The Hottest, and Most Liquid, Liquid in the Universe

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National Nuclear Physics Summer School
University of William and Mary
Wiliamsburg, VA, June 17-18, 2014

Liquid Quark-Gluon Plasma: Opportunities and Challenges

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

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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.

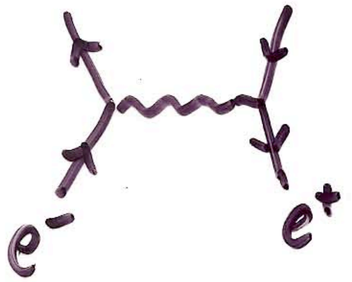
- Using five detectors (PHENIX & STAR @ RHIC; ALICE, ATLAS & CMS @ LHC) scientists are answering questions about the microseconds-old universe that cannot be addressed by any conceivable astronomical observations made with telescopes and satellites.

- 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?

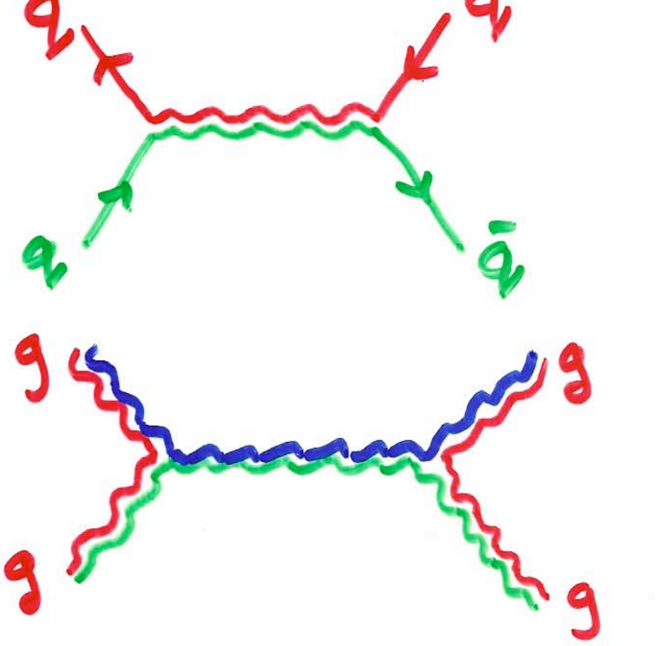
- A theory of quarks and gluons
- Its Lagrangian suggests it is not too different from QED, which is a theory of electrons and photons:

QED



e^-: charge -1
γ: neutral

QCD



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

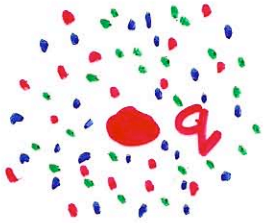
ASYMPTOTIC FREEDOM

Gross, Wilczek, Politzer (1973)

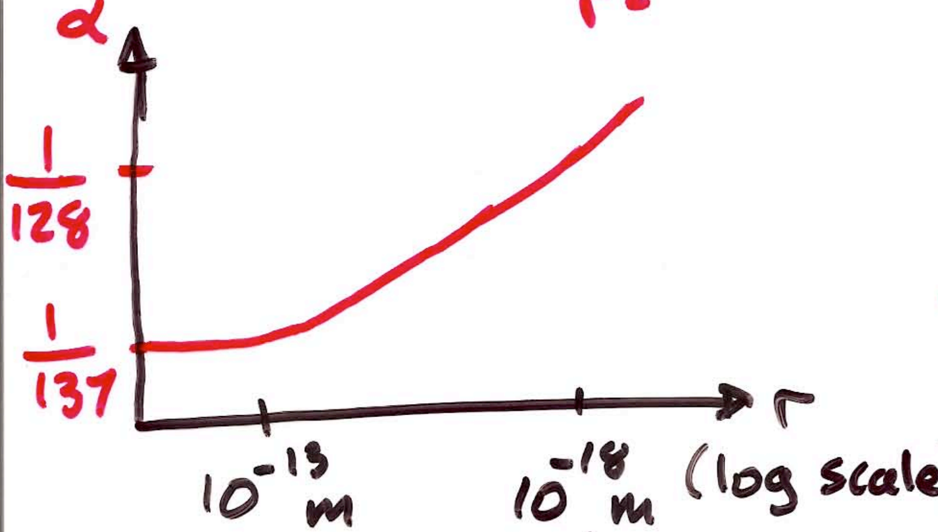
In quantum field theory, the vacuum is a medium which can screen charge.

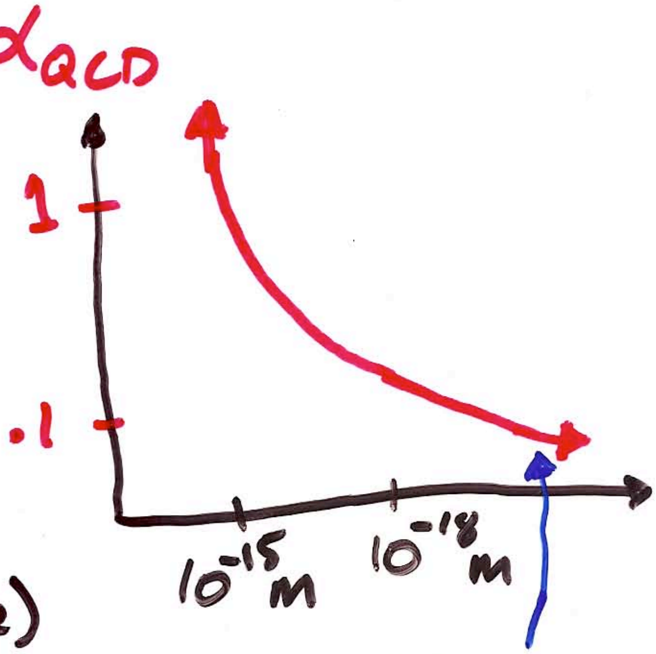
QED

QCD



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





experiments at CERN

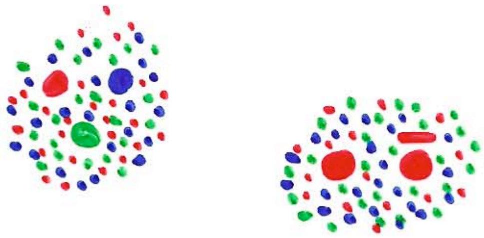
asymptotic freedom, or anti-screening. (That's why Friedman, Kendall, Taylor were able to see weakly interacting quarks.)

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

WHAT DOES QCD DESCRIBE?

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

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



These *hadrons* are the *quasiparticles* of the *QCD vacuum*.

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

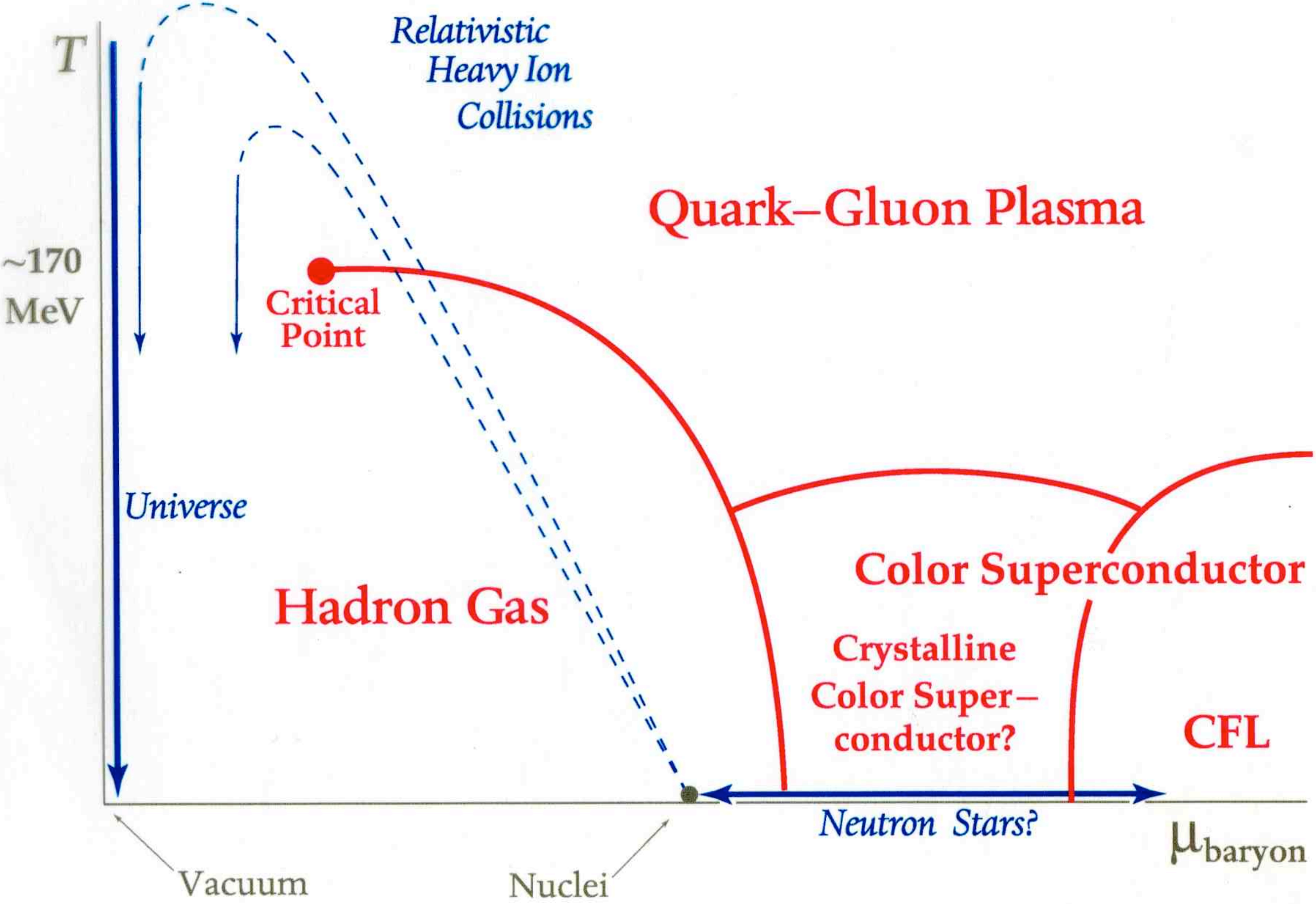
WHY STUDY QCD?
WHY IS IT A CHALLENGE?

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

HOW DO WE RESPOND TO THE CHALLENGE?

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

EXPLORING *the* PHASES *of* QCD



Quark-Gluon Plasma

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

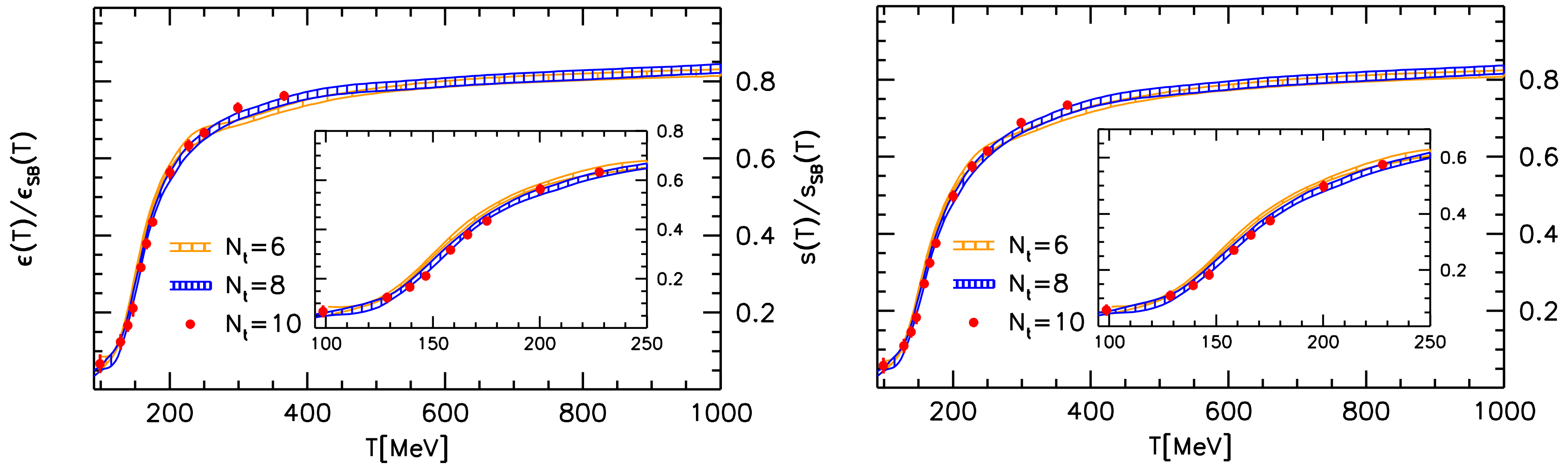
- Asymptotic freedom tells us that, for $T \to \infty$, QGP must be weakly coupled quark and gluon quasiparticles.

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

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

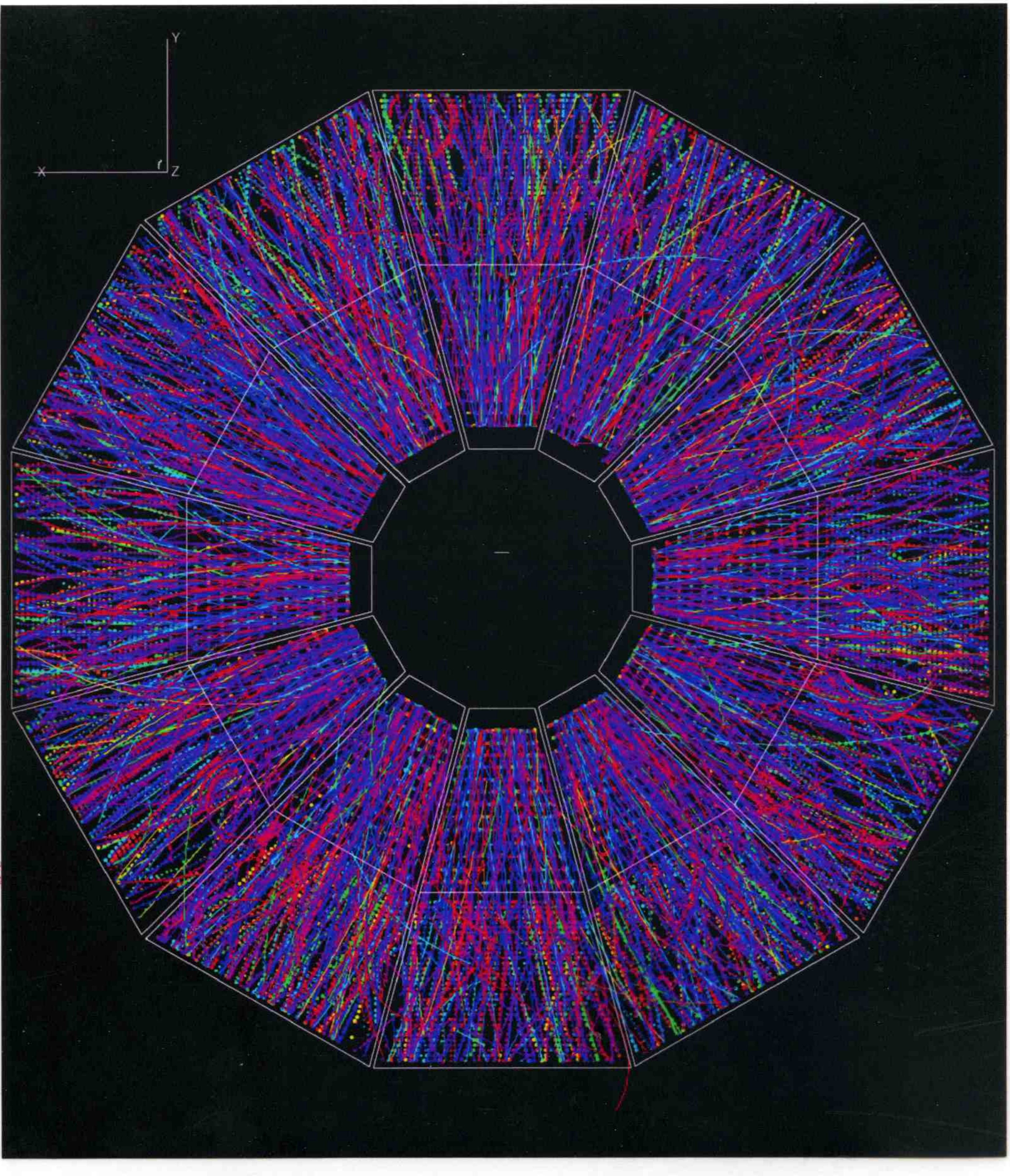
QGP Thermodynamics on the Lattice

Endrodi et al. 2010



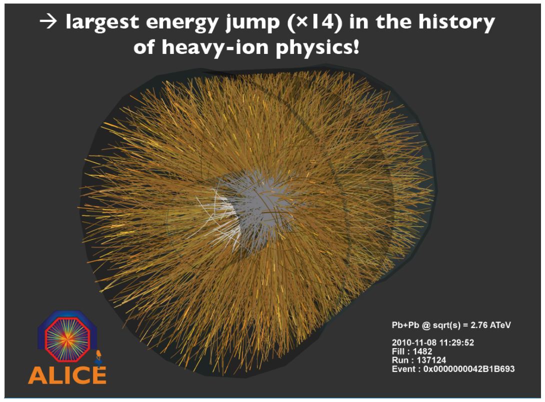
Above $T_{\text{crossover}} \sim$ 150-200 MeV, QCD = QGP. QGP static properties can be studied on the lattice.

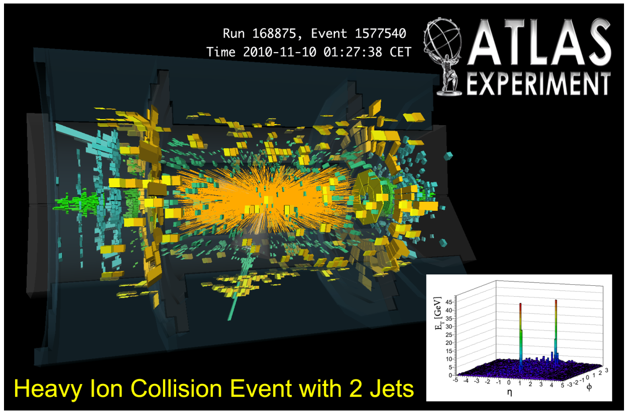
Lesson of the past decade: don't try to infer dynamic properties from static ones. Although its thermodynamics is almost that of ideal-noninteracting-gas-QGP, this stuff is very different in its dynamical properties. [Lesson from experiment+hydrodynamics. But, also from the large class of gauge theories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



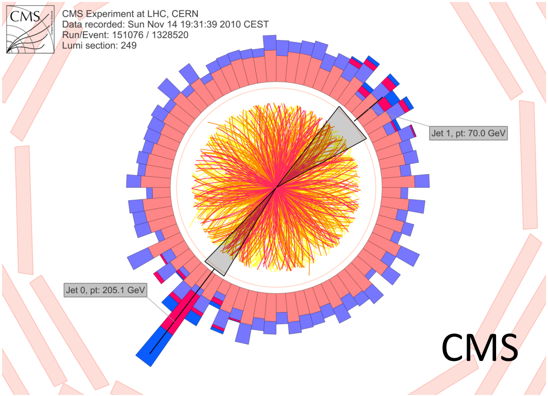
STAR

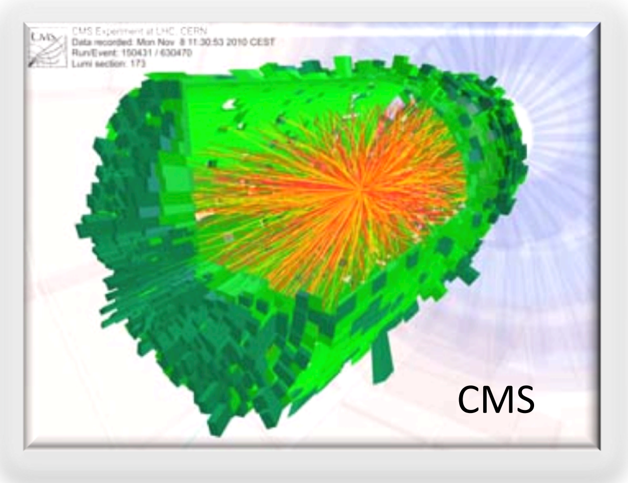
Nov 2010 first LHC Pb+Pb collisions





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

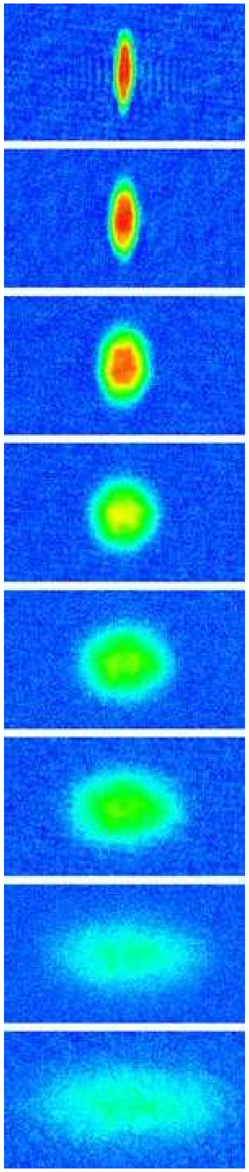
- Ultracold cloud of trapped fermionic atoms, with their two-body scattering cross-section tuned to be infinite. A strongly coupled liquid indeed. (Even though it's conventionally called the "unitary Fermi gas".)

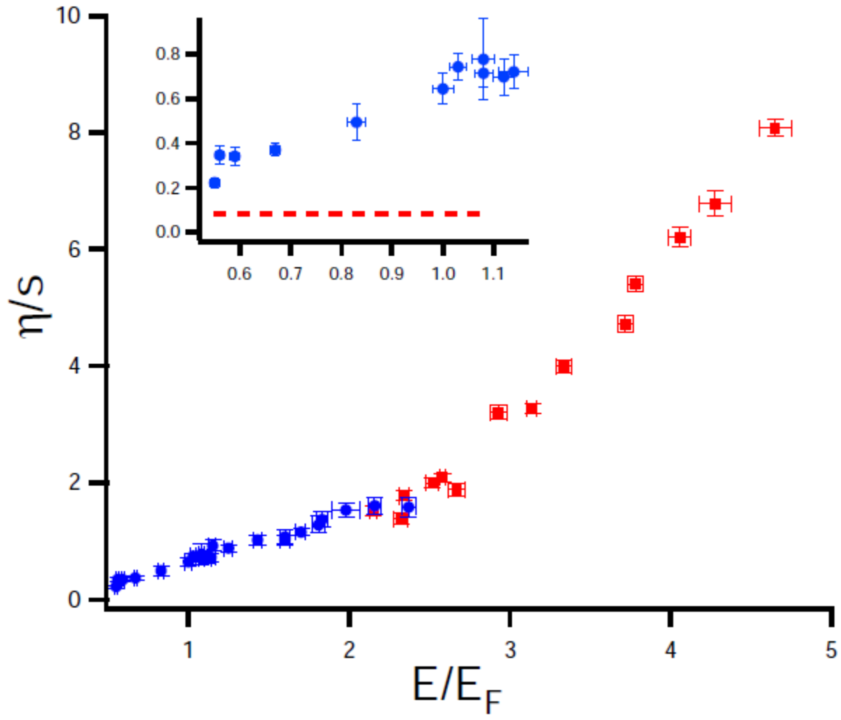
- Data on elliptic flow (and other hydrodynamic flow patterns that can be excited) used to extract η/s as a function of temperature$\ldots$

Viscosity to entropy density ratio

consider both collective modes (low T)

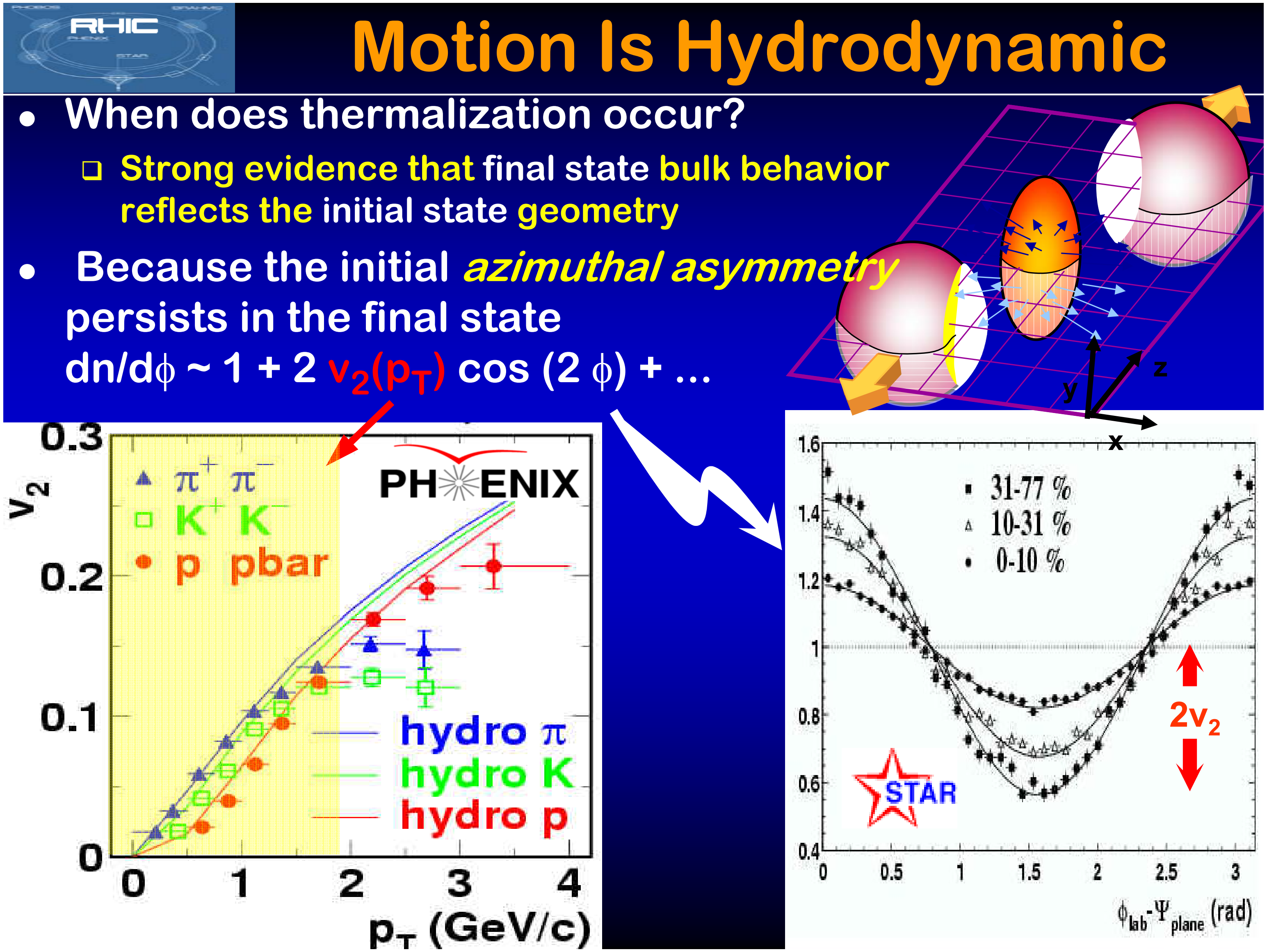
and elliptic flow (high T)





Cao et al., Science (2010)

$$\eta/s \leq 0.4$$



RHIC

Motion Is Hydrodynamic

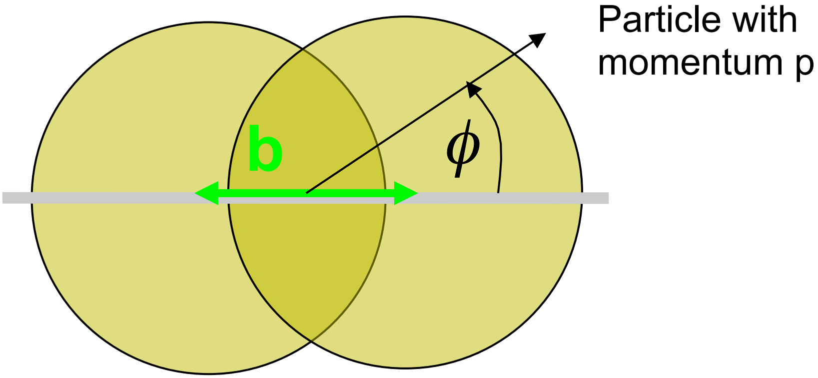
- When does thermalization occur?
  - ❑ Strong evidence that final state bulk behavior reflects the initial state geometry
- Because the initial *azimuthal asymmetry* persists in the final state $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

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

Particle production w.r.t. reaction plane

Consider single inclusive particle momentum spectrum

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



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

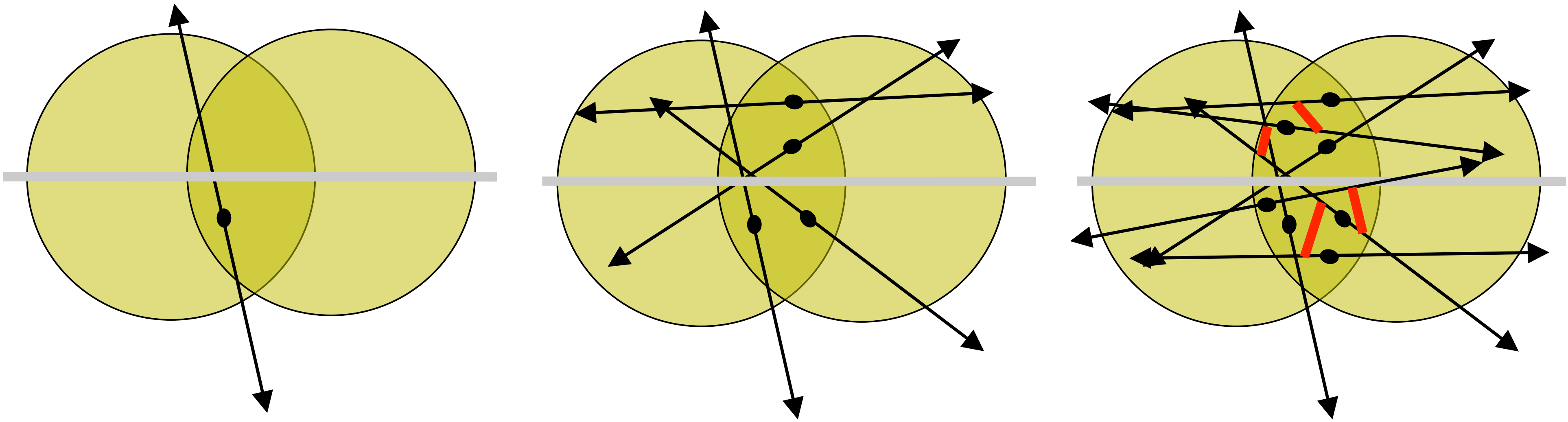
To characterize azimuthal asymmetry, measure n-th harmonic moment of f(p).

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

n-th order flow

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

How to measure flow?



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

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

$$\sim 1/\sqrt{N}$$

- NOT correlated to the reaction plane

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

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

The appropriate dynamical framework

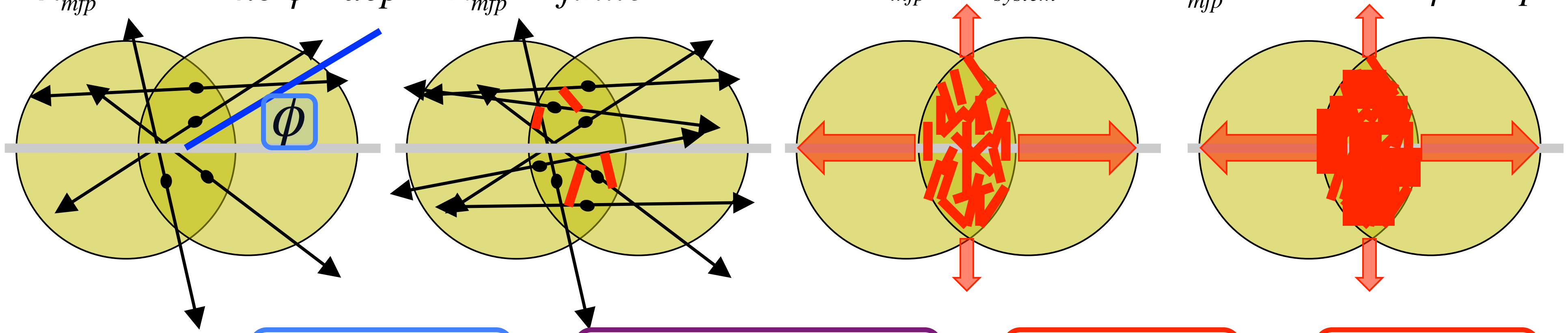
- depends on mean free path
  (more precisely: depends on applicability of a quasi-particle picture)

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

$\lambda_{mfp} \approx finite$

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

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



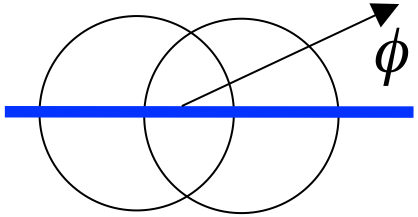
Theory
tools:

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

System p+p ?? … pA …?? … AA … ??

Measuring flow – one procedure

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



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

But reaction plane is unknown ...

- Have to measure particle correlations:

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

"Non-flow effects"

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

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

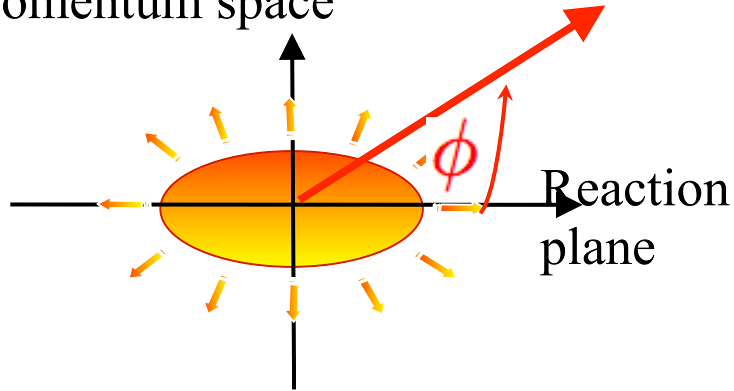
- Improve measurement with higher cumulants: Borghini, Dinh, Ollitrault, PRC (2001)

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

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

v_2 @ LHC

- Momentum space



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

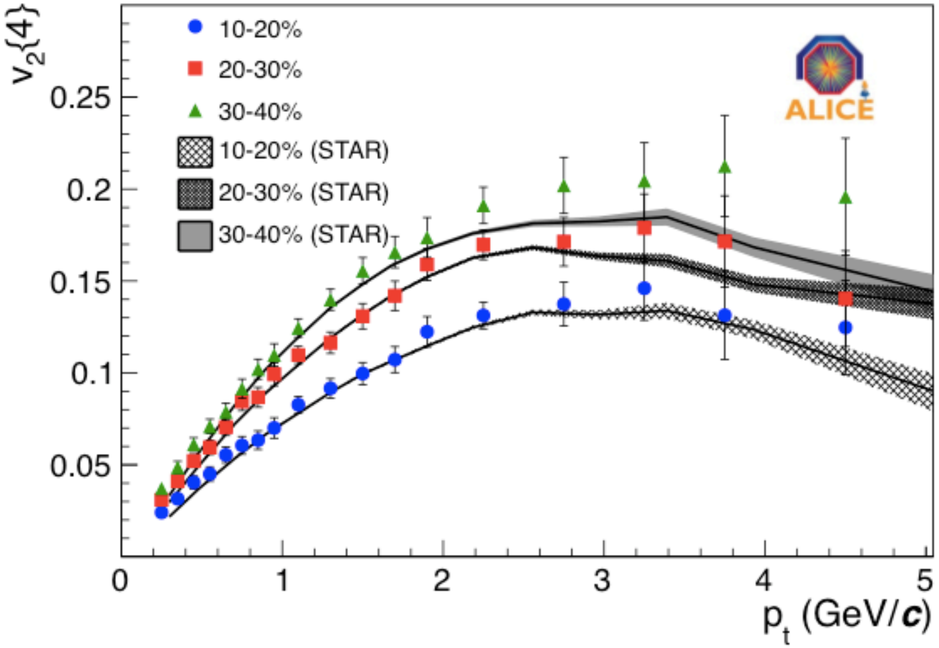
- Signal $v_2 \approx 0.2$ implies 2-1 asymmetry of particles production w.r.t. reaction plane.
- 'Non-flow' effect for 2nd order cumulants

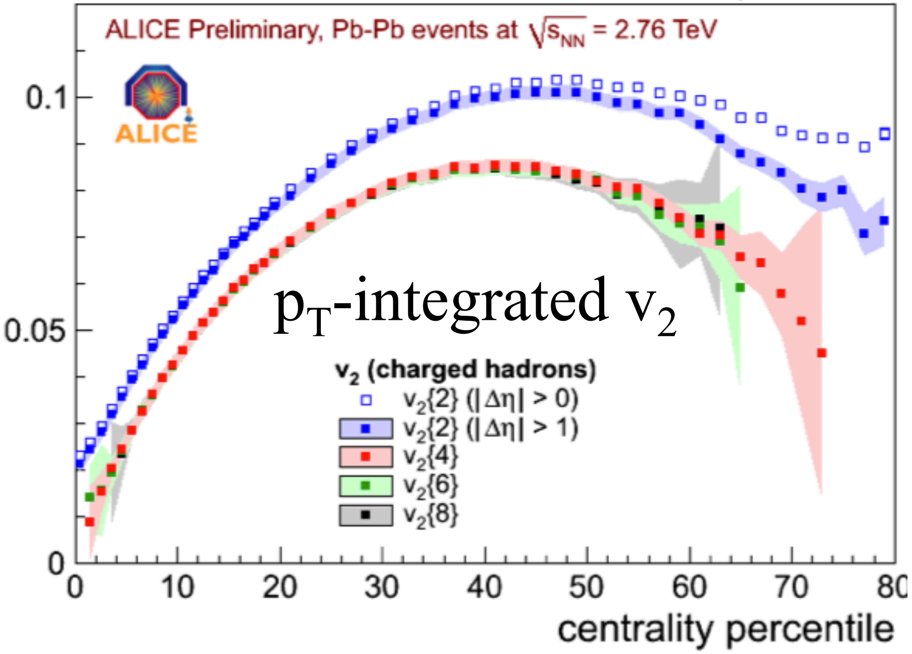
$$N \sim 100-1000 \Rightarrow 1/\sqrt{N} \sim 0.1 \sim O(v_2)\,??$$

2nd order cumulants do not characterize solely collectivity.

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

→ **Strong Collectivity !**





p_T-integrated v_2

The appropriate dynamical framework

- depends on mean free path
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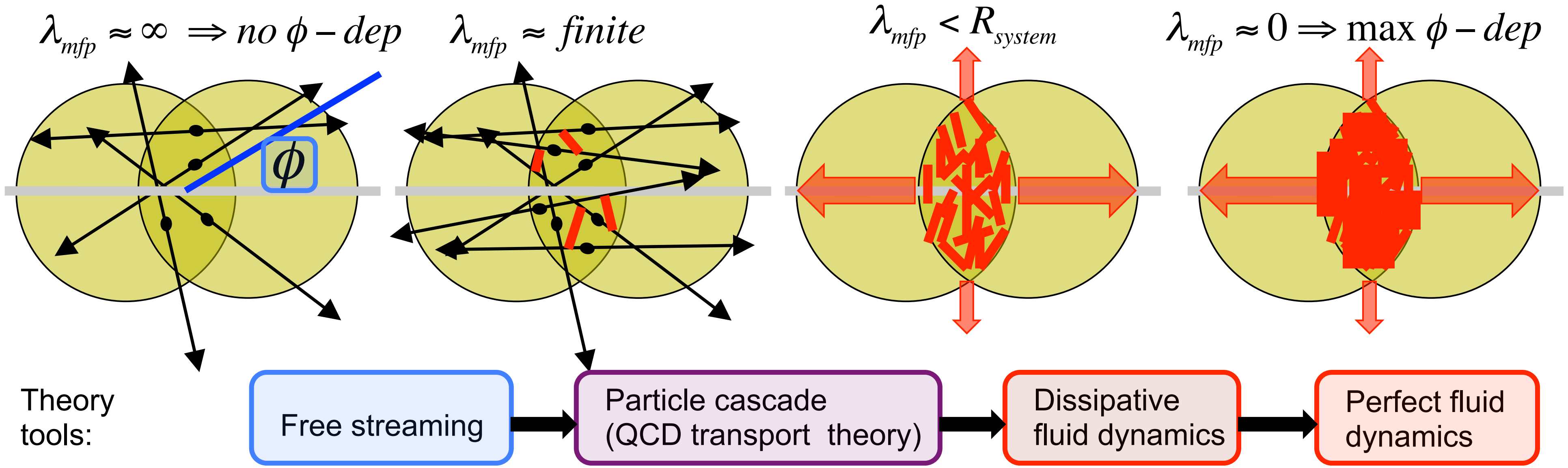


Theory tools:

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

System p+p ?? … pA …?? … AA … ??

Rapid Equilibration?

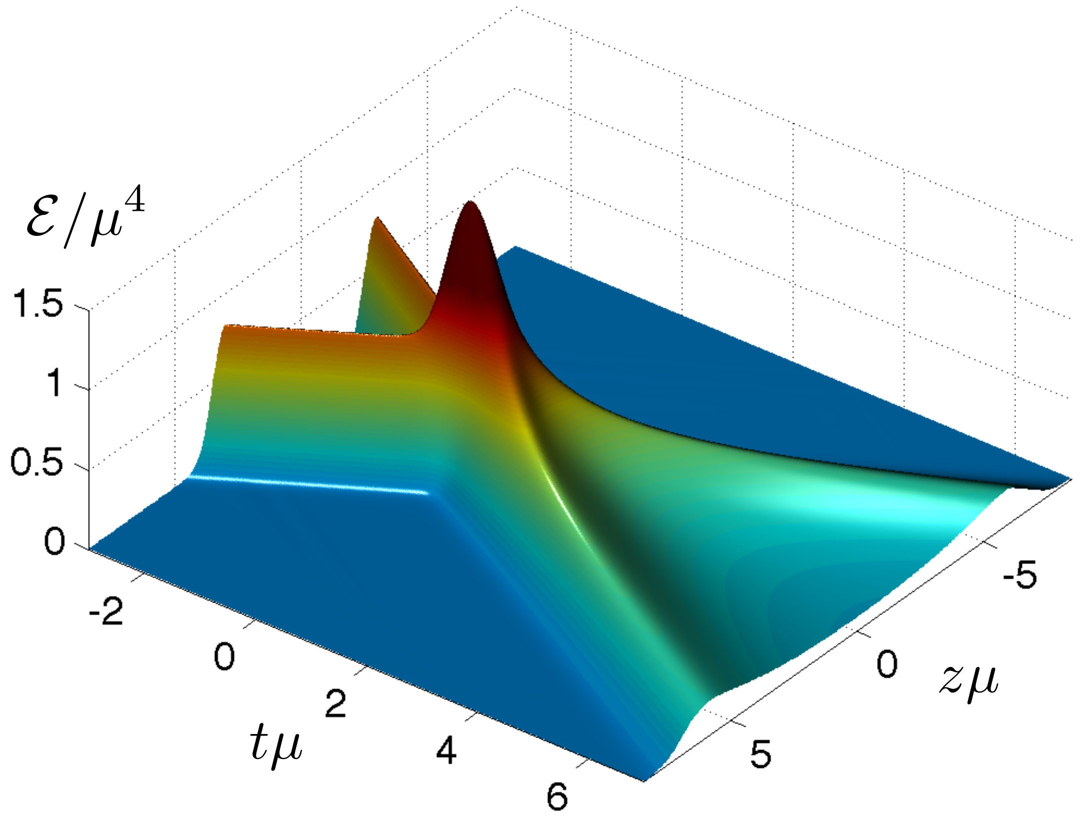
- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.

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

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

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

Colliding Strongly Coupled Sheets of Energy



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

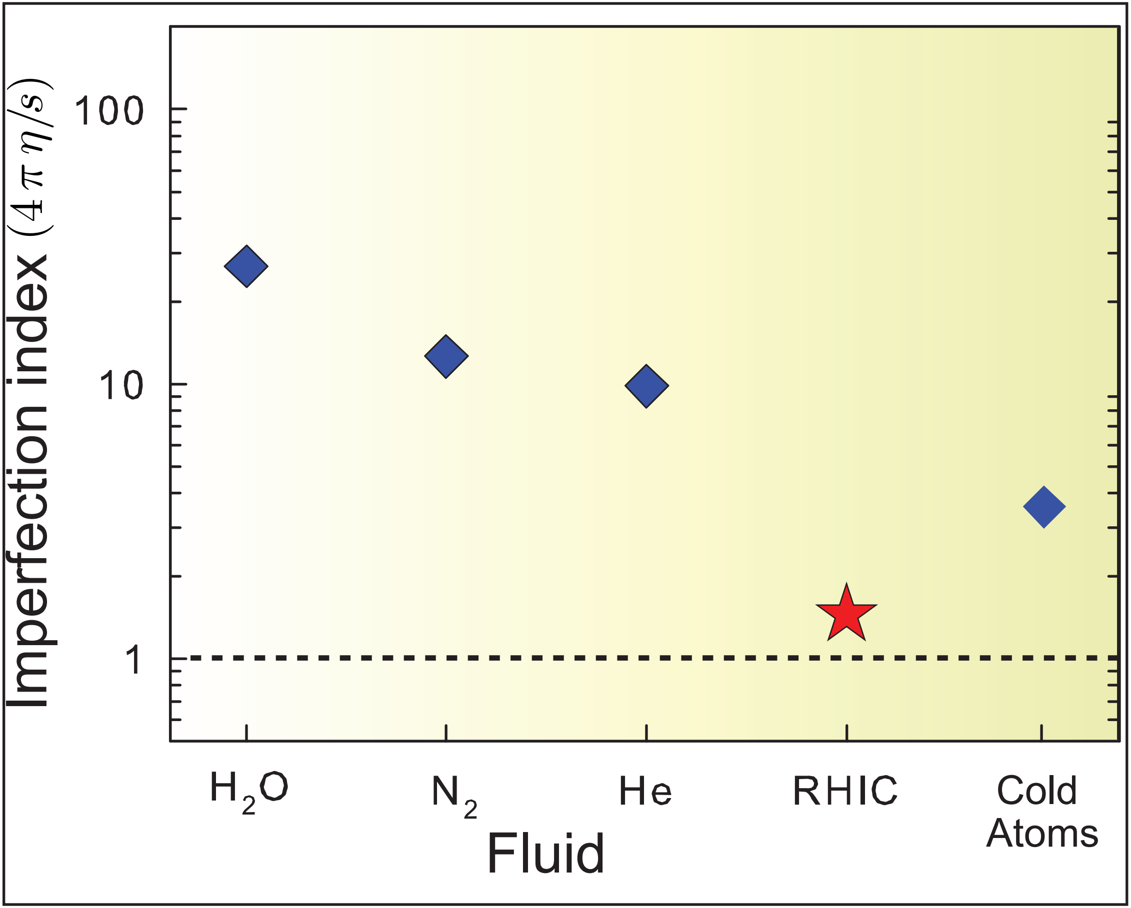
Determining η/s from RHIC data

- 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...

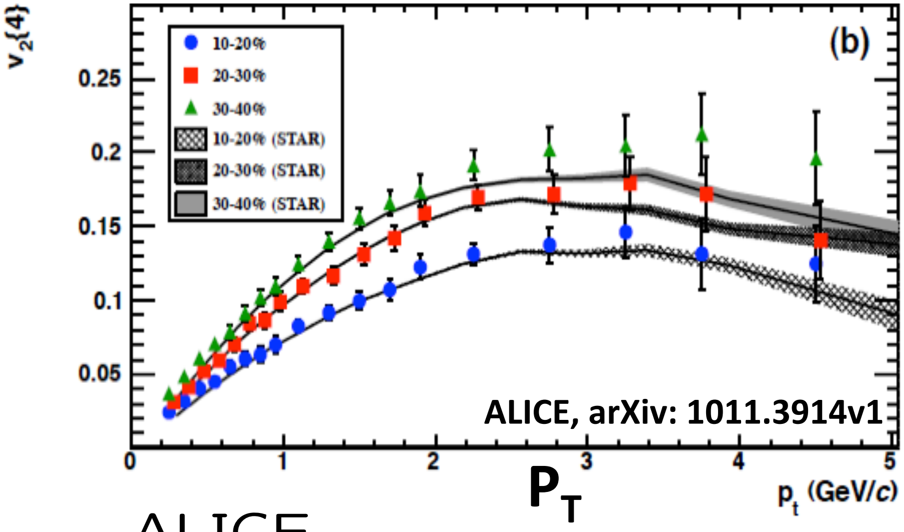
- Circa 2010/2011: QGP@RHIC, with $T_c < T \lesssim 2T_c$, has $1 < 4\pi\eta/s < 2.5$. [Largest remaining uncertainty: assumed initial density profile across the "almond".] Song, Bass, Heinz, Hirano, Shen arXiv:1101.4638

- $4\pi\eta/s \sim 10^4$ 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.

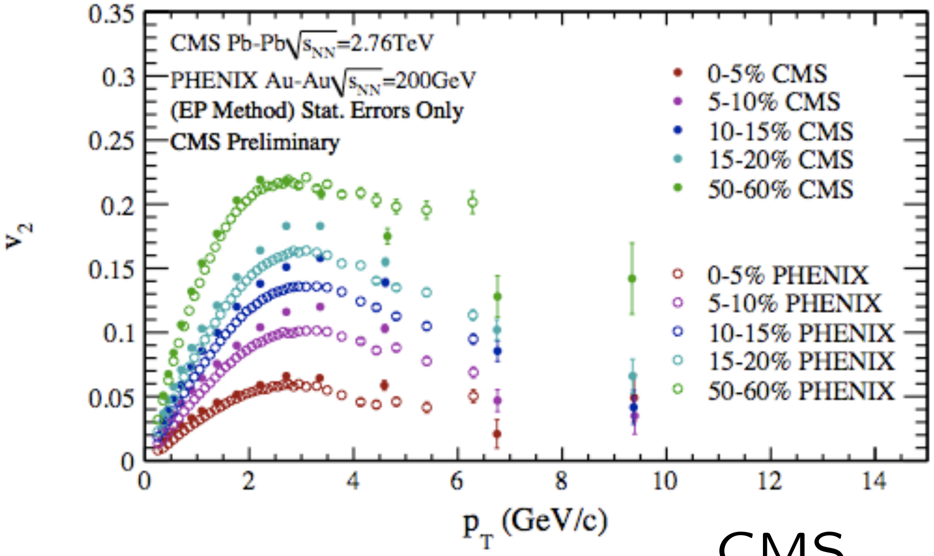
- $4\pi\eta/s = 1$ for any (of the by now very many) known strongly coupled gauge theory plasmas that are the "hologram" of a (4+1)-dimensional gravitational theory "heated by" a (3+1)-dimensional black-hole horizon.


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

What changes at the LHC?



ALICE

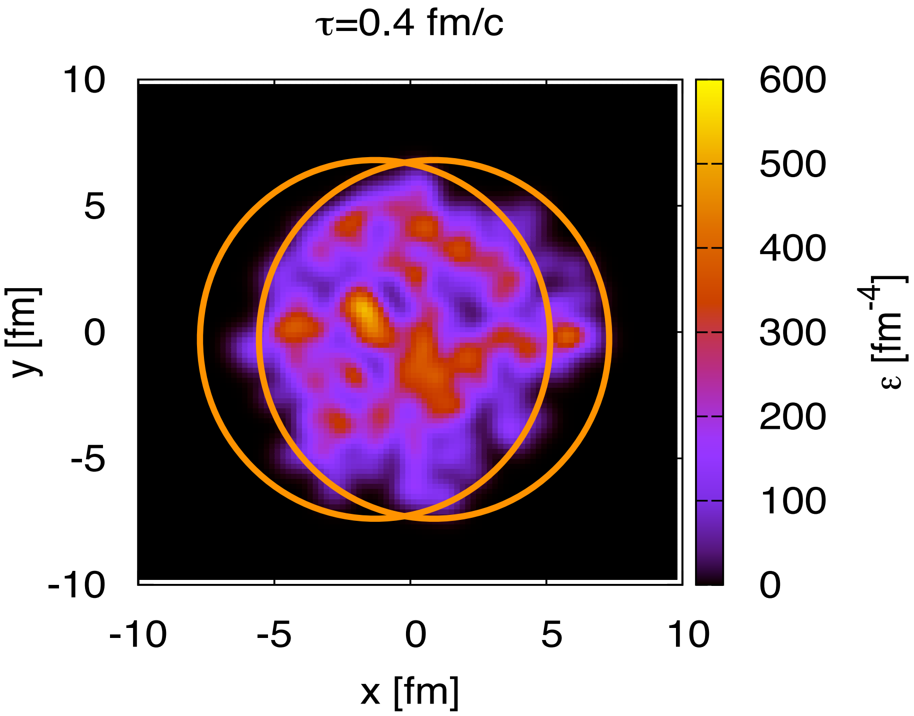


CMS

$v_2(p_T)$ **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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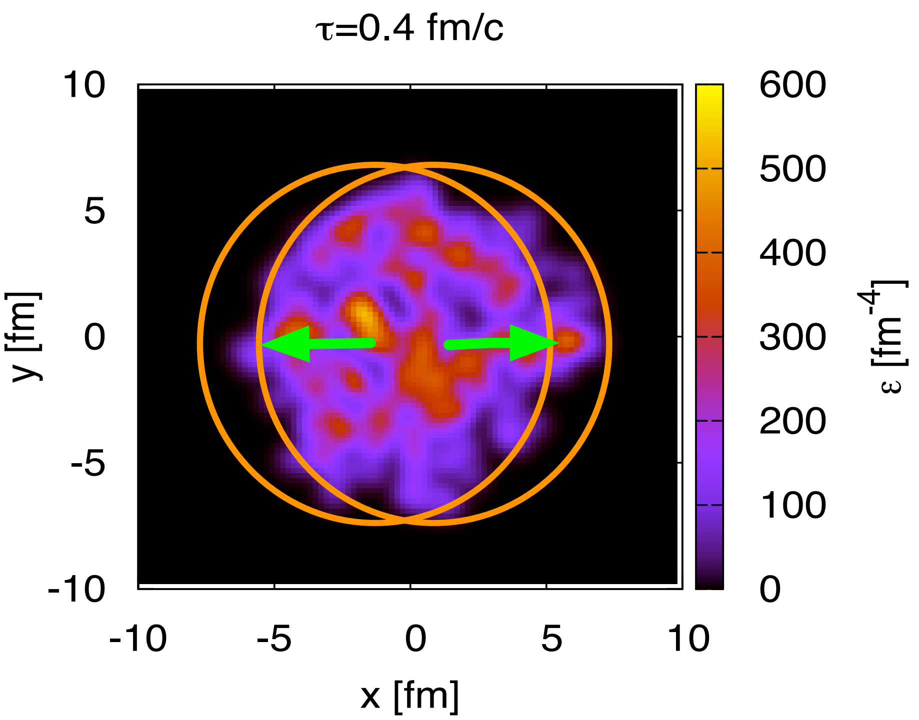

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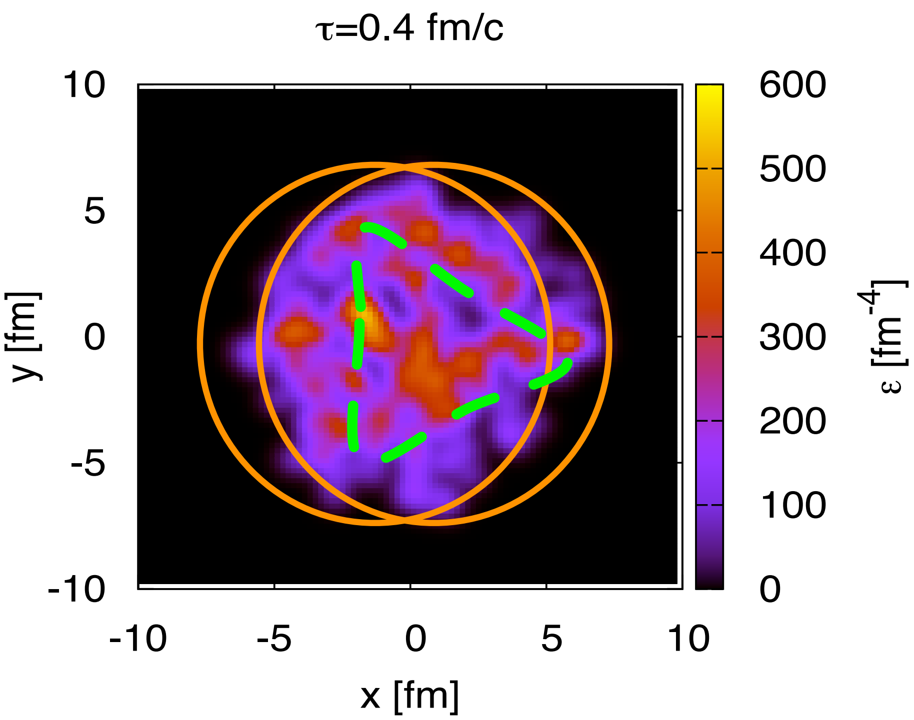

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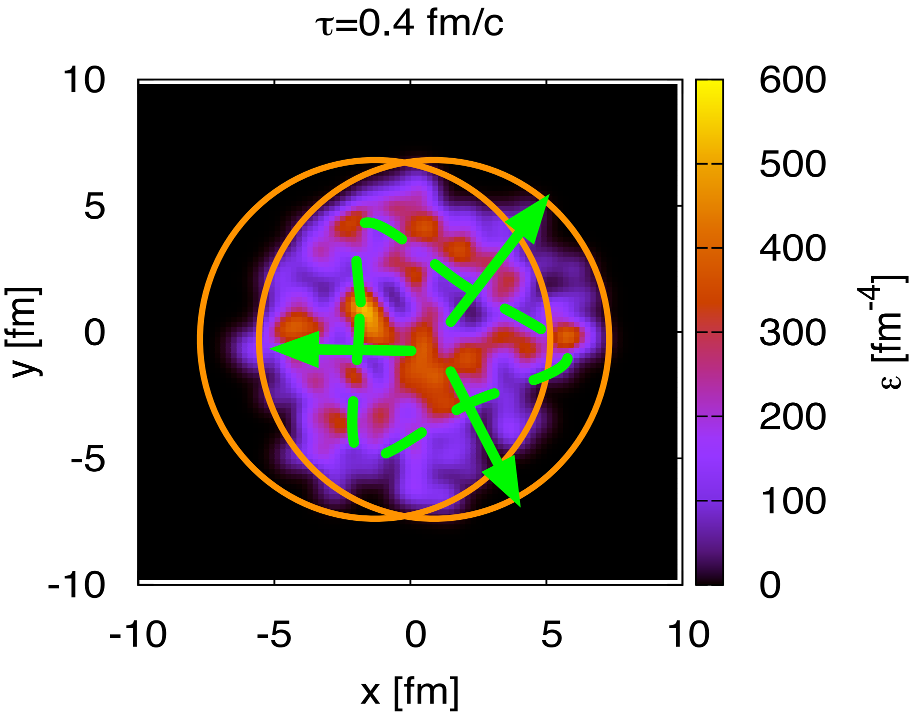

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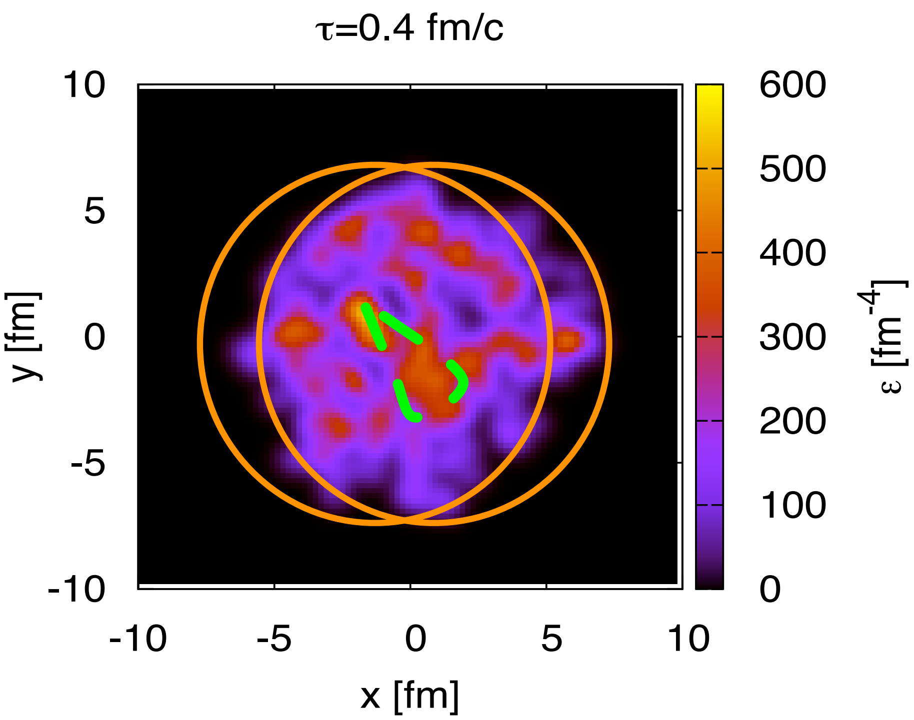

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$$v_2 = \langle \cos 2\phi_{\mathbf{p}} \rangle$$

2. Around almond shape are *fluctuations*

   Triangular Shape → v_3 Alver, Roland, 2010

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

3. Hot-spots give *correlated* higher harmonics

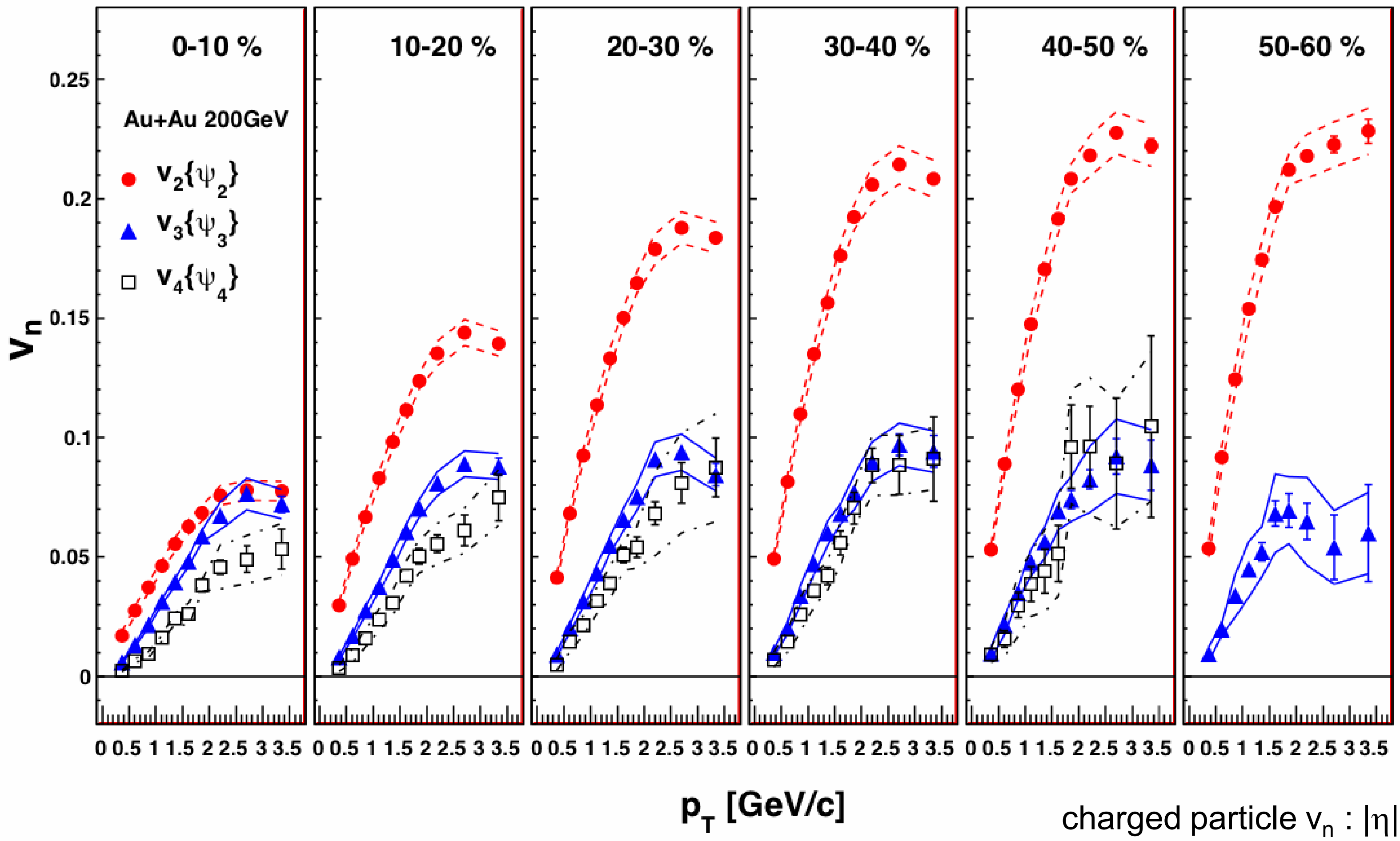
$$v_n = \langle \cos n(\phi_{\mathbf{p}} - \Psi_n) \rangle$$

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.

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

arXiv:1105.3928

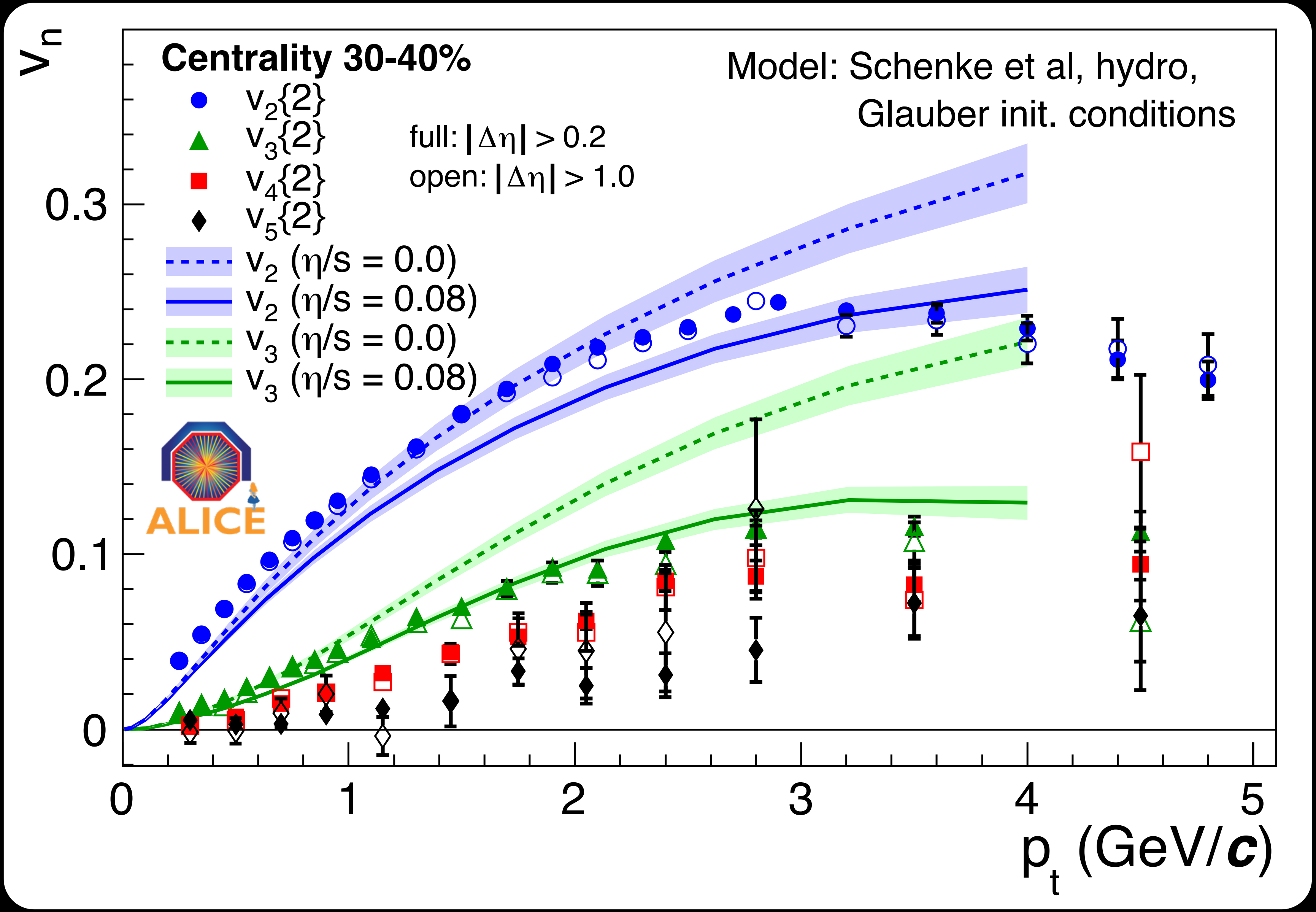


charged particle v_n : $|\eta|<0.35$
reaction plane Φ_n : $|\eta|=1.0\sim2.8$

(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



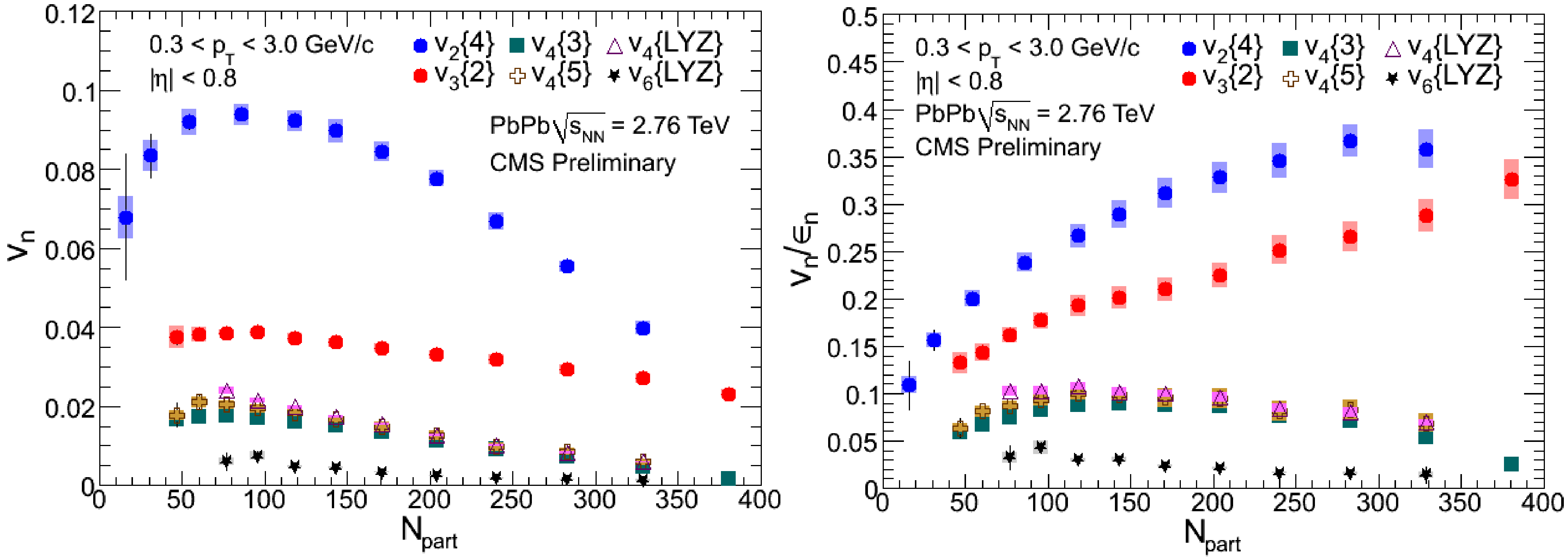
ALICE Collaboration, arXiv:1105.3865

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

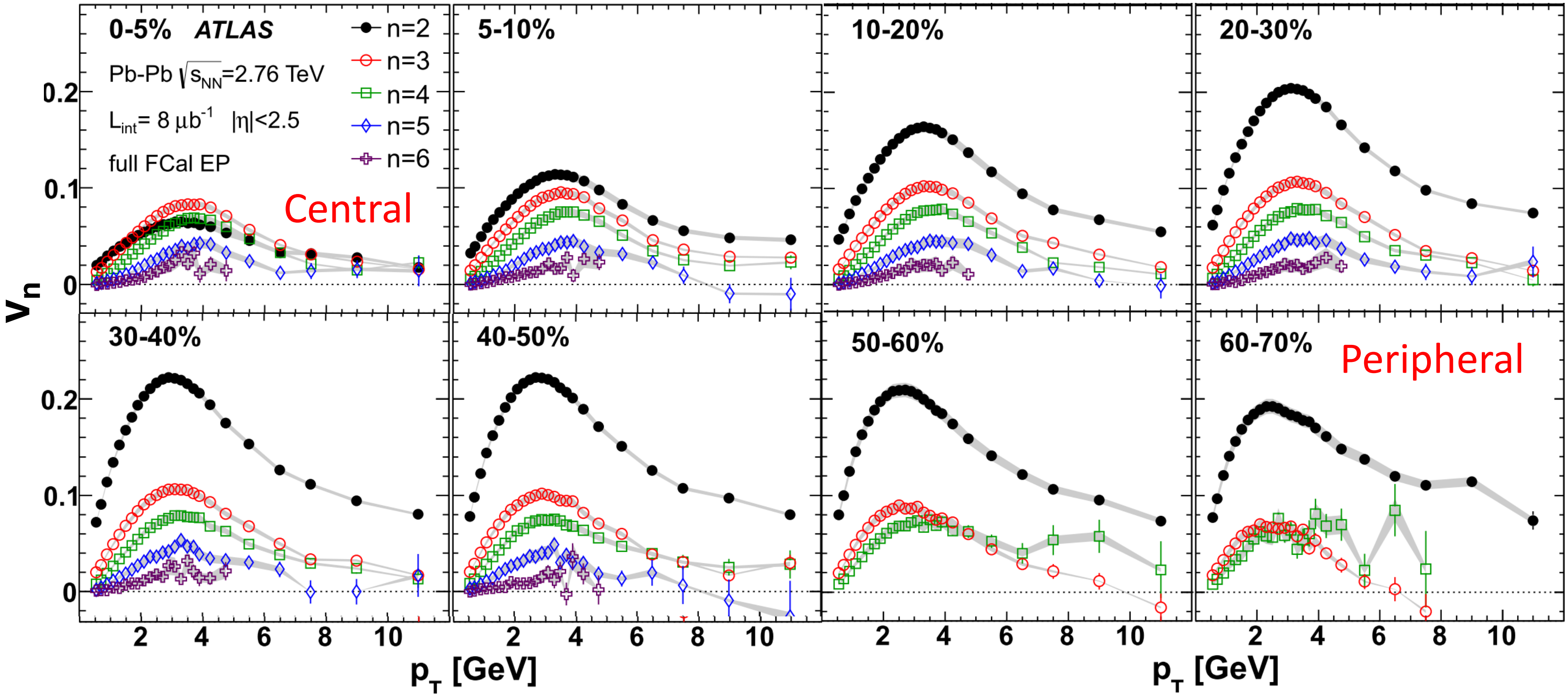
The full harmonic spectrum



- 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)



Central

Peripheral

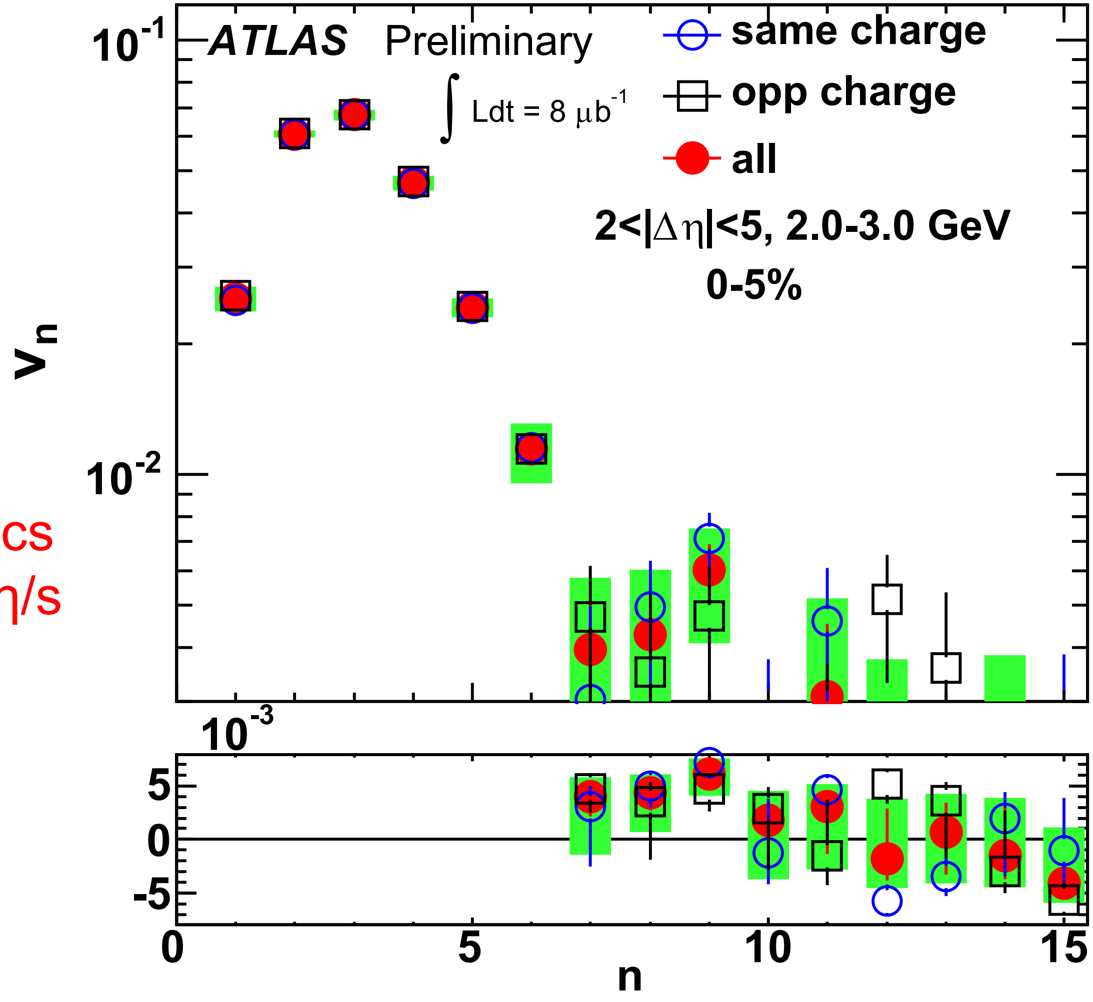
- Significant $v_2 - v_6$ are measured in broad range of p_T, η and centrality
- p_T dependence for all measured amplitudes show similar trend
- Stronger centrality dependence of v_2 than higher order harmonics
- In most central collisions (0-5%): v_3, v_4 can be larger than v_2

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

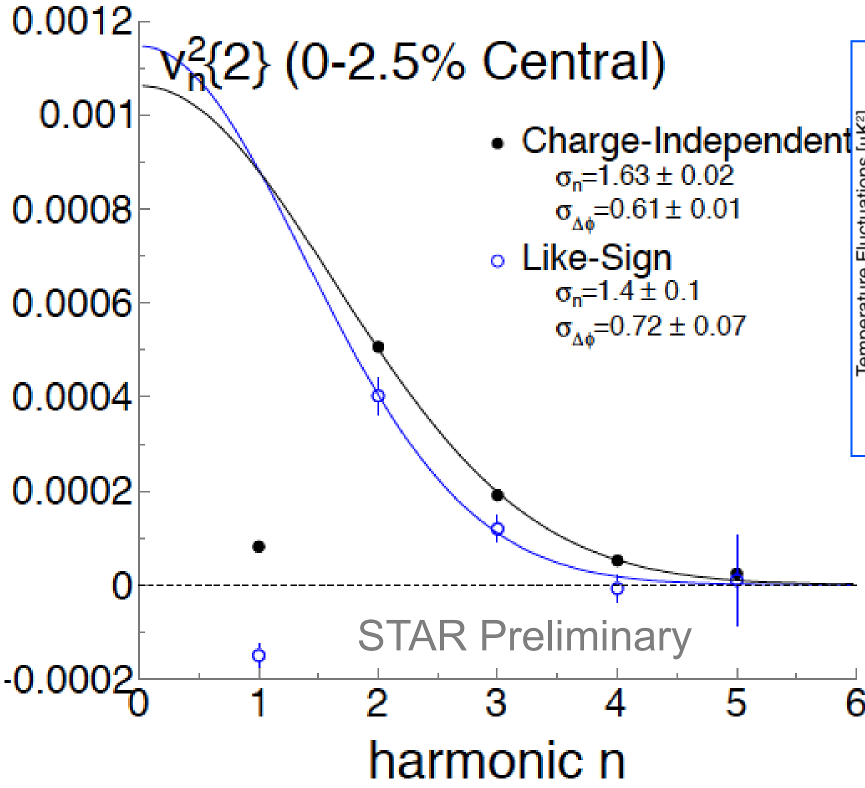
Damping of higher order harmonics provides important constraint on η/s

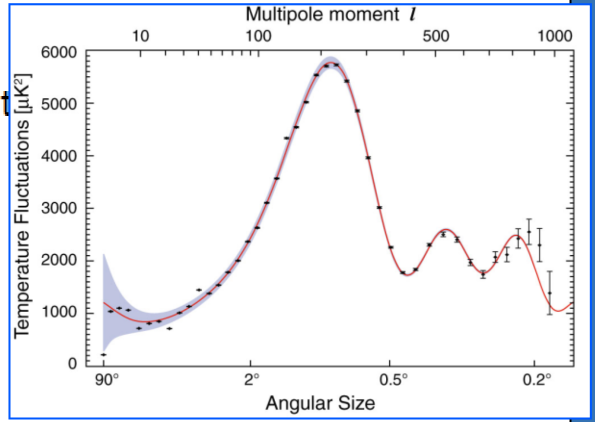


The error on $v_n=\sqrt{v_{n,n}}$ is highly non-Gaussian

$v_n^2\{2\}$ 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)…

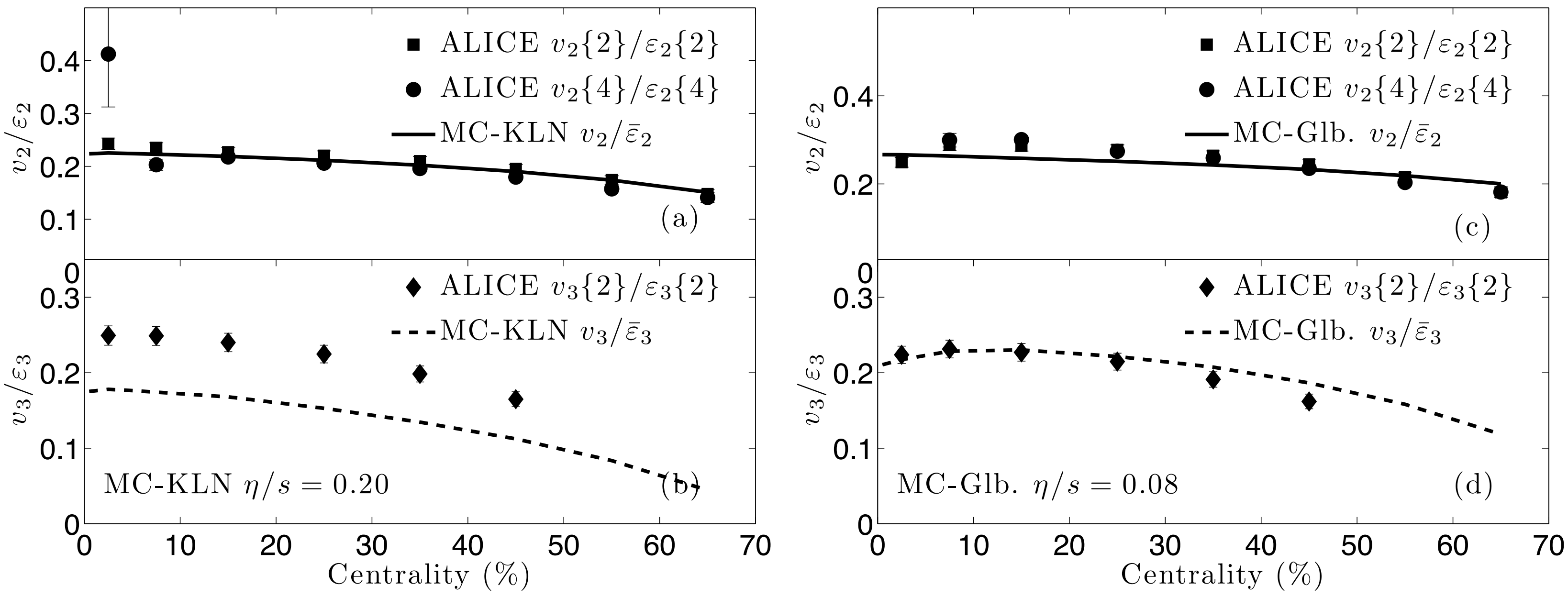
P. Staig and E. Shuryak, arXiv:1008.3139 [nucl-th]
A. Mocsy, P. S., arXiv:1008.3381 [hep-ph]
A. Adare [PHENIX], arXiv:1105:3928

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**

Early Responses to Flood of Data

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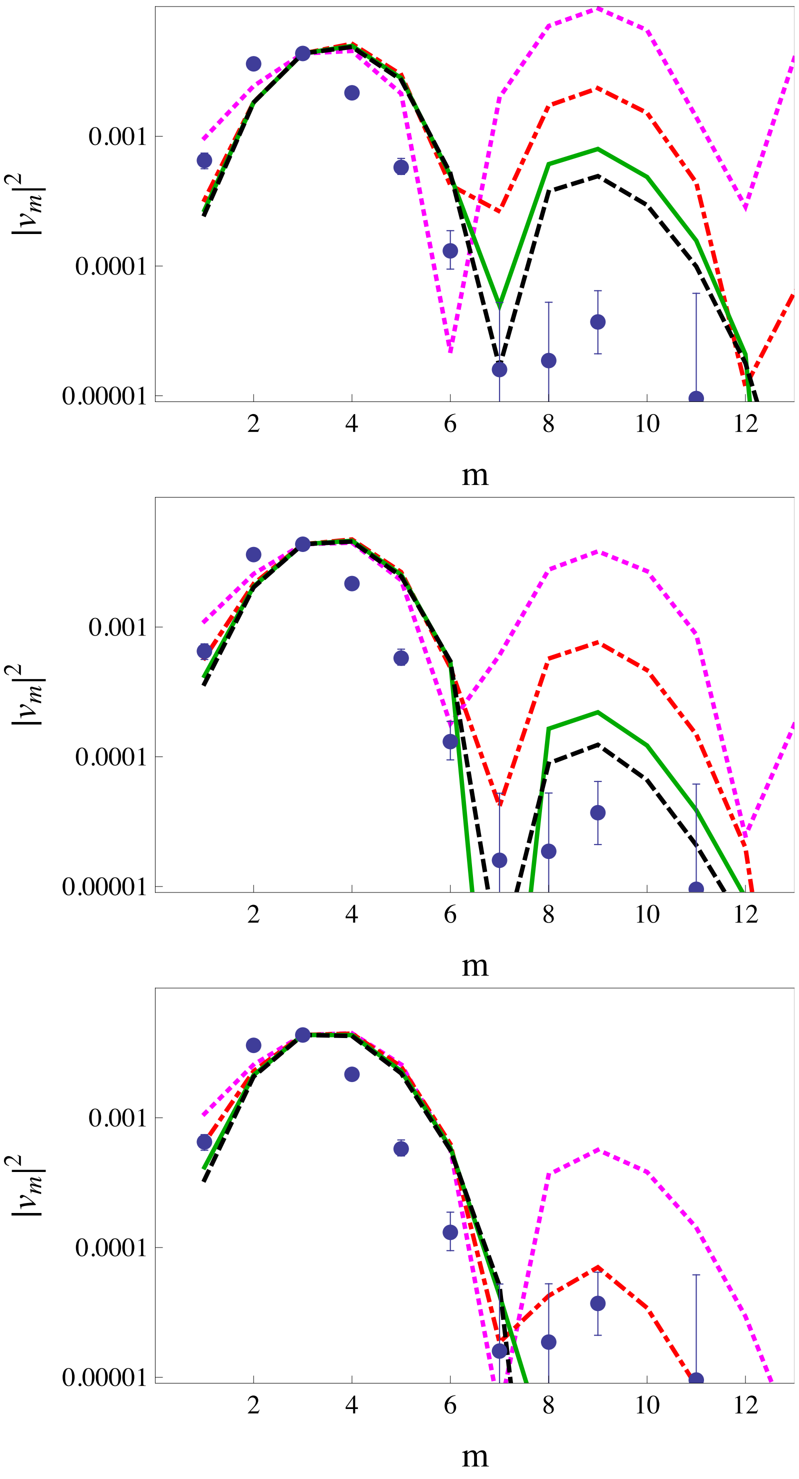
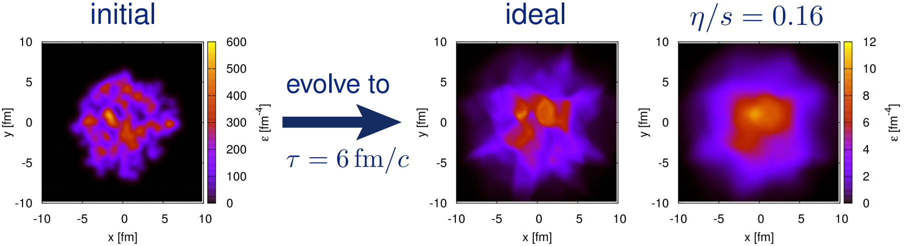


- **Analytic calculation of "shape" of v_n's in a simplified geometry with small fluctuations of a single size.**
- **Panels, top to bottom, are for fluctuations with size 0.4, 0.7 and 1 fm.**
- **Colors show varying η/s, with magenta, red, green, black being η/s =0, 0.08, 0.134, 0.16.**
- **Evidently,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

Staig, Shuryak, 1105.0676



initial

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

ideal

$\eta/s = 0.16$

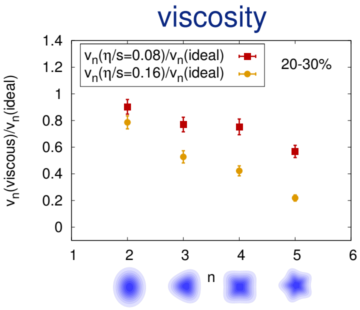
Flow analysis B. Schenke, S. Jeon, C. Gale, Phys. Rev. C85, 024901 (2012)

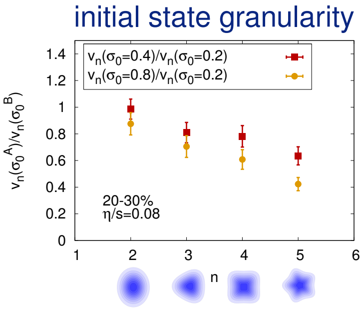
After Cooper-Frye freeze-out and resonance decays in each event we compute

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

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

Sensitivity of event averaged v_n on





Sensitivity to viscosity and initial state structure increases with n

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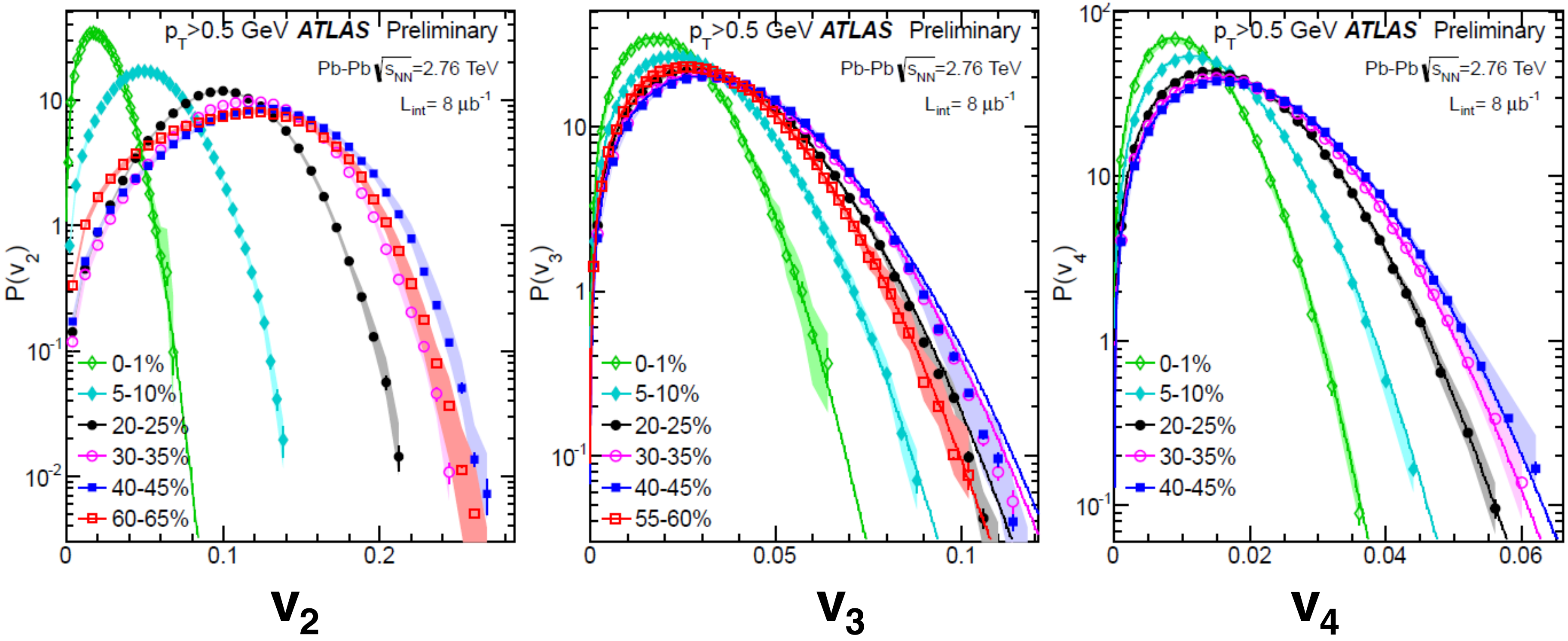
- Systematic, state-of-the-art, analyses are coming, but take longer. The shape of things to come . . .

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 $\langle v_n \rangle$
  - for v_2 only in the 0-2% of most central collisions
  - for v_3 and v_4 over all centralities

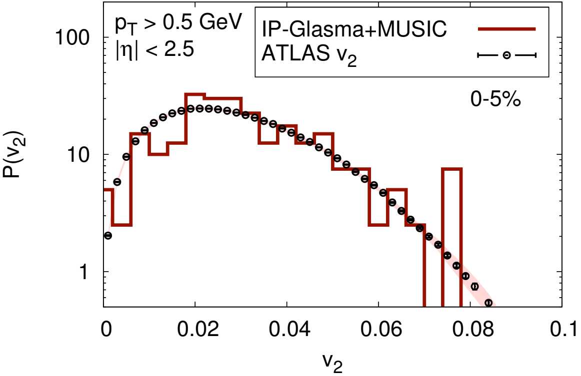
Direct measure of flow harmonics fluctuations

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.

Event-by-event distributions of v_n

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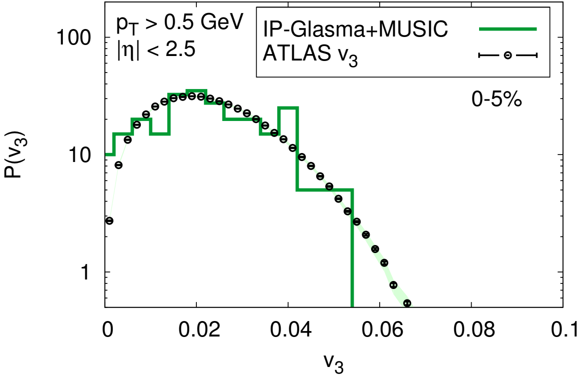

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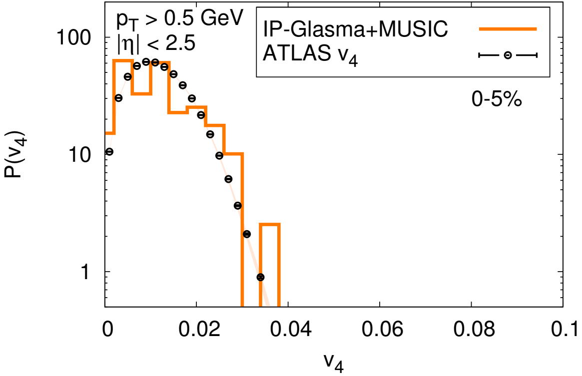
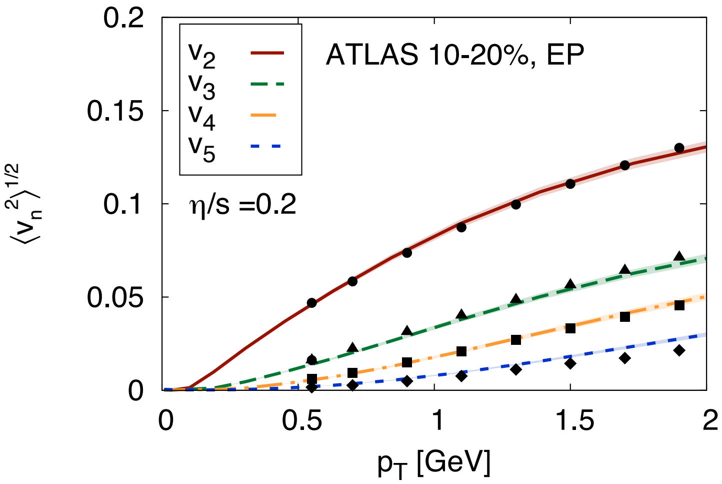
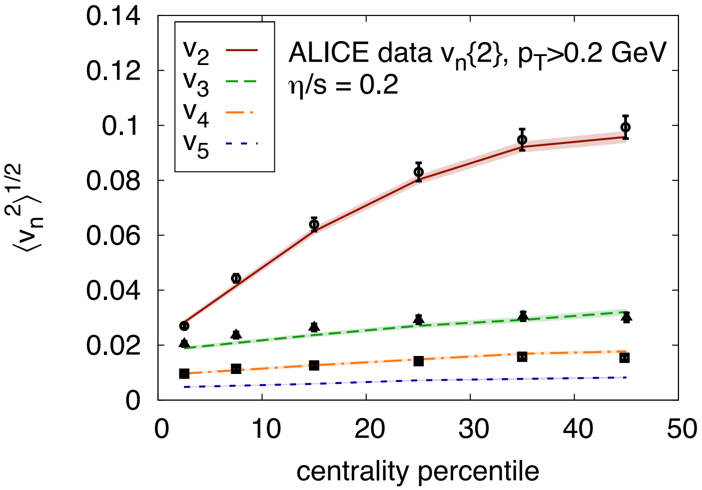


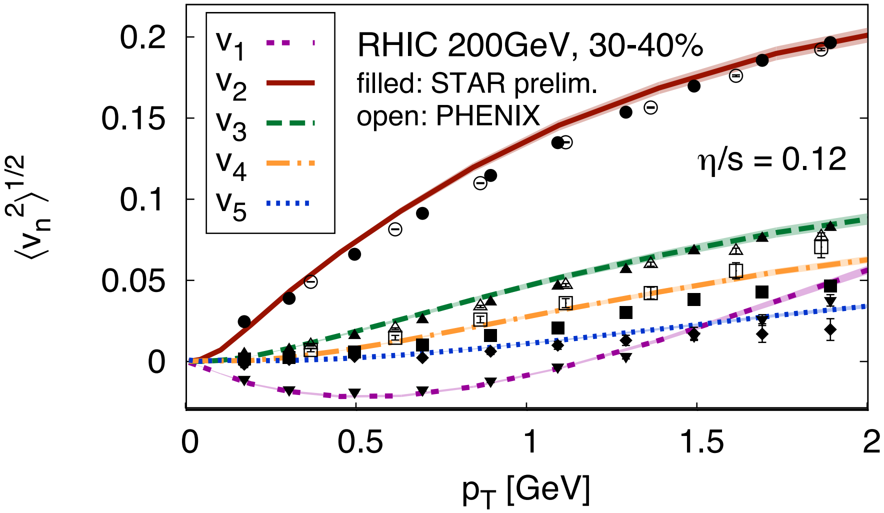
Preliminary results: Statistics to be improved.

Example of State-of-the-art

Gale, Jeon, Schenke, Tribedy, Venugopalan, 2013



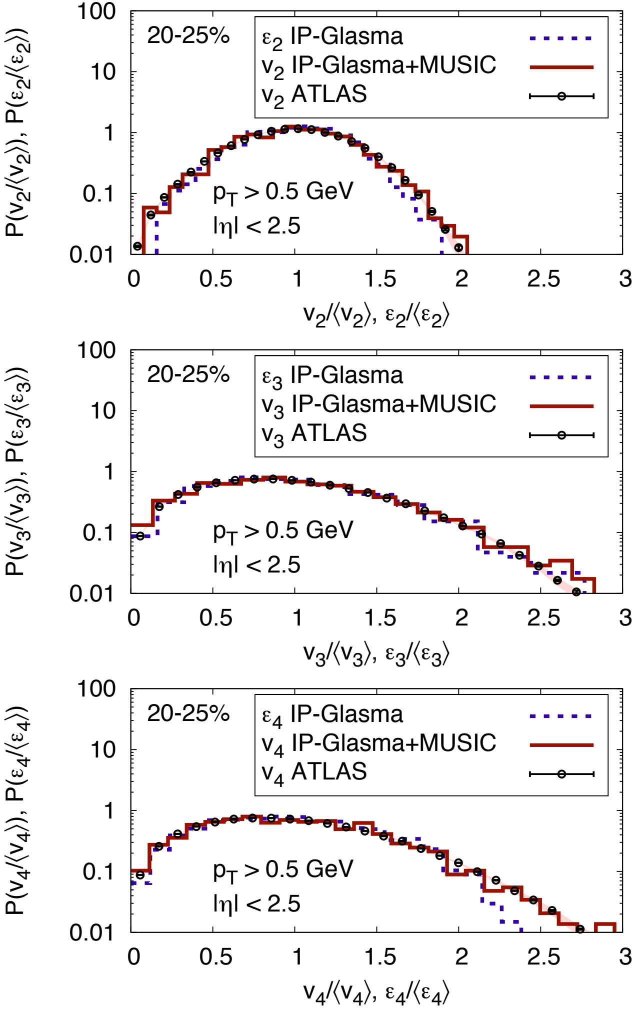




Good fit to RHIC data (with $\eta/s = 0.12$) and LHC data (with $\eta/s = 0.20$) for one model of initial fluctuations.

Example of State-of-the-art

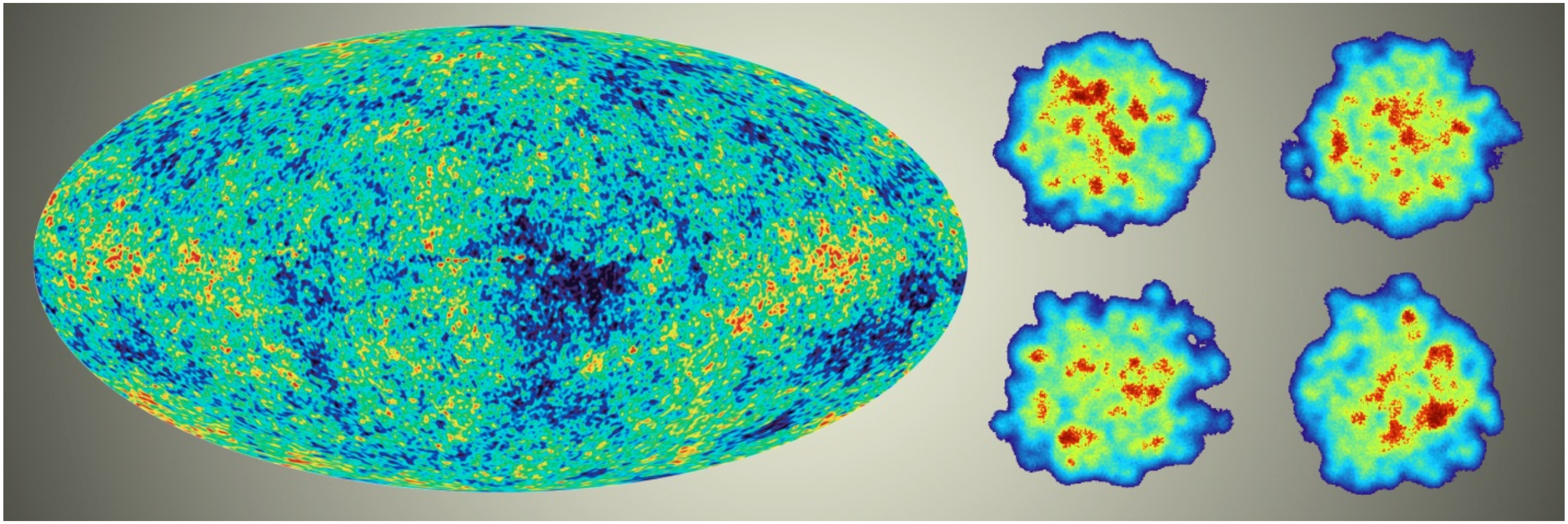
Gale, Jeon, Schenke, Tribedy, Venugopalan, 2013



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...

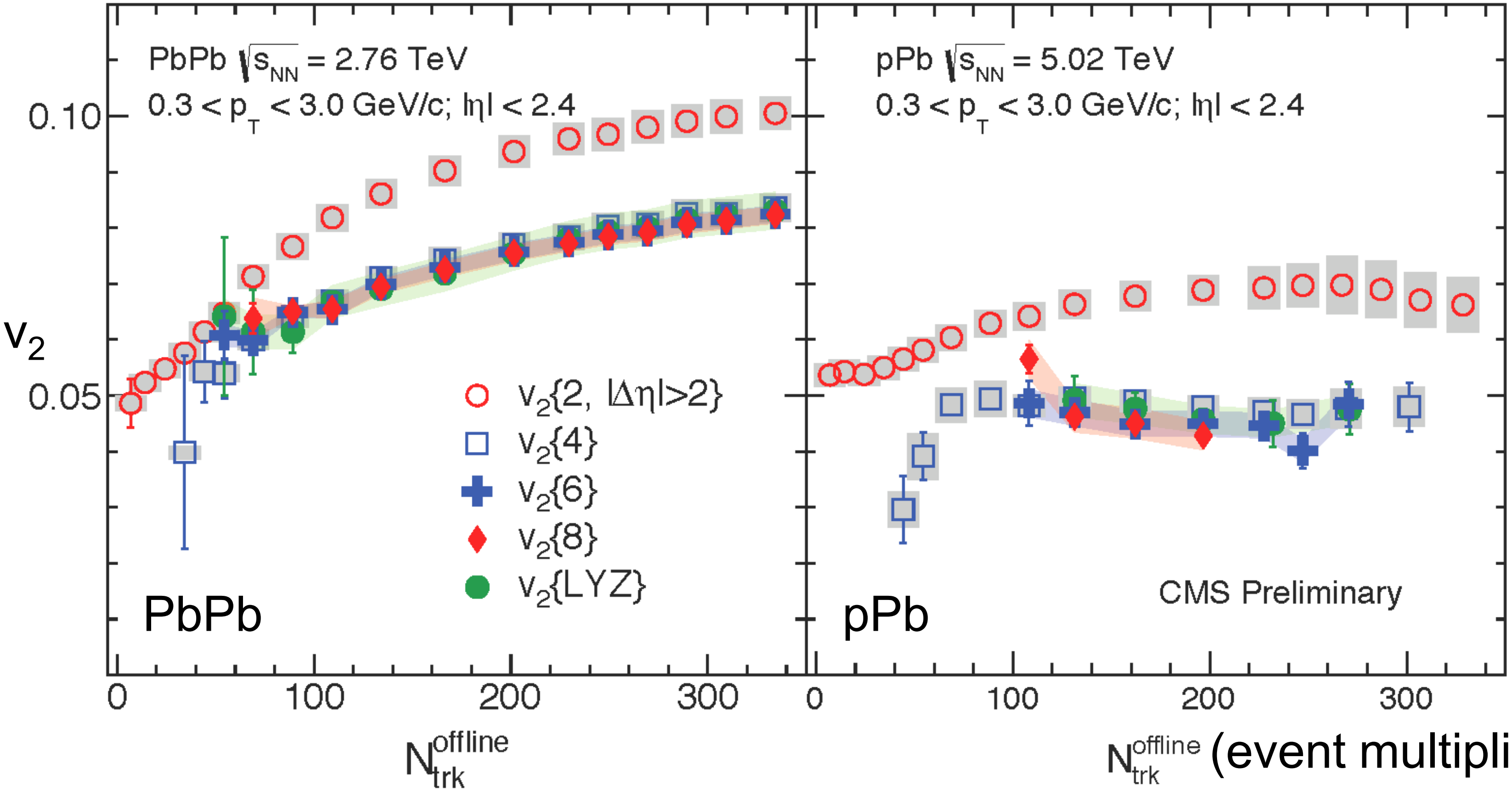
New Experiments

- 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...

Multiparticle correlations

- v_2 stays large when calculated with multi-particles
  - $v_2(4)=v_2(6)=v_2(8)=v_2(LYZ)$ within 10%
  - True collectivity in pPb collisions!

Talk by Wang
PAS-HIN-14-006

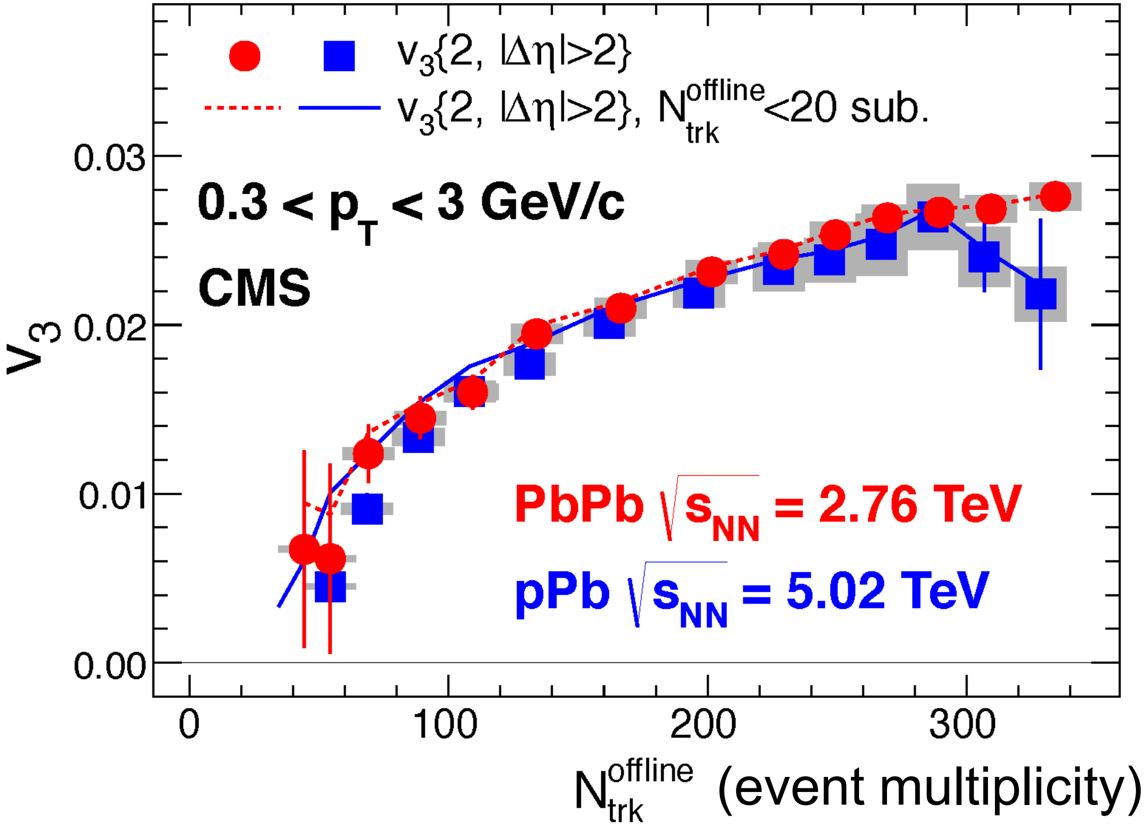


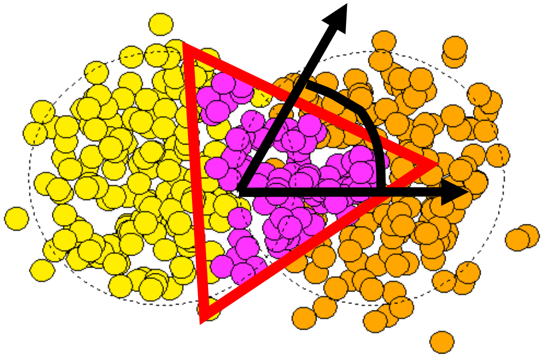
$N_{trk}^{offline}$ (event multiplicity)

Triangular flow

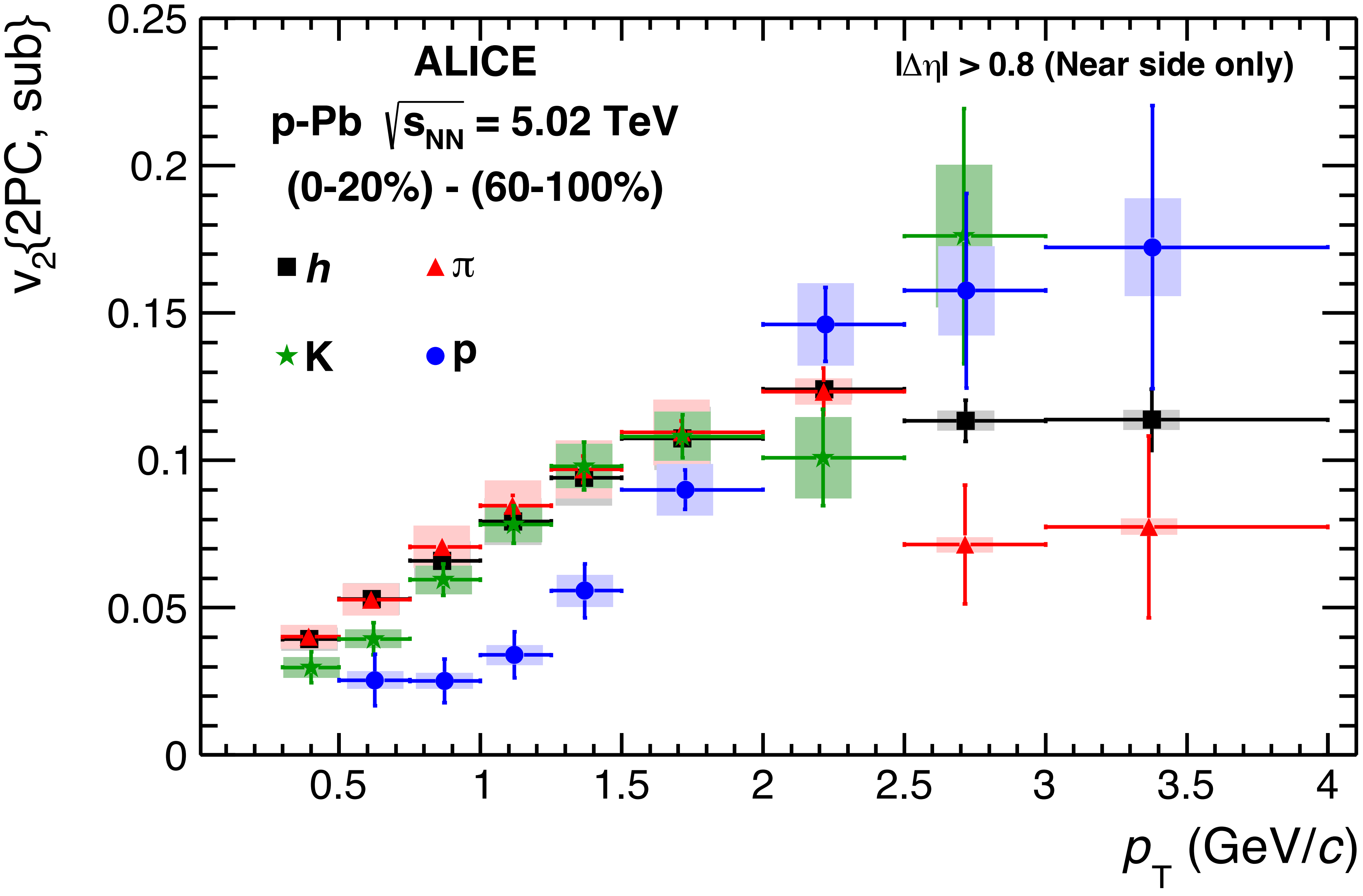
- Remarkable similarity in the v_3 signal as a function of multiplicity in pPb and PbPb

PLB724 (2013) 213





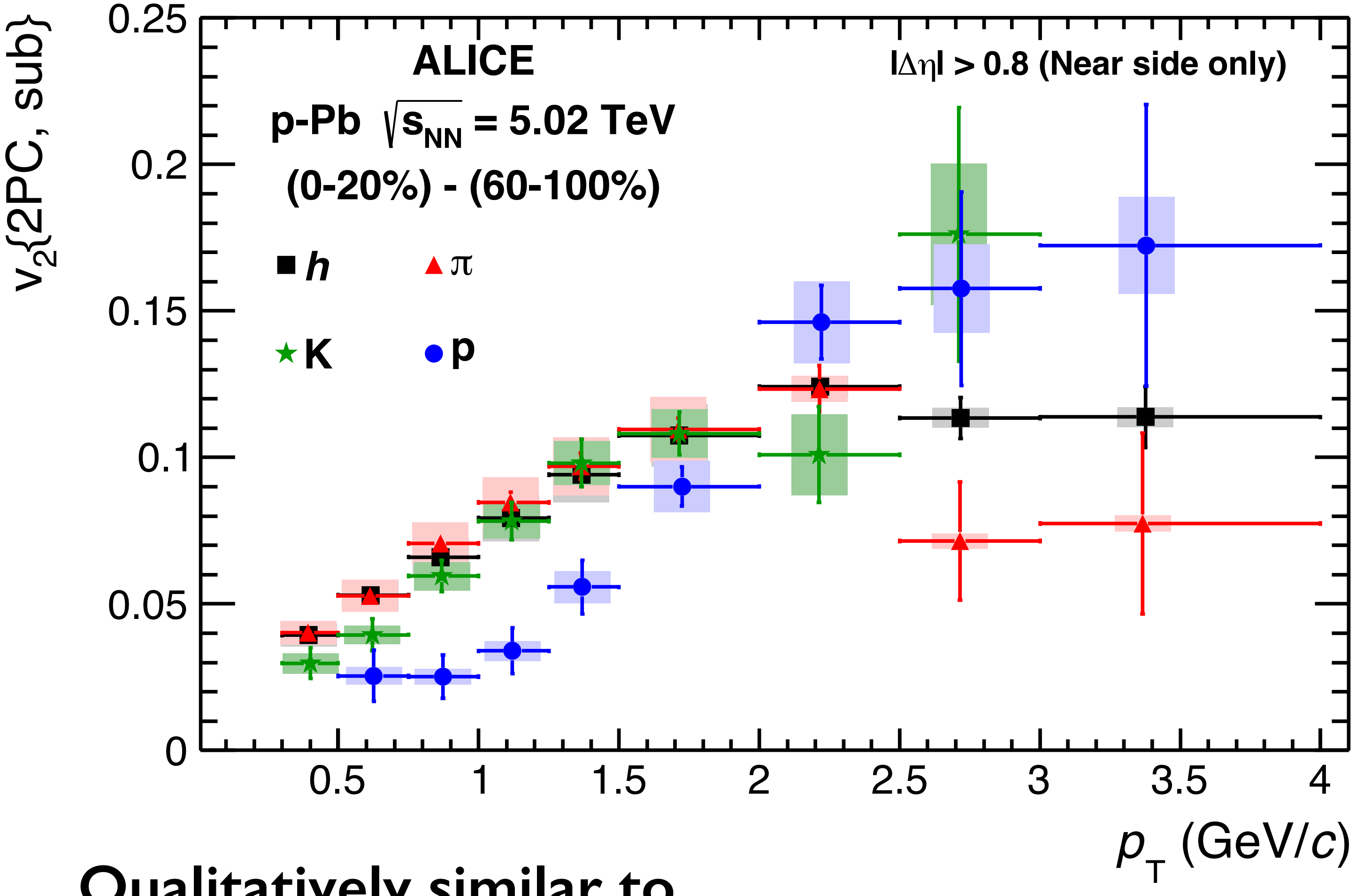
v_2 of π, K, p in high-multiplicity p-Pb



- $v_{2,\pi}$ similar to $v_{2,h}$
- hint of $v_{2,K}$ smaller than $v_{2,\pi}$ at low p_T
- $v_{2,p}$ smaller than $v_{2,\pi}$ below 2 GeV/*c* and larger above
- crossing at about 2 GeV/c

ALICE, Physics Letters B 726 (2013) 164-177

v_2 of π, K, p in high-multiplicity p-Pb



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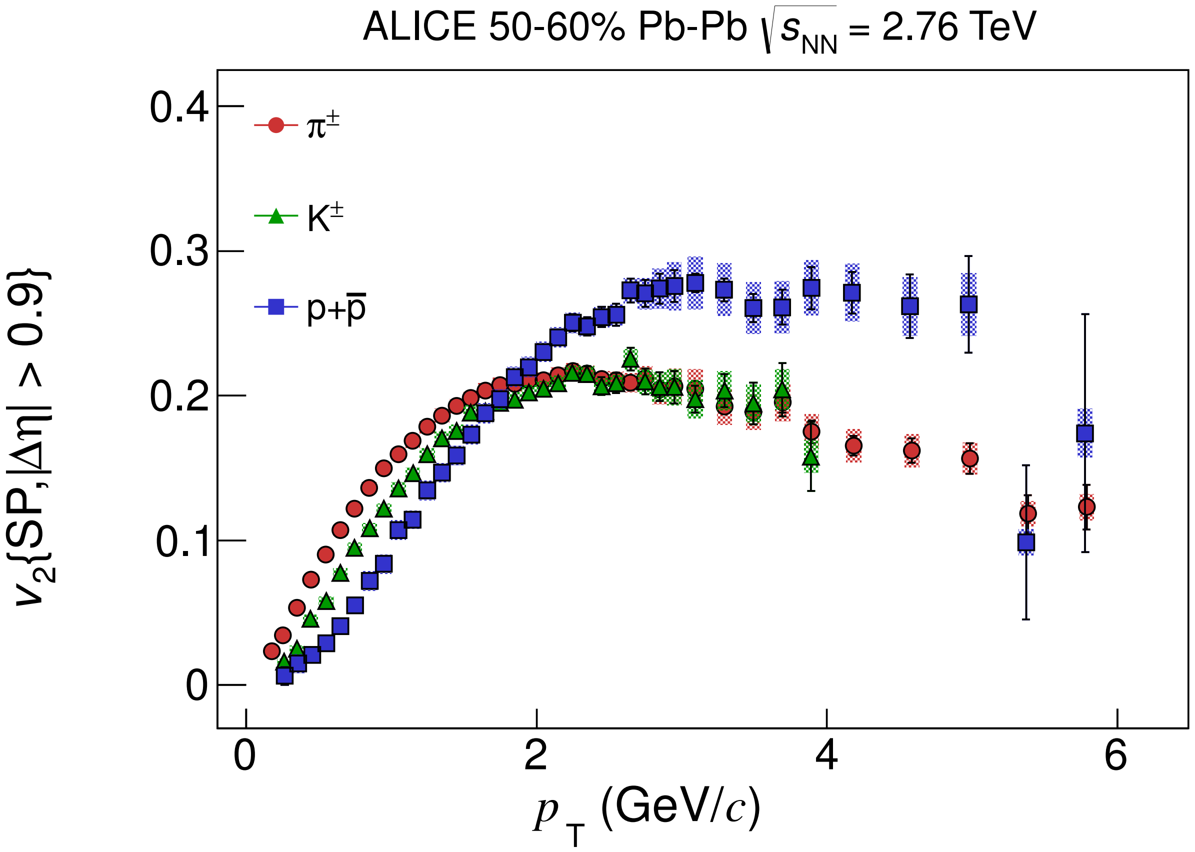
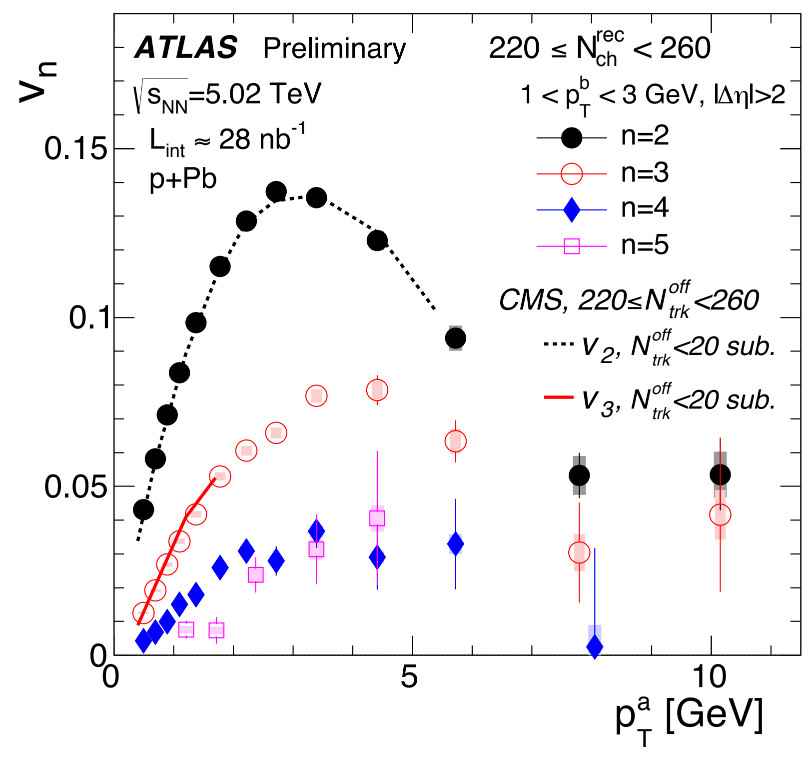


arXiv:1405.4632 [nucl-ex]

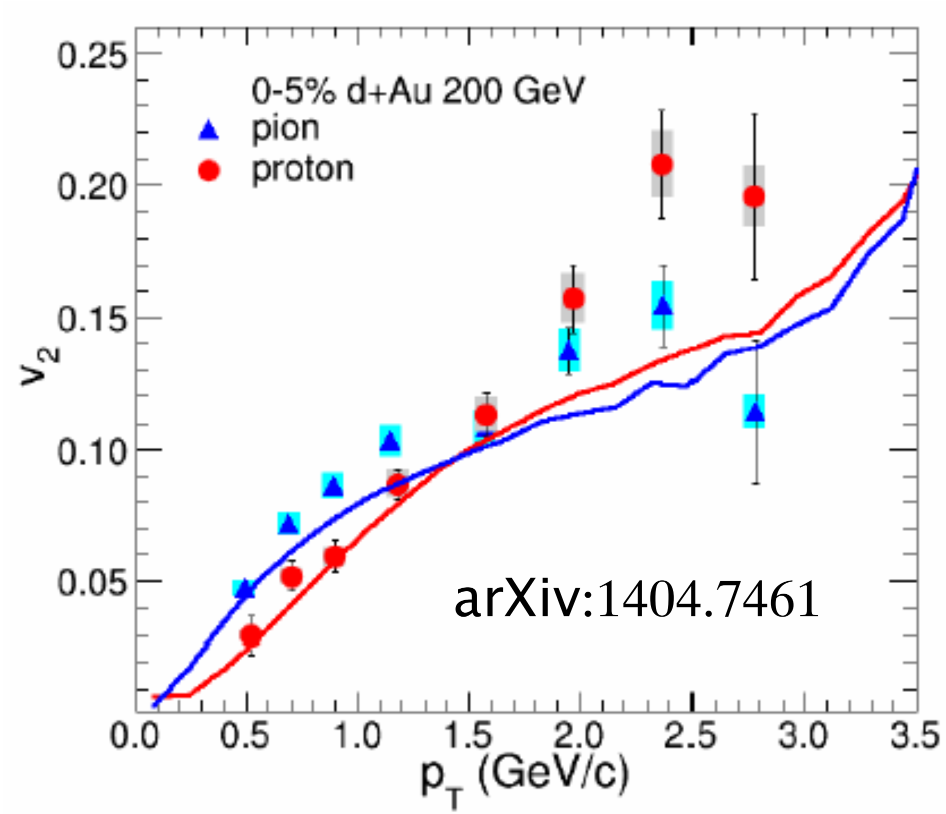
Qualitatively similar to Pb-Pb collisions

p+Pb 2-particle $v_n(p_T)$

- **Observe:**
  - significant values for n = 2,3,4,5
    - ⇒For n = 2,3 to 10 GeV



d+Au @ 200 GeV: Flow in Small Systems?



v_2 measured with 2.75 unit rapidity gap between EP and particle

Characteristic mass ordering is observed

Viscous Hydrodynamics (η/s = 1/4π) + Hadronic Cascade qualitatively describes features.

Hydrodynamics in pPb collisions?

- Almost nobody expected this. pPb collisions supposed to be a control experiment. Too small for hydrodynamics.
- But... how small is too small for hydrodynamics? In $\mathcal{N}=4$ SYM plasma, hydro applies to arbitrarily small droplet. Not so in QCD. But, how small is too small?
- But... how large *is* the 'hot-spot' made when a proton blasts through a nucleus? Maybe as large as 2-3 fm across?? [Bozek] If hydro describes this, that is 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'?
- 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.

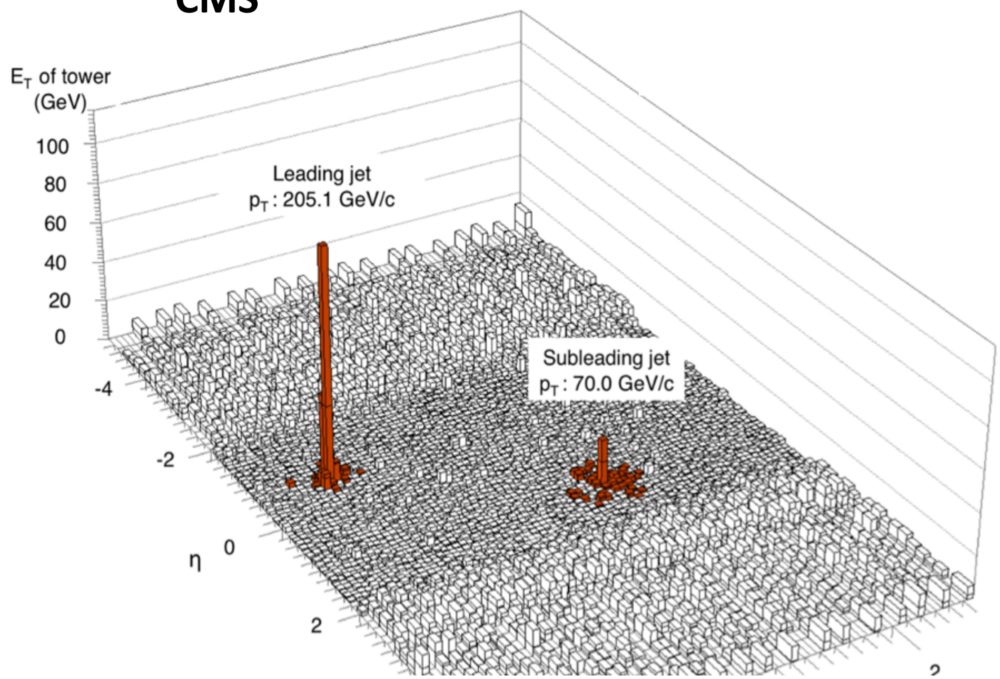
- We can quantify the properties and dynamics of Liquid QGP at it's natural length scales, where it has no quasiparticles.

- 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.

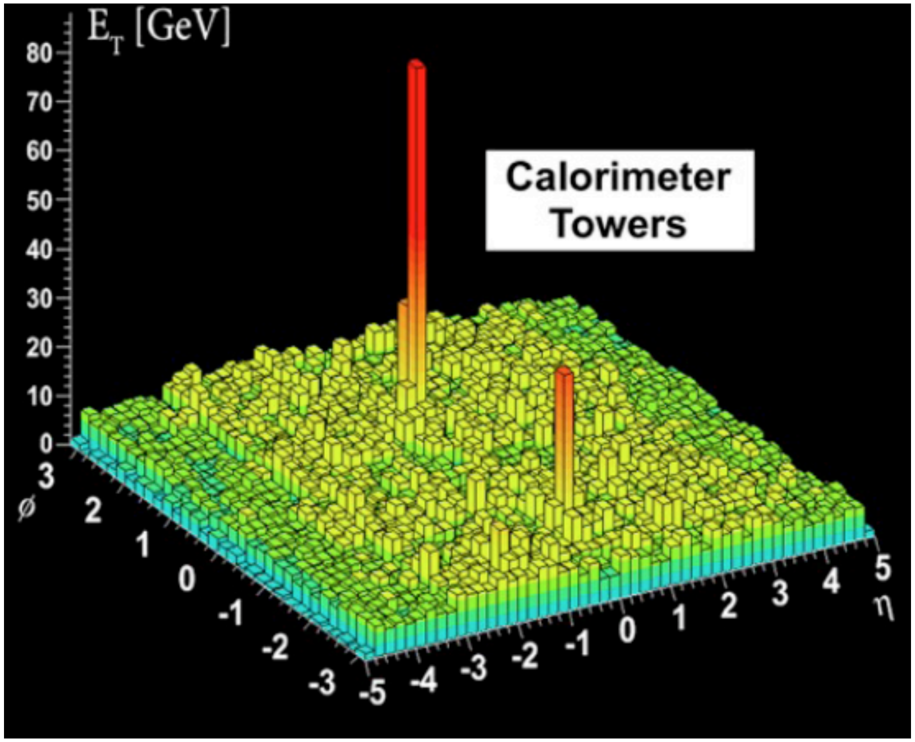
- The LHC and newly upgraded RHIC offer new probes and open new frontiers.

Jet Quenching at the LHC

CMS



ATLAS



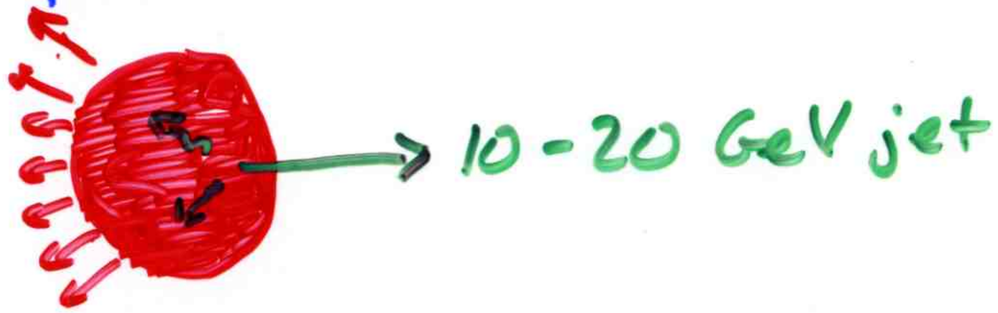
A very large effect at the LHC. 200 GeV jet back-to-back with a 70 GeV jet. A strongly coupled plasma indeed.... Jet quenching was discovered at RHIC (via the associated diminution in the number of high-p_T hadrons) but here it is immediately apparent in a single event.

Jet Quenching @ LHC

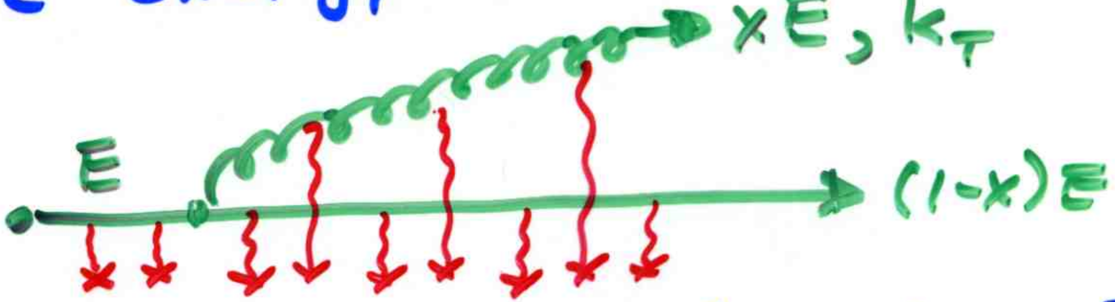
- Jet quenching apparent at the LHC, eg in events with, say, 205 GeV jet back-to-back with 70 GeV jet.
- But, the 70 GeV jet looks almost like a 70 GeV jet in pp collisions. It has lost a lot of energy passing through the QGP but emerges looking otherwise ordinary. Almost same fragmentation function; 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. ($E \gg k_T \gg T$)

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: $\omega \frac{dI}{d\omega} \sim \alpha \sqrt{\frac{\hat{q}}{\omega}} L$

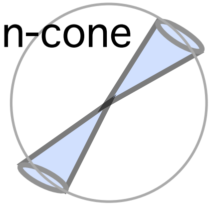
for $\omega < \hat{q} L^2$

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

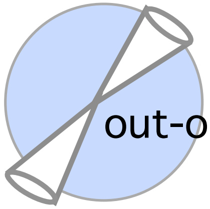
Jet Quenching @ LHC

- 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.

Missing-$p_T^{||}$

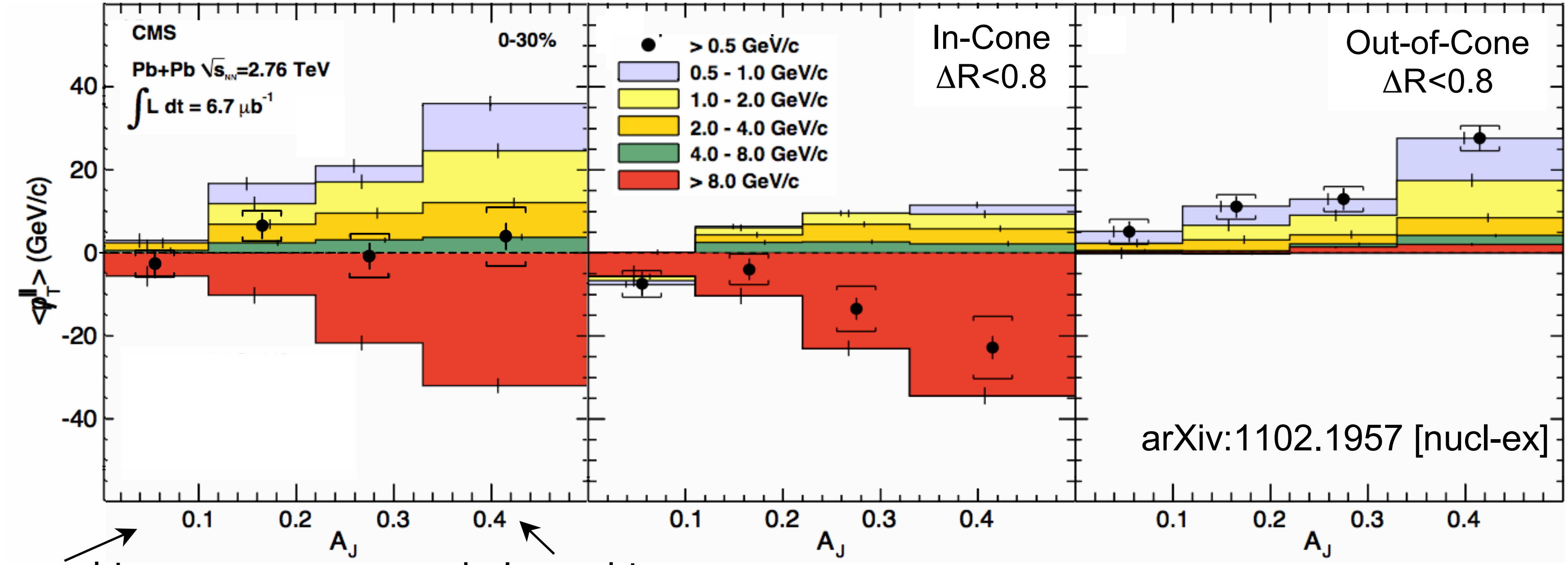


in-cone



out-of-cone

0-30% Central PbPb



arXiv:1102.1957 [nucl-ex]

balanced jets

unbalanced jets

- 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’ ...

Some Jet Quenching Questions

- How can a jet plowing through strongly coupled quark-gluon plasma lose a decent fraction of its energy and still emerge looking pretty much like an ordinary jet?
- Partial answer: if "lost" energy ends up as soft particles with momenta $\sim \pi T$ with directions (almost) uncorrelated with jet direction. Eg more, or hotter, or moving, plasma. Natural expectation in a strongly coupled plasma...
- Still, how do the jets themselves emerge from the strongly coupled plasma looking so similar to vacuum jets?
- Best way to answer this question: a hybrid approach to jet quenching. Treat hard physics with pQCD and energy loss as at strong coupling, see what happens, for example to jet fragmentation functions, and compare to data.
- But, what is dE/dx for a "parton" in the strongly coupled QGP in $\mathcal{N} = 4$ SYM theory? And, while we are at it, what do "jets" in that theory look like when *they* emerge from the strongly coupled plasma of *that* theory?

What happens to the lost energy?

- **Initially, hydrodynamic modes with wave vector $\lesssim \pi T$.**
- **The attenuation distance for sound with wave vector q is**

$$x_{\text{damping}}^{\text{sound}} = v^{\text{sound}} \frac{1}{q^2} \frac{3Ts}{4\eta}$$

which means that for $q \sim \pi T$ (or $q \sim \pi T/2$) and $v^{\text{sound}} \sim 1/\sqrt{3}$ and $\eta/s \sim 2/4\pi$ we have

$$x_{\text{damping}}^{\text{sound}} \sim \frac{0.3}{T} \left(\text{or} \sim \frac{1.2}{T} \right) .$$

- **Energy lost more than a few $x_{\text{damping}}^{\text{sound}}$ before the jet emerges will have thermalized, becoming soft particles in random directions. Only the energy lost within a few $x_{\text{damping}}^{\text{sound}}$ before the jet emerges will persist as sound waves moving in roughly the same direction as the jet, resulting in a pile of soft particles around the jet. Should be easier to see in lower temperature plasma, where $x_{\text{damping}}^{\text{sound}}$ is longer.**

Some Jet Quenching Questions

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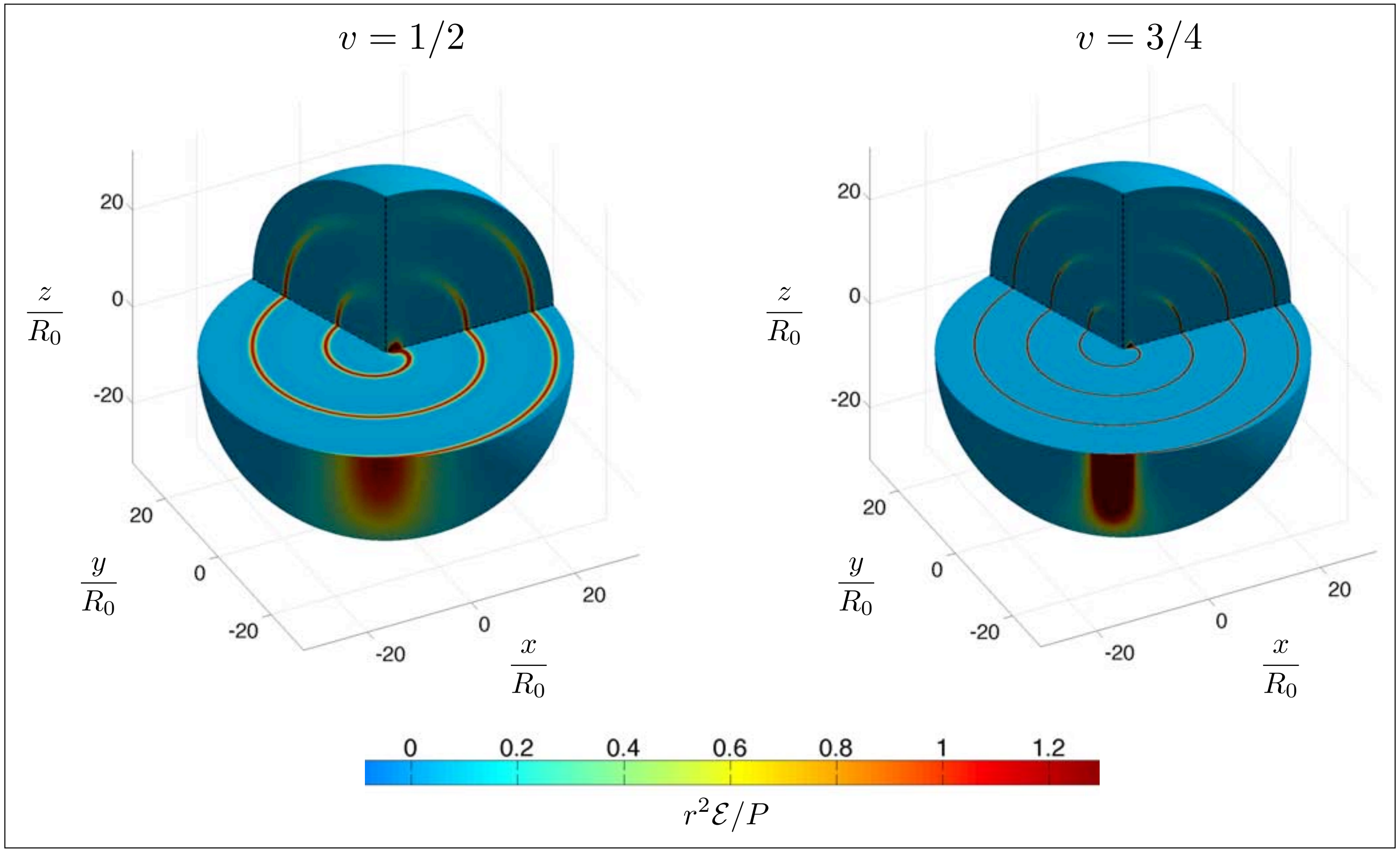
One More Question

- So, why did I write "jets" instead of jets? Which is to say, what is a jet in $\mathcal{N}=4$ SYM theory, anyway? There is no one answer, because hard processes in $\mathcal{N}=4$ SYM theory don't make jets. Hatta, Iancu, Mueller; Hofman, Maldacena.
- The formation of (two) highly virtual partons (say from a virtual photon) and the hard part of the fragmentation of those partons into jets are all weakly coupled phenomena, well described by pQCD.
- Nevertheless, different theorists have come up with different "jets" in $\mathcal{N}=4$ SYM theory, namely proxies that share some features of jets in QCD, and have then studied the quenching of these "jets".
- For example, Chesler, Ho and KR (arXiv:1111.1691) made a collimated gluon beam, and watched it get quenched by the strongly coupled plasma. Qualitative lessons, including about stopping length, but no quantitative calculation of energy loss.

Synchrotron Radiation in Strongly Coupled Gauge Theories

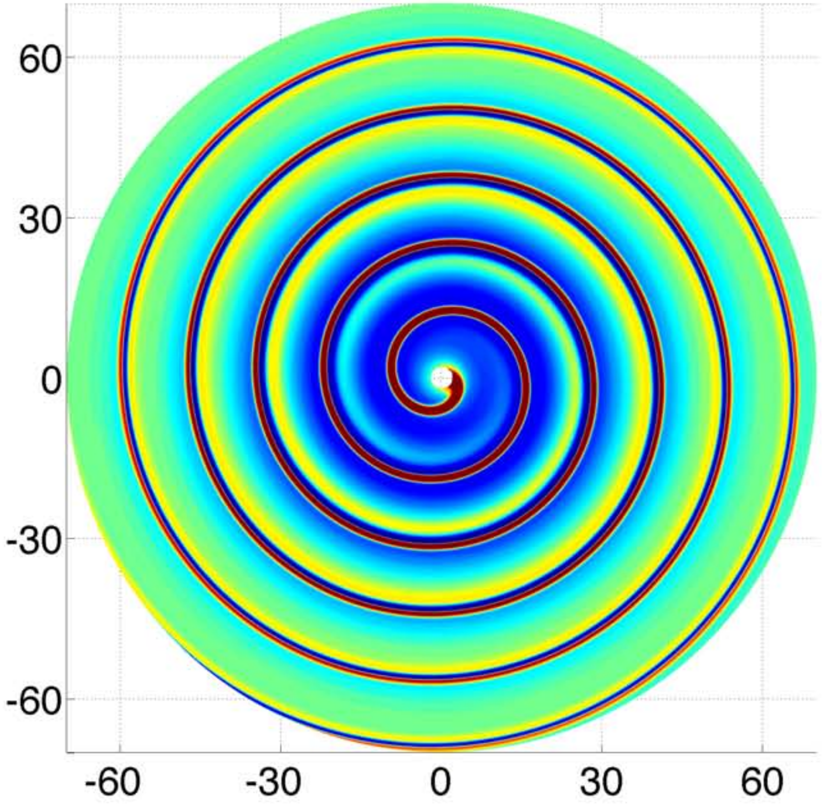
Athanasiou, Chesler, Liu, Nickel, Rajagopal; arXiv:1001.3880

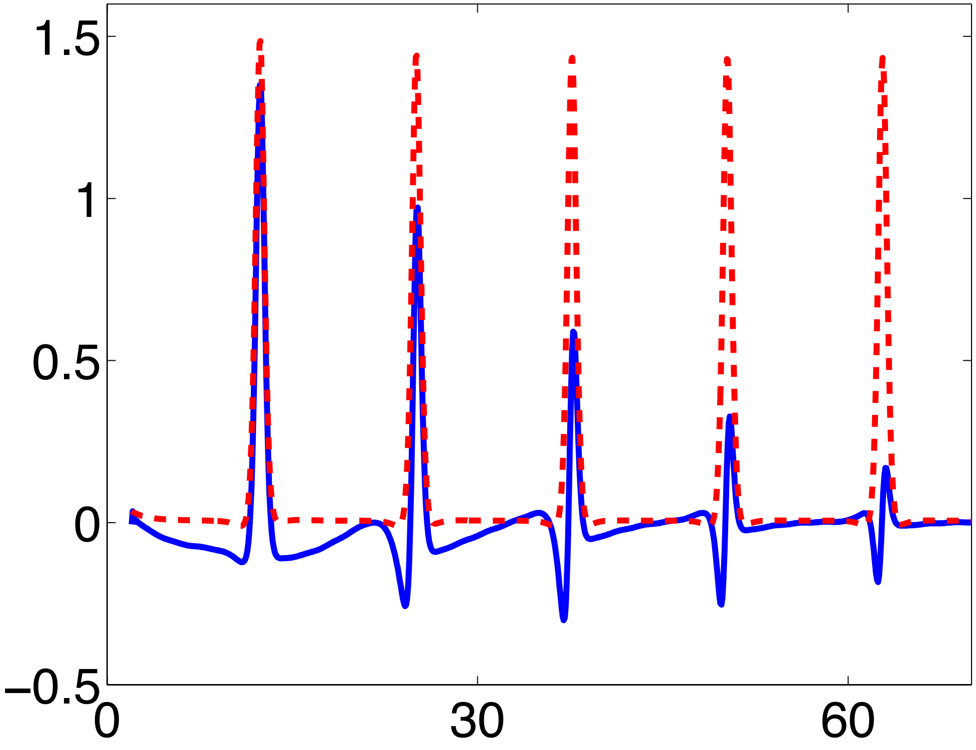


Fully *quantum mechanical* **calculation of gluon radiation from a rotating quark in a** *strongly coupled* **large** N_c *non abelian* **gauge theory, done via gauge/gravity duality. "Lighthouse beam" of synchrotron radiation. Surprisingly similar to classical electrodynamics. Now, shine this beam through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

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691

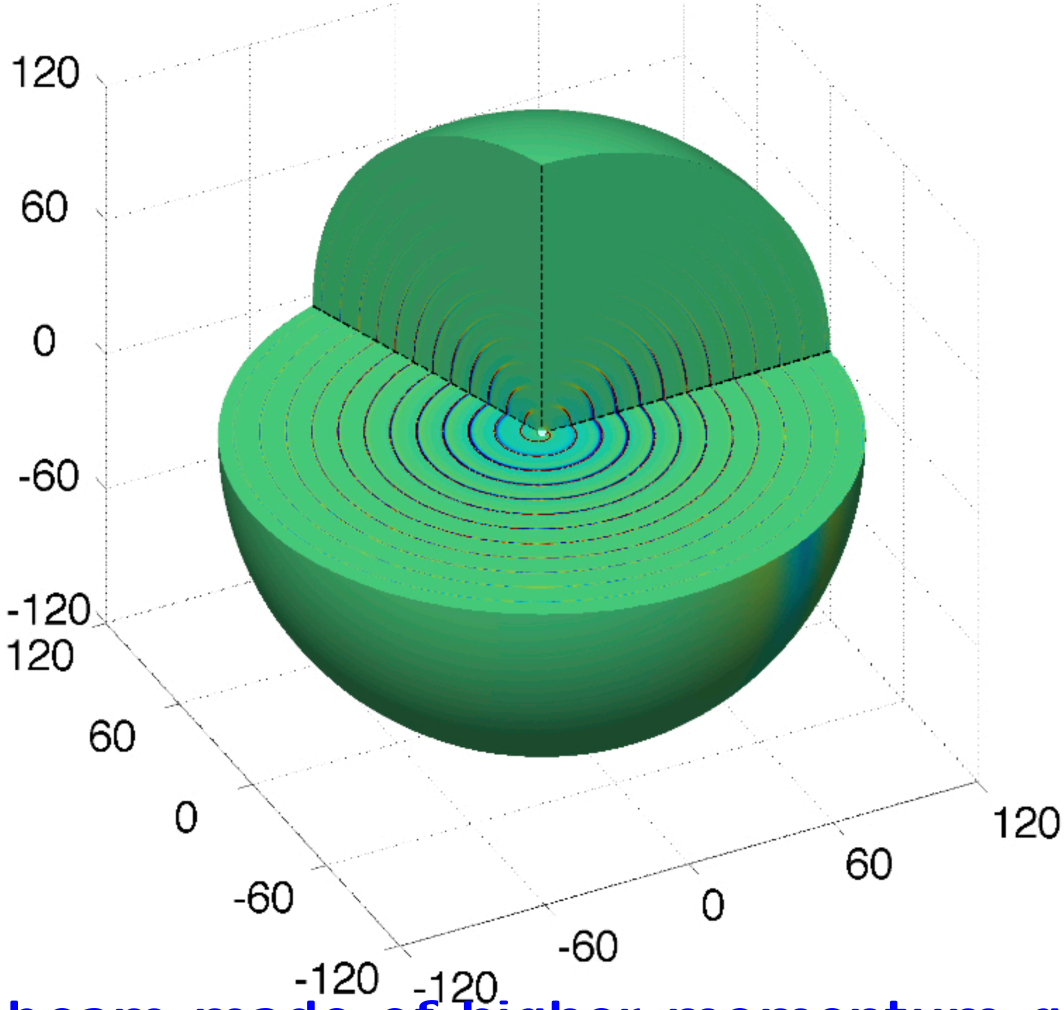




Quark in circular motion ($v = 0.5$; $R\pi T = 0.15$) makes a beam of gluons that is attenuated dramatically by the plasma, without being significantly broadened — in angle or in momentum distribution.

Quenching a Beam of Gluons

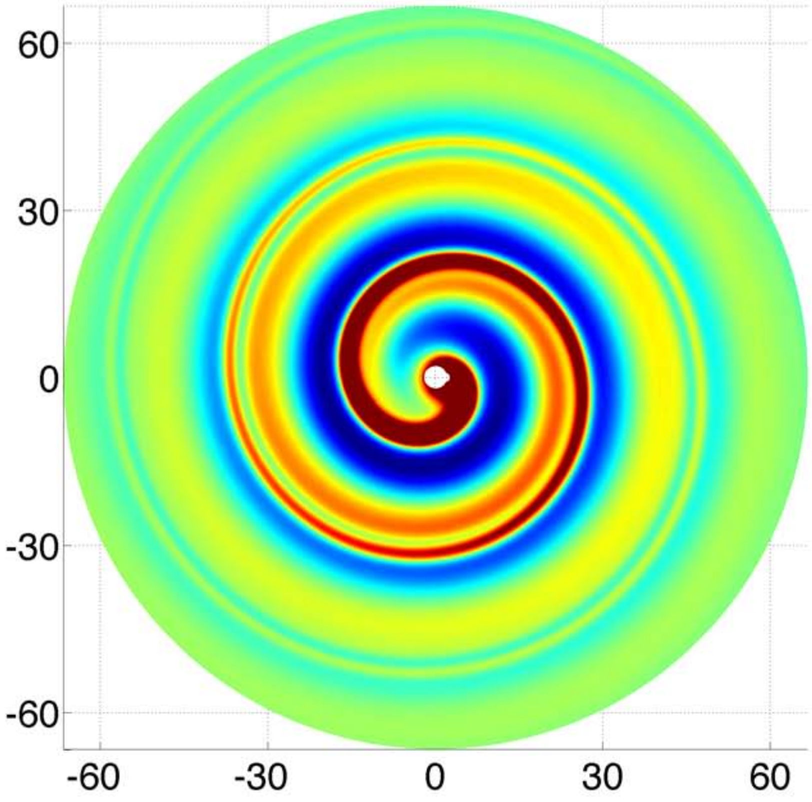
Chesler, Ho, Rajagopal, arXiv:1111.1691

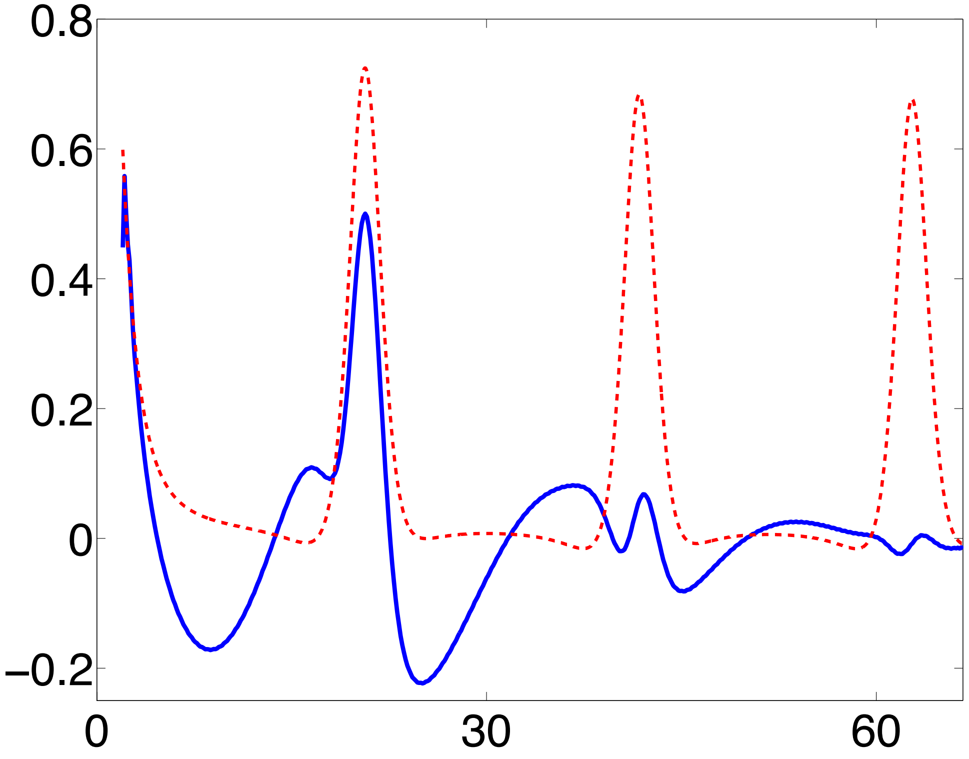


A narrower beam made of higher momentum gluons travels farther, still gets attenuated without spreading in angle or degradation of its momentum distribution.

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

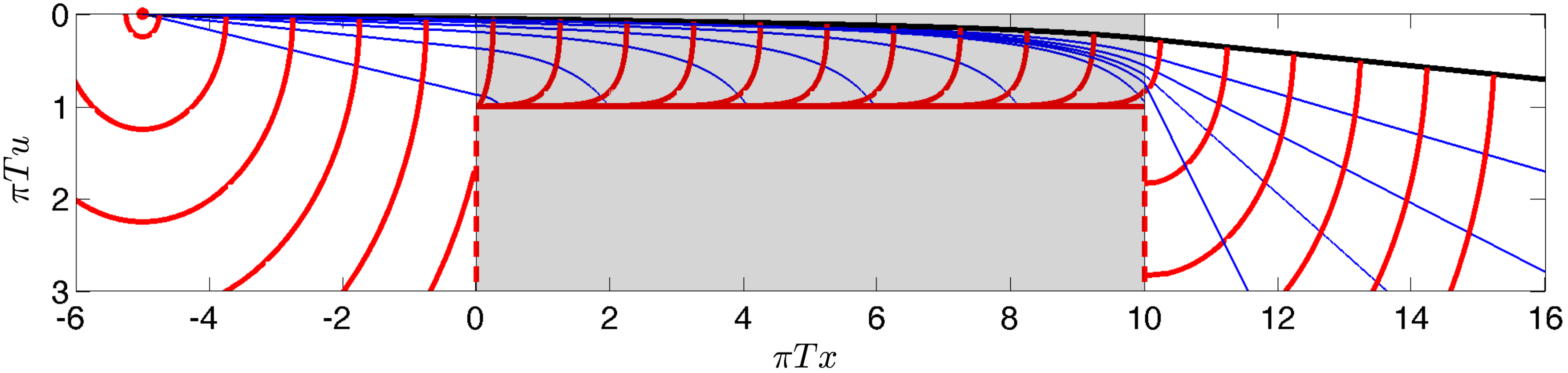
- **A beam of gluons with wave vector $q \gg \pi T$ shines through the strongly coupled plasma at close to the speed of light, and is attenuated over a distance $\sim q^{1/3}(\pi T)^{-4/3}$.**
- **Beam shows no tendency to spread in angle, or shift toward longer wavelengths, even as it is completely 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.)**

What have we done?

- We take a highly boosted light quark (Gubser et al; Chesler et al; 2008) and shoot it through a slab of strongly coupled plasma. (G and C et al computed the stopping distance for such "jets" in infinite plasma.)
- We do the AdS/CFT version of the "brick of plasma problem". (As usual, brick of plasma is not a hydrodynamic solution.)
- Focus on what comes out on the other side of the brick. How much energy does it have? How does the answer to that question change if you increase the thickness of the brick from x to $x + dx$? That's dE/dx.
- Yes, what goes into the brick is a "jet", not a pQCD jet. But, we can nevertheless look carefully at what comes out on the other side of the brick and compare it carefully to the "jet" that went in.
- Along the way, we will get a fully geometric characterization of energy loss. Which is to say a new form of intuition.

Quenching a Light Quark “Jet”

Chesler, Rajagopal, 1402.6756

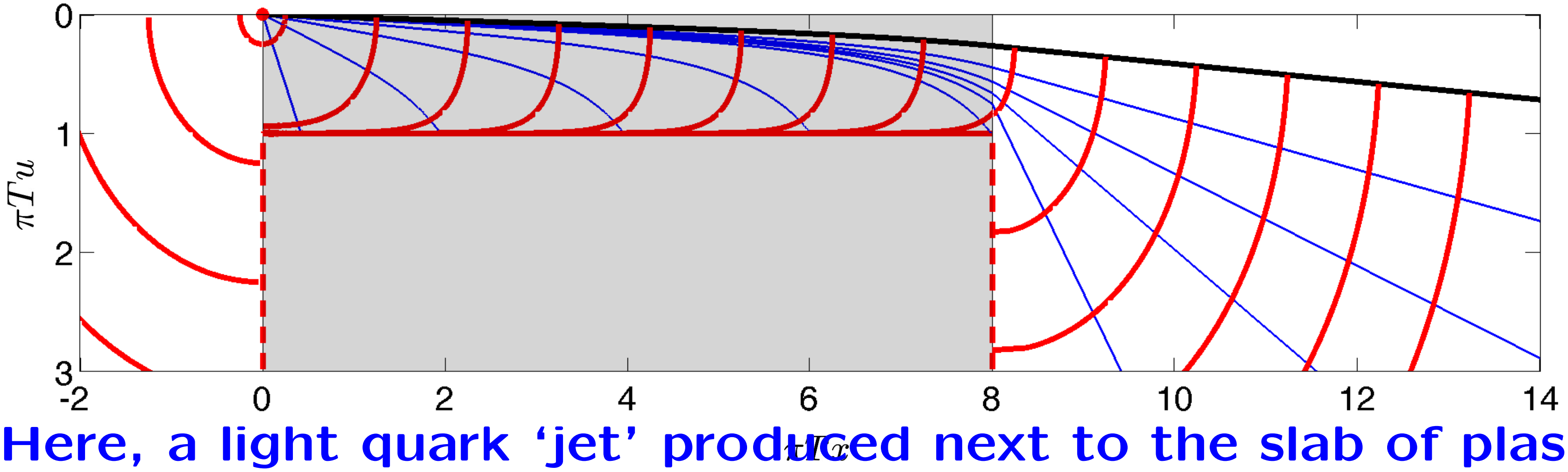


A light quark “jet”, incident with E_{in}, shoots through a slab of strongly coupled $\mathcal{N} = 4$ SYM plasma, temperature T, thickness $L\pi T = 10$, assumed $\gg 1$. What comes out the other side? A “jet” with $E_{\text{out}} \sim 0.64 E_{\text{in}}$; just like a vacuum “jet” with that lower energy, and a broader opening angle.

And, the entire calculation of energy loss is geometric! Energy propagates along the blue curves, which are null geodesics in the bulk. Some of them fall into the horizon; that’s energy loss. Some of them make it out the other side. Geometric optics intuition for *why* what comes out on the other side looks the way it does, so similar to what went in.

Quenching a Light Quark “Jet”

Chesler, Rajagopal, 1402.6756

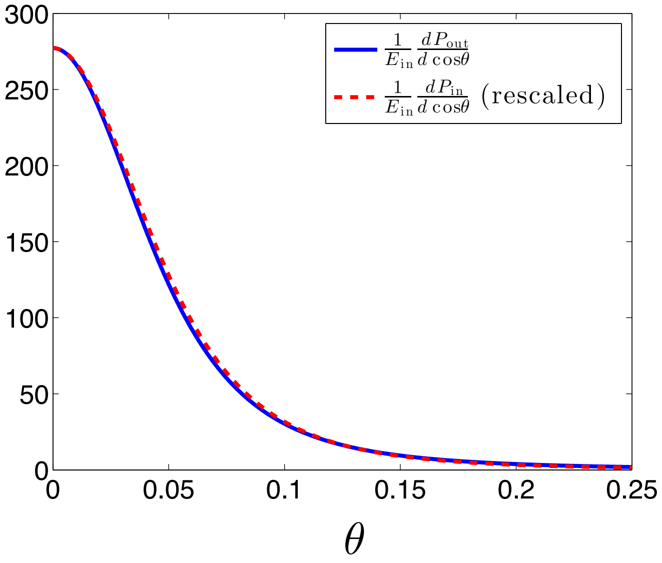


Here, a light quark ‘jet’ produced next to the slab of plasma with incident energy $E_{\text{in}} = 87\sqrt{\lambda}\pi T \sim 87\sqrt{\lambda}$ GeV shoots through the slab and emerges with $E_{\text{out}} \sim 66\sqrt{\lambda}$ GeV. Again, the “jet” that emerges looks like a vacuum “jet” with that energy.

Geometric understanding of jet quenching is completed via a holographic calculation of the string energy density along a particular blue geodesic, showing it to be $\propto 1/\sqrt{\sigma - \sigma_{\text{endpoint}}}$, with σ the initial downward angle of that geodesic. Immediately implies Bragg peak (maximal energy loss rate as the last energy is lost). Also, opening angle of “jet” ↔ downward angle of string endpoint.

Quenching a Light Quark “Jet”

Chesler, Rajagopal, 1402.6756

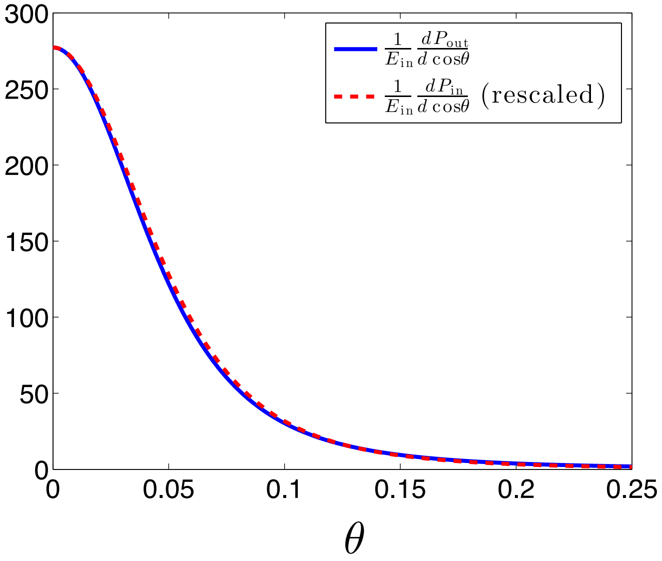


Shape of outgoing “jet” is the same as incoming “jet”, except broader in angle and less total energy.

We have computed the energy flow infinitely far downstream from the slab, as a function of the angle θ relative to the “jet” direction.

Quenching a Light Quark “Jet”

Chesler, Rajagopal, 1402.6756



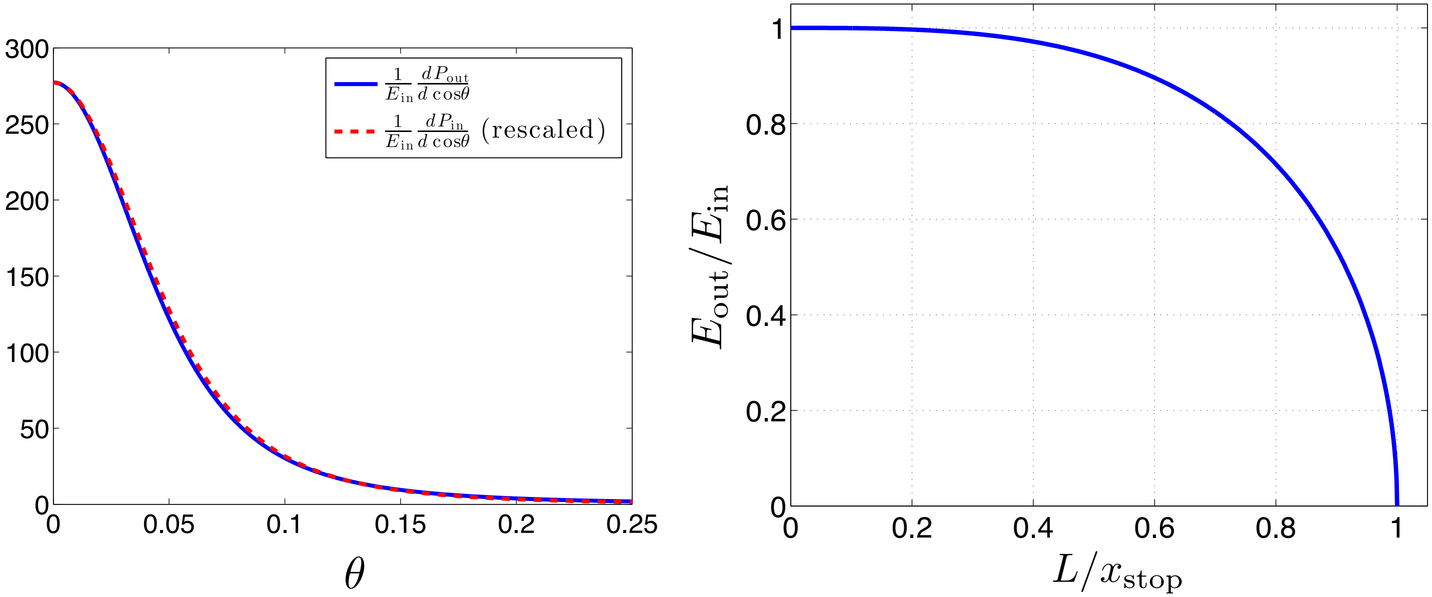
Blue curve is angular shape of the “jet” that emerges from the slab after having been quenched.

Red dashed curve is shape of vacuum “jet”, in the absence of any plasma, with θ axis stretched by some factor f (outgoing “jet” is broader in angle) and the vertical axis compressed by more than f^2 (outgoing “jet” has lost energy).

After rescaling, look at how similar the shapes of the incident and quenched “jets” are!

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756



We compute E_{out} analytically, by integrating the power at infinity over angle or by integrating the energy density of the string that emerges from the slab. Geometric derivation of analytic expression for dE_{out}/dL, including the Bragg peak:

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

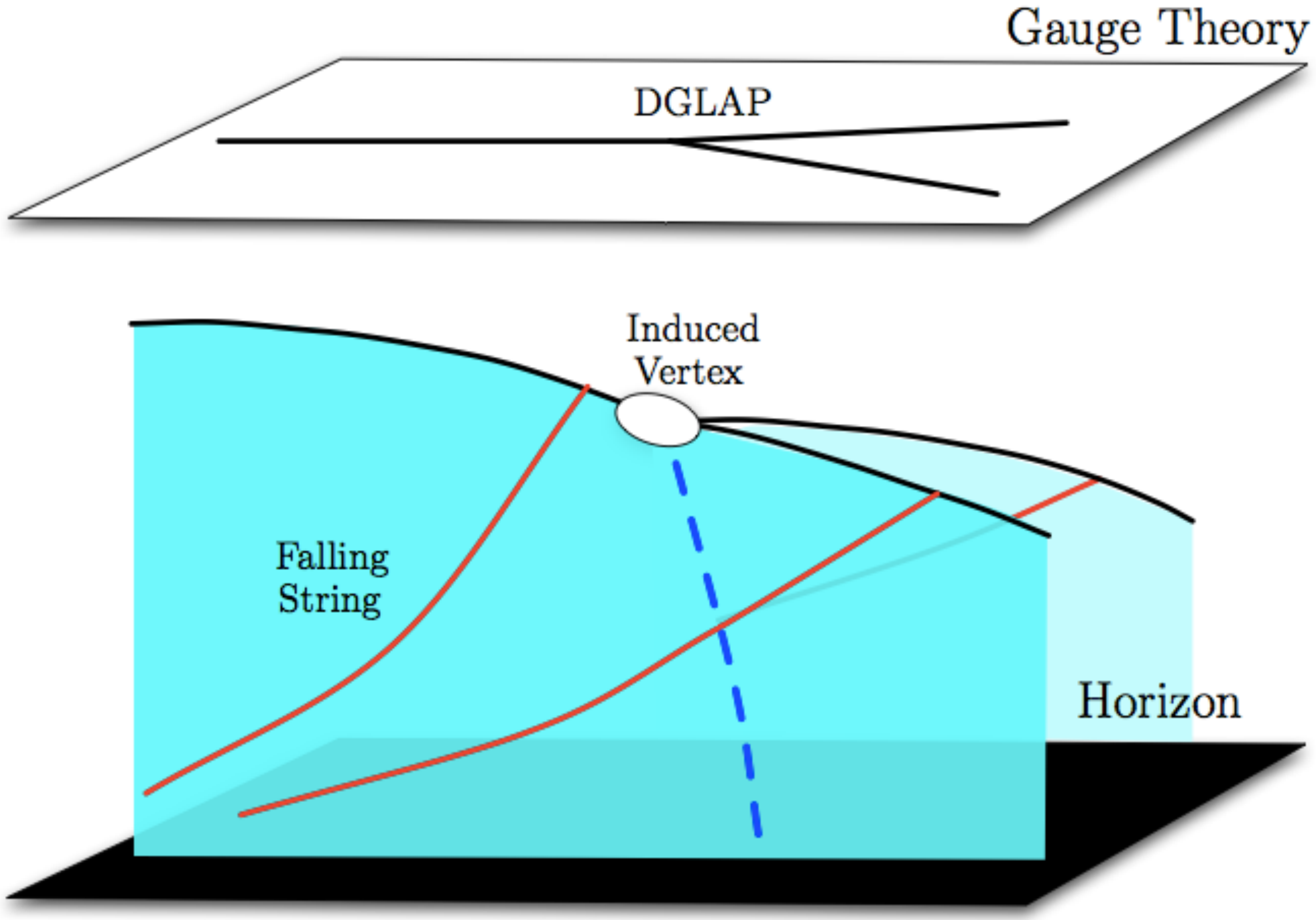
where $\pi T x_{\text{stop}} \propto (E_{\text{in}}/(\sqrt{\lambda}\pi T))^{1/3}$. (Not a power law in L, E_{in}, or T; it has a Bragg peak.)

A Hybrid Weak+Strong Coupling Approach to Jet Quenching?

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, arXiv:1405.3864

- **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.**

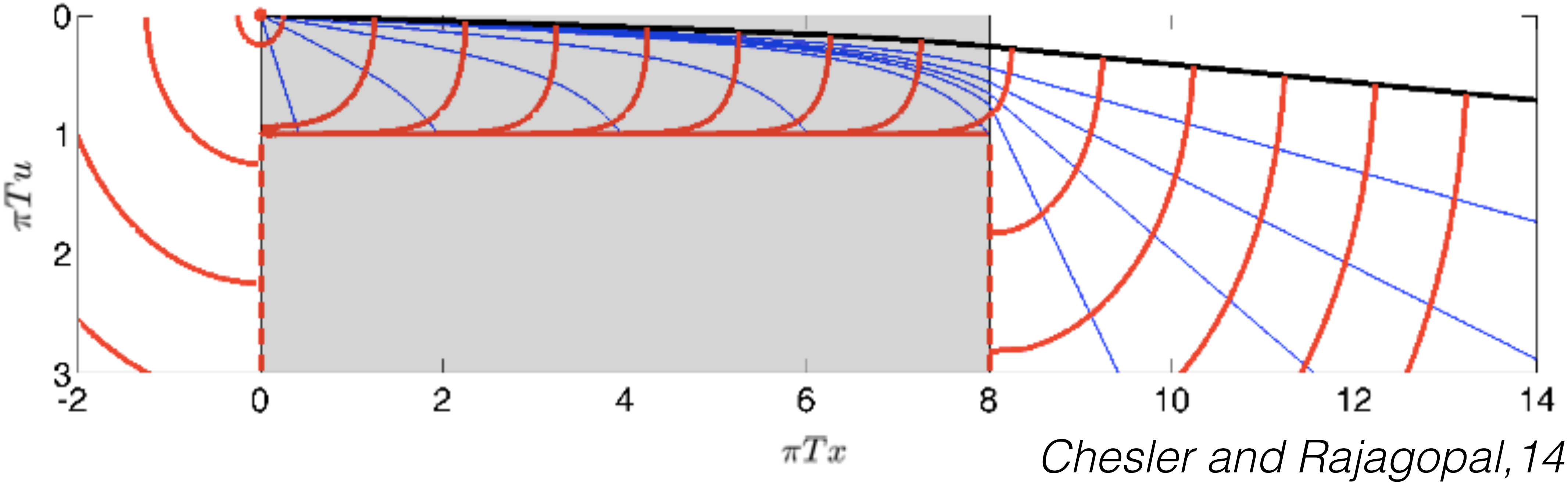
Hybrid Model



- Jet shower perturbative (PYTHIA)
- Additional loss in rungs → strongly coupled, non-perturbative
- Assign a lifetime $\tau_f = 2\frac{E}{Q^2}$ to every rung. Final partons fly until critical temperature is reached
- Embed hard collision into hydrodynamic plasma with $180 < T_c < 200$ MeV

  Bazazov et al, 0903.4379 *Hirano et al, 1012.3955*
- We don't hadronize in order to keep model assumptions minimal; therefore consider jet observables only (we checked we have little sensitivity on Q_0)

Energetic light quark traversing a supersymmetric plasma



Chesler and Rajagopal, 1402.6756

(as explained in Krishna Rajagopal's talk)

- Rather intrincated path length dependence with a Bragg-like peak

(see P. Arnold's talk)

$$\frac{1}{E_i}\frac{dE}{dx} = -\frac{4x^2}{\pi x_{stop}^2\sqrt{x_{stop}^2 - x^2}} \qquad x_{stop} = \frac{E_i^{1/3}}{2T^{4/3}\kappa_{SC}}$$

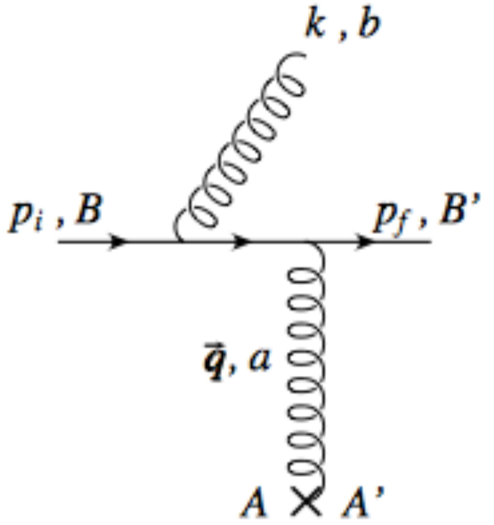
- Gluons get a smaller stopping distance according to $\kappa_{SC}^{G} = \kappa_{SC}^{Q}\left(\frac{C_A}{C_F}\right)^{\frac{1}{3}}$

Perturbative benchmarks

- To understand the predictivity of our strongly coupled model

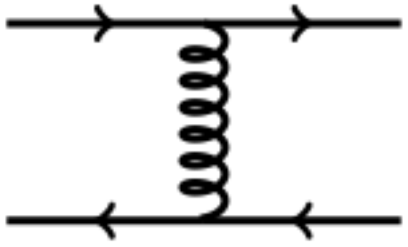
-Radiative

$$\frac{dE}{dx} = -\kappa_R \frac{C_R}{C_F} T^3 x$$



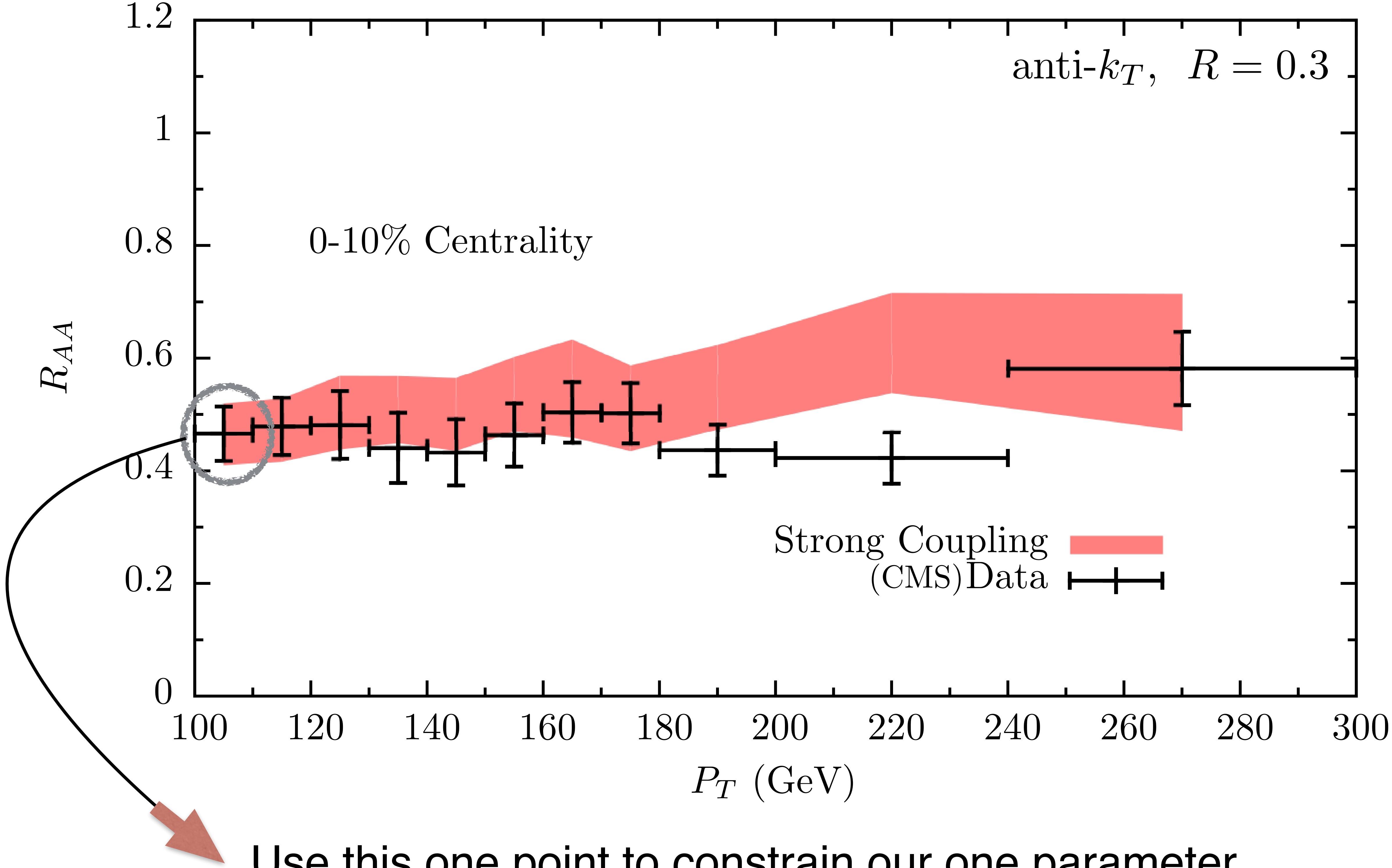
-Collisional

$$\frac{dE}{dx} = -\kappa_C \frac{C_R}{C_F} T^2$$



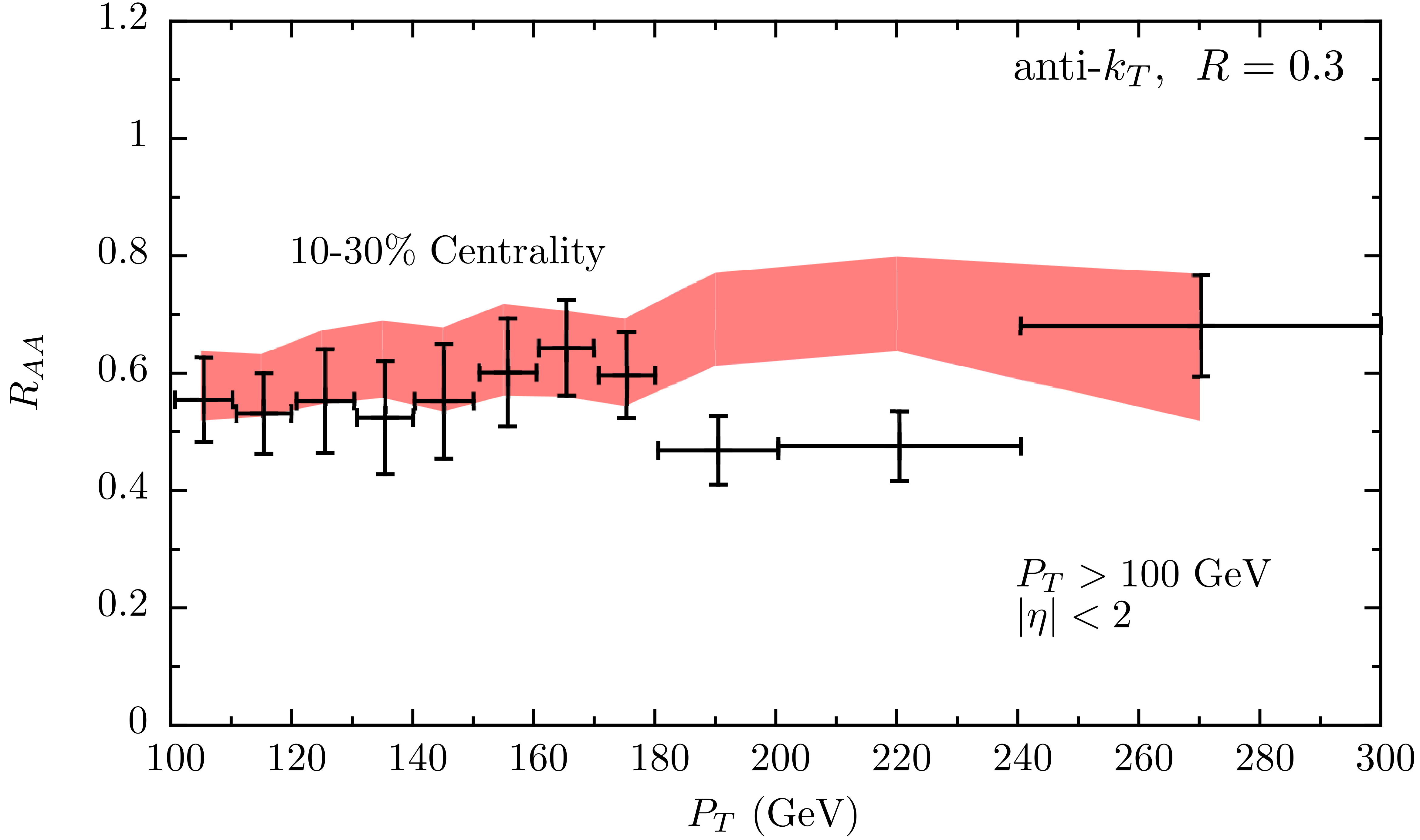
- Not aimed at superseding more sophisticated computations

R_{AA}

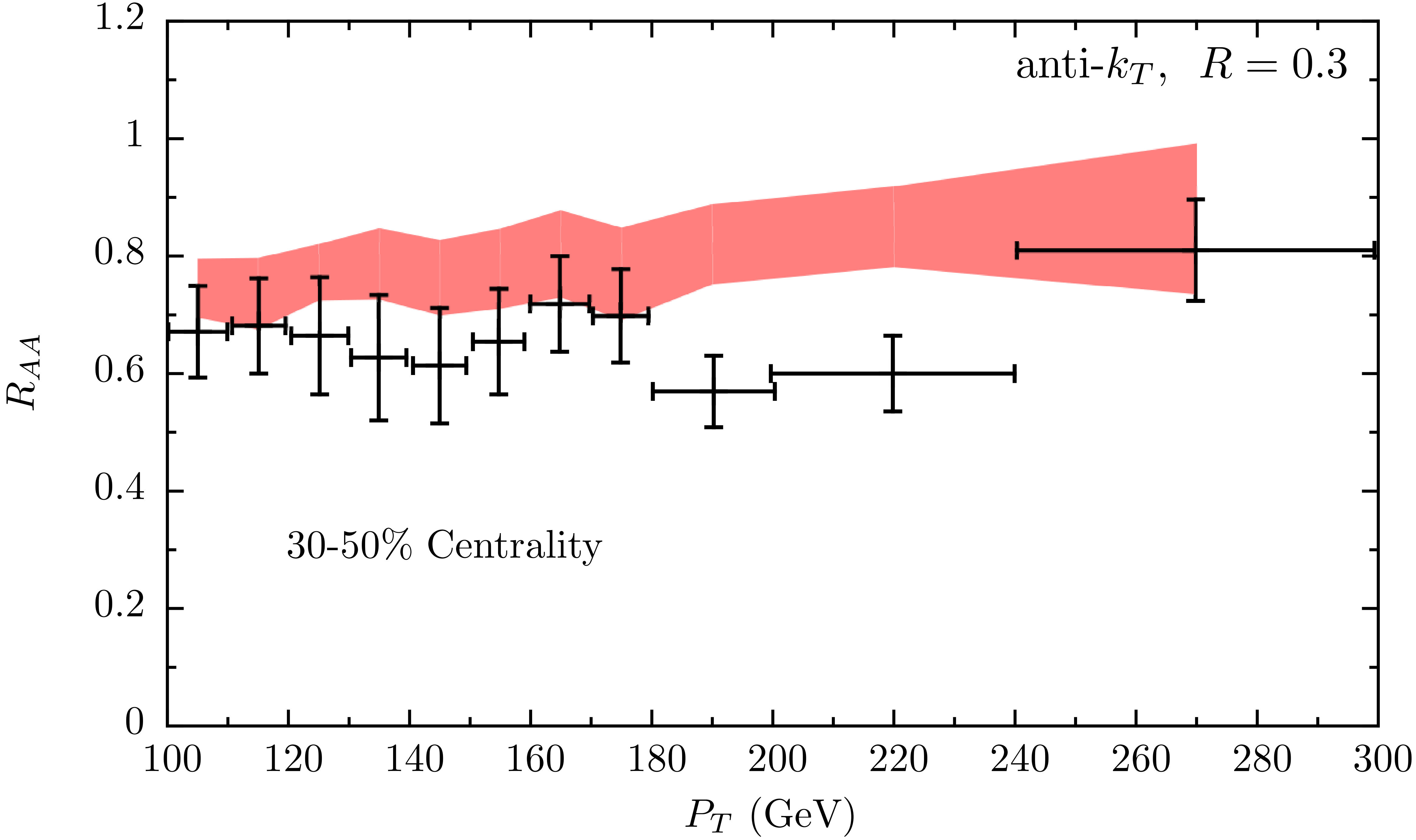


Use this one point to constrain our one parameter
Rest of R_{AA} is all postdicted

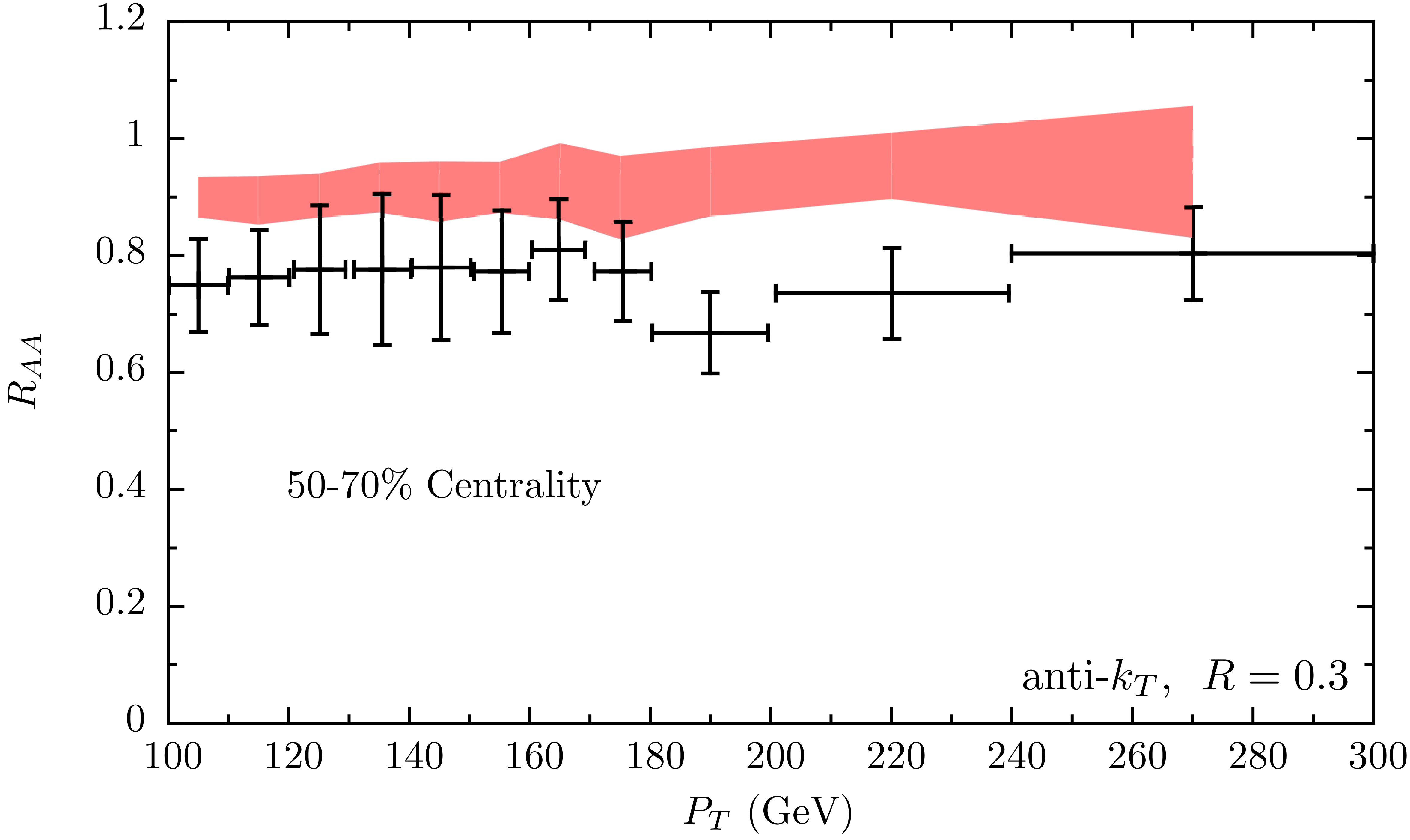
R_{AA}


anti-k_T, $R = 0.3$
10-30% Centrality
$P_T > 100$ GeV
$|\eta| < 2$
R_{AA}
P_T (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
100
120
140
160
180
200
220
240
260
280
300

R_{AA}

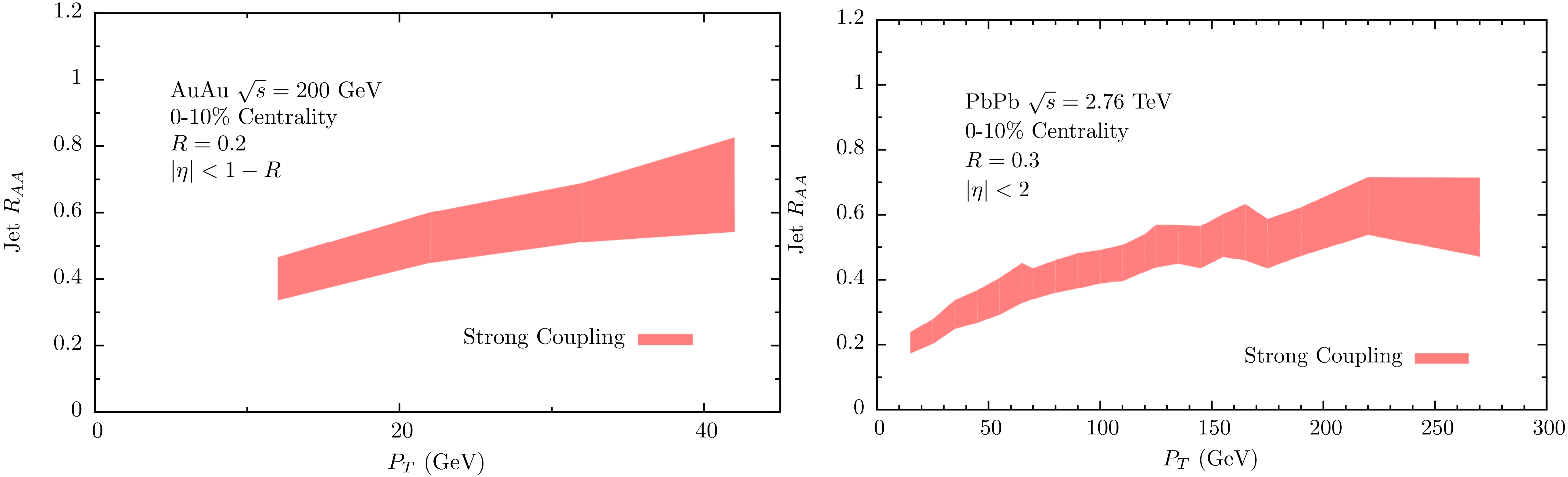

anti-k_T, $R = 0.3$
30-50% Centrality
R_{AA}
P_T (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
100
120
140
160
180
200
220
240
260
280
300

R_{AA}



Mild disagreement towards peripheral bins may indicate the importance of quenching in the hadron gas phase

RHIC vs LHC

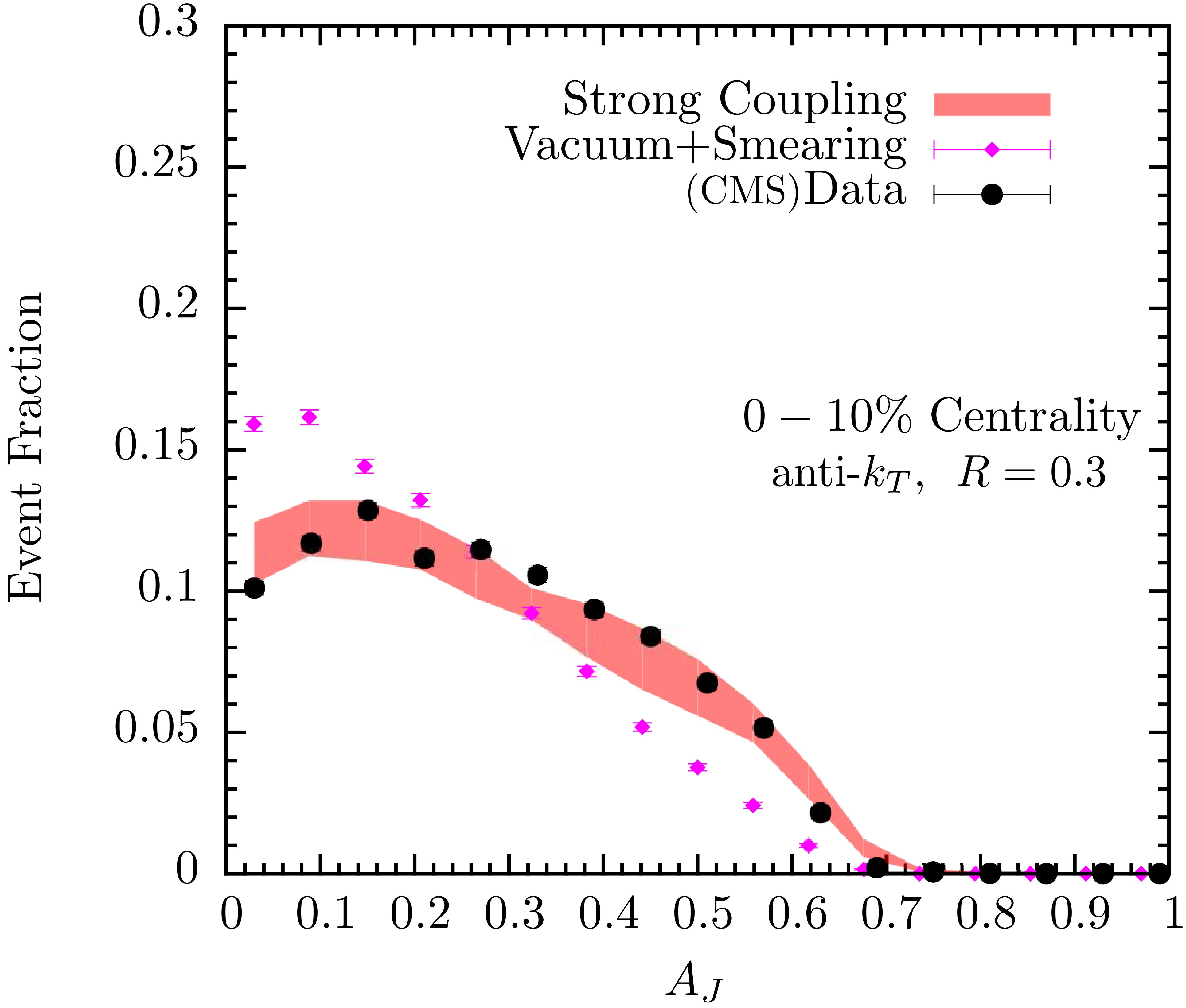


With the same value of the fit parameter we get reasonable results for RHIC as well as for LHC

Our model agrees with RHIC jet data that we have seen so far, eg on charged-jet R_{AA}. We look forward to further comparisons

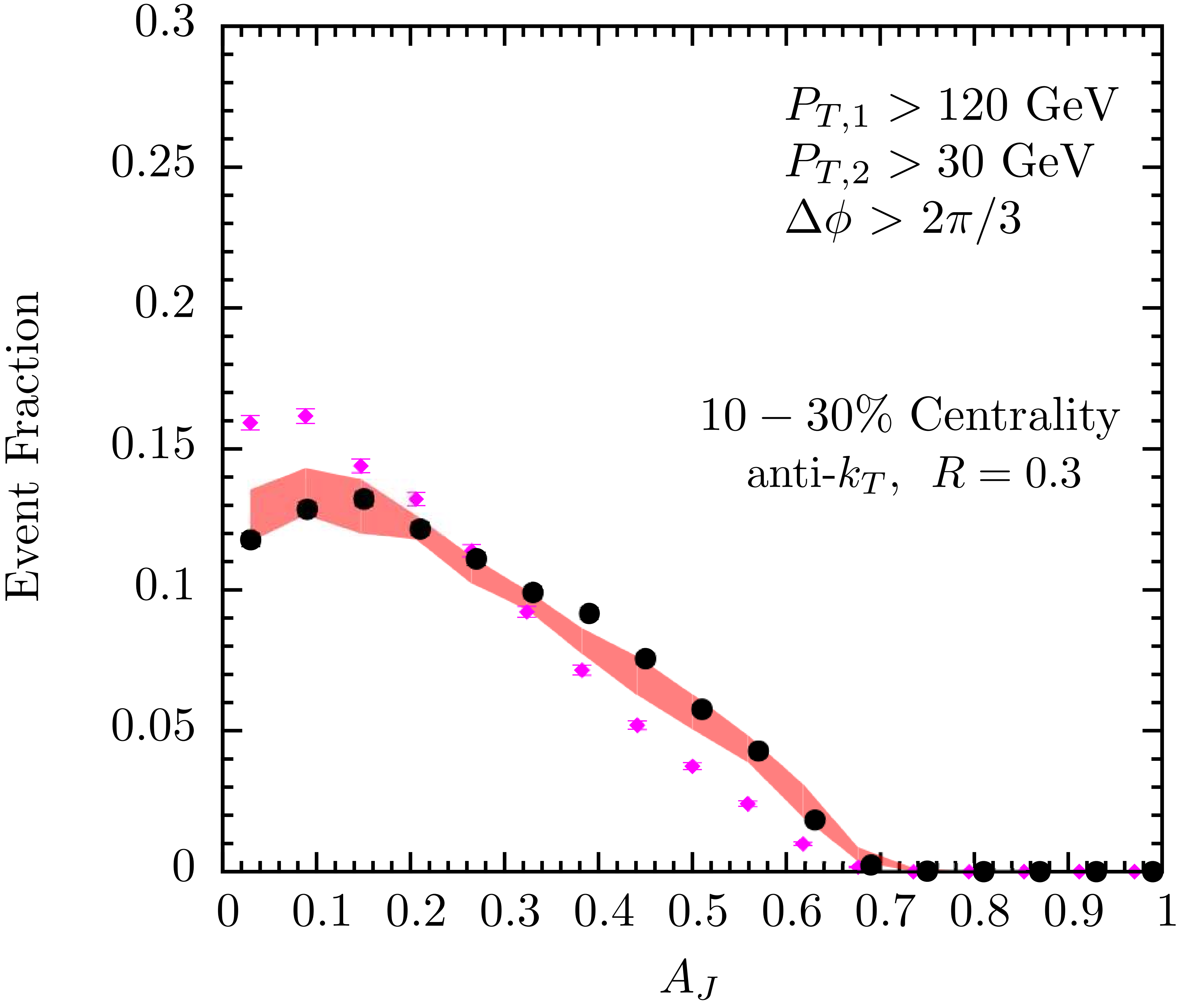
$$A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Dijet Asymmetry



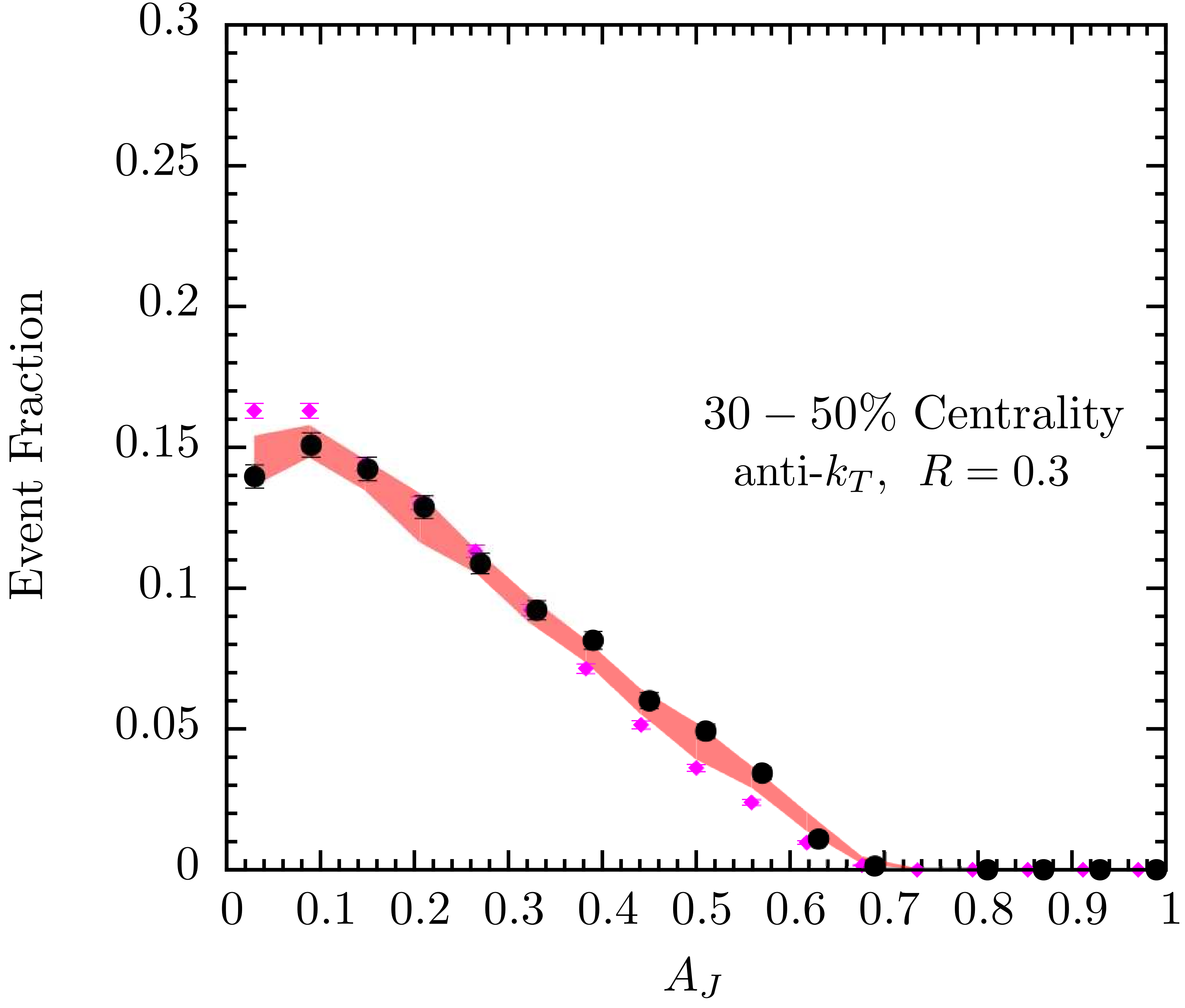
$$A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Dijet Asymmetry



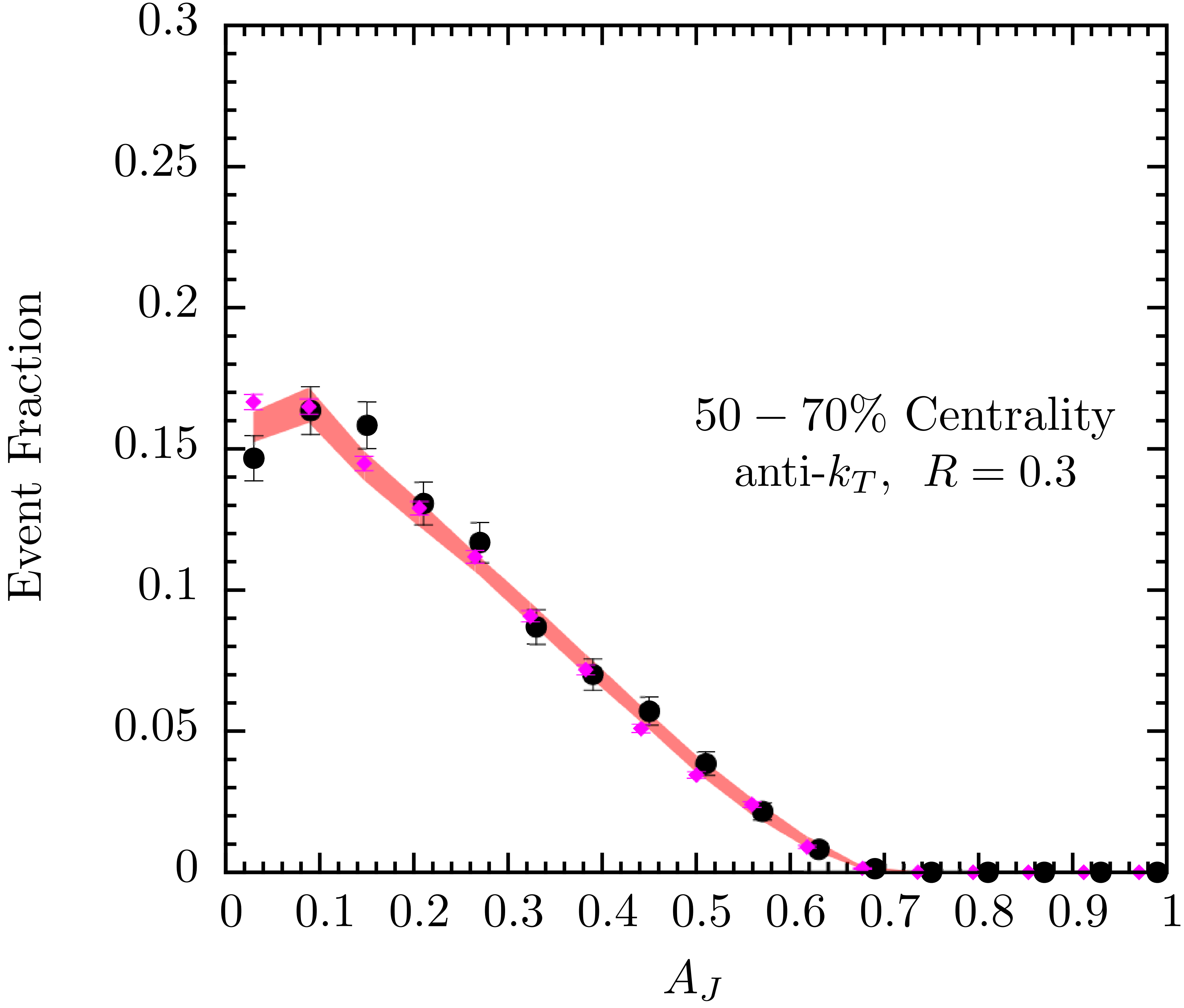
$$A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Dijet Asymmetry

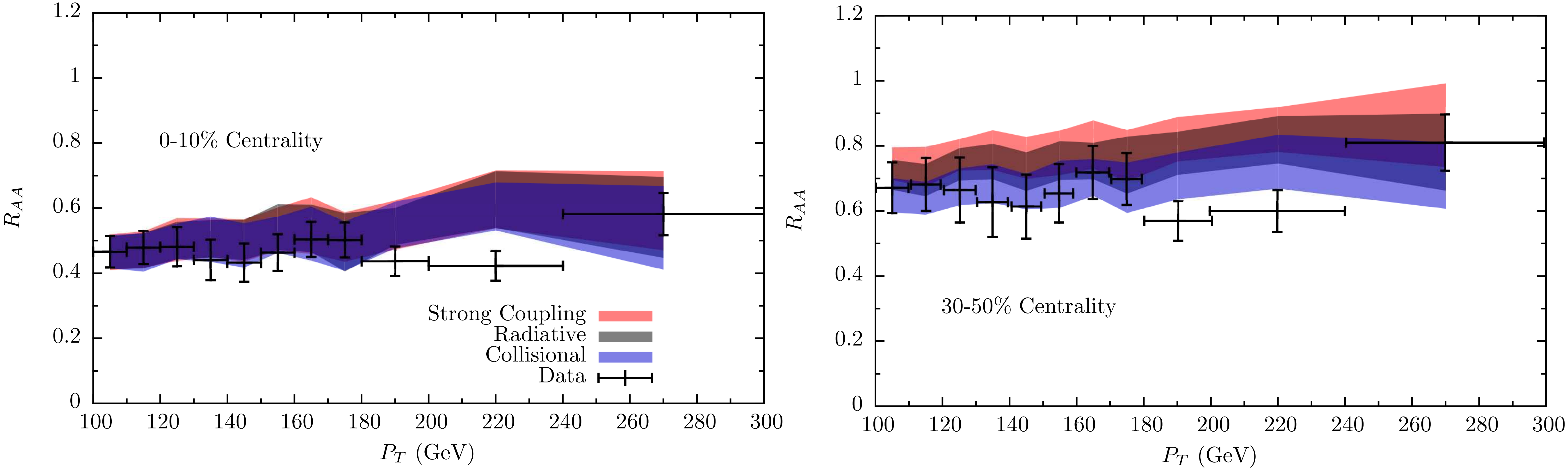


$$A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Dijet Asymmetry



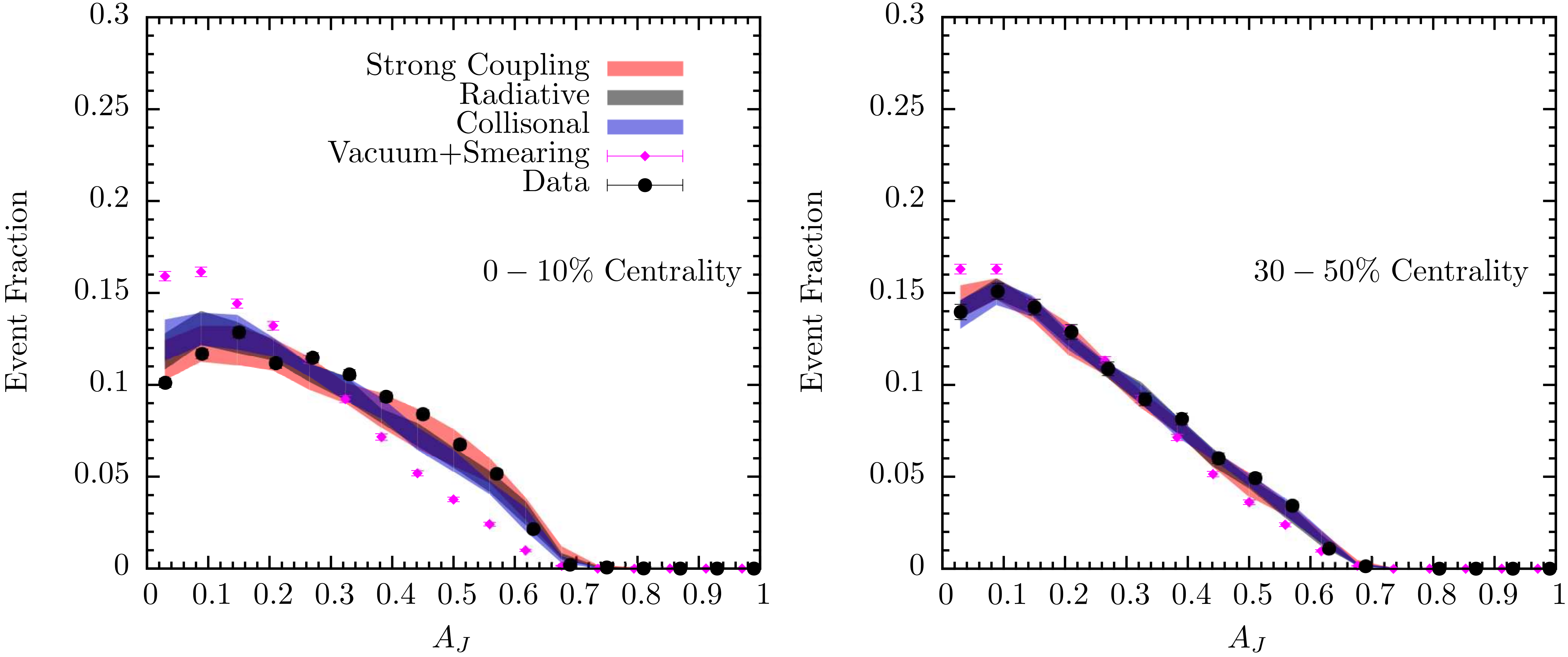
R_{AA}



Similar trend in all models

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

Dijet Asymmetry



Similar trend in all models

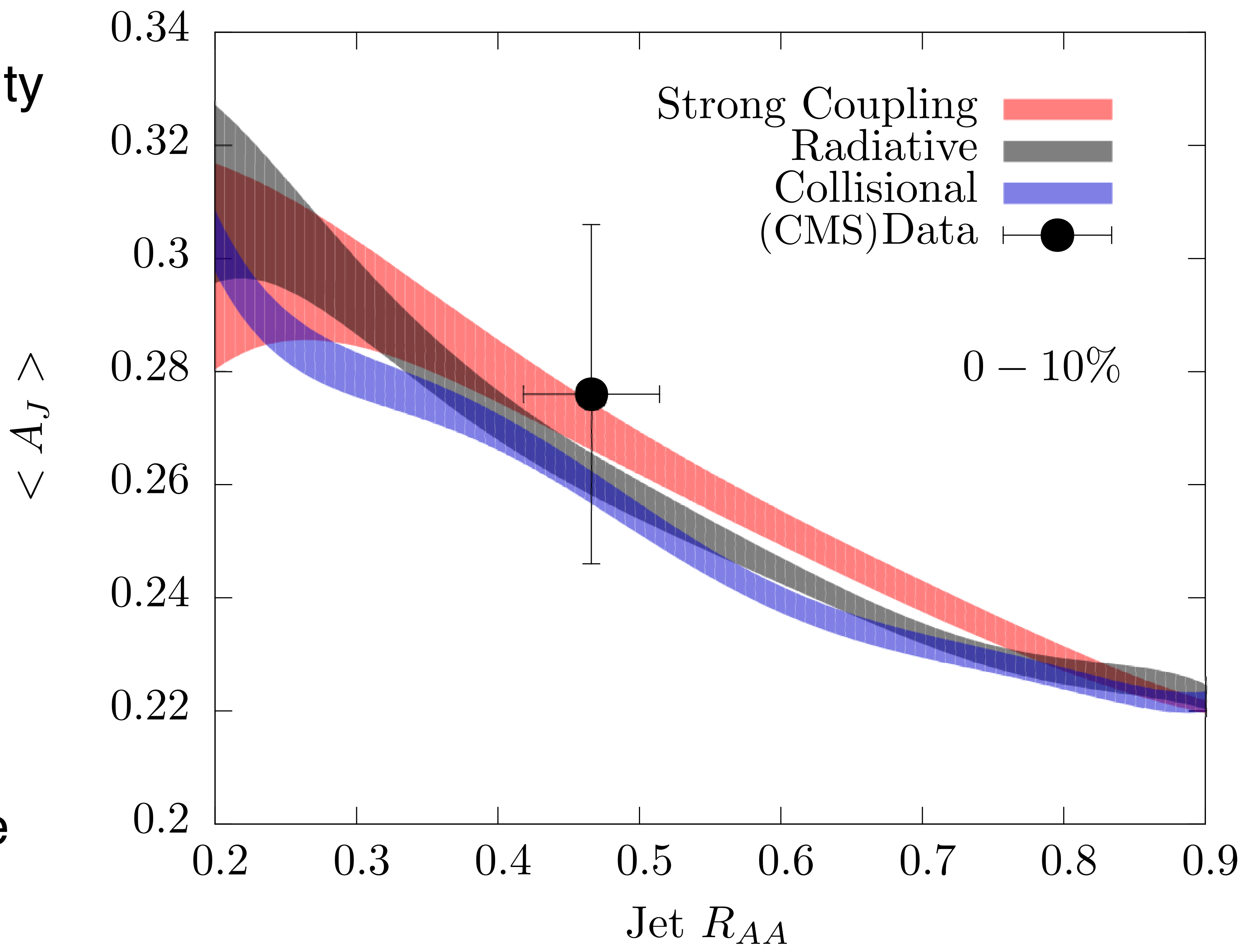
Parameter Space Scan of Inclusive Observables

All three models can reproduce R_{AA} and A_J data; little sensitivity of inclusive observables

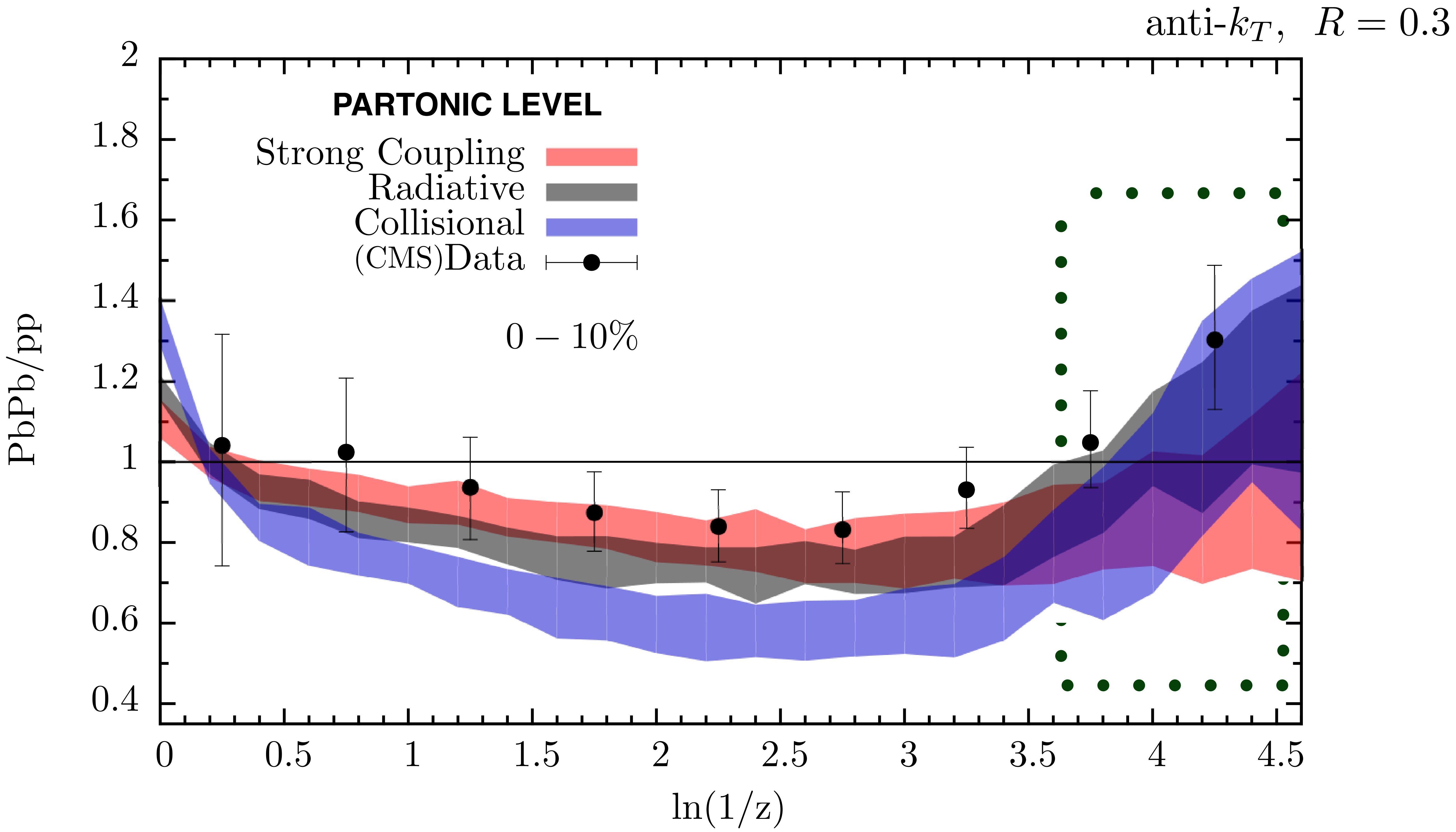
Strongly Coupled agrees slightly better with the data

Less inclusive observables required in order to discriminate

We need better systematics to distinguish

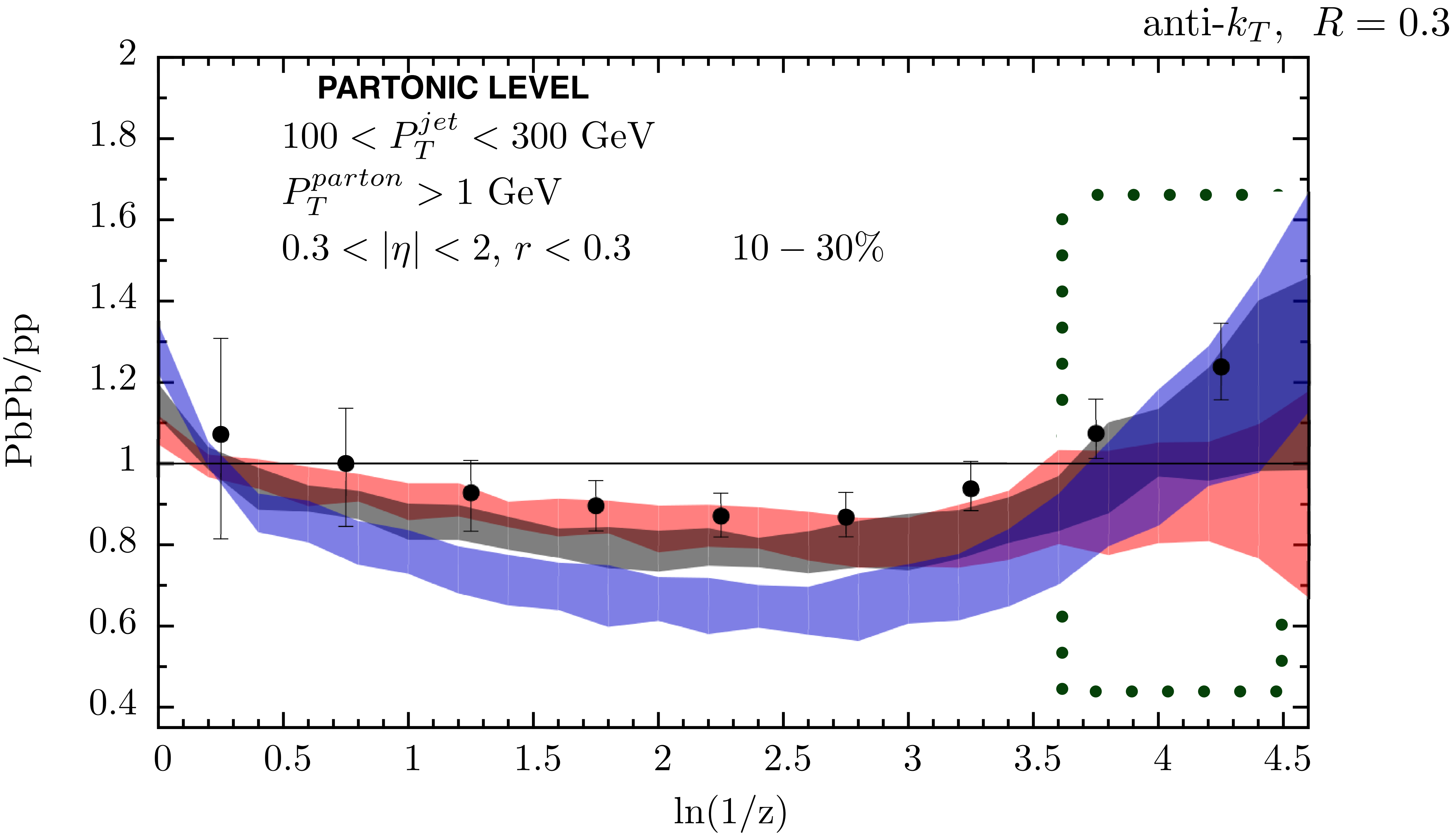


Fragmentation Functions Ratio



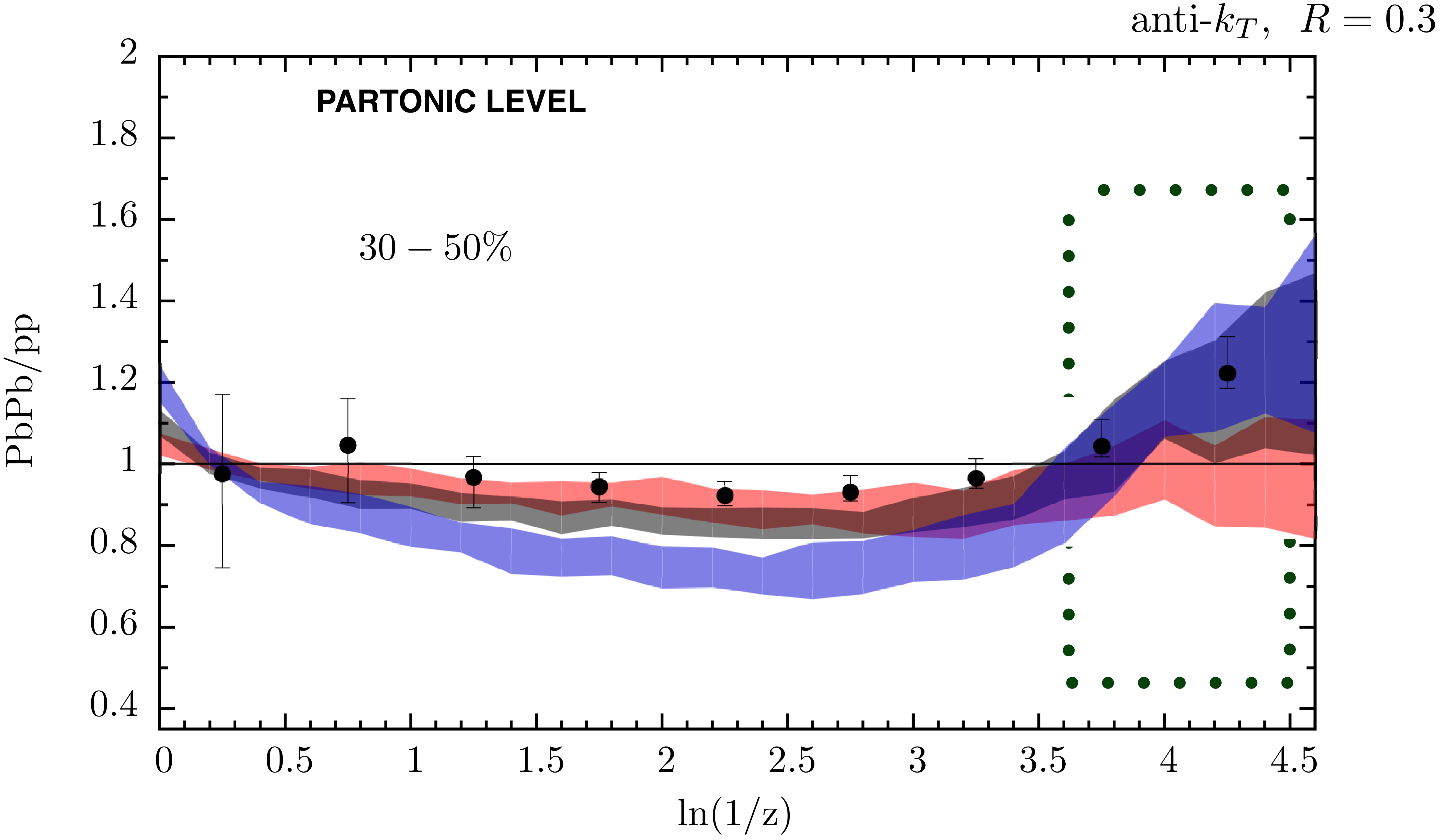
Very soft region highly sensitive to background subtraction

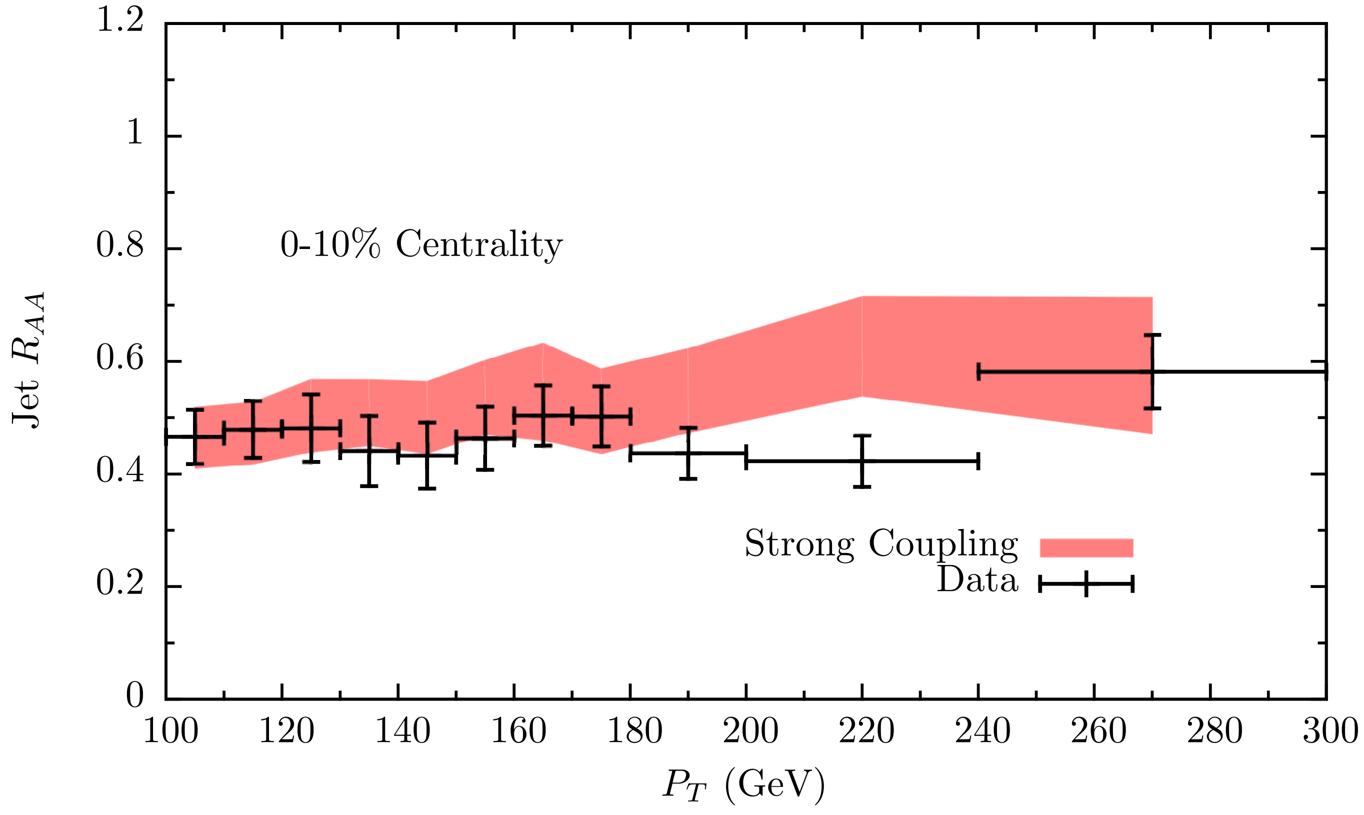
Fragmentation Functions Ratio

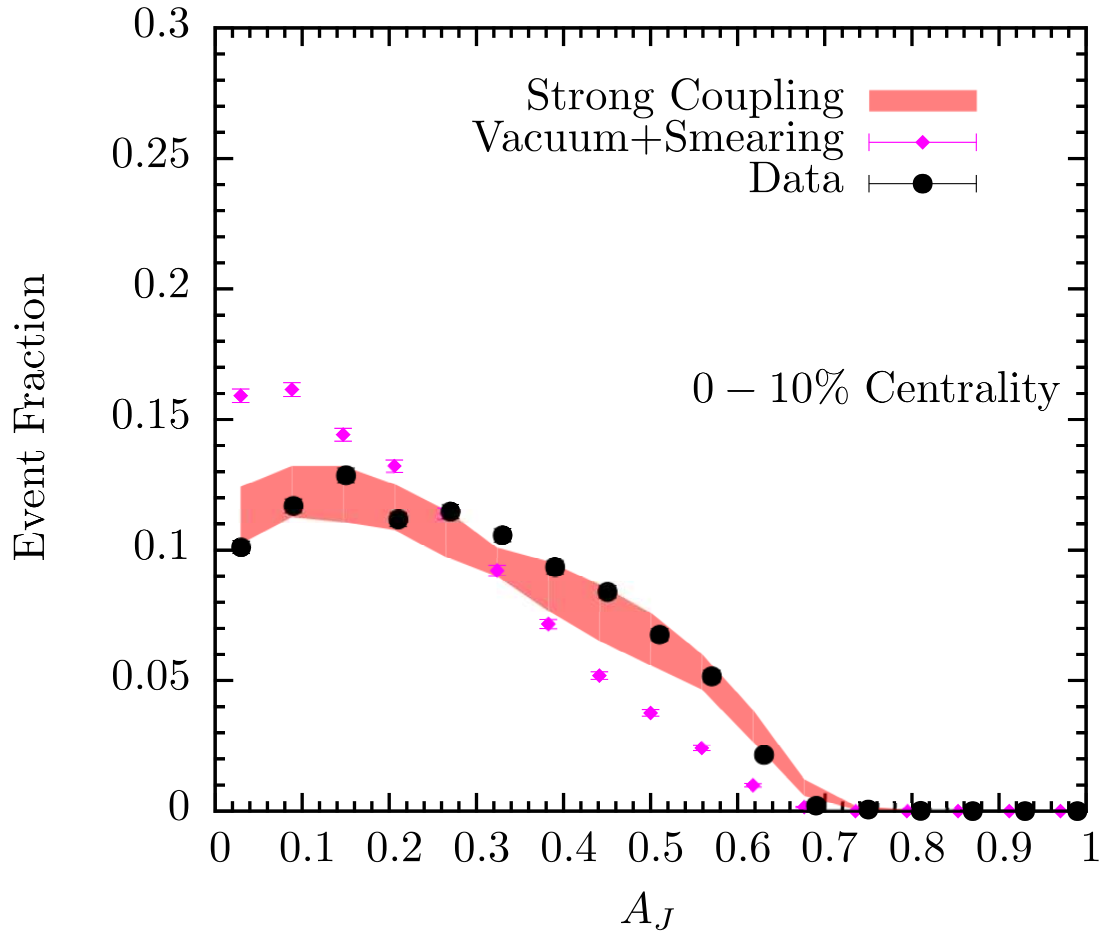


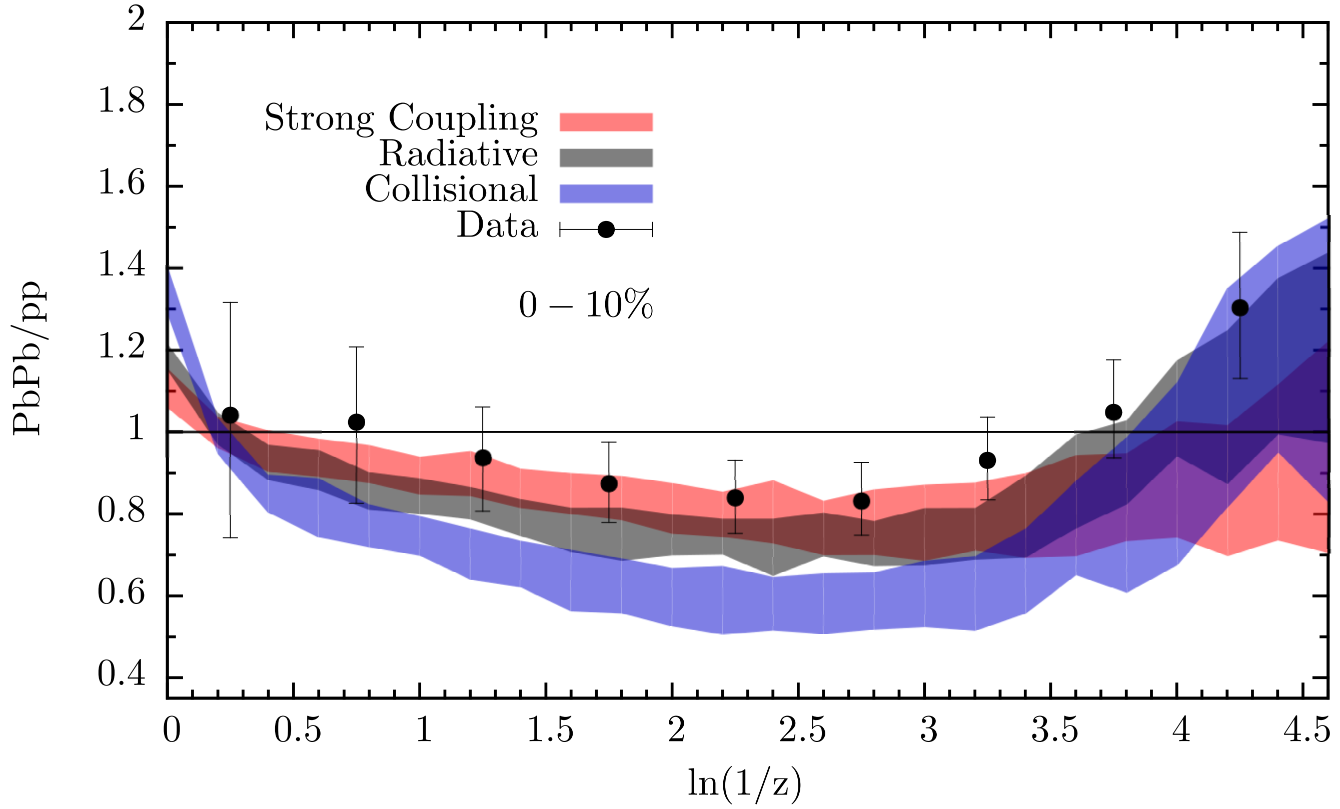
Very soft region highly sensitive to background subtraction

Fragmentation Functions Ratio









Simultaneous description of several data sets, including centrality dependence, after fitting only one parameter

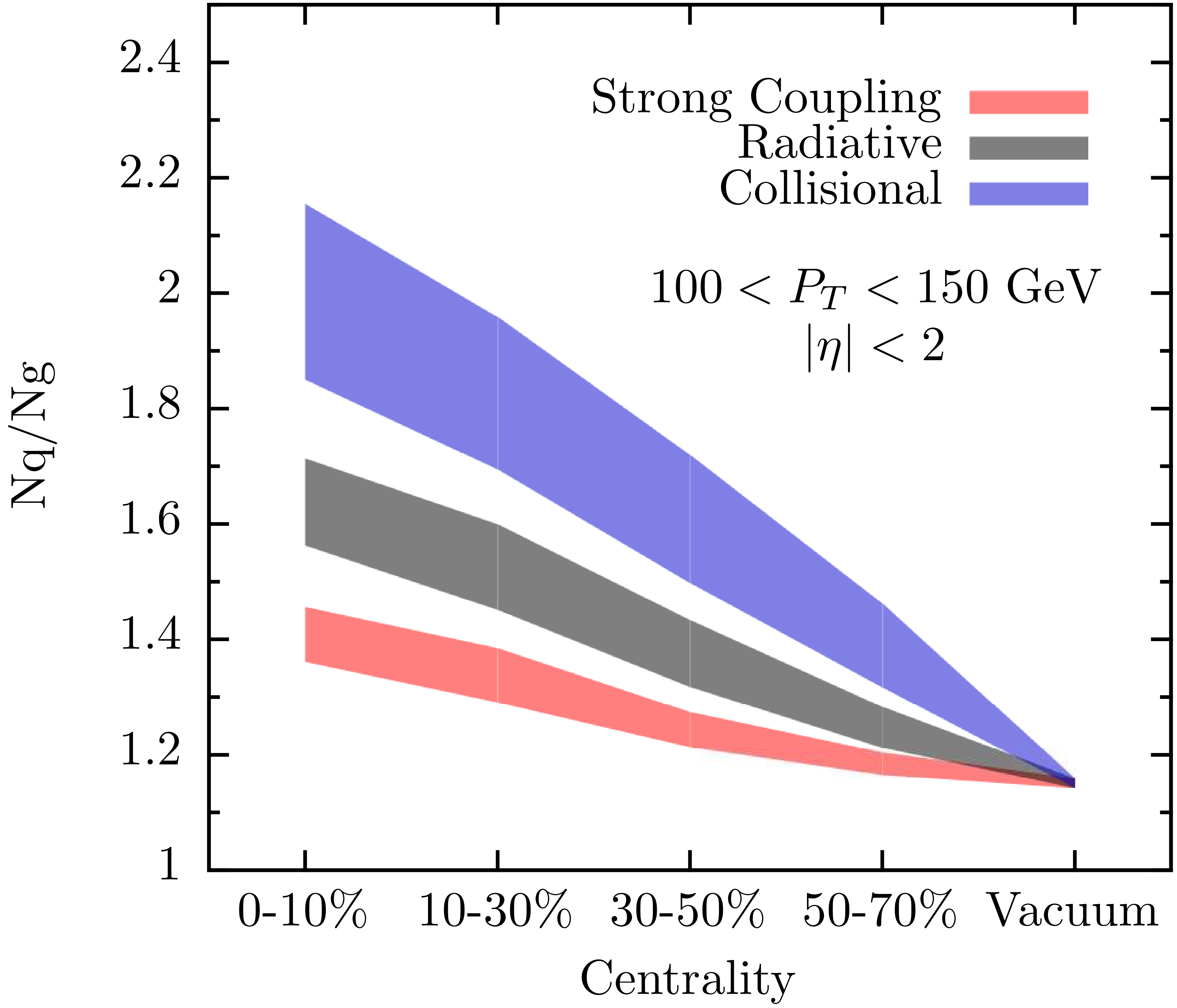
A Hybrid Weak+Strong Coupling Approach to Jet Quenching

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, arXiv:1405.3864

- **Upon fitting one parameter, lots of data described well. Value of the fitted parameter? $x_{\rm stop}$ is about three to four times longer in QCD plasma than in $\mathcal{N} = 4$ SYM plasma. This is not unreasonable. We are taking all the dependences of dE/dx from the strongly coupled calculation, but not the purely numerical factor since after all the two theories have different degrees of freedom.**
- **Jet quenching *might* be perturbative fragmentation plus strongly coupled energy loss.**
- **We need further, more discriminating, observables. b-quark energy loss? Dijets? Photon+jet? And, most of all, we need to add “transverse momentum broadening”, since jet quenching is not only about energy loss.**
- **All this success poses a critical question: if jet quenching observables see the liquid as a liquid, how *can* we see the pointlike quasiparticles at short distance scales?**

Colour charge dependence

Quark Initiated Jets / # Gluon Initiated Jets



Non-trivial C_R dependence yields change of species

Additional discriminant between models

To be studied:

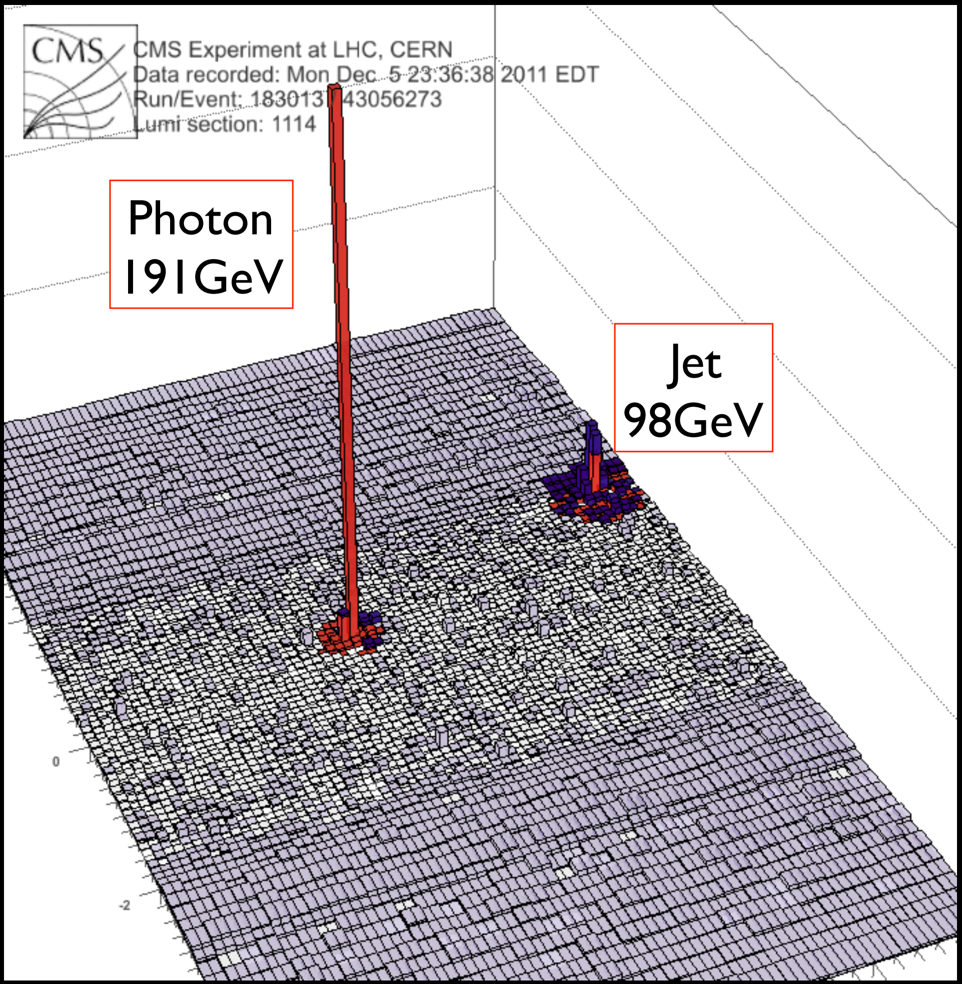
b to inclusive yield as a potential observable

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 $\sim$ 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:

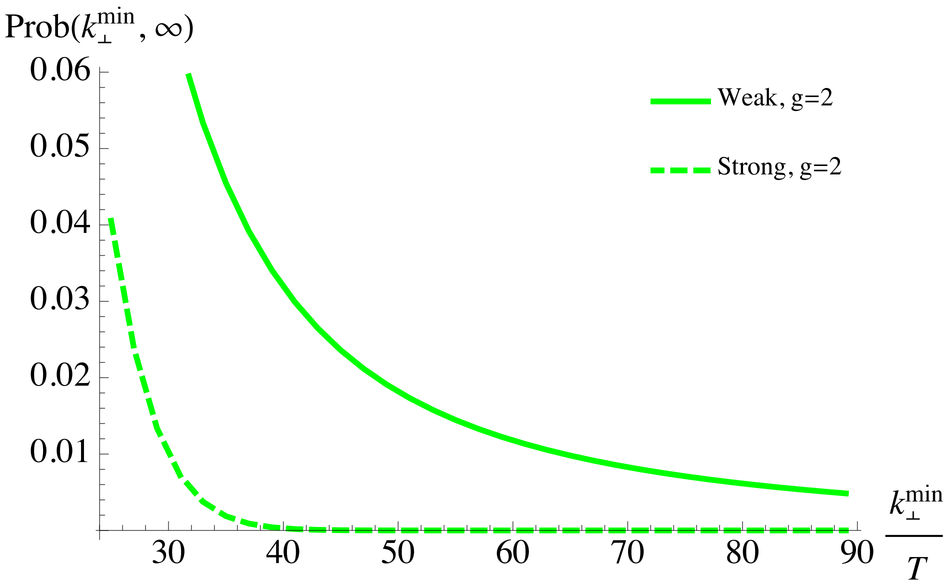
- $P(k_\perp) \propto \exp(-\# k_\perp^2/(T^3 L))$ **in strongly coupled plasma. Qualitative calculation, done via holography.**

  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 $k_\perp$.

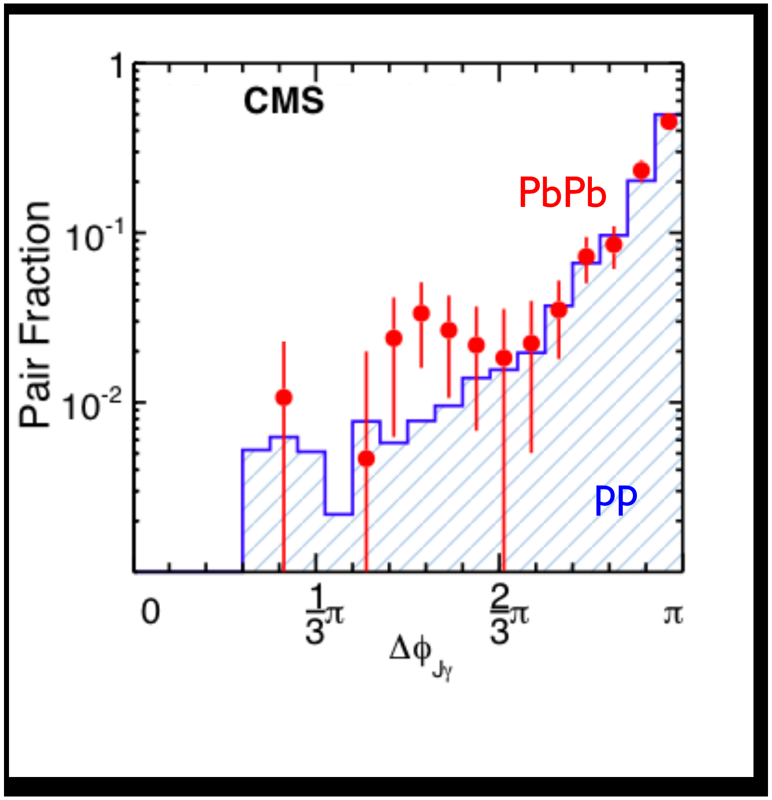
Large deflections rare, but not as rare as if the liquid were a liquid on all scales. They indicate point-like scatterers.



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

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

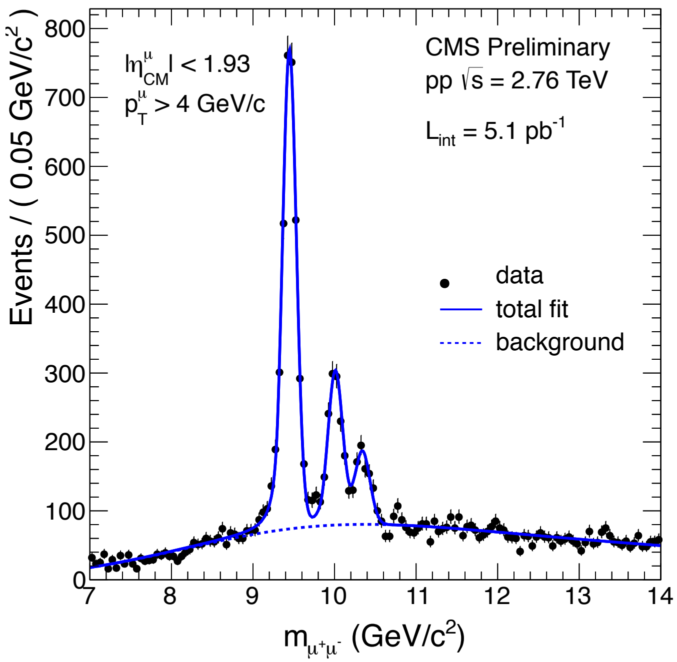
Need many more events before this can be a “QGP Rutherford Experiment”. Something to look forward to circa 2015?

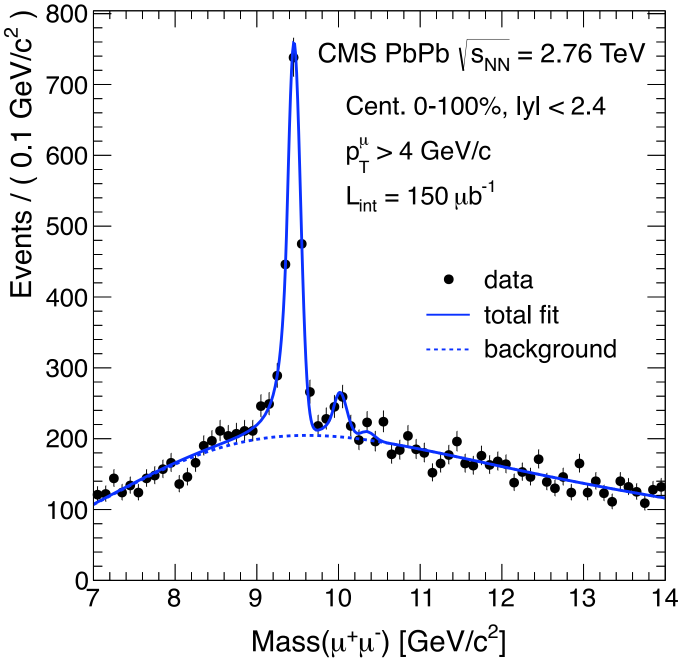
Heavy quarks? Upsilons?

- **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.**

Upsilon 2S Suppression in PbPb

CMS 1208.2826 and CMS-HIN-13-003





- Sequential suppression of Υ states in PbPb: No sign of Υ(3S). Υ(2S) substantially suppressed.
- It will be very interesting to see how the right-hand plot changes for higher p_T Υs. As you increase p_T, expect Υ(2S) to go the way of the Υ(3S). And then, in principal, above some rather high p_T the Υ(1S) also.

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.

Significance of extracted parameters

Success of models depends on the freedom to choose the fitting parameter

	Strong Coupling	Radiative	Collisional
Parameter	$0.29 < \kappa_{\rm sc} < 0.41$	$1.1 < \kappa_{\rm rad} < 2.3$	$3.1 < \kappa_{\rm coll} < 5.9$

For Perturbative Benchmarks

Either the strong coupling constant is large (non-perturbative regime)
or
the kinematical logarithms are large (resummation needed)

Casalderrey-Solana and Wang, 0705.1352
Blaizot and Mehtar-Tani, 1403.2323

(see Yacine's talk)

For Strong Coupling

$$1.2 \lesssim {\kappa_{SC}}^{\mathcal{N}=4} \lesssim 1.6$$ (not robust)

(see P. Arnold's talk)

x_{stop} in QCD plasma is three or four times longer than in $\mathcal{N}=4$ plasma,
as expected due to fewer degrees of freedom at same T

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

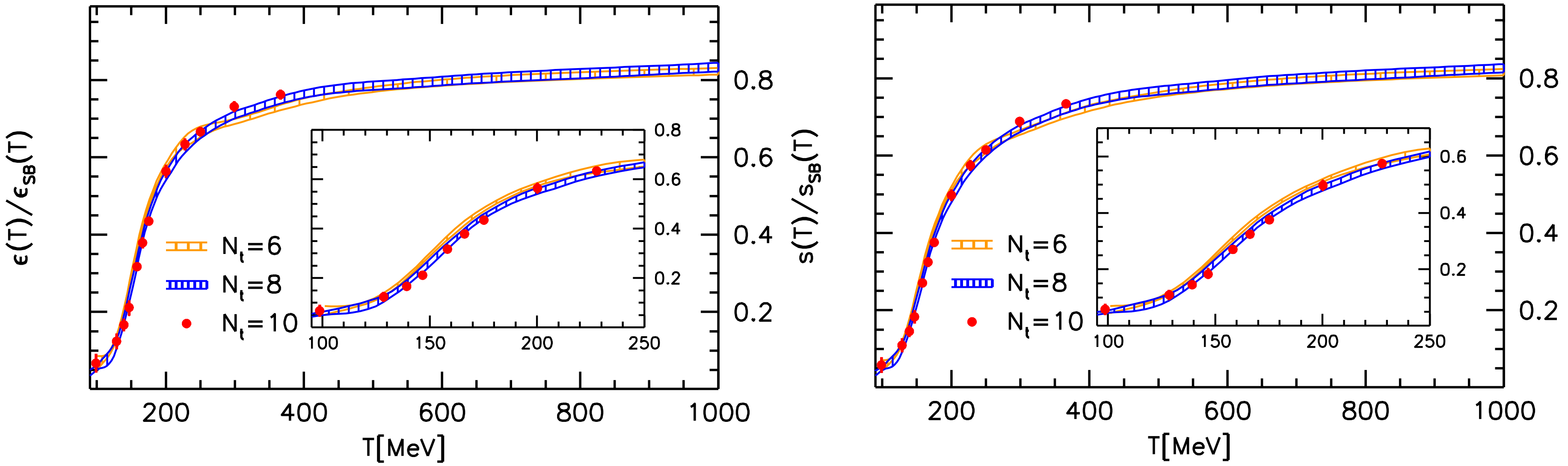
Krishna Rajagopal

MIT

National Nuclear Physics Summer School
University of William and Mary
Wiliamsburg, VA, June 17-18, 2014

QGP Thermodynamics

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, a result that goes back to 1996 that was not appreciated initially.]

Rapid Equilibration?

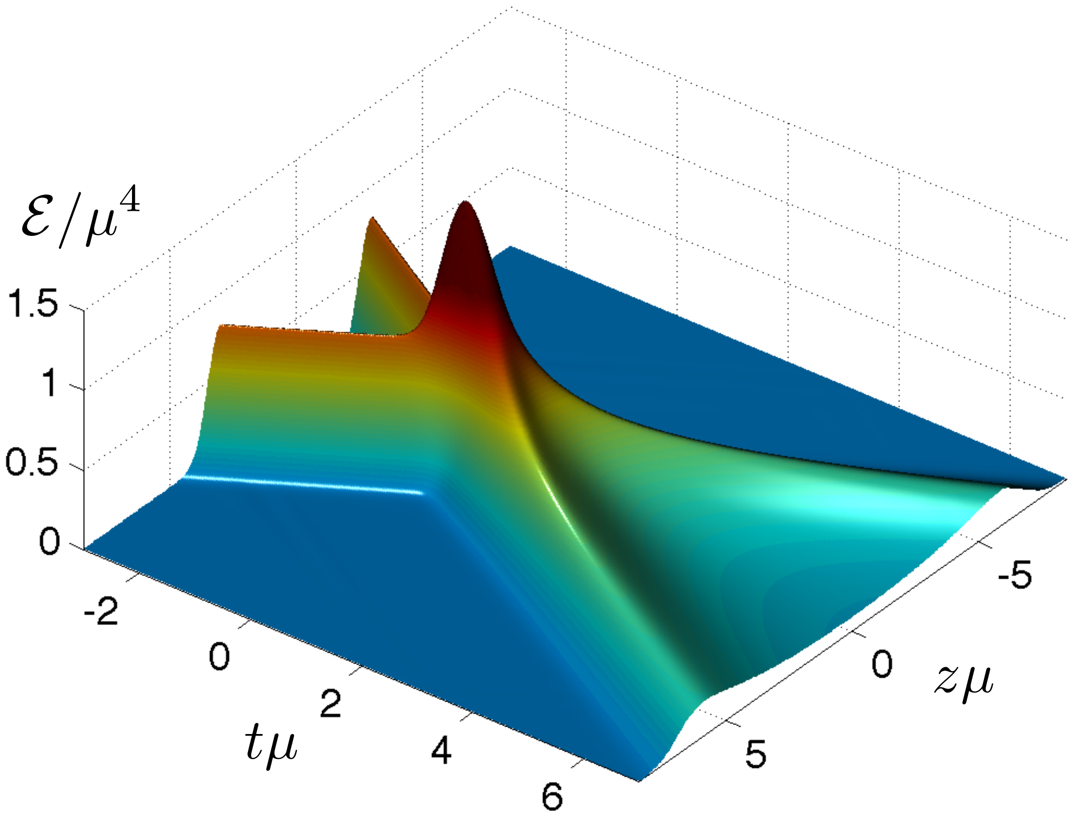
- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.

- 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.

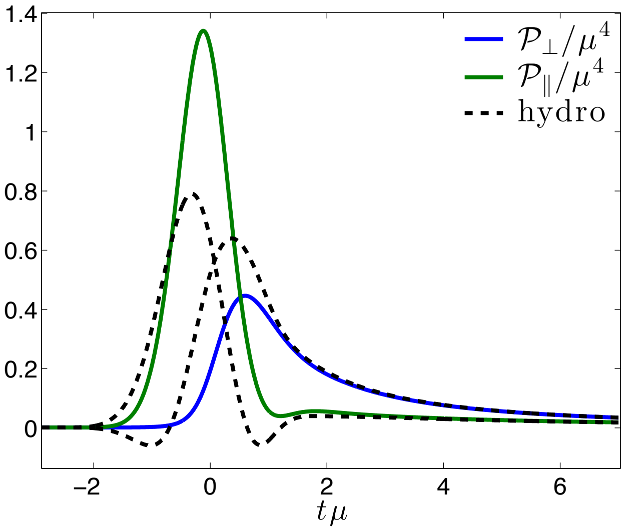
- But, is it really? How rapidly does equilibration occur in a strongly coupled theory?

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

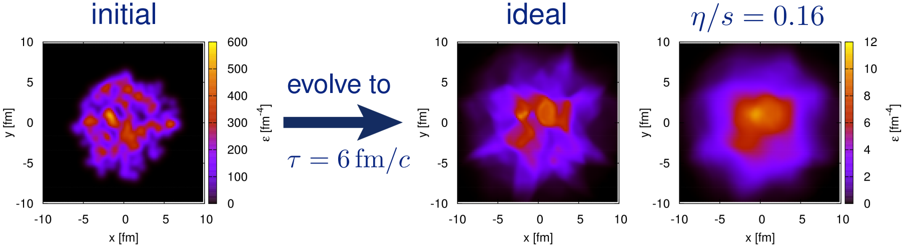
Anisotropic Viscous Hydrodynamics



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

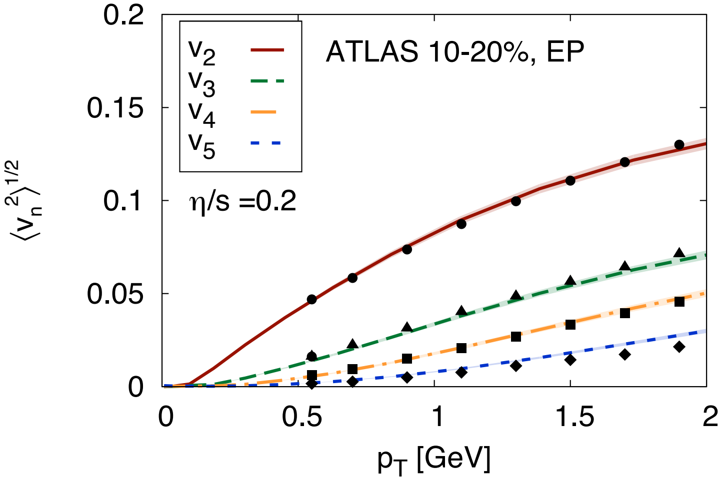
This has now been seen in very many strongly coupled analyses of hydrodynamization. Janik et al., Chesler et al., Heller et al., ...

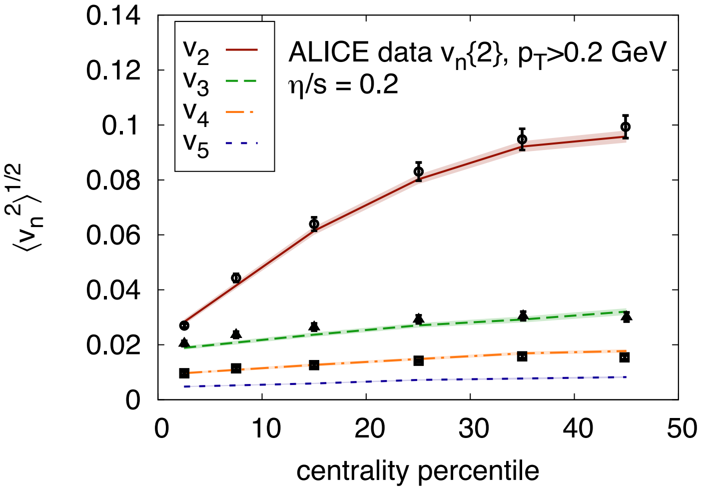
Could have been anticipated as a possibility without holography. But, it wasn’t — because in a weakly coupled context isotropization happens first.

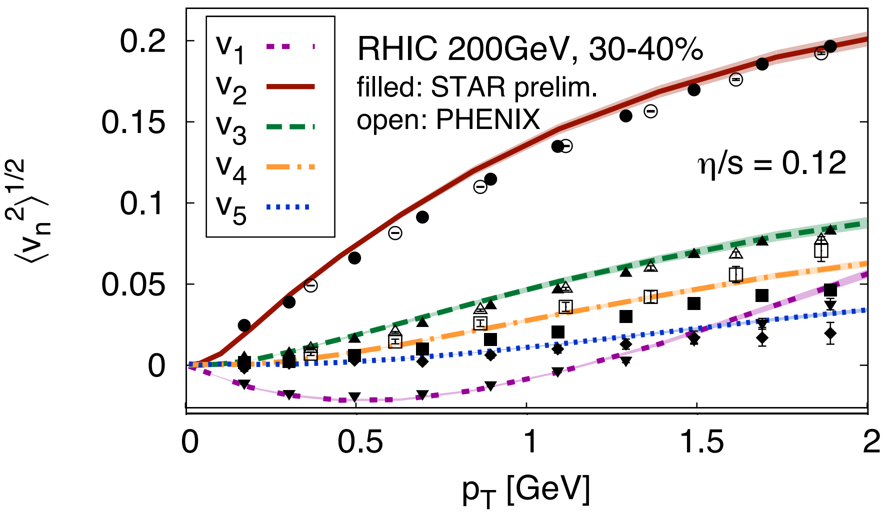

initial
evolve to
$\tau = 6\,\mathrm{fm}/c$
ideal
$\eta/s = 0.16$
10
5
0
-5
-10
y [fm]
x [fm]
600
500
400
300
200
100
0
ε [fm^{-4}]
12
10
8
6
4
2
0

Example of State-of-the-art

Gale, Jeon, Schenke, Tribedy, Venugopalan, 2013



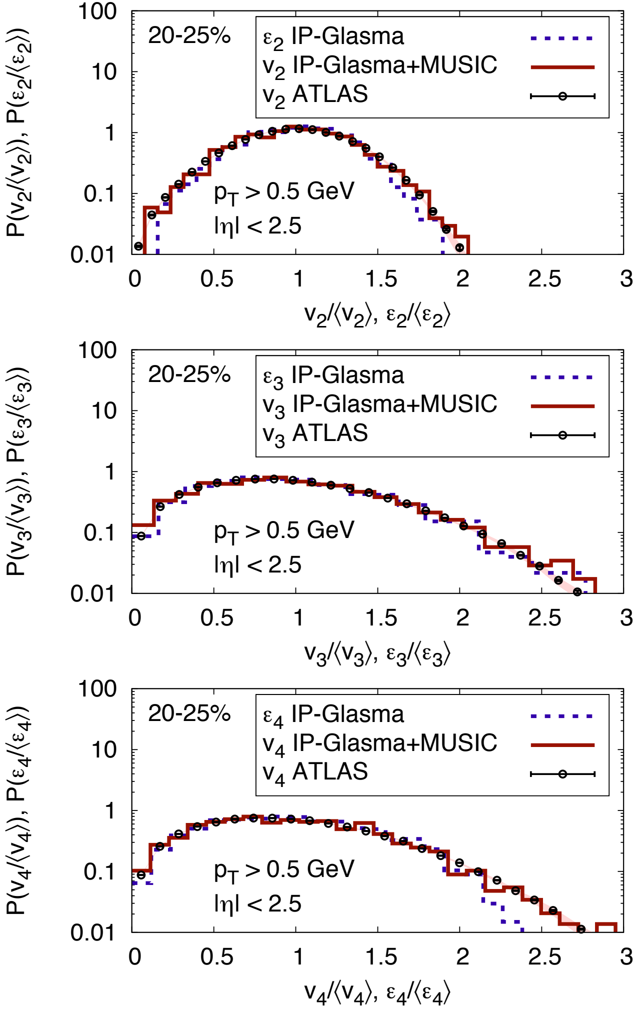




Good fit to RHIC data (with $\eta/s = 0.12$) and LHC data (with $\eta/s = 0.20$) for one model of initial fluctuations, and with a simplified treatment of the hadronic final state.

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.

η/s and Holography

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

Why care about the value of η/s?

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

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

Myers, Paulos, Sinha

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

- **A more serious answer...**

Hydrodynamics in pPb collisions?

- Almost nobody expected this. pPb collisions supposed to be a control experiment. Too small for hydrodynamics.
- But... how small is too small for hydrodynamics? In $\mathcal{N} = 4$ SYM plasma, hydro applies to arbitrarily small droplet. Not so in QCD. But, how small is too small?
- But... how large *is* the 'hot-spot' made when a proton blasts through a nucleus? Maybe as large as 2-3 fm across?? [Bozek] If hydro describes this, that is 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'?
- Experimental and theoretical investigations still in progress. Systematic investigation of initial conditions now requires confronting PbPb and pPb data at LHC and RHIC.

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...

From $\mathcal{N} = 4$ SYM to QCD

- **Two theories differ on various axes. But, their plasmas are *much* more similar than their vacua. Neither is supersymmetric. Neither confines or breaks chiral symmetry.**
- **$\mathcal{N} = 4$ SYM is conformal. QCD thermodynamics is reasonably conformal for $2T_c \lesssim T <$?. In model studies, adding the degree of nonconformality seen in QCD thermodynamics to $\mathcal{N} = 4$ SYM has *no* effect on η/s and little effect on other observables in this talk.**
- **The fact that the calculations in $\mathcal{N} = 4$ SYM are done at strong coupling is a feature, not a bug.**
- **Is the fact that the calculations in $\mathcal{N} = 4$ SYM are done at $1/N_c^2 = 0$ rather than $1/9$ a bug??**
- **In QCD thermodynamics, fundamentals are as important as adjoints. No fundamentals in $\mathcal{N} = 4$ SYM, and so far they have only been added as perturbations. This, and $1/N_c^2 = 0$, are in my view the biggest reasons why our goals must at present be limited to qualitative insights.**

Two Early Lessons from Holographic Calculations

- **'Jet quenching parameter' $\hat{q}$ (mean k_T^2 picked up per distance travelled) *not* proportional to "number of scattering centers", which is $\propto N_c^2$.** Liu, Rajagopal, Wiedemann, 2006

  $$\hat{q} \propto \sqrt{g^2 N_c}\, T^3$$

  After all, there are no scattering centers if the liquid is strongly coupled on all length scales.

- **Heavy quarks with mass M lose energy via drag, or friction,** Gubser, 2006; Herzog, Karch, Kovtun, Kozcaz, Yaffe, 2006; Casalderrey-Solana, Teaney, 2006

  $$\frac{dE}{dt} \propto -E\,\frac{T^2}{M}\ ,$$

  and then diffuse with $D \sim 1/(2\pi T)$. So, the heavy quarks quickly end up "going with the flow". Lost energy becomes sound waves. This latter is generic (to energy loss of anything) in strongly coupled liquid; more below.

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"......

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.⌋

$\mathcal{N}=4$ 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: $\underbrace{AdS_5}_{4+1 \text{ ``big'' dimensions}} \times \underbrace{S_5}_{} \rightarrow$ 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

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

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

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^2N_c means $g_{string} \to 0$⌋

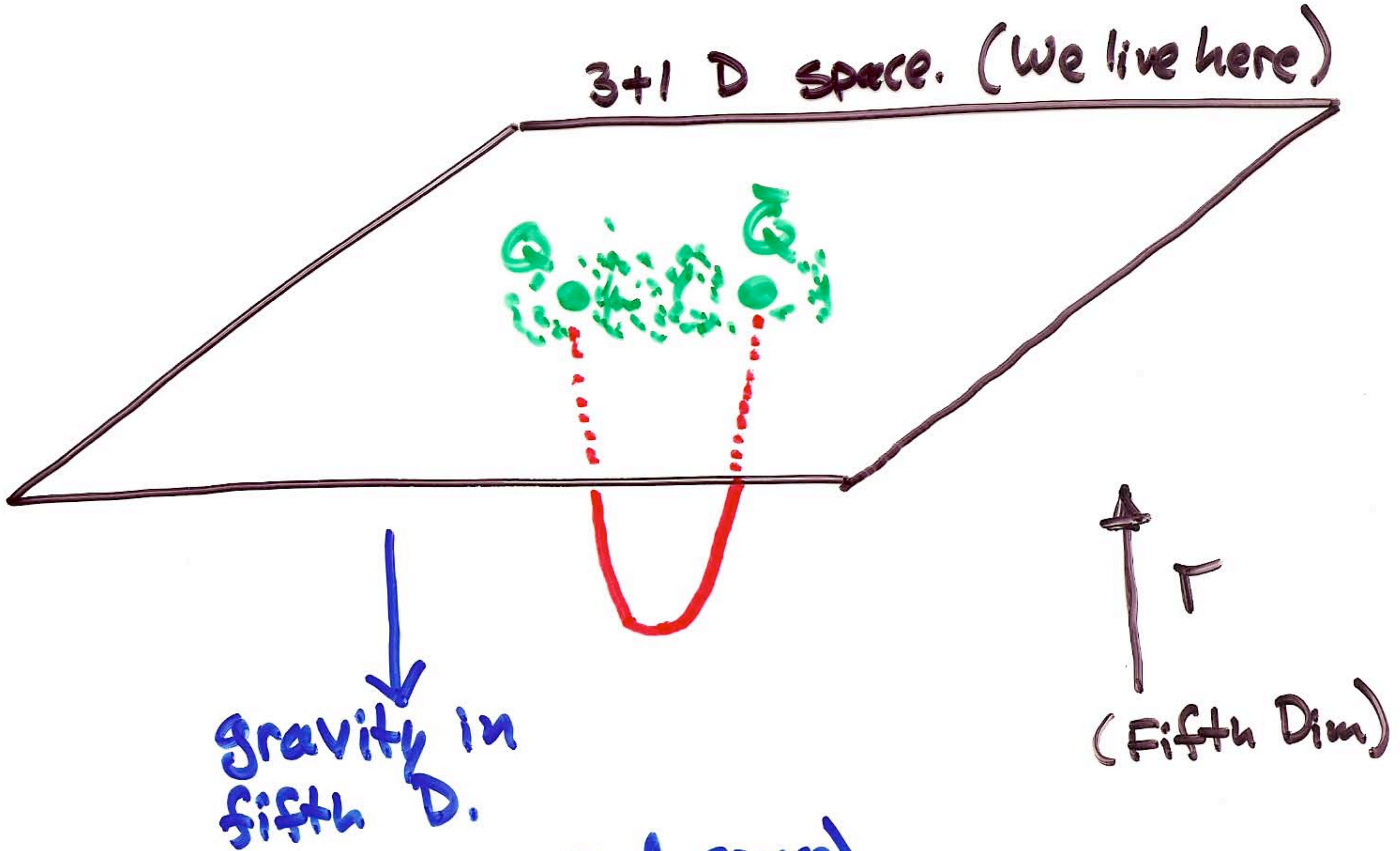
$$\sqrt{g^2 N_c} = R^2/\alpha'$$

⌈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?

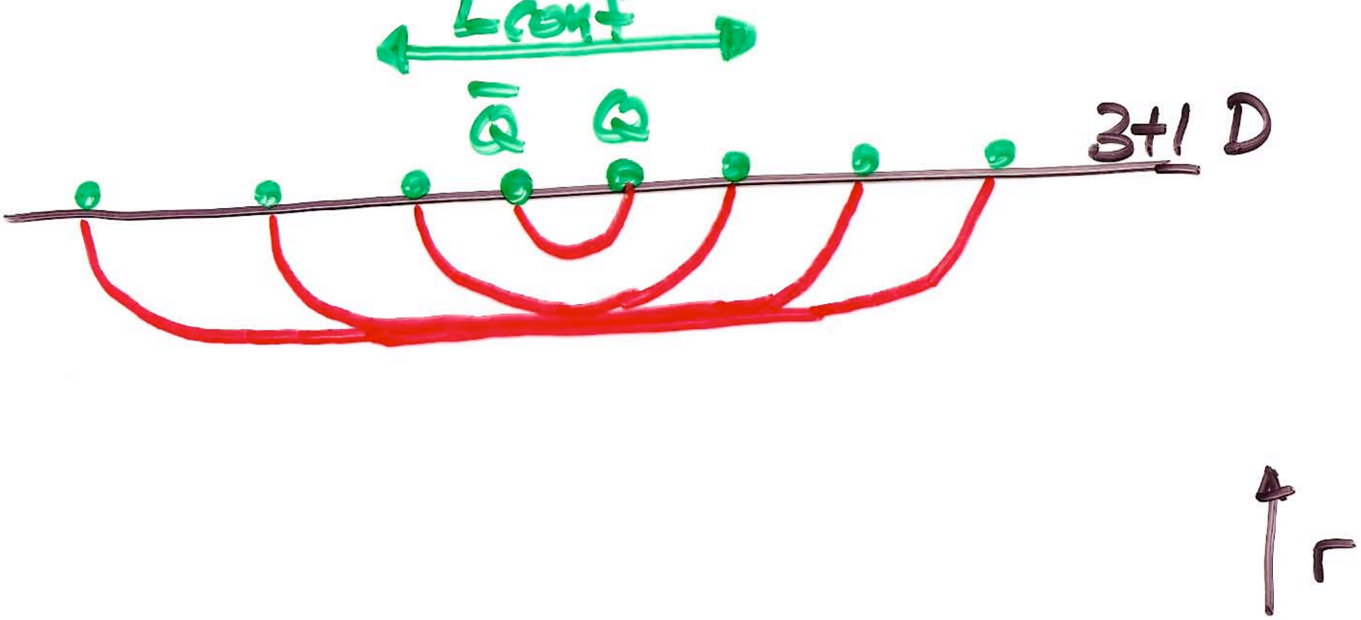


(AdS is a curved space)

- 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.
- $$\text{Force between } Q \text{ and } \bar{Q} = \frac{d}{d\,\text{separation}}\left(\text{Energy of string}\right)$$

CONFINEMENT?

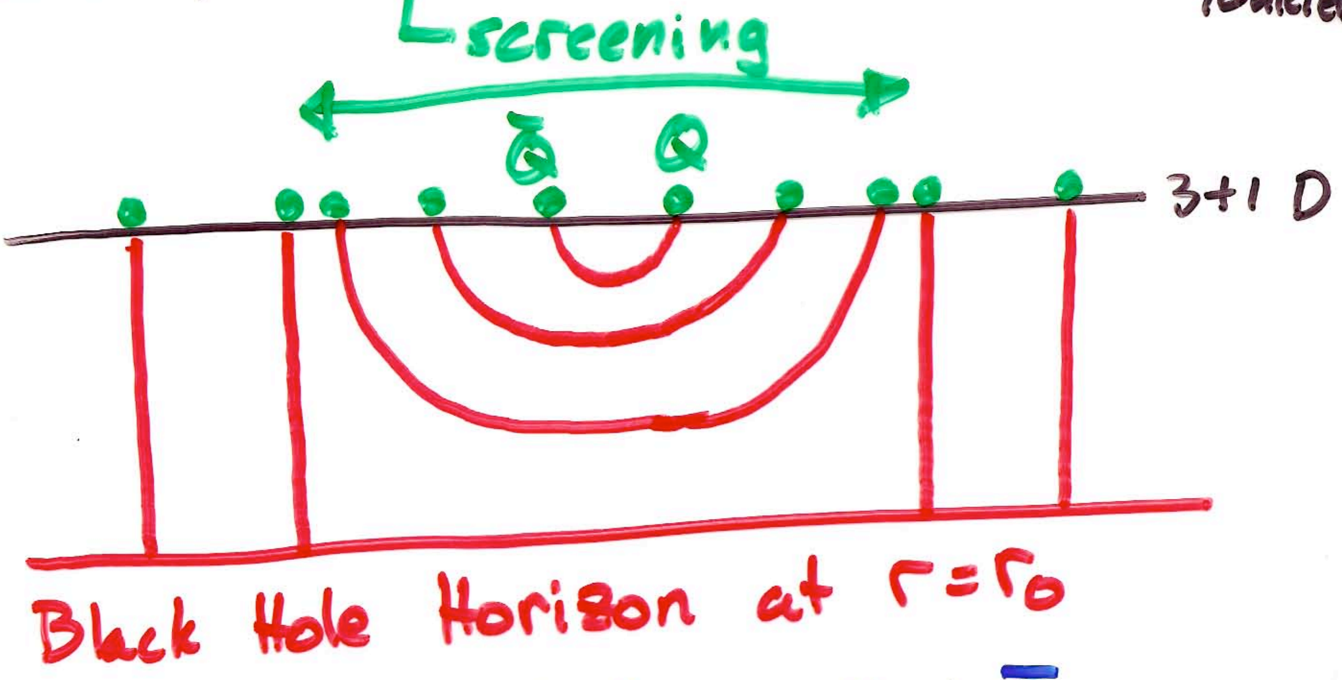
Here's how confinement can arise ....



- 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



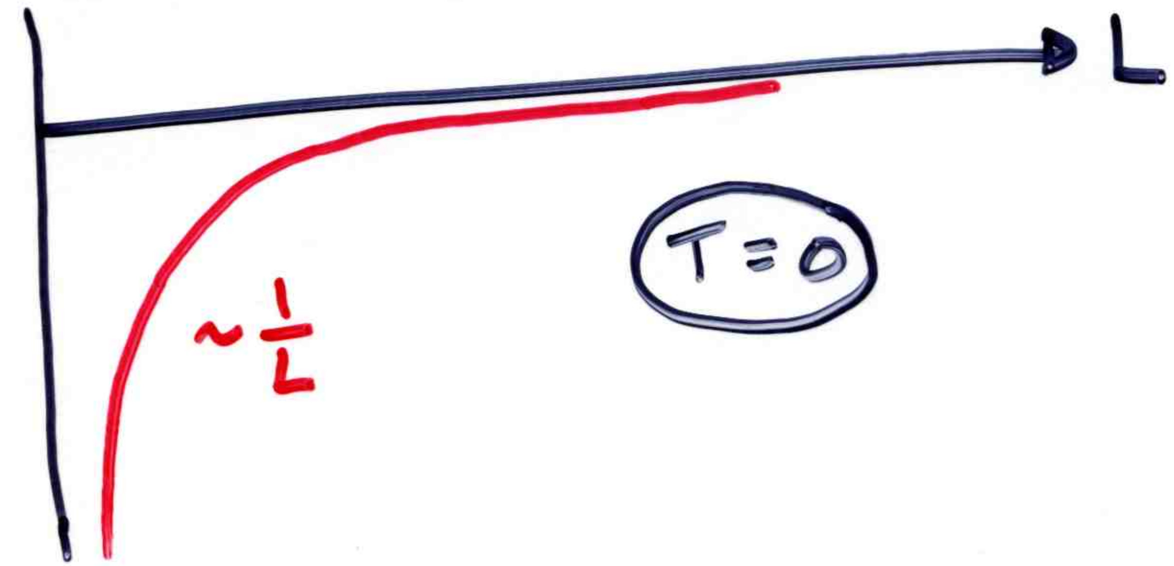
- For $L < L_s$, force between Q & $\bar{Q}$.
- For $L > L_s$, force is screened. Q & $\bar{Q}$ deconfined.
- In $N=4$ SUSY QCD,

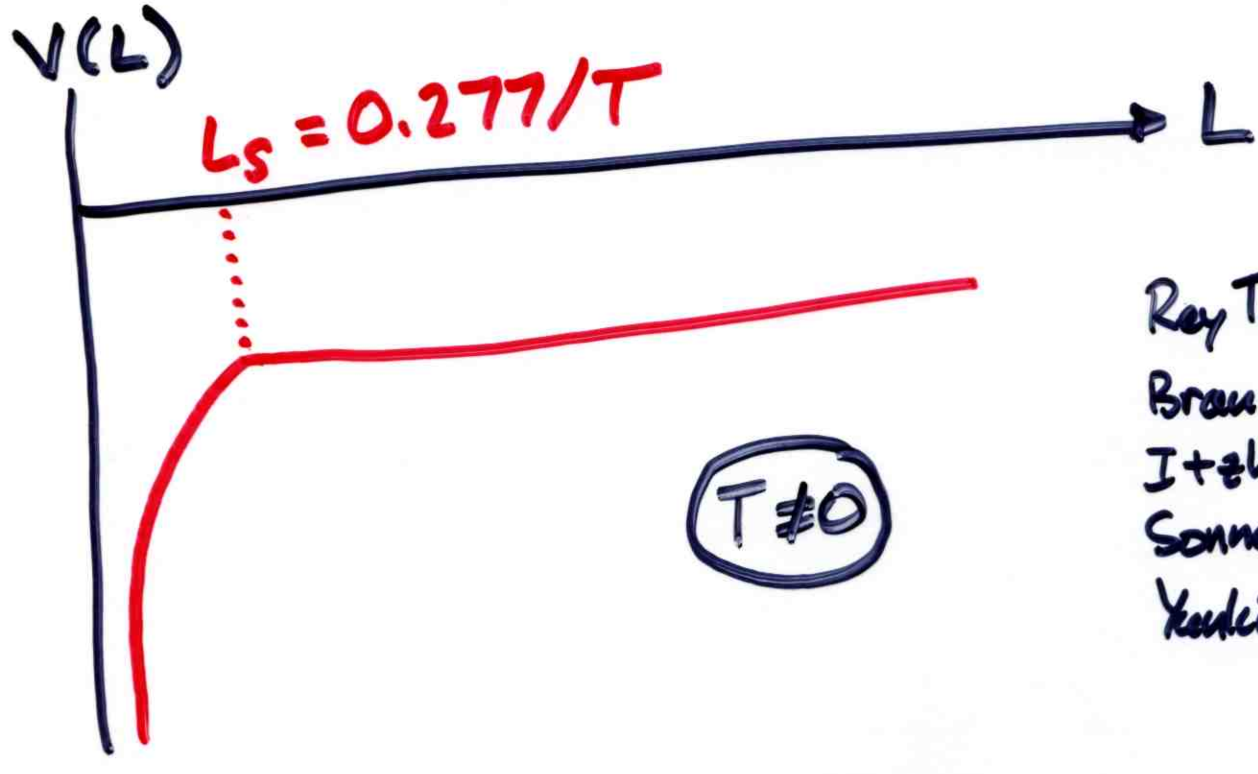
$$L_s = \frac{0.277}{T}$$

- 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 & $\bar{Q}$

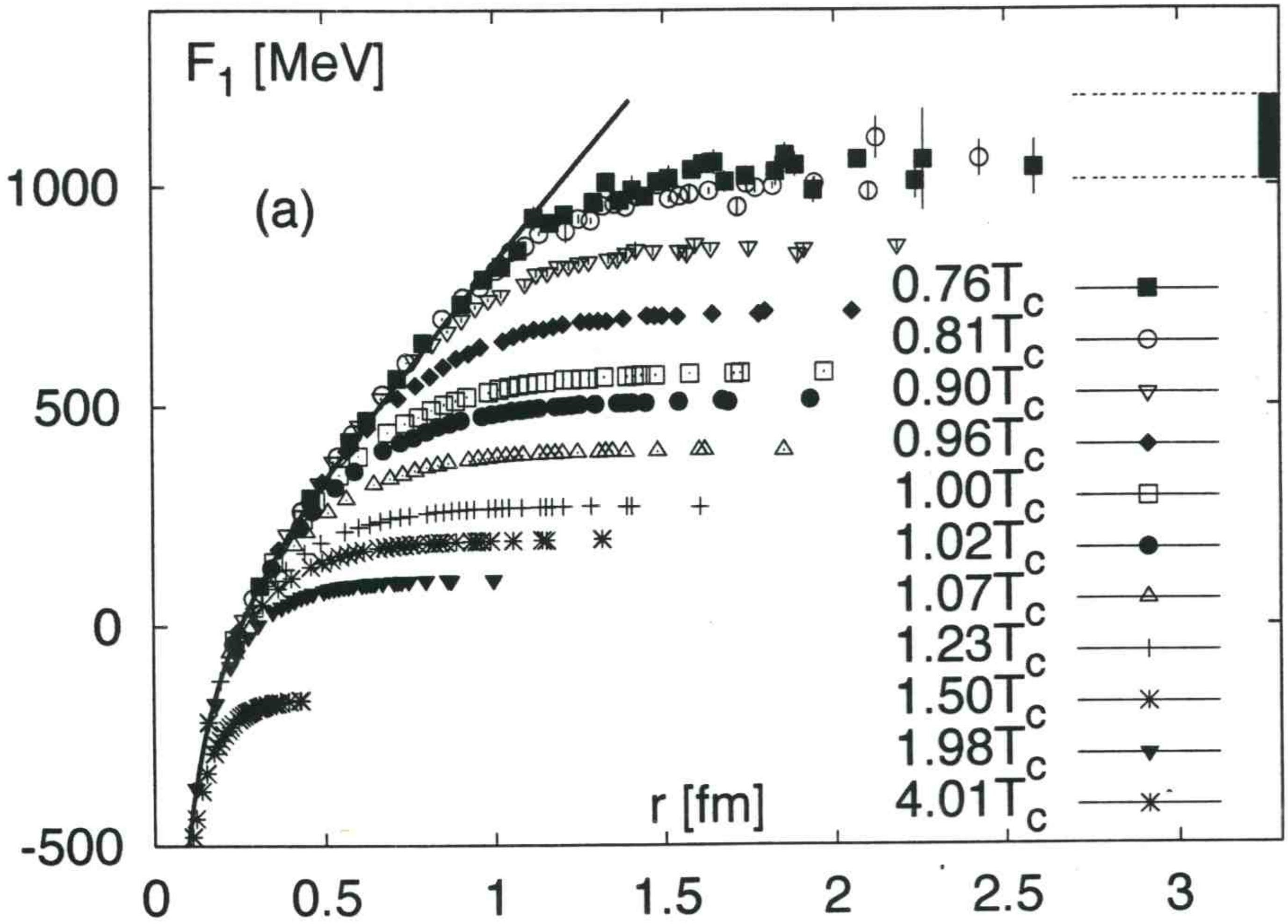




Rey Theisen Yee;
Brandhuber
Itzhaki
Sonnenschein
Yankielowicz

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

SCREENING IN QCD



Kaczmarek, Zantow

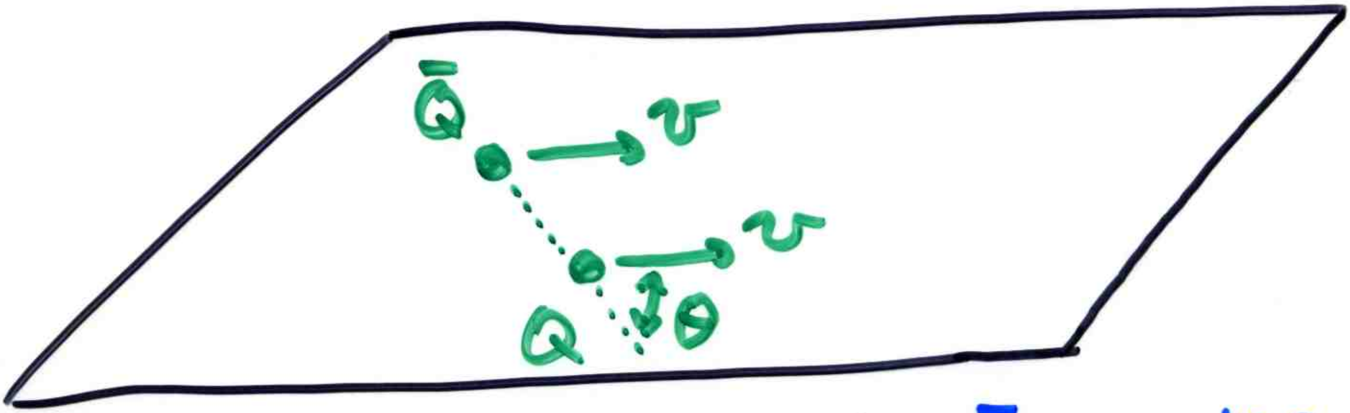
lattice QCD calculation

[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 $Q + \bar{Q}$ <u>moving</u> through the N=4 QGP. (Not known how to do this calculation in QCD.) Find:

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

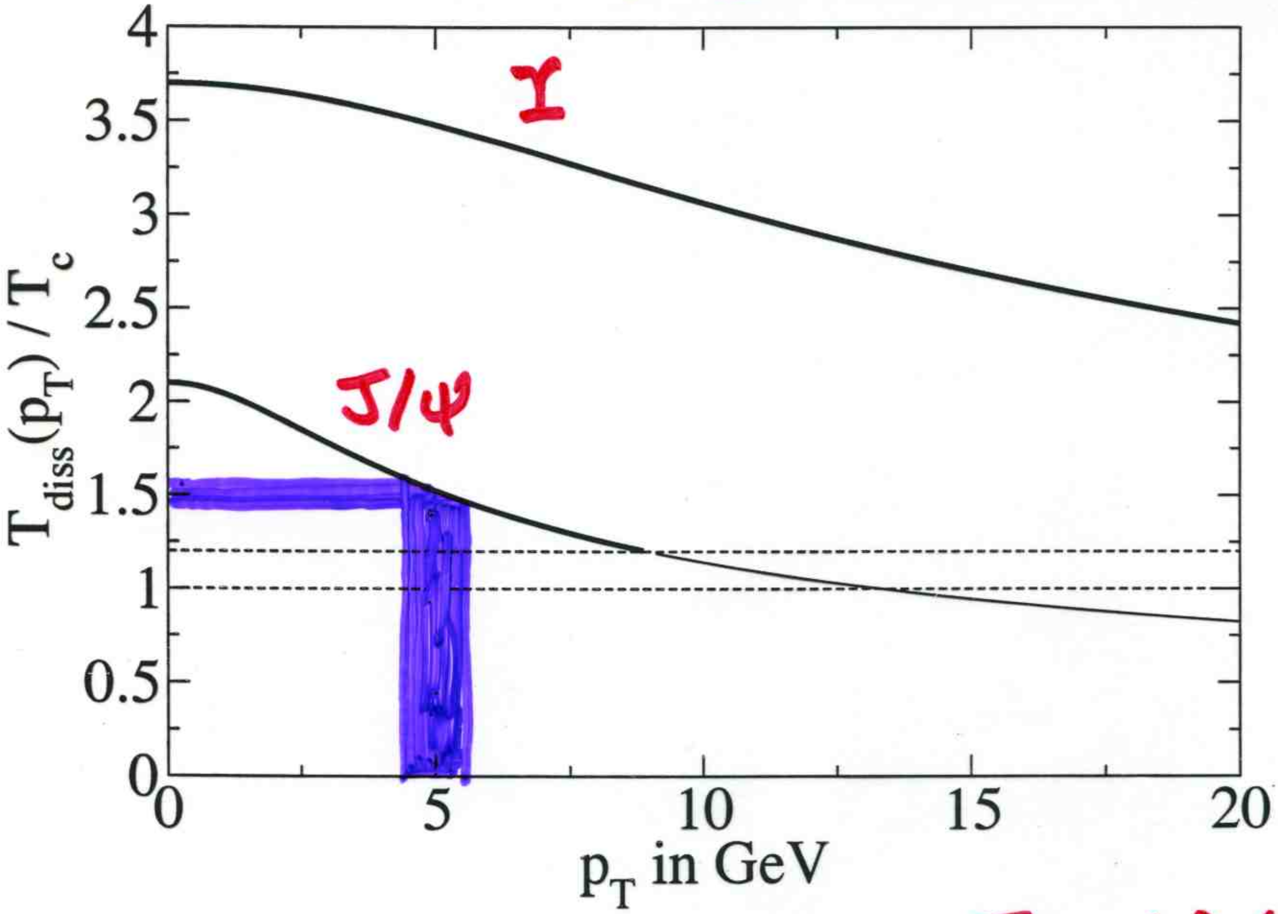
LRW; Peeters etal; Chernicoff etal; Caceres etal

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 $P_T=0$, $T^{J/\psi}_{diss} \simeq 2.1\,T_c$, 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 $2.1\,T_c < T_{RHIC} < 1.2\,T_c$)

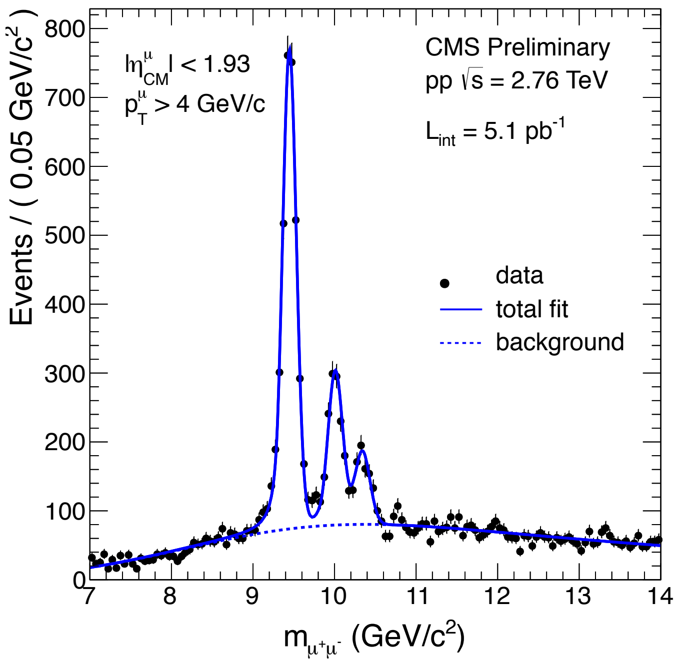
$\Rightarrow$ J/ψ <u>themselves</u> dissociate for

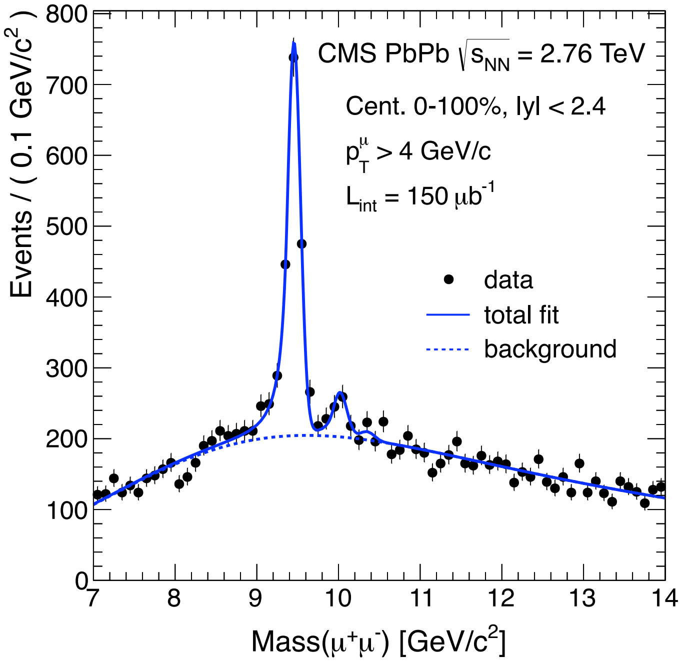
$P_T > 5\,\text{GeV}$ if $T_{RHIC} \sim 1.5\,T_c$

$P_T > 9\,\text{GeV}$ if $T_{RHIC} \sim 1.2\,T_c$

Upsilon 2S Suppression in PbPb

CMS 1208.2826 and CMS-HIN-13-003





- **Sequential suppression of Υ states in PbPb: No sign of Υ(3S). Υ(2S) substantially suppressed.**
- **It will be very interesting to see how the right-hand plot changes for higher p_T Υs. As you increase p_T, expect Υ(2S) to go the way of the Υ(3S). And then, in principal, above some rather high p_T the Υ(1S) also.**

Dragging a Heavy Quark through Strongly Coupled Plasma

HKKKY, G, 2006

- One of the first holographic calculations related to *probing* strongly coupled plasma.

- To drag a heavy quark, $M \to \infty$, with constant velocity $\vec{\beta}$ through the static, homogeneous, equilibrium strongly coupled plasma with temperature T of $\mathcal{N} = 4$ SYM theory requires exerting a *drag force*:

$$\vec{f} = \frac{\sqrt{\lambda}}{2\pi} (\pi T)^2 \gamma \vec{\beta} \propto \frac{\vec{p}}{M}$$

  with $\lambda \equiv g^2 N_c$ the 't Hooft coupling.

- *Caveat emptor:* At finite M, this picture only applies for

$$\sqrt{\gamma} \ll \frac{M}{T\sqrt{\lambda}} \ .$$

  Eg for b quarks at the LHC validity is $p_T \lesssim 20 - 40$ GeV. Higher p_T heavy quarks behave like light quarks.

Dragging a Heavy Quark through Strongly Coupled Plasma

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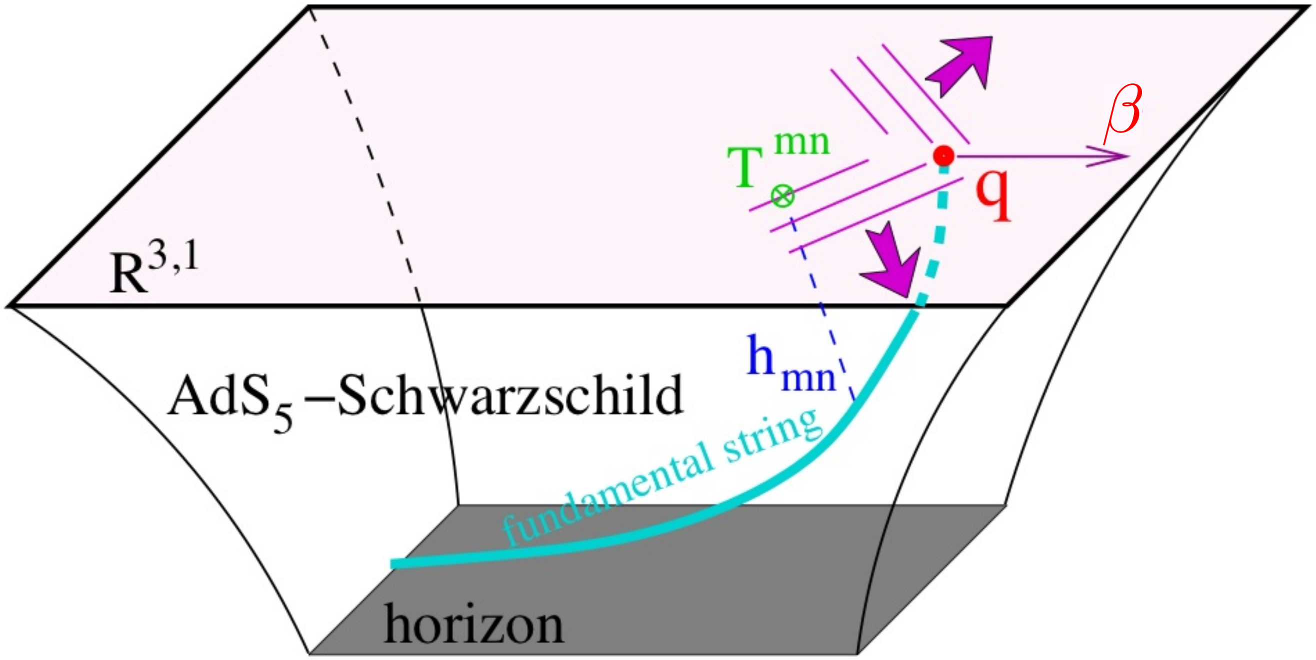

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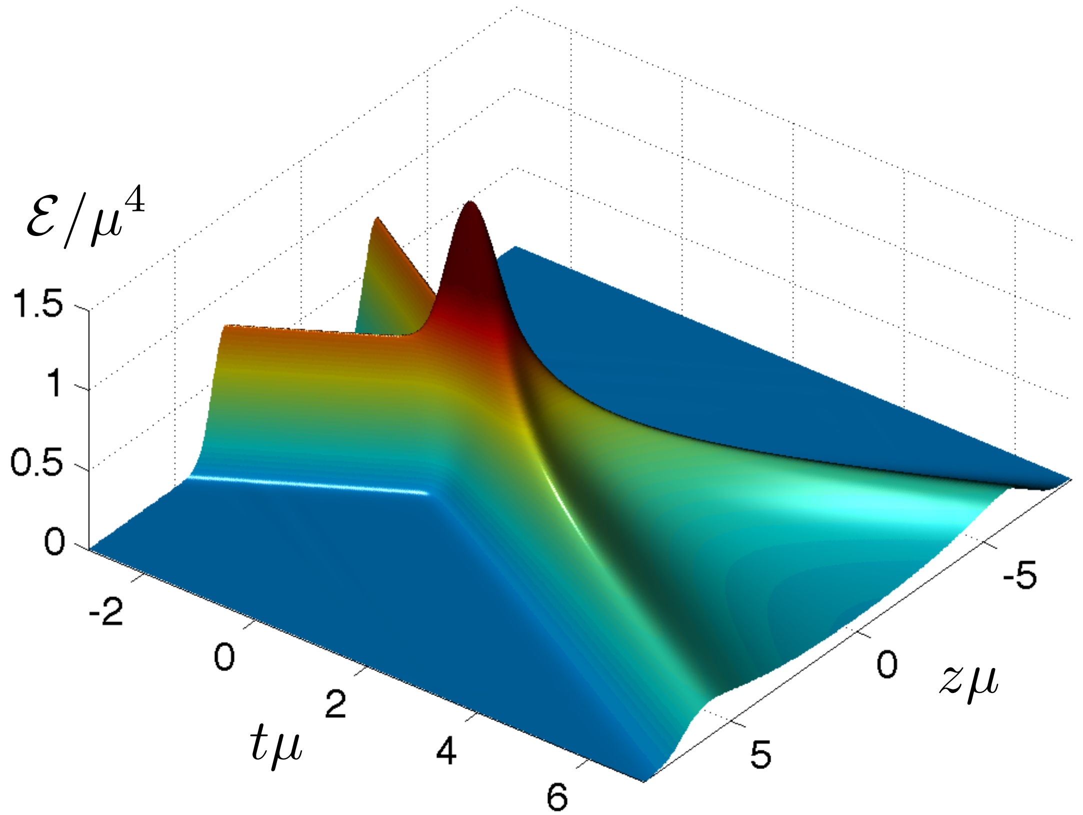
Dragging a Heavy Quark through Strongly Coupled Plasma

- The basic picture of how heavy quarks behave in strongly coupled plasma is that first they lose energy (to heat and sound in the plasma, the latter itself quickly becoming heat) and then many of them end up diffusing with diffusion constant $D \approx 1/(2\pi T)$, which is to say a very short mean free path if a mean free path can even be defined. Ie many of them end up "going with the flow".
- Heavy quarks with the same p/M have the same dp/dt.
- *Caveat emptor:* the fluid produced in heavy ions is not homogeneous, and although hydrodynamized it is not in static equilibrium.
- How do gradients in the fluid and temporal variations of the fluid (lets call both together "fluid gradients") affect the drag force? Ripples in the fluid become ripples in the horizon and metric. Those cause the string to ripple. That affects the drag force.

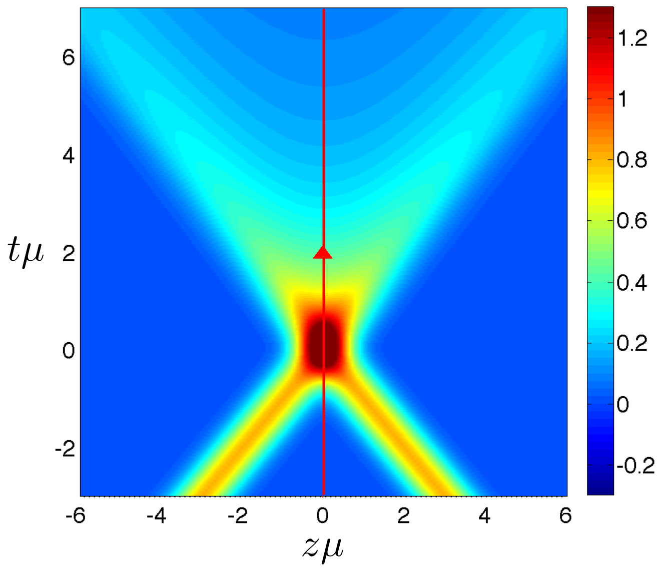
Colliding Strongly Coupled Sheets of Energy

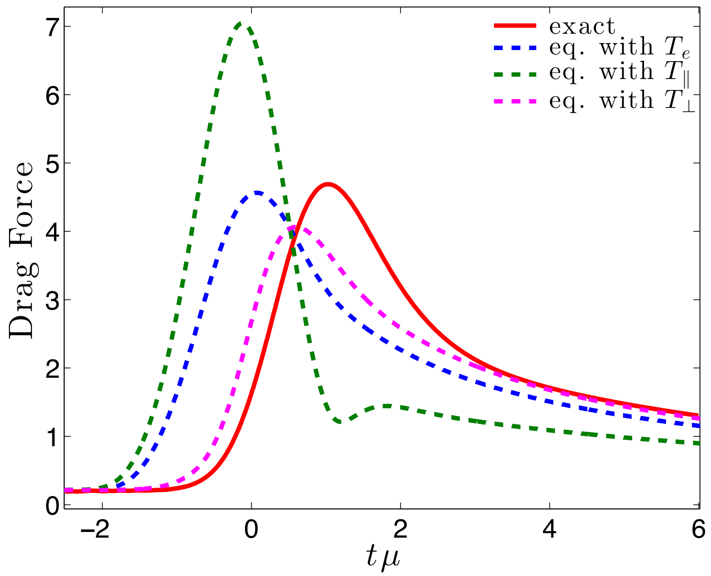


Hydrodynamics valid ~ 3 **sheet thicknesses after the collision, i.e.** ~ 0.35 **fm after a RHIC collision. Equilibration after** ~ 1 **fm need not be thought of as rapid.** Chesler, Yaffe 1011.3562; generalized in C-S,H,M,vdS 1305.4919; CY 1309.1439 **Similarly 'rapid' hydrodynamization times** ($\tau T \lesssim 0.7 - 1$) **found for** ***many*** **non-expanding or boost invariant initial conditions.** Heller and various: 1103.3452, 1202.0981, 1203.0755, 1304.5172

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 in strongly coupled $\mathcal{N} = 4$ SYM theory.
- Guidance for modeling heavy quark energy loss early in a heavy ion collision: at mid-rapidity, eqbm expectations provide a reasonable guide to magnitude, but there is a time delay. Surprises at nonzero rapidity. (Discuss later).
- Analytic calculation of effect of $\vec{\nabla} v^{\text{fluid}}$ on energy loss is possible. We have done this to first order in gradients. Lekaveckas, Rajagopal, 1311.5577.

Effects of Fluid Gradients on Drag

Lekaveckas, Rajagopal, 1311.5577

- **Some notation:** $b \equiv 1/(\pi T_e)\,,$

  where T_e is defined from ε via $\varepsilon = (3\pi^2/8)N_c^2 T_e^4$.

  Fluid four-velocity: $u^\mu = \gamma_v(1, \vec{v})$.

  Heavy quark four-velocity: $w^\mu = \gamma(1, \vec{\beta})$.

  The one Lorentz-scalar with no ∂ is: $s \equiv u^\mu w_\mu$.

  All these quantities vary in space and time.
- **Write the drag force as an expansion in powers of $\partial_\alpha u_\beta$, to first order:**

$$f^\mu = f^\mu_{(0)} + f^\mu_{(1)} + \dots$$

  (Note: use first order viscous hydro to relate $\partial_\alpha b$ to $\partial_\alpha u_\beta$; expansion is in powers of gradients of T and v_{fluid}.)
- **We already have $f^\mu_{(0)}$: drag force to zeroth order in gradients is drag force in homogeneous plasma**

$$f^\mu_{(0)} = -\frac{\sqrt{\lambda}}{2\pi}\frac{1}{\gamma b^2}\left(s\,w^\mu + u^\mu\right)$$

Effects of Fluid Gradients on Drag

Lekaveckas, Rajagopal, 1311.5577

- **We obtain a fully general result for $f^\mu_{(1)}$:**

$$f^\mu_{(1)} = -\frac{\sqrt{\lambda}}{2\pi}\frac{1}{b\gamma}\Big[c_1(s)\Big(u^\mu w^\alpha \partial_\alpha s - s\partial^\mu s - s(s\,u^\alpha + w^\alpha)\partial_\alpha U^\mu\Big)$$

$$+c_2(s)U^\mu \partial_\alpha u^\alpha - \sqrt{-s}u^\alpha \partial_\alpha U^\mu\Big]$$

where

$$U^\mu \equiv u^\mu + s\,w^\mu$$

$$c_1(s) \equiv \frac{1}{4}\left[2\,\mathrm{arctan}\left(\frac{1}{\sqrt{-s}}\right) - \log\left(\frac{(1-s)(1+\sqrt{-s})^2}{s^2}\right)\right]$$

$$c_2(s) \equiv \frac{1}{3}\left(\sqrt{-s} + (1+s^2)c_1(s)\right)$$

This is for any configuration of fluid flow, to lowest order in gradients.

Effects of Fluid Gradients on Drag

Lekaveckas, Rajagopal, 1311.5577

- For a quark at rest, in a fluid that is instantaneously at rest but has $\partial_t u^3 \neq 0$, we find $f^z_{(1)} = (\sqrt{\lambda}/2\pi b)\partial_t u^3$. This is exactly the value of the drag force a time $\Delta t = b$ ago. A very simple example of time delay in the response of the drag force to changing fluid conditions.

- Suppose the fluid is expanding à la Bjorken, in the z-direction. Suppose that, in the fluid rest frame, the heavy quark starts at $z = t = 0$ and has $\beta_x \neq 0$. Then,

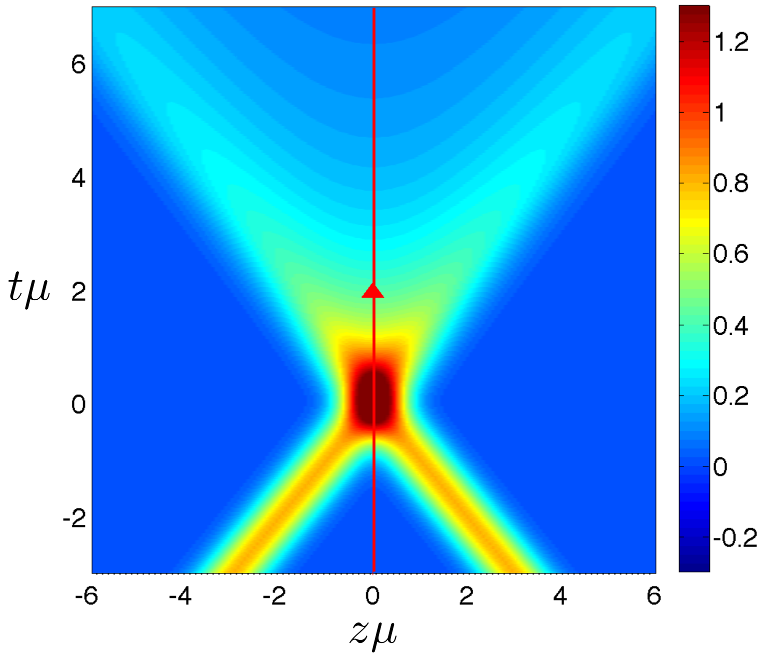
$$f^x = \frac{\sqrt{\lambda}}{2\pi} \frac{\gamma\beta_x}{b(\tau)^2} \left(1 + \frac{b(\tau)}{\tau} c_2(-\gamma)\right)$$

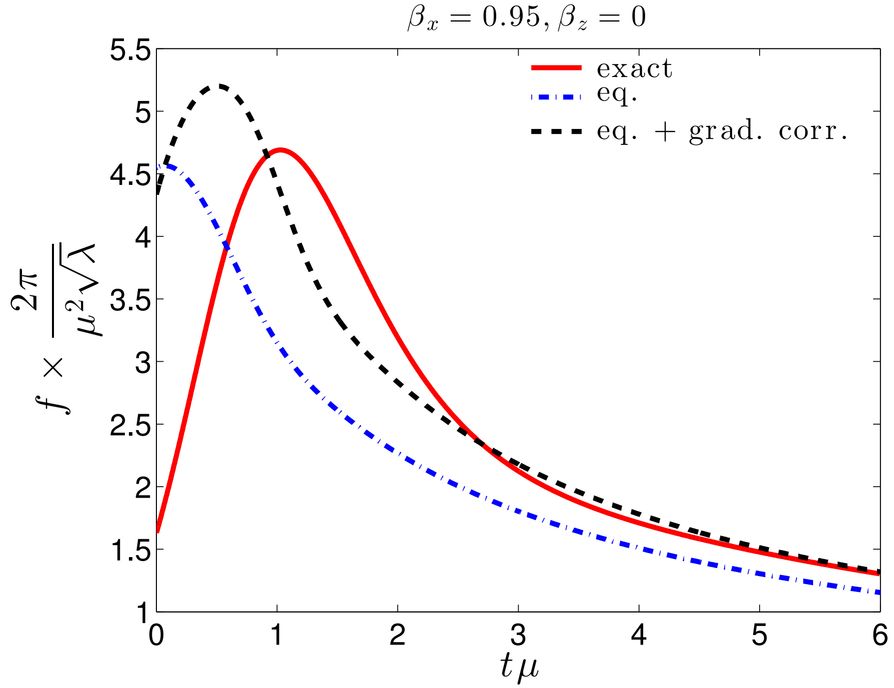
  Results in other frames and for other directions of motion of the quark in the paper.

- And, results for the heavy quark that finds itself in the middle of those colliding sheets, after hydrodynamization. . .

Heavy Quark Energy Loss, Zero-Rapidity

Lekaveckas, Rajagopal 1311.5577

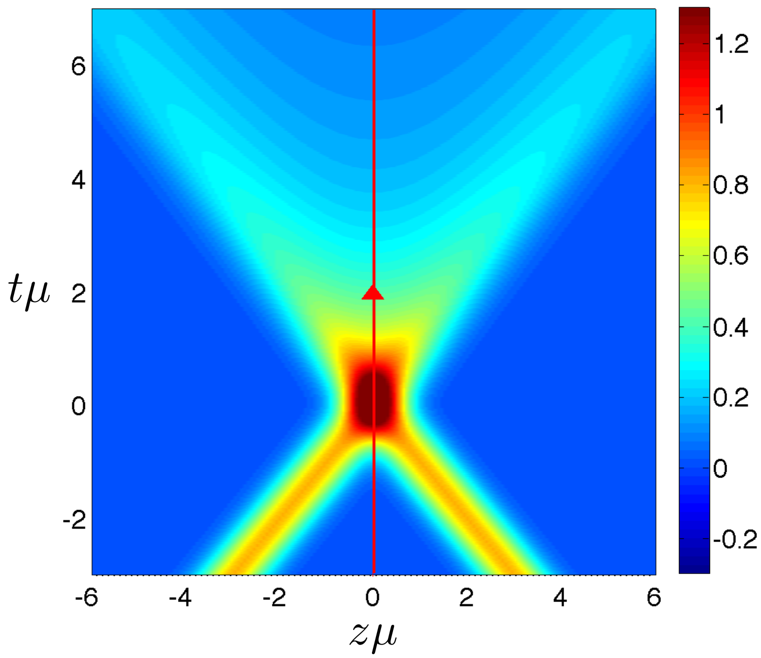


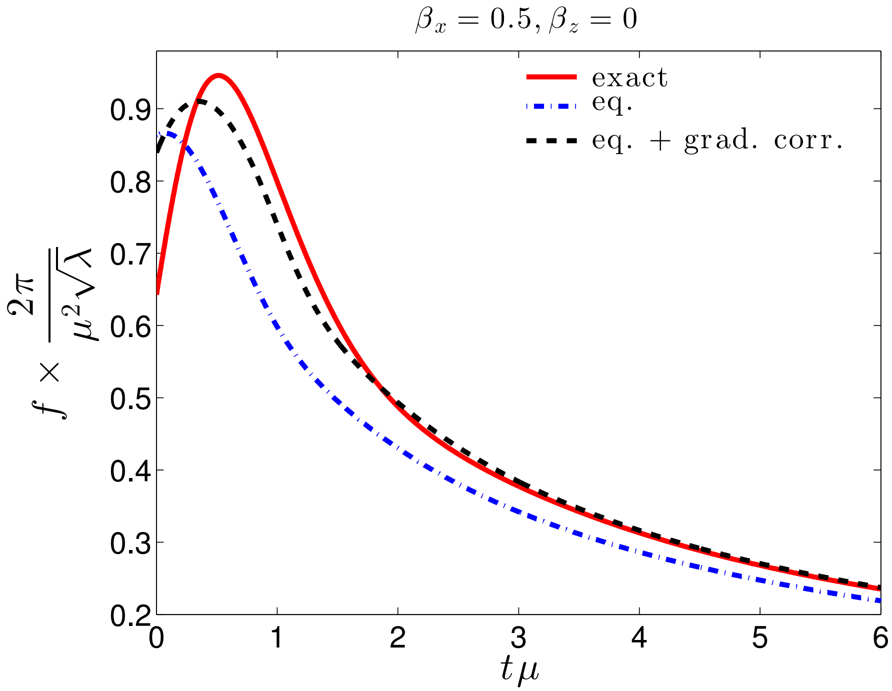


- **After hydrodynamization, first order contribution to drag force does a very good job of describing the discrepancy identified previously.**

Heavy Quark Energy Loss, Zero-Rapidity

Lekaveckas, Rajagopal 1311.5577

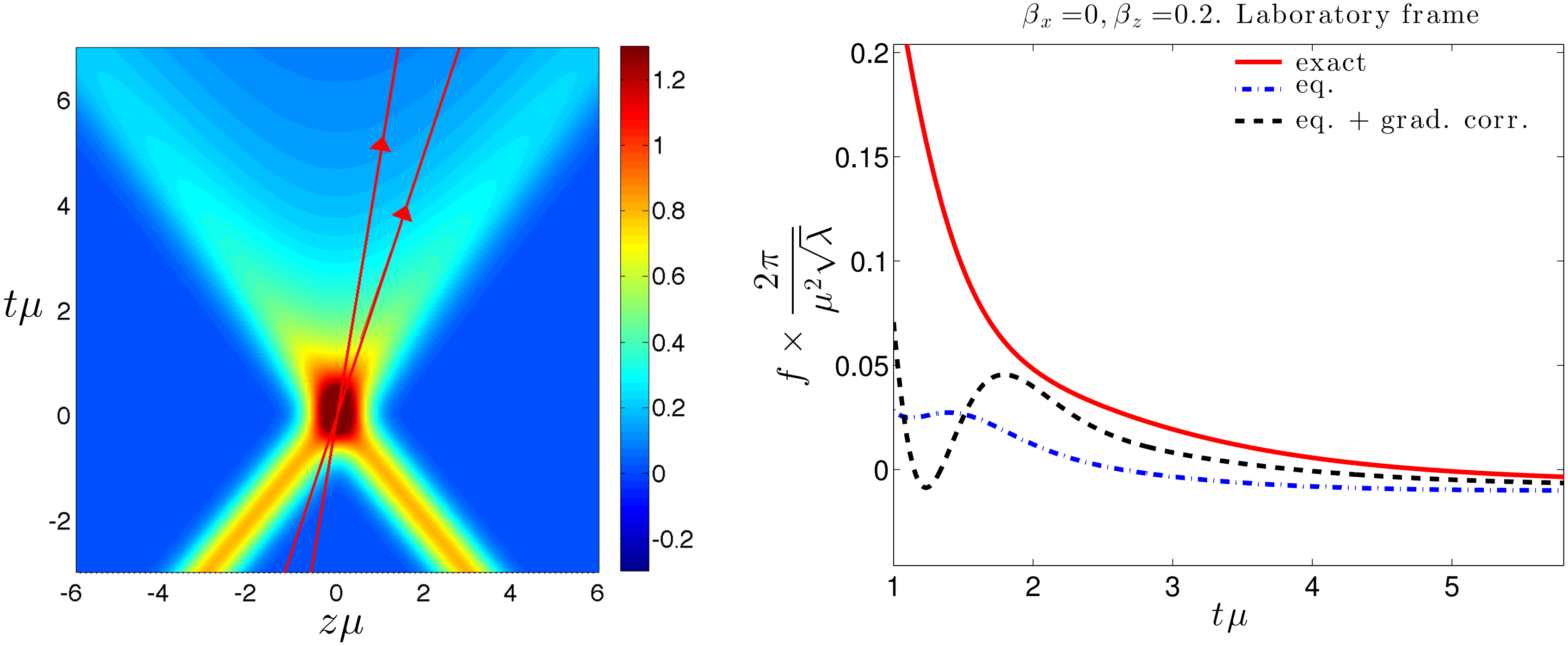




- **Even better for quark with $\beta_x = 0.5$ instead of $\beta_x = 0.95$.**
- **The calculation seems to break down if the heavy quark is moving too fast through a changing fluid. Valid for $b\sqrt{\gamma} \lesssim 1/|\partial_t u^3|$ and $b\sqrt{\gamma} \lesssim 1/|\partial_z u^3|$.**

Heavy Quark Energy Loss, Nonzero-Rapidity

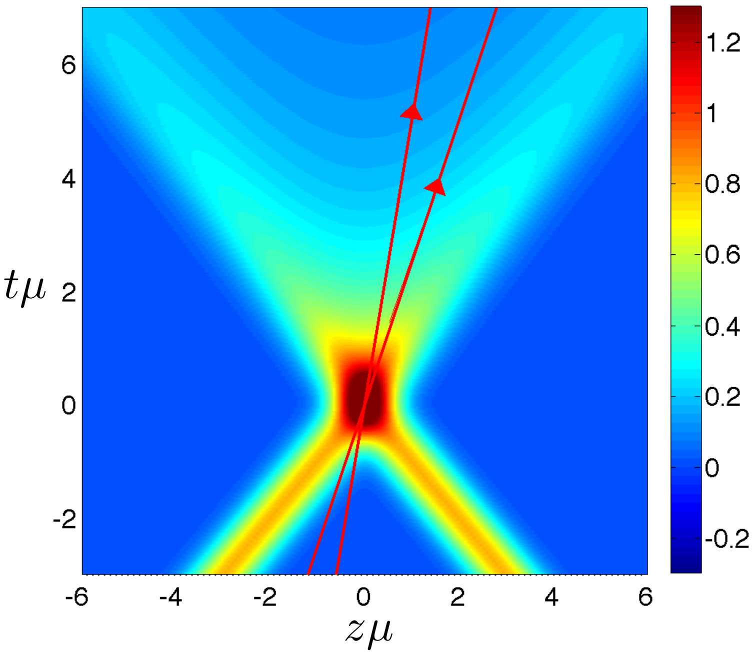
Lekaveckas, Rajagopal 1311.5577

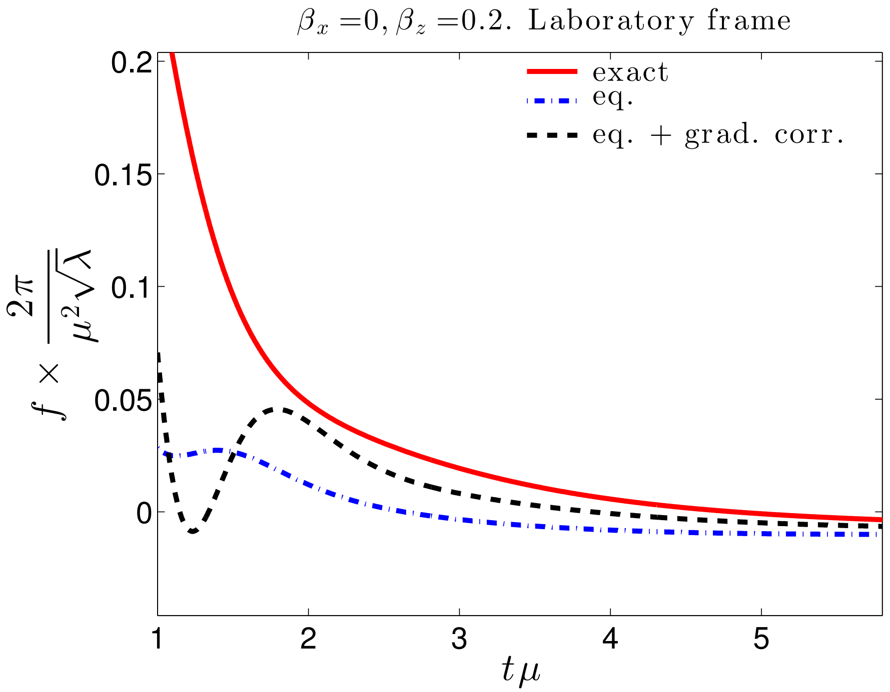


- Here, $\beta_z = 0.2$ and $\beta_x = 0$. Relative velocity of quark and fluid would be zero if expansion were boost invariant. Here, relative velocity, and force, is *small*.
- Absolute magnitude of deviation between first order result and exact result is comparable to what we have seen in other cases.

Heavy Quark Energy Loss, Nonzero-Rapidity

Lekaveckas, Rajagopal 1311.5577

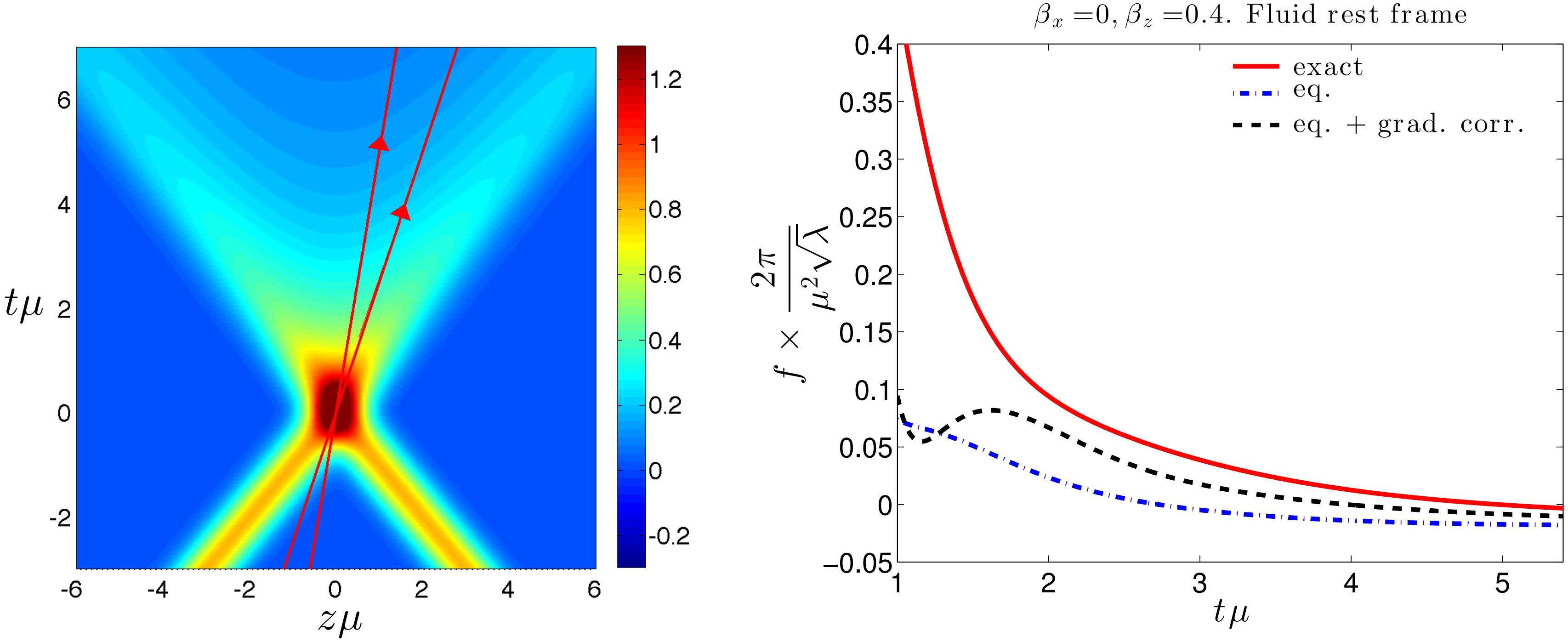




- **Relative velocity, and therefore $f_{(0)}$, flips sign at $t\mu = 2.63$. First order gradients give qualitative explanation of regime where actual ‘drag’ force hasn’t yet flipped, meaning you have to pull the quark in the direction opposite its motion! Drag force exerted by the fluid on the quark is in the direction of its motion! We now see, by analytic calculation, that this is a consequence of the gradients in the fluid.**

Heavy Quark Energy Loss, Nonzero-Rapidity

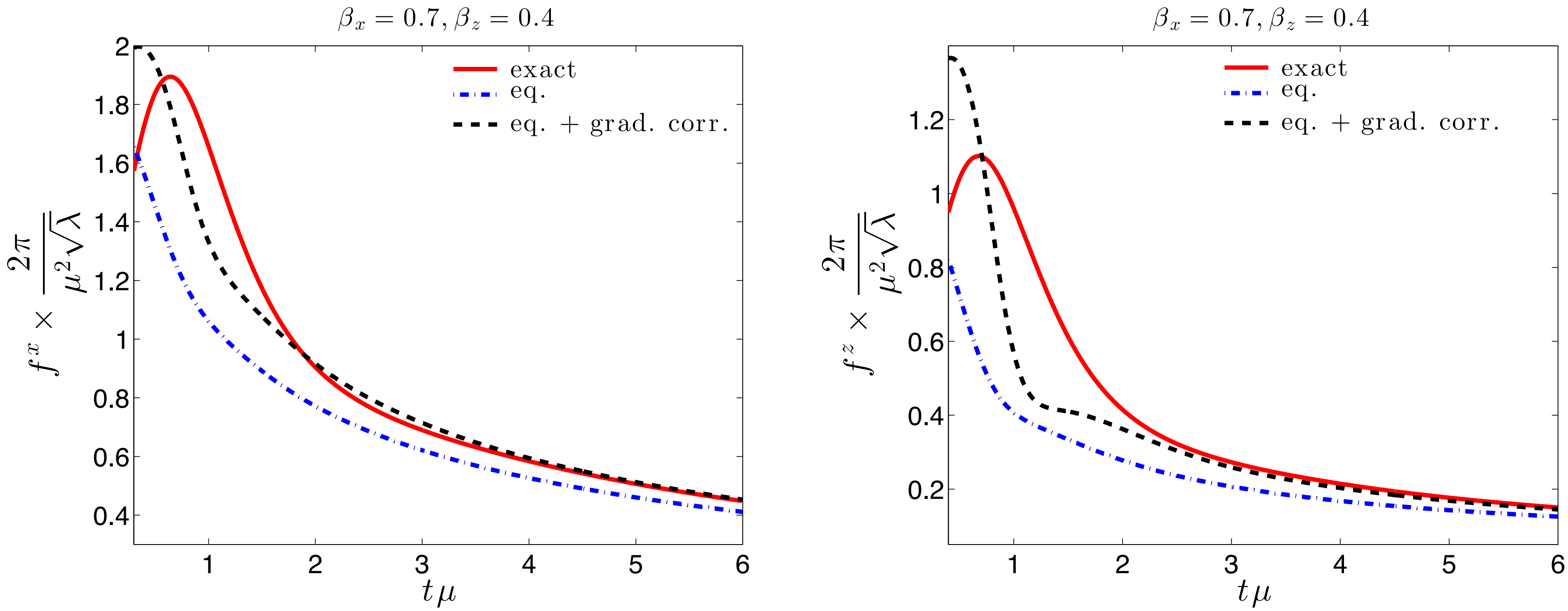
Lekaveckas, Rajagopal 1311.5577



- **Here, $\beta_z = 0.4$ and $\beta_x = 0$. Relative velocity of quark and fluid would be zero if expansion were boost invariant. Here, relative velocity, and force, is *small*. Relative velocity, and therefore $f_{(0)}$, flips sign at $t\mu = 2.73$.**
- **Again, first order gradients explain regime where actual drag force has not yet flipped and so looks backwards.**

Heavy Quark Energy Loss, Nonzero-Rapidity

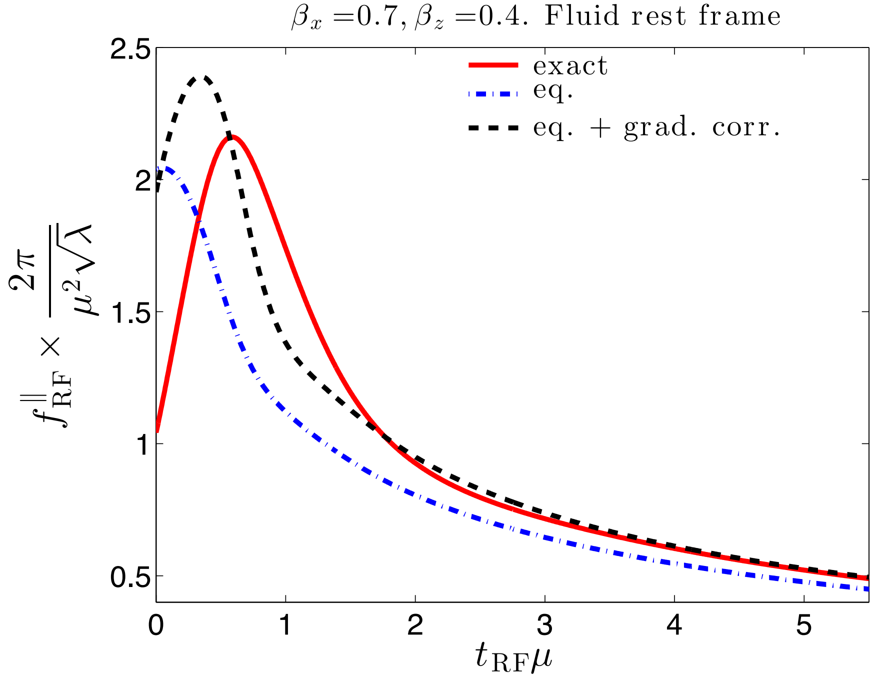
Lekaveckas, Rajagopal 1311.5577

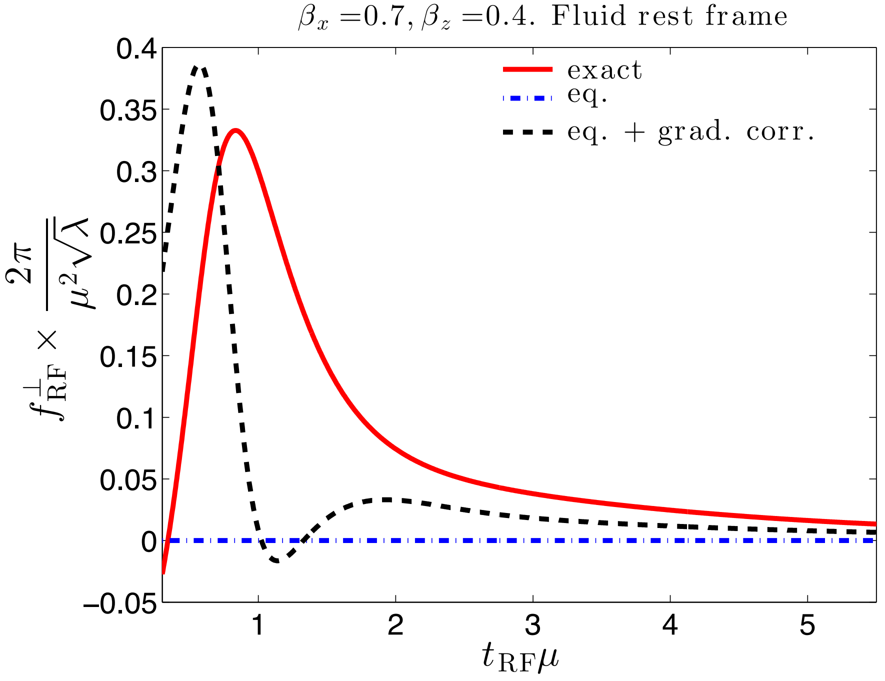


- **Here, $\beta_z = 0.4$ and $\beta_x = 0.7$. f^x and f^z in the lab frame described well at first order in gradients.**

Heavy Quark Energy Loss, Nonzero-Rapidity

Lekaveckas, Rajagopal 1311.5577





- **Here, $\beta_z = 0.4$ and $\beta_x = 0.7$. $f^{\parallel}$ and $f^{\perp}$, ie parallel and perpendicular to $\vec{\beta}$,** *in the local fluid rest frame.*
- **In the local fluid rest frame, $\vec{f}_{(0)}$ must be parallel to motion of quark. Actual 'drag' force is not: small perpendicular component! This too is explained qualitatively by first order effects of gradients.**

Effects of Fluid Velocity Gradients on Heavy Quark Energy Loss

Lekaveckas, Rajagopal, 1311.5577

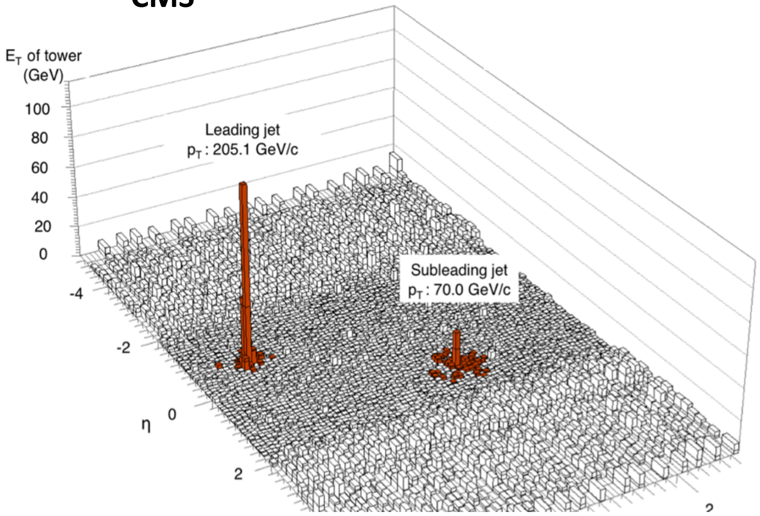
- For heavy quark at zero rapidity, zeroth order result — what the drag force would be in a homogeneous static fluid with the same instantaneous energy density — does a reasonable job, but there is a time delay. Adding corrections that are first order in gradients describes the exact result after hydrodynamization very well.

- For a heavy quark with nonzero rapidity, ie whose velocity has a component in the beam direction, there are small but counterintuitive effects that do not look at all like drag. They are all explained qualitatively by the first order effects of fluid gradients.

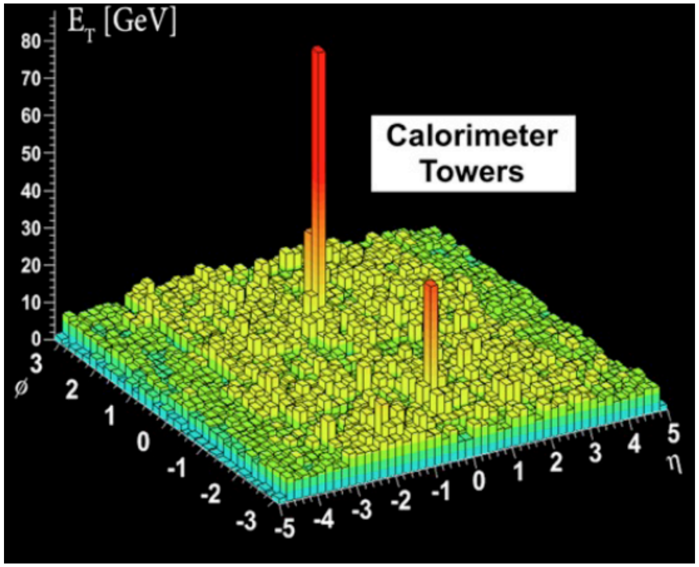
- Would be very interesting to try a holographic analysis of the effects of fluid gradients on light quark quenching, or photon emission, or quark-antiquark screening and quarkonium binding.

Jet Quenching, in brief

CMS



ATLAS

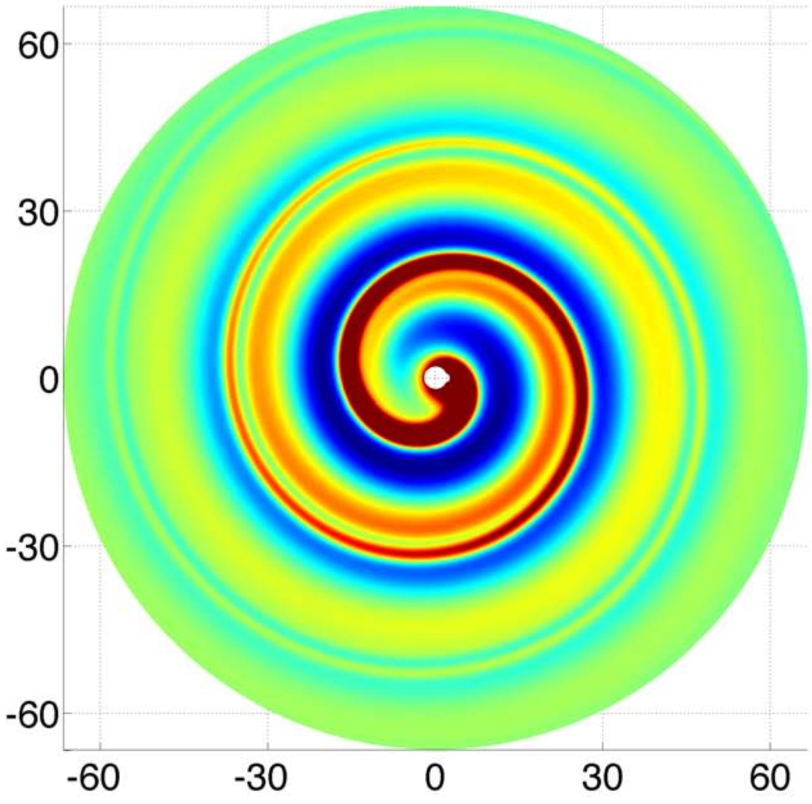


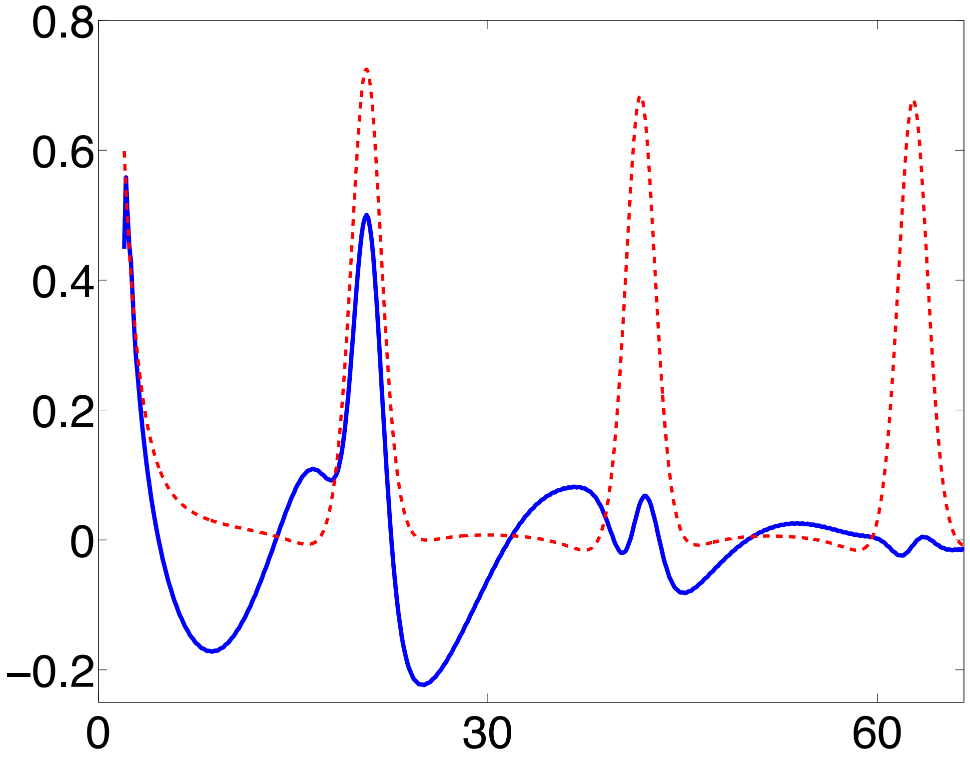
Caricature of jet quenching @ RHIC & LHC:

- 200+ GeV jets lose many tens of GeV passing through the liquid QGP, but jets emerge looking in other respects rather ordinary.
- Lost energy turns into many soft particles at all angles.
- Lower energy jets, seen by ALICE and at RHIC, may emerge surrounded by their debris?

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691





Beam of lower momentum gluons quenched rapidly, and is followed closely by its ‘debris’ — a sound wave.

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691

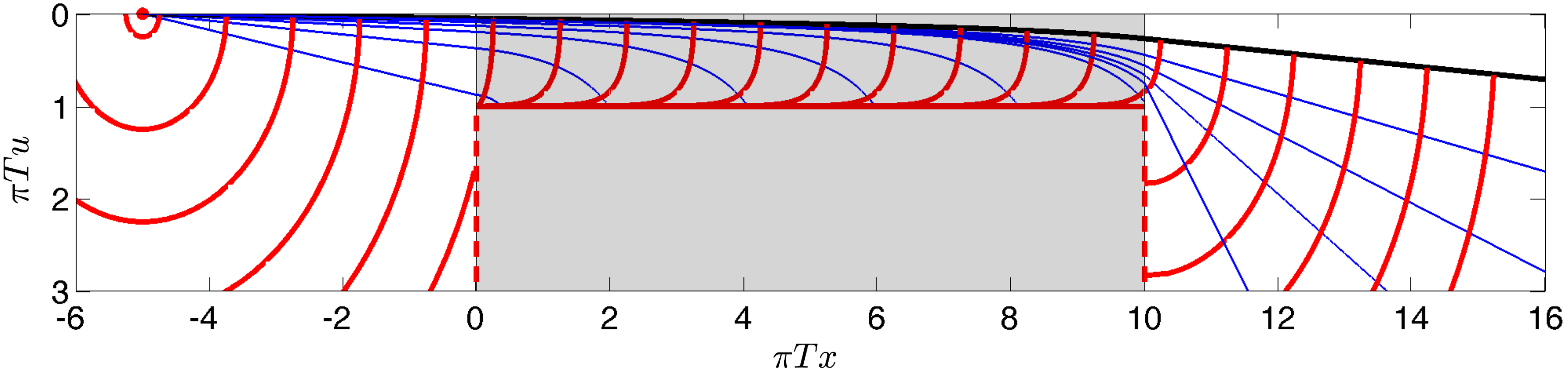
- A beam of gluons with wave vector $q \gg \pi T$ shines through the strongly coupled plasma at close to the speed of light, and is attenuated over a distance $\sim q^{1/3}(\pi T)^{-4/3}$.

- 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

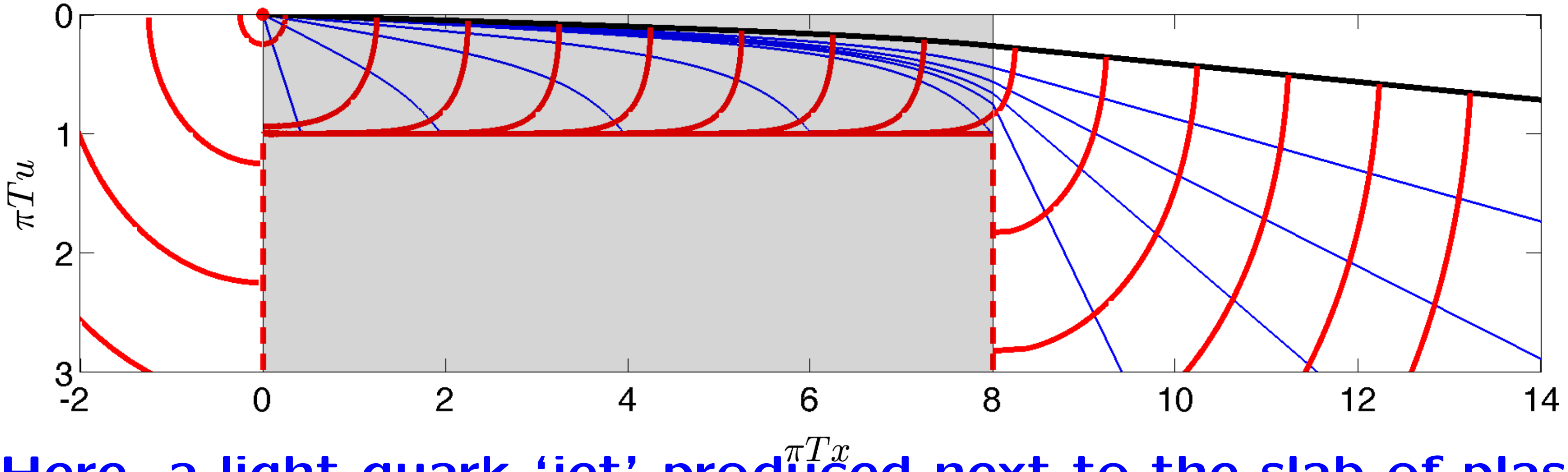


A light quark ‘jet’, incident with energy E_{in}, shoots through a slab of strongly coupled $\mathcal{N}=4$ SYM plasma, temperature T, thickness $L\pi T = 10$. What comes out the other side? A ‘jet’ with $E_{\text{out}} \sim 0.64 E_{\text{in}}$, that looks just like a vacuum ‘jet’ with that lower energy and a broader opening angle. 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

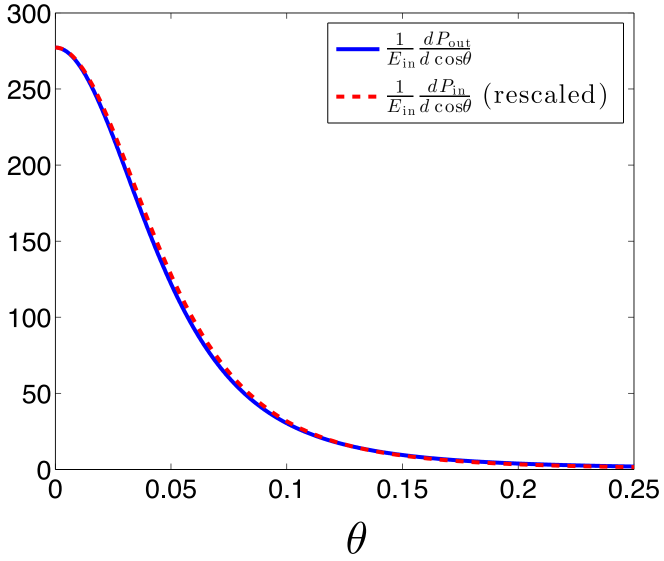


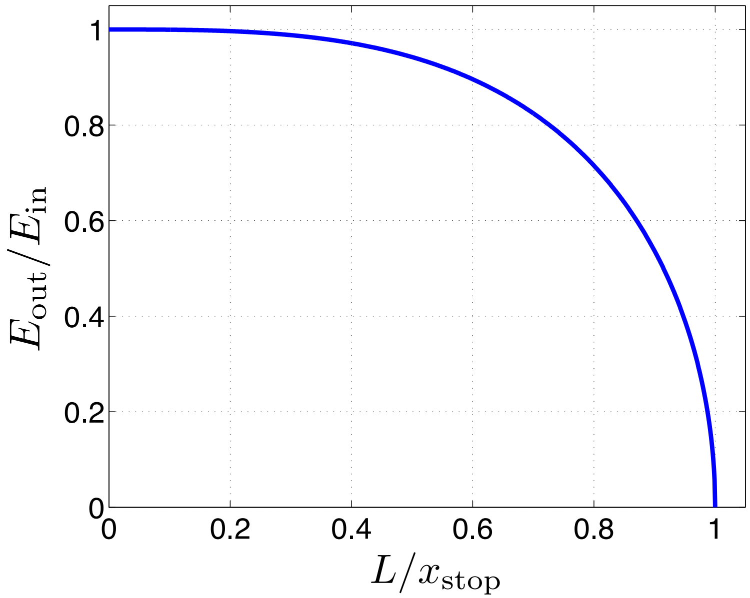
Here, a light quark 'jet' produced next to the slab of plasma with incident energy $E_{\text{in}} = 87\sqrt{\lambda}\pi T \sim 87\sqrt{\lambda}$ GeV shoots through the slab and emerges with $E_{\text{out}} \sim 66\sqrt{\lambda}$ GeV. Again, the 'jet' that emerges looks like a vacuum 'jet' with that energy.

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. Opening angle of 'jet' $\leftrightarrow$ downward angle of string endpoint.

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 $dE_{\rm out}/dL$ and $E_{\rm out}/E_{\rm in}$ including the Bragg peak:

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

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

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 lost energy quickly becomes one with the medium.**
- **A hybrid approach may be worthwhile. Eg make each parton in a parton shower lose energy to "friction", à la light quark in strongly coupled liquid, see previous slide.**
- **We are exploring various different ways of adding "friction" to PYTHIA, looking at R_{AA}, energy loss distribution, dijet asymmetry, jet fragmentation function.**

Gauge/String Duality, Hot QCD and Heavy Ion Collisions

Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann

A 460 page book. We finished the manuscript a few months ago. To appear June 2014, Cambridge University Press.

Intro to heavy ion collisions and to hot QCD, including on the lattice. Intro to string theory and gauge/string duality. Including a 'duality toolkit'.

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

Heavy ion collision experiments recreating the quark–gluon plasma that filled the microseconds-old universe have established that it is a nearly perfect liquid that flows with such minimal dissipation that it cannot be seen as made of particles. String theory provides a powerful toolbox for studying matter with such properties.

This book provides a comprehensive introduction to gauge/string duality and its applications to the study of the thermal and transport properties of quark–gluon plasma, the dynamics of how it forms, the hydrodynamics of how it flows, and its response to probes including jets and quarkonium mesons.

Calculations are discussed in the context of data from RHIC and LHC and results from finite temperature lattice QCD. The book is an ideal reference for students and researchers in string theory, quantum field theory, quantum many-body physics, heavy ion physics, and lattice QCD.

Jorge Casalderrey-Solana is a Ramón y Cajal Researcher at the Universitat de Barcelona. His research focuses on the properties of QCD matter produced in ultra-relativistic heavy ion collisions.

Hong Liu is an Associate Professor of Physics at MIT. His research interests include quantum gravity and exotic quantum matter.

David Mateos is a Professor at the Universitat de Barcelona, where he leads a group working on the connection between string theory and quantum chromodynamics.

Krishna Rajagopal is a Professor of Physics at MIT. His research focuses on QCD at high temperature or density, where new understanding can come from unexpected directions.

Urs Achim Wiedemann is a Senior Theoretical Physicist at CERN, researching the theory and phenomenology of ultra-relativistic heavy ion collisions.

Cover illustration: an artist's impression of the hot matter produced by a heavy ion collision falling into the black hole that provides its dual description. Created by Mathias Zwygart and inspired by an image, courtesy of the ALICE Collaboration and CERN.

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Casalderrey-Solana, Liu, Mateos, Rajagopal and Wiedemann

Gauge/String Duality, Hot QCD and Heavy Ion Collisions

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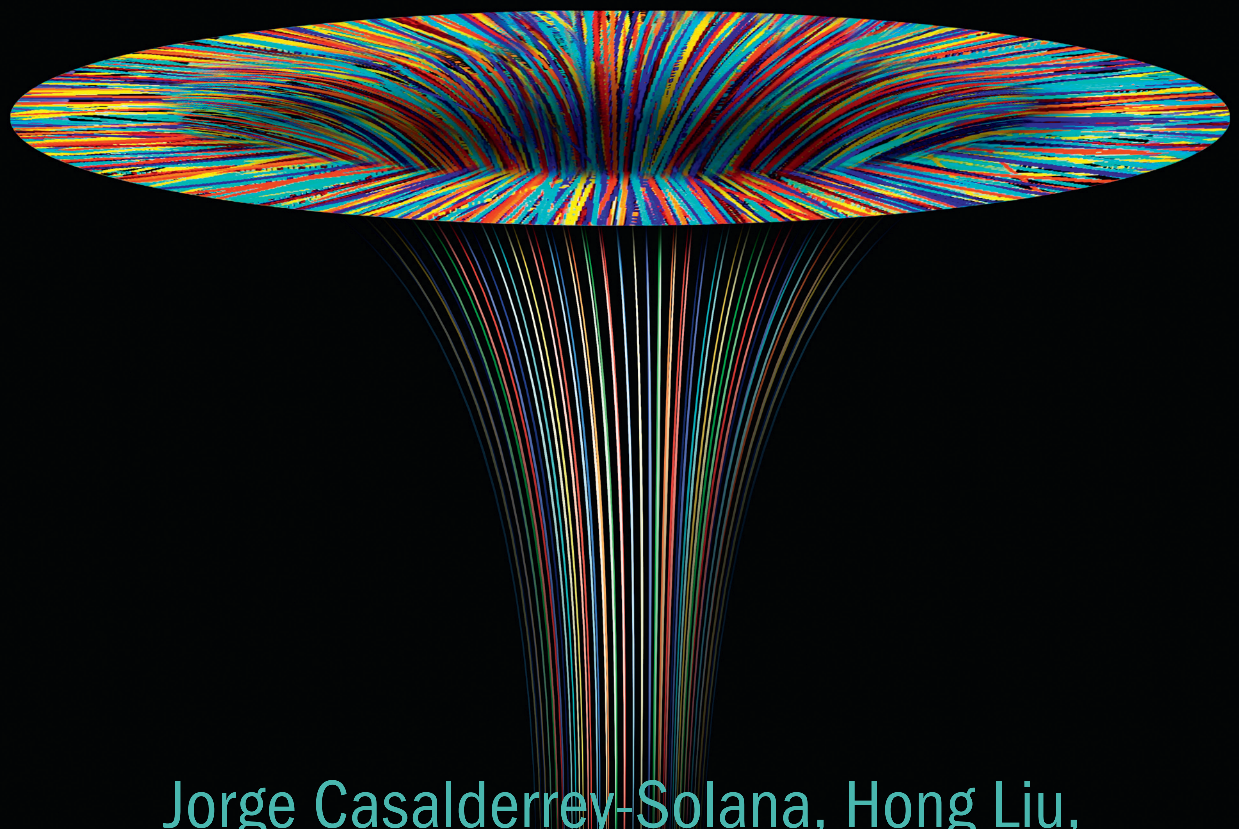

Jorge Casalderrey-Solana, Hong Liu,
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and Urs Achim Wiedemann

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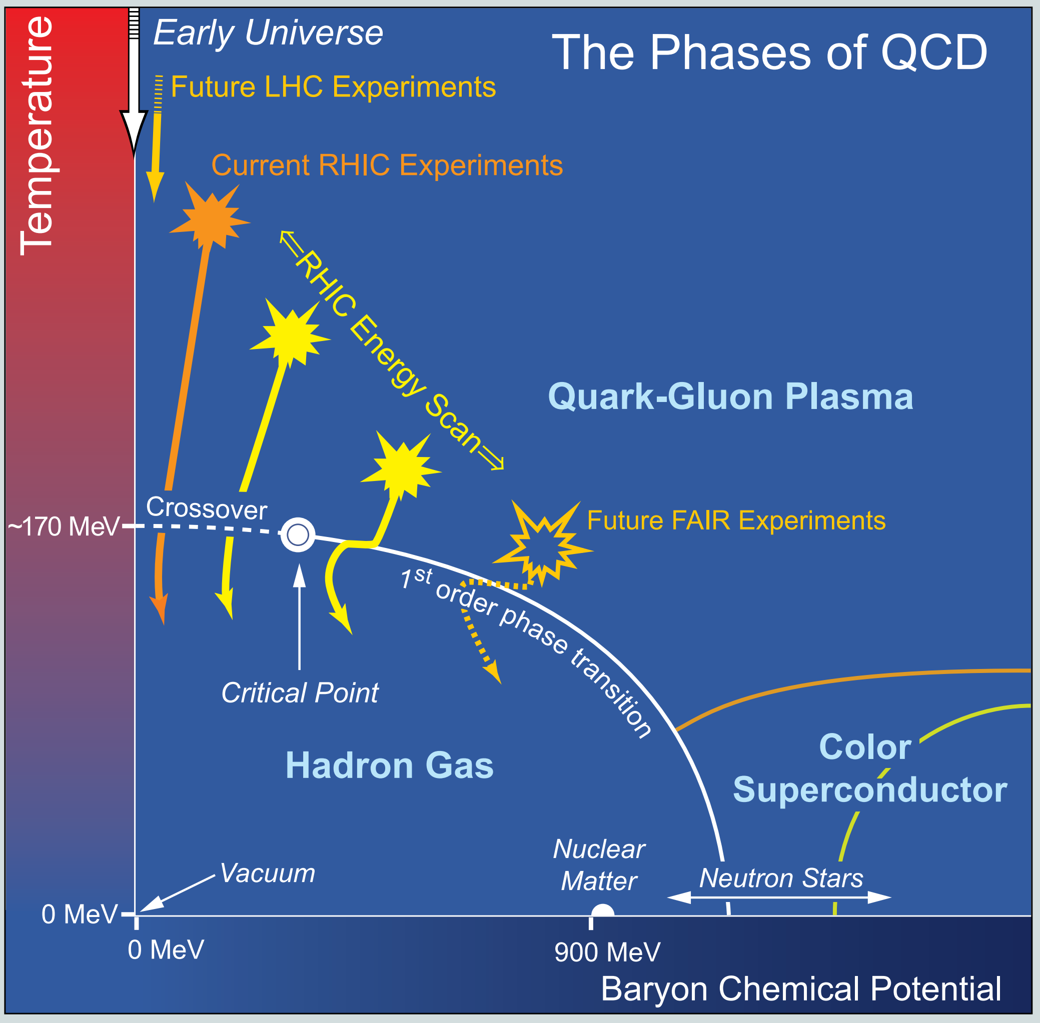
Contents

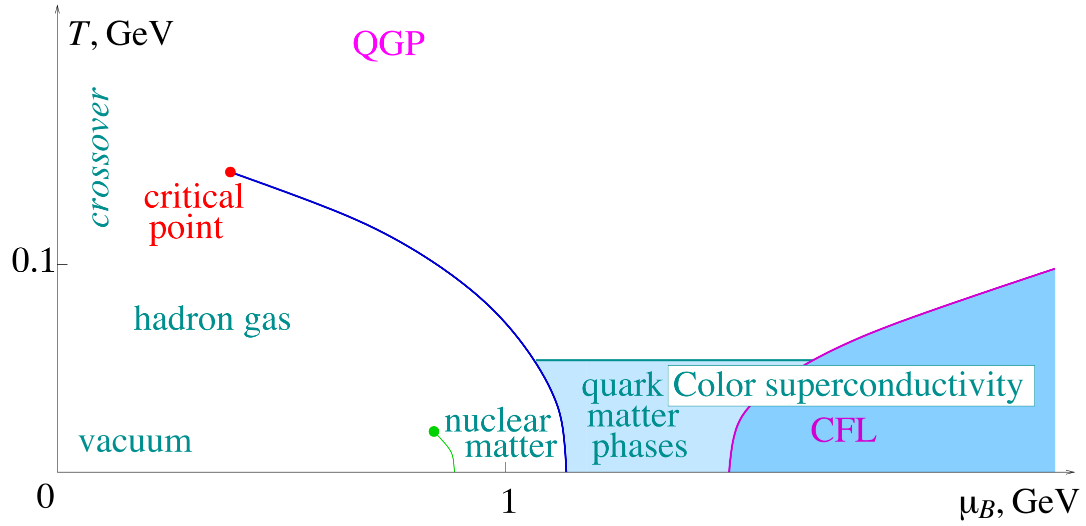
Seeking the QCD Critical Point

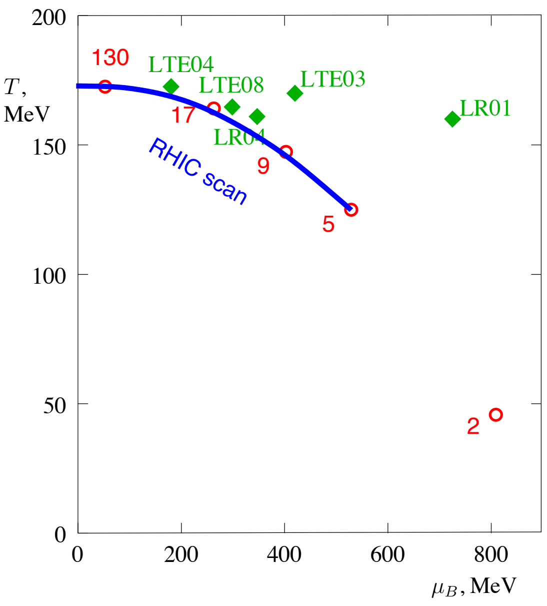


2007 NSAC Long Range Plan

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

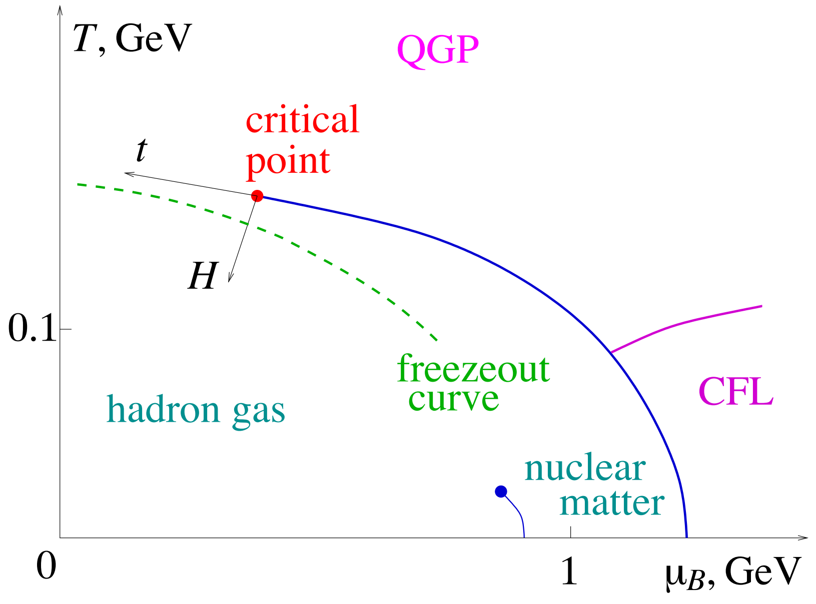
QCD phase diagram, critical point and RHIC

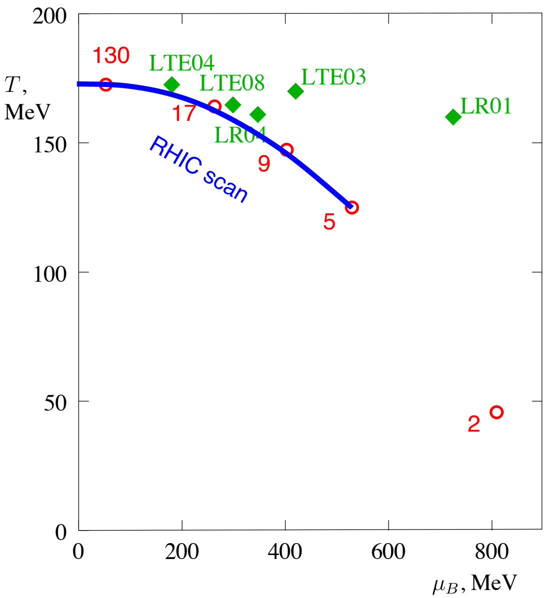




- Models (and lattice) suggest the transition becomes 1st order at some μ_B.
- Can we observe the critical point in heavy ion collisions, and how?
- Near critical point fluctuations grow and become more non-Gaussian.
- Challenge: develop measures most sensitive to the critical point and use them to locate the critical point by scanning in $\sqrt{s}$ and therefore in $\mu_{\rm freezeout}$.
- 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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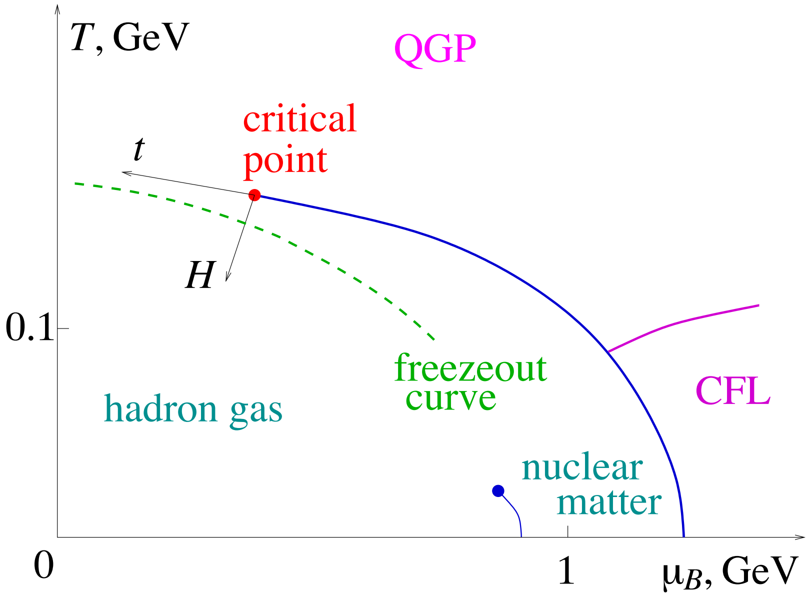

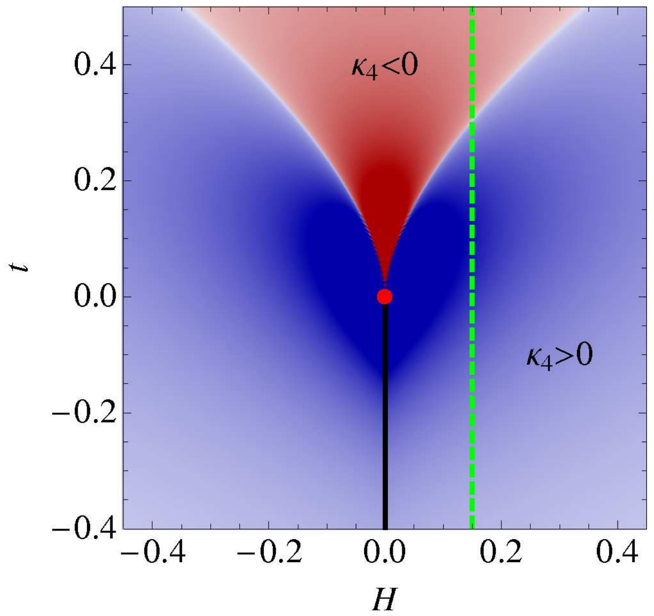

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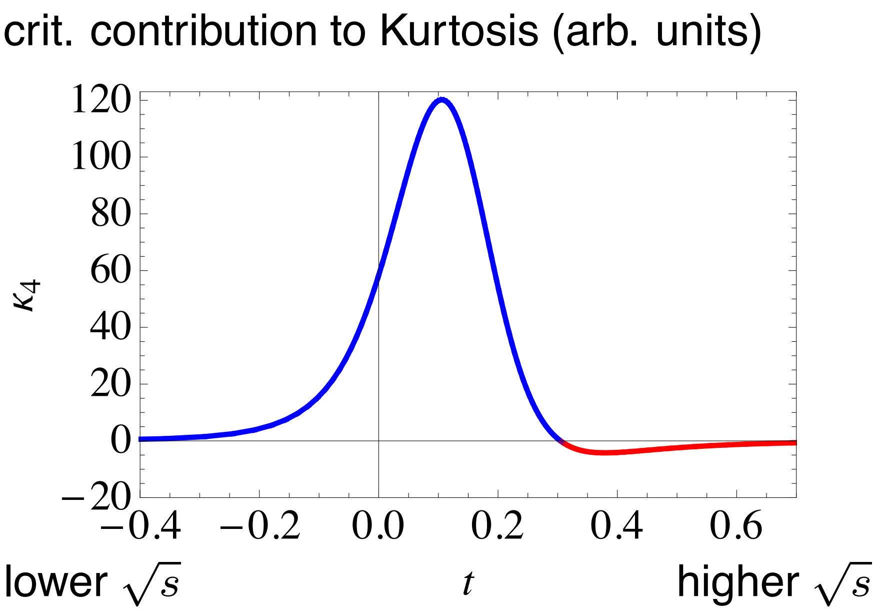

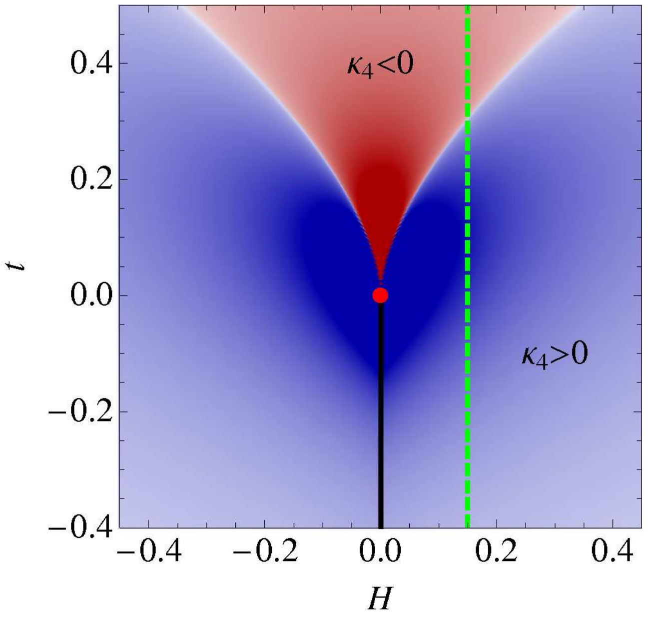

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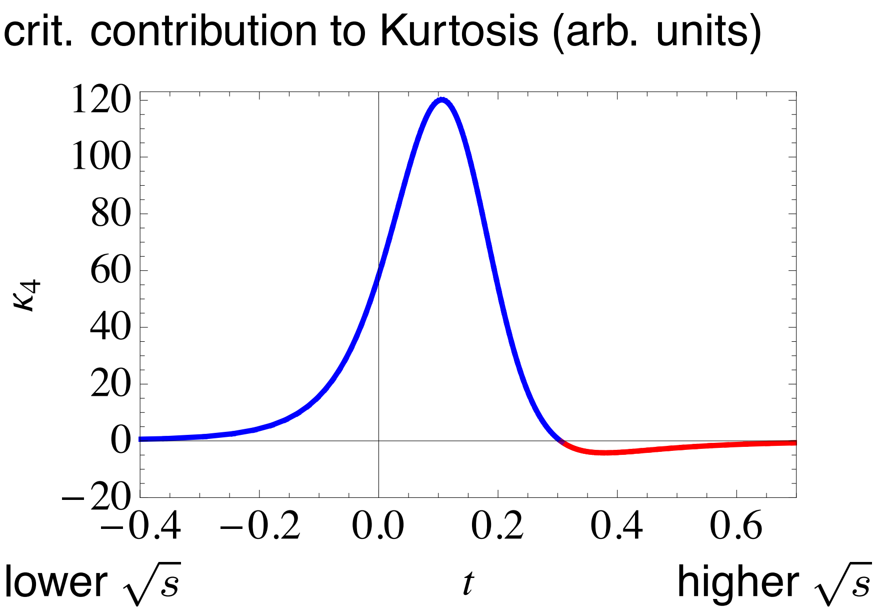

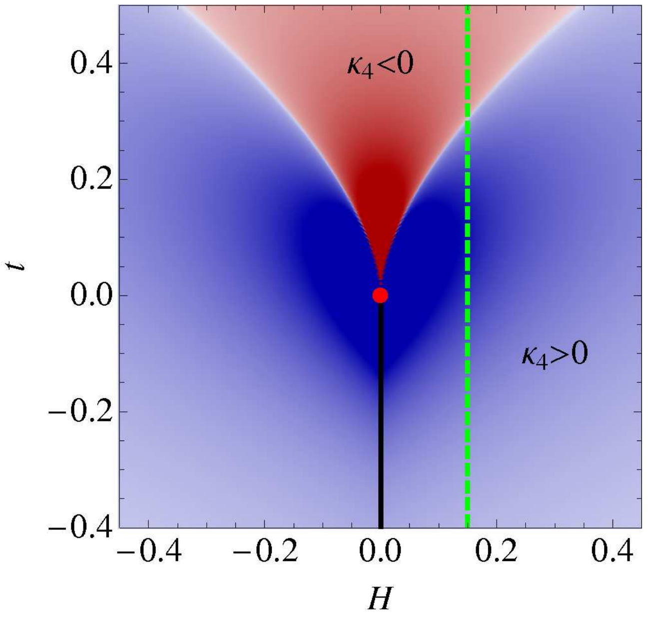

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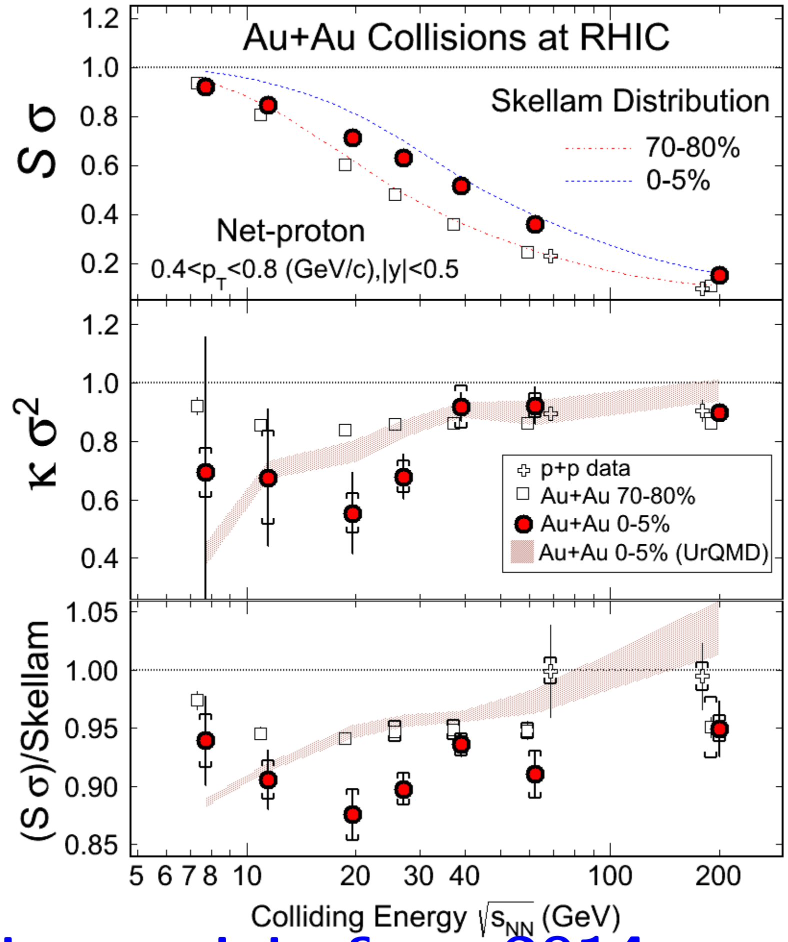
- Once we find the μ (i.e. the $\sqrt{s}$) where the critical contribution to κ_4 is large enough — e.g. the “blue peak” — then there are then robust, parameter-independent, predictions for various ratios of the kurtosis and skewness of protons and pions. Athanasiou, Stephanov, Rajagopal 1006.4636.

Early RHIC Energy Scan Data



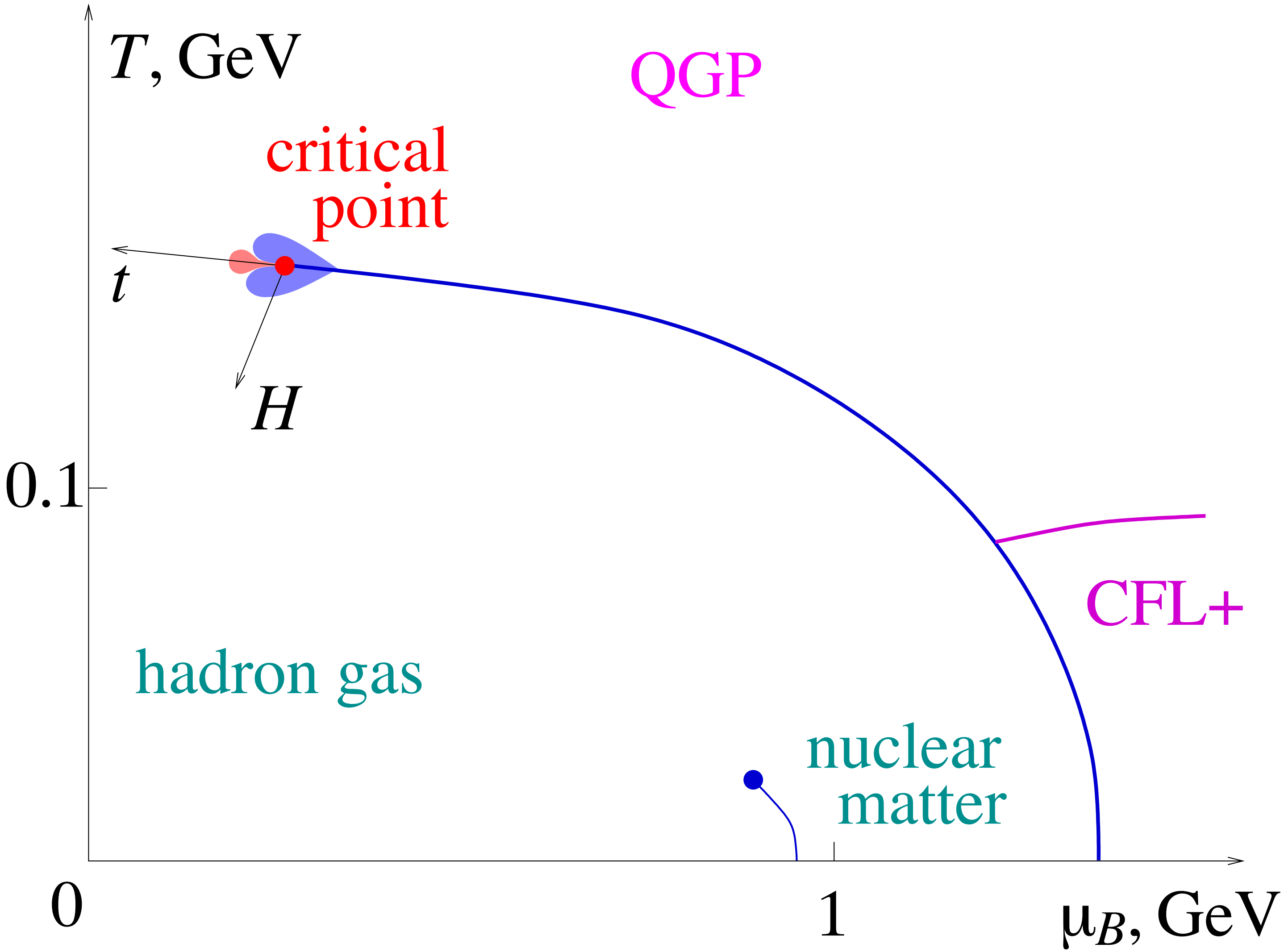
STAR, 2013

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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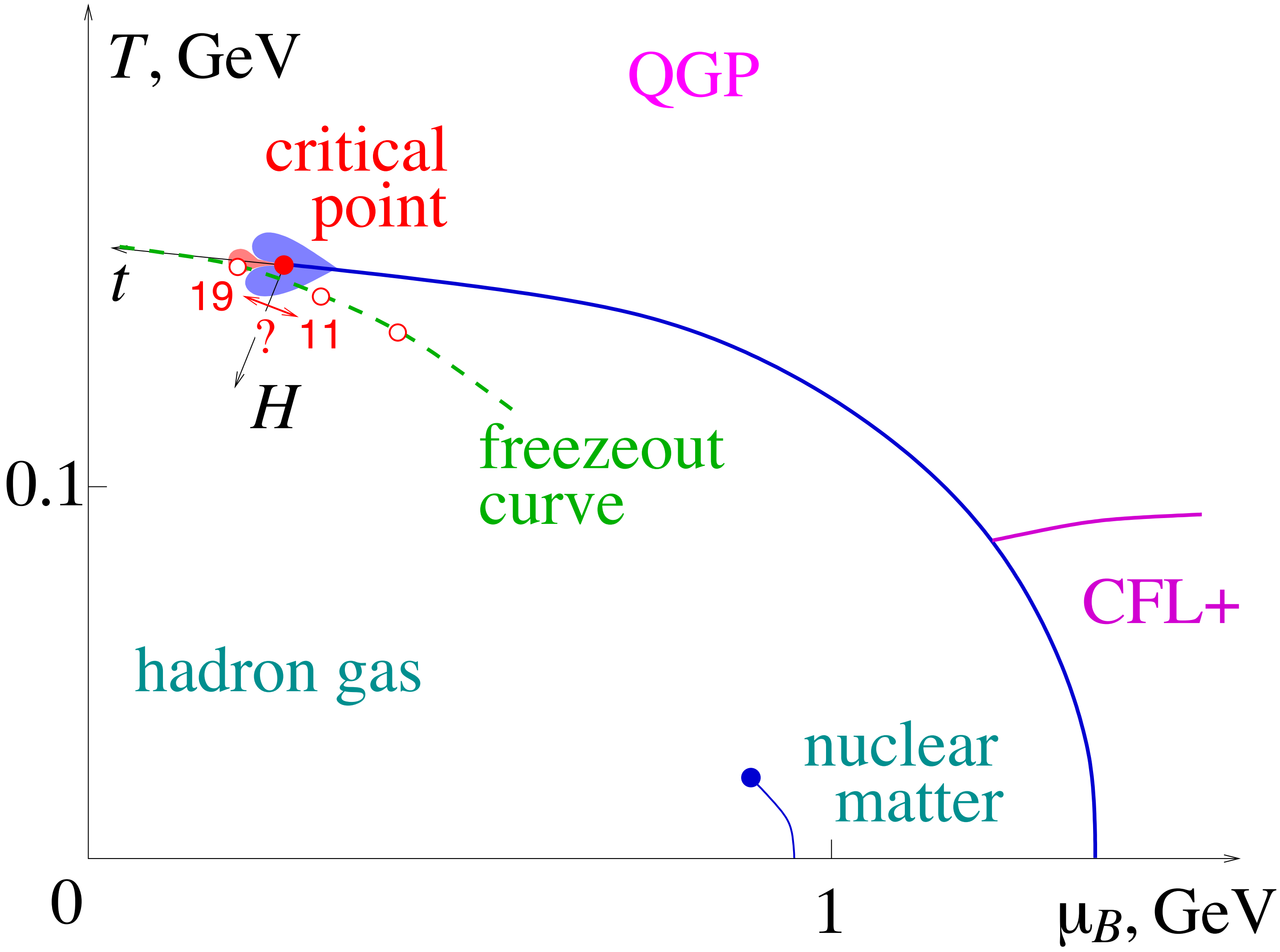
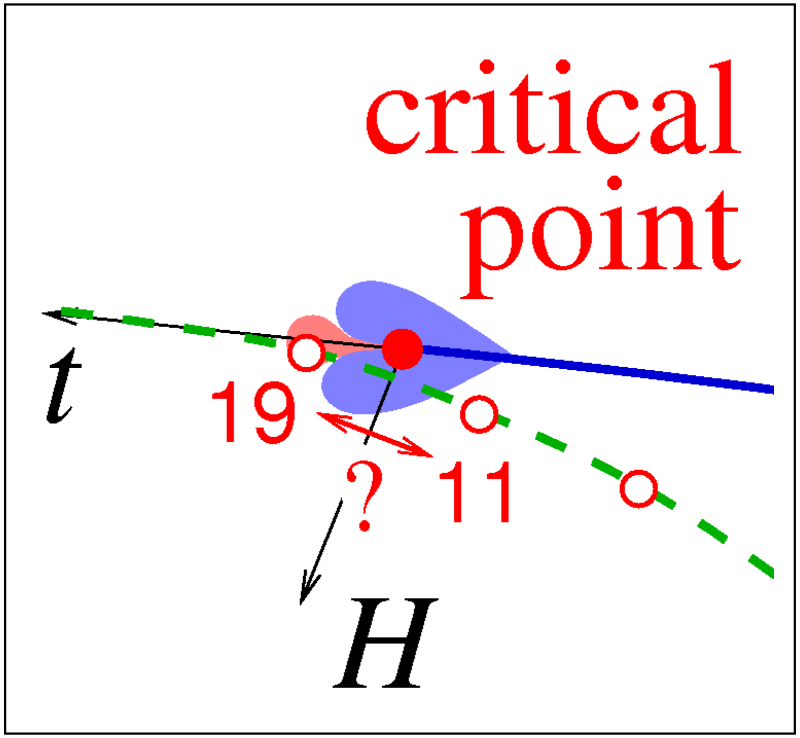
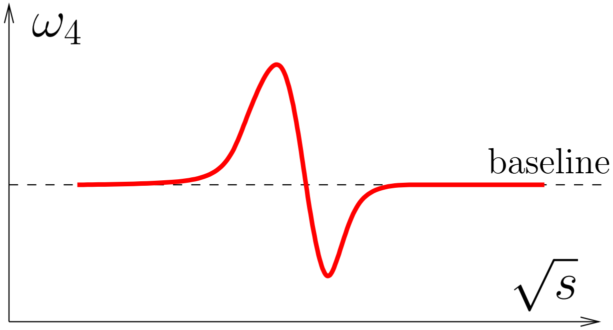


- If the kurtosis stays significantly below Poisson value in 19 GeV data, the logical place to take a closer look is between 19 and 11 GeV.

Implications for the energy scan





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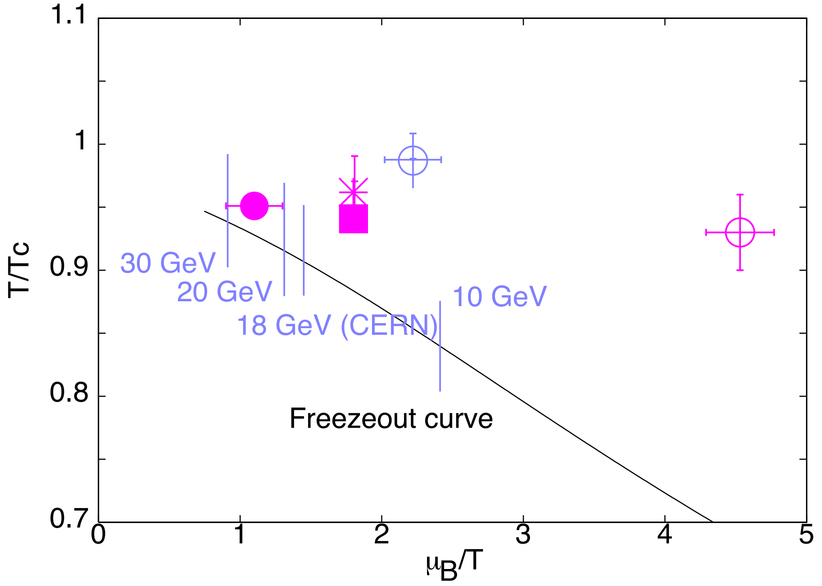
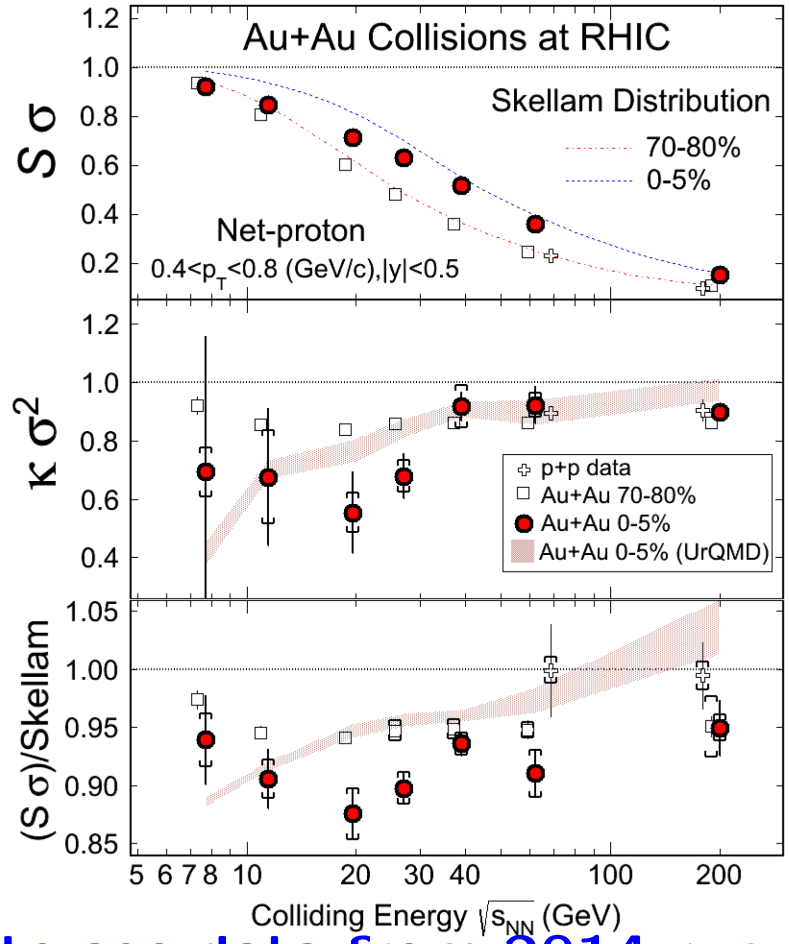
Latest Lattice Calculations. . .



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...

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 $\text{const} \sim$ few percent.]**

- **Chiral anomaly can be written**

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

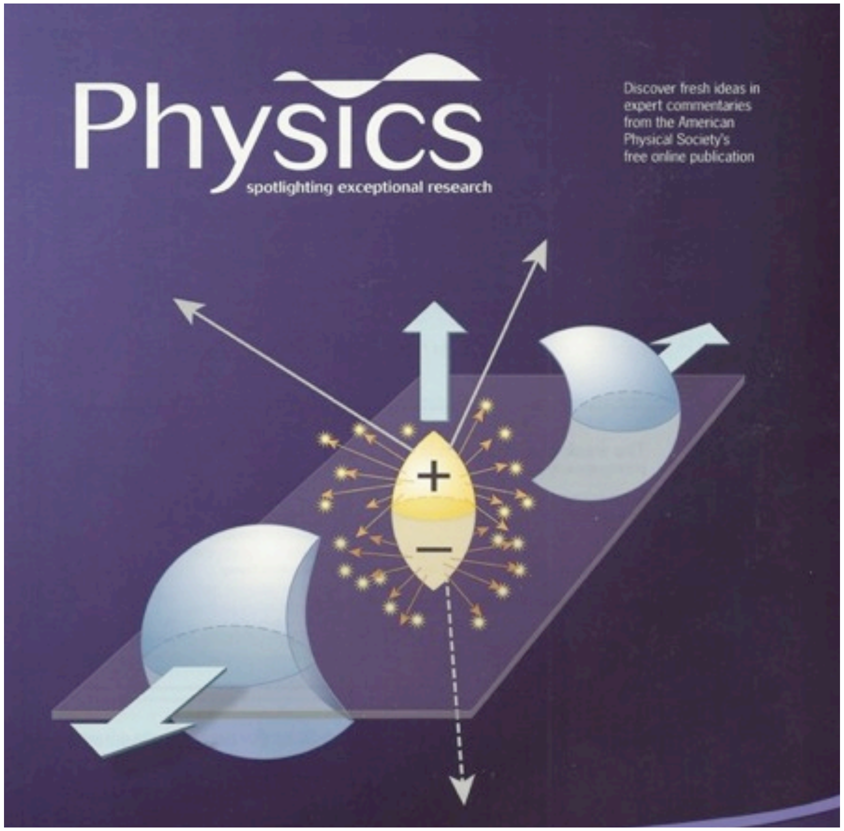
  so, in the presence of a magnetic field, an excess of R quarks (ie $\mu_A > 0$) results in an electric current!

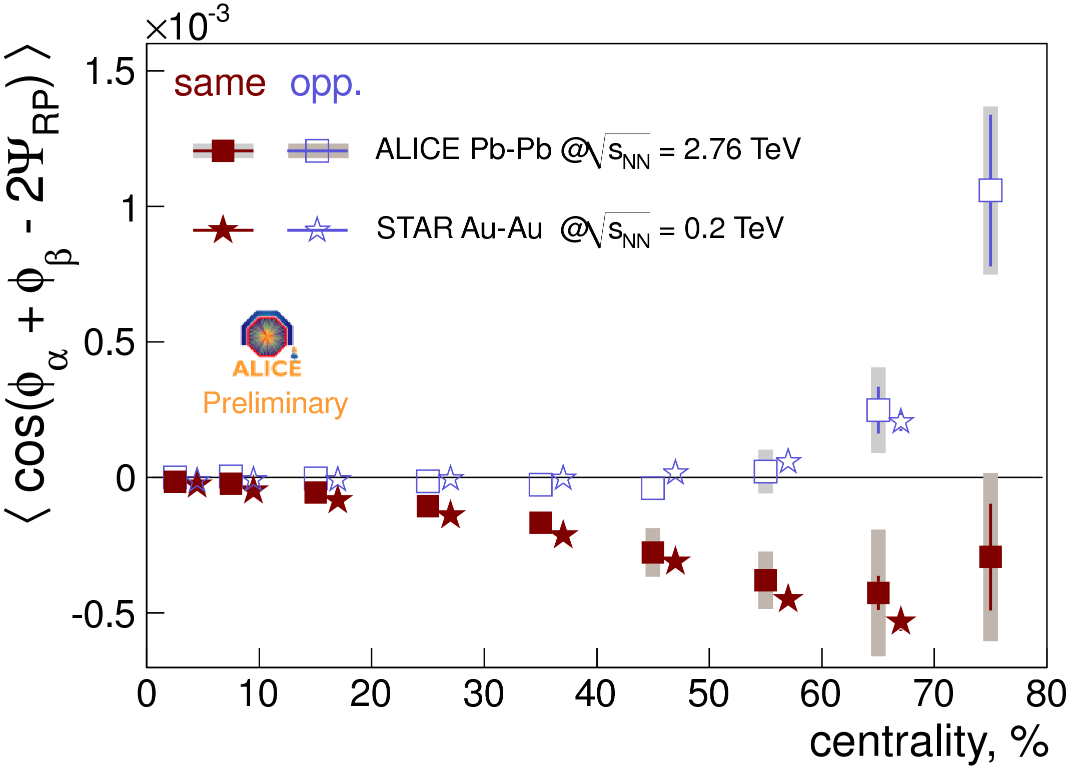
- **Spectator nuclei create $B \sim 10^{18-19}$ gauss in top energy RHIC collisions with decent impact parameter. At LHC, larger B, but it lasts for a shorter time.**

- **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





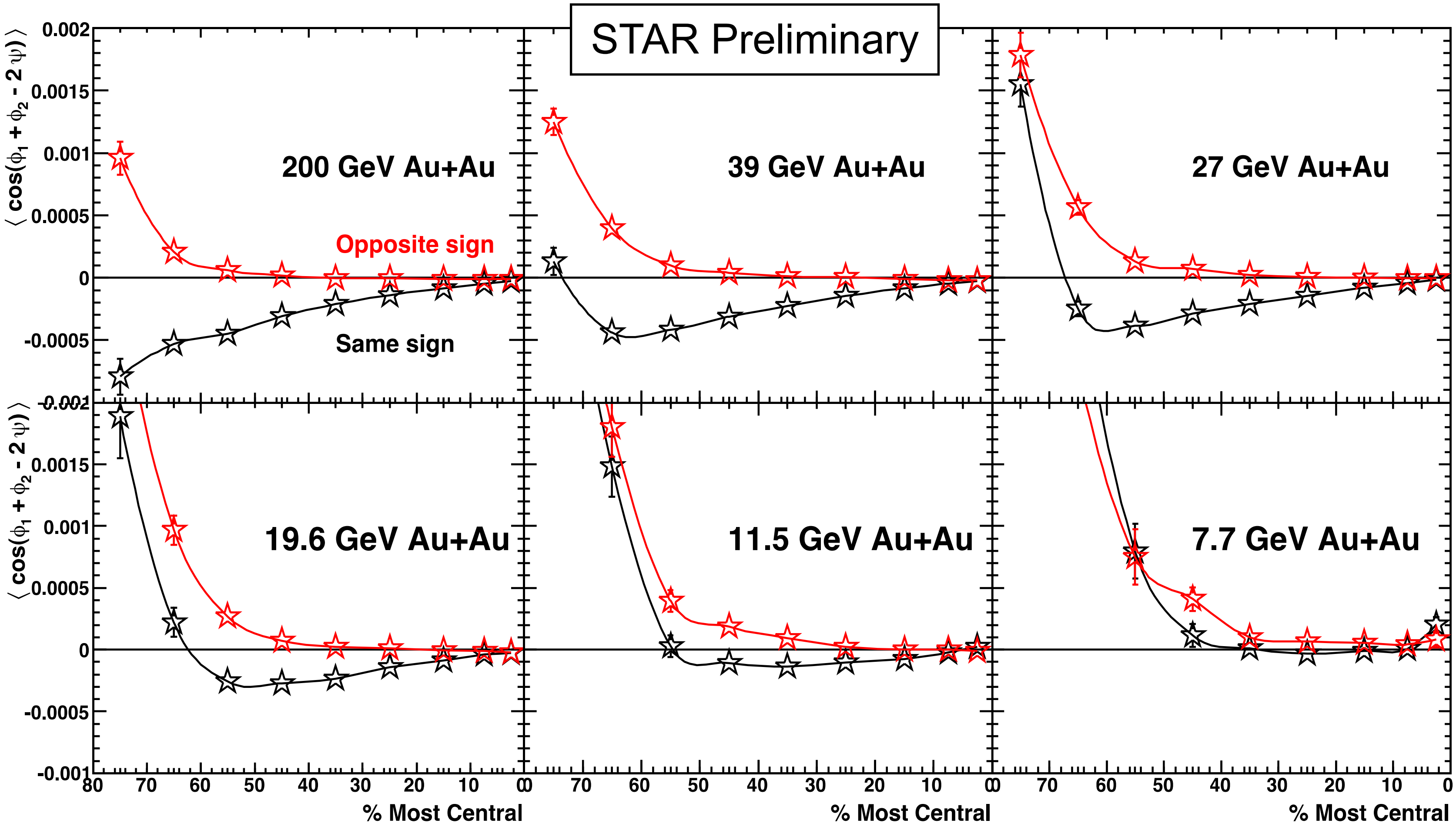
Does Reality Bite?

- 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...

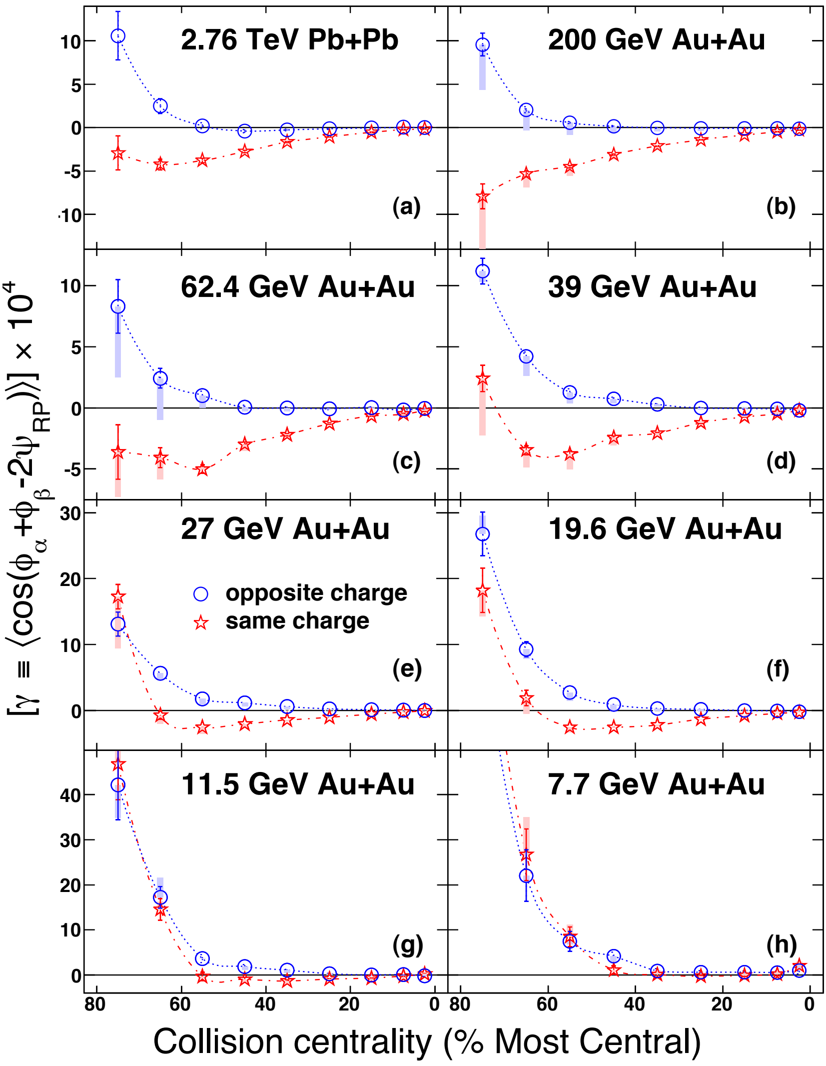
Disappearance of Charge Separation w.r.t. EP



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)!


2.76 TeV Pb+Pb
(a)
200 GeV Au+Au
(b)
62.4 GeV Au+Au
(c)
39 GeV Au+Au
(d)
27 GeV Au+Au
opposite charge
same charge
(e)
19.6 GeV Au+Au
(f)
11.5 GeV Au+Au
(g)
7.7 GeV Au+Au
(h)
$[\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle] \times 10^4$
Collision centrality (% Most Central)
80
60
40
20
0

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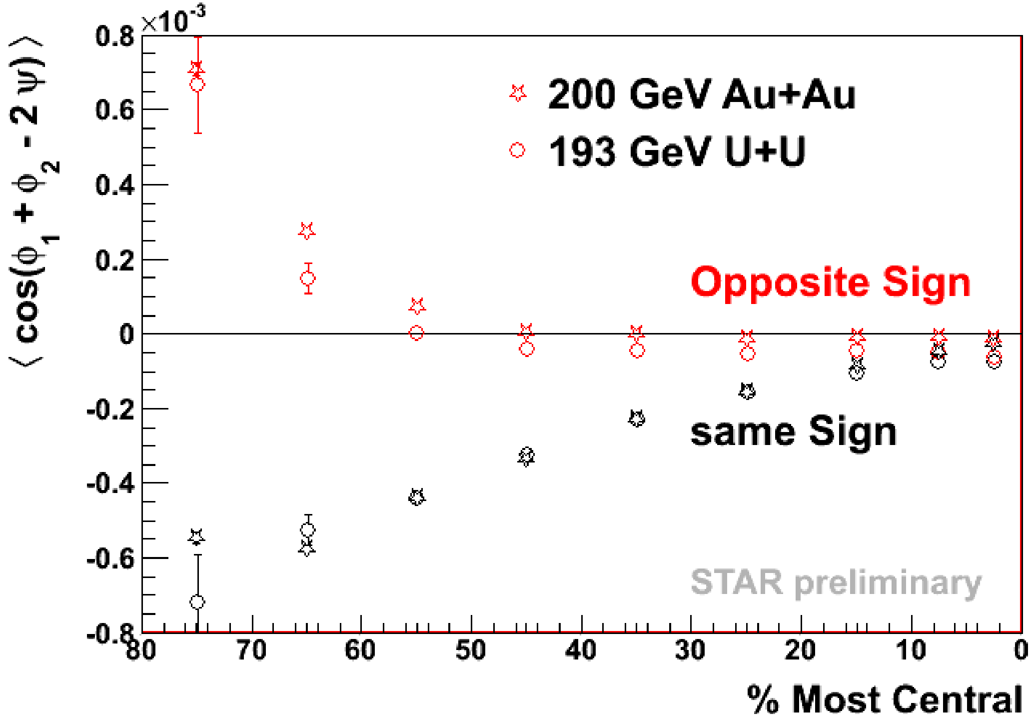
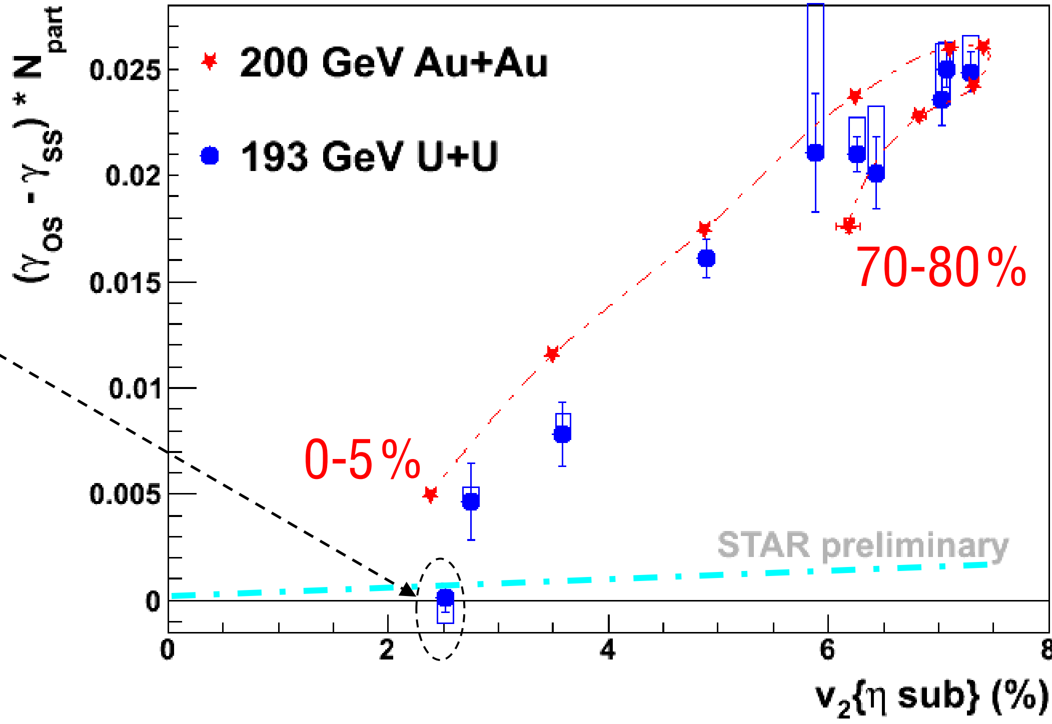
  Select events with nonzero charge density, and look for…

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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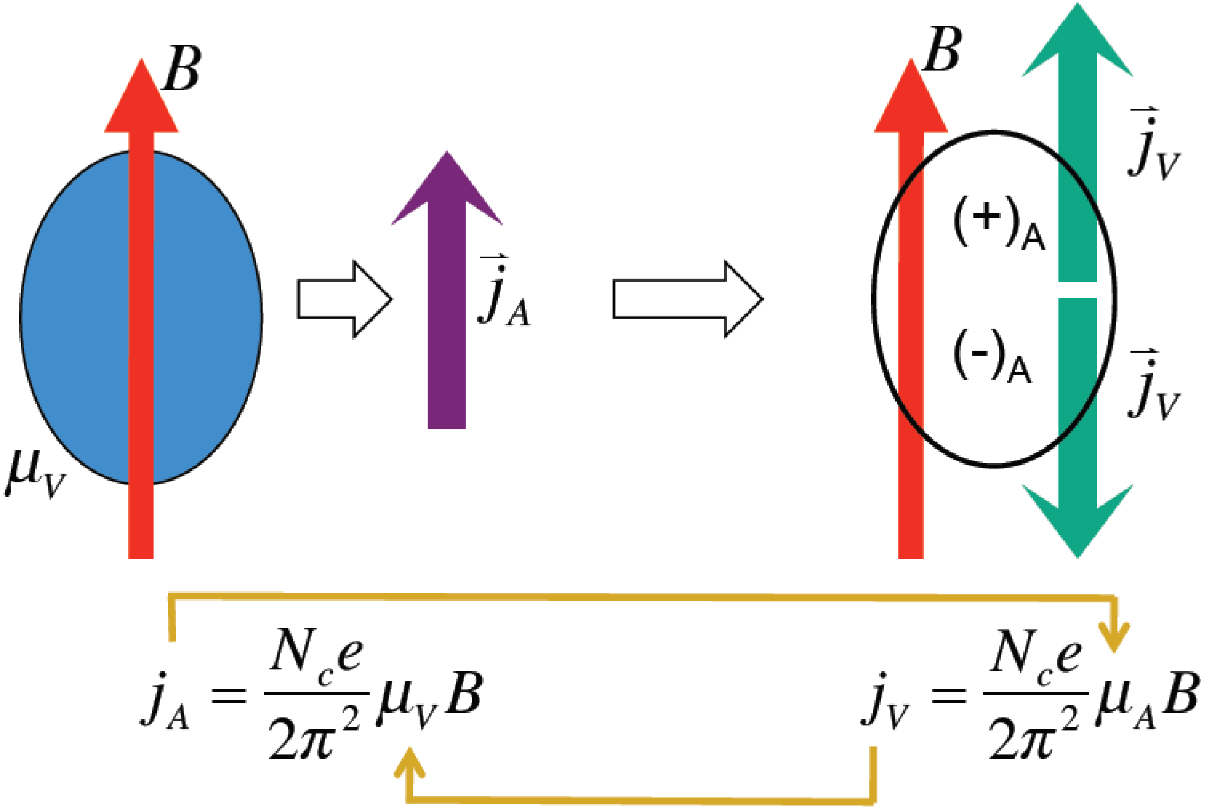
  Select events with nonzero charge density, and look for…

Motivation

CSE + CME → Chiral Magnetic Wave:

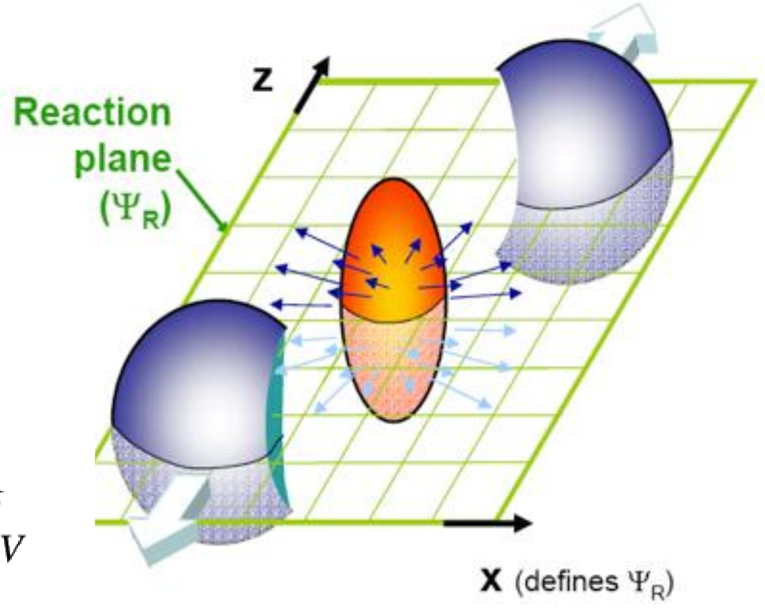
- collective excitation
- signature of Chiral Symmetry Restoration



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

Chiral Separation Effect

Chiral Magnetic Effect

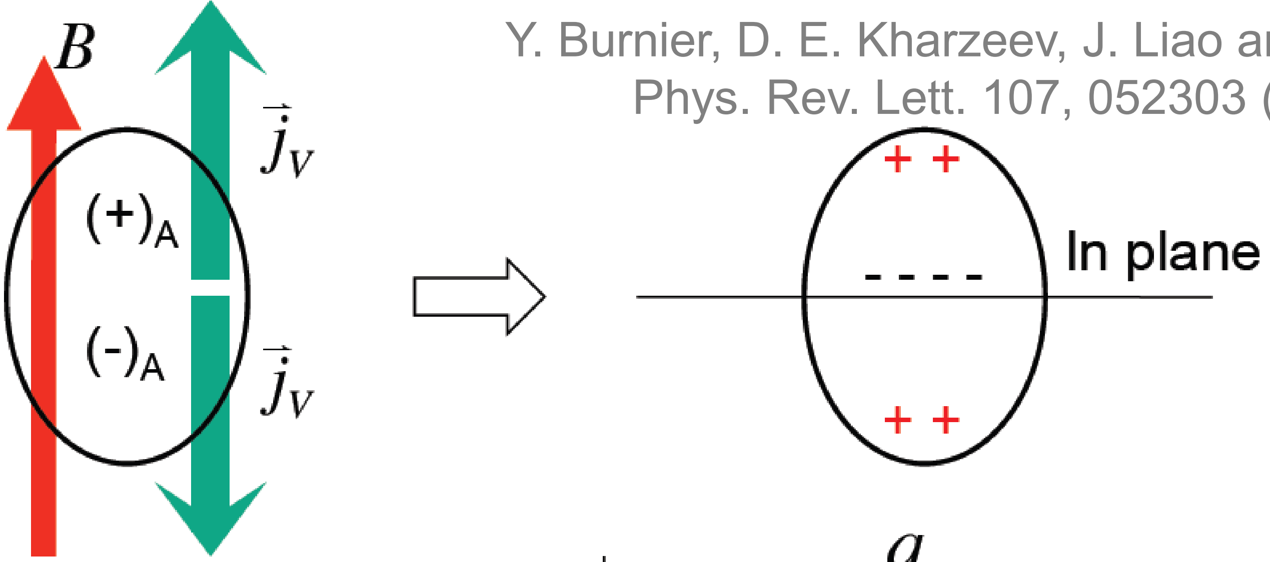


Peak magnetic field ~ 10^{15} Tesla !

(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)

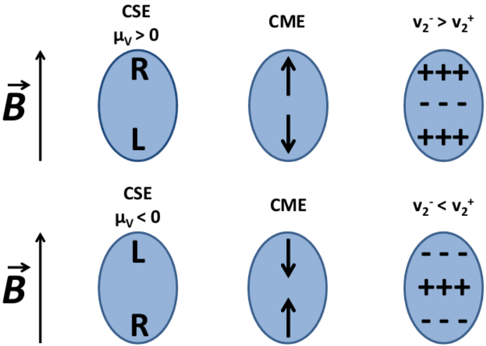


Formation of electric quadrupole: $v_2^{\pm} = v_2 \mp (\frac{q_e}{\bar{\rho}_e}) A_{\pm}$,

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

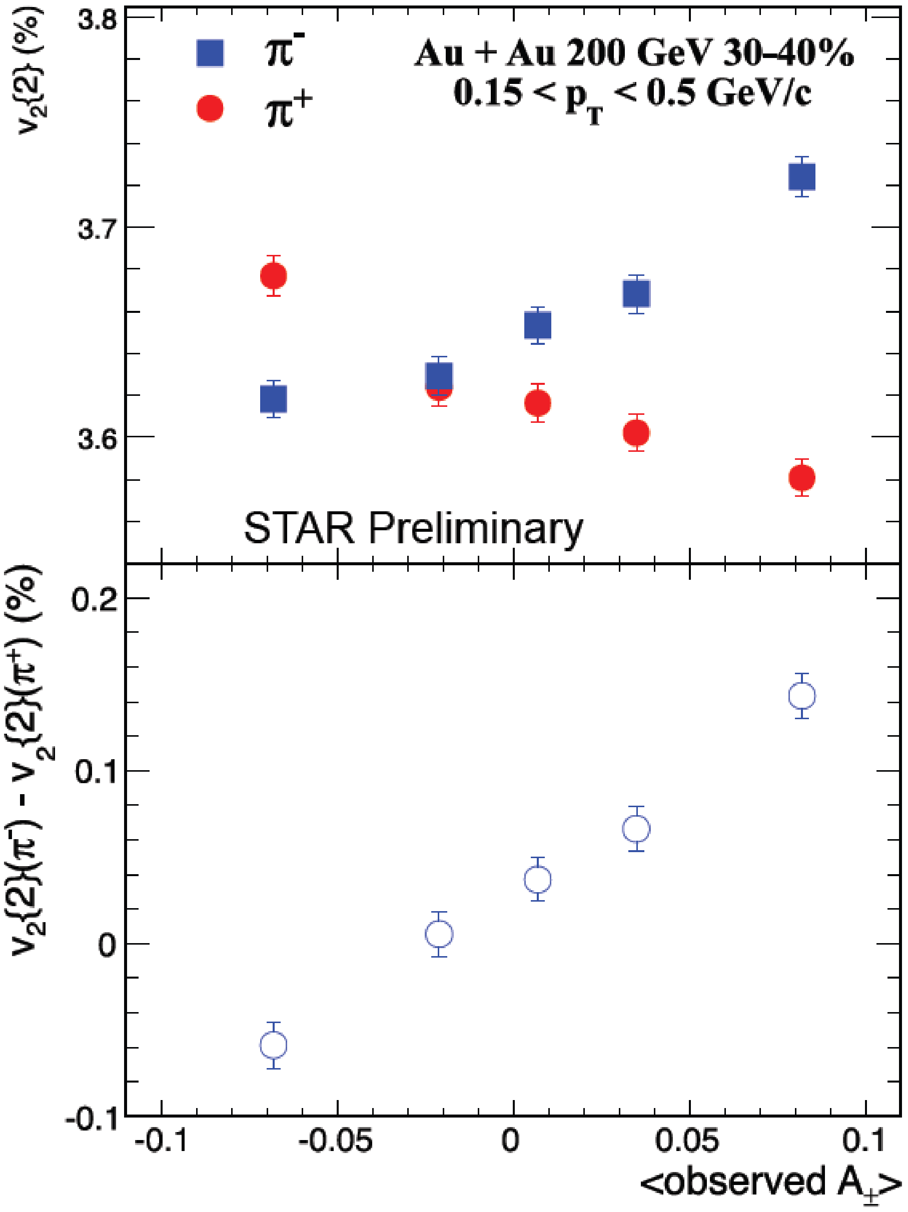
Then π^- v_2 should have a positive slope as a function of $A_{\pm}$,
and π^+ v_2 should have a negative slope with the same magnitude.
The integrated v_2 of π^- is not necessarily bigger than π^+: (other physics)
only the $A_{\pm}$ dependency matters for CMW testing.

Physics Motivation: the Chiral Magnetic Wave



- Coupling between Chiral Magnetic Effect (CME) and Chiral Separation Effect (CSE) leads to wave propagation of electric quadrupole moment, which leads to charge dependence of elliptic flow
- Kharzeev and Yee, Phys. Rev. D83, 085007 (2011)
- Burnier, Kharzeev, Liao, and Yee, Phys. Rev. Lett. 107, 052303 (2011)

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?

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

CMW. STAR results (QM2012)

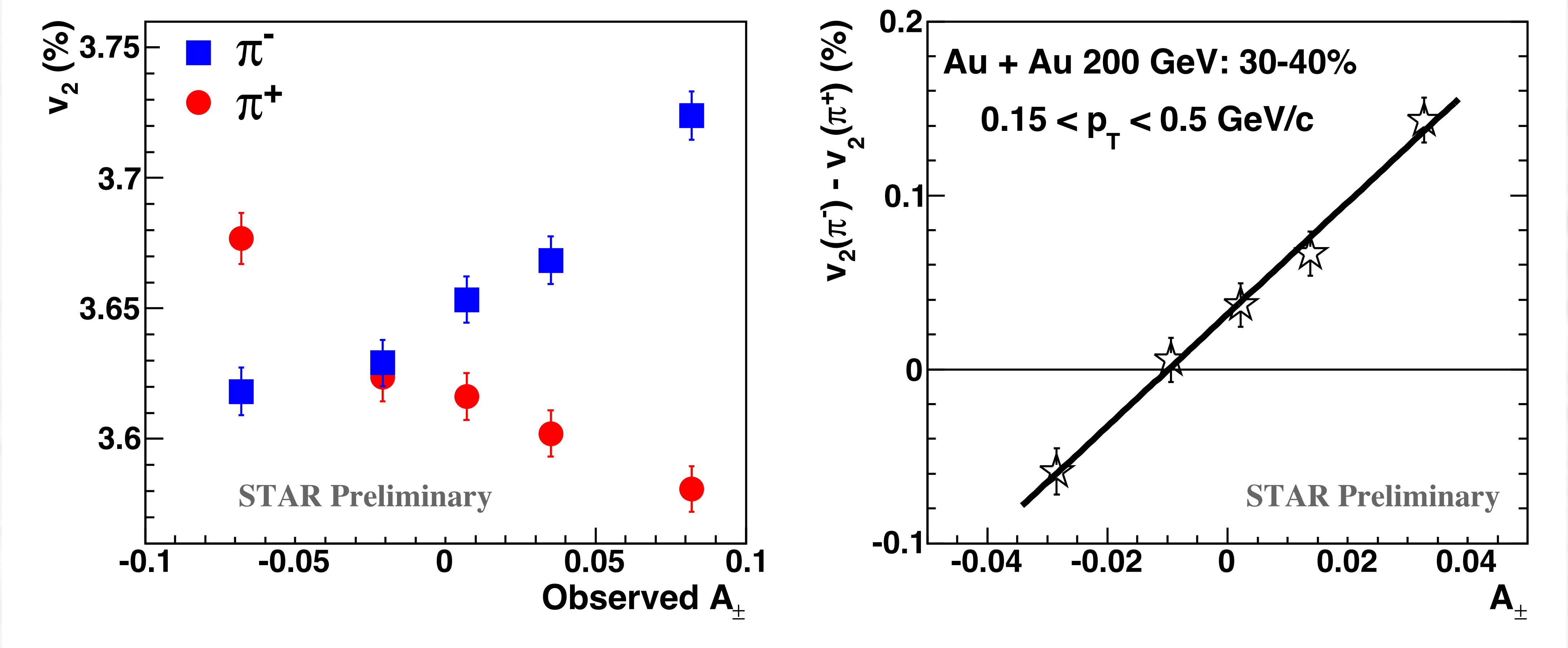
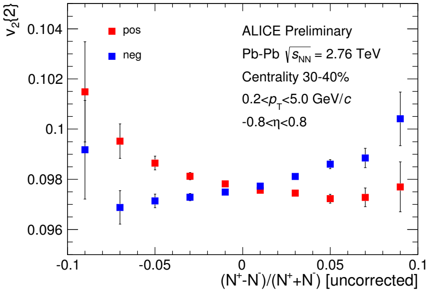


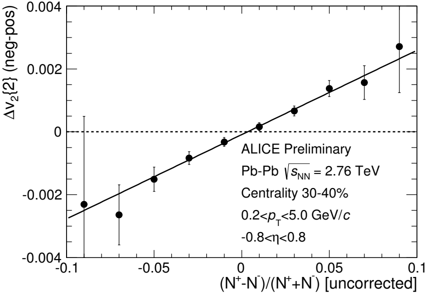
Figure 1: (Color online) The example of 30-40% Au+Au collisions at 200 GeV [22]. (Left) Pion $v_2\{2\}$ as a function of observed charge asymmetry. (Right) v_2 difference between π^- and π^+ as a function of charge asymmetry with the tracking efficiency correction. The errors are statistical only.

A need for detailed predictions (collision energy dependence, dependence on the size of rapidity window used to calculate charge asymmetry, etc.)

$v_2^{\pm}$ and Δv_2 vs A, 30–40% centrality in ALICE



ALI-PREL-70889



ALI-PREL-70893

- Strong, clear signal
- Qualitatively consistent with STAR results

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.

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

- aka the Chiral Magnetic Wave phenomenon
- Macroscopic realization of a quantum anomaly! Chiral symmetry restored!
- Prosaic explanations currently being tested (ruled out?) with further measurements. Eg prosaic explanations tend to give a small charge-dependent contribution to v_3 and v_4 and $\ldots$ also, and that is not seen.
- We really need to see whether the CMW effect persists to lower energies and then turns off at the same collision energy $\sqrt{s} \sim 7.7$ GeV where the CME effect turns off. This needs the higher statistics that RHIC will provide in 2018-2019.
- Also, it would be good to detect observable consequences of the early $\vec{B}$ that arise just due to Maxwell's Equations $\ldots$

Magnetohydrodynamics, charged currents and directed flow in heavy ion collisions

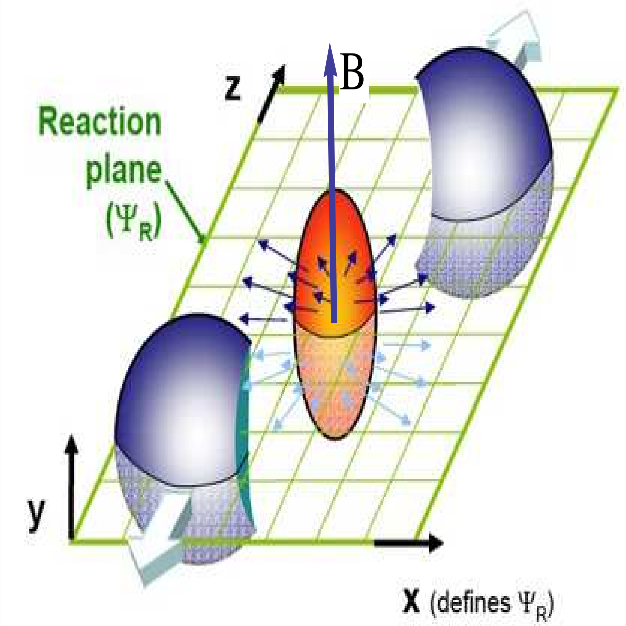
Umut Gürsoy

Utrecht University

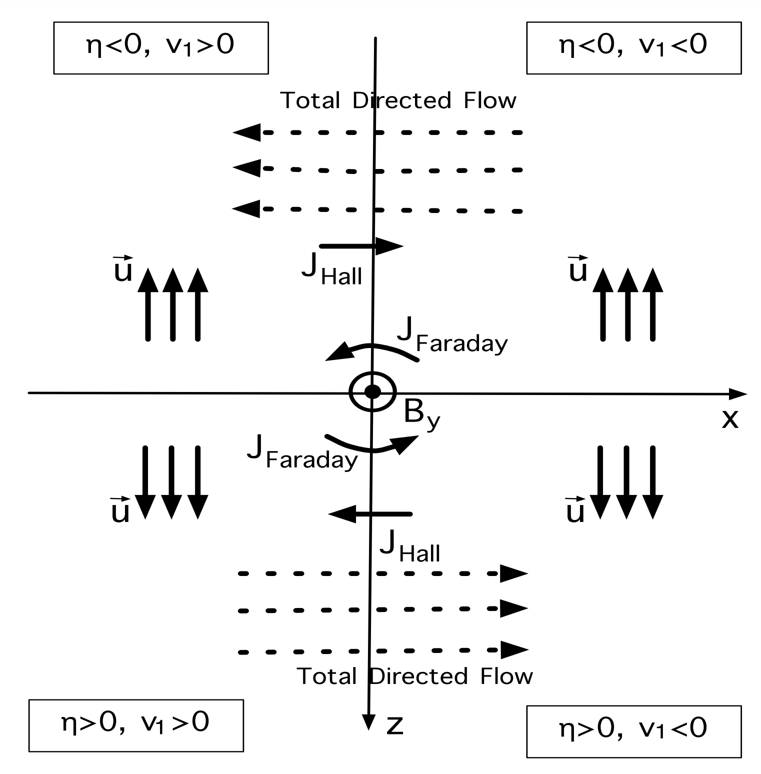
Quark Matter 2014, Darmstadt 20.5.2014

with D. Kharzeev and K. Rajagopal
Phys. Rev. C, 089 (2014), arXiv:1401.3805

Heavy ion collisions and magnetic fields



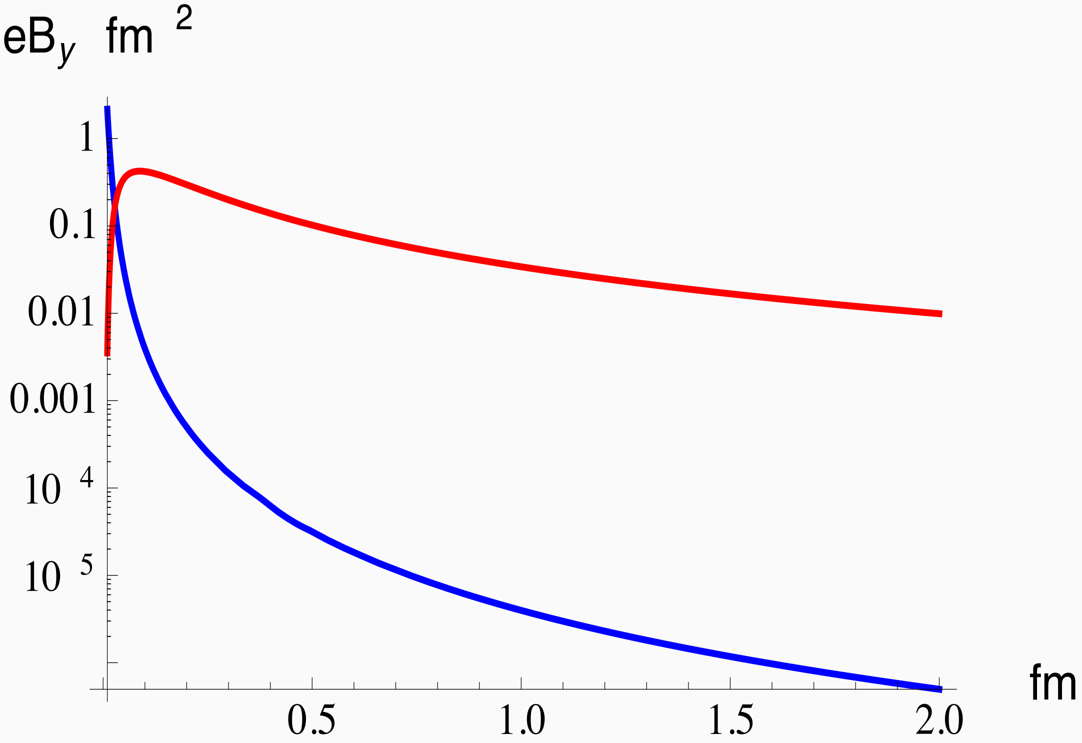
- Initial magnitude of B
- Bio-Savart: $B_0 \sim \gamma Z e \frac{b}{R^3} \Rightarrow eB \approx 5 - 15 \times m_\pi^2$ at RHIC (LHC).
- In this talk $b = 7\text{fm}$ and $R = 7\text{fm}$.
- Motivation: find observables that are directly tied to the presence of B



"Classical" currents in charged and expanding medium:

- Faraday currents $\vec{J}_F \sim \sigma \vec{E}_F$ with $\nabla \times \vec{E}_F = -\frac{\partial \vec{B}}{\partial t}$
- Hall currents $\vec{J}_H \sim \sigma \vec{E}_H$ with $\vec{E}_H = \vec{u} \times \vec{B}$
- Also a "quantum" current $\vec{J}_{CME} \sim \mu_5 \vec{B}$, not considered here.

Time profile of B at LHC



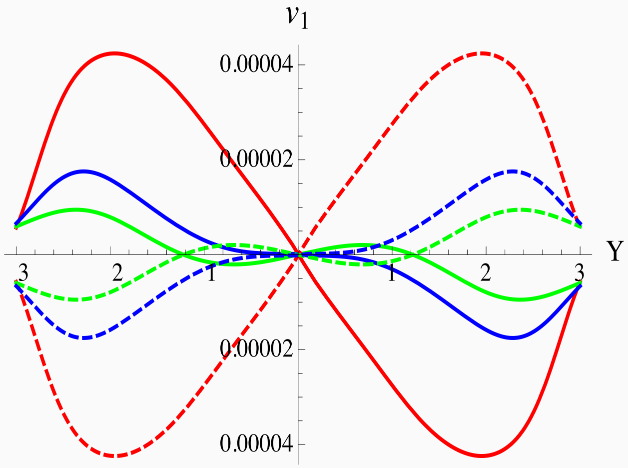
with $\sigma = 0.023\text{fm}^{-1}$ and with $\sigma = 0$

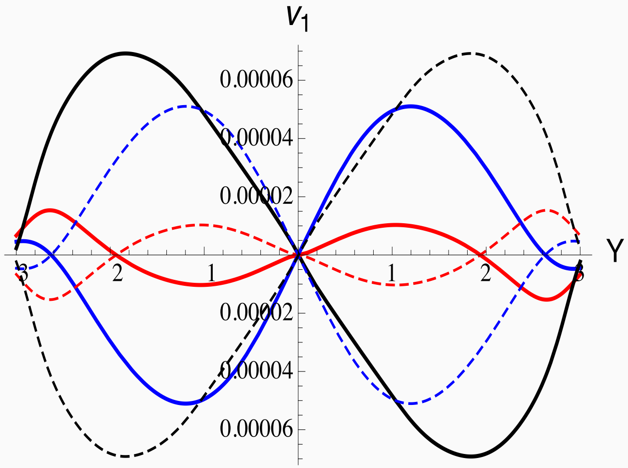
- Simplifying assumption hard-sphere distribution for spectators and participants
- For participants empirical distribution over Y: Kharzeev et al. 2007

$$f(Y_b) = (4\sinh(Y_0/2))^{-1}\, e^{Y_b/2}, \qquad -Y_0 \le Y_b \le Y_0$$

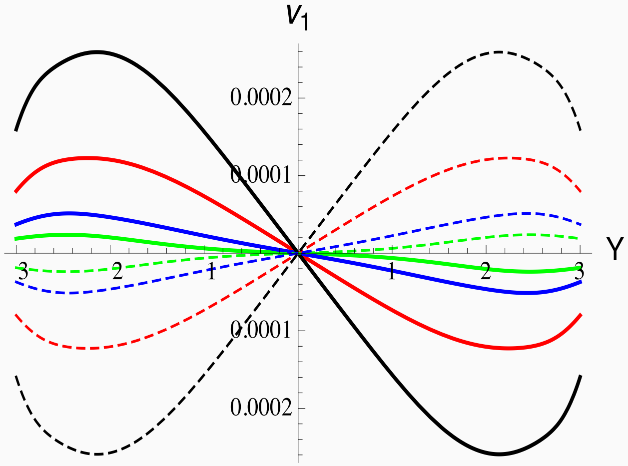
Predictions for charge identified v_1

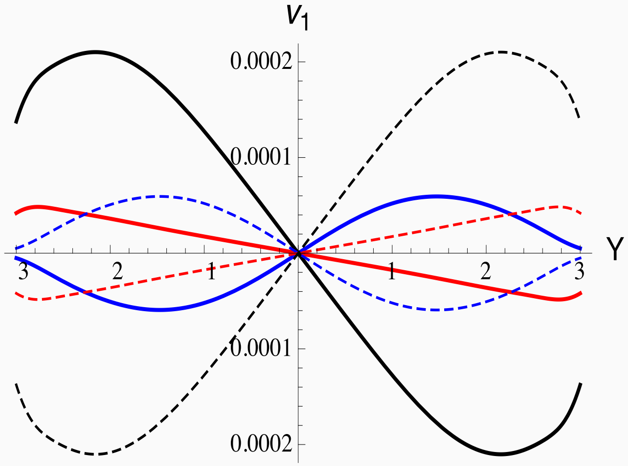
- Pions and protons at LHC





- Pions and protons at RHIC





Proposal for observables

- Define $A_1^{+-}(Y_1, Y_2) = v_1^+(Y_1) - v_1^-(Y_2)$,
  $A_1^{++}(Y_1, Y_2) = v_1^+(Y_1) - v_1^+(Y_2)$, etc.
  to eliminate charge independent contributions to v_1 produced in event-by-event fluctuations
- Look at quadratic observables
  $C_1^{+-,+-}(Y, Y) = \langle A_1^{+-}(Y, Y) A_1^{+-}(Y, Y)\rangle = 4\langle v_1^+(Y) v_1^+(Y)\rangle$
  to eliminate event-by-event fluctuations in direction of B.
- To be compared with data ...

- Summary:
  - Calculated the contribution of the time-varying B in an expanding plasma, using a perturbative approach to magnetohydrodynamics.
  - Effect odd under charge and rapidity.
  - Competition between Faraday and “Hall” effects.
  - However the magnitude is small.
- Outlook:
  - Time dependence of σ, μ, T etc.
  - More realistic hydrodyamics.
  - Backreaction of EM on hydro $\Rightarrow$ full magnetohydrodynamics
  - More realistic distributions for the sources

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 . . .

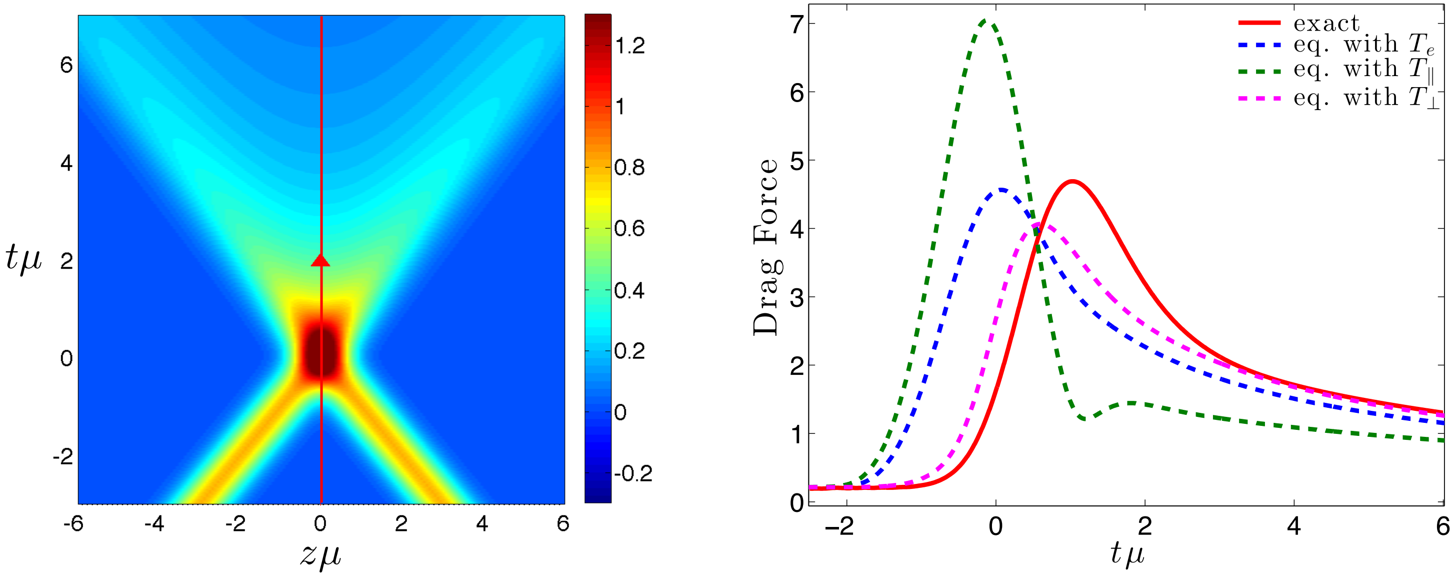
Probing the Liquid QGP. Jet quenching. Heavy quark energy loss. Upsilons. Photons. Photon+jet. Each of these is a story now being written. Seeing, and then understanding, how the liquid QGP emerges from asymptotically free quarks and gluons remains a challenge, as well as an opportunity. . .

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

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

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.**