Jets, Holographic and Hybrid, and their Evolution in Strongly Coupled Plasma

Krishna Rajagopal
MIT

Based on work done in collaboration with Chesler;
Casalderrey-Solana, Gulhan, Milhano & Pablos;
Hulcher & Pablos;
Brewer, Sadofyev & van der Schee

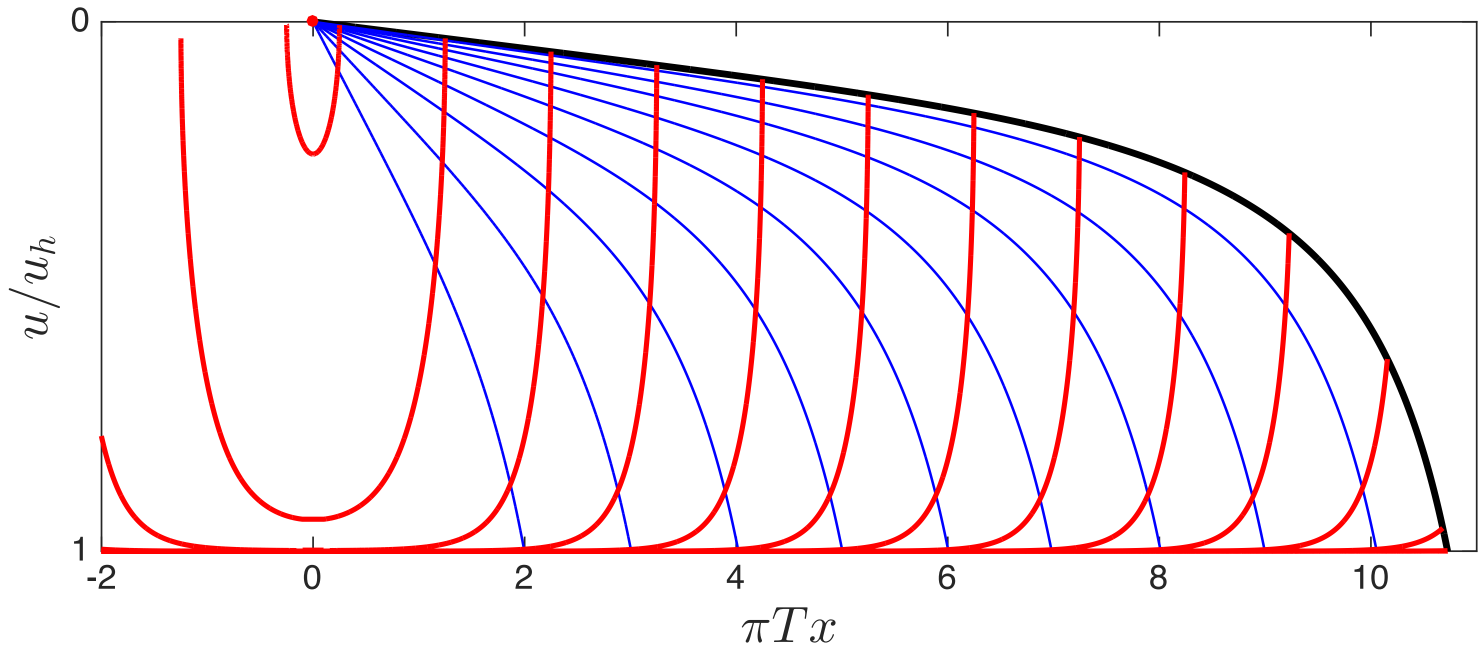
Canterbury Tales of Hot QFTs in the LHC Era
Oxford, UK, July 11, 2017

The Long View

- Seeing how strongly coupled liquid emerges at scales $\sim 1/T$ from an asymptotically free gauge theory will require high statistics data from sPHENIX and the high luminosity LHC on rare events in which jet partons scatter off QGP partons by a sufficient angle to yield observable consequences.
- Theorists need to use the data of today to build the baseline of understanding with and against which to look for and interpret such effects.
- There are various theoretical frameworks for understanding jets in plasma. I'm going to show you how we wrestle with the challenge above in the context of the Hybrid Model — which I shall introduce momentarily. This should be, and is being, done in other contexts too.
- I will try to draw lessons that are more general than the Hybrid Model itself.
- Before getting to the Hybrid Model, I need to tell you about holographic calculations by themselves, as a source of qualitative insight in their own right.

Quenching a Light Quark "Jet"

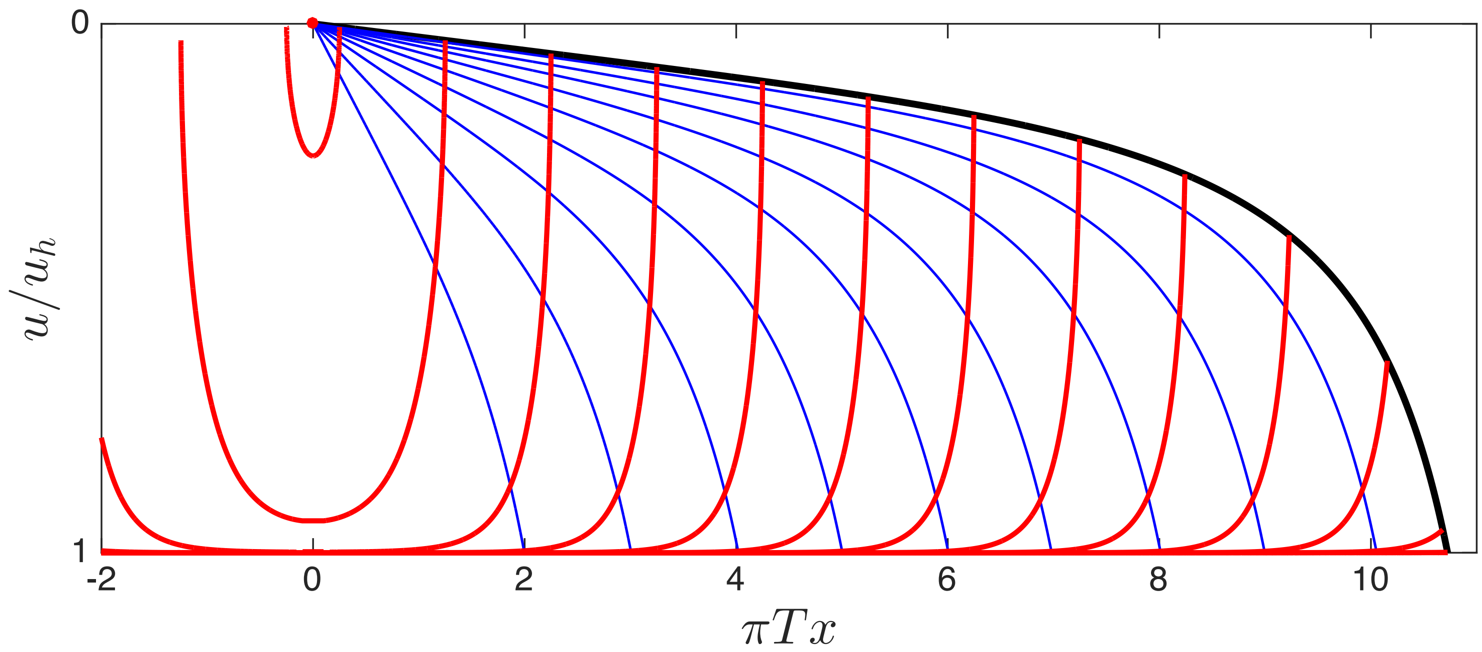
Chesler, Rajagopal, 1402.6756, 1511.07567



- Take a highly boosted light quark and shoot it through strongly coupled plasma. . .
- A fully geometric characterization of energy loss. Which is to say a new form of intuition. Energy propagates along the blue curves, which are null geodesics in the bulk. When one of them falls into the horizon, that's energy loss! Precisely equivalent to the light quark losing energy to a hydrodynamic wake in the plasma.

Quenching a Light Quark "Jet"

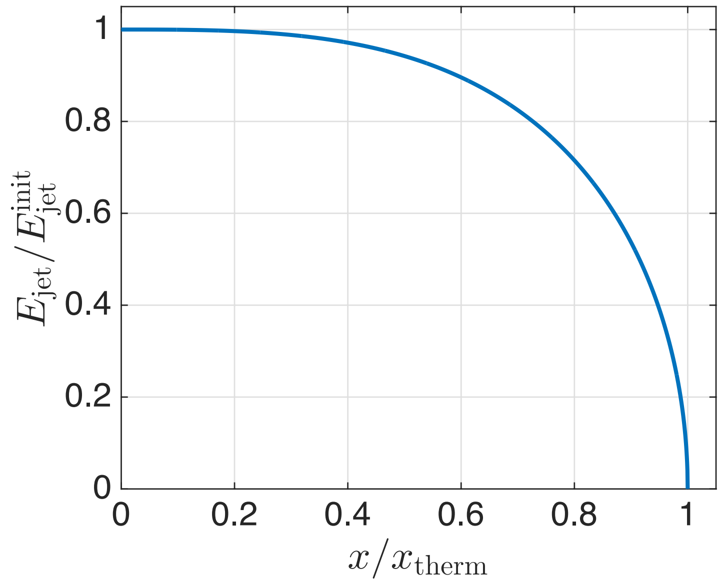
Chesler, Rajagopal, arXiv:1402.6756, 1511.07567



- Can try to interpret this object as a toy model for a jet.
- Depth into the bulk $\leftrightarrow$ transverse size of the gauge theory object being described.
- Thus, downward angle into the bulk $\leftrightarrow$ opening angle.
- This calculation describes a "jet" with some initial $\theta_{\rm jet}^{\rm init} \propto$ initial downward angle of the endpoint.

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756, 1511.07567



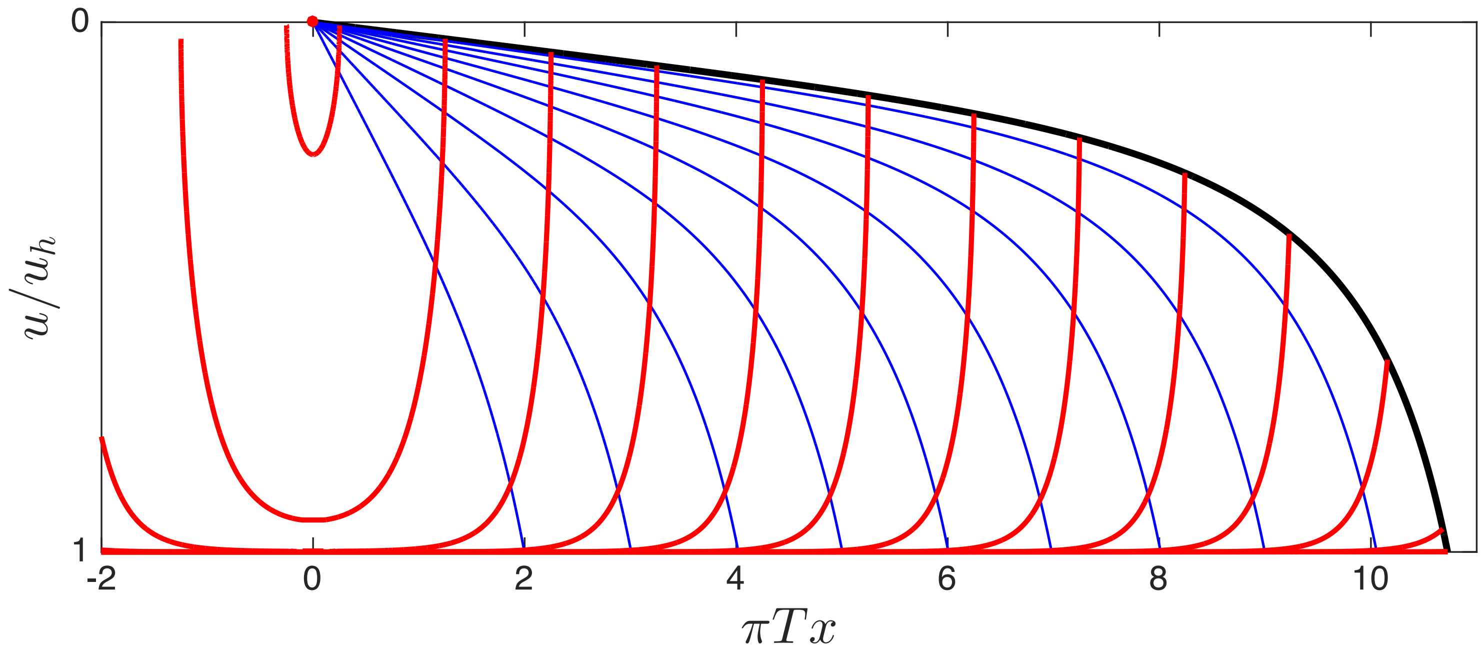
We compute E_{jet} analytically, by integrating the energy flowing into hydrodynamic modes, and showing its equivalence to that falling into the horizon. Geometric derivation of analytic expression for dE_{jet}/dx

$$\frac{1}{E_{\text{jet}}^{\text{init}}}\frac{dE_{\text{jet}}}{dx} = -\frac{4x^2}{\pi x_{\text{therm}}^2}\frac{1}{\sqrt{x_{\text{therm}}^2 - x^2}}$$

where $T x_{\text{therm}} = \mathcal{C}(E_{\text{jet}}^{\text{init}}/(\sqrt{\lambda}T))^{1/3}$ where $\mathcal{C}$ is $\mathcal{O}(1)$, depends on how the quark "jet" is prepared, and has a maximum possible value $\simeq 1$.

Quenching a Holographic Jet

Chesler, Rajagopal, arXiv:1511.07567

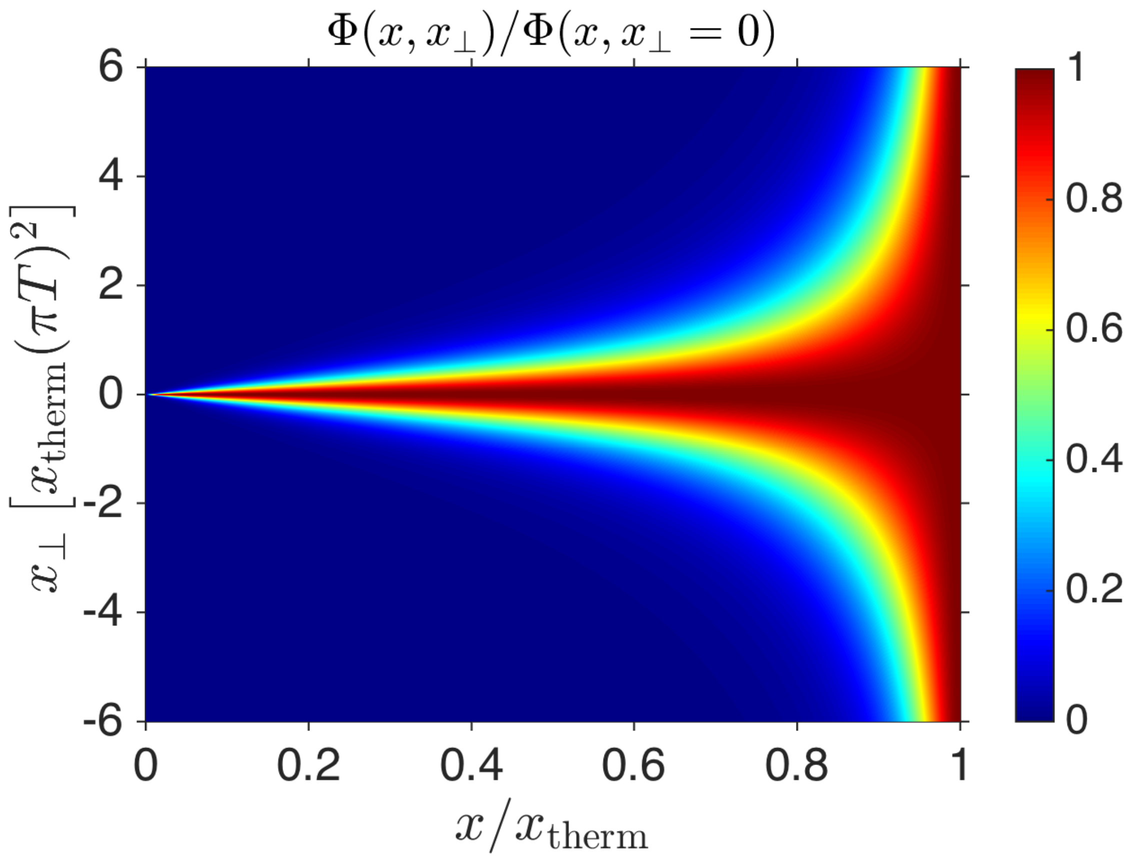


Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

- **First, every jet broadens in angle as it propagates through the strongly coupled plasma.** θ_{jet} **increases as** E_{jet} **decreases.**

Holographic "Jet" Energy Loss

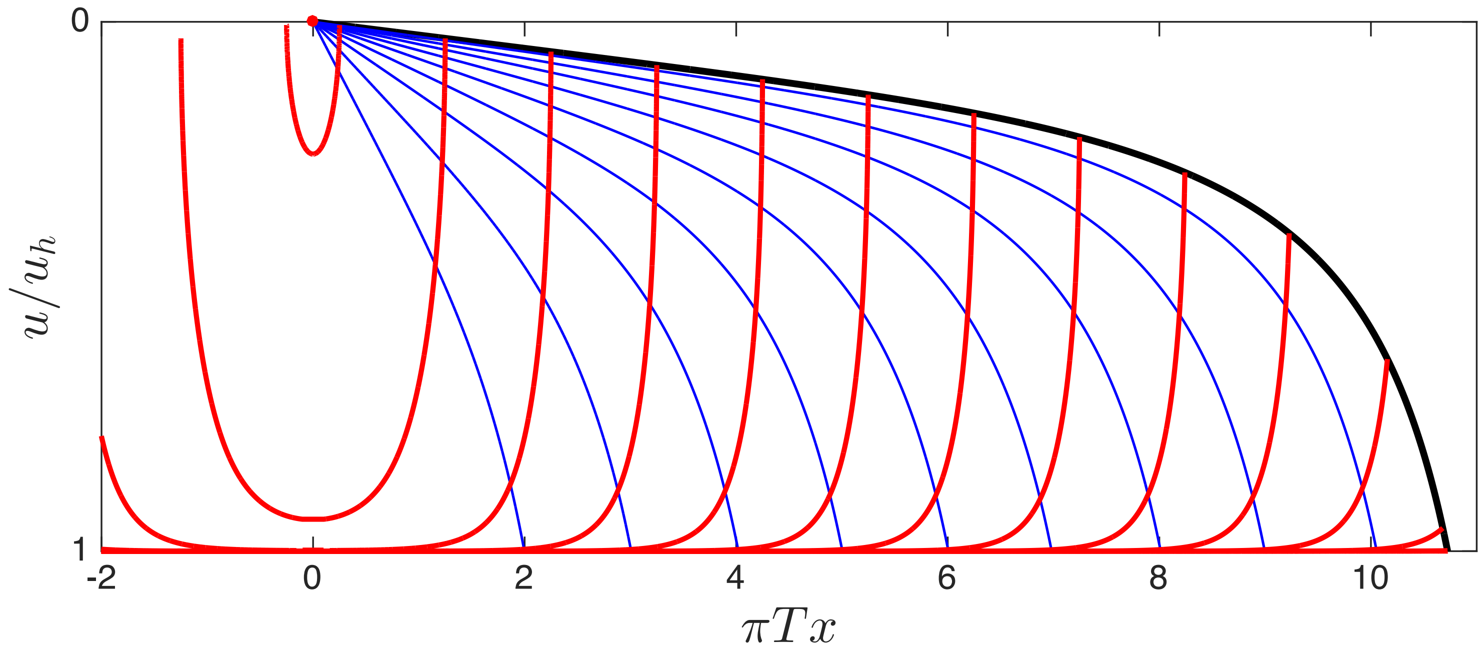
Chesler, Rajagopal, arXiv:1511.07567



- **First, every jet broadens in angle as it propagates through the strongly coupled plasma. $\theta_{\rm jet}$ increases as $E_{\rm jet}$ decreases. (What is plotted here is energy flux, renormalized at every x so loss of energy is not visible. Plot is for the small $\theta_{\rm jet}^{\rm init}$ limit.)**

Holographic “Jet” Energy Loss

Chesler, Rajagopal, arXiv:1511.07567



Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

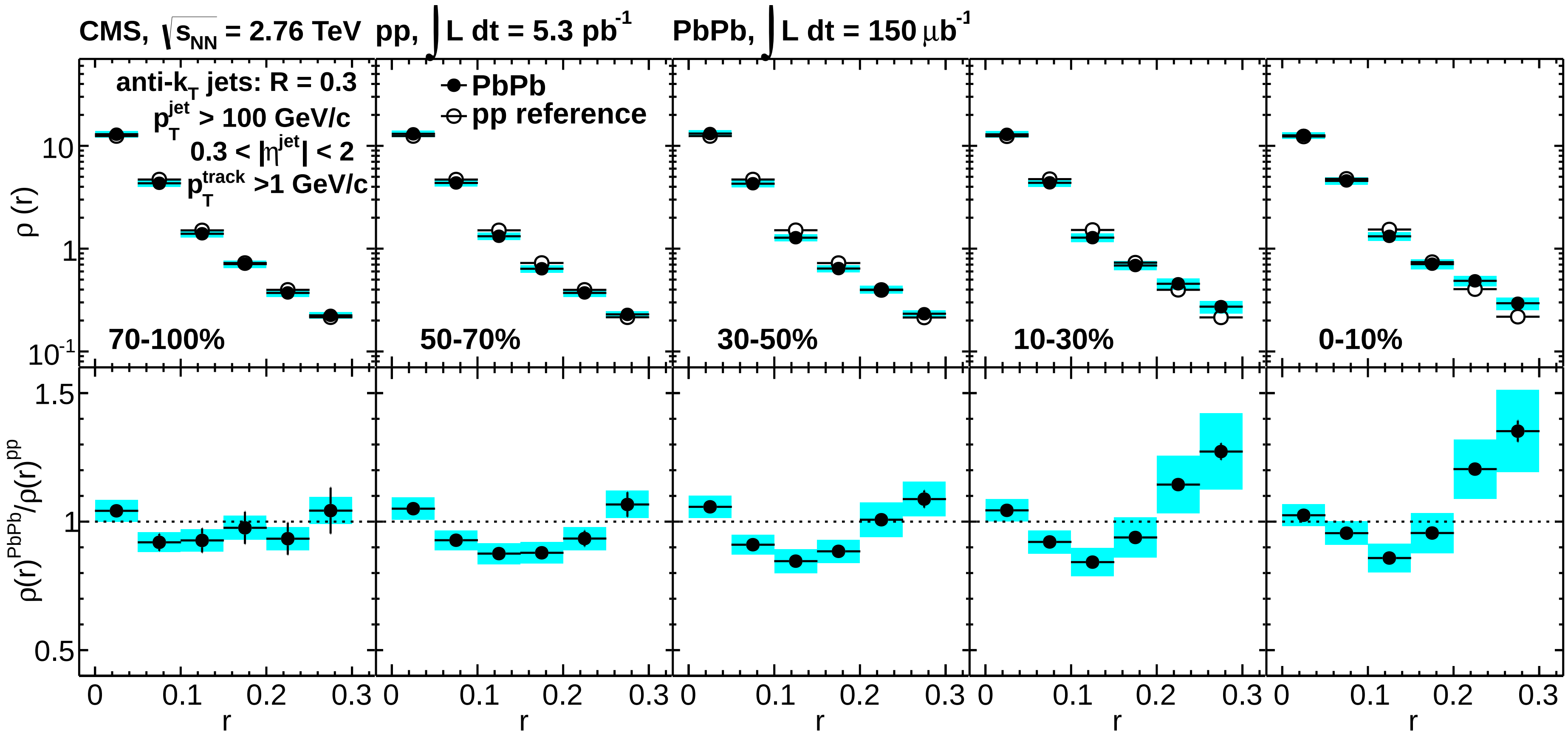
- **Second, jets with smaller initial $\theta_{\rm jet}^{\rm init}$ have a longer $x_{\rm therm}$. They lose their energy more slowly, over a longer distance. (In fact, $T x_{\rm therm} \propto 1/\sqrt{\theta_{\rm jet}^{\rm init}}$.)**
- **That is, for jets with the same $E_{\rm jet}^{\rm init}$ that travel through the same plasma, those with larger $\theta_{\rm jet}^{\rm init}$ will lose more energy.**

Two Approaches

- There is no single "right" way to use holographic calculations to gain qualitative insights into jet quenching. Judicious use of these calculations in modelling jet quenching must take into account that some aspects of the physics of jet production+propagation+quenching in QCD are weakly coupled and some aspects are strongly coupled.
- One approach: use the holographic jets as models for jets in QCD. But, choose an ensemble of holographic jets with their initial energies and initial opening angles distributed as in pQCD, i.e. as in pp collisions.
  KR, Sadofyev, van der Schee, 1602.04187; Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress
- Another approach: start with an ensemble of pQCD jets from PYTHIA. Think of each parton in a parton shower à la PYTHIA losing energy à la dE/dx for light quarks in strongly coupled liquid, from a previous slide.
  Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1405.3864,1508.00815, and 1609.05842; Hulcher, Pablos, KR, in progress; C-S,G,H,M,P,R, in progress

Experimental Results

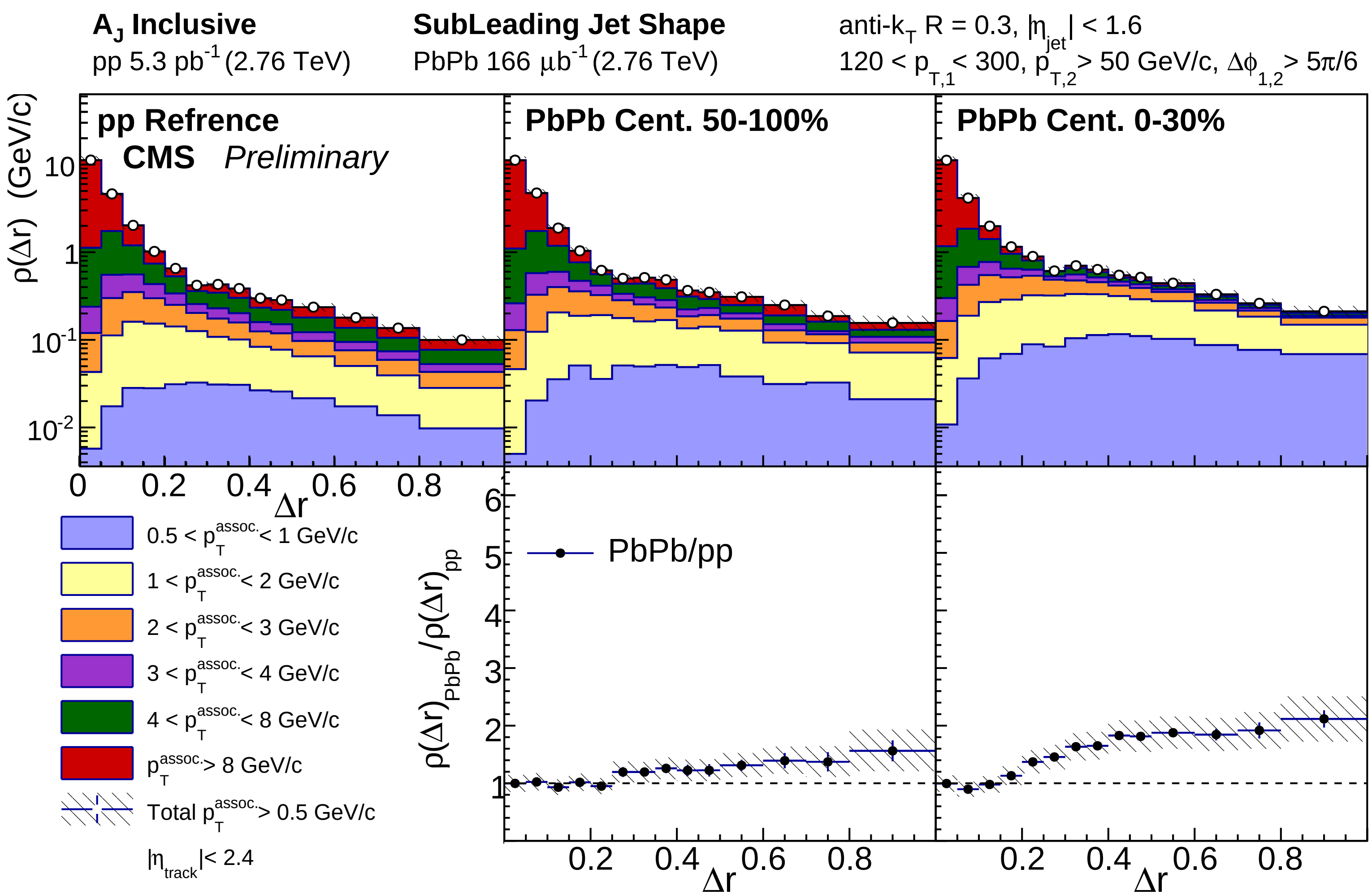
CMS, arxiv:1310.0878



Jets in PbPb are a little narrower than jets with the same energy in pp at small r. Then get a little wider at larger r.

Experimental Results

CMS, HIN-15-011



The narrowing at small angles comes from the hard component of the jet. The broadening at large, and very large, angles is in the softest particles, likely those coming from the wake in the plasma that are reconstructed as part of the jet.

A Contradiction?

In the holographic calculation, every jet gets wider as it propagates through the plasma.

When you compare jets in PbPb and pp collisions *with the same final energy* the quenched jets in PbPb collisions may be a bit narrower, and certainly are not significantly wider.

Is this a contradiction? Not necessarily...

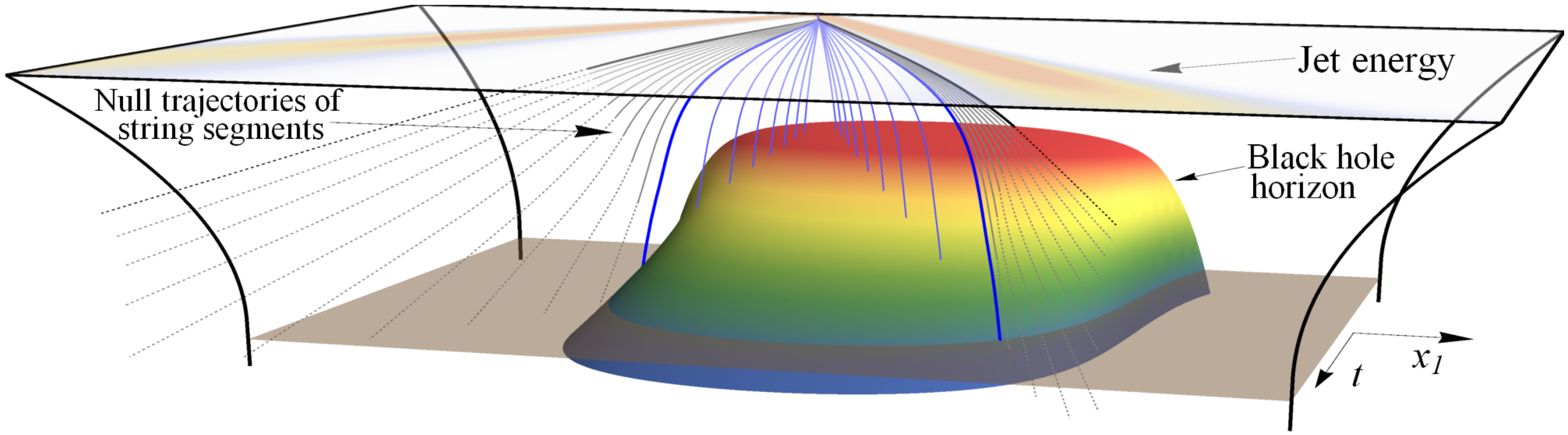
In order to compare quenched jets and unquenched jets with the same final energy, we need to follow what happens to an ensemble of jets.

Since energy loss depends on initial opening angle, we need an ensemble with a reasonable distribution of both initial opening angle and initial energy. (The angle and energy that the jet would have had if not plasma.)

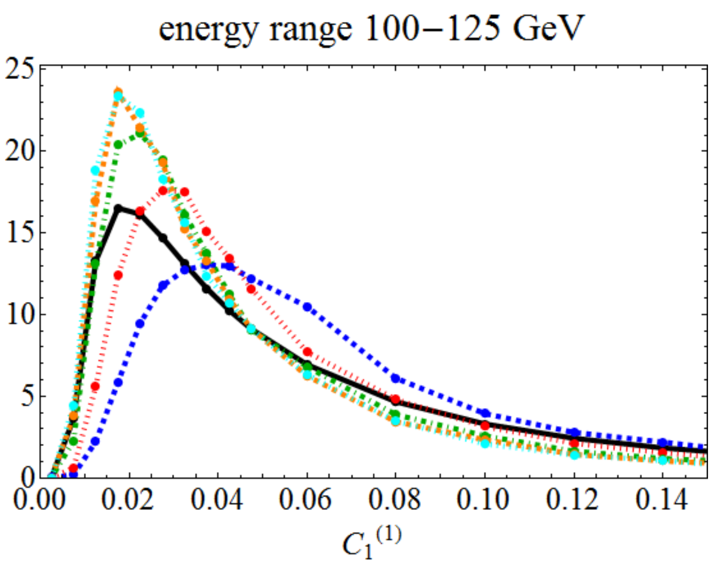
Our goal is to assess whether there is a blatant contradiction. And qualitative insight. So we will simplify many things...

Evolution of Jet Opening Angle Distribution

Rajagopal, Sadofyev, van der Schee, 1602.04187



Holographic model for jet quenching. ***Ensemble*** **of ∼50,000 holographic jets, with initial energies** *and opening angles* **distributed as in pQCD, i.e. as in pp collisions. Send through expanding cooling droplet of plasma, see how distribution changes. Every jet in the ensemble broadens in angle...**



...but, at large opening angle the opening angle distribution for jets with specified $E_{\rm jet}$ is pushed *down*. **(Because** *wider jets lose much more energy* **and drop out of the energy bin.)** *Mean* **opening angle easily pushed downward, as data indicate, even though opening angle of every jet in the ensemble increases.**

Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

Choose an ensemble of holographic jets, distributed as follows:

- **Initial energy distributed** $\propto (E_{\rm jet}^{\rm init})^{-6}$.
  - **(The energy density on the string is** $A/(\sigma^2\sqrt{\sigma - \sigma_{\rm endpoint}^{\rm init}})$**; this specifies the distribution of** A.**)**

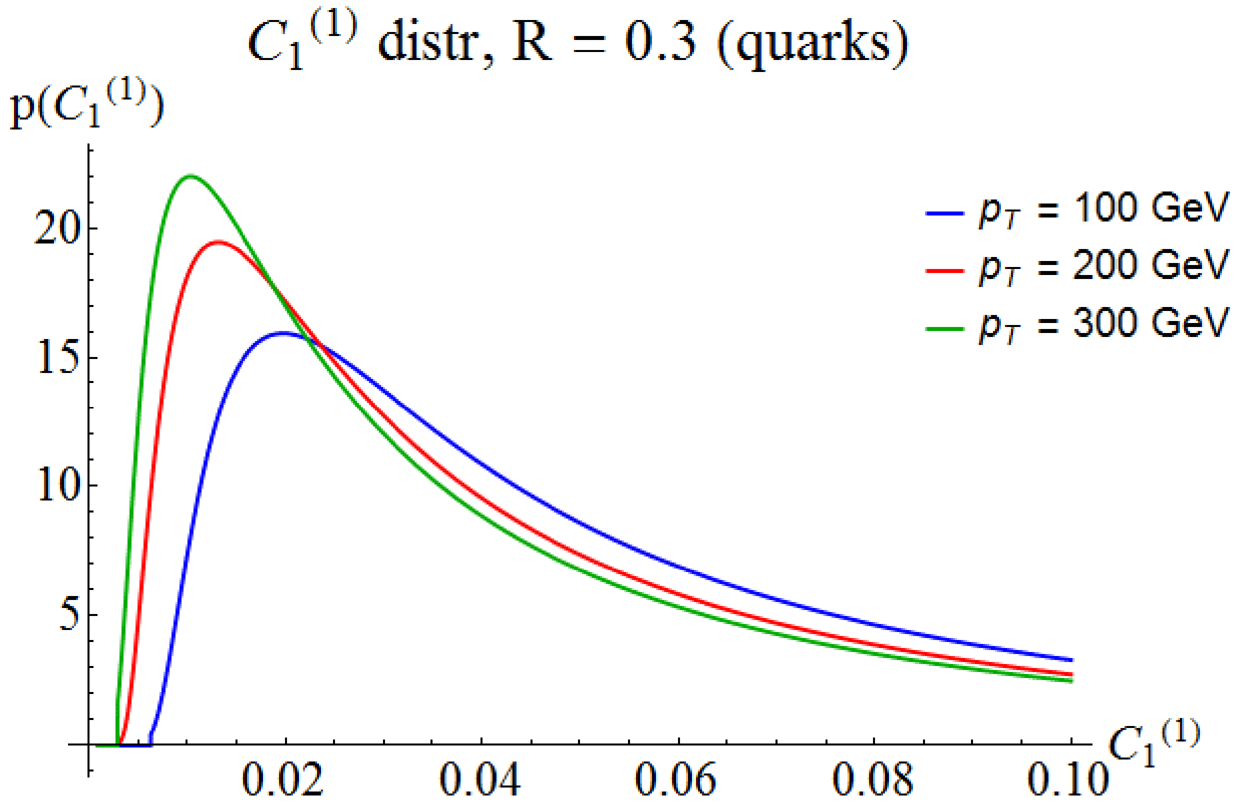
- **We take advantage of a pQCD calculation of the distribution for**

$$C_1^{(1)} \equiv \sum_{i,j} z_i z_j \left(\frac{|\theta_{ij}|}{R}\right) ,$$

a measure of the opening angle of a jet, for $R = 0.3$ **jets with a given energy in** pp **collisions with** $\sqrt{s} = 2.76$ **TeV.** (Larkoski, Salam, Thaler 1305.0007; Larkoski, Marzani, Soyez, Thaler 1402.2657)
  - **(For us,** $C_1^{(1)} = a\,\sigma_{\rm endpoint}^{\rm init}$. **Crude calculation gives** $a \sim 1.7$ **but we take** a **as the first of two free parameters in the model. So, this specifies distribution of** $\sigma_{\rm endpoint}^{\rm init}$.**)**

Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187



Larkoski, Marzani, Soyez, Thaler 1402.2657

Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

Choose an ensemble of holographic jets, distributed as follows:

- **Initial energy distributed** $\propto (E_{\rm jet}^{\rm init})^{-6}$.
  - **(The energy density on the string is** $A/(\sigma^2\sqrt{\sigma - \sigma_{\rm endpoint}^{\rm init}})$; **this specifies the distribution of** A.)
- **We take advantage of a pQCD calculation of the distribution for**

$$C_1^{(1)} \equiv \sum_{i,j} z_i z_j \left(\frac{|\theta_{ij}|}{R}\right) \ ,$$

a measure of the opening angle of a jet, for $R = 0.3$ **jets with a given energy in** pp **collisions with** $\sqrt{s} = 2.76$ **TeV.**
(Larkoski, Salam, Thaler 1305.0007; Larkoski, Marzani, Soyez, Thaler 1402.2657)
  - **(For us,** $C_1^{(1)} = a\,\sigma_{\rm endpoint}^{\rm init}$. **Crude calculation gives** $a \sim 1.7$ **but we take** a **as the first of two free parameters in the model. So, this specifies distribution of** $\sigma_{\rm endpoint}^{\rm init}$.)

Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

... and follow the propagation of this ensemble through an AdS/BH metric with a space-time varying horizon that describes strongly coupled plasma with a spacetime-varying temperature. We assume boost-invariant longitudinal expansion and a blast-wave approximation (taken from Ficnar, Gubser, Gyulassy 1311) for the transverse expansion:

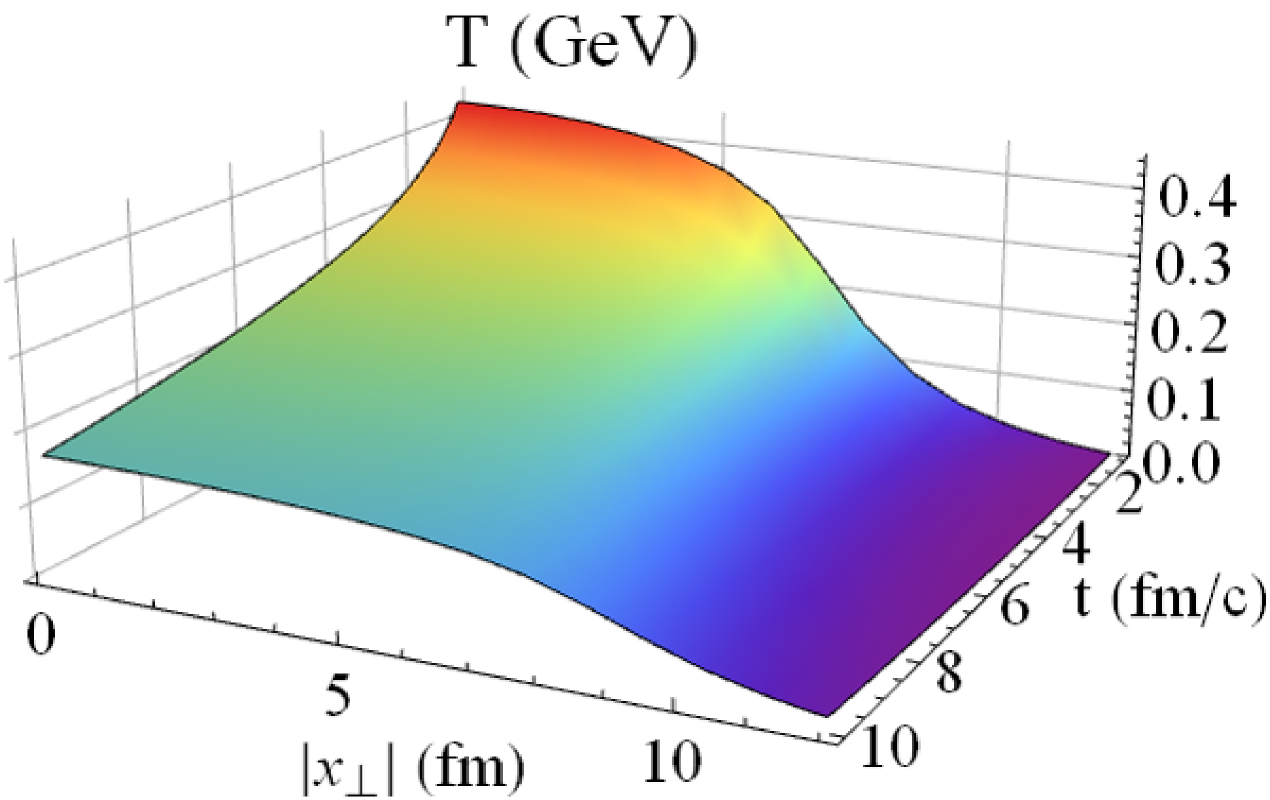
$$T(\tau, \vec{x}_\perp) = b \left[\frac{dN_{\text{ch}}}{dy} \frac{1}{N_{\text{part}}} \frac{\rho_{\textbf{part}}(\vec{x}_\perp / r_{\textbf{bl}}(\tau))}{\tau \, r_{\textbf{bl}}(\tau)^2} \right]^{1/3},$$

where $r_{\textbf{bl}}(\tau) \equiv \sqrt{1 + (v_T \tau / R_{\text{Pb}})^2}$, and where we take $N_{\text{part}} = 383$, $dN_{\text{ch}}/dy = 1870$, $v_T = 0.6$, $R_{\text{Pb}} = 6.7$ fm and $\rho_{\text{part}}(\vec{x}_\perp)$ is given by an optical Glauber model.

A naive calculation gives $b \sim 0.8$, but recognizing that the strongly coupled plasma of $\mathcal{N} = 4$ SYM theory and QCD differ (in s/T^3, for example) we treat b as the second free parameter in the model.

Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187



Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

. . . and follow the propagation of this ensemble through an AdS/BH metric with a space-time varying horizon that describes strongly coupled plasma with a spacetime-varying temperature. We assume boost-invariant longitudinal expansion and a blast-wave approximation (taken from Ficnar, Gubser, Gyulassy 1311) for the transverse expansion:

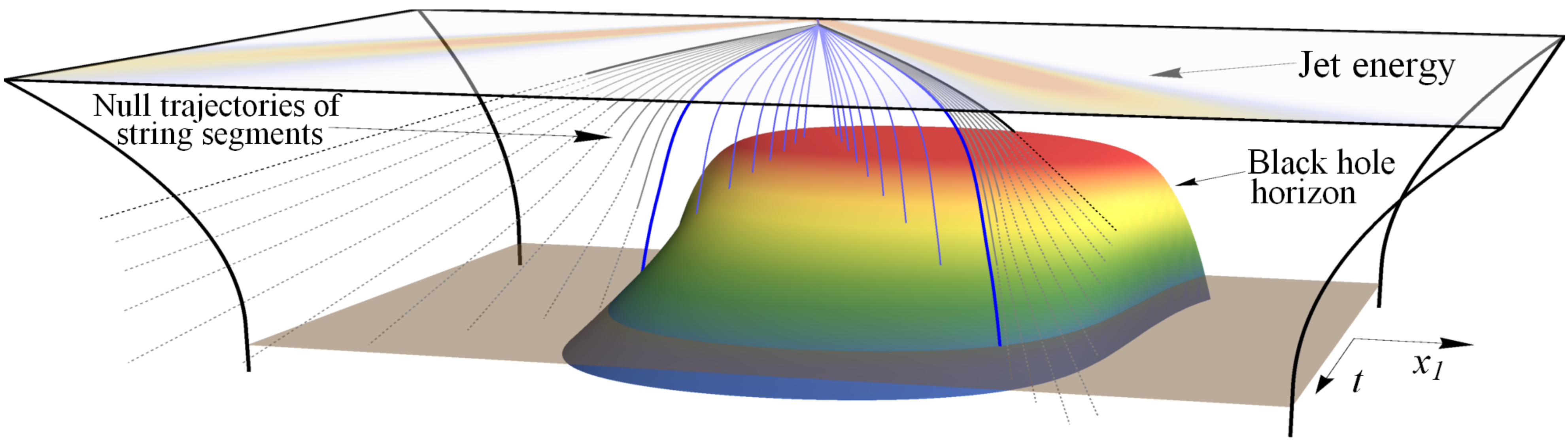
$$T(\tau, \vec{x}_\perp) = b \left[\frac{dN_{\rm ch}}{dy} \frac{1}{N_{\rm part}} \frac{\rho_{\bf part}(\vec{x}_\perp / r_{\bf bl}(\tau))}{\tau\, r_{\bf bl}(\tau)^2} \right]^{1/3},$$

where $r_{\bf bl}(\tau) \equiv \sqrt{1 + (v_T \tau / R_{\rm Pb})^2}$, and where we take $N_{\rm part} = 383$, $dN_{\rm ch}/dy = 1870$, $v_T = 0.6$, $R_{\rm Pb} = 6.7$ fm and $\rho_{\rm part}(\vec{x}_\perp)$ is given by an optical Glauber model.

A naive calculation gives $b \sim 0.8$, but recognizing that the strongly coupled plasma of $\mathcal{N} = 4$ SYM theory and QCD differ (in s/T^3, for example) we treat b as the second free parameter in the model.

Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187



Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

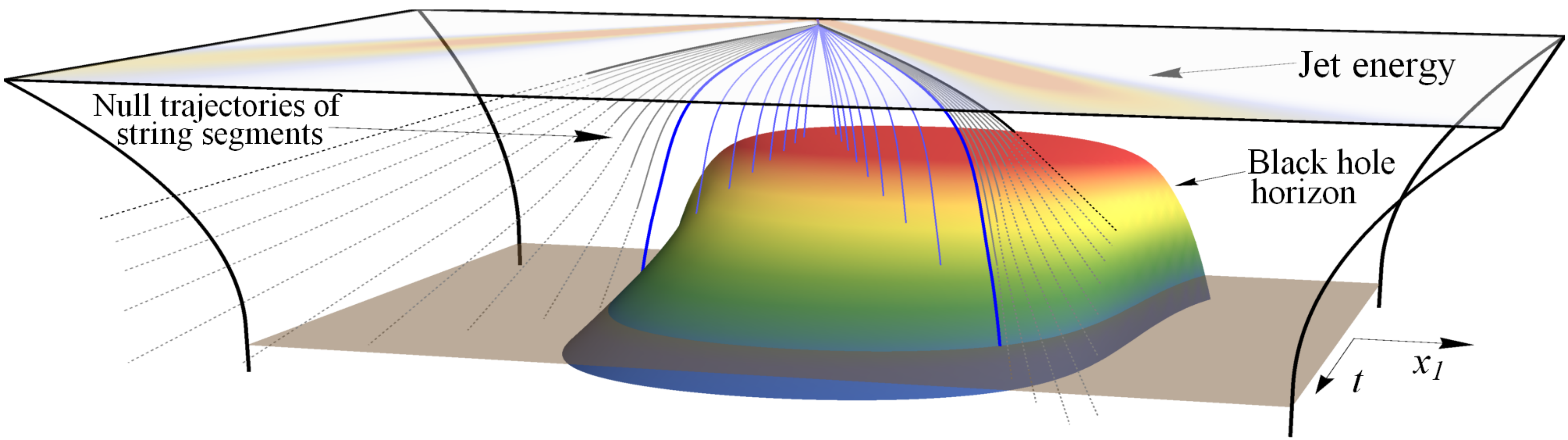
We initialize our simplified model for the expanding cooling droplet of plasma at $\tau = 1$ fm$/c$, and initialize our ensemble of jets at the same τ, choosing their initial transverse position $\propto \rho_{\rm part}(\vec{x}_\perp)^2$ and choosing their transverse direction randomly. (Clearly, early time physics could be improved.)

For each value of the two model parameters a and b, we generate an ensemble of many tens of thousands of jets as described, send them through the droplet of plasma, and turn quenching off when T drops below 175 MeV. (Clearly, late time physics could be improved.)

We track $E_{\rm jet}$ and $\sigma_{\rm endpoint}$, and extract the modified distribution of jet energies and opening angles.

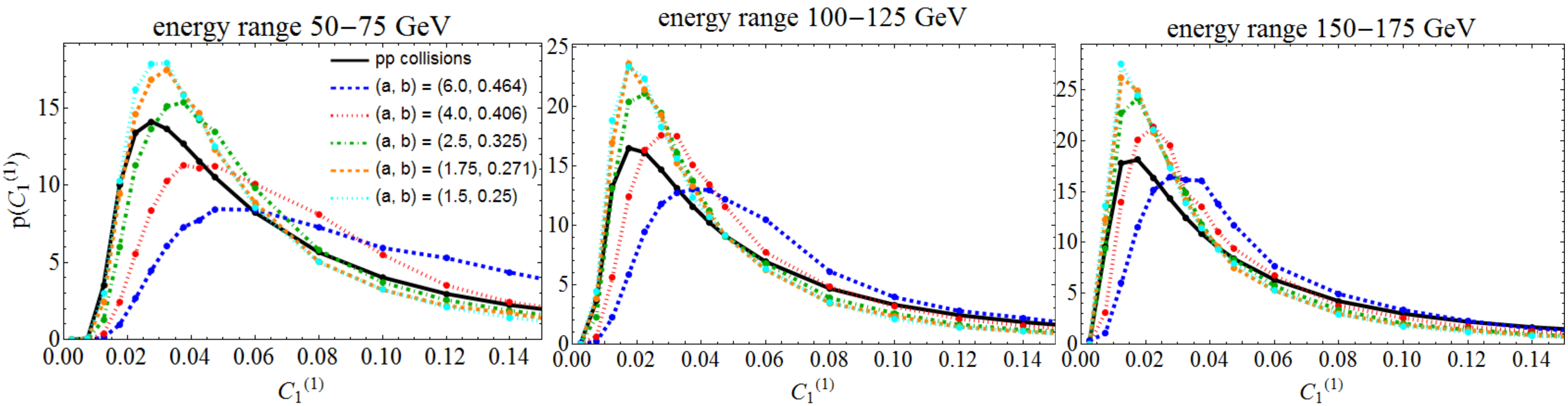
Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187



Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

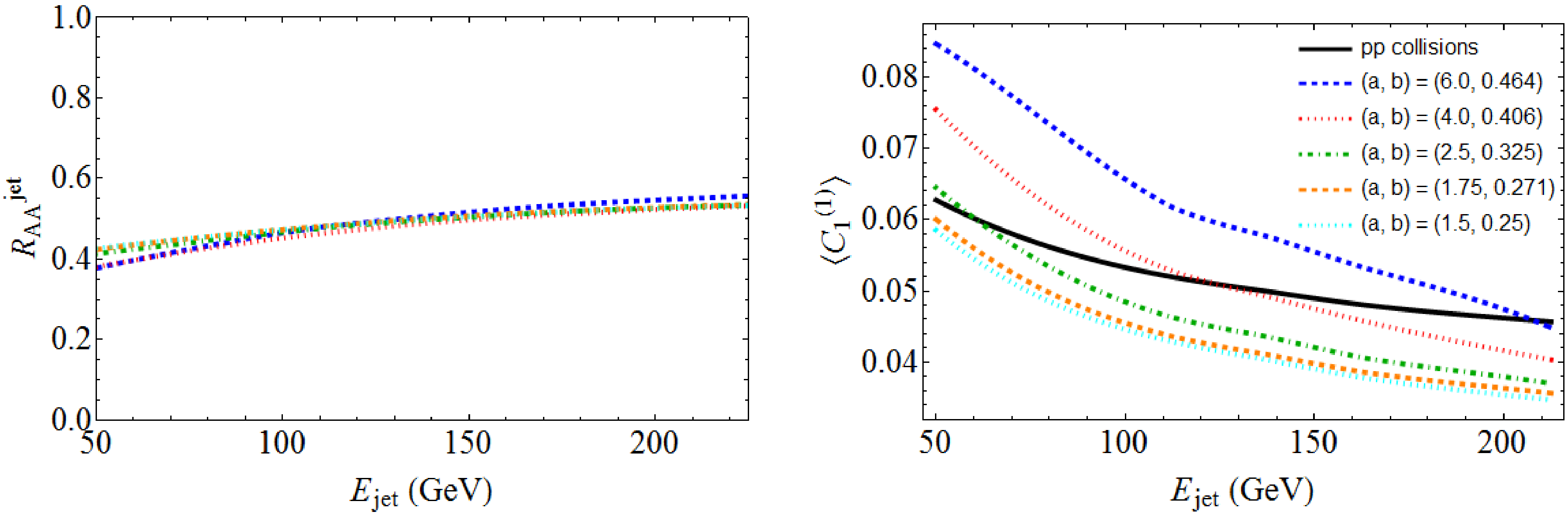


For small angles, opening angle distribution pushed toward larger angles. (Every jet gets wider as it propagates.)

At large angles, opening angle distribution pushed down, and therefore toward smaller angles. (Jets that are initially wider lose more energy. And, the jet energy distribution is steeply falling.)

Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187



All our choices of a, b give same, not unreasonable, suppression in the number of jets in the final ensemble with a given $E_{\rm jet}$ relative to that number in the initial distribution.

The *mean* opening angle of the jets with a given $E_{\rm jet}$ in the final ensemble can easily be pushed downward, even though the opening angle of every jet in the ensemble increases.

Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

There is no contradiction.

- **Because of inescapable qualitative fact # 2 (holographic jets that are initially wider lose more energy)...**
- **... and because of the steeply falling $E_{\rm jet}$ distribution...**
- **... there is no contradiction between inescapable qualitative fact #1 (every holographic jet broadens in angle as it propagates through strongly coupled plasma) ...**
- **... and the indication from CMS data that jets in PbPb with $E_{\rm jet} > 100$ GeV or $E_{\rm jet} > 50$ GeV are a little narrower than jets in pp with the same energy, if you focus on the harder particles in the jet so as not to be distracted by particles coming from the wake in the plasma.**

Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

Bottom line: because wider jets with a given initial energy lose more energy than narrower jets with that energy, quenching can make the mean width of jets with a given energy narrower – even as every individual jet gets wider as it loses energy.

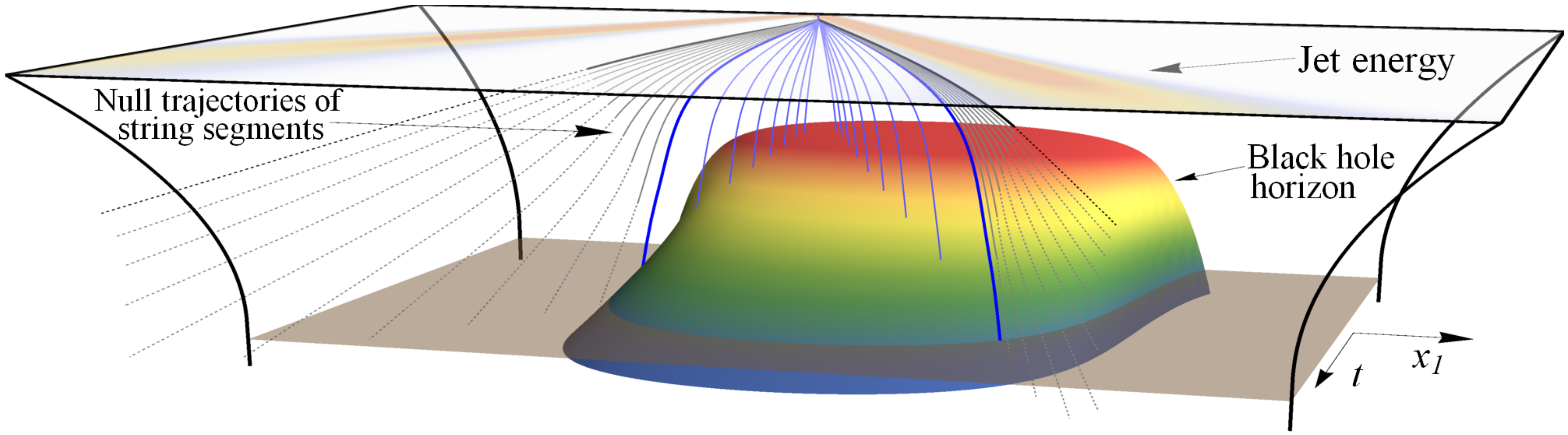
Same effect seen in an ensemble of weakly coupled jets in JEWEL (Milhano, Zapp 1512). At weak coupling, initially wider jets lose more energy than initially narrower ones because they contain more energy-losers (Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 1210). Similar conclusion also from weakly coupled calculation of large event-by-event fluctuations of parton multiplicity in jets and jet energy loss (Escobedo, Iancu 1605)

Same effect seen in hybrid model also (Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1609.05842).

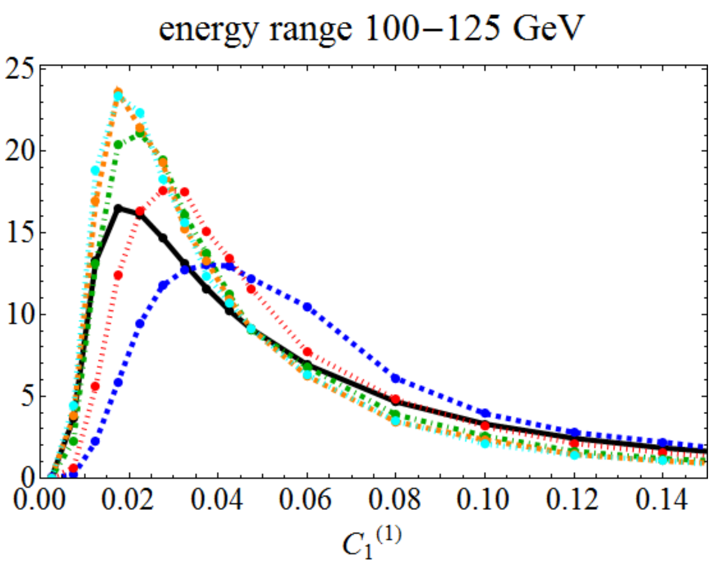
Prospects for experimental analyses of event-by-event distribution of jet widths?

Evolution of Jet Opening Angle Distribution

Rajagopal, Sadofyev, van der Schee, 1602.04187



Holographic model for jet quenching. ***Ensemble*** **of ∼50,000 holographic jets, with initial energies *and opening angles* distributed as in pQCD, i.e. as in pp collisions. Send through expanding cooling droplet of plasma, see how distribution changes. Every jet in the ensemble broadens in angle. . .**



. . .but, at large opening angle the opening angle distribution for jets with specified E_{jet} is pushed *down*. (Because *wider jets lose much more energy* and drop out of the energy bin.) *Mean* opening angle easily pushed downward, as data indicate, even though opening angle of every jet in the ensemble increases.

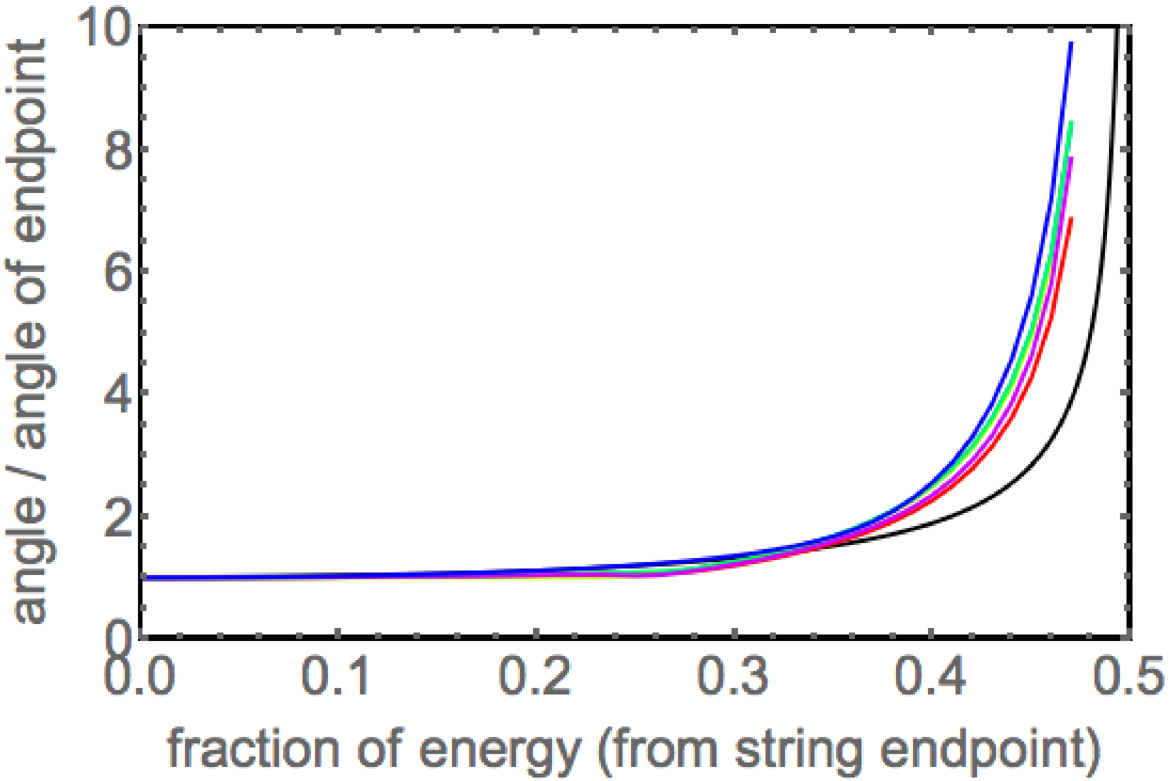
Evolution of an Ensemble of Holographic (Di)jets

(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)

- Check that full string dynamics "nullifies" and reproduces energy distribution along the string from Chesler et al.
- Tailor an ensemble of holographic jets with initial jet shape is as in p-p collisions; only tailoring needed is choice of parameter a. Analyze the modification of jet shape due to passage through plasma. Jet shape; not just width.
- Construct an ensemble of back-to-back dijets, with initial dijet asymmetry as in p-p collisions. Analyze modification of the dijet asymmetry due to passage through plasma.
- Construct an ensemble of dijet and trijet events, the latter constructed à la Casalderrey-Solana and Ficnar, taking distributions for all energies and angles from pQCD as in p-p collisions. Redo computation of how dijet asymmetry is modified, now starting from an unquenched ensemble in which the dijet asymmetry has the appropriate origin.
- Analysis of ensembles of holographic jets yield qualitative insights. For quantitative comparison to data...

Evolution of an Ensemble of Holographic (Di)jets

(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)



- **Full string dynamics "nullifies" and reproduces energy distribution along the string from near-endpoint approximation used by Chesler et al. (black curve). Colored curves are 6 different initial conditions for full string dynamics.**

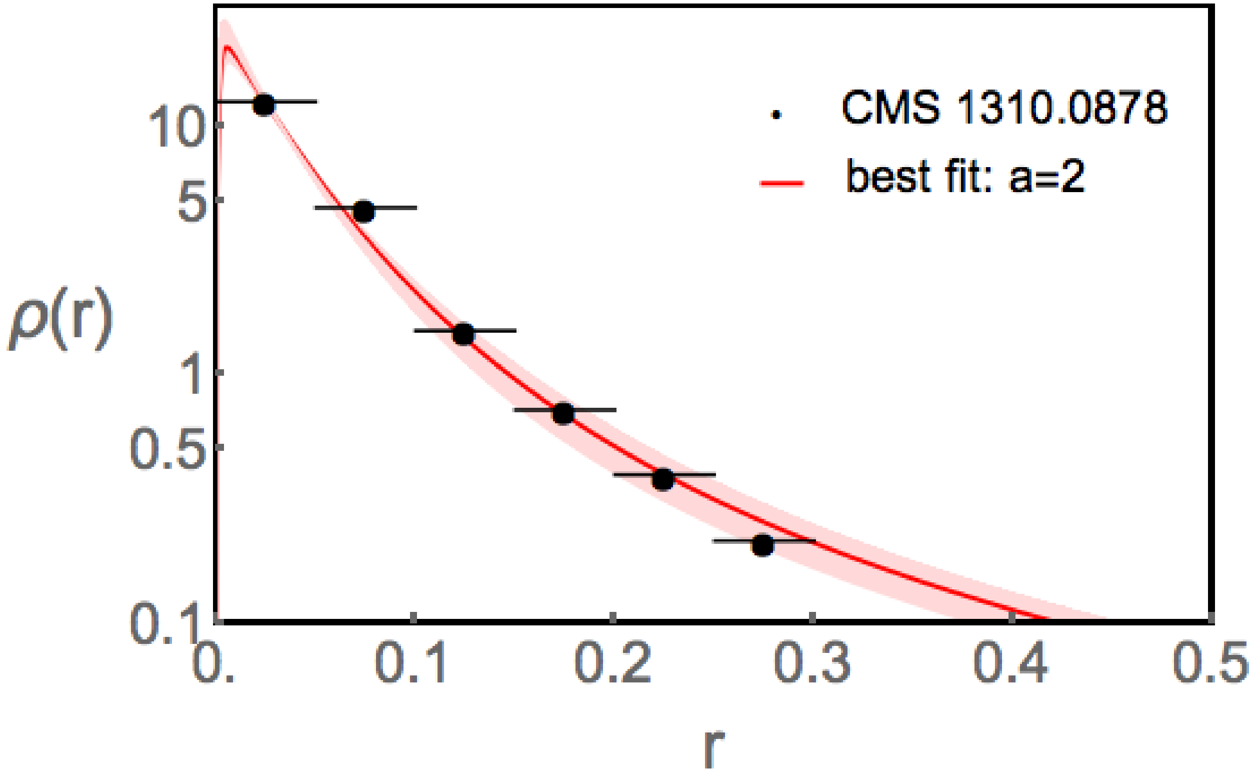
Evolution of an Ensemble of Holographic (Di)jets

(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)

- Check that full string dynamics "nullifies" and reproduces energy distribution along the string from Chesler et al.
- Tailor an ensemble of holographic jets with initial jet shape is as in p-p collisions; only tailoring needed is choice of parameter a. Analyze the modification of jet shape due to passage through plasma. Jet shape; not just width.
- Construct an ensemble of back-to-back dijets, with initial dijet asymmetry as in p-p collisions. Analyze modification of the dijet asymmetry due to passage through plasma.
- Construct an ensemble of dijet and trijet events, the latter constructed à la Casalderrey-Solana and Ficnar, taking distributions for all energies and angles from pQCD as in p-p collisions. Redo computation of how dijet asymmetry is modified, now starting from an unquenched ensemble in which the dijet asymmetry has the appropriate origin.
- Analysis of ensembles of holographic jets yield qualitative insights. For quantitative comparison to data...

Evolution of an Ensemble of Holographic (Di)jets

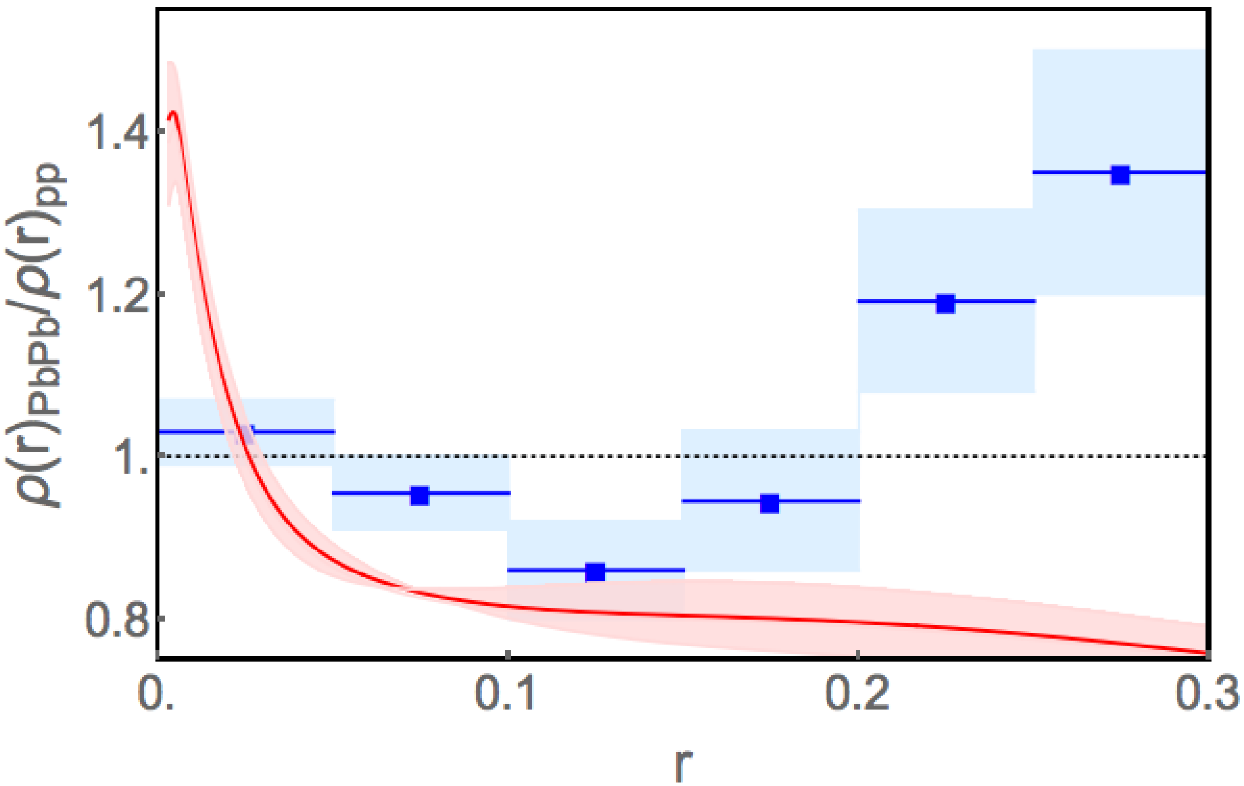
(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)



- Tailor an ensemble of holographic jets with $p_T > 100$ GeV to get initial jet shape is as in p-p collisions. Only tailoring needed is choice of parameter a: $1.8 < a < 2.5$. Data is from jets in p-p collisions. (Then choose b to get reasonable suppression in the number of jets in final ensemble.)

Evolution of an Ensemble of Holographic (Di)jets

(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)



- **Analyze the modification of jet shape due to passage through plasma. Jet shape; not just width. Passage through plasma results in an ensemble of narrower jets (because wider jets lose more energy). Degree of narrowing qualitatively reproduces that seen in data.**

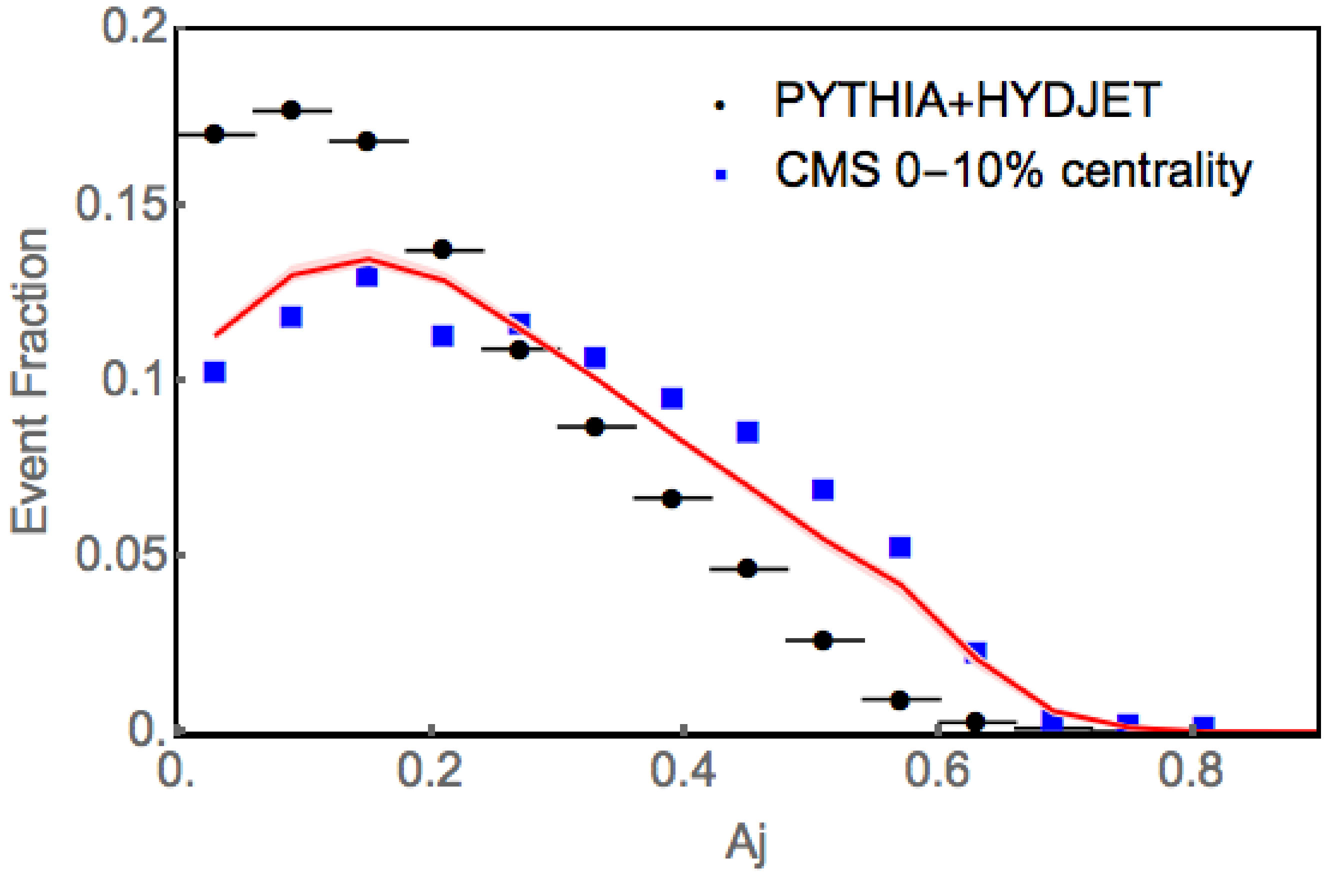
Evolution of an Ensemble of Holographic (Di)jets

(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)

- Check that full string dynamics "nullifies" and reproduces energy distribution along the string from Chesler et al.
- Tailor an ensemble of holographic jets with initial jet shape is as in p-p collisions; only tailoring needed is choice of parameter a. Analyze the modification of jet shape due to passage through plasma. Jet shape; not just width.
- Construct an ensemble of back-to-back dijets, with initial dijet asymmetry as in p-p collisions. Analyze modification of the dijet asymmetry due to passage through plasma.
- Construct an ensemble of dijet and trijet events, the latter constructed à la Casalderrey-Solana and Ficnar, taking distributions for all energies and angles from pQCD as in p-p collisions. Redo computation of how dijet asymmetry is modified, now starting from an unquenched ensemble in which the dijet asymmetry has the appropriate origin.
- Analysis of ensembles of holographic jets yield qualitative insights. For quantitative comparison to data...

Evolution of an Ensemble of Holographic (Di)jets

(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)



- **Construct an ensemble of back-to-back dijets, with initial dijet asymmetry as in p-p collisions. Analyze modification of the dijet asymmetry due to passage through plasma.**

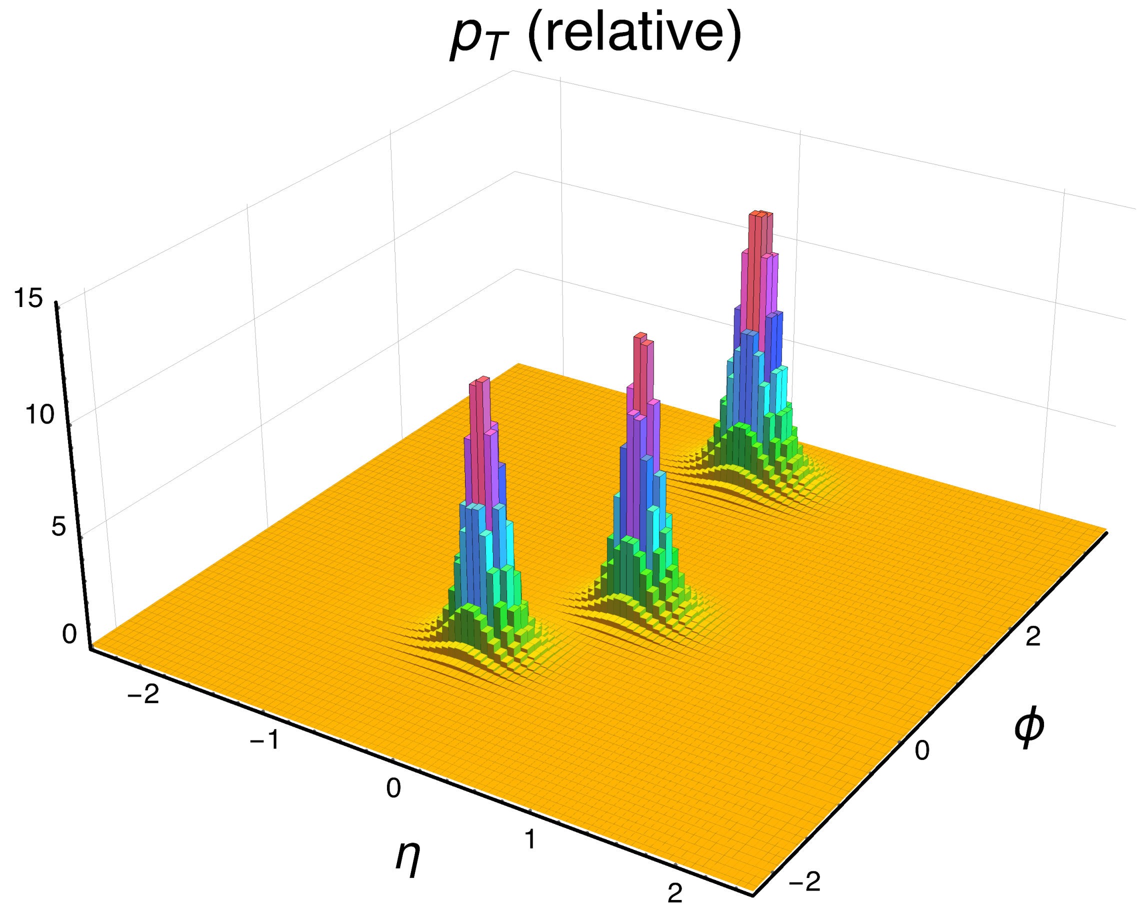
Evolution of an Ensemble of Holographic (Di)jets

(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)

- Check that full string dynamics "nullifies" and reproduces energy distribution along the string from Chesler et al.
- Tailor an ensemble of holographic jets with initial jet shape is as in p-p collisions; only tailoring needed is choice of parameter a. Analyze the modification of jet shape due to passage through plasma. Jet shape; not just width.
- Construct an ensemble of back-to-back dijets, with initial dijet asymmetry as in p-p collisions. Analyze modification of the dijet asymmetry due to passage through plasma.
- Construct an ensemble of dijet and trijet events, the latter constructed à la Casalderrey-Solana and Ficnar, taking distributions for all energies and angles from pQCD as in p-p collisions. Redo computation of how dijet asymmetry is modified, now starting from an unquenched ensemble in which the dijet asymmetry has the appropriate origin.
- Analysis of ensembles of holographic jets yield qualitative insights. For quantitative comparison to data. . .

Evolution of an Ensemble of Holographic (Di)jets

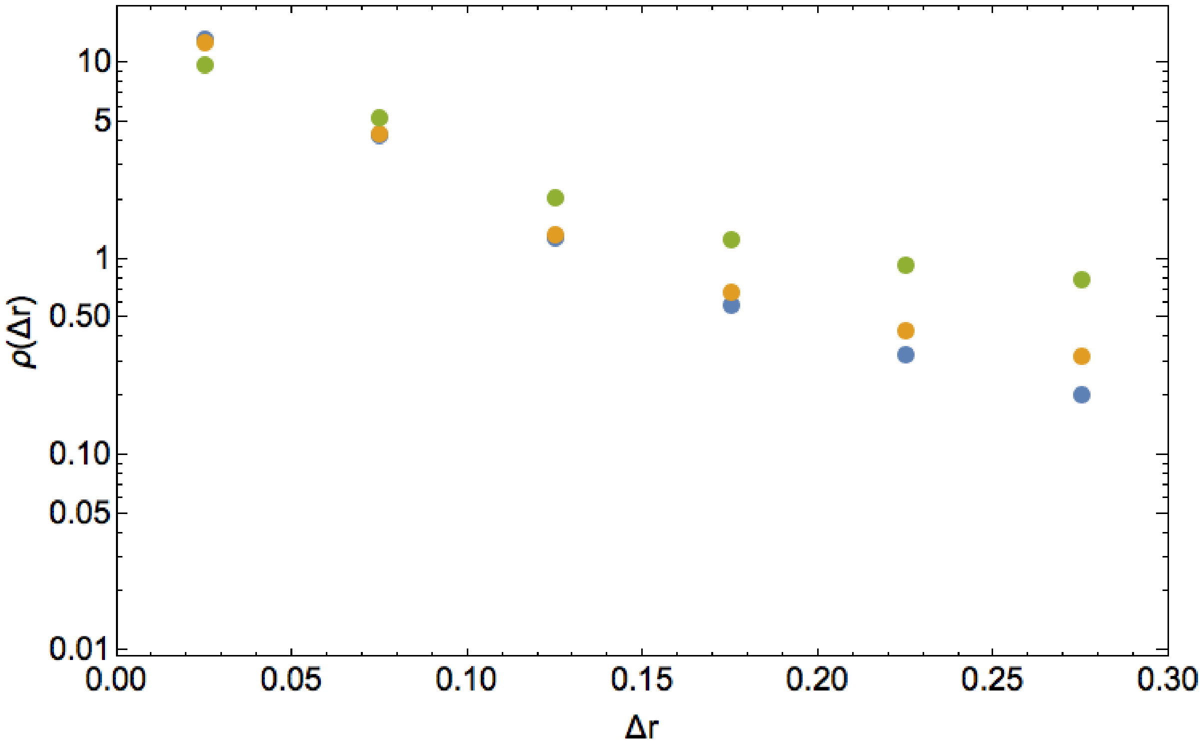
(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)



- Construct an ensemble of dijet and trijet events, the latter constructed à la Casalderrey-Solana and Ficnar...

Evolution of an Ensemble of Holographic (Di)jets

(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)



- The ensemble is still under construction, but here is a preliminary look at the jet shape for the leading, subleading, and third jets in an ensemble of three jet events, before quenching. Probablity distributions for all relevant angles and energies chosen from pQCD using MadGraph.

Evolution of an Ensemble of Holographic (Di)jets

(Brewer, KR, Sadofyev, van der Schee, 1704.05455 and in progress)

- Check that full string dynamics "nullifies" and reproduces energy distribution along the string from Chesler et al.
- Tailor an ensemble of holographic jets with initial jet shape is as in p-p collisions; only tailoring needed is choice of parameter a. Analyze the modification of jet shape due to passage through plasma. Jet shape; not just width.
- Construct an ensemble of back-to-back dijets, with initial dijet asymmetry as in p-p collisions. Analyze modification of the dijet asymmetry due to passage through plasma.
- Construct an ensemble of dijet and trijet events, the latter constructed à la Casalderrey-Solana and Ficnar, taking distributions for all energies and angles from pQCD as in p-p collisions. Redo computation of how dijet asymmetry is modified, now starting from an unquenched ensemble in which the dijet asymmetry has the appropriate origin.
- Analysis of ensembles of holographic jets yield qualitative insights. For quantitative comparison to data...

A Hybrid Approach

Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1405.3864,1508.00815, 1609.05842; Hulcher, Pablos, KR, 2017

- **Hard scattering and the fragmentation of a hard parton produced in a hard scattering are weakly coupled phenomena, well described by pQCD.**
- **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.**
- **Try a hybrid approach. Think of each parton in a parton shower à la PYTHIA losing energy à la dE/dx for light quarks in strongly coupled liquid from a previous slide.**
- **We have looked at R_{AA}, dijet asymmetry, jet fragmentation function, photon-jet and Z-jet observables. Upon fitting one parameter, *lots* of data described well. Value of the fitted parameter is reasonable: x_{therm} in QGP is 3-4 times longer than in $\mathcal{N} = 4$ SYM plasma with same T.**
- **Most recently: adding momentum broadening and the wake in the plasma, adding resolution effects, looking at jet shapes, jet masses and related observables.**

Implementation of Hybrid Model

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

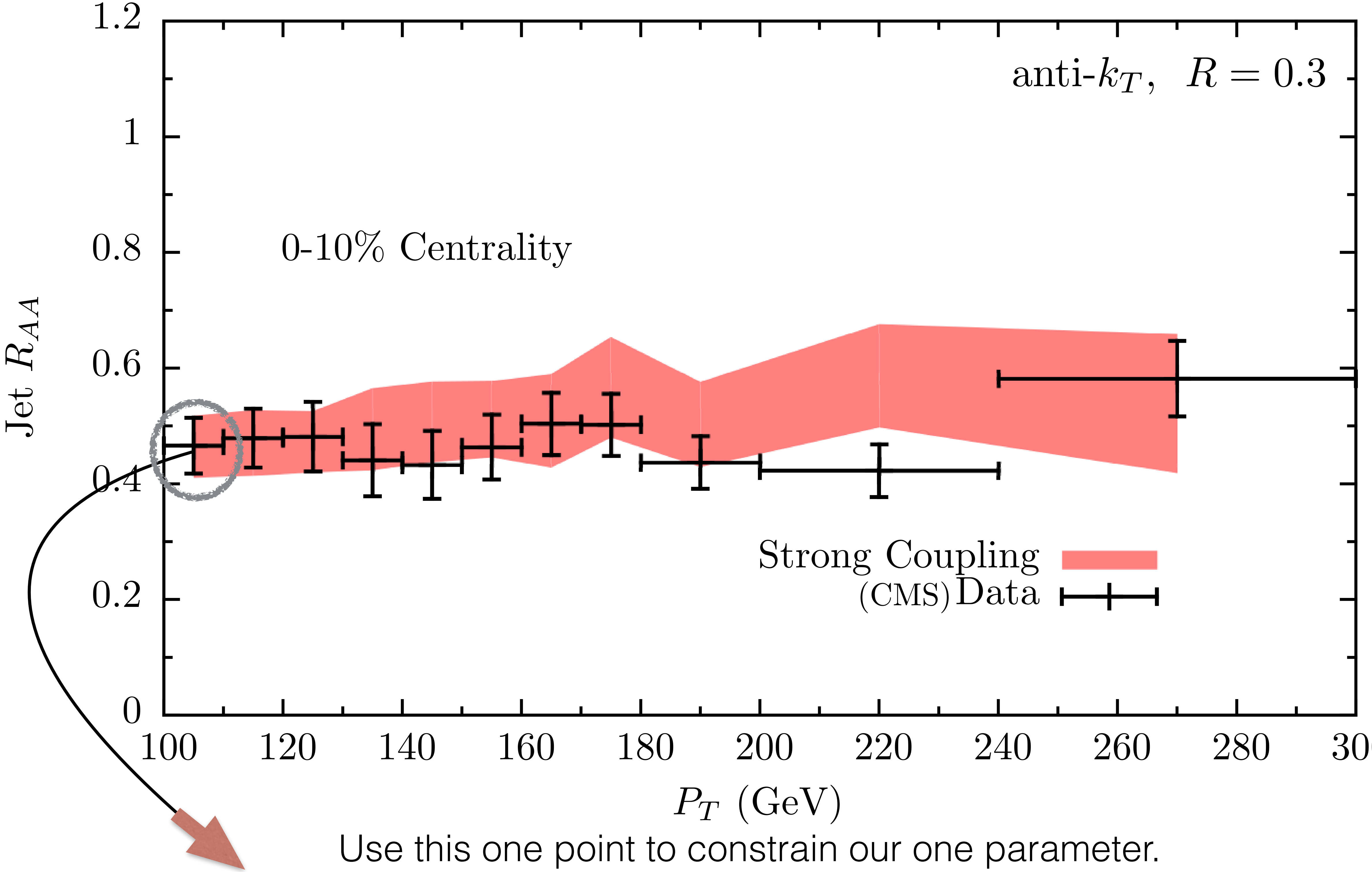
- **Jet production and showering from PYTHIA.**
- **Embed the PYTHIA parton showers in hydro background. (2+1D hydro from Heinz and Shen.)**
- **Between one splitting and the next, each parton in the branching shower loses energy according to**

$$\frac{1}{E_{\rm in}}\frac{dE}{dx} = -\frac{4x^2}{\pi x^2_{\rm therm}}\frac{1}{\sqrt{x^2_{\rm therm} - x^2}}$$

where $x_{\rm therm} \equiv E_{\rm in}^{1/3}/(2\kappa_{\rm sc}T^{4/3})$ **with** $\kappa_{\rm sc}$ **one free parameter that to be fixed by fitting to one experimental data point. (**$\kappa_{\rm sc} \sim 1 - 1.5$ **in** $\mathcal{N} = 4$ **SYM; smaller** $\kappa_{\rm sc}$ **means** $x_{\rm therm}$ **is longer in QGP than in** $\mathcal{N} = 4$ **SYM plasma with same** T**.)**

- **Turn energy loss off when hydrodynamic plasma cools below a temperature that we vary between 145 and 170 MeV. (This, plus the experimental error bar on the one data point, becomes the uncertainty in our predictions.)**
- **Reconstruct jets using anti-**k_T**.**

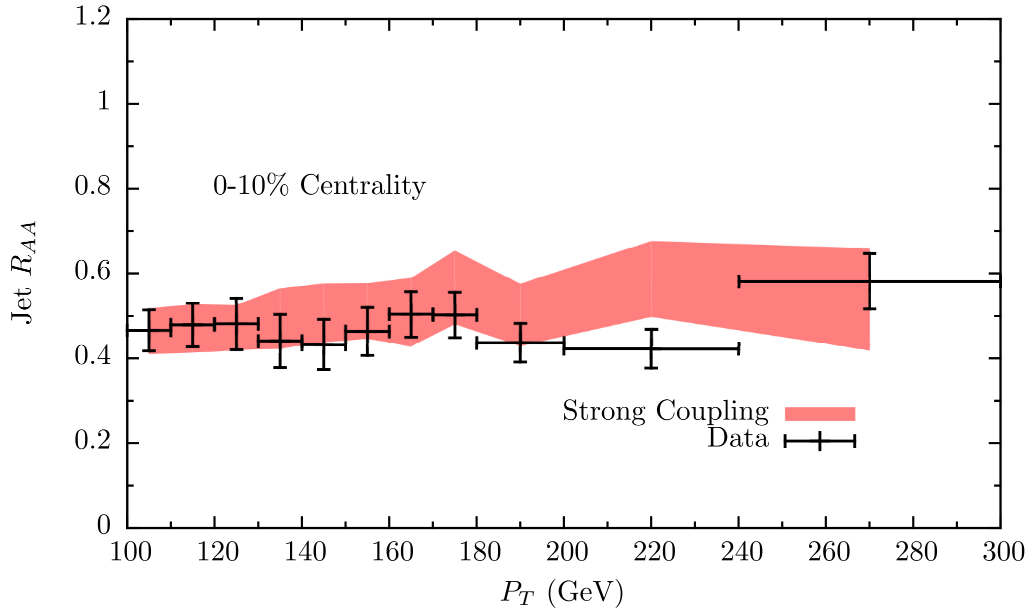
R_{AA}

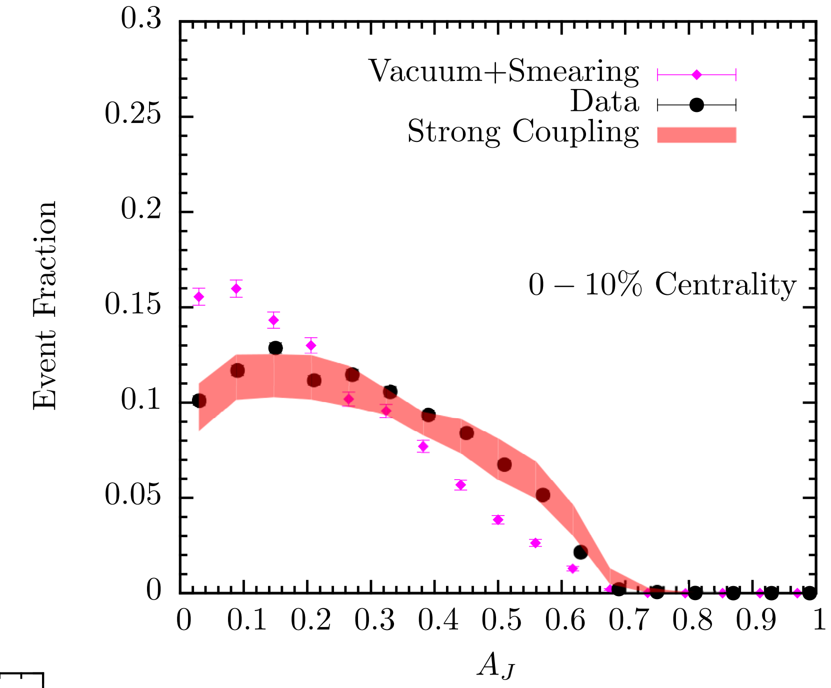


Use this one point to constrain our one parameter.

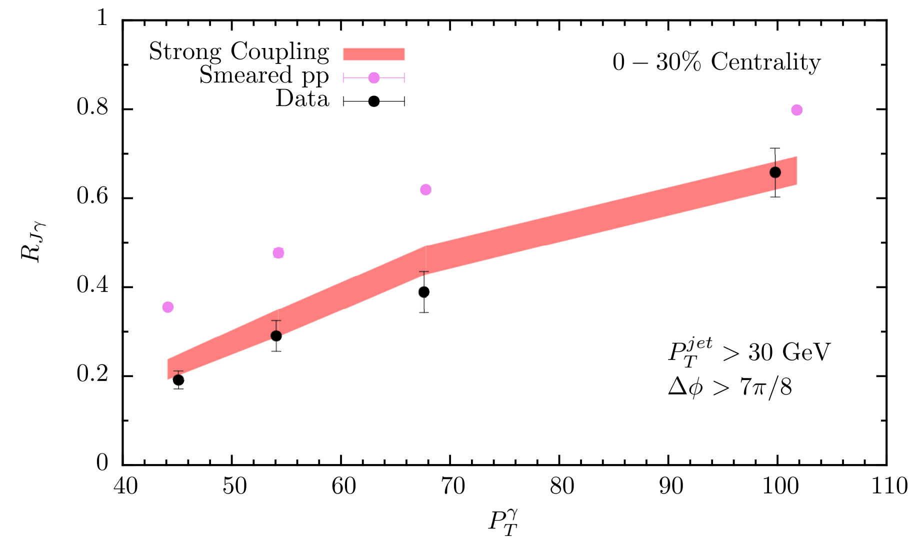
Bands come from experimental uncertainty on this point

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





5 observables
and centrality dependence
all described with
single parameter

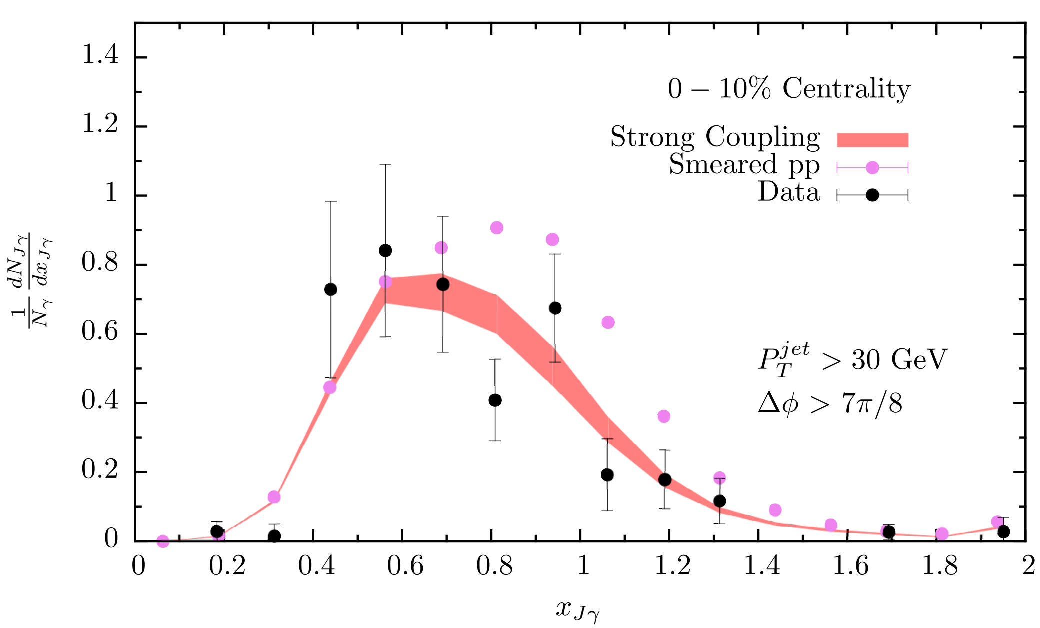


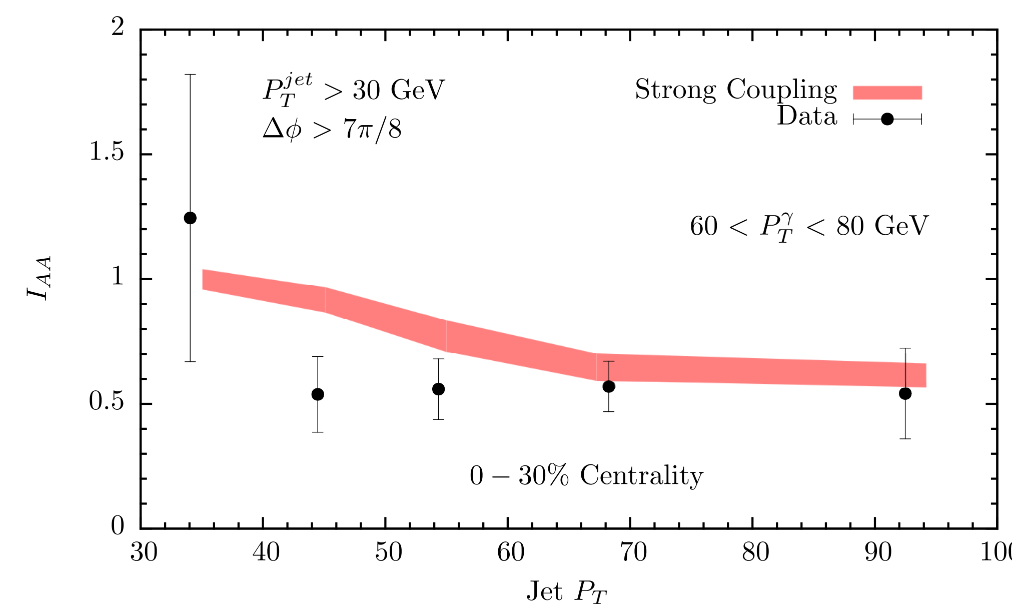
Bands in all plots correspond to

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

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

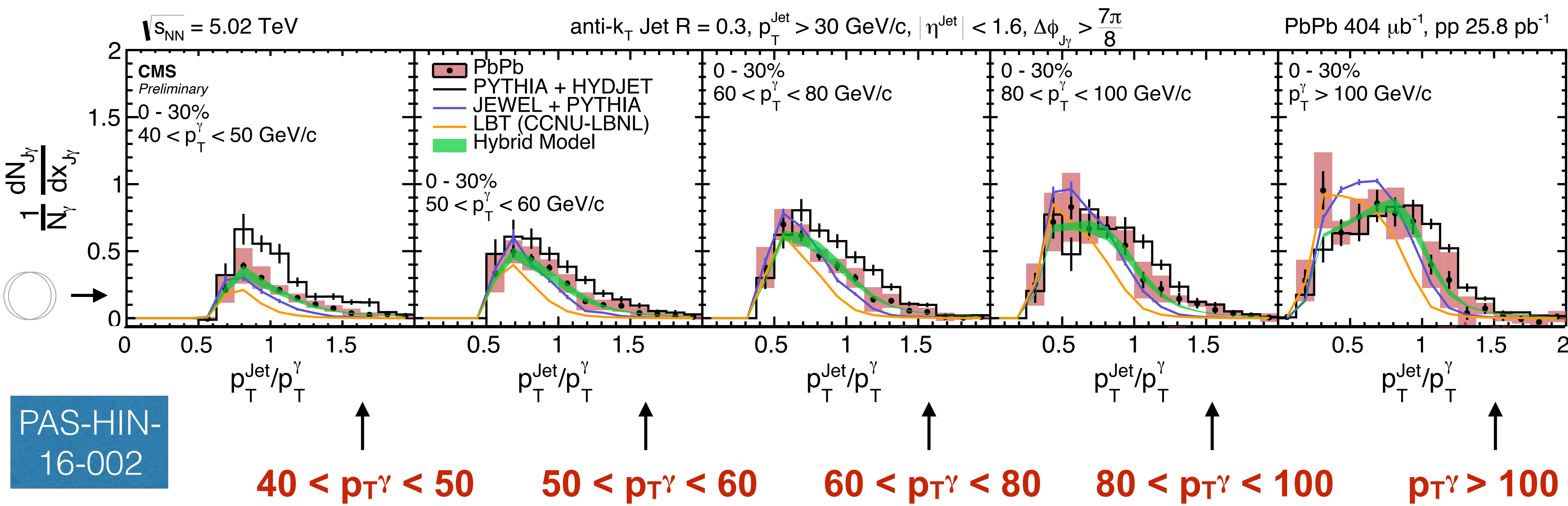
$$x_{stop}^{QCD} \sim (3-4)\, x_{stop}^{\mathcal{N}=4}$$





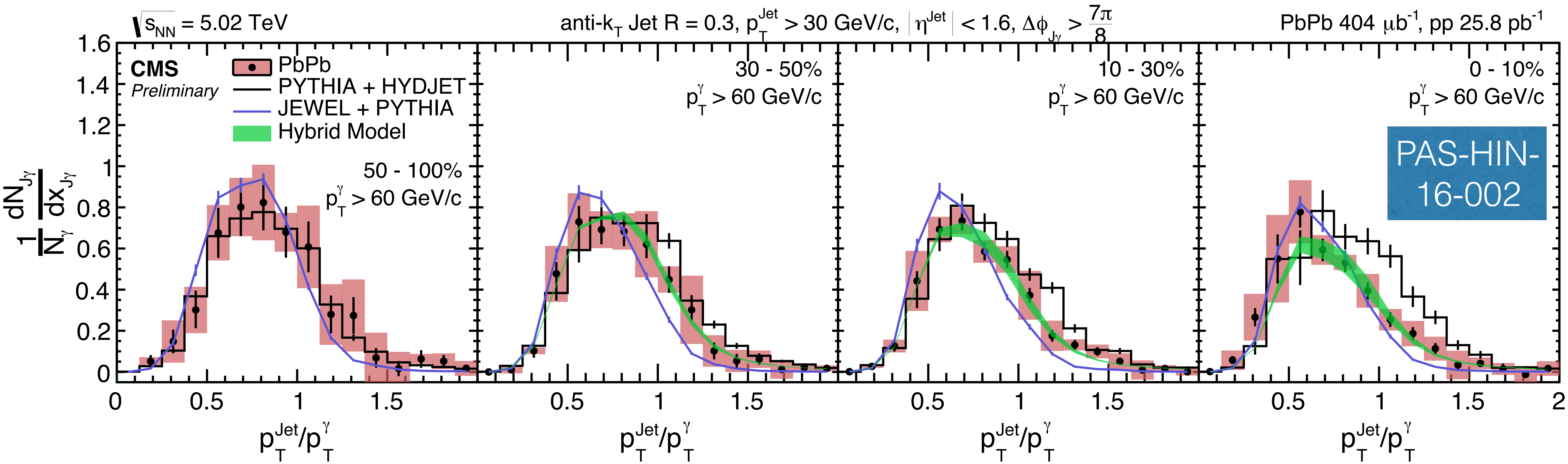
Predictions

Theory Comparison: Central PbPb $x_{J\gamma}$

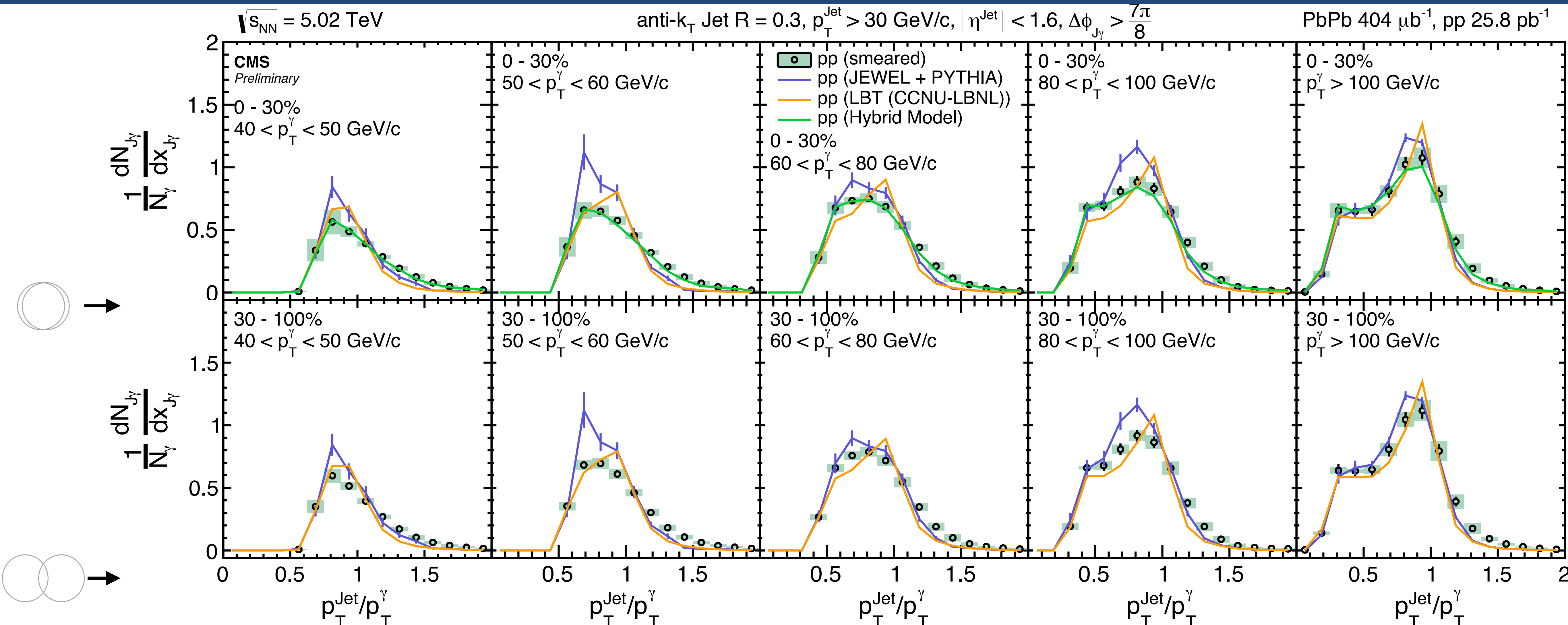


- In general, models appear to describe $x_{J\gamma}$
  - LBT has normalization issue relative to other curves
    - To be fixed in conjunction with analyzers
  - JEWEL and HYBRID comparable through all bins

Theory Comparison: $x_{J\gamma}$ in PbPb



Theory Comparison: Distribution of $x_{J\gamma}$ vs. γ p_T

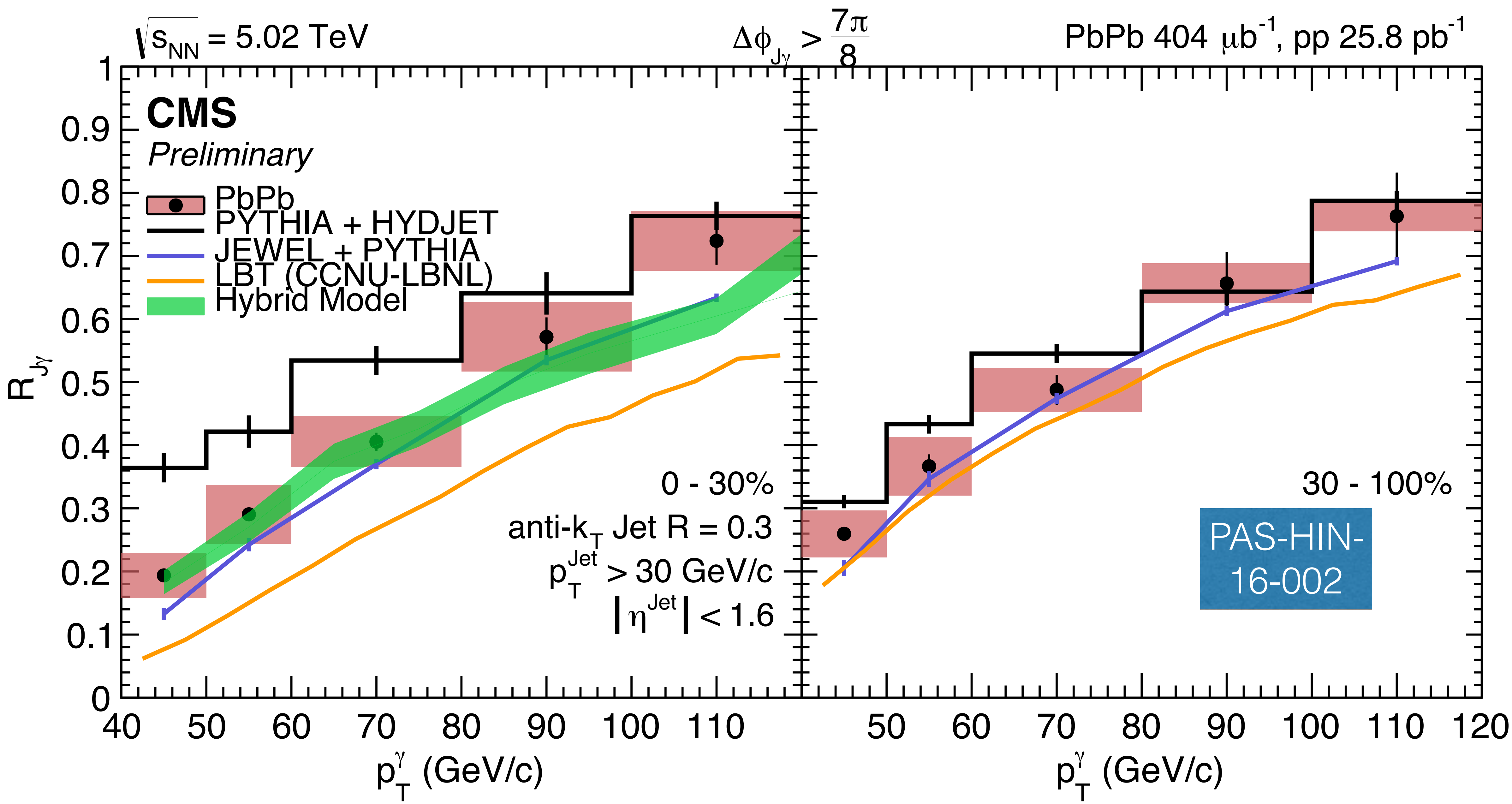


PAS-HIN-16-002

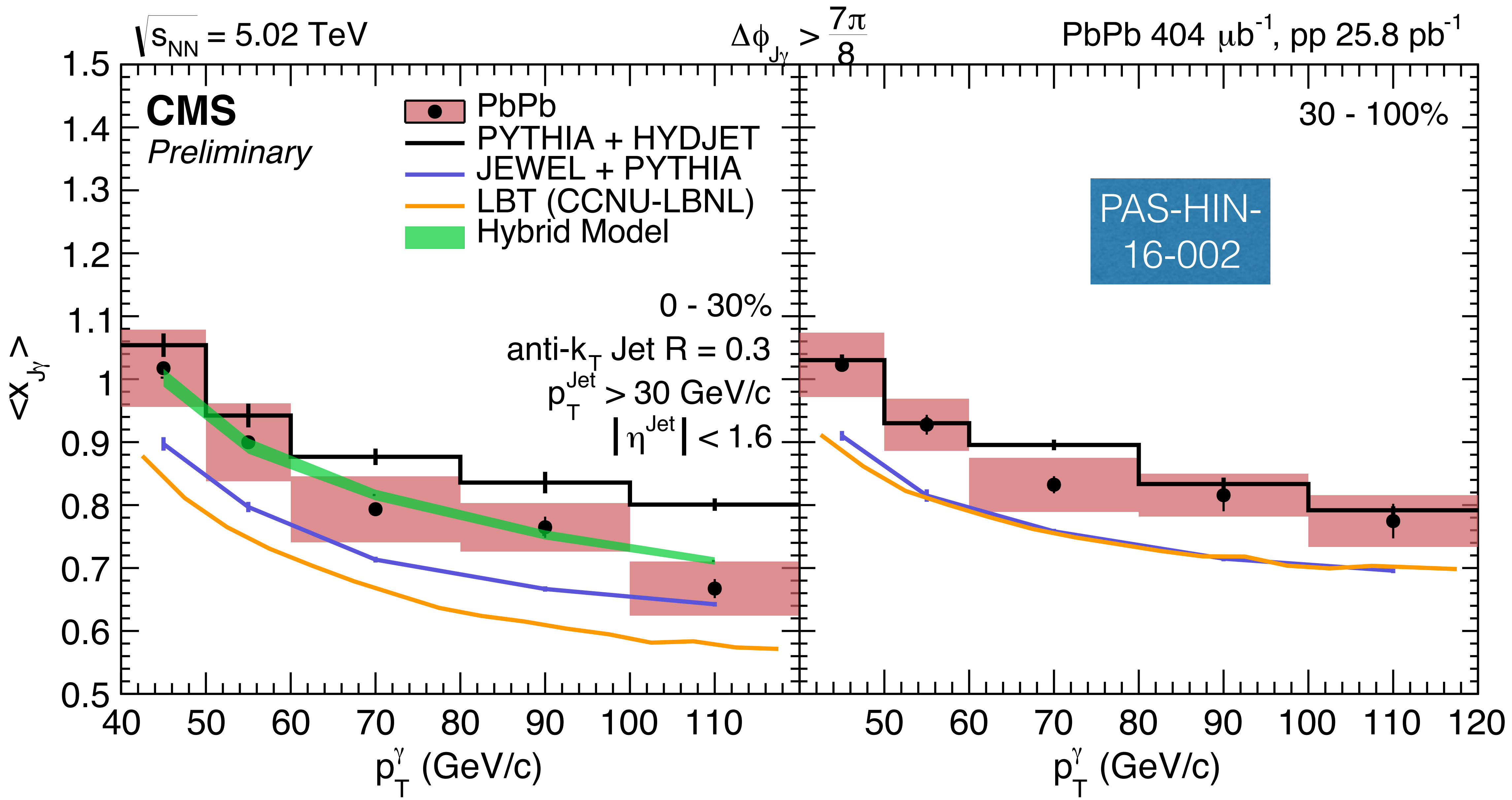
40 < p_T^γ < 50 **50 < p_T^γ < 60** **60 < p_T^γ < 80** **80 < p_T^γ < 100** **p_T^γ > 100**

- Overlaid PYTHIA, JEWEL, LBT and Hybrid Model

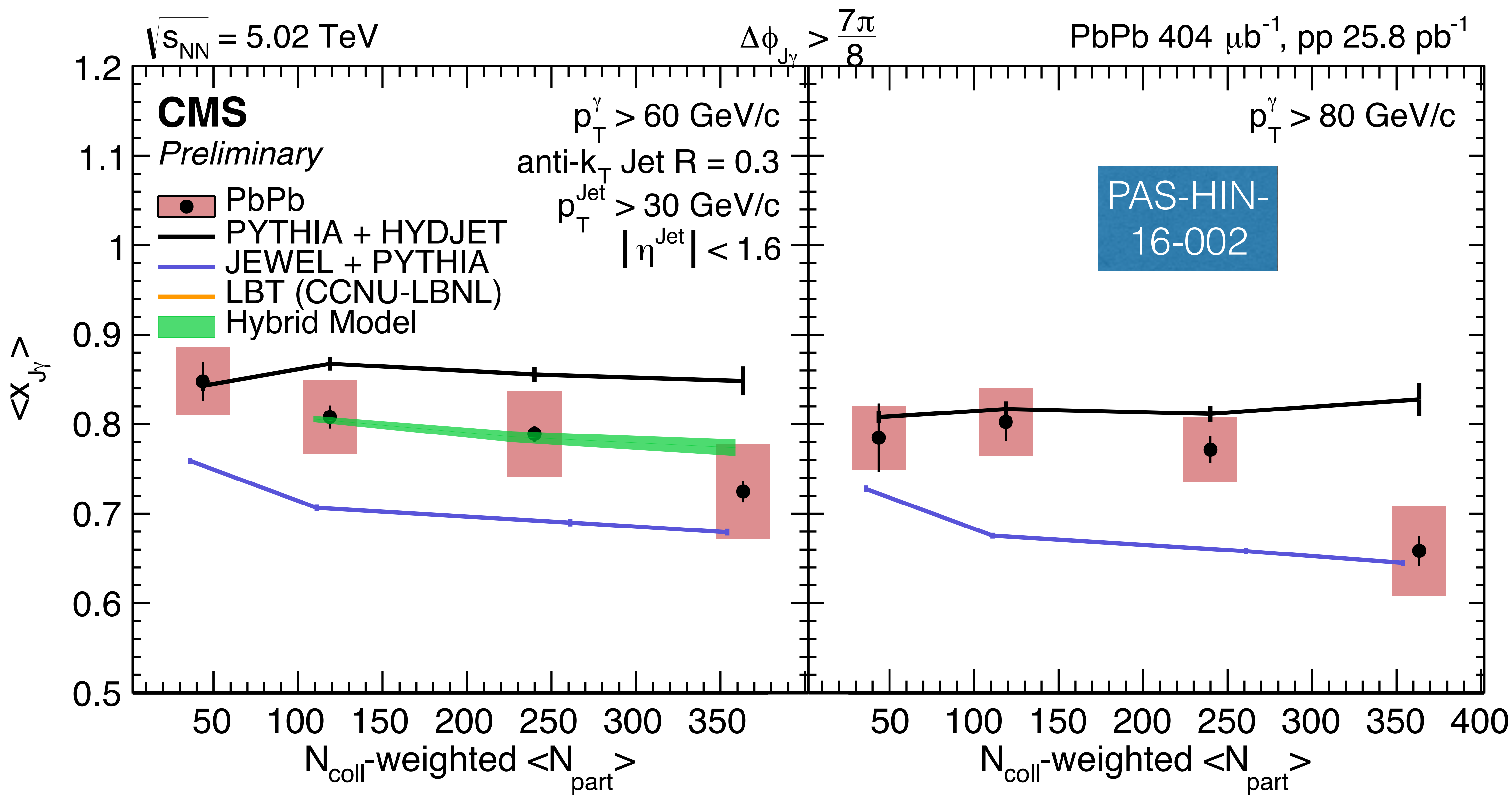
Theory Comparison: $R_{J\gamma}$ in PbPb



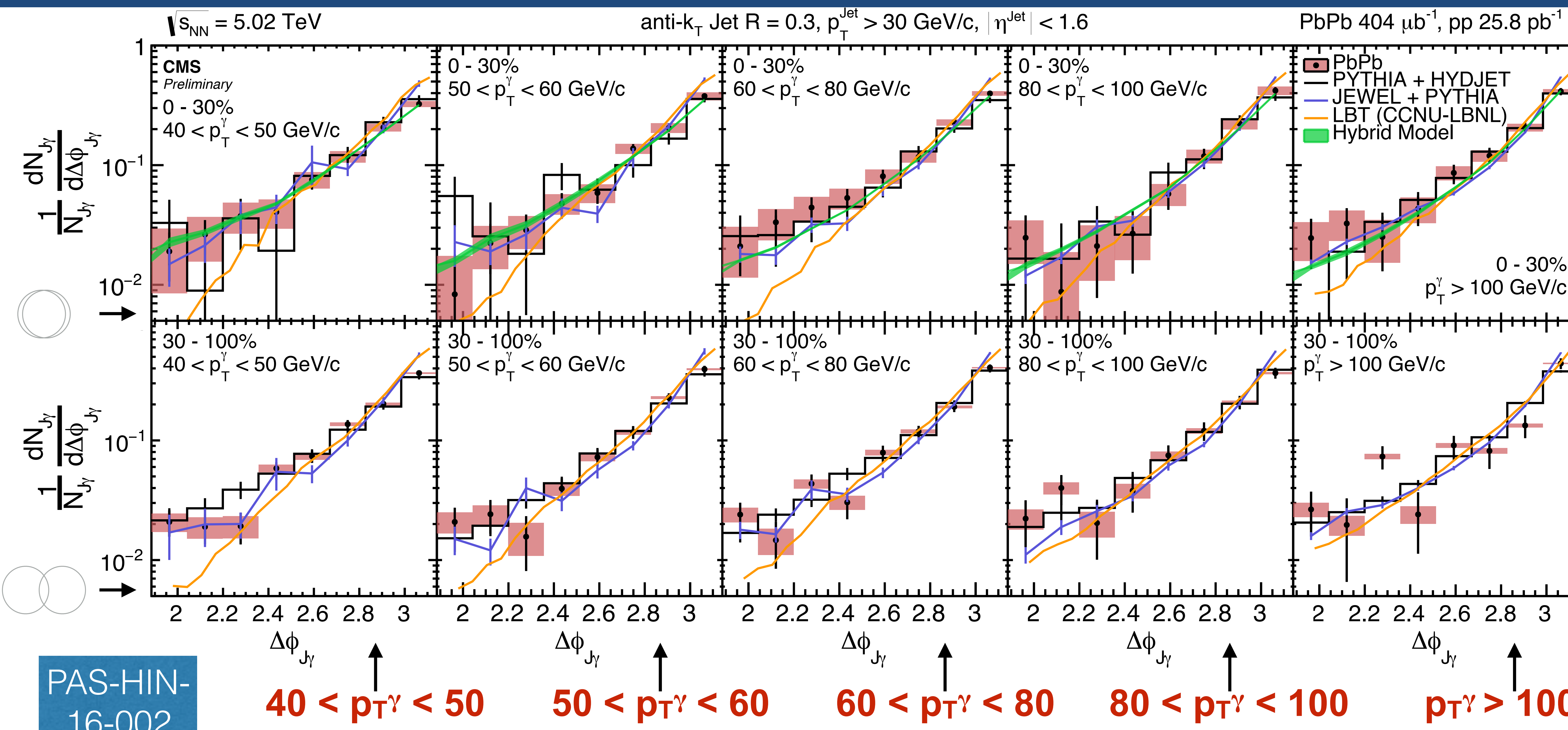
Theory Comparison: $x_{J\gamma}$ in PbPb



Theory Comparison: $x_{J\gamma}$ in PbPb

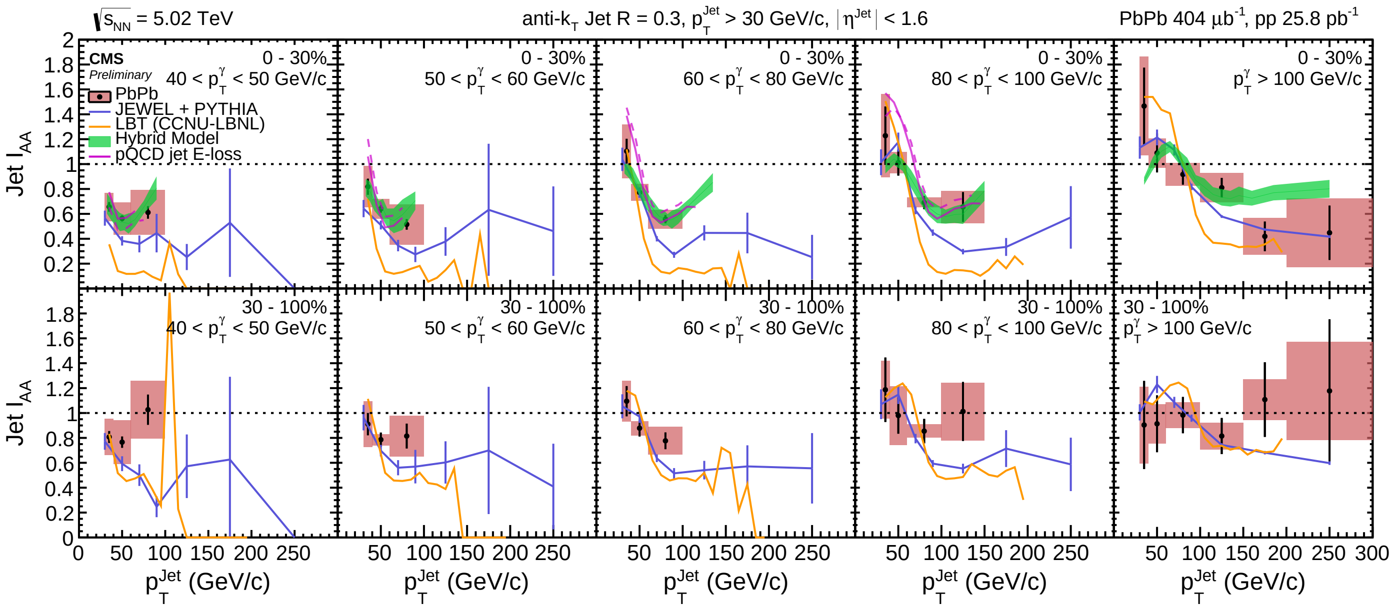


Theory Comparison: $\Delta\phi_{J\gamma}$ in PbPb



PAS-HIN-16-002

- Overlaid PYTHIA+HYDJET, JEWEL, LBT and Hybrid Model



$\sqrt{s_{NN}}$ = 5.02 TeV
anti-k_T Jet R = 0.3, p_T^{Jet} > 30 GeV/c, $|\eta^{Jet}|$ < 1.6
PbPb 404 μb^{-1}, pp 25.8 pb^{-1}
CMS
Preliminary
PbPb
JEWEL + PYTHIA
LBT (CCNU-LBNL)
Hybrid Model
pQCD jet E-loss
0 - 30%
$40 < p_T^{\gamma} < 50$ GeV/c
$50 < p_T^{\gamma} < 60$ GeV/c
$60 < p_T^{\gamma} < 80$ GeV/c
$80 < p_T^{\gamma} < 100$ GeV/c
$p_T^{\gamma} > 100$ GeV/c
30 - 100%
Jet I_{AA}
p_T^{Jet} (GeV/c)

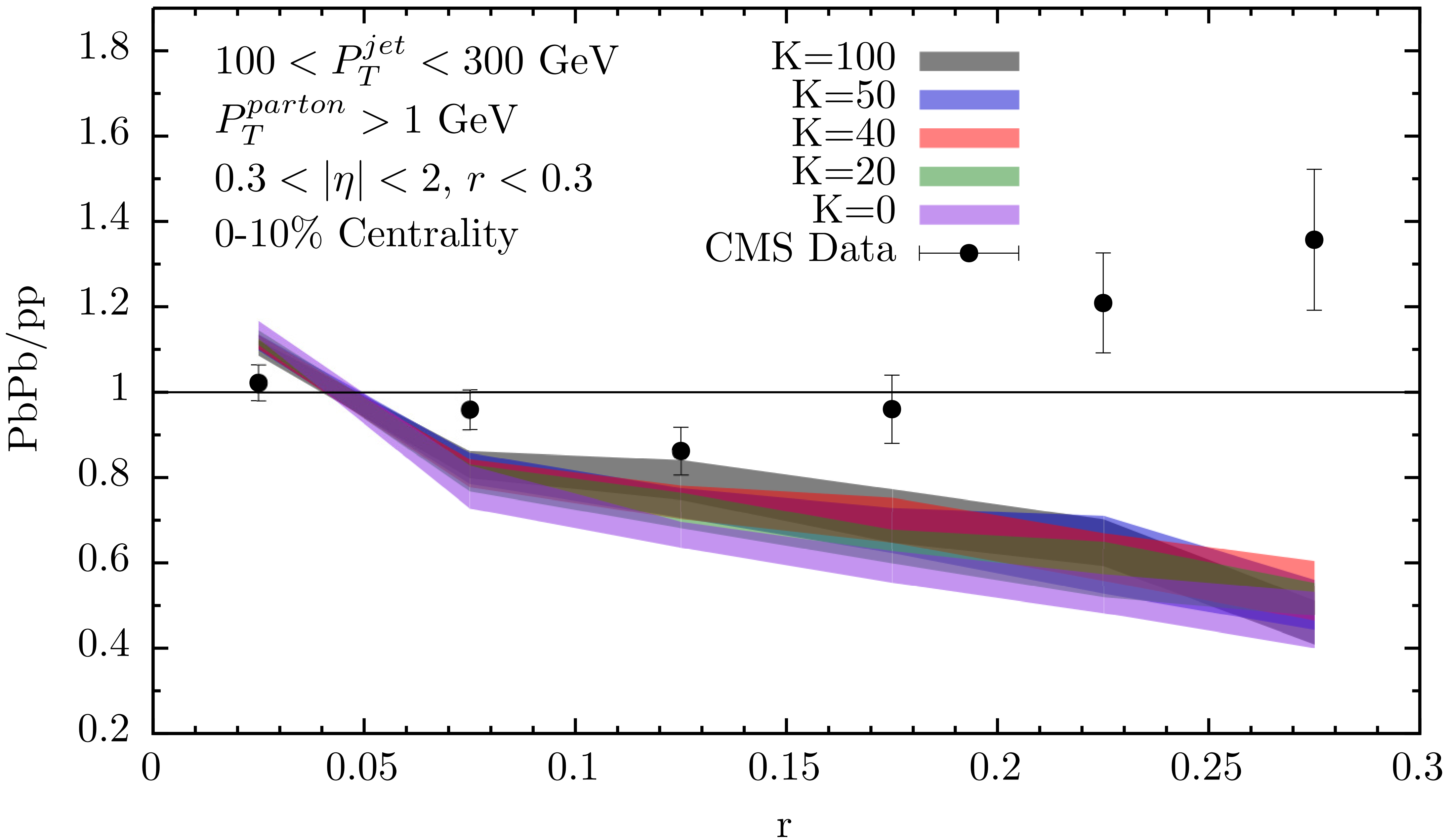
Desiderata

- **Increasingly precise tests of the result that strongly coupled form for dE/dx, but with $x^{\mathrm{QCD}}_{\mathrm{therm}} \sim (3-4) x^{\mathcal{N}=4}_{\mathrm{therm}}$ describes** *jet observables sensitive to parton energy loss***.**
- **Use of best-available photon-jet data to compare hybrid model predictions with strongly coupled form for dE/dx to those with $dE/dx \propto T^2$ and $dE/dx \propto T^3 x$.**
- **This is all good. It is bringing us understanding. But it does not get us to the goal of using jets to probe the microscopic structure of QGP. That has to come from looking at scattering of partons in the jet off (quasiparticles in) QGP. So we have to look at the modifications to the shape of jets.**
- **And, at this point, in order to learn something interesting we need to start seeing where the one parameter hybrid model described to this point fails to describe data.**

Modifications to Shape of Jets?

- **Ultimately, we want to use the scattering of partons in a jet off the QGP to probe its microscopic structure. So, lets start looking at the effects of transverse kicks received by partons in a jet on the jet shape.**
- **Expectation in a strongly coupled liquid? Partons pick up transverse momentum according to a Gaussian distribution. (Rutherford's original expectation.) Here, the width of the Gaussian distribution after propagation in the liquid for a distance dx is KT^3dx, with K a new parameter in the hybrid model.**
- **In perturbative formulations, K is related to energy loss as well as to transverse kicks, and can be constrained from data. The JET collaboration finds $K_{\text{pert}} \simeq 5$.**
- **In the strongly coupled plasma of $\mathcal{N} = 4$ SYM theory, $K_{\mathcal{N}=4} \simeq 24$ for 't Hooft coupling $\lambda = 10$. In the strongly coupled plasma of QCD, K should be less than this.**
- **Lets look at the jet shape, with $0 \leq K \leq 100$. (Even though in reality we expect $K < 20$.)**

Small sensitivity of standard jet shapes to broadening



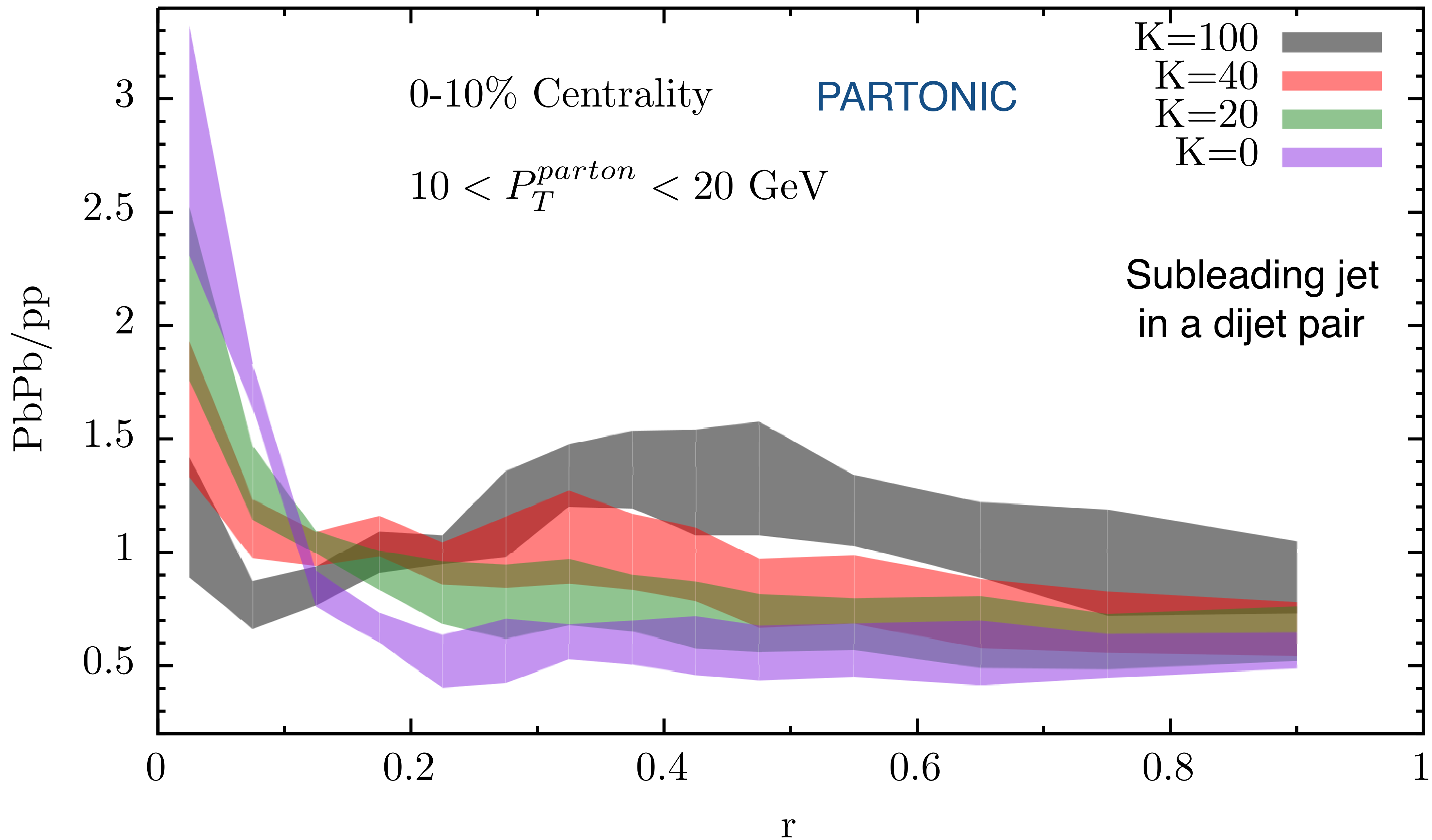
Small sensitivity of jet shapes to broadening:

- strong quenching removes soft fragments that appear early
- remaining soft tracks fragment late

Modifications to Shape of Jets?

- Jets with a given energy seem to get narrower, as long as you look only at small r. In data, and in the hybrid model. Even when partons in the jets get strong transverse kicks. This narrowing is a consequence of energy loss. Jets with a given energy after quenching are narrower than those that had that energy before quenching because wide jets lose more energy than narrow ones.
- So, how can we construct an observable that *is* sensitive to the value of K?
- The model is obviously missing something or somethings important at larger r. (This is good. It would be really frustrating if a model as brutally simple as this kept working for every observable. Seeing how a model like this fails, and hence learning what physics must be added to it, is the point.)

A New Observable, Sensitive to Broadening

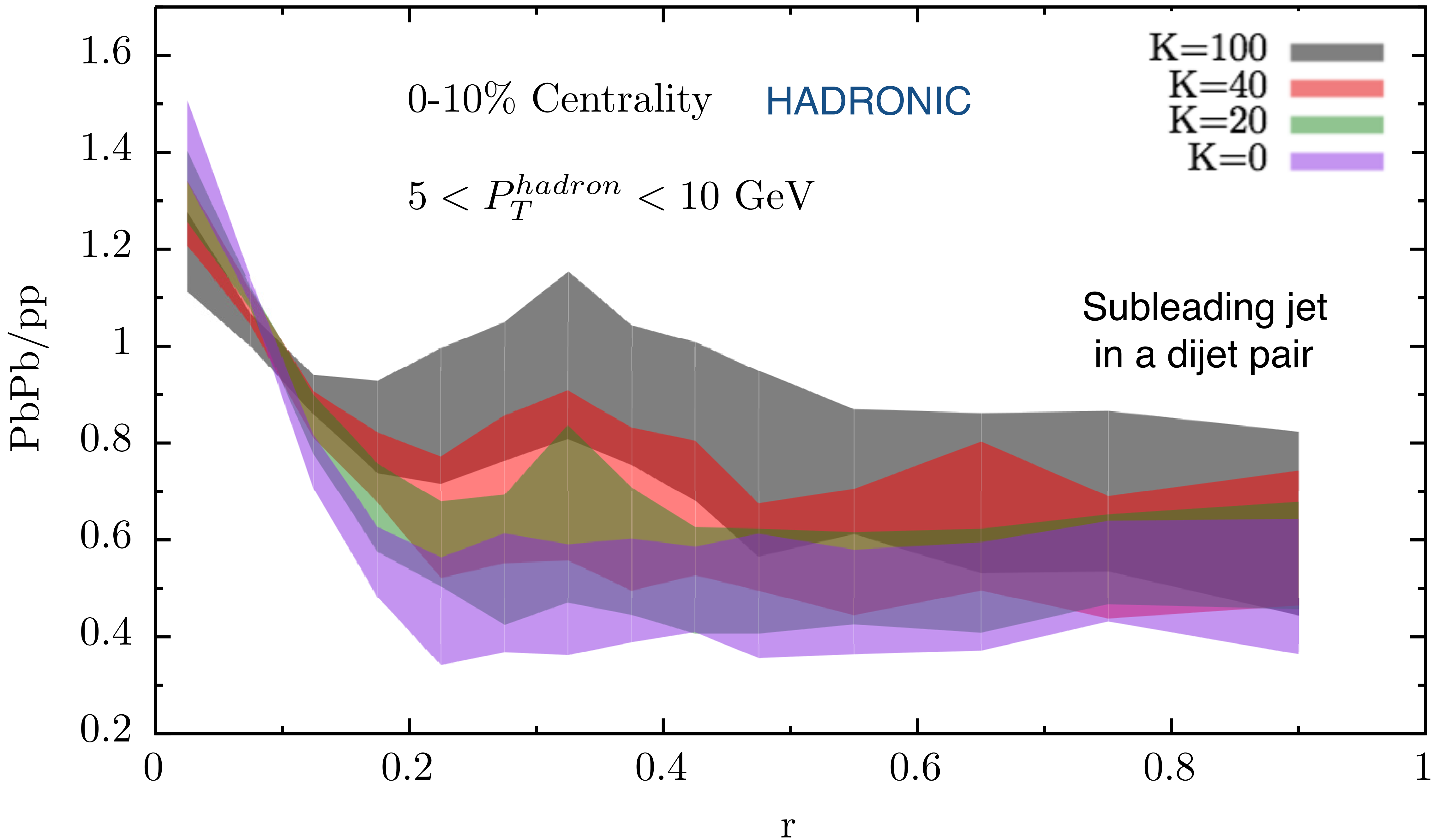


Kinematical cuts for partons chosen such that:

- there is no effect from background (soft tracks)
- we focus on jets without unfragmented cores (hard tracks)

A New Observable, Sensitive to Broadening

motivated by CMS analysis CMS-HIN-15-011



Hadrons with a given range of momenta
originate from partons with a wider range of momenta

Direct experimental determination of Gaussian broadening strength

Looking Ahead to the 2020s

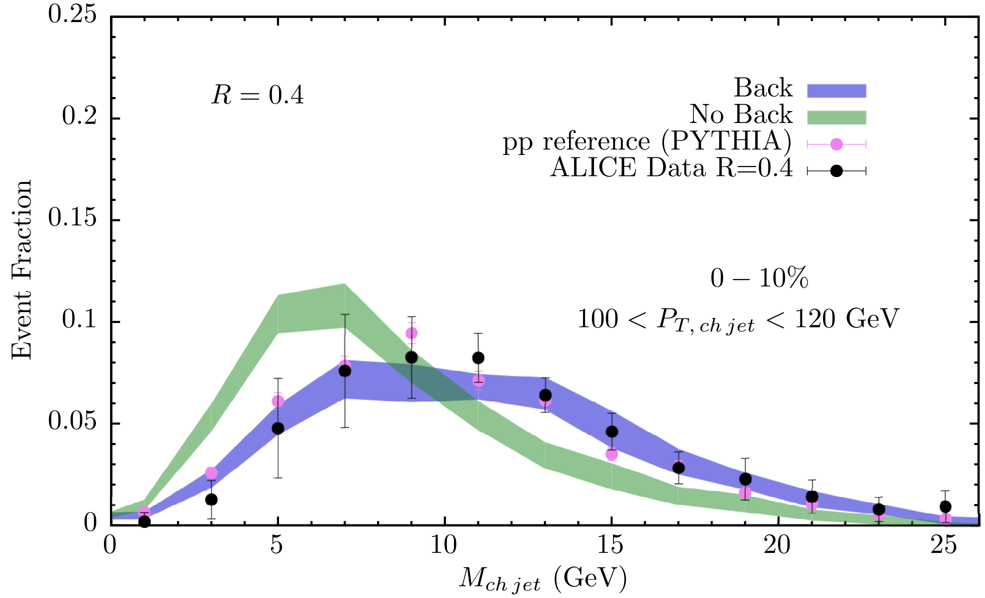
- Before then, via the use of differential jet shape ratios and similar observables that are sensitive to the angular distribution of 10-20 GeV partons in the jet it will be possible to constrain the value of K, the width of the Gaussian distribution of transverse momentum received. Can differential jet shape ratios be measured in photon-jet events?
- Goal for the 2020s: look for the rare (but only power-law rare not Gaussianly rare) larger angle scatterings caused by the presence of quark and gluon quasiparticles in the soup when the short-distance structure of the soup is probed. D'Eramo, Lekaveckas, Liu, KR 1211.1922; Kurkela, Wiedemann, 1407.0293; D'Eramo, KR, Yin, in progress
- In the 2020s, what will be interesting will be rare. In a sense event-by-event jet physics, although need not be literally so with enough statistics.
- In the 2020s, what will be interesting is deviations from the descendant of the hybrid model.

What is Missing?

- **The jet loses energy** *and momentum* **to the plasma. It leaves behind a wake in the plasma, a wake with net momentum in the direction of the jet.**
- **When experimentalists reconstruct a jet and subtract background, what they reconstruct and call a jet** *must* **include particles originating from the hadronization of the plasma+wake, with momentum in the jet direction.**
- **We need to add background to our hybrid model, add the effects of the wake, and implement background subtraction as experimentalists do. This will add soft particles at all angles, in particular at large r.** CGMPR 1609.05842
- **Our hybrid model over-quenches soft particles because when a parton in the shower splits it is treated as two separate energy-losers from the moment of the splitting. Really, the medium will see it as a single energy-loser until the two partons are separated beyond some resolution length $L_{\rm res}$. Introducing this effect will reduce the quenching of soft particles.** Hulcher, Pablos, KR 2017

Jet Mass

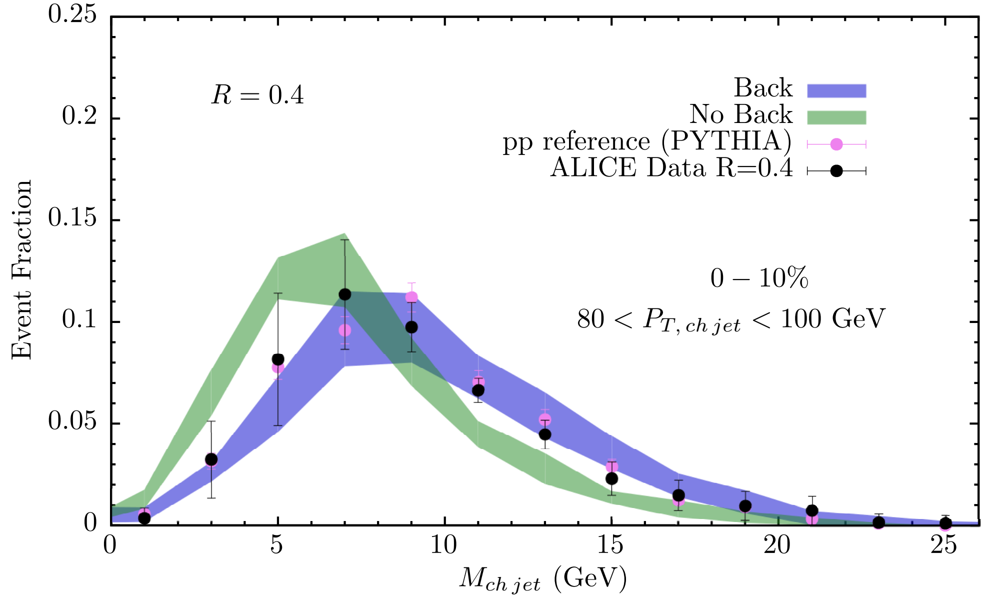
Casalderrey-Solana, Gulhan, Hulcher, Milhano, Pablos, KR, 2017



- Ratio of jet mass to jet energy is a measure of jet width.
- Because wider jets lose more energy, after quenching jets with a given energy narrower than before.
- Adding the soft particles coming from the wake in the plasma makes the jets, as reconstructed, wider.
- Two effects ∼cancel, yielding agreement with ALICE data.
- Although our treatment of the wake is inadequate in other ways (see below) the fact that it and quenching push jet shape in opposite directions is generic.

Jet Mass

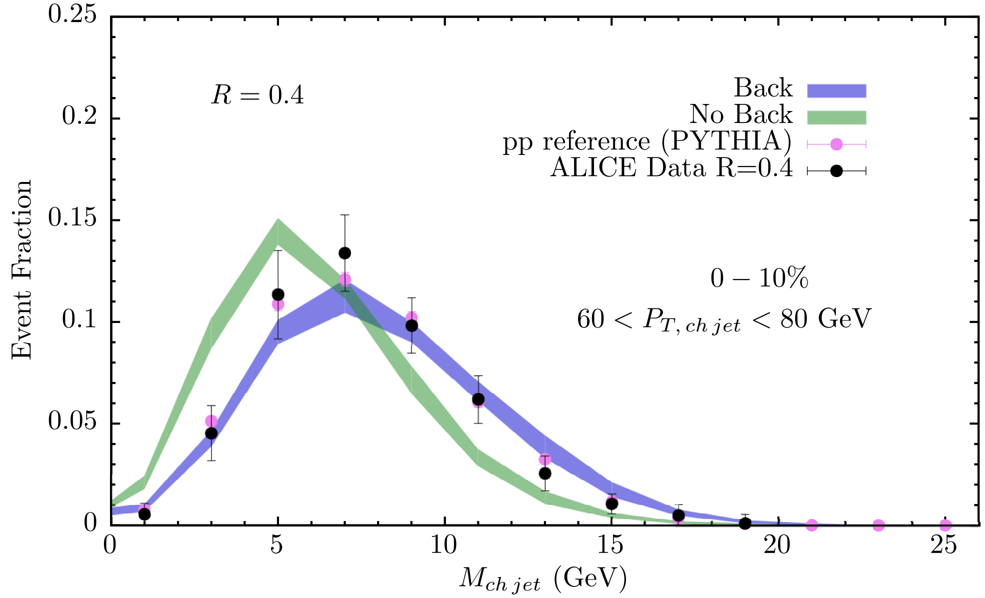
Casalderrey-Solana, Gulhan, Hulcher, Milhano, Pablos, KR, 2017



- **Ratio of jet mass to jet energy is a measure of jet width.**
- **Because wider jets lose more energy, after quenching jets with a given energy narrower than before.**
- **Adding the soft particles coming from the wake in the plasma makes the jets, as reconstructed, wider.**
- **Two effects ∼cancel, yielding agreement with ALICE data.**
- **Although our treatment of the wake is inadequate in other ways (see below) the fact that it and quenching push jet shape in opposite directions is generic.**

Jet Mass

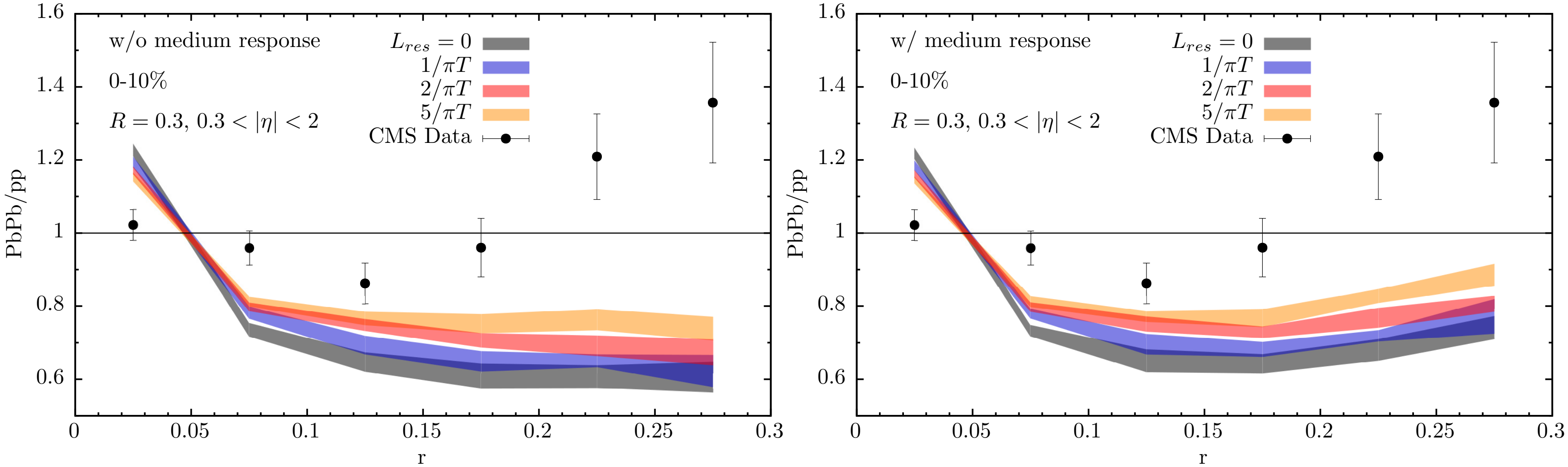
Casalderrey-Solana, Gulhan, Hulcher, Milhano, Pablos, KR, 2017



- Ratio of jet mass to jet energy is a measure of jet width.
- Because wider jets lose more energy, after quenching jets with a given energy narrower than before.
- Adding the soft particles coming from the wake in the plasma makes the jets, as reconstructed, wider.
- Two effects ~cancel, yielding agreement with ALICE data.
- Although our treatment of the wake is inadequate in other ways (see below) the fact that it and quenching push jet shape in opposite directions is generic.

Jet Shape Ratio

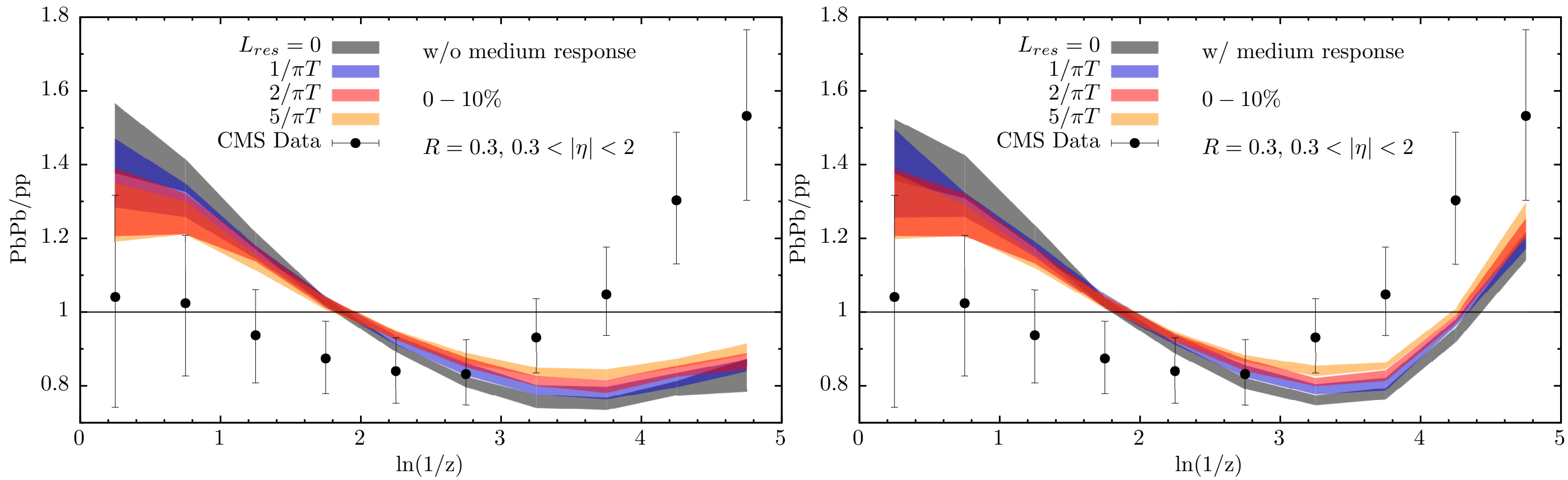
CGMPR 1609.05842; Hulcher, Pablos, KR, 2017



- **Introducing a resolution length of $L_{\rm res} = 1/(\pi T)$ or $L_{\rm res} = 2/(\pi T)$ pushes the jet shape ratio up at intermediate and large r.**
- **Introducing the soft particles from the wake in the plasma created by the jet pushes the jet shape ratio up at large r, but not as much as in the data.**

Fragmentation Function Ratio

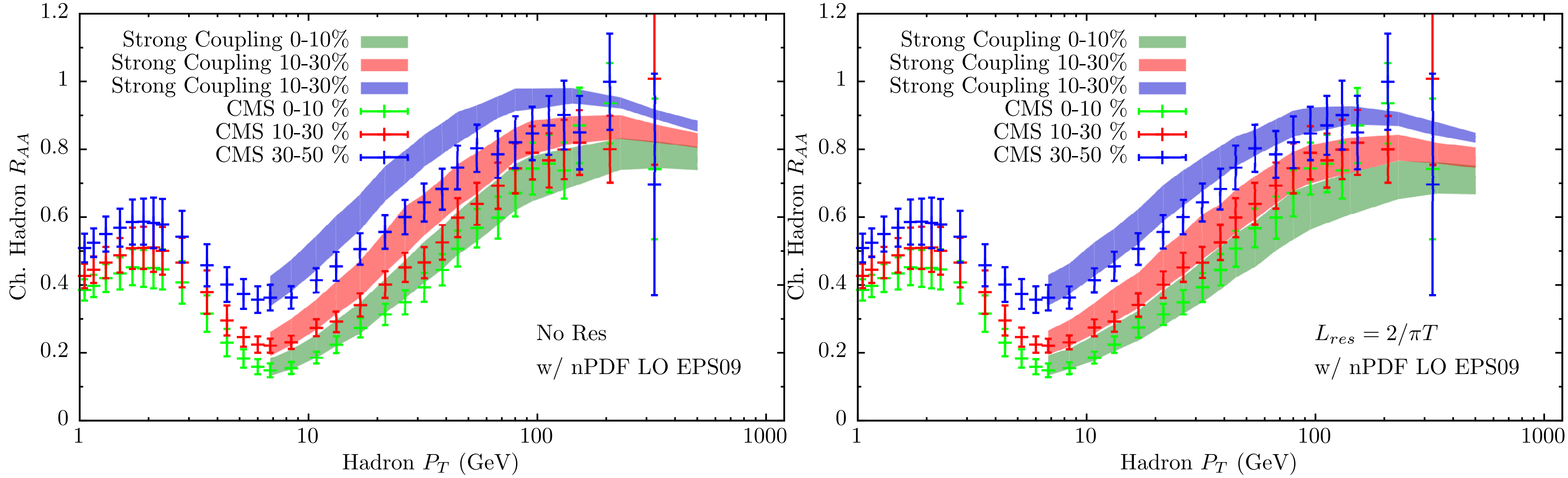
CGMPR 1609.05842; Hulcher, Pablos, KR, 2017



- **Introducing a resolution length of $L_{\rm res} = 1/(\pi T)$ or $L_{\rm res} = 2/(\pi T)$ pushes the fragmentation function ratio up at intermediate and soft fragment-p_T.**
- **Introducing the soft particles from the wake in the plasma created by the jet pushes the fragmentation function ratio up at soft fragment-p_T, but not as much as in the data.**

Hadron R_{AA}

Casalderrey-Solana, Gulhan, Hulcher, Milhano, Pablos, KR, 2017

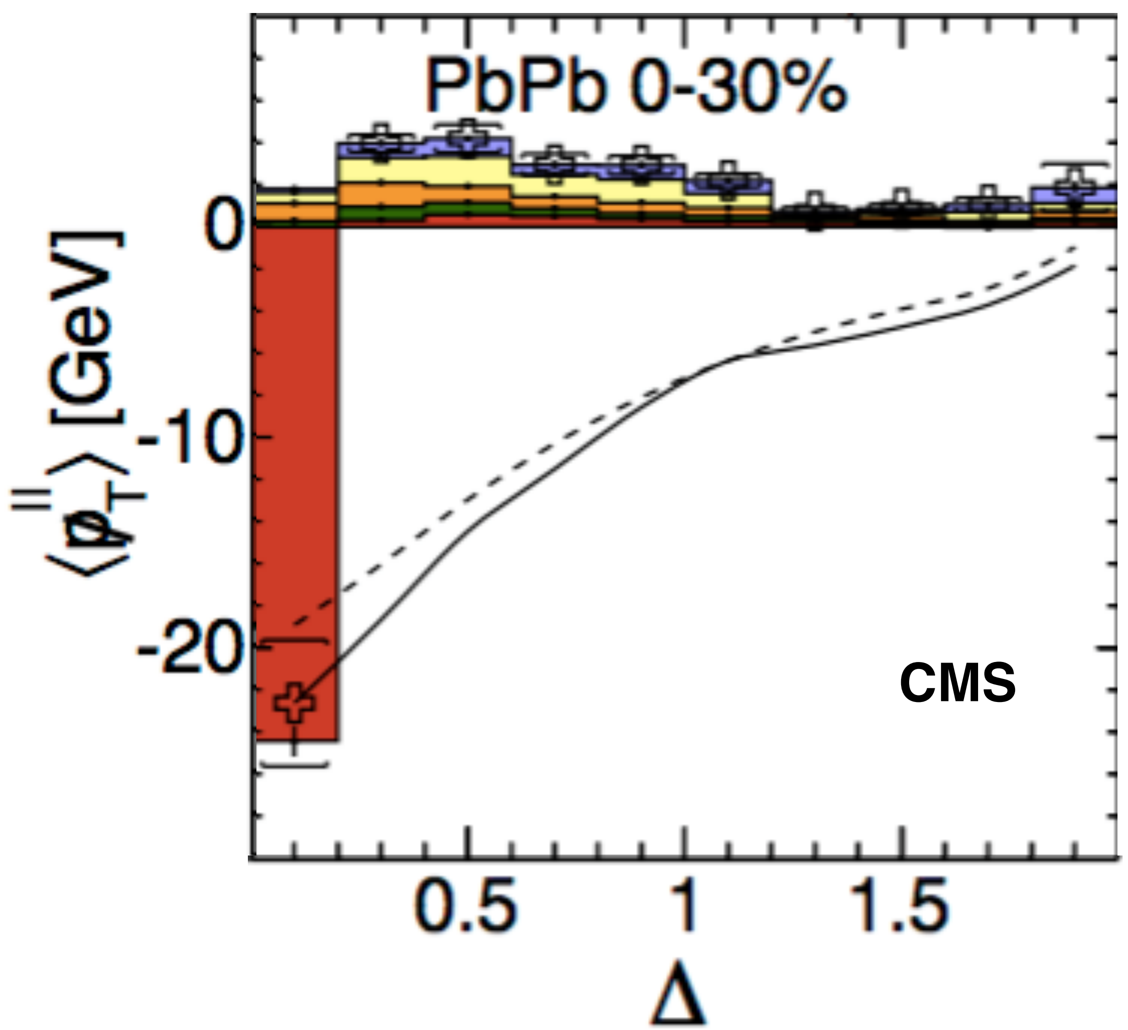


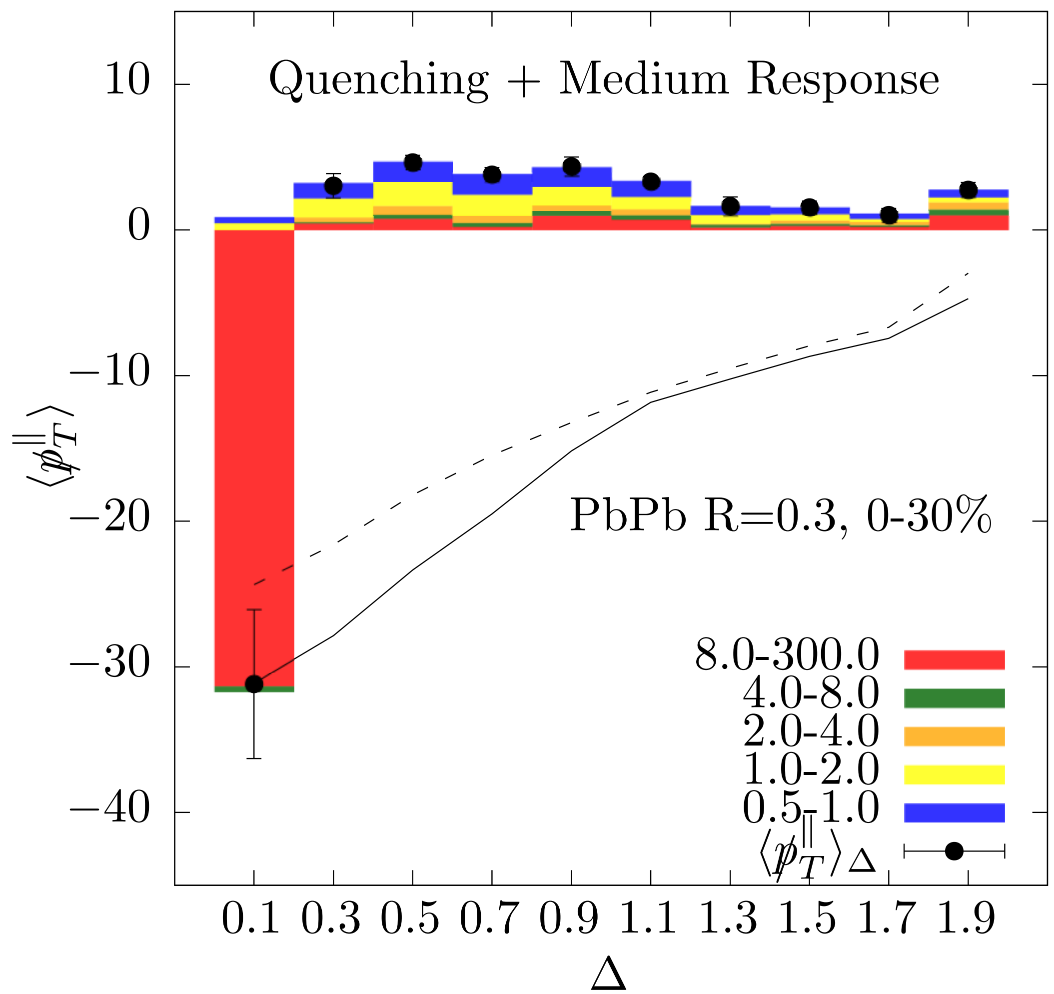
- **As an aside, note that with these extensions we can now also calculate R_{AA} for hadrons from our model, finding good agreement with data.**
- **R_{AA} for hadrons in the hybrid model with $L_{res} = 2/(\pi T)$ is in better agreement with data than if we take $L_{res} = 0$.**

Missing p_T observables

- Adding the soft particles from the wake is clearly a big part of what we were missing. It also seems that our treatment of the wake does not yet fully capture what the data calls for.
- If our goal is quantifying broadening, and ultimately seeing rare-but-not-too-rare larger angle scattering of partons in the jet, we can forget about the wake and look at observables sensitive to 10-20 GeV partons in the jet.
- But, what if we want to understand the wake? What was our key oversimplification?
- We *assumed* that the wake equilibrates, in the sense that it becomes a small perturbation on the hydro flow and hence a small perturbation to the final state particles. The only thing the thermalized particles in the final state remembers is the energy and net momentum deposited by the jet.
- To diagnose whether this equilibration assumption (which is natural at strong coupling) is justified in reality we need more sophisticated observables...

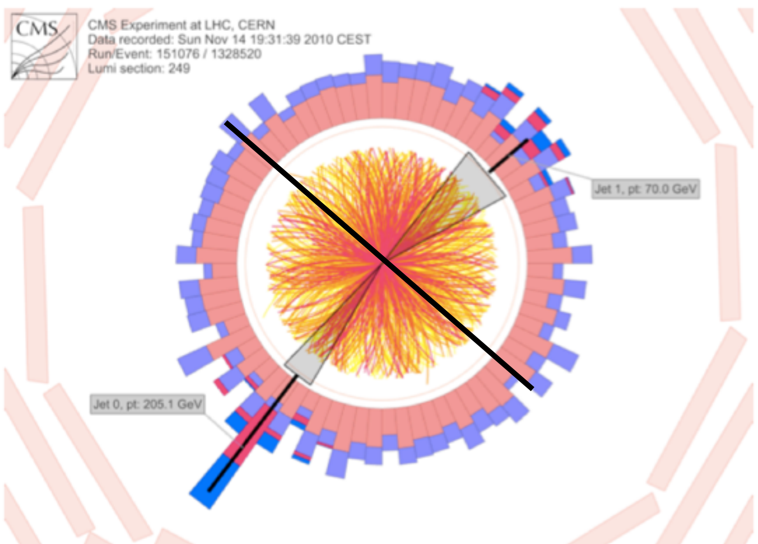
Recovering Lost Energy: Missing Pt



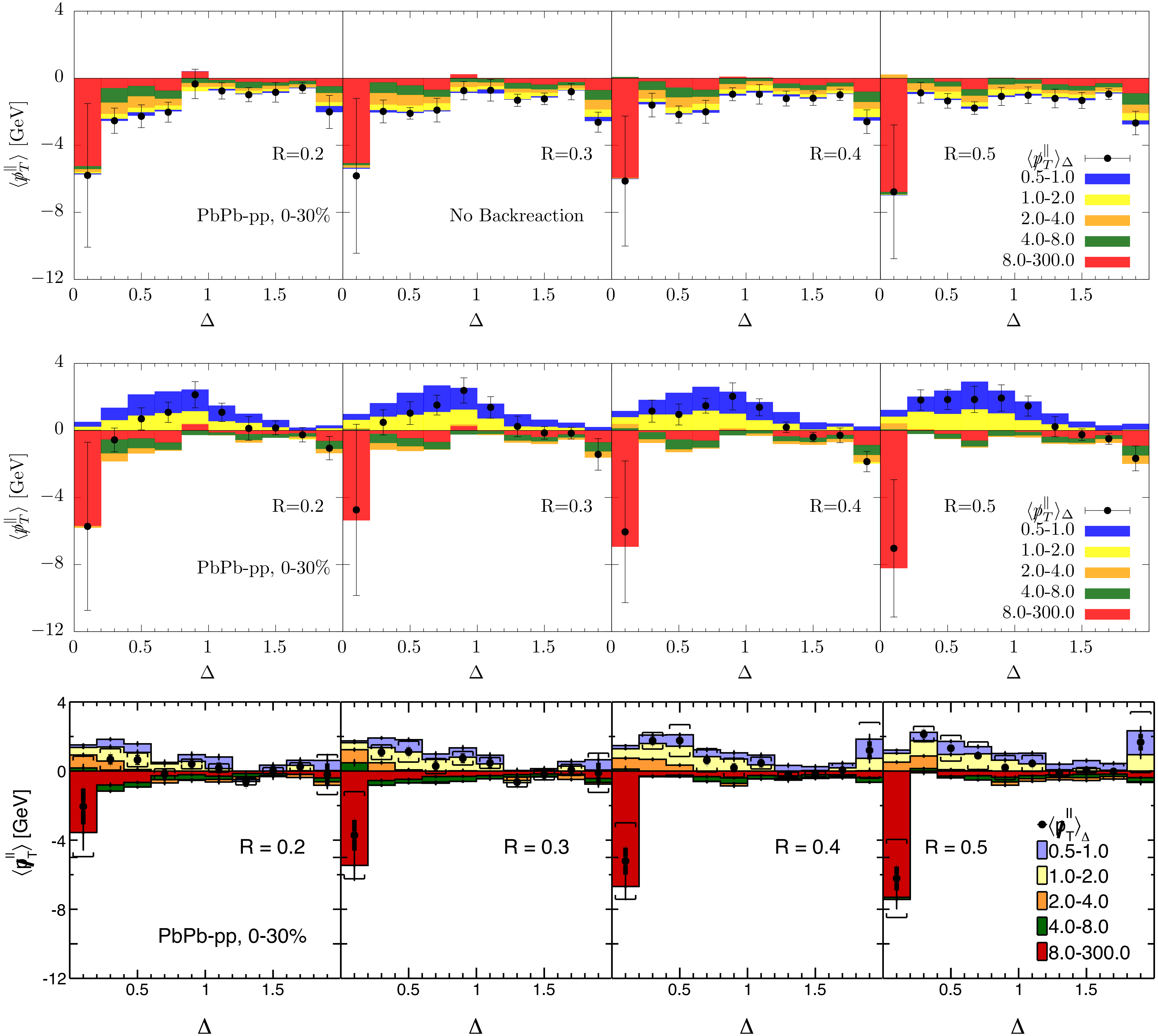


- Energy is recovered at large angles in the form of soft particles

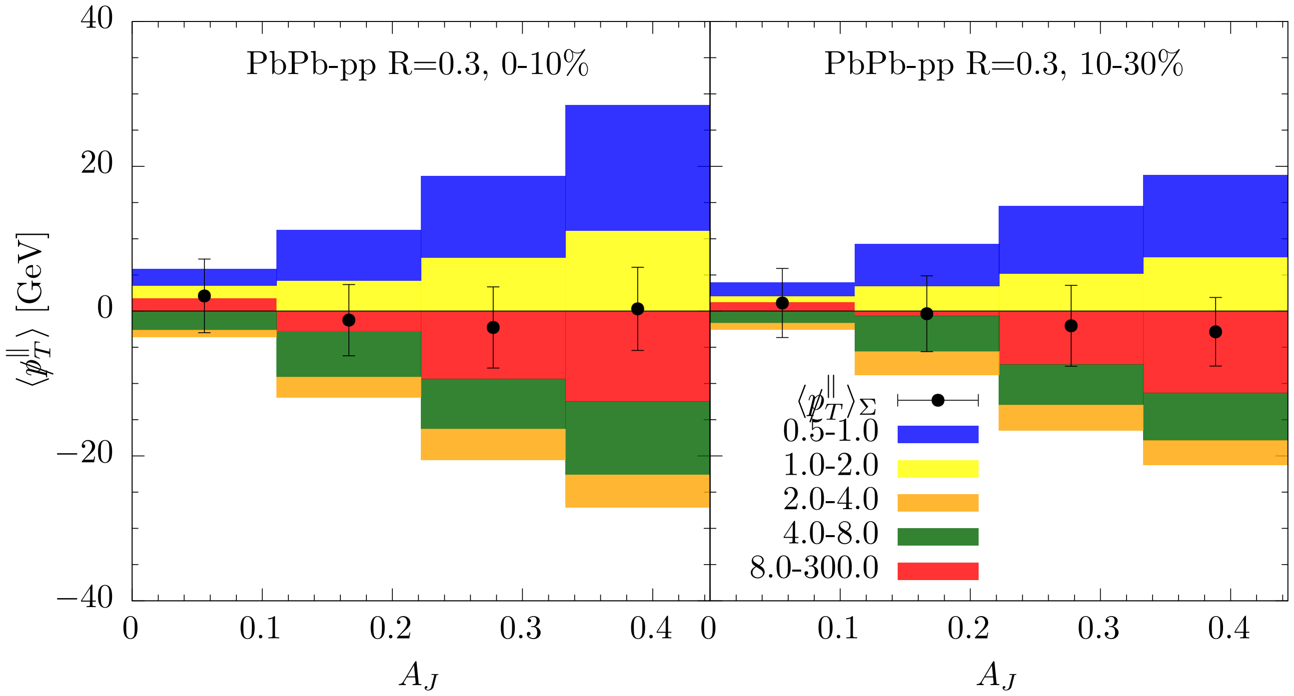
- Adding medium response is essential for a full understanding of jet quenching

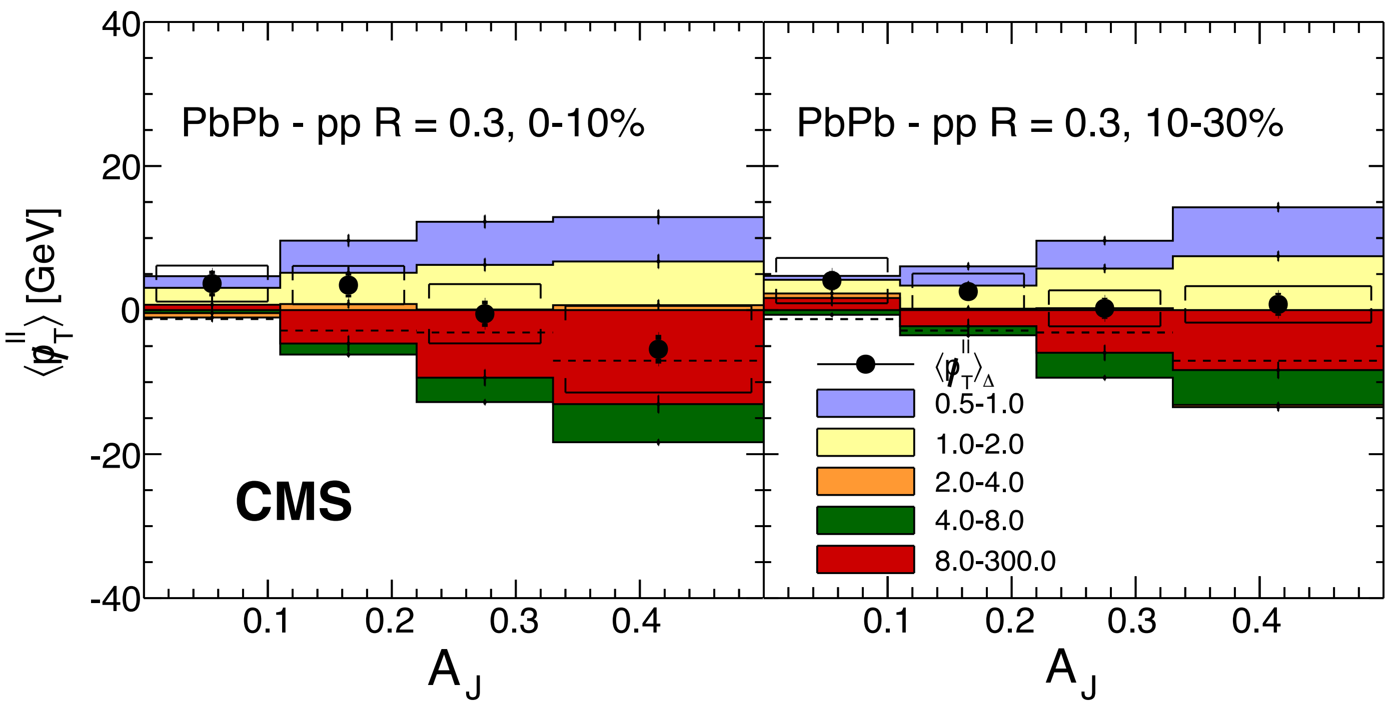


Jet radius dependence of Missing Pt



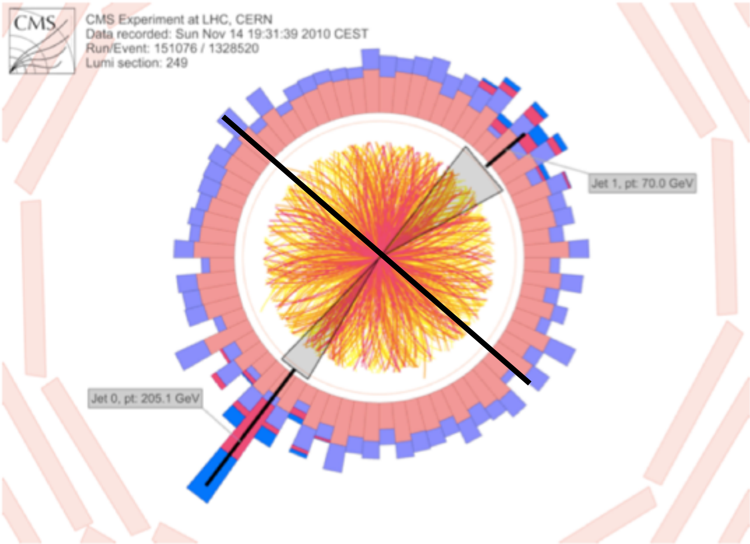
Recovering Lost Energy: Missing Pt





- In PbPb, more asymmetric dijet events are dominated by soft tracks in the subleading jet side

- Discrepancies w.r.t. data in the semi-hard regime motivate improvements to our model



Missing p_T observables

- Our characterization of the wake is on a good track. BUT:
- We have too many particles with 0.5 GeV$< p_T <$2 GeV.
- We have too few particles with 2 GeV$< p_T <$4 GeV.
- The energy and momentum given to the plasma by the jet does *not* fully thermalize. Further improving our model to describe the low-p_T component of jets, as reconstructed, requires full-fledged calculation of the wake.
- This is not necessary for the analysis of the $p_T \sim$ 10-20 GeV component of jets that will be the key to looking for rare large angle scattering.
- The larger question of how QGP hydrodynamizes, which is to say How does the strongly coupled liquid emerge so rapidly starting from weakly coupled physics at $t = 0$ in a collision? has attracted substantial *theoretical* attention, but almost by definition experimental access to pre-hydrodynamic physics is difficult. (Thermalization means forgetting.) So, gaining *experimental* access to how the wake of a jet thermalizes is a big deal.

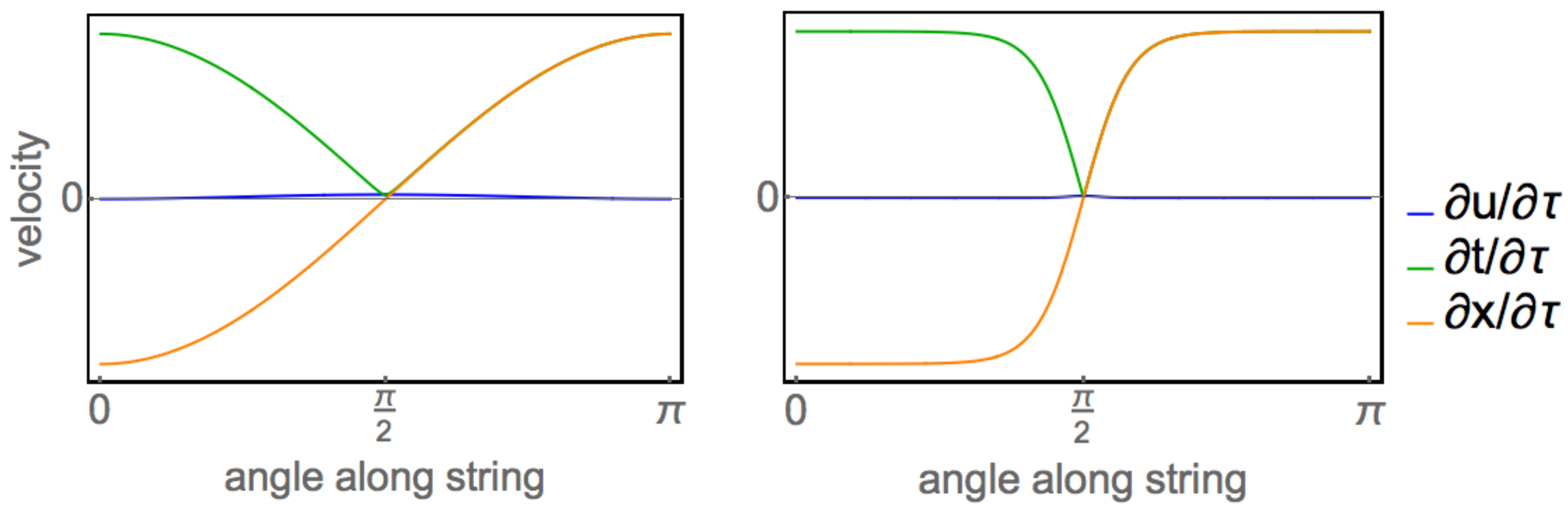
The Long View

- Today: combining pQCD branching as in vacuum à la PYTHIA with strongly coupled dE/dx à la AdS/CFT gives a good baseline for many energy loss observables.
- The effects of the wake in the plasma are key to understanding full jet shape observables. By detailed comparison between our current baseline, which assumes a hydrodynamized wake, and data we learn to what degree the wake does *and does not* thermalize. $\rightarrow$ experimental access to the "as a function of time" variant of How does the liquid emerge from weakly coupled degrees of freedom?
- Next: determine magnitude of K, the strength of the Gaussian distribution of transverse kicks felt by the partons in the jet. (Via suitably differential jet shape observables.)
- Early 2020s: use high statistics sPHENIX and LHC data, e.g. on differential jet shape ratio in γ-jet events, to focus on rare events in which the 10-20 GeV partons in the jet scatter off quasiparticles in the soup. $\rightarrow$ experimental access to the "microscopy variant" of How does the liquid emerge from an asymptotically free gauge theory?

Solving full string equations of motion

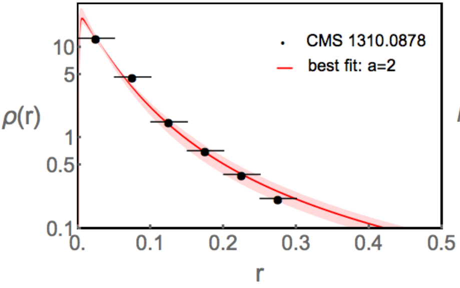
- Freedom to specify initial conditions

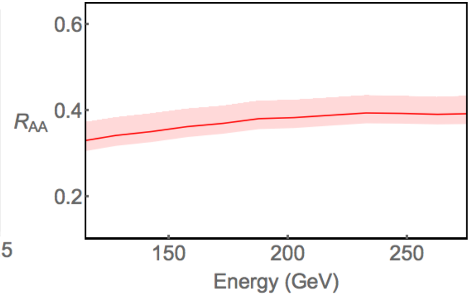
Example velocity initial conditions



See e.g. [0810.1985]

Fitting pp-shape and R_{AA} by the free parameters

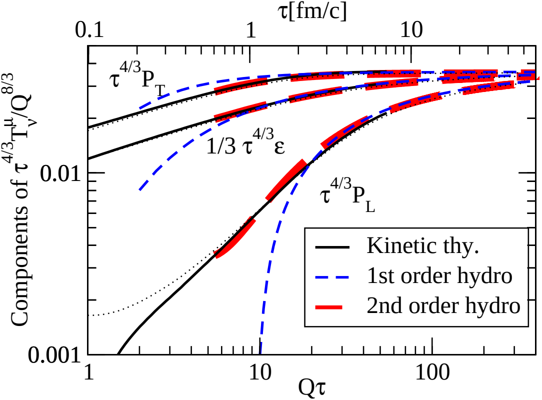




$$p_T > 100\text{GeV} \quad , \quad 0.3 < |\eta| < 2 \quad , \quad R = 0.3$$
$$a = 2 \quad , \quad b = 0.203$$

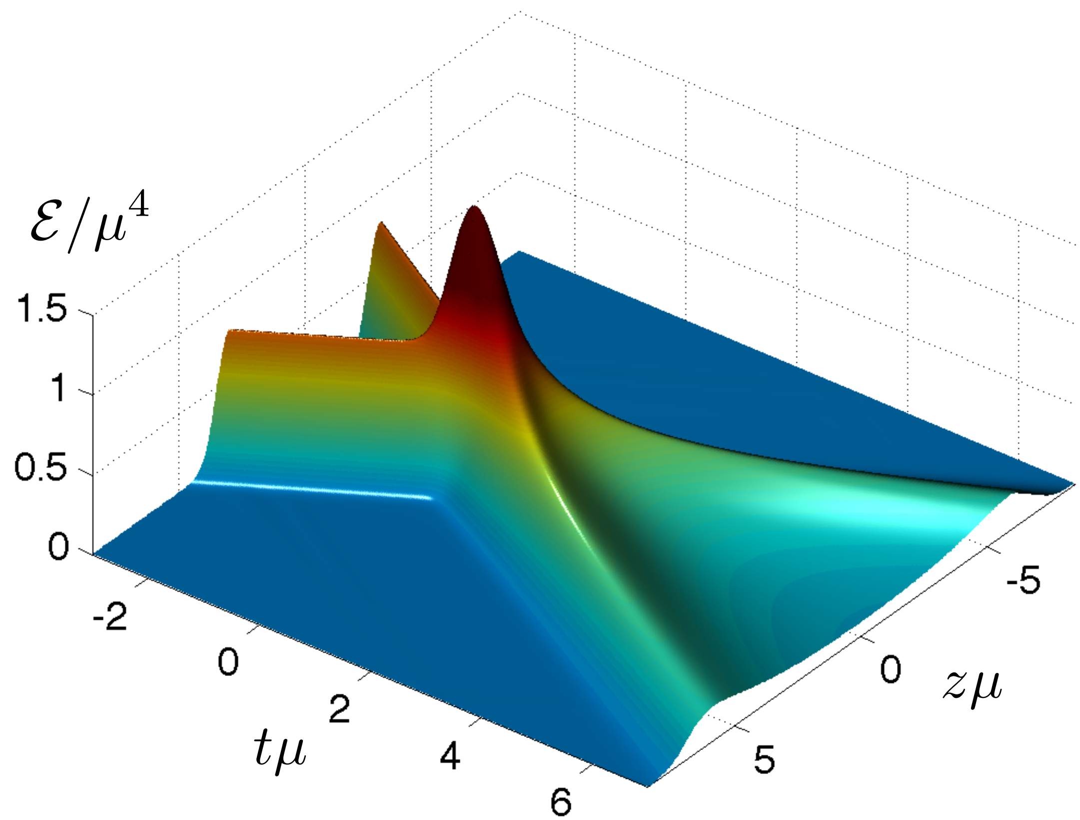
From $\mathcal{N} = 4$ SYM to QCD

- 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.
- But, the fact that strongly coupled $\mathcal{N} = 4$ SYM is strongly coupled at all scales, including short length scales, is a bug.
- $\mathcal{N} = 4$ SYM calculations done at $1/N_c^2 = 0$ rather than $1/9$.
- 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.
- For the last three reasons, our goals must at present be limited to qualitative insights.



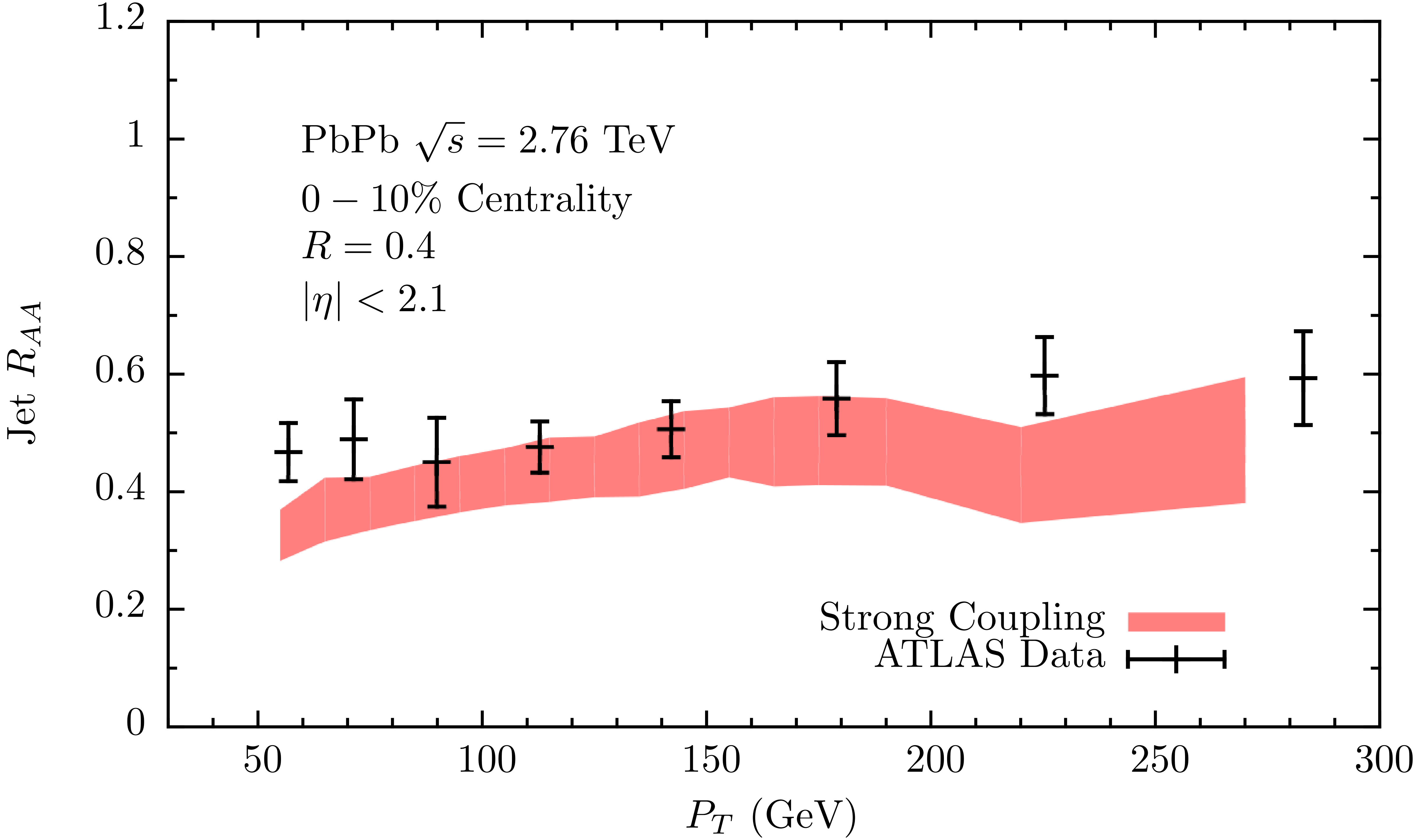
τ[fm/c]
0.1
1
10
$\tau^{4/3}P_T$
$1/3\ \tau^{4/3}\varepsilon$
$\tau^{4/3}P_L$
Components of $\tau^{4/3}T^\mu_\nu/Q^{8/3}$
0.01
0.001
1
10
100
Qτ
Kinetic thy.
1st order hydro
2nd order hydro

Colliding Strongly Coupled Sheets of Energy



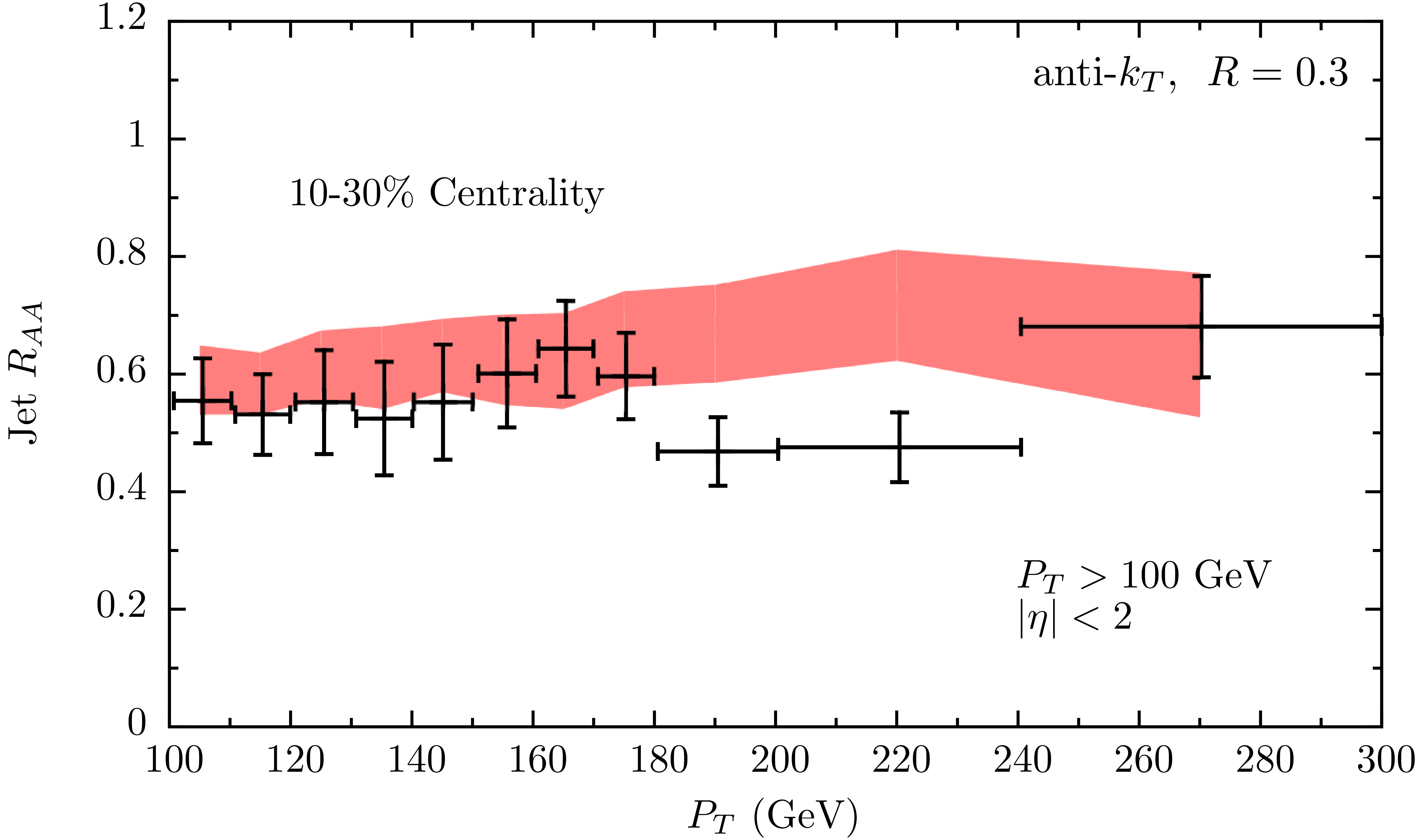
Hydrodynamics valid ~ 3 sheet thicknesses after the collision, i.e. ~ 0.35 fm after a RHIC collision. Equilibration after ~ 1 fm need not be thought of as rapid. Chesler, Yaffe 1011.3562; generalized in C-S,H,M,vdS 1305.4919; CY 1309.1439 **Similarly 'rapid' hydrodynamization times ($\tau T \lesssim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

R_{AA}



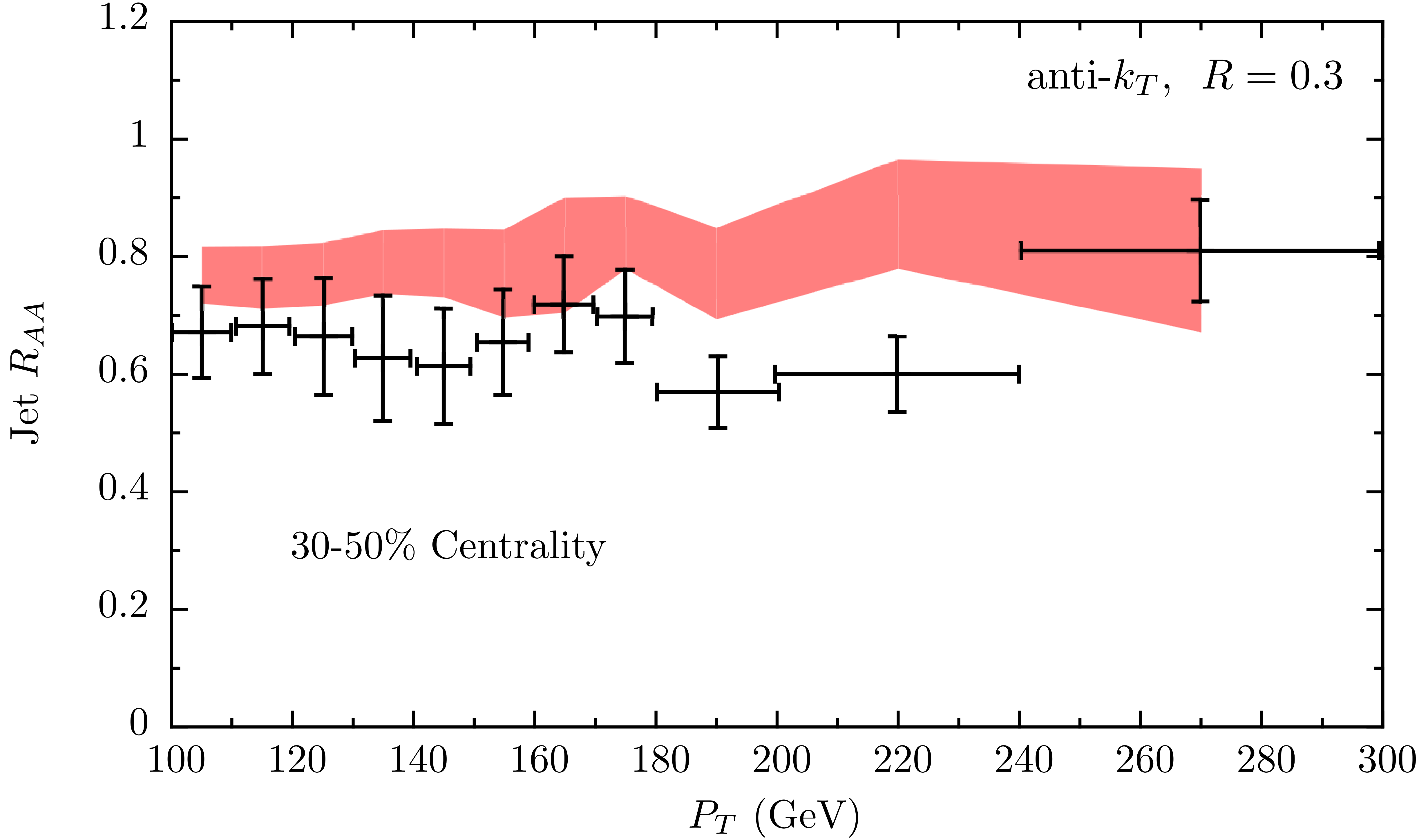
With current implementation, slightly more quenching for bigger jet radius

R_{AA}



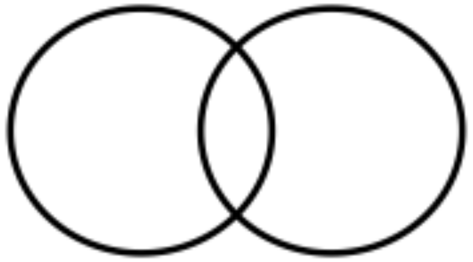
anti-k_T, $R = 0.3$
10-30% Centrality
$P_T > 100$ GeV
$|\eta| < 2$
Jet R_{AA}
P_T (GeV)
1.2
1
0.8
0.6
0.4
0.2
0
100
120
140
160
180
200
220
240
260
280
300

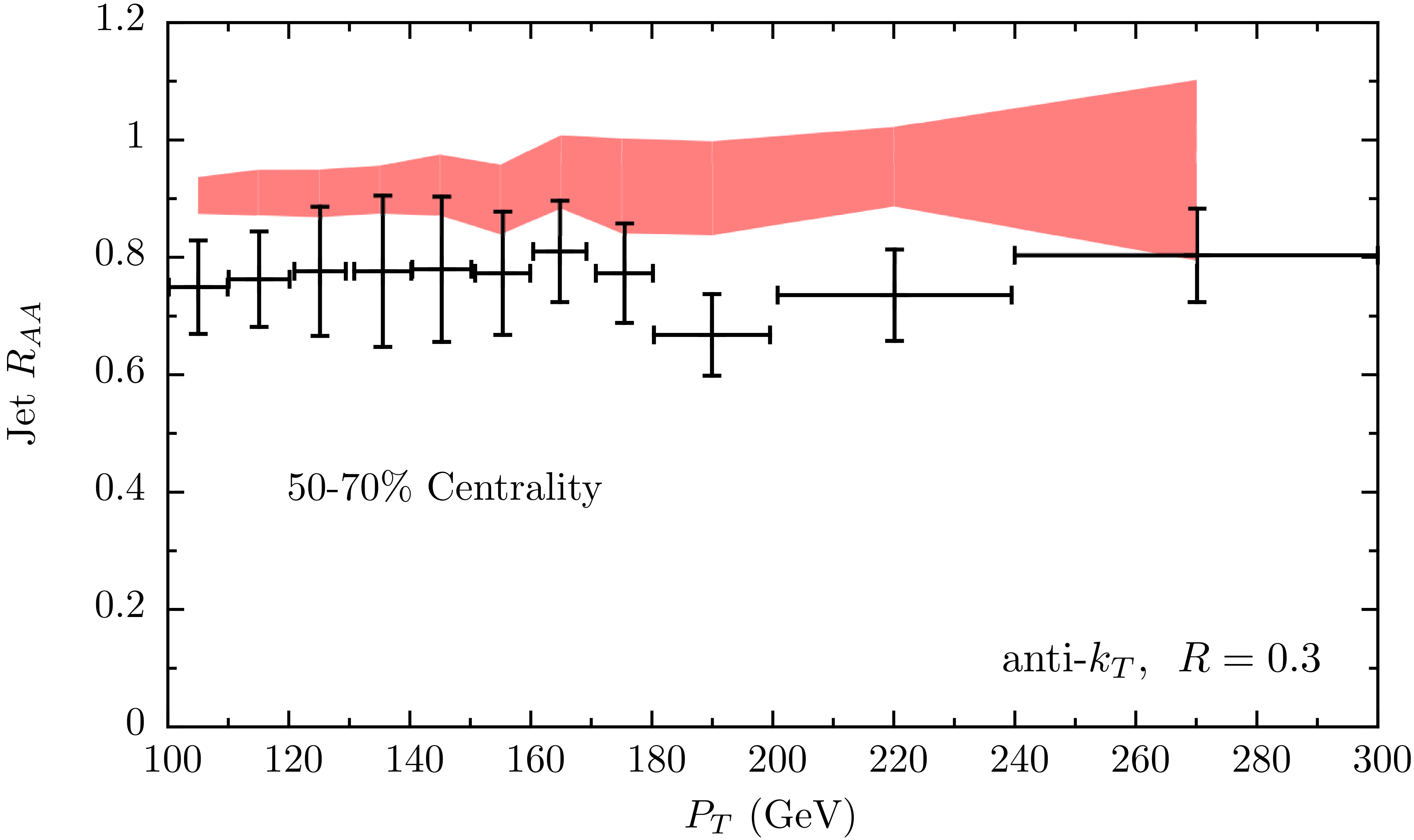
R_{AA}



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

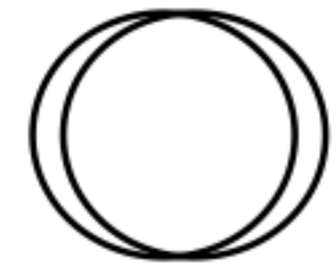
R_{AA}

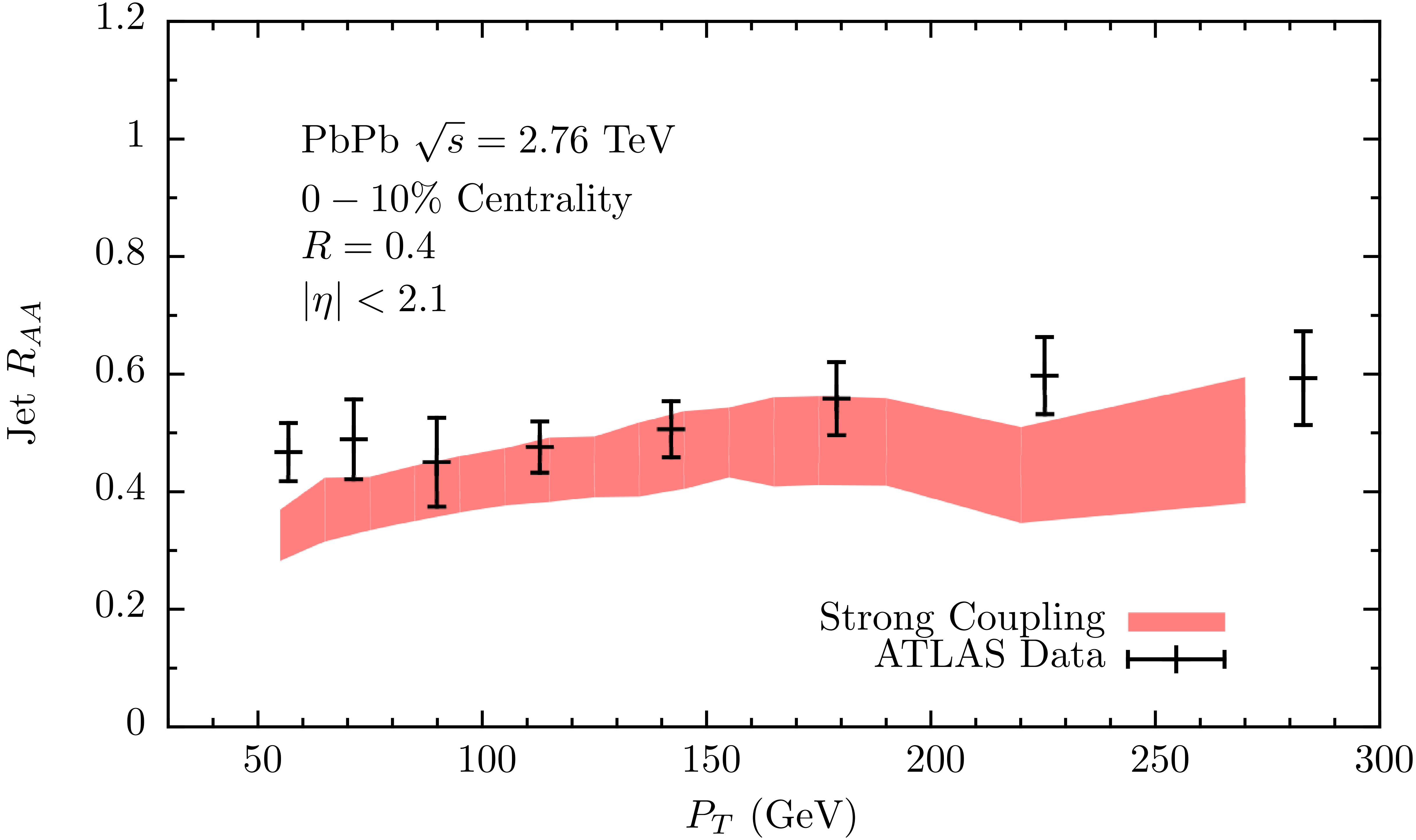




We have only simulated the QGP phase

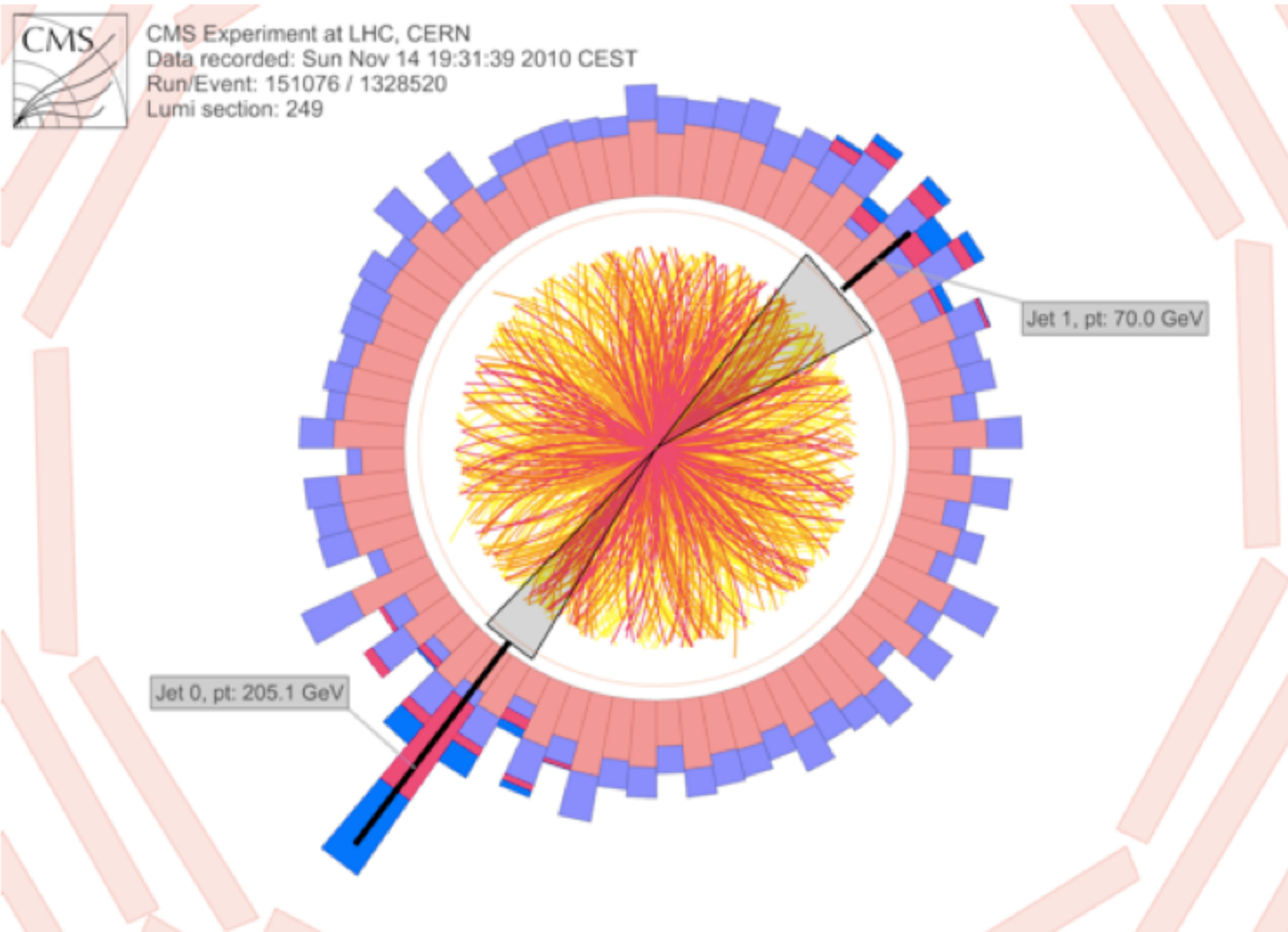
R_{AA}

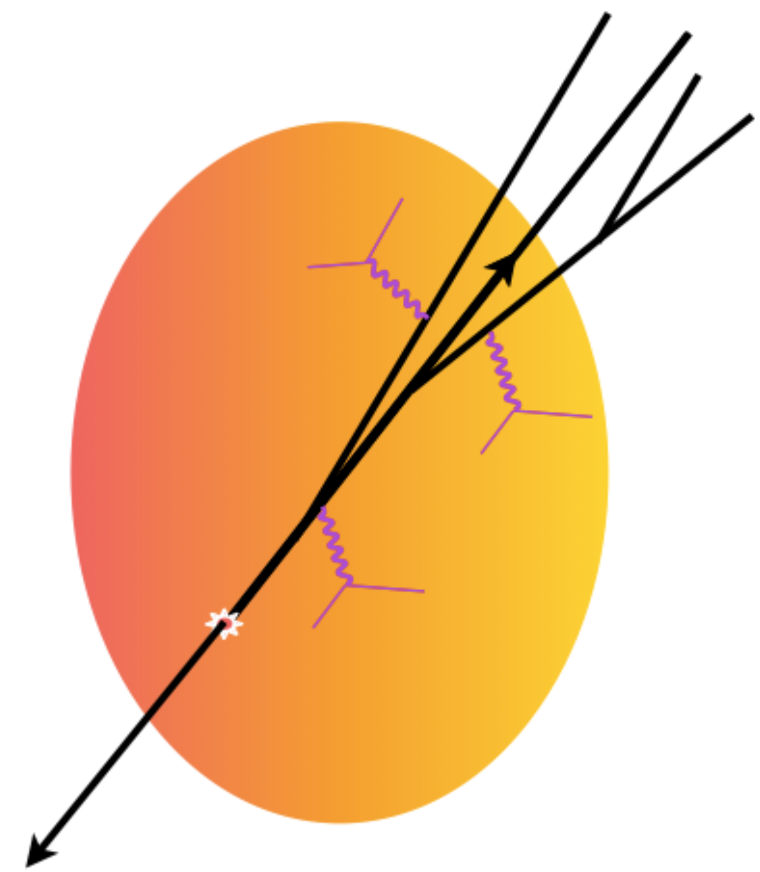




With current implementation, slightly more quenching for bigger jet radius

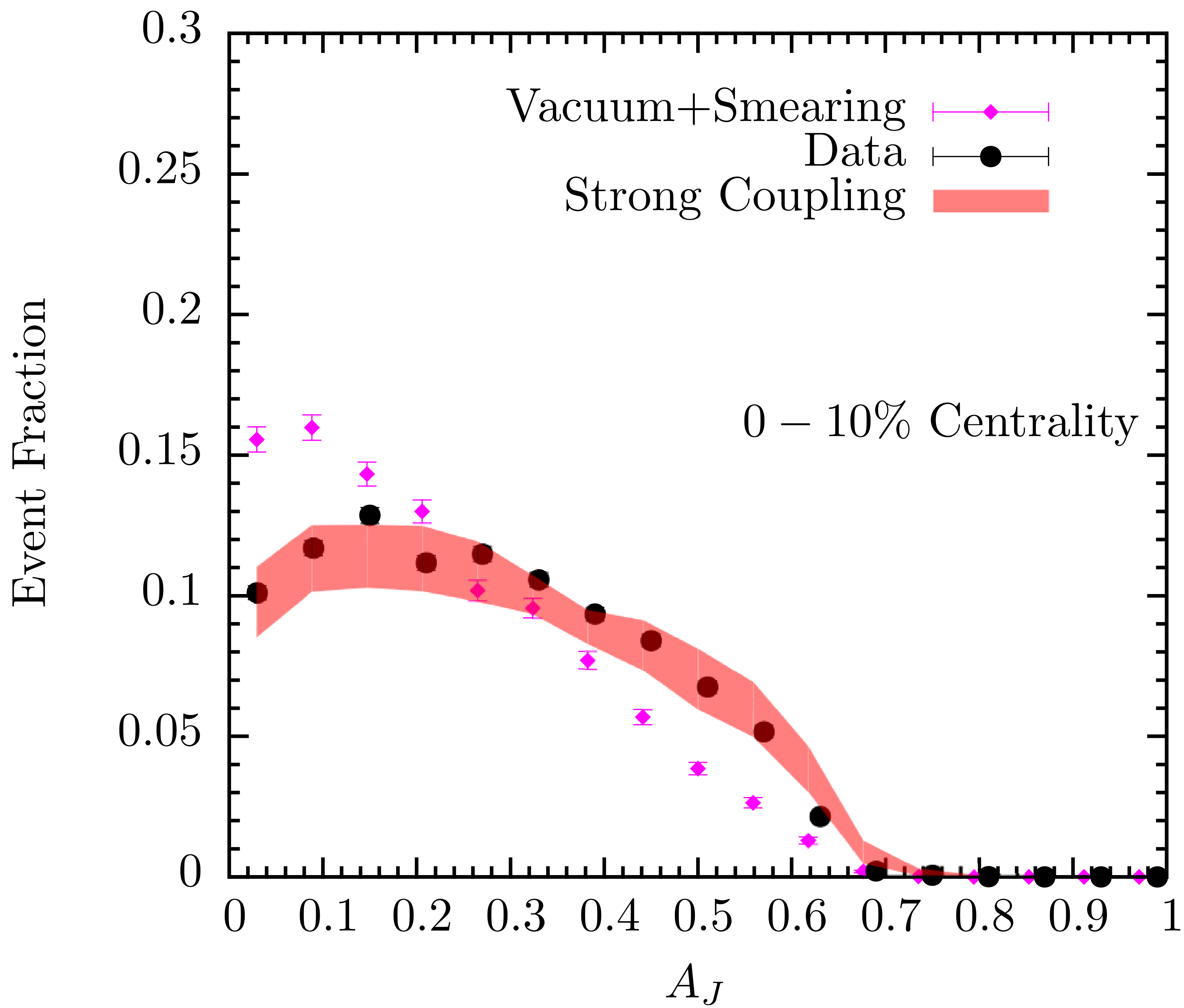
Dijets





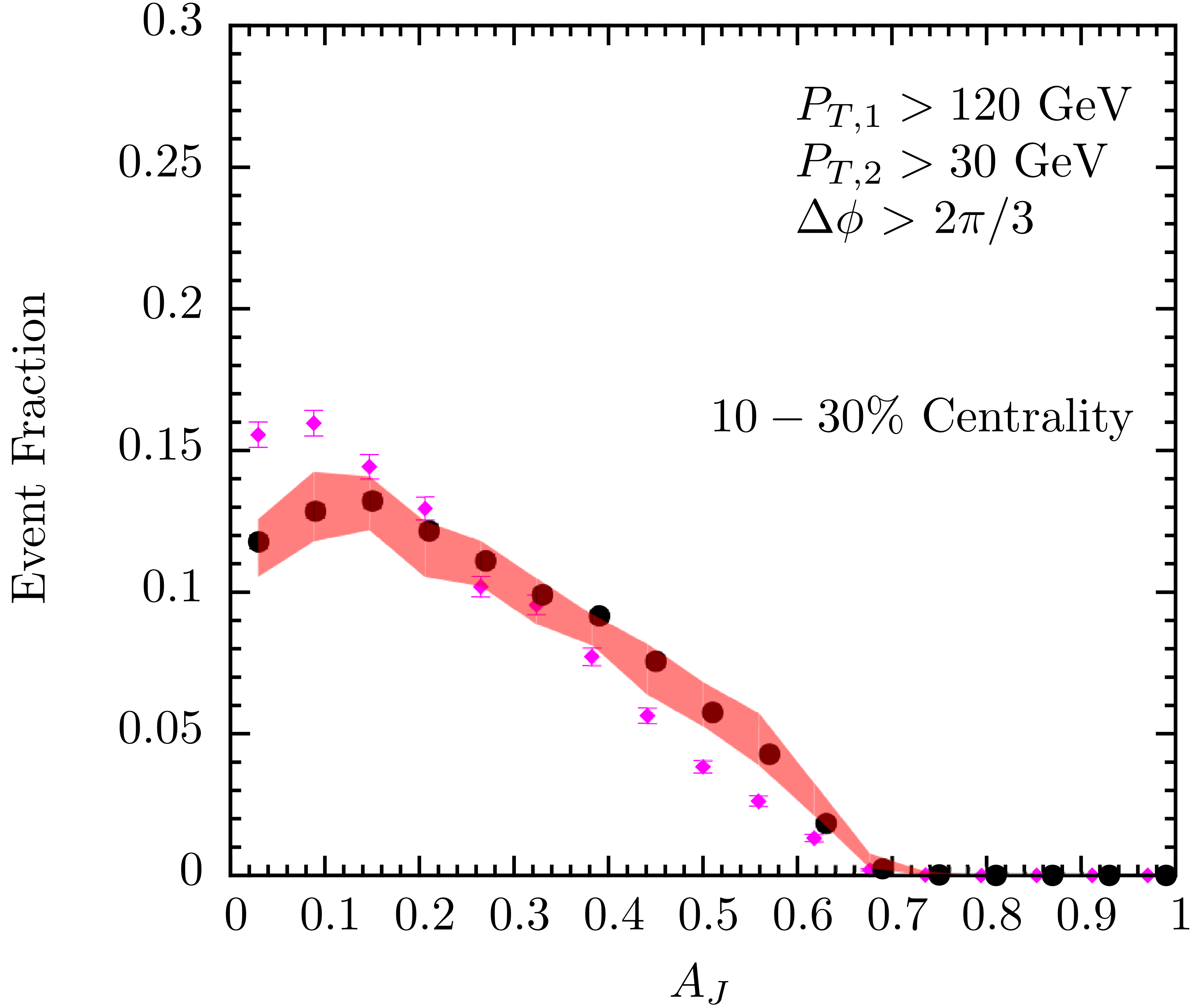
$$A_J = \frac{p_{T_1} - p_{T_2}}{p_{T_1} + p_{T_2}}$$

Imbalance



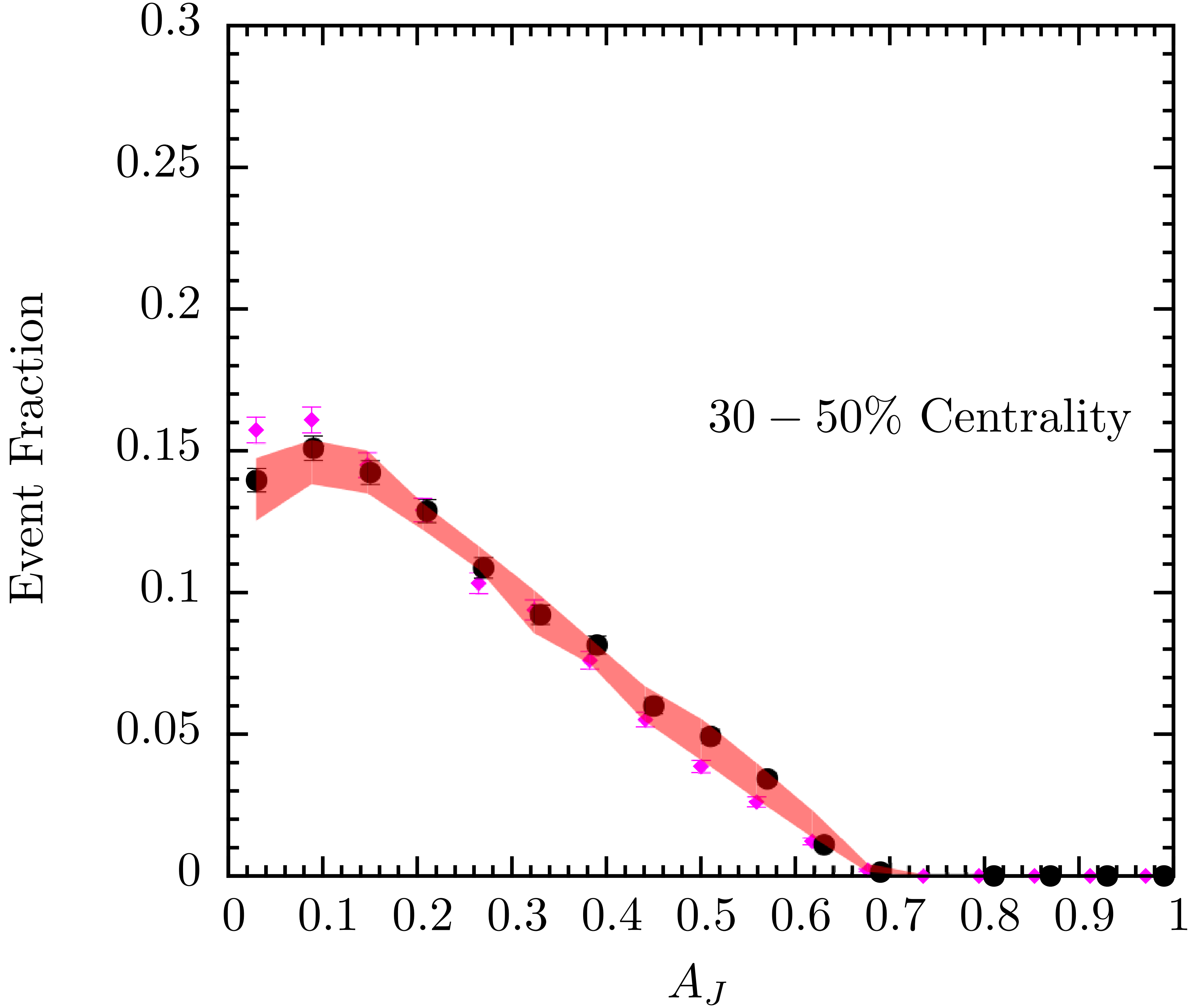
Vacuum+Smearing
Data
Strong Coupling
0 – 10% Centrality
Event Fraction
A_J
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Imbalance



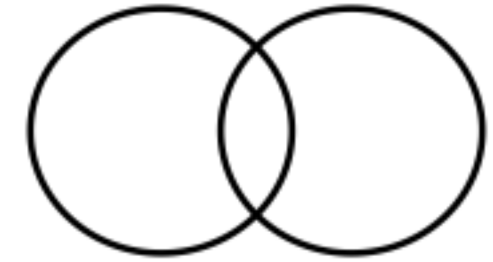
$P_{T,1} > 120$ GeV
$P_{T,2} > 30$ GeV
$\Delta\phi > 2\pi/3$
$10 - 30\%$ Centrality
Event Fraction
A_J
0
0.05
0.1
0.15
0.2
0.25
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

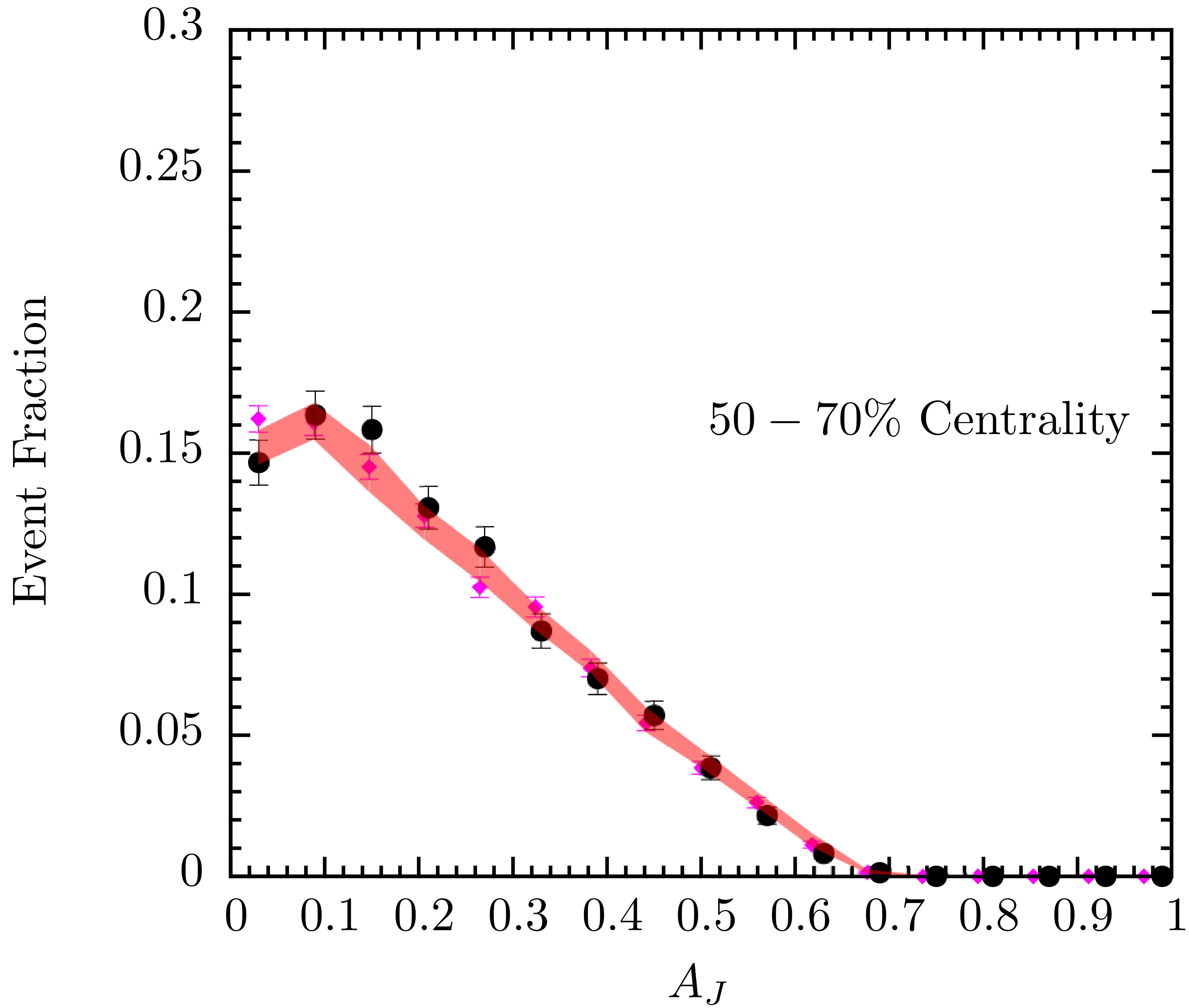
Imbalance



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

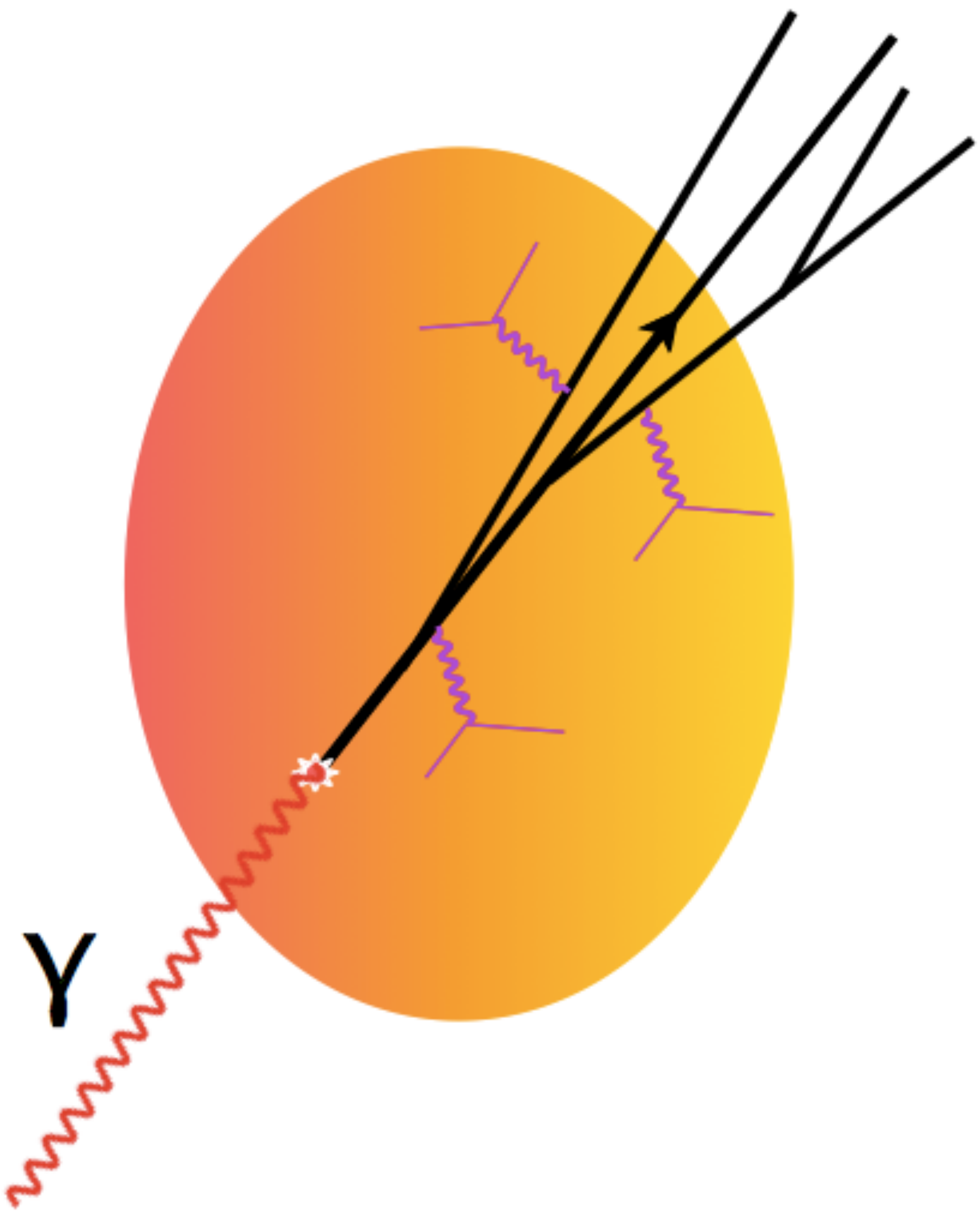
Imbalance





Event Fraction
A_J
50 − 70% Centrality
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

Photon Jet



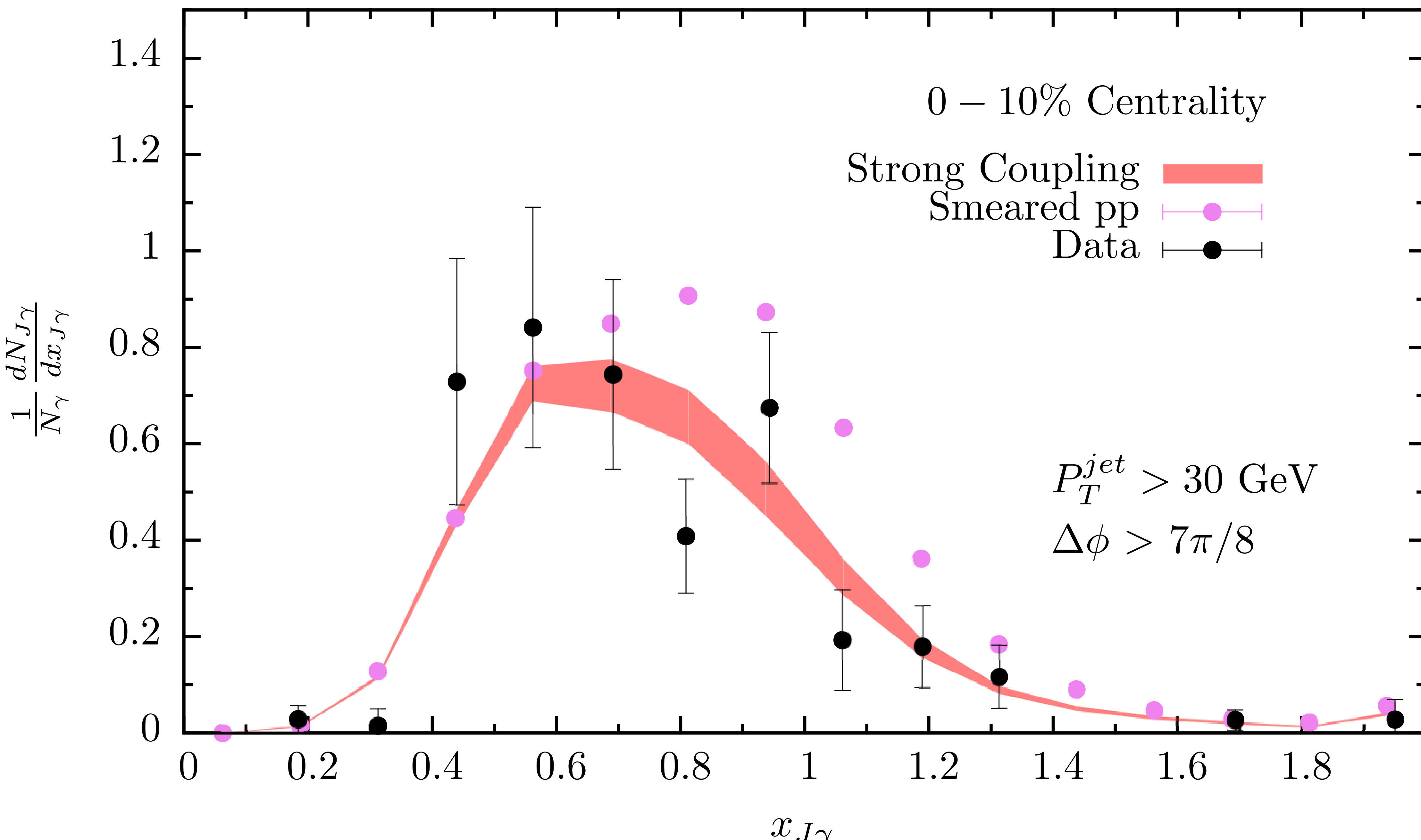
- Photons do not interact with plasma
- Look for associated jet

  -Different geometric sampling

  -Different species composition

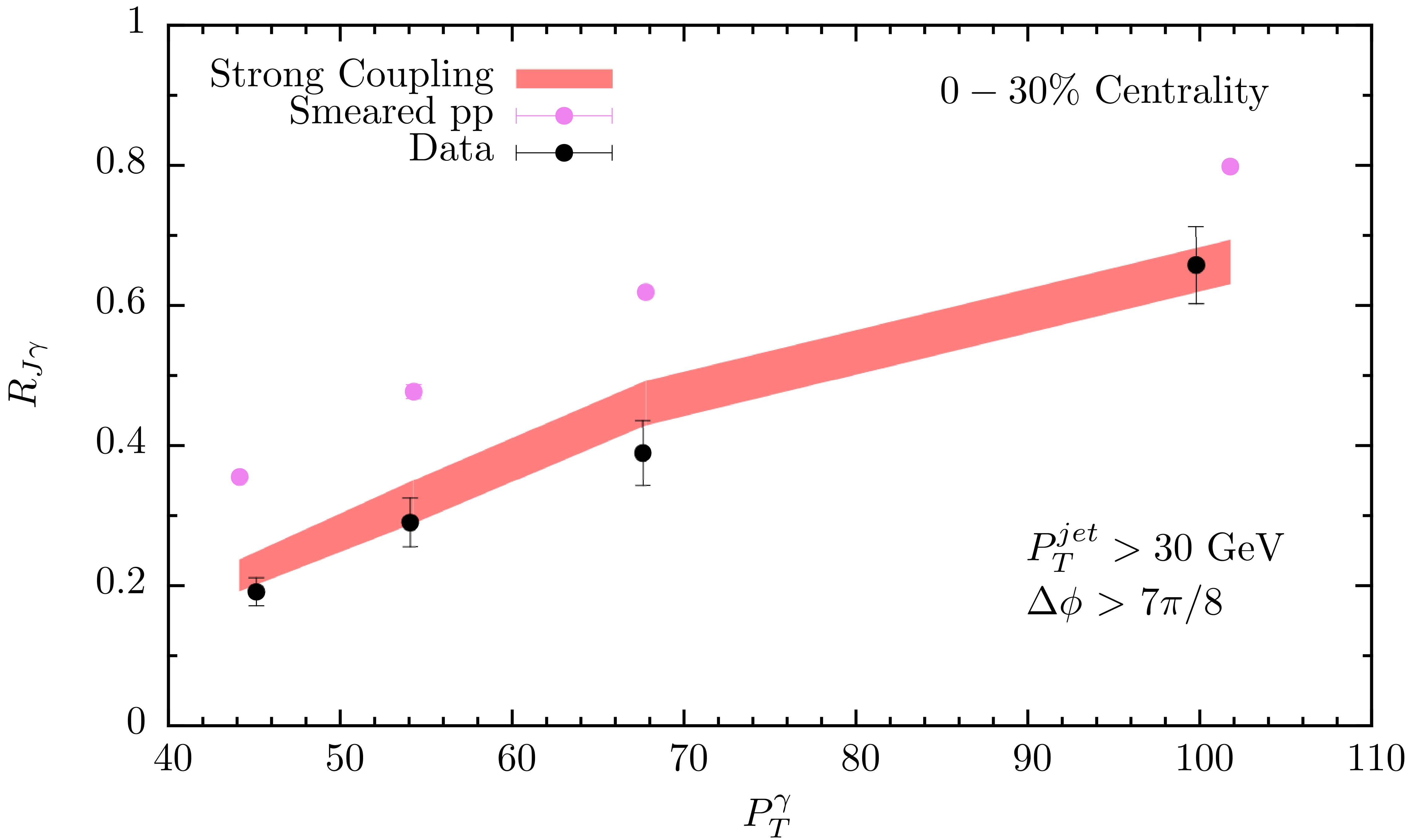
  -E_γ proxy for E_{jet}

Imbalance



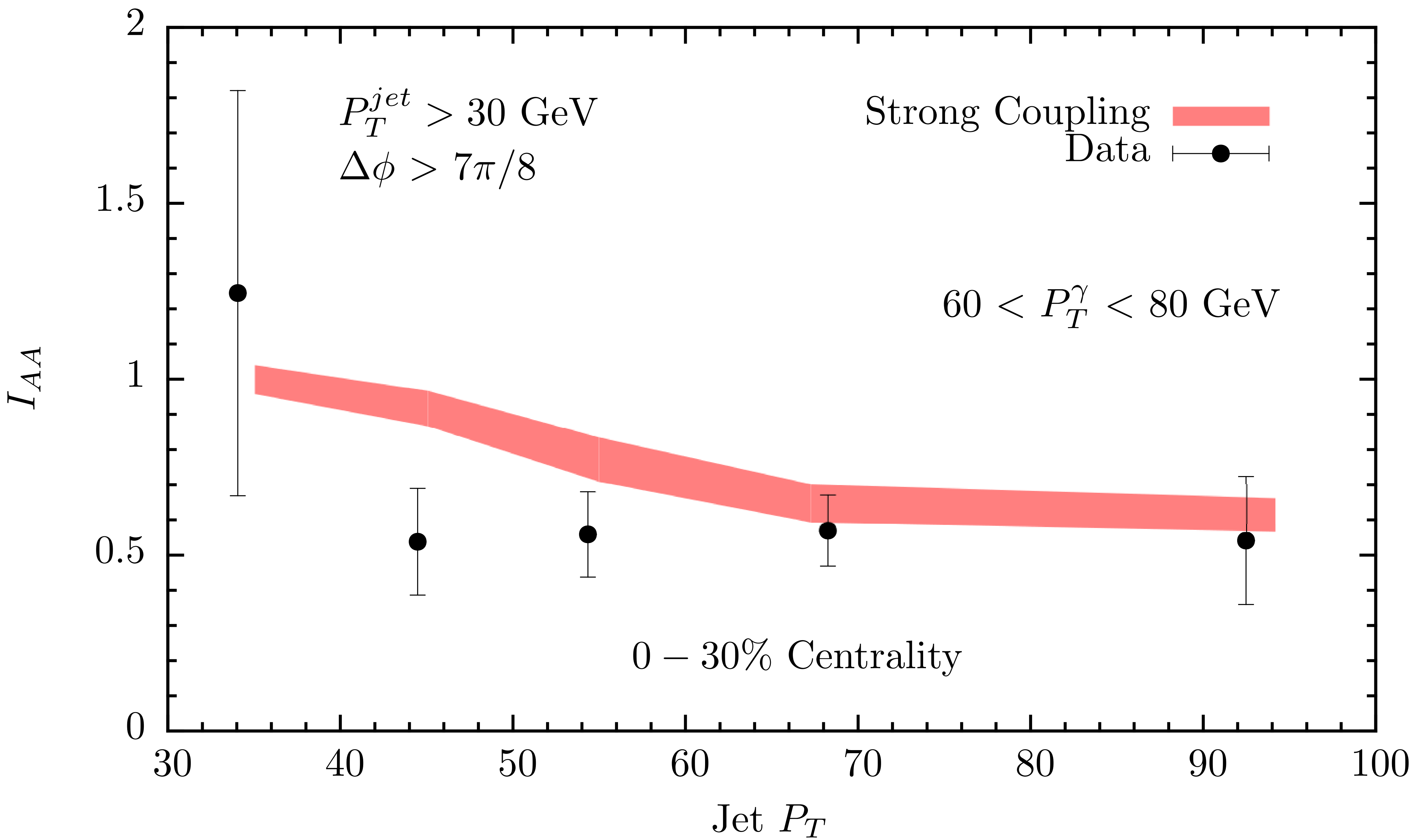
$$x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

Jet Suppression



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

Spectrum



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