Doping and Probing the Original Liquid: Opportunities and Challenges from Heavy Ion Collisions

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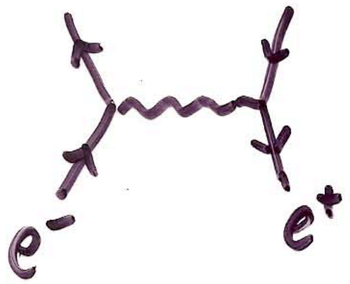
Yesterday's Discoveries. . .

- Nuclear collisions at RHIC and the LHC are recreating droplets of the matter that filled the microseconds-old universe. . .
- QGP turns out to be a liquid! And, not just any liquid:
- The hottest liquid phase of matter we know, and likely the hottest liquid phase of matter there has ever been.
- The most liquid liquid we know: it flows with the lowest specific viscosity η/s of any liquid known.
- Discoveries that have taken on an importance that extends well beyond the boundaries of nuclear physics: connections to, and impacts on, string theory, cold atom physics and condensed matter physics.
- . . . pose today's questions. But first, a look back.

WHAT IS QCD?

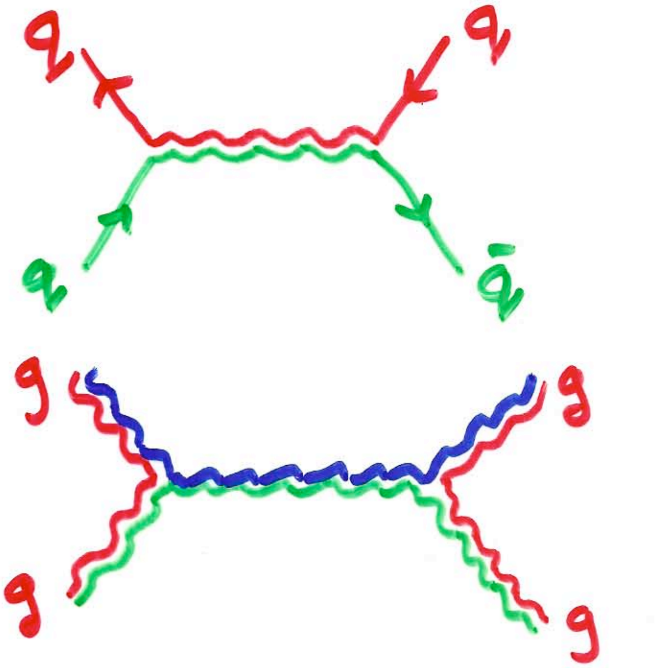
- A theory of quarks and gluons
- Its Lagrangian suggests it is not too different from QED, which is a theory of electrons and photons:

QED



e^-: charge -1
γ: neutral

QCD



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

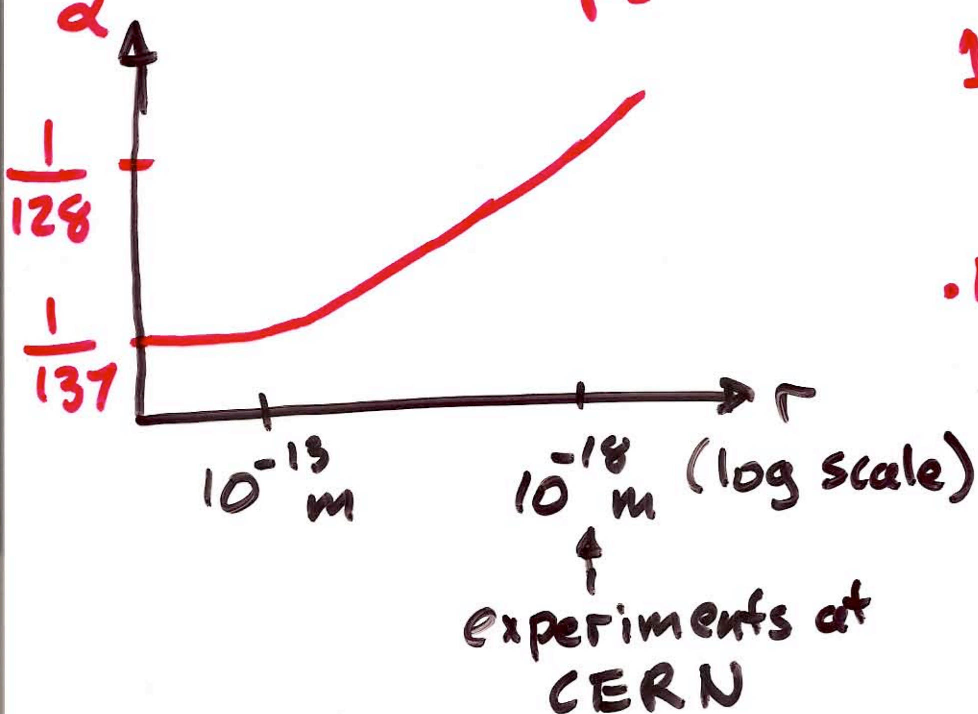
ASYMPTOTIC FREEDOM

Gross, Wilczek, Politzer (1973)

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

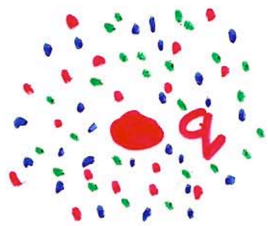
QED

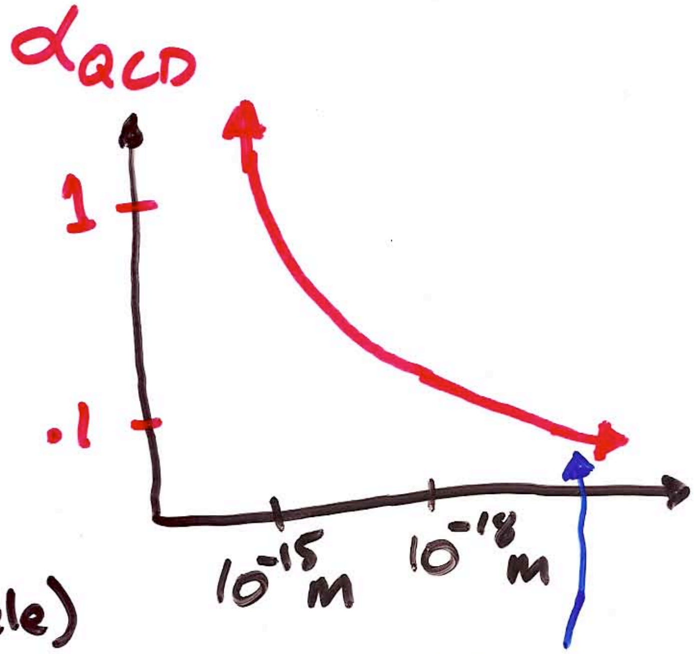
α: Force between electrons ~ $\frac{\alpha(r)}{r^2}$



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

QCD





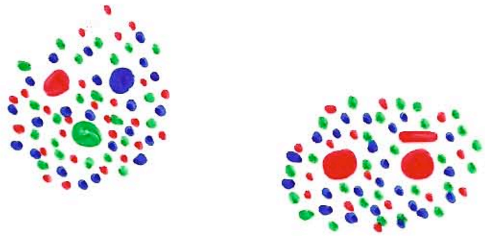
asymptotic freedom, or anti-screening. (That's why Friedman, Kendall, Taylor were able to see weakly interacting quarks.)

WHAT DOES QCD DESCRIBE?

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

protons, neutrons, ...

pions, kaons, ...



These hadrons are the quasiparticles of the QCD vacuum.

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

WHY STUDY QCD?
WHY IS IT A CHALLENGE?

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

HOW DO WE RESPOND TO THE CHALLENGE?

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

Quark-Gluon Plasma

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

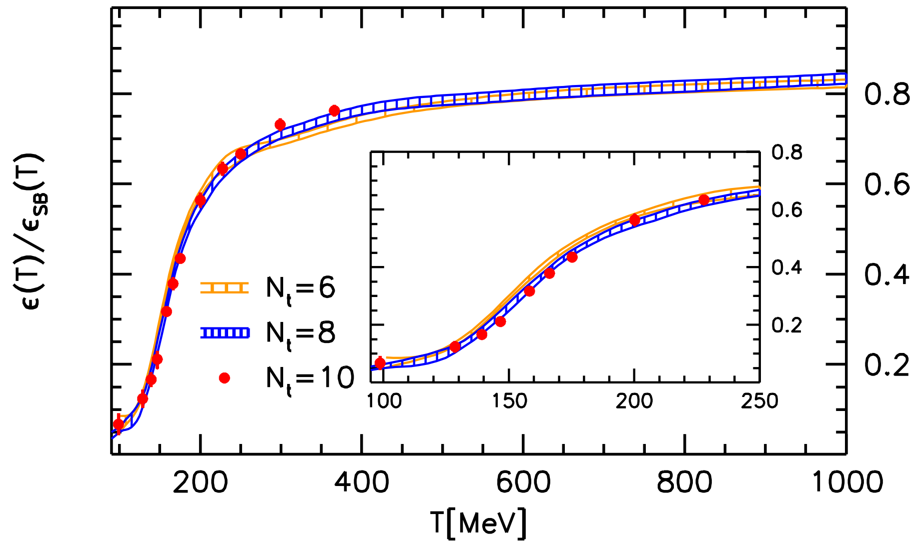
- Asymptotic freedom tells us that, for $T \to \infty$, QGP must be weakly coupled quark and gluon quasiparticles.

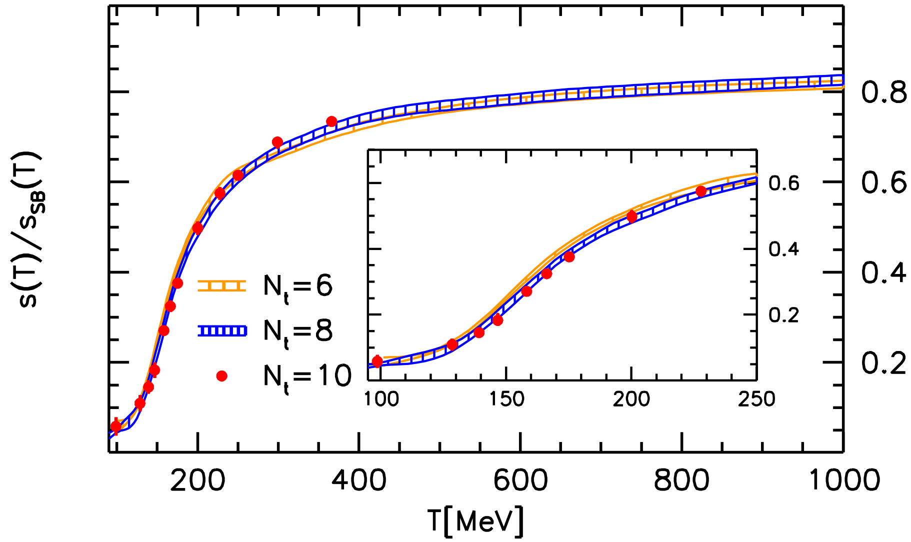
- Lattice calculations of QCD thermodynamics reveal a smooth crossover, like the ionization of a gas, occurring in a narrow range of temperatures centered at a $T_c \simeq 150$ MeV $\simeq 2$ trillion °C ~ 20 μs after big bang. At this temperature, the QGP that filled the universe broke apart into hadrons and the symmetry-breaking order that characterizes the QCD vacuum developed.

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

QGP Thermodynamics on the Lattice

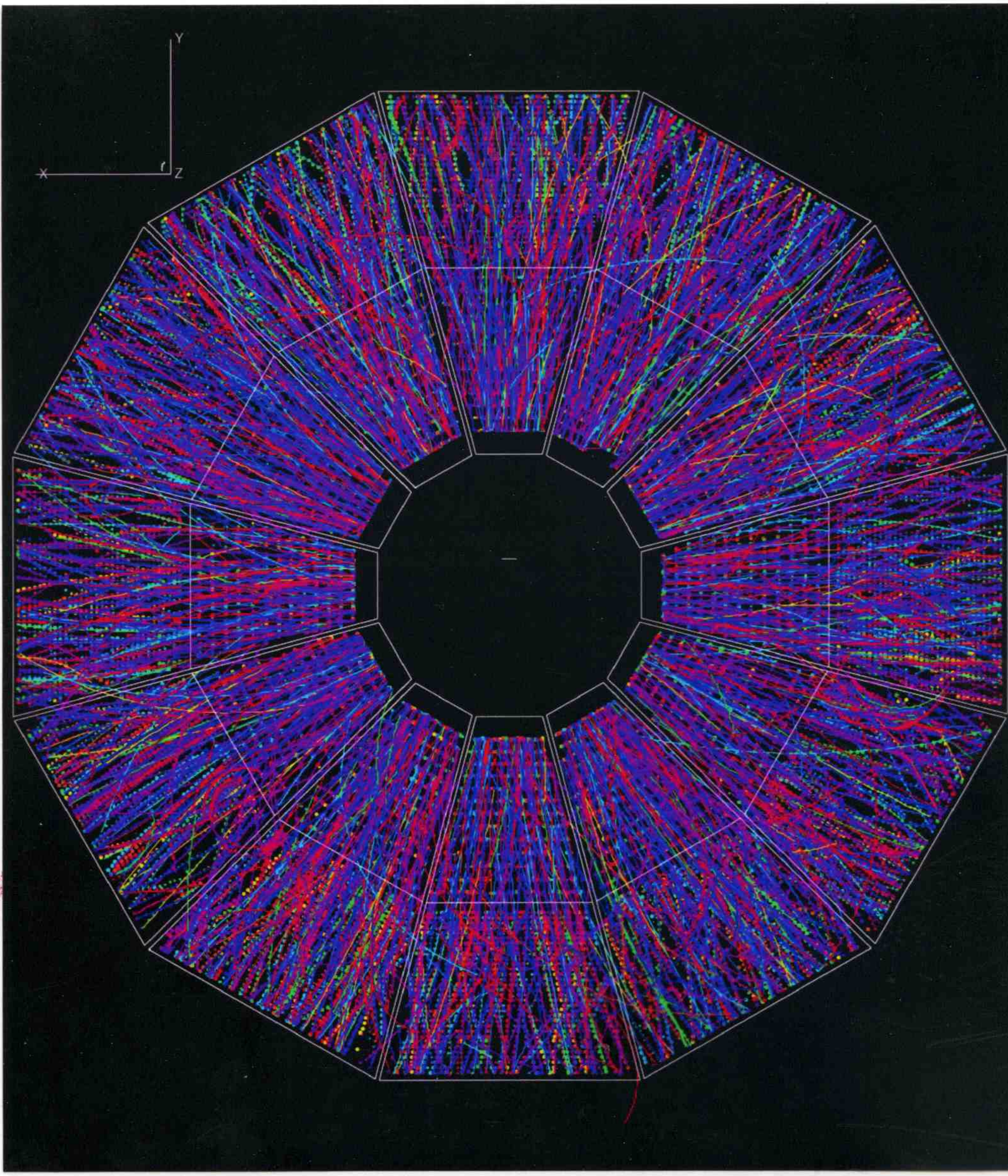
Endrodi et al, 2010





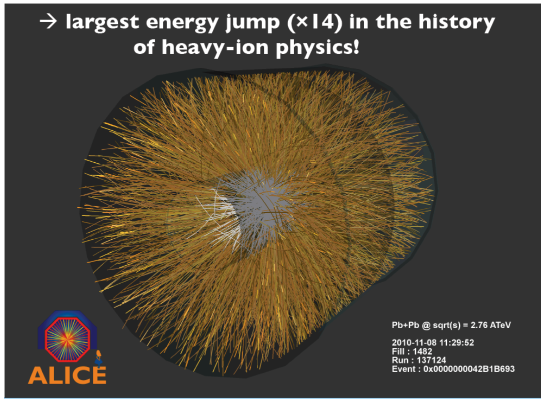
Above $T_{\text{crossover}} \sim$ 150-200 MeV, QCD = QGP. QGP static properties can be studied on the lattice.

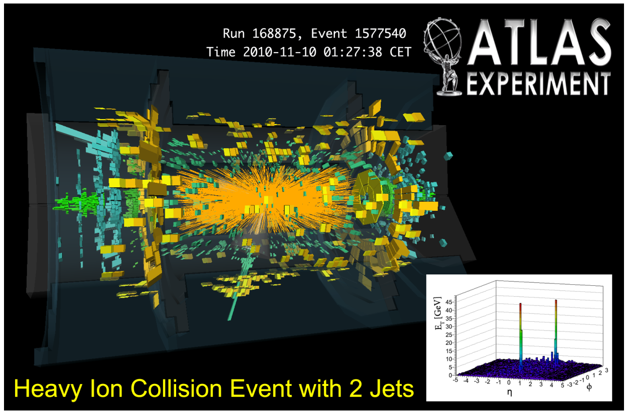
Lesson of the past decade: don't try to infer dynamic properties from static ones. Although its thermodynamics is almost that of ideal-noninteracting-gas-QGP, this stuff is very different in its dynamical properties. [Lesson from experiment+hydrodynamics. But, also from the large class of gauge theories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



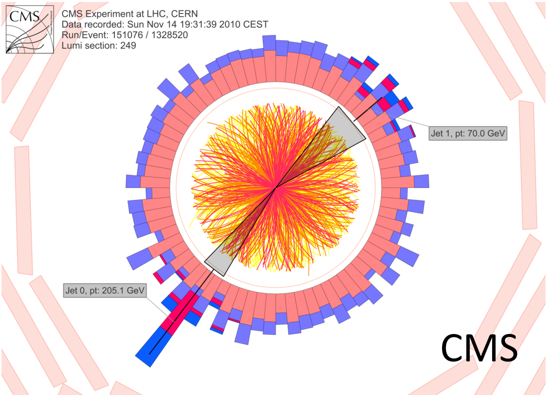
STAR

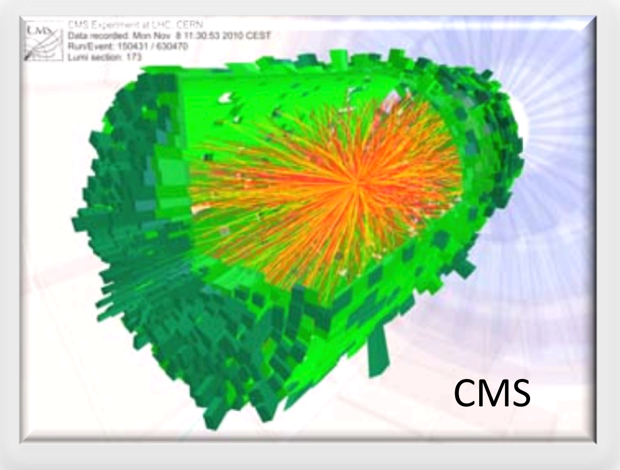
Nov 2010 first LHC Pb+Pb collisions





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





Integrated Luminosity = 10 μb^{-1}

Liquid Quark-Gluon Plasma

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

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

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

- Does the story change at the LHC?

Ultracold Fermionic Atom Fluid

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

- NanoKelvin temperatures, instead of TeraKelvin.

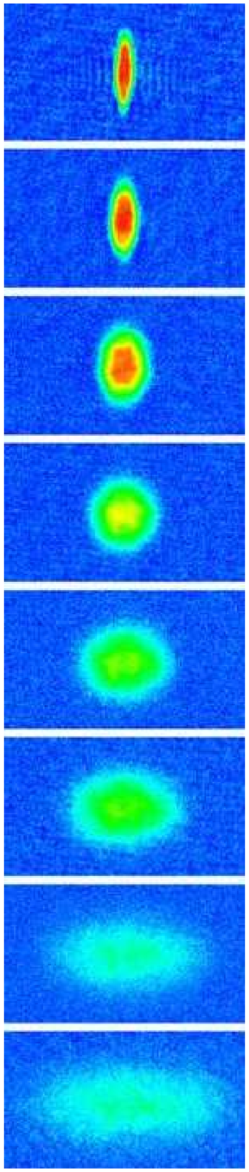
- Ultracold cloud of trapped fermionic atoms, with their two-body scattering cross-section tuned to be infinite. A strongly coupled liquid indeed. (Even though it's conventionally called the "unitary Fermi gas".)

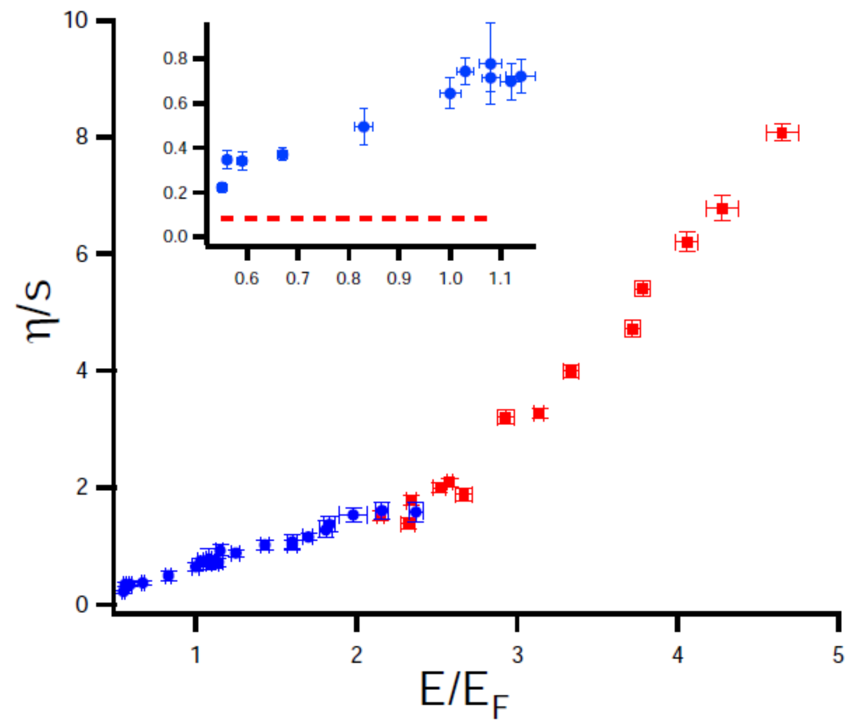
- Data on elliptic flow (and other hydrodynamic flow patterns that can be excited) used to extract η/s as a function of temperature...

Viscosity to entropy density ratio

consider both collective modes (low T)

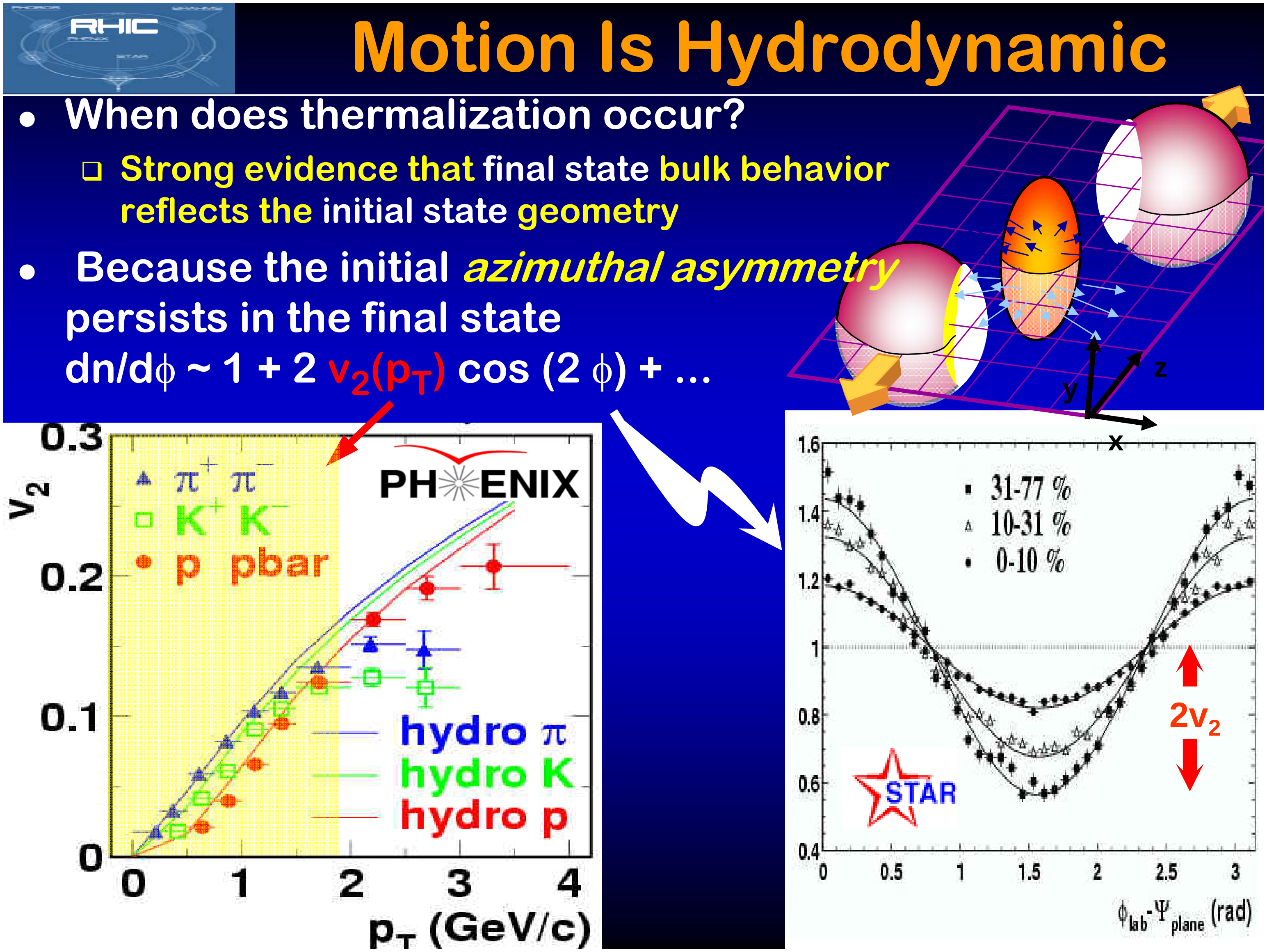
and elliptic flow (high T)





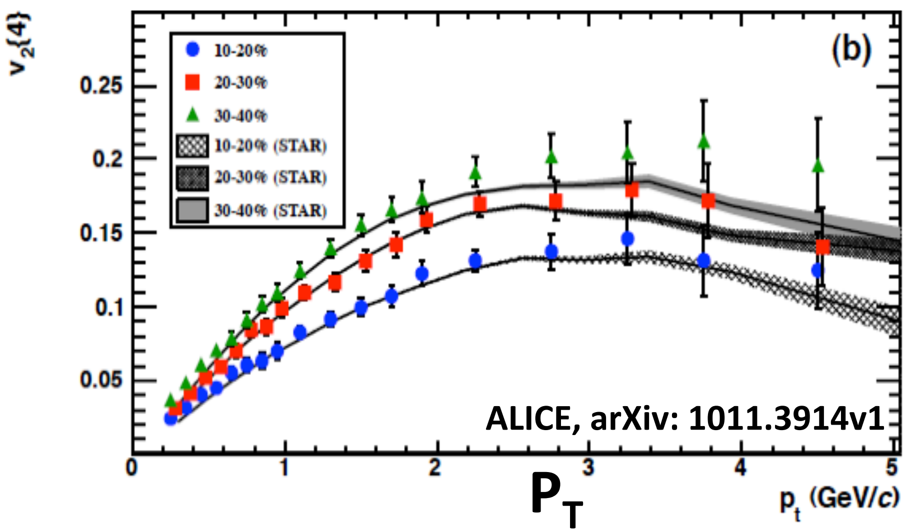
Cao et al., Science (2010)

$$\eta/s \leq 0.4$$

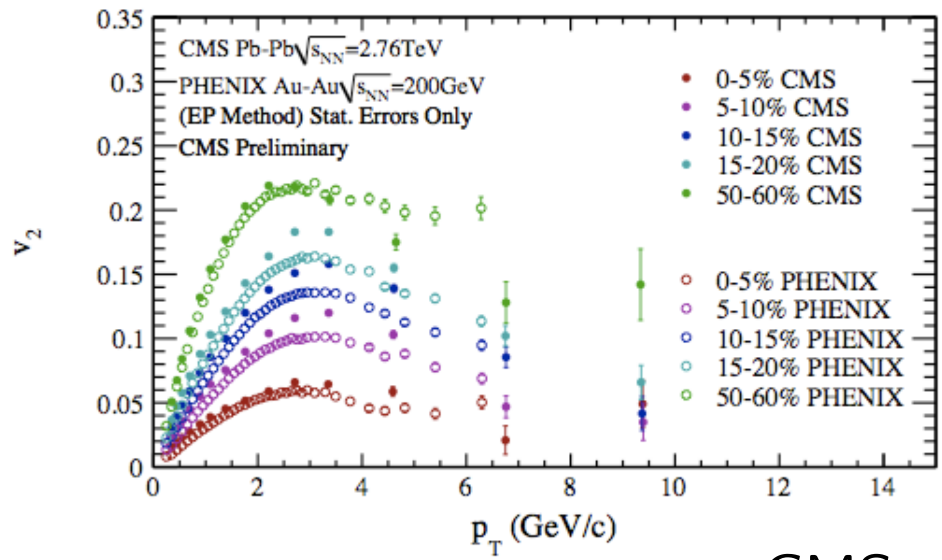


This old slide (Zajc, 2008) gives a sense of how data and hydrodynamic calculations of v_2 are compared, to extract η/s.

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.**

Rapid Equilibration?

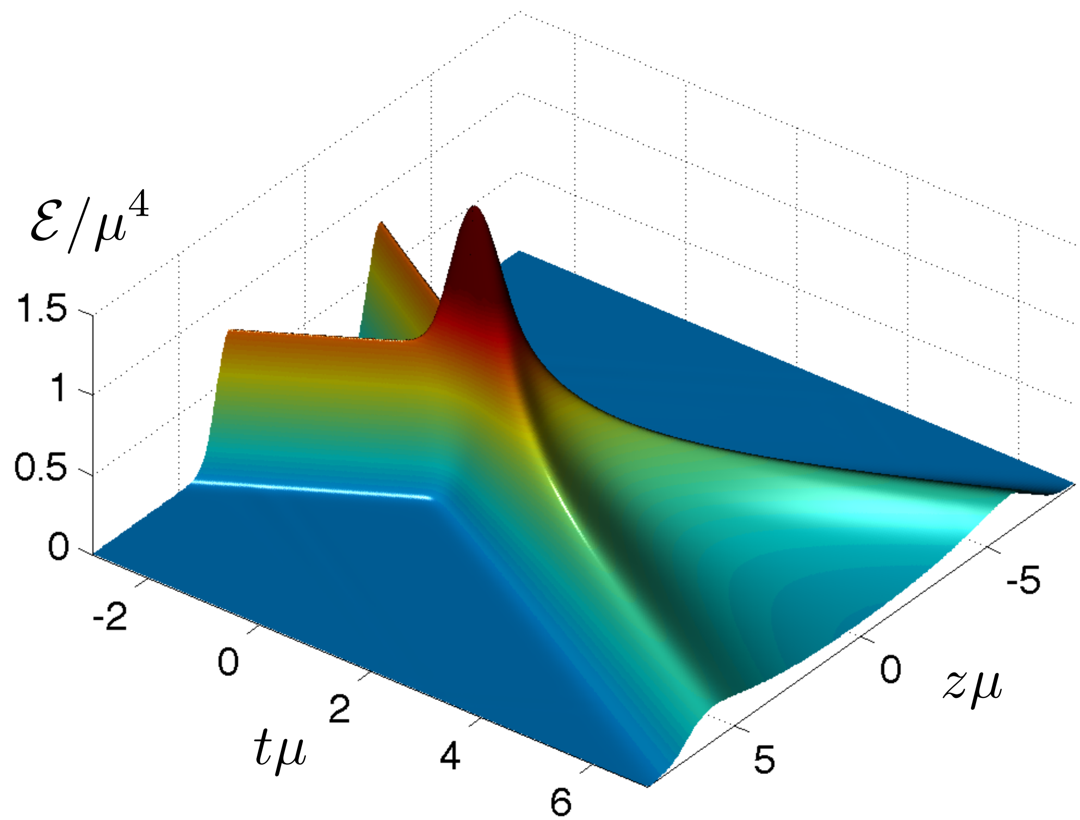
- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.

- 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?

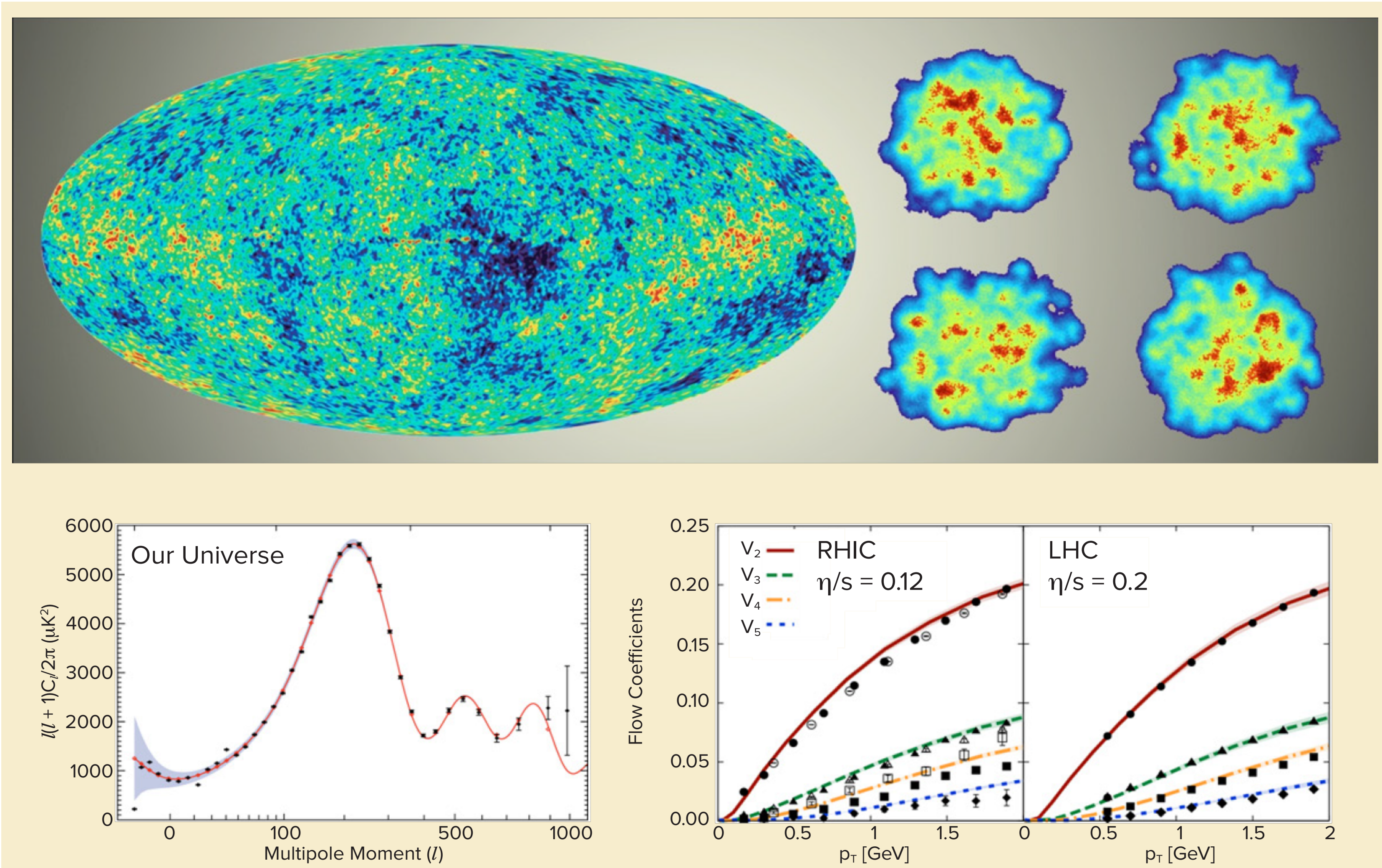
Colliding Strongly Coupled Sheets of Energy



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

η/s from RHIC and LHC data

- **I have given you the beginnings of a story that has played out over the past decade. I will now cut to the chase, leaving out many interesting chapters and oversimplifying.**
- **Using relativistic viscous hydrodynamics to describe expanding QGP,** *produced in an initially lumpy heavy ion collision*, **using microscopic transport to describe late-time hadronic rescattering, and using RHIC data on pion and proton spectra and** v_2 *and* v_3 *and* v_4 *and* v_5 *and* v_6 ... **as functions of** p_T **and impact parameter**...
- **QGP@RHIC, with** $T_c < T \lesssim 2T_c$**, has** $1 < 4\pi\eta/s < 2$ **and QGP@LHC with** $T_c < T \lesssim 3T_c$ **has** $1 < 4\pi\eta/s < 3$**.**
- $4\pi\eta/s \sim 10^4$ **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.**



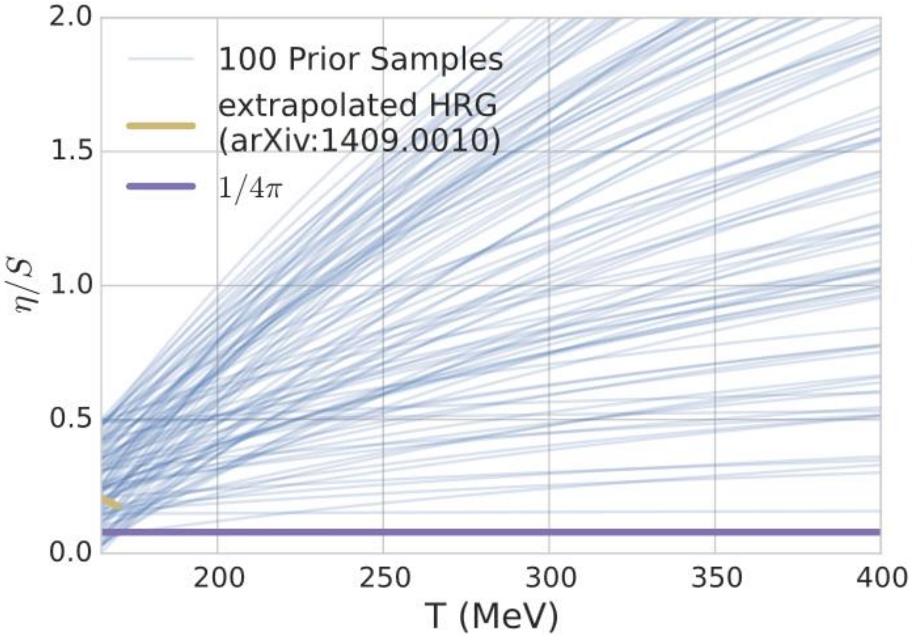
Our Universe
$l(l+1)C_l/2\pi$ (μK^2)
Multipole Moment (l)
0
1000
2000
3000
4000
5000
6000
0
100
500
1000
Flow Coefficients
V_2
V_3
V_4
V_5
RHIC
$\eta/s = 0.12$
LHC
$\eta/s = 0.2$
0.00
0.05
0.10
0.15
0.20
0.25
0
0.5
1
1.5
2
p_T [GeV]
p_T [GeV]

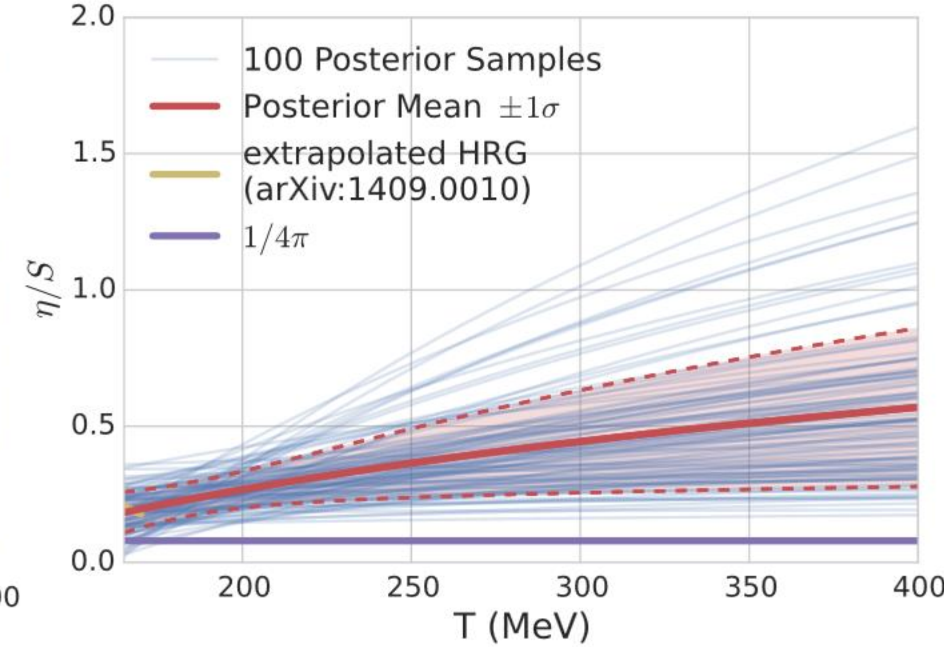
QGP cf CMB

- 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...

Toward Error Bars on $\eta/s(T)$

Sangaline, Pratt





Exploring parametrized space of possible initial conditions and equations of state and $\eta/s(T)$ and seeing how data sets, plural, constrain what is allowed.

In this study to date, no v_n data for $n > 2$ used, and initial conditions assumed smooth not lumpy. This methodology, when applied to a parametrized space of lumpy initial conditions, is the path toward robust constraints on $\eta/s(T)$.

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;... Among the grand challenges at the frontiers of condensed matter physics today.

- In all these cases, after discovery two of the central strategies toward gaining understanding are *probing* and *doping*. To which we now turn...

Today's Questions

- How does QGP work? What is its microscopic structure? How does its liquidness emerge from microscopic dynamics? QGP is in a sense the simplest complex matter, and was certainly the first; how does it emerge from an asymptotically free gauge theory? We need probes that can "see" short-distance structure of QGP.

- What is the smallest possible droplet of QGP with a certain temperature that behaves hydrodynamically?

- Origins of QGP in HICs? Different than its origins in cosmology. HICs are lumpy and fast. How does hydrodynamization happen so quickly? Near-perfect fluidity of QGP means its origins can be seen in its debris. Ultimately, compare what we learn of its origins in HIC to what we learn about nuclear wave functions from an EIC.

- What is the phase diagram of doped QGP?

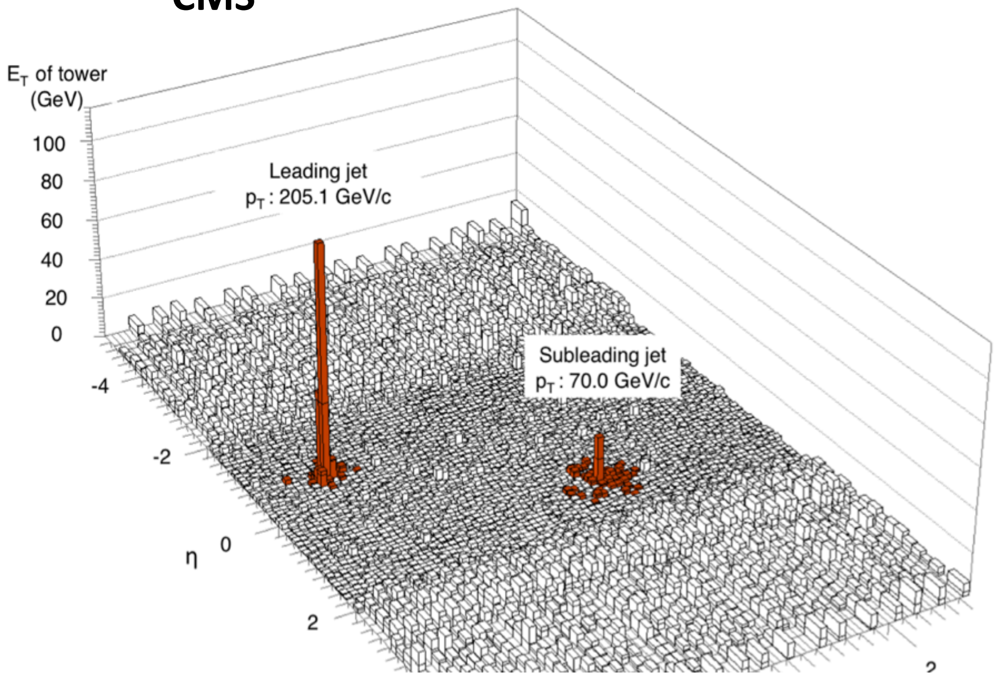
- Can we see the quantum aspects of QGP?

How does QGP work?

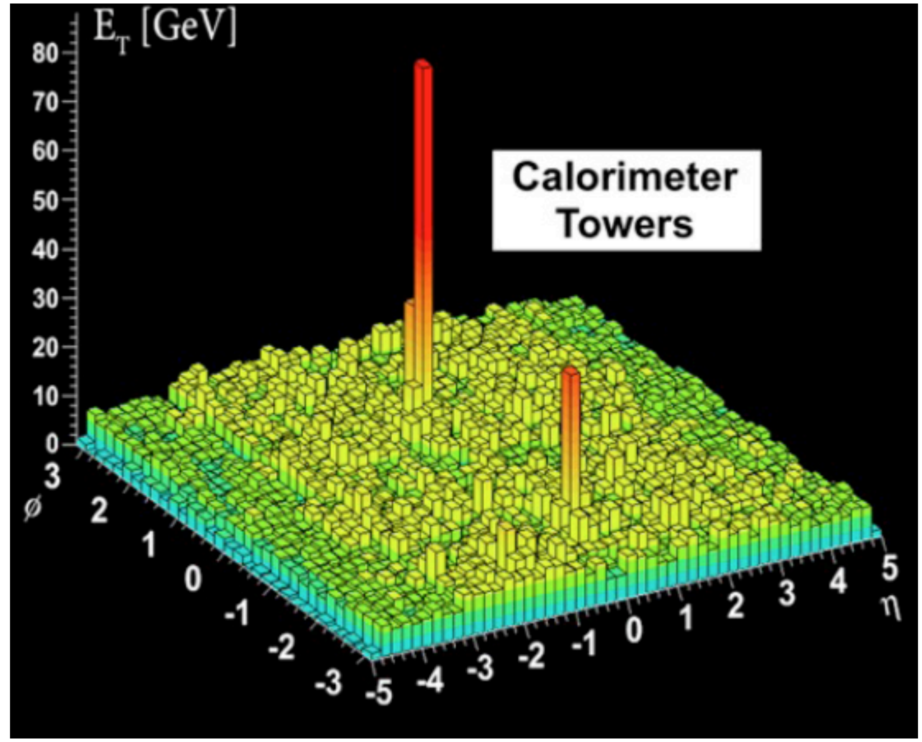
- We can quantify the properties of Liquid QGP at it's natural length scales, where it has no quasiparticles.
- What is its microscopic structure? This we know. QCD is asymptotically free. When looked at with sufficiently high resolution, QGP must be made of weakly coupled quarks and gluons.
- How does the strongly coupled liquid, that does what we see it doing, emerge from an asymptotically free gauge theory?
- Maybe answering this question could help to understand how strongly coupled matter emerges in contexts in condensed matter physics where this is also a central question.
- The first step to addressing this question experimentally is finding experimental evidence for point-like scatterers in QGP when QGP is probed with large momentum transfer. Which is to say we need a high-resolution microscope trained upon a droplet of QGP. $\rightarrow$ Jets in QGP.

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.

- As if an initially-200-GeV parton/jet in an LHC collision just heats the plasma it passes through, losing significant energy in so doing. 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 a strongly coupled approach to jet quenching, even if just as a foil with which to develop new intuition.

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

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?

One More Question

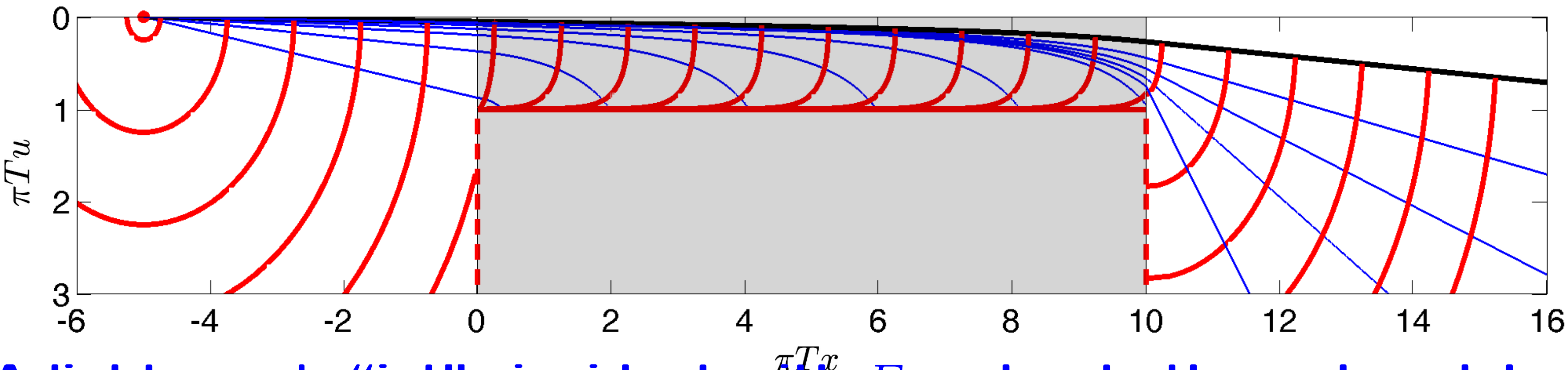
- **So, why did I write "jets" instead of jets? Which is to say, what is a jet in $\mathcal{N} = 4$ SYM theory, anyway? There is no one answer, because hard processes in $\mathcal{N} = 4$ SYM theory don't make jets.** Hatta, Iancu, Mueller; Hofman, Maldacena.
- **The formation of (two) highly virtual 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".**

What have we done?

- We (Chesler+KR) 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

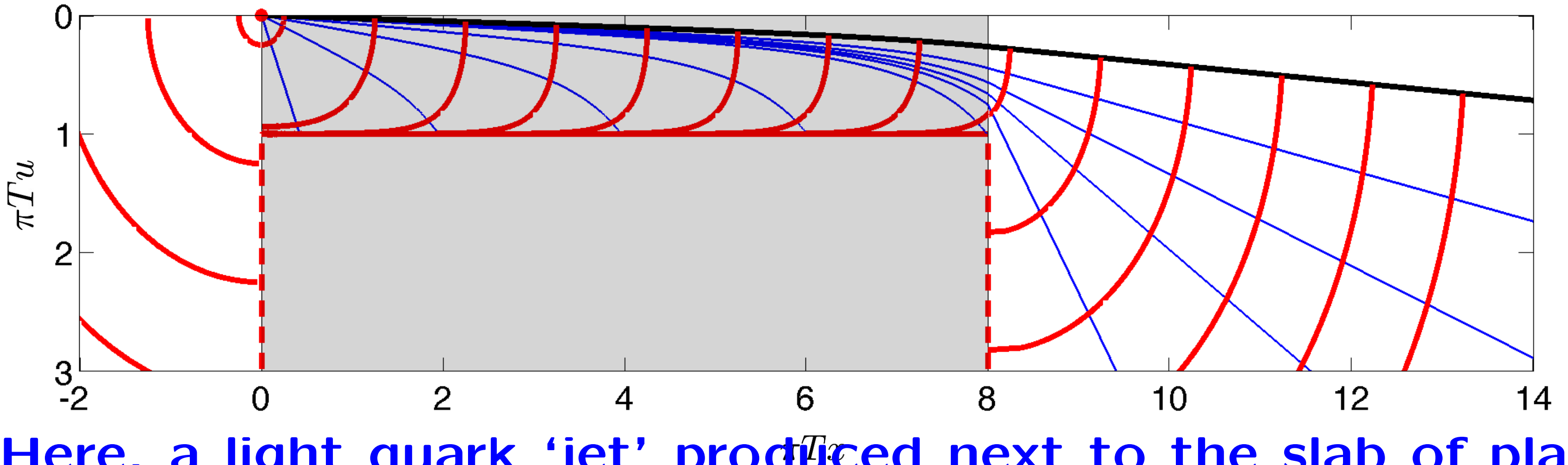


A light quark "jet", incident with E_{in}, shoots through a slab of strongly coupled $\mathcal{N} = 4$ SYM plasma, temperature T, thickness $L\pi T = 10$, assumed $\gg 1$. What comes out the other side? A "jet" with $E_{\text{out}} \sim 0.64 E_{\text{in}}$; just like a vacuum "jet" with that lower energy,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

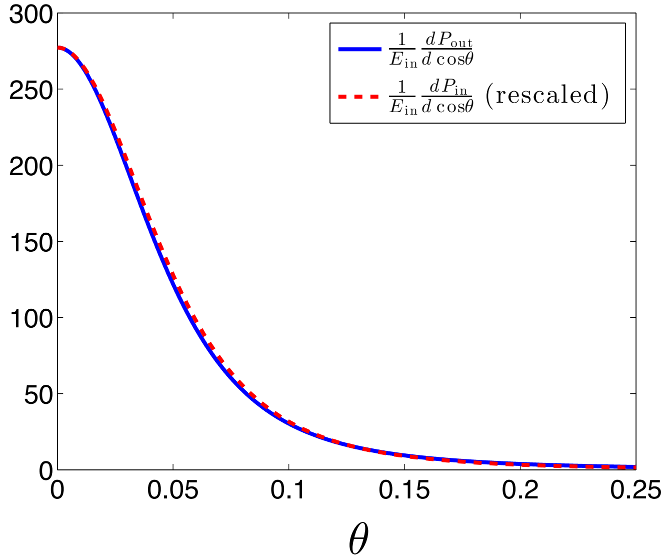


Here, a light quark 'jet' produced next to the slab of plasma with incident energy $E_{\text{in}} = 87\sqrt{\lambda}\pi T \sim 87\sqrt{\lambda}$ GeV shoots through the slab and emerges with $E_{\text{out}} \sim 66\sqrt{\lambda}$ GeV. Again, the "jet" that emerges looks like a vacuum "jet" with that energy.

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" $\leftrightarrow$ downward angle of string endpoint.

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756

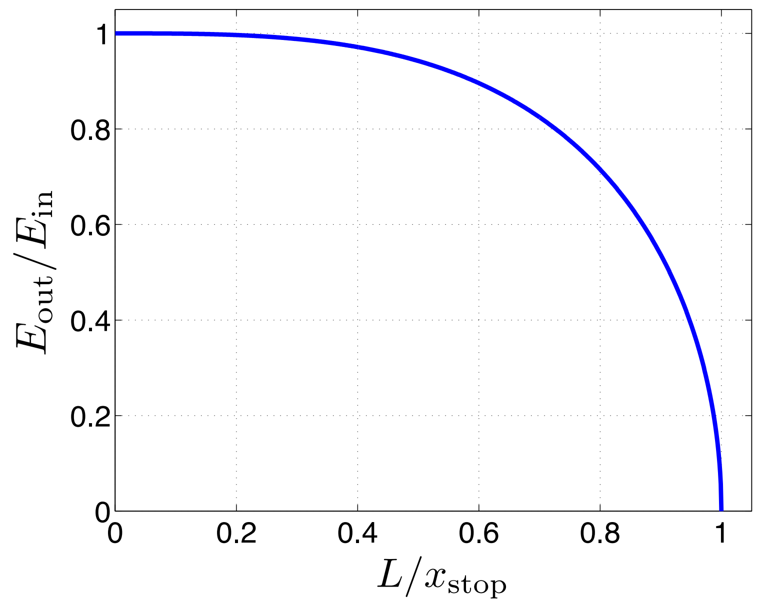


Shape of outgoing "jet" is the same as incoming "jet", except broader in angle and less total energy.

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



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

Quenching a Light Quark "Jet"

One more thing we need is dE_{out}/dL for a gluon "jet". Use the fact (Chesler et al, 2008) that a gluon "jet" with energy E is like 2 quark "jets" each with energy $E/2$, where both the 2's are the large-N_c value of C_A/C_F. So, for gluon "jets":

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

where

$$x_{\text{stop}}^{\text{gluon}} = \left(\frac{C_F}{C_A}\right)^{1/3} \boldsymbol{x}_{\text{stop}}^{\text{quark}} \ .$$

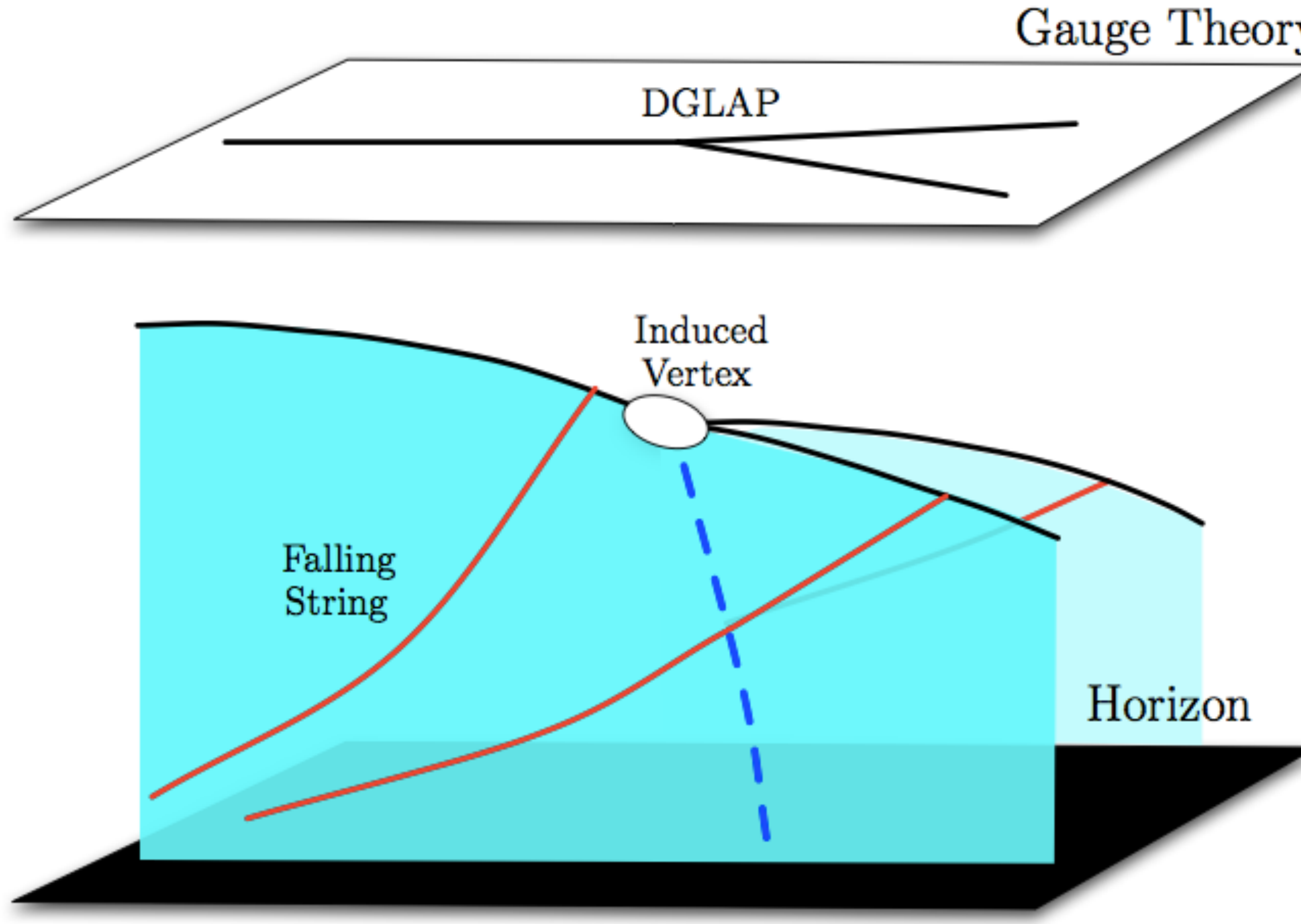
(Note: gluon stopping length is much less different from quark stopping length than weak coupling intuition would suggest. This has implications for energy loss at LHC relative to that at RHIC.)

A Hybrid Weak+Strong Coupling Approach to Jet Quenching?

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, 1405.3864,1508.00815

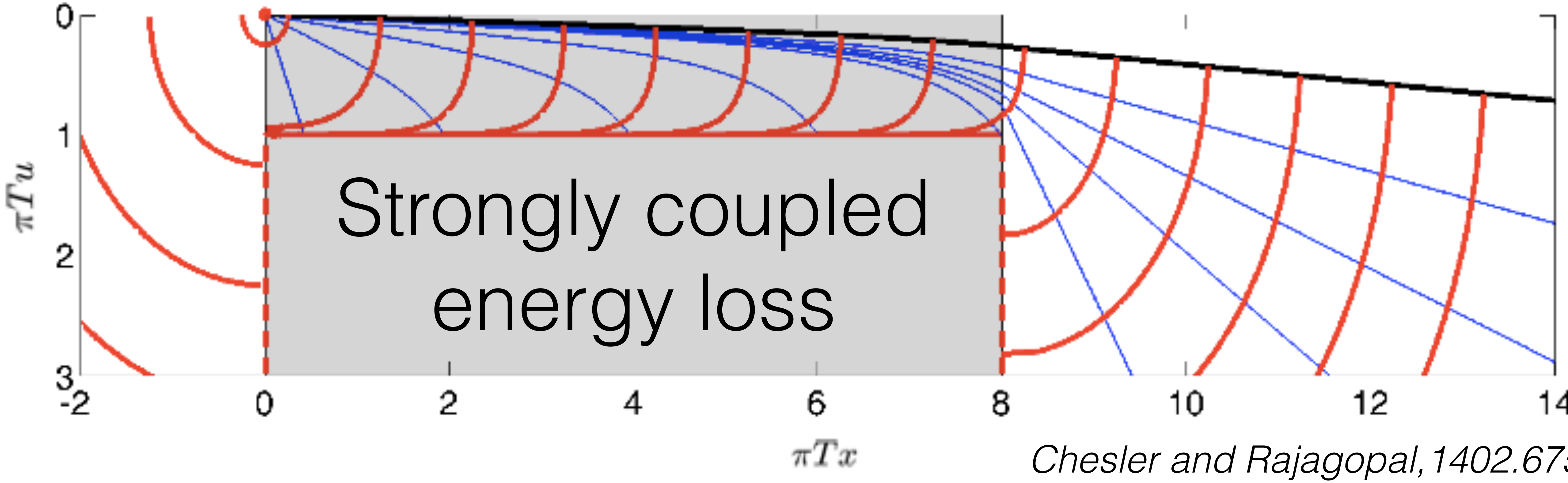
- **Although various holographic approaches at strong coupling capture many qualitative features of jet quenching it seems quite unlikely that the high-momentum "core" of a quenched LHC jet can be described quantitatively in any strong coupling approach. (Precisely because so similar to jets in vacuum.)**
- **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}, dijet asymmetry, jet fragmentation function, photon-jet and Z-jet observables.**

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)



Chesler and Rajagopal, 1402.6756

String based formula for energetic quark in strongly coupled plasma

$$\frac{1}{E_i}\frac{dE}{dx} = -\frac{4x^2}{\pi x_{stop}^2 \sqrt{x_{stop}^2 - x^2}}$$

$E^{\frac{1}{3}}$ dependence robust. Value of κ_{sc} depends on theory and on implementation of jets

$$x_{stop} = \frac{E_i^{1/3}}{2T^{4/3}\kappa_{SC}}$$

Use κ_{sc} as fitting parameter

Smaller stopping distance for gluons

$$\kappa_{SC}^{G} = \kappa_{SC}^{Q}\left(\frac{C_A}{C_F}\right)^{\frac{1}{3}}$$

Control Models

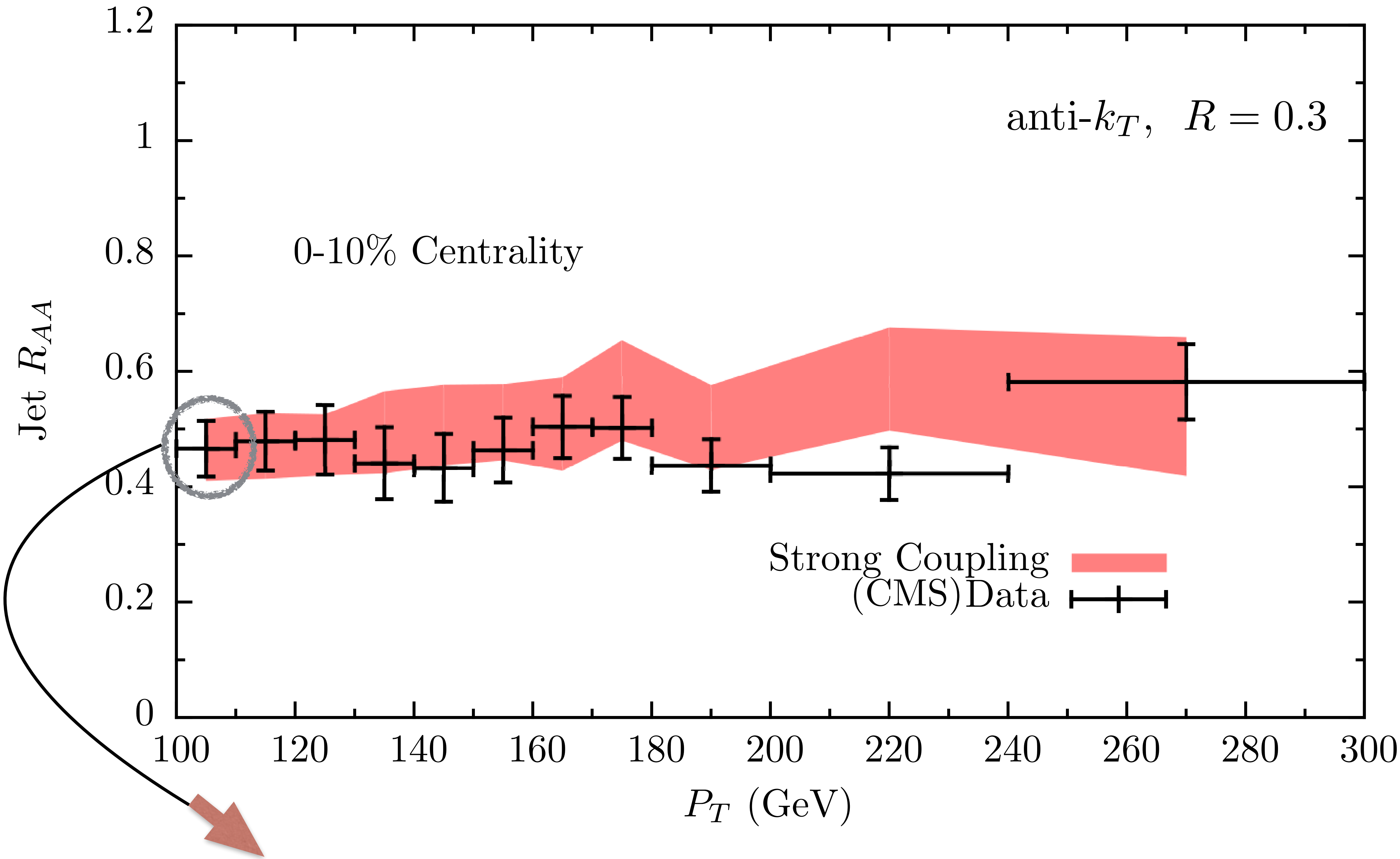
Radiative

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

Collisional

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

R_{AA}

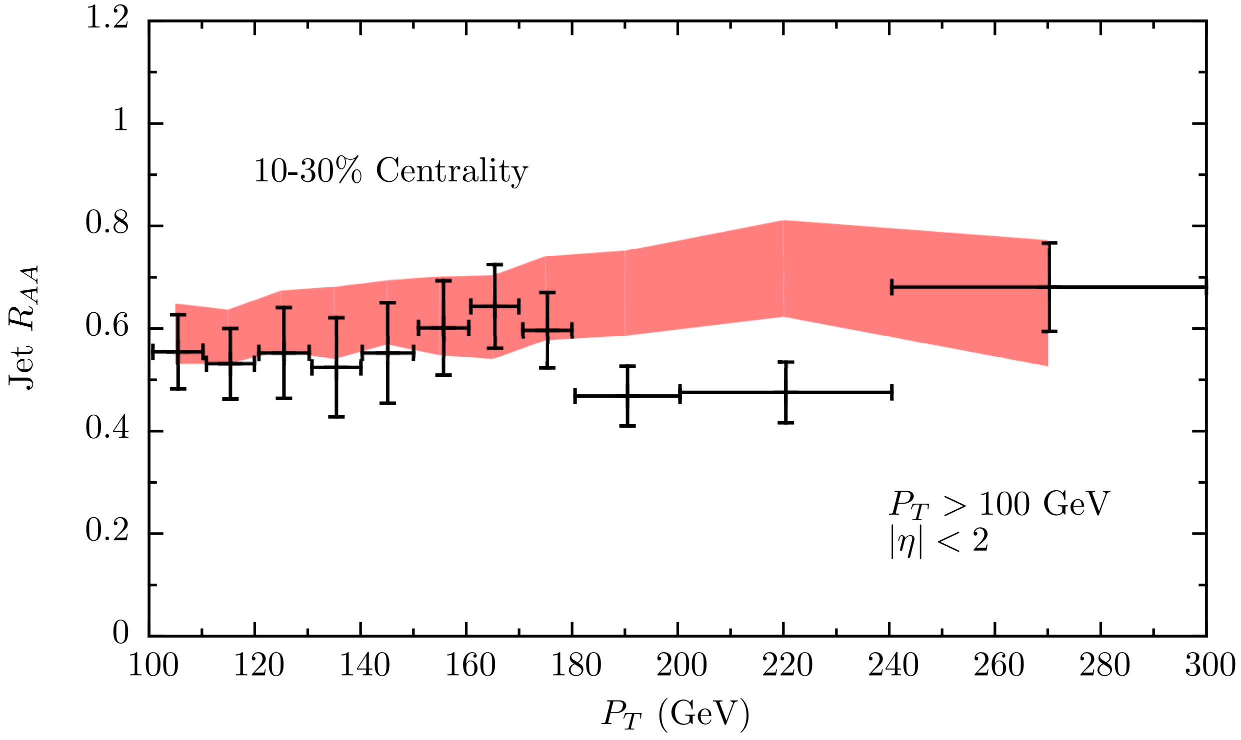


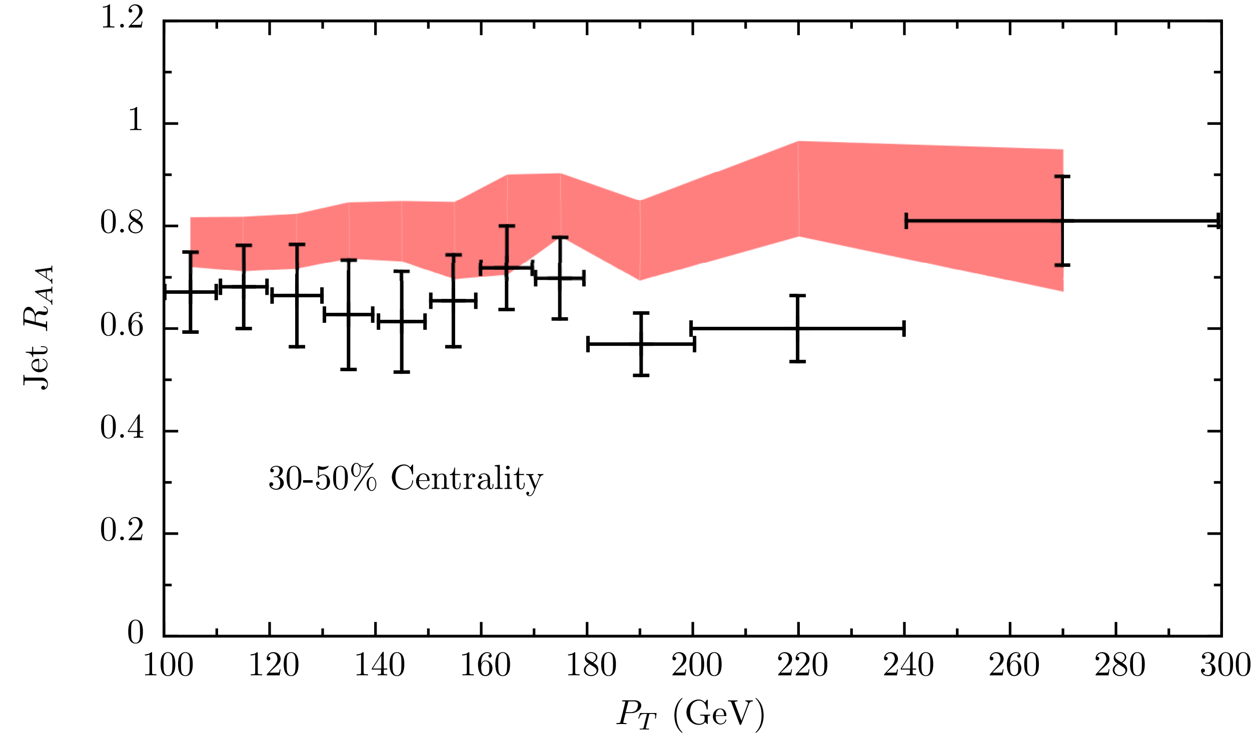
Use this one point to constrain our one parameter.

Bands come from experimental uncertainty on this point

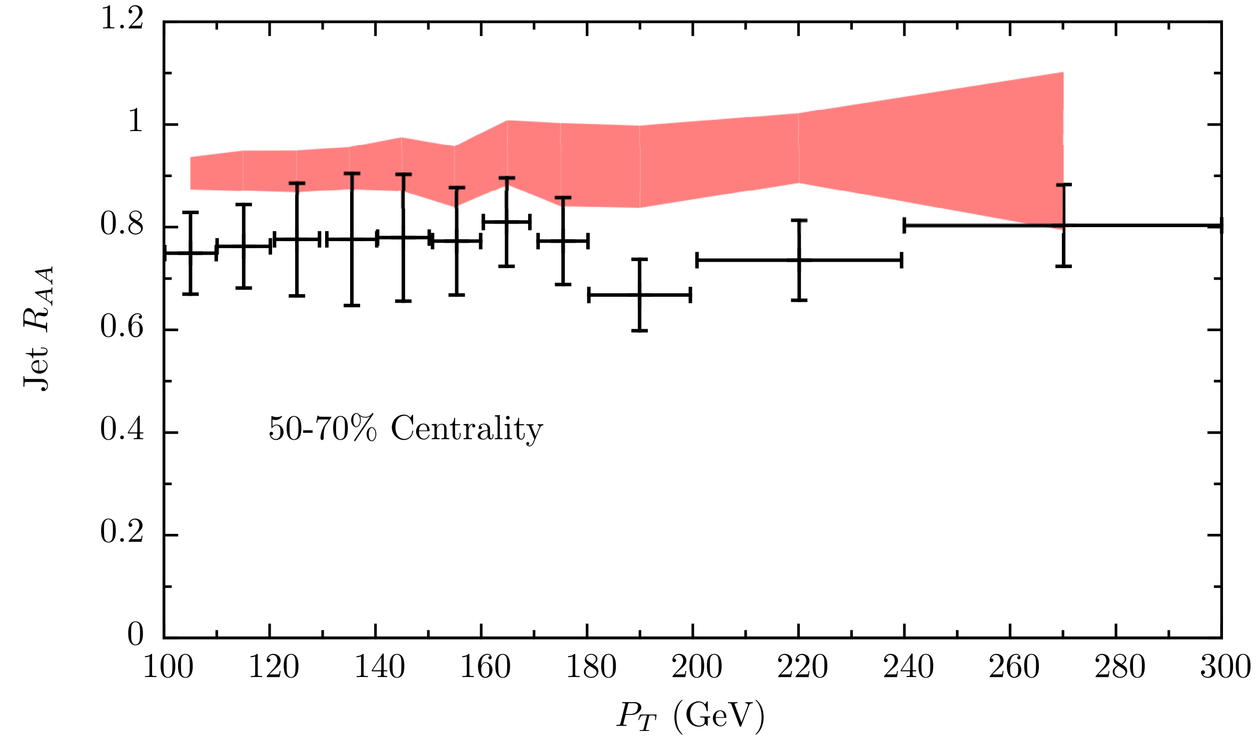
plus varying T_c over $145 < T_c < 170\,\mathrm{MeV}$

R_{AA}

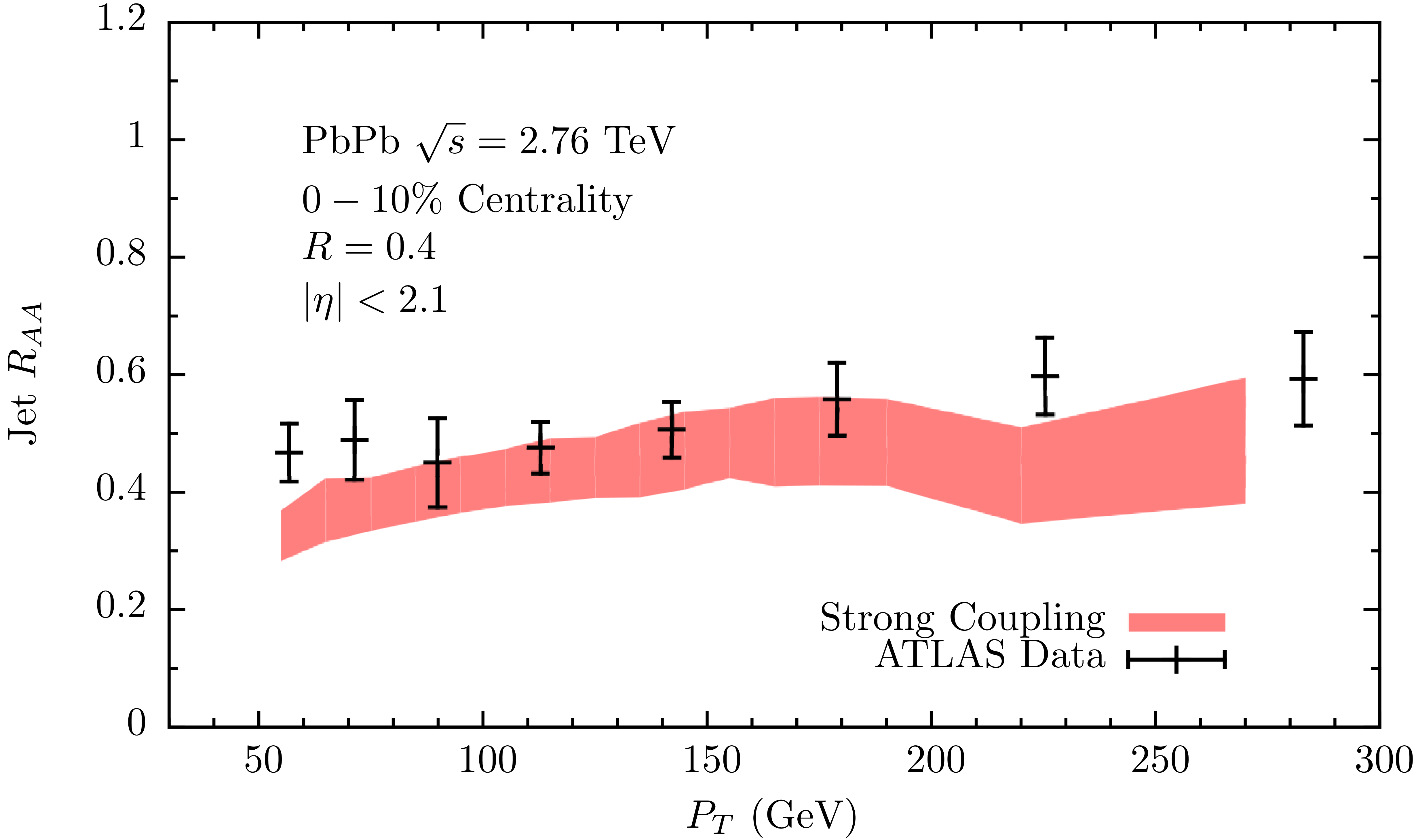




We are not considering quenching in hadron gas phase



R_{AA}

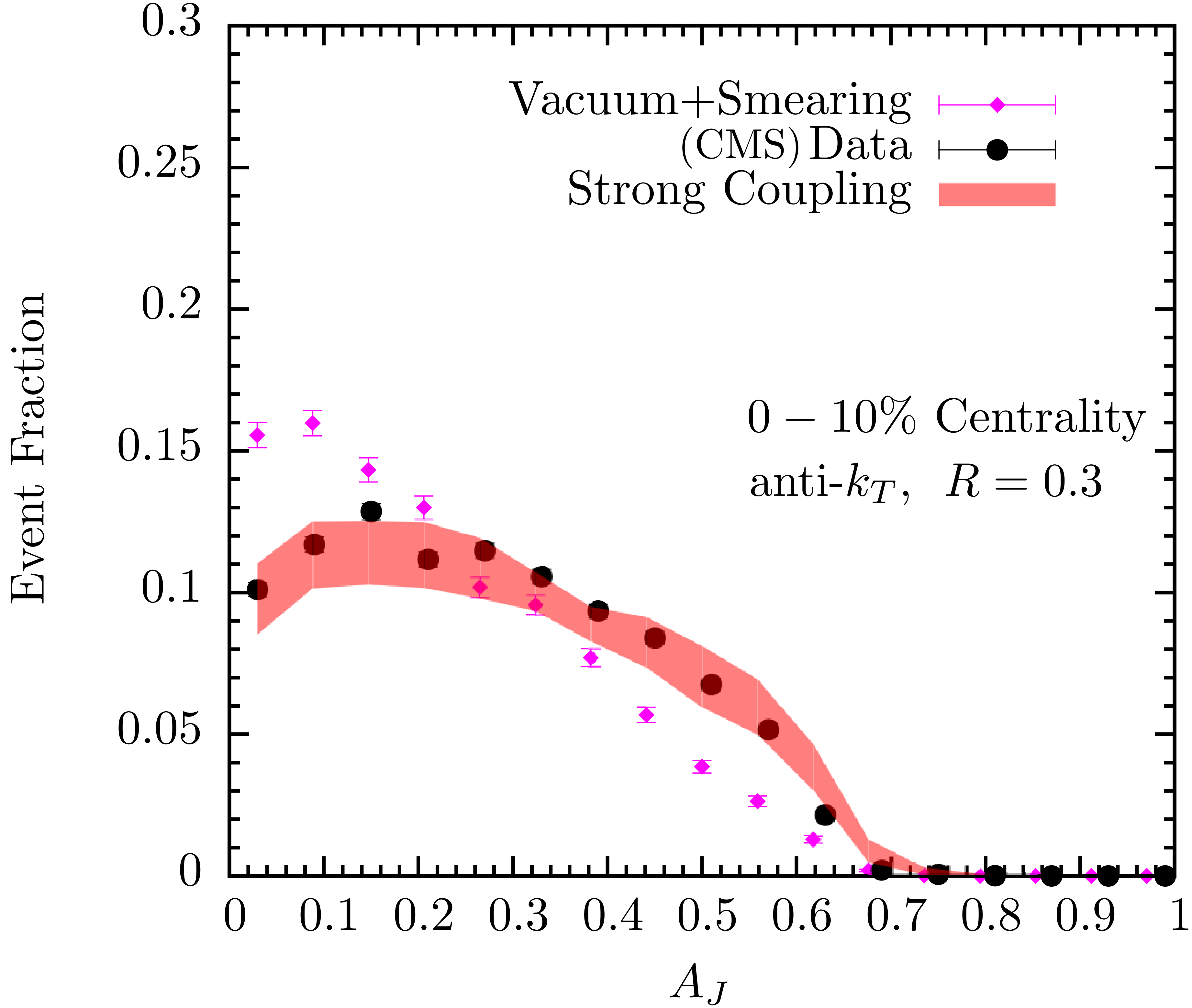


Good agreement over a long range of momentum
with different kinematical cuts

Dijet

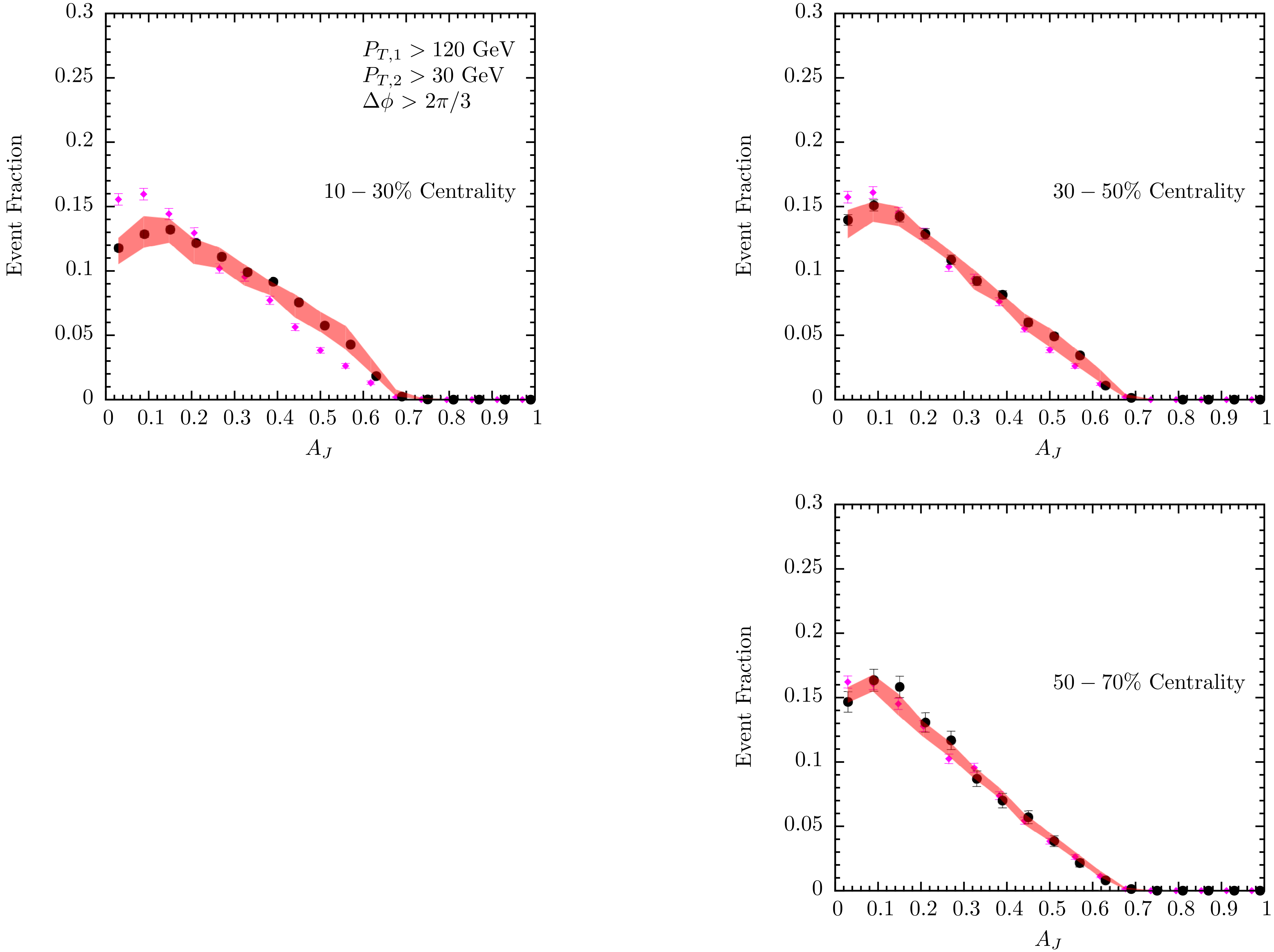
$$A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Dijet Asymmetry



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

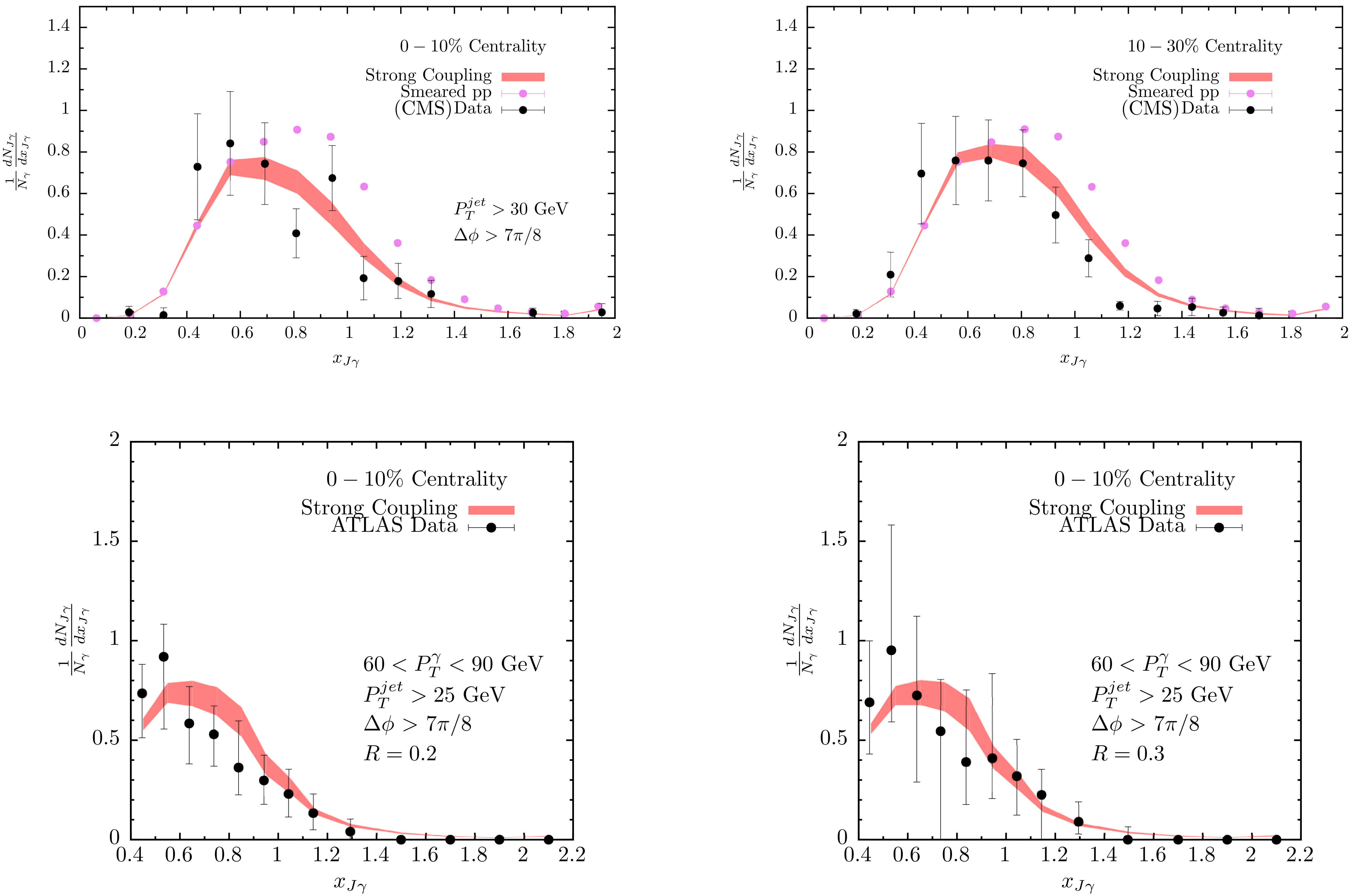
Dijet Asymmetry



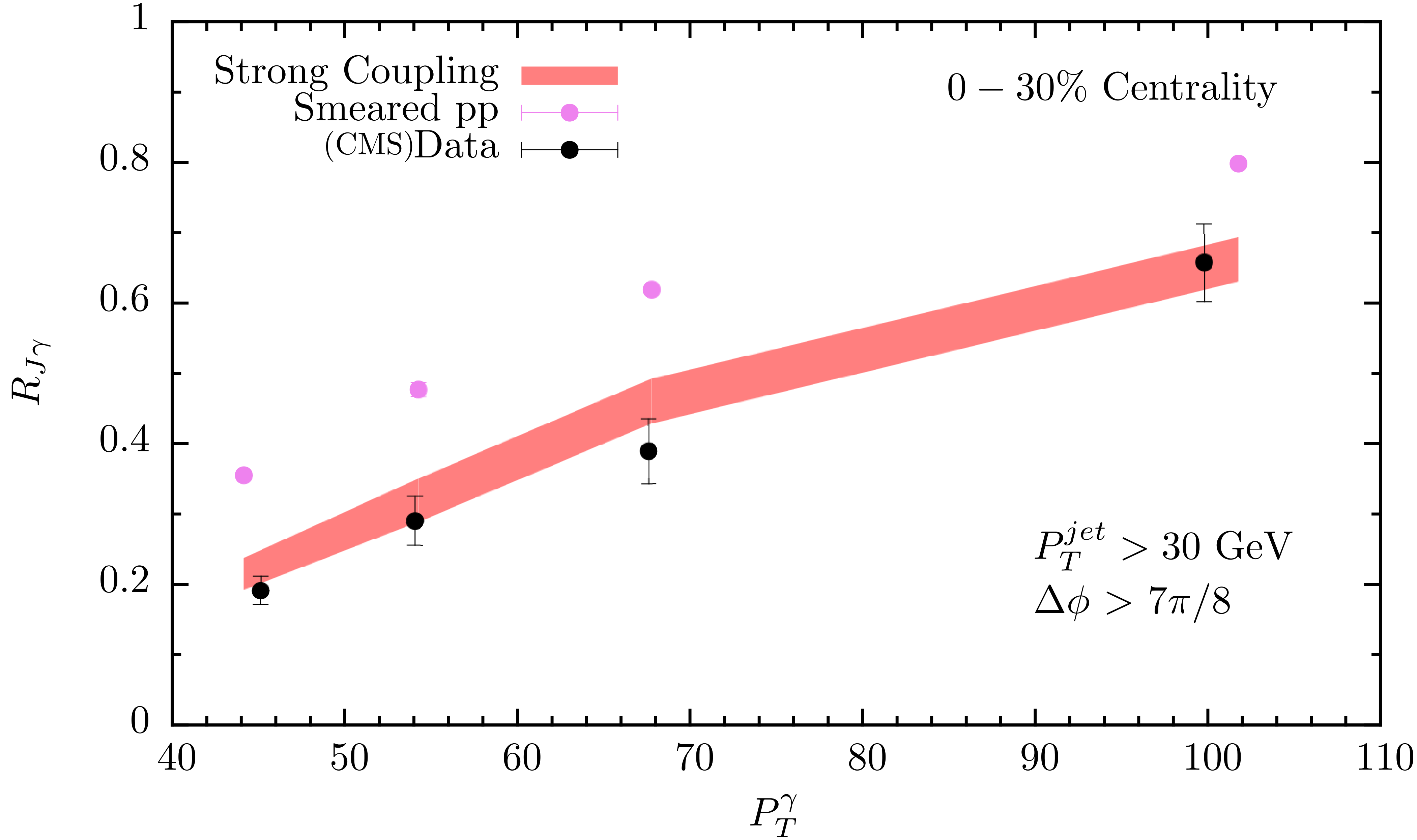
Boson-Jet

$$x_{J\gamma} \equiv \frac{P_T^{jet}}{P_T^{\gamma}}$$

Photon-Jet Imbalance

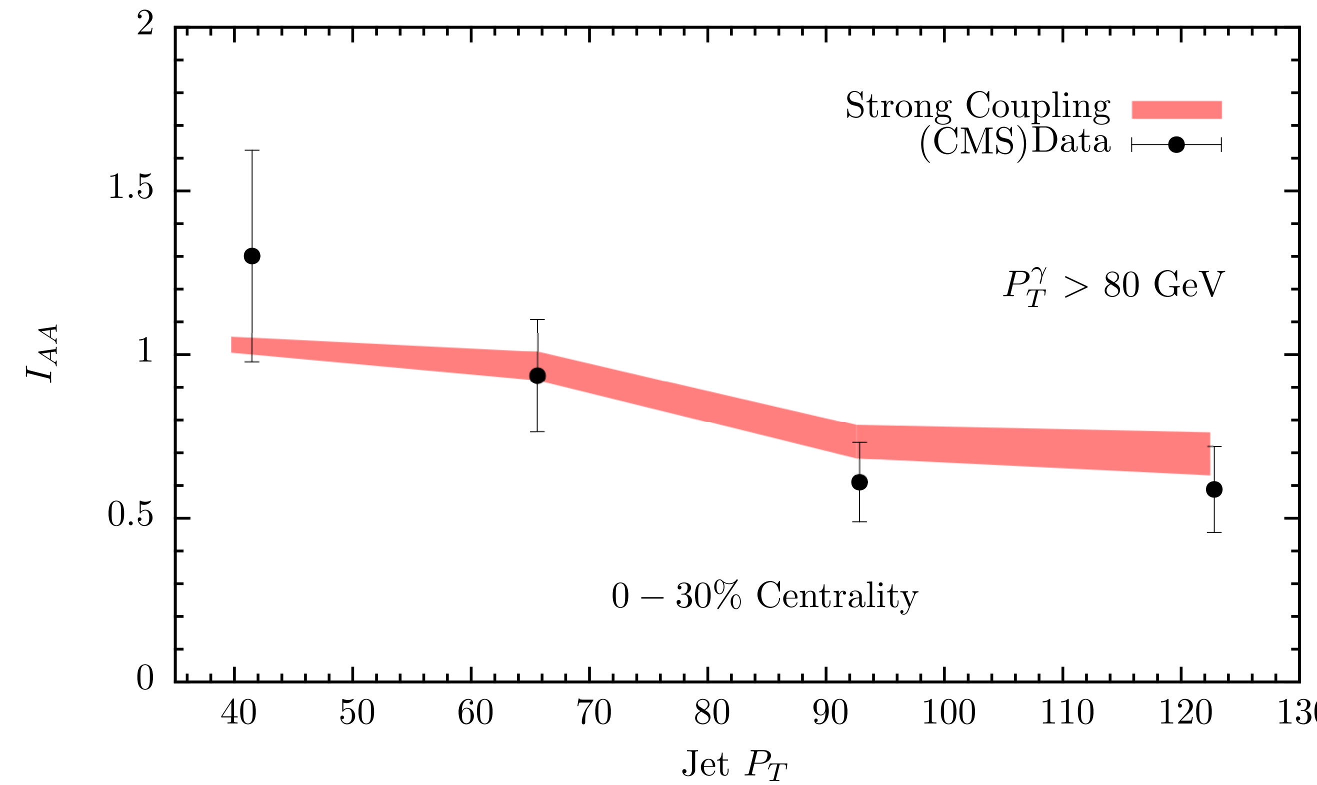


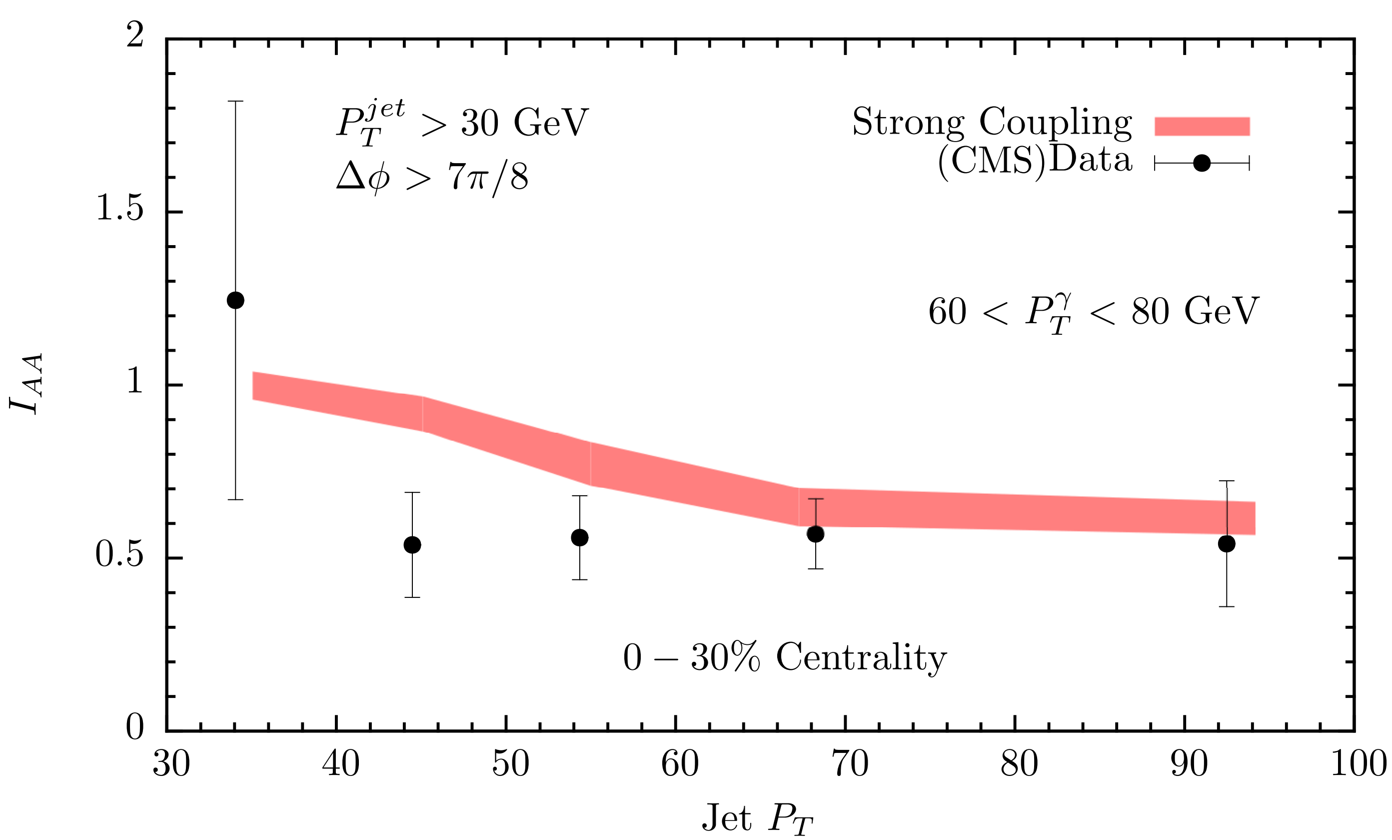
Jetless photons

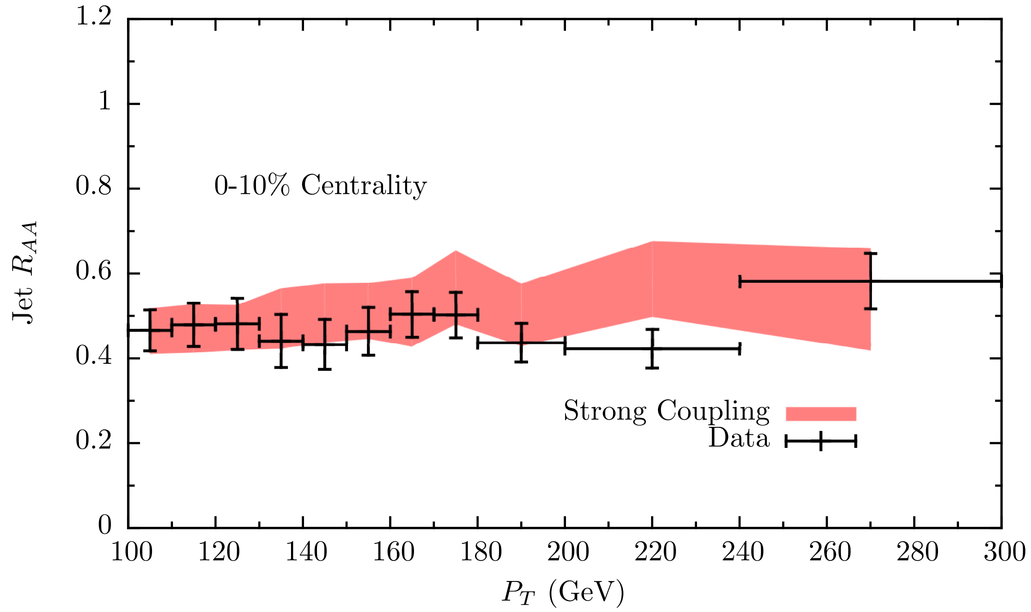


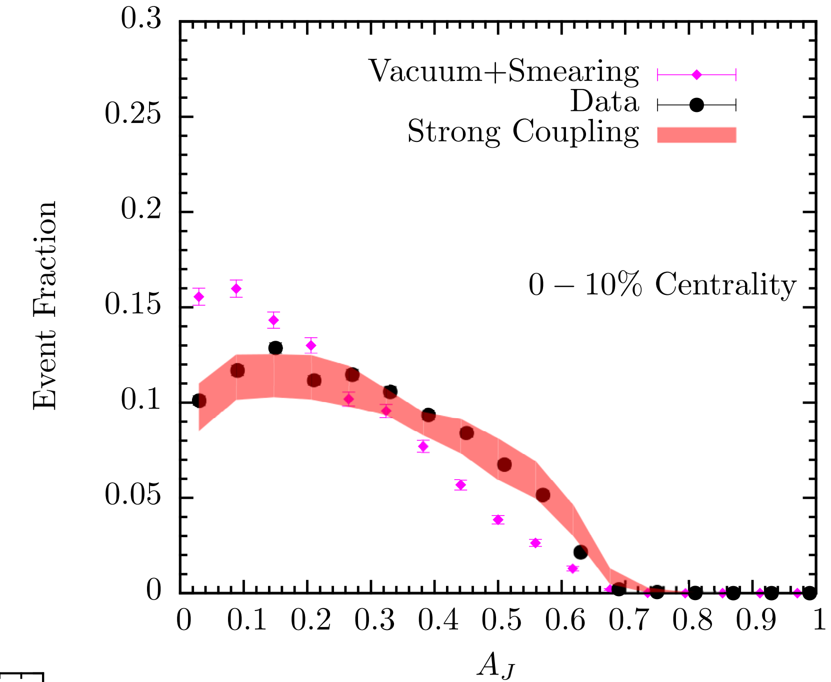
Number of photons with an associated jet

Associated Jet Spectrum

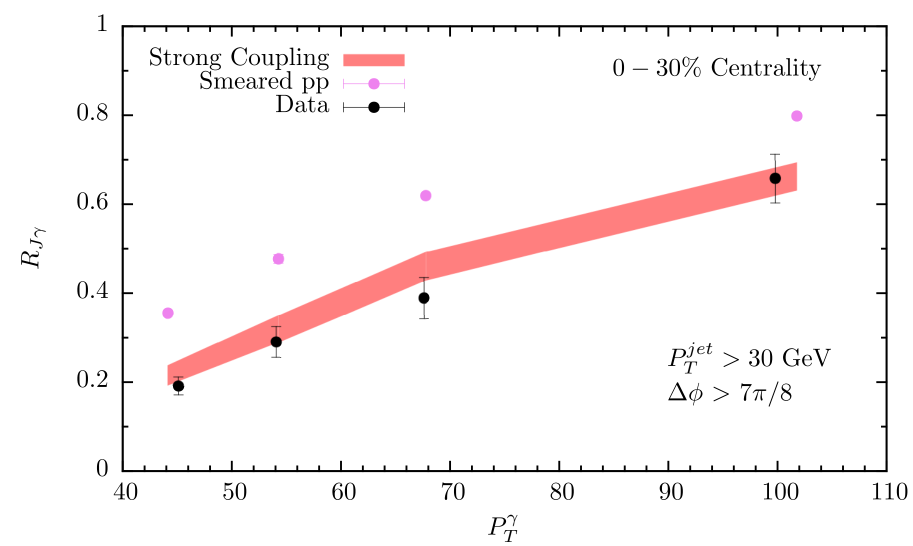








5 observables
and centrality dependence
all described with
single parameter

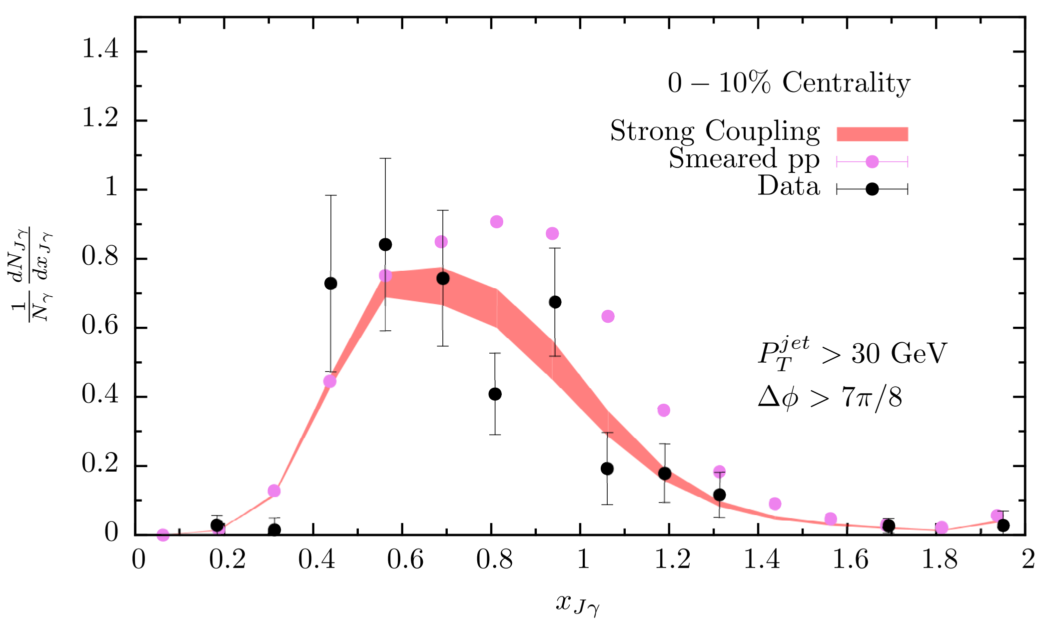


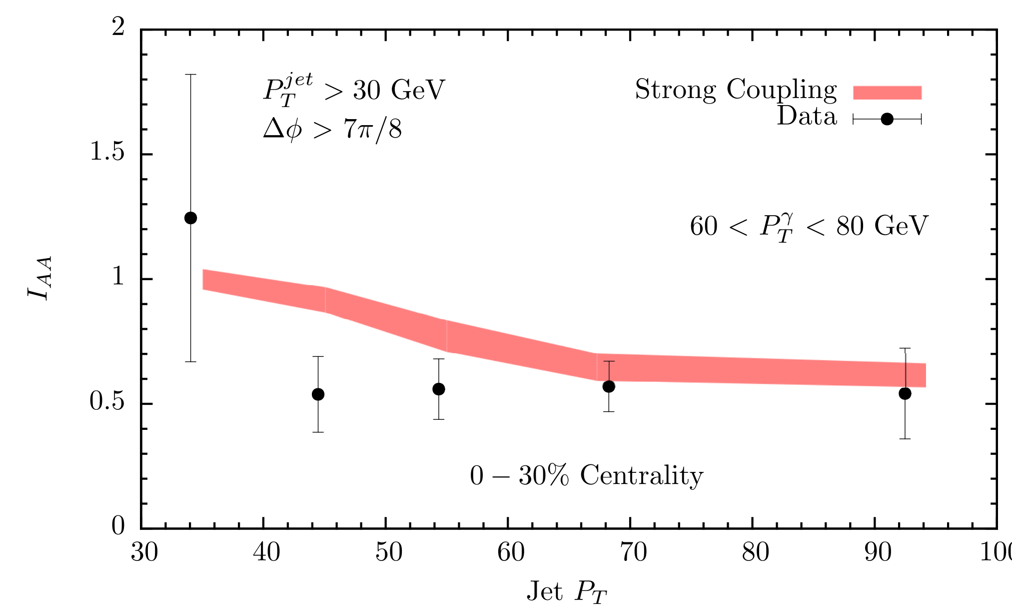
Bands in all plots correspond to

$$0.32 < \kappa_{sc} < 0.41$$

$\mathcal{O}(1)$ as expected.

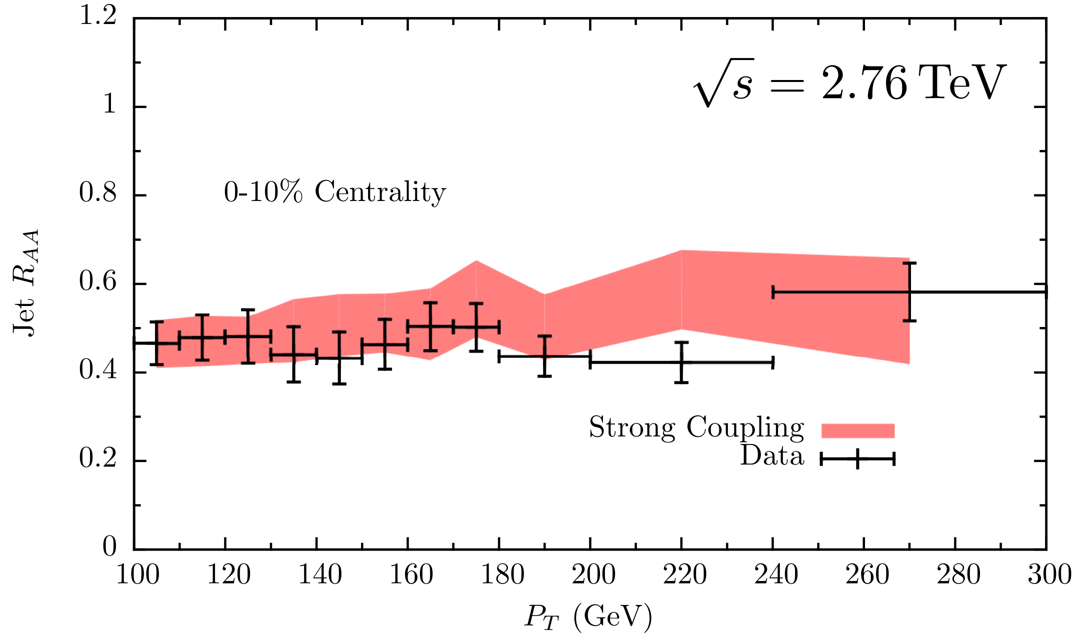
$$x_{stop}^{QCD} \sim (2 - 3) x_{stop}^{\mathcal{N}=4}$$



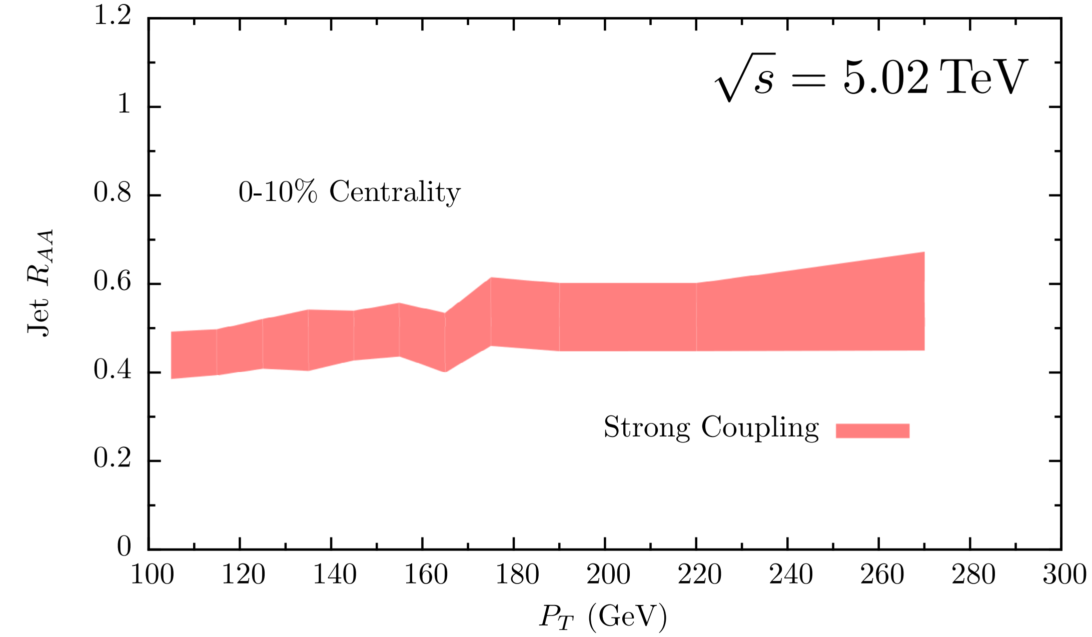


Predictions

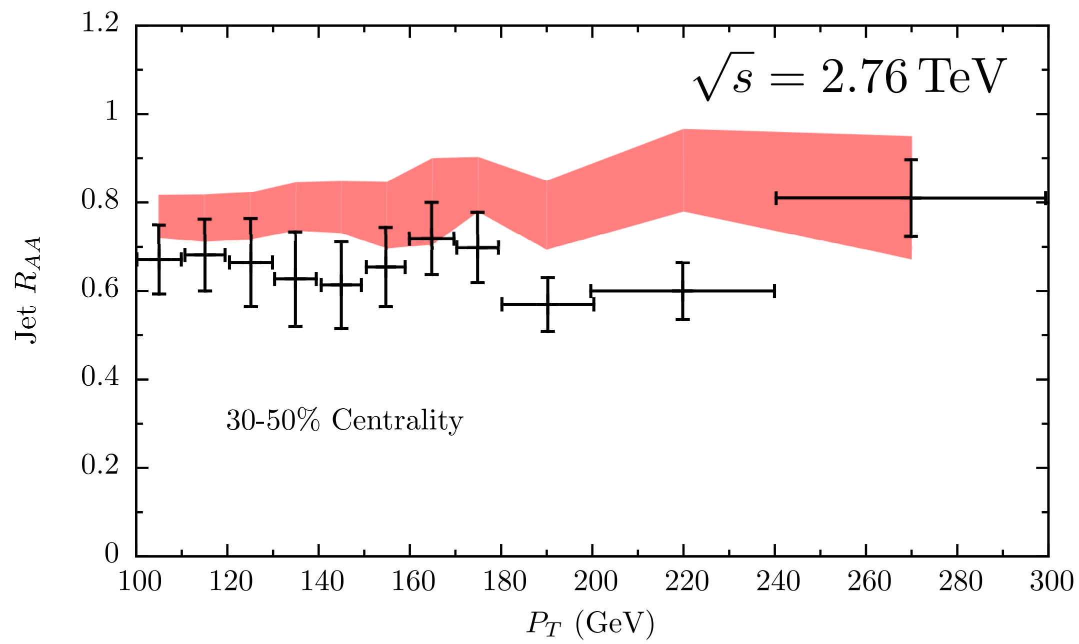
Dijet



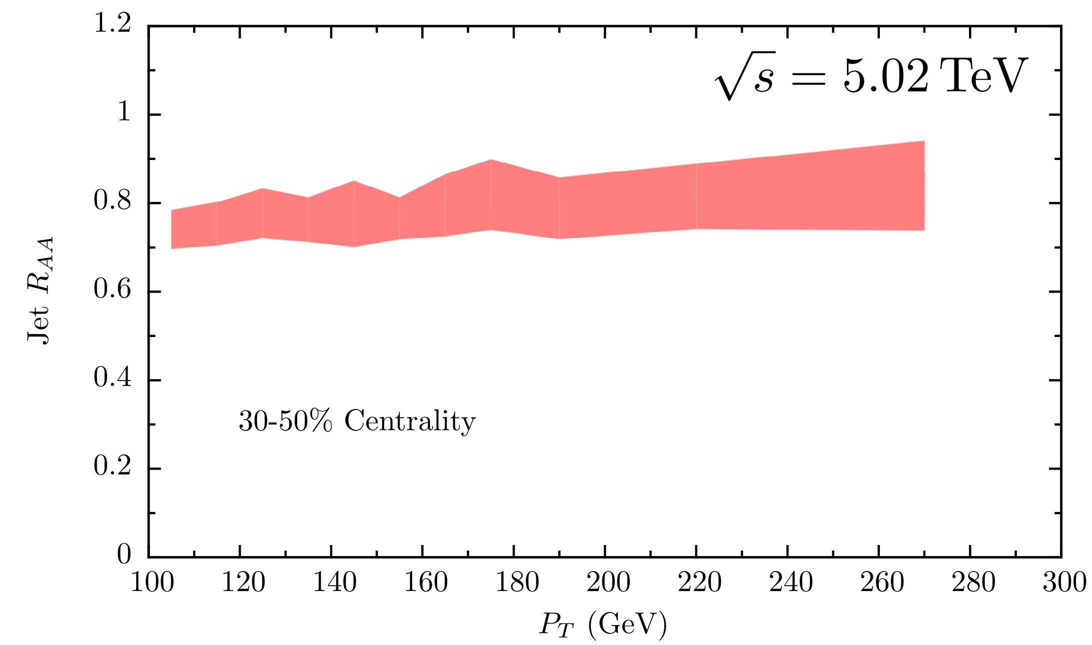
$\sqrt{s} = 2.76\,\mathrm{TeV}$
0-10% Centrality
Strong Coupling
Data
Jet R_{AA}
P_T (GeV)



$\sqrt{s} = 5.02\,\mathrm{TeV}$
0-10% Centrality
Strong Coupling
Jet R_{AA}
P_T (GeV)

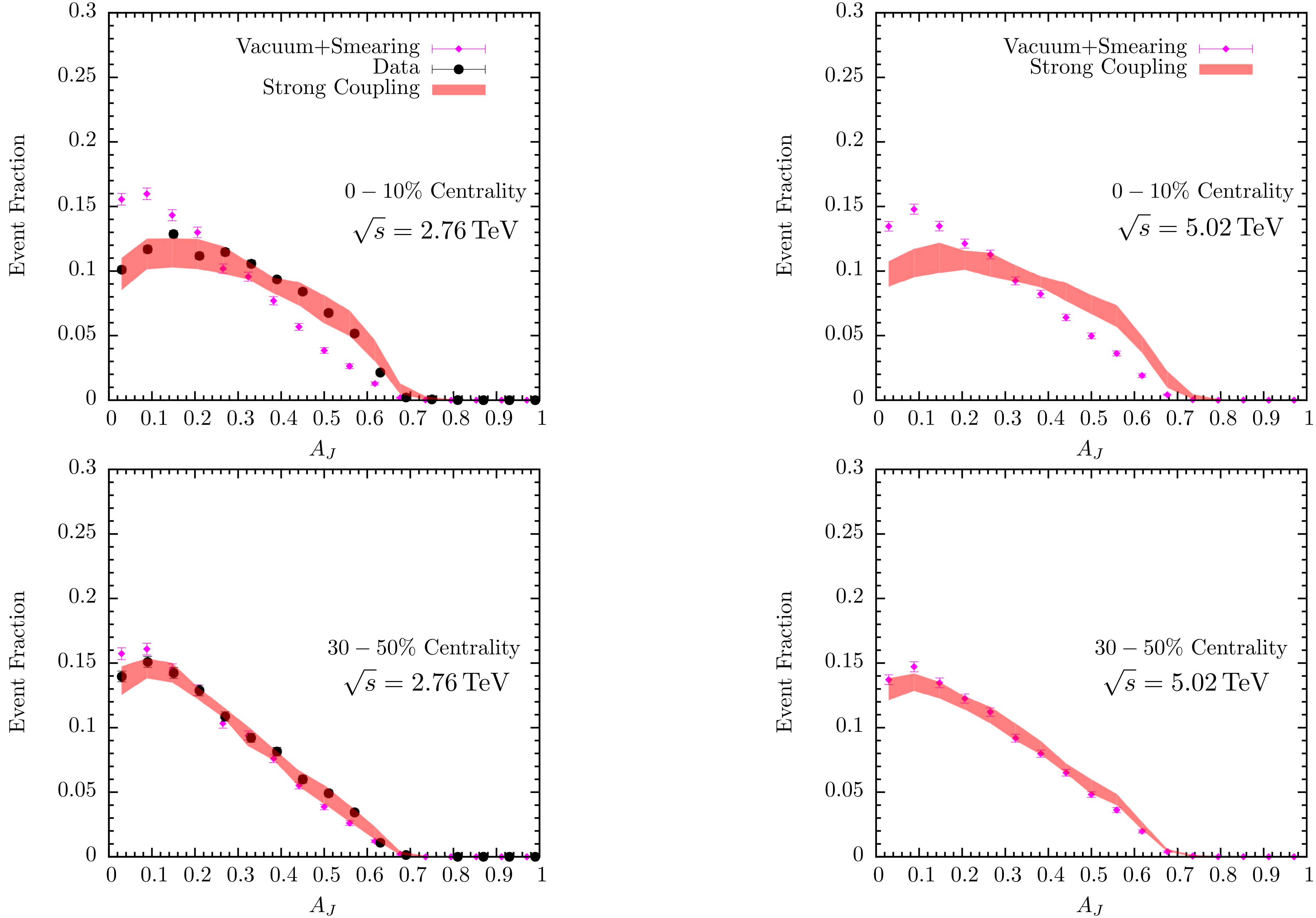


$\sqrt{s} = 2.76\,\mathrm{TeV}$
30-50% Centrality
Jet R_{AA}
P_T (GeV)



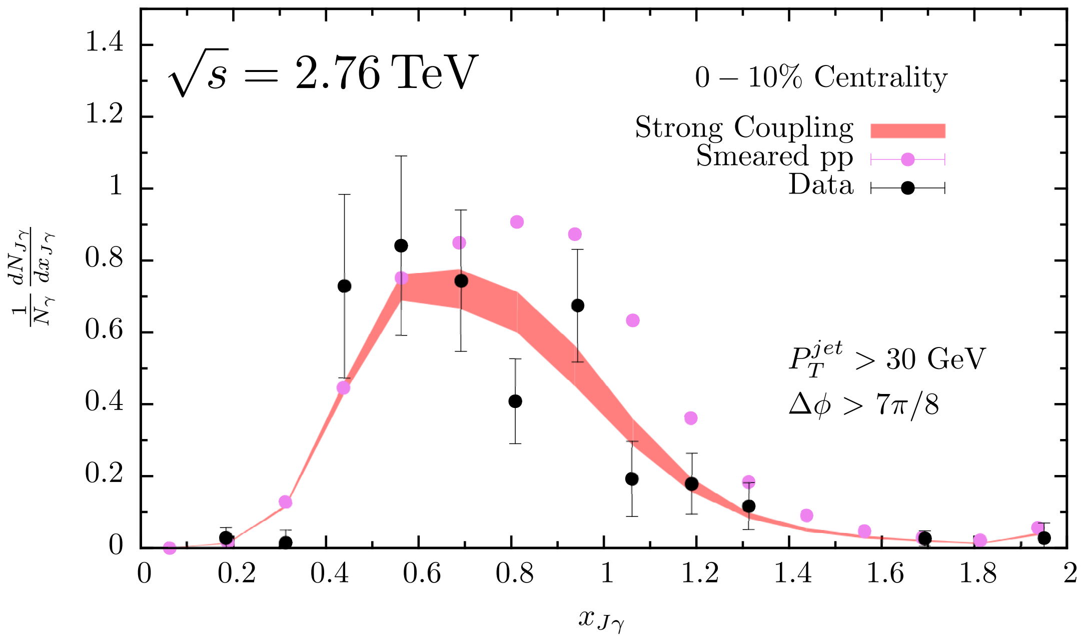
$\sqrt{s} = 5.02\,\mathrm{TeV}$
30-50% Centrality
Jet R_{AA}
P_T (GeV)

Dijet

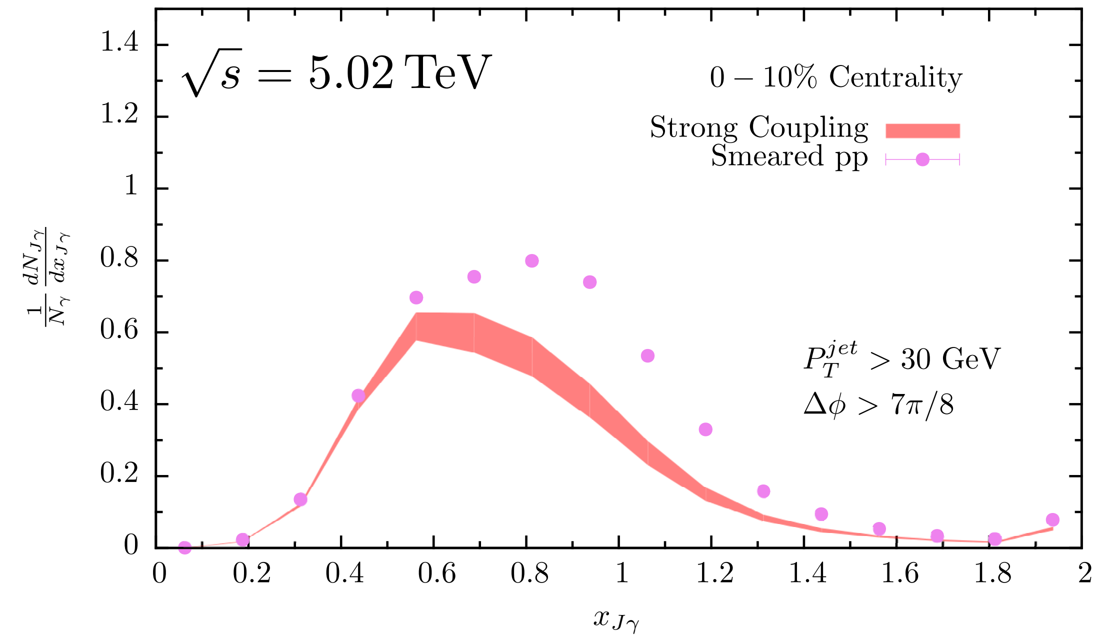


Vacuum+Smearing
Data
Strong Coupling
0 – 10% Centrality
$\sqrt{s} = 2.76$ TeV
$\sqrt{s} = 5.02$ TeV
30 – 50% Centrality
Event Fraction
A_J
0.3
0.25
0.2
0.15
0.1
0.05
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

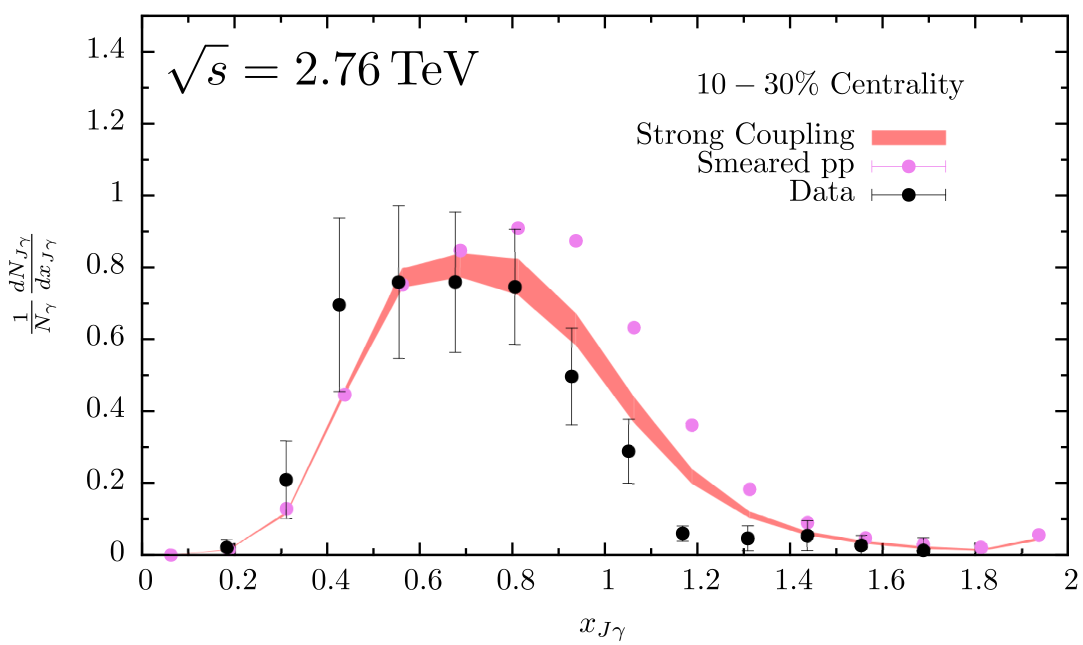
Photon-Jet



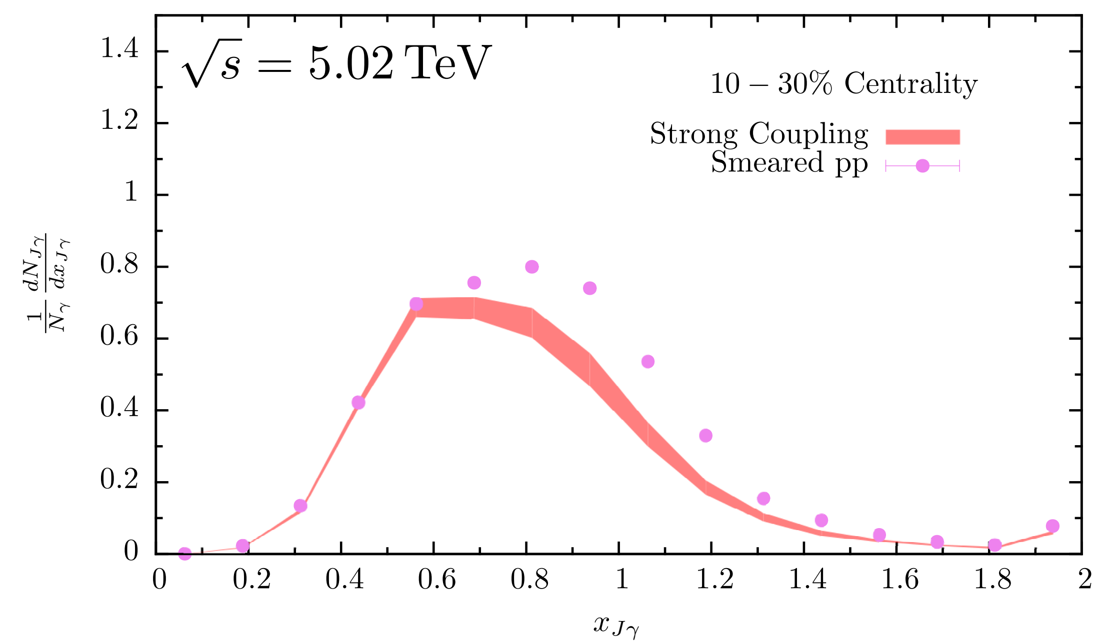
$\sqrt{s} = 2.76$ TeV
$0 - 10\%$ Centrality
Strong Coupling
Smeared pp
Data
$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\frac{1}{N_\gamma}\frac{dN_{J\gamma}}{dx_{J\gamma}}$
$x_{J\gamma}$



$\sqrt{s} = 5.02$ TeV
$0 - 10\%$ Centrality
Strong Coupling
Smeared pp
$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\frac{1}{N_\gamma}\frac{dN_{J\gamma}}{dx_{J\gamma}}$
$x_{J\gamma}$

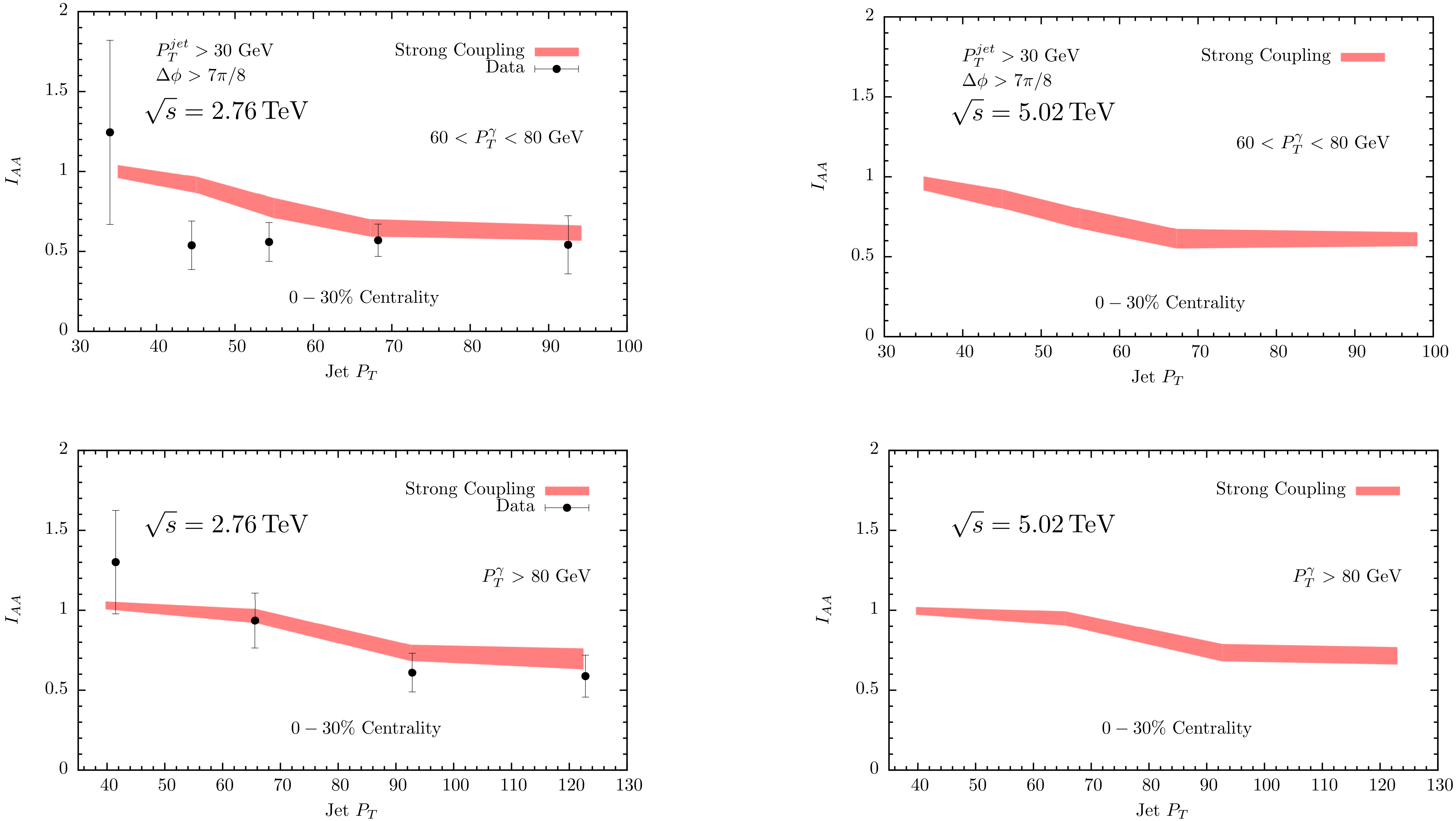


$\sqrt{s} = 2.76$ TeV
$10 - 30\%$ Centrality
Strong Coupling
Smeared pp
Data
$\frac{1}{N_\gamma}\frac{dN_{J\gamma}}{dx_{J\gamma}}$
$x_{J\gamma}$



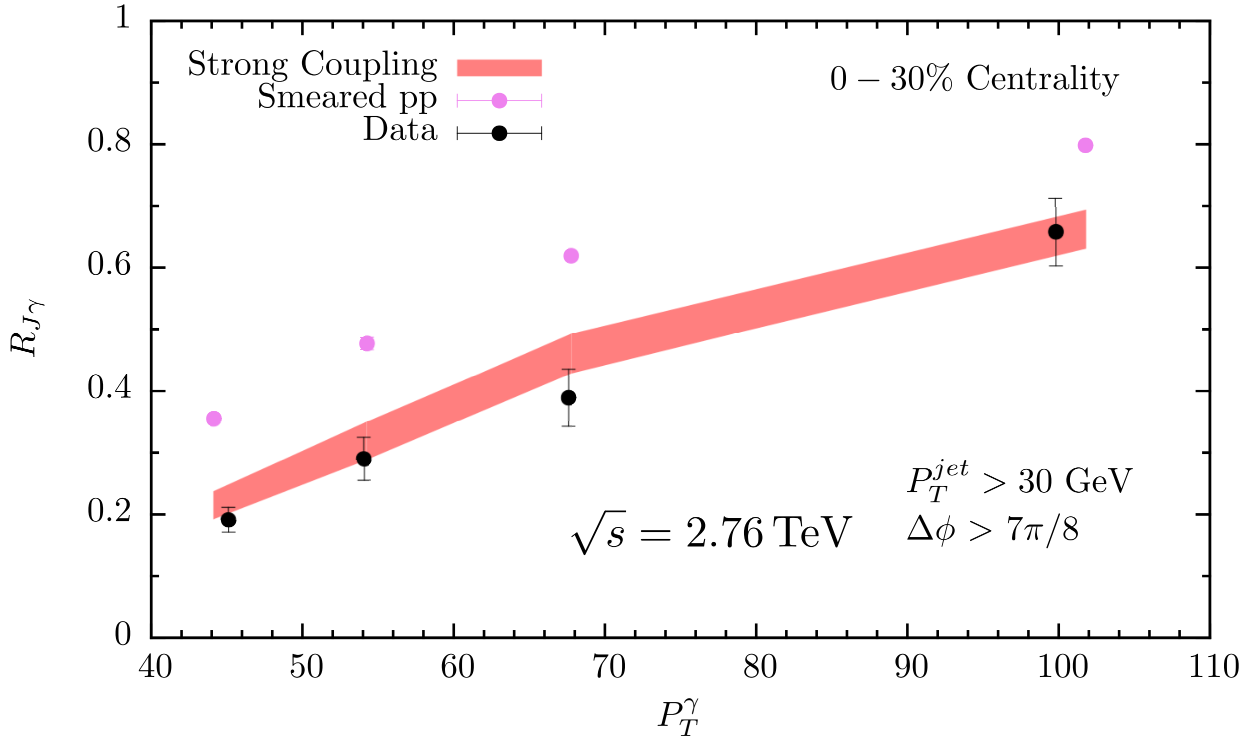
$\sqrt{s} = 5.02$ TeV
$10 - 30\%$ Centrality
Strong Coupling
Smeared pp
$\frac{1}{N_\gamma}\frac{dN_{J\gamma}}{dx_{J\gamma}}$
$x_{J\gamma}$

Photon-Jet

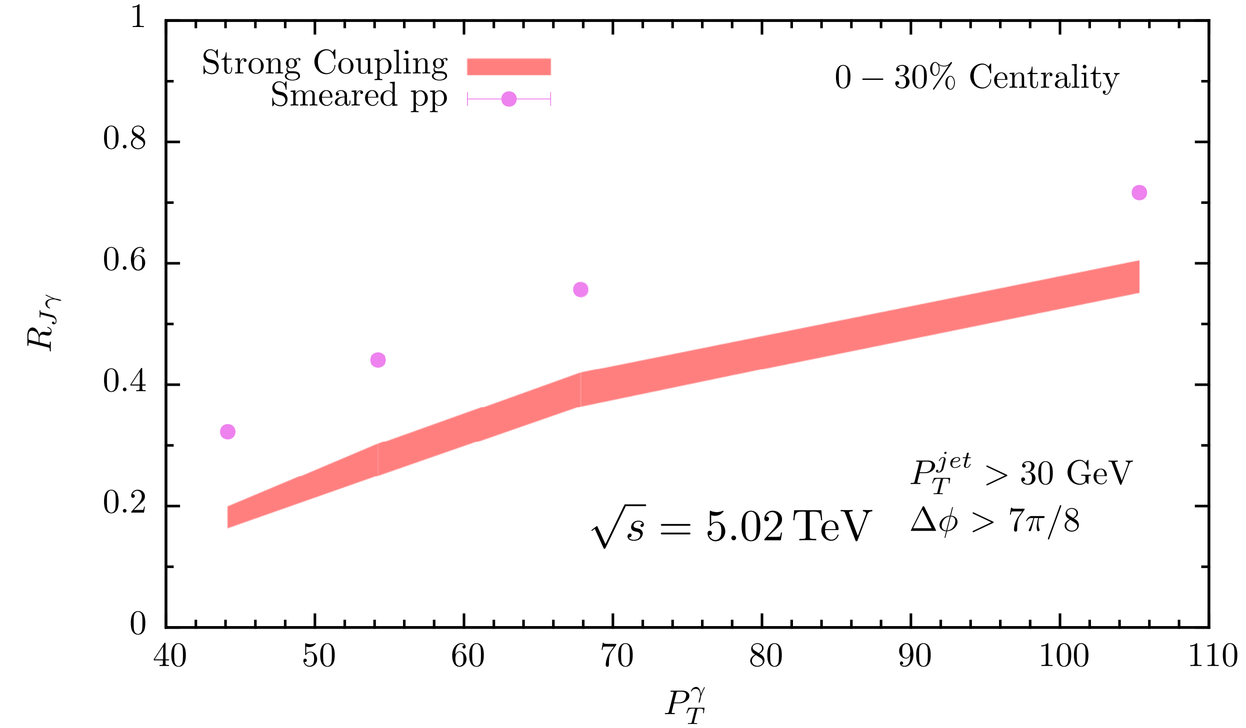


$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\sqrt{s} = 2.76$ TeV
Strong Coupling
Data
$60 < P_T^{\gamma} < 80$ GeV
0 – 30% Centrality
I_{AA}
Jet P_T
$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\sqrt{s} = 5.02$ TeV
Strong Coupling
$60 < P_T^{\gamma} < 80$ GeV
0 – 30% Centrality
I_{AA}
Jet P_T
$\sqrt{s} = 2.76$ TeV
Strong Coupling
Data
$P_T^{\gamma} > 80$ GeV
0 – 30% Centrality
I_{AA}
Jet P_T
$\sqrt{s} = 5.02$ TeV
Strong Coupling
$P_T^{\gamma} > 80$ GeV
0 – 30% Centrality
I_{AA}
Jet P_T

Photon-Jet

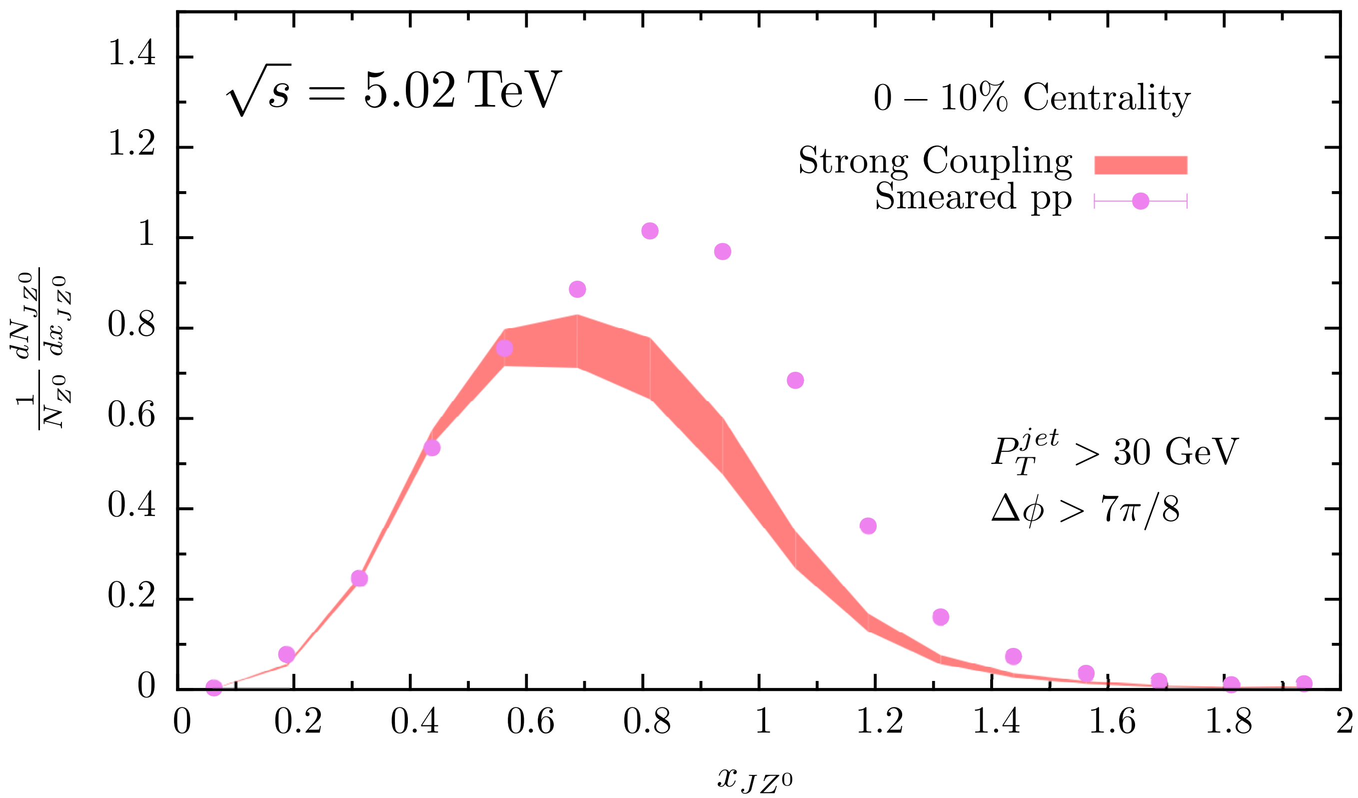


Strong Coupling
Smeared pp
Data
0 − 30% Centrality
$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\sqrt{s} = 2.76$ TeV
$R_{J\gamma}$
P_T^γ

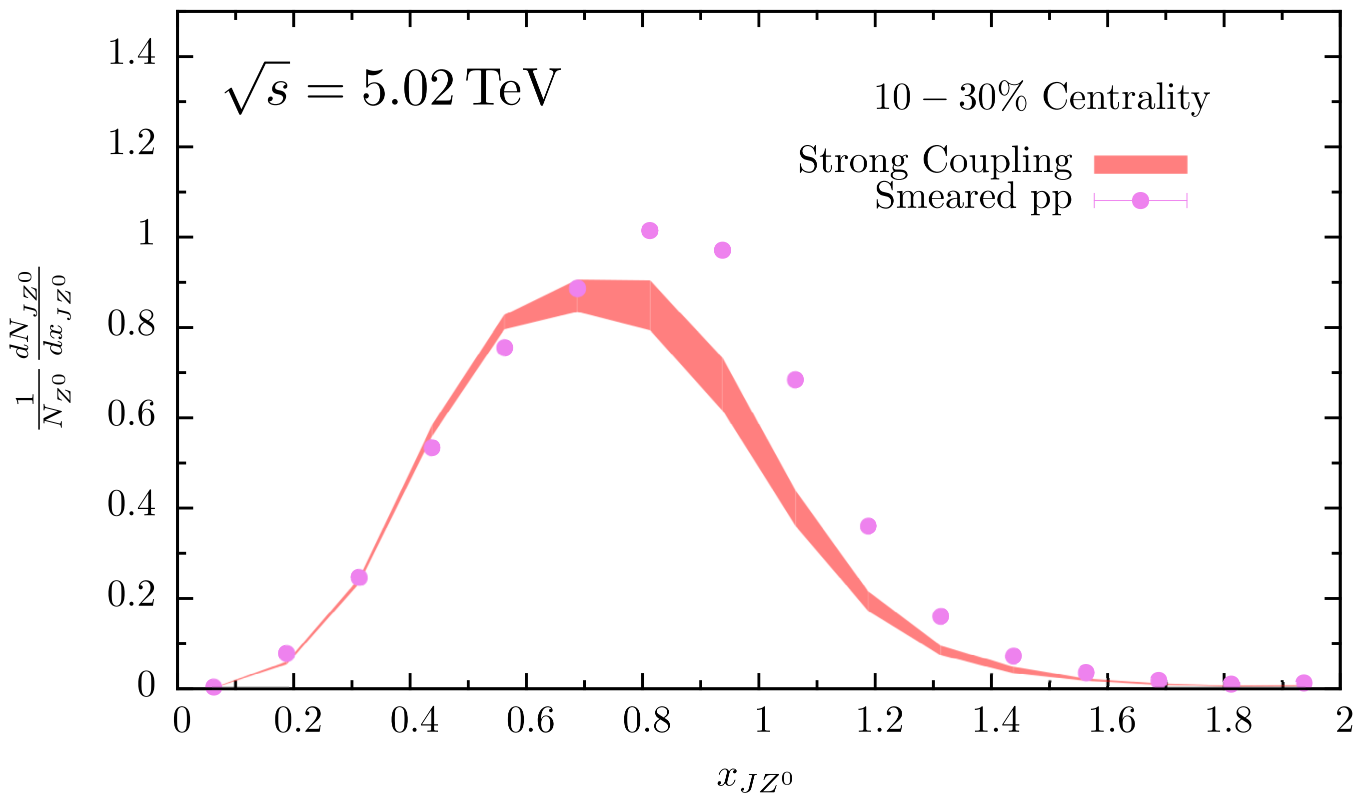


Strong Coupling
Smeared pp
0 − 30% Centrality
$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\sqrt{s} = 5.02$ TeV
$R_{J\gamma}$
P_T^γ

Z-Jet

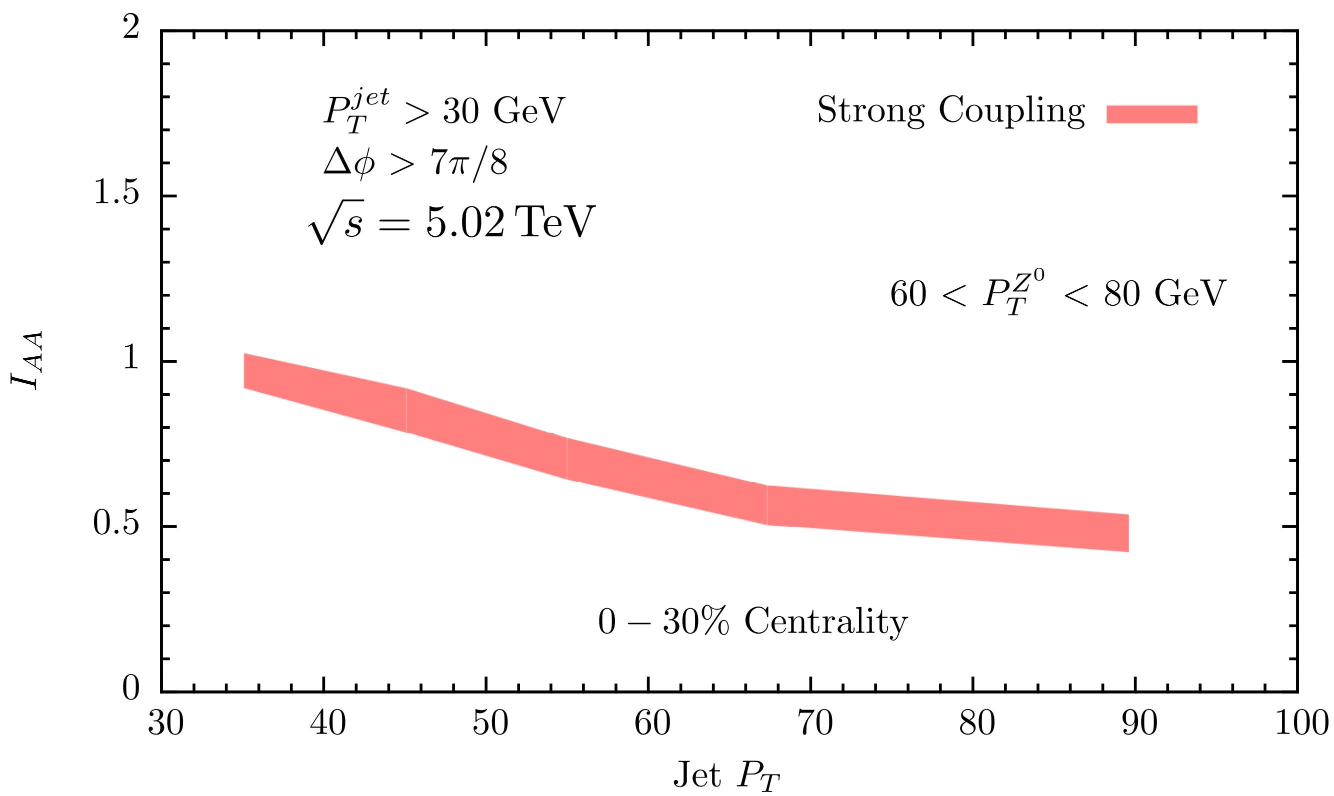


$\sqrt{s} = 5.02$ TeV
$0 - 10\%$ Centrality
Strong Coupling
Smeared pp
$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\frac{1}{N_{Z^0}} \frac{dN_{JZ^0}}{dx_{JZ^0}}$
x_{JZ^0}

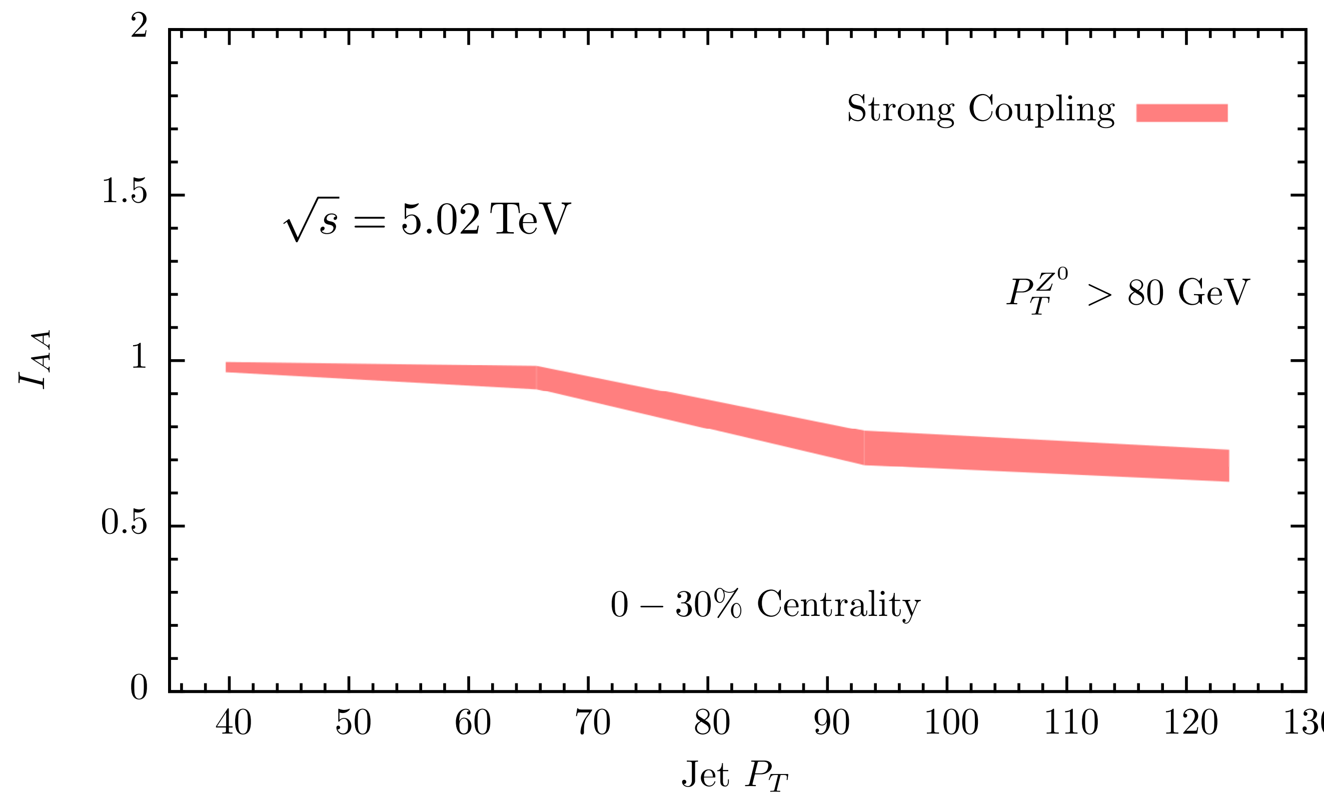


$\sqrt{s} = 5.02$ TeV
$10 - 30\%$ Centrality
Strong Coupling
Smeared pp
$\frac{1}{N_{Z^0}} \frac{dN_{JZ^0}}{dx_{JZ^0}}$
x_{JZ^0}

Z-Jet

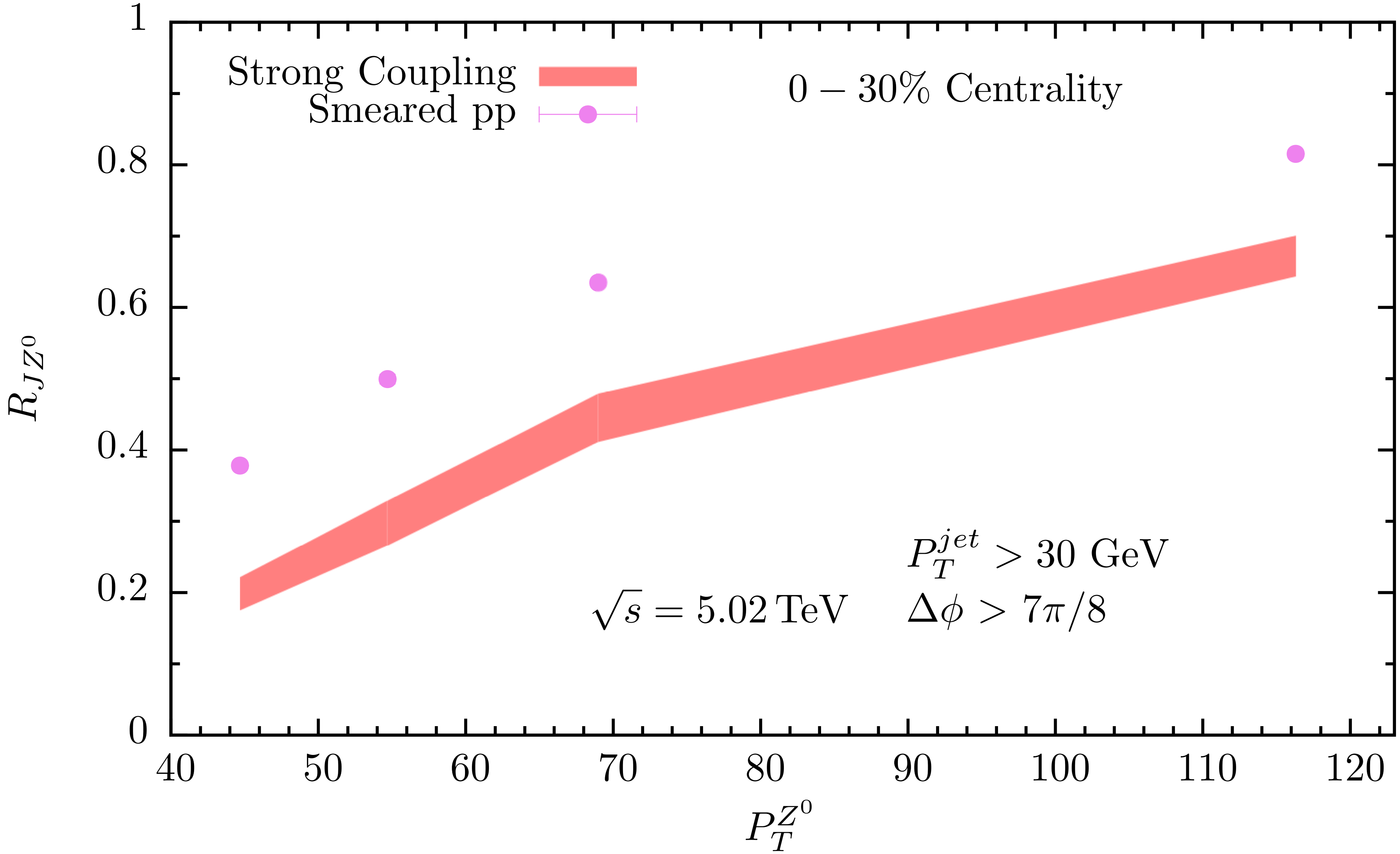


$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\sqrt{s} = 5.02$ TeV
Strong Coupling
$60 < P_T^{Z^0} < 80$ GeV
$0 - 30\%$ Centrality
I_{AA}
Jet P_T



Strong Coupling
$\sqrt{s} = 5.02$ TeV
$P_T^{Z^0} > 80$ GeV
$0 - 30\%$ Centrality
I_{AA}
Jet P_T

Z-Jet

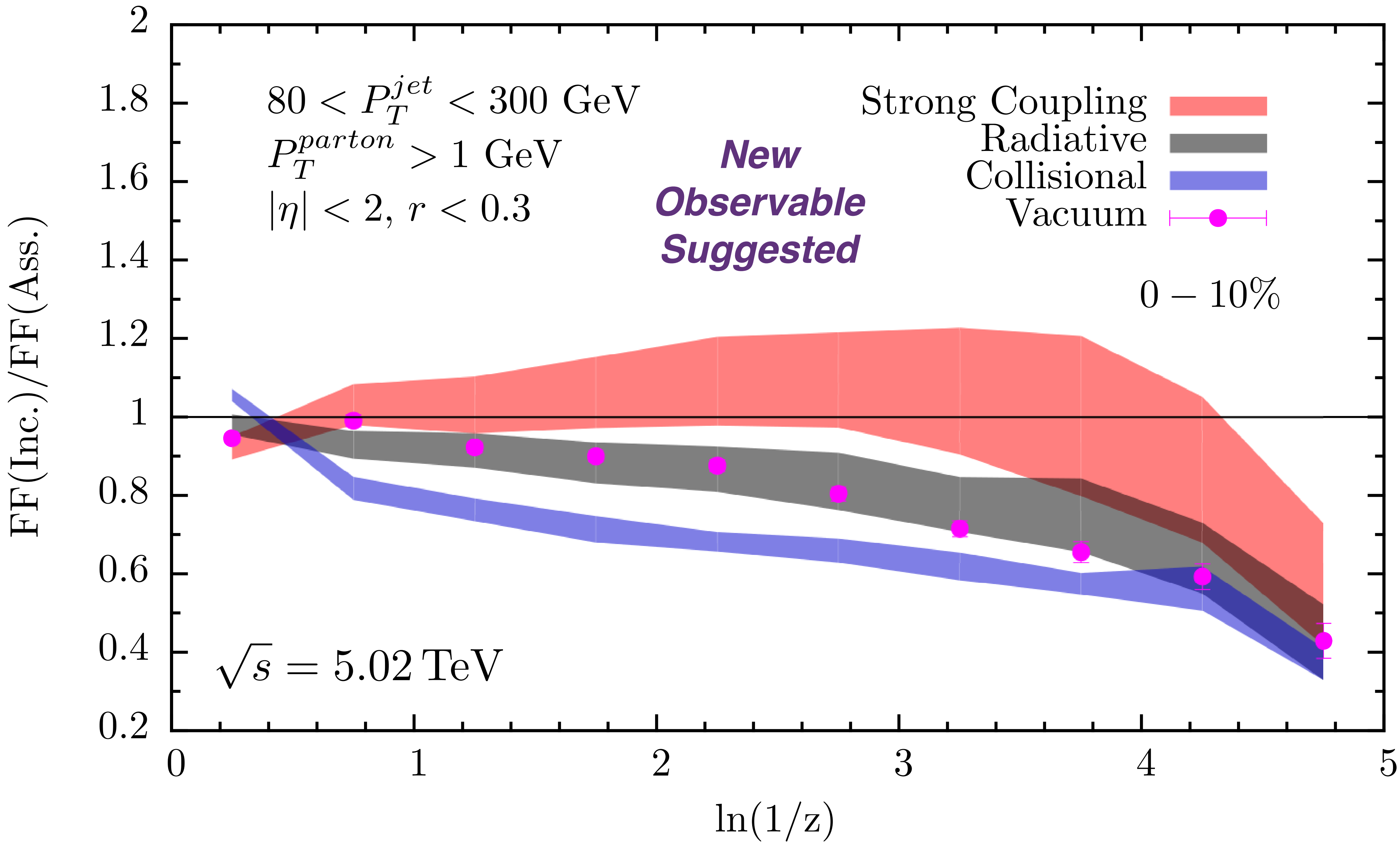


Strong Coupling
Smeared pp
0 – 30% Centrality
$P_T^{jet} > 30$ GeV
$\sqrt{s} = 5.02\,\mathrm{TeV}$
$\Delta\phi > 7\pi/8$
R_{JZ^0}
$P_T^{Z^0}$
1
0.8
0.6
0.4
0.2
0
40
50
60
70
80
90
100
110
120

$z \equiv \frac{P_{\parallel}^{track}}{P_T^{jet}}$

Inclusive over Associated Frag. Func.

Associated FF is FF of subleading jet in a dijet pair (leading jet Pt>120 GeV)



Ratio of two different PbPb fragmentation functions.

Ratio of FF of less quenched jet to FF of more quenched jet

A Hybrid Weak+Strong Coupling Approach to Jet Quenching

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, 1405.3864,1508.00815

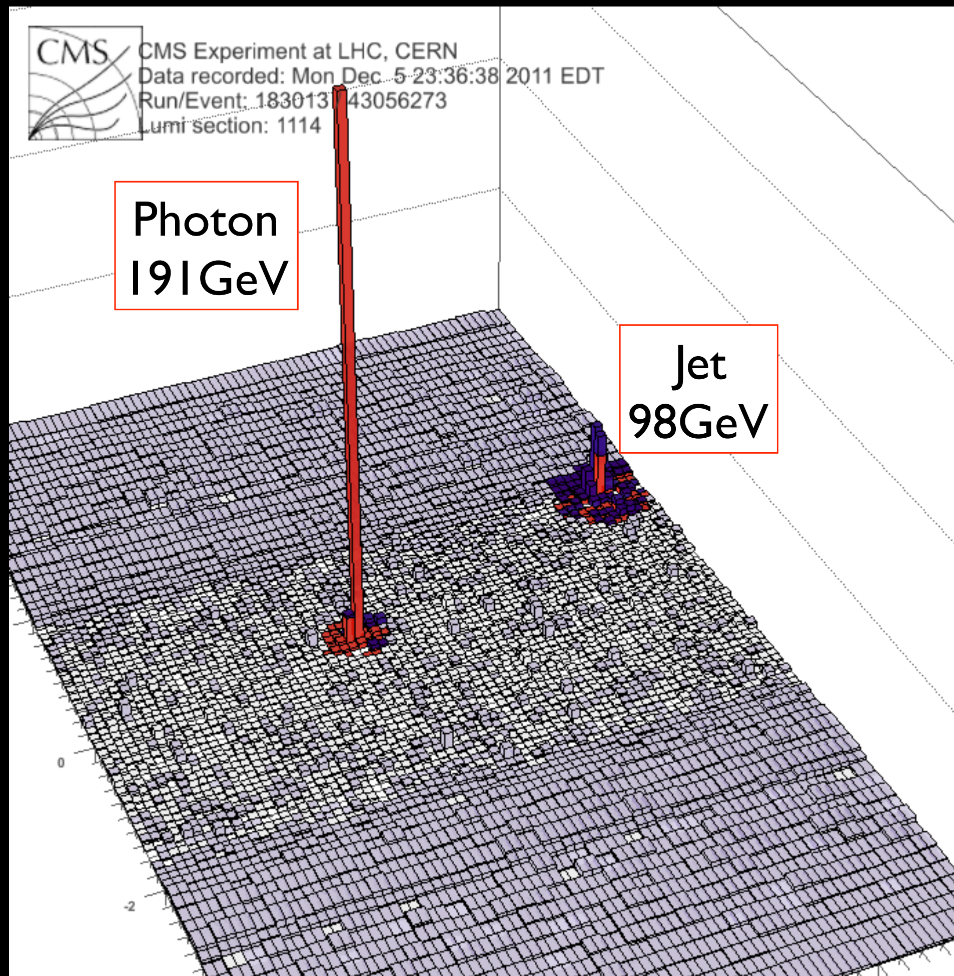
- **Upon fitting one parameter, *lots* of data described well. Value of the fitted parameter? $x_{\rm stop}$ is about two to three times longer in QCD plasma than in $\mathcal{N} = 4$ SYM plasma. This is not unreasonable. We are taking all the dependences of dE/dx from the strongly coupled calculation, but not the purely numerical factor since after all the two theories have different degrees of freedom.**
- **Higher-statistics, more discriminating, data is coming. We need further, more discriminating, observables. We need to add "transverse momentum broadening", since jet quenching is not only about energy loss, and then look at jet shapes.**
- **All this success is in a sense *frustrating*. It 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??**

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.**

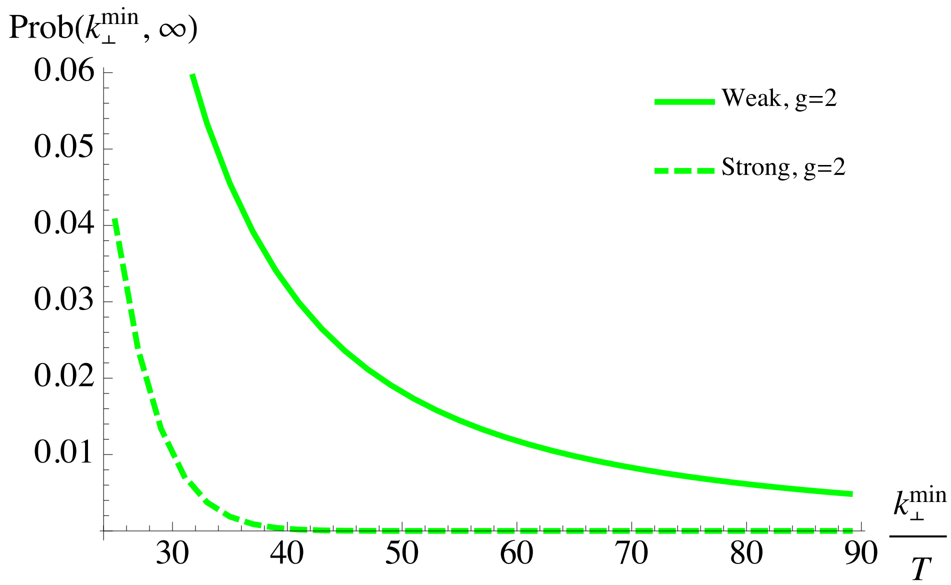
  D'Eramo, Liu, Rajagopal, arXiv:1006.1367

- **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 $k_\perp$.

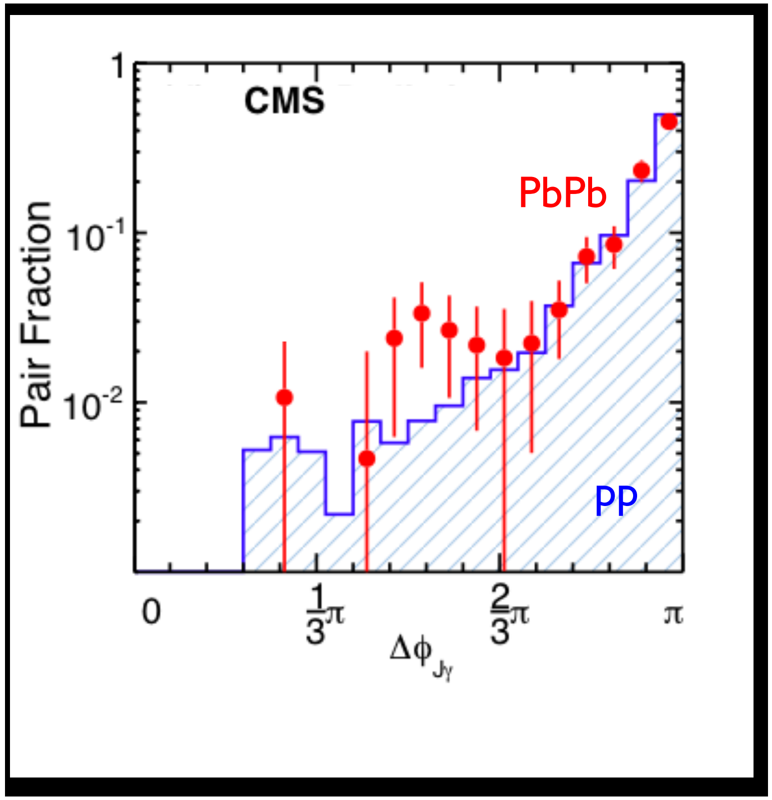
Large deflections rare, but not as rare as if the liquid were a liquid on all scales. They indicate point-like scatterers.



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

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

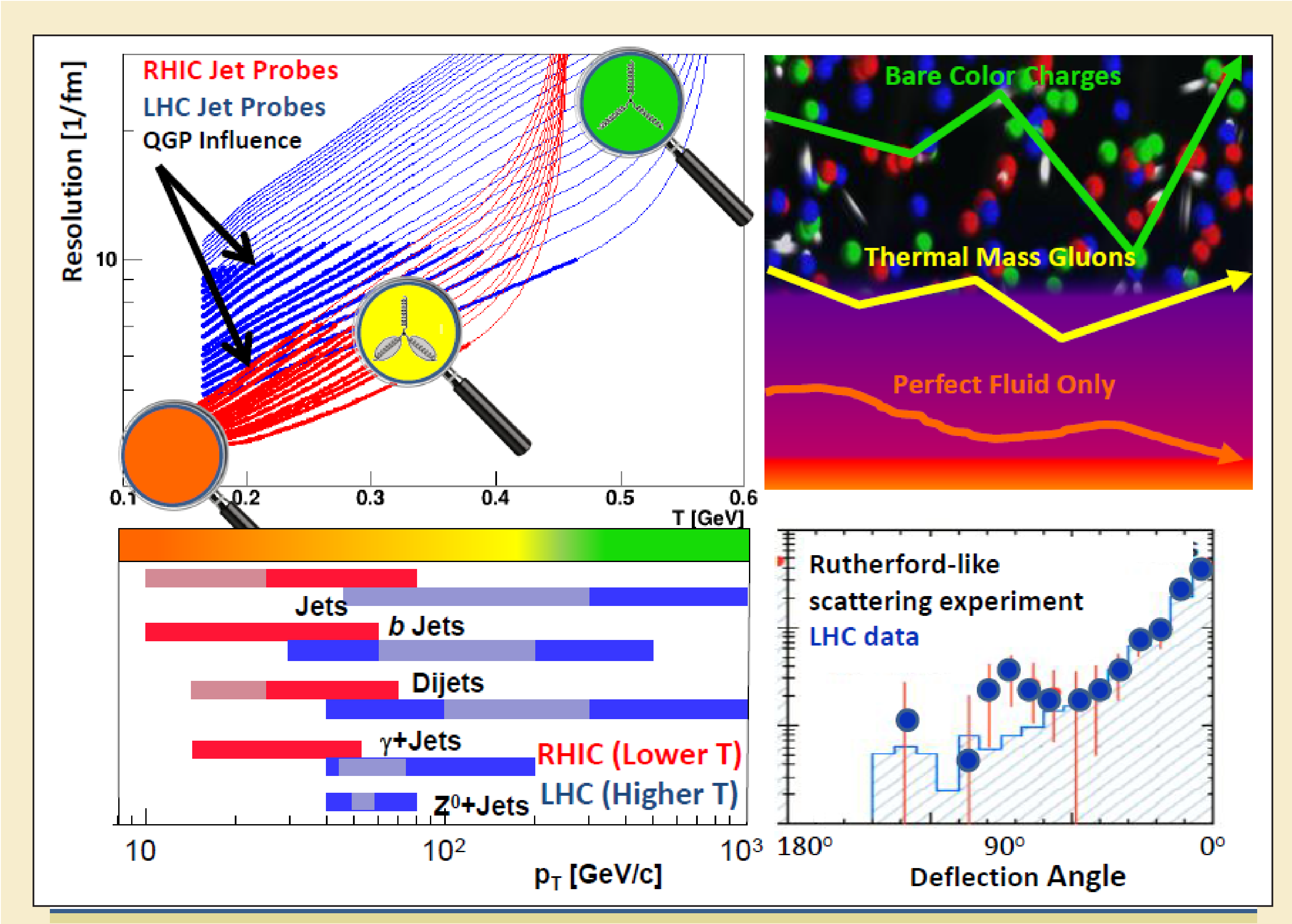


CMS, arXiv:1205.0206

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

How to see weakly coupled q & g in Liquid QGP

- Generalizing the idea: (Kurkela and Wiedemann)
  - Look at jets back-to-back with a photon, but instead of looking for kicks felt by the whole jet look for kicks felt by partons within the jet, say with $10 \text{ GeV} < p_T < 20 \text{ GeV}$.
  - Kicks by a detectable angle much more likely than for kicks to the entire jet.
  - Not looking at soft partons avoids confusion due to background subtraction, response of medium to the jet.
  - Still a high statistics, precision measurement.
- And, we very much need a state-of-the-art jet detector to make these measurements also at RHIC. To take advantage of the lever arm in jet energy, spatial resolution, QGP temperature that will come from comparing precise jet measurements at RHIC and the LHC. $\rightarrow$ sPHENIX.



RHIC Jet Probes
LHC Jet Probes
QGP Influence
Resolution [1/fm]
10
0.1
0.2
0.3
0.4
0.5
0.6
T [GeV]
Bare Color Charges
Thermal Mass Gluons
Perfect Fluid Only
Jets
b Jets
Dijets
γ+Jets
Z0+Jets
RHIC (Lower T)
LHC (Higher T)
10
10²
10³
pT [GeV/c]
Rutherford-like
scattering experiment
LHC data
180°
90°
0°
Deflection Angle

How does QGP work?

- The open theory questions are still big. How best to see point-like scatterers? And, then, how best to operationalize the question of how the liquid emerges?

- Ideas to date focus on jet quenching phenomena, as they involve physics at varied scales. A Gaussian distribution of typical transverse momentum broadening arises in a strongly coupled liquid, or via point-like scatterers. A power-law tail in the distribution of rare harder transverse scattering can only come from point-like scatterers. Need to look for the scattering of moderate-momentum partons within a jet. Need precise measurements of how the medium modifies the angular distribution of those partons with a given momentum within a jet.

- First steps, both experiment and theory, have been taken. But only first steps. Need higher statistics dijet and gamma-jet data coming at the LHC. And, need to be able to compare the modification of the structure of jets at LHC and RHIC (sPHENIX). And, need new ideas.

Smallest possible droplet of liquid?

- Discoveries beget new questions: What is the smallest possible droplet of QGP that behaves hydrodynamically? Anyone doing holographic calculations in toy models in which there is no smallest droplet at high enough temperature, or anyone seeing effects of rather small lumps in the initial state visible in the final state, could have asked this question, but didn't. Question was asked by data: pPb collisions @LHC, then dAu and ^{3}HeAu data @RHIC.

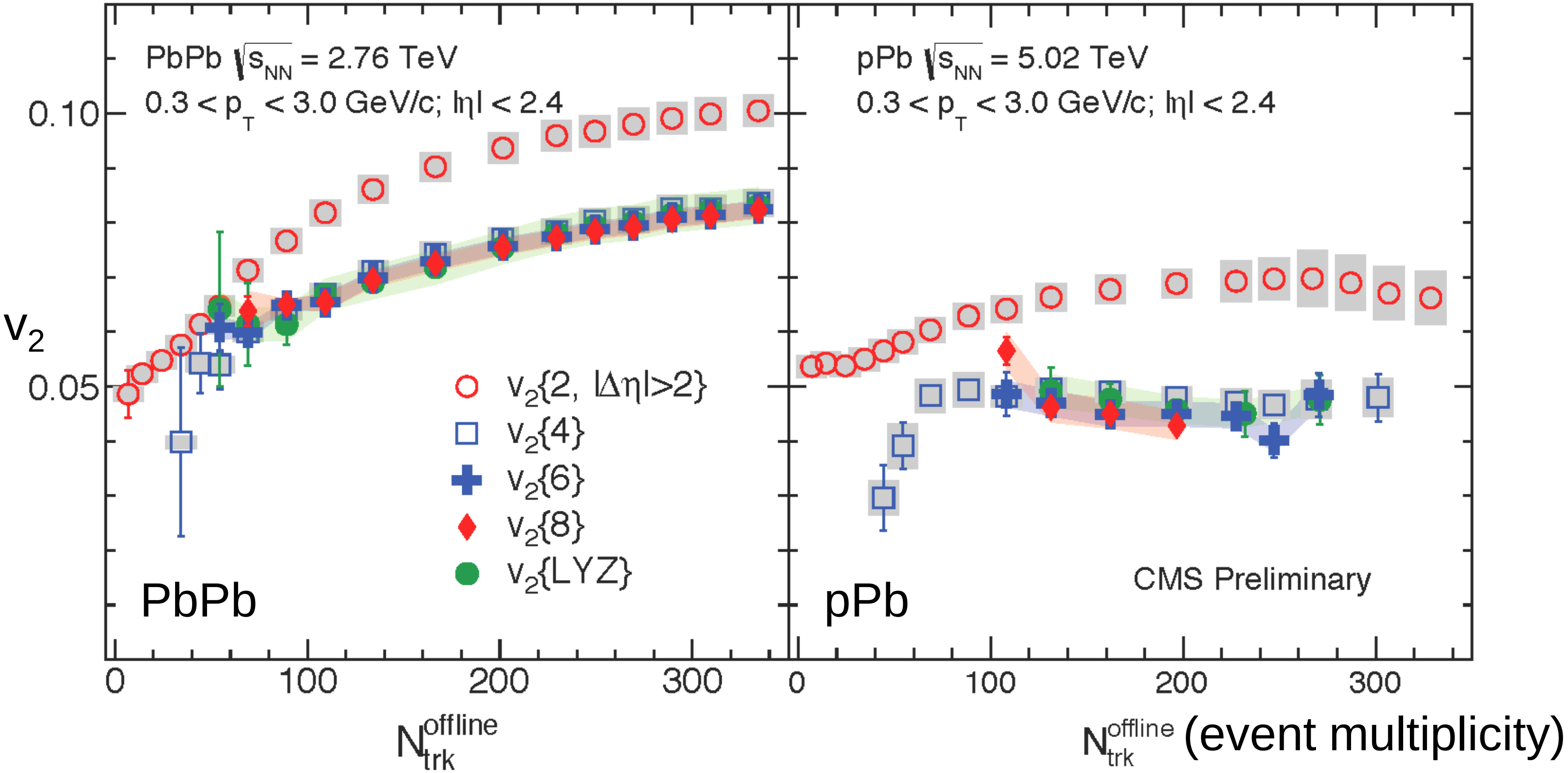
- Subsequently, holographic calculations of a "proton" of radius R colliding with a sheet show hydrodynamic flow in the final state as long as the collision has enough energy such that $RT_{\text{hydrodynamization}} \gtrsim 0.5$ to 1. (Chesler, 1506.02209)

- Makes it less surprising, *a posteriori*, to see hydrodynamic behavior in small-big collisions at top RHIC energy and LHC energy. Makes it very interesting to look at small-big collisions at lower energies at RHIC, to see whether and how hydrodynamics turns off. (Interesting in holography too; how does black hole formation turn off?)

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!

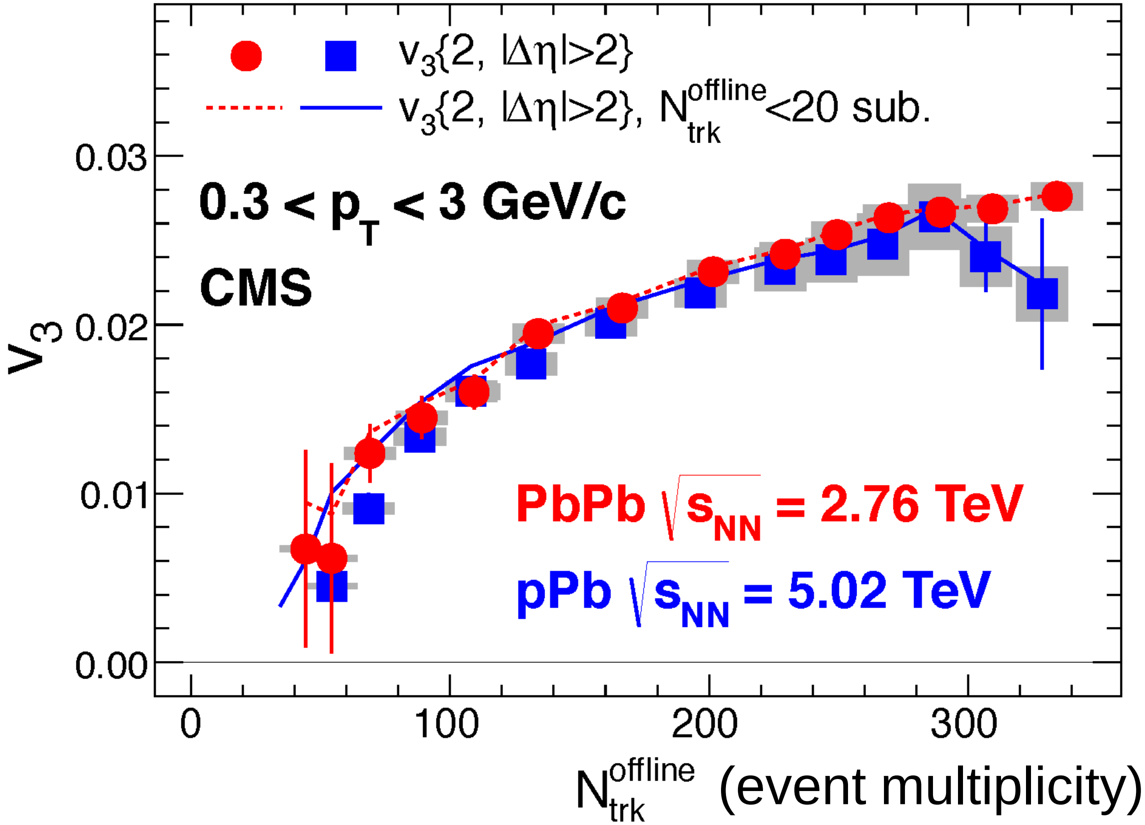
Talk by Wang
PAS-HIN-14-006

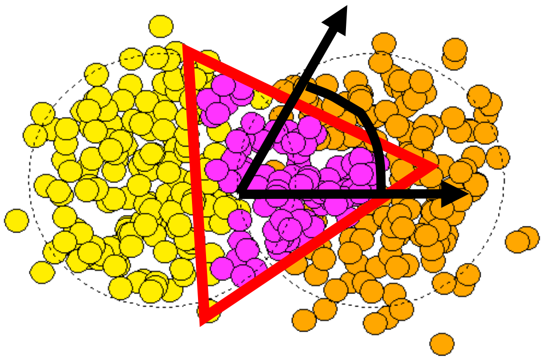


Triangular flow

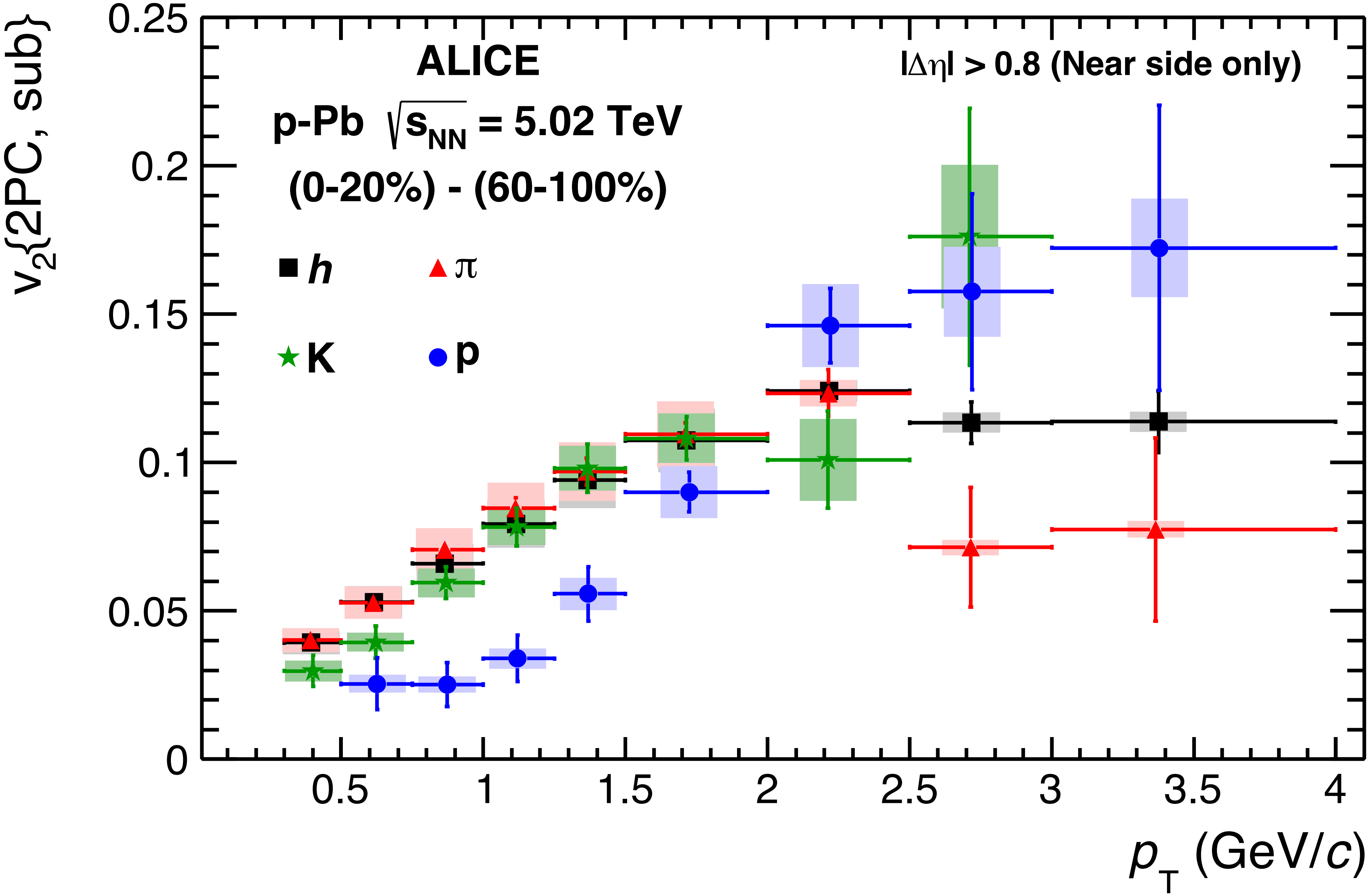
- Remarkable similarity in the v_3 signal as a function of multiplicity in pPb and PbPb

PLB724 (2013) 213





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

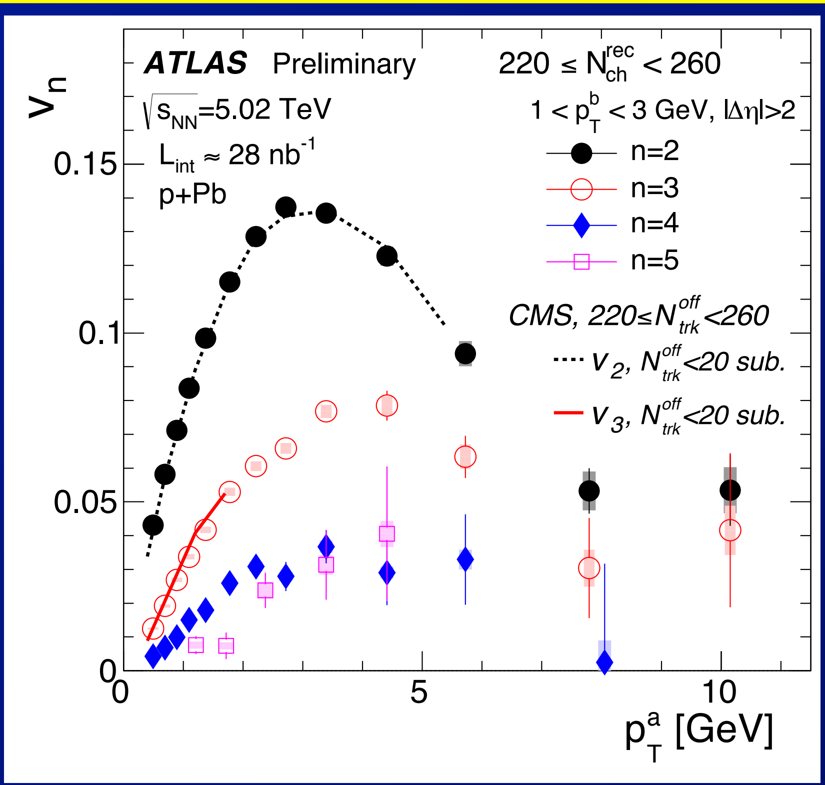


- $v_{2,\pi}$ similar to $v_{2,h}$
- hint of $v_{2,K}$ smaller than $v_{2,\pi}$ at low p_T
- $v_{2,p}$ smaller than $v_{2,\pi}$ below 2 GeV/c and larger above
- crossing at about 2 GeV/c

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

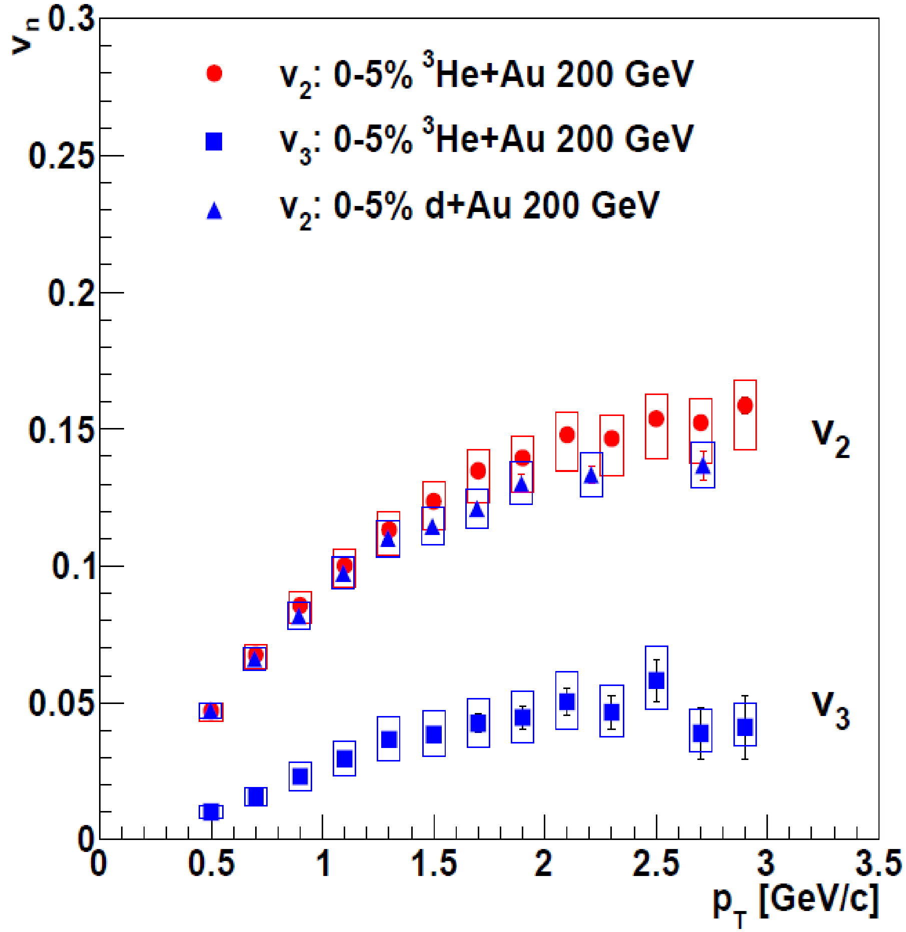
p+Pb 2-particle $v_n(p_T)$

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



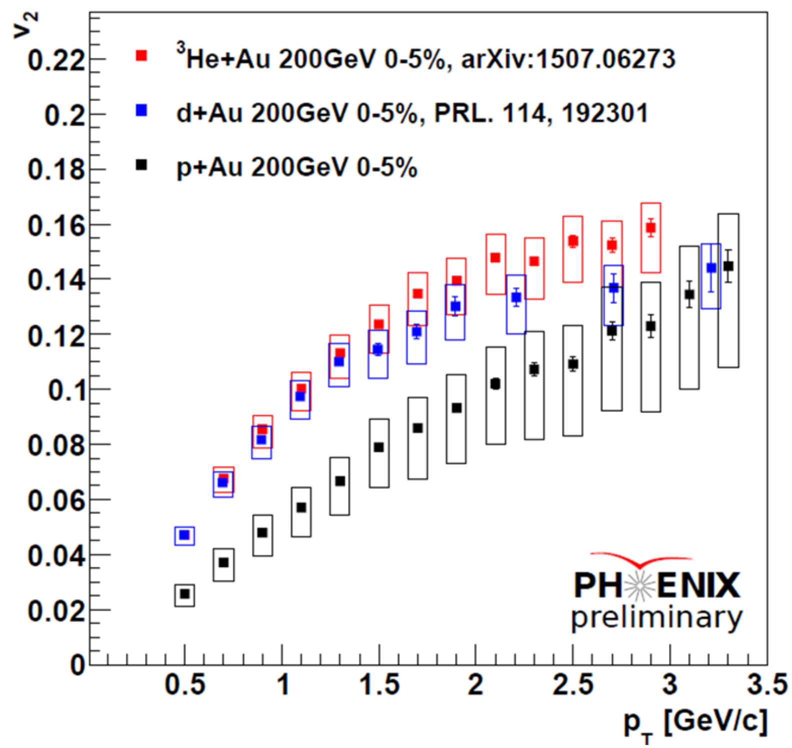
Flow in Small Systems at $\sqrt{s_{NN}}$ = 200 GeV

PHENIX ^{3}HeAu: Phys. Rev. Lett. 115, 142301 (2015)
PHENIX dAu: Phys. Rev. Lett. 114, 192301 (2015)



Top 5% in centrality

$$v_2^{^3HeAu} \geq v_2^{dAu} > v_2^{pAu}$$



Collective motion: Large anisotropy v_2 in p+Au, d+Au, and v2, v3 ^{3}He-Au

Stony Brook University

PHENIX

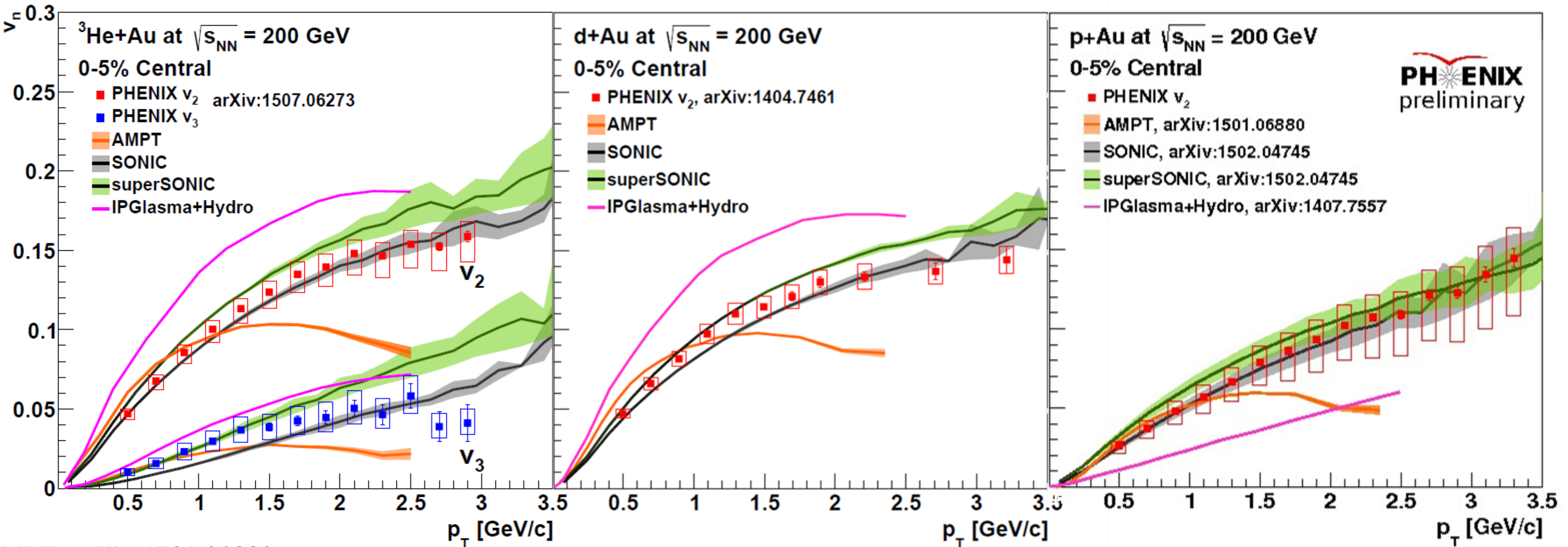
Comparison to Model Predictions

SONIC Glauber + hydro + hadron cascade
super SONIC + pre-equilibrium
} predicts v_n

IPGlasma + hydrodynamic

AMPT parton + hadron cascade

3He(d)+A ↑ v_n , p+A ↓ v_n
under predicts v_n at high p_T



AMPT: arXiv:1501.06880
SONIC: arXiv:1502.04745
IP+Hydro:arXiv:1407:7557

Sensitivity to initial conditions and early time evolution

Stony Brook University

PHENIX

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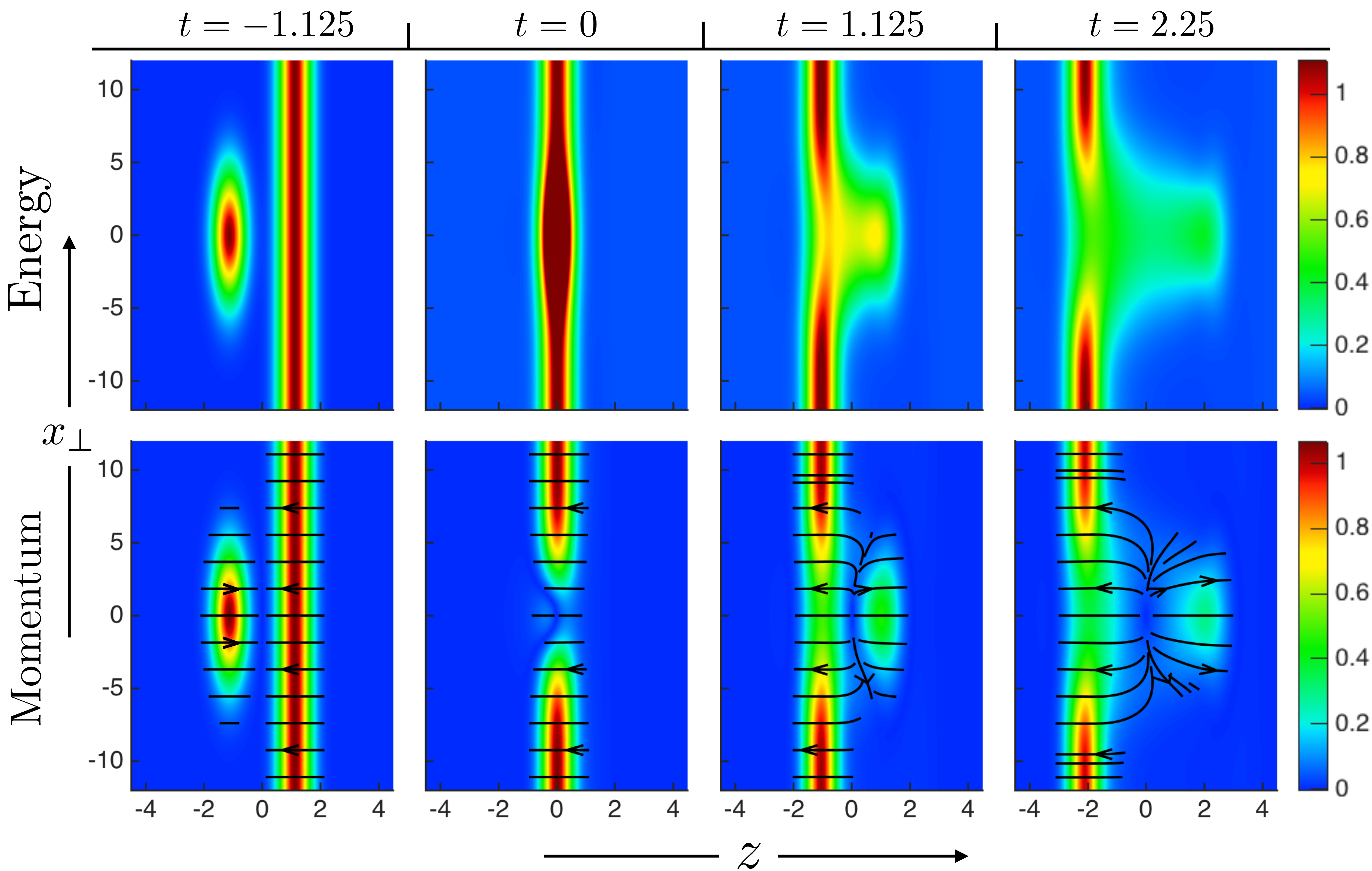
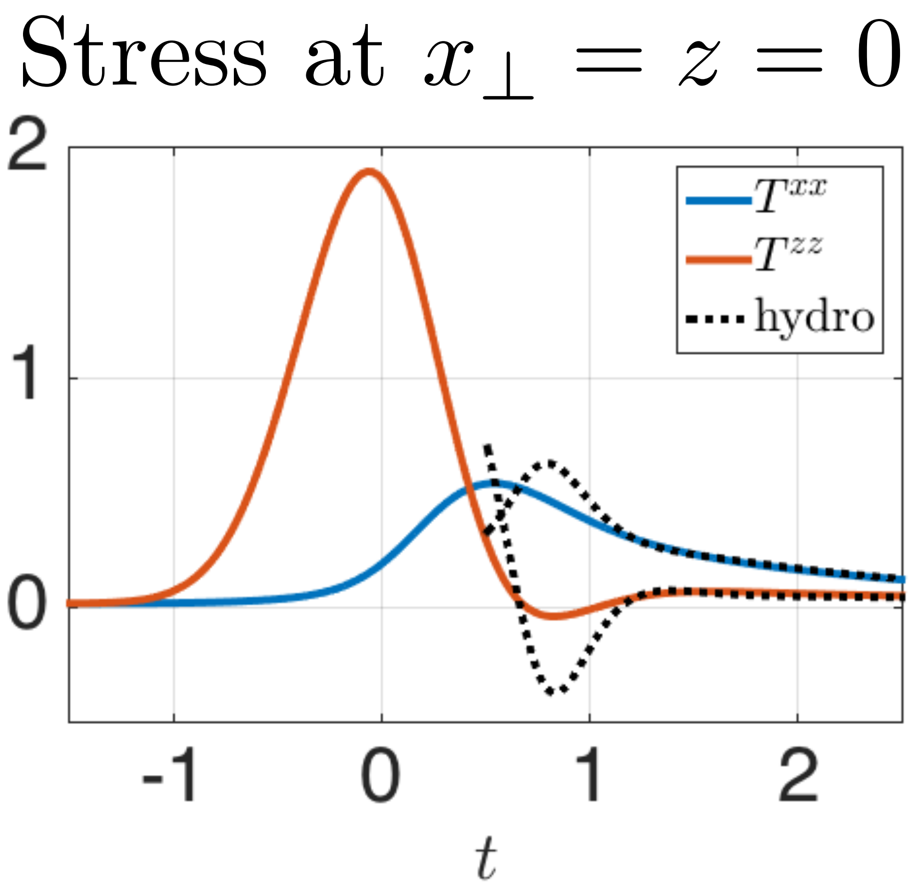
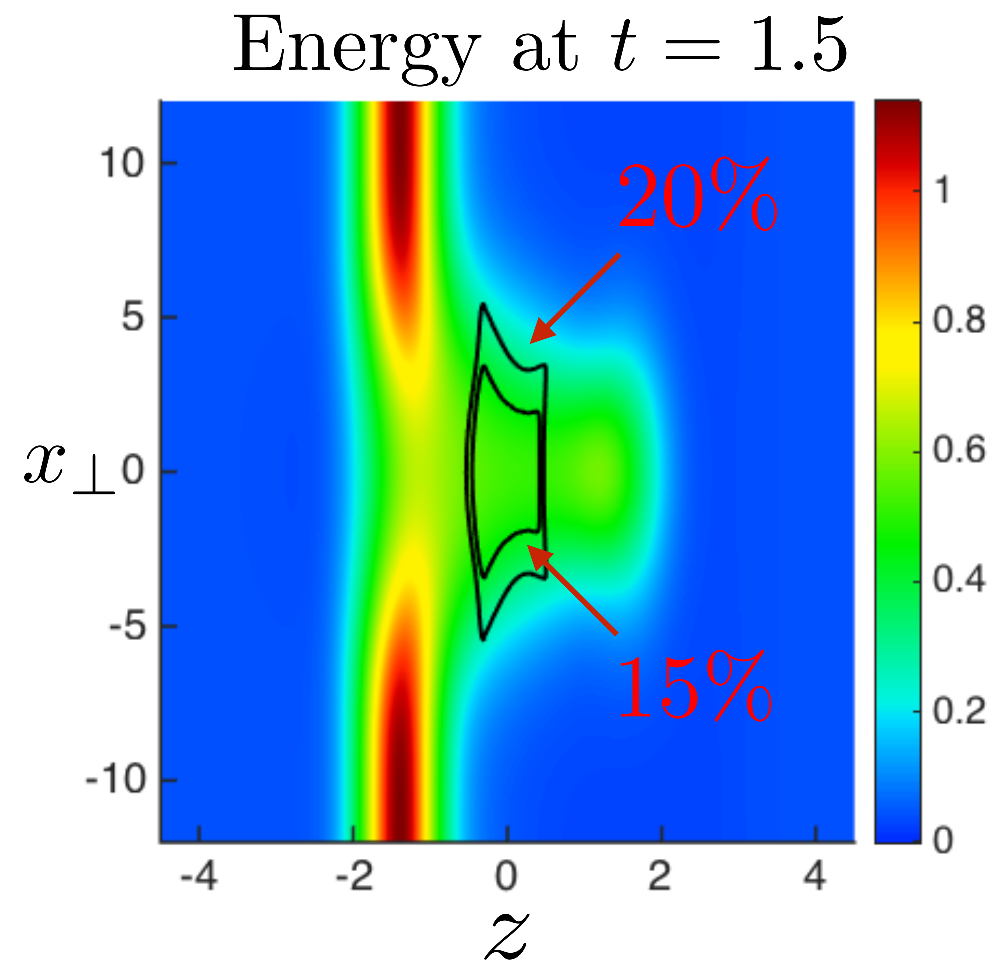
Results illustrated

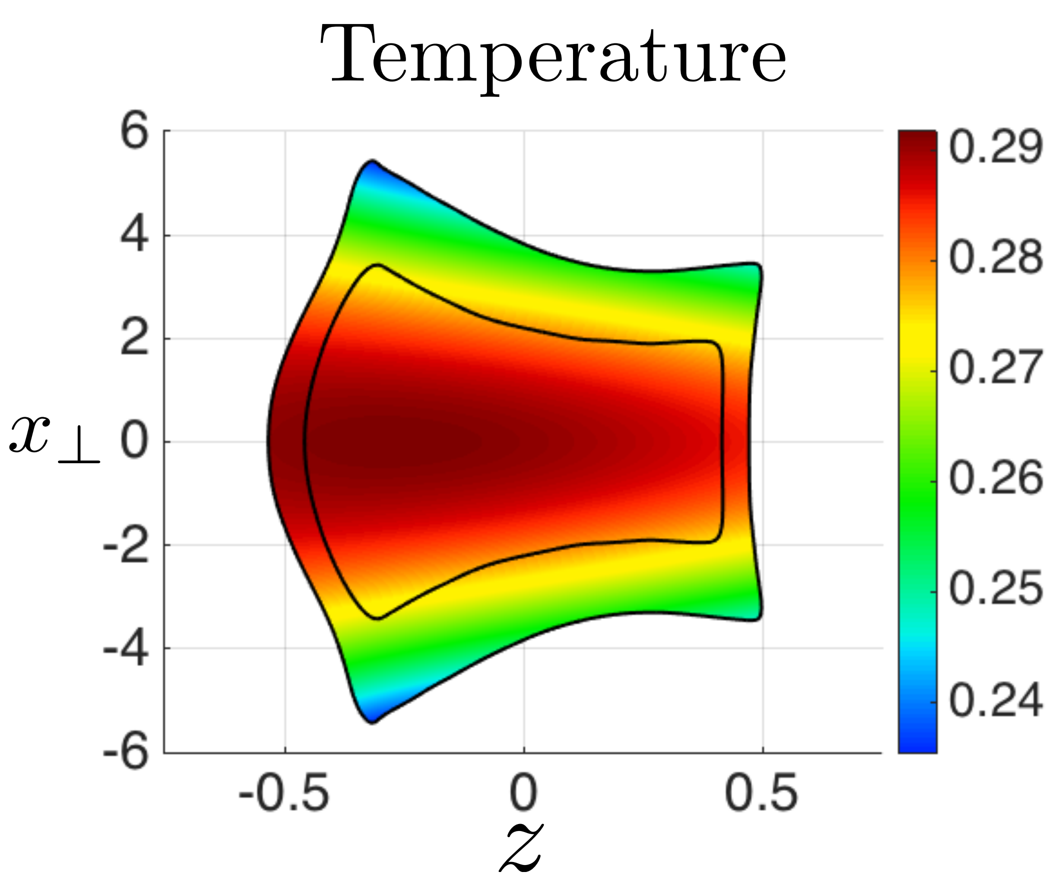
[PC: 1506.02209]



A tiny drop of liquid







How small of a droplet?

- Effective temperature

$$T_{\rm eff}^{-1} \equiv \frac{\partial s_{\rm eq}}{\partial \epsilon_{\rm eq}}\Big|_{\epsilon_{\rm eq}=\epsilon}.$$

- **Result:** $RT_{\rm eff} \approx 1$.

Rapid equilibration?

- **Result:** $t_{\rm hydro} T_{\rm eff} \approx 0.3$.

Smallest possible droplet of liquid?

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Origins of QGP in HIC?

- Wave functions of incident hadrons and nuclei are of fundamental interest. Experimental study of the initial state via eA collisions at a future Electron Ion Collider.
- The decoherence of these wave functions in HIC and the evolution of this initial state to the strongly coupled liquid are being constrained by HIC data. Because QGP is such a good liquid, HICs offer a window back to the physics of equilibration in QCD, and to aspects of the initial state.
- Recent advances in weakly coupled calculations, that connect smoothly onto a weakly coupled initial quantum state but can have difficulty connecting to hydrodynamics.
- Recent advances in strongly coupled calculations — collisions of sheets and now disks of cold strongly coupled matter — yield hydrodynamic fluids smoothly and automatically but that assume a strongly coupled initial quantum state. New hybrid holographic→hydro→hadro calculations.

Origins of QGP in HIC?

- In reality, almost certainly the initial state is weakly coupled gluons with momenta well above some scale Q_s and strongly coupled gluons well below Q_s. How can we use eA collisions at an EIC to provide direct experimental evidence that the initial state is not just lots of gluons, counted up in a gluon pdf? That when you tickle one below-Q_s gluon, many of them sneeze?

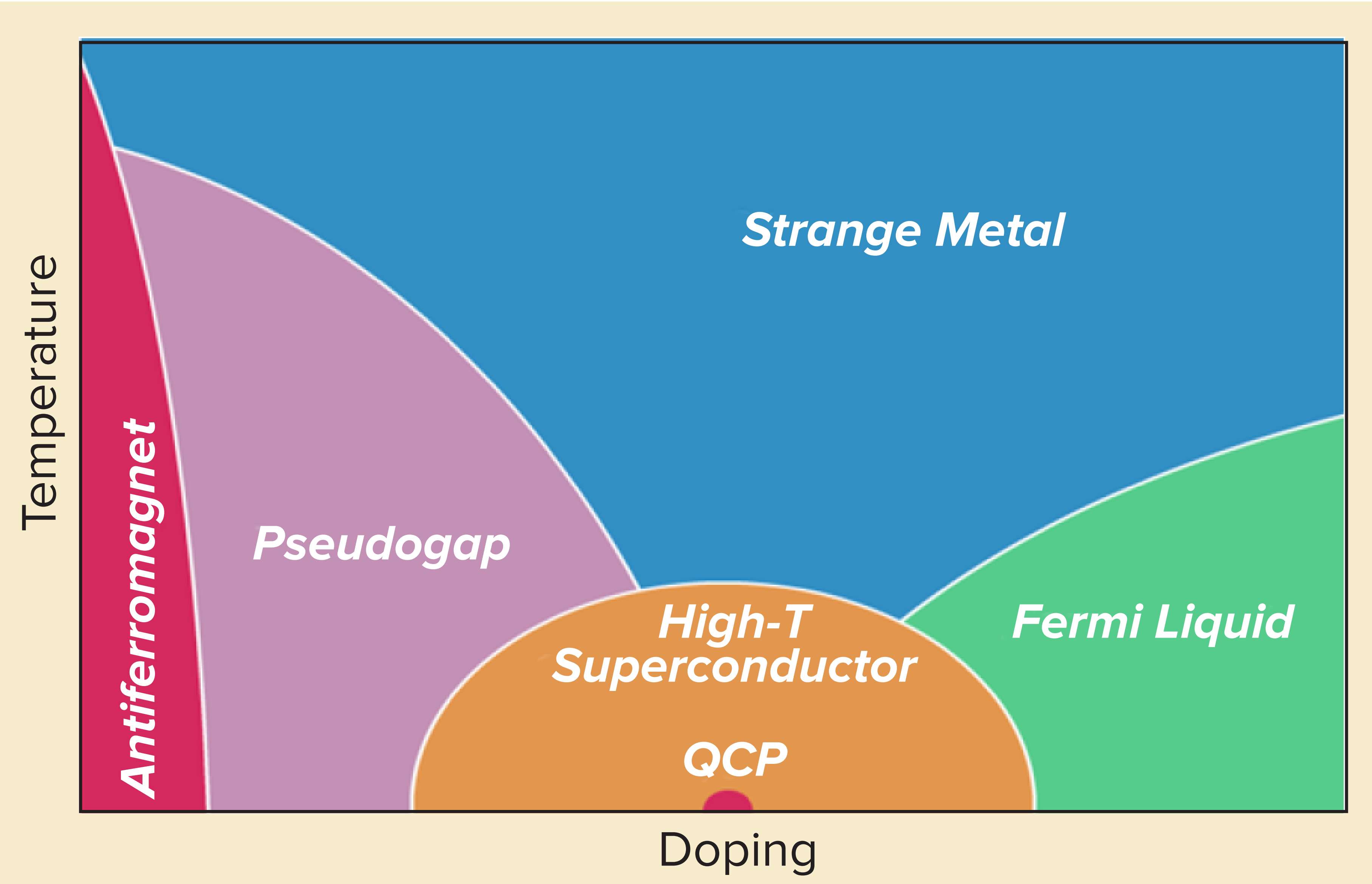
- Need the analogue in our field of what ARPES has done for strongly correlated electron systems. Which is to say we need direct experimental evidence of what those below-Q_s gluons are *doing*. $\rightarrow$ EIC.

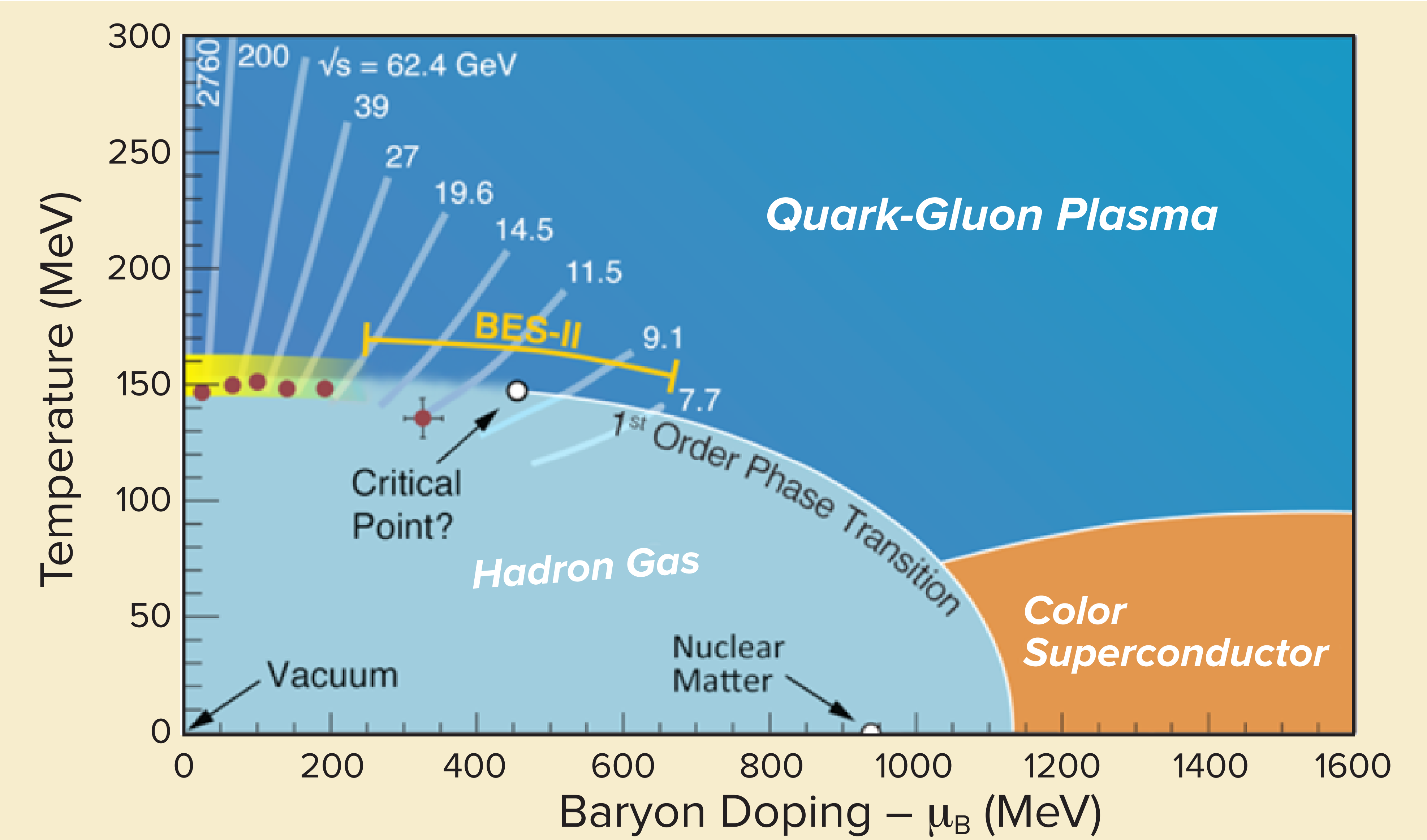
- Could it be that the reason hydrodynamization in HIC is so fast is that the below-Q_s gluons are in a strongly coupled, maybe strongly entangled, state to start with?

- Can a scale Q_s, below which one has strongly coupled gluons but not above, be built into the initial state of the colliding disks in the holographic calculations?

Origins of QGP in HIC?

- Thinking of the lessons of history, odds are very good we have not yet asked the most interesting questions about the initial state that an EIC will answer. I certainly hope so. Terra incognita awaits.


Strange Metal
Antiferromagnet
Pseudogap
High-T
Superconductor
Fermi Liquid
QCP
Temperature
Doping



Temperature (MeV)
Baryon Doping – μB (MeV)
2760
200
√s = 62.4 GeV
39
27
19.6
14.5
11.5
9.1
7.7
BES-II
Quark-Gluon Plasma
Critical Point?
1st Order Phase Transition
Hadron Gas
Color Superconductor
Vacuum
Nuclear Matter

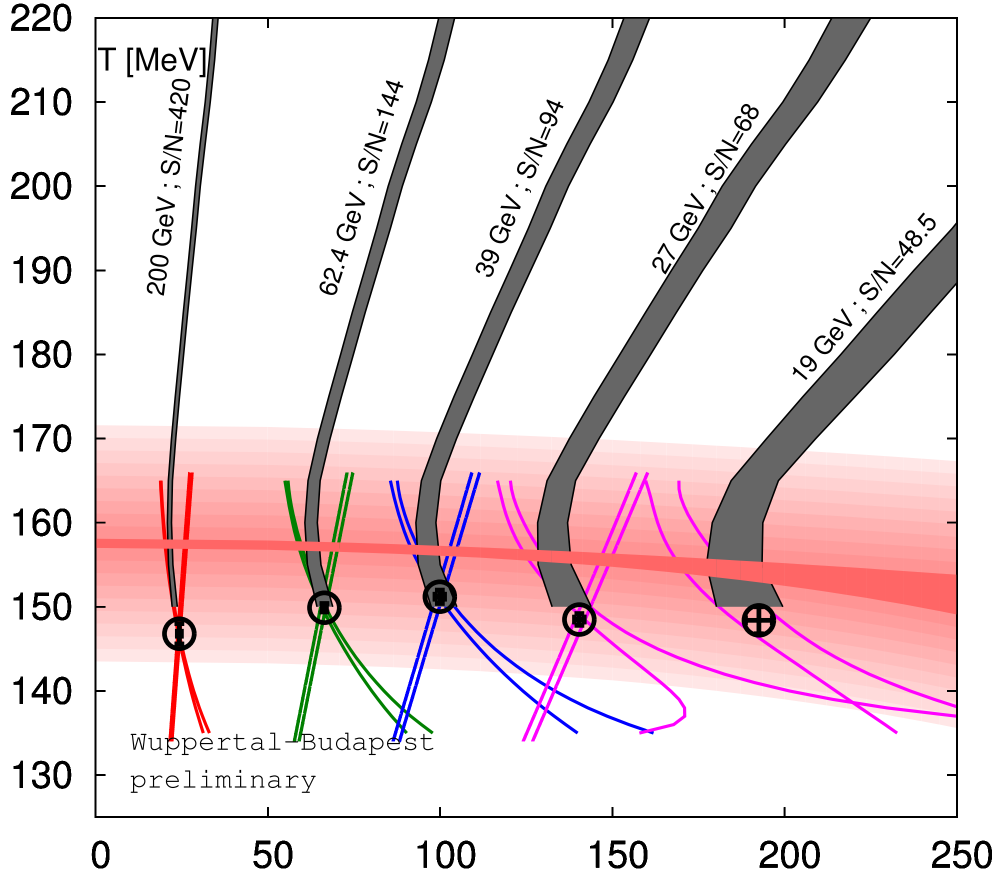
Mapping the QCD Phase Diagram

- How does QGP change as you "dope" it with a larger and larger excess of quarks over antiquarks, i.e. larger and larger μ_B? Substantial recent progress in answering questions like this on the lattice, e.g. doping-dependence of equation of state and susceptibilities, as long as the doping is not too large. Combining lattice and RHIC Beam Energy Scan results to map the crossover region.

- How is the crossover between QGP and hadrons affected by doping? Does it turn into a first order transition above a critical point?

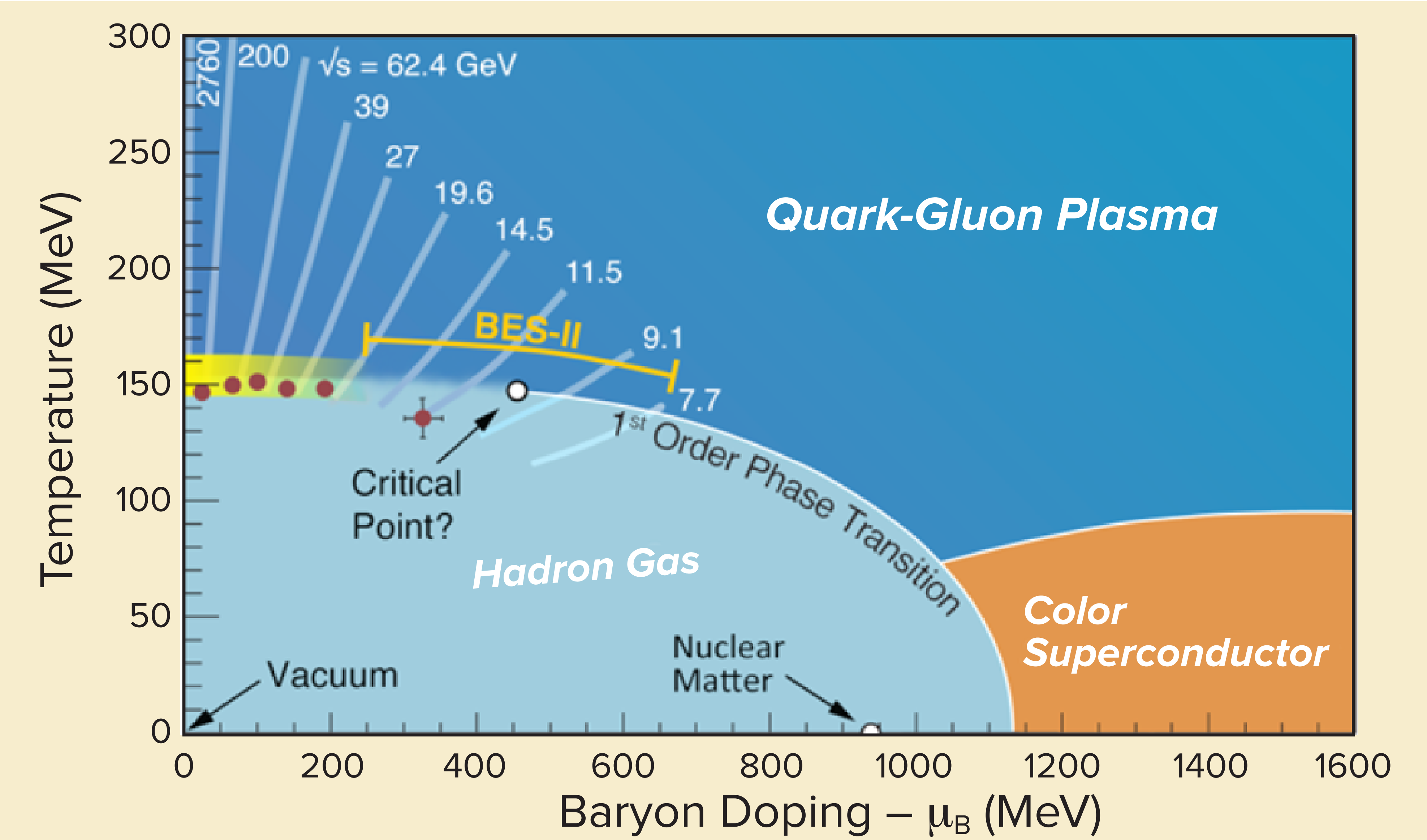
- Answering this question via theory will need further advances in lattice "technology". Impressive recent progress advancing established Taylor-expansion methods. New ideas (complex Langevin) also being evaluated. Nevertheless, at present theory is good at telling us what happens near a critical point or first order transition, but cannot tell us where they may be located.

Mapping the Crossover Region



Wuppertal-Budapest-Houston, 1601.00466

Lattice determination of crossover region compared with freeze-out points obtained from the intersection of: (i) lattice calculations and exptl measurements of magnitude of charge fluctuations and proton number fluctuations; (ii) hadron resonance gas calculations of and exptl measurements of S/N.



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Critical Point?
1st Order Phase Transition
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Color Superconductor
Nuclear Matter
Vacuum
Temperature (MeV)
Baryon Doping – μB (MeV)
0
50
100
150
200
250
300
0
200
400
600
800
1000
1200
1400
1600

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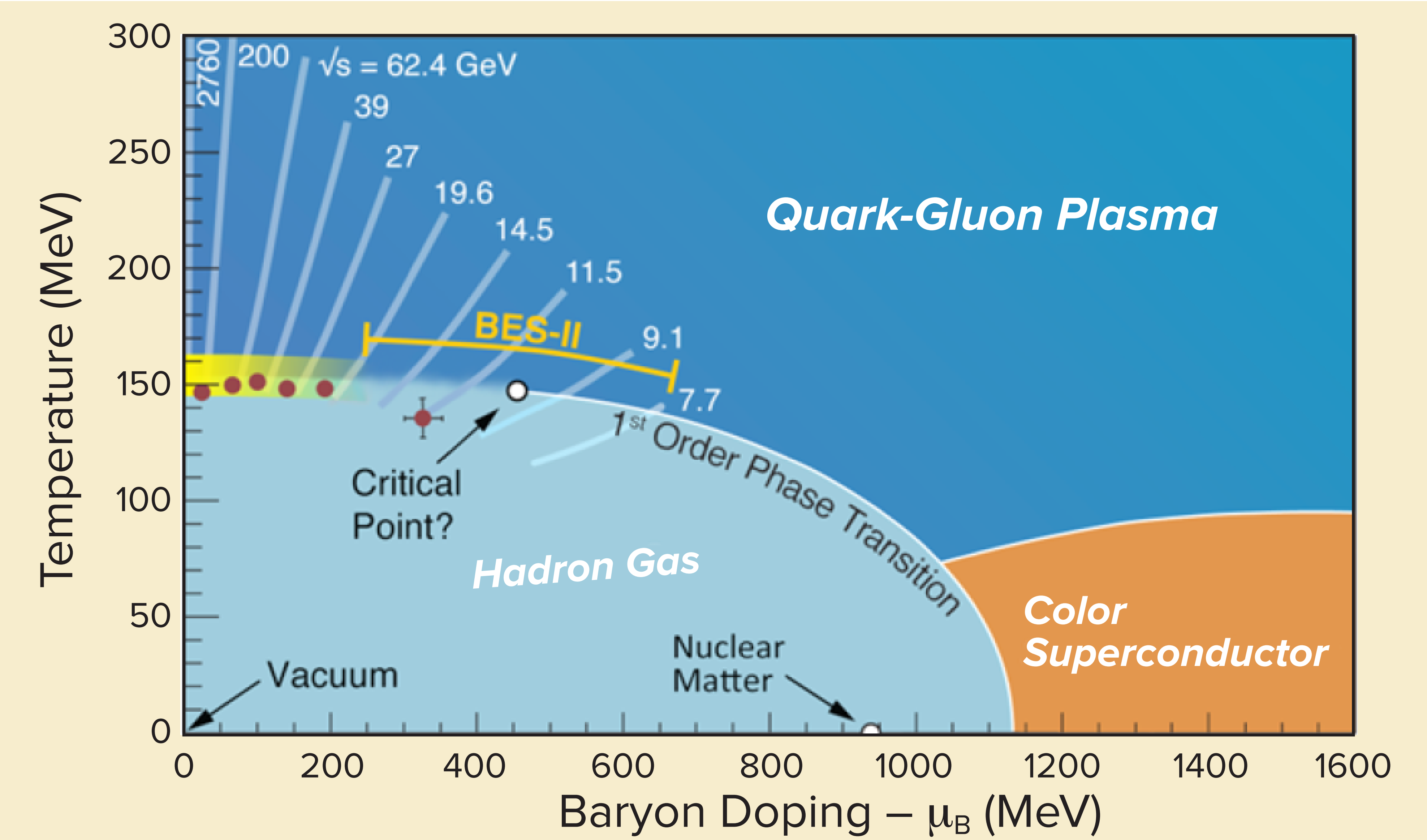

Temperature (MeV)
300
250
200
150
100
50
0
2760
200
√s = 62.4 GeV
39
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19.6
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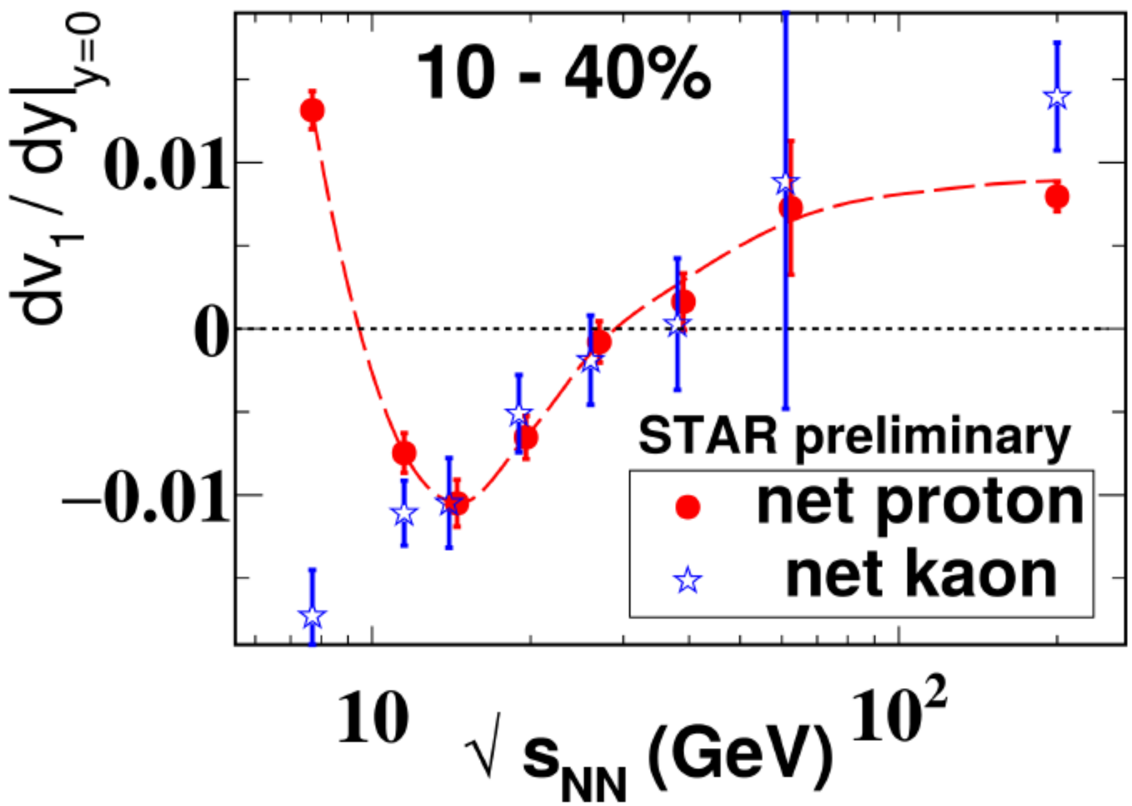
0
200
400
600
800
1000
1200
1400
1600
Baryon Doping – μB (MeV)

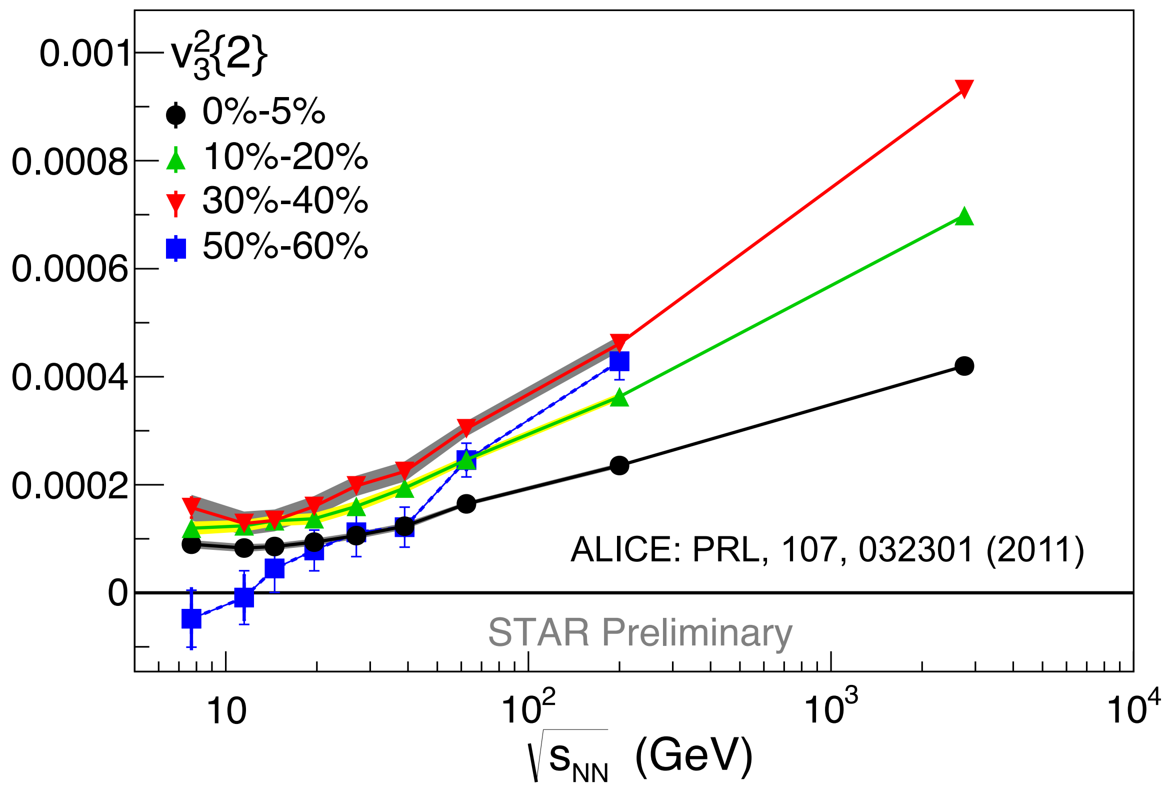
Mapping the QCD Phase Diagram

- Exploring the phase diagram is the goal of the RHIC Beam Energy Scan. Beautiful results from BES-I, 2011-14. Suggestive variations in flow and fluctuation observables as a function of $\sqrt{s}$, and hence μ_B. Strong motivation for higher statistics data at and below $\sqrt{s} = 20$ GeV.

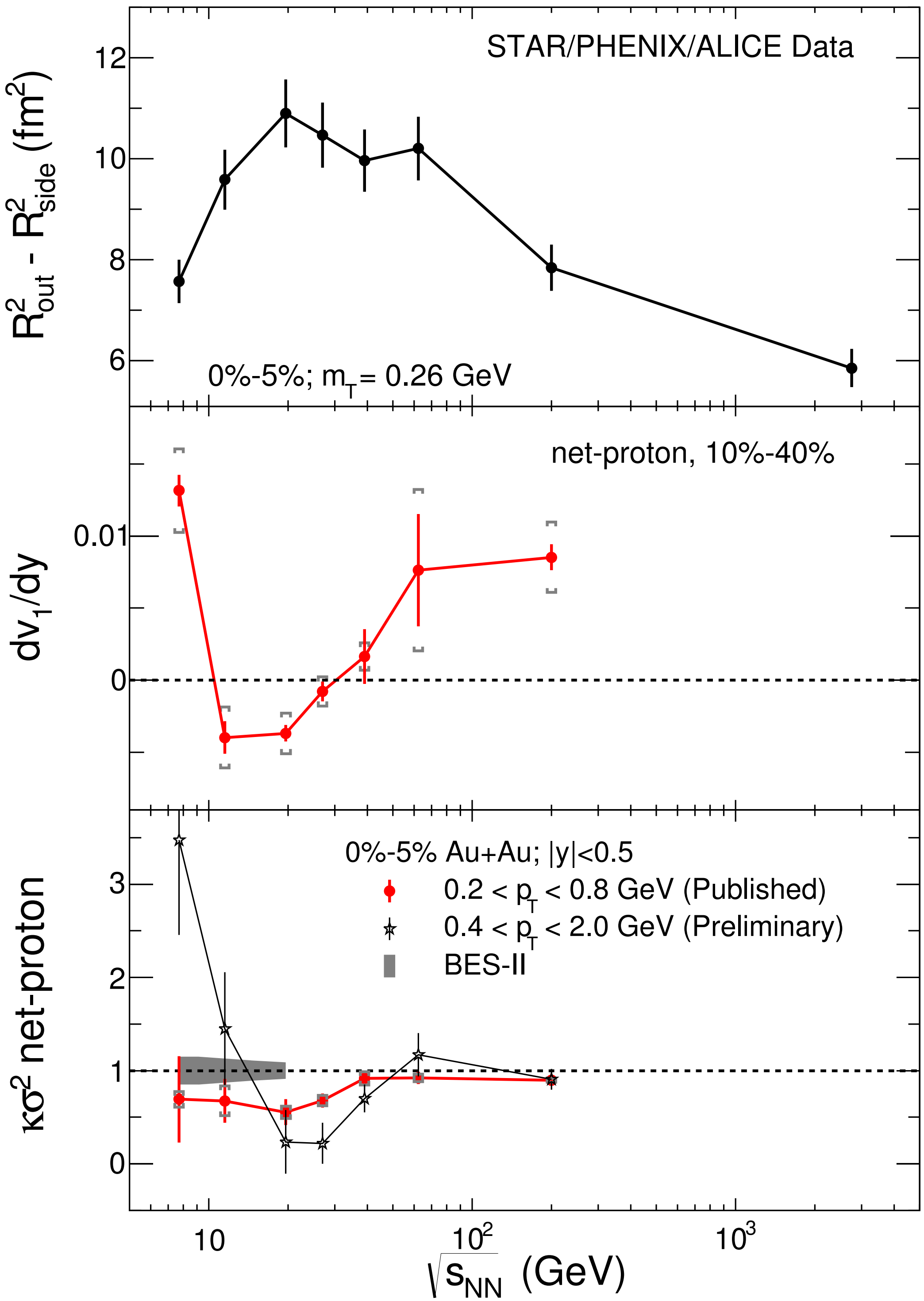
- BES-I results present an outstanding opportunity for theory. E.g. intriguing $\sqrt{s}$-dependence of dv_1/dy, possibly due to a softening of the EoS. Validating/quantifying this interpretation *requires* 3+1-D viscous hydrodynamic calculations at BES energies, since "EoS" only has meaning in the context of hydro. And, hydro calculations at these lower energies present new challenges (j_B^μ in addition to $T^{\mu\nu}$) and must include state-of-the-art treatment of the hadrodynamics: relative importance of hadrodynamic effects on all observables grows. Also need baryon stopping and state-of-the-art initial state fluctuations. BES-I data demand that the sophistication that has been applied at top energies be deployed at BES energies.

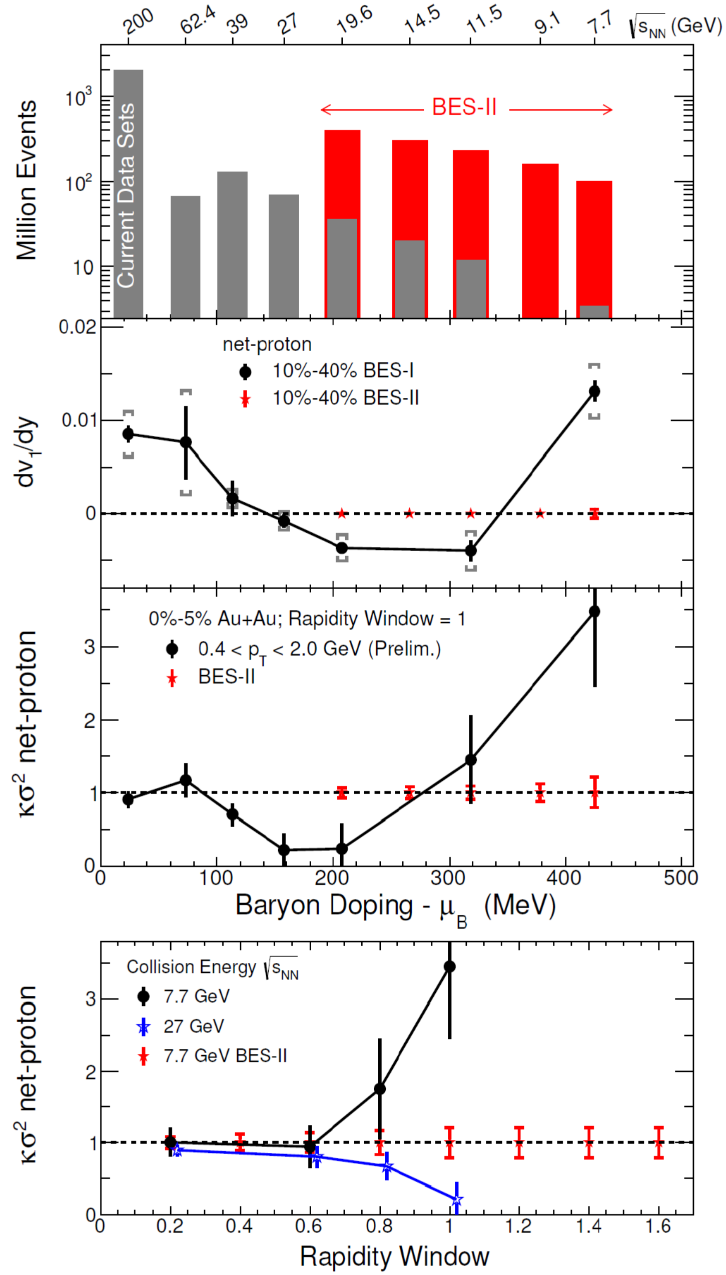


10 - 40%
STAR preliminary
net proton
net kaon
dv1 / dy|y=0
0.01
0
−0.01
10
10^2
√ sNN (GeV)



$v_3^2\{2\}$
0%-5%
10%-20%
30%-40%
50%-60%
0.001
0.0008
0.0006
0.0004
0.0002
0
ALICE: PRL, 107, 032301 (2011)
STAR Preliminary
10
10^2
10^3
10^4
$\sqrt{s_{NN}}$ (GeV)


STAR/PHENIX/ALICE Data
$R^2_{out} - R^2_{side}$ (fm^2)
0%-5%; m_T = 0.26 GeV
net-proton, 10%-40%
dv_1/dy
0%-5% Au+Au; |y|<0.5
0.2 < p_T < 0.8 GeV (Published)
0.4 < p_T < 2.0 GeV (Preliminary)
BES-II
$\kappa\sigma^2$ net-proton
$\sqrt{s_{NN}}$ (GeV)

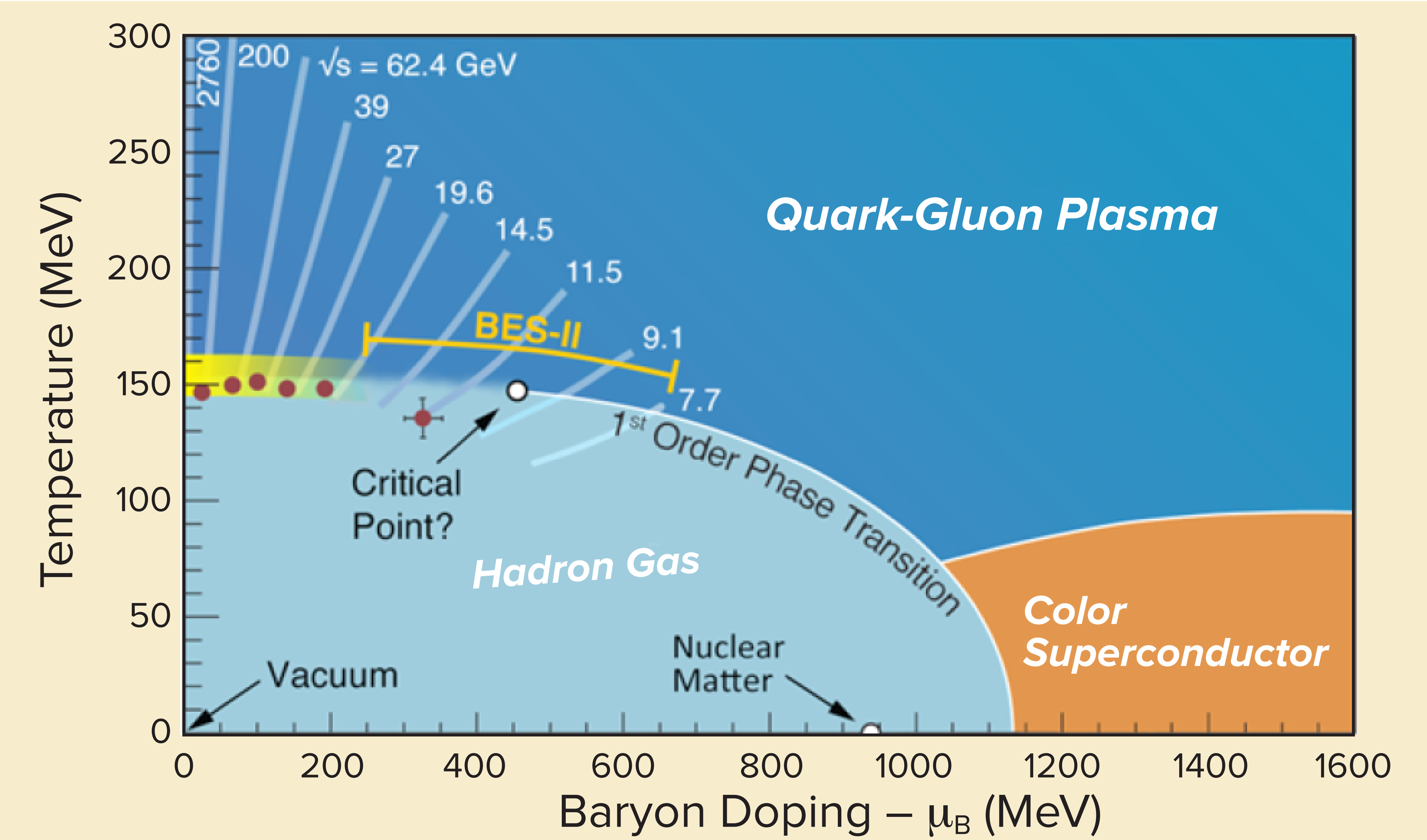


200
62.4
39
27
19.6
14.5
11.5
9.1
7.7
$\sqrt{s_{NN}}$ (GeV)
Million Events
Current Data Sets
BES-II
net-proton
10%-40% BES-I
10%-40% BES-II
dv_1/dy
0%-5% Au+Au; Rapidity Window = 1
$0.4 < p_T < 2.0$ GeV (Prelim.)
BES-II
$\kappa\sigma^2$ net-proton
Baryon Doping - μ_B (MeV)
Collision Energy $\sqrt{s_{NN}}$
7.7 GeV
27 GeV
7.7 GeV BES-II
Rapidity Window

Mapping the QCD Phase Diagram

- **Mapping the crossover region of the phase diagram comes first. How do the properties of the liquid QGP, and the matter in the crossover region, say with $\mu_B \lesssim 200$ MeV, change with doping? This program is well underway, with contributions from experiment, lattice, and dynamical modeling and the ball presently in the theorists' court.**

- **How can we detect the presence of a critical point on the phase diagram, if there is one, in HIC data?**



Temperature (MeV)
300
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2760
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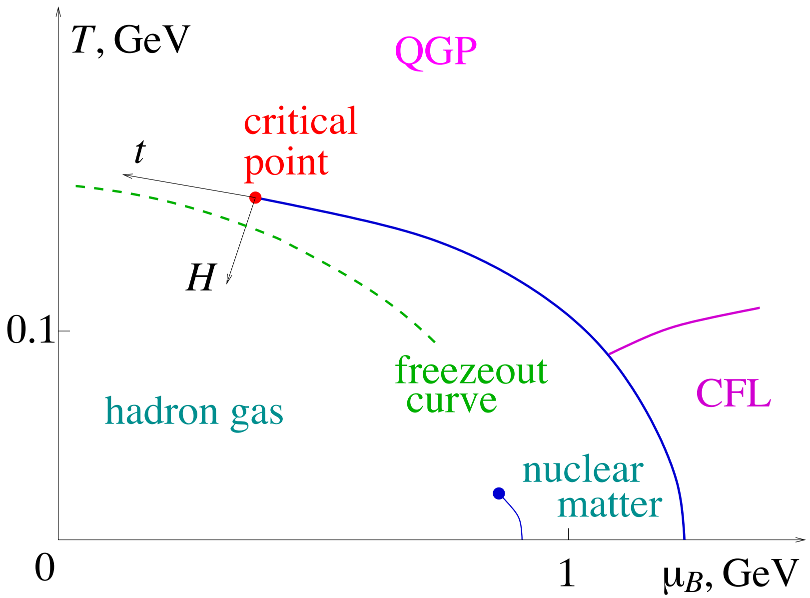
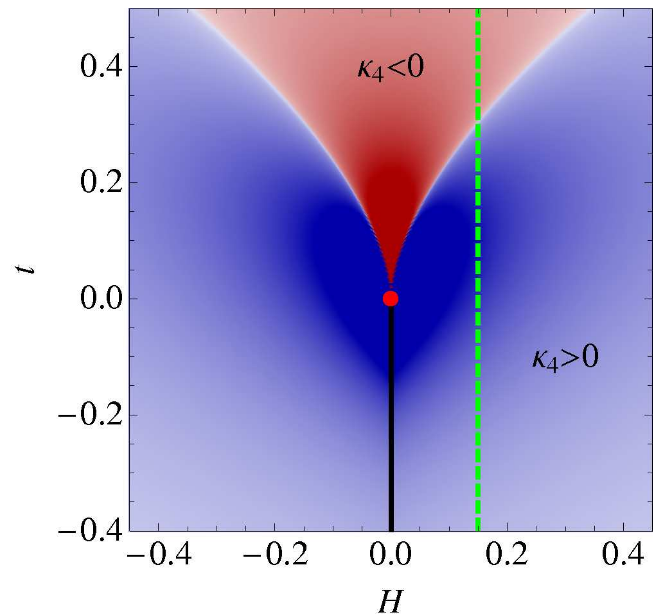
Baryon Doping – μB (MeV)

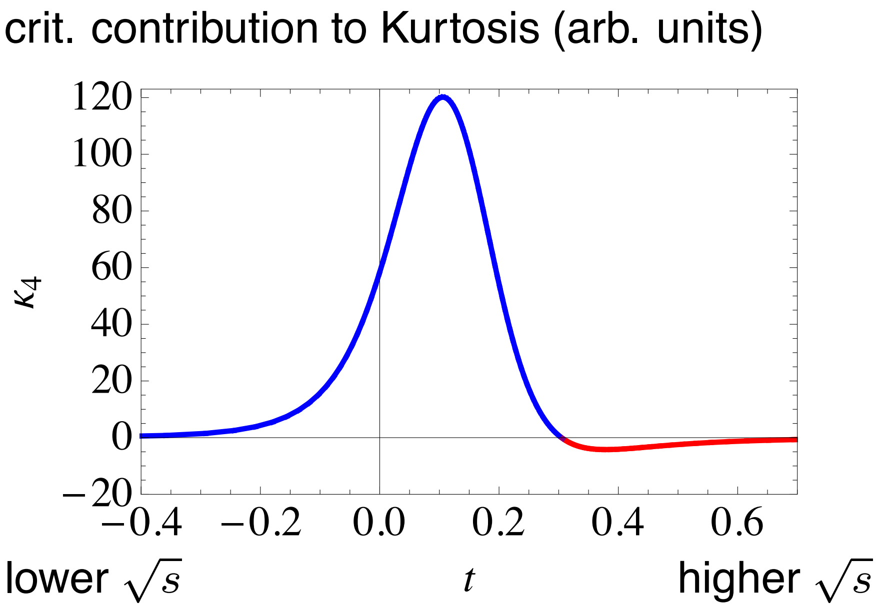
QCD phase diagram, critical point and RHIC

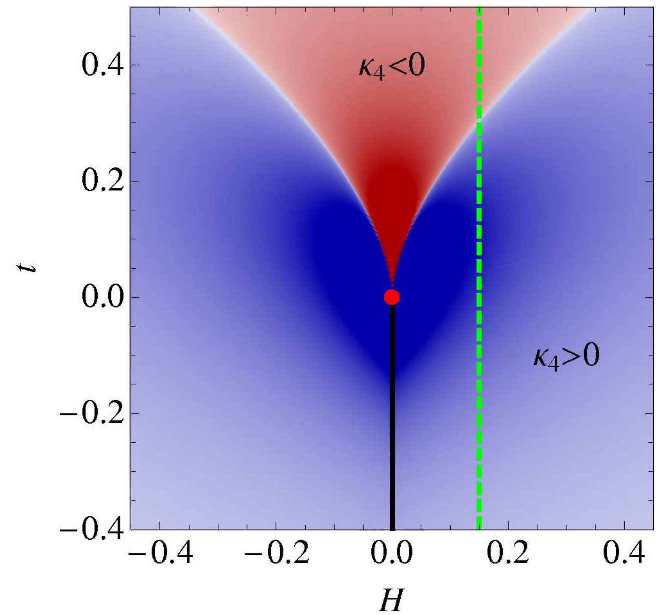




- Models (and lattice) suggest the transition becomes 1st order at some μ_B.
- Can we observe the critical point in heavy ion collisions, and how?
- Near critical point fluctuations grow and become more non-Gaussian.
- Challenge: develop measures most sensitive to the critical point and use them to locate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

QCD phase diagram, critical point and RHIC





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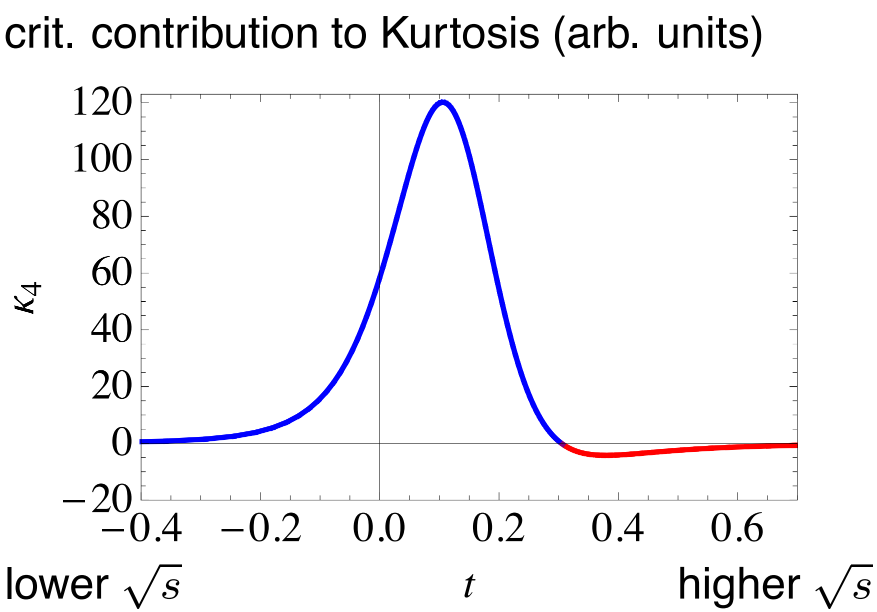

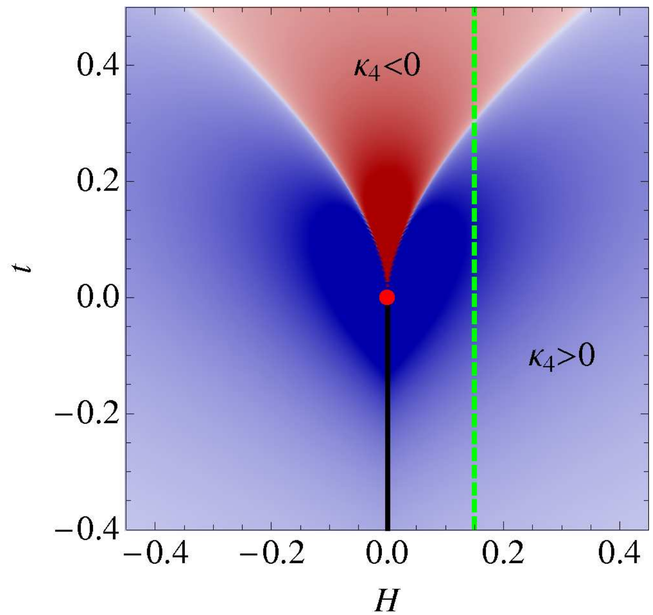

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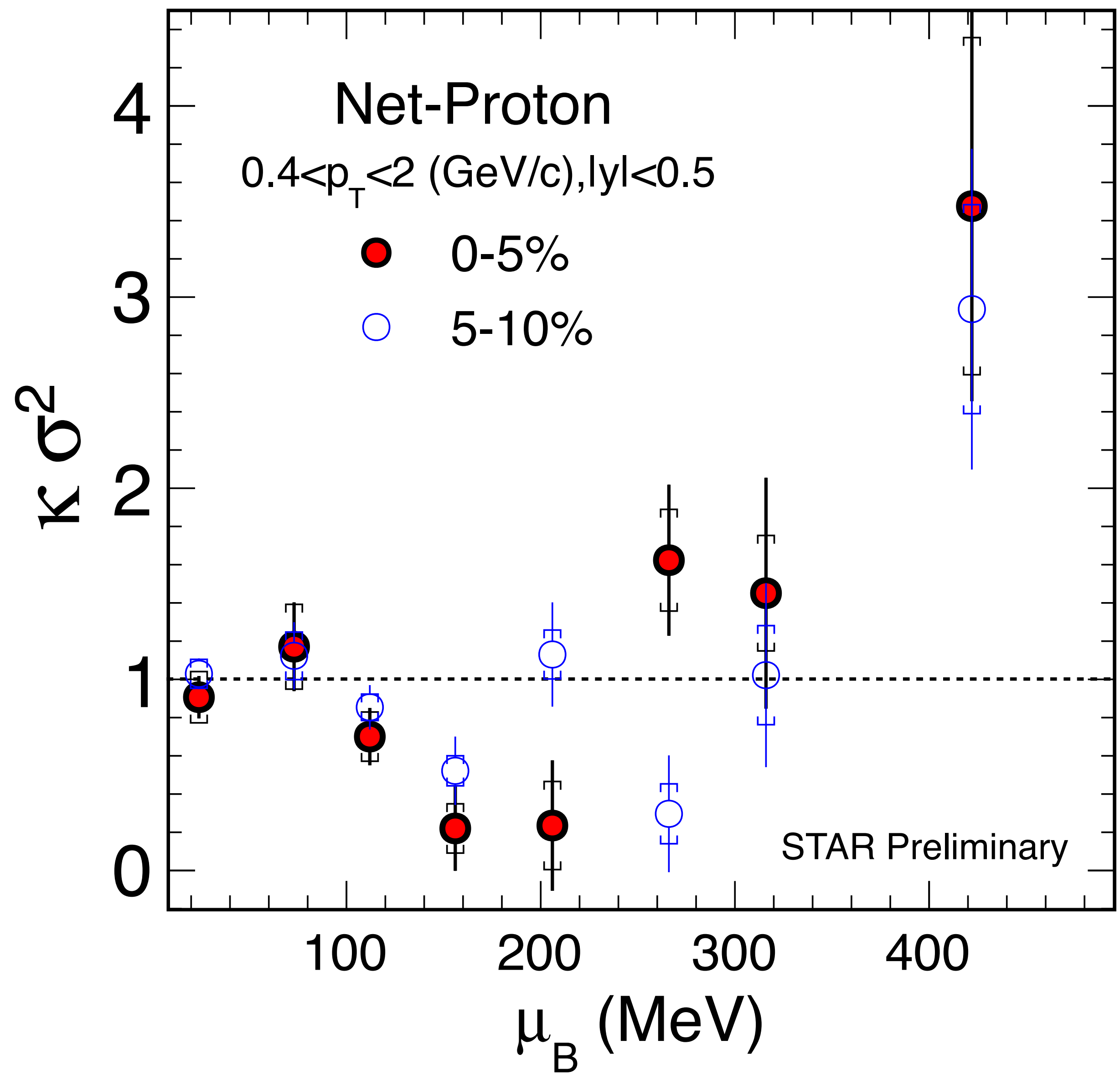
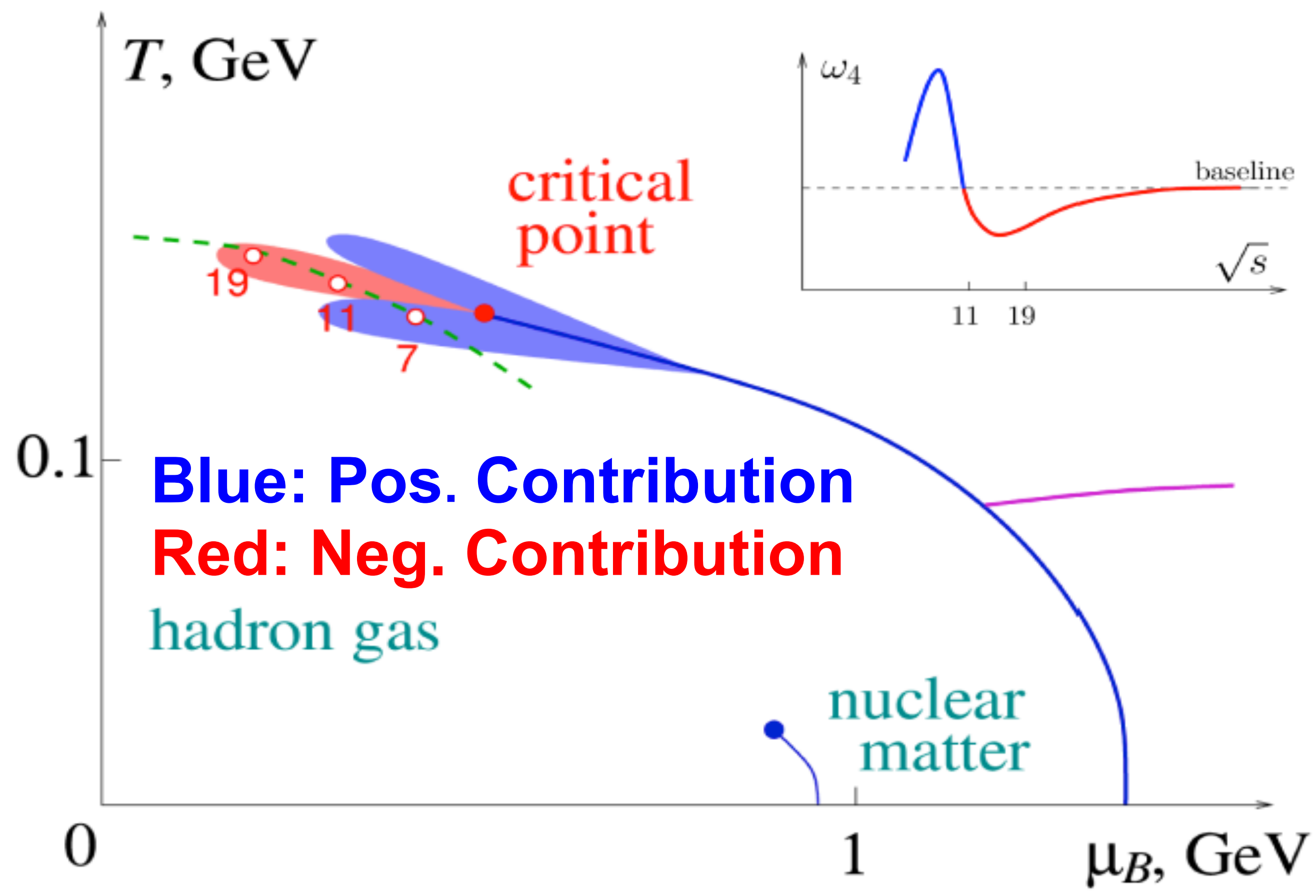
- Once we find the μ (i.e. the $\sqrt{s}$) where the critical contribution to κ_4 is large enough — e.g. the "blue peak" — then there are then robust, parameter-independent, predictions for various ratios of the kurtosis and skewness of protons and pions. Athanasiou, Stephanov, Rajagopal 1006.4636.



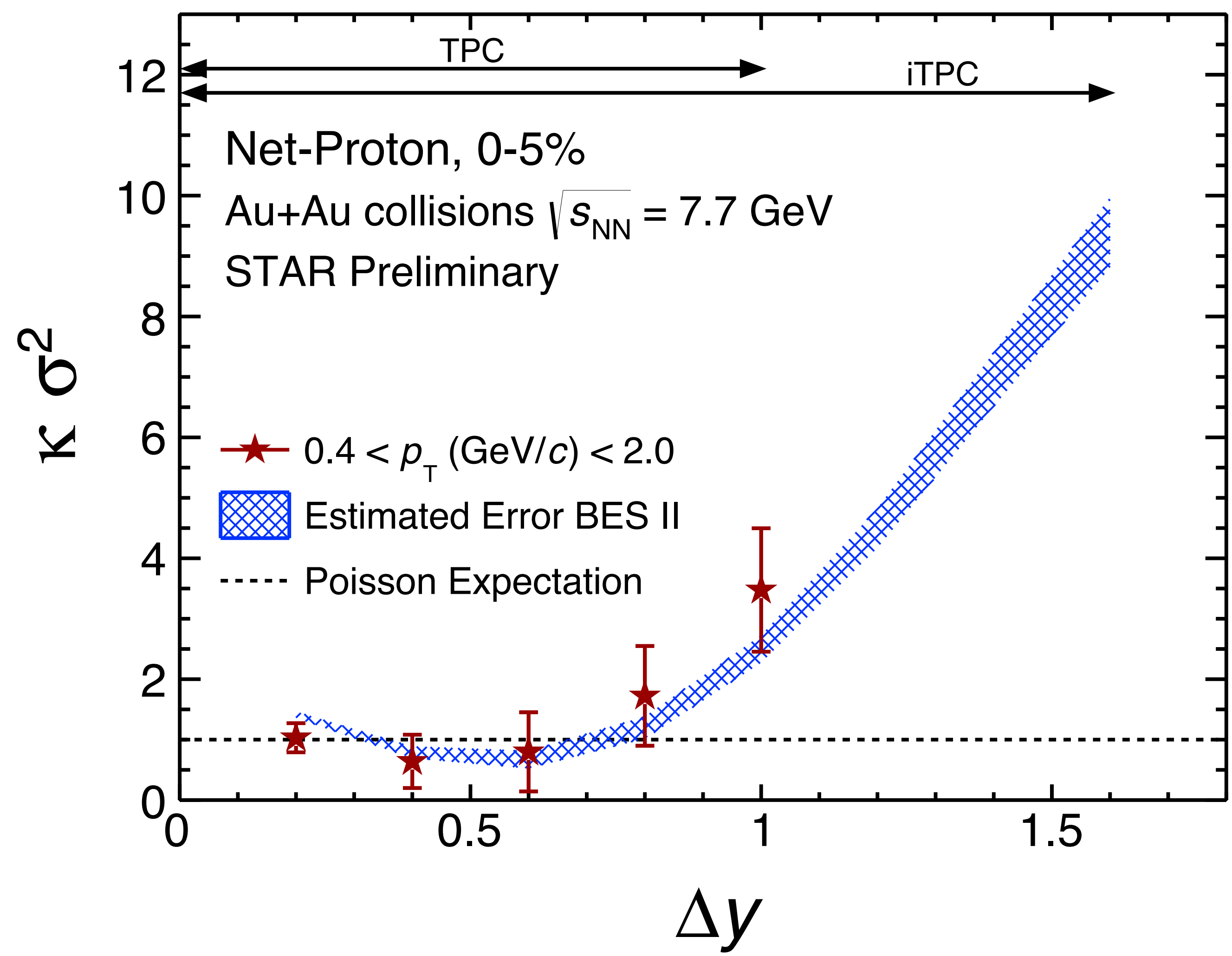
Net-Proton
0.4<p_T<2 (GeV/c),|y|<0.5
0-5%
5-10%
STAR Preliminary
κ σ²
μ_B (MeV)
0
1
2
3
4
100
200
300
400



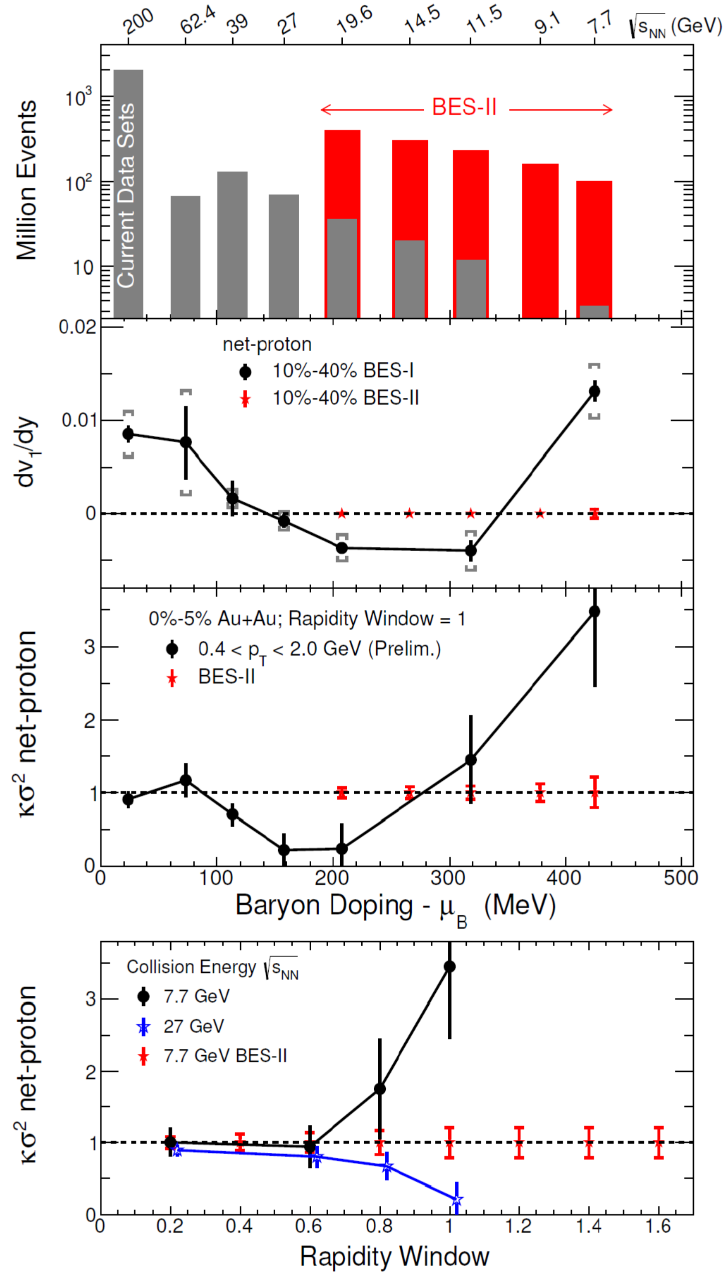
T, GeV
0.1
0
1
μB, GeV
critical
point
19
11
7
ω4
baseline
√s
11
19
Blue: Pos. Contribution
Red: Neg. Contribution
hadron gas
nuclear
matter

Mapping the QCD Phase Diagram

- **How can we detect the presence of a critical point on the phase diagram, if there is one, in HIC data?**
- **A negative contribution to the proton kurtosis at $\mu_B \sim 150-200$ MeV is established. Is this a harbinger of the approach toward a critical point at larger μ_B? The signs of an upturn at larger μ_B are encouraging, as is the dependence on the rapidity window Δy used in the analysis. (Critical contribution to kurtosis grows like Δy^3 for $\Delta y \lesssim 2$.) Higher statistics data, and larger Δy, are needed. As is a substantial advance on the theory side...**
- **Once you have a validated hydrodynamic + hadrodynamic model at BES energies, then you can add both hydrodynamic fluctuations and the critical fluctuations of the chiral order parameter. Need to source them, evolve them, and describe their consequences at freezeout. Need hydro+hadro+chiral treatment in order to quantify the finite-time limitation on the growth of the correlation length near, and the signatures of, a possible critical point.**



TPC
iTPC
Net-Proton, 0-5%
Au+Au collisions $\sqrt{s_{NN}}$ = 7.7 GeV
STAR Preliminary
$\kappa\,\sigma^2$
0.4 < p_T (GeV/c) < 2.0
Estimated Error BES II
Poisson Expectation
Δy
0
2
4
6
8
10
12
0.5
1
1.5



200
62.4
39
27
19.6
14.5
11.5
9.1
7.7
$\sqrt{s_{NN}}$ (GeV)
Million Events
Current Data Sets
BES-II
net-proton
10%-40% BES-I
10%-40% BES-II
dv_1/dy
0%-5% Au+Au; Rapidity Window = 1
0.4 < p_T < 2.0 GeV (Prelim.)
BES-II
$\kappa\sigma^2$ net-proton
Baryon Doping - μ_B (MeV)
Collision Energy $\sqrt{s_{NN}}$
7.7 GeV
27 GeV
7.7 GeV BES-II
$\kappa\sigma^2$ net-proton
Rapidity Window

Mapping the QCD Phase Diagram

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- Once you have a validated hydrodynamic+hadrodynamic model at BES energies, then you can add both hydrodynamic fluctuations and critical fluctuations of the chiral order parameter. Need to source them, evolve them, and describe their consequences at freezeout. Need hydro+hadro+chiral treatment in order to quantify the finite-time limitation on the growth of the correlation length near, and the signatures of, a possible critical point.
- Theory needs to be ready in time for BES-II in 2019-20, when error bars will shrink and today's tantalizing hints, e.g. of non-monotonic behavior in dv_1/dy and in the kurtosis of the proton multiplicity distribution, will become ... ?

Opportunities and Challenges @ BES-II

- On the experimental side, onward to BES-II!
- To answer the big questions, on the theory side we need:
  - a validated, quantitative description of initial fluctuations and baryon stopping, and the hydrodynamics and hadrodynamics including the dynamics of conserved quantities
  - to which can be added the dynamical evolution of hydrodynamic fluctuations and of critical fluctuations of the chiral order parameter, including its observable consequences at freezeout
  - as well as chiral magnetohydrodynamics effects, namely the dynamics of axial charges including anomalous couplings between $\vec{B}$, hydrodynamics, and gauge field fluctuations.
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- **In place, tested against the BES-I data that motivates this effort, before BES-II. Ready for a comprehensive comparison to BES-II data, allowing quantitative inference of how QGP properties and chiral-anomaly-induced effects change with μ_B, and of whether and if so where a critical point has been found.**
- **Many theorists are hard at work building parts of what is needed, but there is room for many further clever ideas.**
- **The new Beam Energy Scan Theory (BEST) Collaboration is forming and aims to play a substantial role in meeting these challenges, so that we are all ready for whatever discoveries await us in BES-II data. (Led by Swagato Mukherjee and Volker Koch. PIs from BNL, LBNL, UConn, McGill, OSU, Stonybrook, Indiana, MSU, MIT, Houston, Chicago, UIC.)**

Today's Questions

- How does QGP work? What is its microscopic structure? How does its liquidness emerge from microscopic dynamics?
- What is the smallest possible droplet of QGP with a certain temperature that behaves hydrodynamically?
- Origins of QGP in HICs? HICs are lumpy and fast. How does hydrodynamization happen so quickly? Near-perfect fluidity of QGP means its origins can be seen in its debris. Ultimately, compare what we learn of its origins in HIC to what we learn about nuclear wave functions from an EIC.
- What is the phase diagram of doped QGP?
- Can we see the quantum aspects of QGP?
- Challenges that can be met with measurements to come at the LHC and at RHIC, including in particular BES-II and sPHENIX, and with new ideas and advances in theory.

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.**

Quantum Aspects of QGP?

- In the strongly coupled "electron fluids" that are the subject of intense interest in condensed matter physics, much recent work on the importance of quantum entanglement. Is this important in QGP? Not known.

- This question, as well as other not-entirely-microscopic "how does QGP work" questions, is inaccessible if all you know is hydrodynamics, transport coefficients, jet quenching, and screening. Could it somehow be addressed via corrections to diffusion for heavy quarks? Or via correlations in EM radiation? Seems very hard.

- But we may have access to a different quantum mechanical feature of QGP, namely the topological fluctuations of the gluon fields within QGP that result in fluctuations in chirality. In QGP in a $\vec{B}$ or $\vec{L}$ these topological fluctuations, together with the chiral anomaly, yield Chiral Magnetic Effects or Chiral Vortical Effects. Possible signatures of both have been seen. Many open questions here...

Quantum Aspects of QGP?

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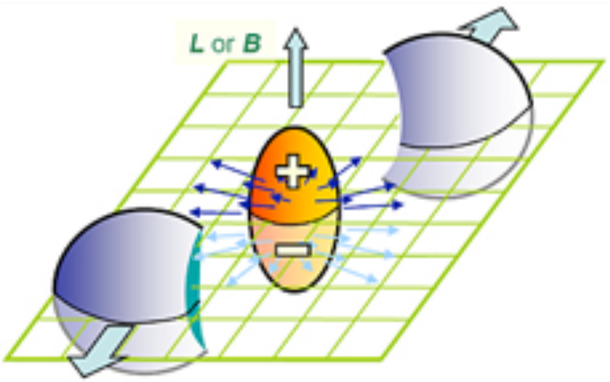
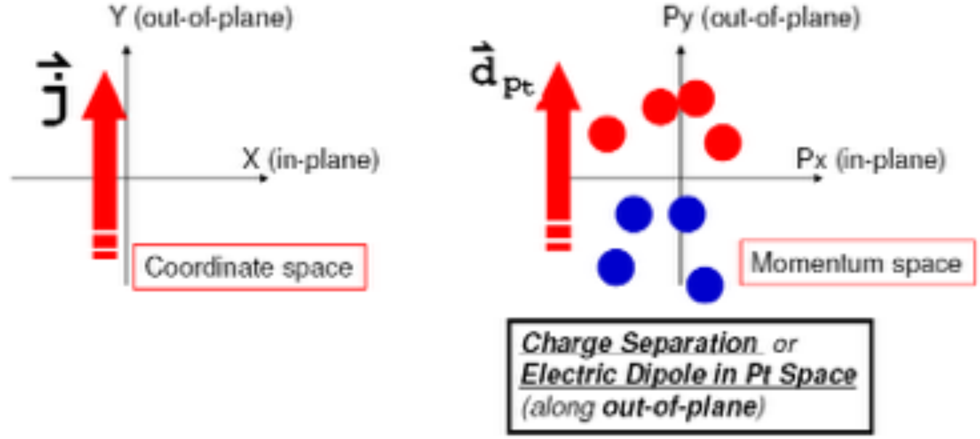
- On the theory side, how to calculate the topological fluctuations in an expanding cooling finite droplet? How are they seeded? How do they evolve?

- A first step to gaining confidence would be detection of prosaic effects of $\vec{B}$, via Faraday and Lorentz and Hall with no 20th or 21st century physics needed.

- A second step to gaining confidence would be a quantitative calculation of the Chiral Magnetic Wave effect, namely the generation of a charge quadrupole in slices of an event in which there is a net charge. This effect has been seen, and the theory behind it is more robust in that it requires $\vec{B}$ and the chiral anomaly but it does not involve the hard-to-calculate topological fluctuations.

From CME Current to Charge Separation





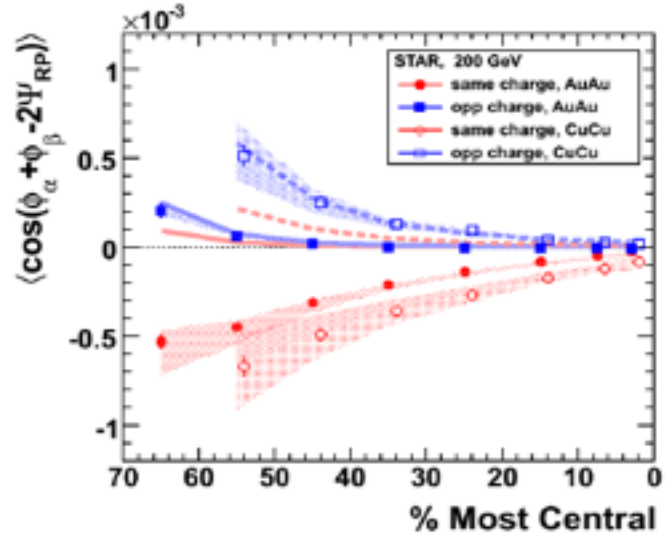
[Kharzeev 2004; Kharzeev, McLerran, Warringa,2008;…]

$$\frac{dN_{\pm}}{d\phi} \propto ... + a_{\pm} \sin(\phi - \Psi_{RP})$$

The dipole flips e-by-e

$$\gamma = \langle cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}] - [\langle a_\alpha a_\beta \rangle + B_{out}]$$

[Voloshin, 2004]

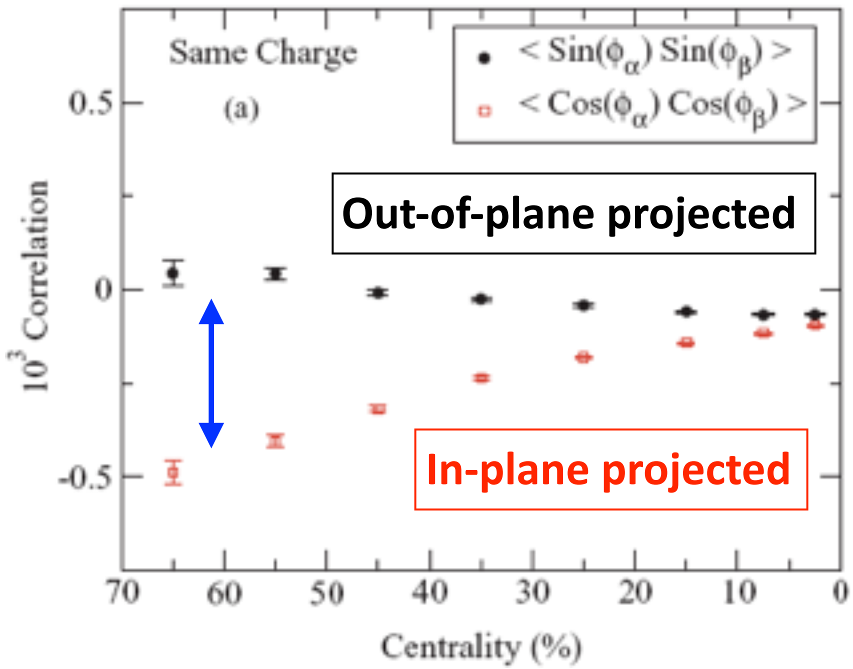


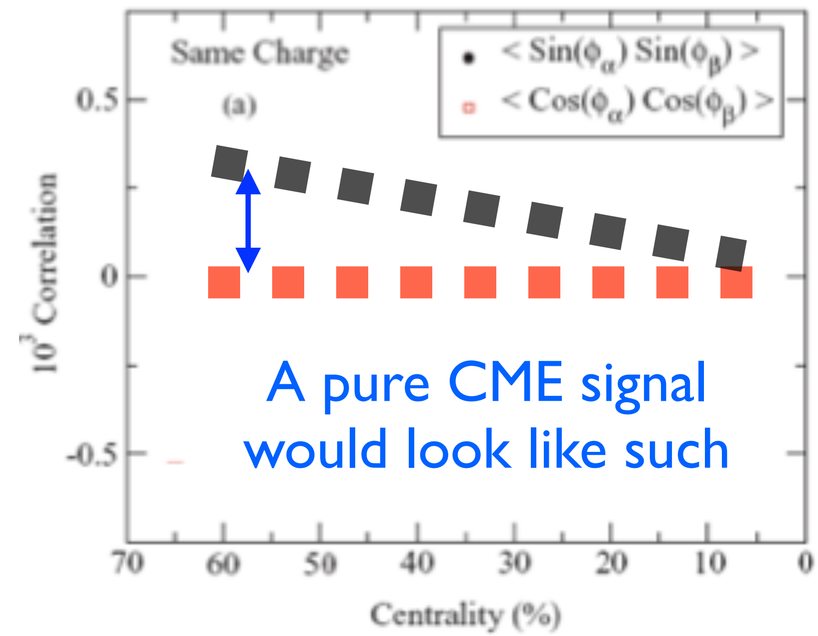
[STAR 2009] ***Data triggered wide initial enthusiasm***

Background! Background! Background!

Close examinations revealed that the INTERPRETATION of the nice data is complicated by backgrounds.

[Bzdak, Koch, JL; FQ Wang; Pratt, Schlichting; Teaney, Yan;…]





$$\left\langle \cos(\phi_\alpha + \phi_\beta) \right\rangle_s = \left\langle \cos(\phi_\alpha) \cos(\phi_\beta) \right\rangle_s - \left\langle \sin(\phi_\alpha) \sin(\phi_\beta) \right\rangle_s < 0$$

$$\langle \cos(\phi_\alpha - \phi_\beta) \rangle = \langle \cos(\phi_\alpha) \cos(\phi_\beta) \rangle + \langle \sin(\phi_\alpha) \sin(\phi_\beta) \rangle$$

Separation of CME & Flow-Driven Background

Could one make some sense of data by two-component picture?

[Bzdak, Koch, JL, 2012; Blocynski, Huang, Zhang, JL, 2013]

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,$$

H: "CME Signal"
F: "Flow Driven Background"

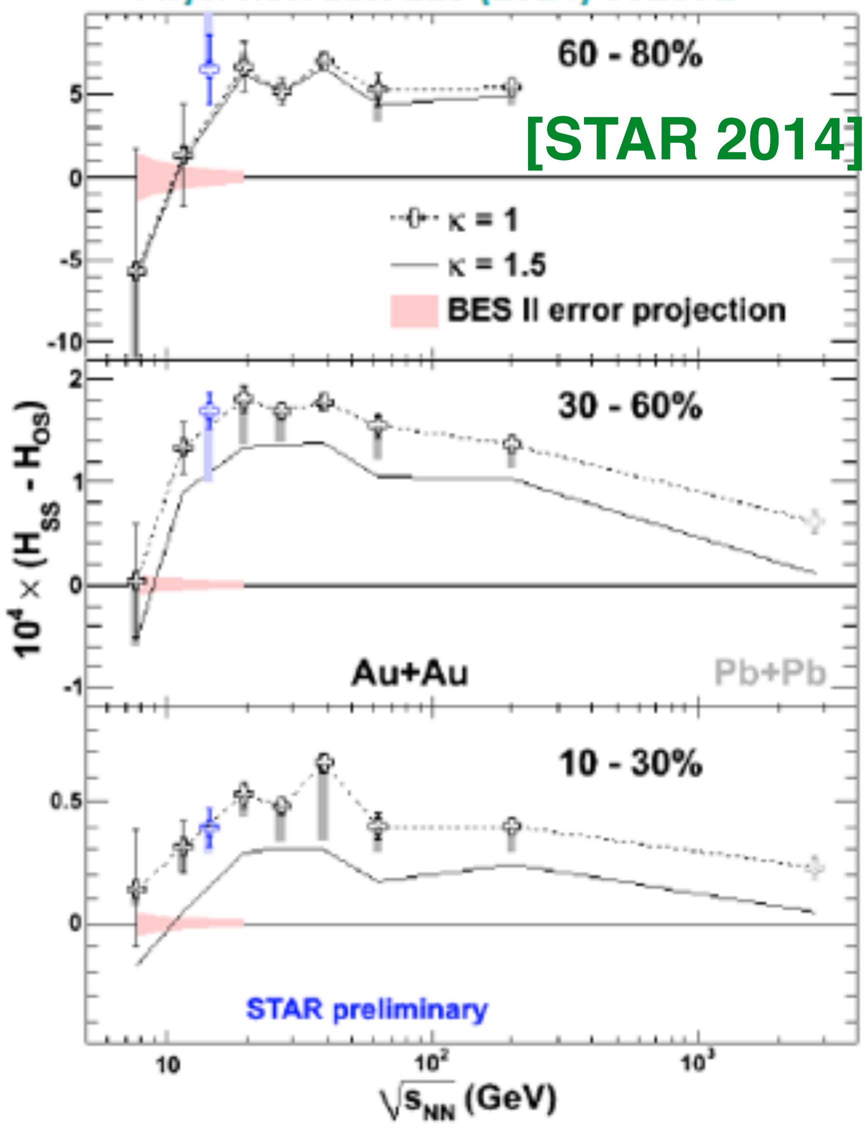
So-extracted signal:

**** is consistent with CME***

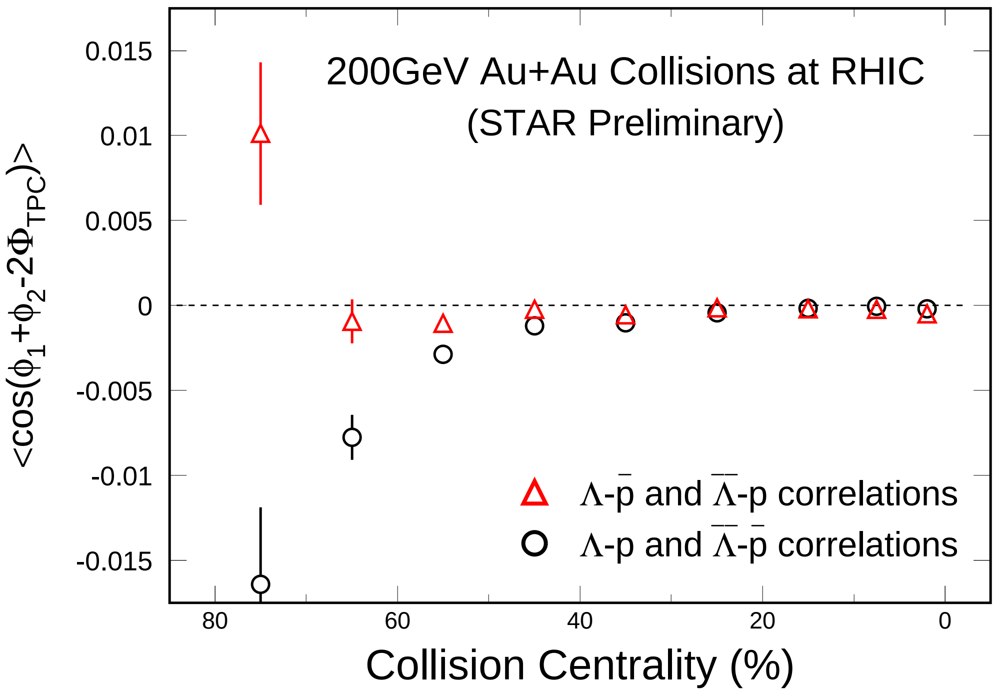
**** disappears at low beam energy***

BES-II data will be crucial!

Phys. Rev. Lett 113 (2014) 052302



Discovery of Chiral Vortical Effect?



A striking observation. Could be baryon number separating fluctuations perpendicular to the reaction plane, due to $\vec{L}+$ chiral anomaly + topological fluctuations.

Could it be anything else? Have confounding effects analogous to those that Bzdak+Koch first pointed out in the CME context been ruled out?

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Quantum Aspects of QGP?

- Again, present data motivates a major theoretical response, with the goal of quantitative understanding of the data and the physics.
- Progress requires the development of relativistic viscous chiral magnetohydrodynamics codes that propagate axial charge density, incorporating anomalous couplings between $\vec{B}$, hydrodynamic flow, and gauge field fluctuations.
- Early work in this direction, learning how to formulate this, is already being applied to simpler chiral systems in condensed matter physics.
- Success in the larger program would constitute the discovery of the onset of chiral symmetry restoration.
- Success in the larger program would constitute the discovery of the QCD analogue of the quantum fluctuations of the electroweak gauge fields that are thought to have generated the matter-antimatter asymmetry of the universe, at temperatures 1000 times hotter than we can recreate in the lab.

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