The Hottest, and Most Liquid, Liquid in the Universe

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MIT

Madan Lal Mehta Memorial Lecture
Tata Institute of Fundamental Research
Mumbai, India, March 25, 2014

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.

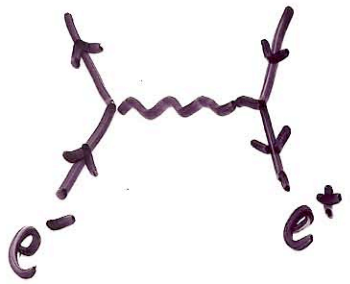
- Using five detectors (PHENIX & STAR @ RHIC; ALICE, ATLAS & CMS @ LHC) scientists are answering questions about the microseconds-old universe that cannot be addressed by any conceivable astronomical observations made with telescopes and satellites.

- 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.

WHAT IS QCD?

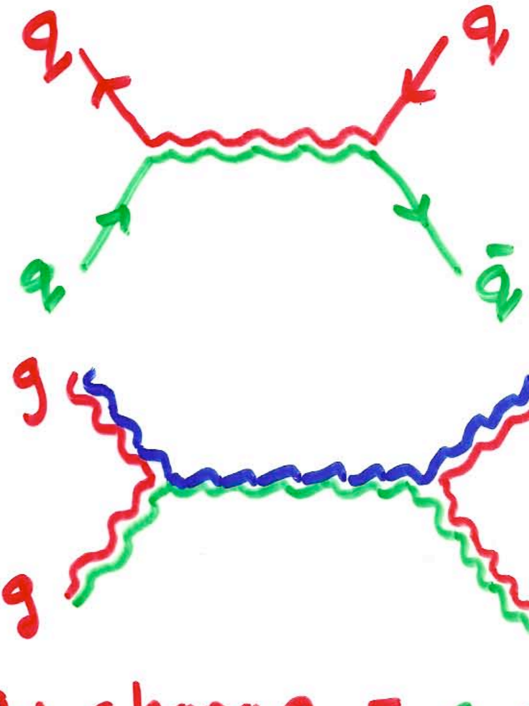
- A theory of quarks and gluons
- Its Lagrangian suggests it is not too different from QED, which is a theory of electrons and photons:

QED



e^-: charge -1
γ: neutral

QCD



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

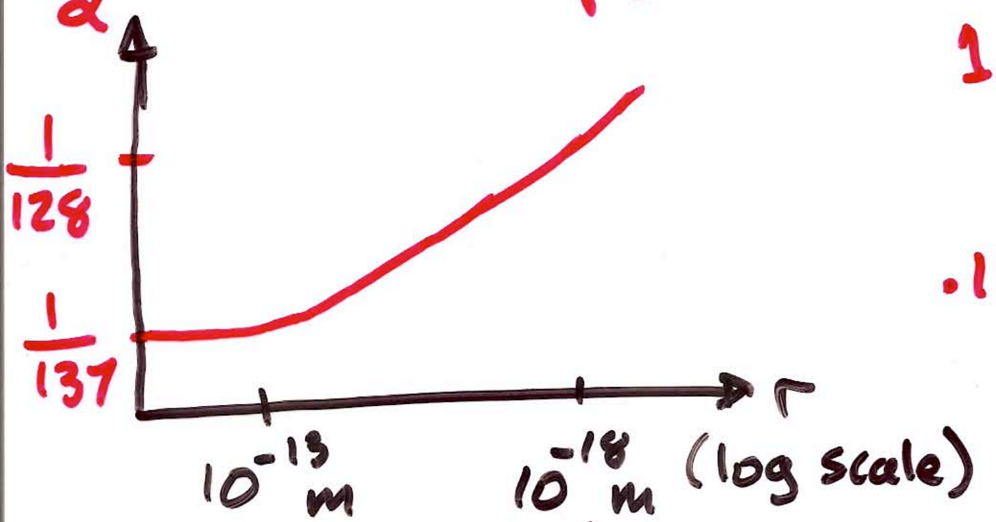
ASYMPTOTIC FREEDOM

Gross, Wilczek, Politzer (1973)

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

QED

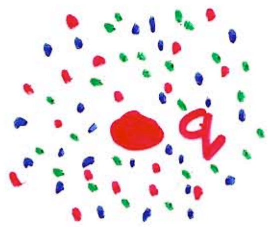
α: Force between electrons $\sim \frac{\alpha(r)}{r^2}$

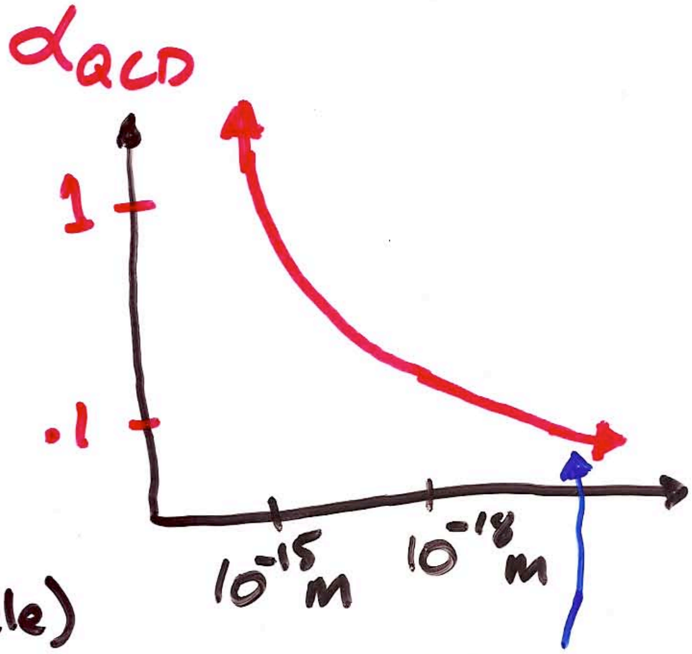


↑ experiments at CERN

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

QCD





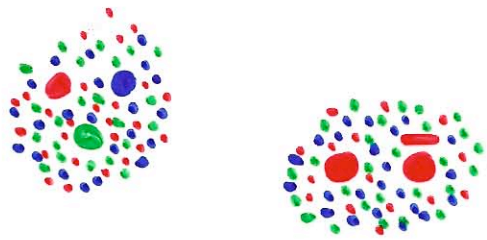
asymptotic freedom, or anti-screening. (That's why Friedman, Kendall, Taylor were able to see weakly interacting quarks.)

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.

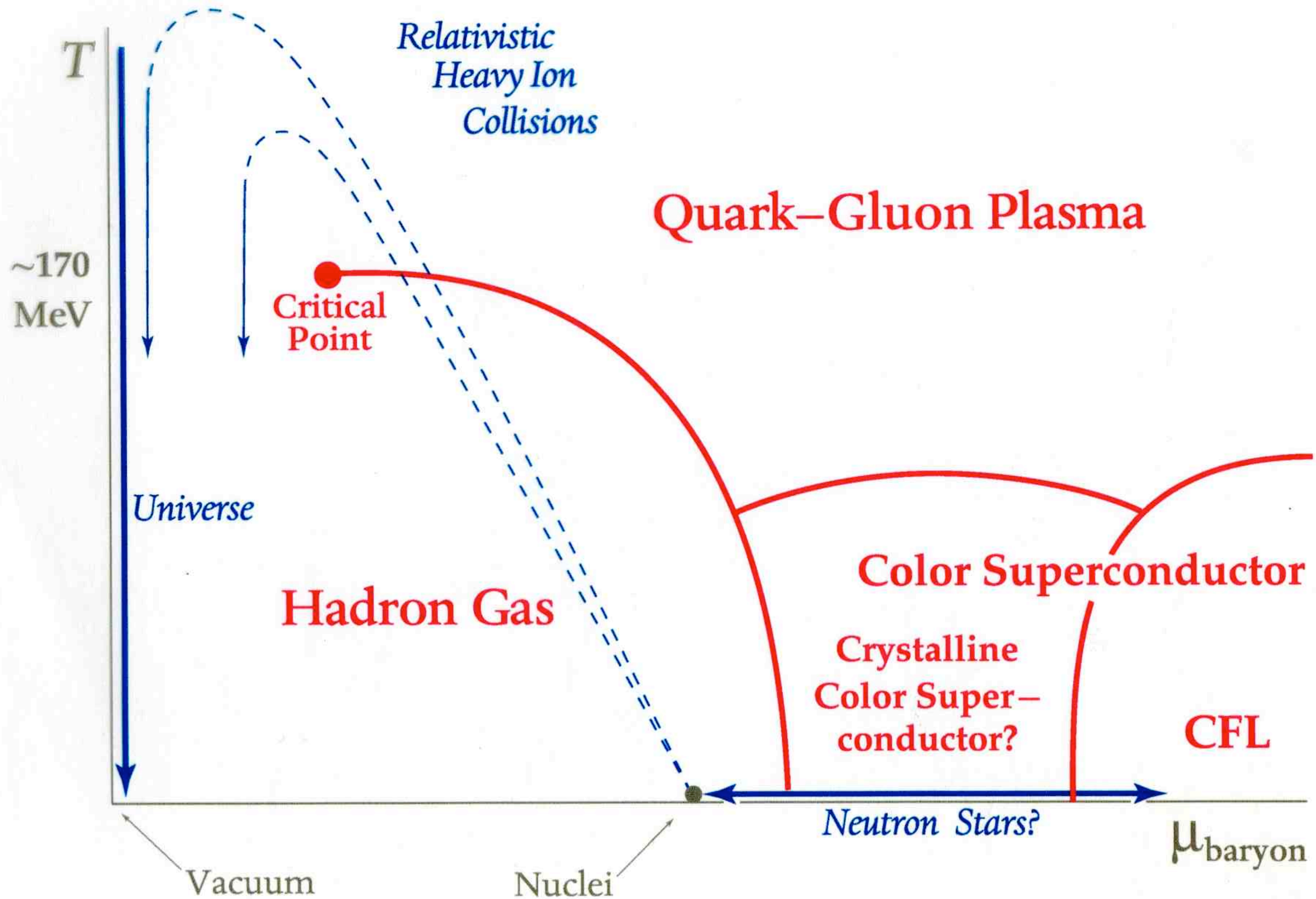
WHY STUDY QCD?
WHY IS IT A CHALLENGE?

- 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.

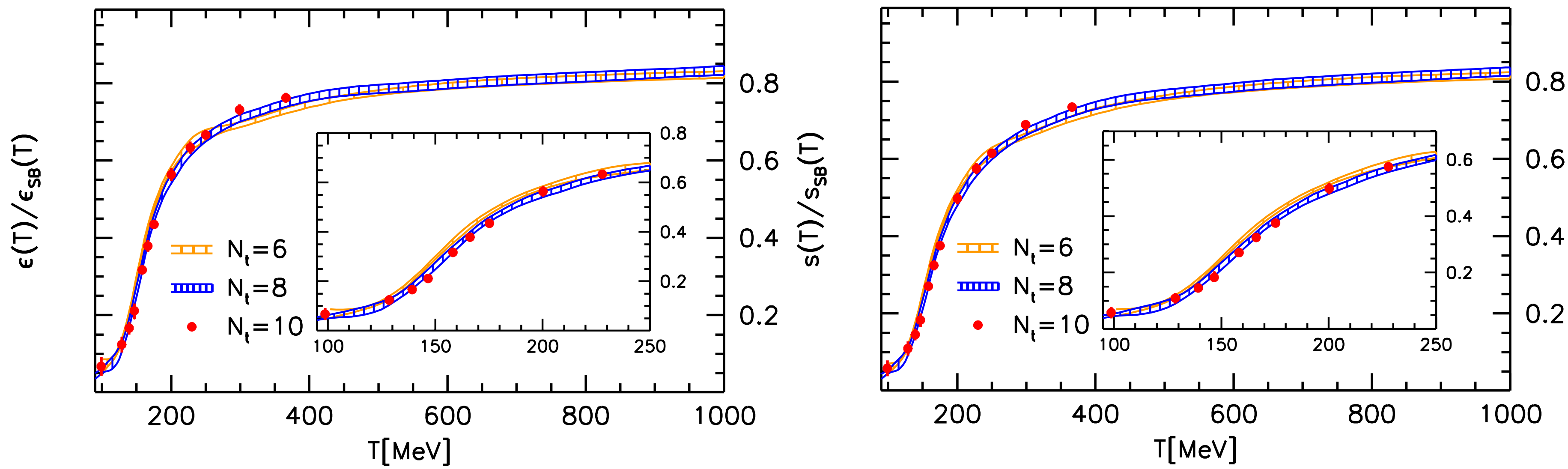
- Asymptotic freedom tells us that, for $T \to \infty$, QGP must be weakly coupled quark and gluon quasiparticles.

- 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.

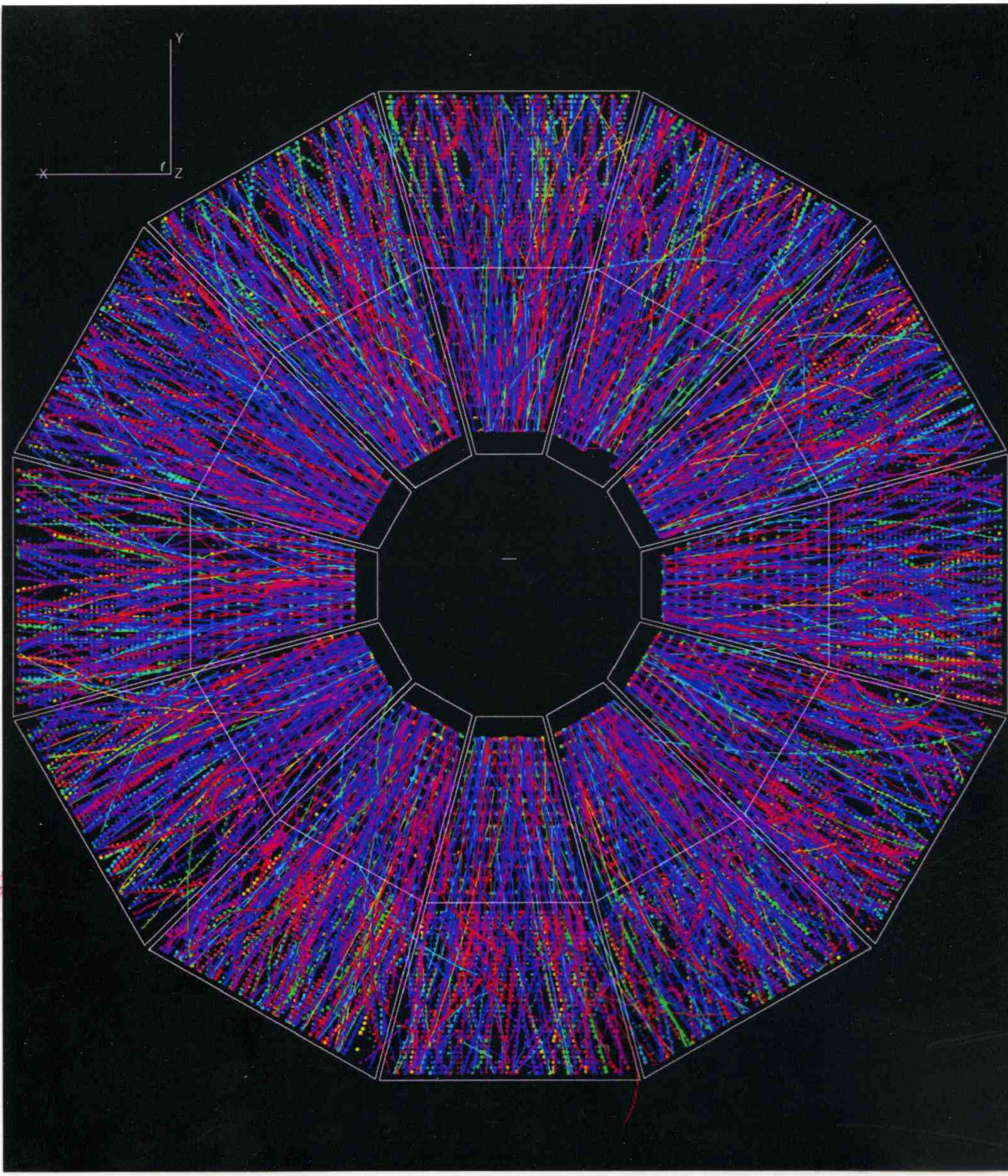
QGP Thermodynamics on the Lattice

Endrodi et al. 2010



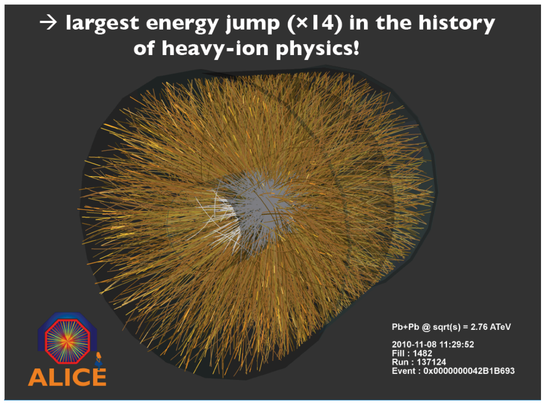
Above $T_{\text{crossover}} \sim$ 150-200 MeV, QCD = QGP. QGP static properties can be studied on the lattice.

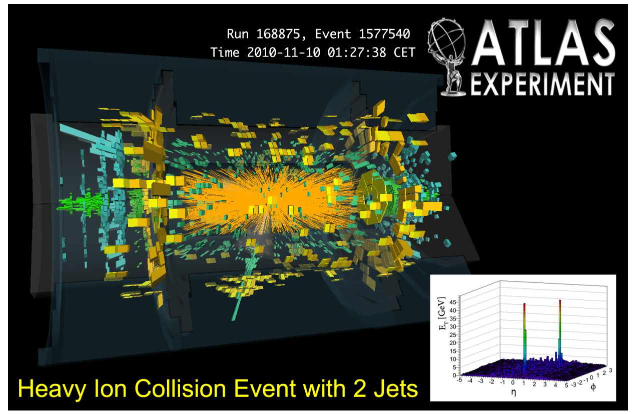
Lesson of the past decade: don't try to infer dynamic properties from static ones. Although its thermodynamics is almost that of ideal-noninteracting-gas-QGP, this stuff is very different in its dynamical properties. [Lesson from experiment+hydrodynamics. But, also from the large class of gauge theories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



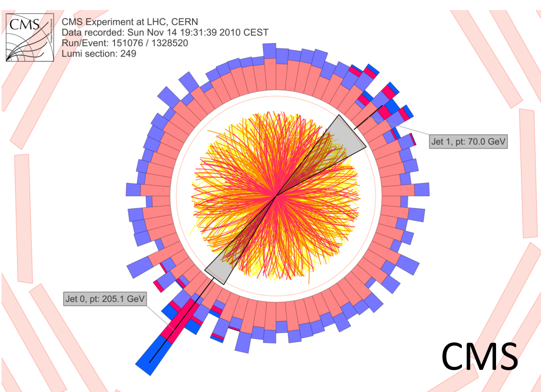
STAR

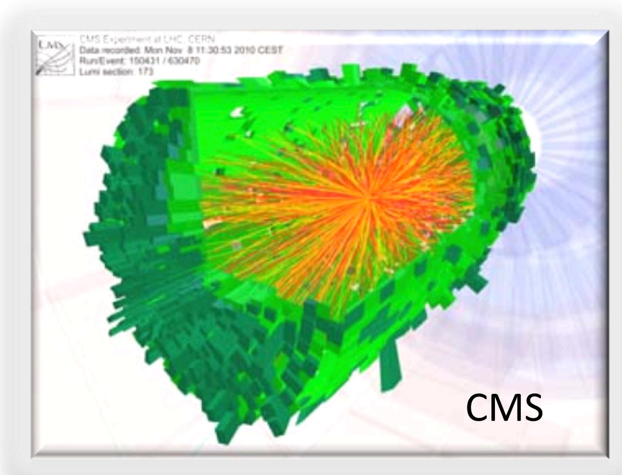
Nov 2010 first LHC Pb+Pb collisions





$\sqrt{s_{NN}}$ = 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?

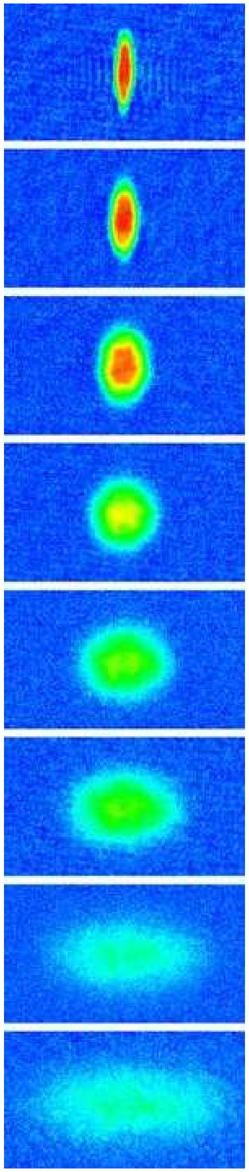
Ultracold Fermionic Atom Fluid

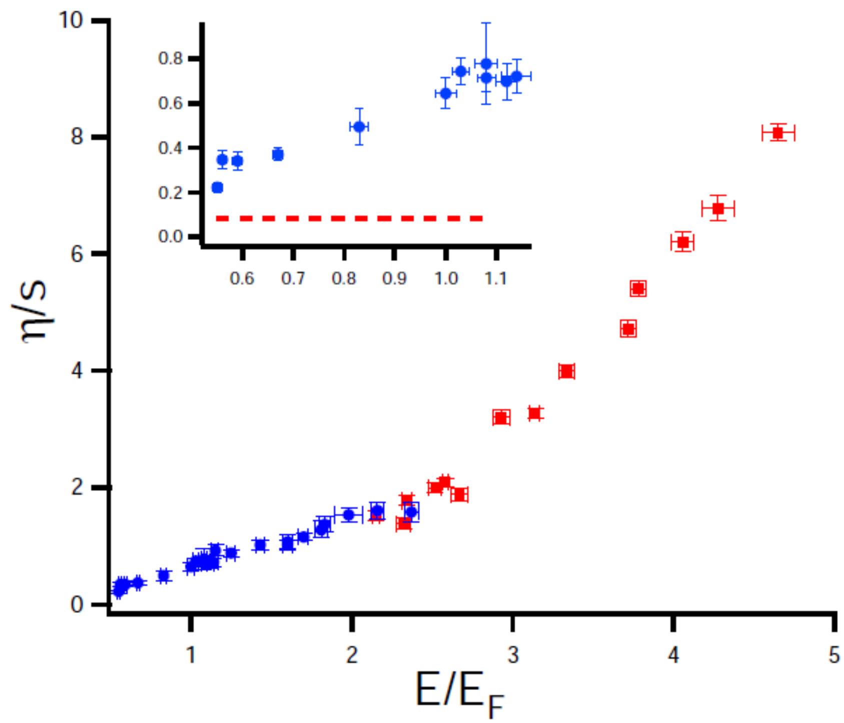
- The one terrestrial fluid with η/s comparably small to that of QGP.
- NanoKelvin temperatures, instead of TeraKelvin.
- Ultracold cloud of trapped fermionic atoms, with their two-body scattering cross-section tuned to be infinite. A strongly coupled liquid indeed. (Even though it's conventionally called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

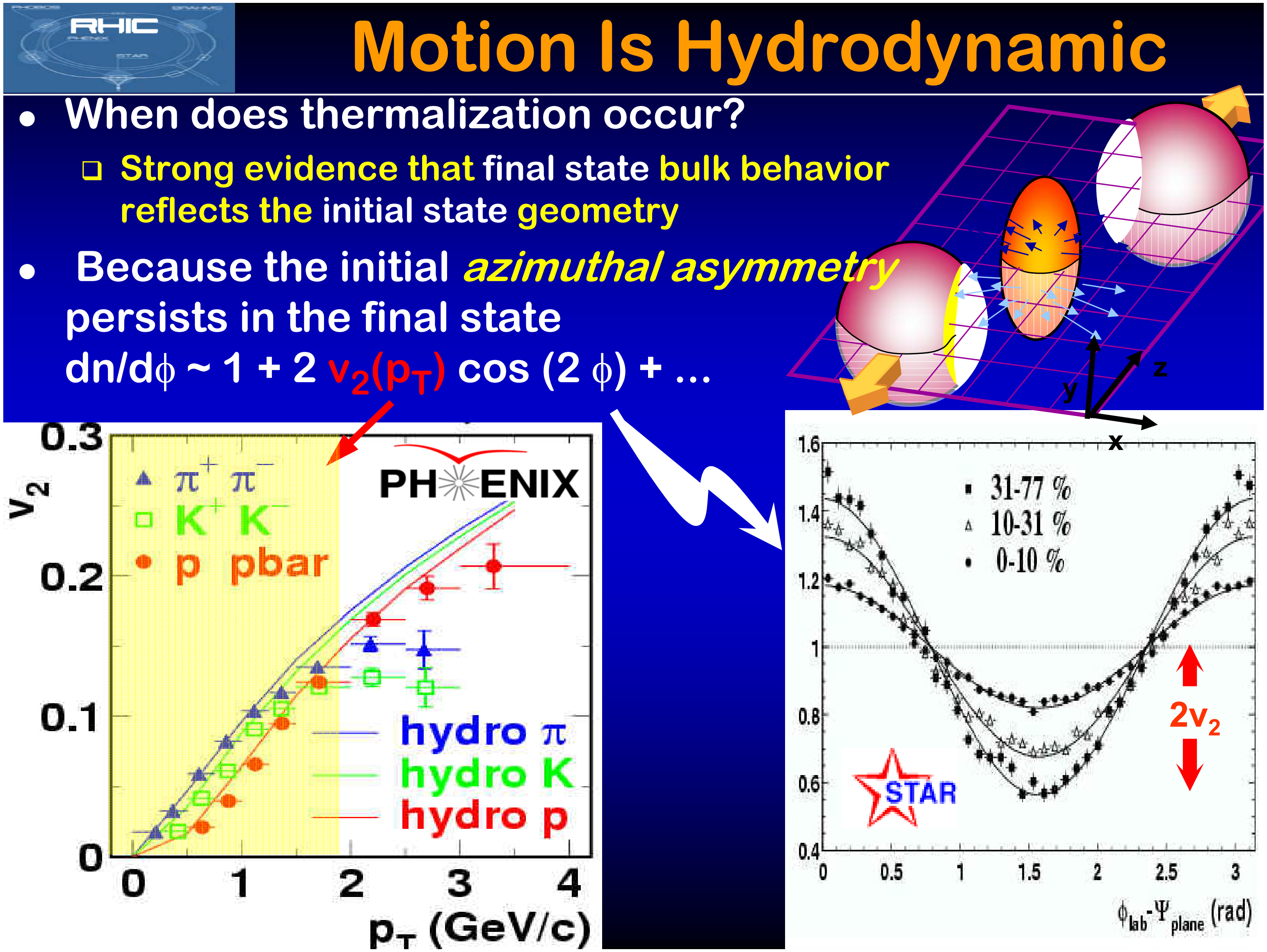
and elliptic flow (high T)





Cao et al., Science (2010)

$$\eta/s \leq 0.4$$



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?

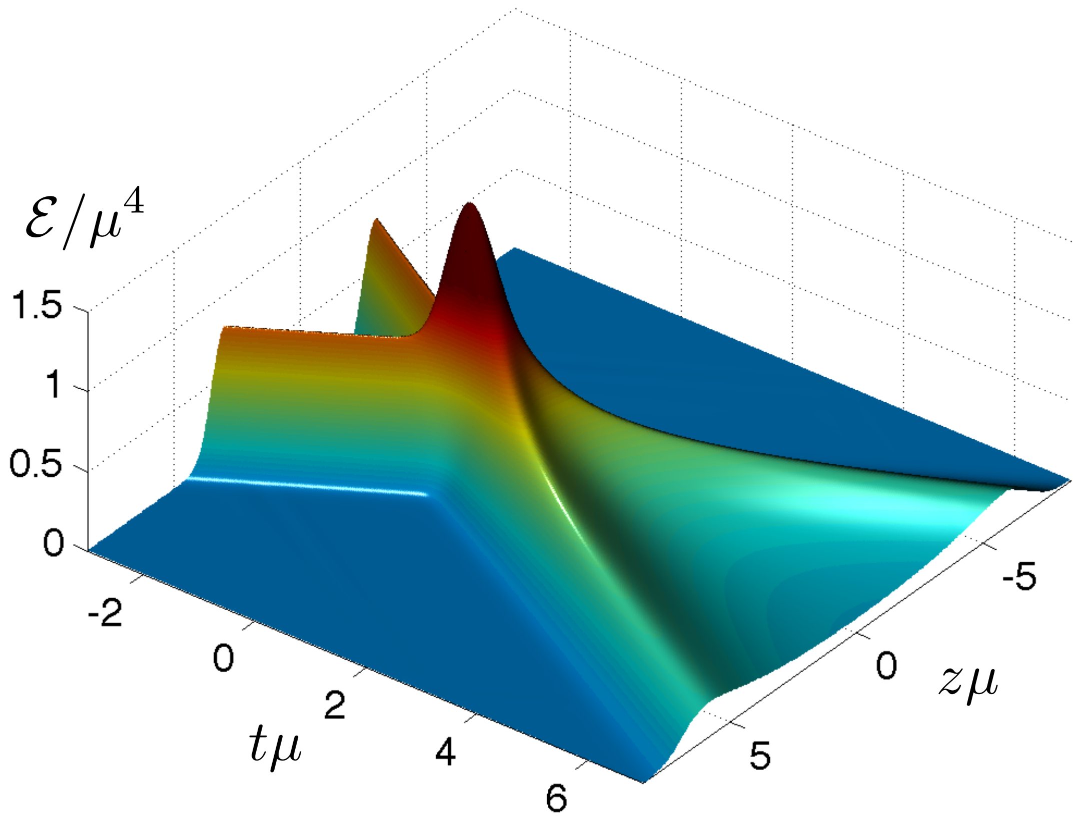
- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.

- 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 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 1011.3562; generalized in C-S,H,M,vdS 1305.4919; CY 1309.1439 **Similarly 'rapid' hydrodynamization times ($\tau T \lesssim 0.7 - 1$) found for *many* non-expanding or boost invariant initial conditions.** Heller and various: 1103.3452, 1202.0981, 1203.0755, 1304.5172

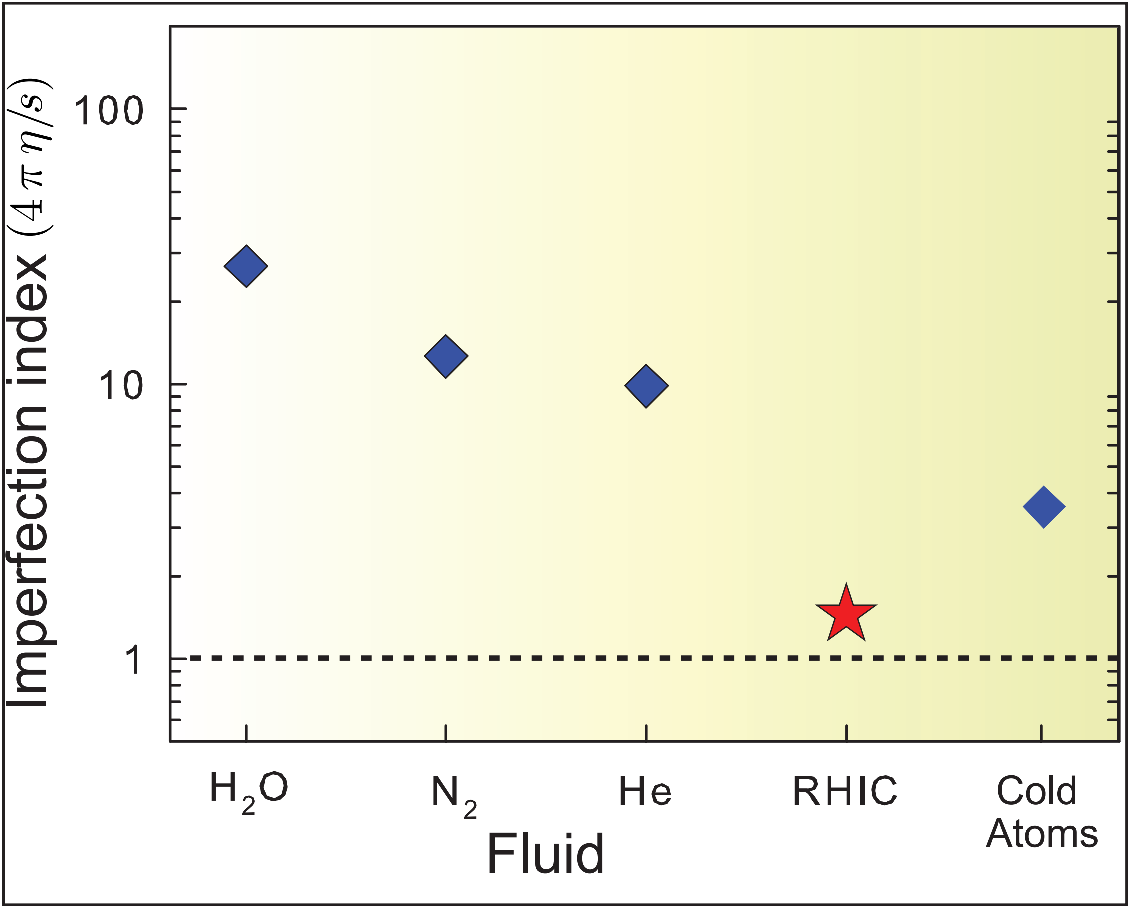
Determining η/s from RHIC data

- 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

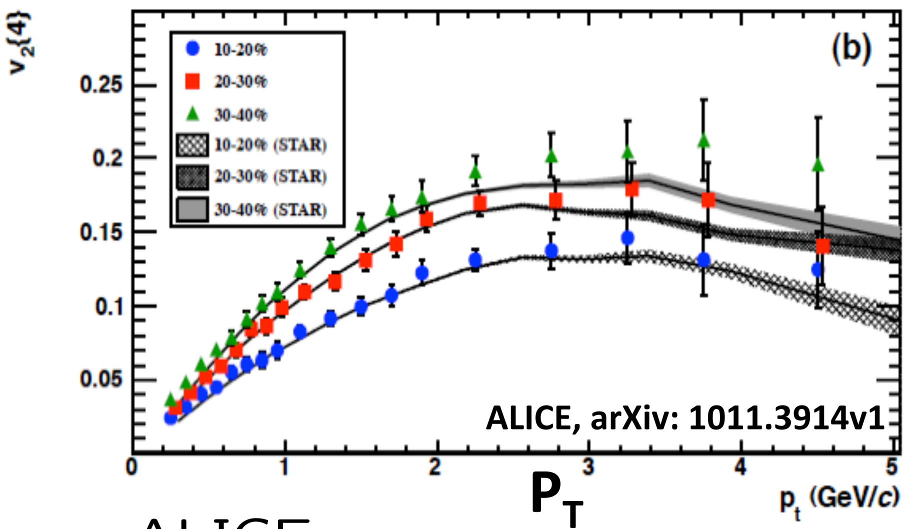
- $4\pi\eta/s \sim 10^4$ for typical terrestrial gases, and 10 to 100 for all known terrestrial liquids except one. Hydrodynamics works much better for QGP@RHIC than for water.

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

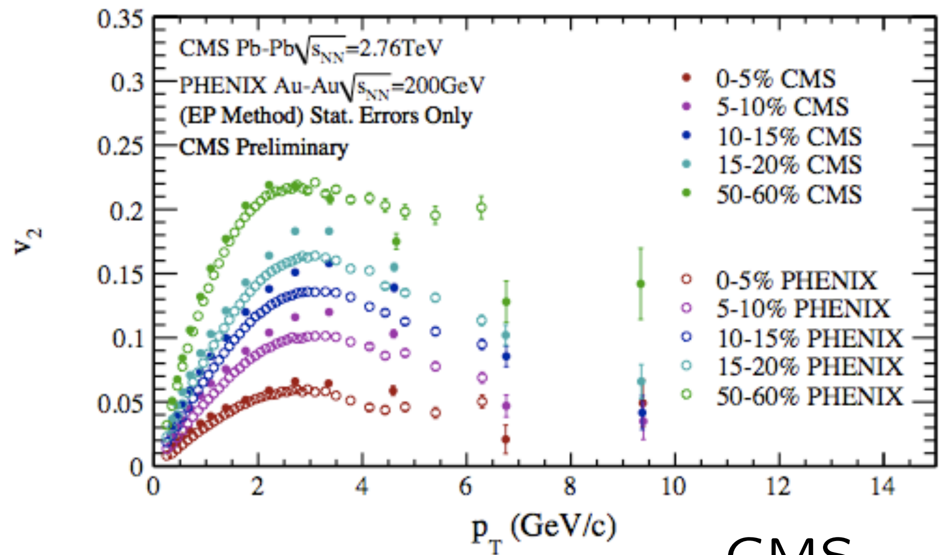


Imperfection index $(4\pi\eta/s)$
100
10
1
H_2O
N_2
He
RHIC
Cold Atoms
Fluid

What changes at the LHC?



ALICE

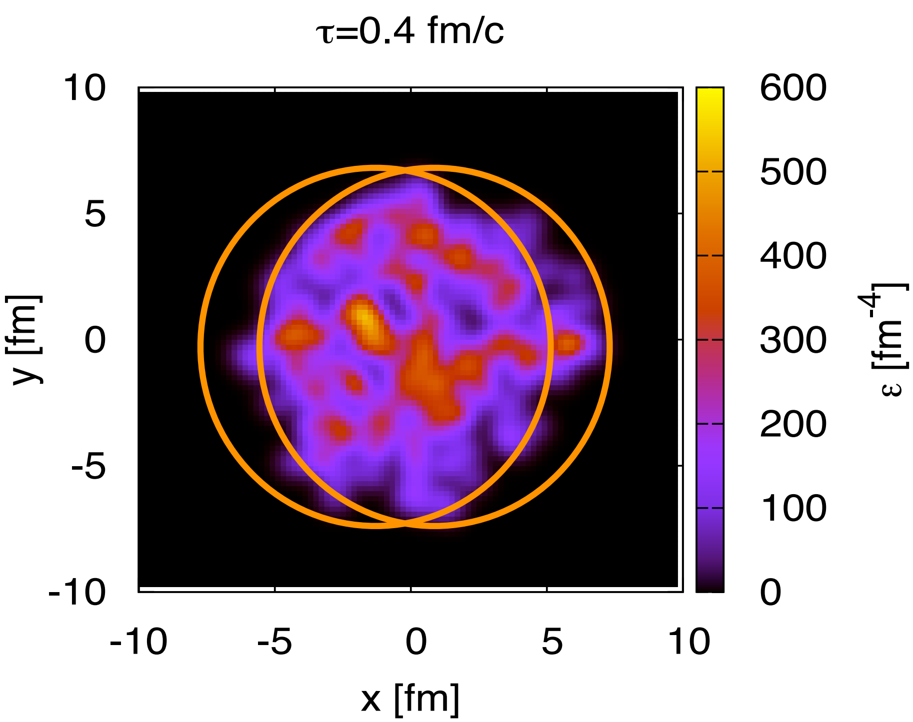


CMS

$v_2(p_T)$ 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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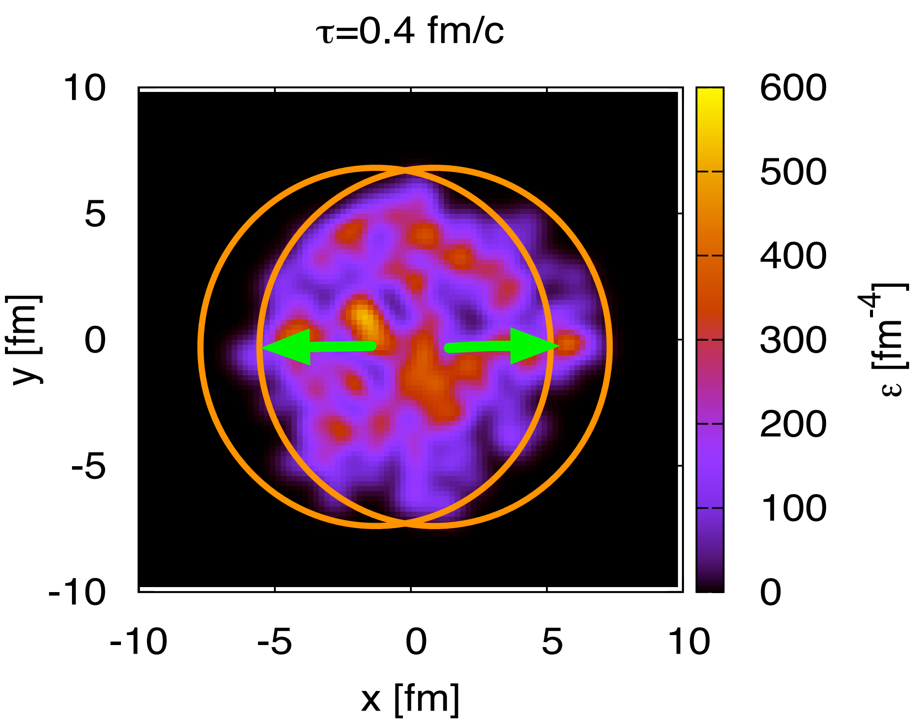

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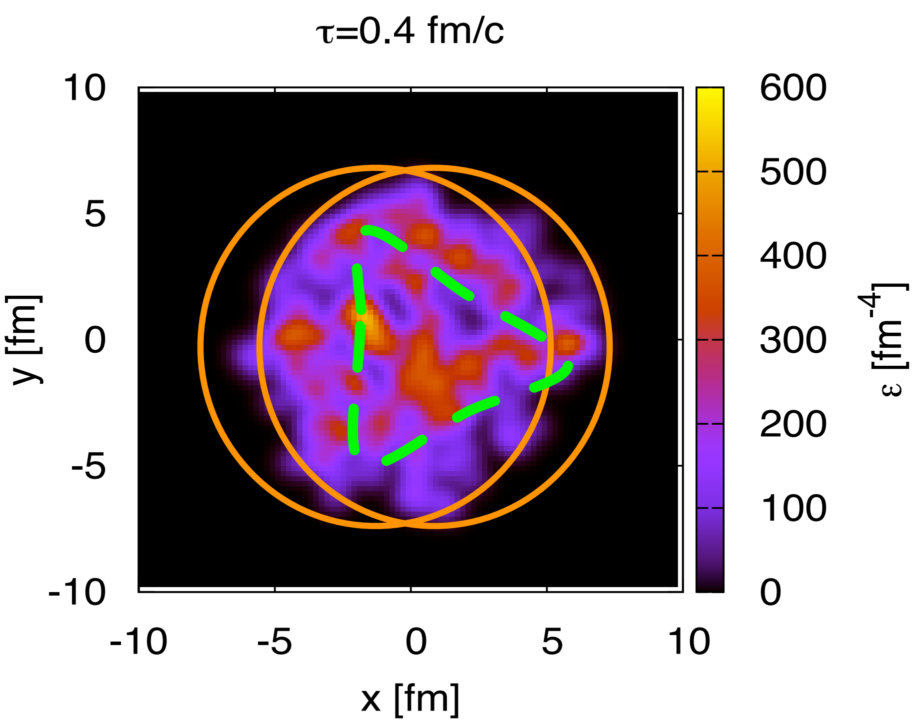

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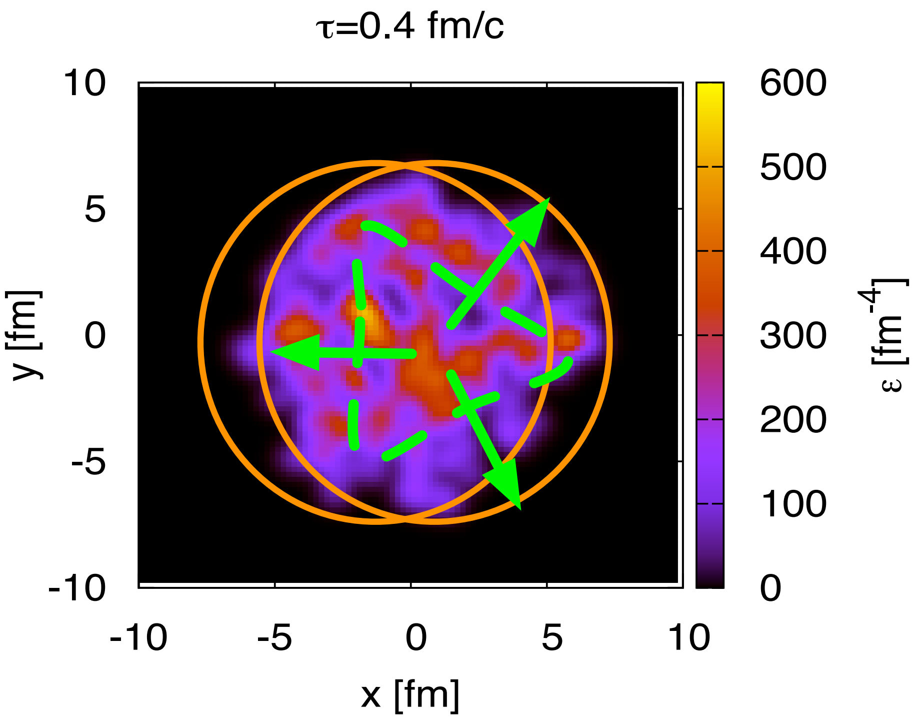

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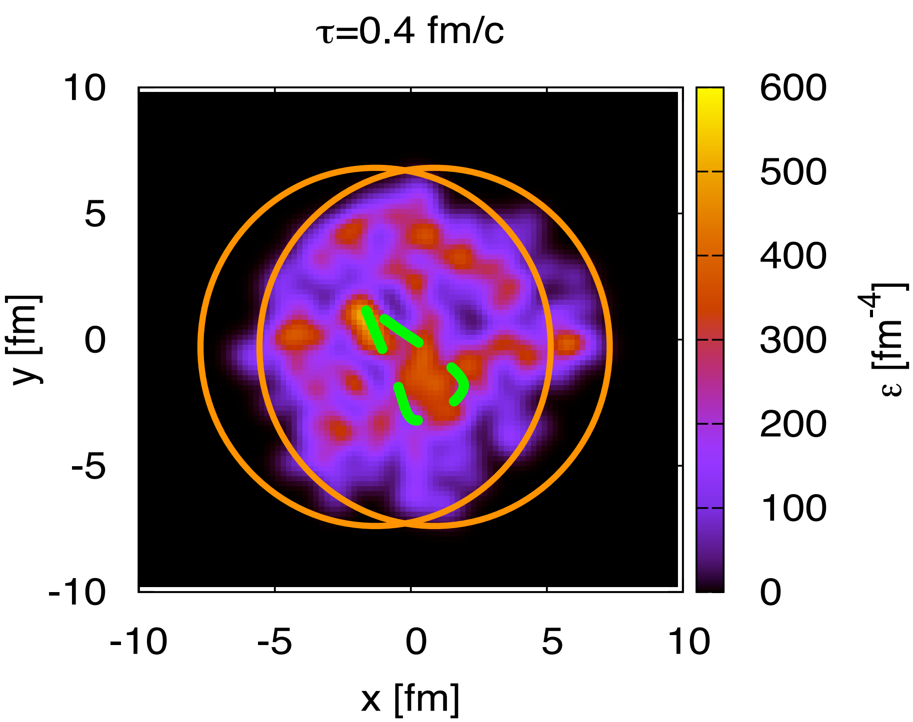

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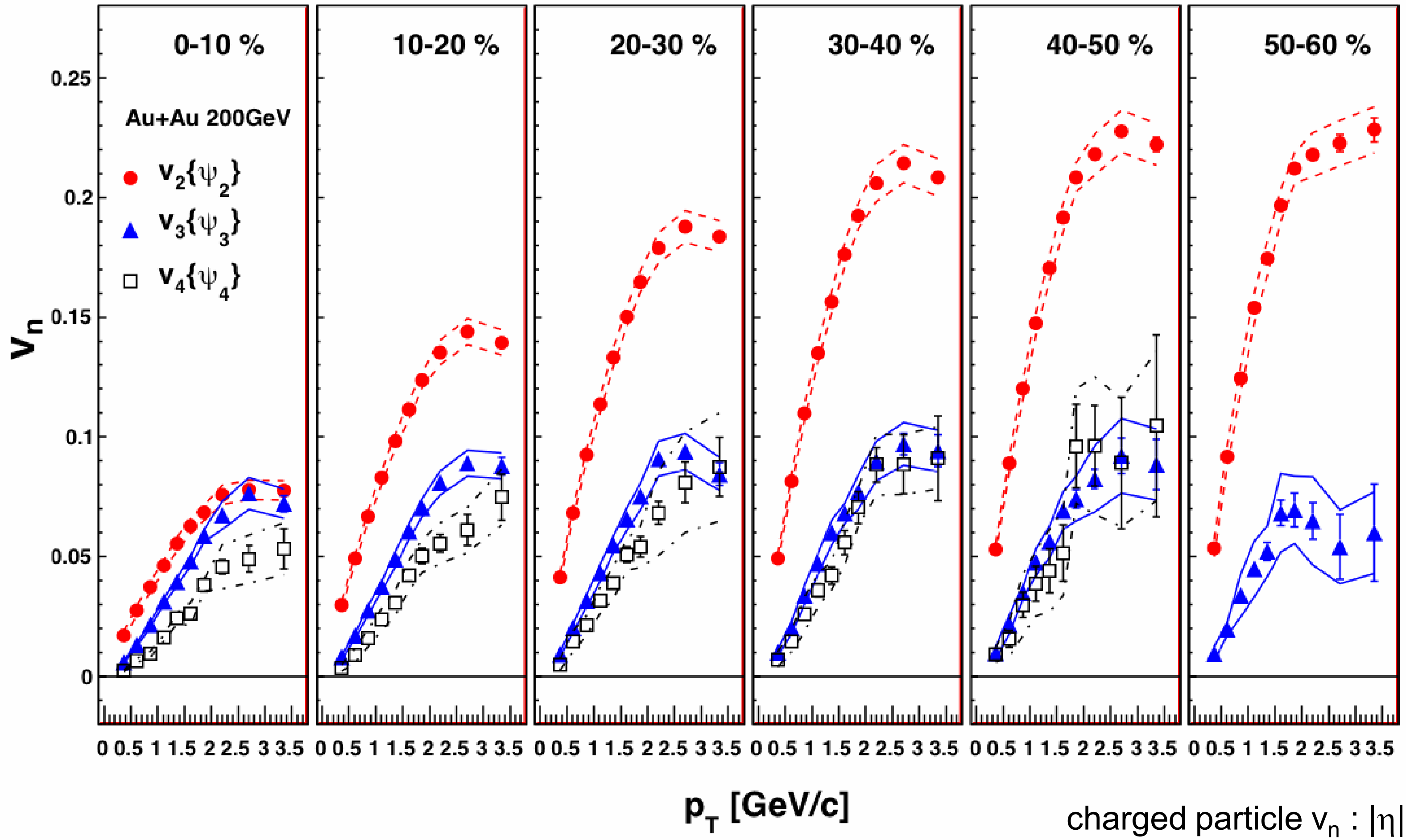
$v_2\{\Phi_2\}$, $v_3\{\Phi_3\}$, $v_4\{\Phi_4\}$ at 200GeV Au+Au

arXiv:1105.3928

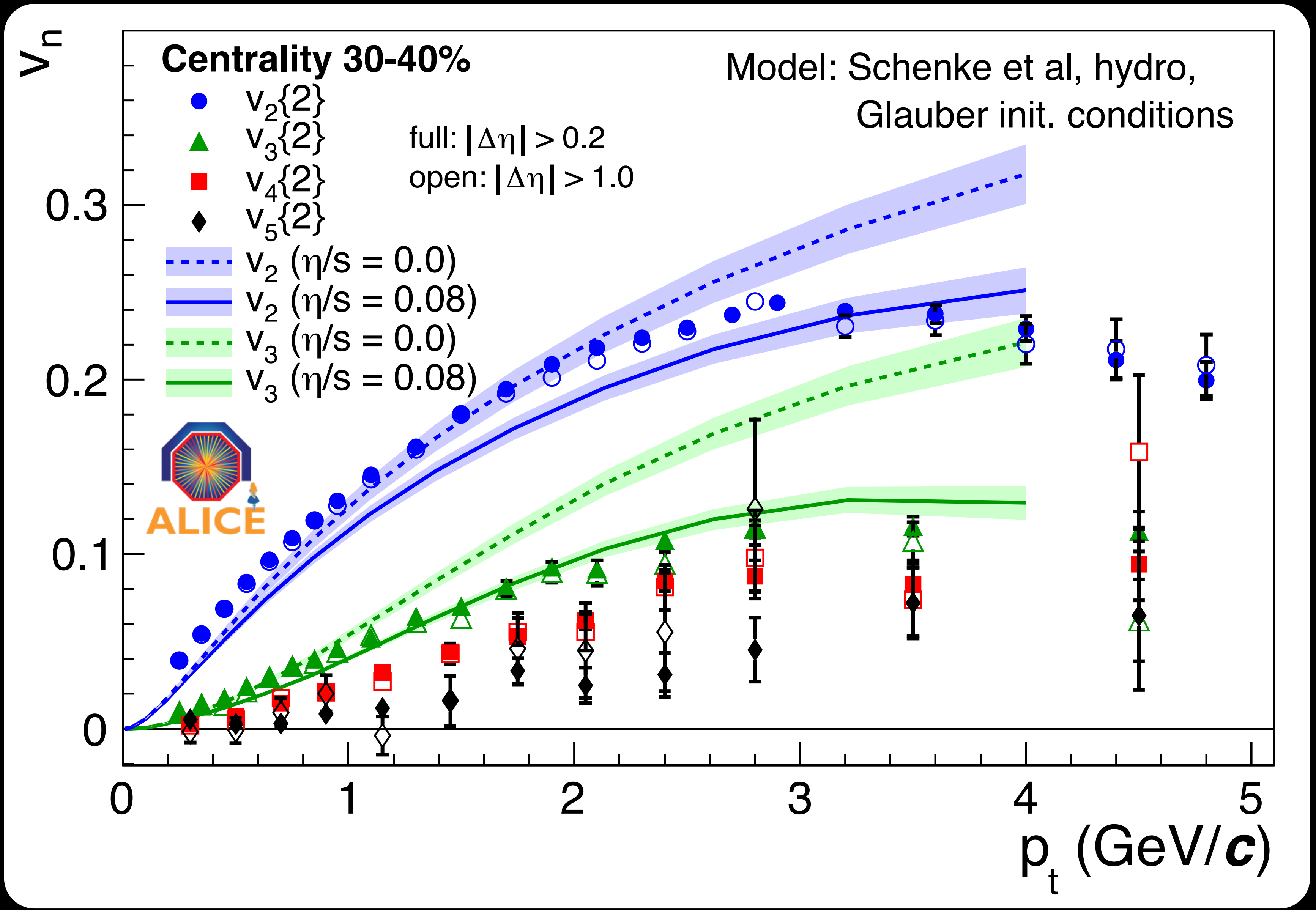


charged particle v_n : $|\eta|<0.35$
reaction plane Φ_n : $|\eta|=1.0\sim2.8$

(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



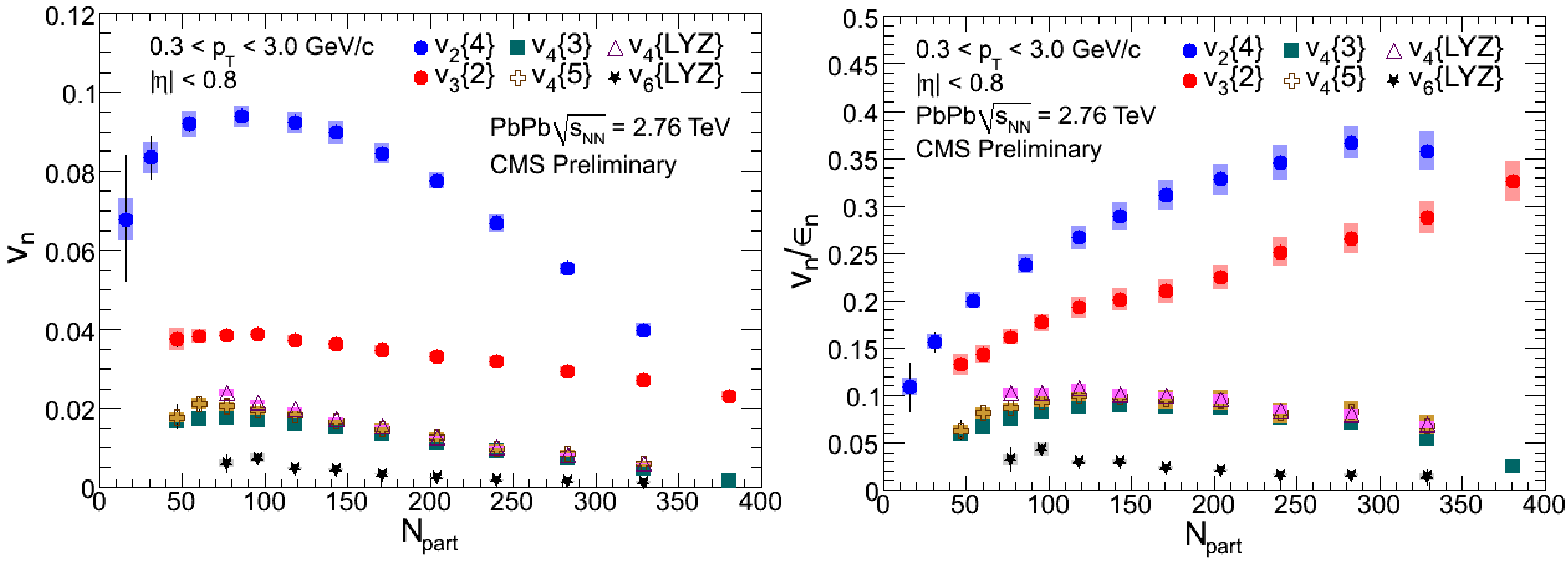
ALICE Collaboration, arXiv:1105.3865

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

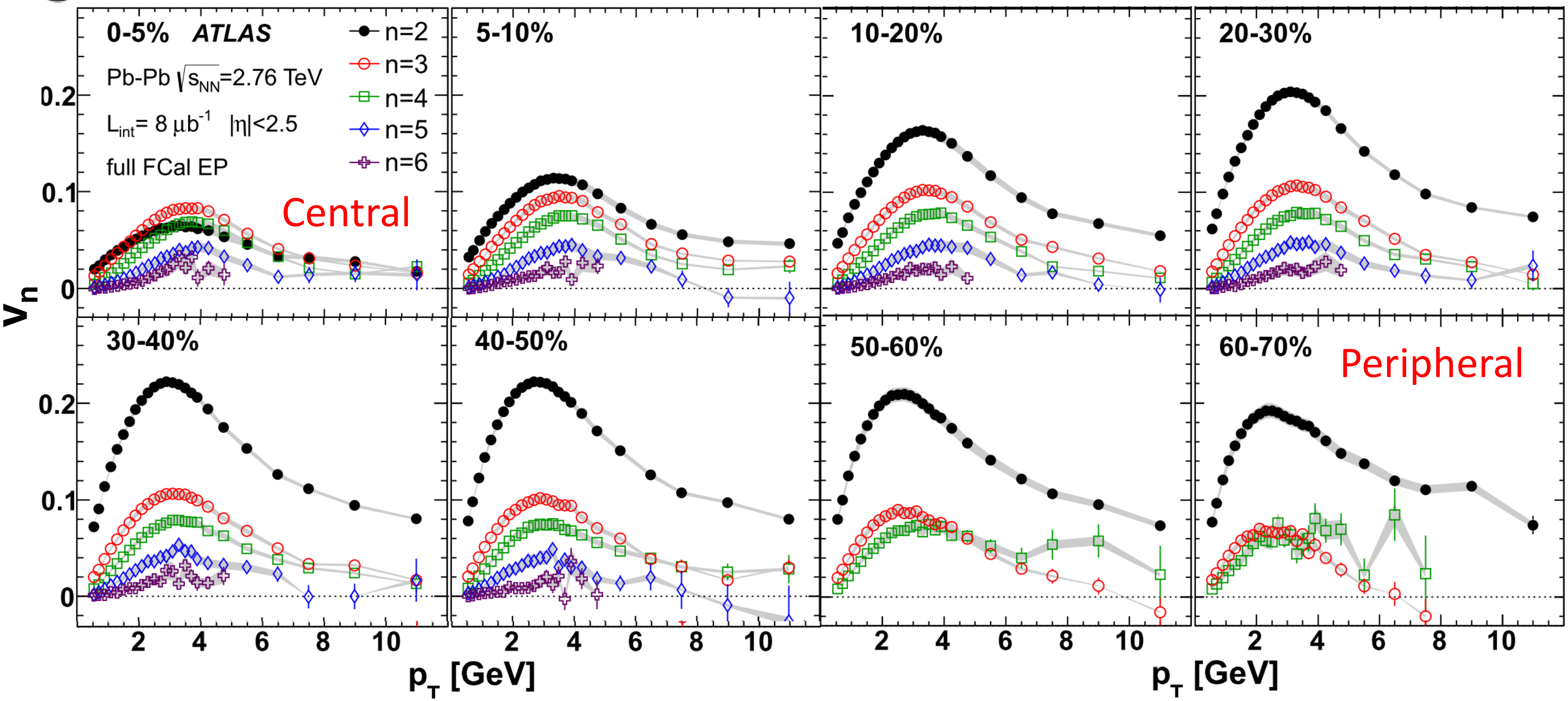
The full harmonic spectrum



- 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)



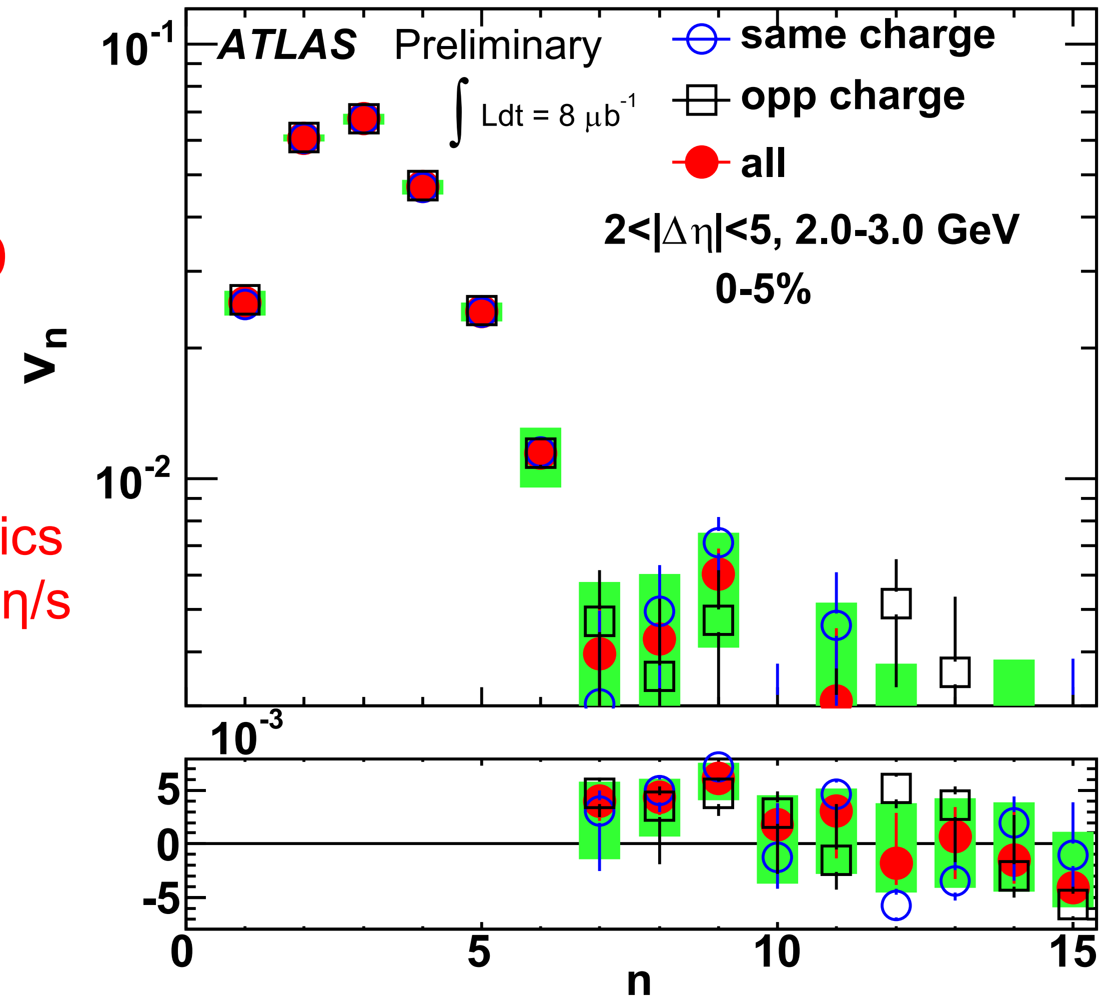
- Significant $v_2 - v_6$ are measured in broad range of p_T, η and centrality
- p_T dependence for all measured amplitudes show similar trend
- Stronger centrality dependence of v_2 than higher order harmonics
- In most central collisions (0-5%): v_3, v_4 can be larger than v_2

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

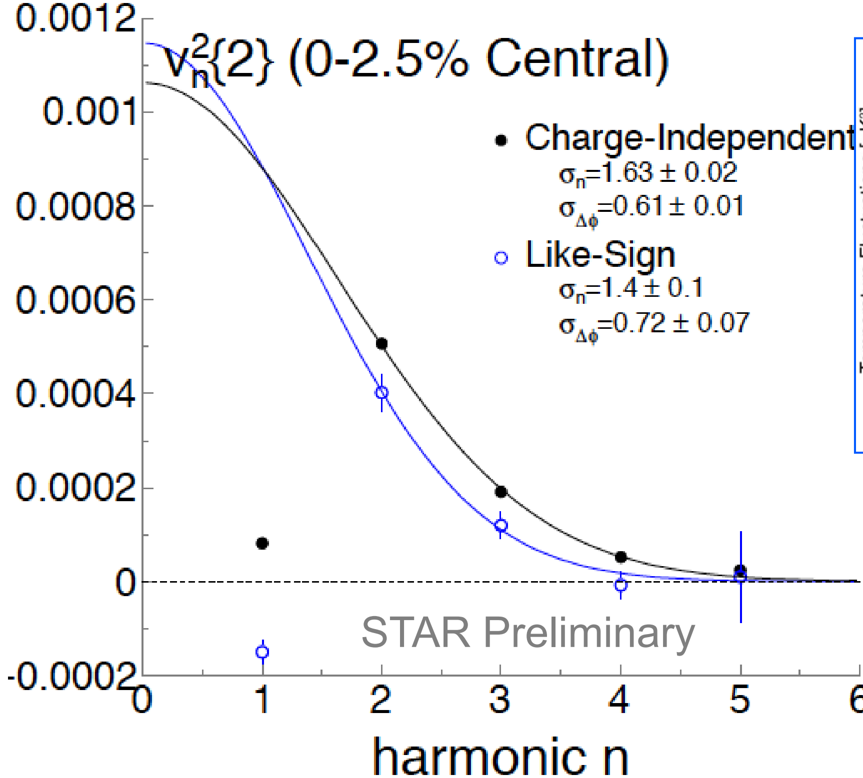
Damping of higher order harmonics provides important constraint on η/s

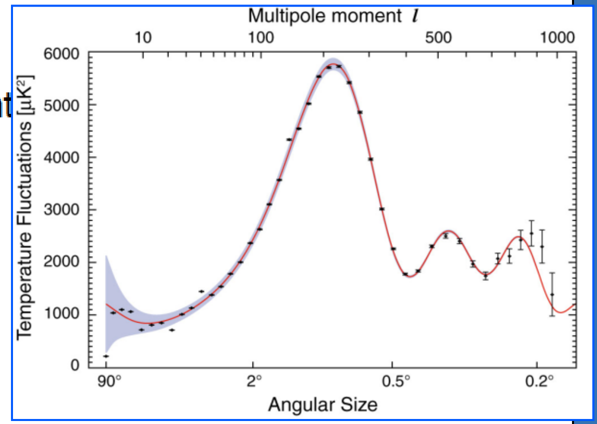


The error on $v_n=\sqrt{v_{n,n}}$ is highly non-Gaussian

$v_n^2\{2\}$ 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)…

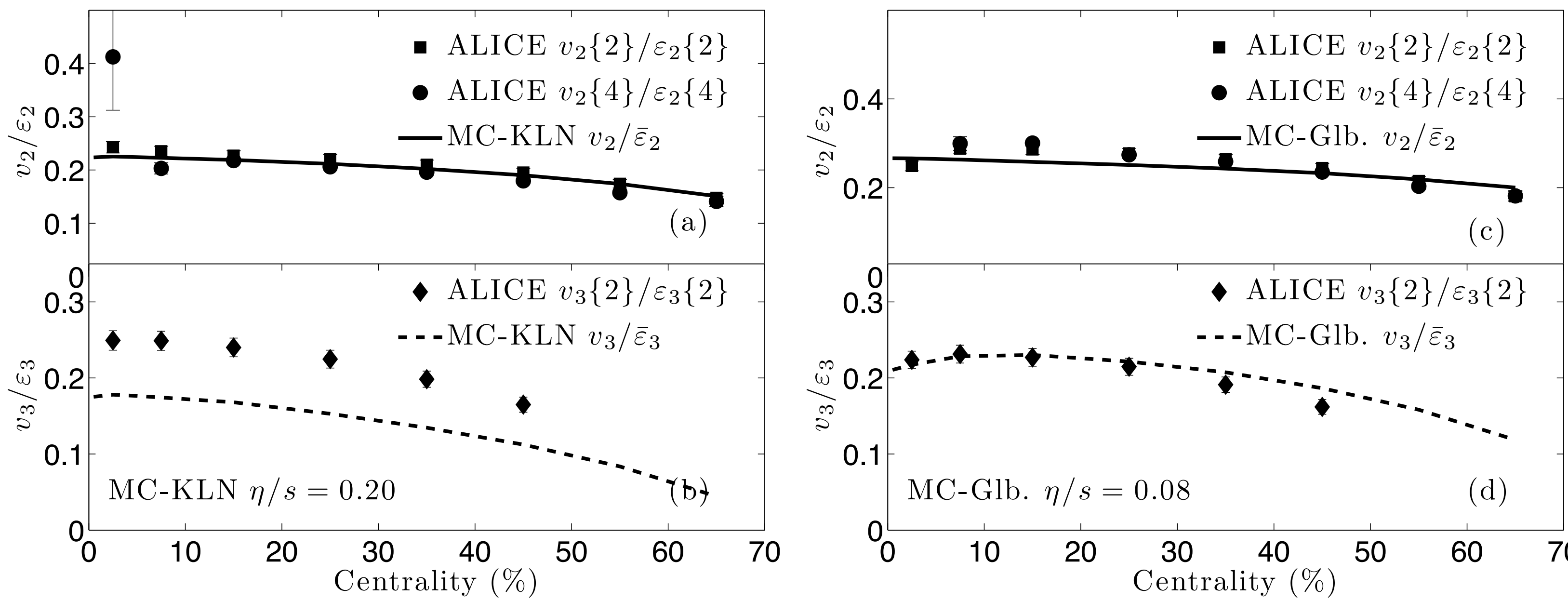
P. Staig and E. Shuryak, arXiv:1008.3139 [nucl-th]
A. Mocsy, P. S., arXiv:1008.3381 [hep-ph]
A. Adare [PHENIX], arXiv:1105:3928

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

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 $v_{3...6}$ 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 ...

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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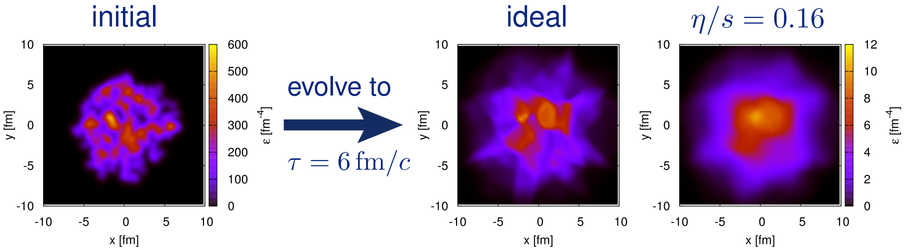


initial
evolve to
$\tau = 6\,\mathrm{fm}/c$
ideal
$\eta/s = 0.16$
x [fm]
y [fm]
ε [fm^{-4}]

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

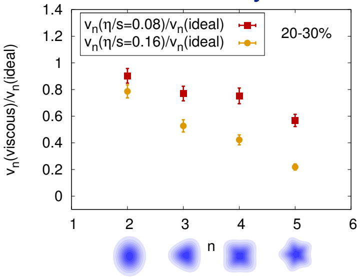
After Cooper-Frye freeze-out and resonance decays in each event we compute

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

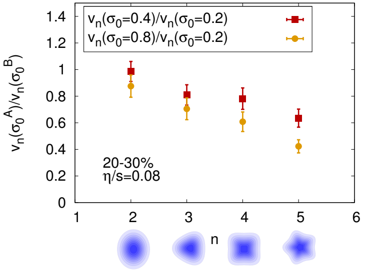
with the event-plane angle $\psi_n = \frac{1}{n} \arctan \frac{\langle \sin(n\phi) \rangle}{\langle \cos(n\phi) \rangle}$

Sensitivity of event averaged v_n on

viscosity



initial state granularity

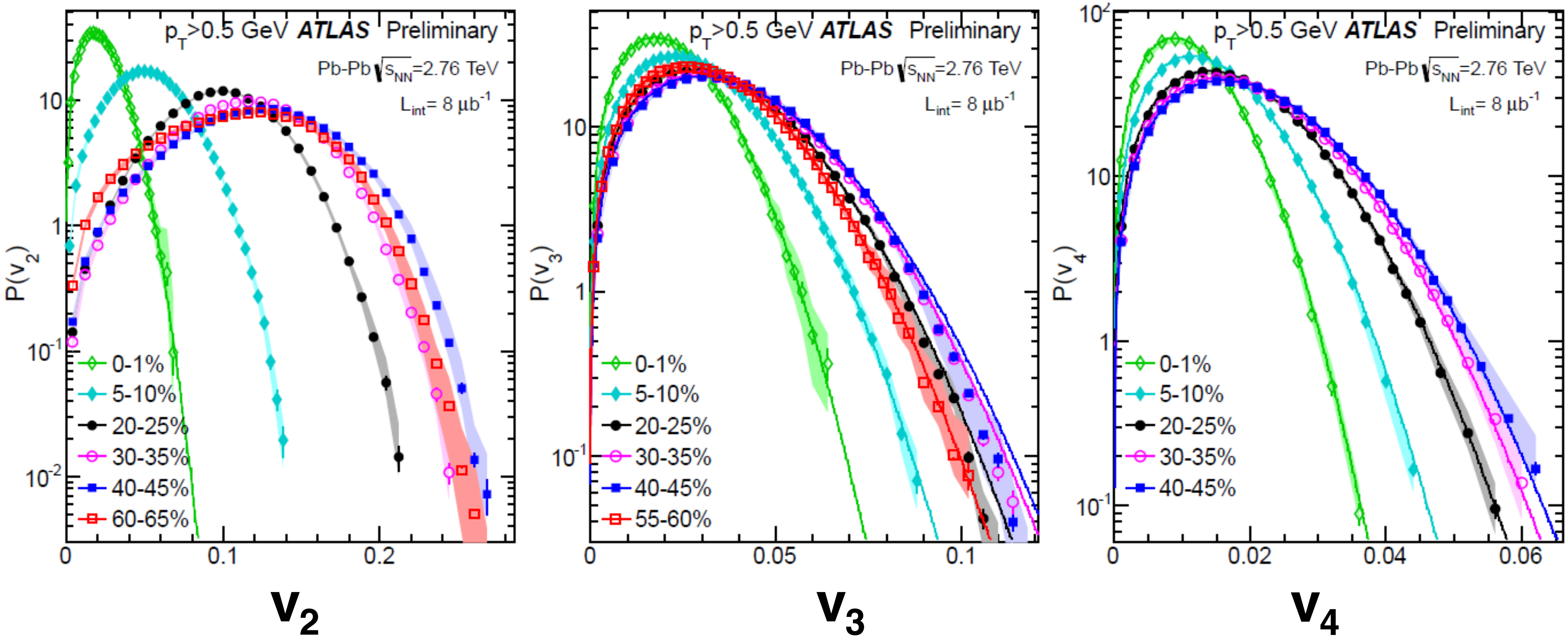


Sensitivity to viscosity and initial state structure increases with n

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 $v_{3...6}$ 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 ...

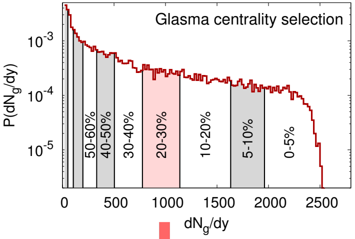
Unfolded v_2, v_3 and v_4 Distributions

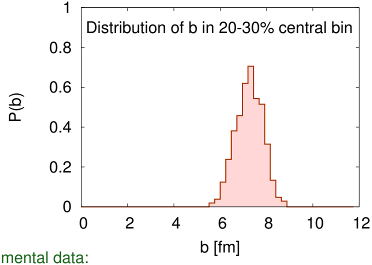


- v_n distributions normalized to unity for n = 2,3 and 4
- Lines represent radial projections of 2D Gaussians, rescaled to <v_n>
  - for v_2 only in the 0-2% of most central collisions
  - for v_3 and v_4 over all centralities

Direct measure of flow harmonics fluctuations

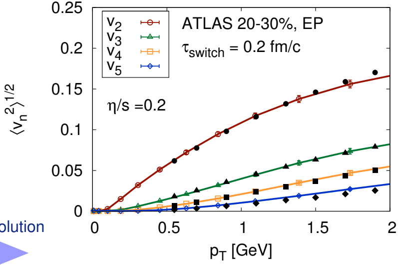
Centrality selection and flow

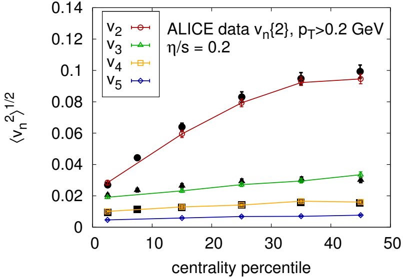




Hydro evolution

MUSIC





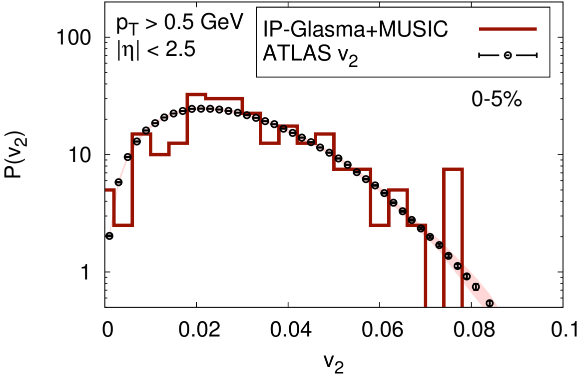
Experimental data:

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

ALICE collaboration, Phys. Rev. Lett. 107, 032301 (2011)

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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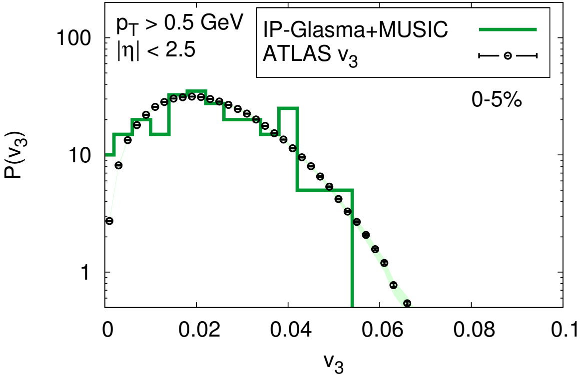

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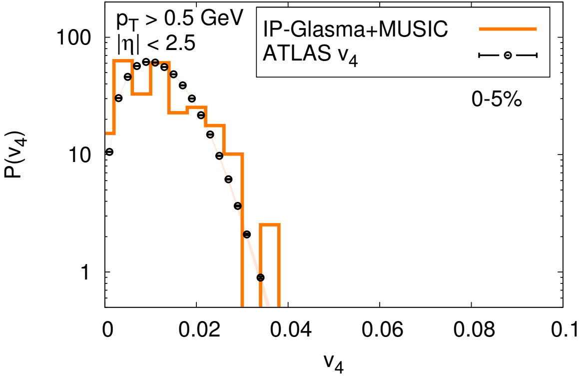
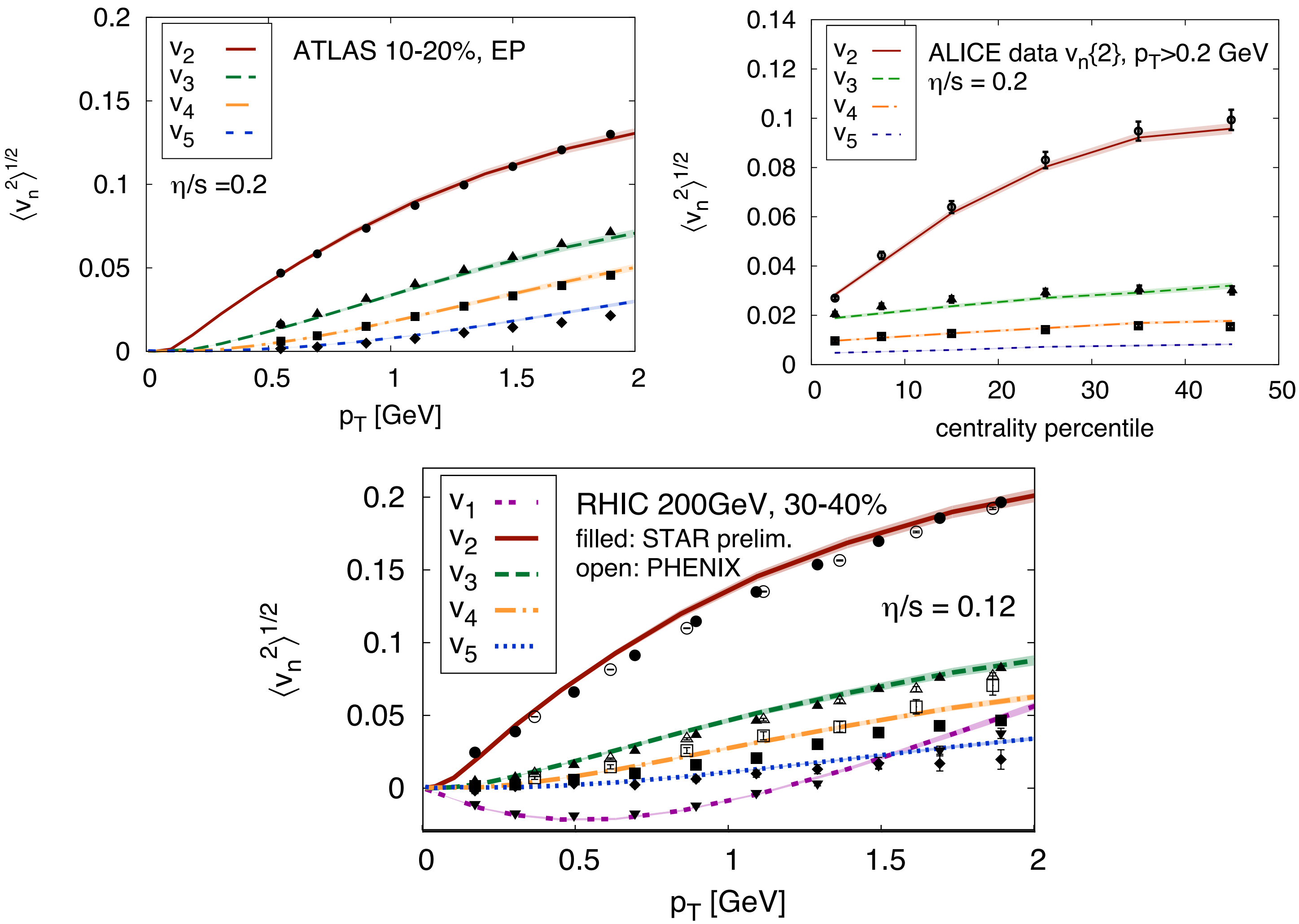


Preliminary results: Statistics to be improved.

Example of State-of-the-art

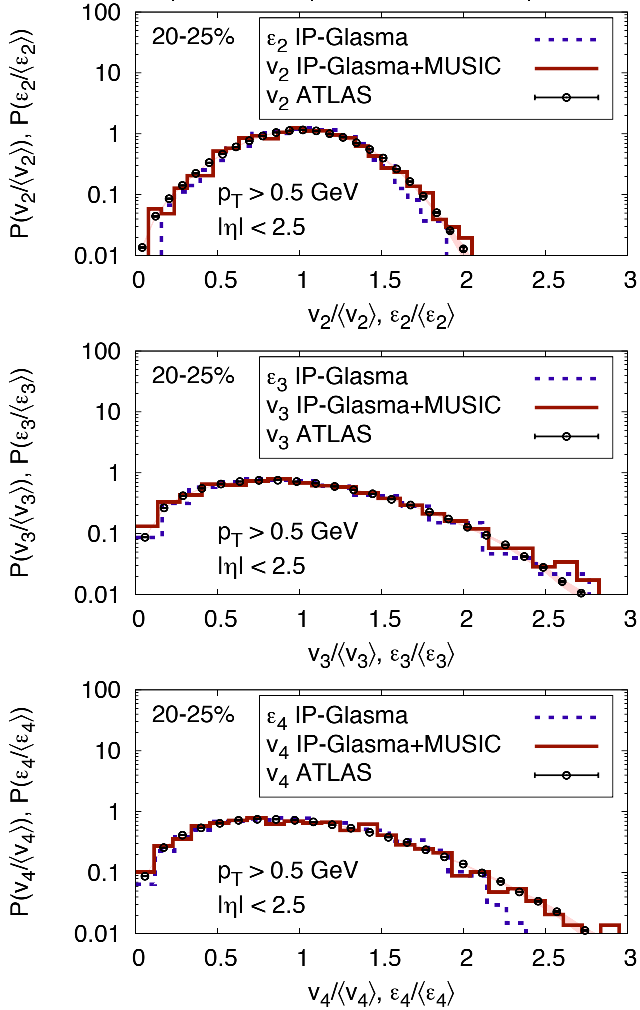
Gale, Jeon, Schenke, Tribedy, Venugopalan, 2013



Good fit to RHIC data (with $\eta/s = 0.12$) and LHC data (with $\eta/s = 0.20$) for one model of initial fluctuations.

Example of State-of-the-art

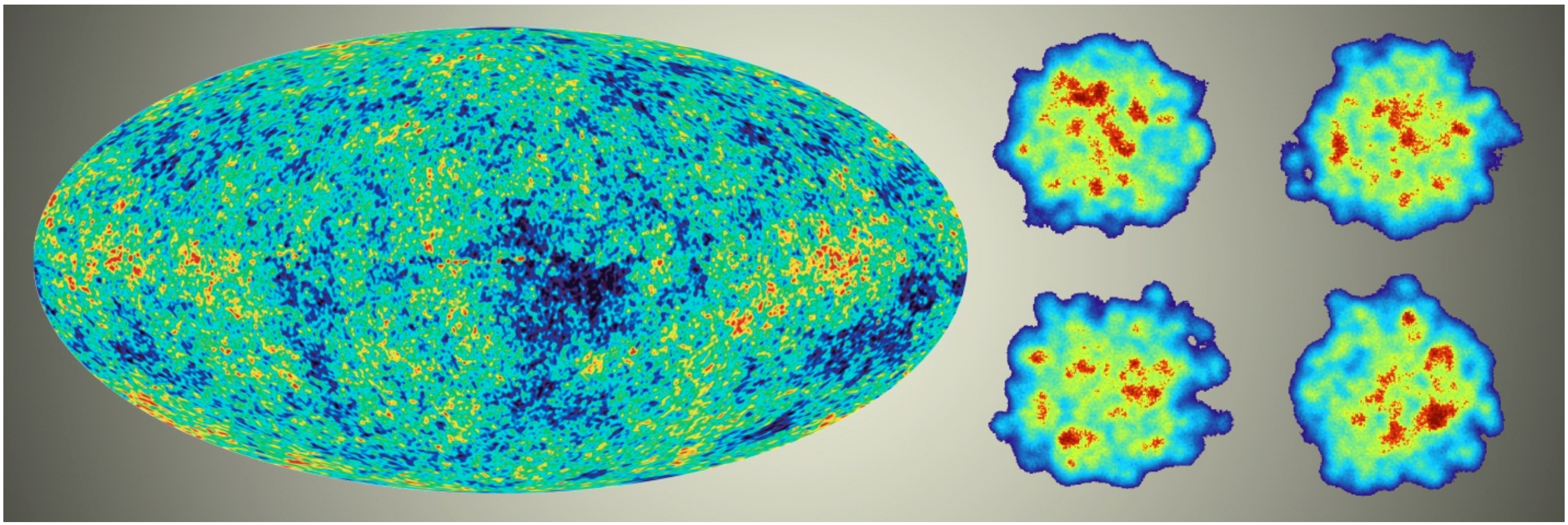
Gale, Jeon, Schenke, Tribedy, Venugopalan, 2013



And v_n-fluctuations in the final state too...

Systematic use of data to constrain initial fluctuations under investigation by several groups.

QGP cf CMB



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...

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.

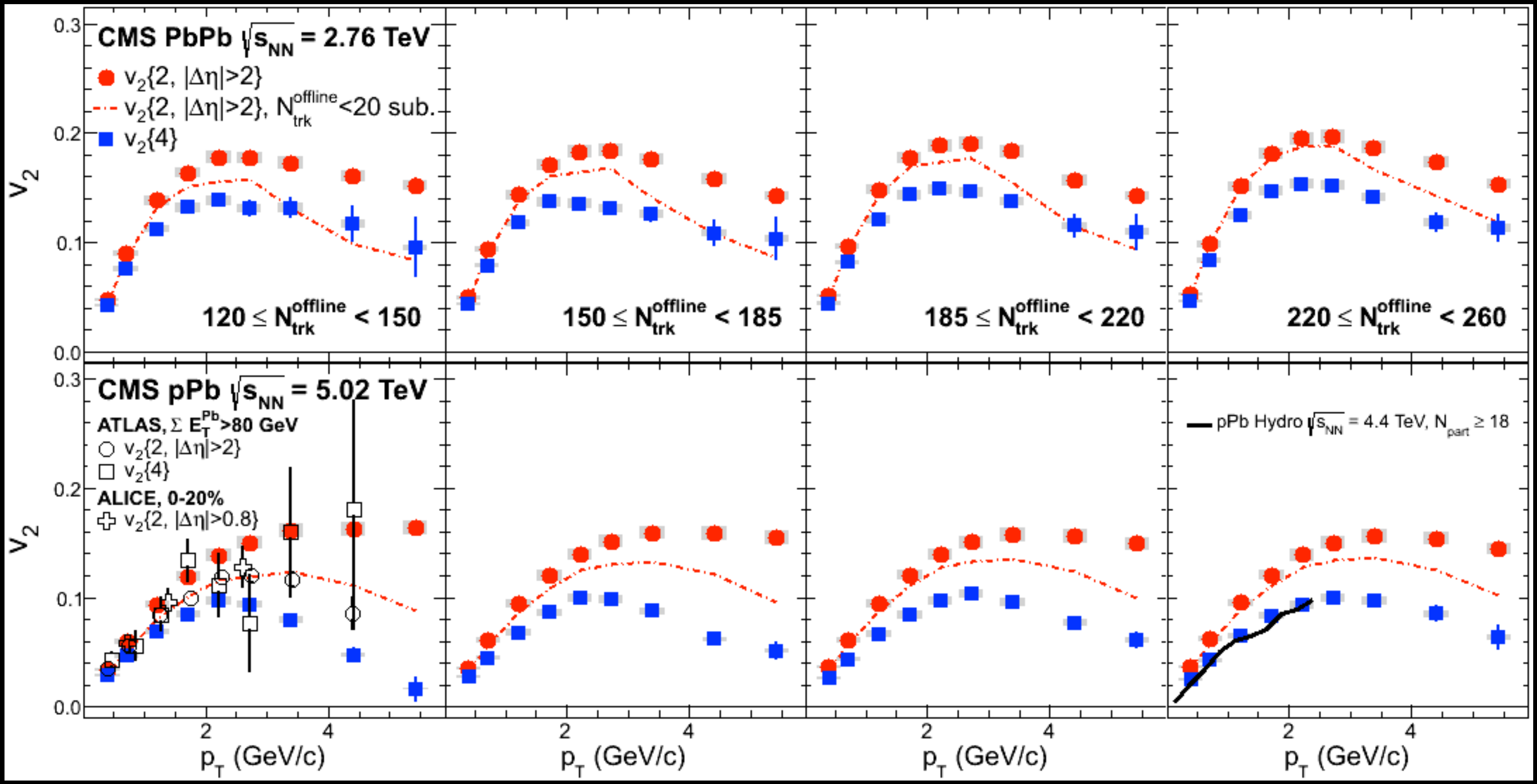
- Both will provide new ways to understand systematics and disentangle effects of η/s. Data from first runs of each being analyzed.

- And, proton-Pb collisions at the LHC? Could such a small droplet of stuff behave hydrodynamically? Surely not...

Direct comparison of v_2 in pPb and PbPb

CMS Phys. Lett. B 724 (2013) 213

ATLAS $v_2\{4\}$: Phys. Lett. B 725 (2013)

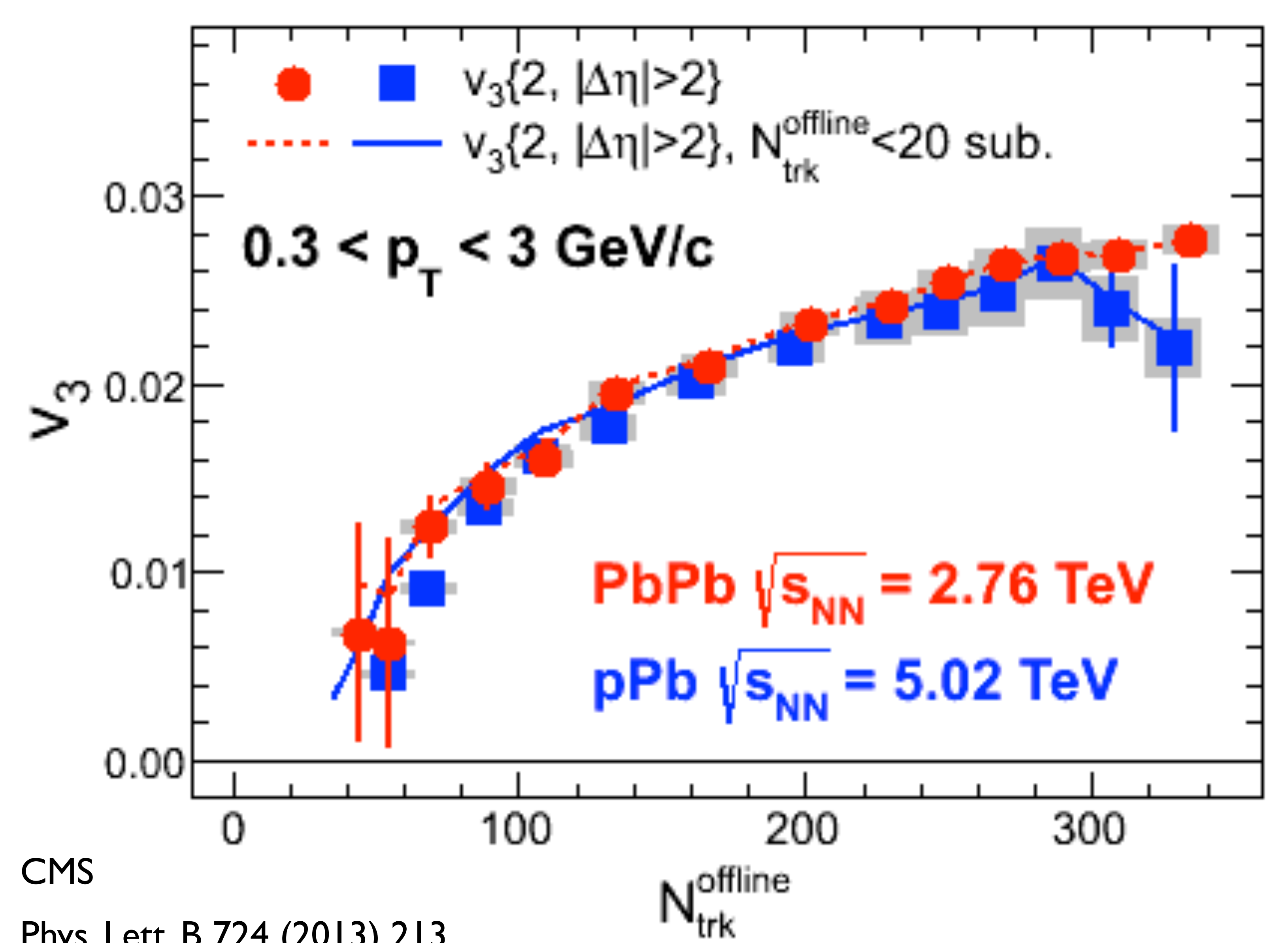


v_2 shows similar shape in pPb and PbPb, but is smaller in pPb

$v_2\{4\}$ is only 20% smaller than $v_2\{2\}$ below 2 GeV/c

"Peripheral subtraction" has small effect at high multiplicity

Direct comparison of v_3 in pPb and PbPb



CMS

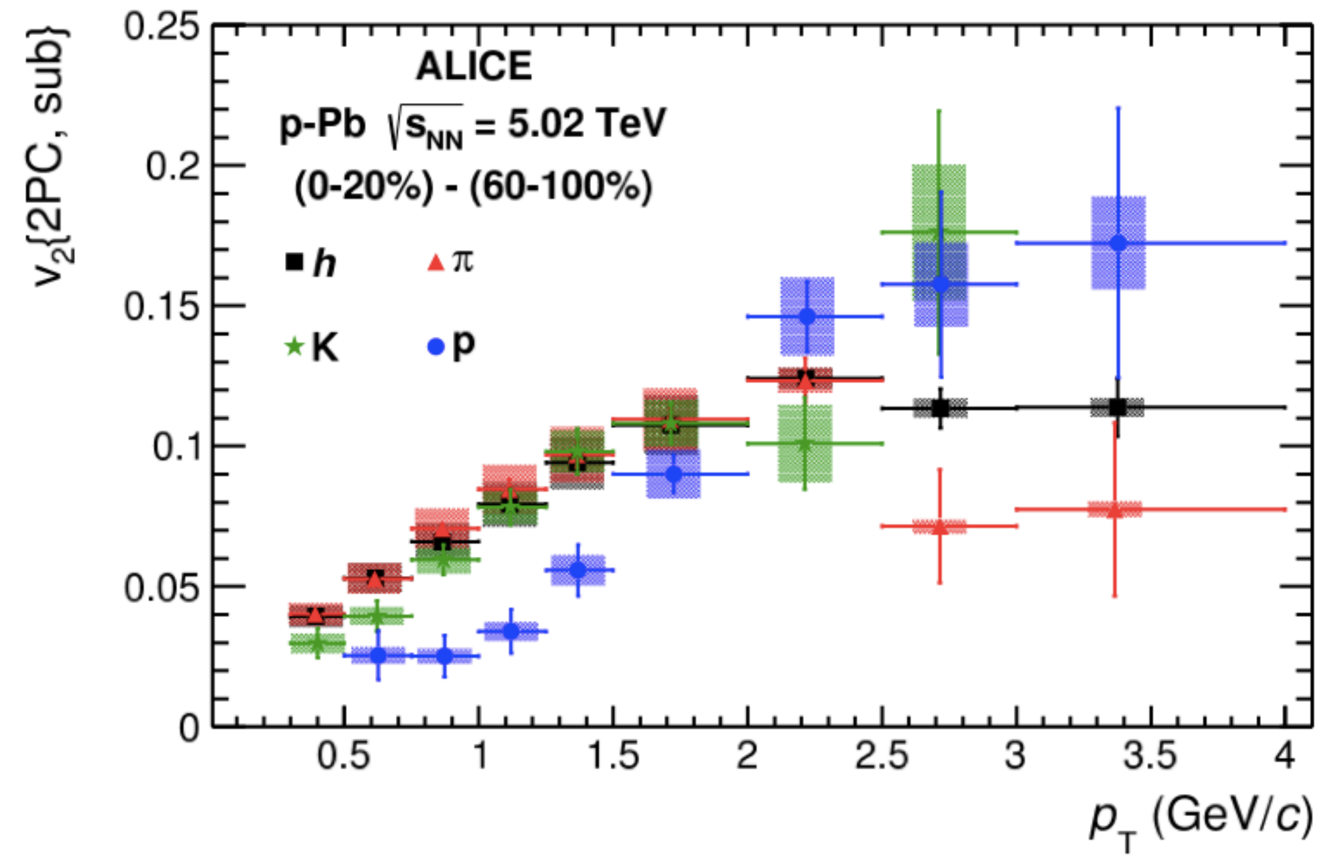
Phys. Lett. B 724 (2013) 213

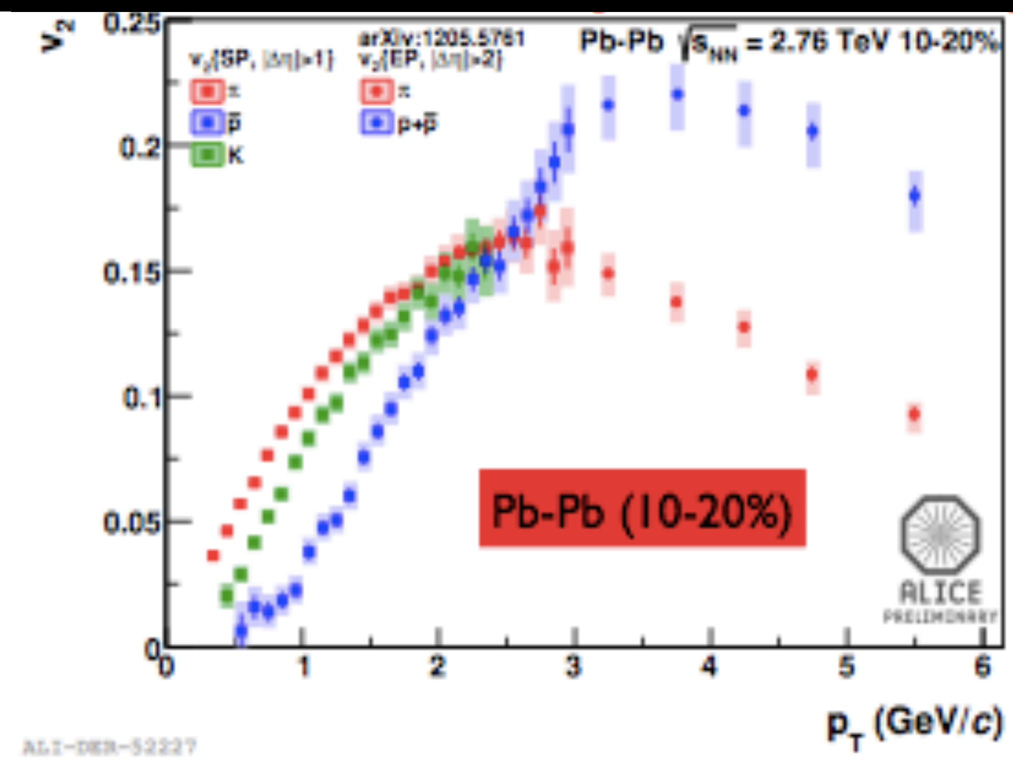
Triangular flow vs multiplicity
rather similar in pPb vs PbPb

PID correlations in pPb vs PbPb

ALICE

arXiv:1307.3237





Mass-ordering of v_2 vs p_T seen in pPb, similar to PbPb

Hydrodynamics in pPb collisions?

- **Almost nobody expected this. pPb collisions supposed to be a control experiment. Too small for hydrodynamics.**
- **But, how large *is* the 'hot-spot' made when a proton blasts through a nucleus? Maybe as large as 2-3 fm across?? [Bozek] Hydrodynamics can work if equilibration time much less than this. This is the case in the strongly coupled plasmas with a holographic description. Further evidence for the strongly coupled liquid nature of QGP?**
- **What are we selecting for when we select high multiplicity pPb collisions? Not just impact parameter. Quantum fluctuations of the proton important? Maybe we are selecting 'fat protons'?**
- **And, PHENIX has now gone back, looked for, and found v_2 in d-Au collisions at RHIC.**
- **Experimental and theoretical investigations still in progress. Systematic investigation of initial conditions now requires confronting PbPb and pPb data at LHC and RHIC.**

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;...

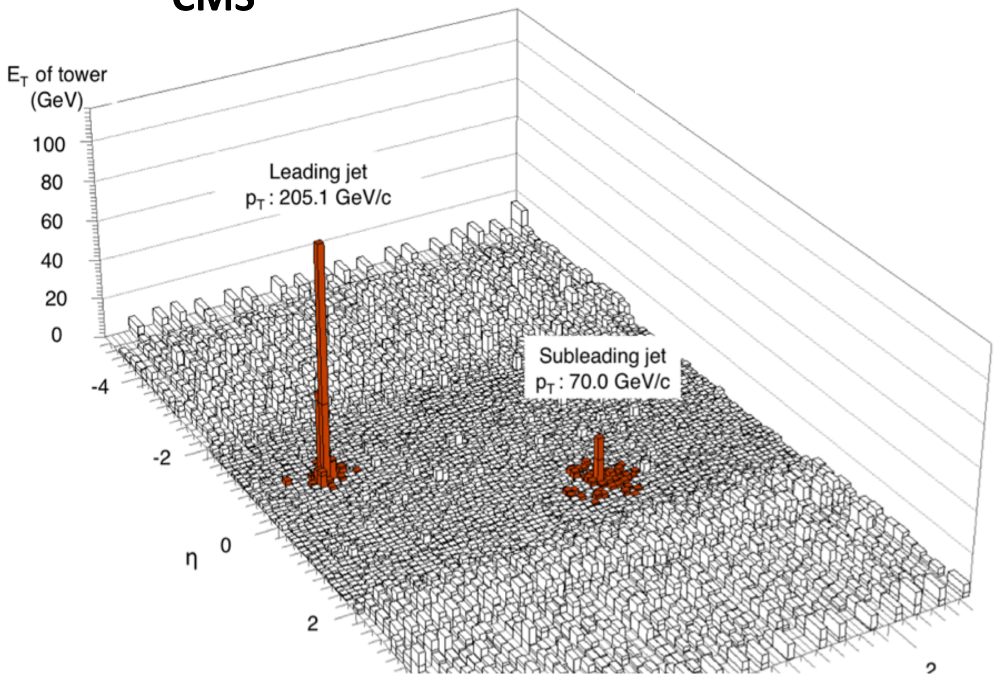
- Emerging hints of how to look at matter in which quasiparticles have disappeared and quantum entanglement is enhanced: "many-body physics through a gravitational lens." Black hole descriptions of liquid QGP and strange metals are continuously related! But, this lens is at present still somewhat cloudy...

A Grand Challenge

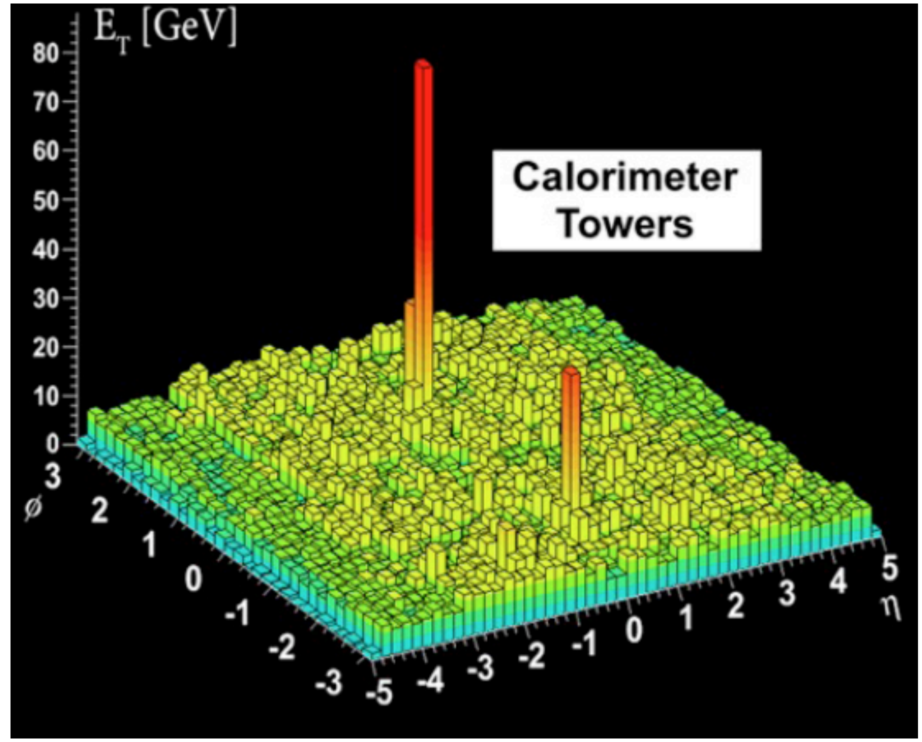
- How can we clarify the understanding of fluids without quasiparticles, whose nature is a central mystery in so many areas of science?
- We have two big advantages: (i) direct experimental access to the fluid of interest without extraneous degrees of freedom; (ii) weakly-coupled quark and gluon quasiparticles 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.

Jet Quenching at the LHC

CMS



ATLAS



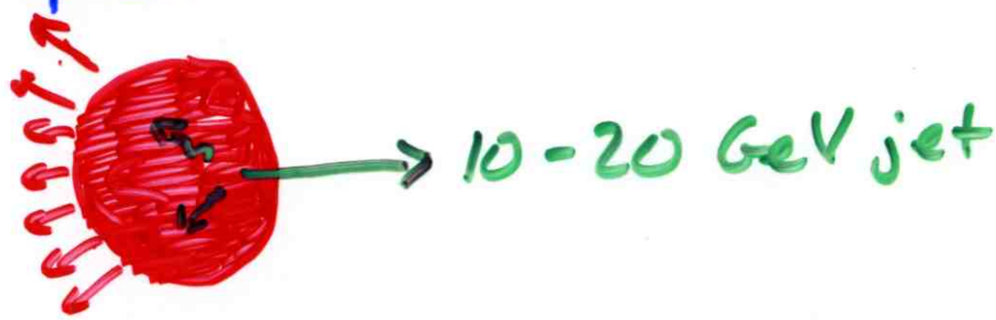
A very large effect at the LHC. 200 GeV jet back-to-back with a 70 GeV jet. A strongly coupled plasma indeed.... Jet quenching was discovered at RHIC (via the associated diminution in the number of high-p_T hadrons) but here it is immediately apparent in a single event.

Jet Quenching @ LHC

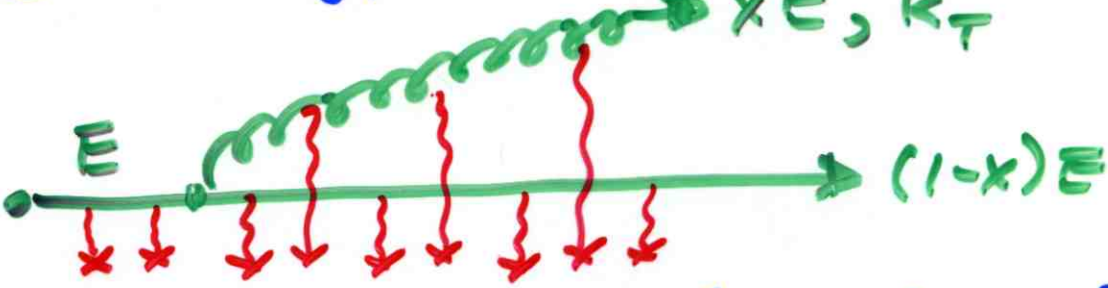
- Jet quenching apparent at the LHC, eg in events with, say, 205 GeV jet back-to-back with 70 GeV jet.
- But, the 70 GeV jet looks almost like a 70 GeV jet in pp collisions. It has lost a lot of energy passing through the QGP but emerges looking otherwise ordinary. Almost same fragmentation function; almost same angular distribution. The "missing" energy is *not* in the form of a spray of softer particles in and around the jet.
- Also, 70 GeV jet seems to be back-to-back with the 205 GeV jet; no sign of transverse kick.
- The "missing" energy is in the form of many ~ 1 GeV particles at large angle to the jet direction.
- Interestingly, STAR, PHENIX and ALICE may see evidence that lower energy jets emerge surrounded by their debris.

JET QUENCHING

Further evidence that QGP@RHIC is strongly coupled.



Radiative energy loss



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

<u>If</u> so (RHIC? LHC?), energy loss sensitive to medium through <u>one</u> 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 $\omega < \hat{q} L^2$

Jet Quenching @ LHC

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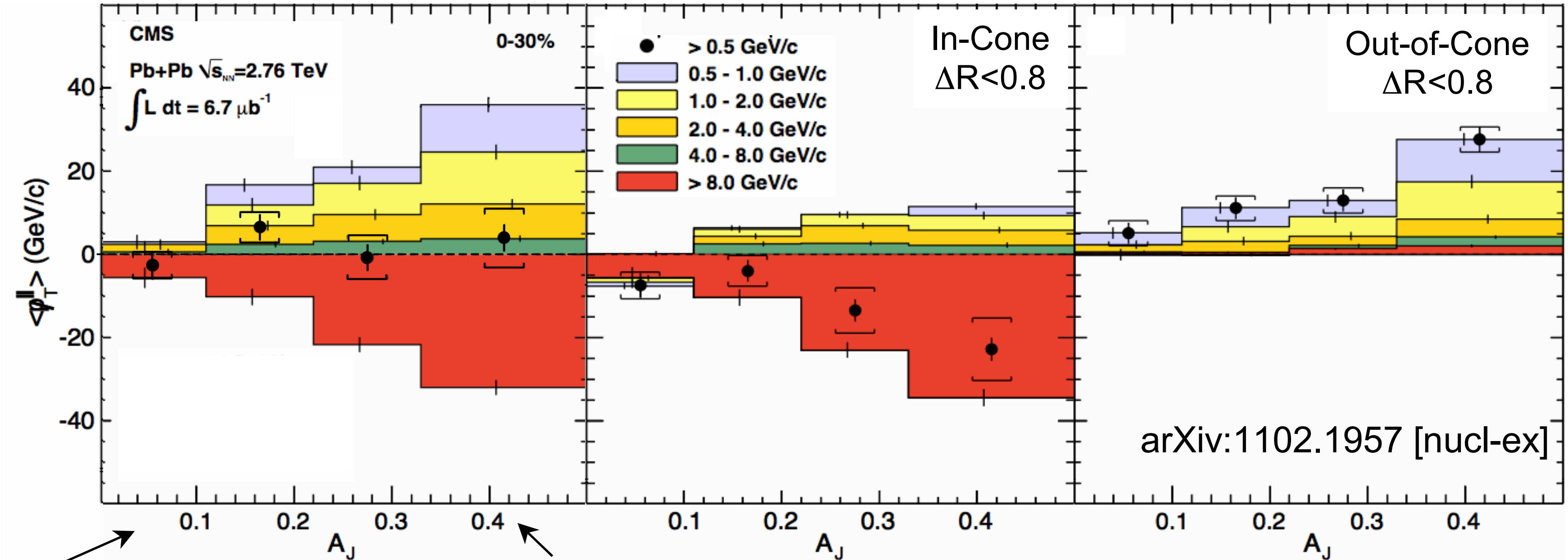
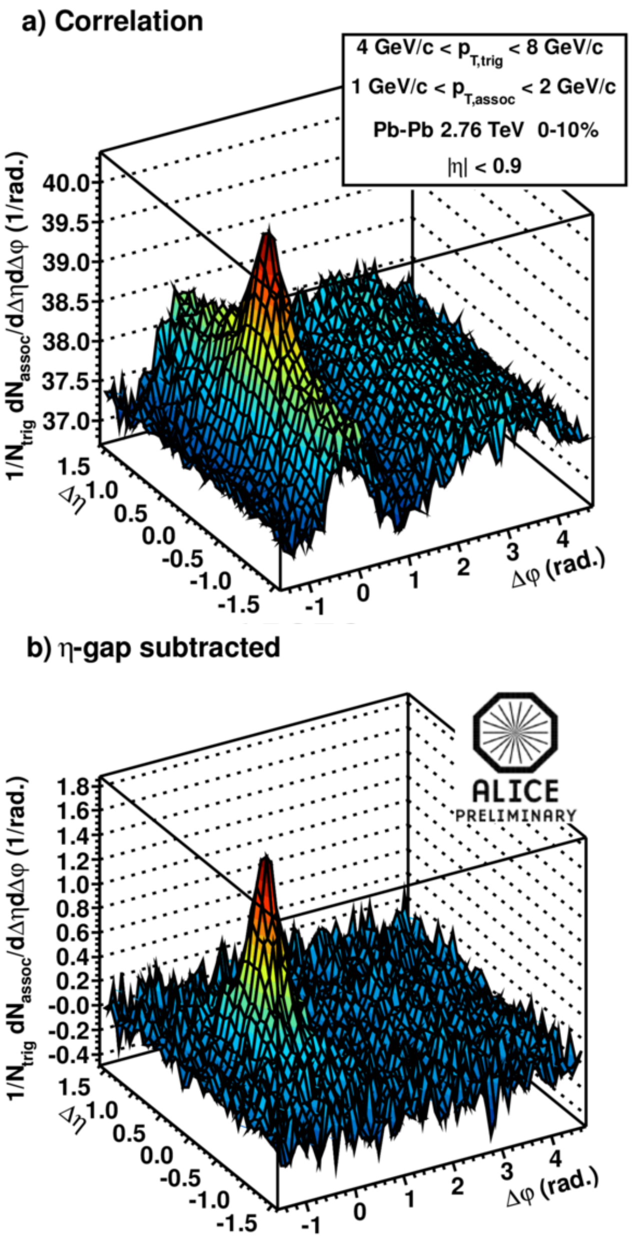
Missing-$p_T^{||}$

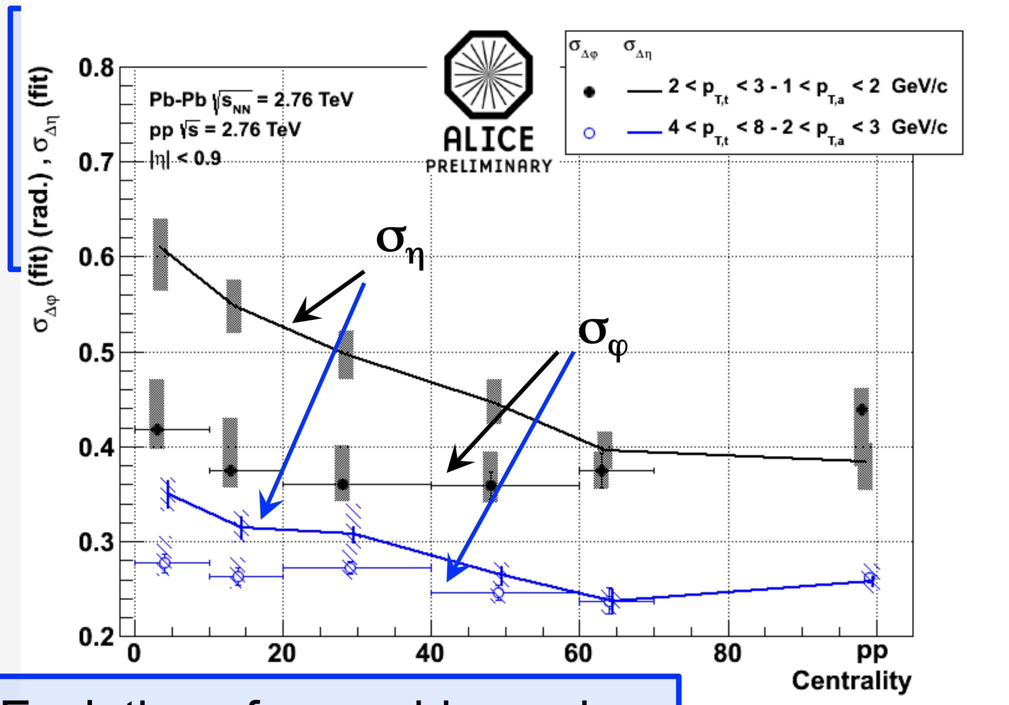
0-30% Central PbPb



balanced jets unbalanced jets

Near-side (jet-like) structure



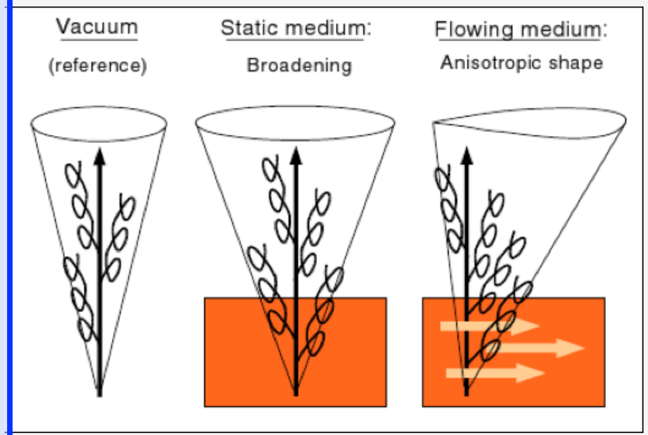


Talks by
A.M.Adare
F.Krizek

Evolution of near-side-peak σ_η and σ_φ with centrality: Strong σ_η increase for central collisions

Interestingly: AMPT describes the data very well

Influence of flowing medium?

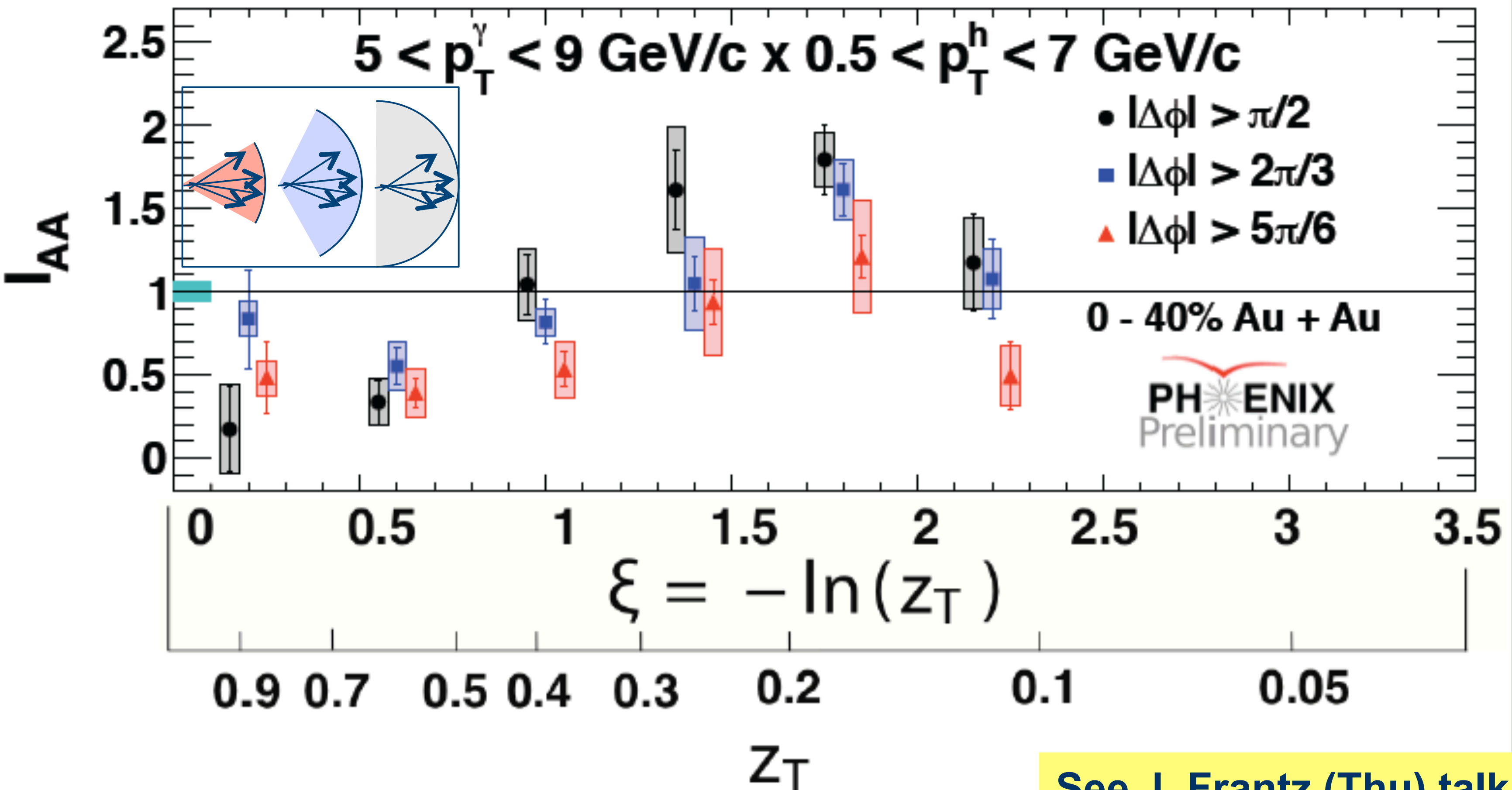


N.Armesto et al., PRL 93, 242301

γ-h correlation in Au+Au

$$I_{AA} \equiv \frac{(1/N_{trig} dN/d\xi)_{AA}}{(1/N_{trig} dN/d\xi)_{pp}}$$

Low z_T away side particles distributed over wider angle

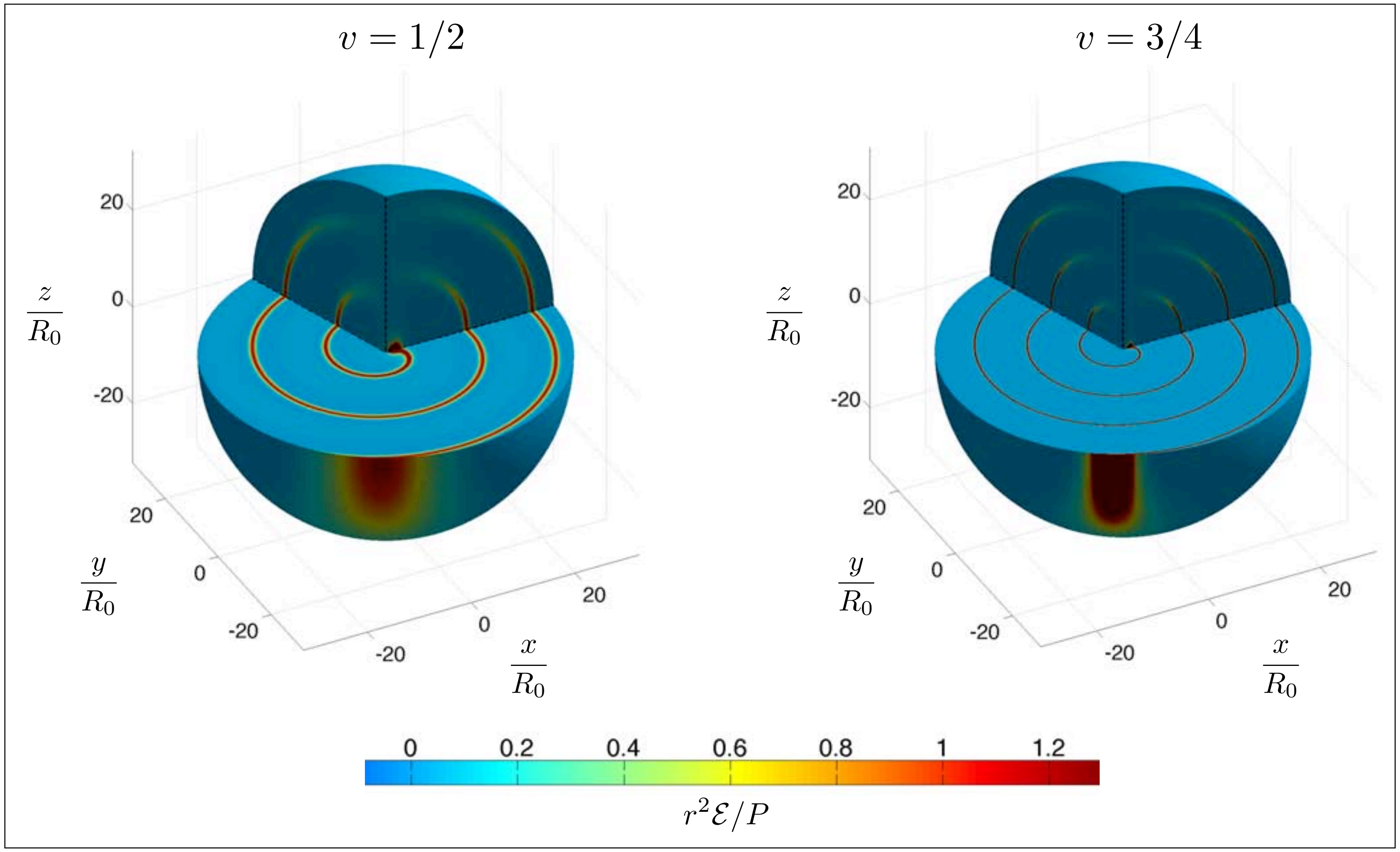


See J. Frantz (Thu) talk

- As if an initially-200-GeV parton/jet in an LHC collision just heats the plasma it passes through, losing significant energy without significant spreading in angle or degradation of its fragmentation function. Are even 200 GeV partons not "seeing" the q+g at short distances?
- One line of theoretical response: more sophisticated analyses of conventional weak-coupling picture of jet quenching. Advancing from parton energy loss and leading hadrons to modification of parton showers and jets.
- We also need strongly coupled approaches 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 beams of gluons... and 'jets' ...

Synchrotron Radiation in Strongly Coupled Gauge Theories

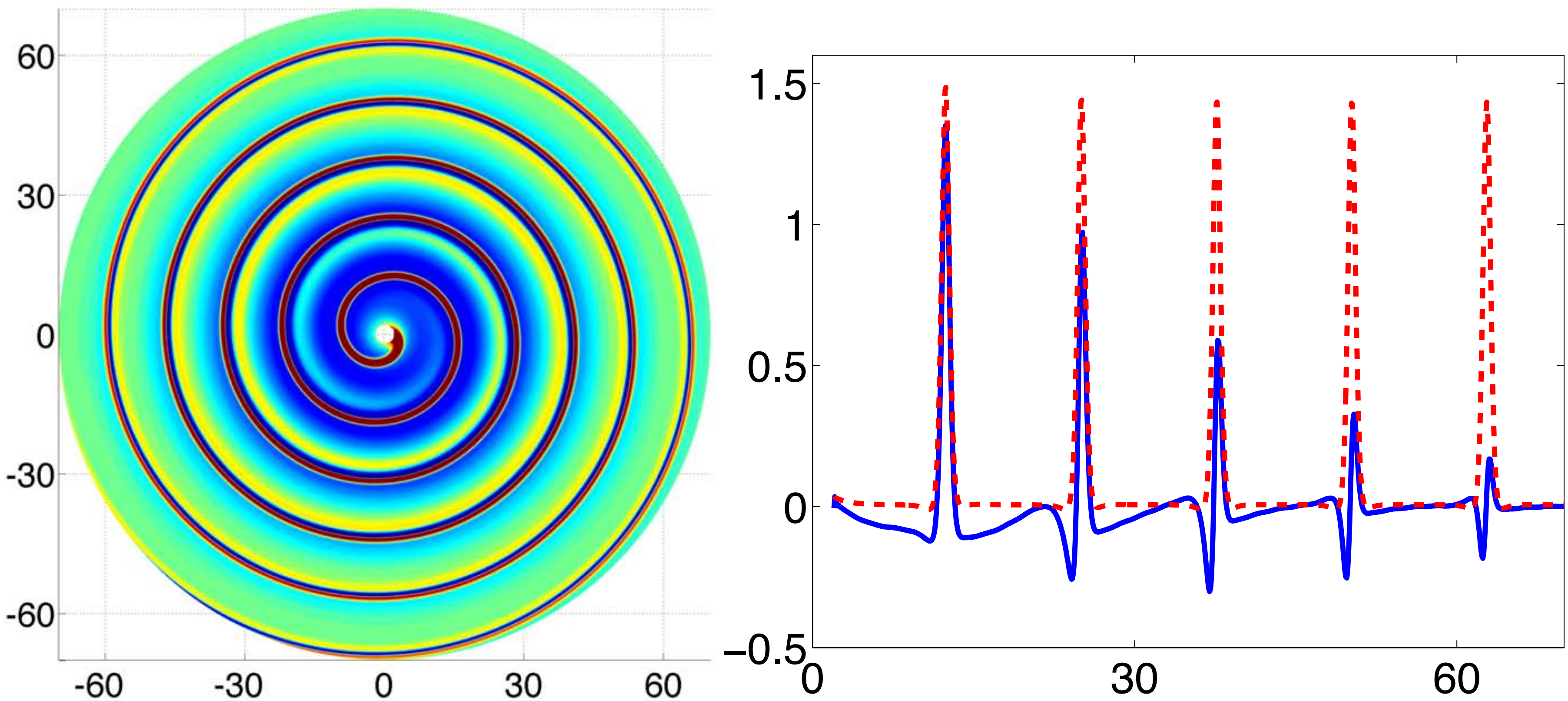
Athanasiou, Chesler, Liu, Nickel, Rajagopal; arXiv:1001.3880



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 Beam of Gluons

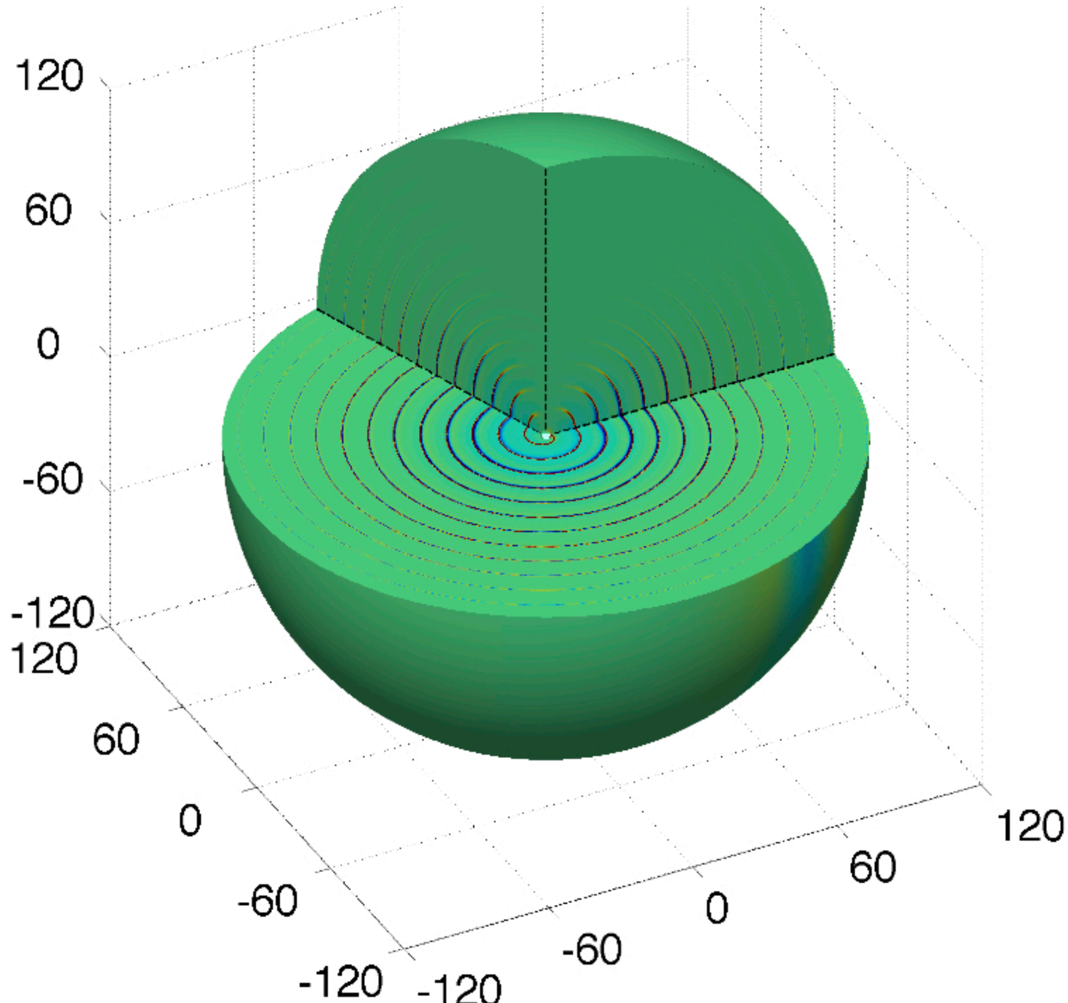
Chesler, Ho, Rajagopal, arXiv:1111.1691



Quark in circular motion ($v = 0.5$; $R\pi T = 0.15$) makes a beam of gluons that is attenuated dramatically by the plasma, without being significantly broadened — in angle or in momentum distribution.

Quenching a Beam of Gluons

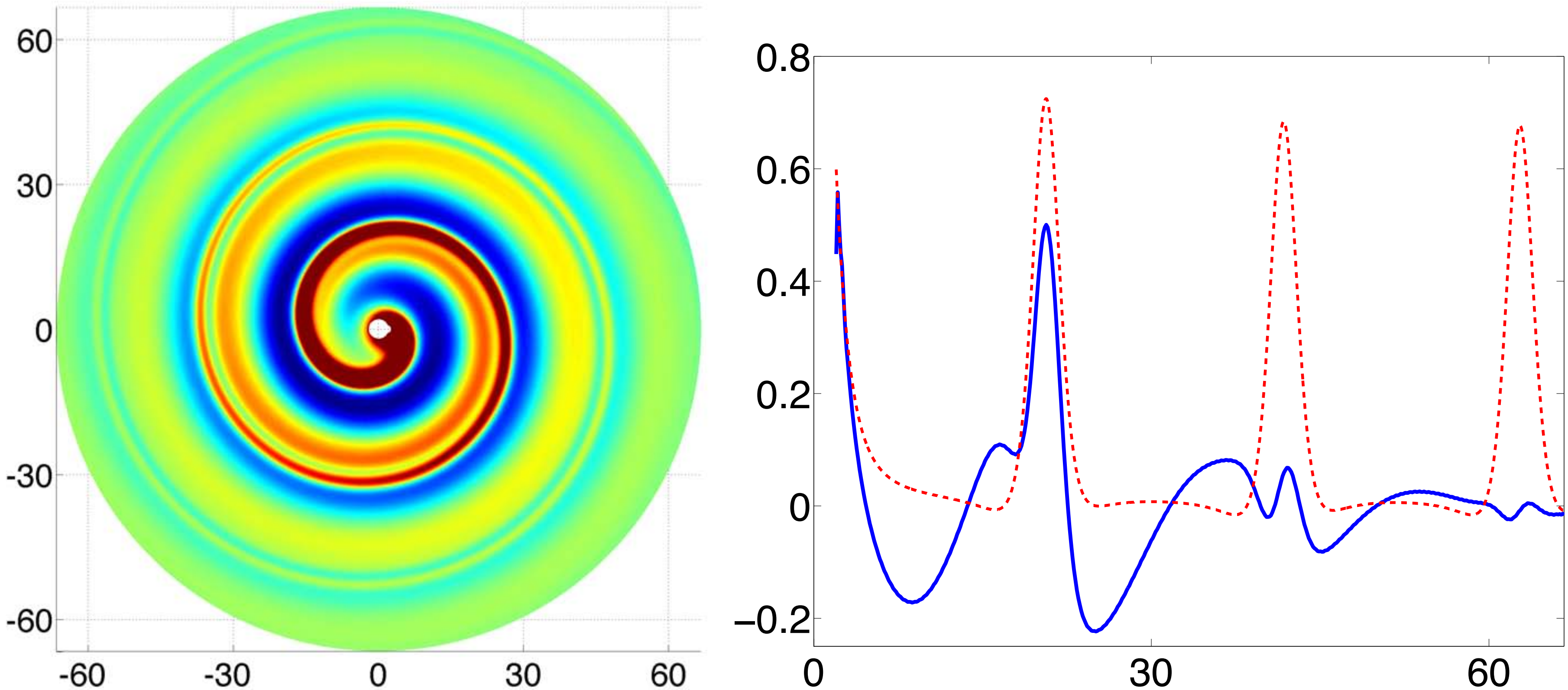
Chesler, Ho, Rajagopal, arXiv:1111.1691



A narrower beam made of higher momentum gluons travels farther, still gets attenuated without spreading in angle or degradation of its momentum distribution.

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691



Quark in circular motion ($v = 0.3$; $R\pi T = 0.15$) makes a beam of lower momentum gluons that is quenched rapidly, and is followed closely by its 'debris' — a sound wave.

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691

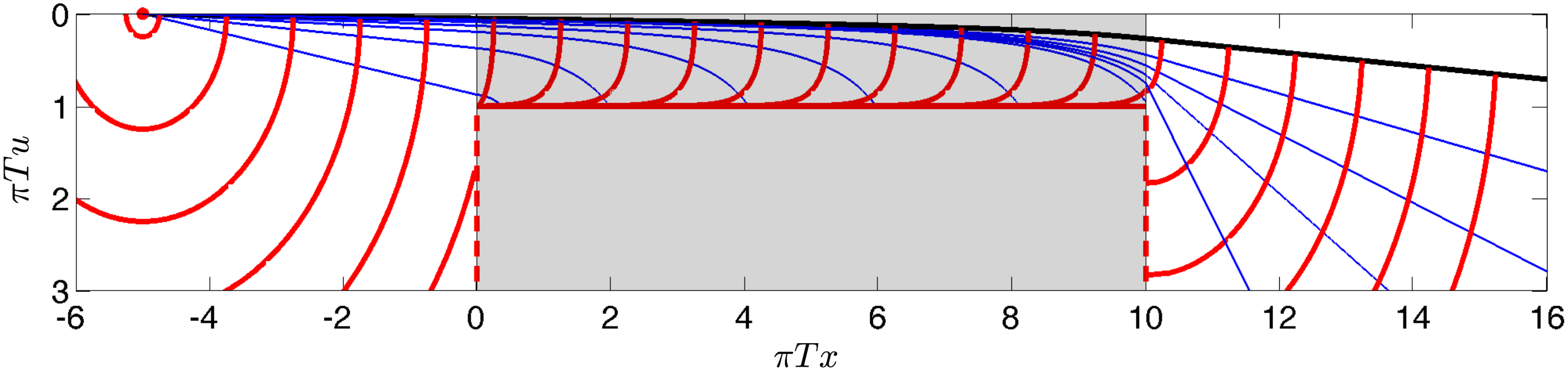
- **A beam of gluons with wave vector $q \gg \pi T$ shines through the strongly coupled plasma at close to the speed of light, and is attenuated over a distance $\sim q^{1/3}(\pi T)^{-4/3}$.**

- **Beam shows no tendency to spread in angle, or shift toward longer wavelengths, even as it is completely attenuated. Like quenching of highest energy jets at LHC?**

- **Beam sheds a trailing sound wave with wave vector $\sim \pi T$. A beam of higher q gluons travels far enough that it leaves the sound far behind; sound thermalizes. (Highest energy LHC jets?) A beam of not-so-high-q gluons does not go as far, so does get far ahead of its trailing sound wave, which does not have time to thermalize. If it were to emerge from the plasma, it would be followed by its 'lost' energy. (Lower energy jets at RHIC and LHC? Moreso at RHIC since sound thermalizes faster in the higher temperature LHC plasma.)**

Quenching a Light Quark 'Jet'

Chesler, Rajagopal, 1402.6756

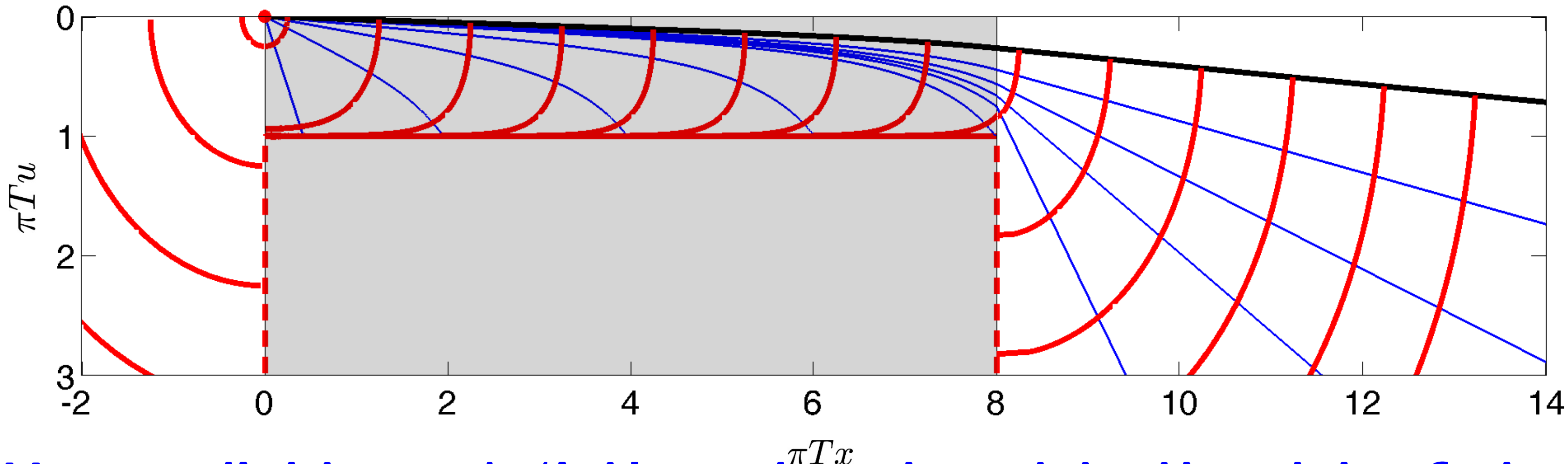


A light quark 'jet', incident with energy E_{in}, shoots through a slab of strongly coupled $\mathcal{N} = 4$ SYM plasma, temperature T, thickness $L\pi T = 10$. What comes out the other side? A 'jet' with $E_{\text{out}} \sim 0.64 E_{\text{i}}$, that looks just like a vacuum 'jet' with that energy. And, entire calculation of energy loss is geometric!

Two very different holographic approaches, quenching a beam of gluons, quenching a light quark 'jet', give similar conclusions, in qualitative agreement with aspects of what is seen.

Quenching a Light Quark 'Jet'

Chesler, Rajagopal, 1402.6756

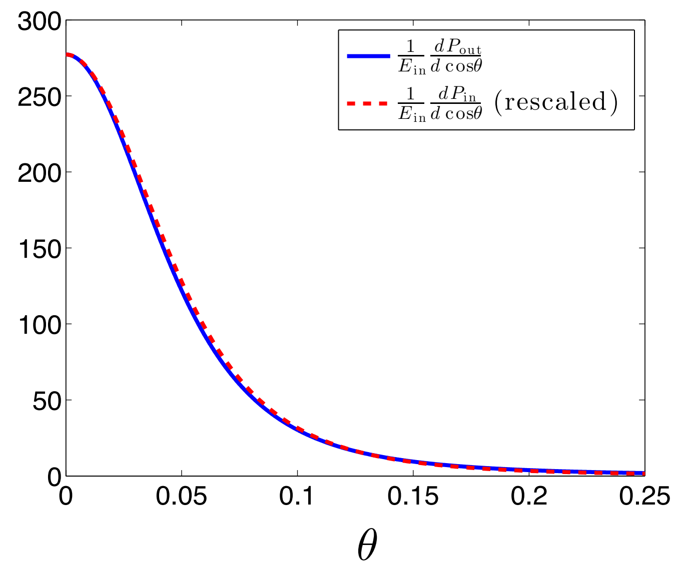


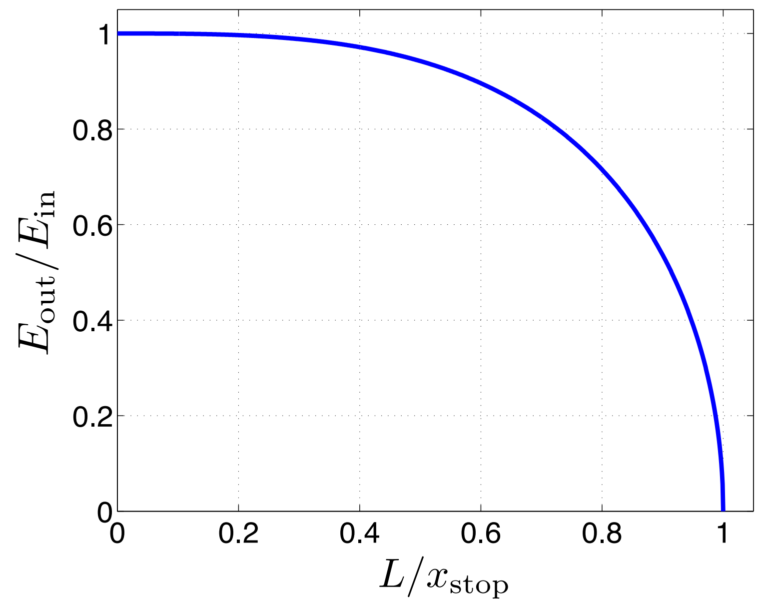
Here, a light quark 'jet' produced next to the slab of plasma with incident energy $E_{\text{in}} = 87\sqrt{\lambda}\pi T \sim 87\sqrt{\lambda}$ GeV shoots through the slab and emerges with $E_{\text{out}} \sim 66\sqrt{\lambda}$ GeV. Again, the 'jet' that emerges looks like a vacuum 'jet' with that energy.

Geometric understanding of jet quenching, and Bragg peak (maximal energy loss rate as the last energy is lost). Energy propagates along the blue curves, which are null geodesics in the bulk.

Quenching a Light Quark 'Jet'

Chesler, Rajagopal, 1402.6756





Shape of outgoing jet is the same as incoming jet, except broader in angle and less total energy.

Geometric derivation of analytic expression for dE_{out}/dL **and** $E_{\text{out}}/E_{\text{in}}$ **including the Bragg peak:**

$$\frac{1}{E_{\text{in}}}\frac{dE_{\text{out}}}{dL} = -\frac{4L^2}{\pi x_{\text{stop}}^2}\frac{1}{\sqrt{x_{\text{stop}}^2 - L^2}}$$

where $\pi T x_{\text{stop}} \propto (E_{\text{in}}/(\sqrt{\lambda}\pi T))^{1/3}$.

A Hybrid Weak+Strong Coupling Approach to Jet Quenching?

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, in progress

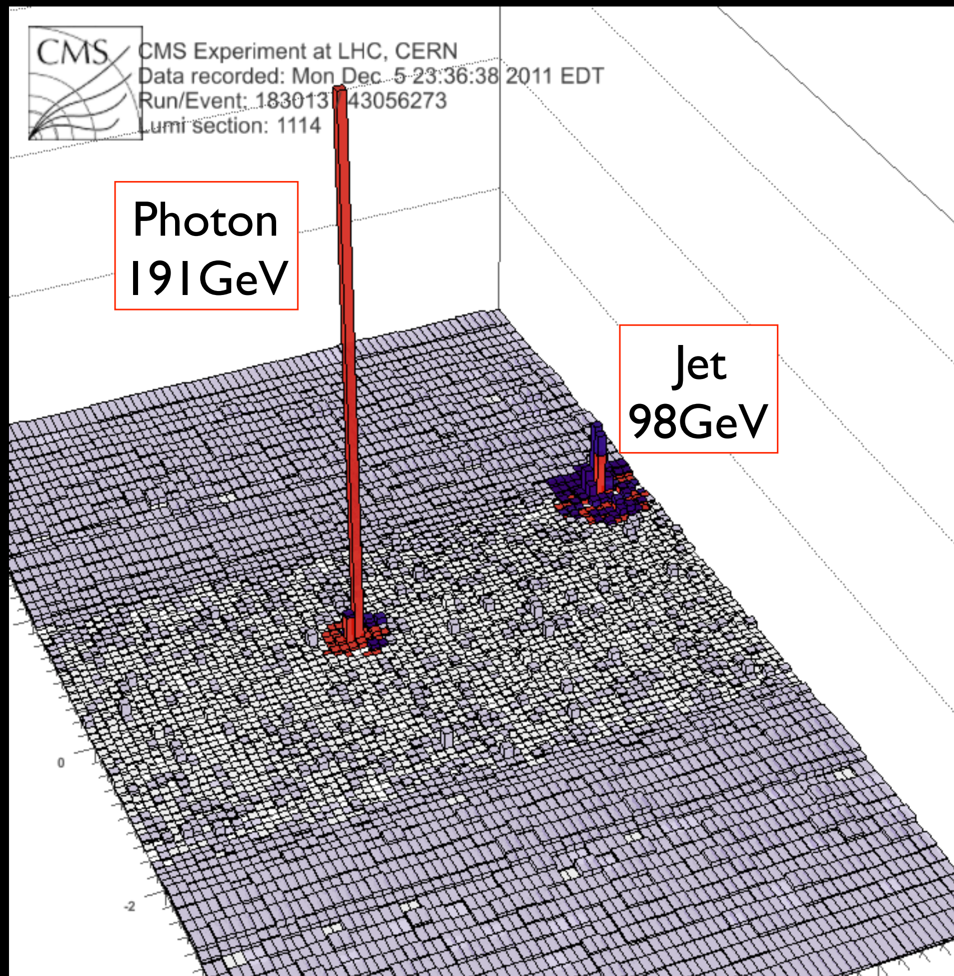
- **Although various holographic approaches at strong coupling capture many qualitative features of jet quenching (e.g. the previous two), it seems quite unlikely that the high-momentum "core" of a quenched LHC jet can be described quantitatively in any strong coupling approach. (Precisely because so similar to jets in vacuum.)**
- **We know that the medium itself is a strongly coupled liquid, with no apparent weakly coupled description. And, the energy the jet loses seems to quickly become one with the medium.**
- **A hybrid approach may be worthwhile. Eg think of each parton in a parton shower losing energy to "friction", à la light quarks in strongly coupled liquid.**
- **We are exploring various different ways of adding "friction" to PYTHIA, looking at R_{AA}, energy loss distribution, dijet asymmetry, jet fragmentation function.**

How to see weakly Coupled q & g in Liquid QGP

D'Eramo, Lekaveckas, Liu, Rajagopal, 1211.1922

- **We *know* that at a short enough length scale, QGP *is* made of weakly coupled quarks and gluons, even though on its natural length scales QGP is a strongly coupled fluid with no quasiparticles.**
- **Long-term challenge: understand *how* liquid QGP emerges from an asymptotically free theory.**
- **First things first: how can we see the point-like quarks and gluons at short distance scales? Need a 'microscope'. Need to look for large-angle scattering not as rare as it would be if QGP were liquid-like on all length scales. (Think of Rutherford.)**
- **γ-jet events: γ tells you initial direction of quark. Measure deflection angle of jet. Closest analogy to Rutherford. (Today, only thousands of events. Many more ~ 2015.)**

2011: Detected 3000 photon-jet pairs in 10^9 PbPb collisions



Unbalanced photon-jet event in PbPb

Momentum Broadening in Weakly Coupled QGP

Calculate $P(k_\perp)$, the probability distribution for the $k_\perp$ that a parton with energy $E \to \infty$ picks up upon travelling a distance L through the medium:

- $P(k_\perp) \propto \exp(-\# k_\perp^2/(T^3 L))$ **in strongly coupled plasma. Qualitative calculation, done via holography.**

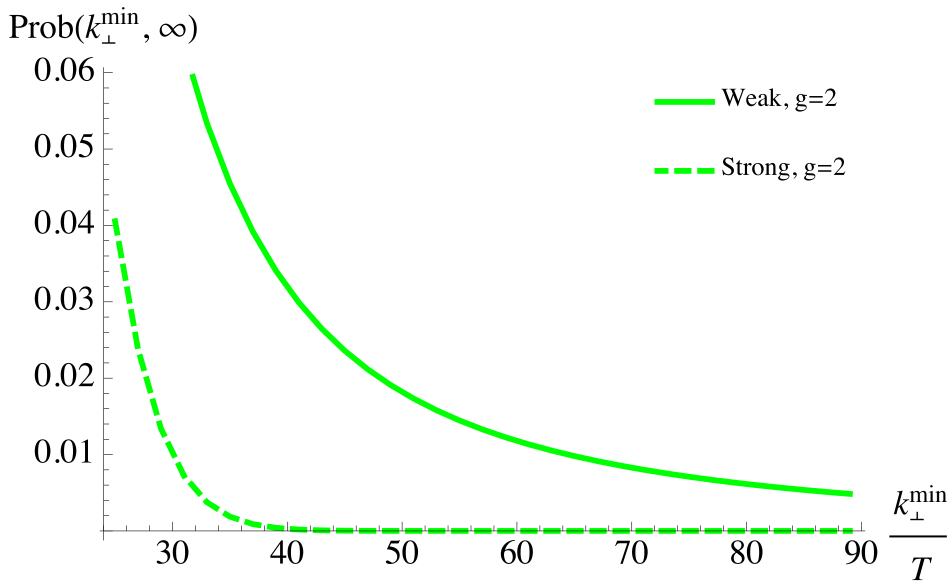
  D'Eramo, Liu, Rajagopal, arXiv:1006.1367

- **For a weakly coupled plasma containing point scatterers $P(k_\perp) \propto 1/k_\perp^4$ at large $k_\perp$. In the strongly coupled plasma of an asymptotically free gauge theory, this must win at large enough $k_\perp$. Quantitative calculation, done using Soft Collinear Effective Theory + Hard Thermal Loops.**

  D'Eramo, Lekaveckas, Liu, Rajagopal, arXiv:1211.1922

Expect: Gaussian at low $k_\perp$; power-law tail at high $k_\perp$.

Large deflections rare, but not as rare as if the liquid were a liquid on all scales. They indicate point-like scatterers.

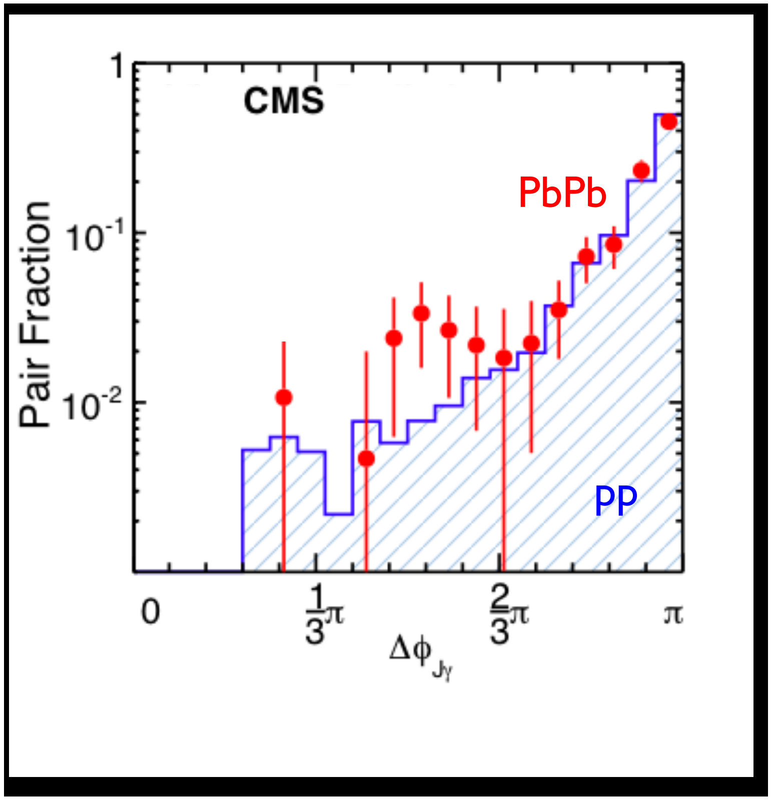


D'Eramo, Lekaveckas, Liu, Rajagopal, arXiv:1211.1922

- **Probability that a parton that travels $L = 7.5/T$ through the medium picks up $k_\perp > k_{\perp \rm min}$, for:**
  - **Weakly coupled QCD plasma, in equilibrium, analyzed via SCET+HTL. With $g = 2$, i.e. $\alpha_{\rm QCD} = 0.32$.**
  - **Strongly coupled $\mathcal{N} = 4$ SYM plasma, in equilibrium, analyzed via holography. With $g = 2$, i.e. $\lambda_{\rm 't\ Hooft} = 12$.**

- **Eg, for $T = 300$ MeV, $L = 5$ fm, a 60 GeV parton that picks up $70\,T$ of $k_\perp$ scatters by 20°. Presence of point-like scatterers gives this a probability $\sim 1\%$, as opposed to negligible.**

Measure the angle between jet and photon



CMS, arXiv:1205.0206

Need many more events before this can be a "QGP Rutherford Experiment". Something to look forward to circa 2015?

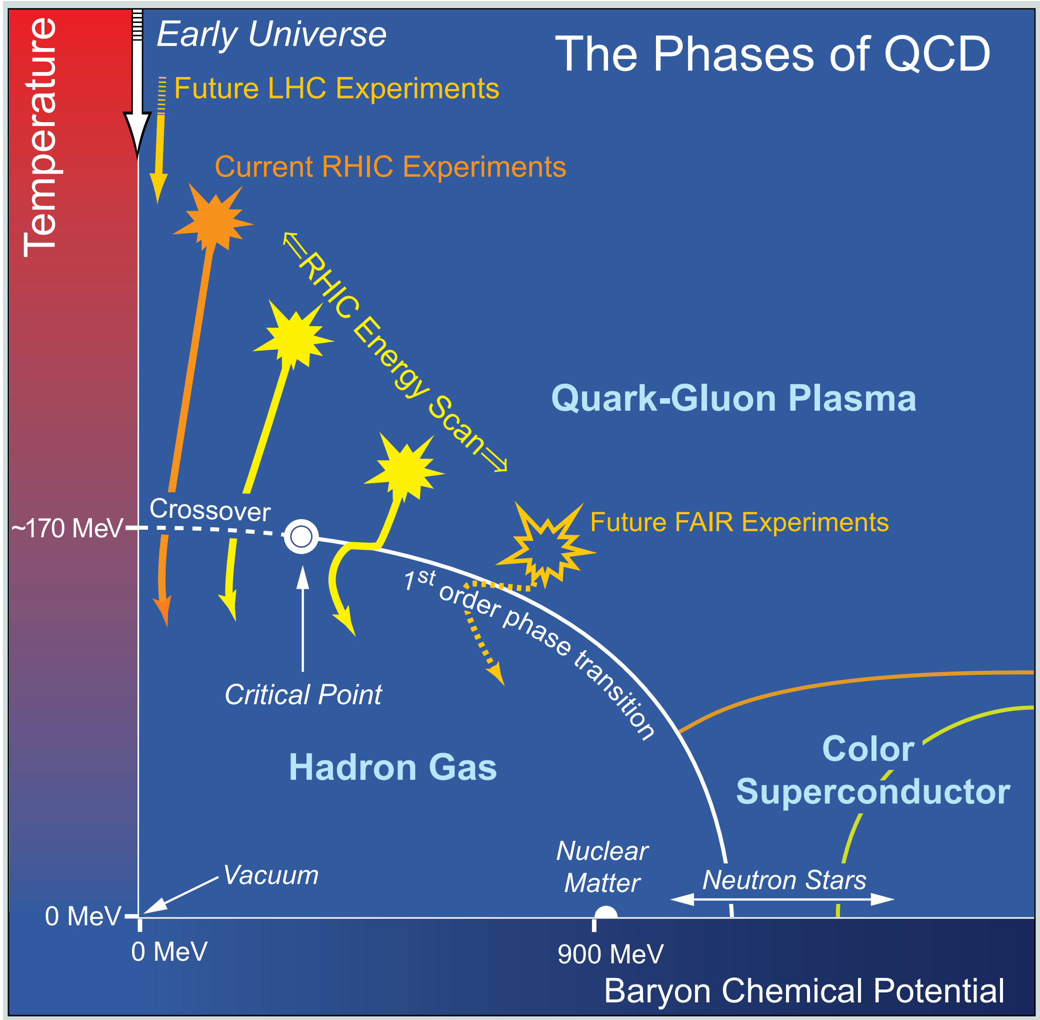
A Grand Challenge

- 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.

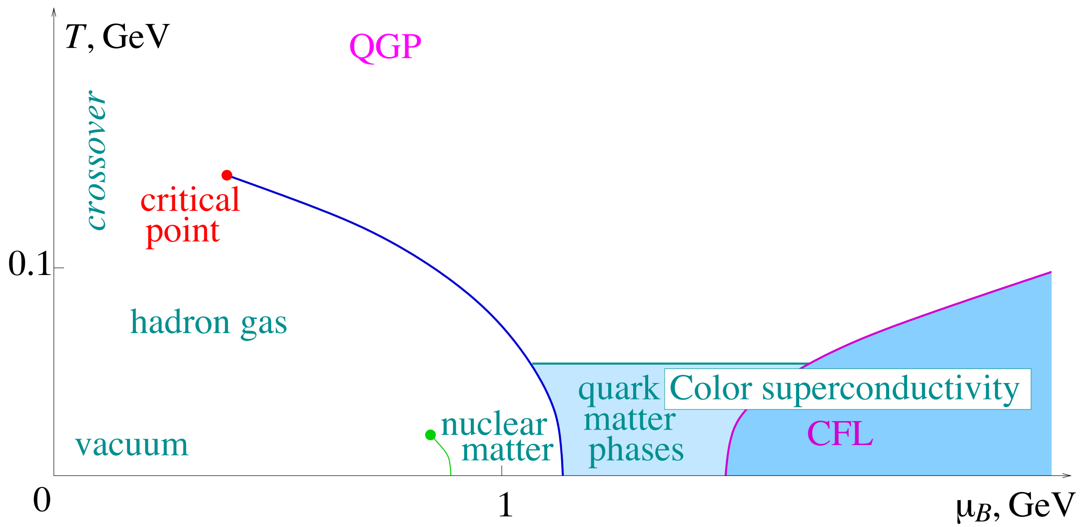
Seeking the QCD Critical Point

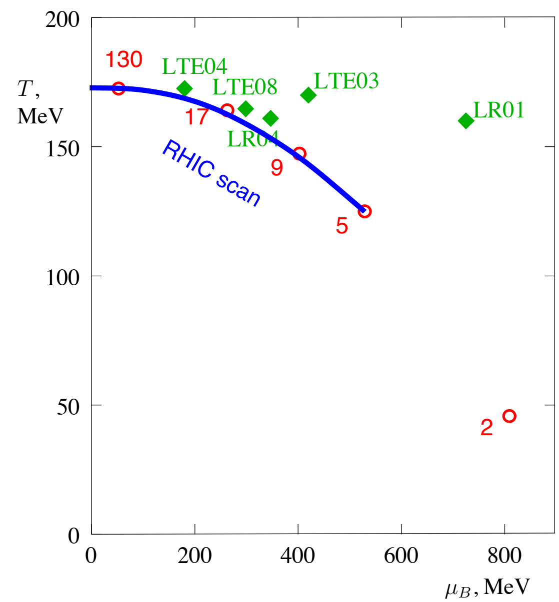


2007 NSAC Long Range Plan

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

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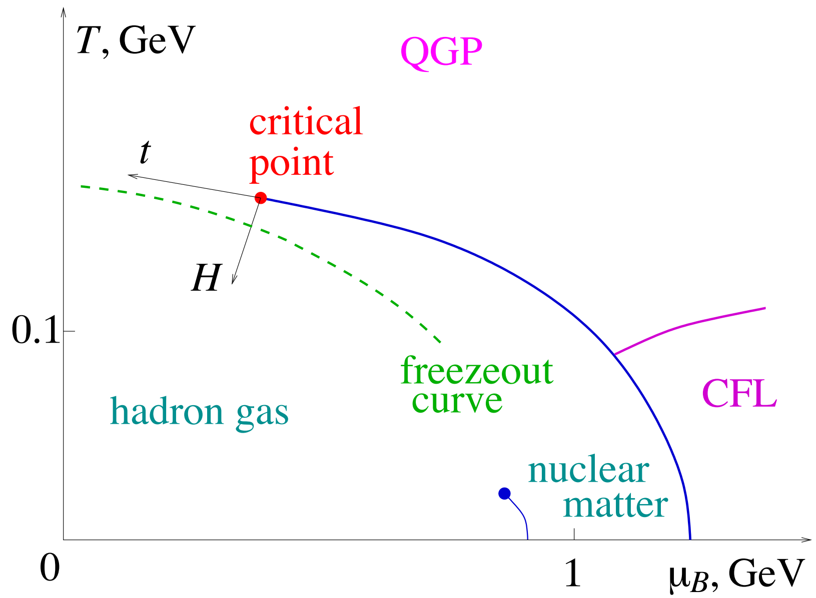

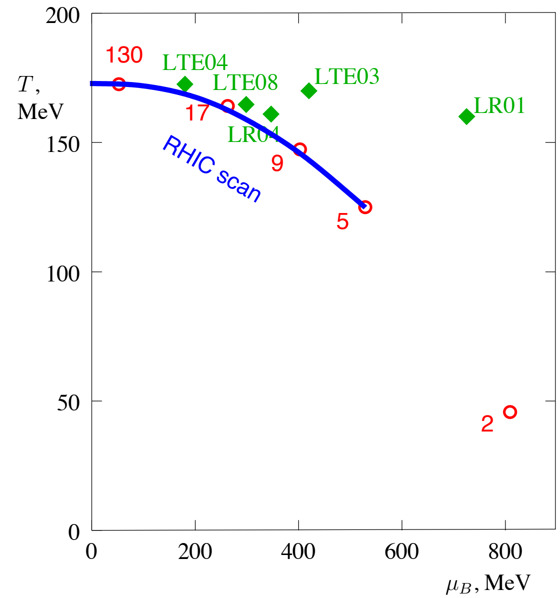

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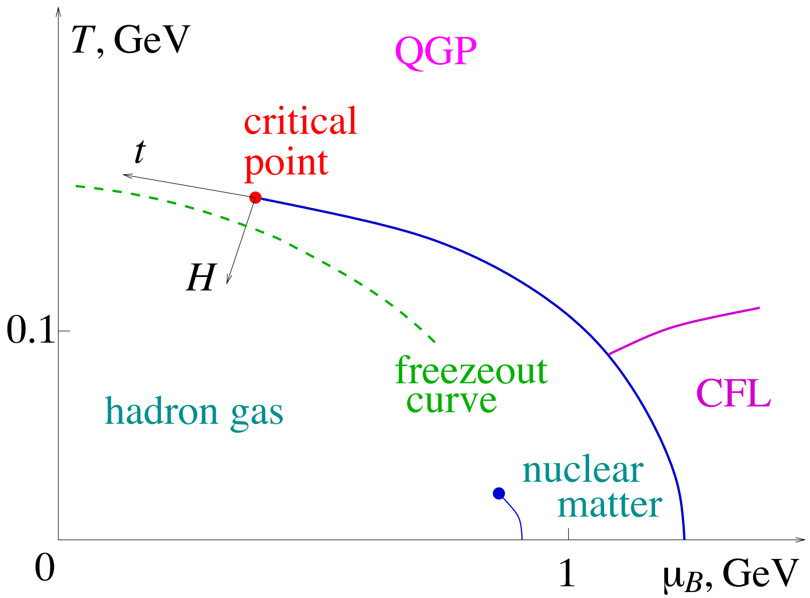

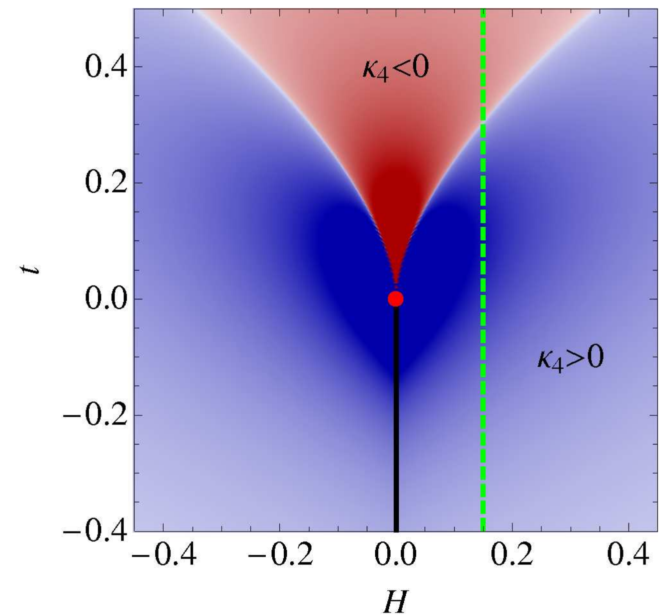

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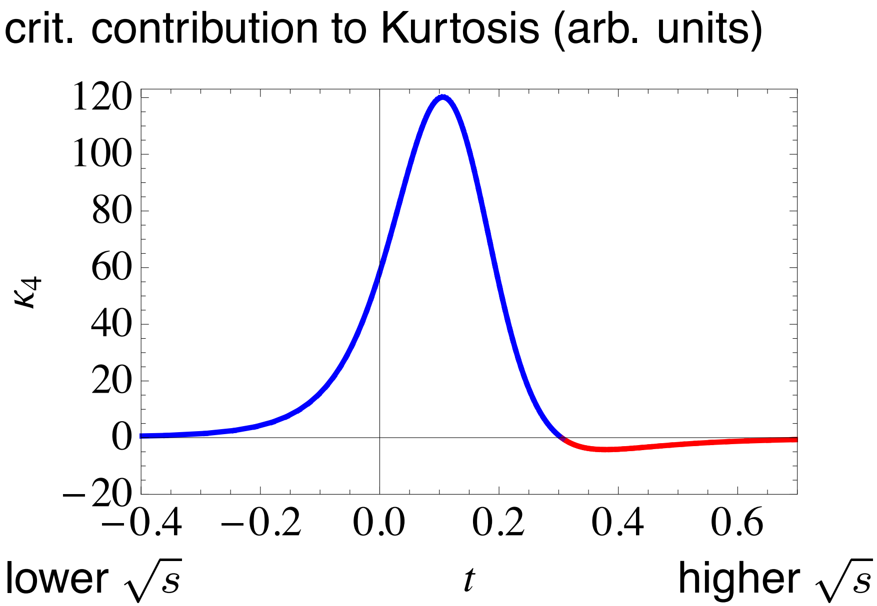

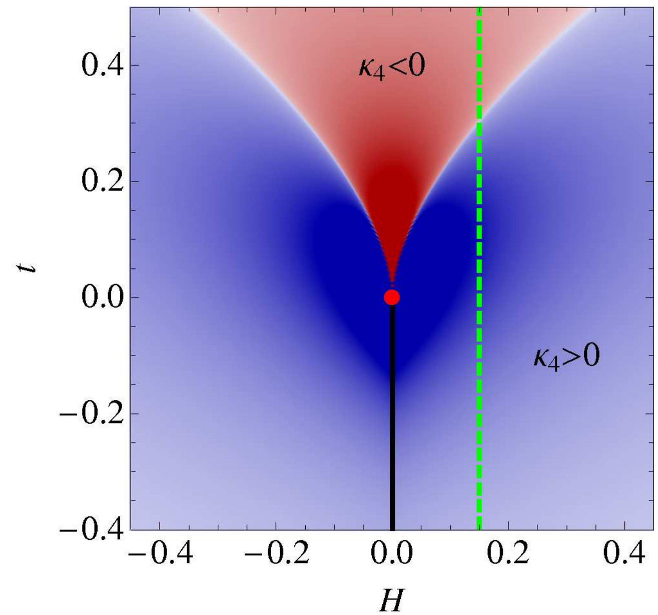

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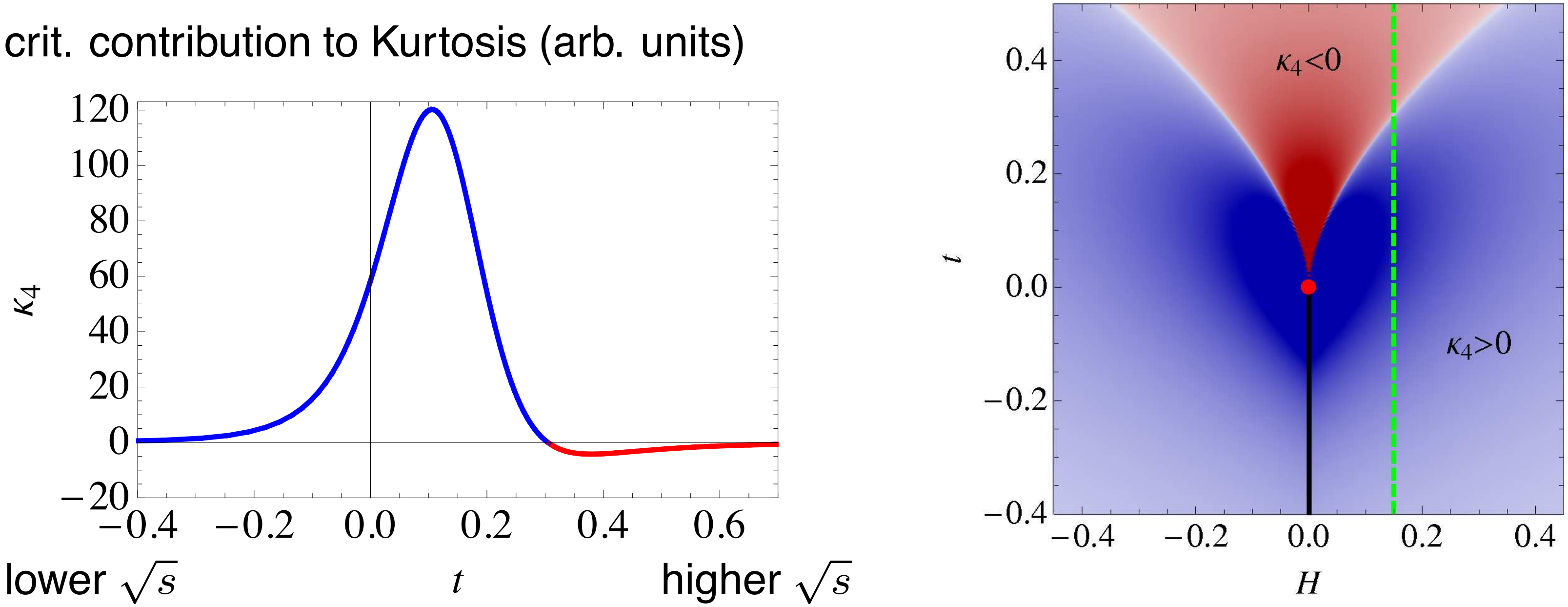

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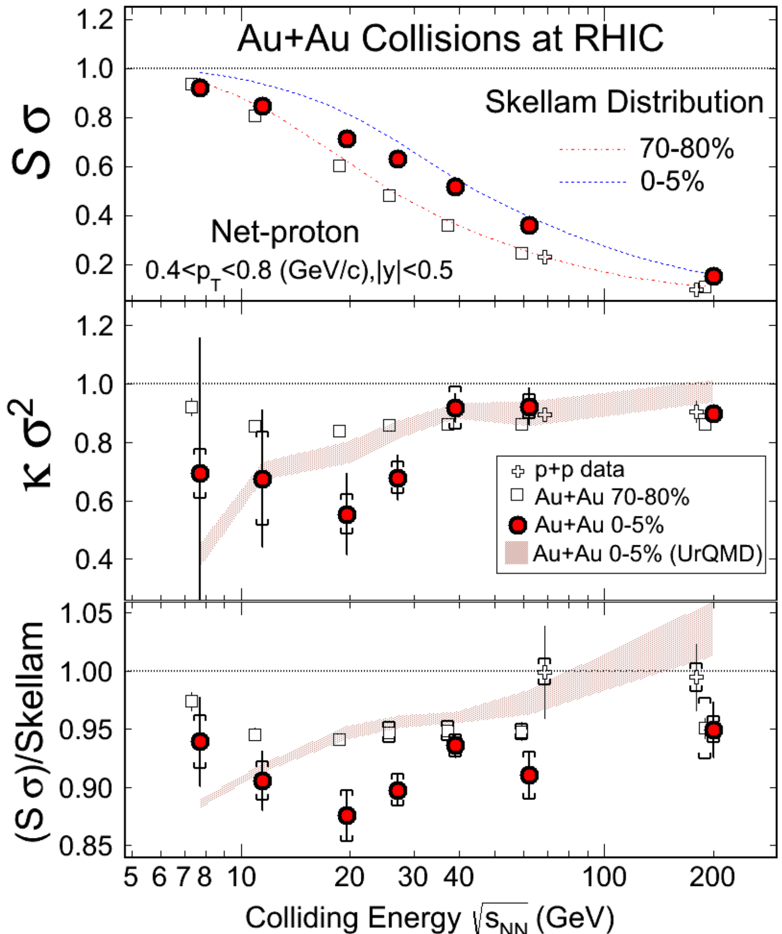
- Challenge: develop measures most sensitive to the critical point and use them to locate the critical point by scanning in $\sqrt{s}$ and therefore in $\mu_{\rm freezeout}$.
- Once we find the μ (i.e. the $\sqrt{s}$) where the critical contribution to κ_4 is large enough — e.g. the "blue peak" — then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

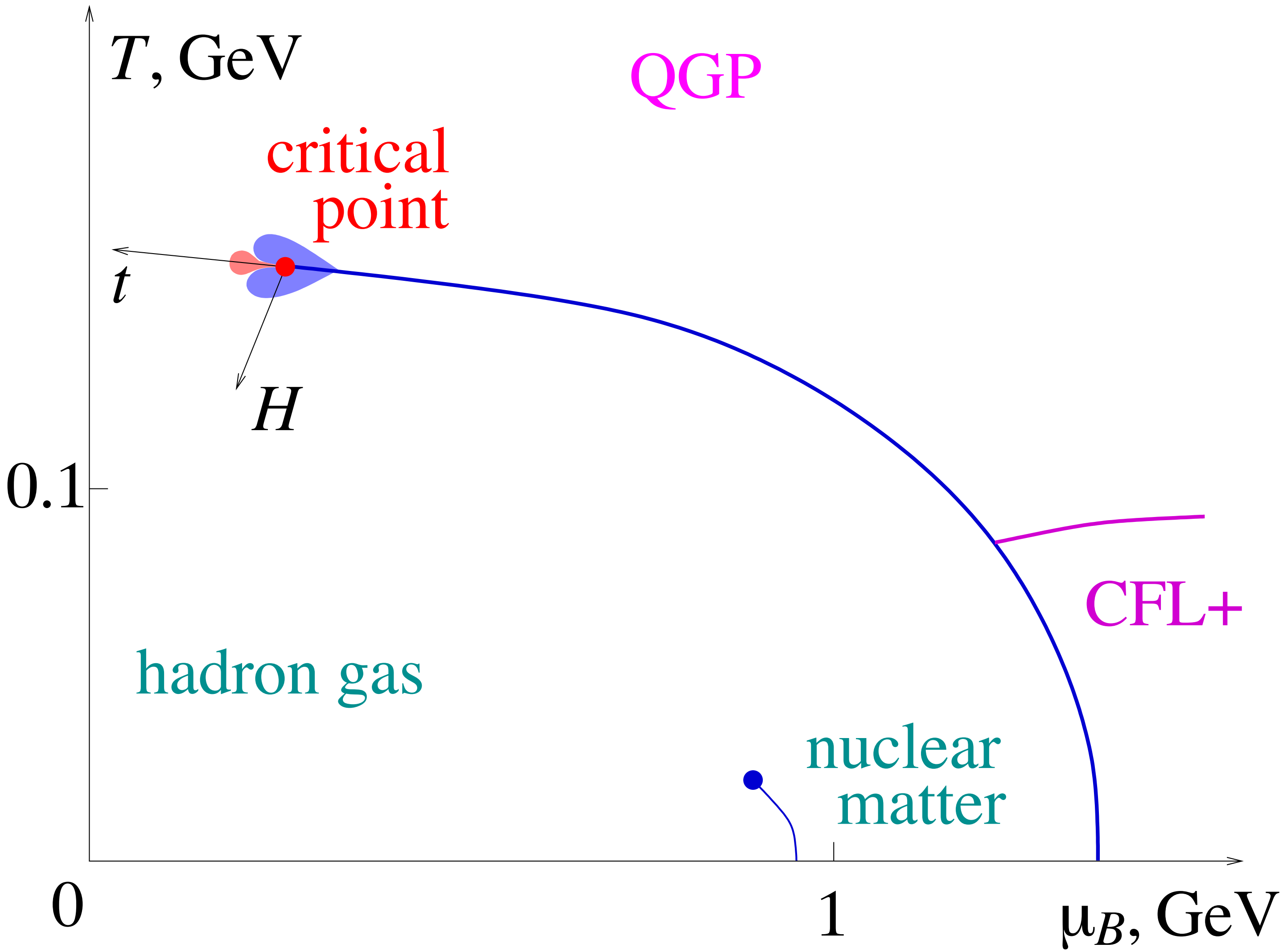
Early RHIC Energy Scan Data



STAR, 2013

Very **interesting to see data from 2014 run at $\sqrt{s} = 14.5$ GeV.**
If **negative kurtosis at $\sqrt{s} = 19.6$ GeV is due to critical point, and *if* critical region is ~ 100 MeV wide in μ_B, then expect positive contribution to kurtosis at $\sqrt{s} = 14.5$ GeV.**
Future: electron cooling $\rightarrow \times 10$ statistics at low $\sqrt{s}$.

Implications for the energy scan



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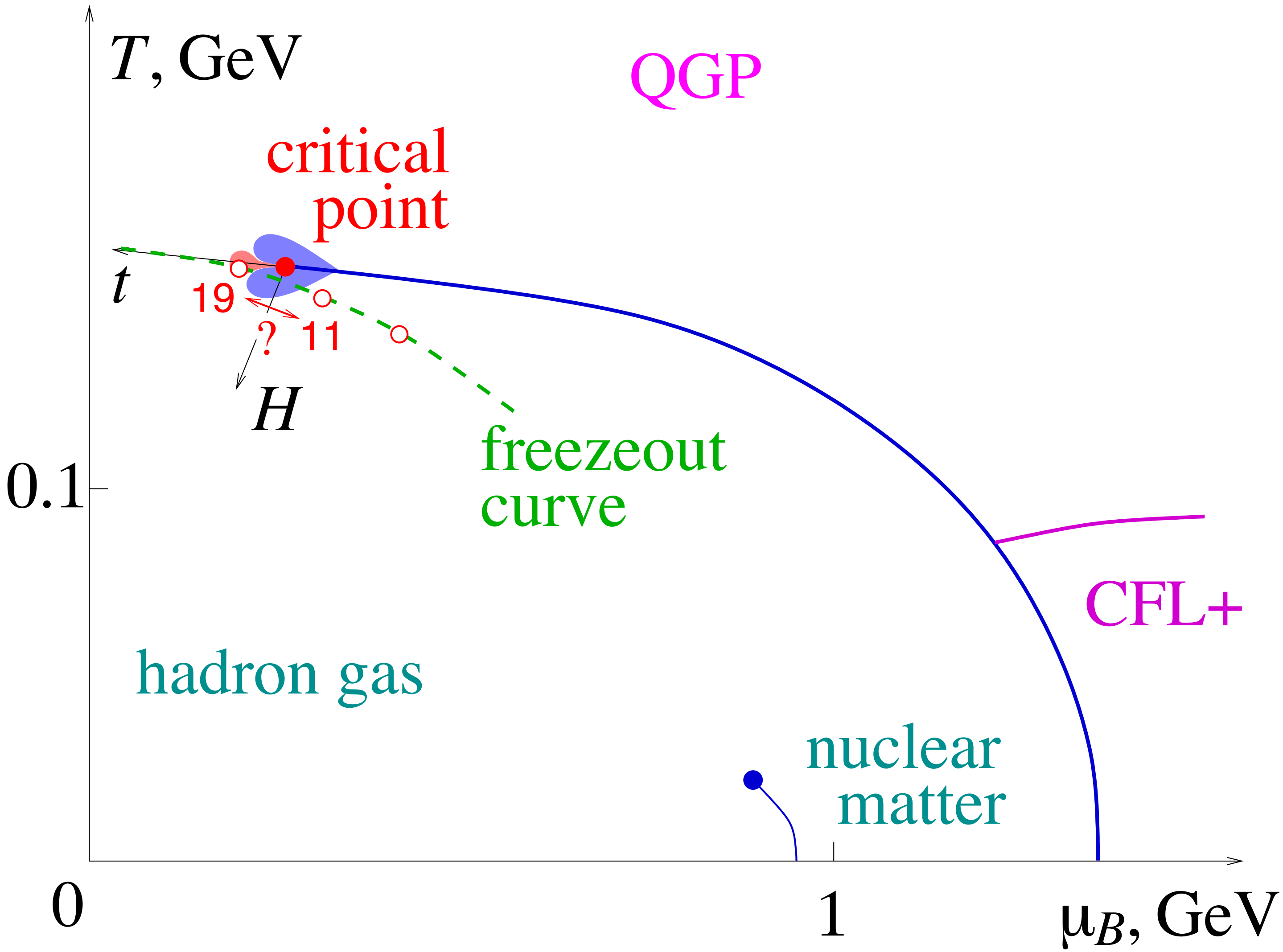

- If the kurtosis stays significantly below Poisson value in 19 GeV data, the logical place to take a closer look is between 19 and 11 GeV.

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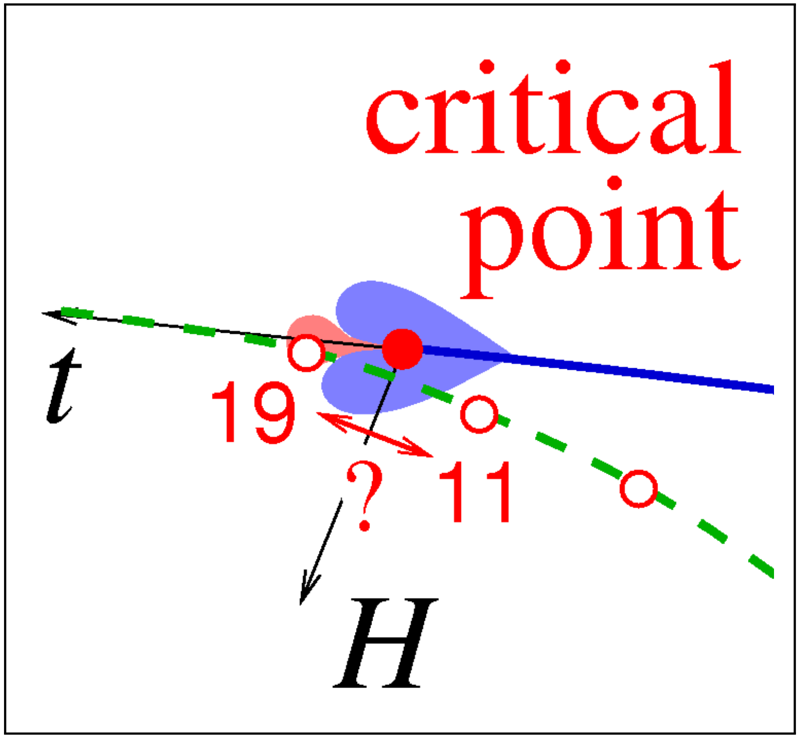

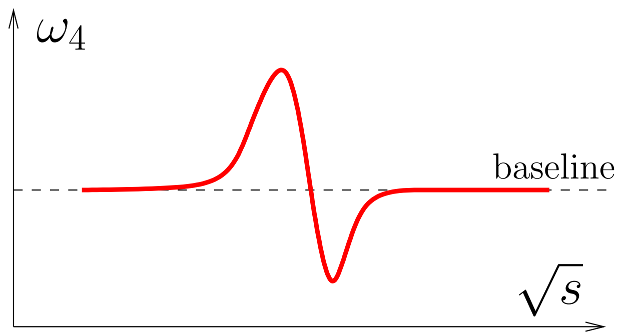

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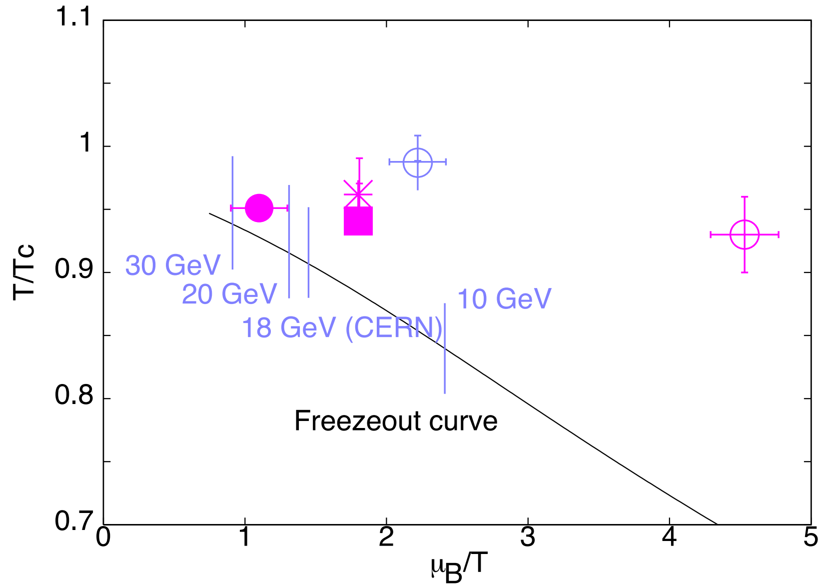
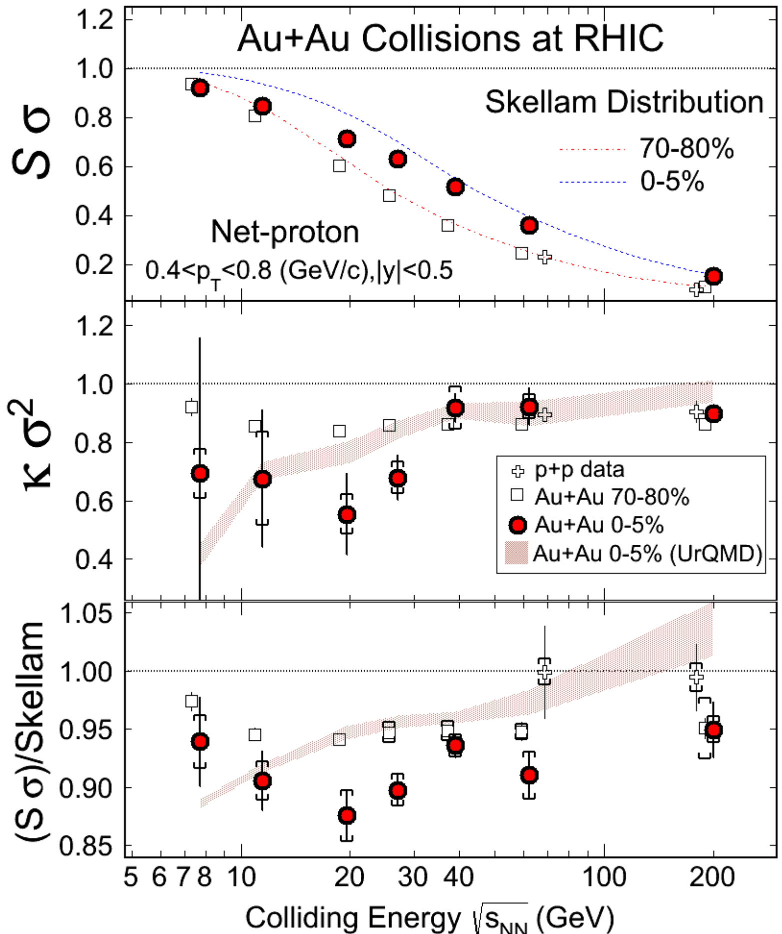
Latest Lattice Calculations. . .



Datta, Gavai and Gupta, 1210.6784

Lattice calculations remain challenging. 'Systematic errors' in methods used by various groups hard to estimate. To their credit, Datta, Gavai and Gupta have stuck their necks out: in their calculations with their two finer lattice spacings, they report evidence for a critical point at μ_B/T, corresponding to where RHIC has just finished taking data.

Early RHIC Energy Scan Data



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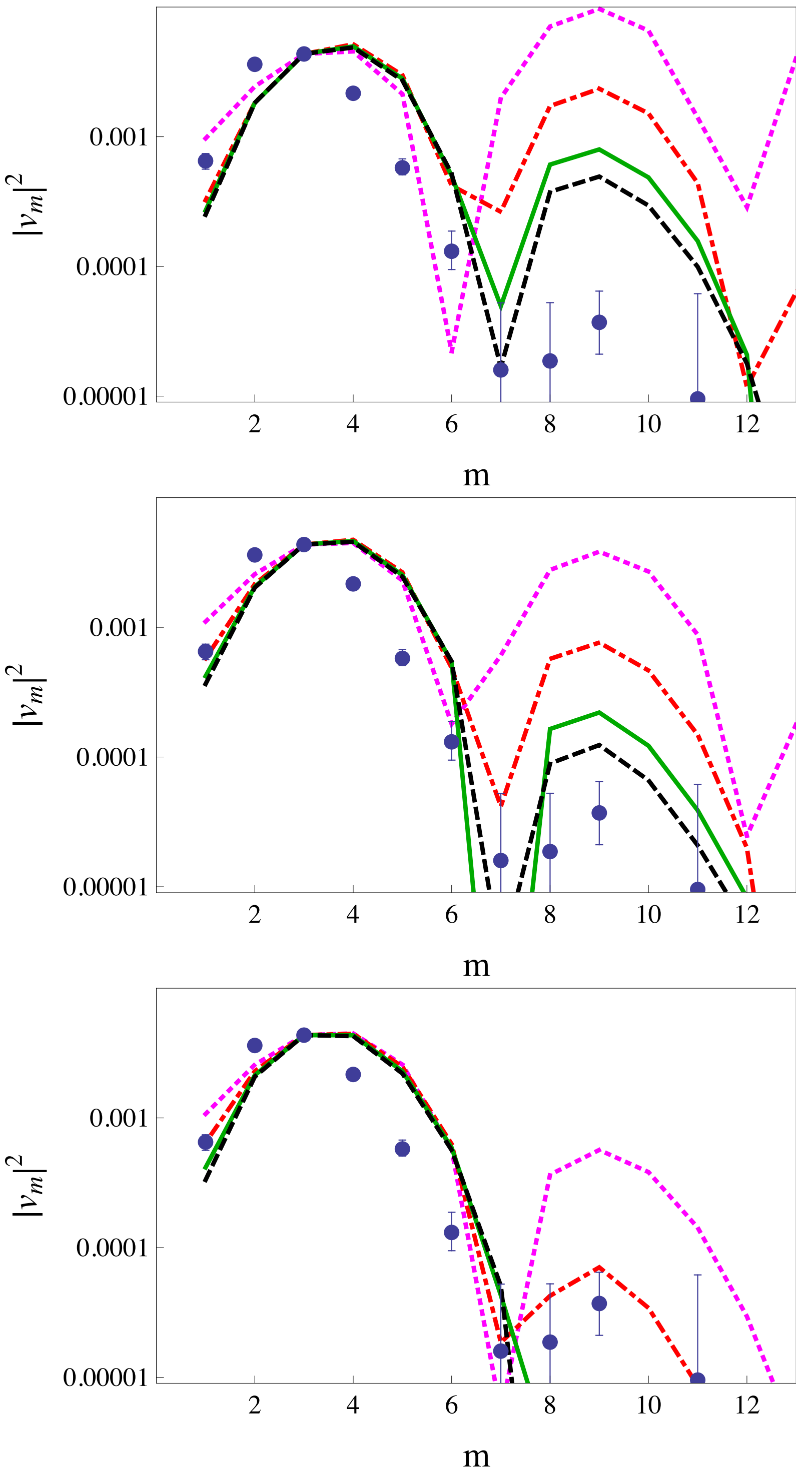
Future: electron cooling $\rightarrow \times 10$ **statistics at low** $\sqrt{s}$**.**

Stay Tuned...

Liquid QGP at LHC and RHIC. New data (v_n at RHIC and LHC; 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. Photon+jet. 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...

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

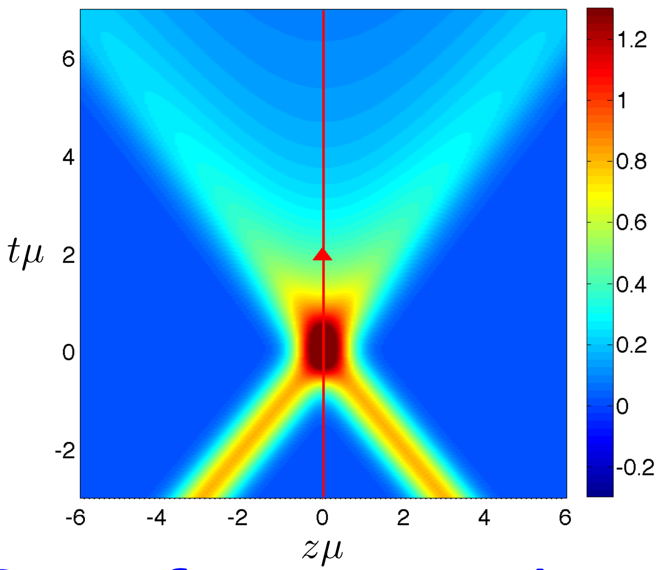


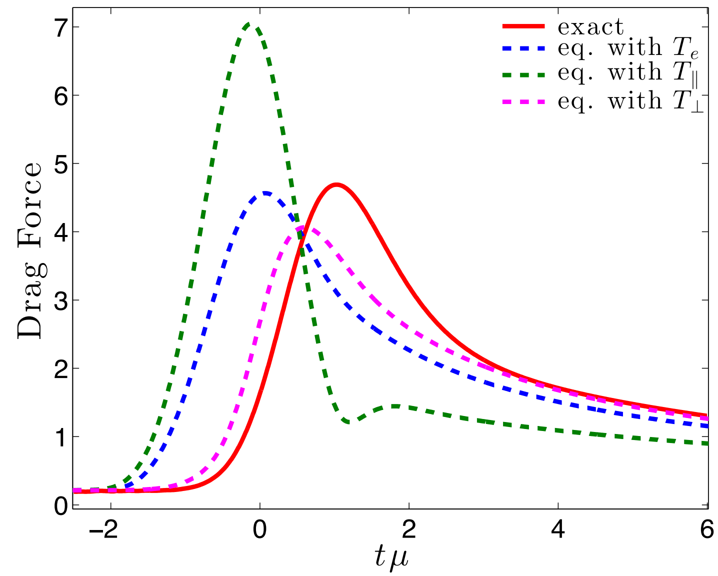
- Analytic calculation of "shape" of v_n's in a simplified geometry with small fluctuations of a single size.
- Panels, top to bottom, are for fluctuations with size 0.4, 0.7 and 1 fm.
- Colors show varying η/s, with magenta, red, green, black being η/s =0, 0.08, 0.134, 0.16.
- Evidently, higher harmonics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

Staig, Shuryak, 1105.0676

Heavy Quark Energy Loss, Far-from-Equilibrium

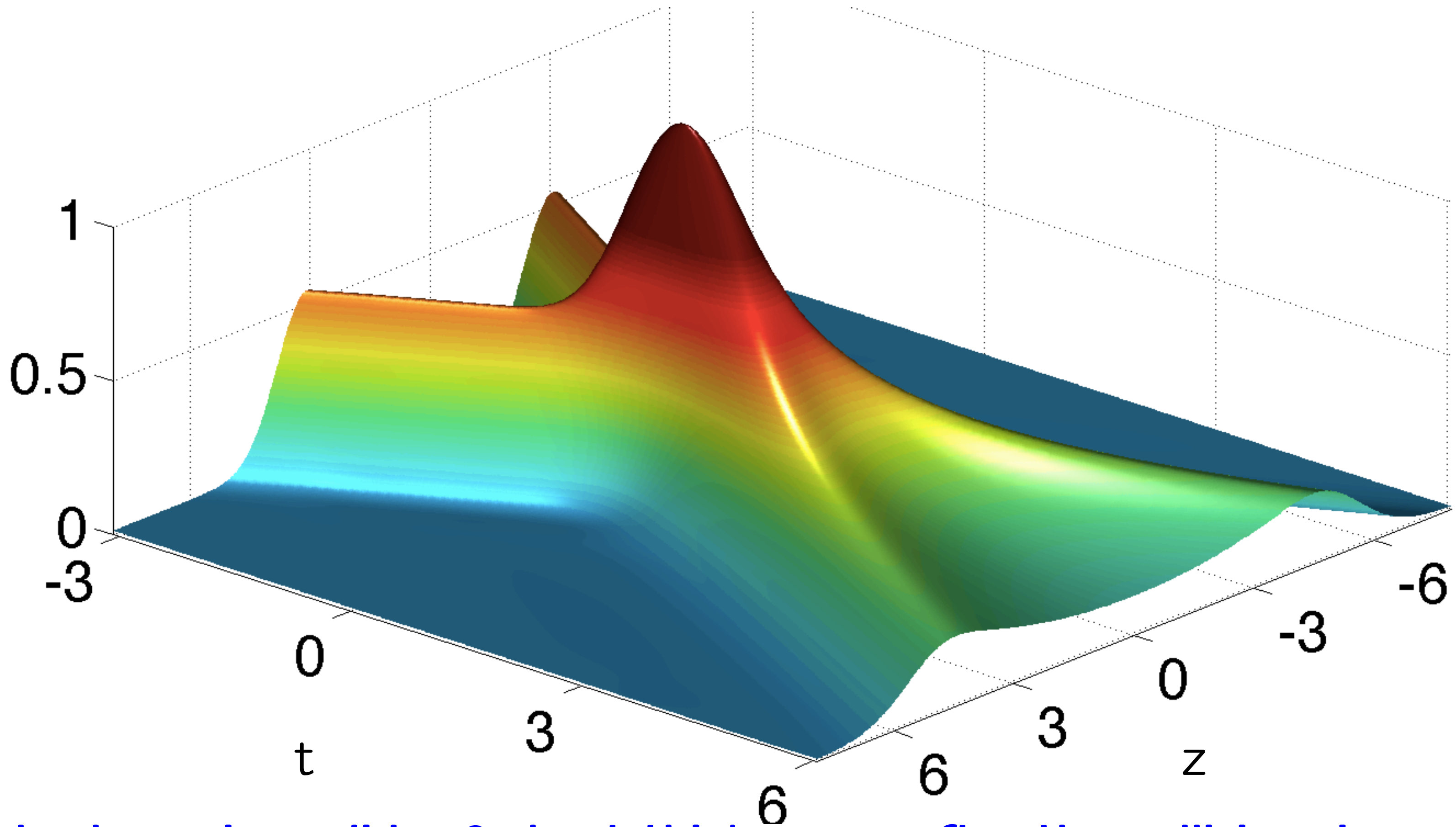
Chesler, Lekaveckas, Rajagopal 1306.0564





- Drag force on a heavy quark moving with $\beta = 0.95c$ through far-from-equilibrium matter, and then anisotropic fluid, made in the collision of two sheets of energy.
- Eqbm plasma with same instantaneous $\mathcal{E}$ provides a reasonable guide to magnitude, but there is a time delay.
- Surprises at nonzero rapidity (not shown).
- Guidance for modeling heavy quark energy loss early in a heavy ion collision.

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

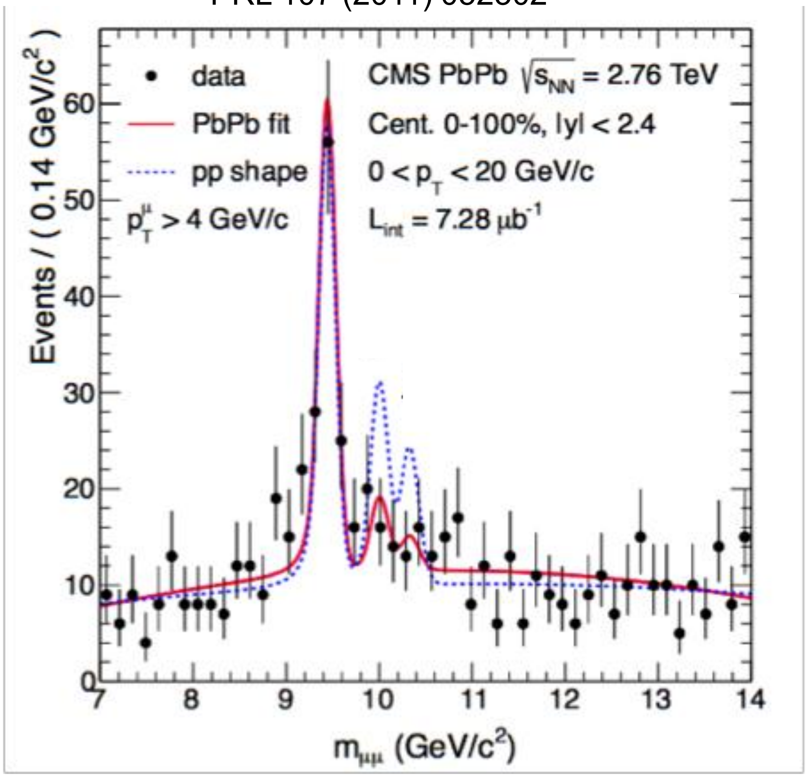
Heavy quarks? Upsilons?

- **Heavy quarks are 'tracers', dragged along by and diffusing in the liquid. Diffusion constant tells you about the medium, complementary to η/s. Holographic calculations indicate the heavy quarks should 'go with the flow'.**
- **If very energetic heavy quarks interact with strongly coupled plasma as holographic calculations indicate, which is to say like a bullet moving through water, b and c quark energy loss is same for quarks with same *velocity*. Quite different than weakly coupled expectations, where both γ and M matter. Want to study b and c quark energy loss vs. momentum. Data on identified b and c quarks coming soon, at RHIC via upgrades being completed.**
- **Upsilons probe plasma on different length scales. 1S state is very small. 3S state is the size of an ordinary hadron. They "melt" (due to screening of $b - \bar{b}$ attraction) at different, momentum-dependent (cf holographic calculations), temperatures. This story is just beginning. Stay tuned.**

Sequential Upsilon suppression

2010 data

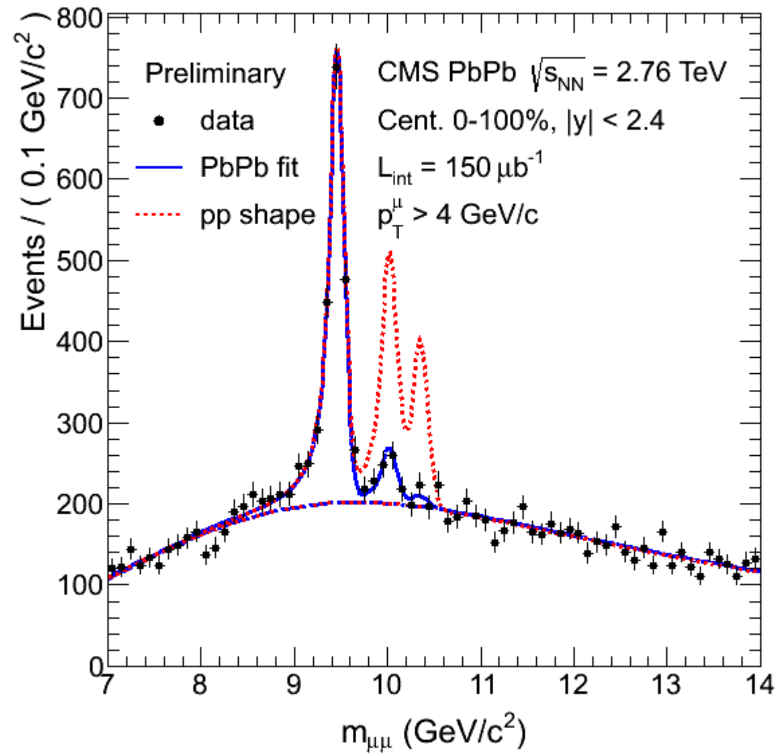
PRL 107 (2011) 052302



Indication of suppression of (Y(2S)+Y(3S)) relative to Y(1S)

→2.4σ significance

2011 data



Observation of sequential suppression of Y family

→Detailed studies

QCD Sphalerons + Anomaly + $\vec{B}$?

- In QGP, QCD sphalerons should be unsuppressed, with a rate per unit volume $\propto \text{const}\, T^4$. Excess R quarks in one event. Excess L quarks in the next. [Both weak and strong coupling estimates suggest const $\sim$ few percent.]

- Chiral anomaly can be written

$$\vec{j}_V = \frac{N_c e}{2\pi^2} \mu_A \vec{B}$$

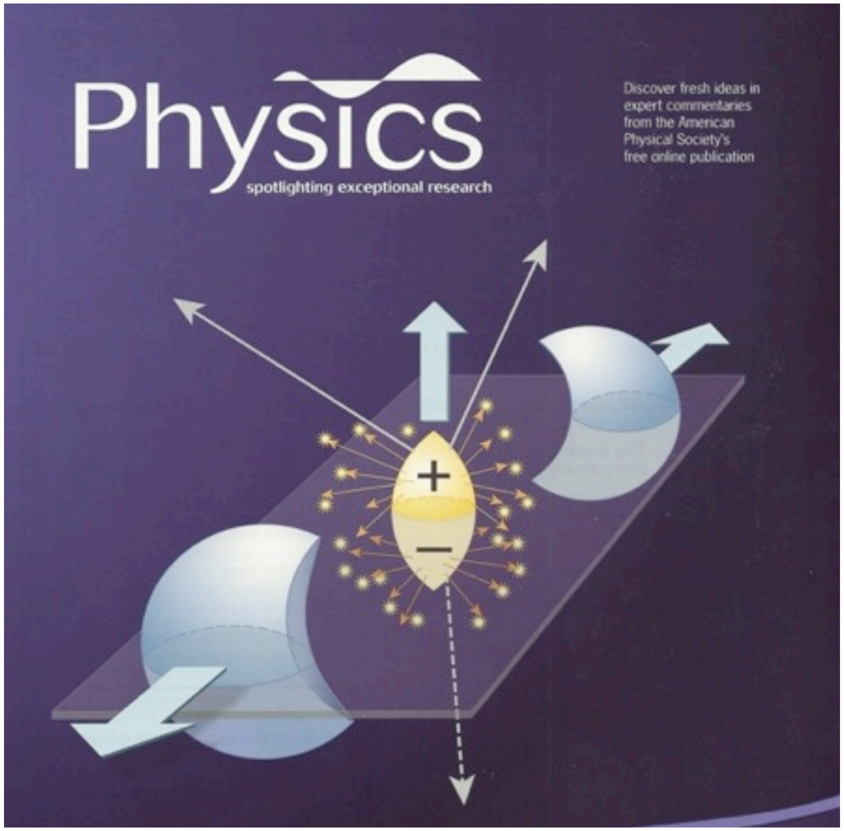
  so, in the presence of a magnetic field, an excess of R quarks (ie $\mu_A > 0$) results in an electric current!

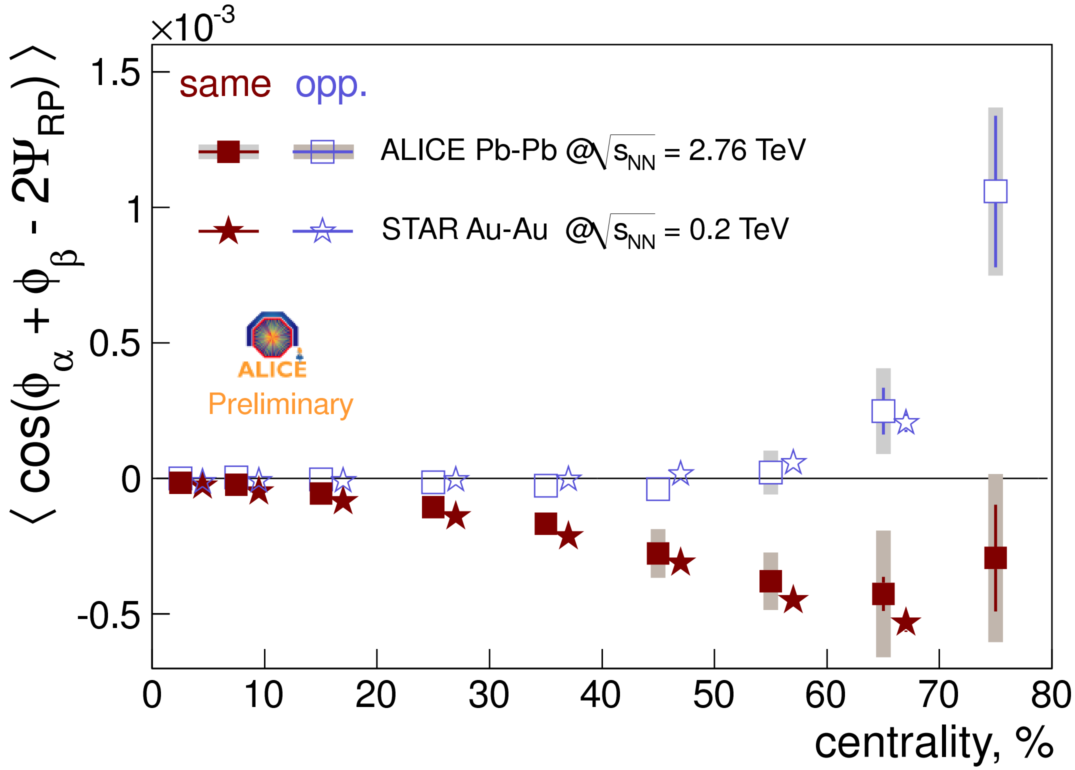
- Spectator nuclei create $B \sim 10^{18-19}$ gauss in top energy RHIC collisions with decent impact parameter. At LHC, larger B, but it lasts for a shorter time.

- So, Kharzeev et al predicted charge-separation, event-by-event parity violation.

- My a priori reaction, and that of many: reality will bite.

Searching for the Chiral Magnetic Effect





Does Reality Bite?

- **A clear signal, first at STAR then ALICE, in an observable that *could* indicate event-by-event charge separation.**

- **BUT: this observable could instead indicate novel, but prosaic, hadron-gas physics. Tendency for opposite-sign hadrons to be near each other, plus v_2, can "fake" this.**

- **So, turn off QGP, keep v_2, and see whether the effect goes away... It does!**

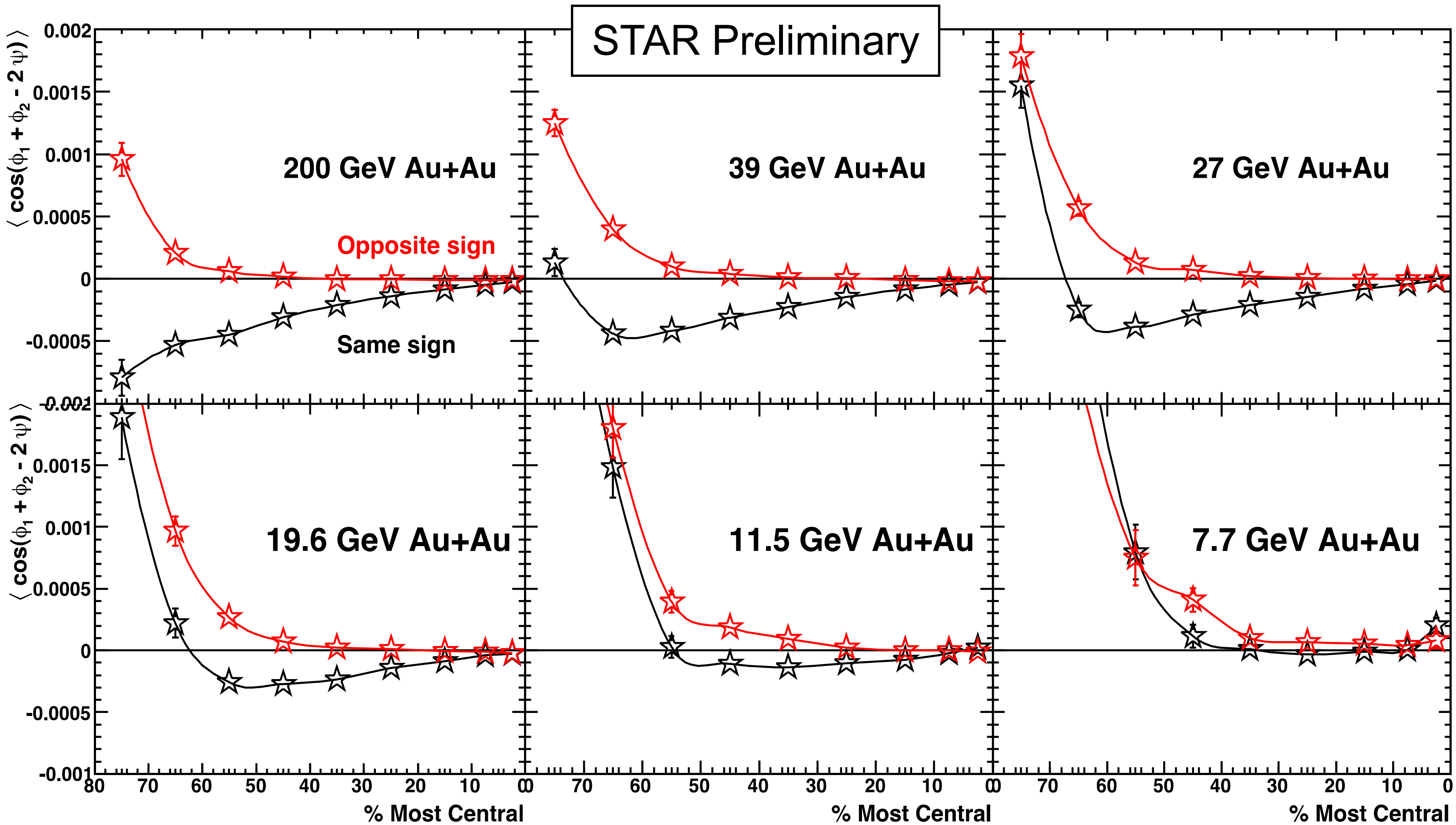
- **So, turn off $\vec{B}$, keep v_2 [by colliding U-U, side-on-side] and see whether the effect goes away... It does!**

- **And, most remarkably, look for a different manifestation of the chiral anomaly one that requires $\vec{B}$, QGP, v_2 and a nonzero electric charge density:**

$$\vec{j}_A = \frac{N_c e}{2\pi^2} \mu_V \vec{B} \qquad\qquad \vec{j}_V = \frac{N_c e}{2\pi^2} \mu_A \vec{B}$$

Select events with nonzero charge density, and look for...

Disappearance of Charge Separation w.r.t. EP



Wang, IVB, Thu.

- Motivated by search for local parity violation. Require sQGP formation.
- The splitting between OS and LS correlations (charge separation) seen in top RHIC energy Au+Au collisions.

This charge separation signal disappears at lower energies (<= 11.5 GeV)!

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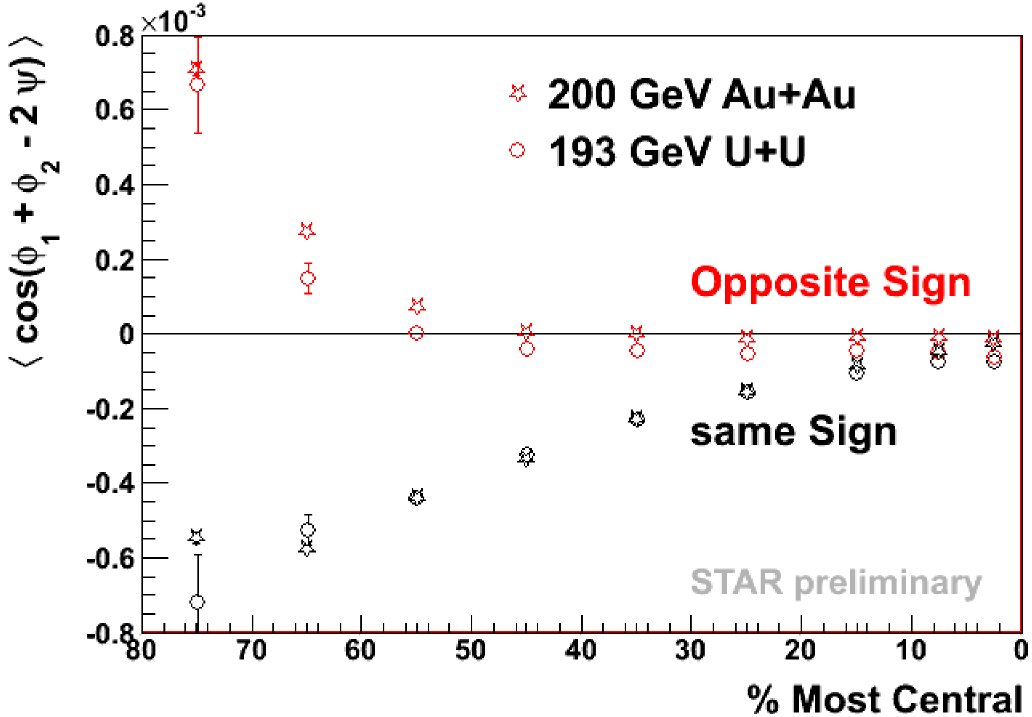
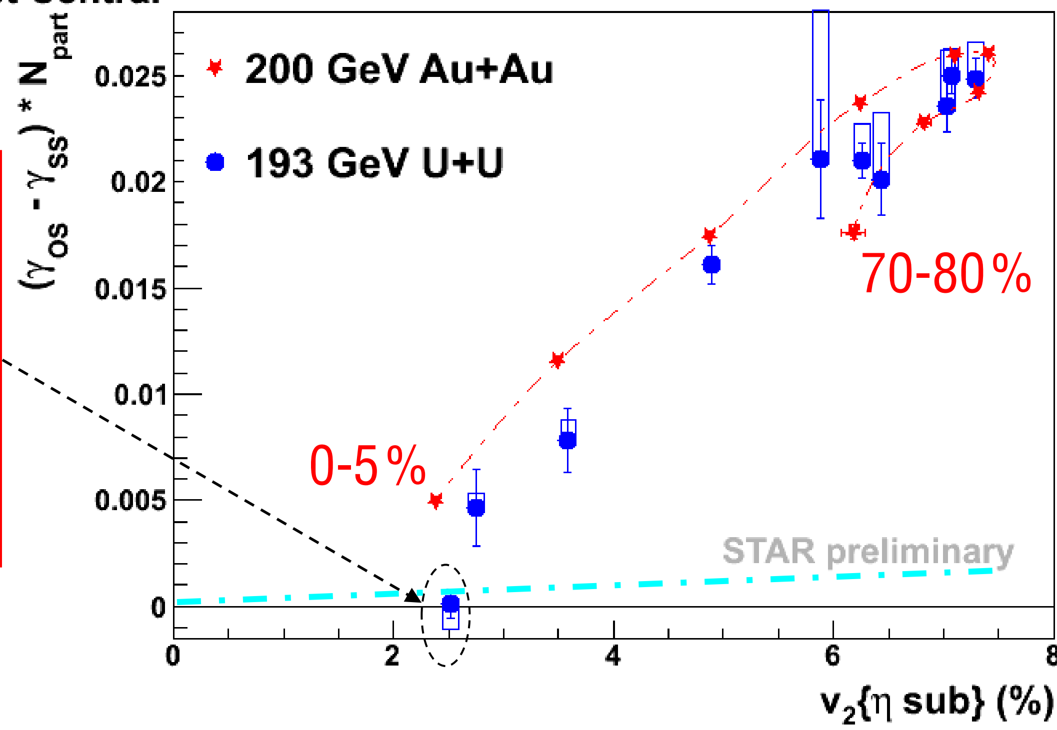
LPV in U+U



- The difference between OS and SS is still there in U+U, with similar magnitudes.
- Consider OS-SS to be the signal
- N_{part} accounts for dilution effects

- A dedicated trigger selected events with 0-1% spectator neutrons.
- With the magnetic field suppressed, the charge separation signal disappears (while v_2 is still ~ 2.5%).



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- **BUT: this observable could instead indicate novel, but prosaic, hadron-gas physics. Tendency for opposite-sign hadrons to be near each other, plus v_2, can "fake" this.**

- **So, turn off QGP, keep v_2, and see whether the effect goes away... It does!**

- **So, turn off $\vec{B}$, keep v_2 [by colliding U-U, side-on-side] and see whether the effect goes away... It does!**

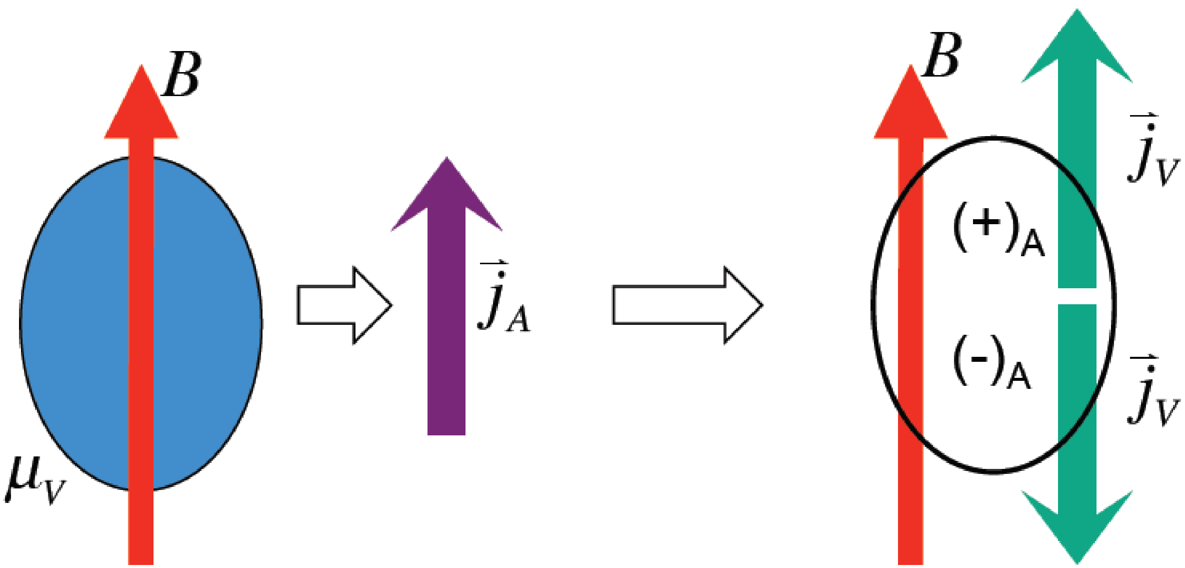
- **And, most remarkably, look for a different manifestation of the chiral anomaly one that requires $\vec{B}$, QGP, v_2 and a nonzero electric charge density:**

$$\vec{j}_A = \frac{N_c e}{2\pi^2}\mu_V\,\vec{B} \qquad\qquad \vec{j}_V = \frac{N_c e}{2\pi^2}\mu_A\,\vec{B}$$

Select events with nonzero charge density, and look for...

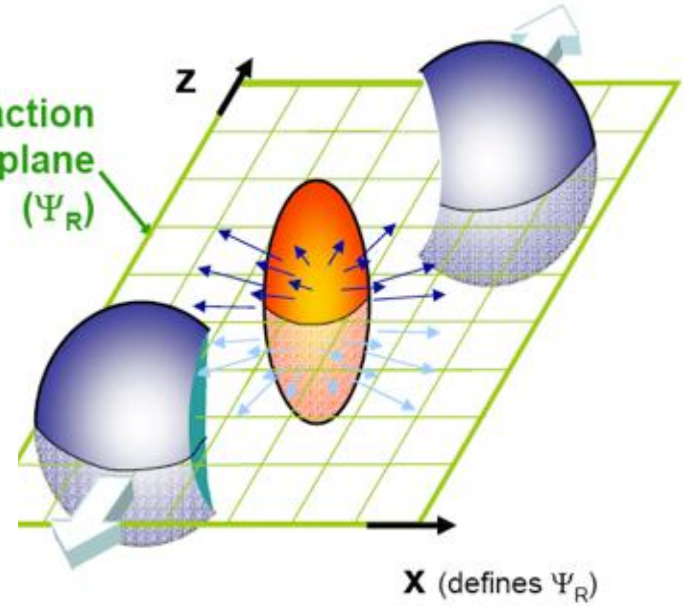
Motivation

CSE + CME → Chiral Magnetic Wave:
- collective excitation
- signature of Chiral Symmetry Restoration



$$j_A = \frac{N_c e}{2\pi^2}\mu_V B \qquad j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

Chiral Separation Effect **Chiral Magnetic Effect**

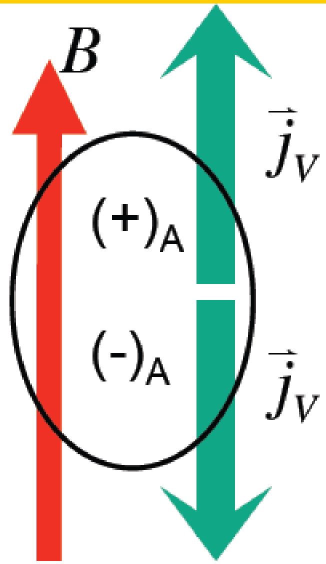


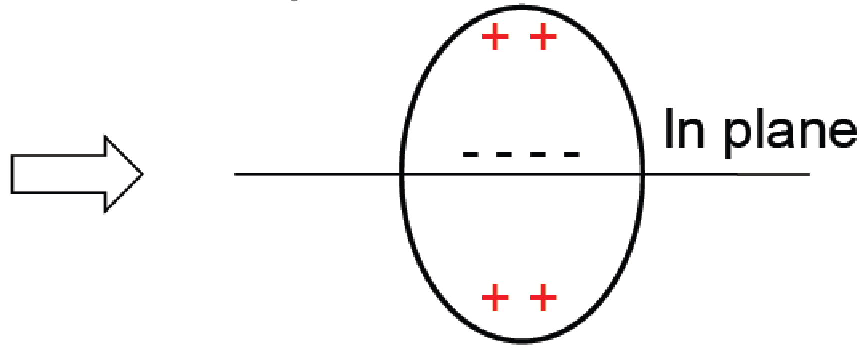
Peak magnetic field ~ 10^{15} Tesla !

(Kharzeev et al. NPA 803 (2008) 227)

Observable I

Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee,
Phys. Rev. Lett. 107, 052303 (2011)



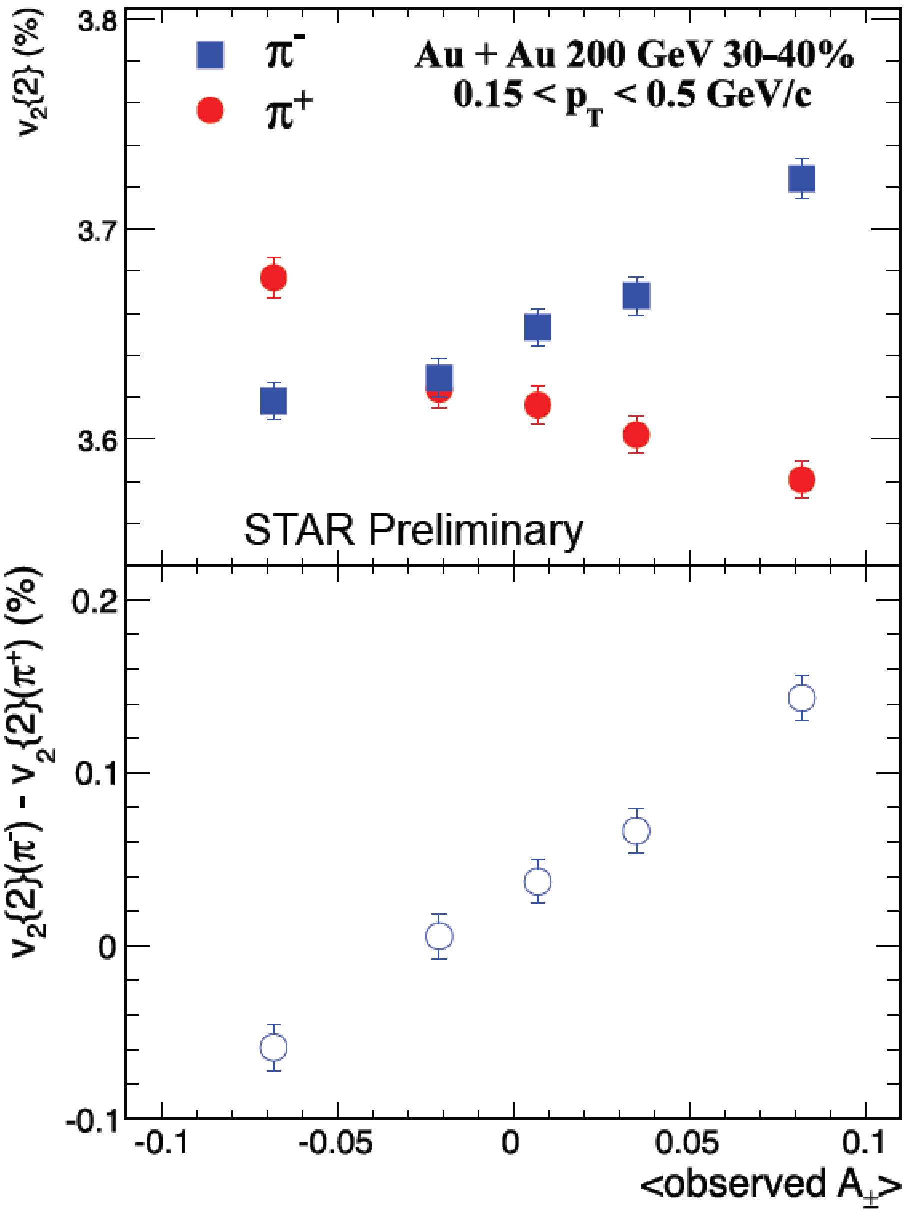


Formation of electric quadrupole: $v_2^{\pm} = v_2 \mp (\frac{q_e}{\bar{\rho}_e}) A_{\pm}$,

where charge asymmetry is defined as $A_{\pm} = \frac{\bar{N}_+ - \bar{N}_-}{\bar{N}_+ + \bar{N}_-}$.

Then π^- v_2 should have a positive slope as a function of $A_{\pm}$,
and π^+ v_2 should have a negative slope with the same magnitude.
The integrated v_2 of π^- is not necessarily bigger than π^+: (other physics)
only the $A_{\pm}$ dependency matters for CMW testing.

Charge asymmetry dependency



- v_2 was measured with the Q-cumulant method.
- Clear $A_{\pm}$ dependency
- $v_2(A_{\pm})$ slopes for $\pi^{\pm}$:
  - opposite sign
  - similar magnitude
- v_2 difference vs $A^{\pm}$ may have a non-zero intercept: other physics?

$$v_2^{\pm} = v_2 \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{\pm}$$

Sphalerons + Anomaly + $\vec{B}$?

- Macroscopic realization of a quantum anomaly! Chiral symmetry restored!

- Sphalerons, the same gauge theory dynamics whose $SU(2)$ incarnation may be responsible for the matter-antimatter excess in the universe — via either leptogenesis or electroweak baryogenesis — subject to experimental investigation!! (Impossible any other way.)

- Sounds too good to be true. And, when more prosaic explanations were posited after the initial discovery, reality seemed to be intervening.

- But, this story has made three subsequent predictions, all of which are now seen. In two cases, only very recently meaning that confirmation and scrutiny are needed. And, much more quantitative modelling. But, it is hard to see how the prosaic can strike back.

Stay Tuned...

Liquid QGP at LHC and RHIC. New data (v_n at RHIC and LHC; 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. Photon+jet. 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...

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

And, maybe, sphaleron dynamics manifest in the laboratory...

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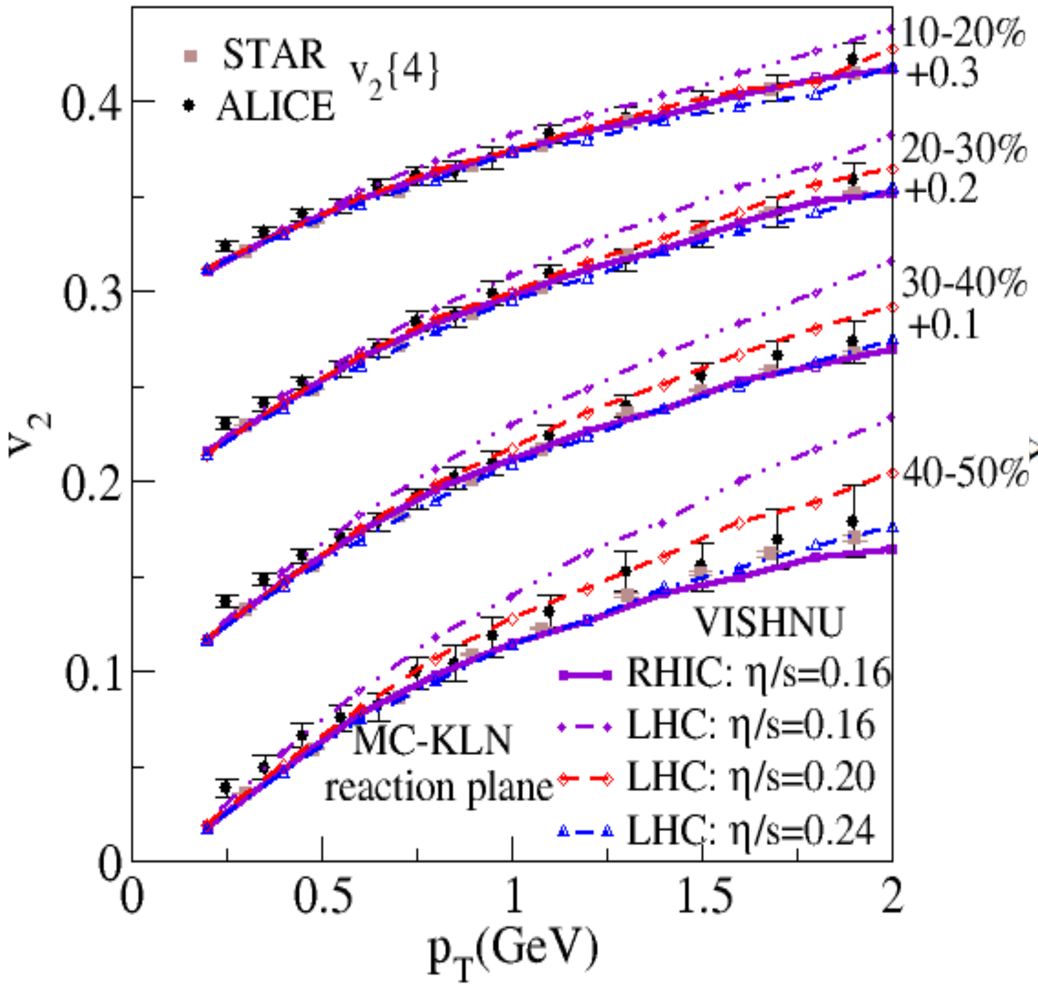
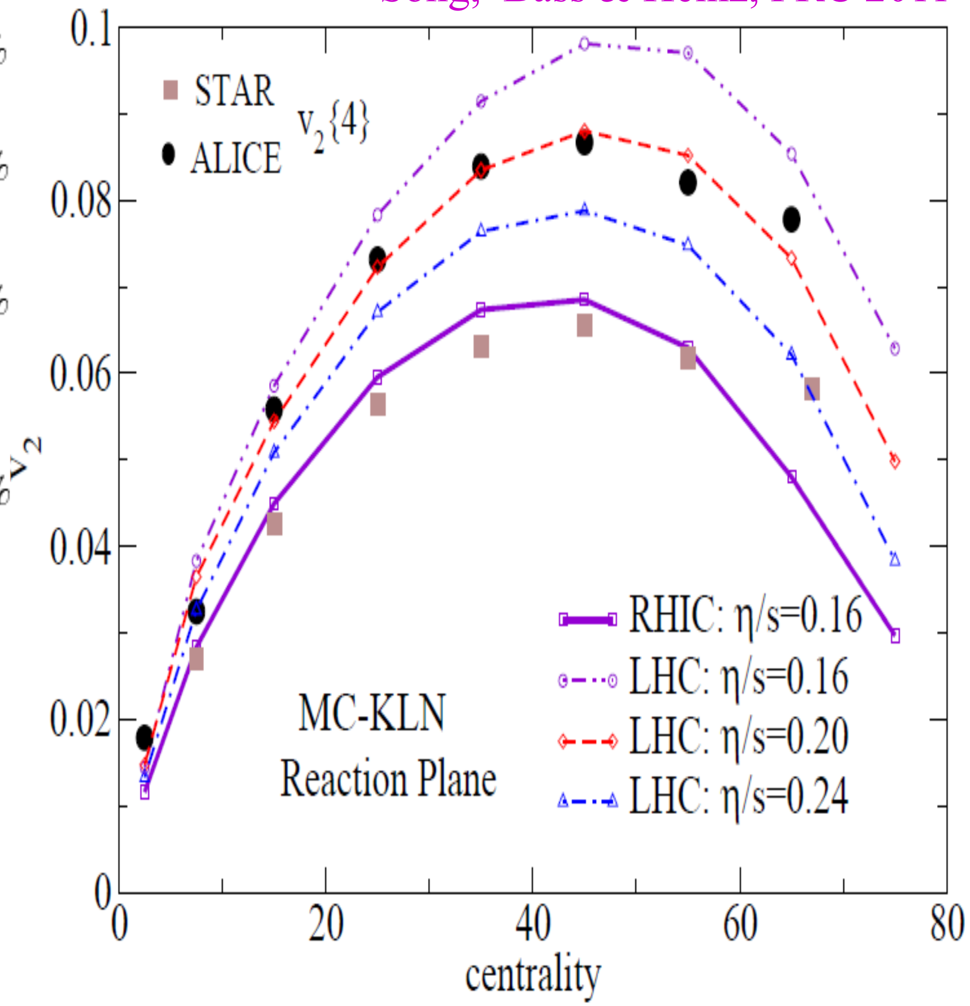
V_2 at RHIC and LHC

Song, Bass & Heinz, PRC 2011



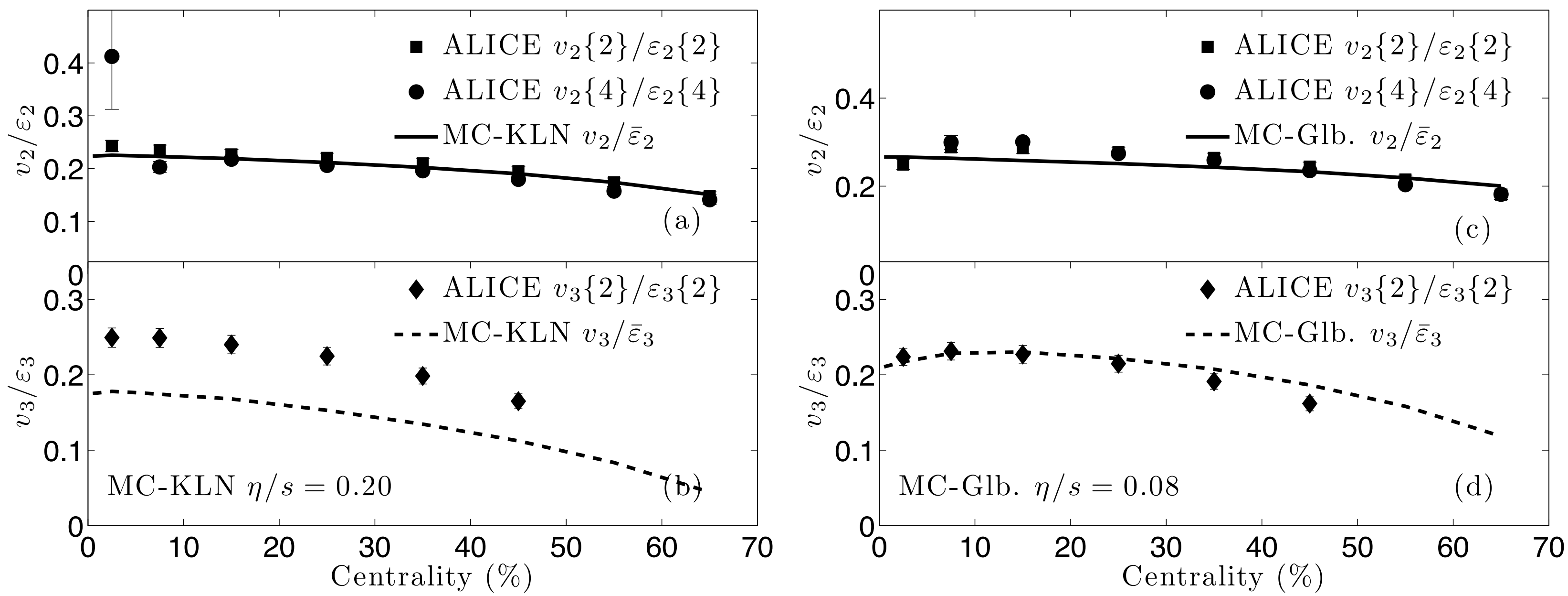


The average QGP viscosity is roughly the same at RHIC and LHC

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 $v_{3...6}$ 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 ...

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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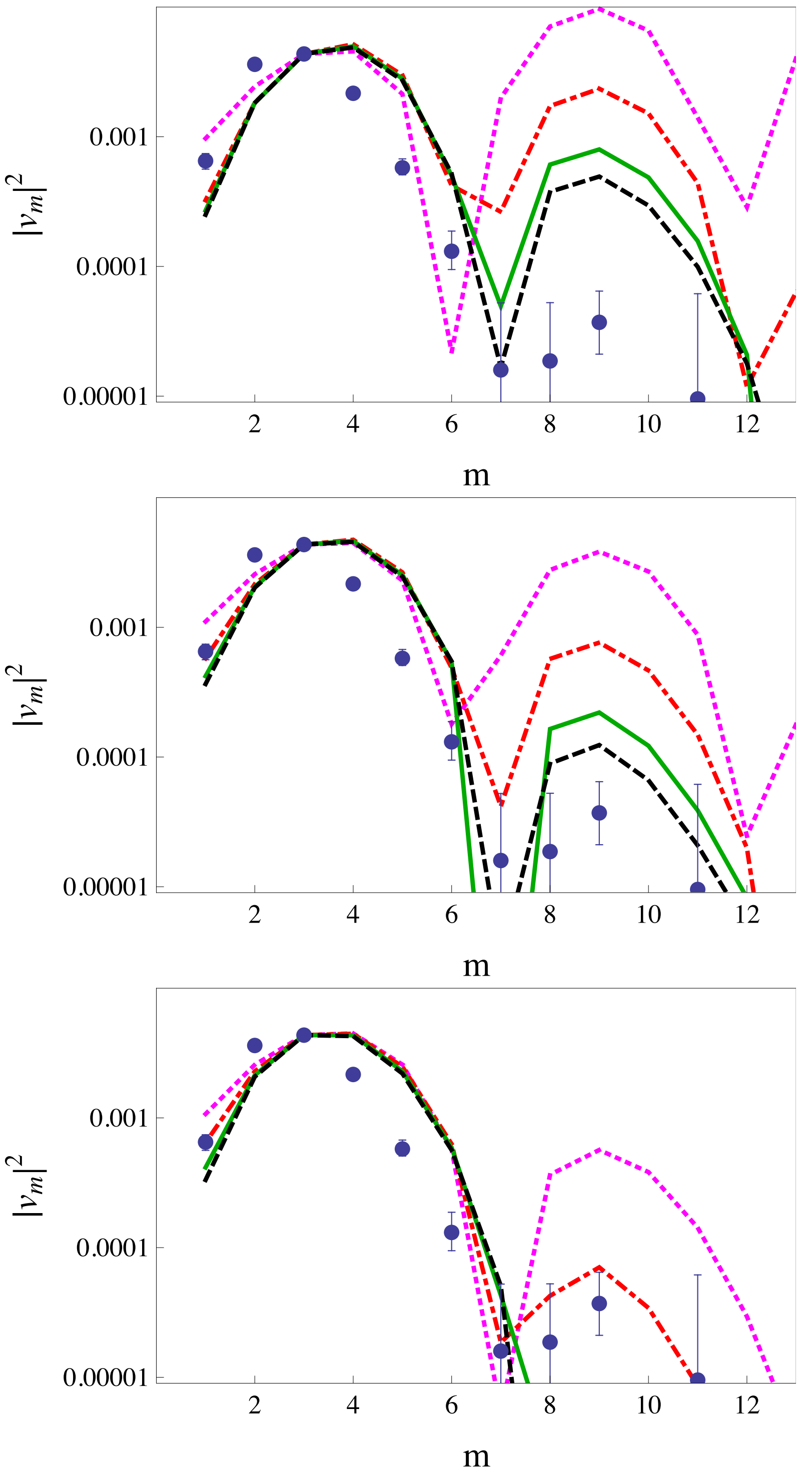


- Analytic calculation of "shape" of v_n's in a simplified geometry with small fluctuations of a single size.
- Panels, top to bottom, are for fluctuations with size 0.4, 0.7 and 1 fm.
- Colors show varying η/s, with magenta, red, green, black being η/s =0, 0.08, 0.134, 0.16.
- Evidently, higher harmonics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

Staig, Shuryak, 1105.0676

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

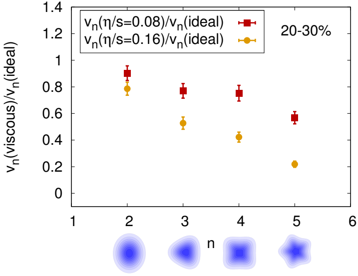
After Cooper-Frye freeze-out and resonance decays in each event we compute

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

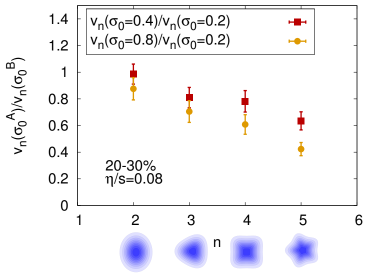
with the event-plane angle $\psi_n = \frac{1}{n} \arctan \frac{\langle \sin(n\phi) \rangle}{\langle \cos(n\phi) \rangle}$

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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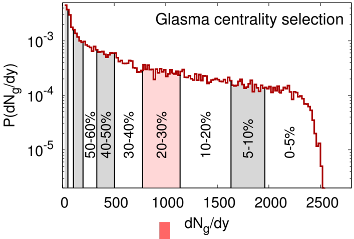
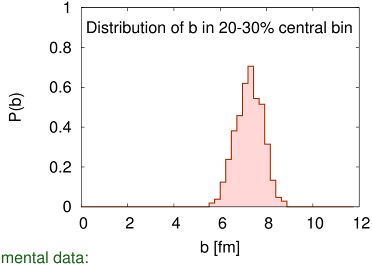
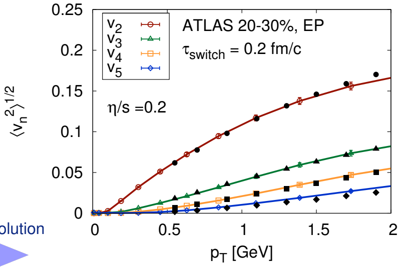
Centrality selection and flow

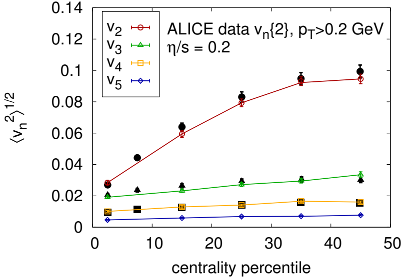




Hydro evolution

MUSIC



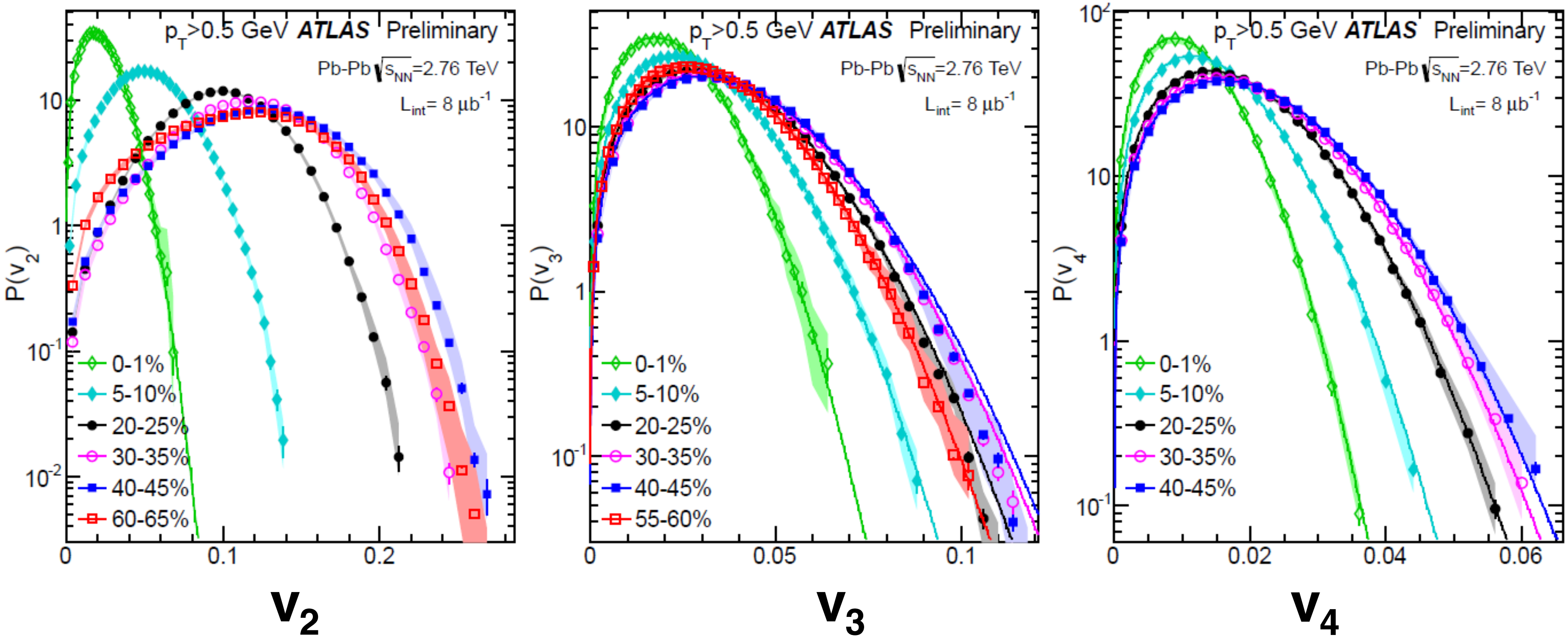


Experimental data:

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

ALICE collaboration, Phys. Rev. Lett. 107, 032301 (2011)

Unfolded v_2, v_3 and v_4 Distributions

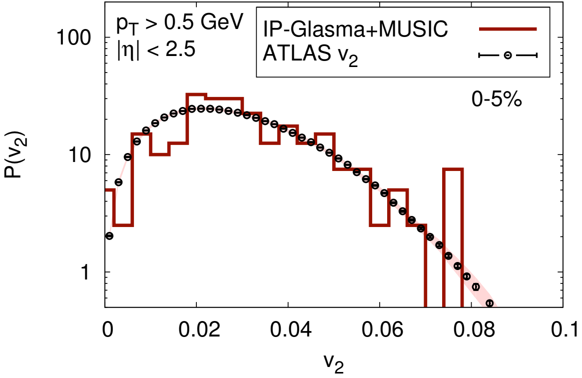


- v_n distributions normalized to unity for n = 2,3 and 4
- Lines represent radial projections of 2D Gaussians, rescaled to $\langle v_n \rangle$
  - for v_2 only in the 0-2% of most central collisions
  - for v_3 and v_4 over all centralities

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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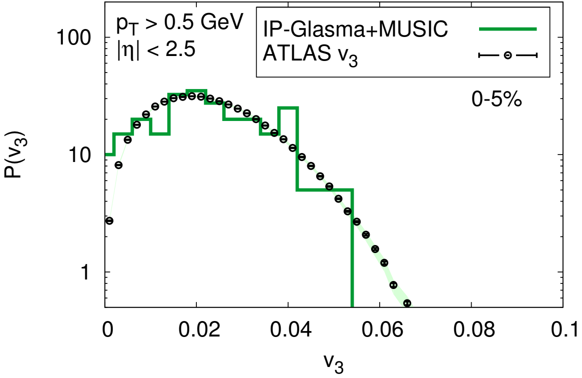

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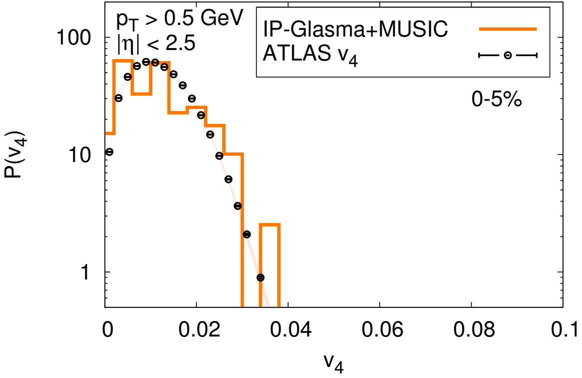

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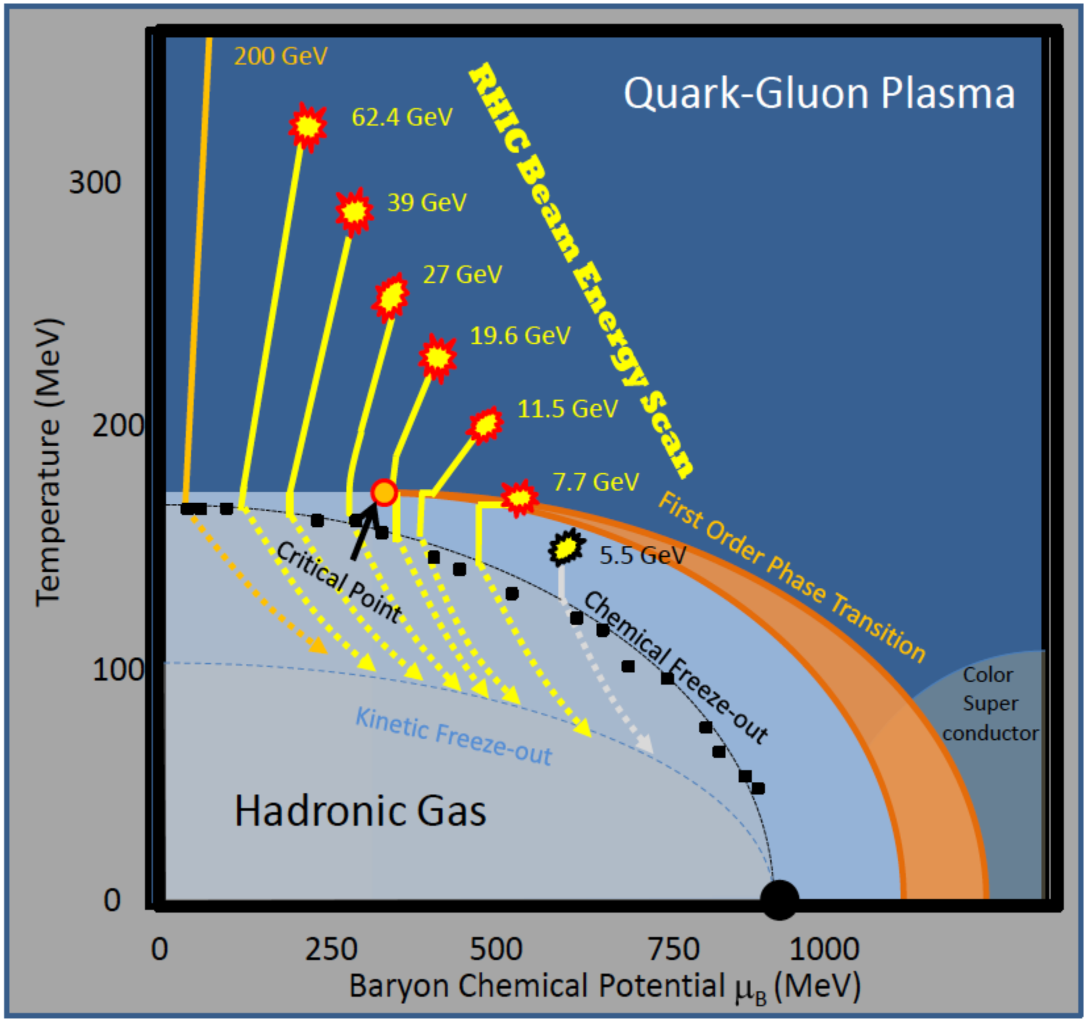
Beam Energy Scan



Kumar, VA, Fri.

0) Turn-off of sQGP signatures

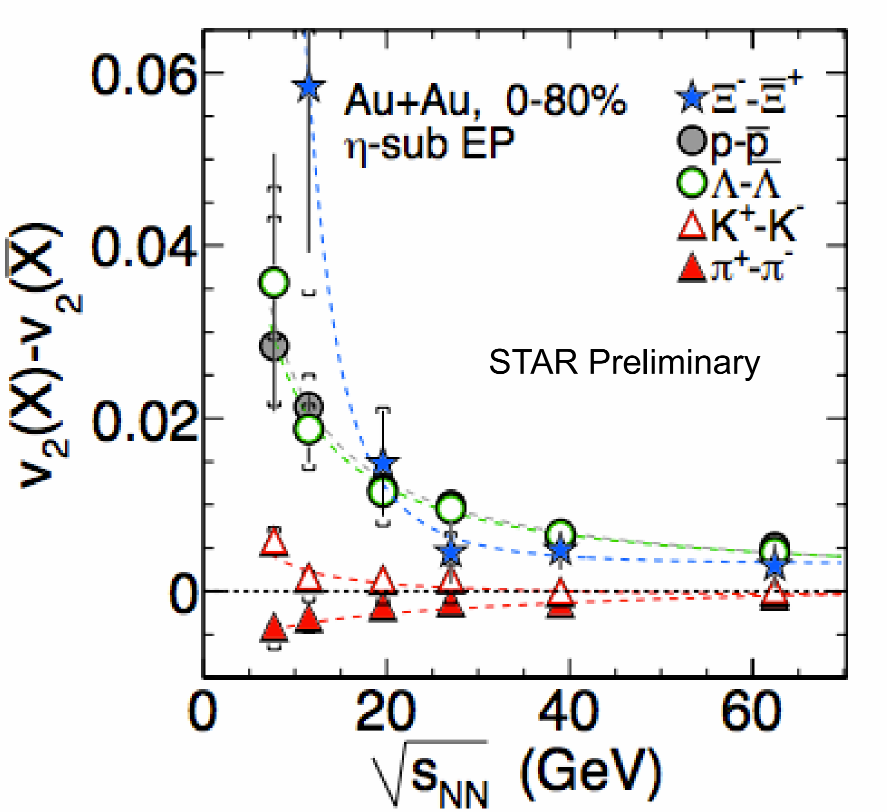
1) Search for the signals of phase boundary

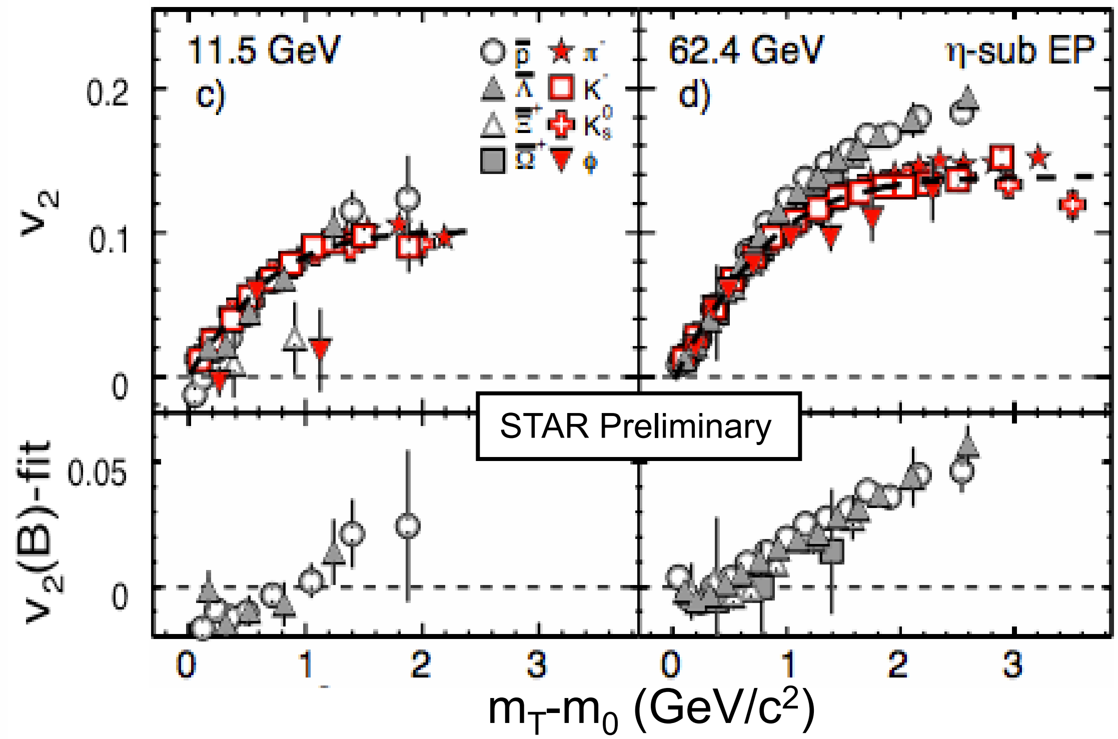
2) Search for the QCD critical point

BES Phase-I

Year	$\sqrt{s_{NN}}$ (GeV)	Events (10^6)
2010	39	130
2011	27	70
2011	19.6	36
2010	11.5	12
2010	7.7	5

Breakdown of NCQ-scaling



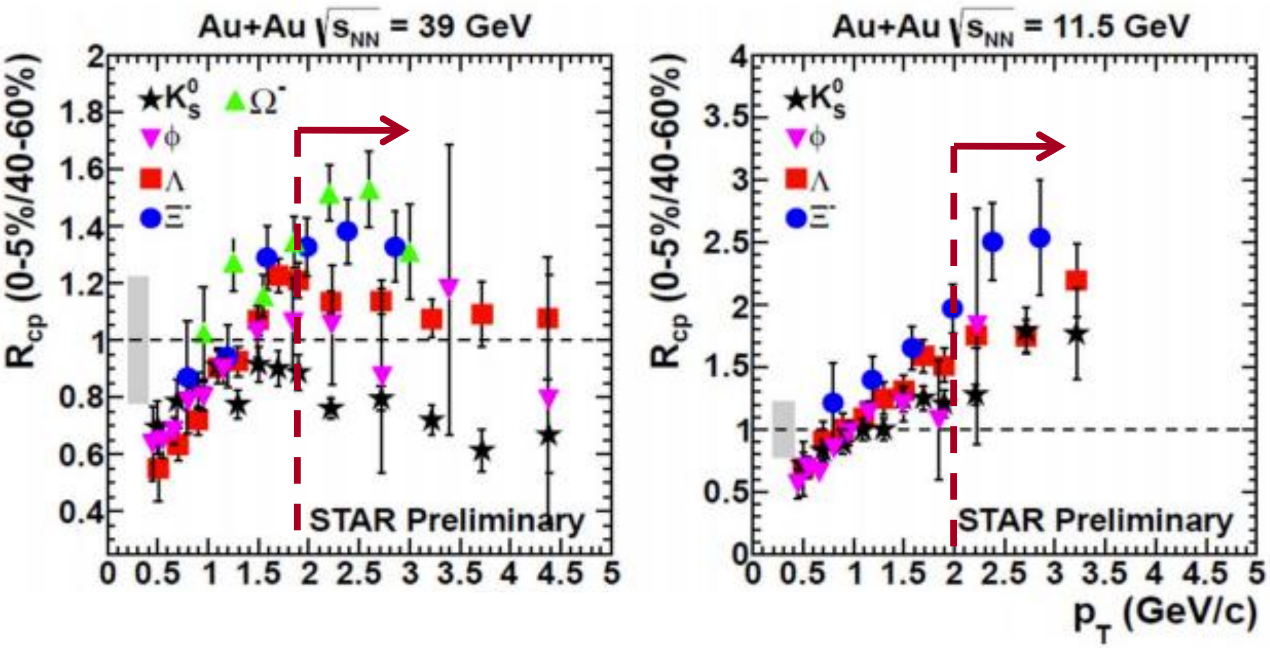


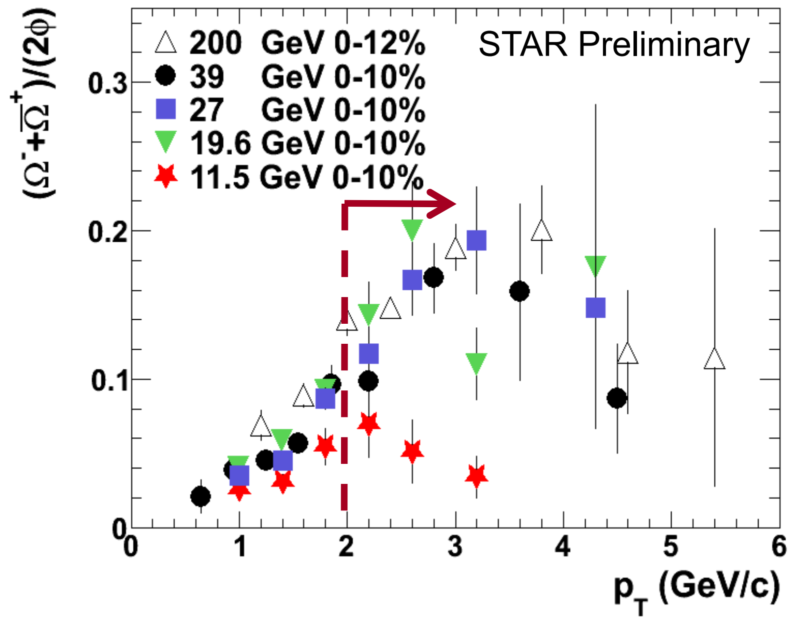
- Significant difference between baryon-antibaryon v_2 at lower energies.
- No clear baryon/meson grouping for anti-particles at <=11.5 GeV.

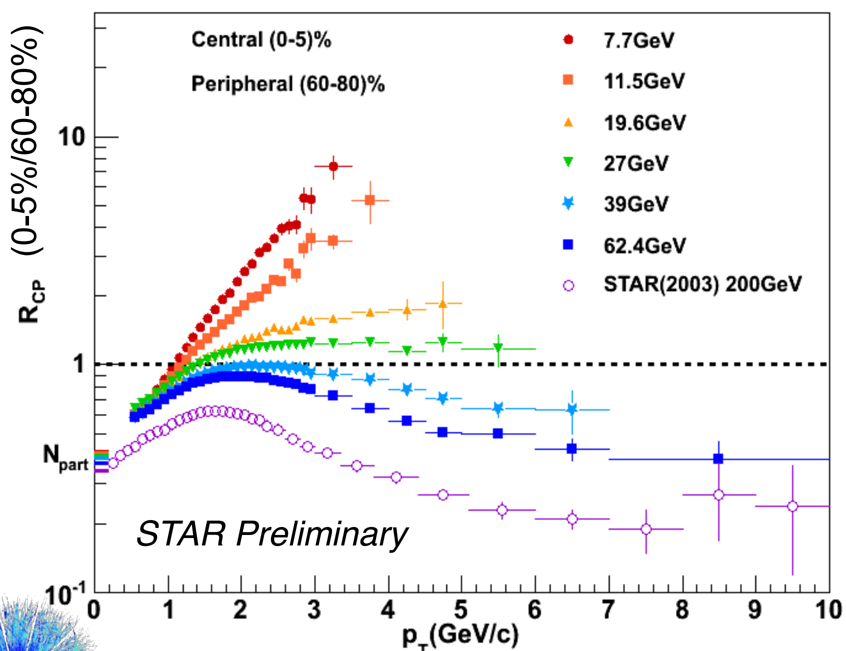
NCQ scaling is broken!

Shi, 6B, Fri; Schmah, poster #141

Disappearance of R_{cp} Suppression







- Baryon-meson splitting reduces and disappears with decreasing energy.
- Ω/ϕ ratio falls off at 11.5 GeV.

- R_{cp} >~ 1 at 11.5, 7.7 GeV. - Cronin effect?

R_{cp} suppression NOT seen at lower energies!

Zhang, 5A, Thu. Sangaline, 5C, Thu. Horvat, poster #94

HOW TO CALCULATE PROPERTIES OF STRONGLY COUPLED QGP LIQUID?

① LATTICE QCD
- perfect for THERMODYNAMICS (ie static properties)
- calculation of η, and other transport coefficients, beginning
- jet quenching and other dynamic properties not in sight

② PERTURBATIVE QCD
- right theory but wrong approximation

③ Calculate QGP properties in other theories that are analyzable at strong coupling.
- Are some dynamical properties universal? I.e. same for strongly coupled plasmas in a large class of theories. What properties? What class of theories?

UNIVERSALITY?

Is there a new notion of universality for strongly coupled, (nearly) scale invariant LIQUIDS?

To what systems does it apply?

- quark-gluon plasma dual to string theory + black hole
- QCD quark-gluon plasma?
- gas of fermionic atoms in the unitary (strongly coupled and scale invariant) regime

To what quantities does it apply?

- η/s ?
- other suggestions on the QCD side relate to "JET QUENCHING"......

$\mathcal{N}=4$ Supersymmetric Yang Mills

- A gauge theory specified by two parameters: N_c and $g^2 N_c \equiv \lambda$.
- Conformal. (λ does not run.)
- If we choose λ large, at $T \neq 0$ we have a strongly coupled plasma.
- This 3+1 dimensional gauge theory is equivalent to a particular string theory in a particular spacetime: $\underbrace{AdS_5}_{4+1 \text{ "big" dimensions}} \times \underbrace{S_5}_{}$ → 5 "curled up" dim.
- In the $N_c \to \infty$, $\lambda \to \infty$ limit, the string theory reduces to classical gravity. ∴ calculations easy at strong coupling.

AdS/CFT

We now know of infinite classes of different gauge theories whose quark-gluon plasmas:

- are all equivalent to string theories in higher dimensional spacetimes that contain a black hole
- all have

$$\frac{\varepsilon}{T^4} = \frac{3}{4}\left(\frac{\varepsilon}{T^4}\right)_0$$

Gubser Klebanov Tseytlin Peet....

$$\eta/s = \frac{1}{4\pi}$$

Son Policastro Starinets Kovtun Buchel Liu ....

in the limit of strong coupling and large number of colors.

[Not known whether QCD in this class.]

AdS / CFT

Maldacena; Witten; Gubser Klebanov Polyakov; ....

N = 4 SYM is equivalent to Type IIB String theory on $\underbrace{AdS_5}_{4+1 \text{ "big" dimensions}} \times \underbrace{S_5}_{5 \text{ curled up dimension}}$

Translation Dictionary:

N=4 SYM gauge theory in 3+1 dim — String theory in 4+1(+5) dim

$$\frac{g^2 N_c}{4\pi N_c} = g_{string}$$

[$N_c \to \infty$ at fixed $g^2 N_c$ means $g_{string} \to 0$]

$$\sqrt{g^2 N_c} = R^2/\alpha'$$

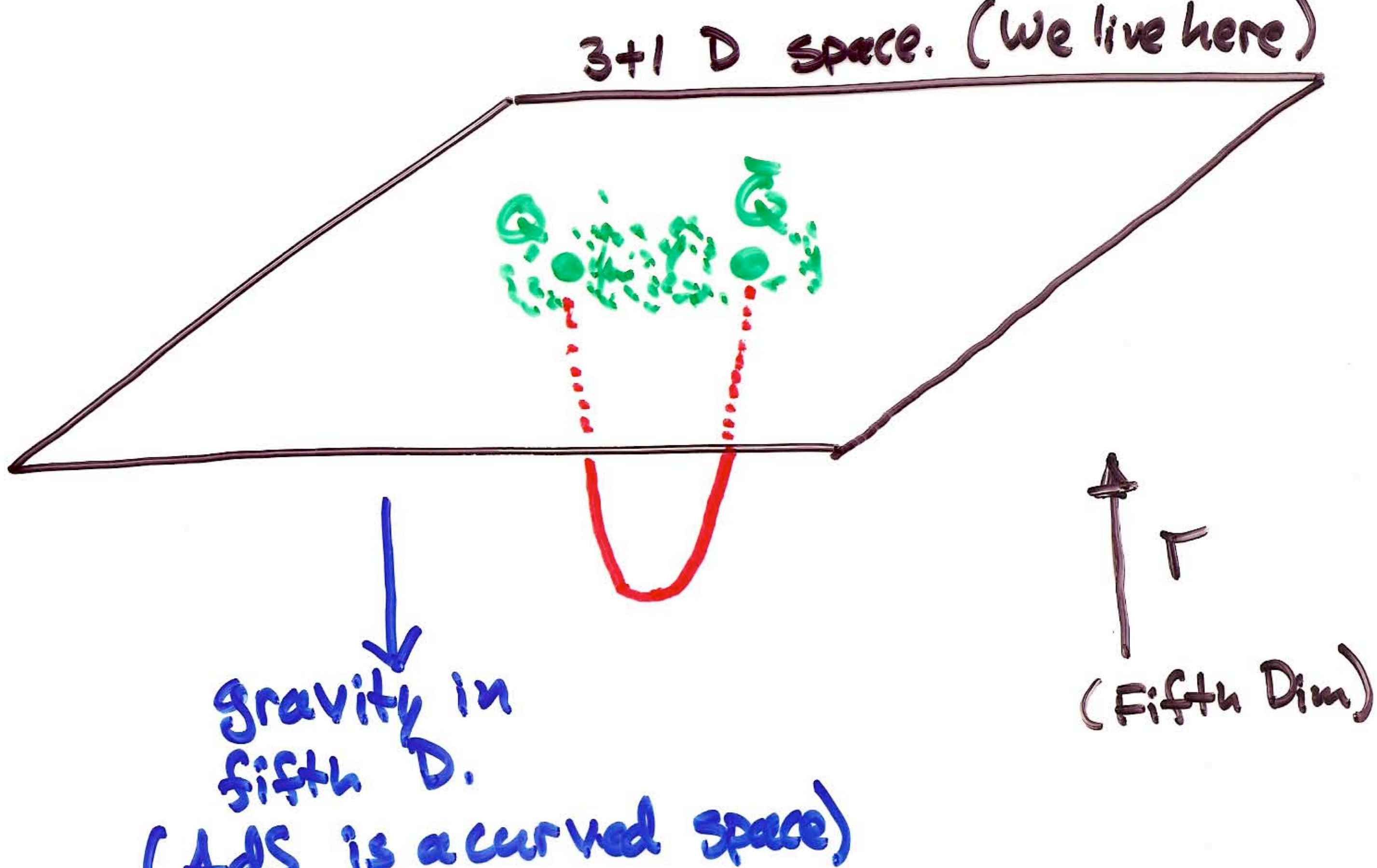
[R : AdS curvature

$\frac{1}{2\pi\alpha'}$: string tension]

Heat the gauge theory to a temperature T. = Add a Black hole in the 5th dimension, with $T_H = r_0/\pi R^2$

[r_0 : location of BH horizon in fifth dim.]

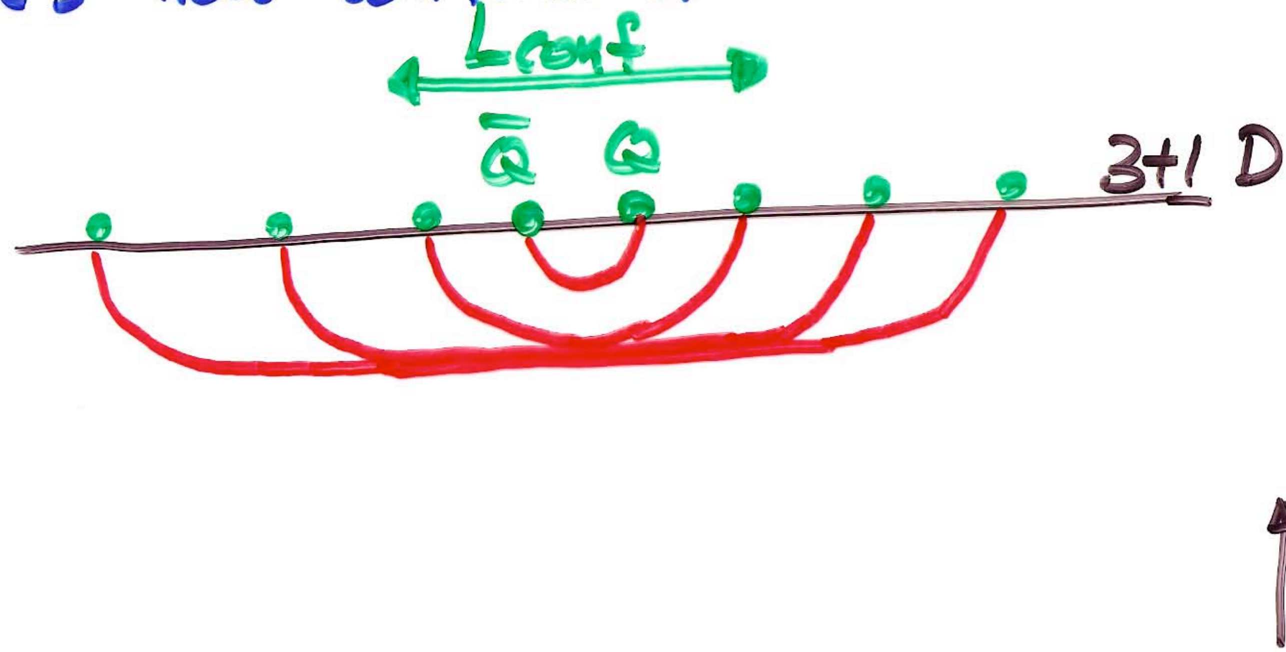
How can strings in $\underline{5D}$ describe, say, force between Q and $\bar{Q}$ in a 4D gauge theory?



- Extremize energy of U string. (Like catenary problem, in unusual gravitational field.)
  - Large $g^2 N_c$ → Large tension → no fluctuation
  - Large N_c → Small g_{string} → no loops break off.
- Force between Q and $\bar{Q}$ $= \dfrac{d}{d\,\text{separation}} \left(\text{Energy of string} \right)$

CONFINEMENT?

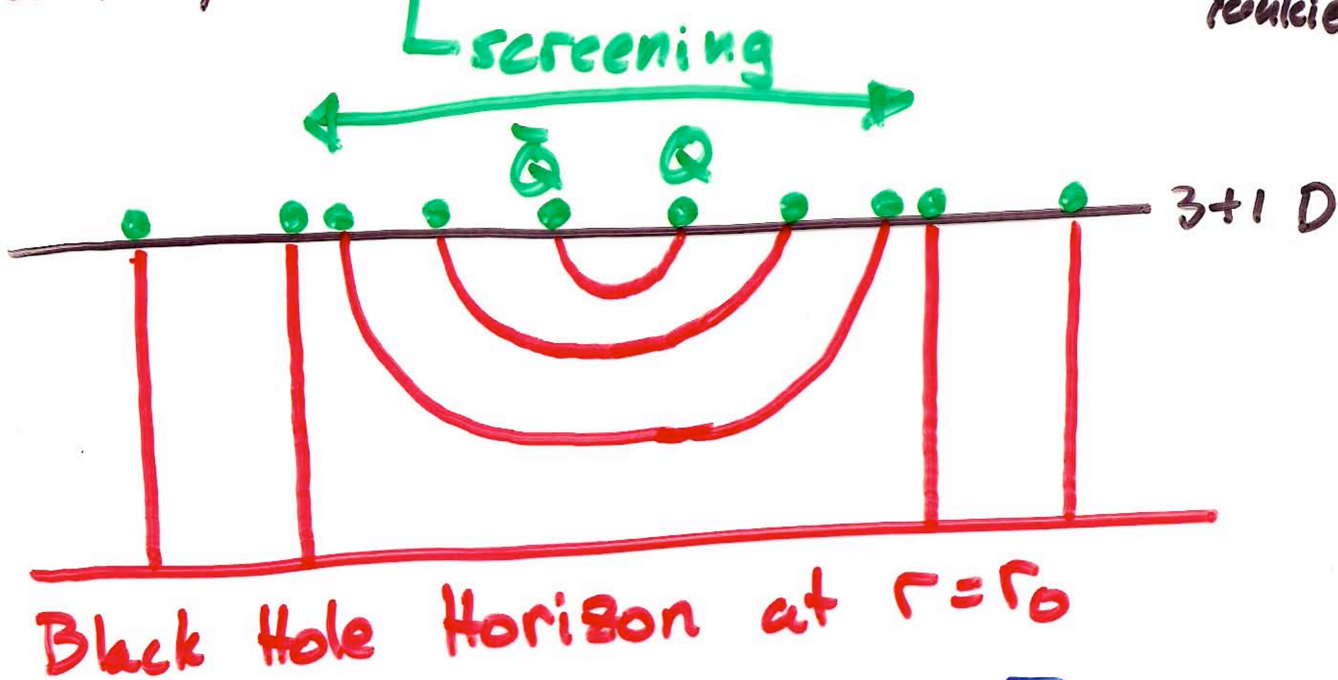
Here's how confinement can arise....



- This does <u>not</u> happen in N=4
  - shape of string stays same as L increases. (N=4 is conformal)
- Confining gauge theories with dual descriptions like this <u>are</u> known.
- QCD not known to have a description like this.
- Don't use N=4 as a guide to QCD at T=0.

DECONFINEMENT AT $T \neq 0$

Maldacena; Rey Yee; Rey Theisen Yee; Brandhuber Itzhaki Sonnenschein Yankielowicz



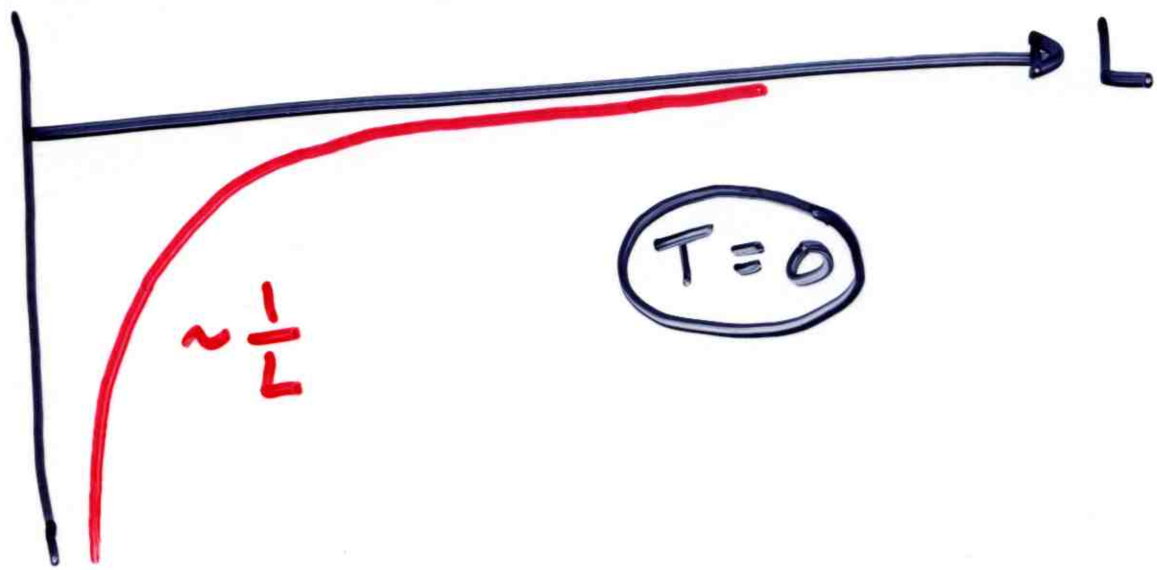
- For $L < L_s$, force between Q & $\bar{Q}$.
- For $L > L_s$, force is screened. Q & $\bar{Q}$ deconfined.
- In N=4 SUSY QCD,

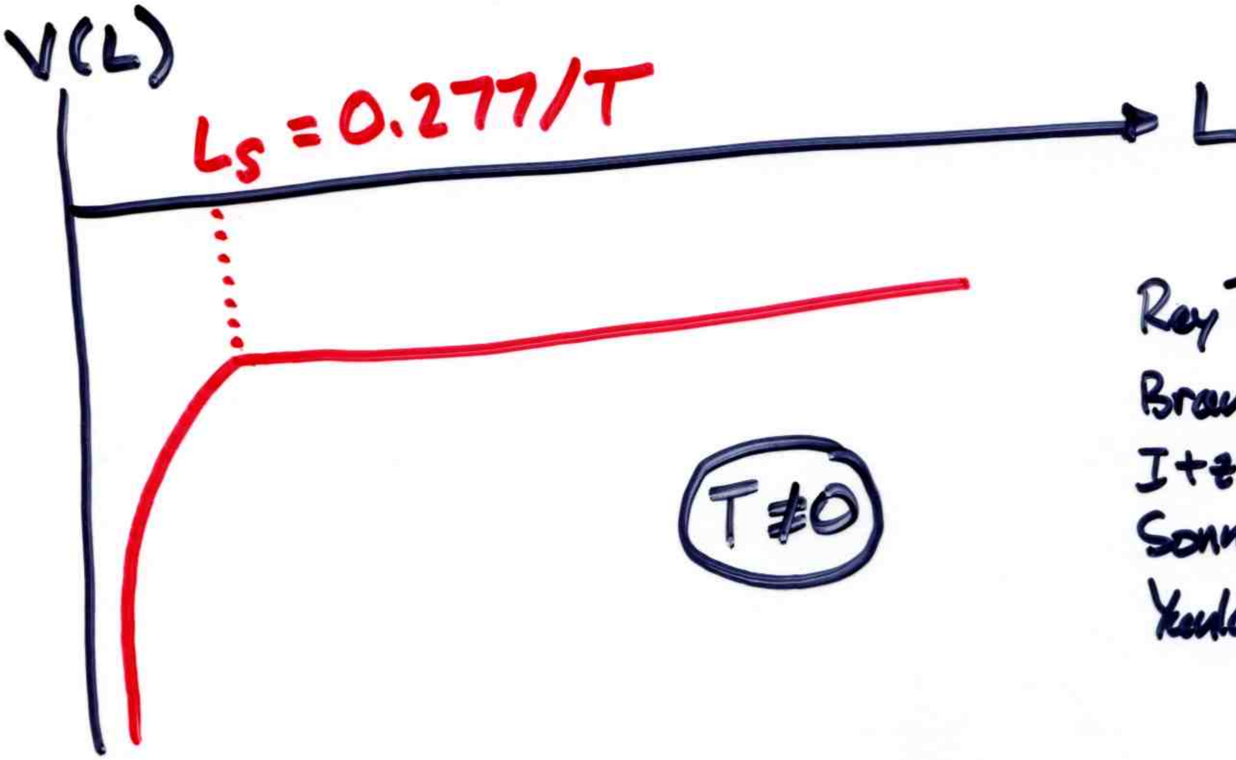
$$L_s = \frac{0.277}{T}$$

- In QCD, force between <u>static</u> Q & $\bar{Q}$ in QGP <u>can</u> be calculated. (Lattice QCD) Can define L_s, though it is not a sharp boundary. Find: $L_s \sim \frac{0.5}{T} \rightarrow \frac{0.7}{T}$ Kaczmarek Karsch Zantow Petreczky
- N=4 gets this feature of the QCD strongly interacting QGP to within factor of 2!

SCREENING IN N=4

V(L) = potential between static Q & $\bar{Q}$

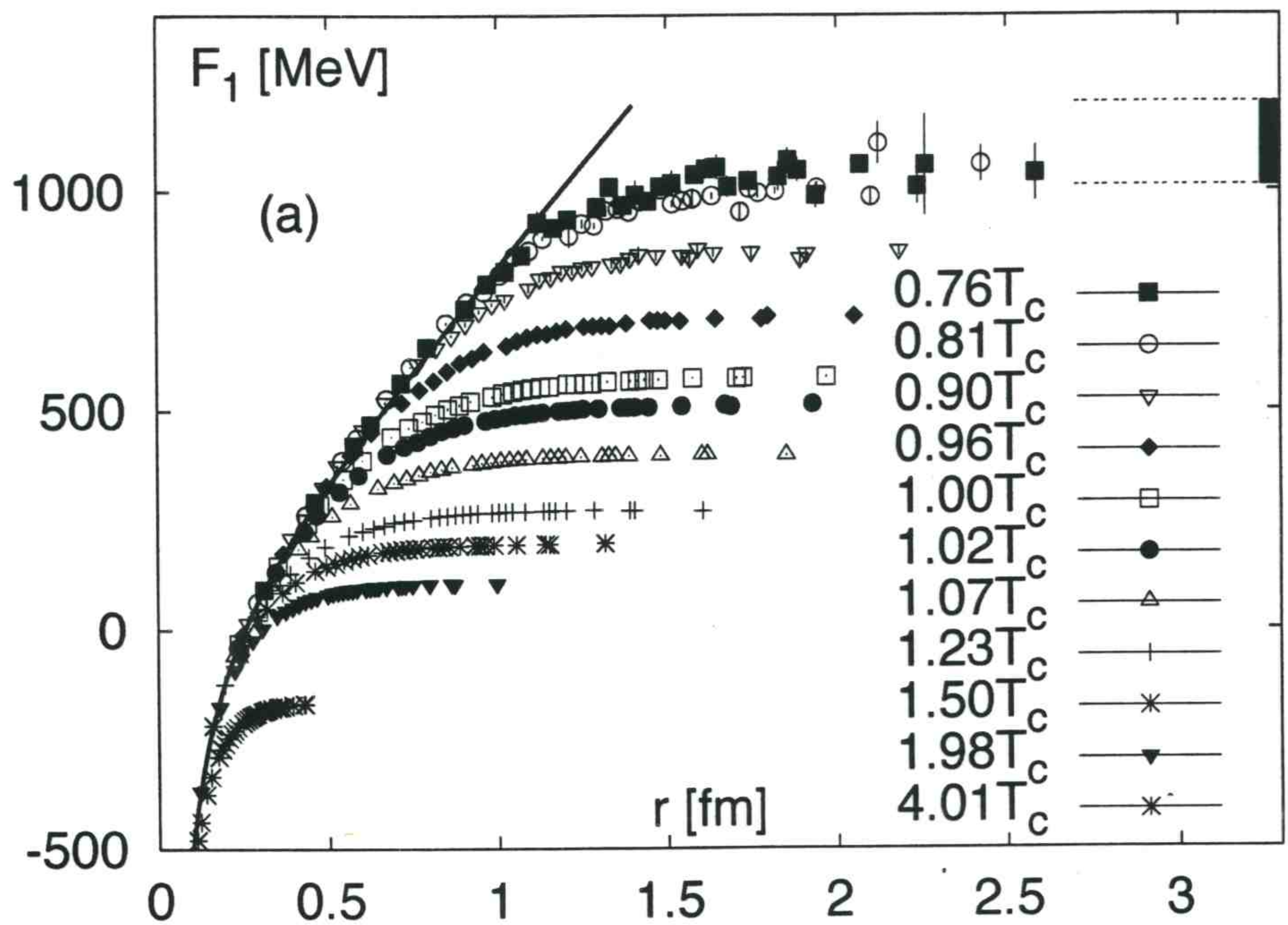




Rey Theisen Yee;
Brandhuber
Itzhaki
Sonnenschein
Yankielowicz

Similar to screening in QCD above QCD's Tc....

SCREENING IN QCD



Kaczmarek, Zantow

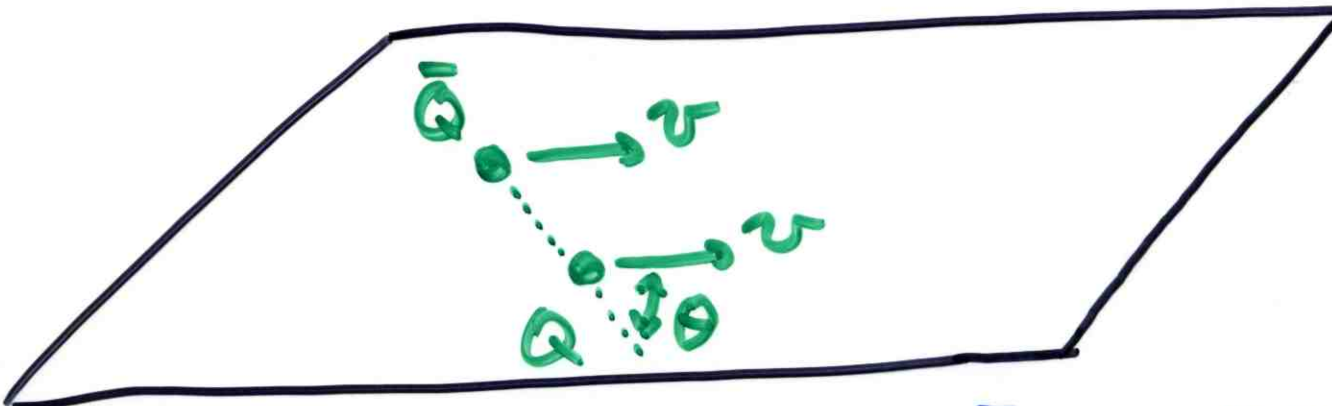
lattice QCD calculation

[Unquenched. $N_f = 2$]

Upon defining an L_s, the authors find $L_s \sim 0.5/T$

A PREDICTION FOR EXPERIMENT

H. Liu, KR, Wiedemann



- Calculate force between $Q + \bar{Q}$ moving through the N=4 QGP. (Not known how to do this calculation in QCD.) Find:

$$L_s = \frac{f(v,\theta)}{\pi T}(1-v^2)^{1/4}$$

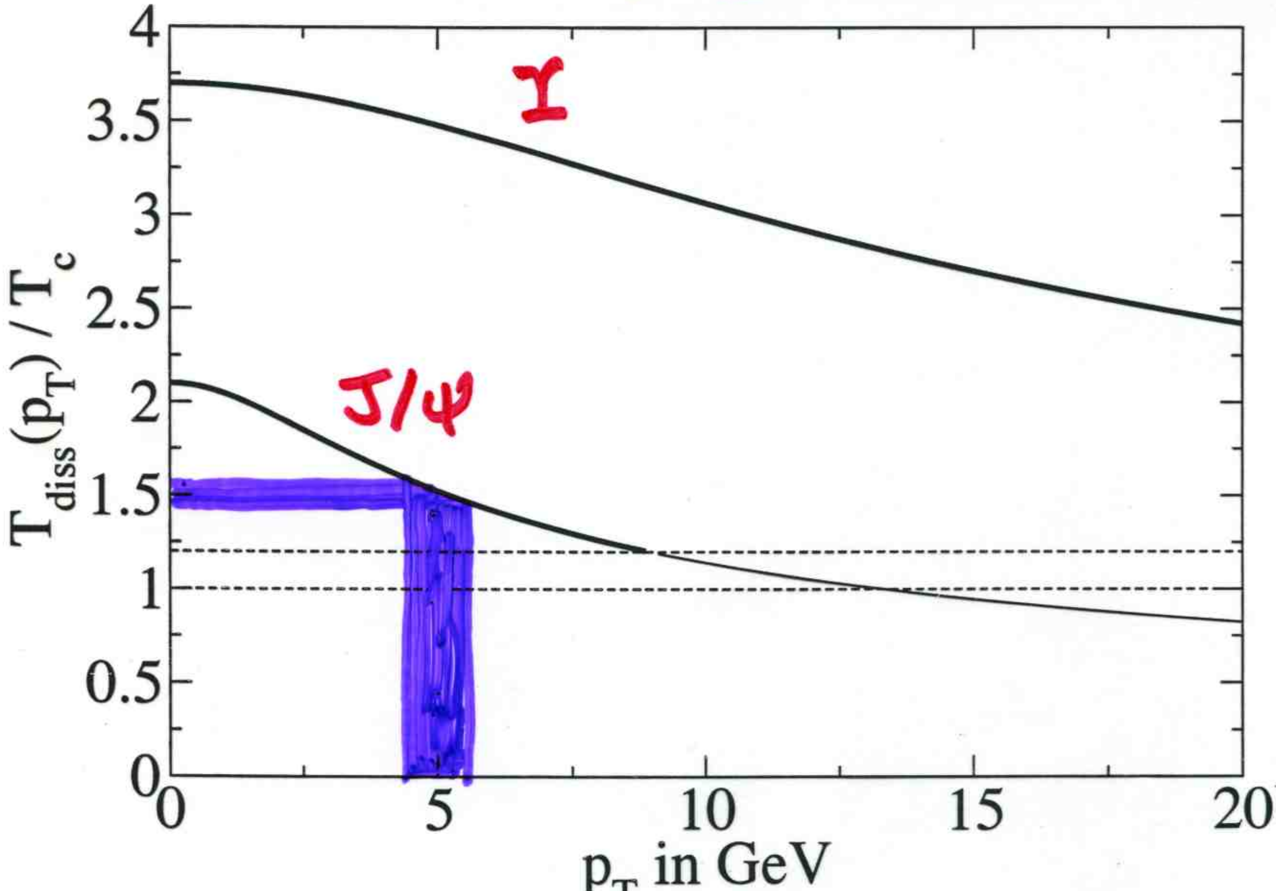
LRW; Peeters et al; Chernicoff et al; Caceres et al

where f is almost a constant. ($f(0,0) = 0.869$, $f(1,\frac{\pi}{2}) = .743$)

- So, $L_s(v,T) \simeq L_s(0,T)/\sqrt{\gamma}$
- Makes sense if L_s controlled by ε, since $\varepsilon \sim T^4$ and $\varepsilon(v) = \varepsilon(0)\gamma^2$.
- J/ψ ($\bar{c}c$) and Υ ($\bar{b}b$) mesons dissociate when T reaches T_{diss}, at which $L_s \sim$ meson size.
- Suggests: $T_{diss}(v) \sim T_{diss}(0)/\sqrt{\gamma}$!

$T_{dissociation}$ vs. P_T

- At $P_T = 0$, $T_{diss}^{J/\psi} \simeq 2.1\, T_c$, from lattice QCD
- Υ curve schematic. (Scaled rel. to J/ψ by meson size in vacuum.)



- Our velocity scaling: $T_{diss}(v) \simeq T_{diss}(0)/\sqrt{\gamma}$

+ Karsch Kharzeev Satz model
  (ie $2.1\, T_c < T_{RHIC} < 1.2\, T_c$)

$\Rightarrow$ J/ψ themselves dissociate for
$P_T > 5$ GeV if $T_{RHIC} \sim 1.5\, T_c$
$P_T > 9$ GeV if $T_{RHIC} \sim 1.2\, T_c$

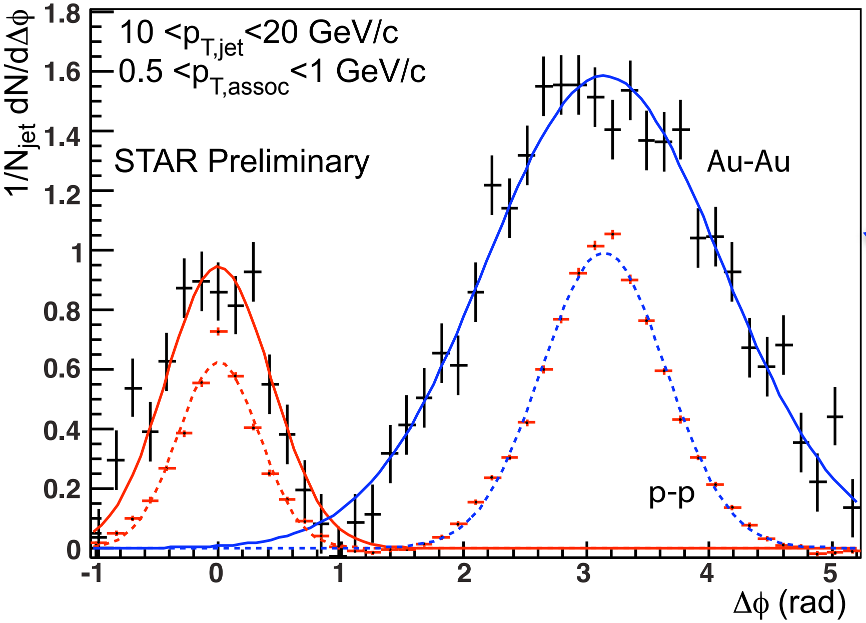
Systematic Uncertainty for η/s

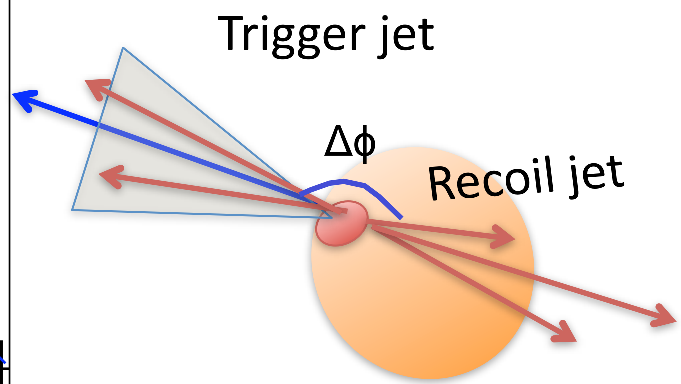
(Preliminary!)

• Experimental uncertainties	± 0.020
• Initial eccentricity	± 0.050
• $v_n/\varepsilon_n =$ constant	$\sim \pm 0.010$
• Thermalization time	± 0.030
• Initialization of shear tensor	± 0.005
• Initial flow	± 0.050
• Equation of State	± 0.015
• Second-order transport coeff.	± 0.005
• Bulk Viscosity	$\sim \pm 0.010$
• Deviation from boost-invariance / longitudinal fluct.	$\sim \pm 0.005$
• Viscous correction to f.o. distribution	± 0.015
• Other aspects of freeze out	$\sim \pm 0.025$

(Preliminary!)

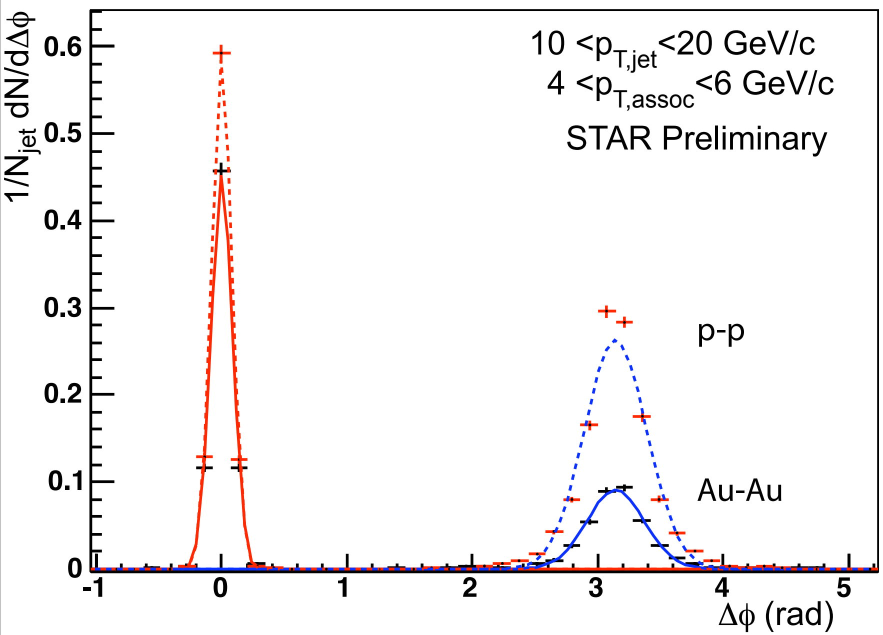
Jet-hadron correlations





Au+Au 0-20%
High Tower Trigger
1 tower
0.05x0.05 (η×φ)
with E_t> 5.4 GeV

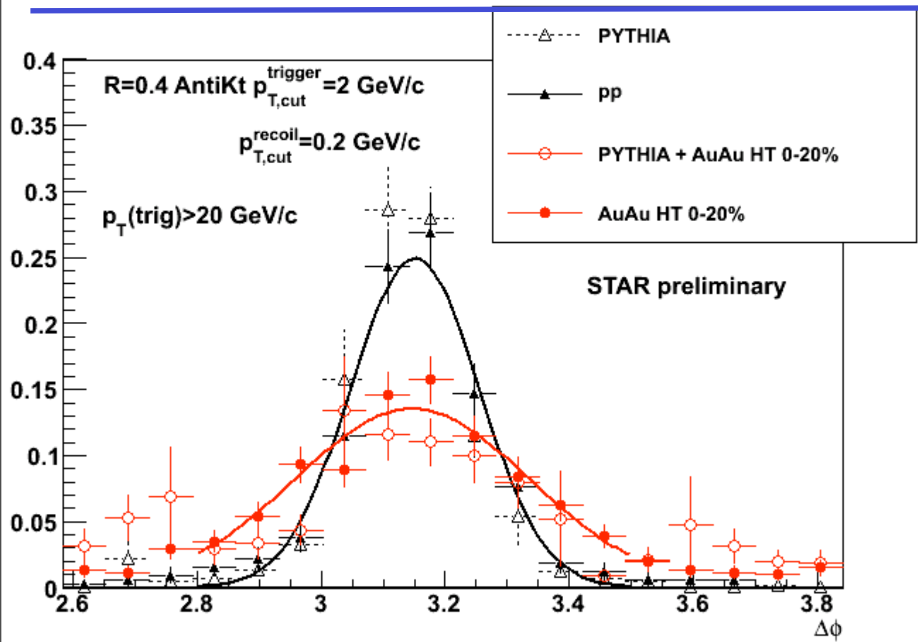
Jet trigger:
Anti-k_T,
R=0.4,
$pt_{,rec}$(jet) using
$p_{t,}$(particle)>2 GeV



Away-side: Broadening
Softening

Direct measurement of modified fragmentation due to presence of sQGP

Broadening not deflection



$p_{Trec,jet}$ > 20 GeV/c, $p_{Trec,dijet}$ > 10 GeV

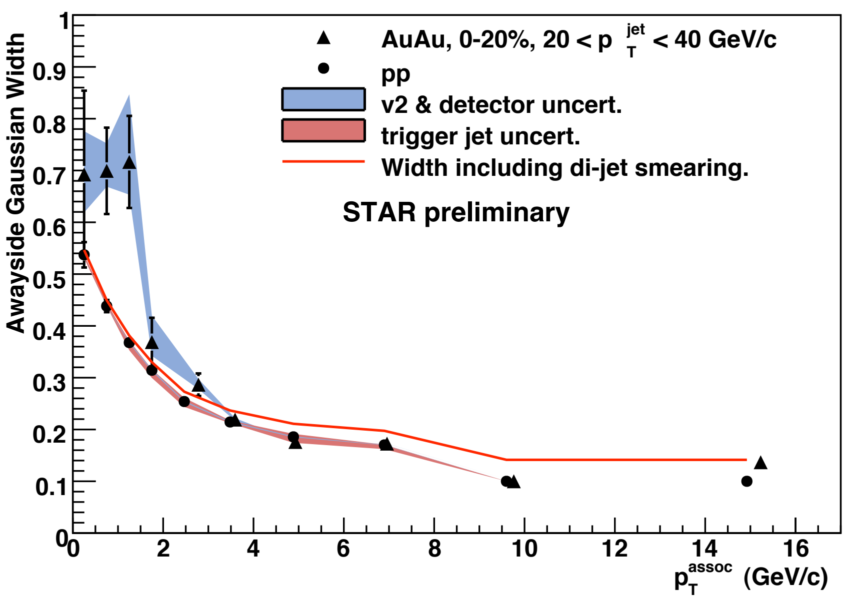
Di-jet: highest p_T with $|\varphi_{jet}-\varphi_{dijet}|$ > 2.6

Δφ of identified di-jets

$\sigma_{Au\text{-}Au}$ ~ 0.2

$\sigma_{PYTHIA,Embed}$ ~ 0.14

$\sigma_{p\text{-}p} \sim \sigma_{PYTHIA}$ ~ 0.1



Low p_T assoc

Au-Au away-side width broader

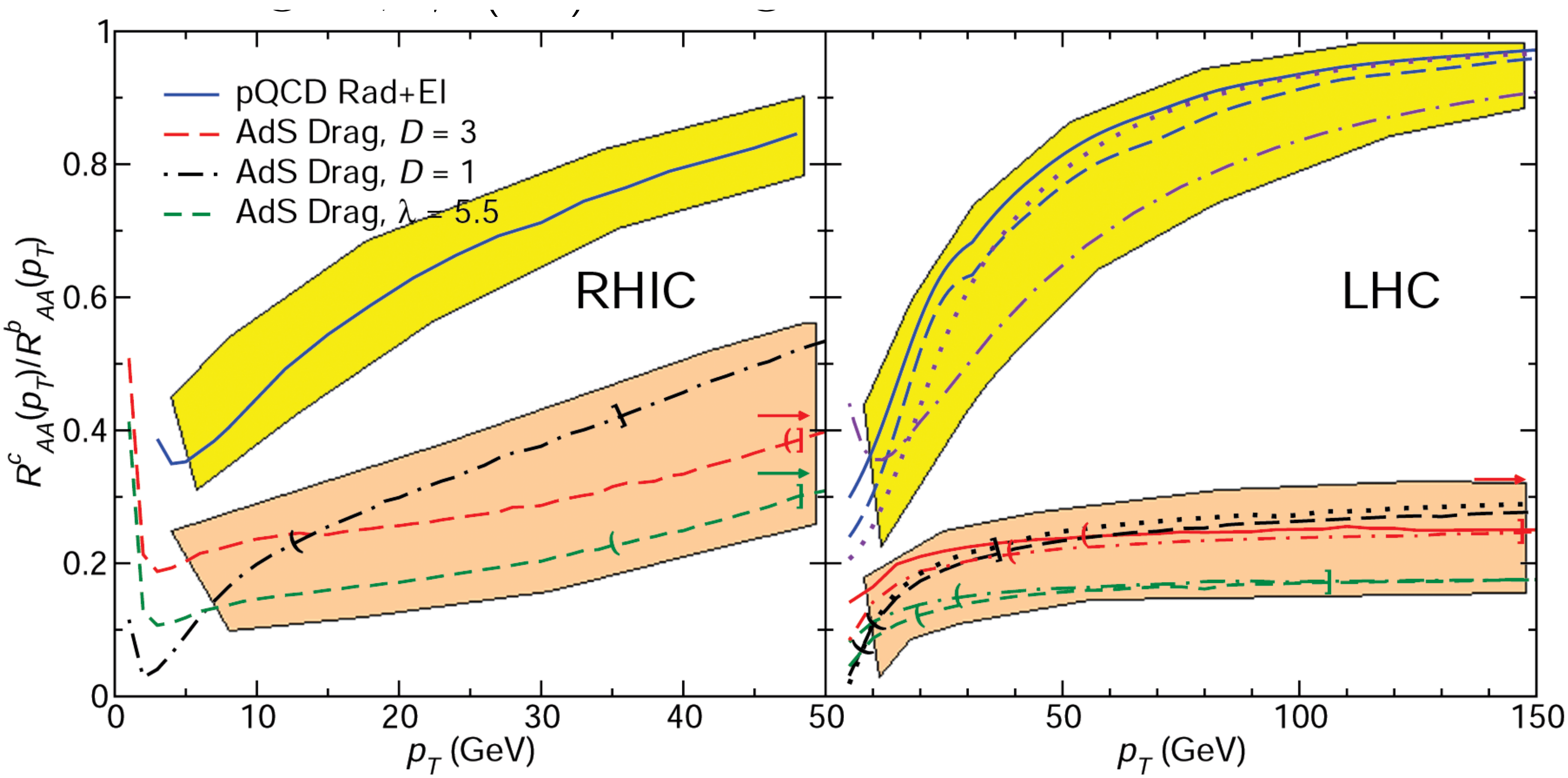
High p_T assoc

Au-Au away-side width same

Majority of broadening due to fragmentation not deflection

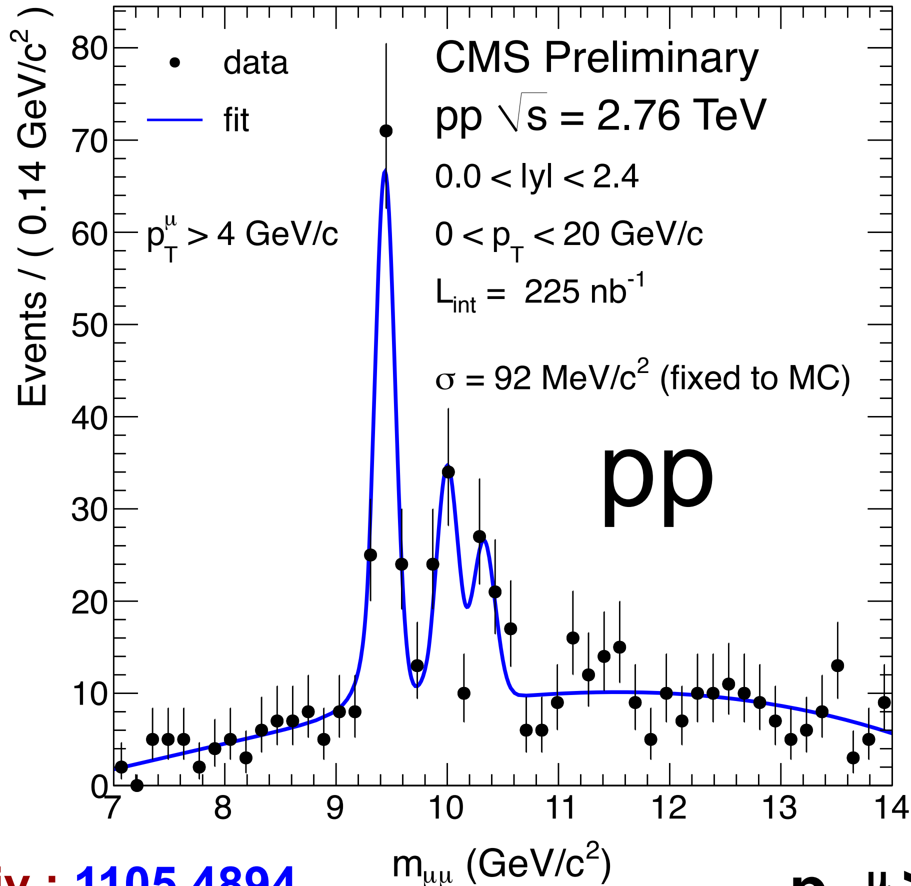
b and c Quark Energy Loss

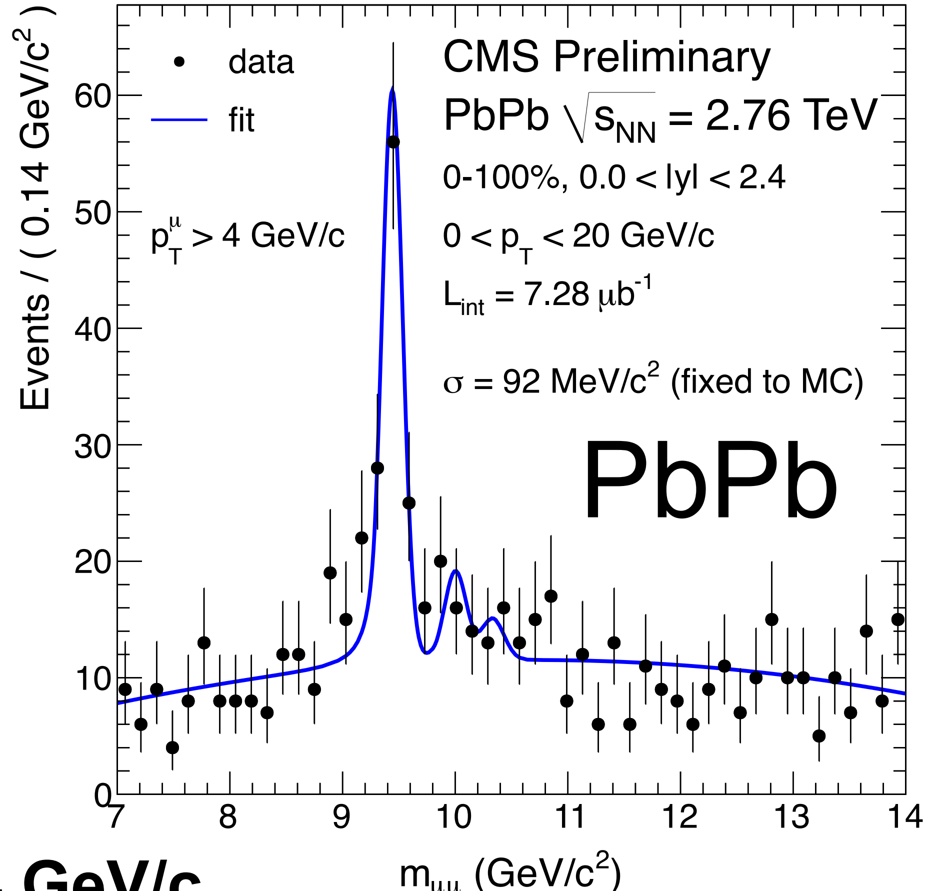
Horowitz and Gyulassy



In strongly coupled plasma, c **and** b *with same* v **lose the same energy, so more energy loss for** c **than for** b *with same momentum*. **In weakly coupled plasma, closer to same energy loss for** c **and** b **with same momentum.**

Υ(2S+3S) Suppression PbPb $\sqrt{s_{NN}}$=2.76 TeV



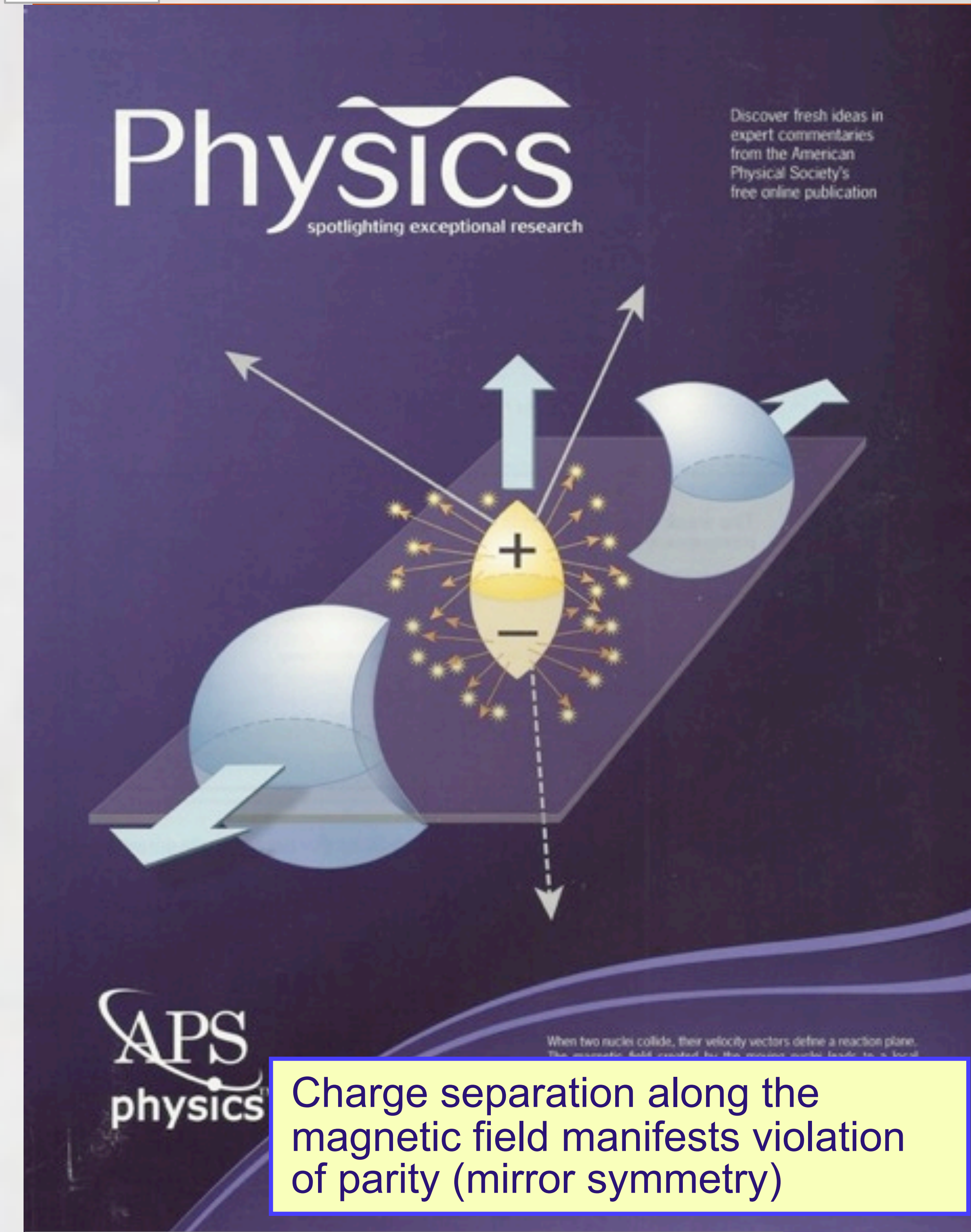


arXiv : 1105.4894
Submitted to PRL

p_T^{μ} > 4 GeV/c

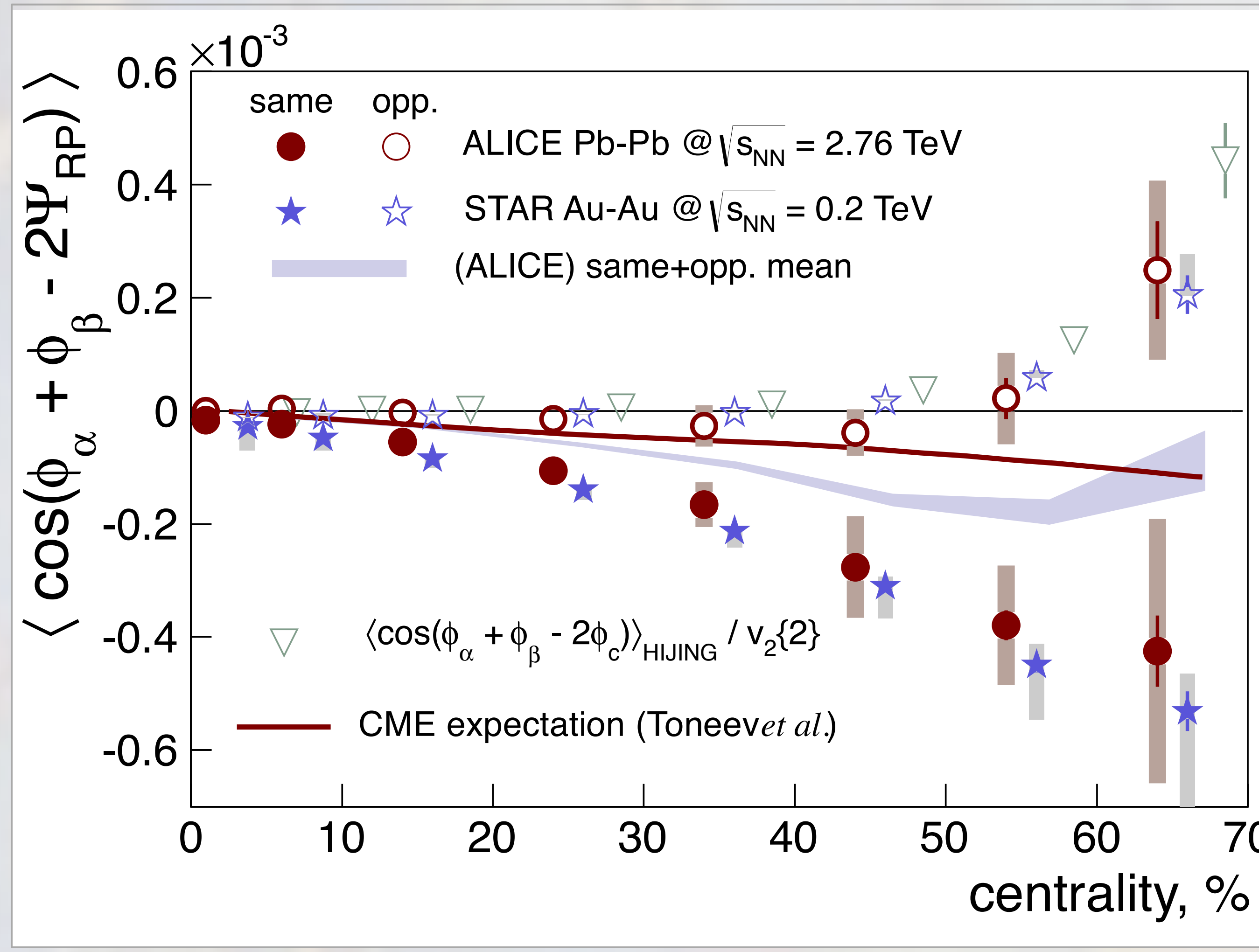
- Υ(2S+3S) production relative to Υ(1S) in pp and PbPb
- Compare pp and PbPb through a simultaneous fit

Searching for the Chiral Magnetic Effect



Charge separation along the magnetic field manifests violation of parity (mirror symmetry)

ALICE: arXiv:1207:3272



ALICE: charge dependent correlations qualitatively consistent with CME, and similar in strength to those observed by STAR.

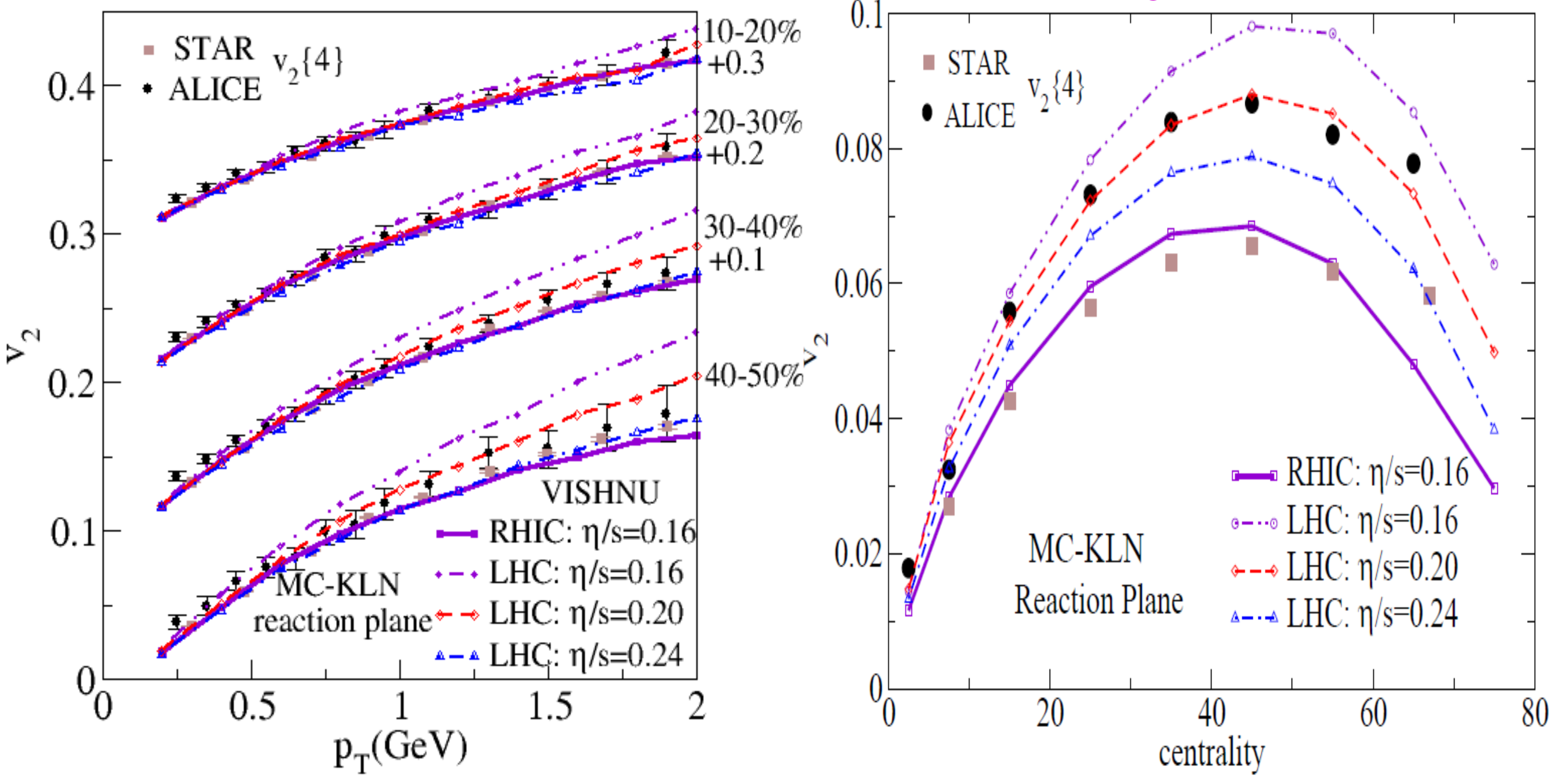
No present event generator can reproduce the signal.

Kharzeev, PLB633 260 (2006)
Kharzeev, Zhitnitski, NPA797 67 (2007)
Khrazeev, McLerran, Waringa, NPA803 227 (2008)
Fukushima, Kharzeev, Waringa, PRD 78 074033 (2008)

Voloshin, PRC70 057901 (2004)

V_2 at RHIC and LHC

Song, Bass & Heinz, PRC 2011



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