Jet Quenching in the Most Liquid Liquid in the Universe

Krishna Rajagopal

MIT

(once upon a time a Sherman Fairchild Fellow here,
at this "scientific oasis")

Walter Burke Institute Inaugural Symposium

Caltech; Pasadena, CA; Feb 24, 2015

A Grand Opportunity

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

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

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

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 $^\circ$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.

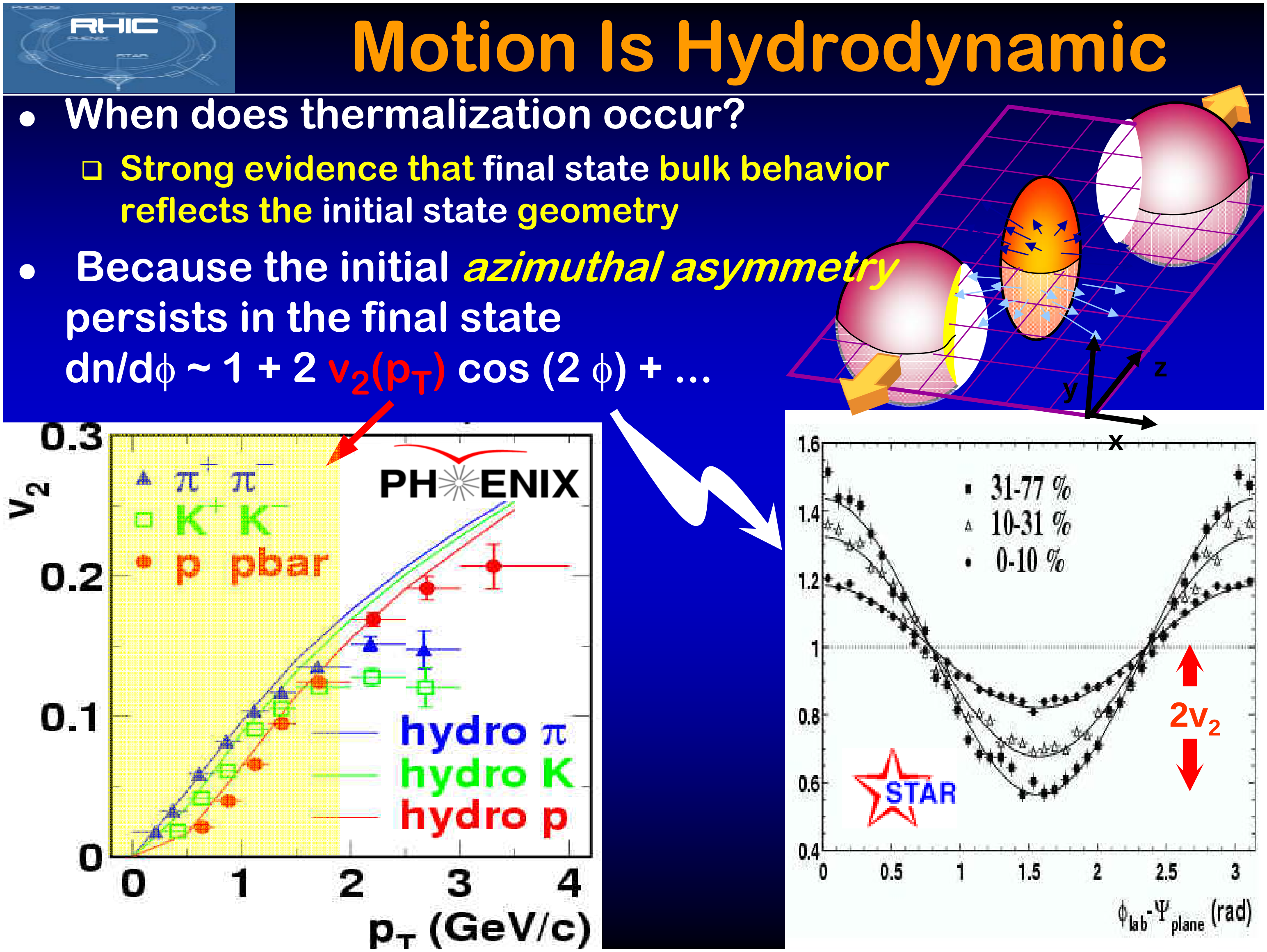
- Experiments now producing droplets of QGP at temperatures several times T_c, reproducing the stuff that filled the few-microseconds-old universe.

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.

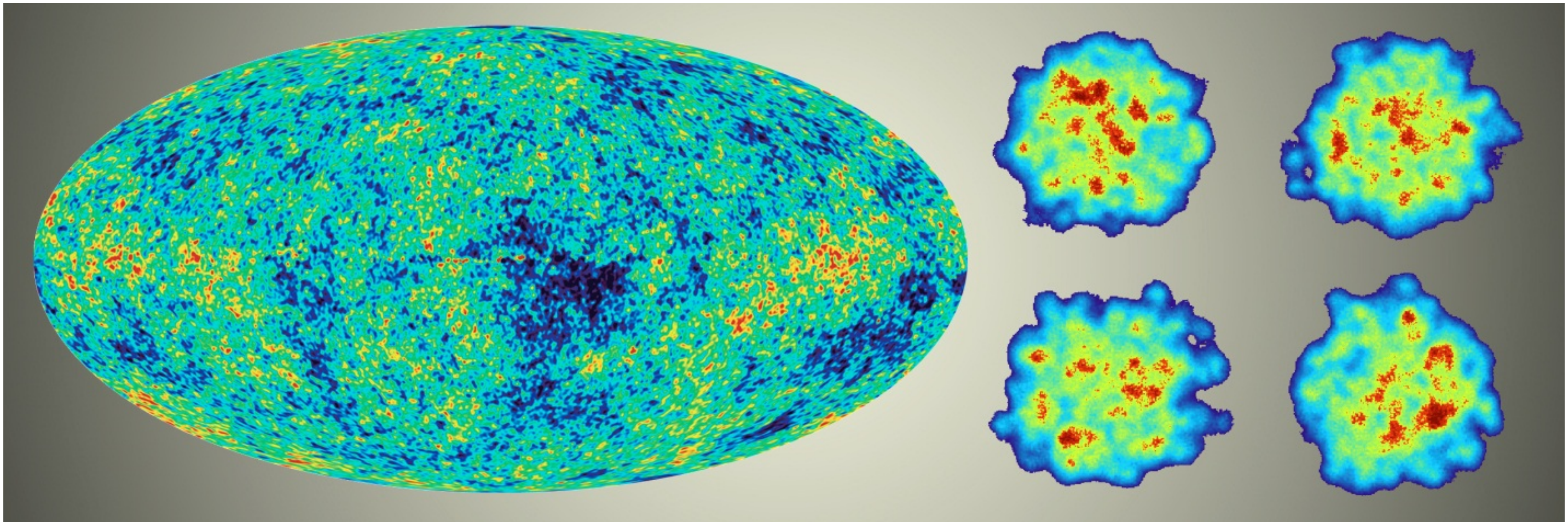
- (Except one: droplet of trapped fermionic atoms at nano-Kelvin temperatures, with atom-atom cross-section tuned to infinity. Its η/s comes close.)

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



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

QGP cf CMB

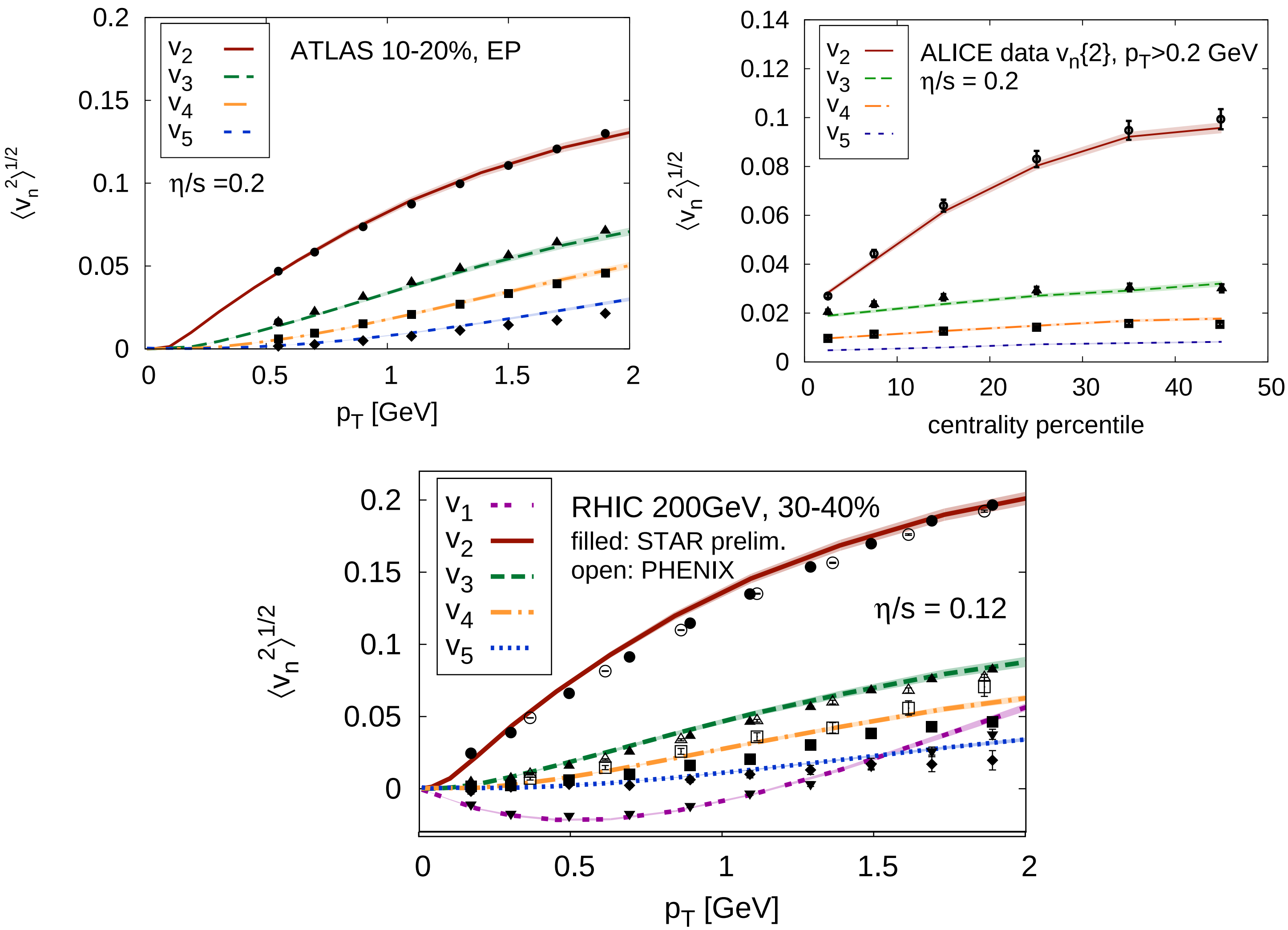


QGP cf CMB

- 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, as functions of p_T and particle species. But, billions of events. And, controlled variations of the initial conditions...
- The fact that the initial ripples persist as ripples in the debris of the explosion (e.g. v_3 and v_5), i.e. that we can see the initial ripples, is evidence for the smallness of η/s.

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.

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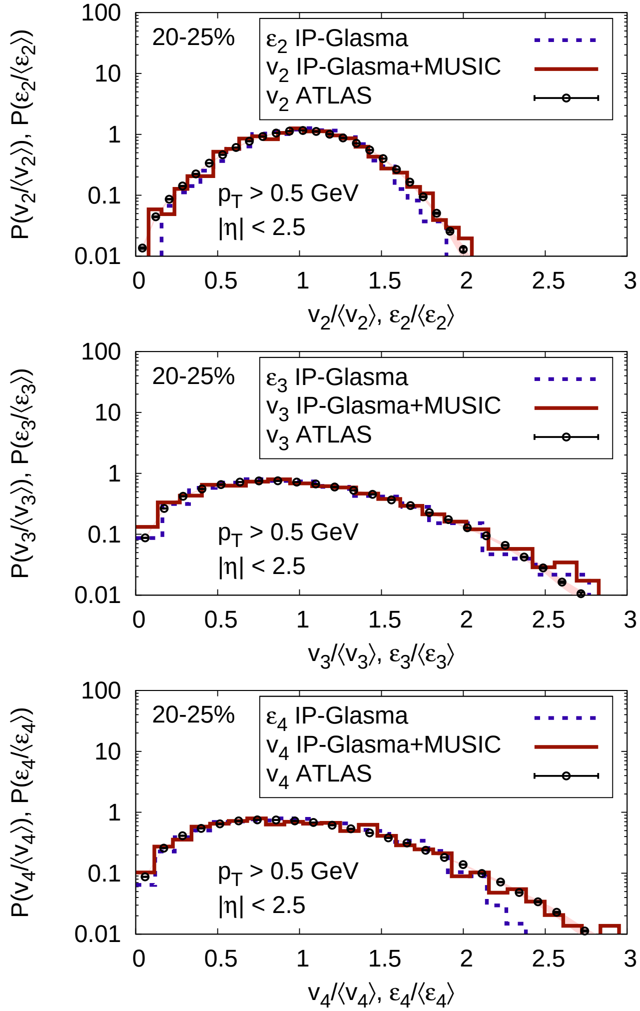


And v_n-fluctuations in the final state too...

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

Determining η/s from HIC

- Using relativistic viscous hydrodynamics to describe expanding QGP, microscopic transport to describe late-time hadronic rescattering, and using RHIC and LHC data on pion and proton spectra and $v_2 \ldots v_6$ as functions of p_T and impact parameter...

- QGP@RHIC ($T_c < T \lesssim 2T_c$) and QGP@LHC ($T_c < T \lesssim 3T_c$) both have $1 < 4\pi\eta/s < 3$, with some evidence that η/s is smaller at lower RHIC temperatures. [Largest remaining uncertainty: treatment of initial fluctuations; extraction from data (rather than modeling them) coming.]

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

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. . .

What Next?

- **So, you've discovered/recreated the hottest liquid phase of matter that has ever existed in the Universe...**

- **And, you've learned that it is the most liquid liquid that we've ever seen in the laboratory...**

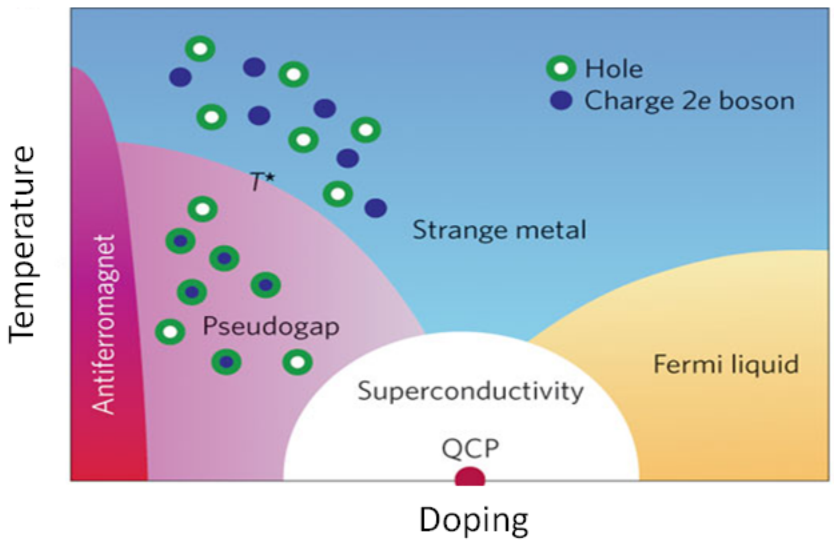
- **Now what do you do with it?**

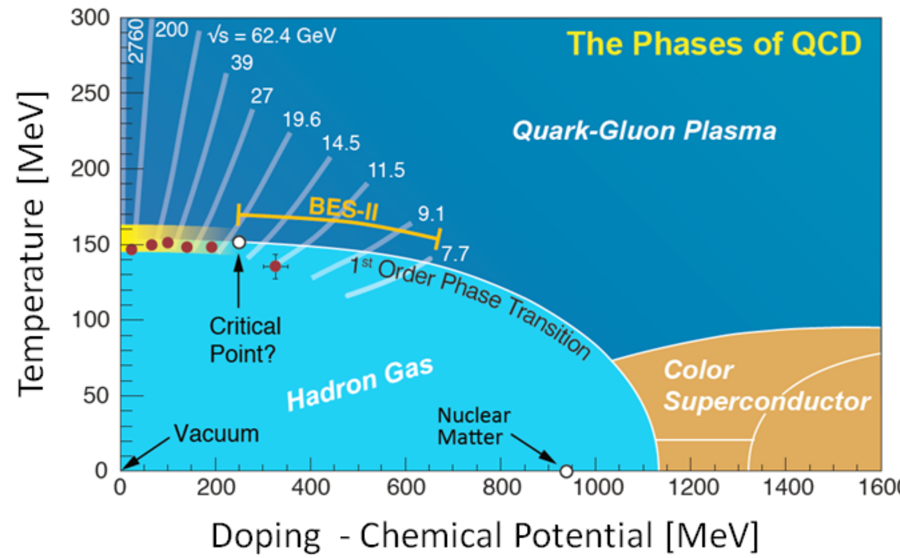
- **Characterize its properties and dynamics, at its natural length scales where it has no quasiparticles.**

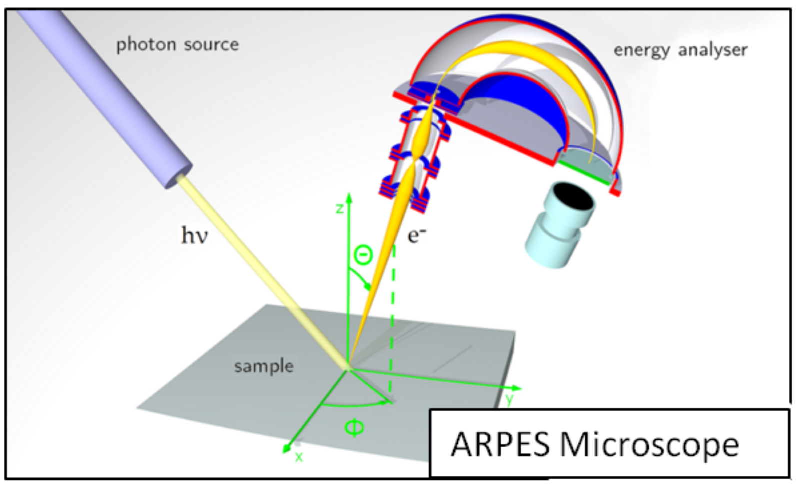
- **Dope it. Map out the phase diagram of QGP as a function of T and excess of quarks over antiquarks.**

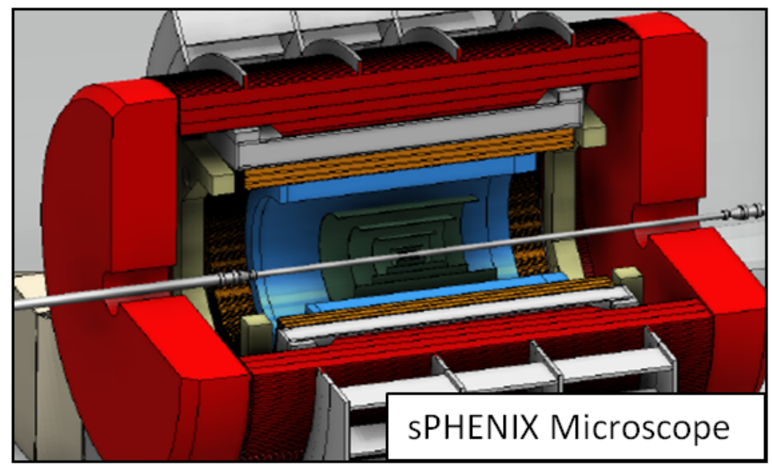
- **Probe it. How does it work? How can we probe and understand liquid QGP at** *short distance scales***? If resolved with a sufficiently powerful microscope, the liquid** *is* **made of well understood weakly coupled quarks and gluons. How does a liquid emerge from an asymptotically free gauge theory?**

Doping and Probing the QGP









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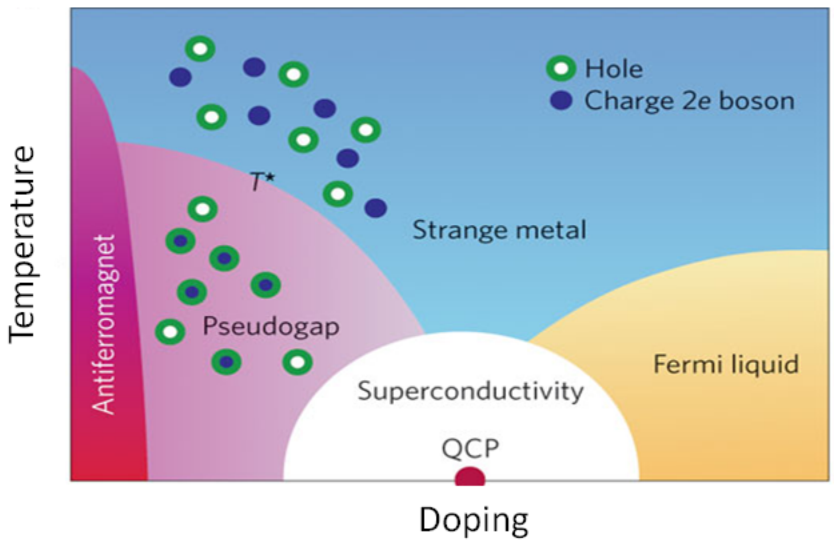
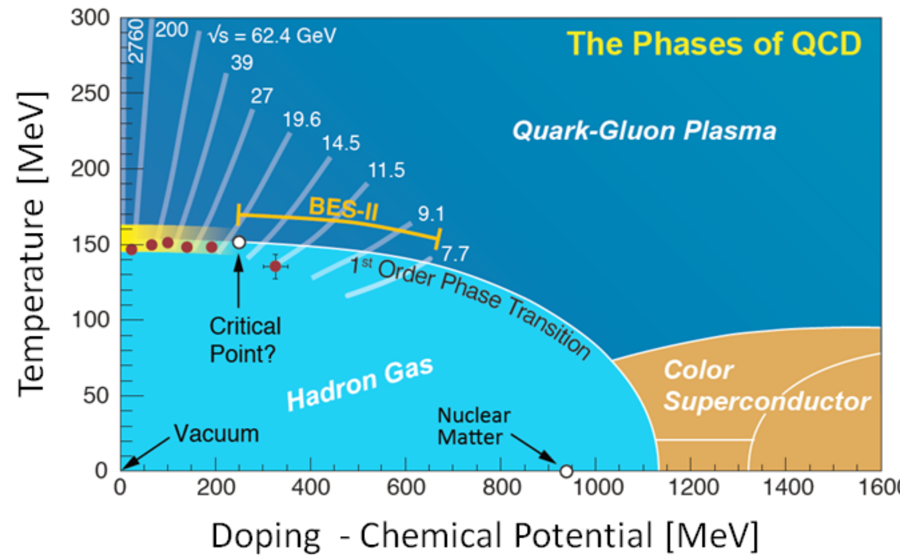
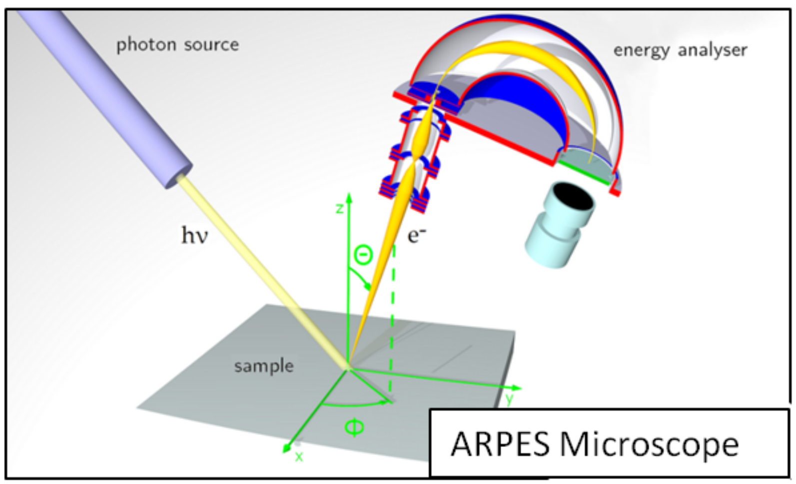
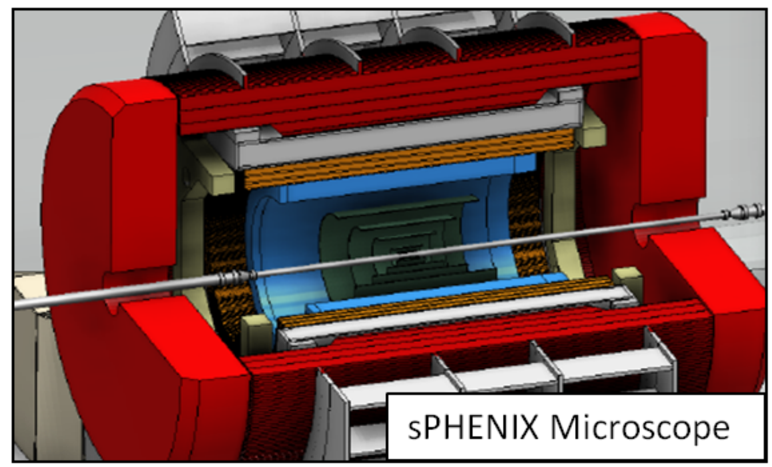
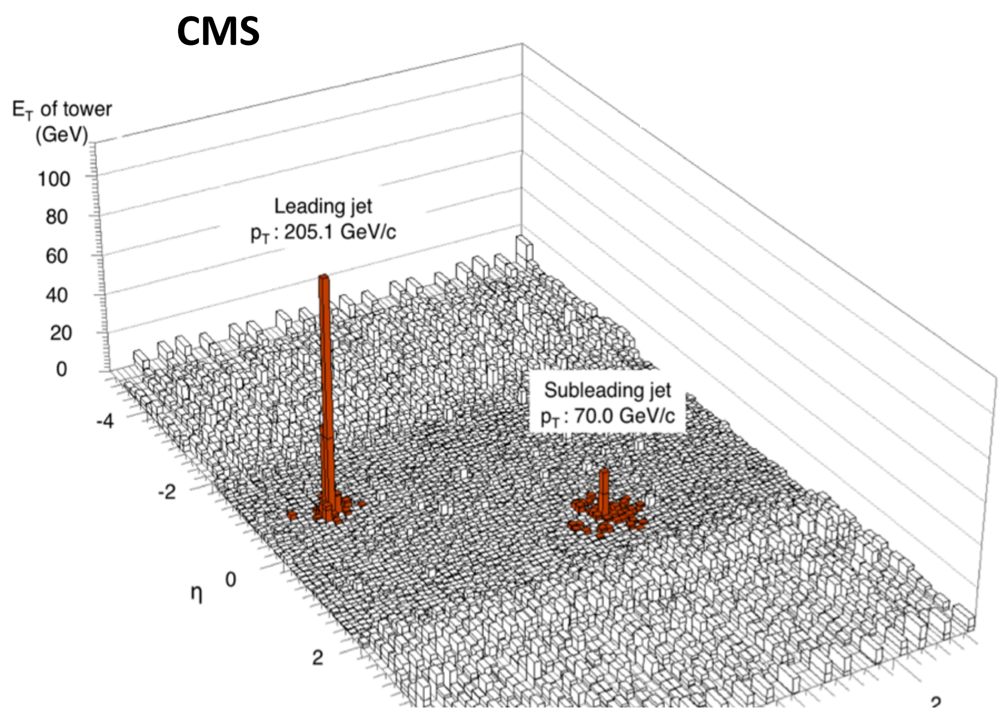


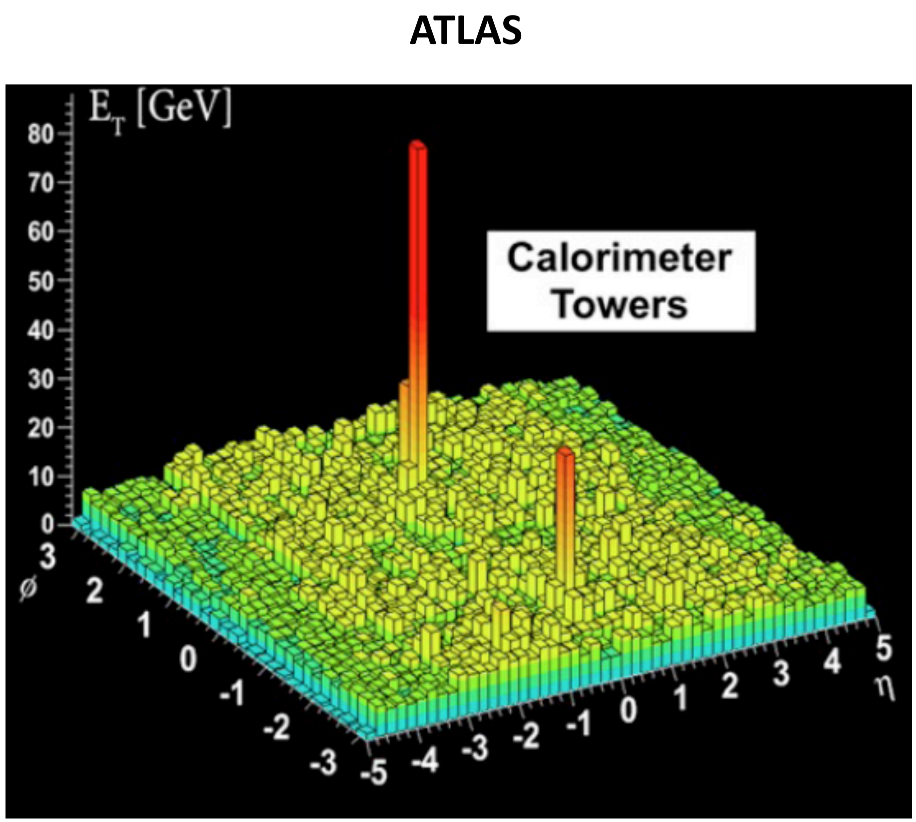






Jet Quenching at the LHC





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.

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? (Later we will focus on the small differences.)
- 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 'lost' energy?

- **In any strongly coupled approach, energy is 'lost' to hydrodynamic modes with wave vector $<$ or $\lesssim \pi T$.**
- **The attenuation distance for sound with wave vector q is**

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

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

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

- **Energy lost more than a few $x^{\text{sound}}_{\text{damping}}$ before the jet emerges will thermalize, becoming soft particles in random directions. Only energy lost within a few $x^{\text{sound}}_{\text{damping}}$ 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. Easier to see in lower T plasma?**

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One More Question

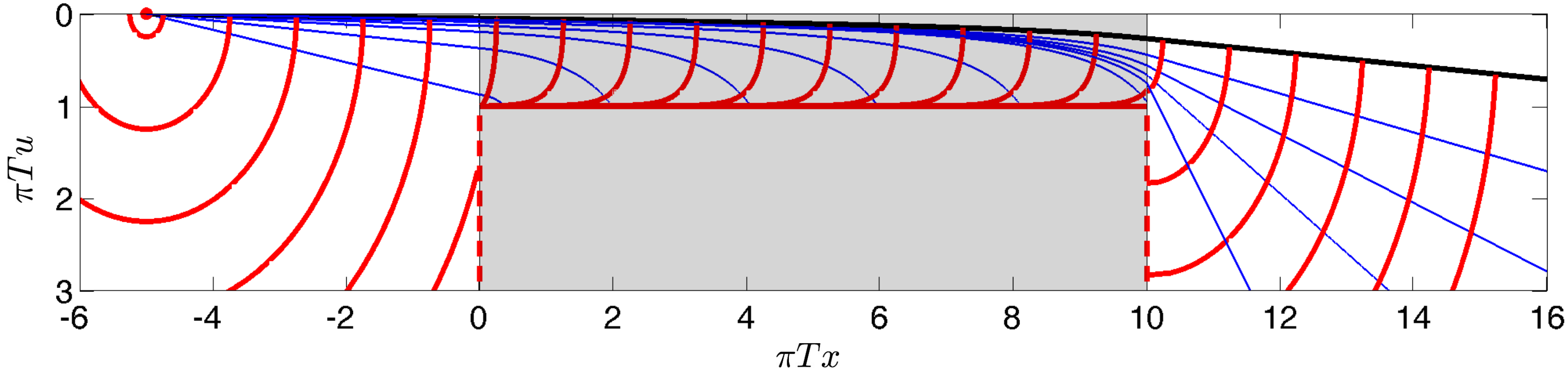
- **So, why did I write "jets" instead of jets? Which is to say, what is a jet in $\mathcal{N} = 4$ SYM theory, anyway? There is no one answer, because hard processes in $\mathcal{N} = 4$ SYM theory don't make jets.** Hatta, Iancu, Mueller; Hofman, Maldacena.
- **The formation of (two) highly virtual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

What have we (PC+KR) 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. Arnold and Vaman did same for differently constructed "jets".)
- We do the AdS/CFT version of the brick 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

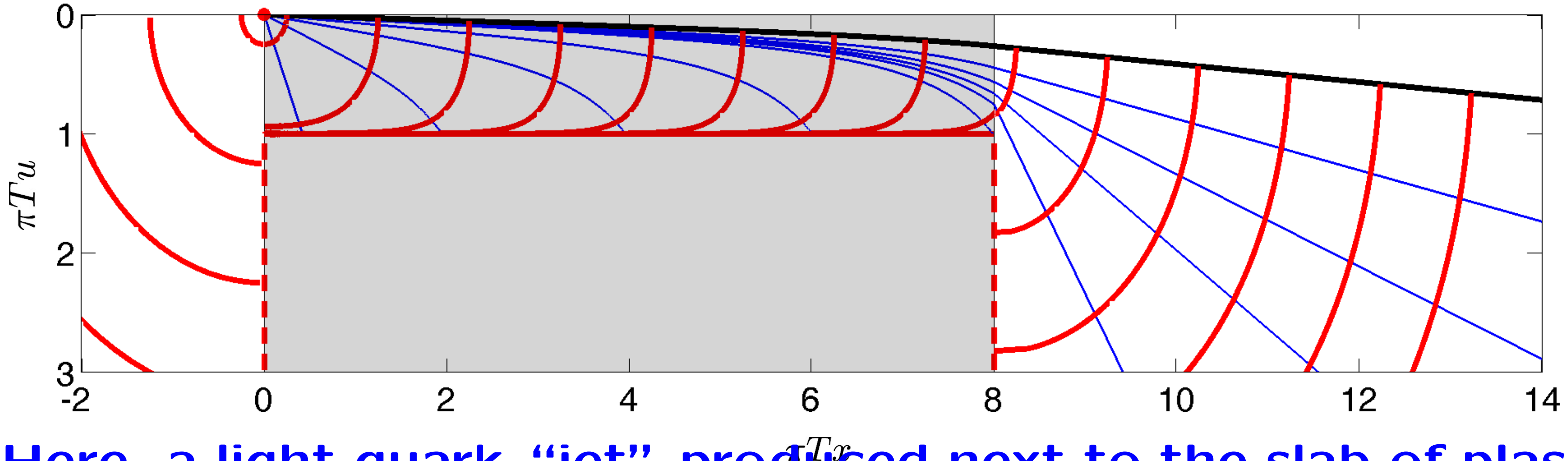


A light quark "jet", incident with E_{in}, shoots through a slab of strongly coupled $\mathcal{N} = 4$ SYM plasma, temperature T, thickness $L\pi T = 10$, assumed $\gg 1$. What comes out the other side? A "jet" with $E_{\text{out}} \sim 0.64 E_{\text{in}}$; just like a vacuum "jet" with that lower energy,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

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"

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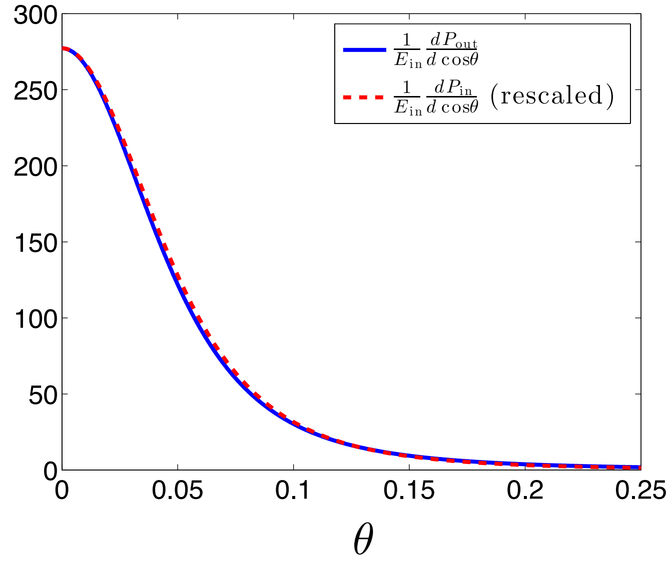
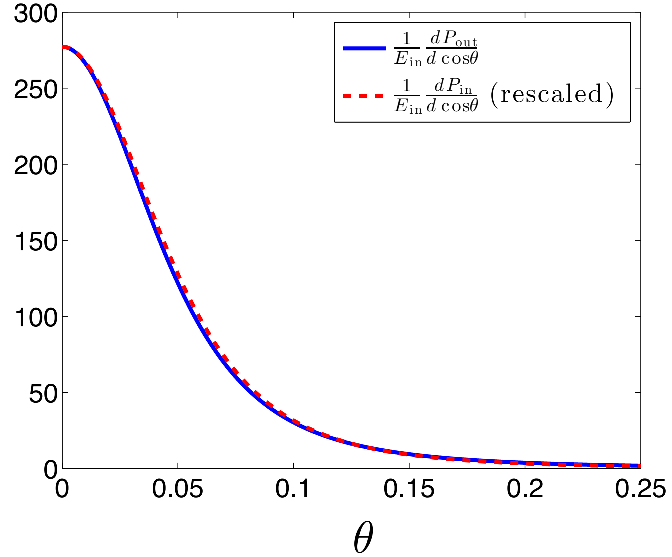


Shape of outgoing "jet" is the same as incoming "jet", except broader in angle and less total energy.

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



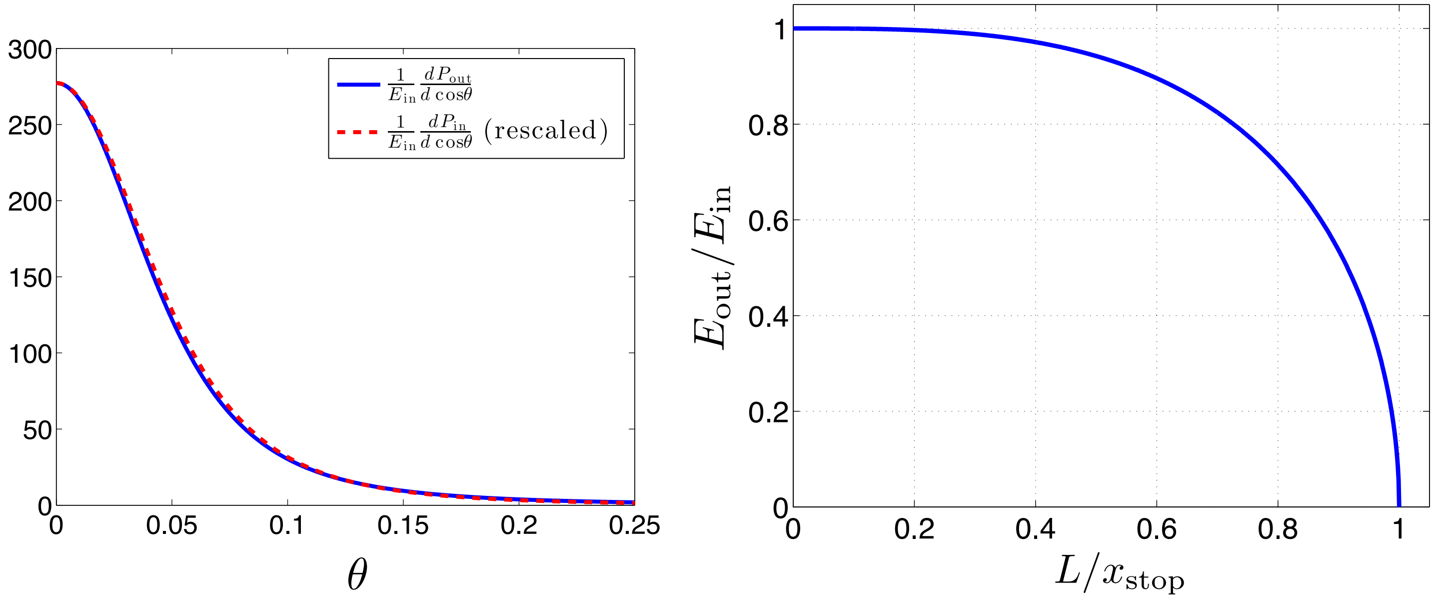
Blue curve is angular shape of the "jet" that emerges from the slab after having been quenched.

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 $E_{\rm out}$ 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 a "Bragg peak":

$$\frac{1}{E_{\rm in}}\frac{dE_{\rm out}}{dL} = -\frac{4L^2}{\pi x_{\rm stop}^2}\frac{1}{\sqrt{x_{\rm stop}^2 - L^2}} \quad \text{where} \quad \pi T x_{\rm stop} = \frac{1}{\kappa}\left(\frac{E_{\rm in}}{\pi T}\right)^{1/3}$$

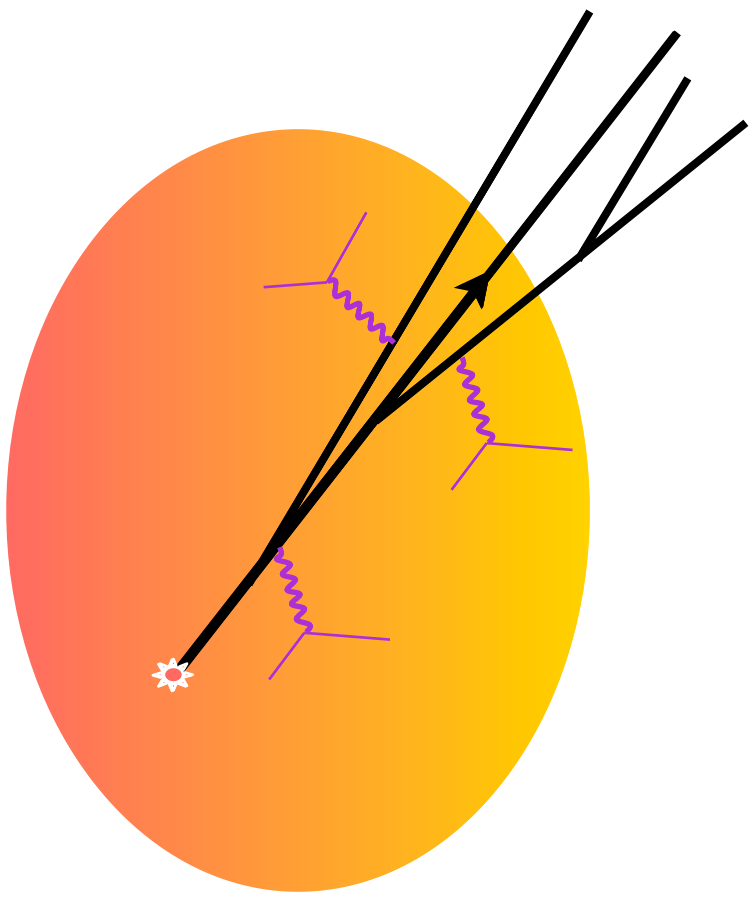
(Not a power law in L, $E_{\rm in}$, or T.) We will use this, treating κ as a parameter fit to data, in the following.

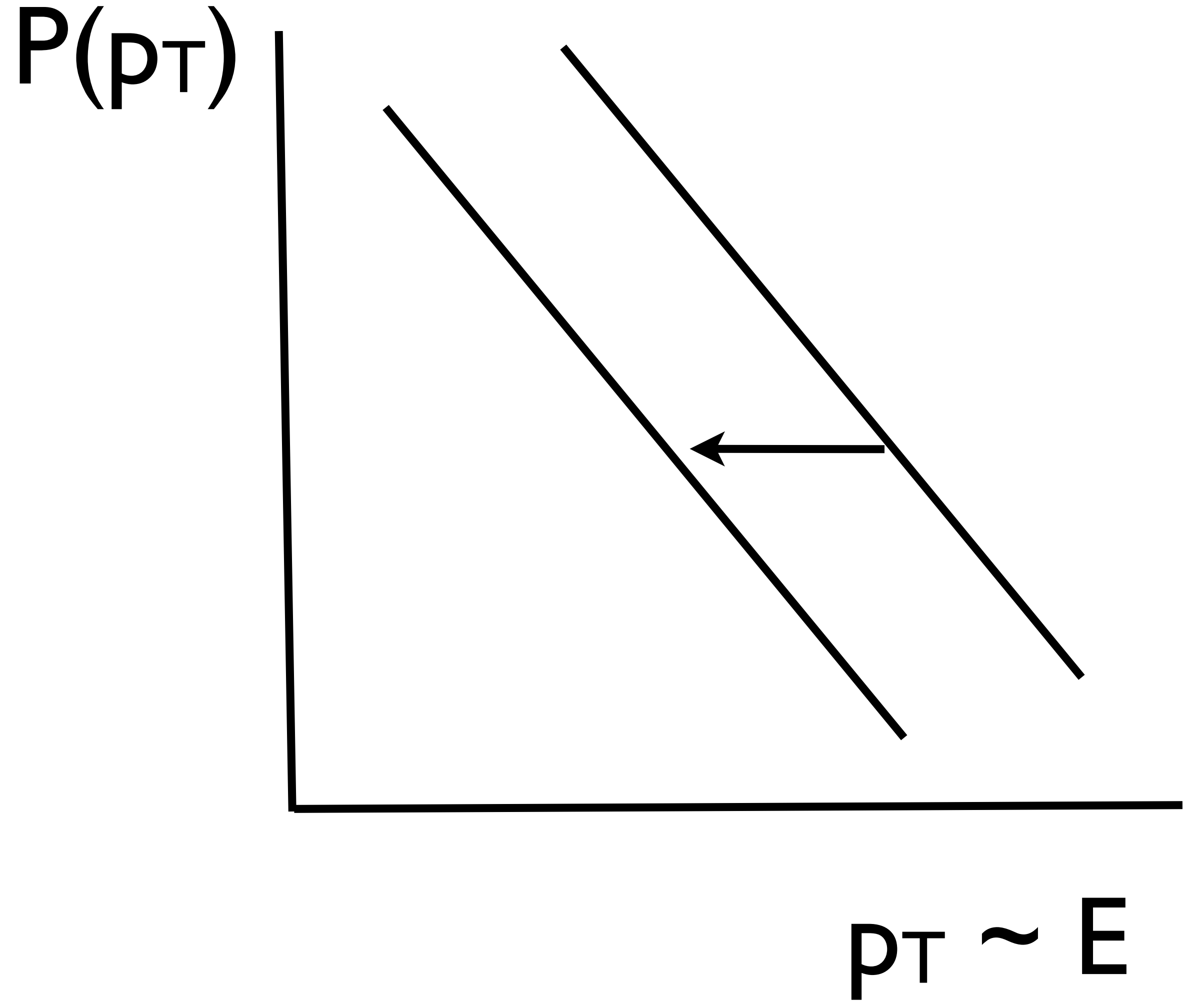
A Hybrid Approach

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

- **A hybrid approach in which the dE/dx above is applied to every parton in a PYTHIA shower. Using PYTHIA to describe the aspects of jet quenching that should be described by pQCD, but assuming that the energy loss of each QCD parton in the shower is as derived above.**
- **Interaction of jet with the medium is intrinsically a multiscale problem. Production, and fragmentation, of the hard parton are perturbative. Soft exchanges between partons in the jet and the medium are strongly coupled.**
- **Embed the jet production, evolution à la PYTHIA, and energy loss, in a droplet of plasma expanding and cooling according to hydrodynamics.**
- **We fit one model parameter, and compute *many* jet observables. (Some well-measured already; some predictions for observables to come.)**

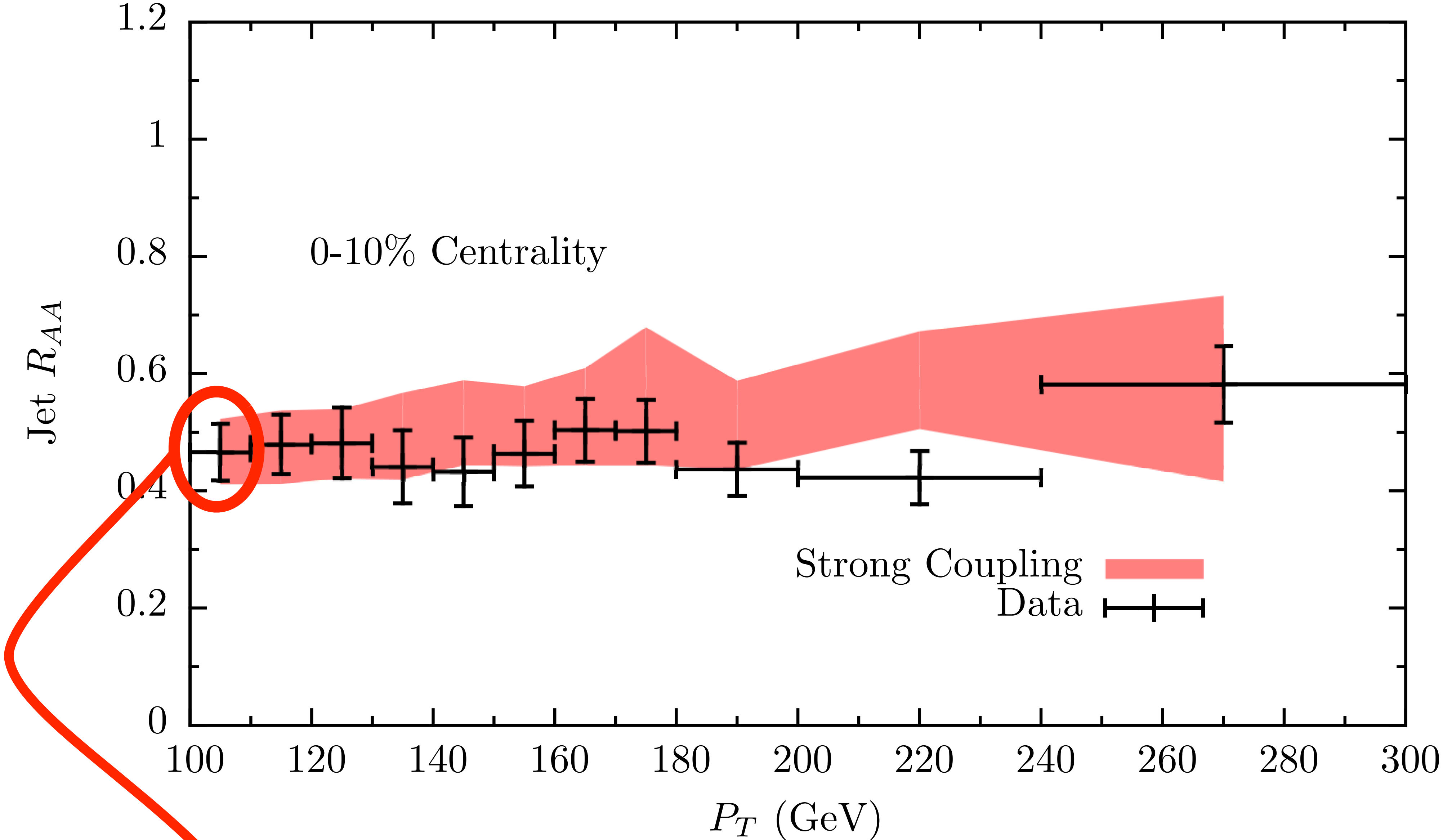
Observable: RAA





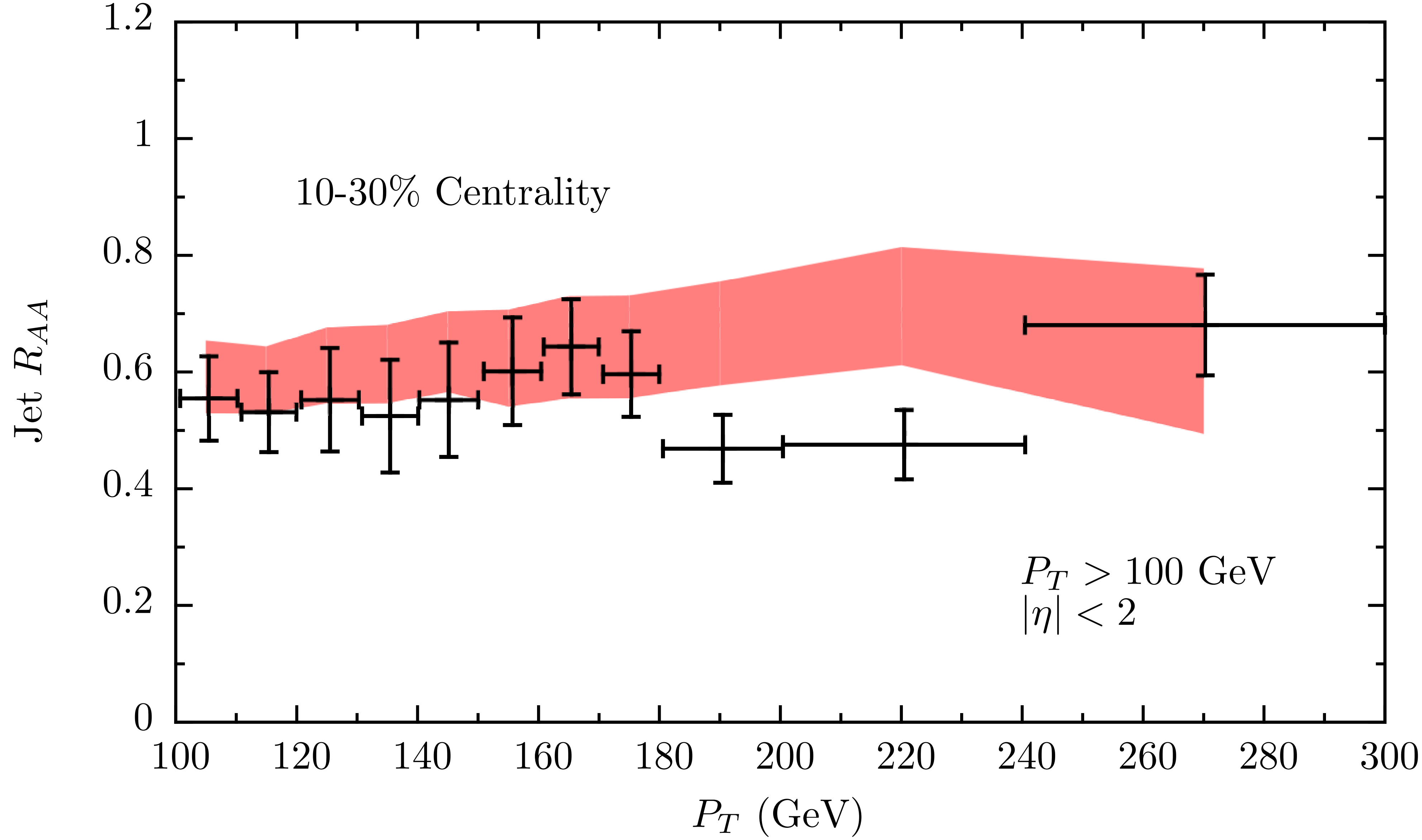
$$R_{AA} = \frac{\text{number of jets in A} - \text{A}}{\text{number of collisions } \times \text{ number of jets in p} - \text{p}}$$

Jet Suppression



Fitted value

Jet Suppression



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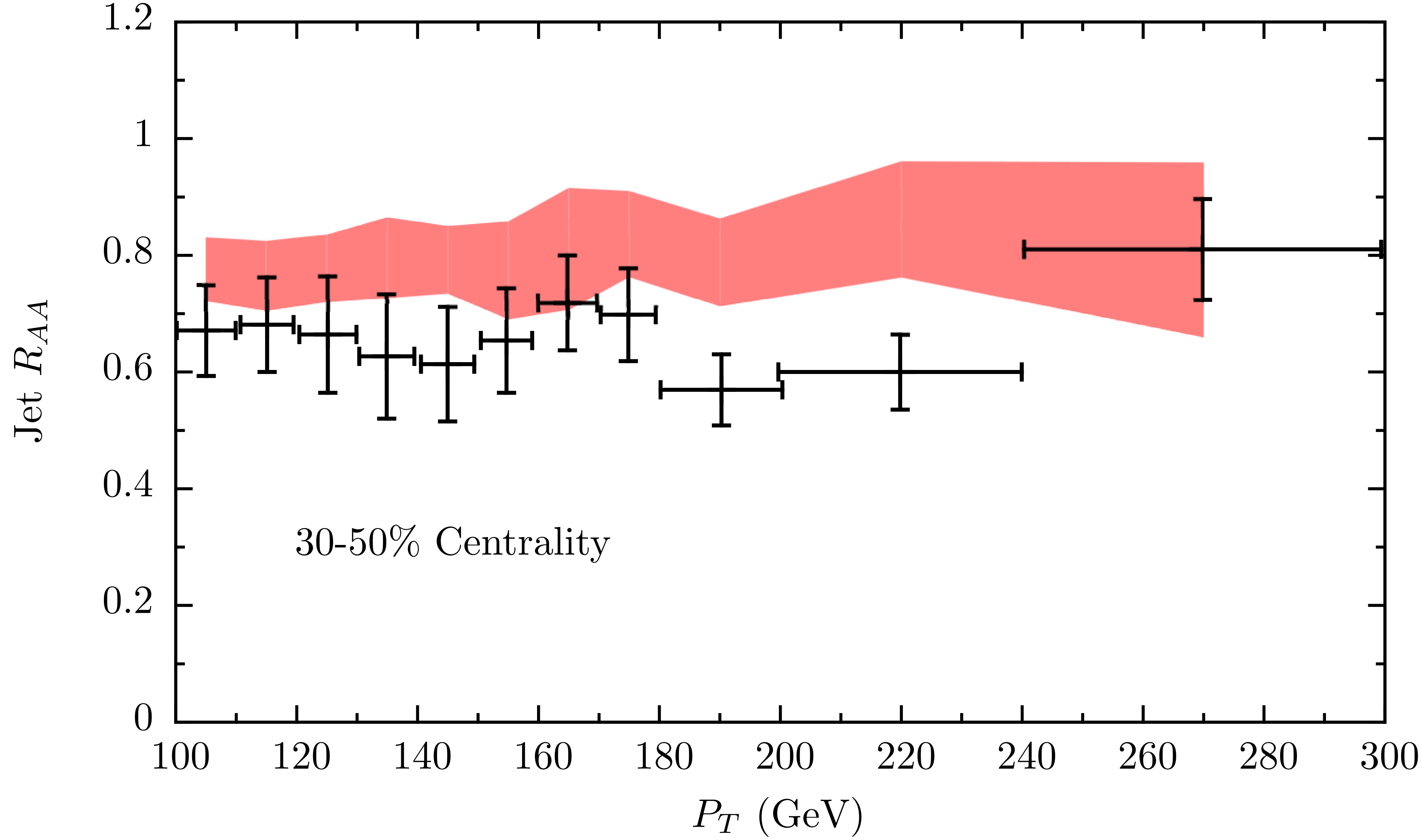

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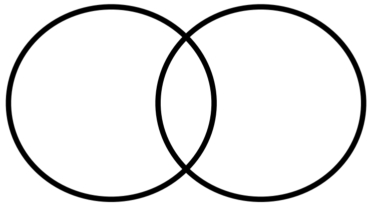
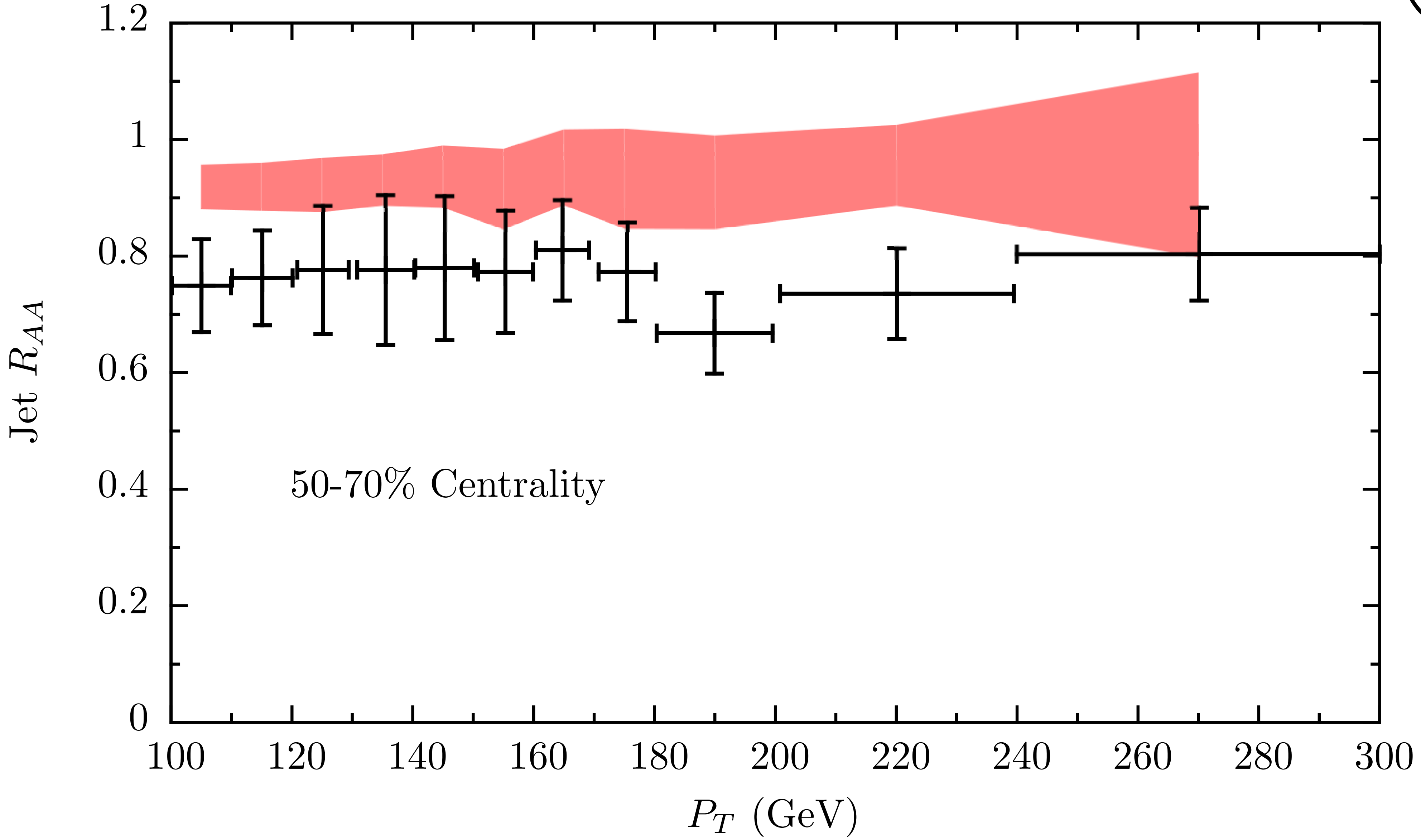
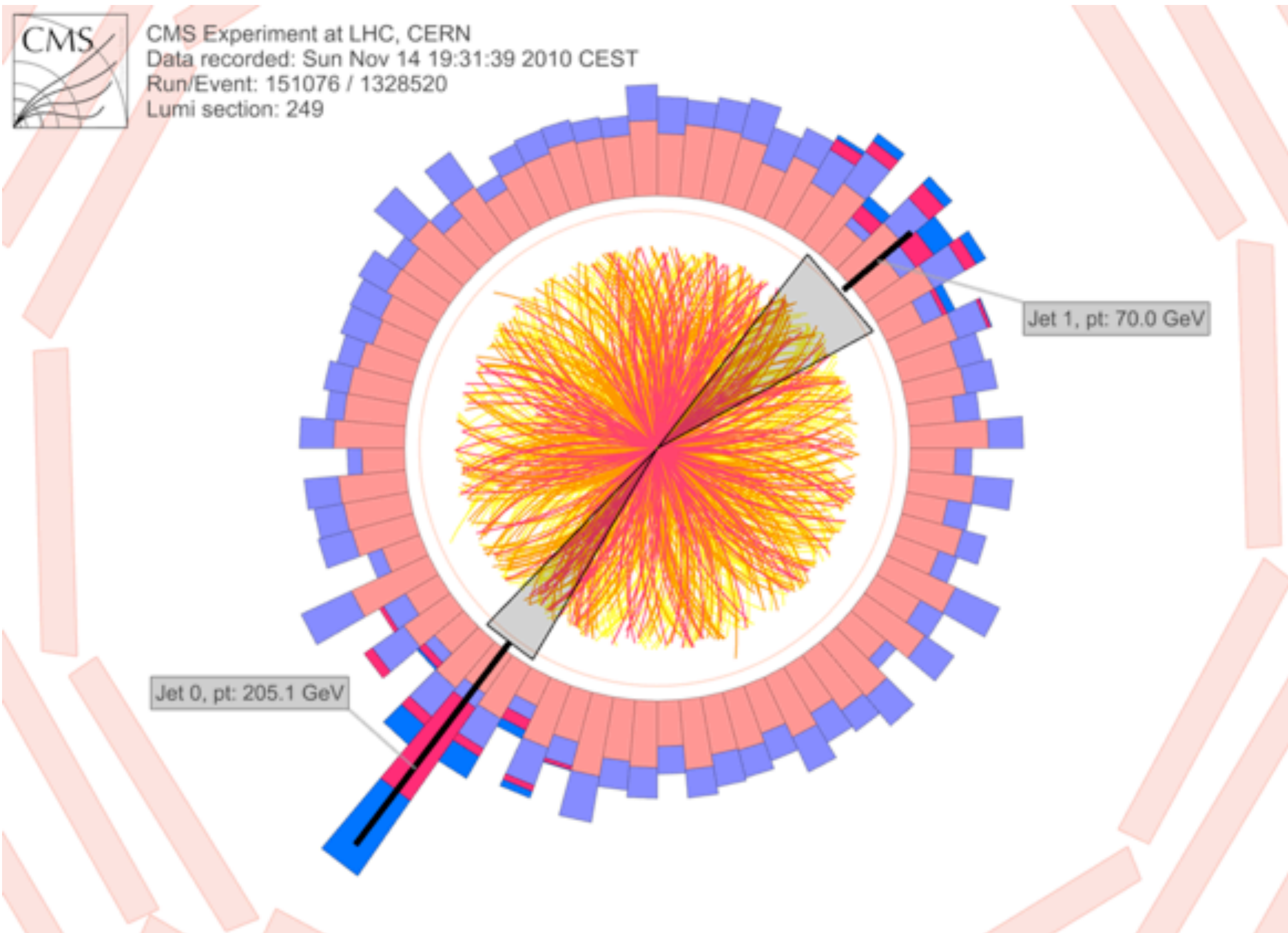
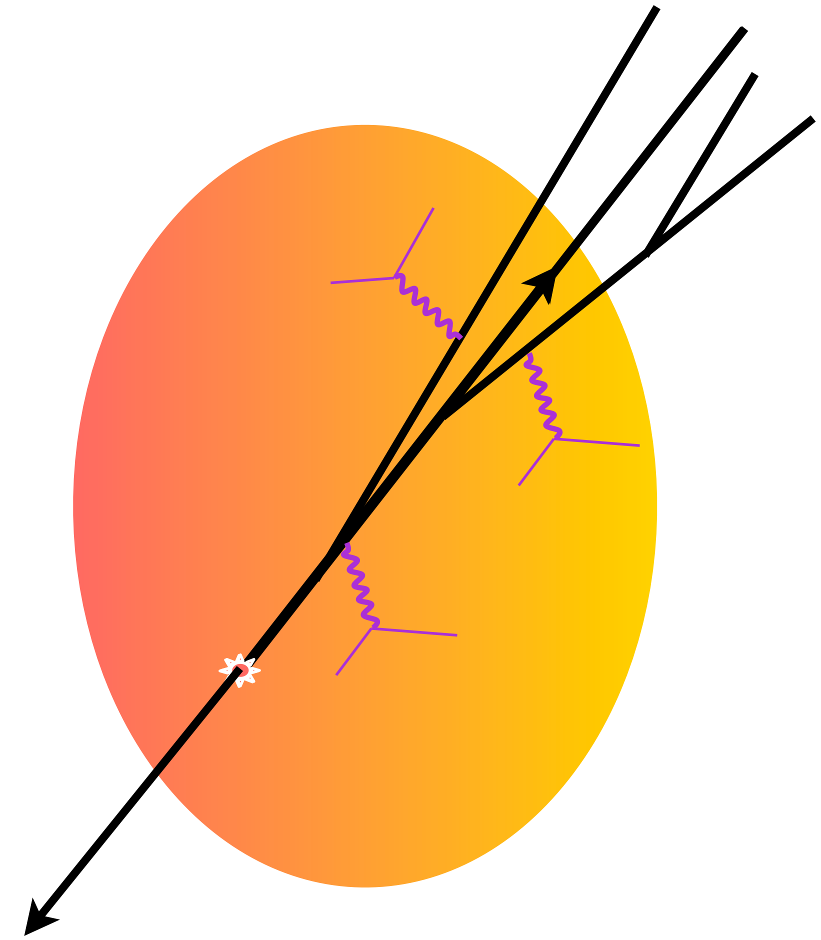




- We have only simulated the QGP phase

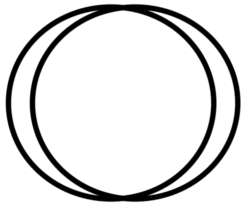
Dijets

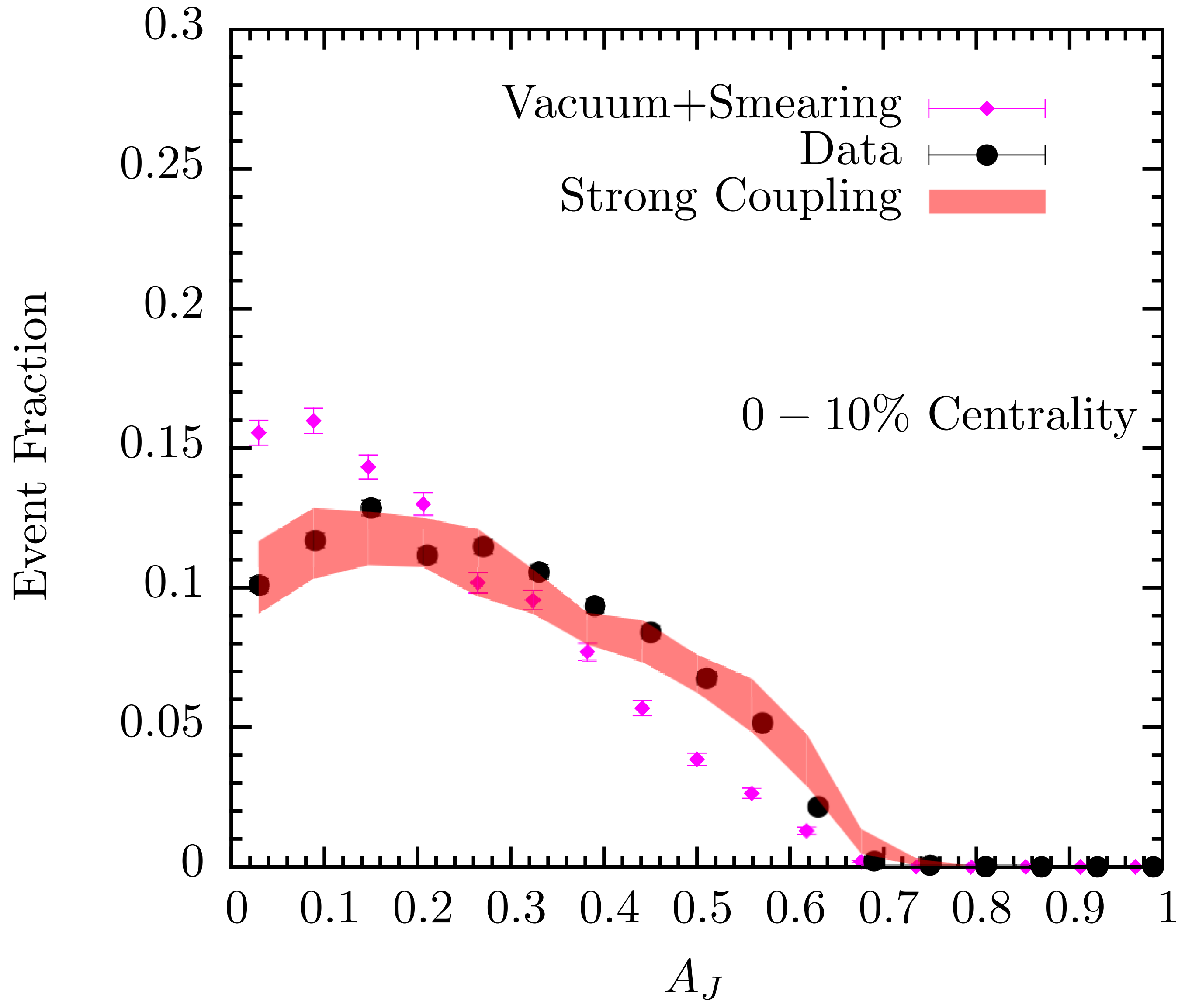




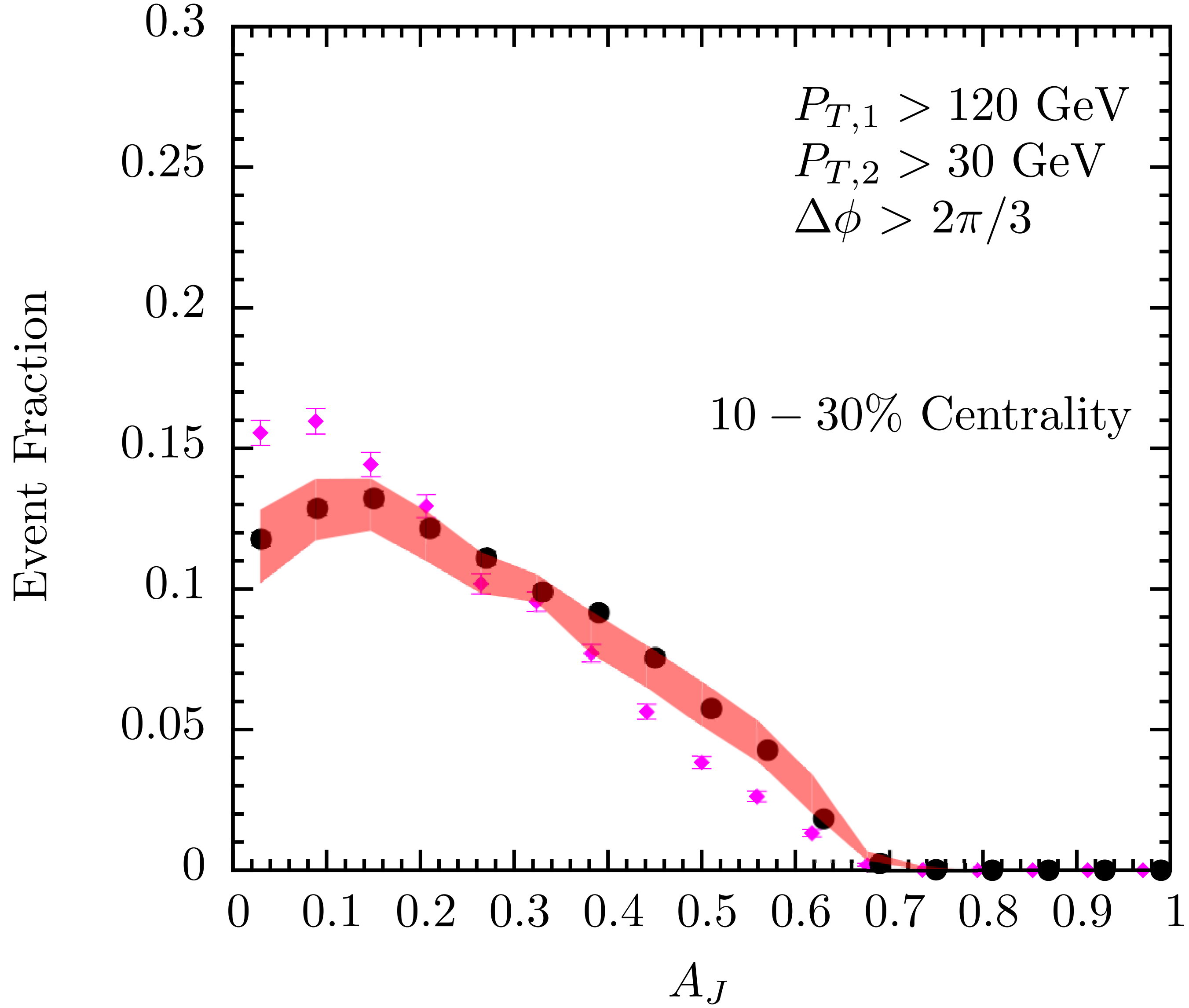
$$A_J = \frac{p_{T_1} - p_{T_2}}{p_{T_1} + p_{T_2}}$$

Imbalance

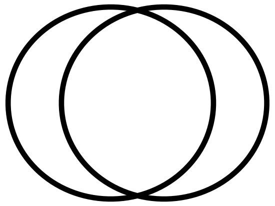



Vacuum+Smearing
Data
Strong Coupling
0 – 10% Centrality
Event Fraction
A_J
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

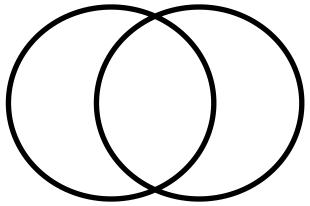
Imbalance

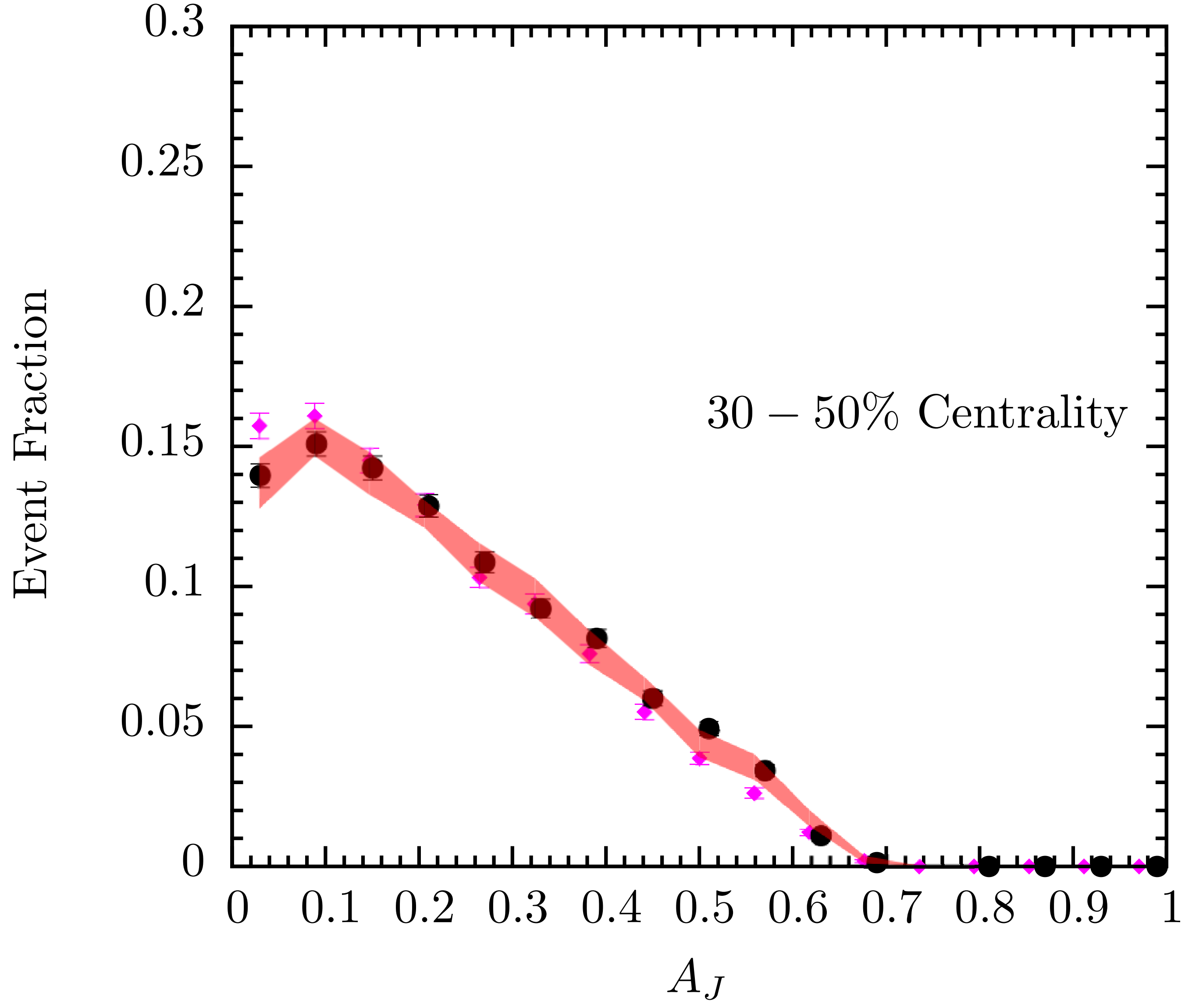


$P_{T,1} > 120$ GeV
$P_{T,2} > 30$ GeV
$\Delta\phi > 2\pi/3$
$10 - 30\%$ Centrality
Event Fraction
A_J
0 0.05 0.1 0.15 0.2 0.25 0.3
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

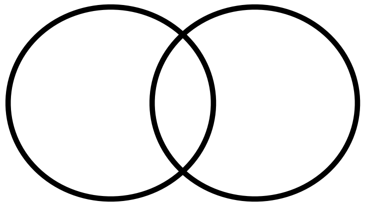


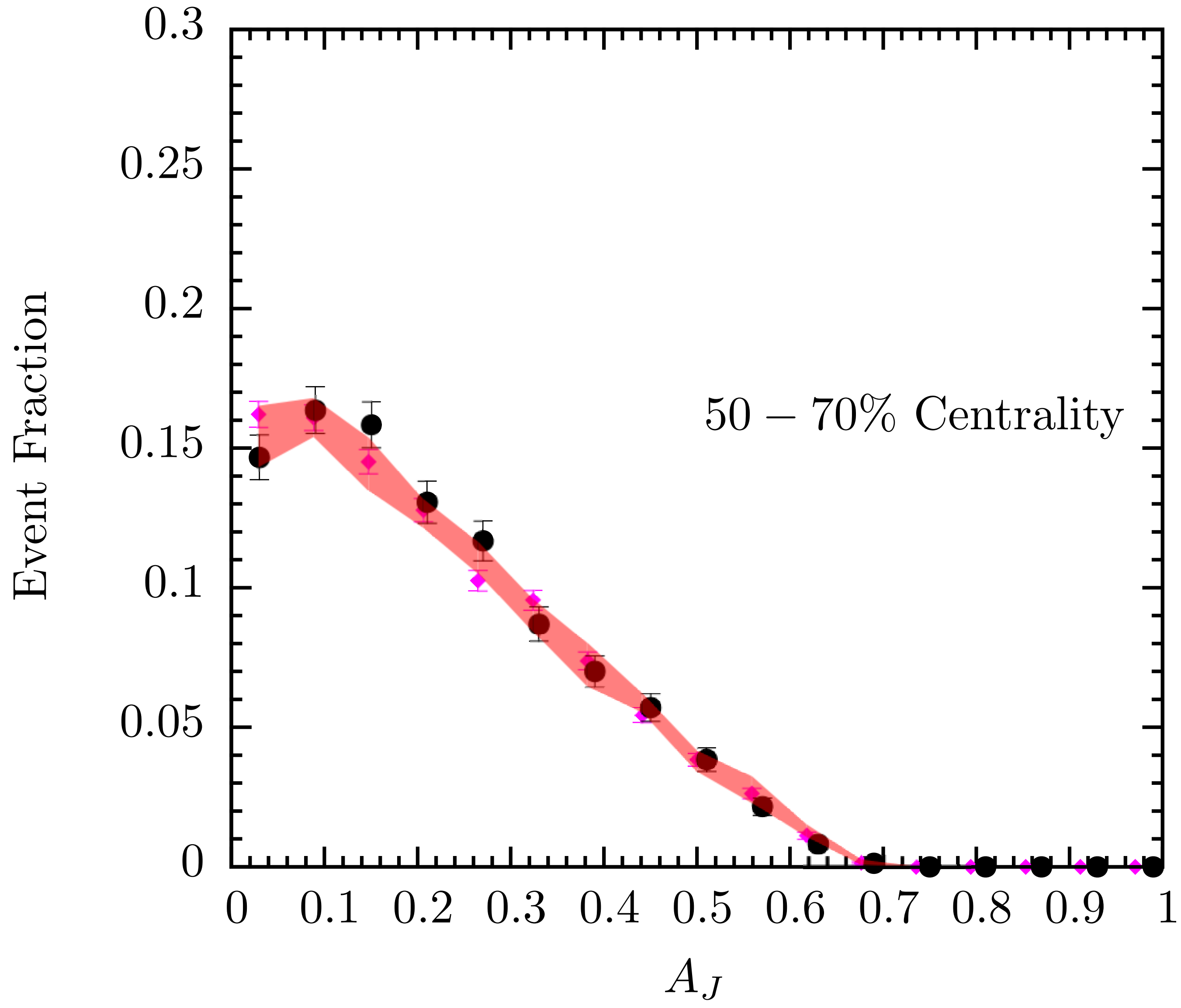
Imbalance




Event Fraction
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
A_J
30 – 50% Centrality

Imbalance

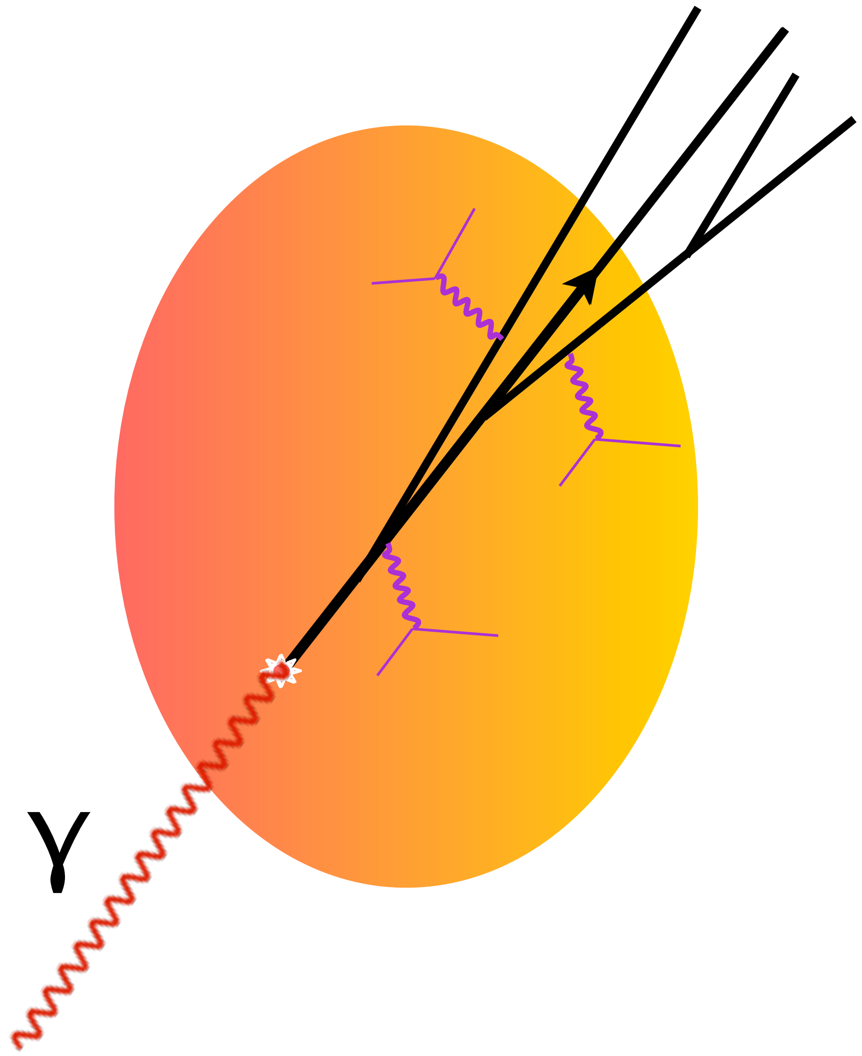




Event Fraction
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
A_J
$50 - 70\%$ Centrality

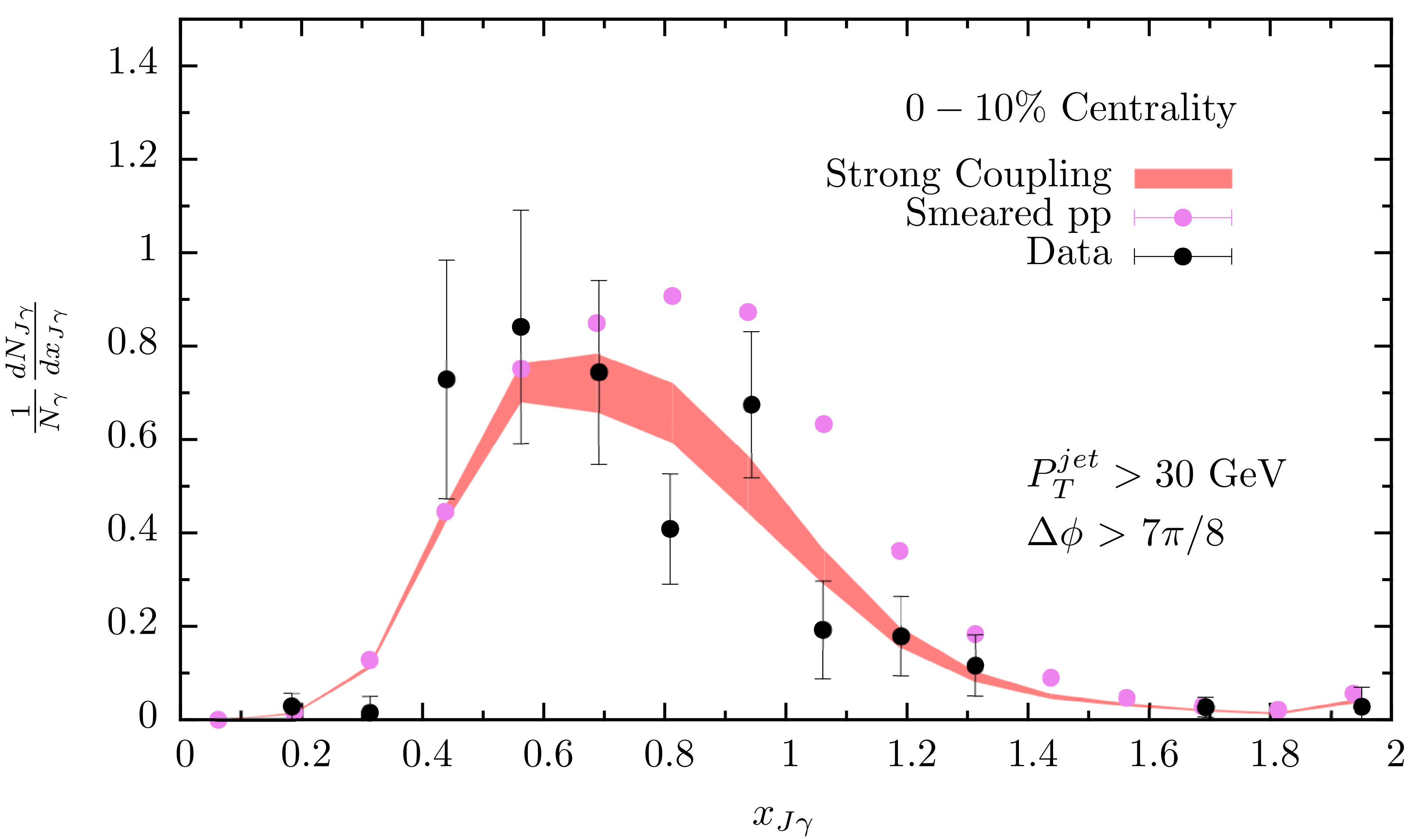
Photon - Jet

JCS, Gulhan, Milhano, Pablos and Rajagopal
(in preparation)



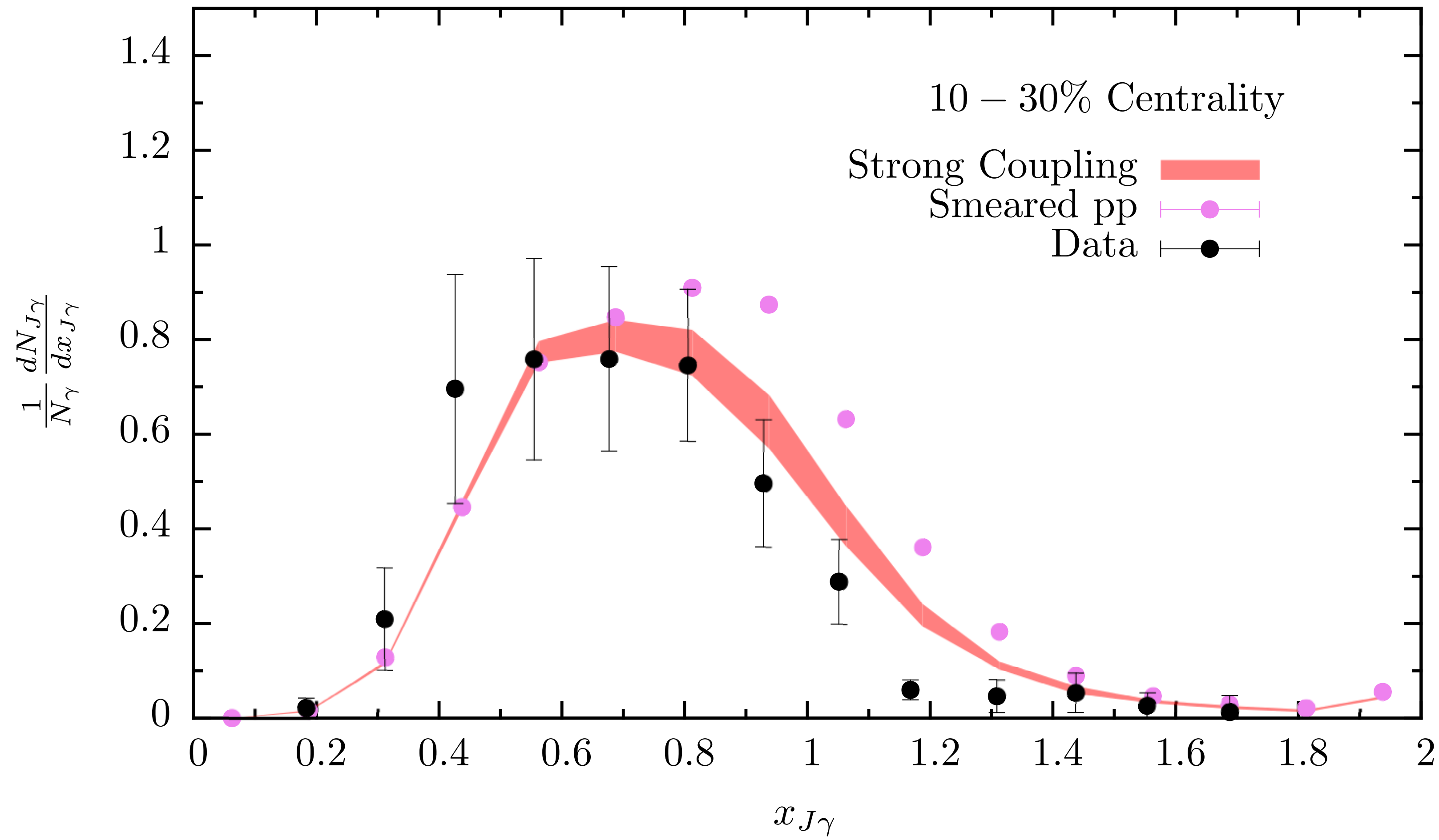
- Photons do not interact with plasma
- Look for associated jet
  - ➤ different geometric sampling
  - ➤ different species composition
  - ➤ E_γ proxy for E_{jet}

Imbalance



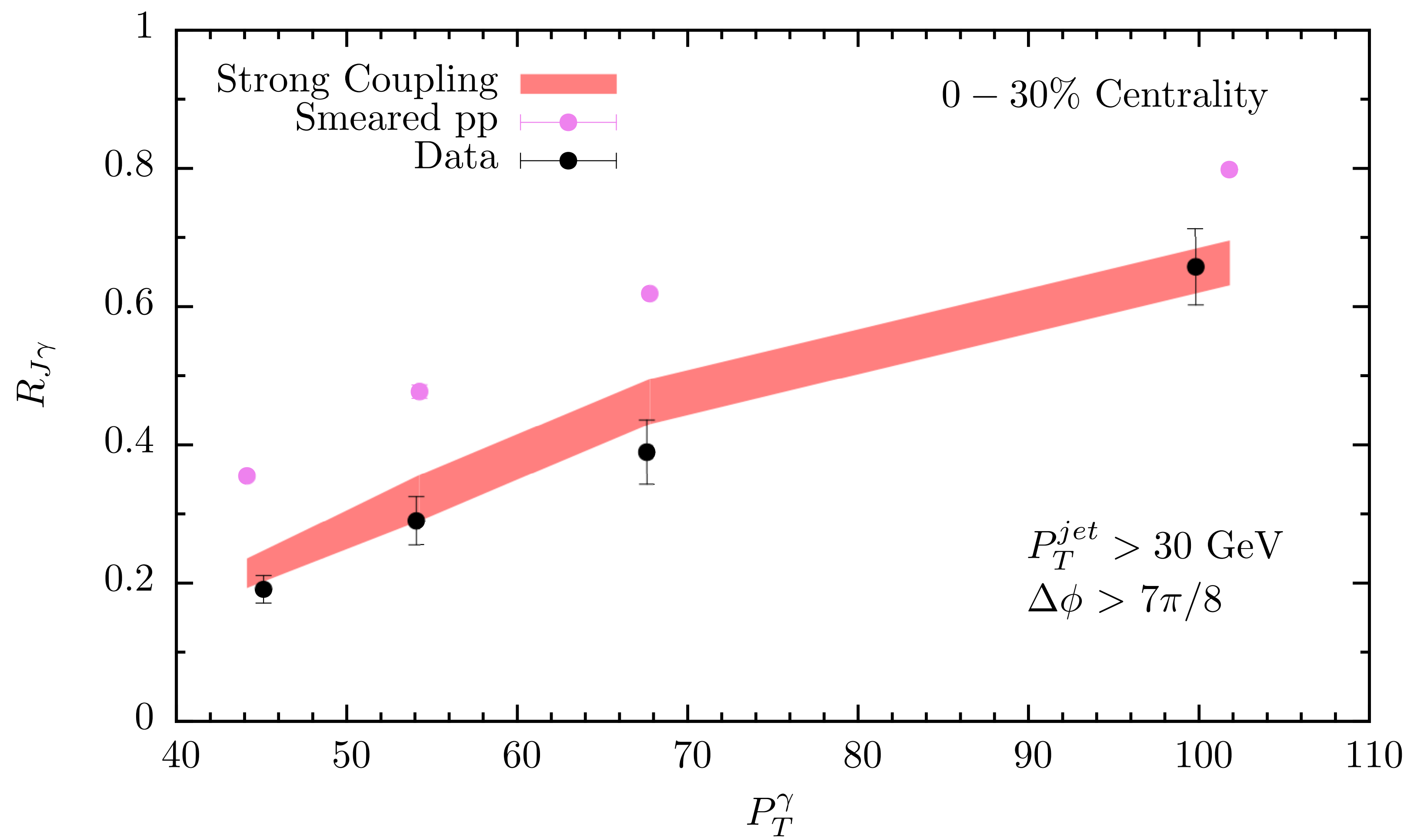
$$x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

Imbalance



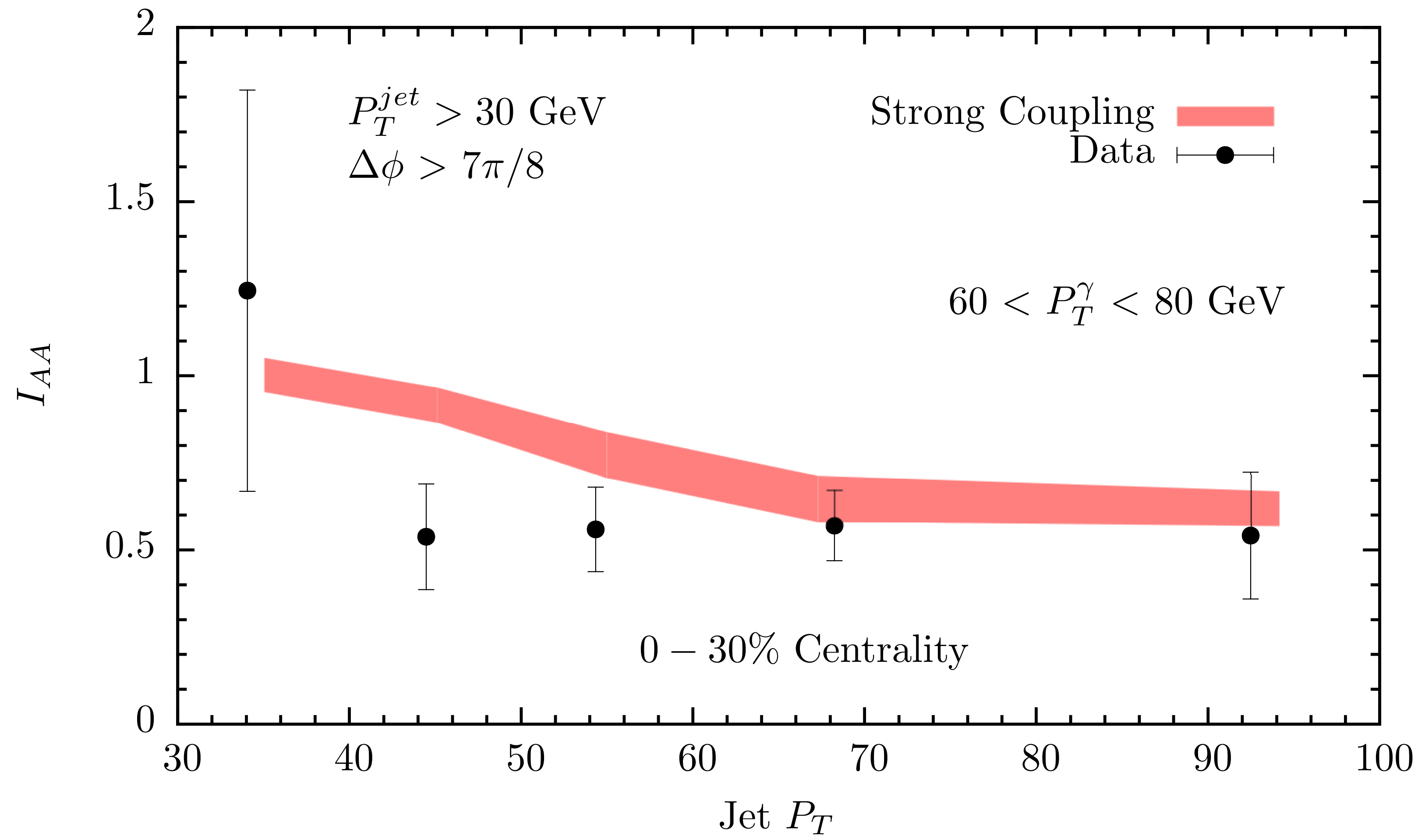
$$x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

Suppression



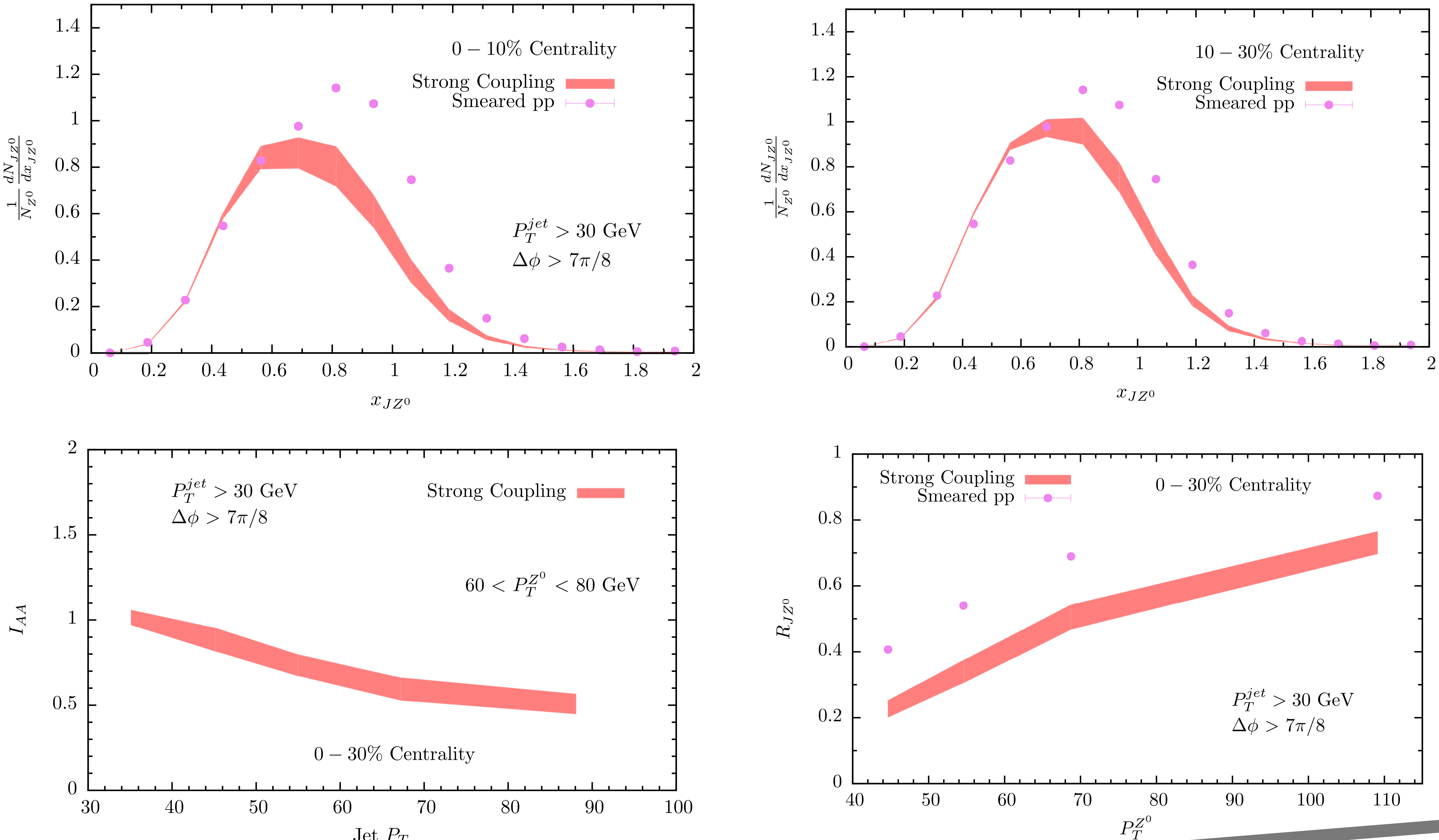
$$R_{J\gamma} = \frac{\text{Number of jets}}{\text{Number of photons}}$$

Spectrum

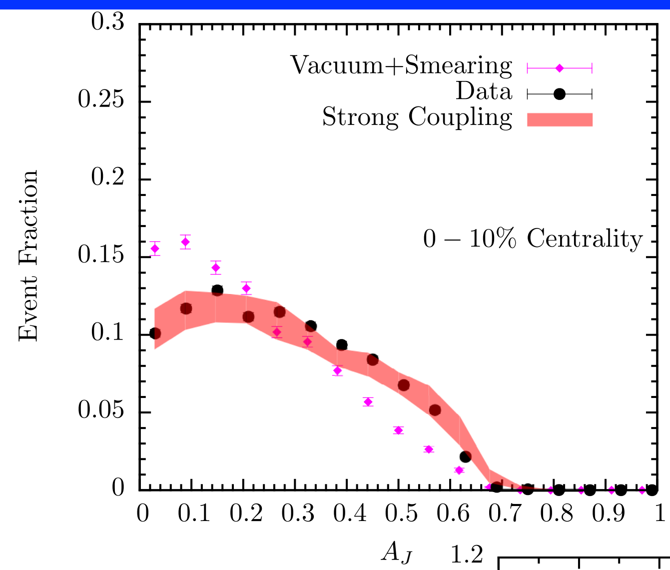


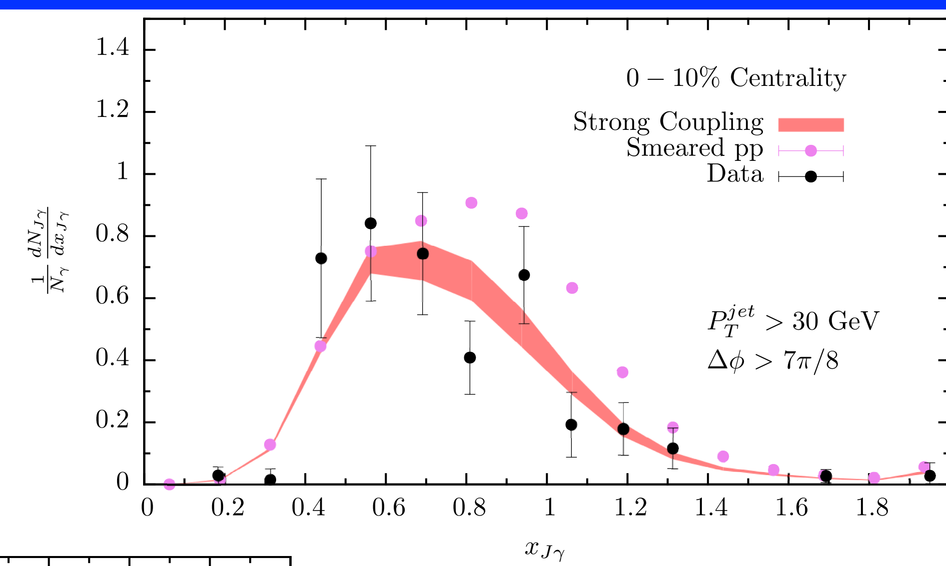
$$I_{AA} = \frac{\text{Number of associated jets in PbPb}}{\text{Number of associated jets in pp}}$$

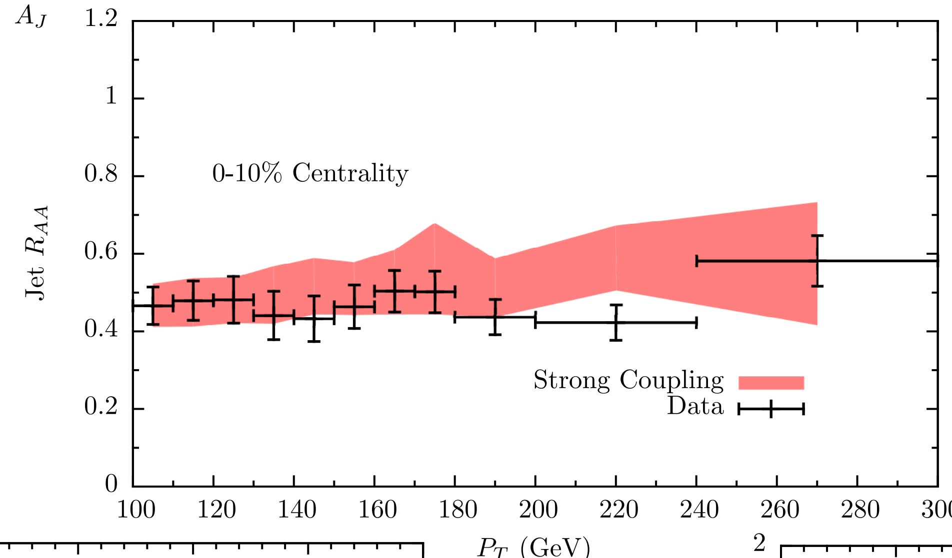
Predictions: Z-Jet correlations



Success of the Hybrid Model



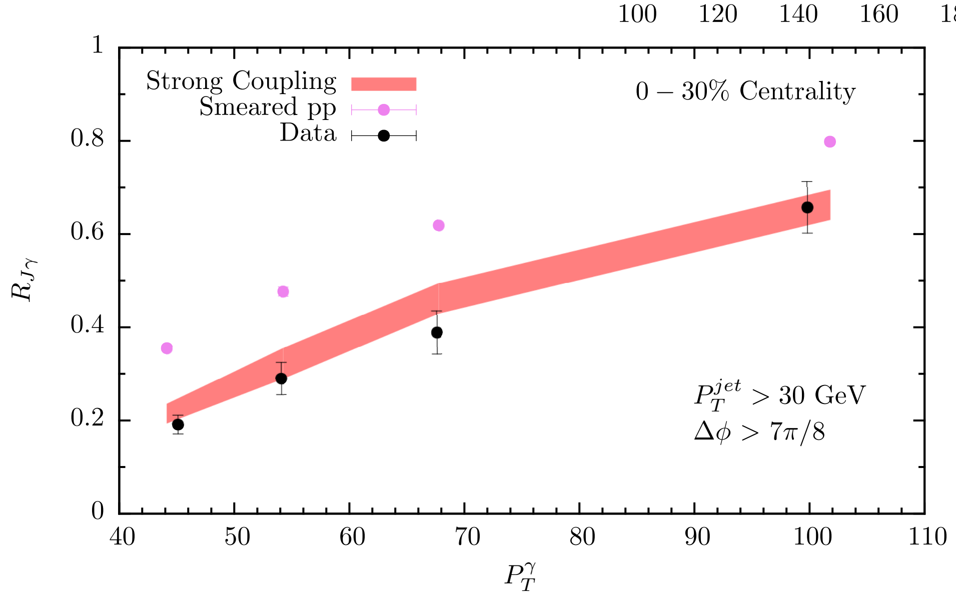


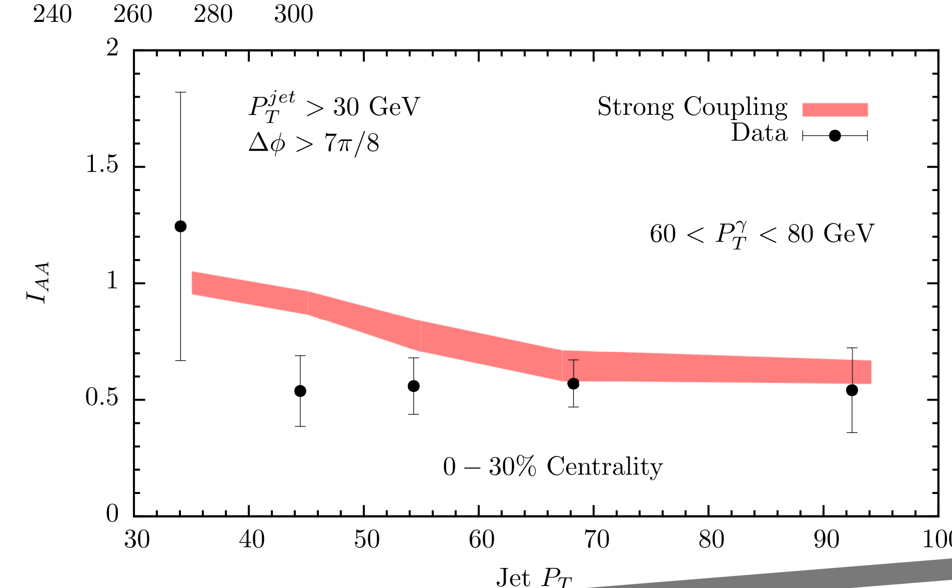


5 observables

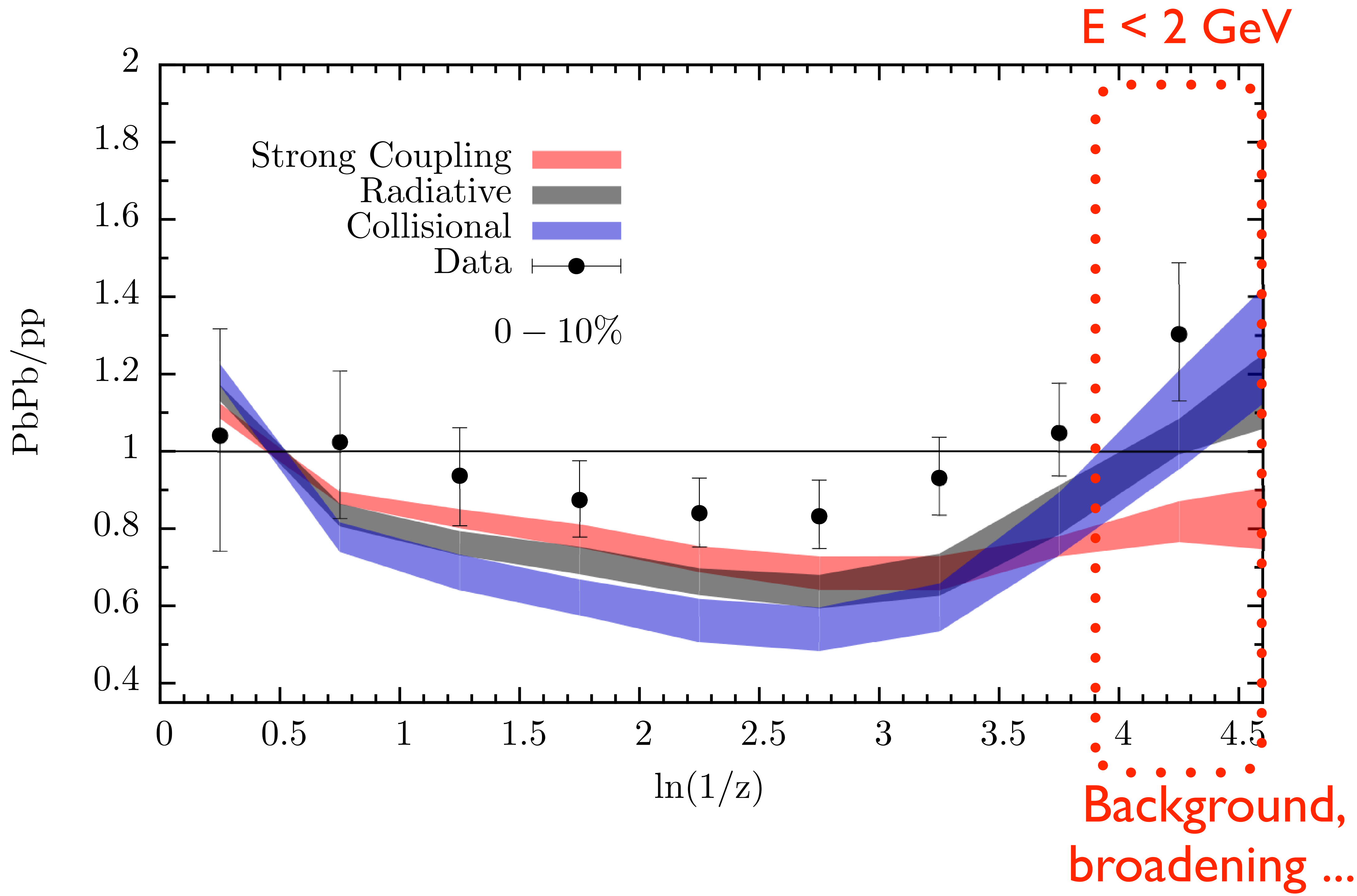
p_T and centrality

1 fit parameter





Fragmentation Function



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, within current error bars. Value of the fitted parameter? x_{stop} is 3 to 4 times longer in QCD plasma than in $\mathcal{N}=4$ SYM plasma at same T. This is not unreasonable. After all, the two theories have different degrees of freedom. Take all dependences of dE/dx from the strongly coupled calculation, but not the purely numerical factor.**
- **Jet quenching** *looks like* **perturbative fragmentation plus strongly coupled energy loss. Could it** *be* **that?**
- **All this success poses a critical question: if jet quenching observables see the liquid as a liquid, how** *can* **we see the point like quasiparticles at short distance scales? This is a prerequisite to understanding** *how* **a strongly coupled liquid can arise in an asymptotically free gauge theory.**

The Jet Quenching Challenge

- **How can we use jets to resolve the short distance structure of the liquid? Jet quenching phenomena involve physics over a range of scales, so jet quenching has long been seen as providing such a microscope. But, how?**
- **In this context, the long list of successful comparisons between jet data and the predictions of the hybrid model represent something of a disappointment!**
- **The hybrid is a hybrid of** *weakly coupled vacuum physics* **and** *strongly coupled energy loss + medium physics*. **To the extent that such an approach describes data, that data may be used to characterize the physics of the plasma on length scales at which it is strongly coupled but it cannot tell us about the** *weakly coupled medium physics.*
- **So, how can we use jets to see the short-distance, particulate, structure of QGP?**
- **The most interesting uses of the hybrid model should in the end be the study of where it fails.**

Jets as Microscopes

- We need further, more discriminating, observables. b-quark energy loss? Photon+jet? And, must add "transverse momentum broadening", since jet quenching is not only about energy loss.
- Look for evidence of rare-but-not-too-rare ($1/k_\perp^4$ vs. $\exp[-k_\perp^2]$, as Rutherford would have understood) hard scattering of partons in a jet off point-like quasiparticles. (D'Eramo, Liu, Rajagopal; Kurkela, Wiedemann)
- Measure the angular distribution of particles within a narrow range of momenta within a jet of a given initial energy. E.g. in high statistics photon+jet. Compare to jets in vacuum with the same initial energy. Do this for QGP with differing temperatures, at RHIC and LHC.
- These measurements need high luminosity: large samples of suitably tagged jets in different energy regimes. Coming at the LHC late in the decade. At RHIC, need a high-rate, state-of-the-art jet detector: sPHENIX, coming circa 2020.

Gauge/String Duality, Hot QCD and Heavy Ion Collisions

Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann

A 460 page book, available from 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.

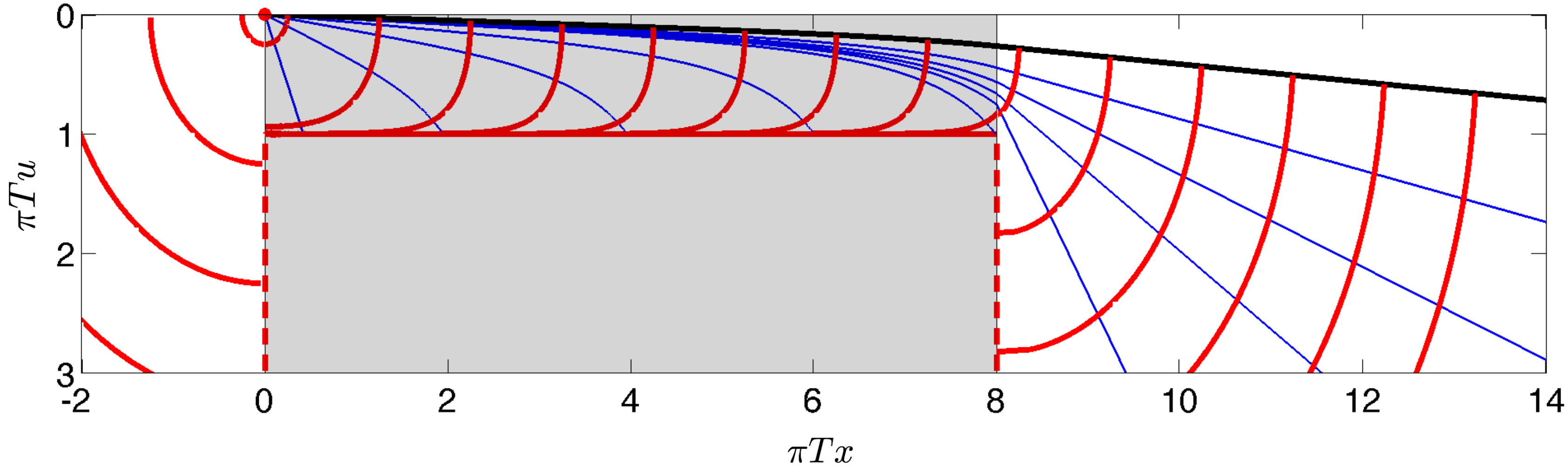
From $\mathcal{N} = 4$ SYM to QCD

- **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 observables like those 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.**

What to do next?

- **Alternatively, try modeling an entire QCD jet as a "jet"** . . .
- **From this perspective, next priority is analysis of broadening of the "jets".**
- **How to characterize opening angle of the "jet"? Easiest for us is** $\theta_{\text{"jet"}} \equiv m_{\text{"jet"}}/E_{\text{"jet"}} \equiv \sqrt{E^2_{\text{"jet"}} - p^2_{\text{"jet"}}}/E_{\text{"jet"}}$**. (But we have the whole profile and so could compare to any jet shape observable.)**
- **QCD predicts the distribution of** m_{in} **(e.g.** θ_{in}**) for each** E_{in}**.** $\mathcal{N} = 4$ **SYM does not; each must be specified separately. Send an ensemble of "jets", with a distribution of** θ_{in}**'s for each** E_{in}**, for example distributed as in QCD, through the brick of plasma. What comes out the other side? The answer turns out to be surprisingly simple, after you flip the question on its head, after first formulating it in the gravitational dual.**

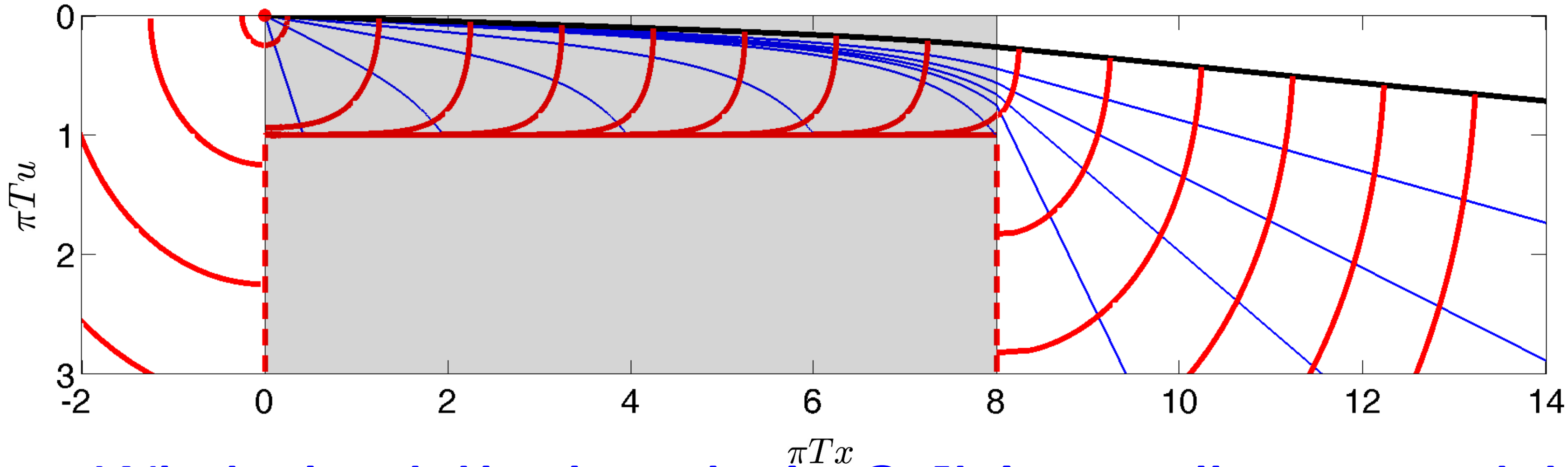
What to do next?



- If there were no plasma, “jet” would have some energy E_{in} and some opening angle $\theta_{\text{in}} \sim \sigma_{\text{in}}$. ($\sigma_{\text{in}}$ is the initial σ of the string endpoint.)
- Due to the slab: $E_{\text{out}} < E_{\text{in}}$, and $\theta_{\text{out}} \sim \sigma_{\text{out}} > \sigma_{\text{in}}$.
- In a sense, everything about the energy loss and the broadening is controlled by $\sigma_{\text{in}} \sim \theta_{\text{in}}$, and the value of E_{in} is, relatively speaking, unimportant.
- Lets start with x_{stop}. It is determined from σ_{in}, as the figure indicates. Explicitly, for small σ_{in} it is given by

$$\pi T\, x_{\text{stop}} = \frac{\Gamma\left(\frac{1}{4}\right)^2}{4\sqrt{\pi}} \frac{1}{\sqrt{\sigma_{\text{in}}}} - 1 + \mathcal{O}\left(\sqrt{\sigma_{\text{in}}}\right) \ .$$

What to do next?



- What about the broadening? It is equally apparent that $\theta_{\text{out}} \sim \sigma_{\text{out}}$ is fully specified by σ_{in} and $\pi T L$.
- What about the energy loss? Rewrite our result as

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

  and see that $E_{\text{out}}/E_{\text{in}}$ is fully specified by L/x_{stop}. And, remember that x_{stop} was fully specified by σ_{in}.
- So, $\sigma_{\text{in}} \sim \theta_{\text{in}}$, the angular size the "jet" would have had if it were in vacuum, tells you how much it broadens and what fraction of its energy it loses.
- Where does E_{in} even enter the gravitational description??

How does E_{in} enter?

- **For a jet with a given σ_{in}, the string energy density is $\propto 1/\sqrt{\sigma - \sigma_{\text{in}}}$. Note the $\propto$. It is in the constant hidden in this $\propto$ that E_{in} enters.**
- **Explicitly, it turns out that**

$$\frac{E_{\text{in}}}{\sqrt{\lambda}\,\pi T} = \frac{\left(\pi T x_{\text{stop}}\right)^3}{\pi^4 \mathcal{C}^3} \propto \frac{1}{\sigma_{\text{in}}^{3/2} \mathcal{C}^3} \ ,$$

  where $1/\mathcal{C}^3$ is proportional to the constant hidden in the $\propto$ above.
- **For a given x_{stop}, and remember that means for a given $\sigma_{\text{in}} \propto 1/(\pi T x_{\text{stop}})^2$, you can pick different values of E_{in} by picking different values of $\mathcal{C}$.**
- **Curiously, from the gravitational calculation there is a maximum allowed value of $\mathcal{C}$, which is $\mathcal{C} \approx 0.526$ (Chesler et al; Ficnar, Gubser). This means that for a given σ_{in} there is a minimum allowed E_{in}. If you try to load less energy than that onto the string, the geodesic approximation breaks down.**

What have we learned?

- **Send an ensemble of "jets", with a distribution of θ_{in}'s for each E_{in}, for example distributed as in QCD, through the brick of plasma. What comes out the other side? We learned to rephrase this...**
- **Send an ensemble of "jets", with a distribution of E_{in}'s for each θ_{in}, for example distributed as in QCD, through the brick of plasma. What comes out the other side?**
- **All "jets" with the same θ_{in} that travel through the same path length of plasma will come out with the same θ_{out}. We can make plots of θ_{out} as a function of θ_{in} and πTL.**
- **All "jets" with the same θ_{in} that travel through the same path length of plasma will come out with the same fractional energy loss $E_{\text{out}}/E_{\text{in}}$.**
- **$E_{\text{out}}/E_{\text{in}}$ is even simpler, since it does not depend separately on θ_{in} and πTL. It only depends on them via the single combination L/x_{stop}.**

What to do next?

- **It is worth asking whether jet quenching phenomenology in QCD simplifies if one asks about the quenching of jets that would have had a given opening angle in vacuum, rather than about the quenching of jets that would have had a given energy in vacuum, as is conventional.**
- **The striking, and simple, regularities that we have just learned should make the notion that "jets" can be used to model the quenching of QCD jets easily falsifiable.**
- **But, doing so is not immediate. In a gamma-jet event, the gamma tells you what the *energy* of the jet would have been in vacuum. How can you know what the opening angle of a jet seen in a PbPb collision would have been, if that jet had been produced in vacuum??**
- **As far as I can see, although the regularities that we have just seen are striking and simple, comparing them against data will need to be done statistically, on an ensemble basis.**
- **I remain hopeful that this approach can be falsified.**