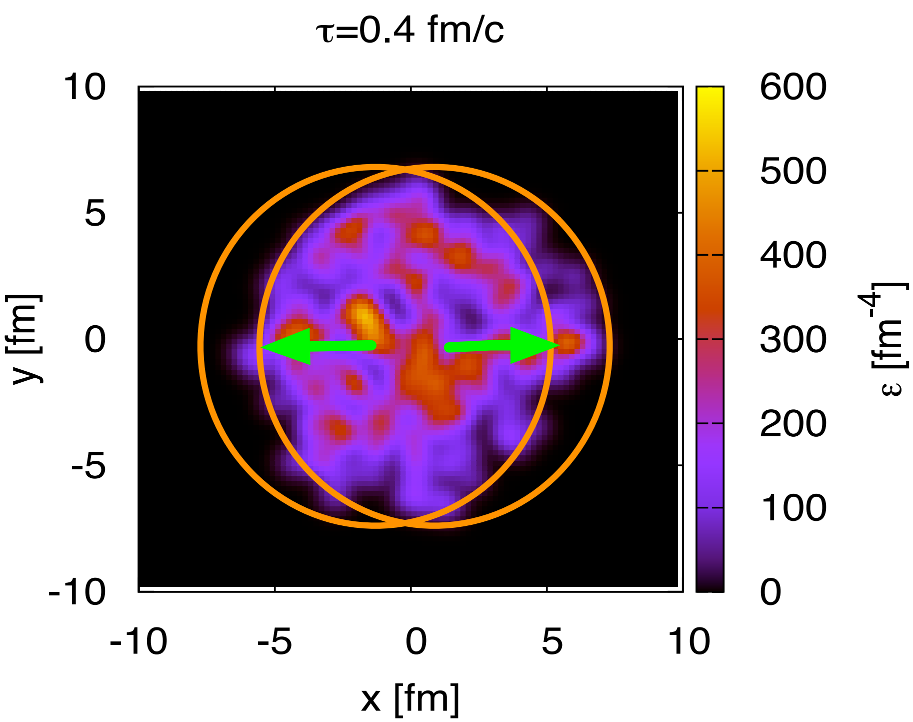

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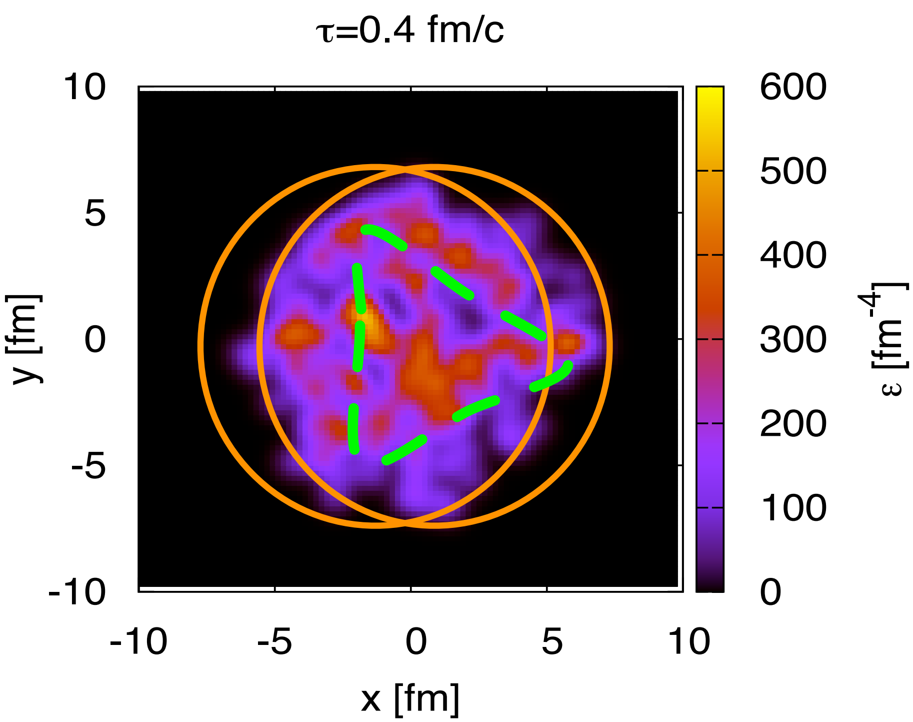

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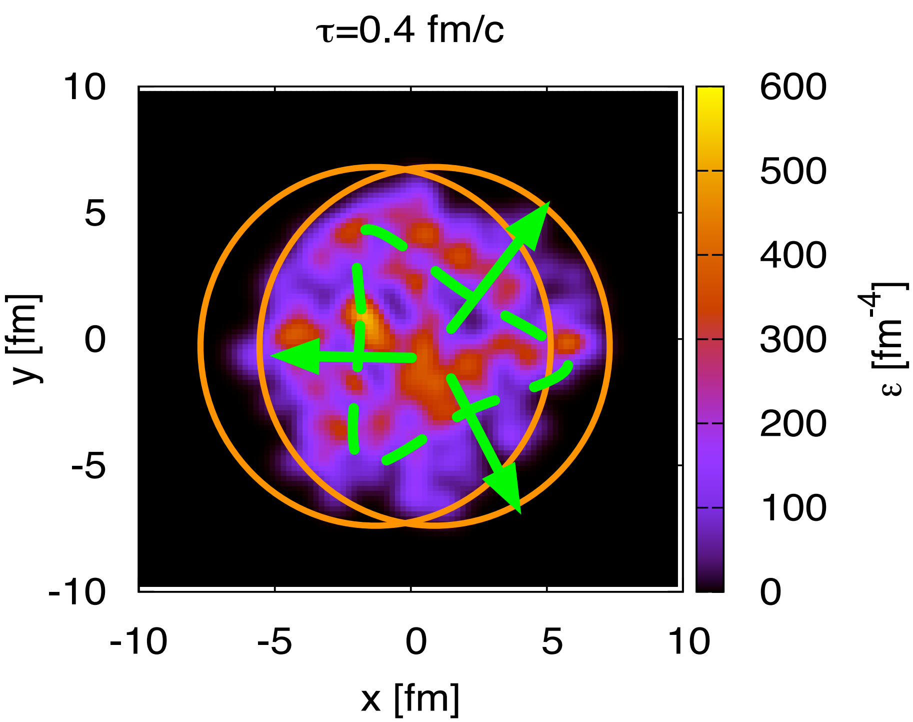

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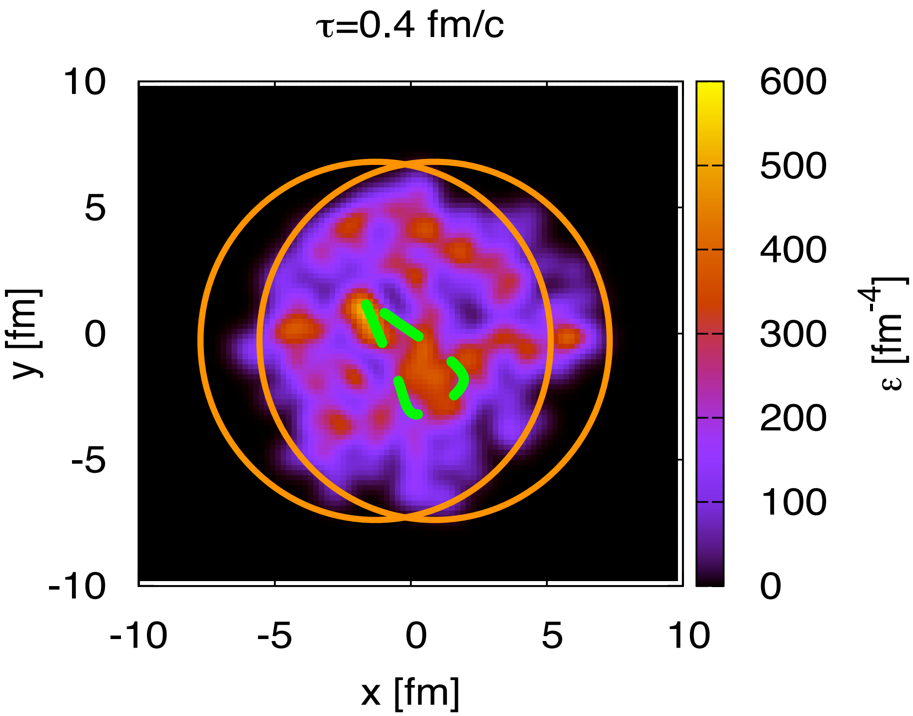

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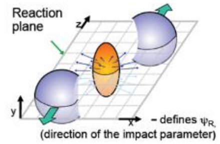
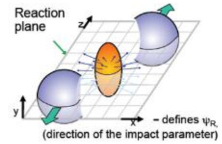
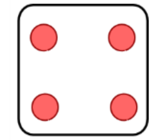
$v_2(p_T)$ at mid-η:PbPb 2.76 TeV – AuAu 0.2 TeV

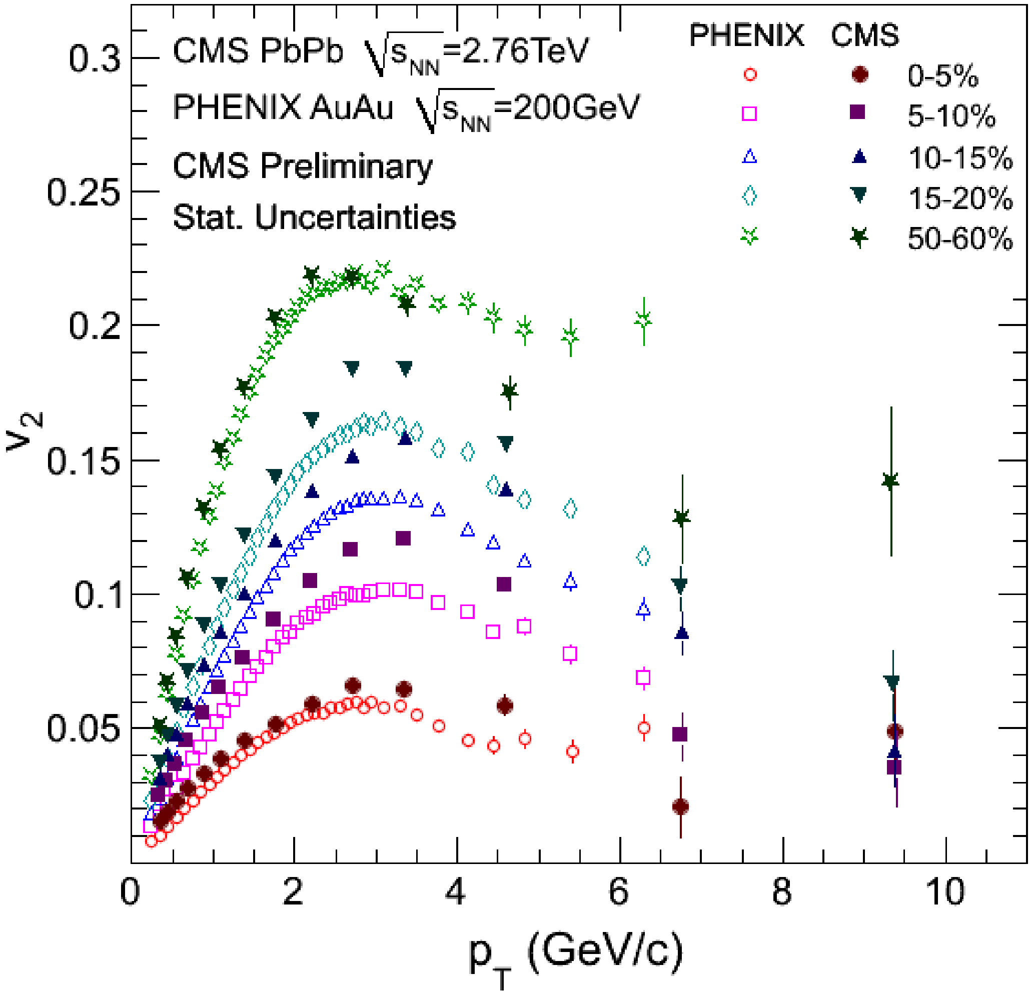


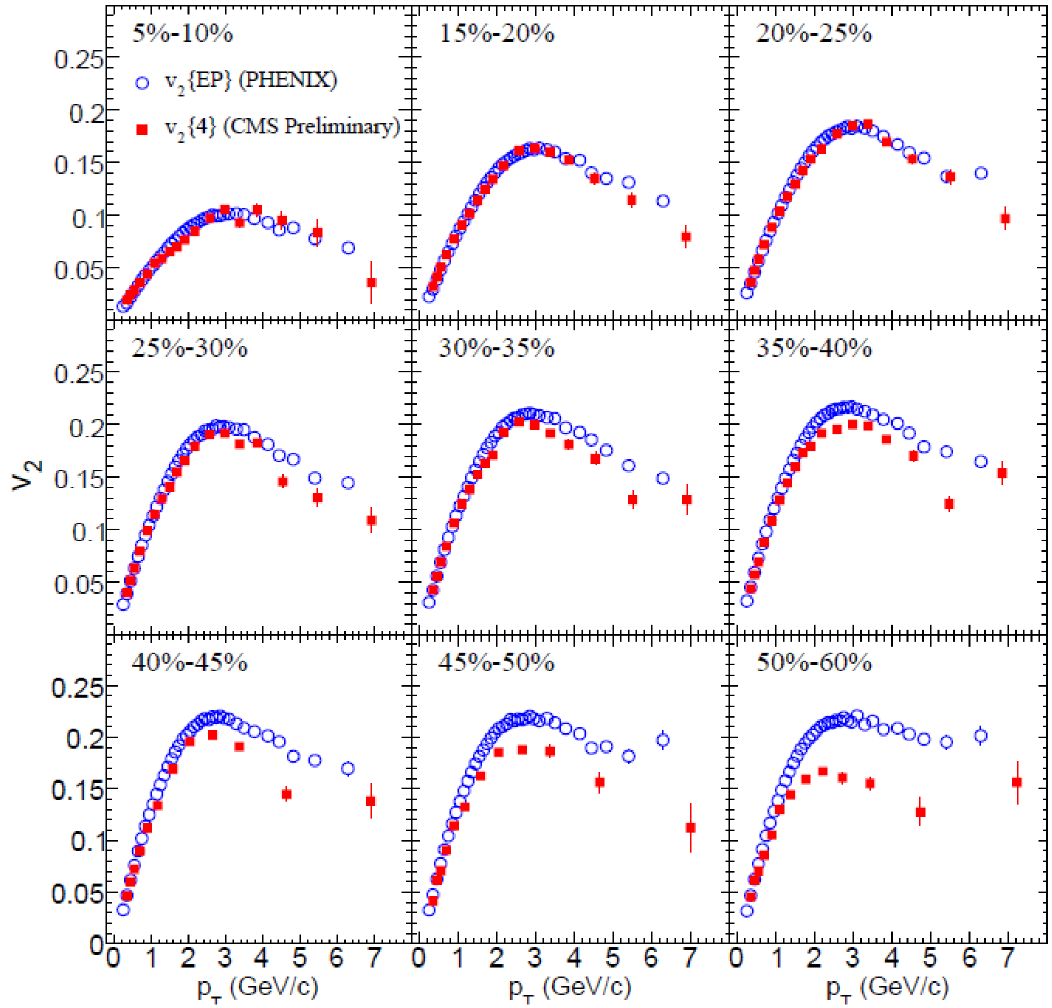
PHENIX





Phys. Rev. Lett. 105, 062301 (2010)

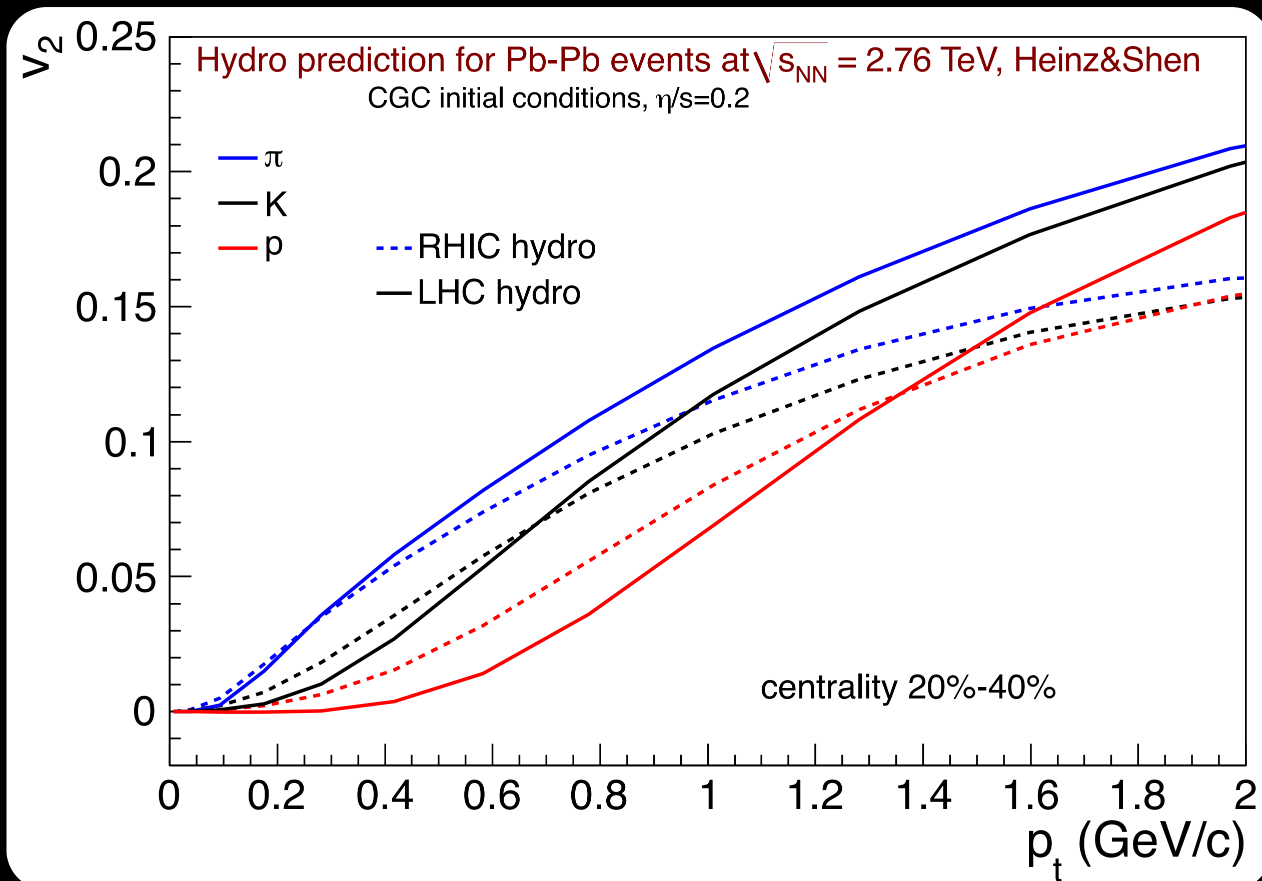




Low p_T – within 15%; High p_T – CMS < PHENIX for cent > 30%

v_2 for identified particles

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226

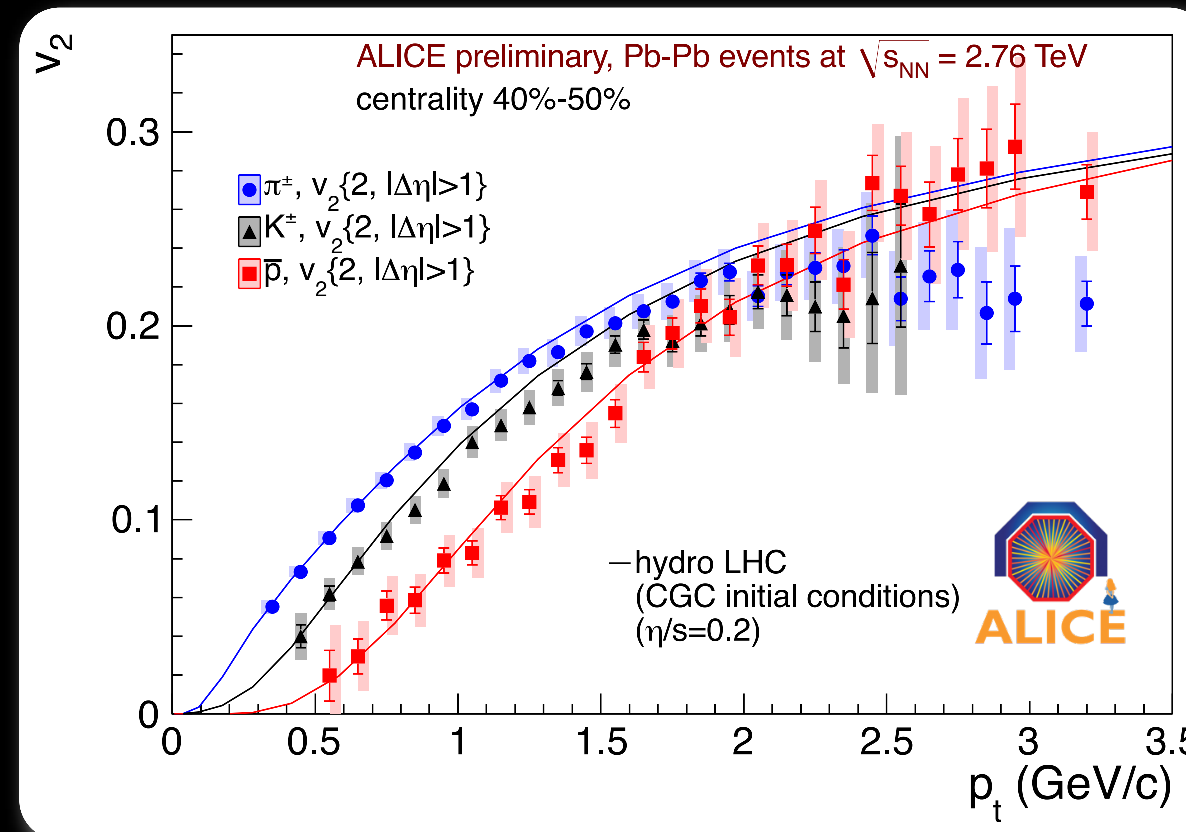


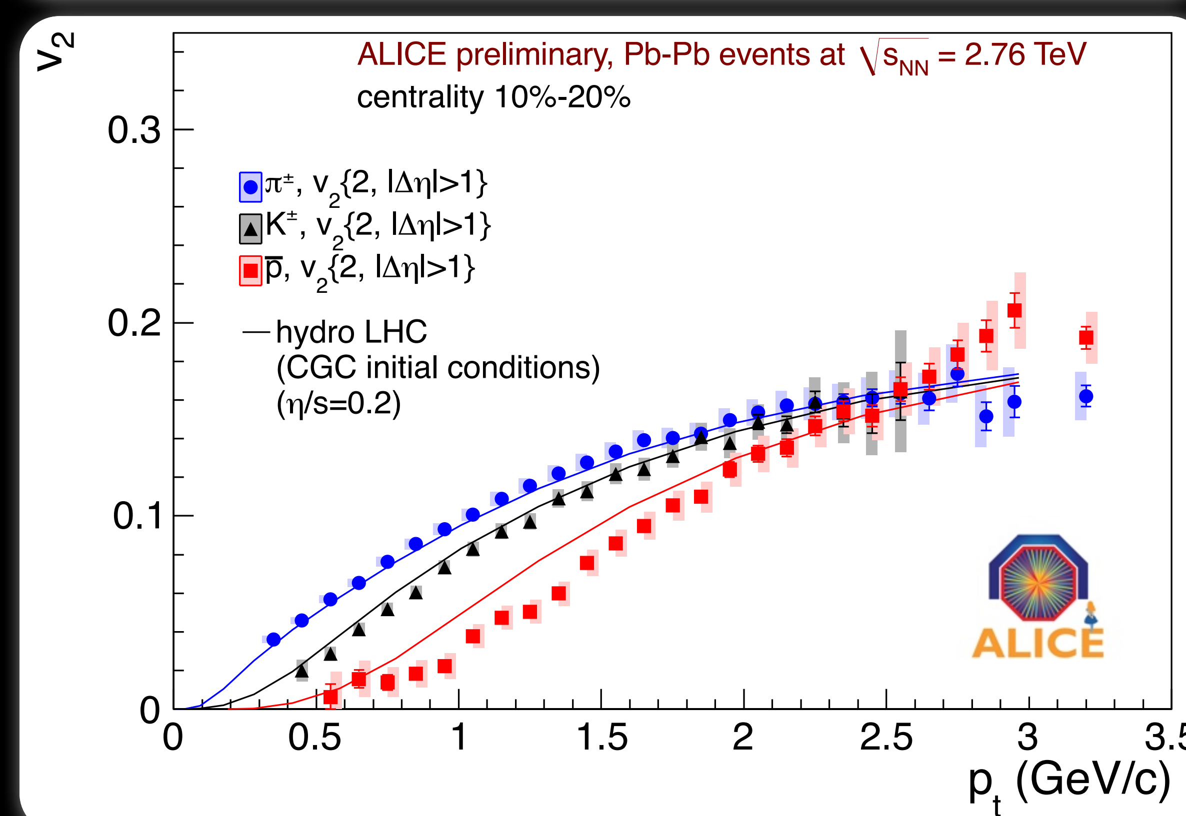
hydro models predict larger mass splitting

data shows mass splitting and agrees well with hydro predictions for mid-central collisions

for more central collisions the anti-proton flow is not described by the same calculations

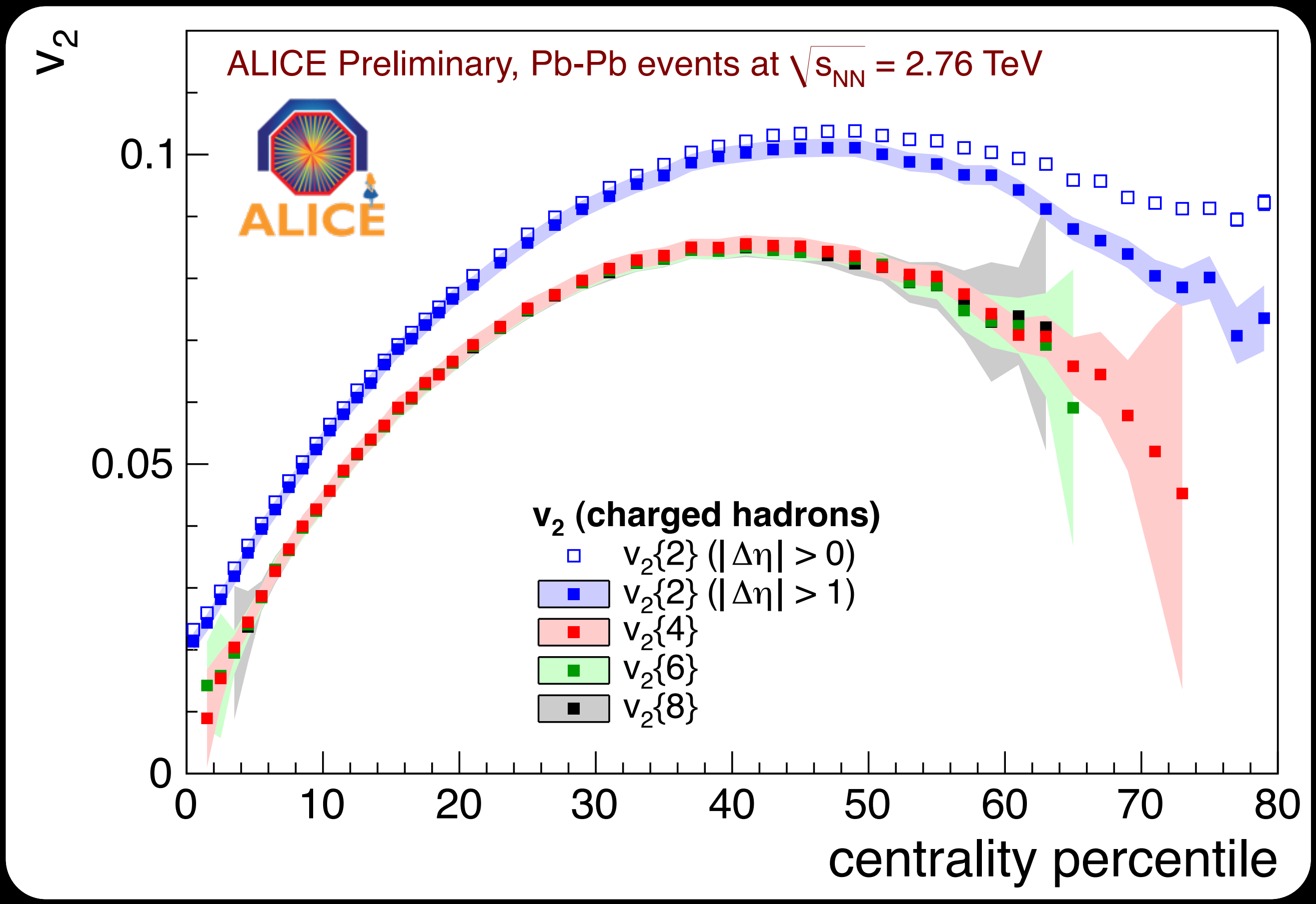
Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226



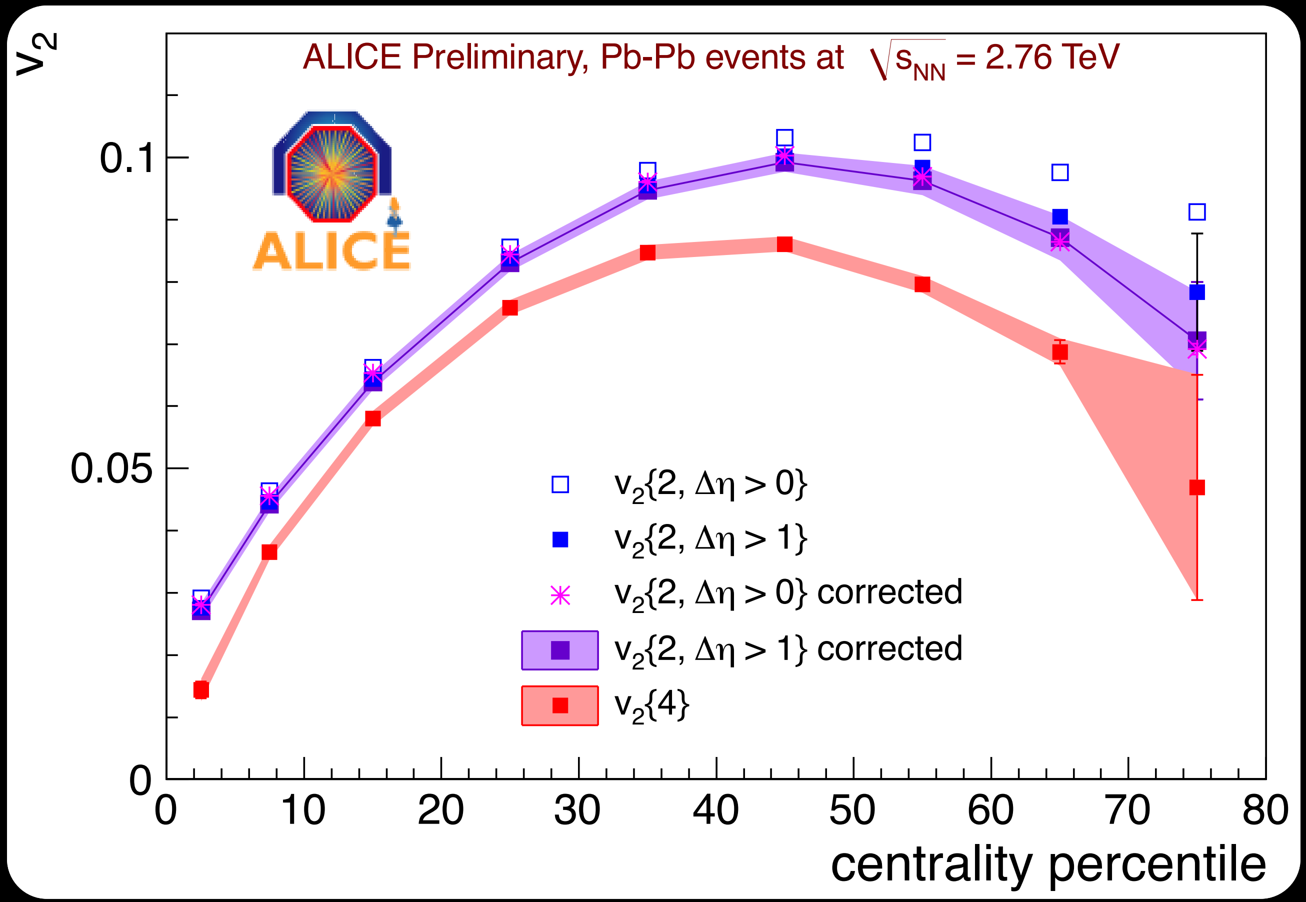


see presentation M. Krzewicki

v_2 versus centrality in ALICE



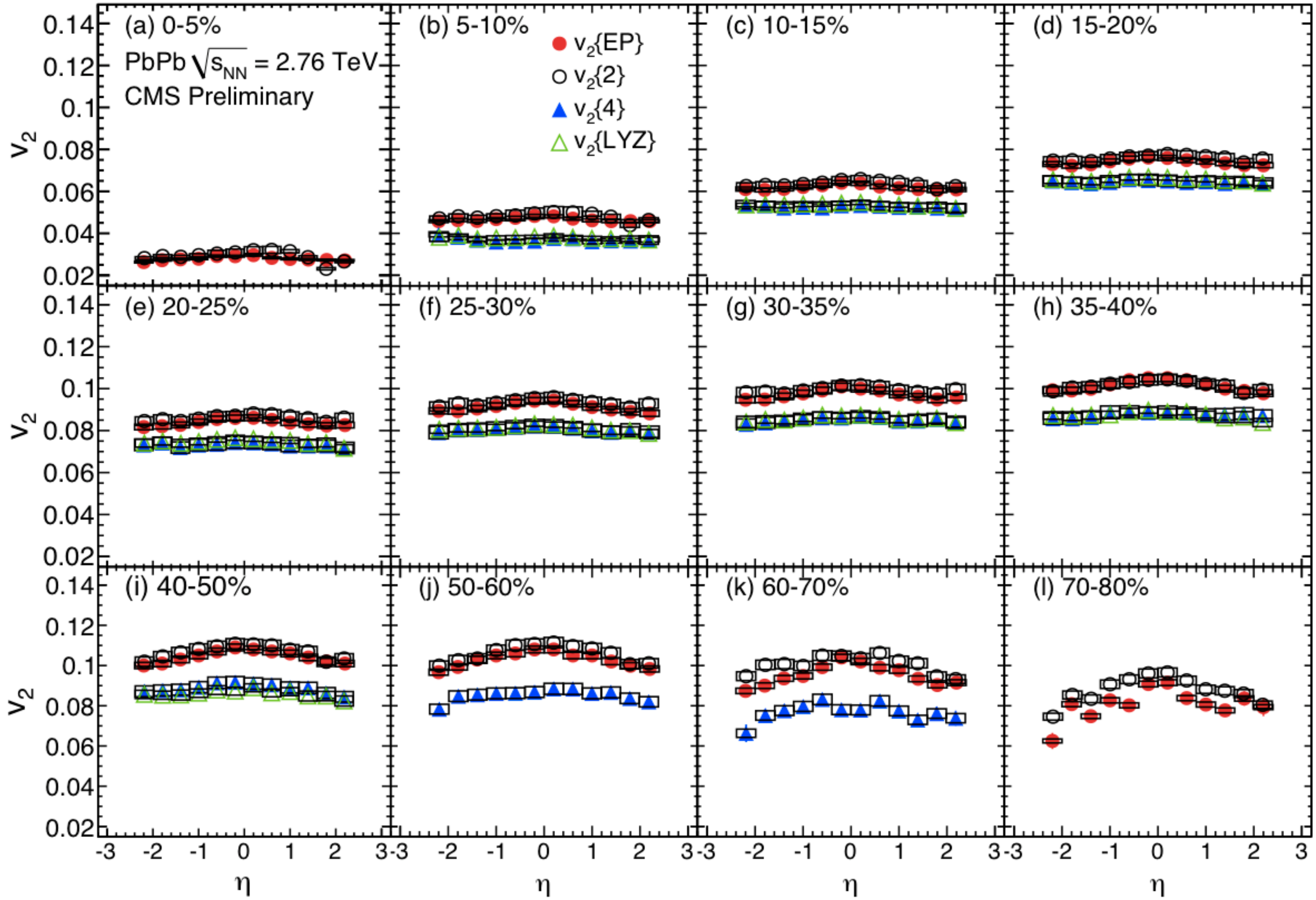
see presentation A. Bilandzic



Two particle v_2 estimates depend on $\Delta\eta$
Higher order cumulant v_2 estimates are consistent within uncertainties

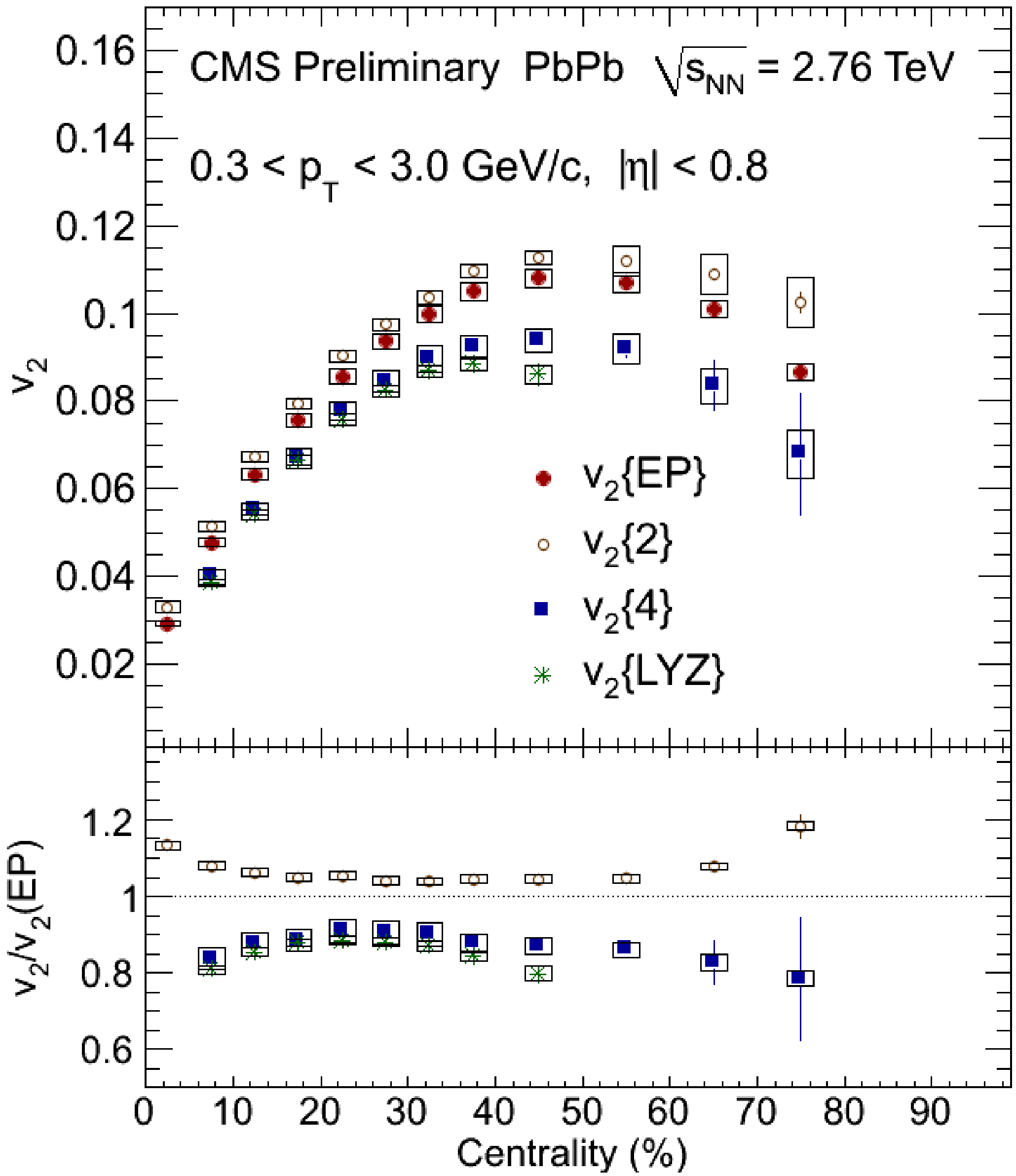
Two particle v_2 estimates are corrected for nonflow based on HIJING
The estimated nonflow correction for $\Delta\eta > 1$ is included in the systematic uncertainty

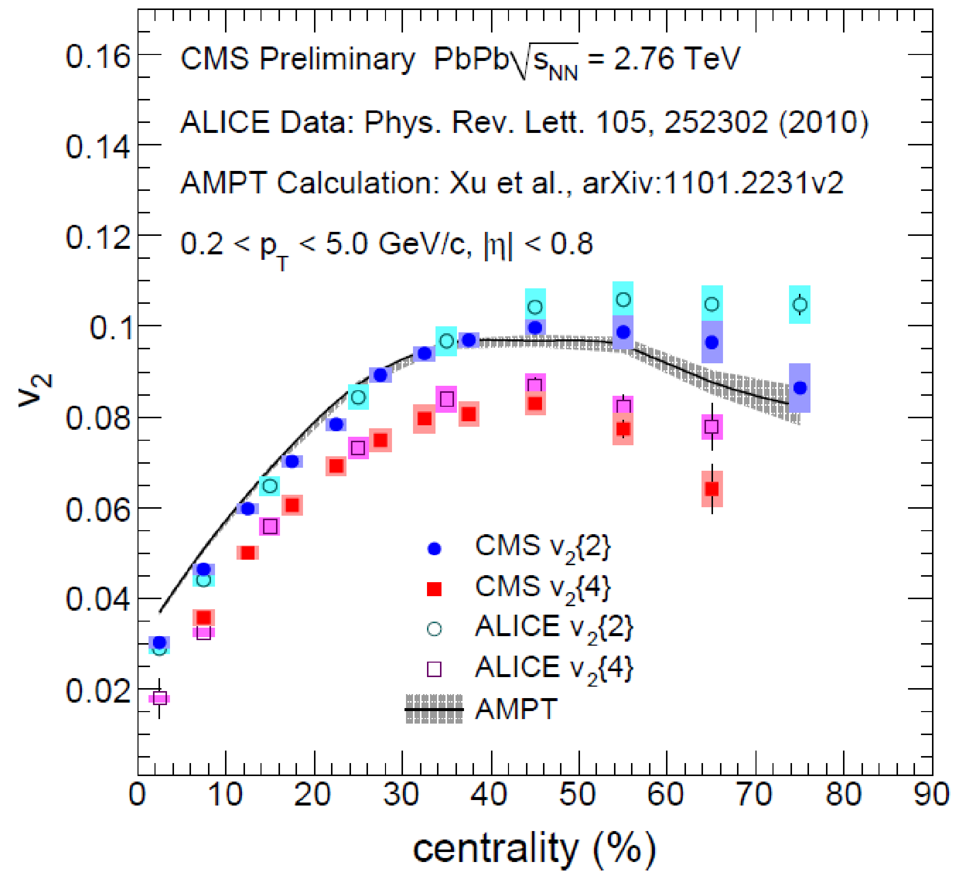
$v_2(\eta)$: centrality dependence



- Weak η- dependence, except for most peripheral (EP and v2{2})
- may constrain descriptions of the longitudinal dynamics

v_2(centrality) at mid-η



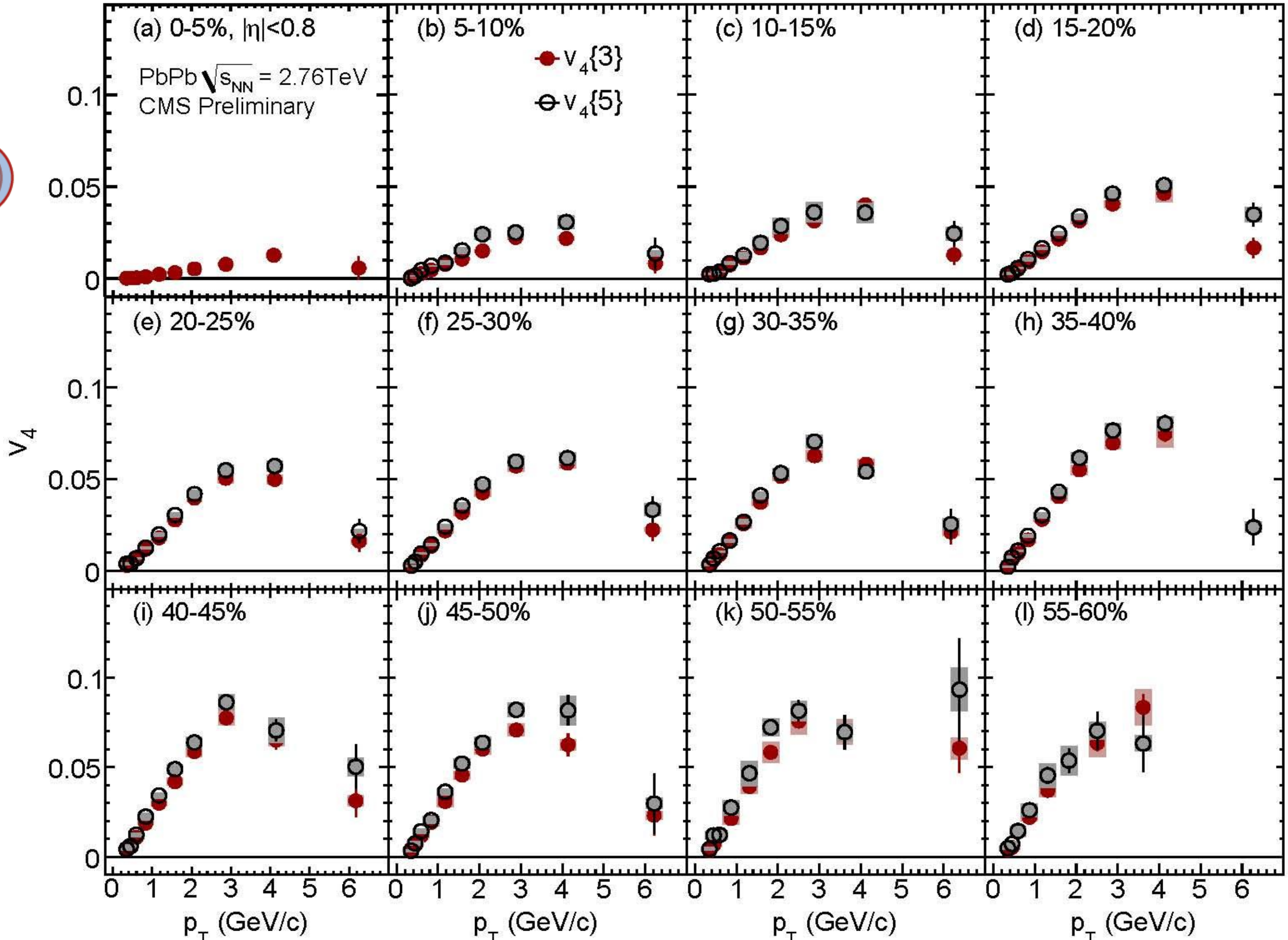


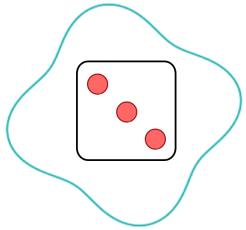
Good agreement with ALICE, except in most peripheral events

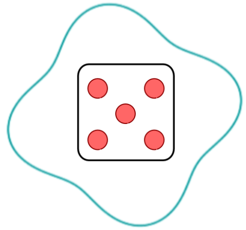
AMPT is consistent with v2{2}

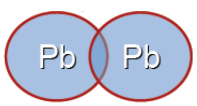
v_2 rises up to 40-50% , then decreases

$v_4(p_T)$ at mid-rapidity $|\eta|< 0.8$ cumulants



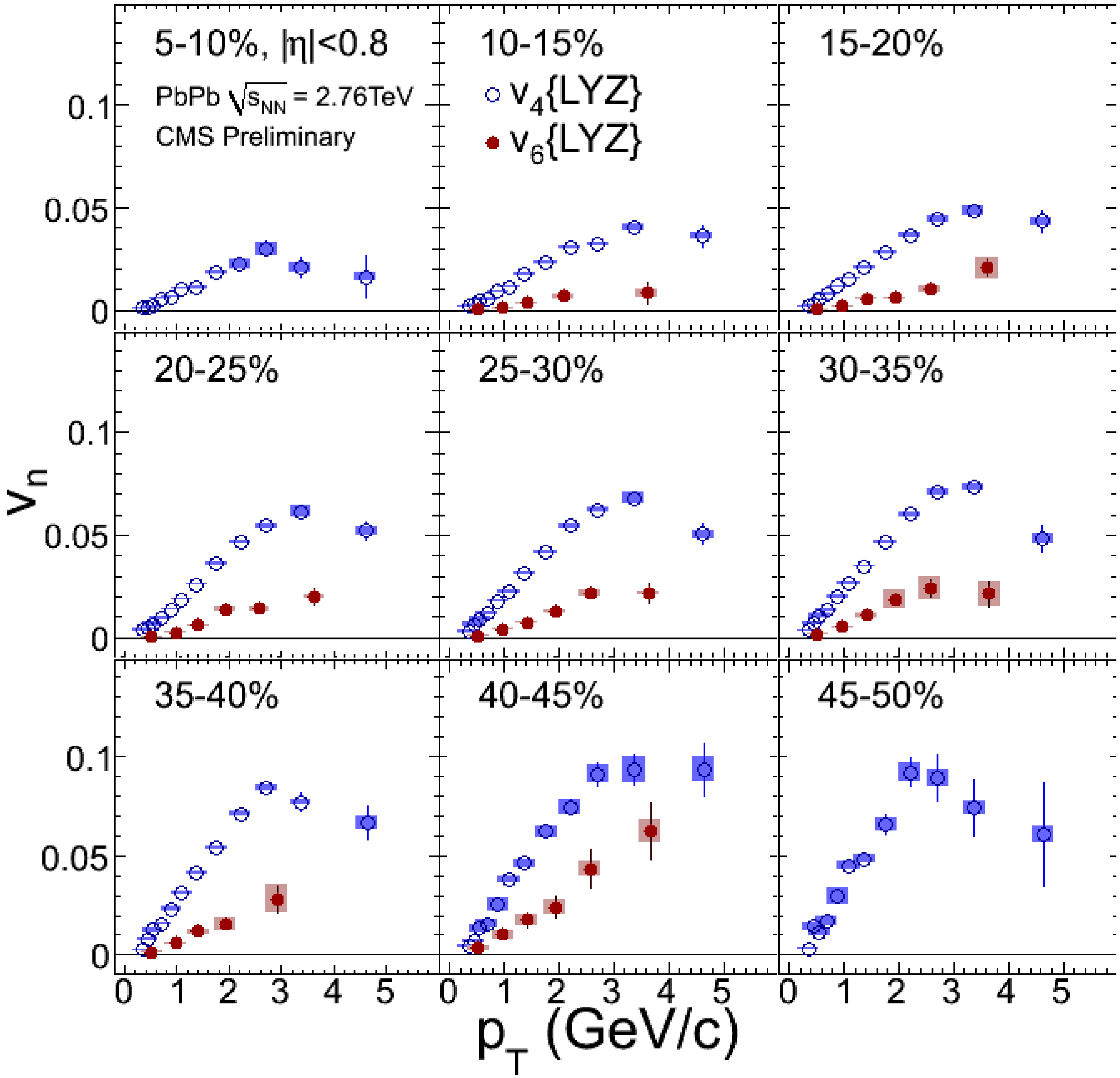


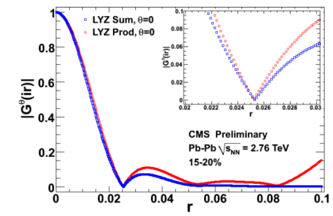


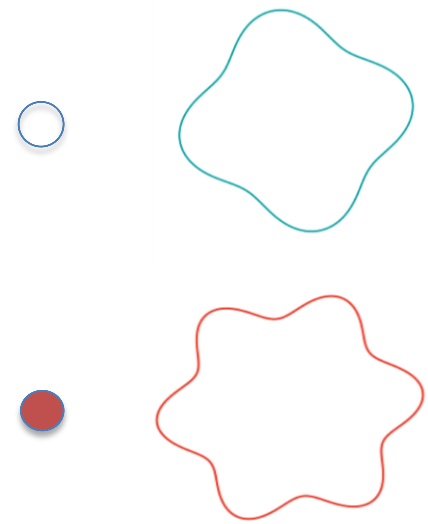


- Similar trend as v_2. The signal is sizable (reaches ~ 6-7%)
- $v_4\{3\}$ and $v_4\{5\}$ comparable in magnitude

LYZ v_4 and v_6 mid-rapidity $|\eta|< 0.8$

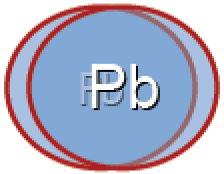


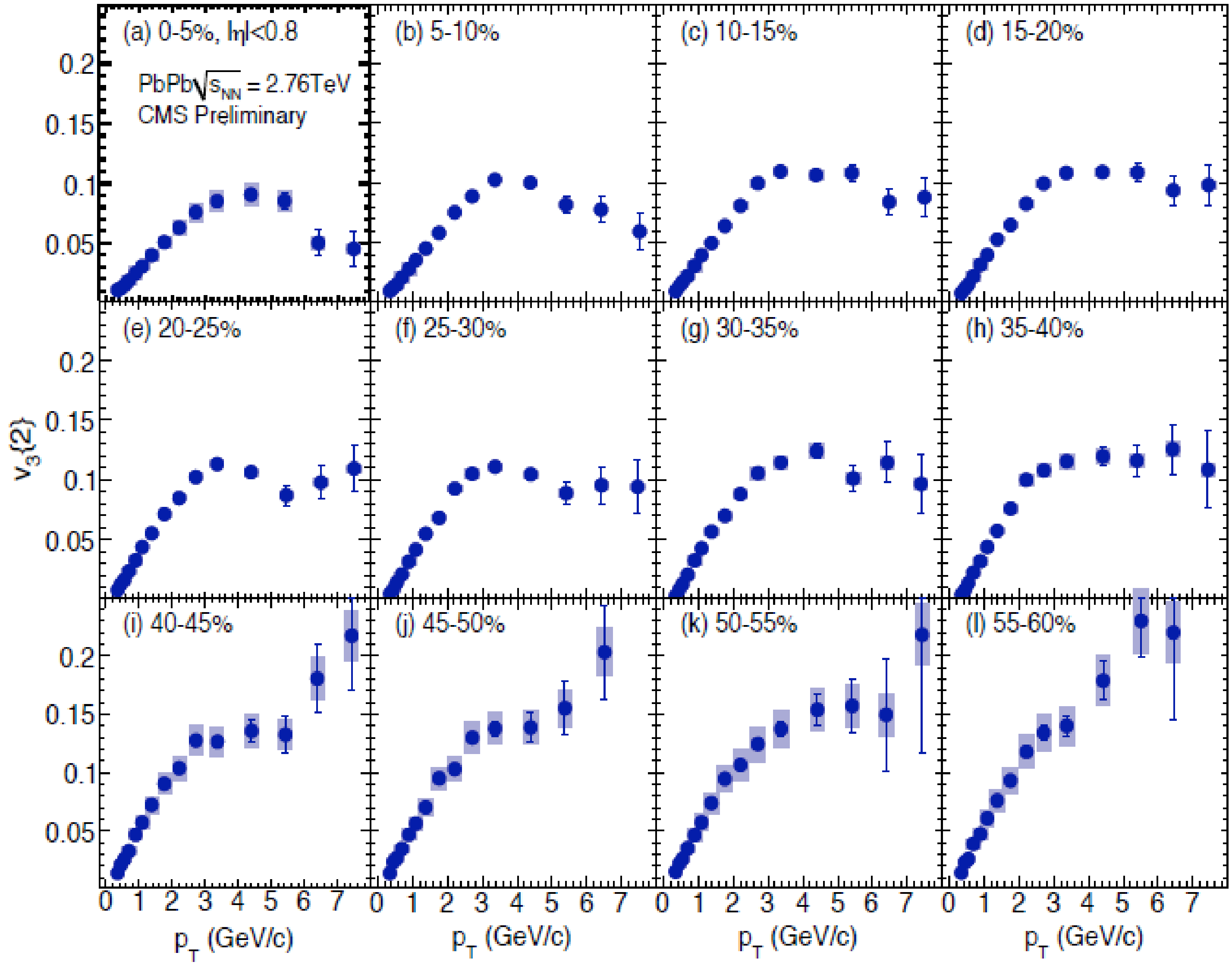


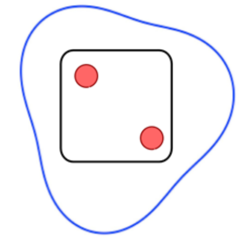


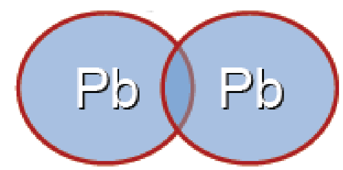
- v_6 (LYZ) is small but finite : reaches 2% in mid-central collisions

$v_3(p_T)$ at mid-rapidity $|\eta|< 0.8$







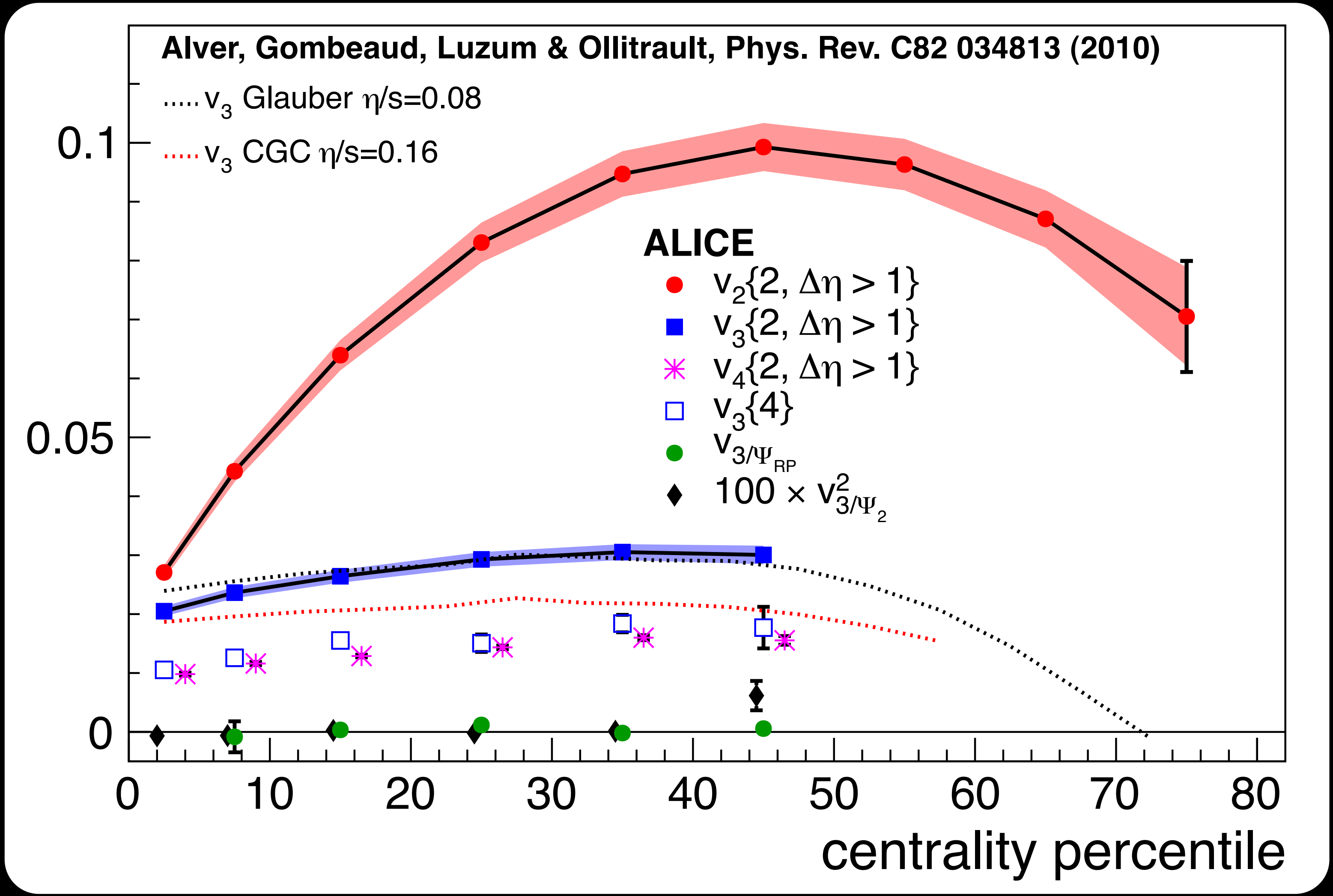


- Sizable signal; weak centrality dependence
- v3 at mid-rapidity driven by fluctuations

Triangular Flow

We observe significant v_3 which compared to v_2 has a different centrality dependence

The centrality dependence and magnitude are similar to predictions for MC Glauber with η/s=0.08 but above MC-KLN CGC with η/s=0.16

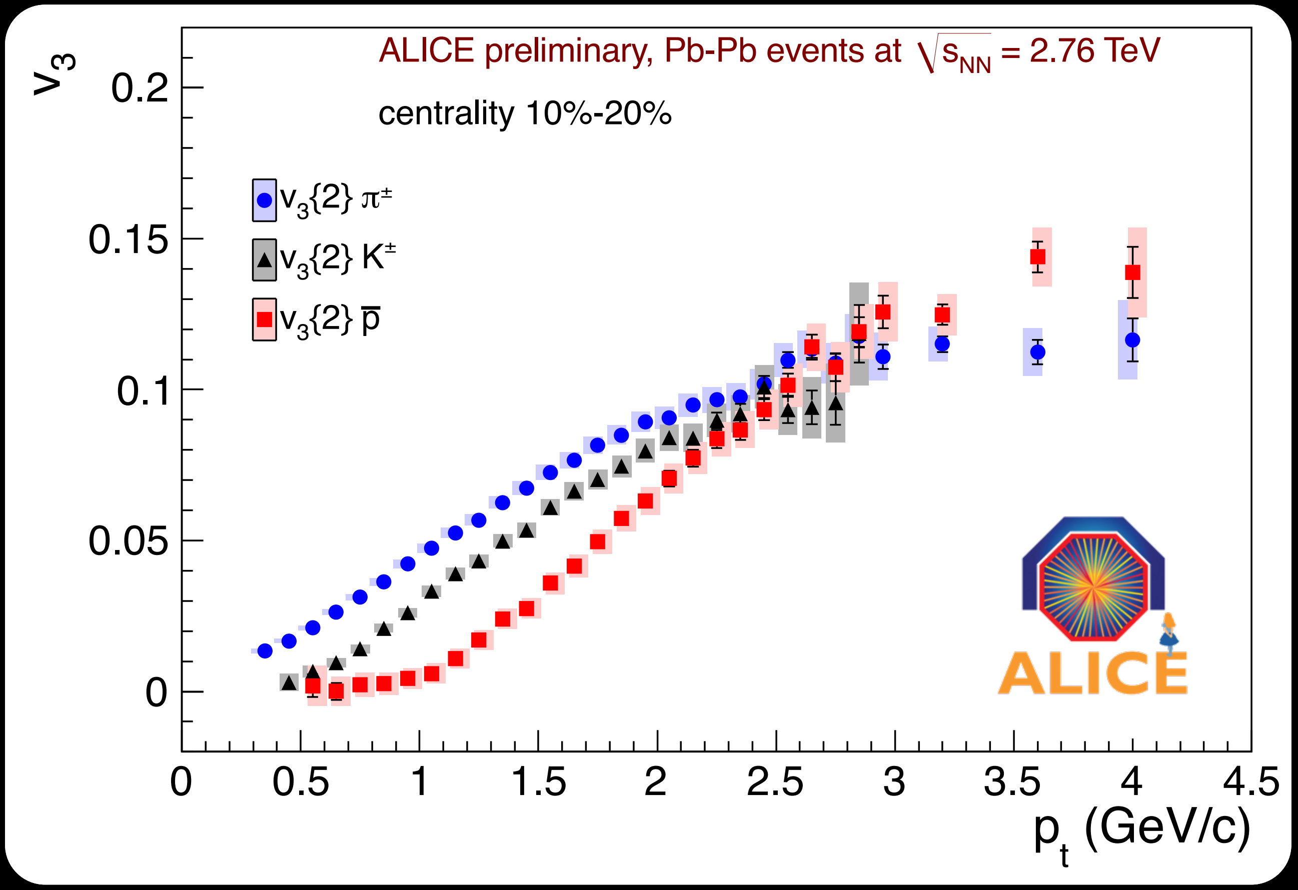


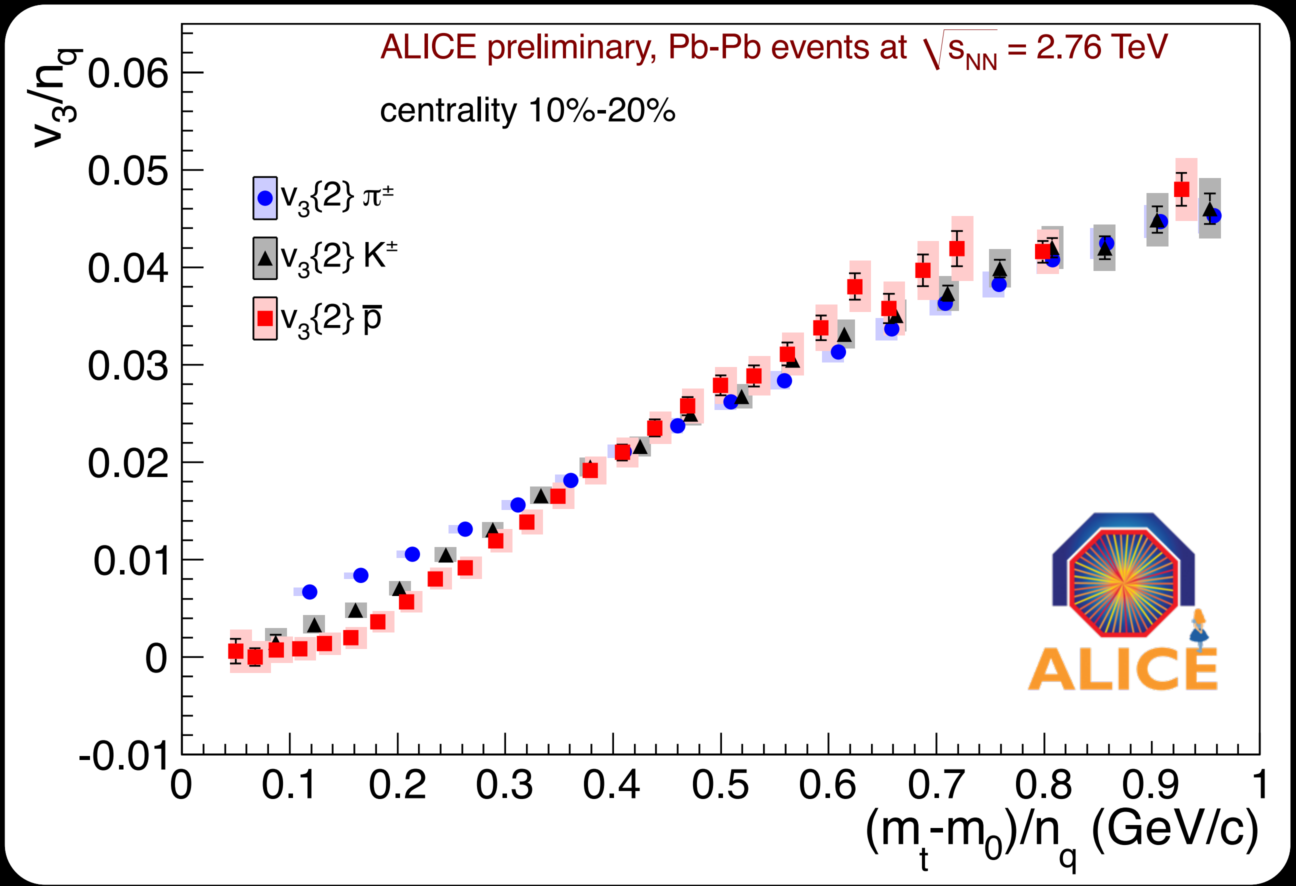
ALICE Collaboration, arXiv:1105.3865

The v_3 with respect to the reaction plane determined in the ZDC and with the v_2 participant plane is consistent with zero as expected if v_3 is due to fluctuations of the initial eccentricity

The $v_3\{2\}$ is about two times larger than $v_3\{4\}$ which is also consistent with expectations based on initial eccentricity fluctuations

Triangular Flow



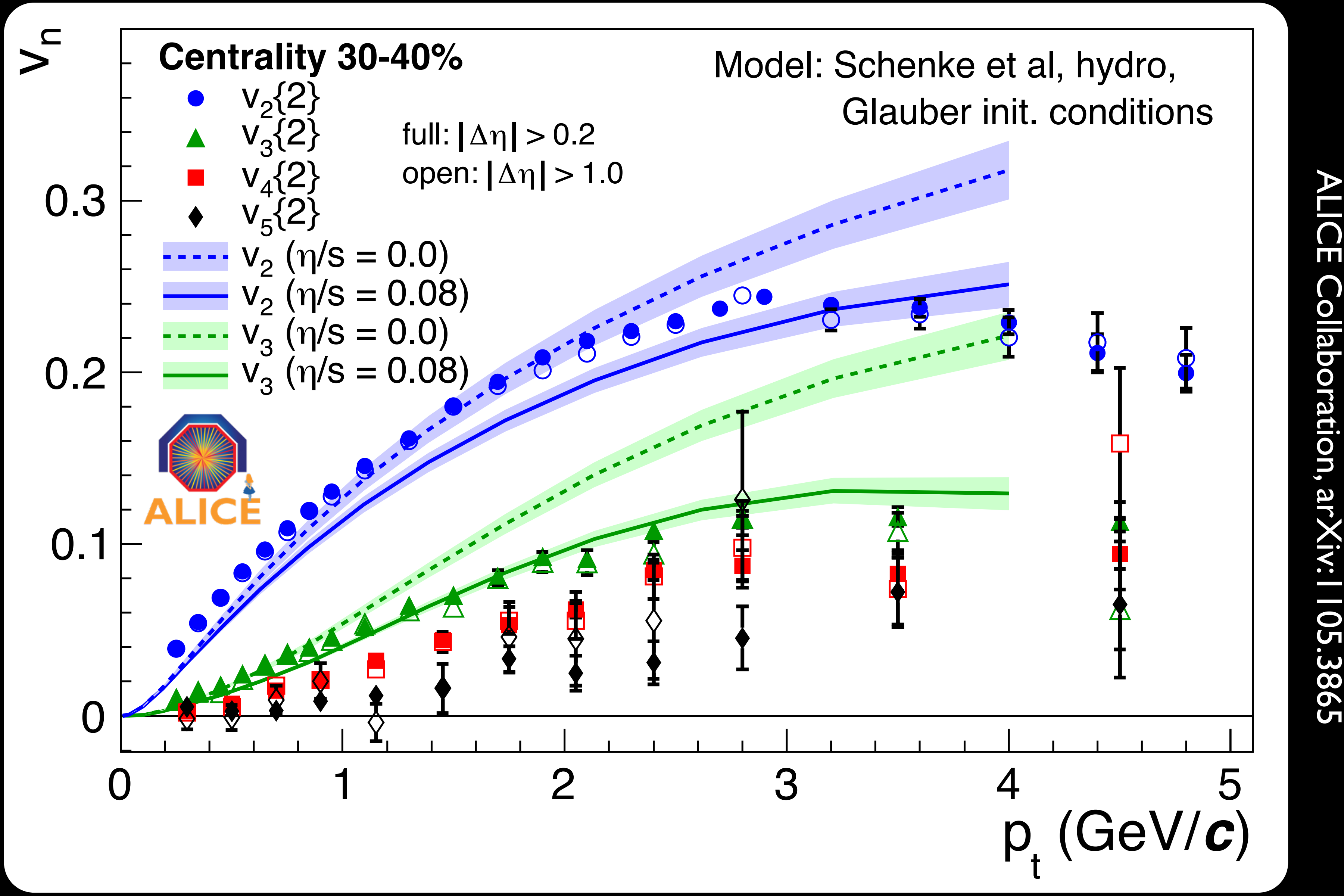


see presentation M. Krzewicki

The behavior of v_3 as function of p_t for pions, Kaons and protons shows the same features as we already observed for v_2

(we observe the mass splitting and, in addition, the crossing of the pions with protons at intermediate p_t, which for v_2 was considered as a signature for coalescence/recombination)

Other Harmonics

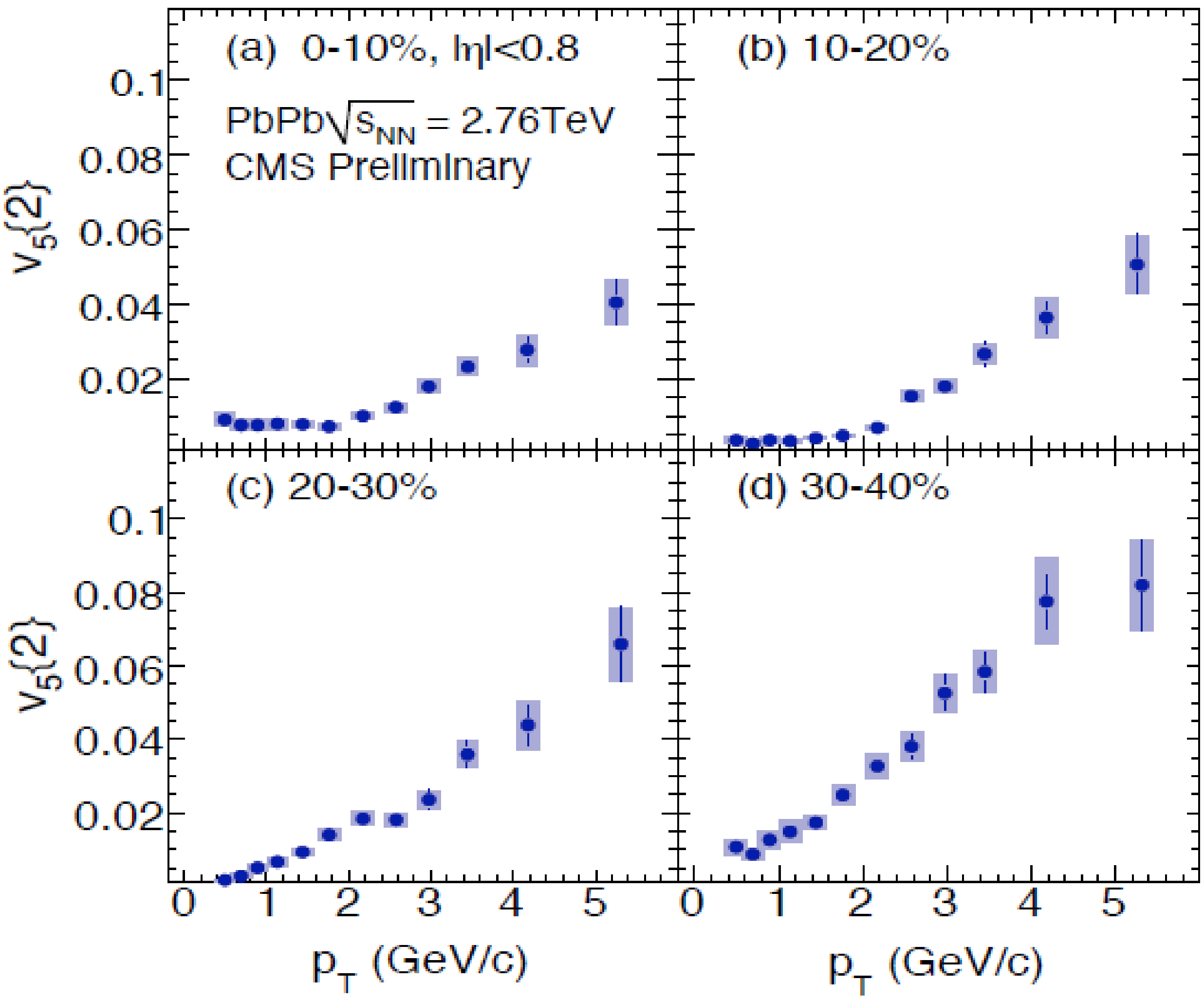


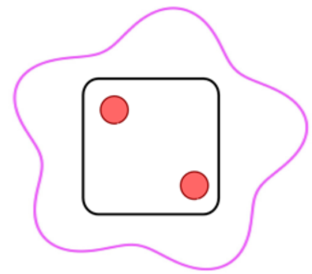
see presentation A. Bilandzic

The overall dependence of v_2 and v_3 is described

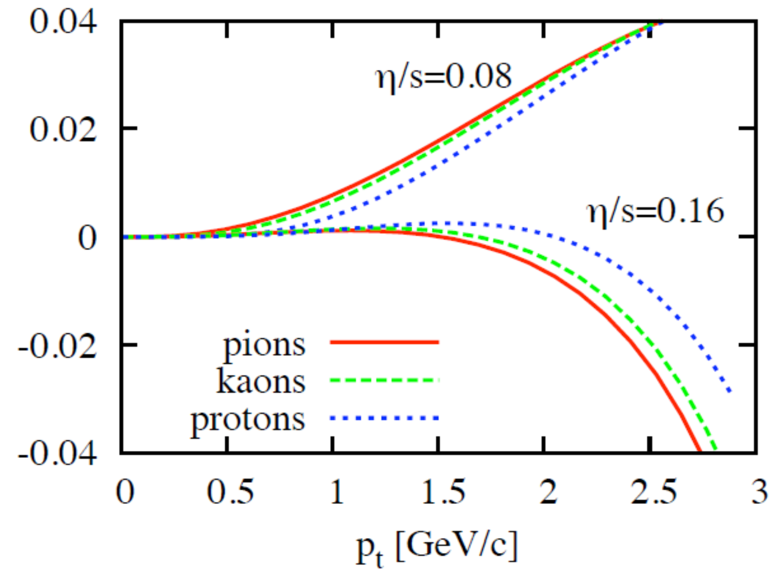
However there is no simultaneous description with a single η/s of v_2 and v_3 for Glauber initial conditions

$v_5(p_T)$ at mid-rapidity $|\eta|< 0.8$



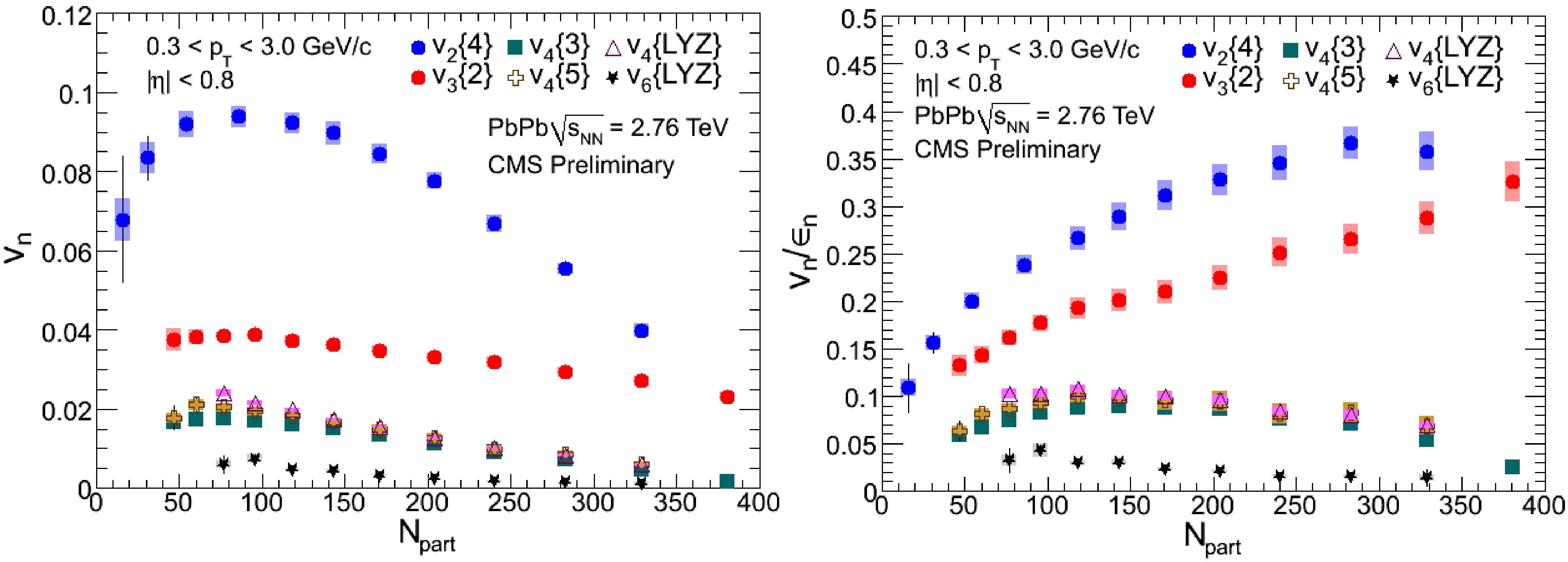


Alver et al Phys. Rev. C82 (2010) 034913
Prediction for RHIC, 0-5% centrality



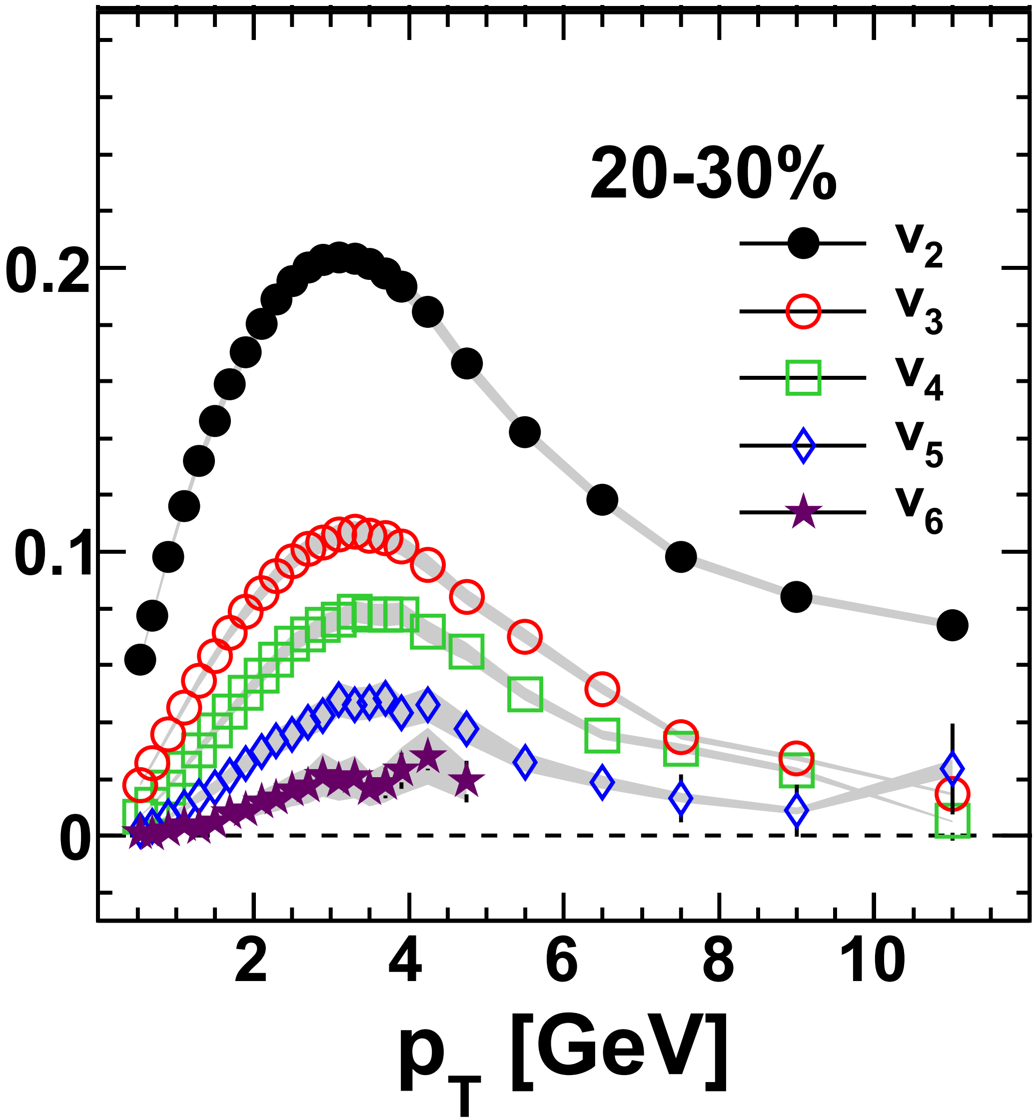
- v_5 rises quadratically with p_T in contrast with other flow harmonics

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

v_n(n=2-6) vs p_T (0.5-12 GeV)



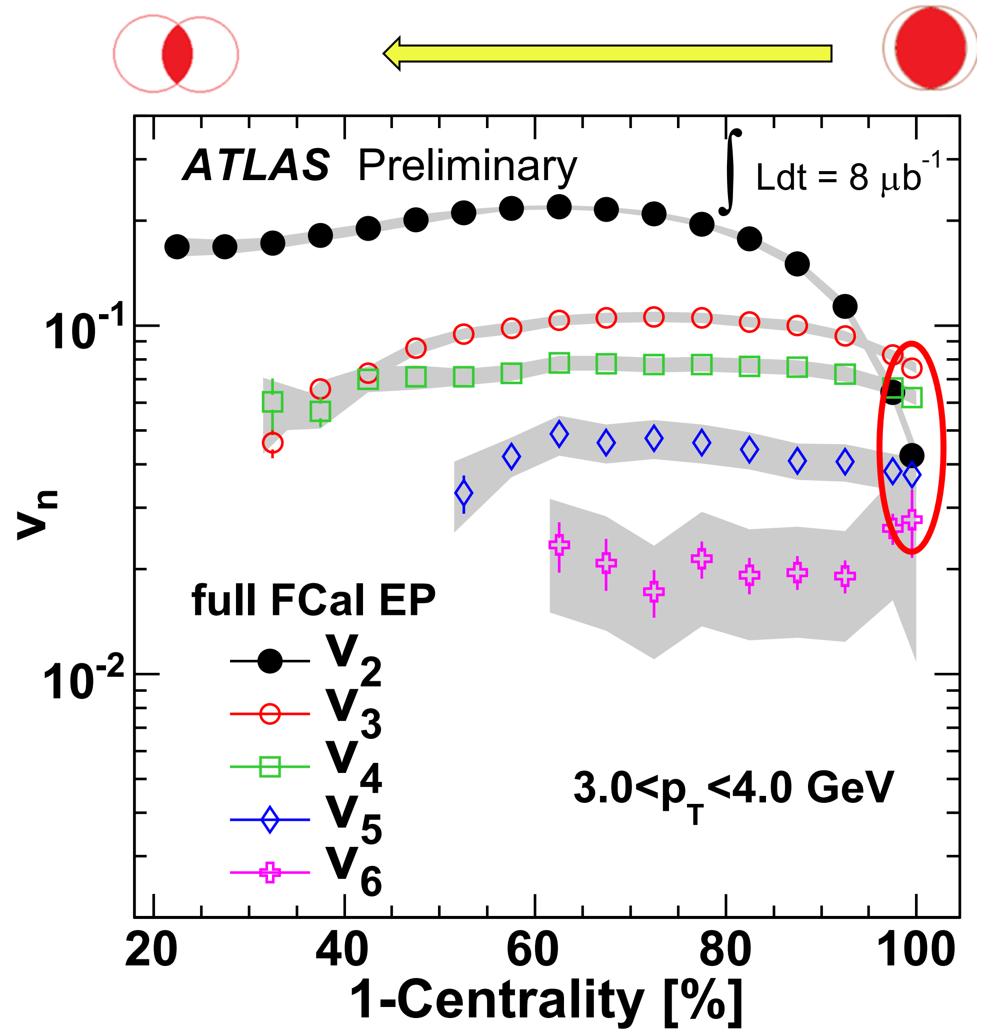
Similar p_T dependence for all n: rise to 3-4 GeV, then falls

v_n vs centrality

- Plot v_n(n=2-6) vs centrality in 5% centrality steps plus a 0-1% most central bin (the right most point)

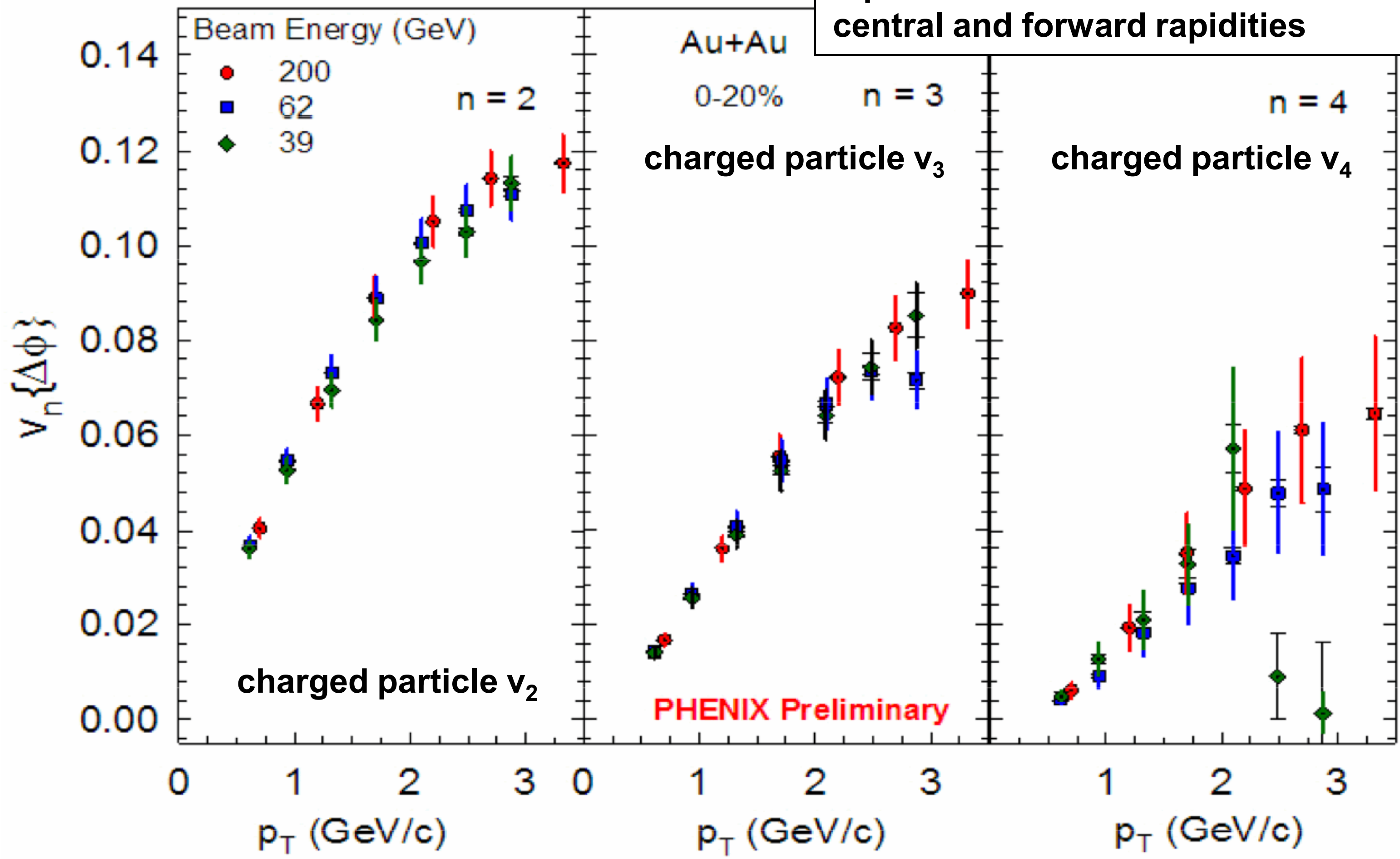
Rise to mid-centrality then falls; higher order v_n is flatter

v_3,v_4 even v_5 exceed v_2 at high p_T in most central collisions



Beam energy dependence 39/62/200GeV Au+Au

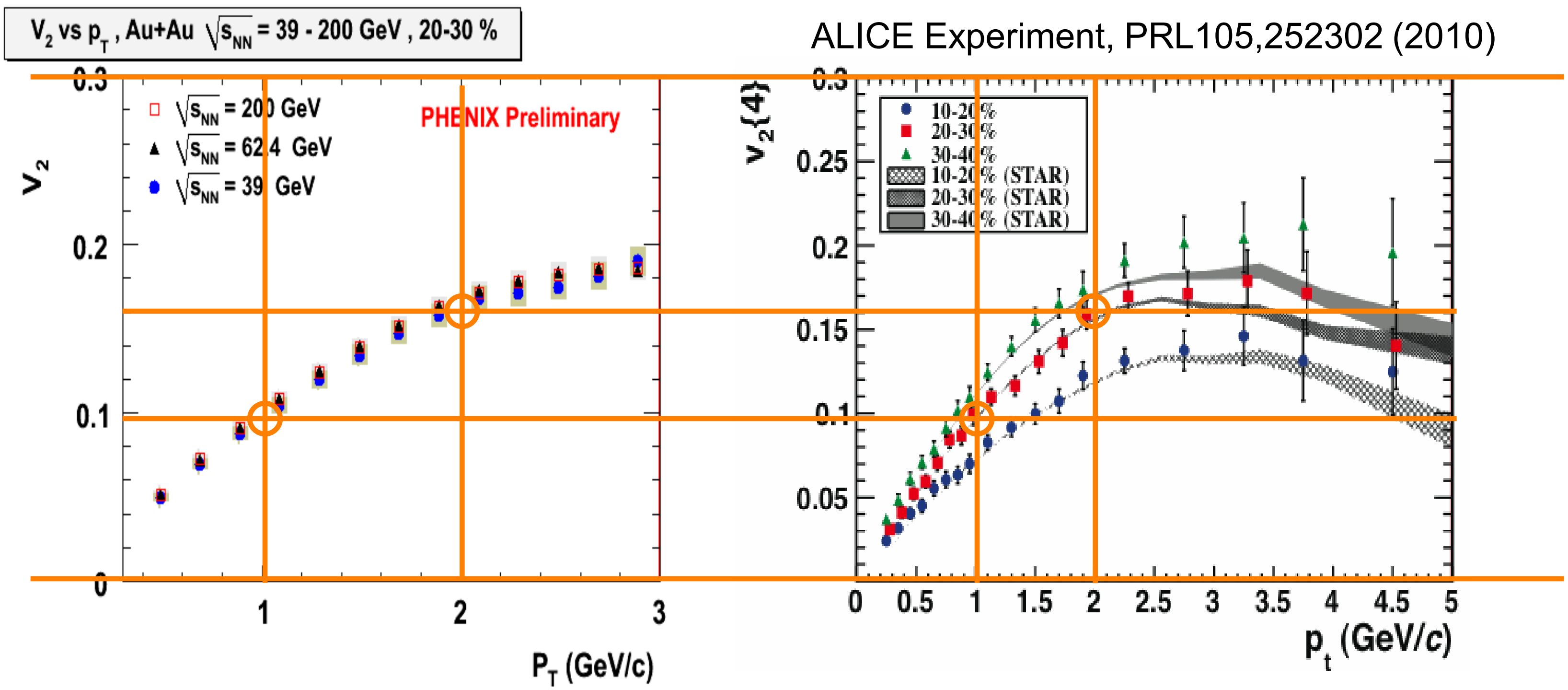
2-particle correlation method between central and forward rapidities



similar hydro-properties down to 39GeV

Comparable v_2 vs p_T from 39GeV to 2.76TeV

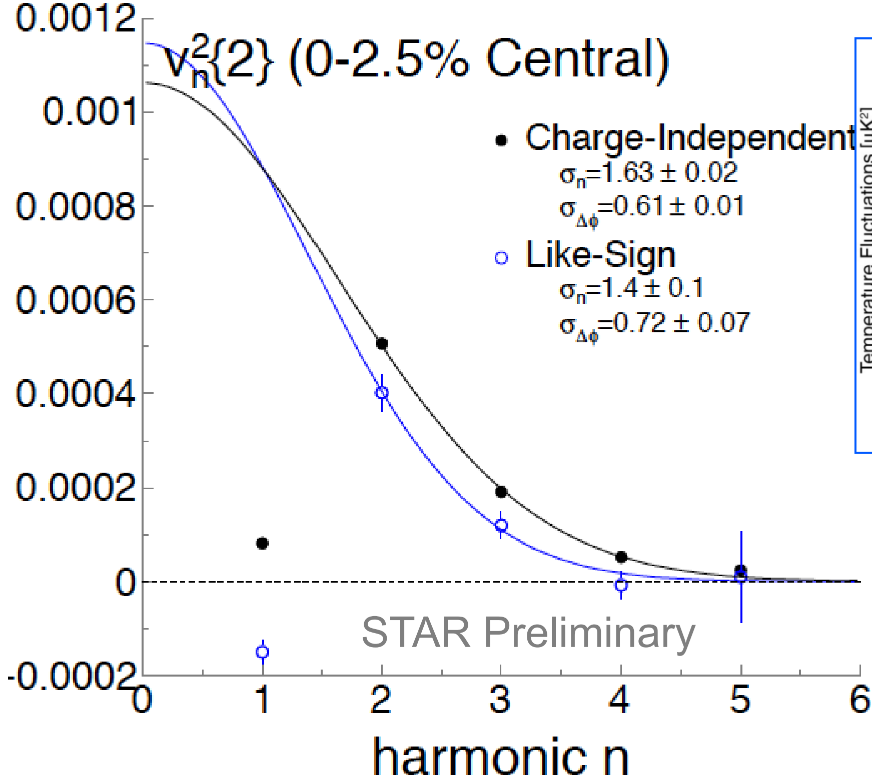
ALICE Experiment, PRL105,252302 (2010)

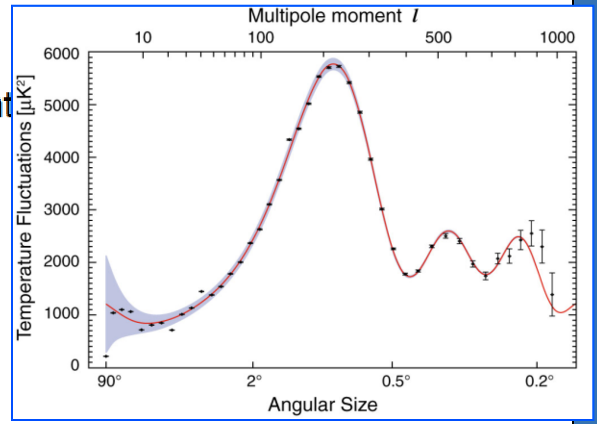


similar hydro-properties from 39GeV to 2.76TeV

$v_n^2\{2\}$ 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

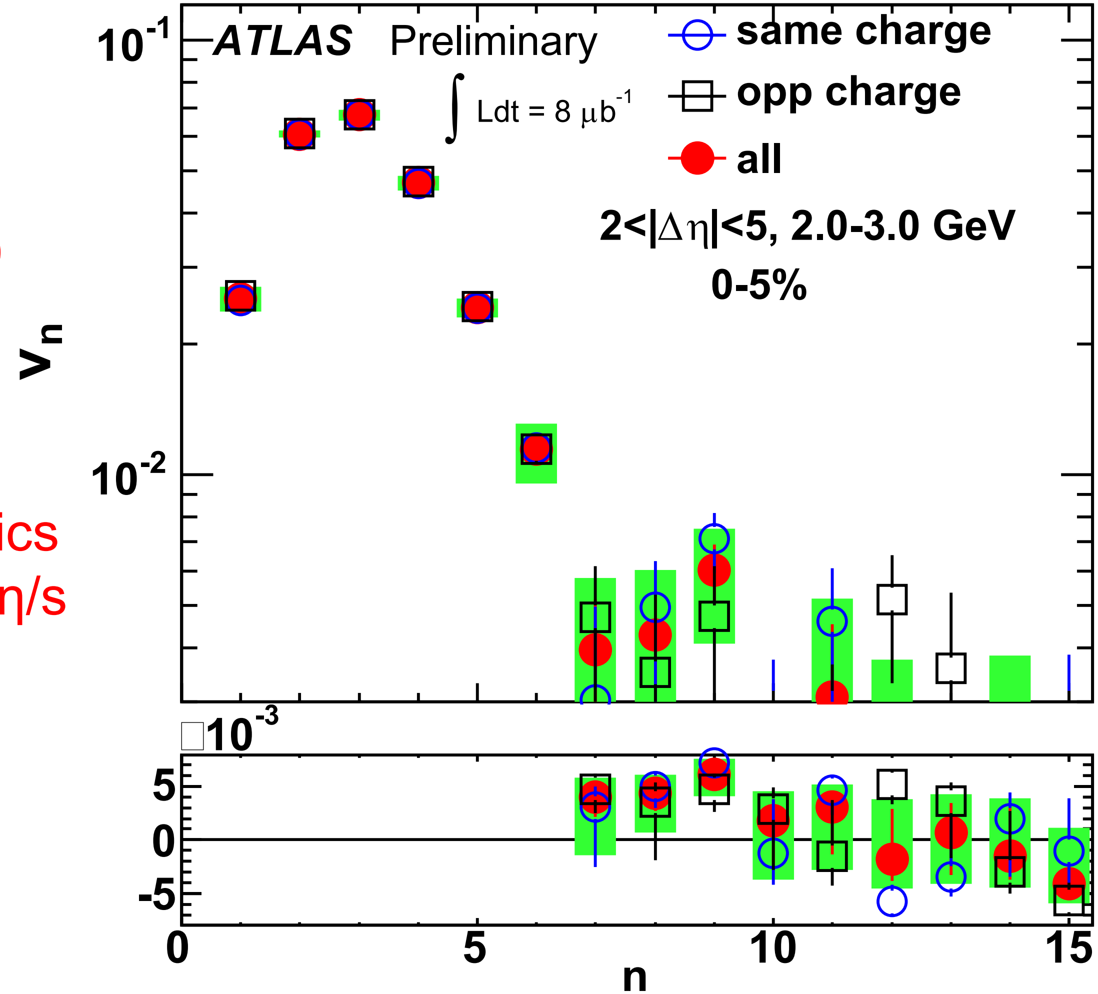
Integrates all Δη within acceptance: we can look more differentially to assess non-flow

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

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 the case of the 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.)**
- **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;...** *The* **grand challenges at the frontiers of condensed matter physics today.**
- **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?**

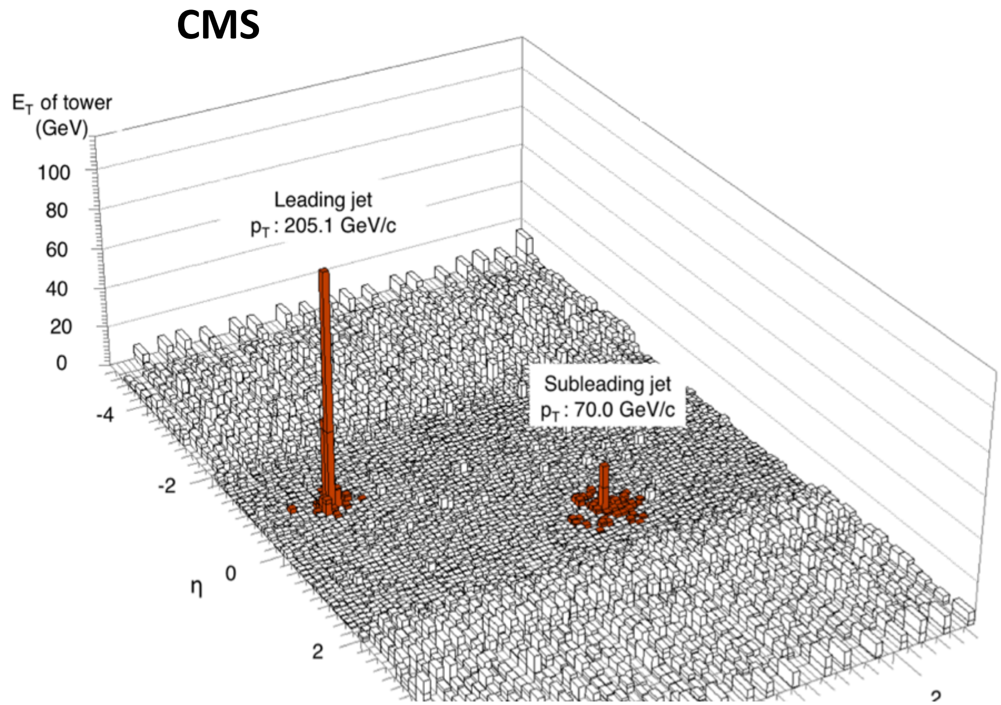
- **We have two big advantages: (i) direct experimental access to the fluid of interest without extraneous degrees of freedom; (ii) weakly-coupled quark and gluon quasiparticles at short distances.**

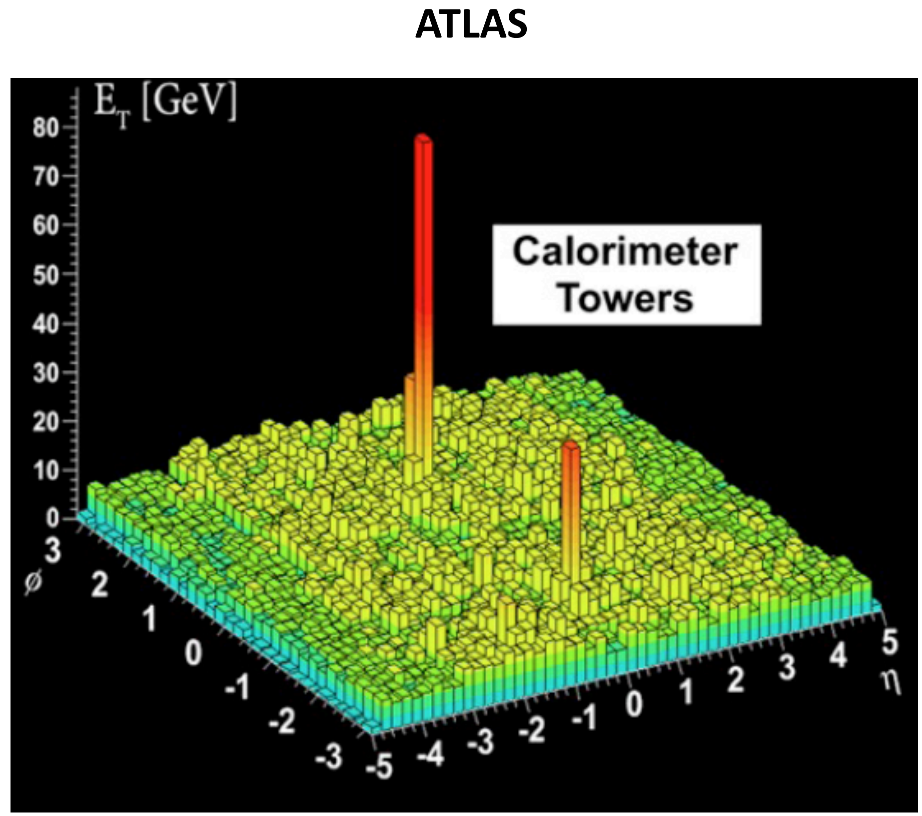
- **We can quantify the properties and dynamics of Liquid QGP at it's natural length scales, where it has no quasiparticles.**

- **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 offers new probes and opens new frontiers.**

Jet Quenching at the LHC





A very large effect at the LHC, immediately apparent in single events. 200 GeV jet back-to-back with a 70 GeV jet. Strongly coupled plasma. Strong jet quenching not a surprise. . .

A Surprise...

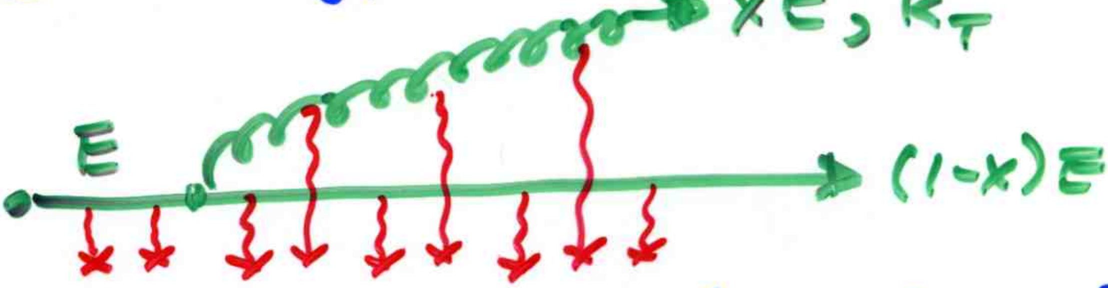
CMS arXiv:1102.1957; ATLAS & CMS @ QM2011

- **The 70 GeV jet looks like a 70 GeV jet in pp collisions. Same fragmentation function; same angular distribution. The "missing" 130 GeV of energy is *not* in the form of a spray of softer particles in and around the jet.**
- **Contradicts the many pre-LHC analyses of jet quenching built upon a picture of a hard parton losing energy by radiating nearly collinear gluons. In such a picture, if a 70 GeV jet gets out it must be surrounded by at least some of its debris.**
- **Also, 70 GeV jet seems to be back-to-back with the 200 GeV jet; no sign of transverse kick.**
- **The "missing" 130 GeV of energy is in the form of many ~ 1 GeV particles at large angle to the jet directions.**
- **(Interestingly, STAR sees evidence of spray of softer particles around the lower energy jets at RHIC.)**

JET QUENCHING

Further evidence that QGP@RHIC is strongly coupled.

Radiative energy loss



dominates in high E limit. ($E \gg k_T \gg T$)

If so (RHIC? LHC?), energy loss sensitive to medium through one parameter $\hat{q}$, k_T^2 picked up by radiated gluon per distance L travelled.

Spectrum of radiated gluons: $\omega \frac{dI}{d\omega} \sim \alpha \sqrt{\frac{\hat{q}}{\omega}}\, L$

Energy loss $\Delta E \sim \alpha \hat{q} L^2$ for $\omega < \hat{q} L^2$

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- **The "missing" 130 GeV of energy is in the form of many ~ 1 GeV particles at large angle to the jet directions.**
- **(Interestingly, STAR sees evidence of spray of softer particles around the lower energy jets at RHIC.)**

- As if an initially-200-GeV jet just heats the plasma it passes through (“makes a little extra plasma”), losing energy without spreading in angle.

- Conventional picture of jet quenching, based on weakly coupled intuition, not valid or needs modification? Are even 200 GeV partons not “seeing” the quasiparticles at short distances?

- We need† a strongly coupled approach to jet quenching, even if just as a foil with which to develop new intuition.

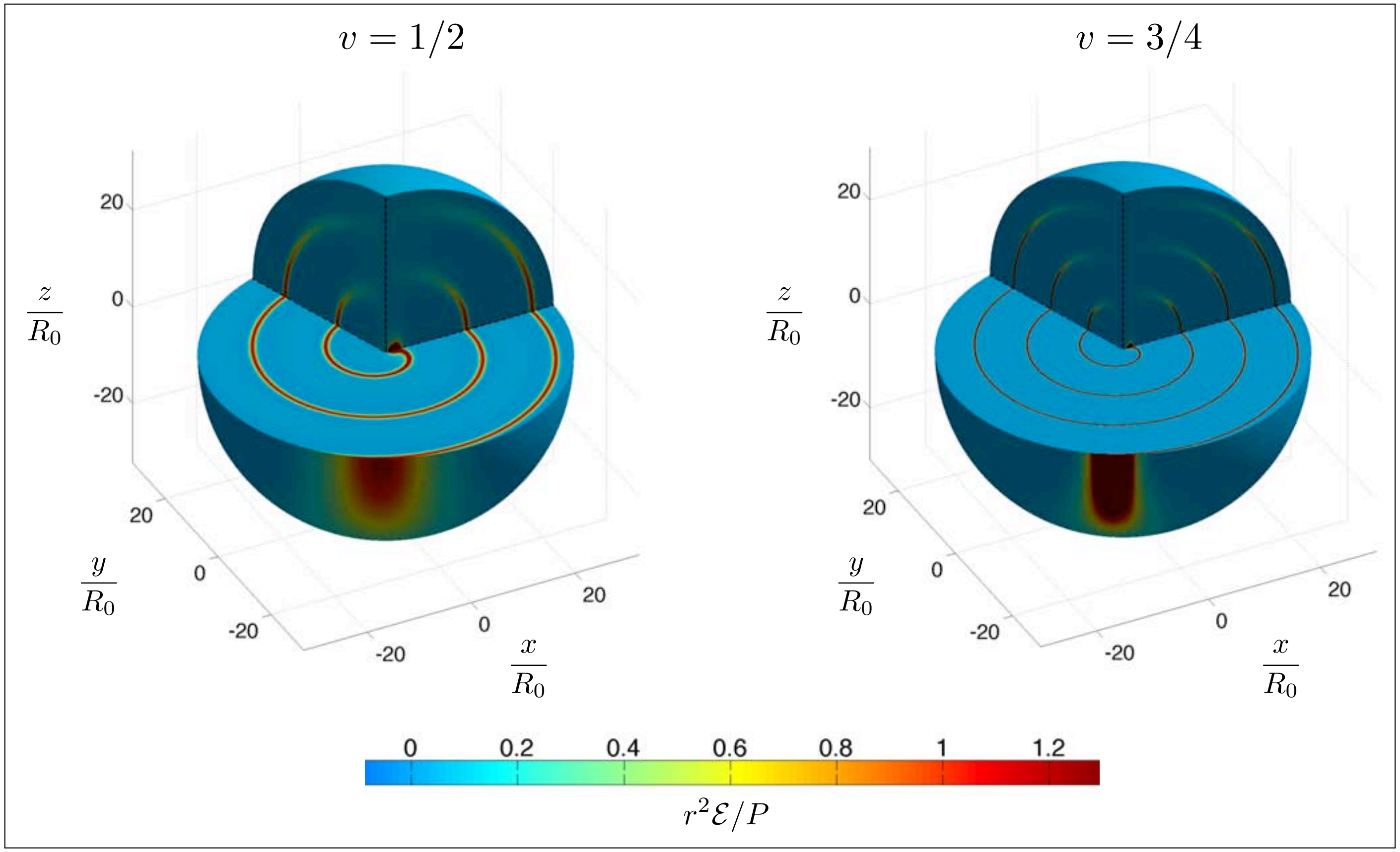
- Problem: jet production is a weakly-coupled phenomenon. There is no way to make jets in the strongly coupled theories with gravity duals.

- But we can make a beam of gluons. . .

†But, I’m hedging my bets. See Lekaveckas’ talk on Thursday for our work deploying SCET within the conventional picture of jet quenching.

Synchrotron Radiation in Strongly Coupled Gauge Theories

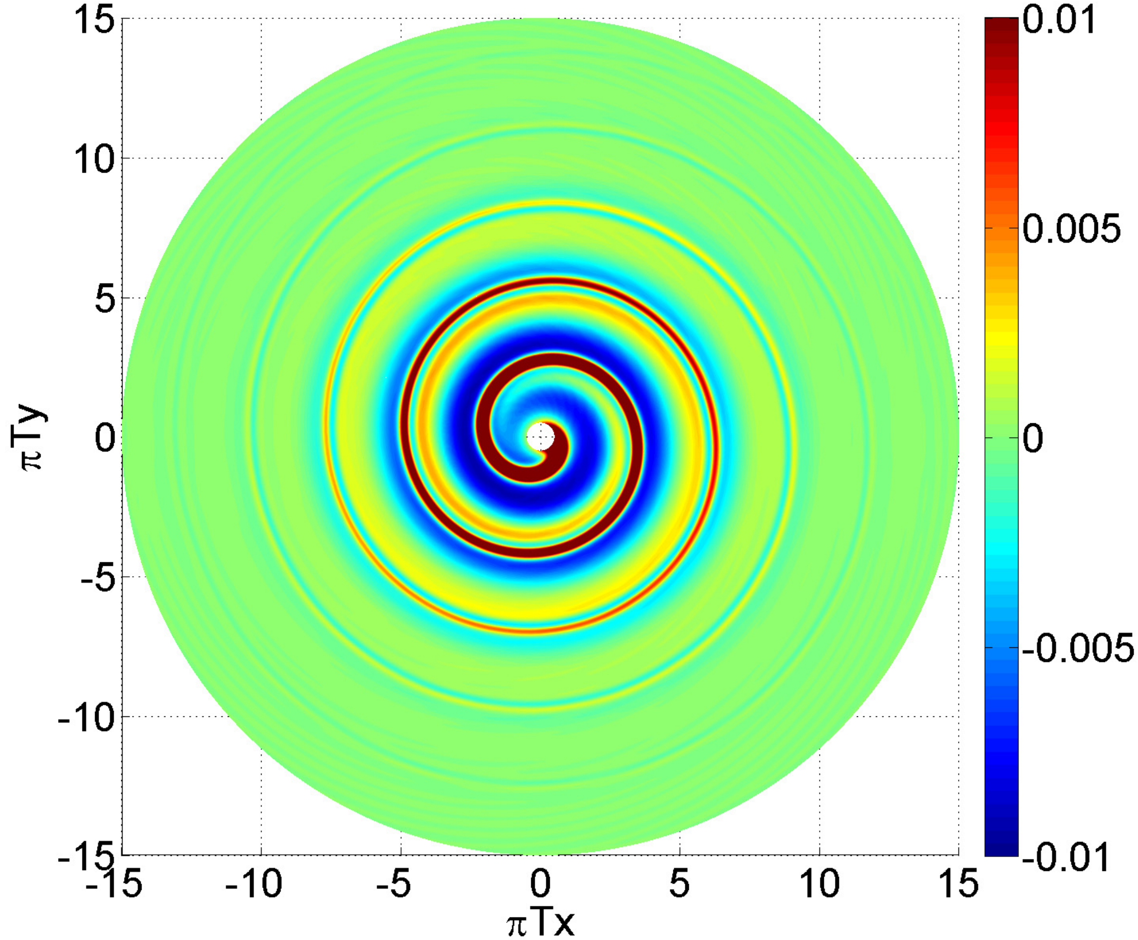
Athanasiou, Chesler, Liu, Nickel, Rajagopal; arXiv:1001.3880



Fully *quantum mechanical* **calculation of gluon radiation from a rotating quark in a** *strongly coupled* **large** N_c *non abelian* **gauge theory, done via gauge/gravity duality. "Lighthouse beam" of synchrotron radiation. Surprisingly similar to classical electrodynamics. Now, shine this beam through strongly coupled plasma. . .**

Quenching a Synchrotron Beam

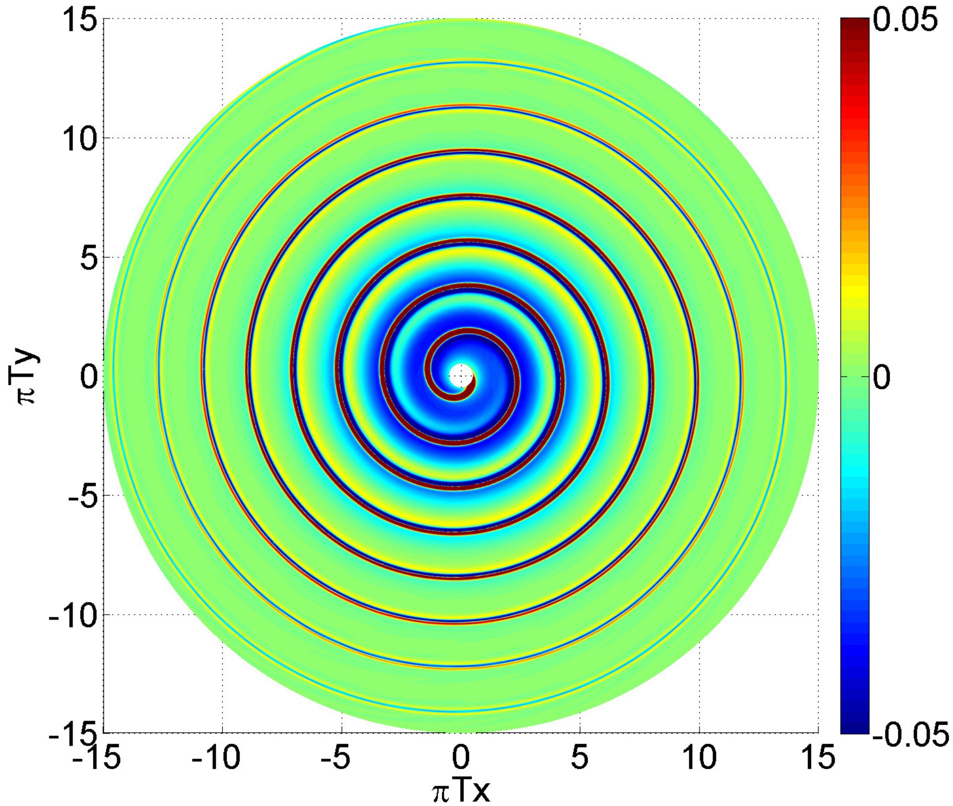
Chesler, Ho, Rajagopal; preliminary

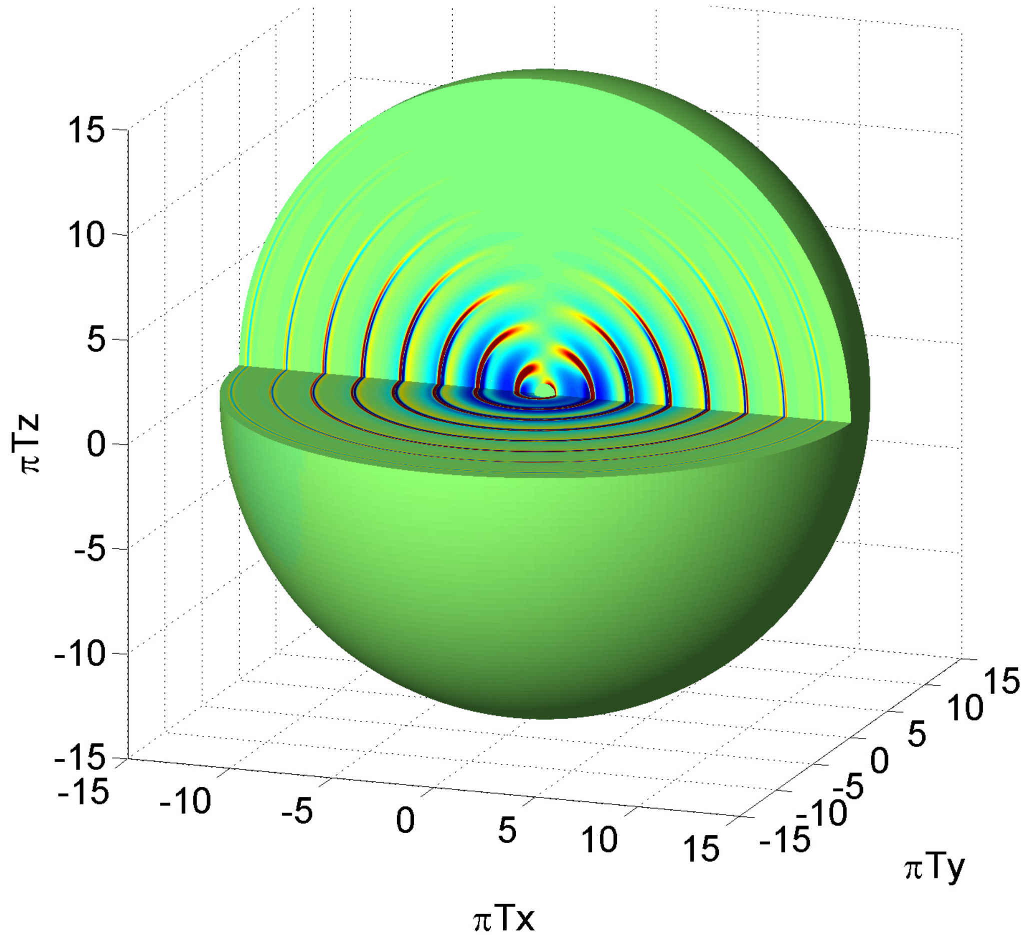


Quark in circular motion ($v = 0.34$; $R\pi T = 0.15$) through the strongly coupled plasma radiates synchrotron radiation that dissipates, *and heats the plasma behind it*.

Quenching a Synchrotron Beam

Chesler, Ho, Rajagopal; preliminary





This time, $v = 0.5 \rightarrow$ higher energy gluon beam. Dissipates *without spreading in angle*. **No sign of spreading of the angular extent of the beam in either azimuthal or polar angle.**

Jet Quenching in Liquid QGP

- We're back at the blind-folk and the elephant stage.
- A beam of gluons loses its energy by heating the strongly coupled plasma it propagates through, not by spreading. At least reminiscent of jet quenching at the LHC.
- Pre-equilibrium parton energy loss may be important.
- If a high energy jet does not "see" the short-distance quasiparticles, perhaps quarkonia or photons will.
- Upsilons have the virtue of being small...
- At some short length scale, a quasiparticulate picture of the QGP must be valid, even though on its natural length scales it is a strongly coupled fluid. It will be a challenge to see and understand *how* the liquid QGP emerges from short-distance quark and gluon quasiparticles.

Heavy quarks?

- **In strongly coupled plasmas with gravitational descriptions, heavy quarks lose energy according to $\frac{dp}{dt} = -F(v)$. The force F depends on v but is independent of the heavy quark mass M.** Herzog et al; Gubser; Casalderrey-Solana, Teaney

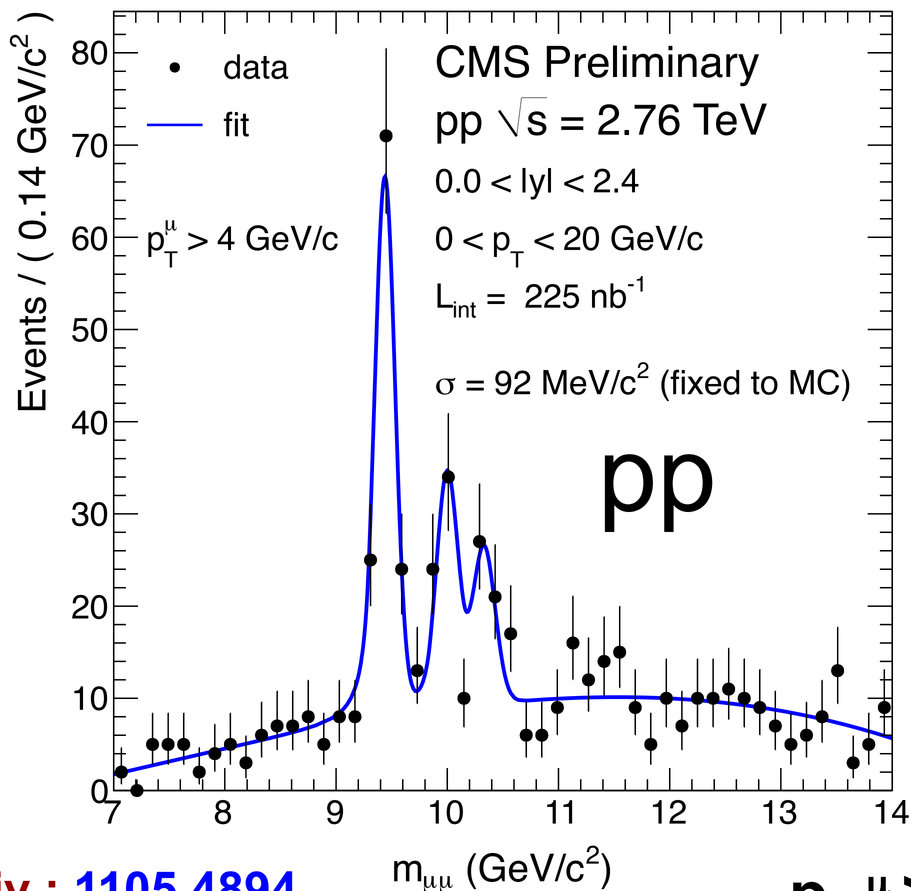
- **Similar behavior in these theories and in the strongly coupled plasma of QCD.** Chesler, Yaffe; Neufeld, Muller, Ruppert

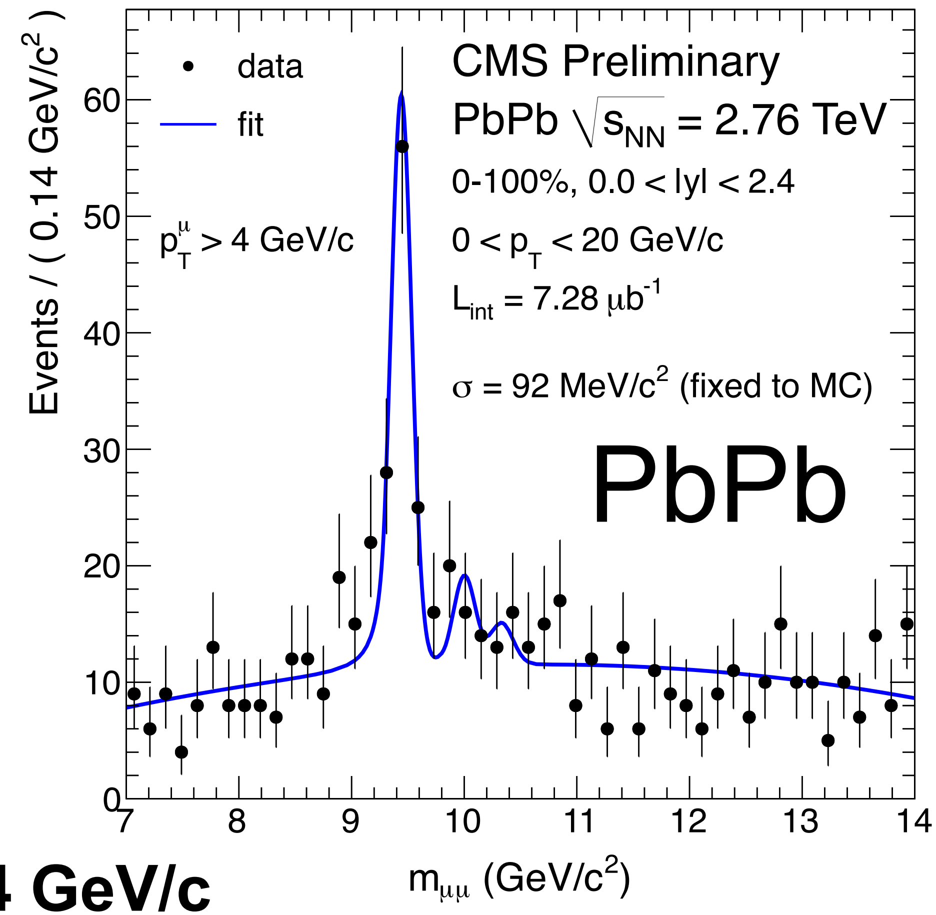
- **Distinctive predictions for experiment, once b and c quarks can be separated, from the prediction of same energy loss for b and c quarks** *with the same v.* Horowitz, Gyulassy

- **If these predictions are confirmed by experiment, it means that the heavy quarks are not behaving like objects of size $1/M$; they are dressing themselves up (with fields) until they have a larger, M-independent, size. Heavy quarks can't "see" short-distance quasiparticles.**

- **Upsilons have the virtue of being small, and color-singlet.**

Υ(2S+3S) Suppression PbPb √s$_{NN}$=2.76 TeV





arXiv : 1105.4894
Submitted to PRL

$p_T^{\mu} > 4$ GeV/c

- Υ(2S+3S) production relative to Υ(1S) in pp and PbPb
- Compare pp and PbPb through a simultaneous fit

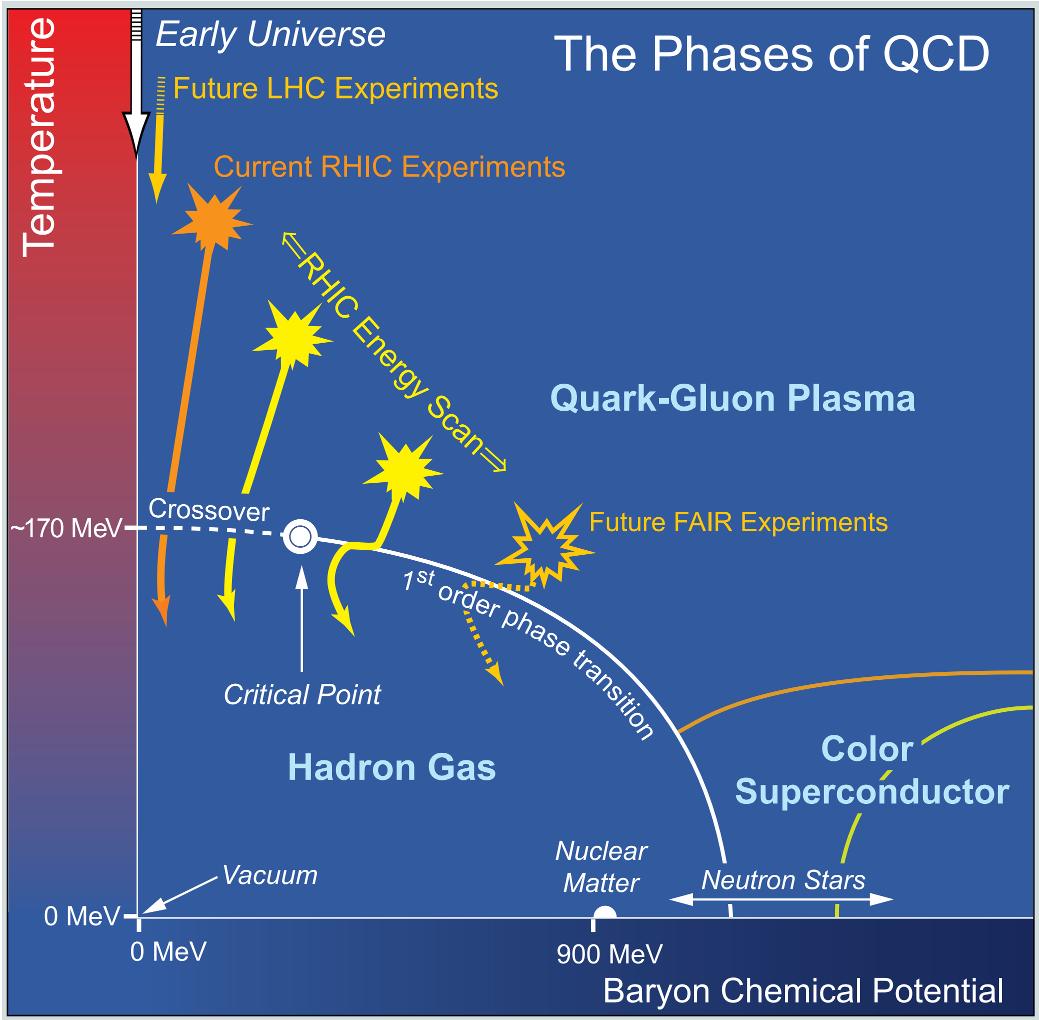
A Grand Challenge

- How can we clarify the understanding of fluids without quasiparticles, whose nature is a central mystery in so many areas of science?

- We are developing more, and better, ways of studying the properties and dynamics of Liquid QGP — "our" example of a fluid without quasiparticles.

- At some short length scale, a quasiparticulate picture of the QGP must be valid, even though on its natural length scales it is a strongly coupled fluid. It will be a challenge to see and understand *how* the liquid QGP emerges from short-distance quark and gluon quasiparticles.

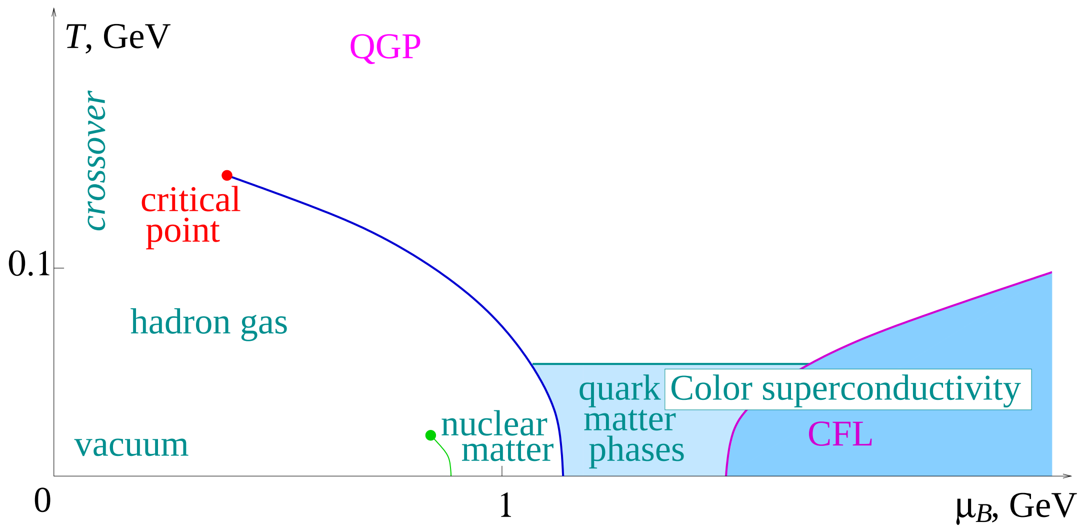
Seeking the QCD Critical Point

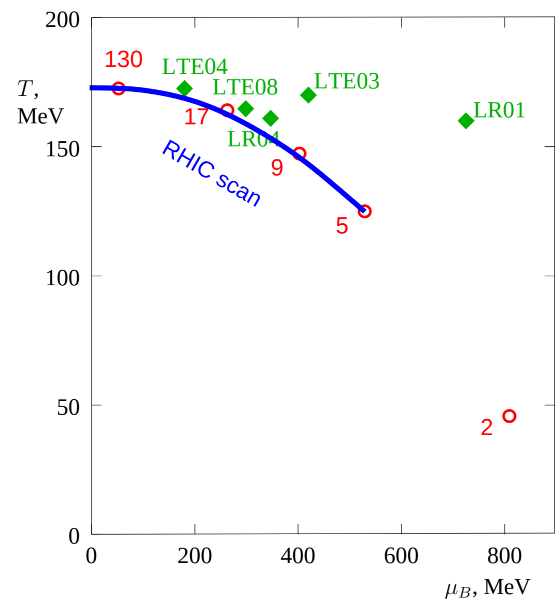


2007 NSAC Long Range Plan

Another grand challenge... Data from first phase of RHIC Energy Scan in 2011. And, a theory development...

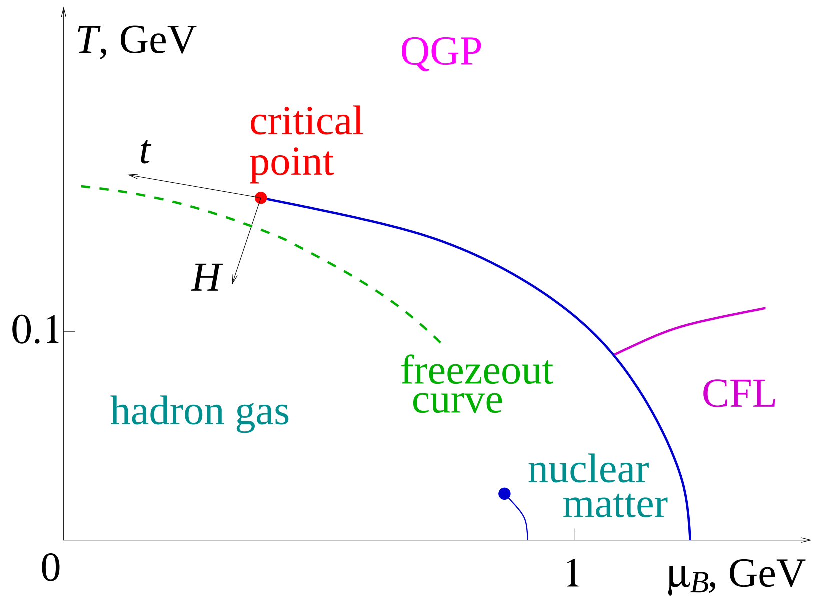
QCD phase diagram, critical point and RHIC

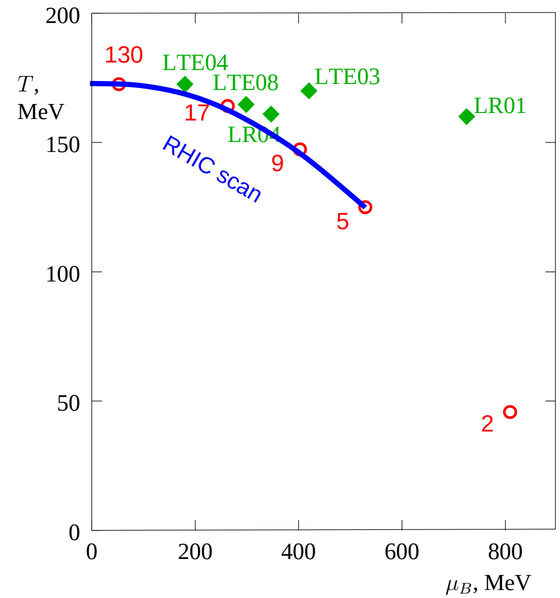




- Models (and lattice) suggest the transition becomes 1st order at some μ_B.
- Can we observe the critical point in heavy ion collisions, and how?
- Near critical point fluctuations grow and become more non-Gaussian.
- Challenge: develop measures most sensitive to the critical point and use them to locate the critical point by scanning in $\sqrt{s}$ and therefore in $\mu_{\text{freezeout}}$.
- Example: kurtosis (of the event-by-event distribution of the number of protons, pions or protons-antiprotons) depend strongly on the correlation length (ξ^7), which is non-trivial, non-monotonic function of μ and therefore $\sqrt{s}$. And, the prefactor in front of ξ^7 changes sign! Stephanov, 1104.1627

QCD phase diagram, critical point and RHIC





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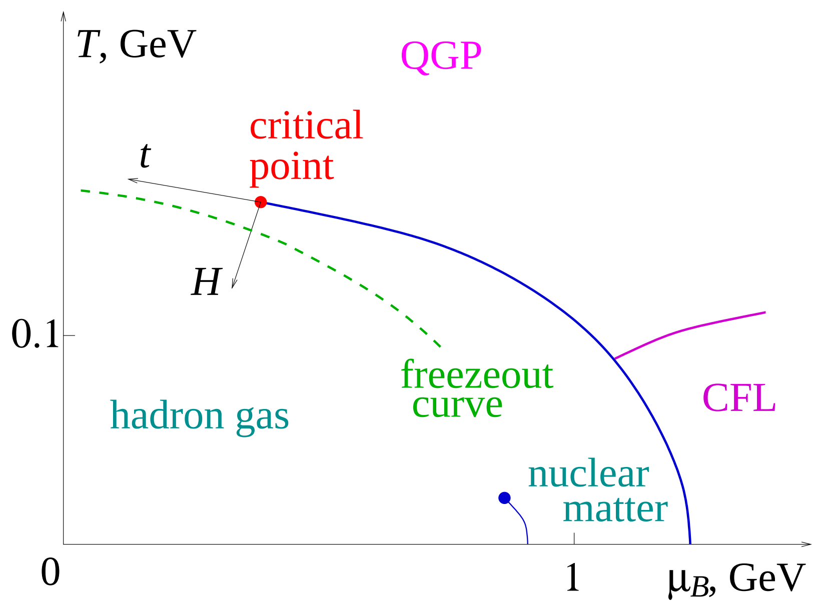

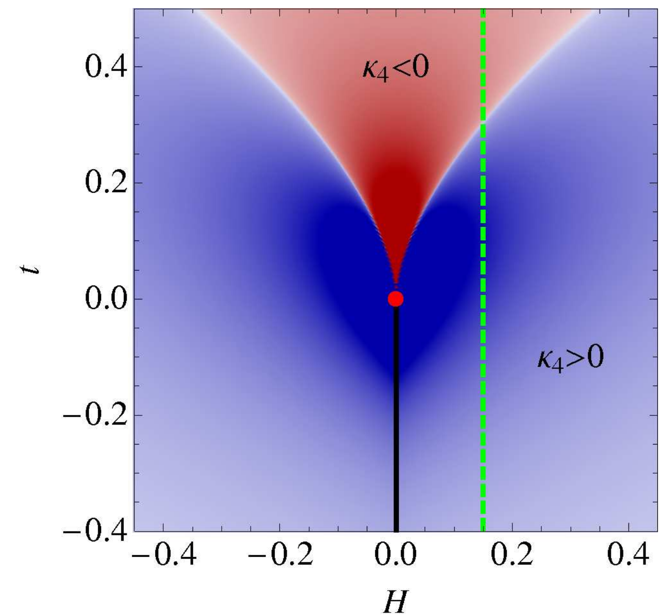

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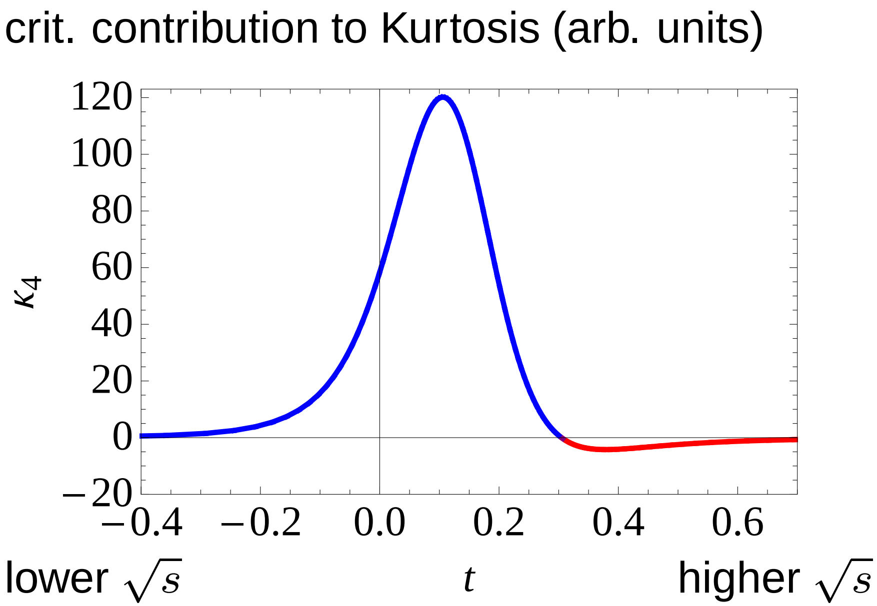

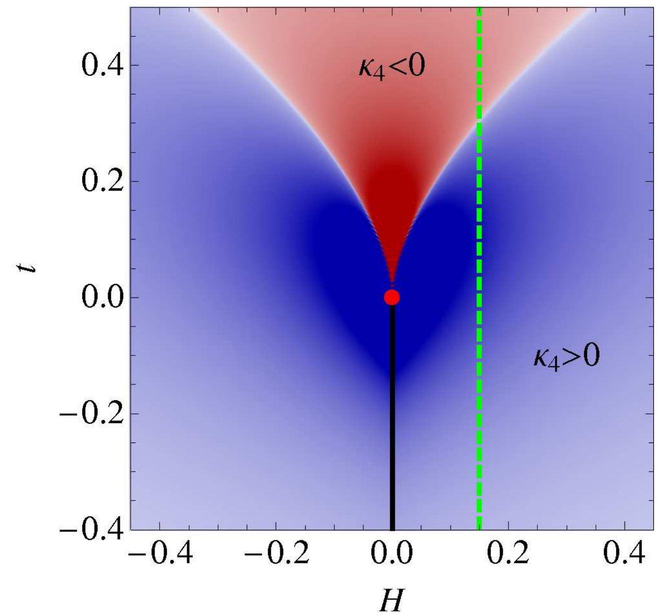

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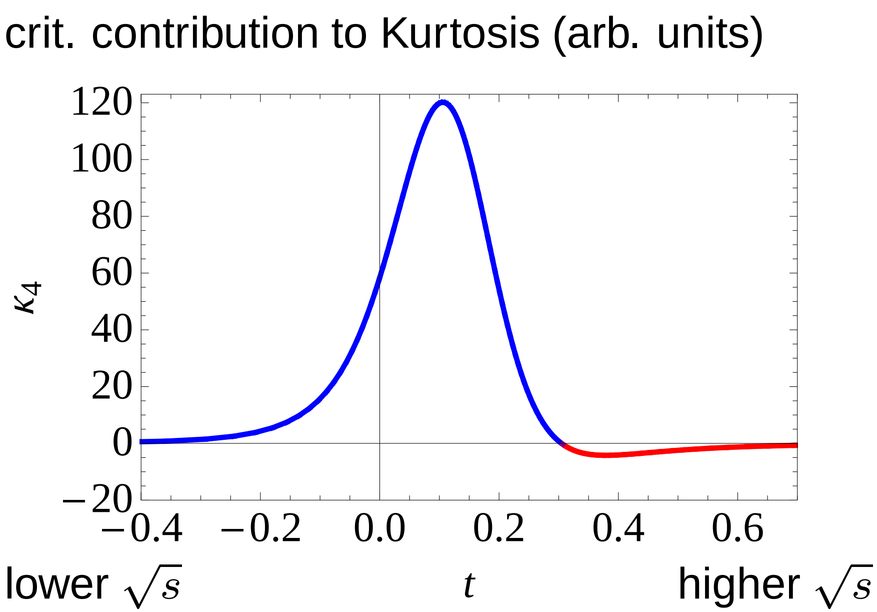

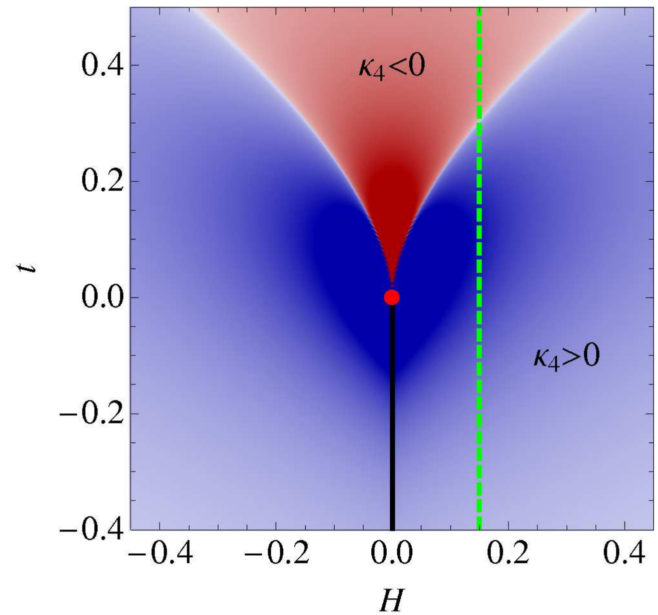

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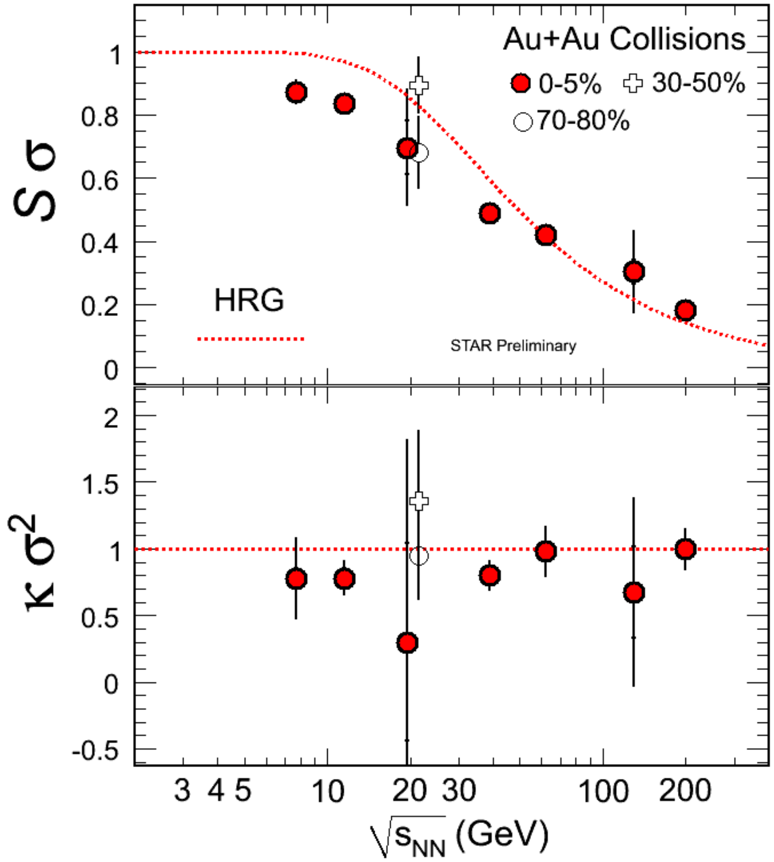
- Near critical point fluctuations grow and become more non-Gaussian.
- Challenge: develop measures most sensitive to the critical point and use them to locate the critical point by scanning in $\sqrt{s}$ and therefore in $\mu_{\text{freezeout}}$.
- Once we find the μ (i.e. the $\sqrt{s}$) where the critical contribution to κ_4 is large enough — e.g. the "blue peak" — then there are then robust, parameter-independent, predictions for various ratios of the kurtosis and skewness of protons and pions. Athanasiou, Stephanov, Rajagopal 1006.4636.

Early RHIC Energy Scan Data



STAR, QM2011

Data at $\sqrt{s} = 19.6$ GeV is few thousand events. Full energy scan data set at this energy was taken in May; results expected this fall. If $\kappa\sigma^2$ were to be below 1 at $\sqrt{s} = 19.6$ GeV, the place to look is just left of there. [One lattice calculation (Gavai, Gupta 2011) finds $-2 < \kappa\sigma^2 < -1$ at μ corresponding to $\sqrt{s} = 19.6$ GeV.]

Stay Tuned...

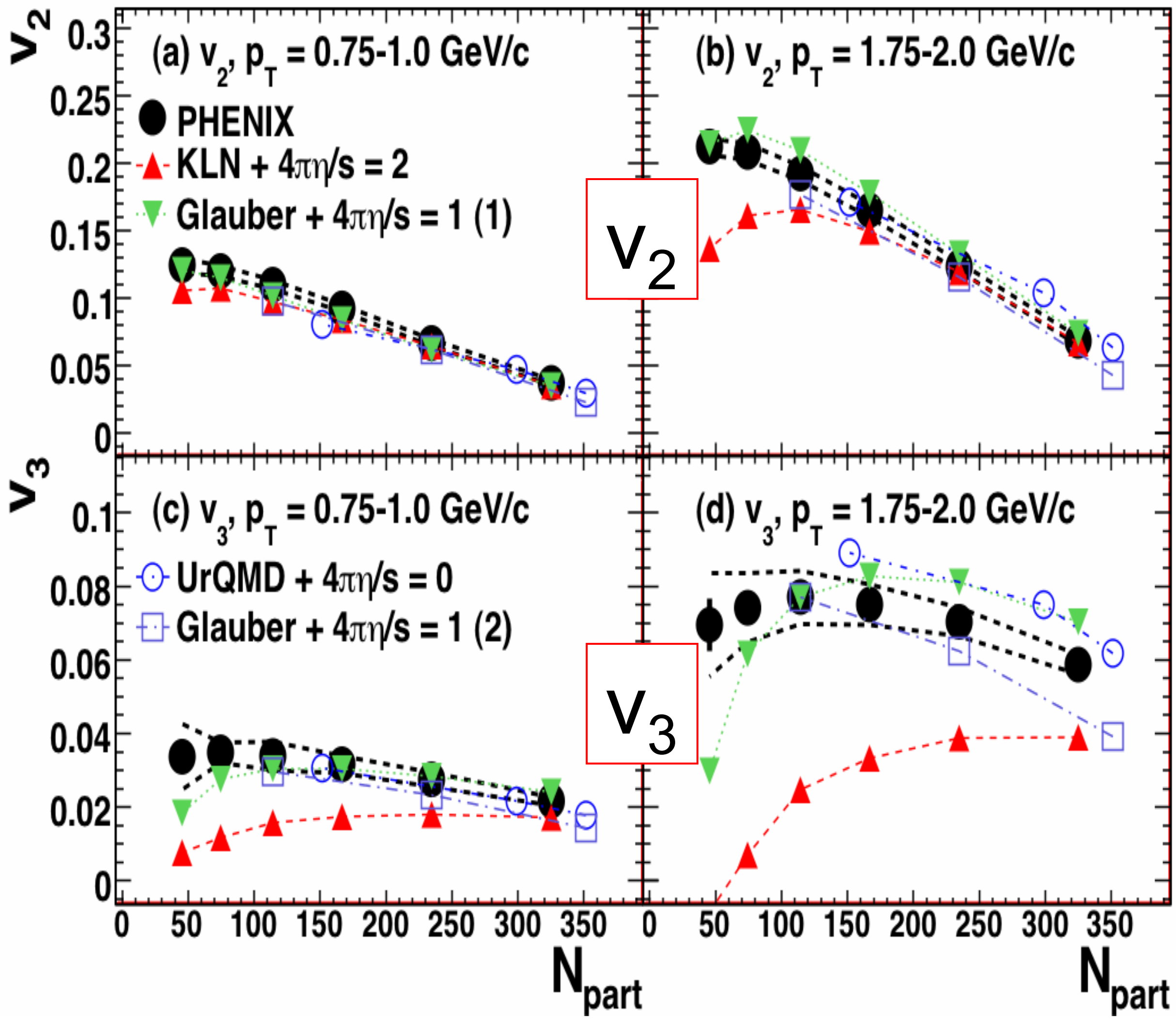
Mapping the QCD phase diagram via the RHIC energy scan has begun...

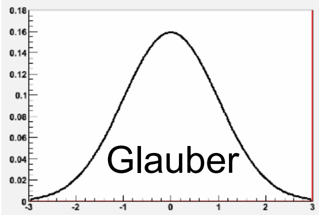
Liquid QGP at LHC and RHIC. New data (v_n at RHIC and LHC; soon, CuAu and UU collisions at RHIC) and new calculations tightening the constraints on η/s and perhaps its T-dependence ...

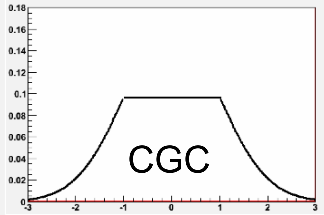
Probing the Liquid QGP. Jet quenching. Heavy quark energy loss. Upsilons. Photons. Each of these is a story now being written. Seeing, and then understanding, how the liquid QGP emerges from asymptotically free quarks and gluons remains a challenge, as well as an opportunity...

v_3 breaks the degeneracy

arXiv:1105.3928







Smaller eccentricity

Larger eccentricity

v_3 provides an additional constraining power on the hydro-model.

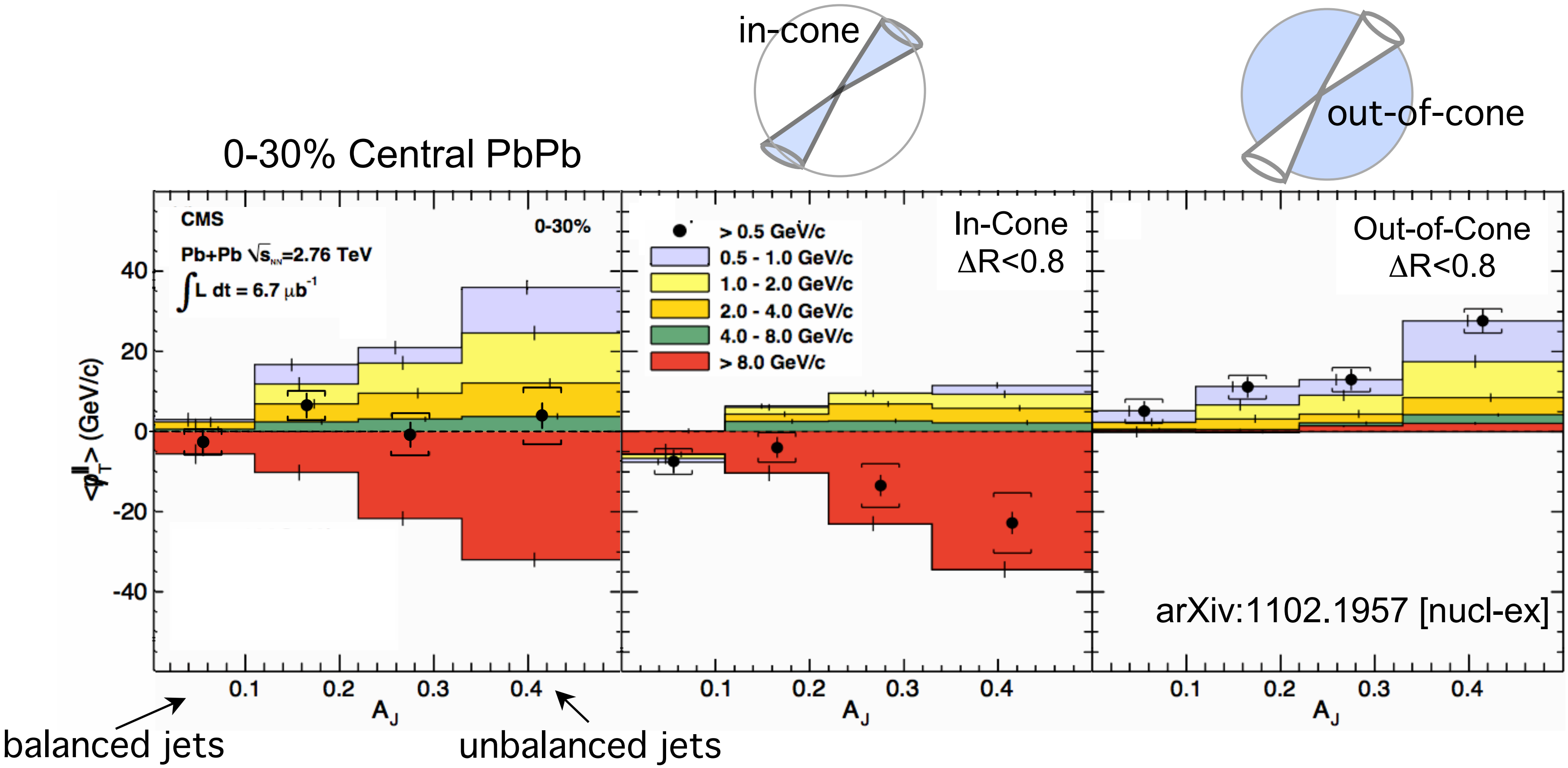
Glauber & $4\pi\eta/s=1$ *works*

CGC-KLN & $4\pi\eta/s=2$ *fails*

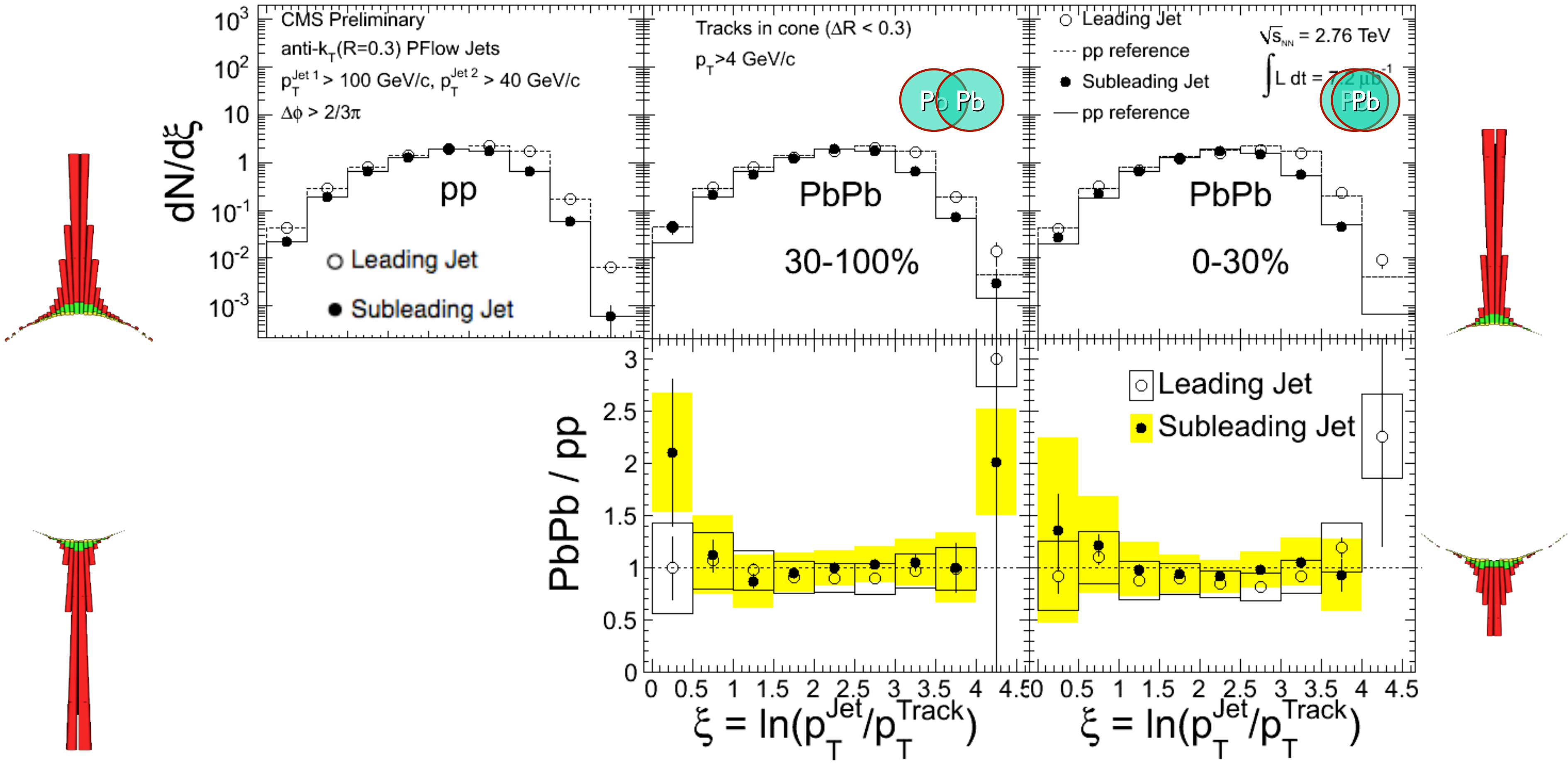
B. Alver et. al., Phys. Rev. C82, 034913(2010).
B. Schenke et. al., Phys. Rev. Lett. 106, 042301(2011).
H. Petersen et. al., Phys. Rev. C82, 041901(2010).

Glauber & $4\pi\eta/s=1$ favored

Missing-$p_T^{||}$


in-cone
out-of-cone
0-30% Central PbPb
CMS
Pb+Pb √sNN=2.76 TeV
∫L dt = 6.7 μb-1
0-30%
> 0.5 GeV/c
0.5 - 1.0 GeV/c
1.0 - 2.0 GeV/c
2.0 - 4.0 GeV/c
4.0 - 8.0 GeV/c
> 8.0 GeV/c
In-Cone
ΔR<0.8
Out-of-Cone
ΔR<0.8
arXiv:1102.1957 [nucl-ex]
<p∥T> (GeV/c)
40
20
0
-20
-40
0.1
0.2
0.3
0.4
AJ
balanced jets
unbalanced jets

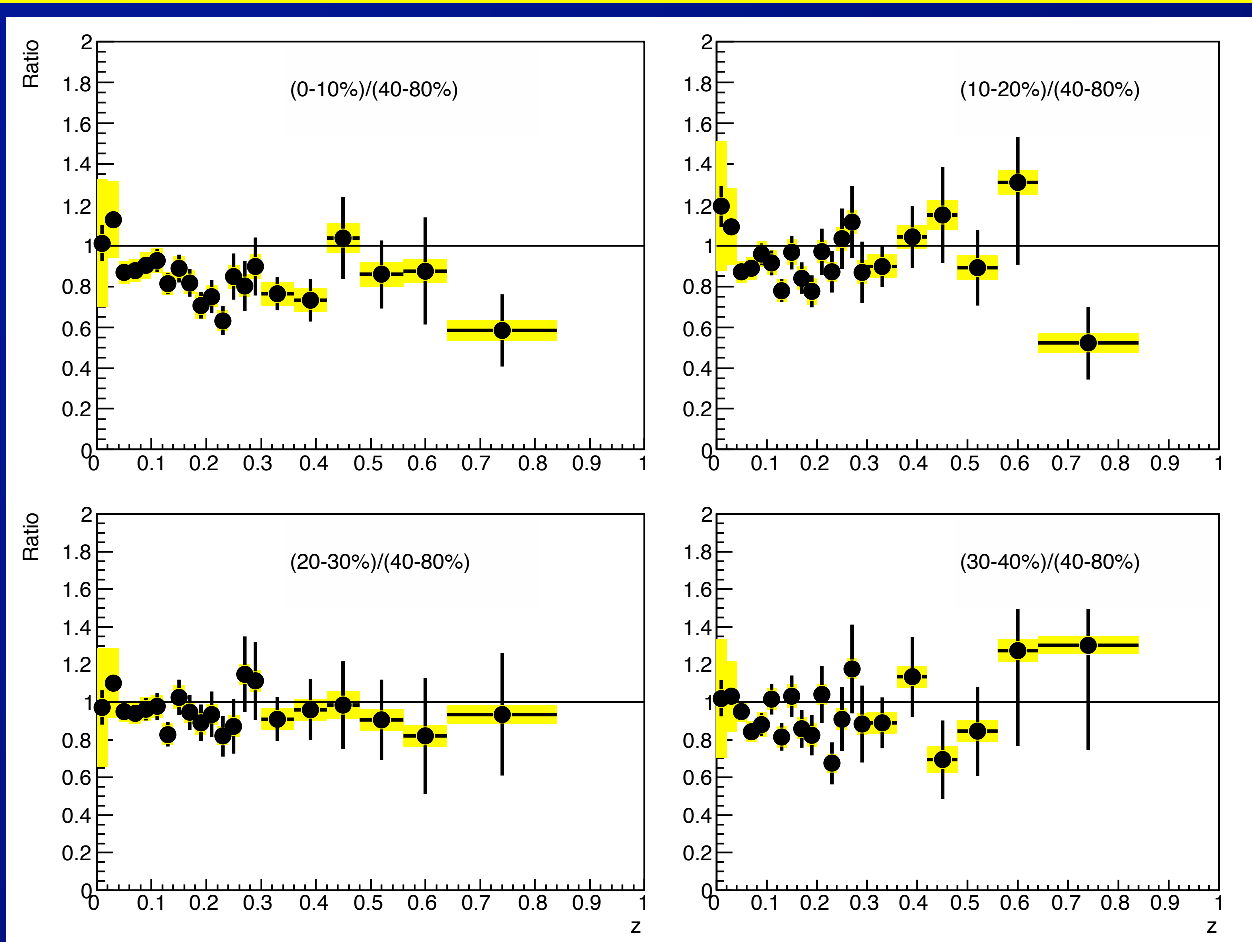
Fragmentation Functions, pp and PbPb



Leading and subleading jet in PbPb fragment like jets of corresponding energy in pp collisions

Jet Fragmentation Ratios (Longitudinal)

R = 0.4
E_T > 100 GeV



- Evaluate ratio of $1/N_{\text{jet}}\, dN/dz$ in different centrality bins to peripheral (40-80%)
  - ⇒At most, small (~ 20%) weakly z-dependent suppression in central (0-10%) collisions.