Recent Results from a Hybrid Model for Jet Quenching and What They Indicate about Using Jets to Probe Strongly Coupled QGP in the 2020s

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Recent RHIC and LHC Results and their
Implications for Heavy Ion Physics in the 2020s
MIT, Oct 29, 2016

Jets as Probes

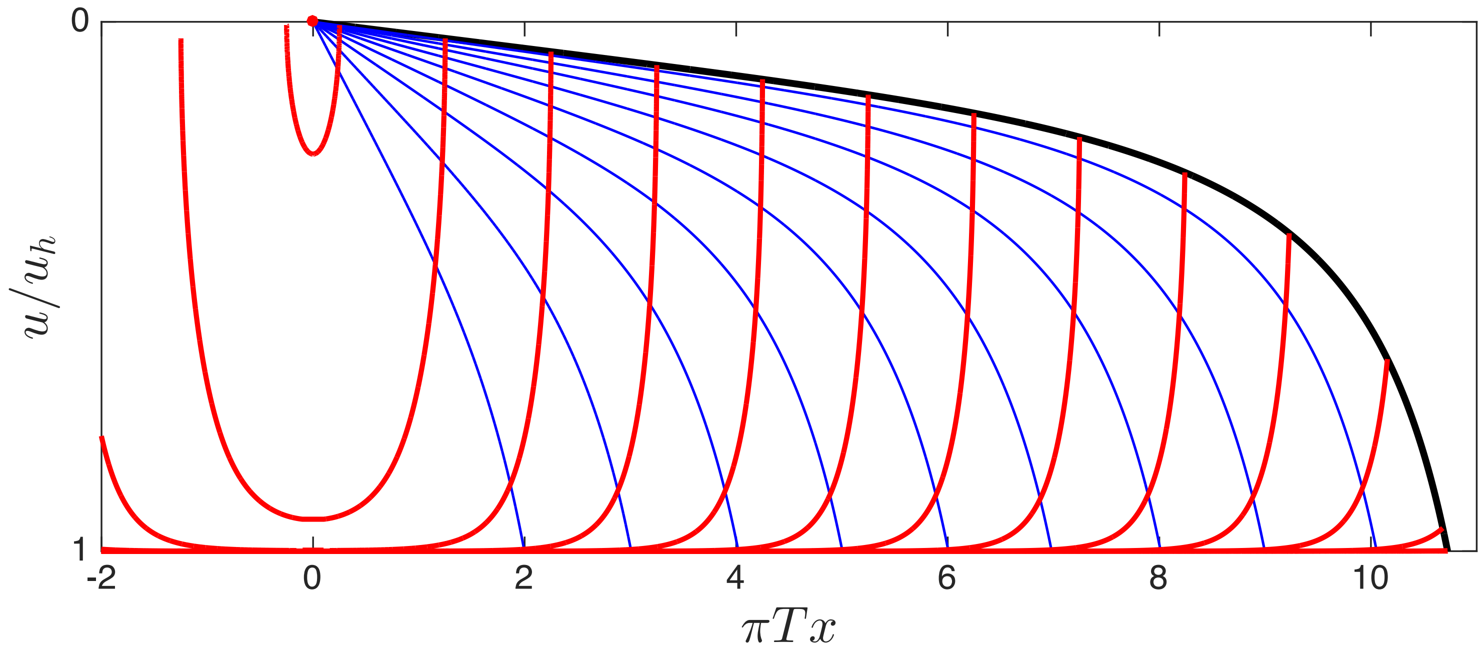
- We can quantify the properties of Liquid QGP at it's natural length scales, where it has no quasiparticles.
- What is its microscopic structure? QCD is asymptotically free. When looked at with sufficient resolution, QGP must be made of weakly coupled quarks and gluons.
- But, how does the strongly coupled liquid emerge from an asymptotically free gauge theory?
- Maybe answering this question could help to understand how strongly coupled matter emerges in contexts in condensed matter physics where this is also a central question.
- To address this question experimentally need experimental evidence for point-like scatterers in QGP when QGP is probed with large momentum transfer. Which is to say we need a high-resolution microscope trained upon a droplet of QGP. $\rightarrow$ Long-term goal of studying jets in QGP.
- Jets in heavy ion collisions are the closest we will ever come to doing a scattering experiment off a droplet of Big Bang matter.

How to Actually do This?

- That is (what I see as) the question we were asked to wrestle with here.
- There are various theoretical frameworks for understanding jets in plasma. It makes sense to wrestle with this question in the context of each of them.
- I will do so in the context of the Hybrid Model – which I shall introduce momentarily.
- I will try to draw lessons for the future (for the near future and for the 2020s) that I think are more general than the Hybrid Model itself, but only time will tell whether I succeed.

Holographic "Parton" Energy Loss

Chesler, Rajagopal, arXiv: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.

Holographic "Parton" Energy Loss

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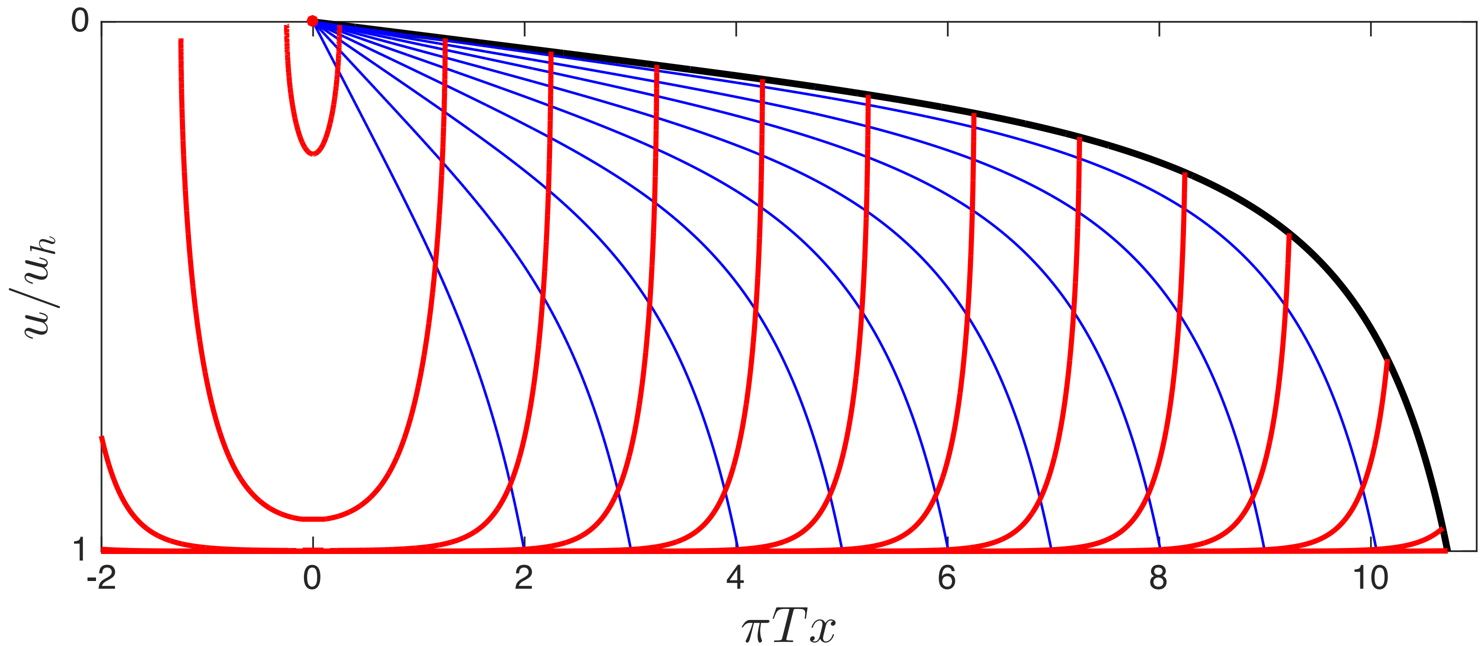
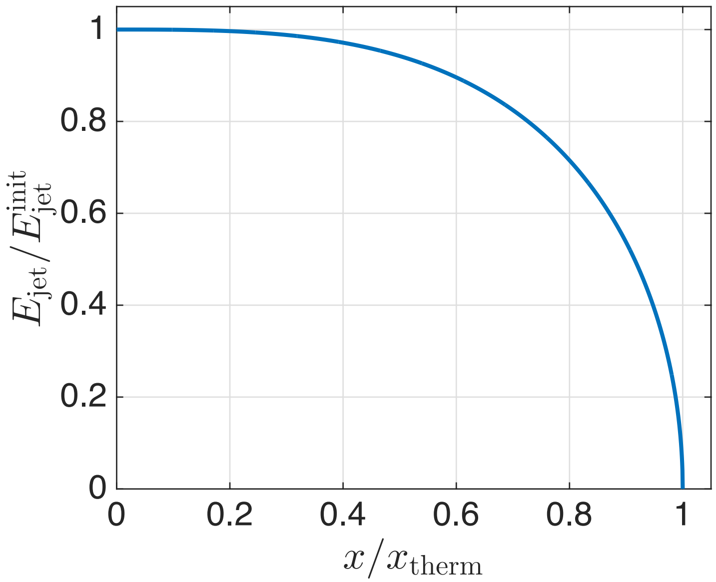


- **A fully geometric characterization of energy loss. Which is to say a new form of intuition. Energy propagates along the blue curves, which are null geodesics in the bulk. When one of them falls into the horizon, that's energy loss!**
- **Calculation shows that energy density on a particular blue geodesic $\propto 1/\sqrt{\sigma - \sigma_{\text{endpoint}}}$, with σ the initial downward angle of that geodesic. Immediately implies maximal energy loss rate as the last energy is lost.**

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

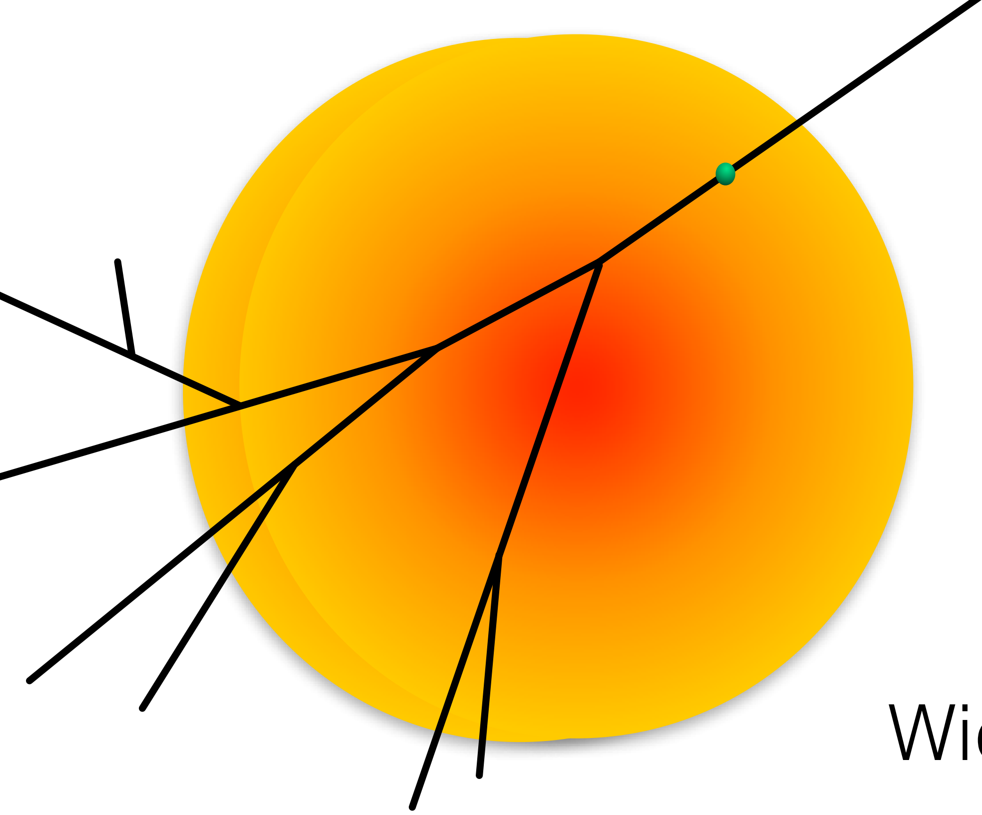
$$\frac{1}{E_{\text{jet}}^{\text{init}}}\frac{dE_{\text{jet}}}{dx} = -\frac{4x^2}{\pi x_{\text{therm}}^2}\frac{1}{\sqrt{x_{\text{therm}}^2 - x^2}}$$

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 $\simeq 1$.

A Hybrid Approach

Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1405.3864,1508.00815, 1609.05842; Hulcher, Pablos, KR, 161n.nnnnn

- **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 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 2-3 times longer than in $\mathcal{N}=4$ SYM plasma with same T.**
- **Most recently, and my focus today: adding momentum broadening and the wake in the plasma, adding resolution effects, looking at jet shapes and related observables.**



A Hybrid Model: Motivation

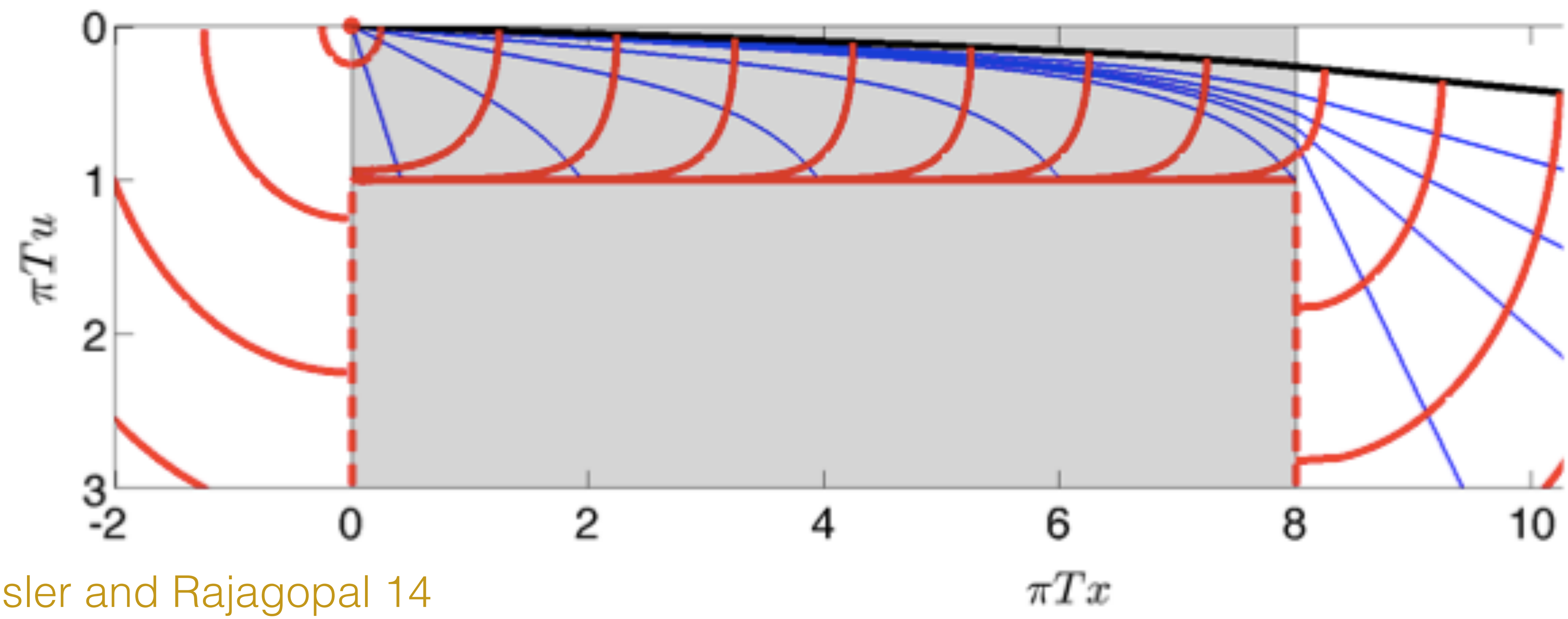
Wide hierarchy of scales in (HE) jet dynamics:

- Production and branching perturbative
- Interaction with QGP non-perturbative

Approached through simple and phenomenological model:

- Vacuum like production and showering
- Differential energy loss rate from holography
- Neglect medium induced modification of splittings (for now)

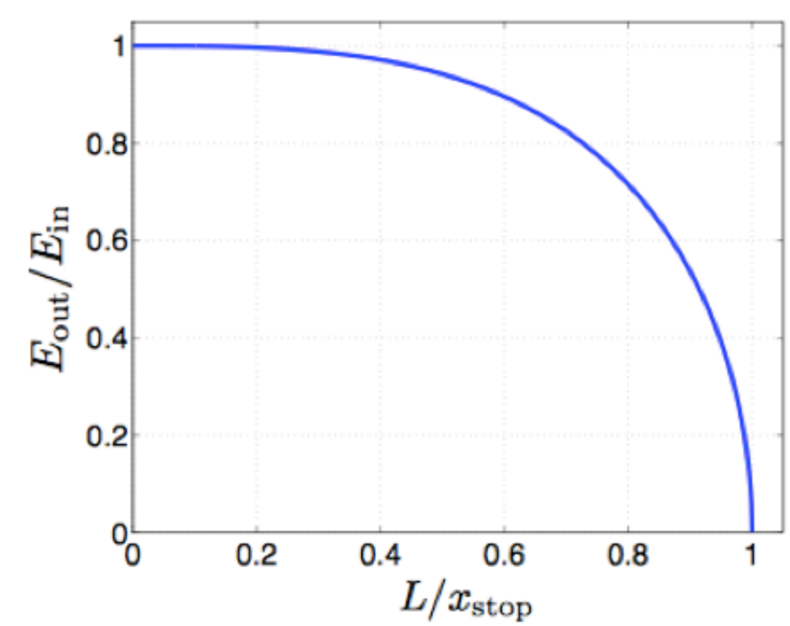
Strongly Coupled Energy Loss



Chesler and Rajagopal 14

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

$$x_{\rm stop} = \frac{1}{2\,\kappa_{\rm sc}}\frac{E_{\rm in}^{1/3}}{T^{4/3}}$$



Value of κ_{sc} different in different theories

$\lambda \equiv g^2 N_c$

$$\kappa_{sc} \sim \lambda^{1/6}$$

String computations

Gubser et al 08, Chesler et al 08, Ficnar and Gubser 13, Chesler and Rajagopal 14

$$\kappa_{sc} \sim \lambda^{0}$$

U(1) field decays

Hatta, Iancu and Mueller 08, Arnold and Vaman 10

$$\lambda \sim 10 \rightarrow \kappa_{sc} \sim \mathcal{O}(1)$$

expect it to be smaller in QCD than in N=4 SYM

We'll use κ_{sc} as our fitting parameter

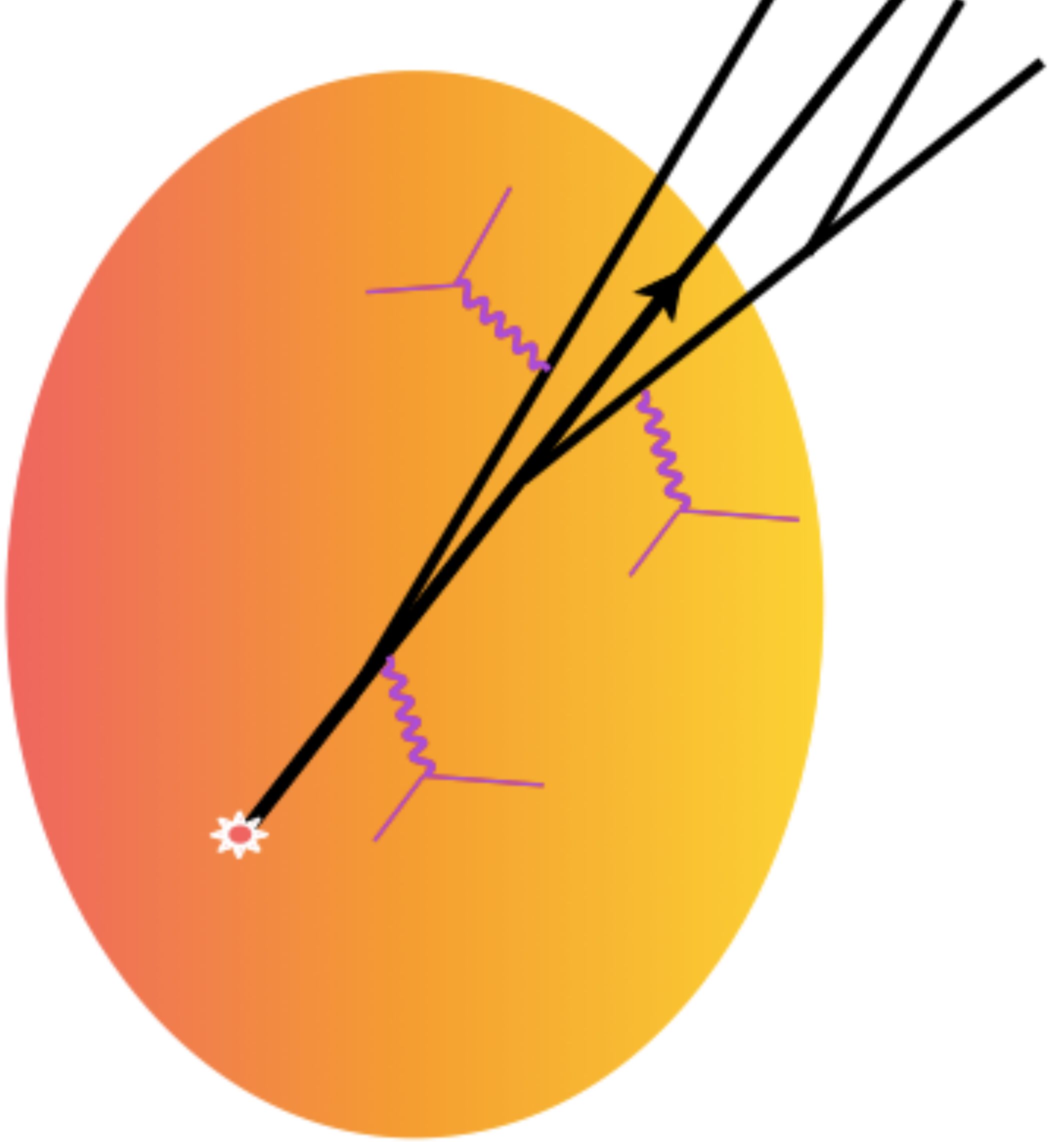
What about gluons?

$$x^{G}_{stop}(E) = x^{Q}_{stop}(E/2)$$

$$\kappa^{G}_{sc} = \kappa^{Q}_{sc} \left(\frac{C_A}{C_F} \right)^{1/3}$$

Chesler et al 08

Monte Carlo Implementation



Jet production and evolution in PYTHIA

Assign spacetime description to parton shower (formation time argument) $\tau_f = \frac{2E}{Q^2}$

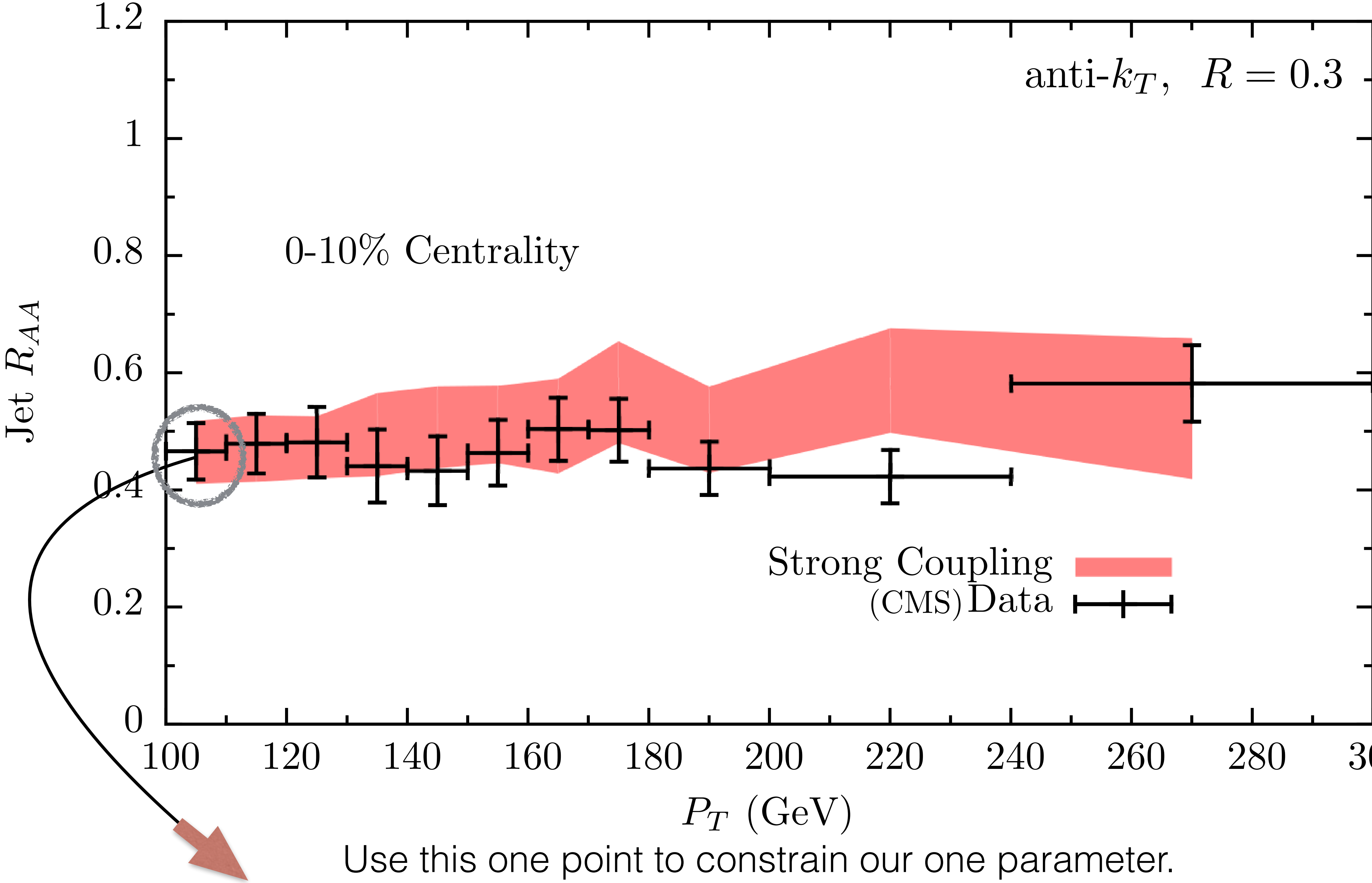
Embed the system into a hydrodynamic background (2+1 hydro code from Heinz and Shen)

Between splittings, partons in the shower interact with QGP, lose energy

Turn off energy loss below a T_c that we vary over $145 < T_c < 170\,\mathrm{MeV}$

Extract jet observables from parton shower

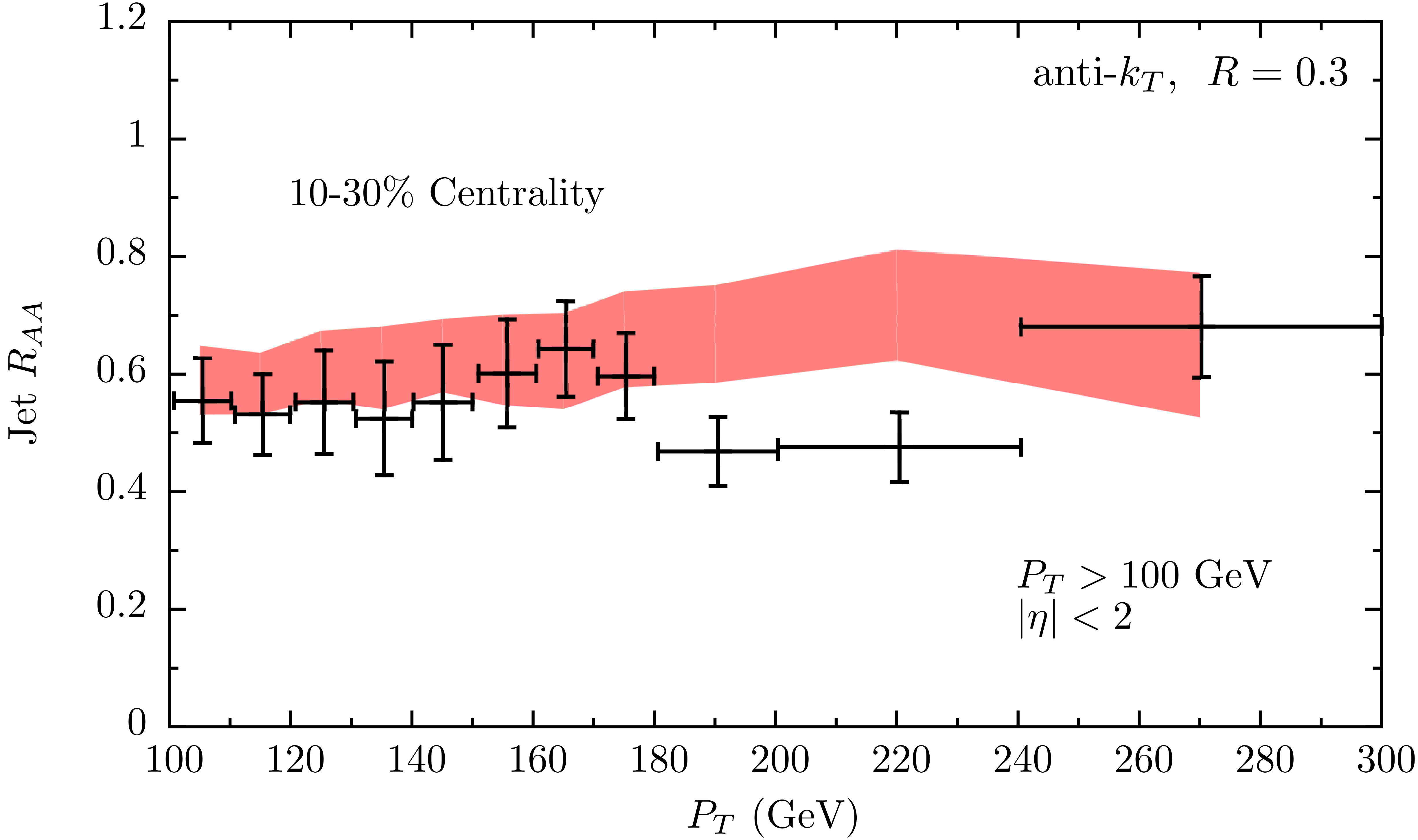
R_{AA}



Use this one point to constrain our one parameter.

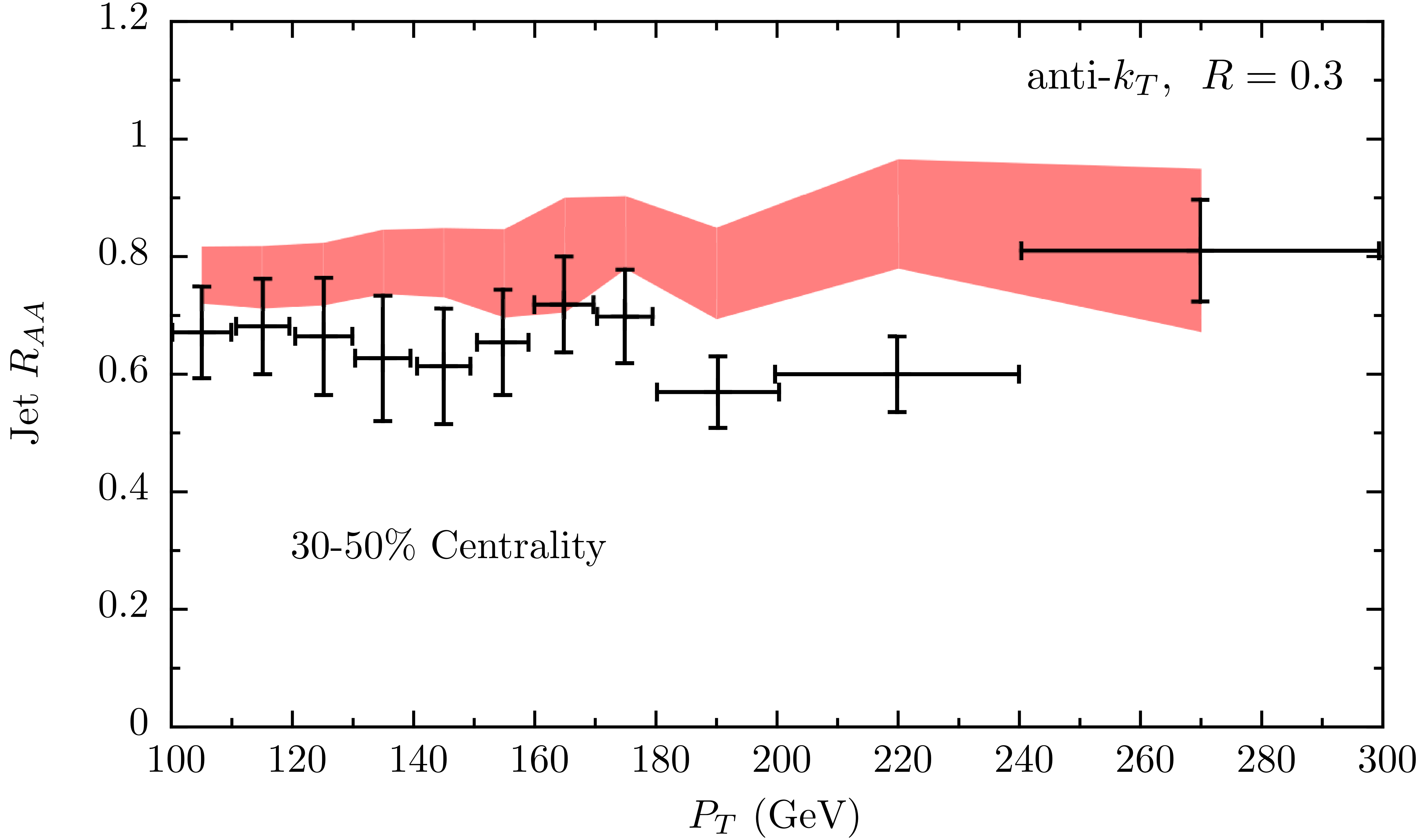
Bands come from experimental uncertainty on this point plus varying T_c over $145 < T_c < 170\,\text{MeV}$

R_{AA}



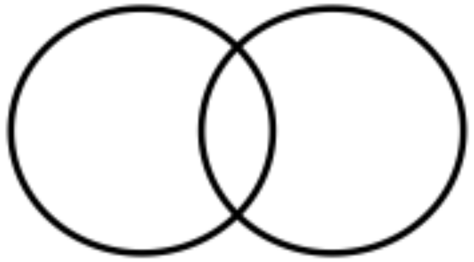
anti-k_T, $R = 0.3$
10-30% Centrality
$P_T > 100$ GeV
$|\eta| < 2$
Jet R_{AA}
P_T (GeV)
1.2
1
0.8
0.6
0.4
0.2
0
100
120
140
160
180
200
220
240
260
280
300

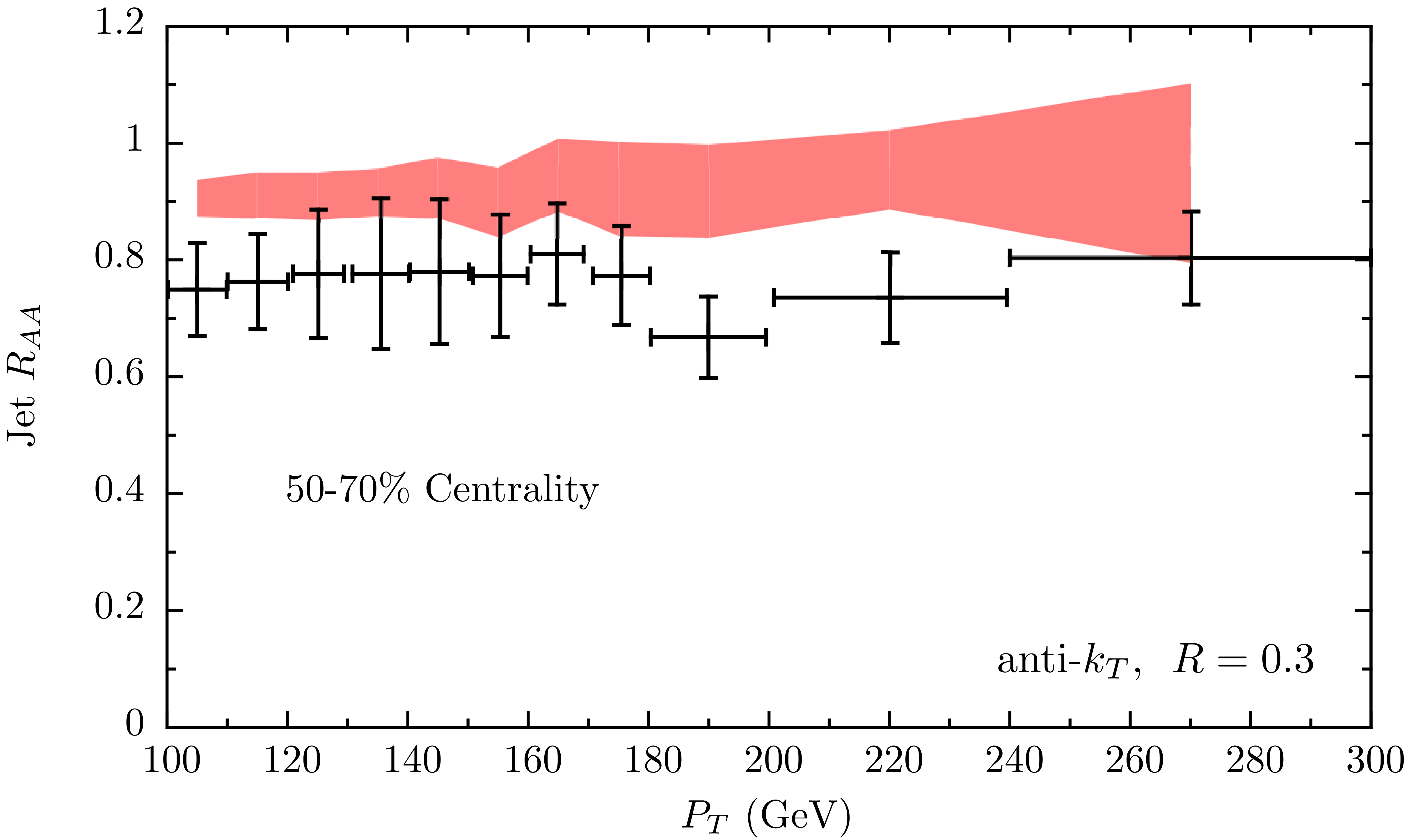
R_{AA}



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

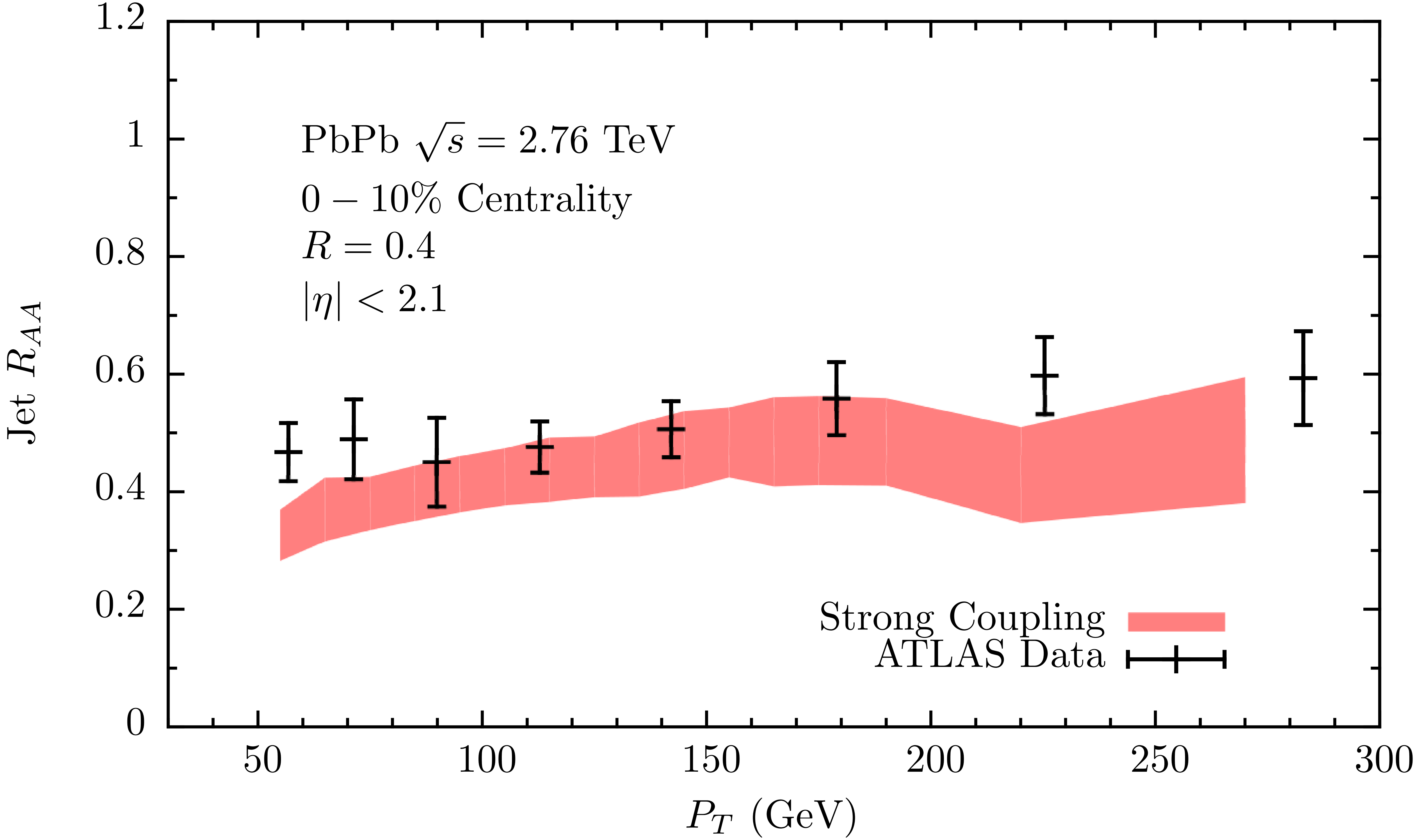
R_{AA}





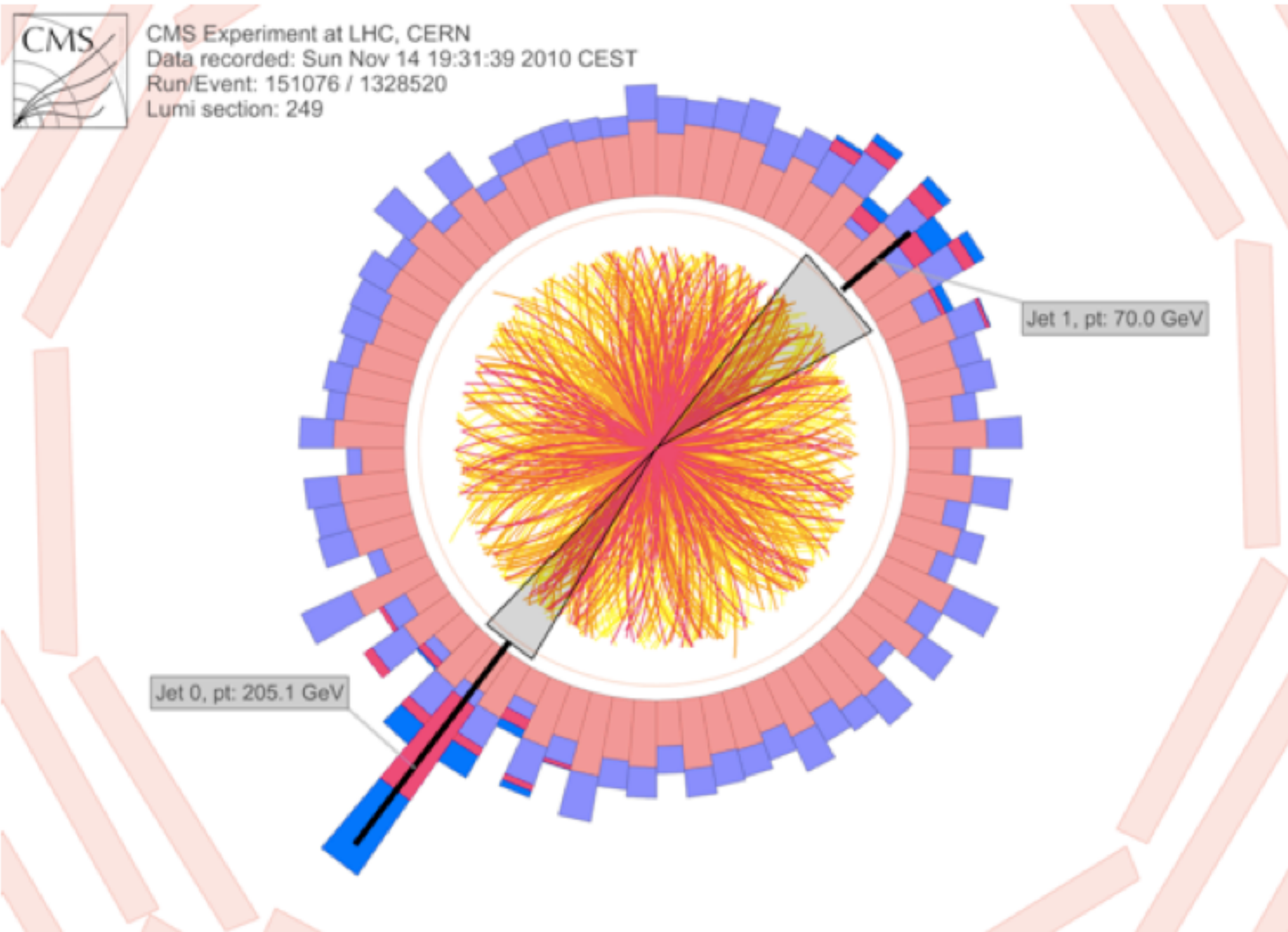
We have only simulated the QGP phase

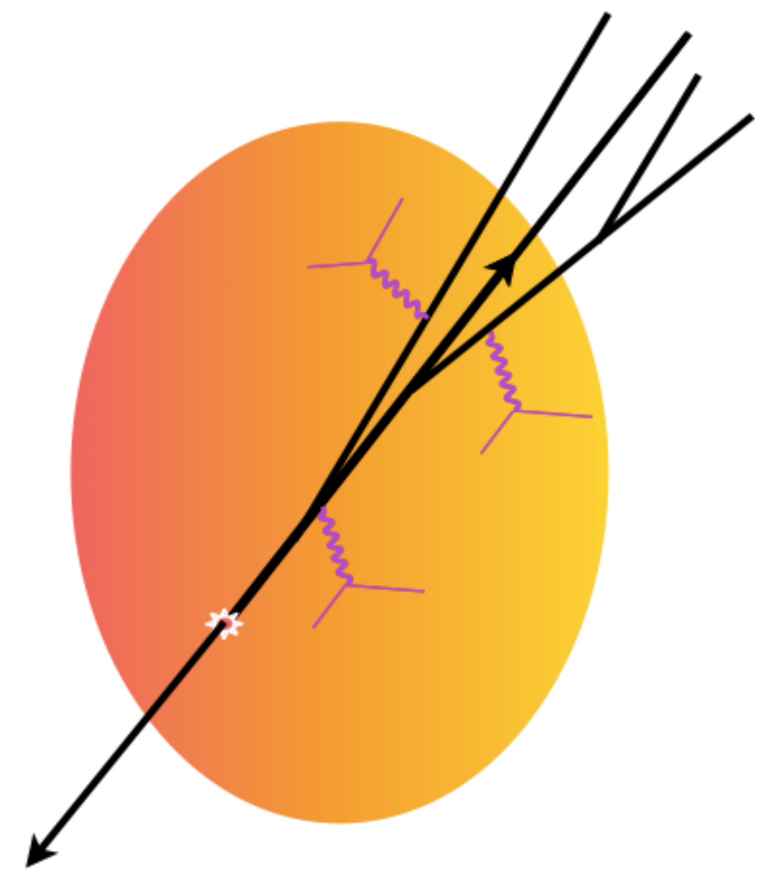
R_{AA}



With current implementation, slightly more quenching for bigger jet radius

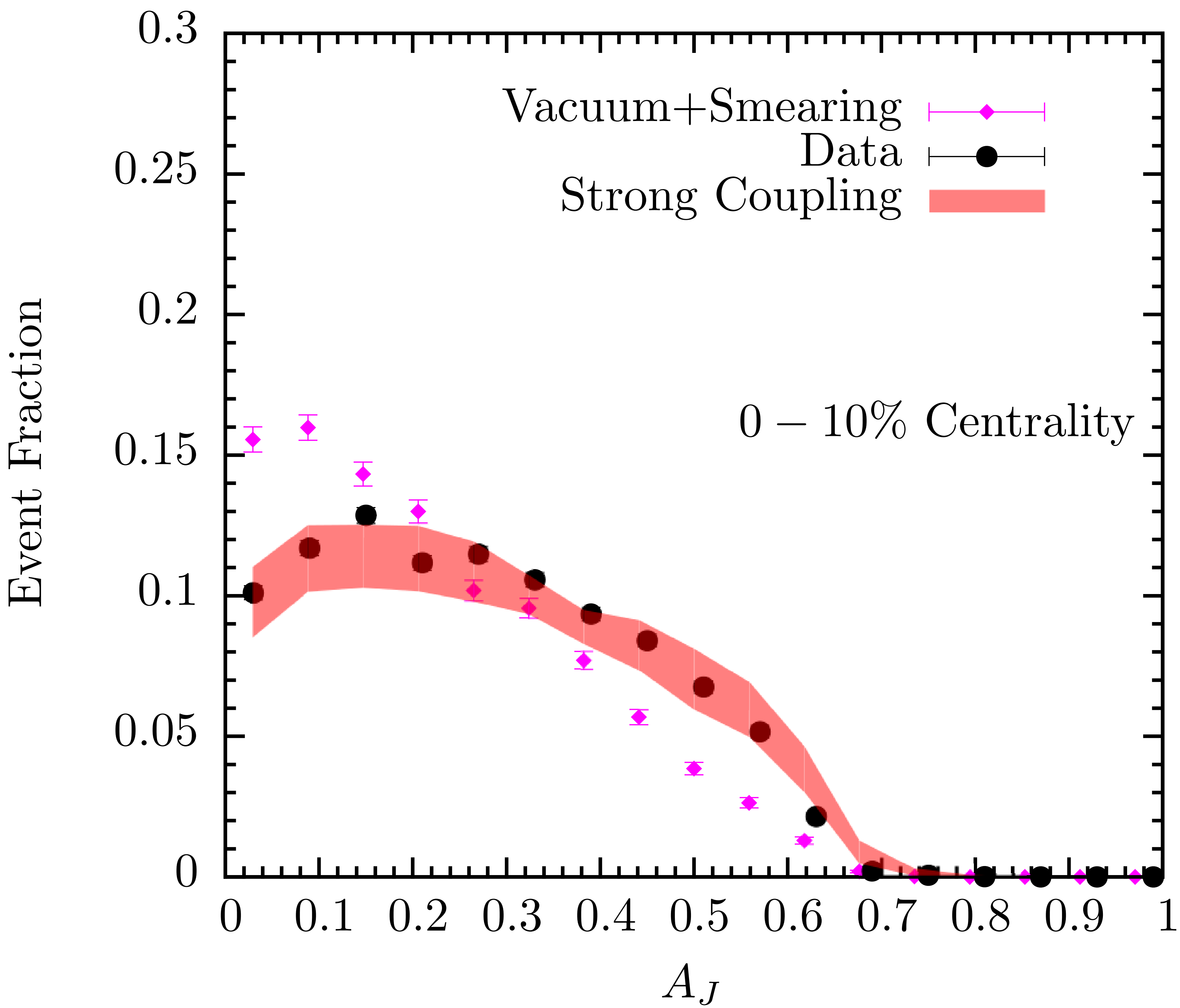
Dijets





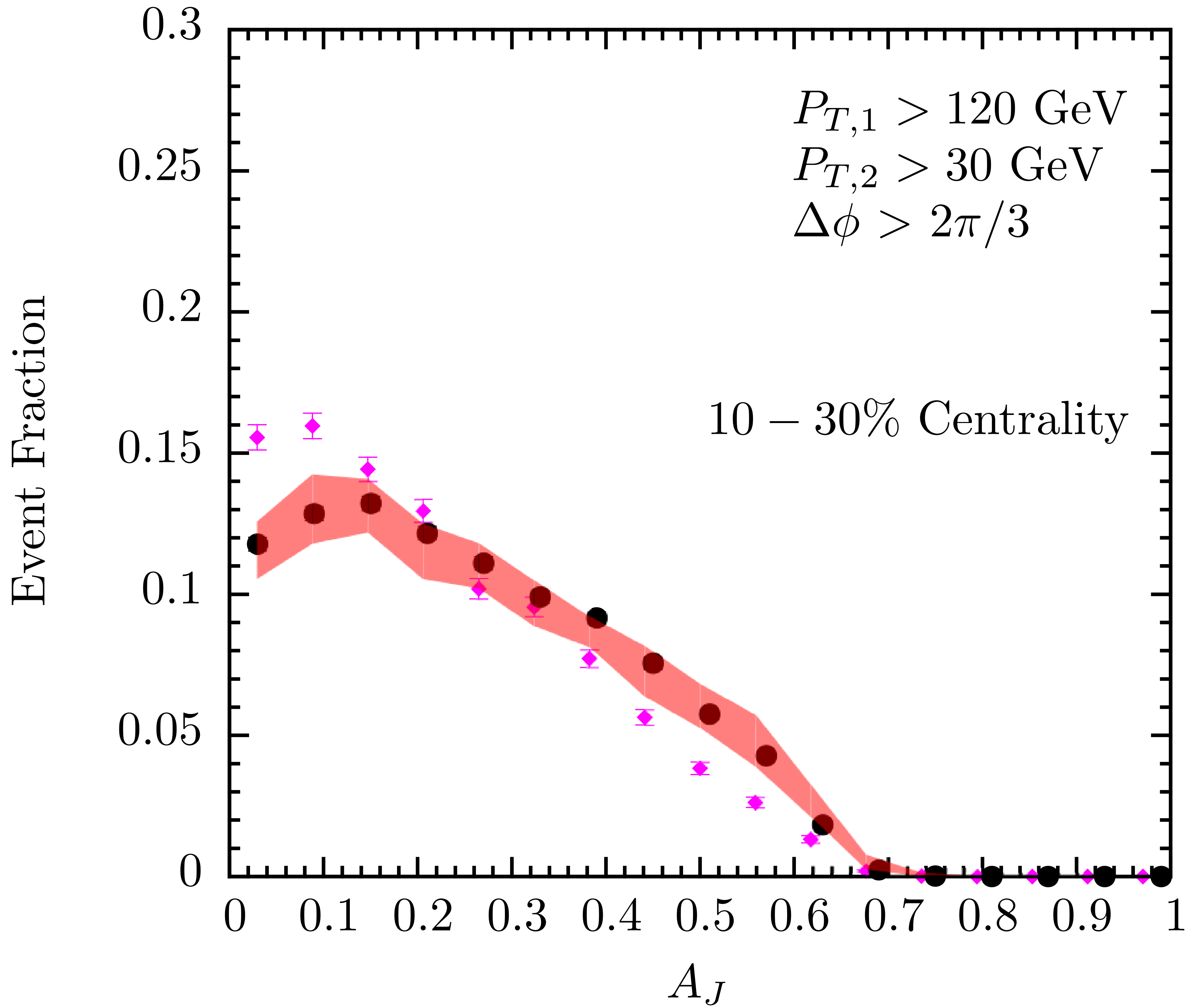
$$A_J = \frac{p_{T_1} - p_{T_2}}{p_{T_1} + p_{T_2}}$$

Imbalance



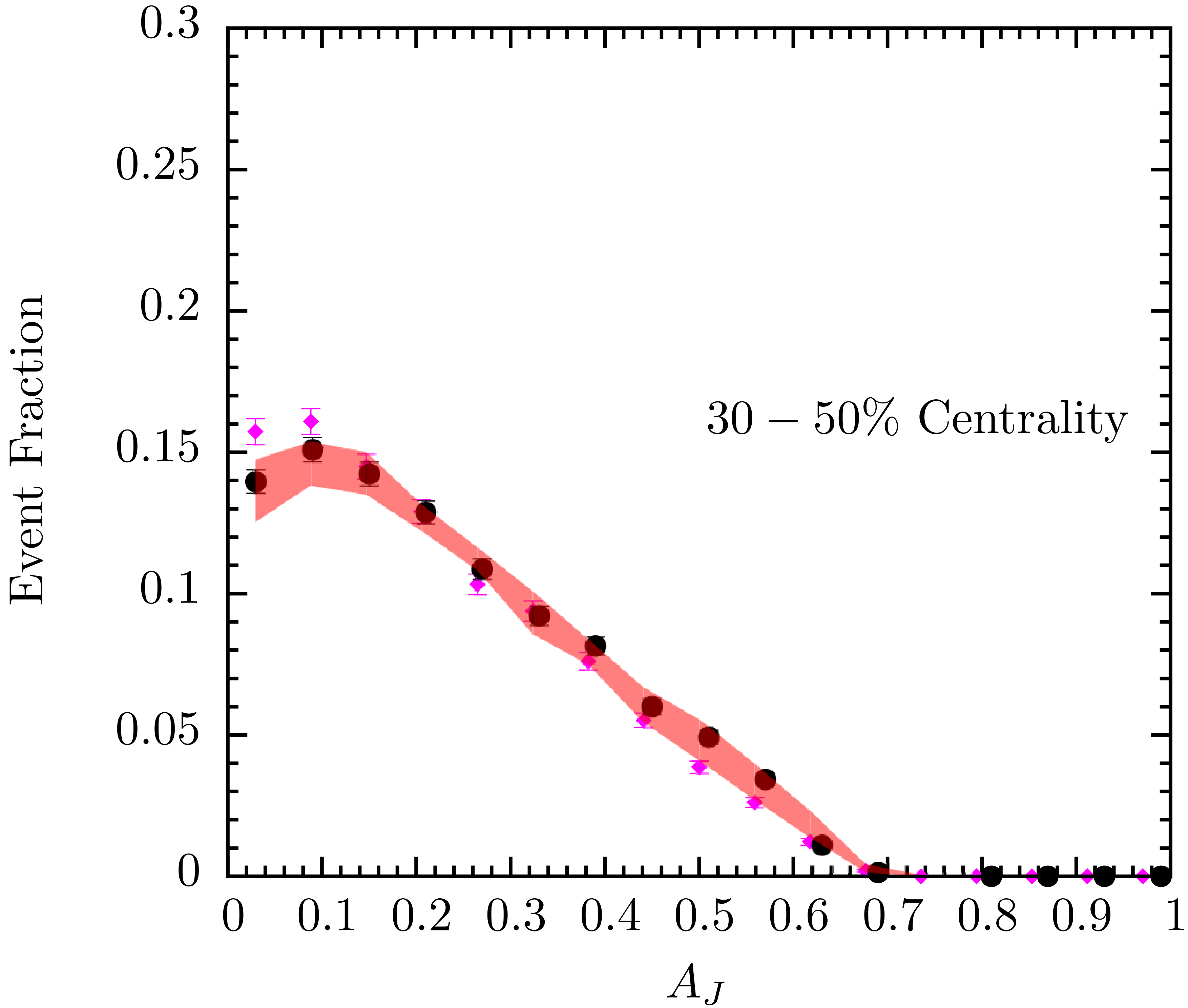
Vacuum+Smearing
Data
Strong Coupling
0 – 10% Centrality
Event Fraction
A_J
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Imbalance



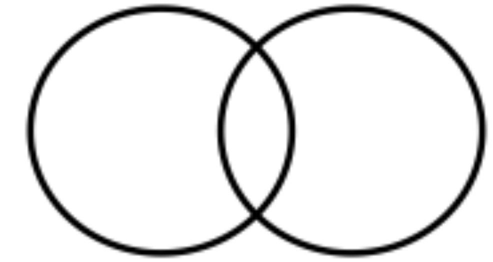
$P_{T,1} > 120$ GeV
$P_{T,2} > 30$ GeV
$\Delta\phi > 2\pi/3$
$10 - 30\%$ Centrality
Event Fraction
A_J
0
0.05
0.1
0.15
0.2
0.25
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

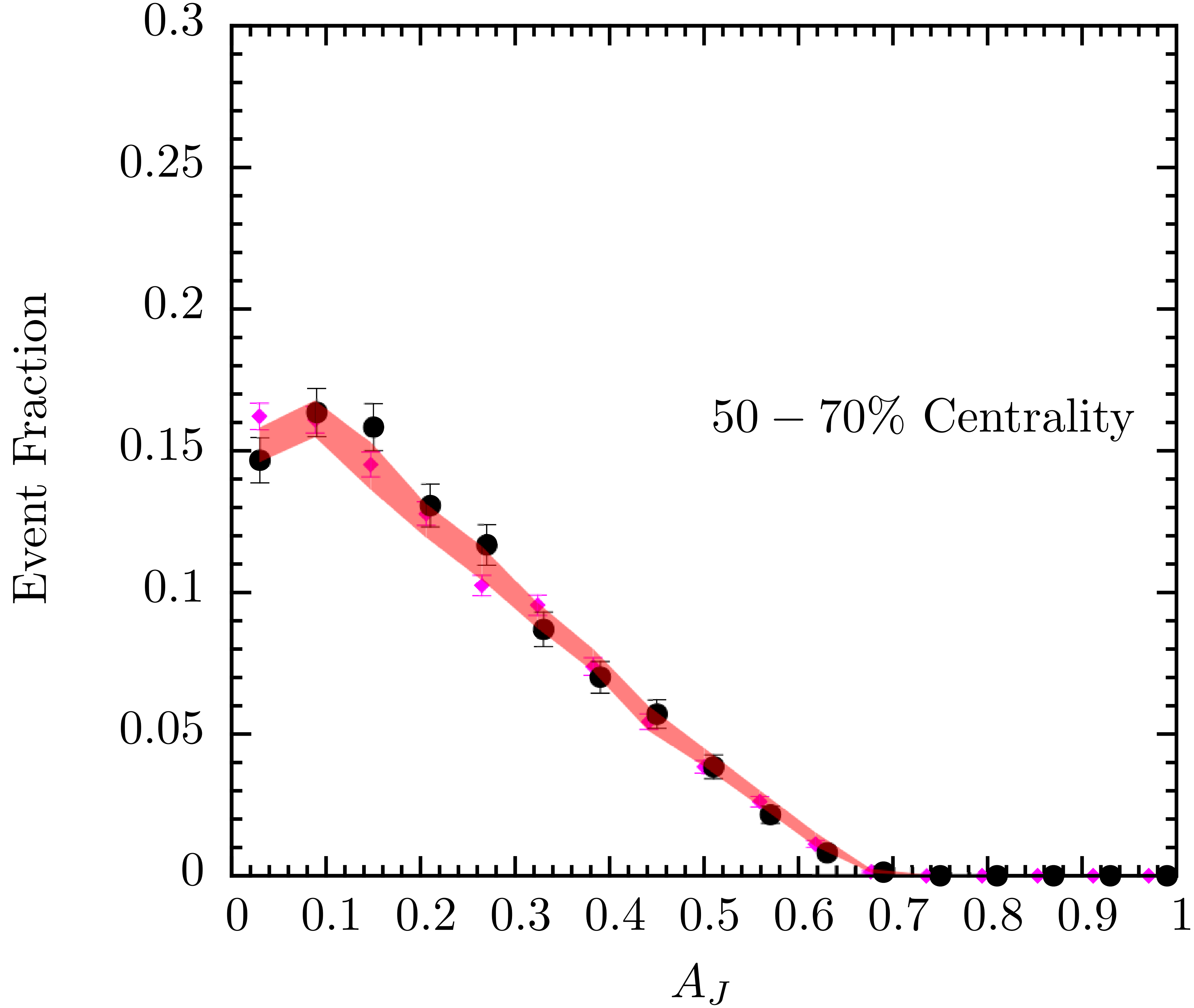
Imbalance



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

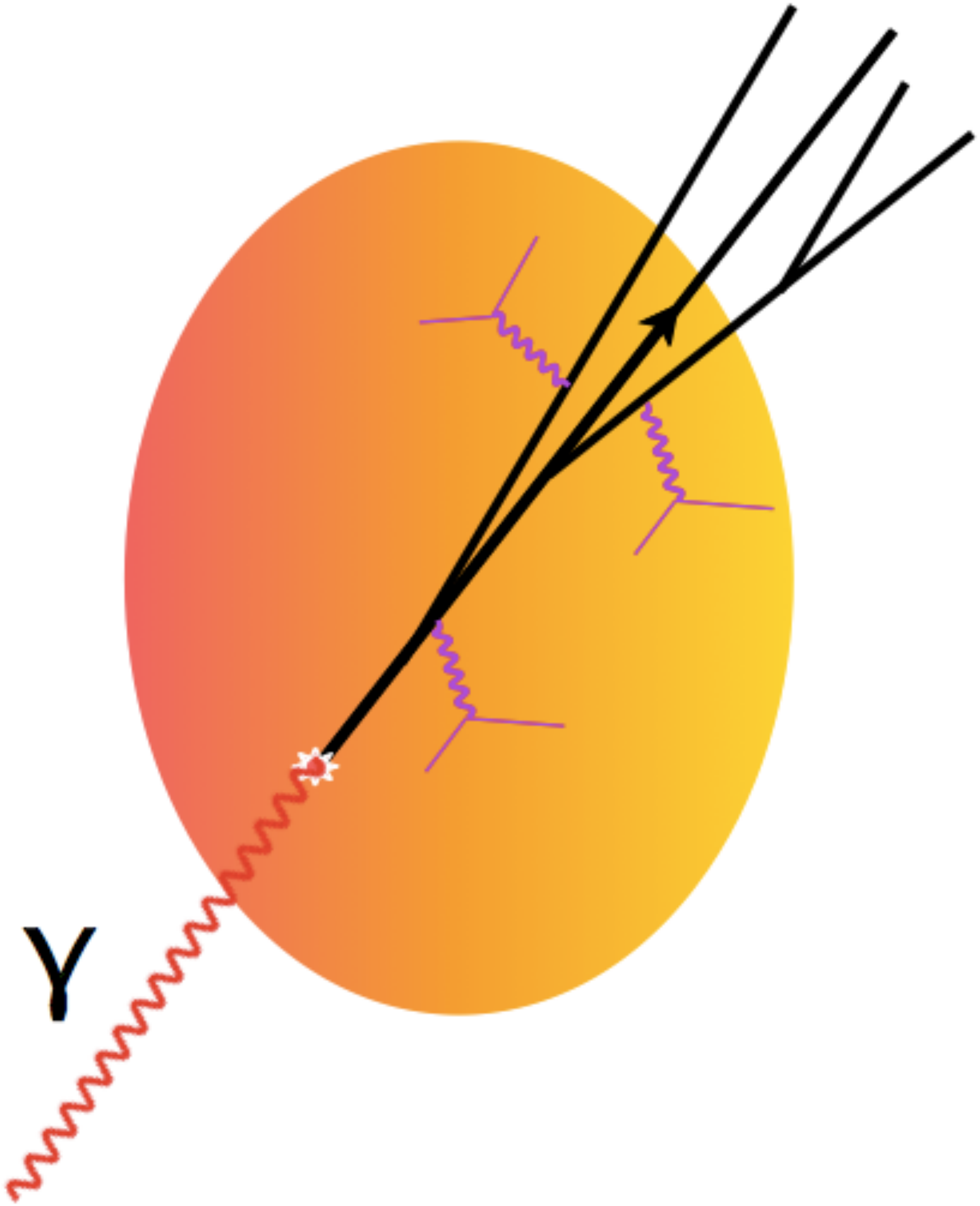
Imbalance





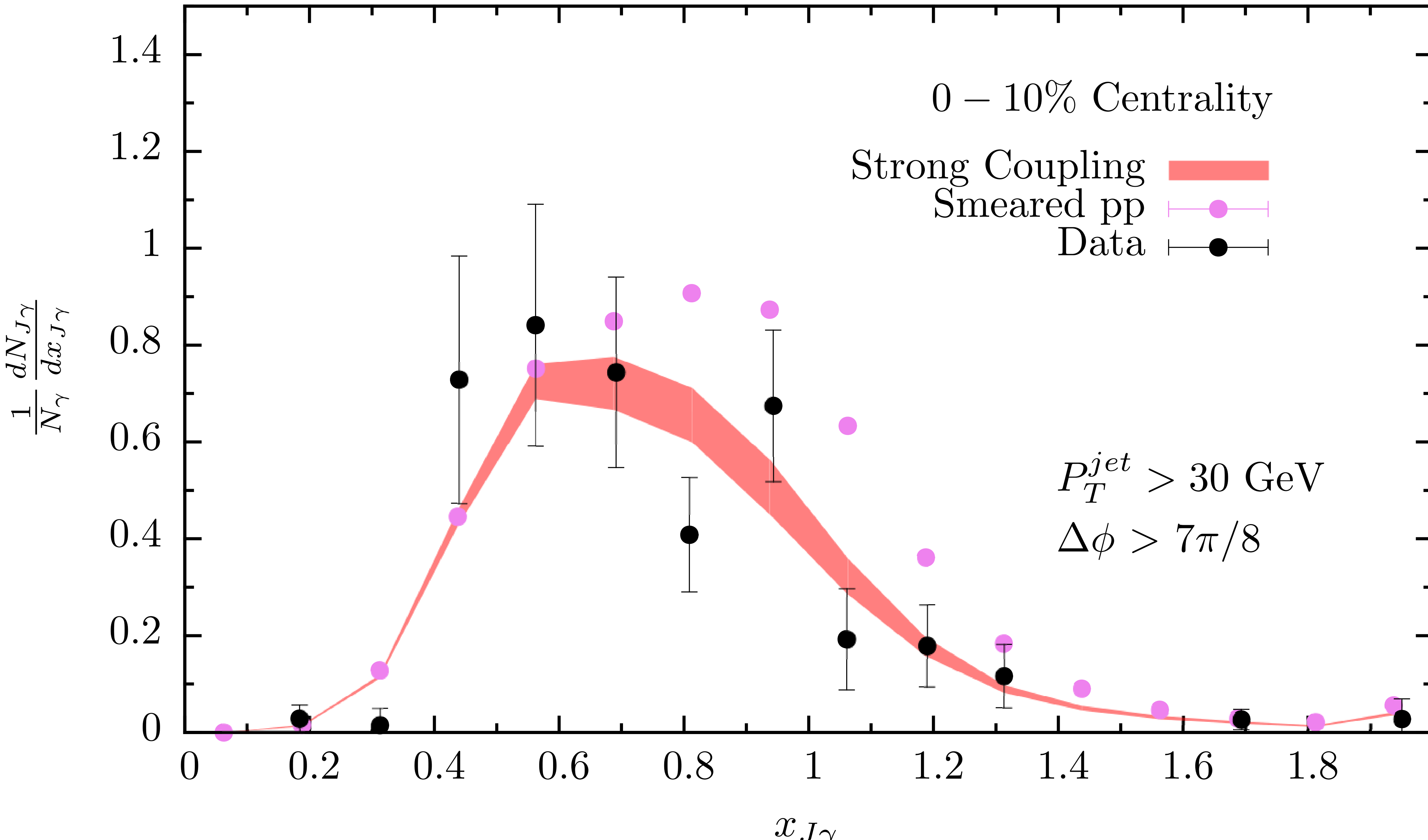
0.3
0.25
0.2
0.15
0.1
0.05
0
Event Fraction
50 − 70% Centrality
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
A_J

Photon Jet



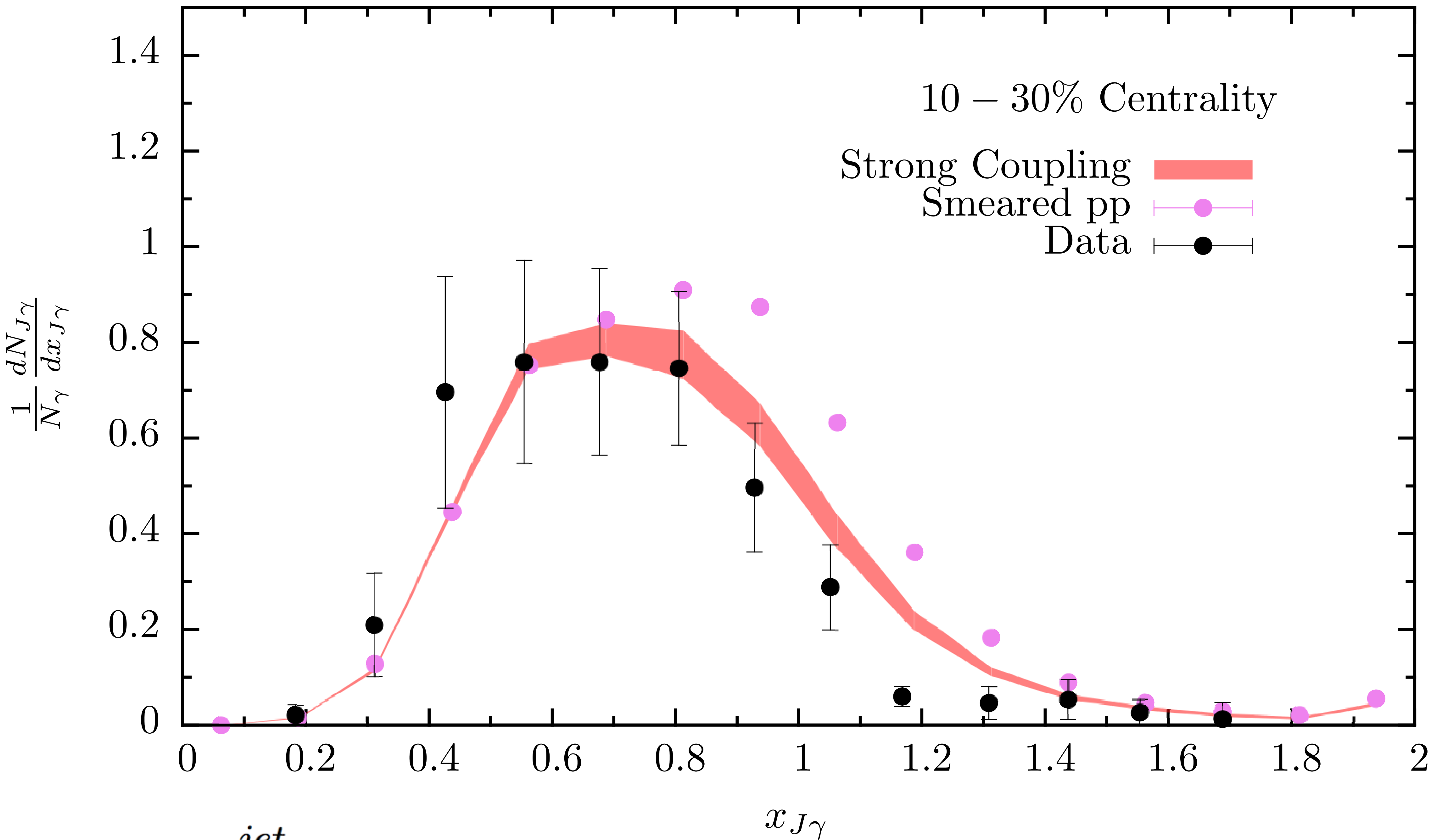
- Photons do not interact with plasma
- Look for associated jet
  - -Different geometric sampling
  - -Different species composition
  - -E_γ proxy for E_{jet}

Imbalance



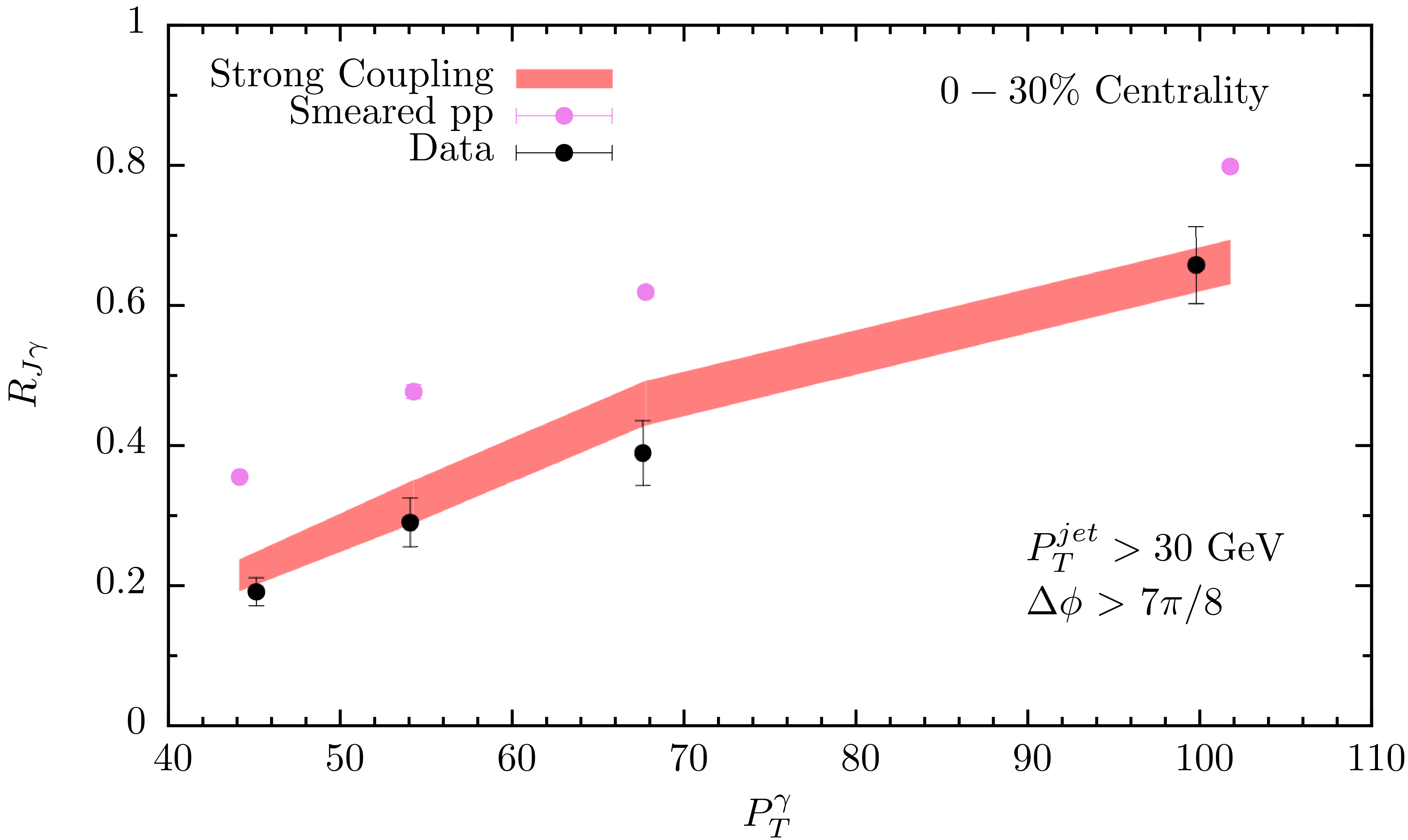
$$x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

Imbalance



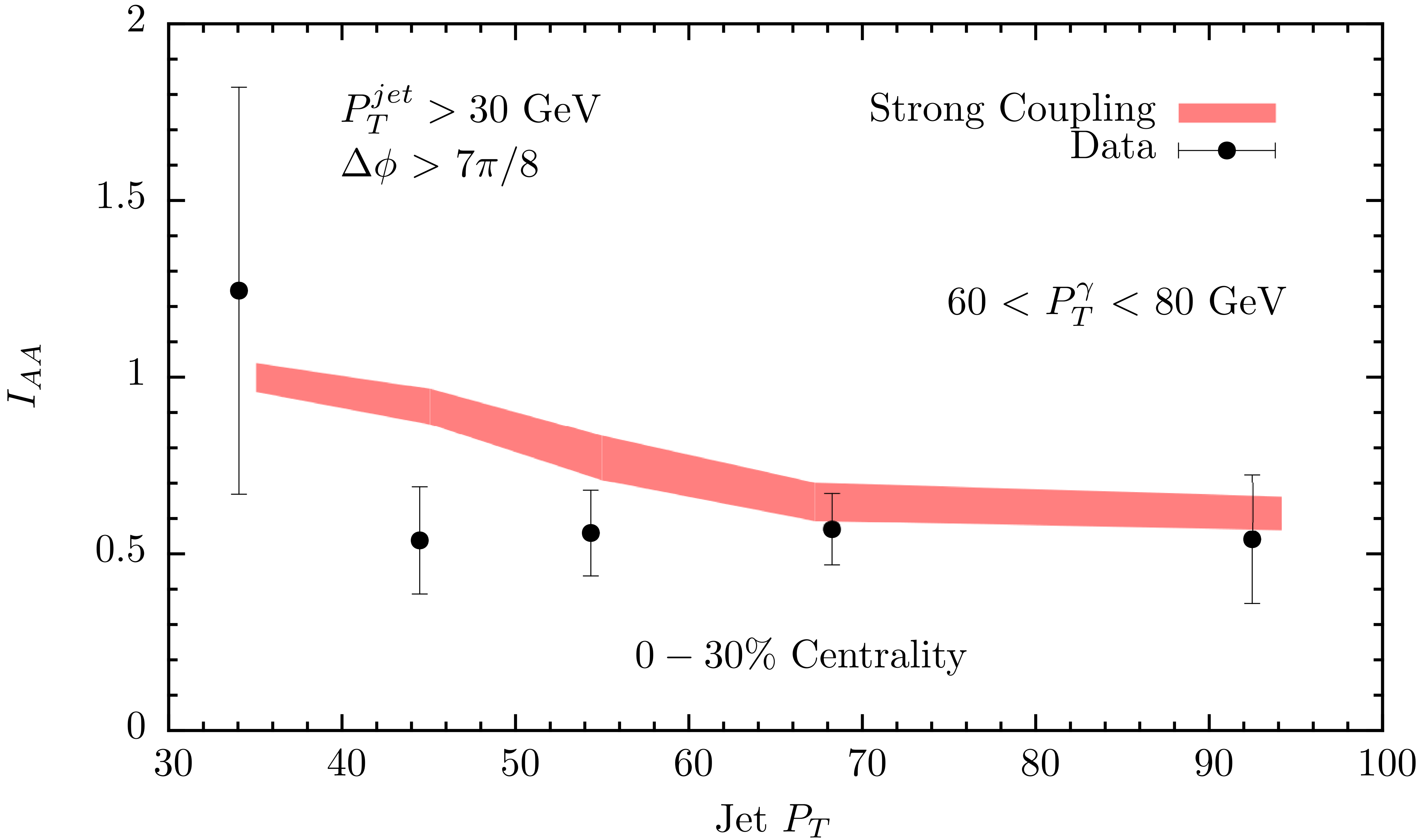
$$x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

Jet Suppression



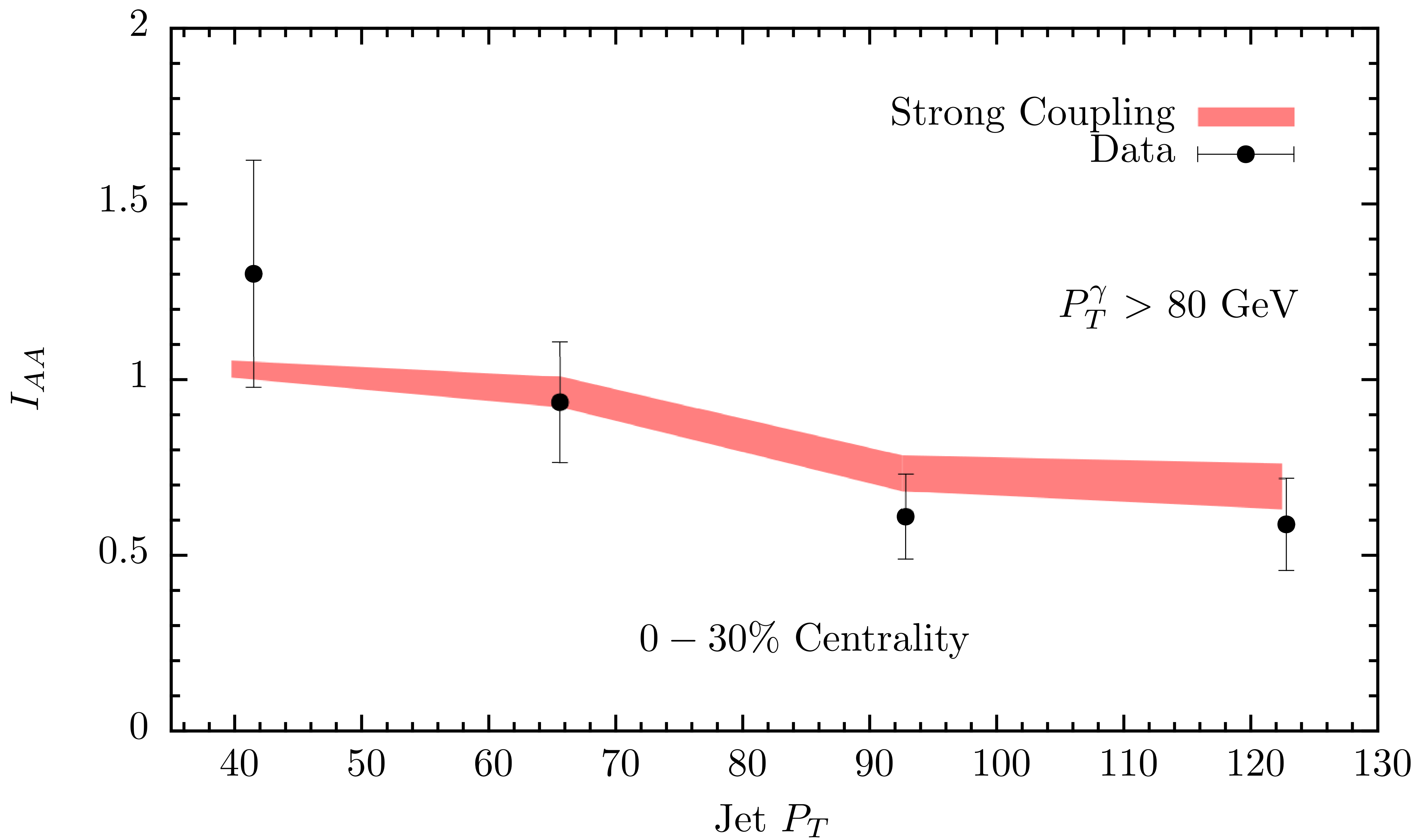
$$R_{J\gamma} = \frac{\text{Number of jets}}{\text{Number of photons}}$$

Spectrum

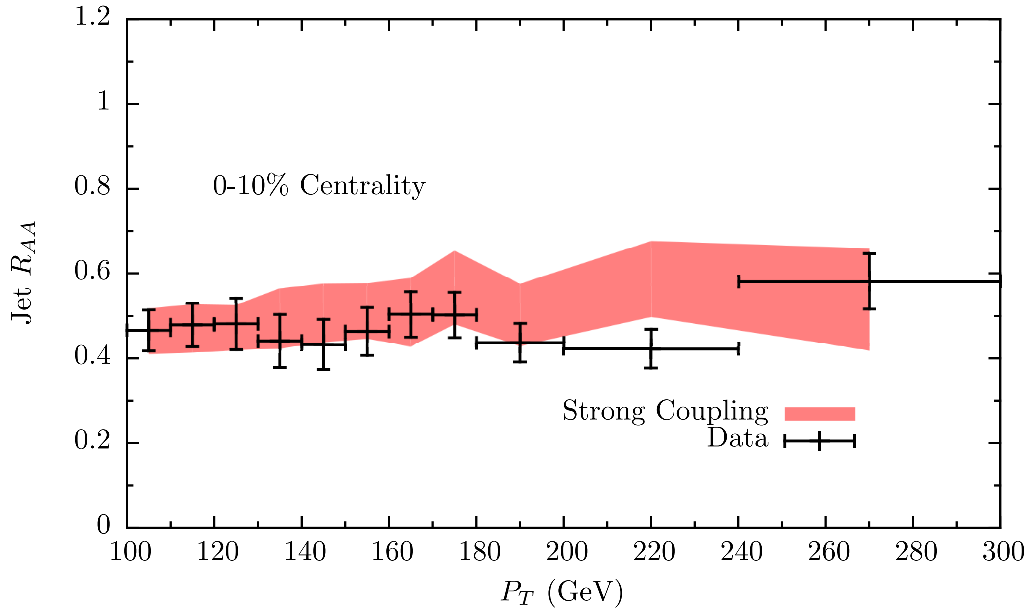


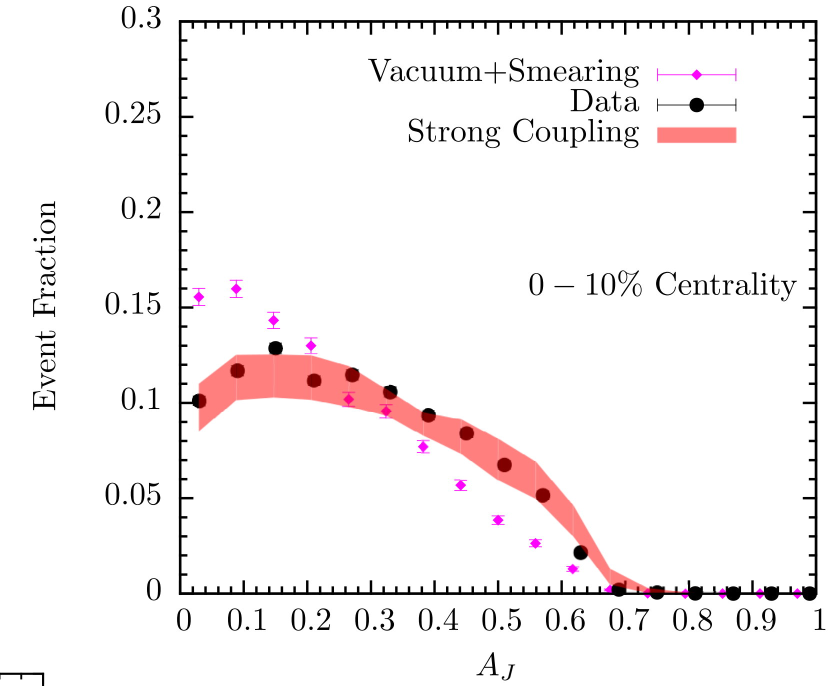
$$I_{AA} = \frac{\text{Number of associated jets in PbPb}}{\text{Number of associated jets in pp}}$$

Spectrum

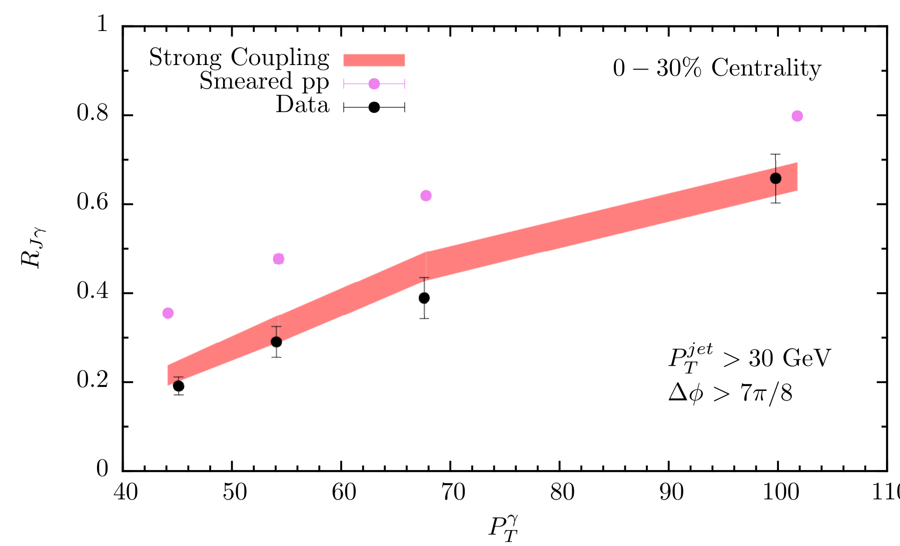


$$I_{AA} = \frac{\text{Number of associated jets in PbPb}}{\text{Number of associated jets in pp}}$$





5 observables
and centrality dependence
all described with
single parameter

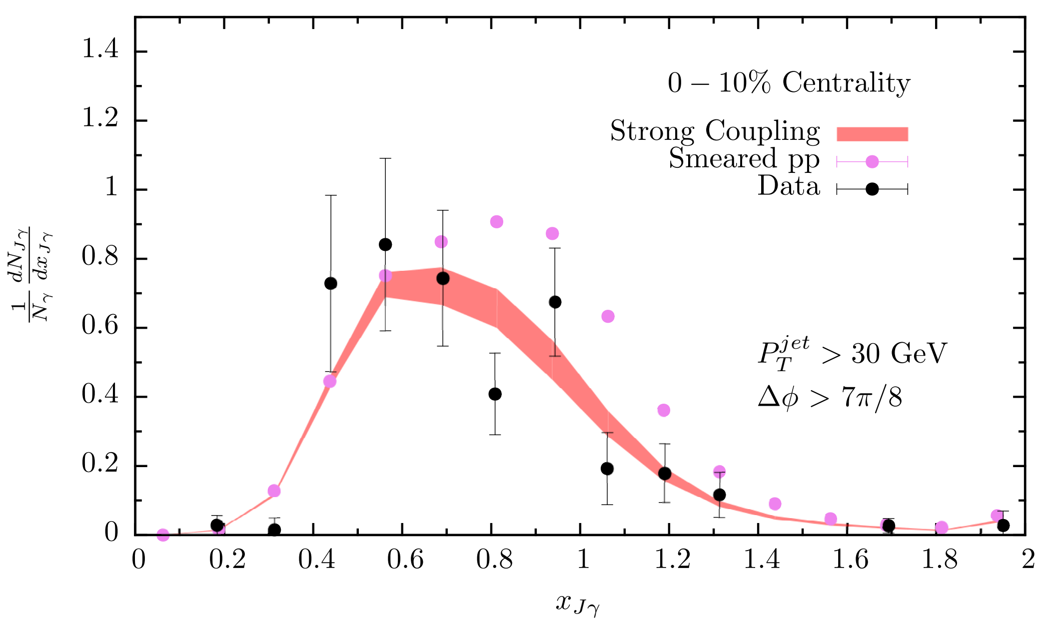


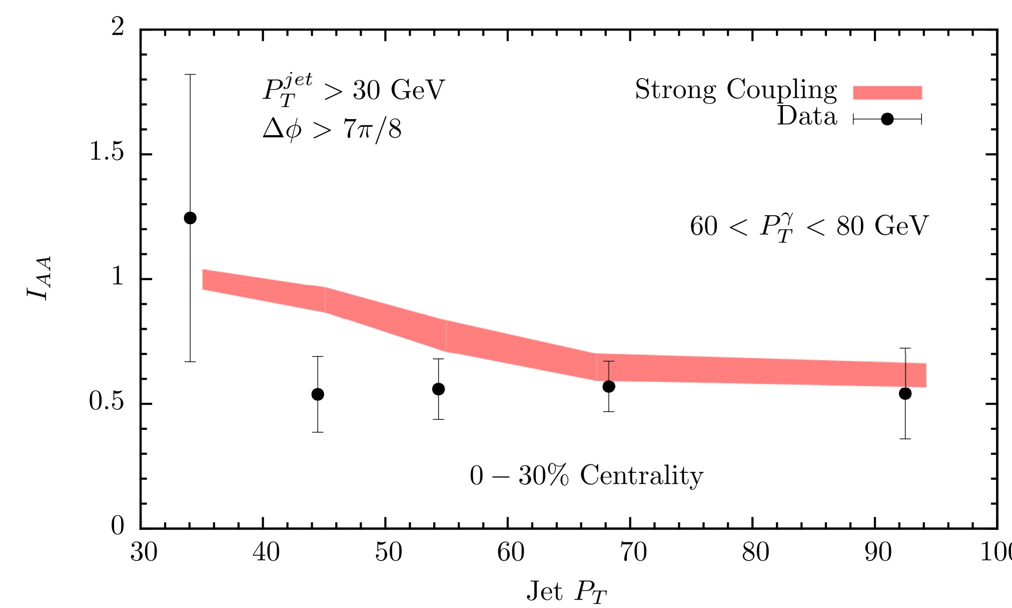
Bands in all plots correspond to

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

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

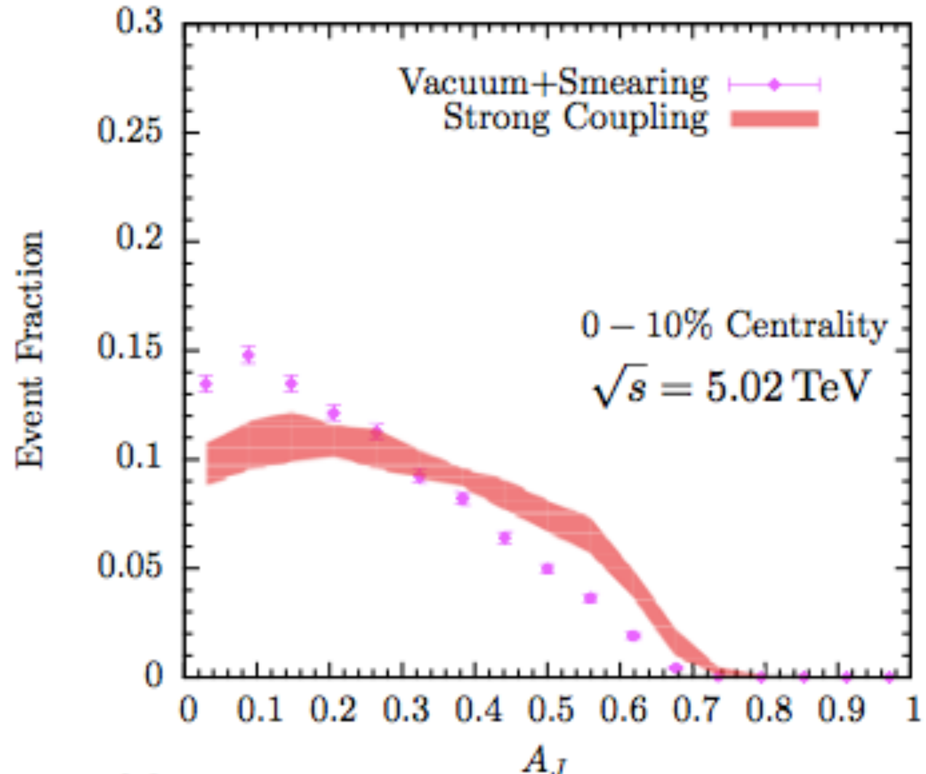
$$x_{stop}^{QCD} \sim (3-4)\, x_{stop}^{\mathcal{N}=4}$$



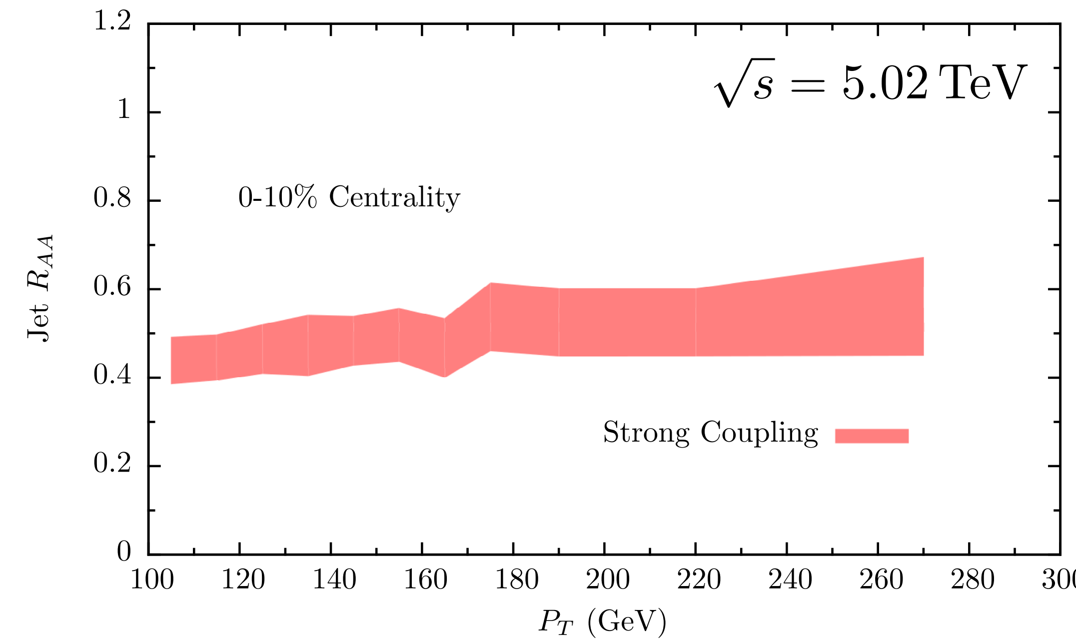


Predictions

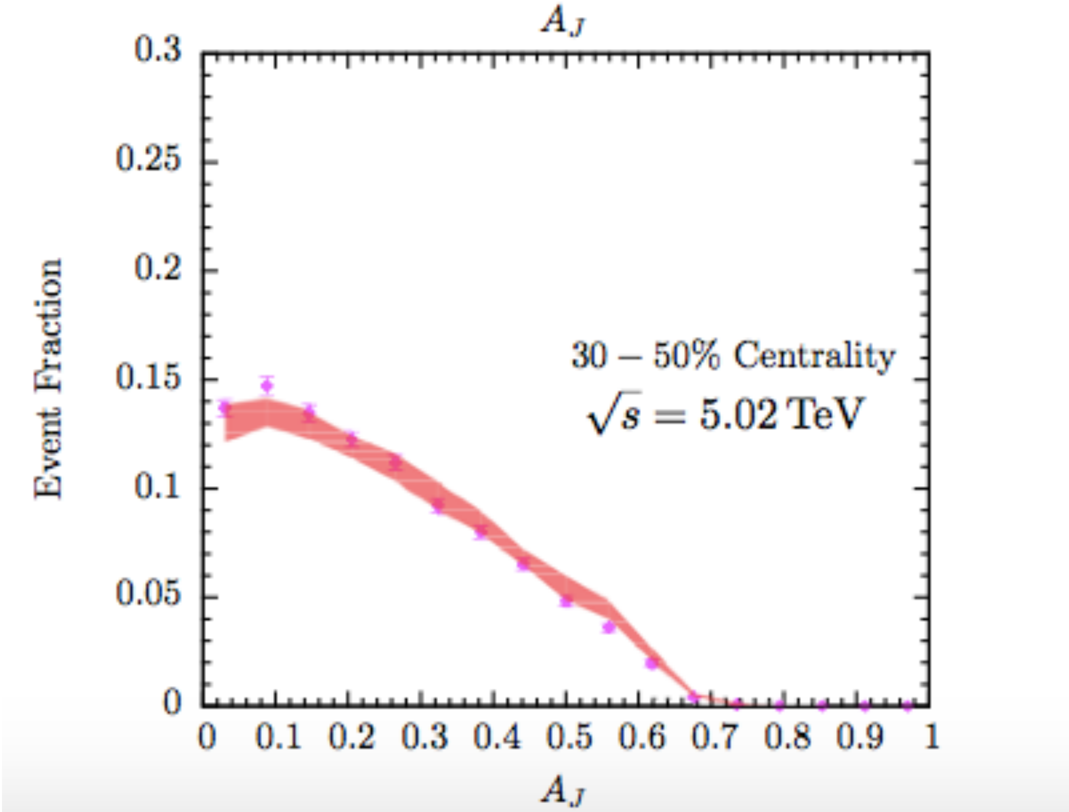
Dijet



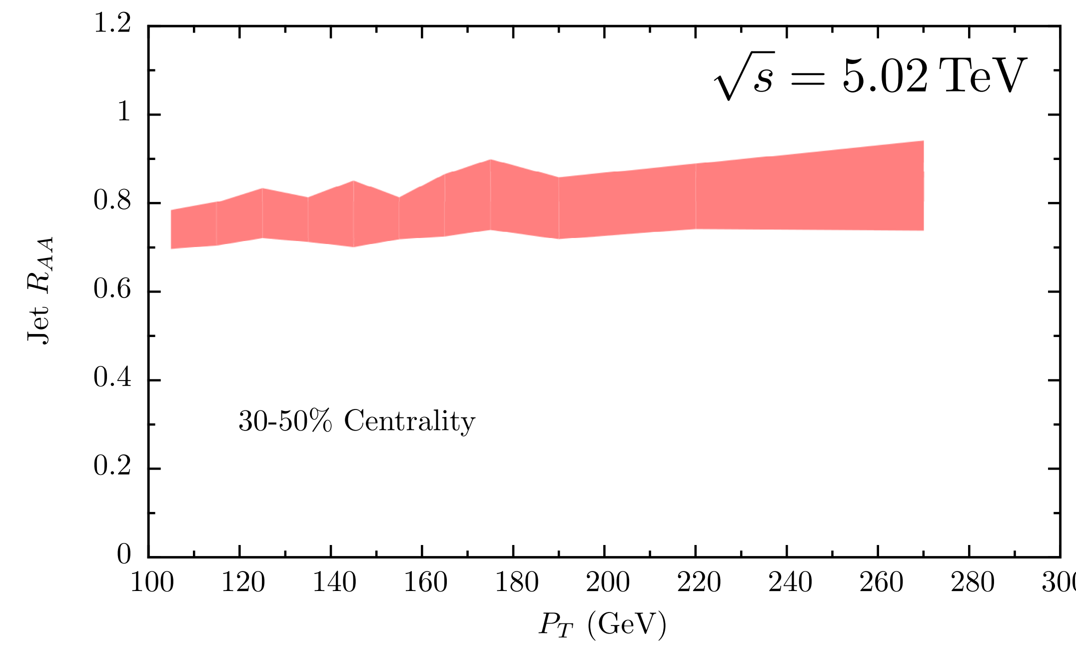
Vacuum+Smearing
Strong Coupling
$0-10\%$ Centrality
$\sqrt{s} = 5.02\,\mathrm{TeV}$
Event Fraction
A_J



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

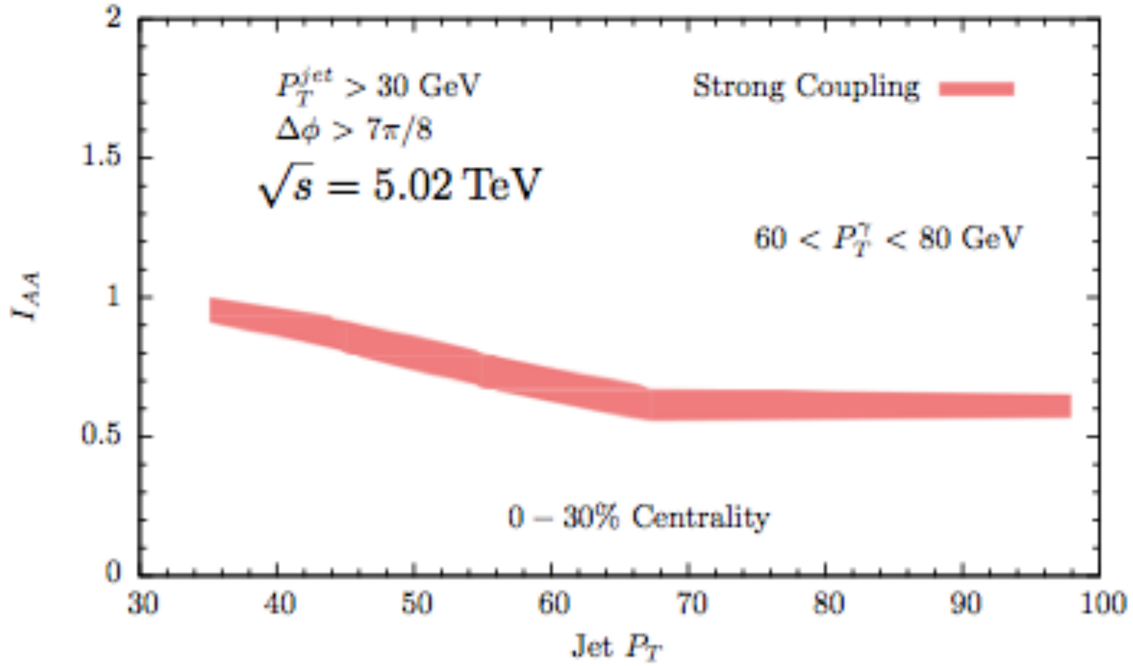


$30-50\%$ Centrality
$\sqrt{s} = 5.02\,\mathrm{TeV}$
Event Fraction
A_J

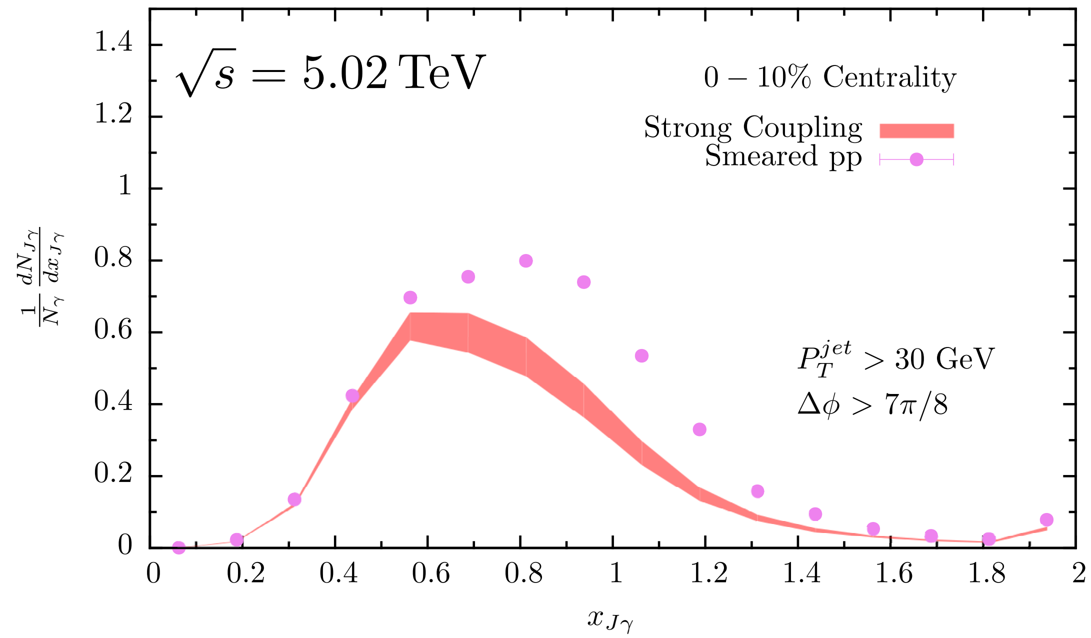


$\sqrt{s} = 5.02\,\mathrm{TeV}$
30-50% Centrality
Jet R_{AA}
P_T (GeV)

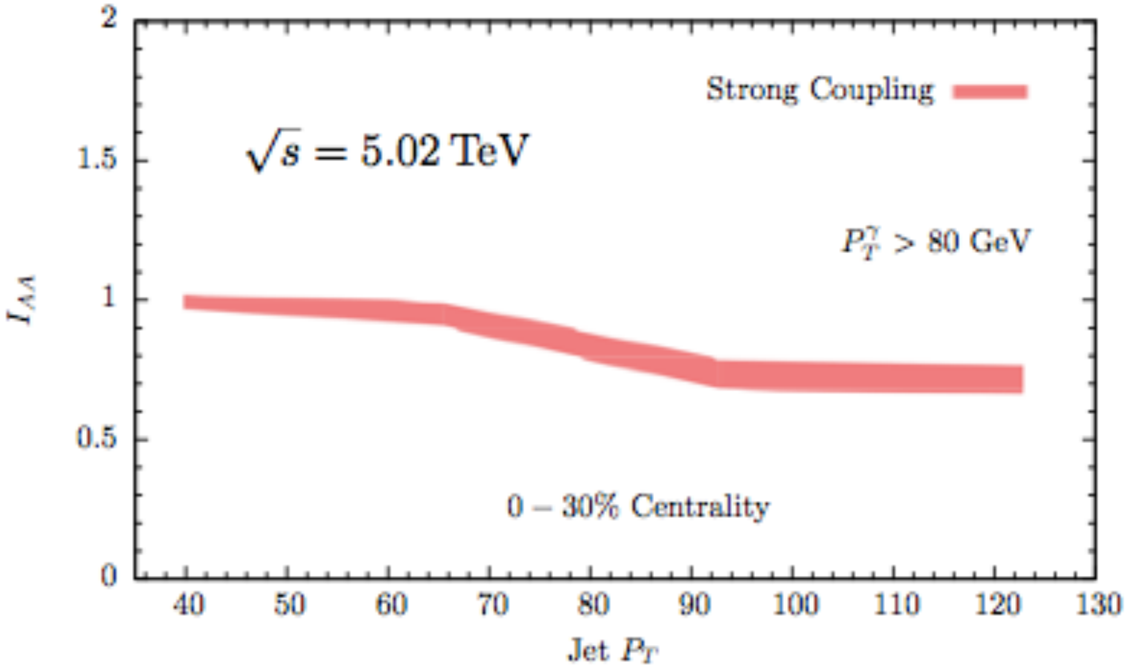
Photon-Jet



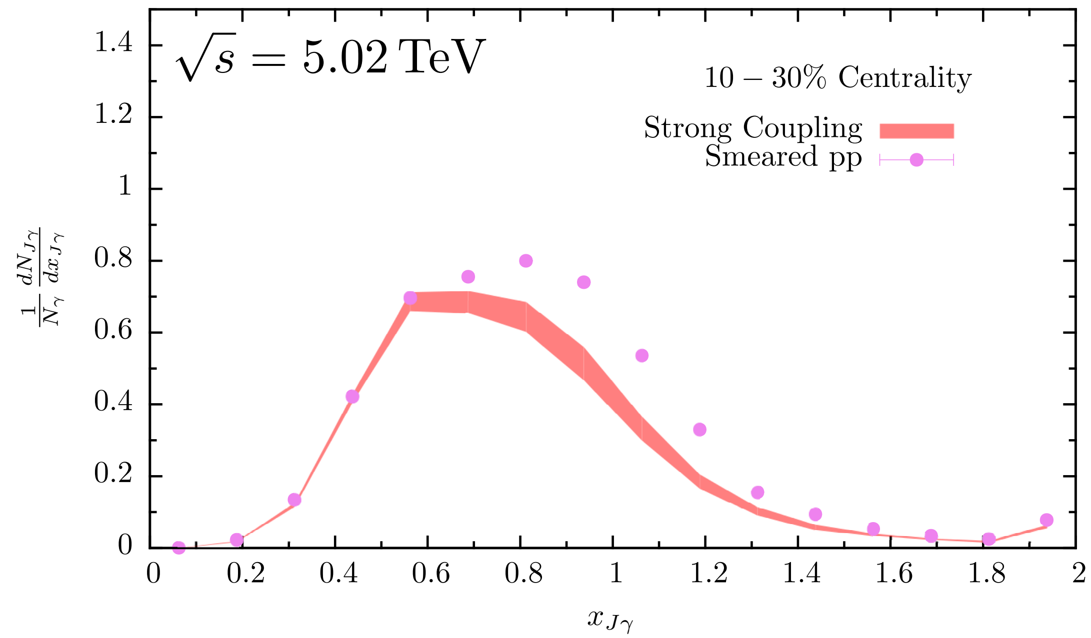
$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\sqrt{s} = 5.02$ TeV
Strong Coupling
$60 < P_T^{\gamma} < 80$ GeV
$0 - 30\%$ Centrality
I_{AA}
Jet P_T



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

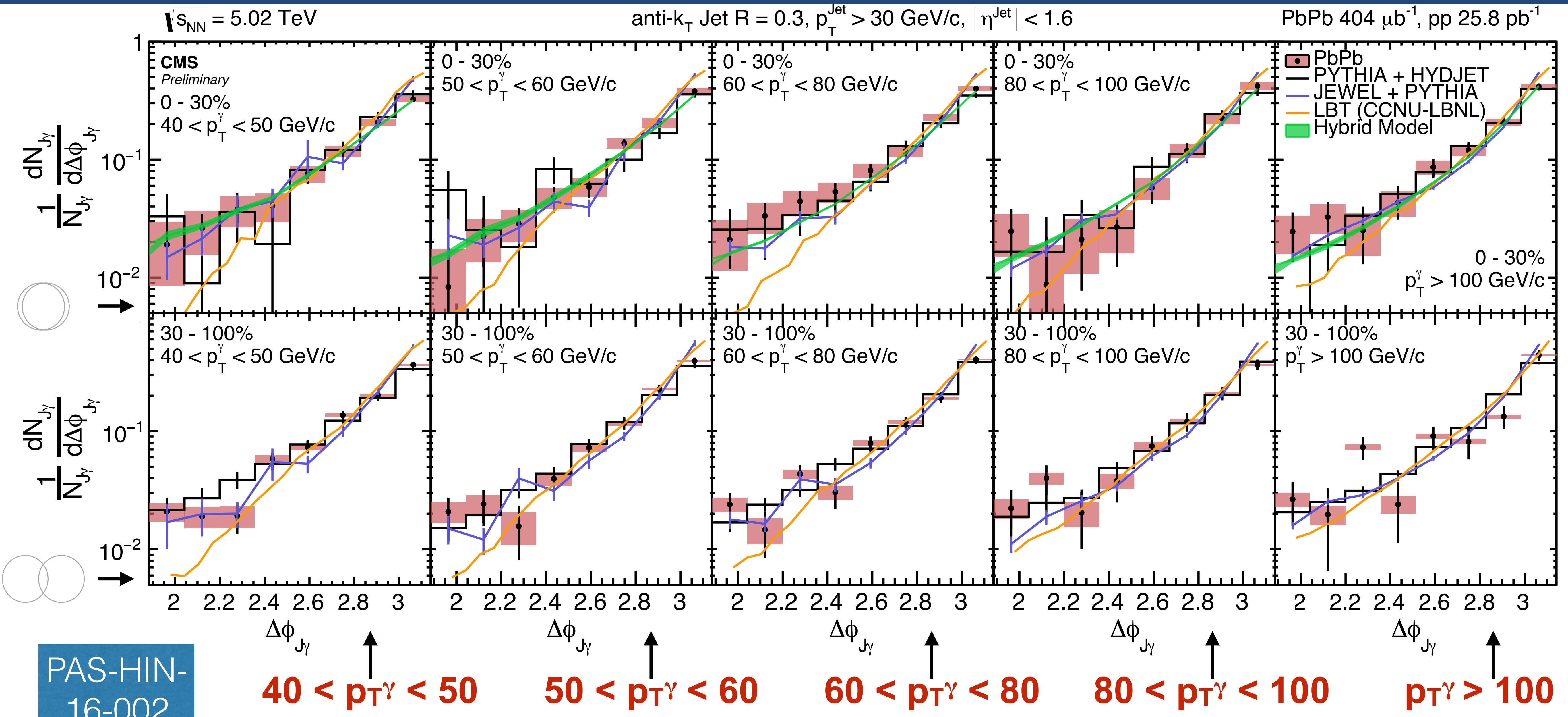


Strong Coupling
$\sqrt{s} = 5.02$ TeV
$P_T^{\gamma} > 80$ GeV
$0 - 30\%$ Centrality
I_{AA}
Jet P_T



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

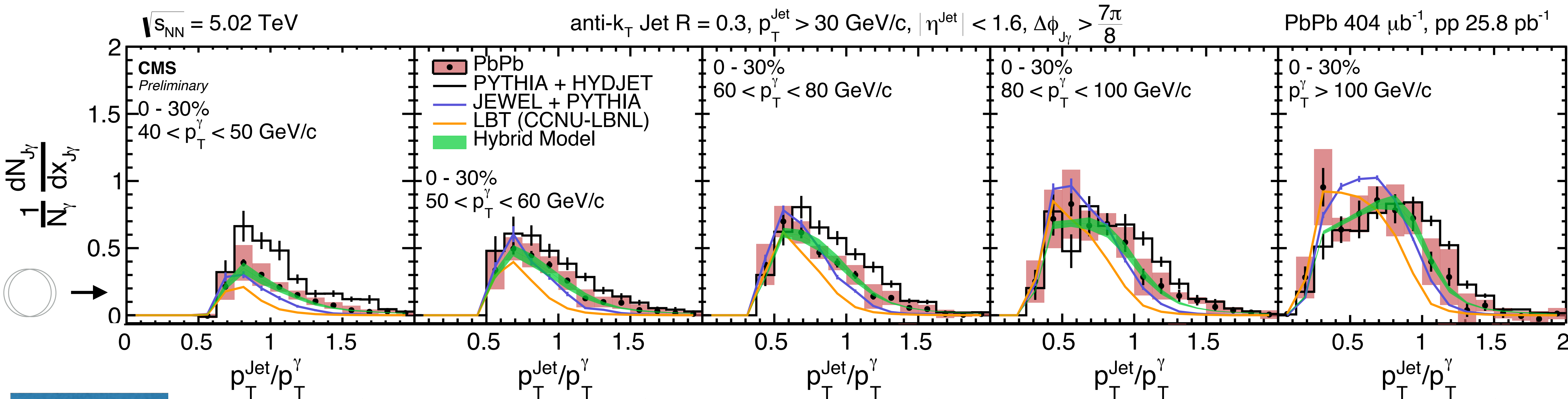
Theory Comparison: $\Delta\phi_{J\gamma}$ in PbPb



PAS-HIN-16-002

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

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

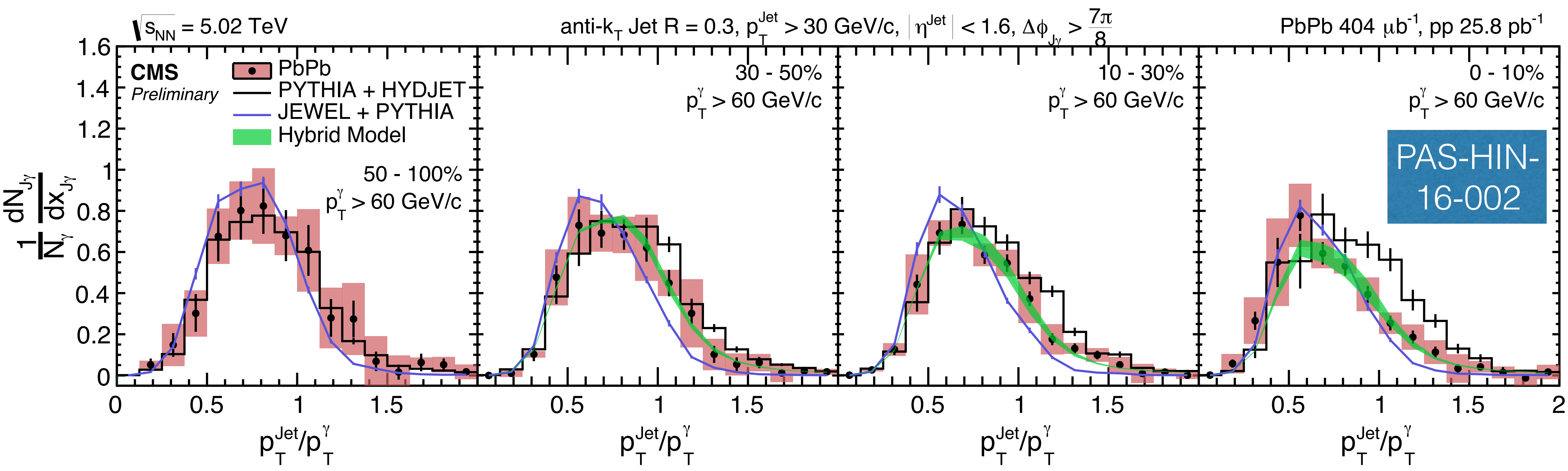


PAS-HIN-16-002

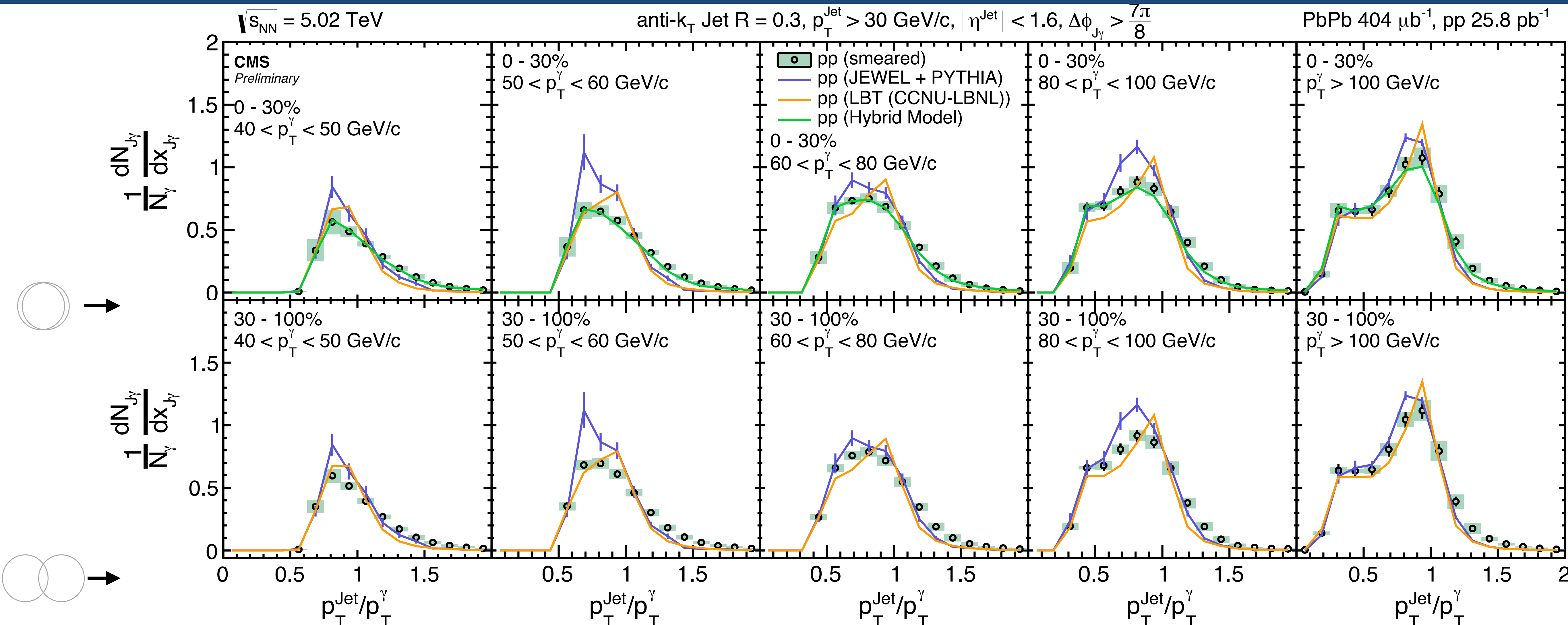
40 < p_T^γ < 50 **50 < p_T^γ < 60** **60 < p_T^γ < 80** **80 < p_T^γ < 100** **p_T^γ > 100**

- 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

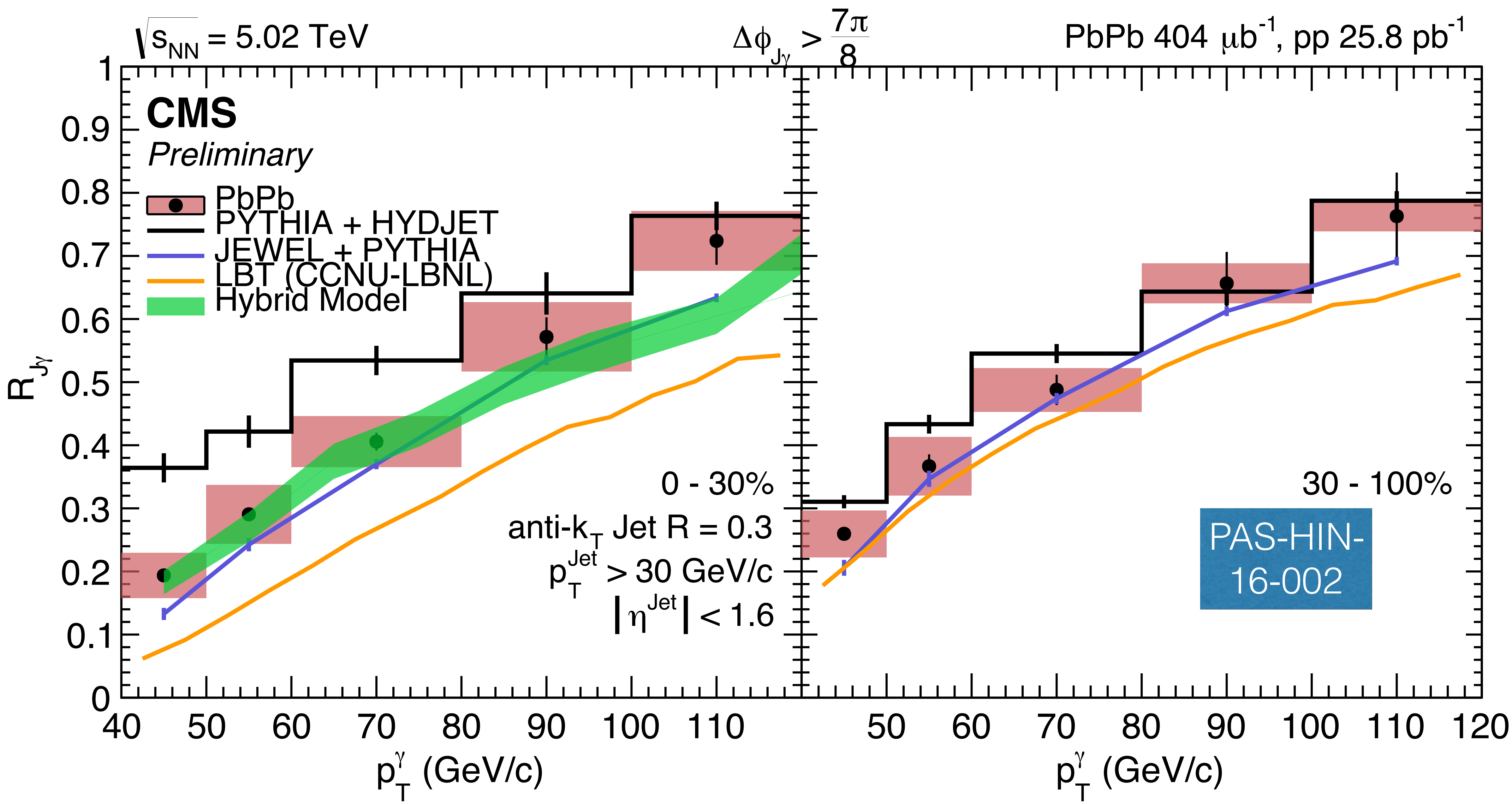


PAS-HIN-16-002

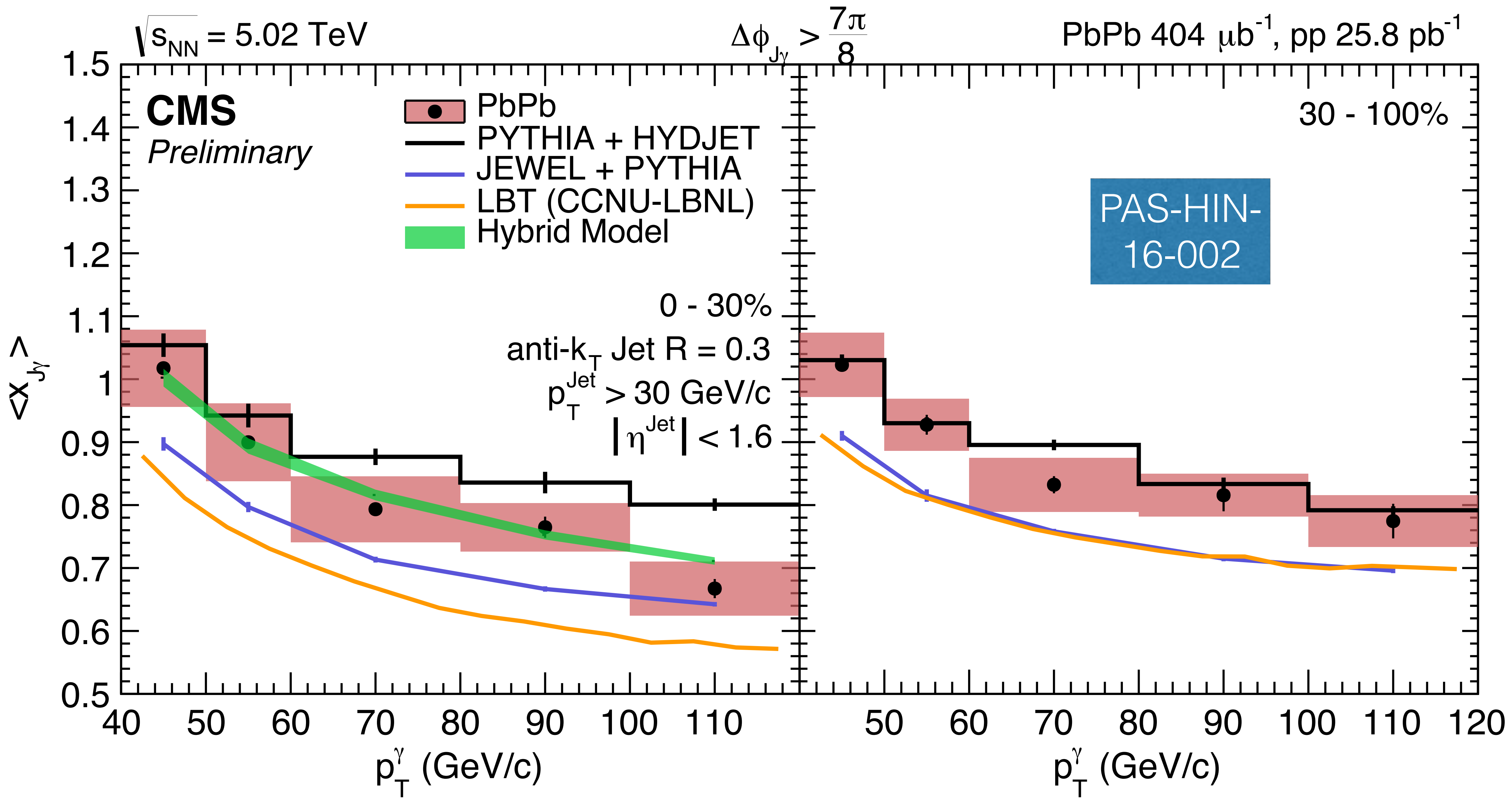
40 < p_T^γ < 50 | 50 < p_T^γ < 60 | 60 < p_T^γ < 80 | 80 < p_T^γ < 100 | p_T^γ > 100

- Overlaid PYTHIA, JEWEL, LBT and Hybrid Model

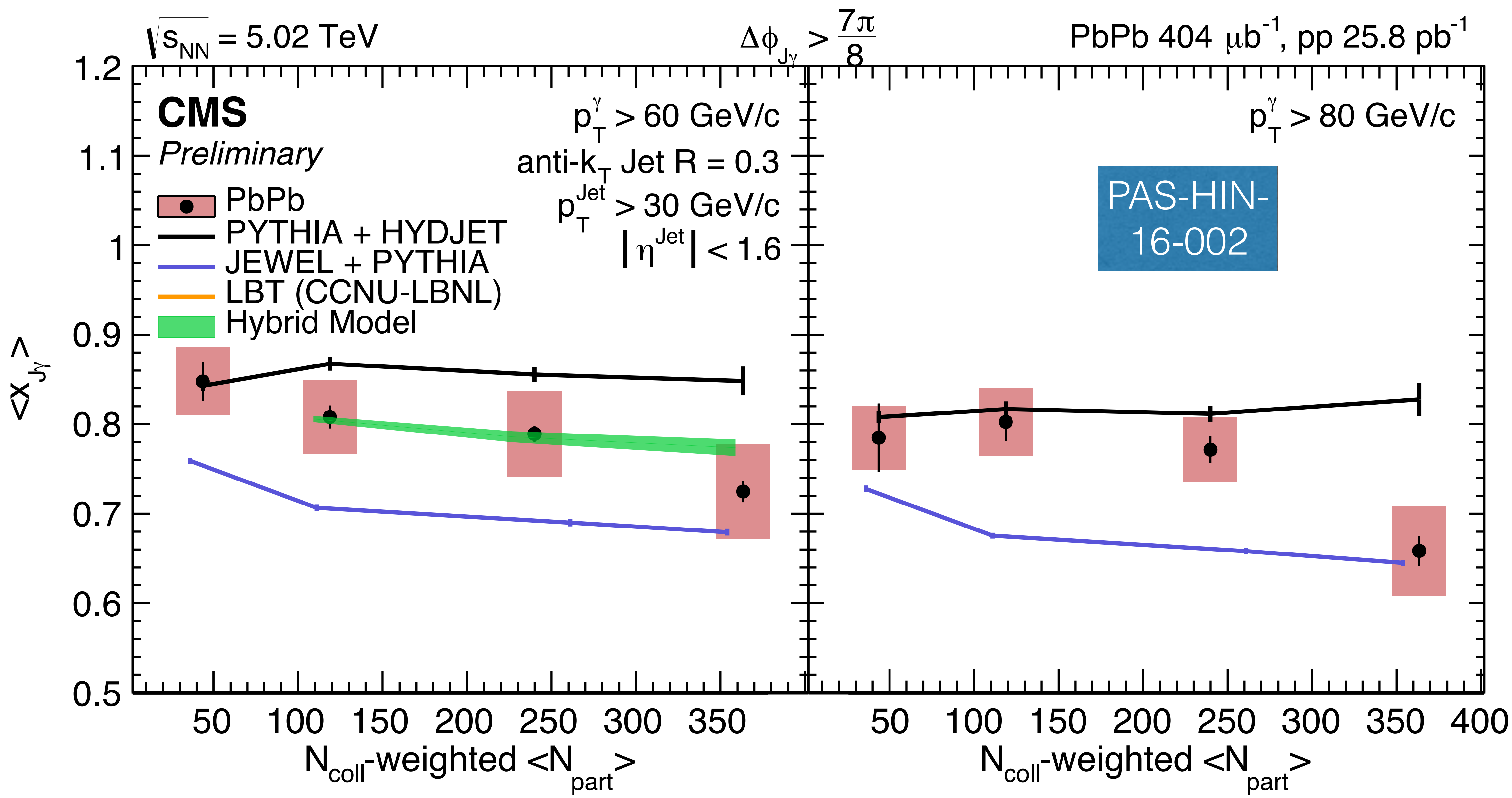
Theory Comparison: $R_{J\gamma}$ in PbPb



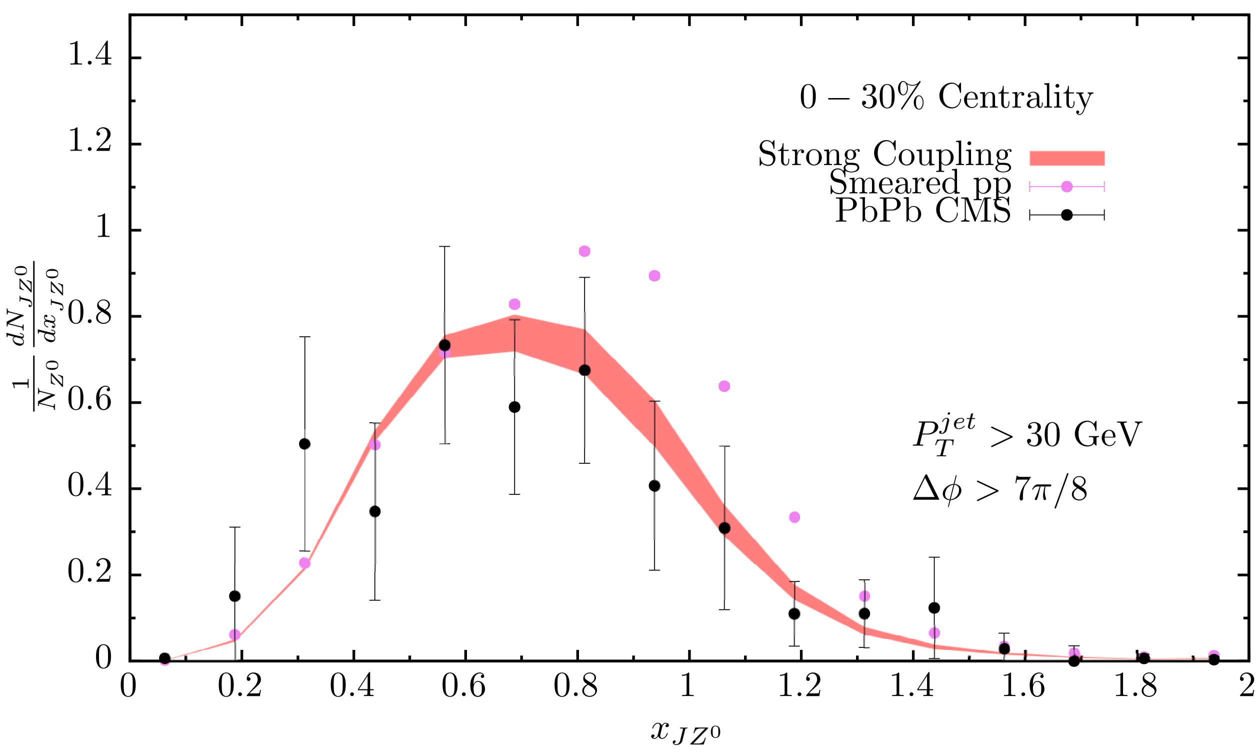
Theory Comparison: $x_{J\gamma}$ in PbPb

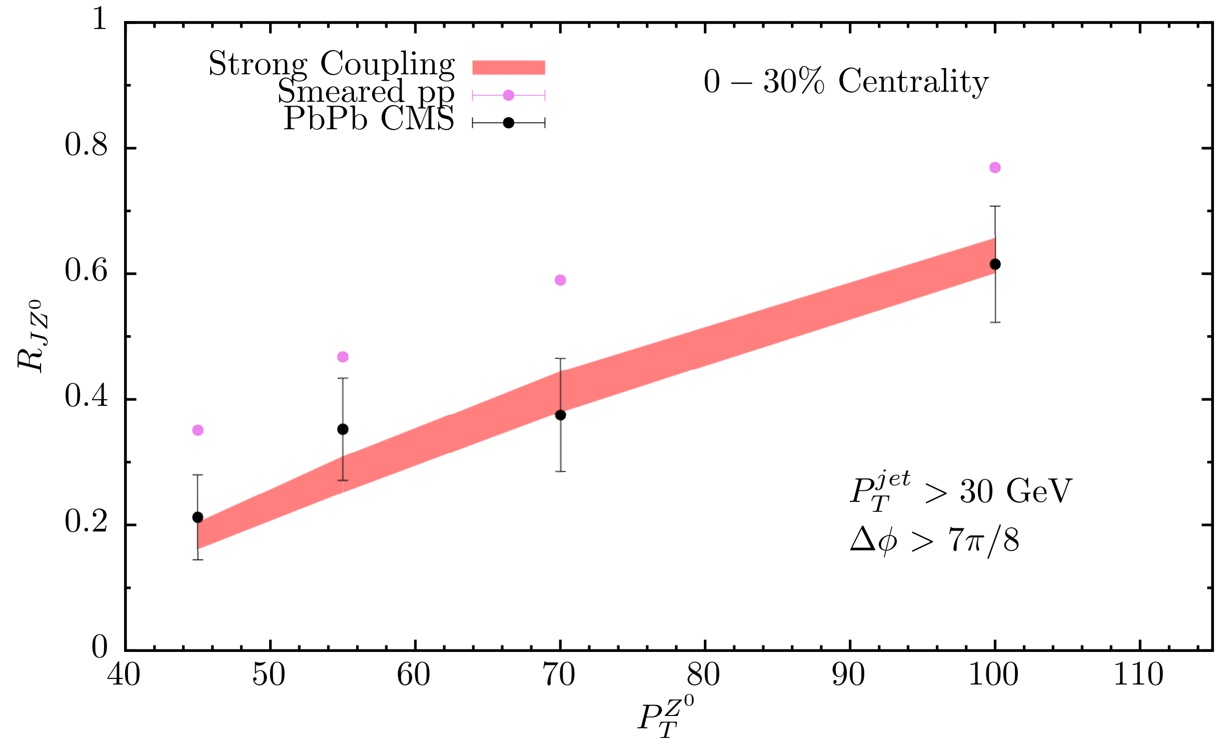


Theory Comparison: $x_{J\gamma}$ in PbPb



Z-Jet (5.02 ATeV)

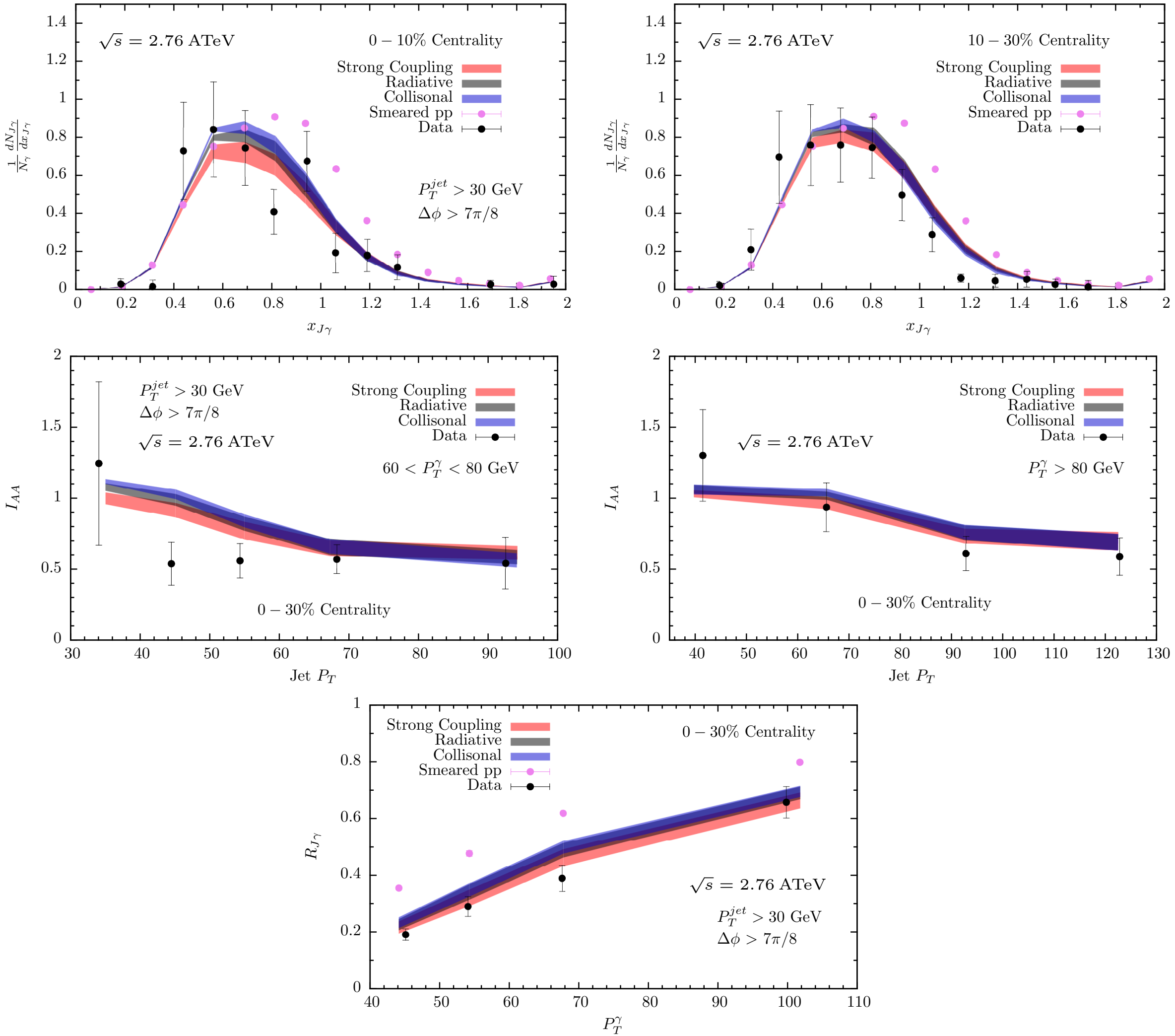




Preliminary CMS data just came out!

Where will we be soon?

- Coming soon from the hybrid model: R_{AA} for hadrons.
- We hope to see soon: 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 $dE/dx \propto T^3 x$.
- Well before 2020s: increasingly precise tests of the result that strongly coupled form for dE/dx, but with $x_{\text{therm}}^{\text{QCD}} \sim (3-4) x_{\text{therm}}^{\mathcal{N}=4}$ describes jet observables sensitive to parton energy loss.
- Well before 2020s: increasingly precise tests of weakly coupled approaches in which $dE/dx \propto T^2$ and/or $dE/dx \propto T^3 x$, albeit with values of coupling that aren't actually weak.
- Well before the 2020s: comparison between the above.
- This is all good. It is bringing us understanding. But it does not get us to the goal with which I began the talk, namely 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.



$\sqrt{s}$ = 2.76 ATeV
0 − 10% Centrality
Strong Coupling
Radiative
Collisonal
Smeared pp
Data
$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\frac{1}{N_\gamma}\frac{dN_{J\gamma}}{dx_{J\gamma}}$
$x_{J\gamma}$
$\sqrt{s}$ = 2.76 ATeV
10 − 30% Centrality
Strong Coupling
Radiative
Collisonal
Smeared pp
Data
$\frac{1}{N_\gamma}\frac{dN_{J\gamma}}{dx_{J\gamma}}$
$x_{J\gamma}$
$P_T^{jet} > 30$ GeV
$\Delta\phi > 7\pi/8$
$\sqrt{s}$ = 2.76 ATeV
Strong Coupling
Radiative
Collisonal
Data
$60 < P_T^\gamma < 80$ GeV
0 − 30% Centrality
I_{AA}
Jet P_T
Strong Coupling
Radiative
Collisonal
Data
$\sqrt{s}$ = 2.76 ATeV
$P_T^\gamma > 80$ GeV
0 − 30% Centrality
I_{AA}
Jet P_T
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$\sqrt{s}$ = 2.76 ATeV
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$\Delta\phi > 7\pi/8$
$R_{J\gamma}$
P_T^γ

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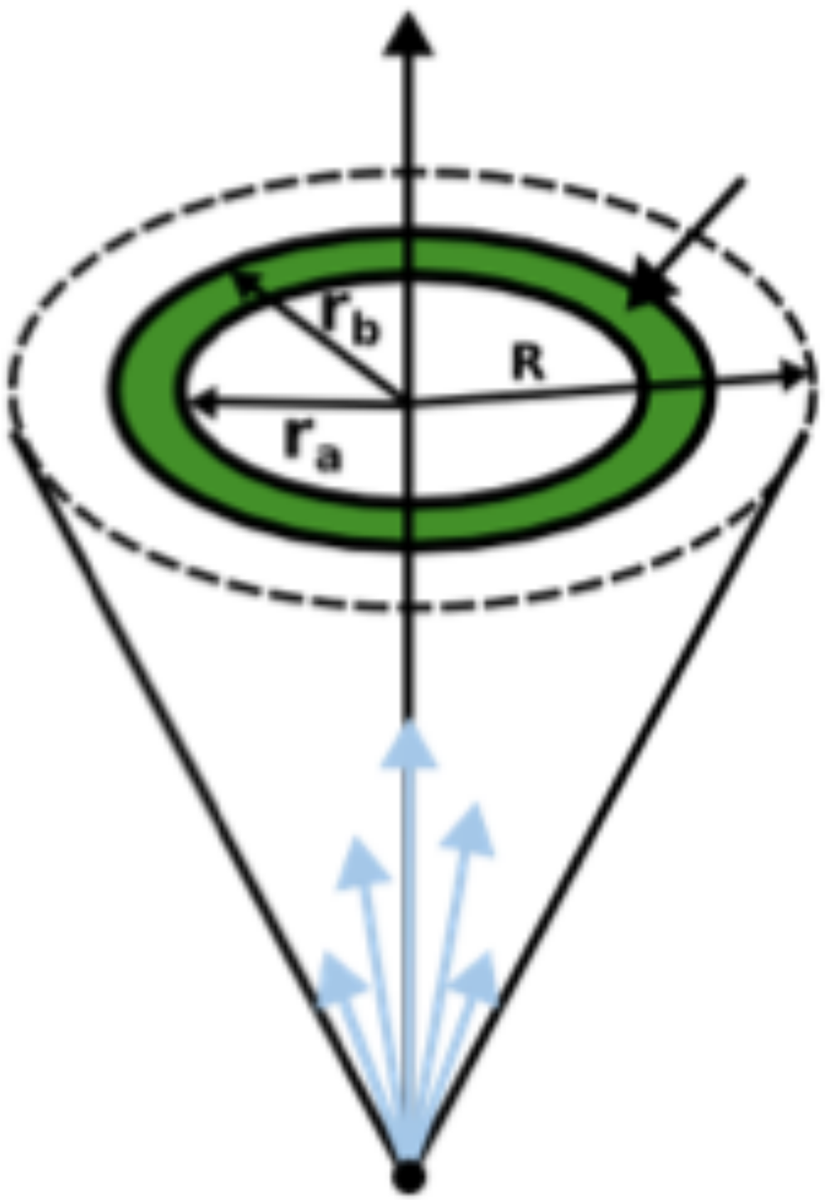
Modifications to Shape of Jets?

- 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 $KT^3 dx$, 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 $K < 20$.)

Jet Shapes

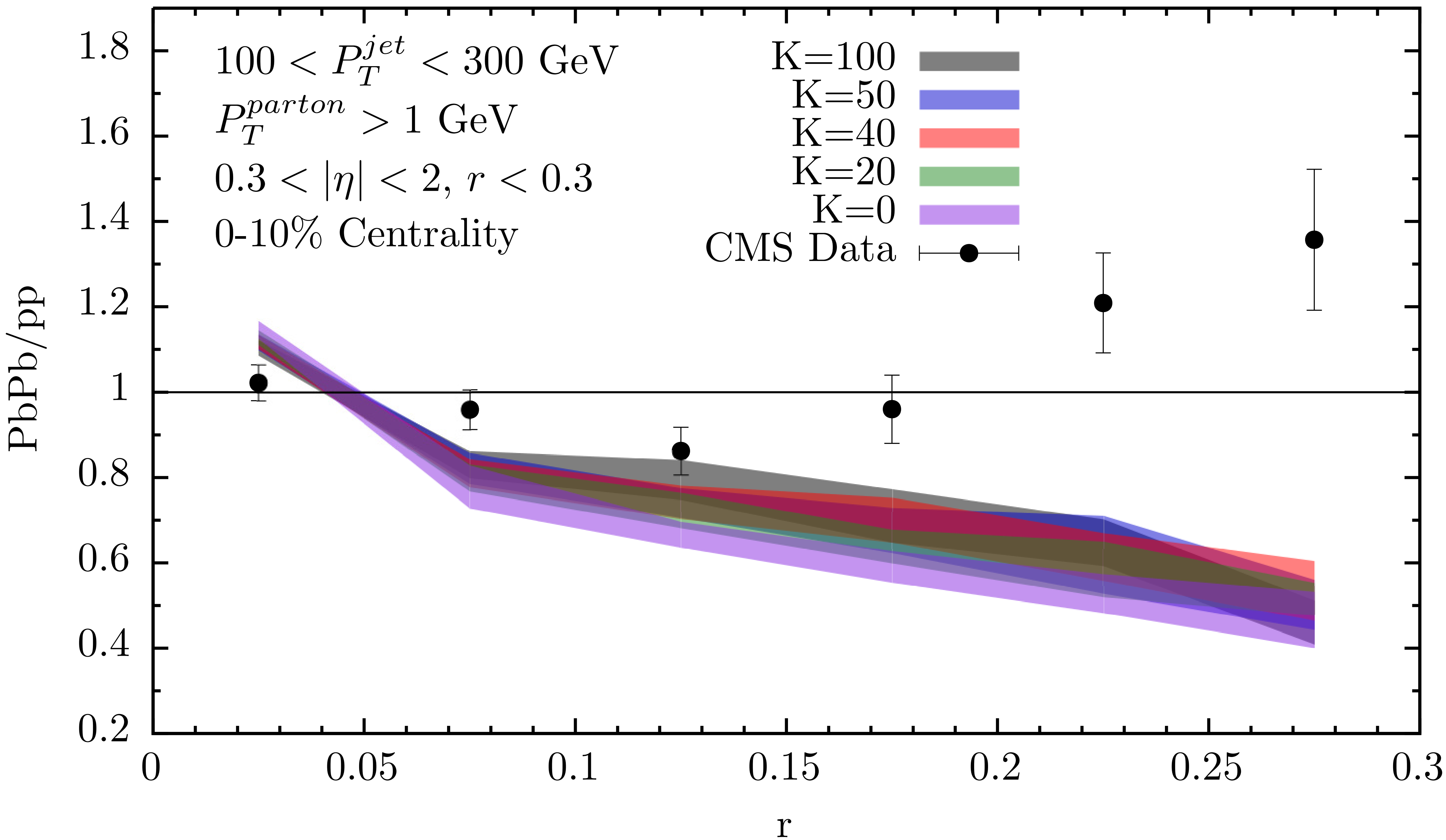


Transverse distribution of energy within the jet

Intra-jet observable robust to hadronization

$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N^{\mathrm{jet}}} \sum_{\mathrm{jets}} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)}$$

Small sensitivity of standard jet shapes to broadening



Small sensitivity of jet shapes to broadening:

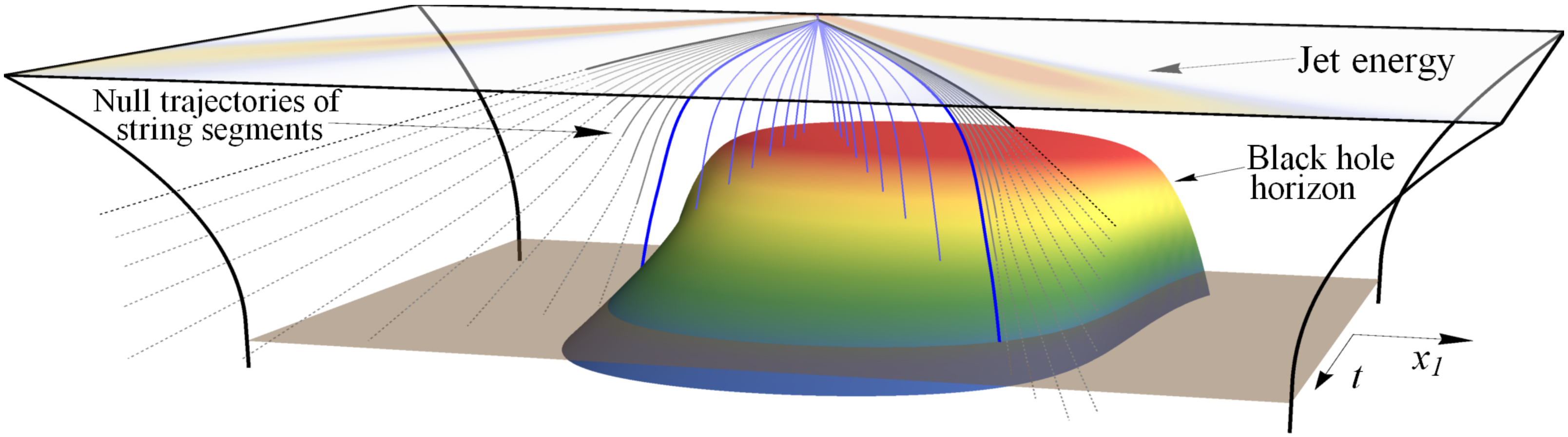
- strong quenching removes soft fragments that appear early
- remaining soft tracks fragment late

Modifications to Shape of Jets?

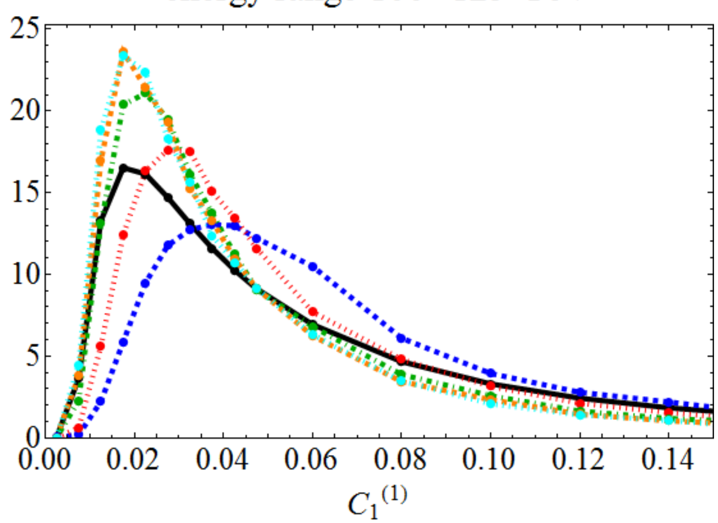
- Jets with a given energy seem to get narrower, as long as you look only at small r. In data, and in the hybrid model. Even when partons in the jets get strong transverse kicks. This narrowing is a consequence of energy loss. Jets with a given energy after quenching are narrower than those that had 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.)

Evolution of Jet Opening Angle Distribution

K. Rajagopal, A. Sadofyev, W. van der Schee, arxiv:1602.04187

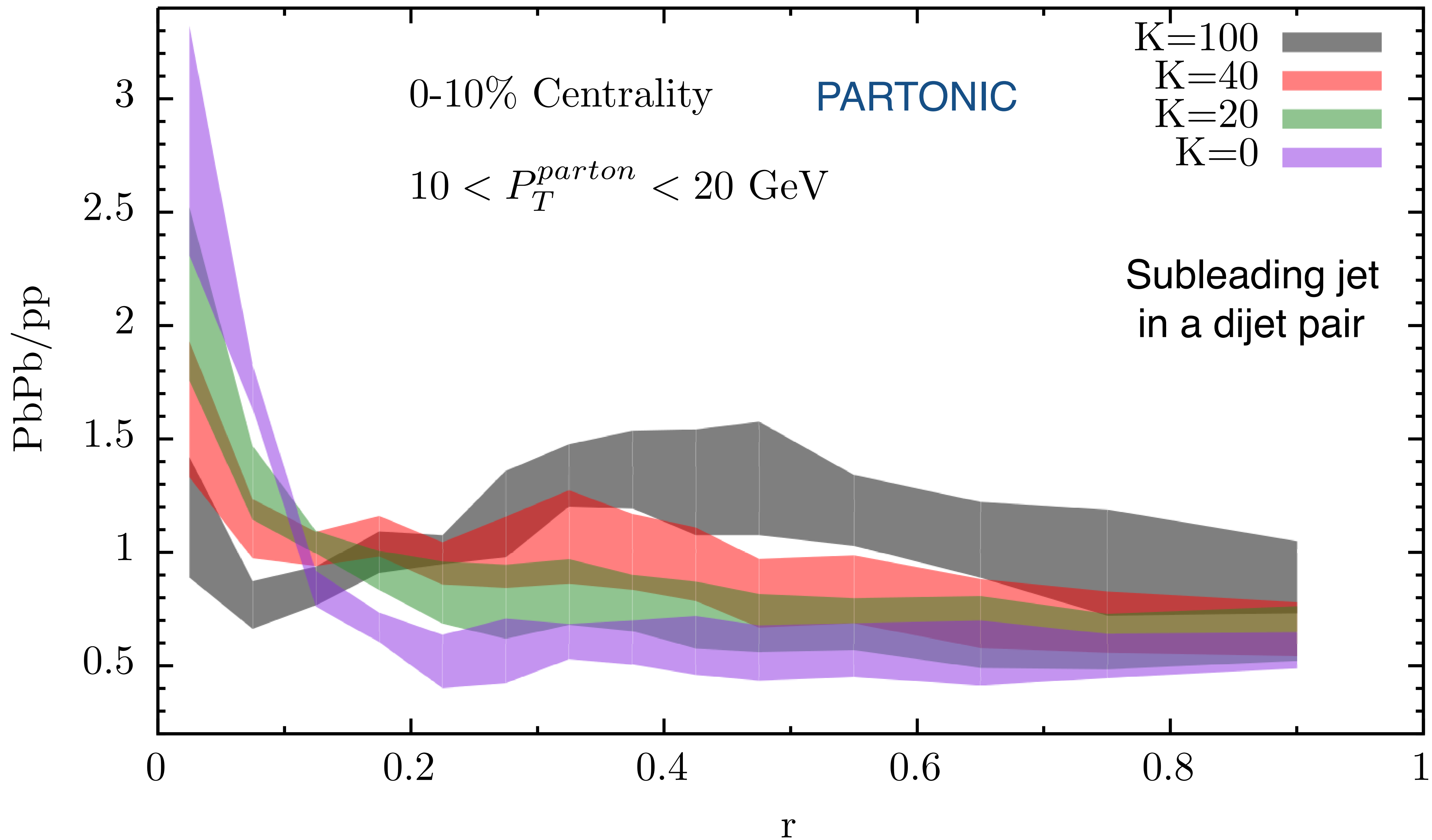


Holographic model for jet quenching. *Ensemble* **of ∼50,000 holographic jets, with initial energies** *and opening angles* **distributed as in pQCD, i.e. as in pp collisions. Send through expanding cooling droplet of plasma, see how distribution changes. Every jet in the ensemble broadens in angle.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



. . .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 CMS data indicate, even though opening angle of every jet in the ensemble increases.**

A New Observable, Sensitive to Broadening

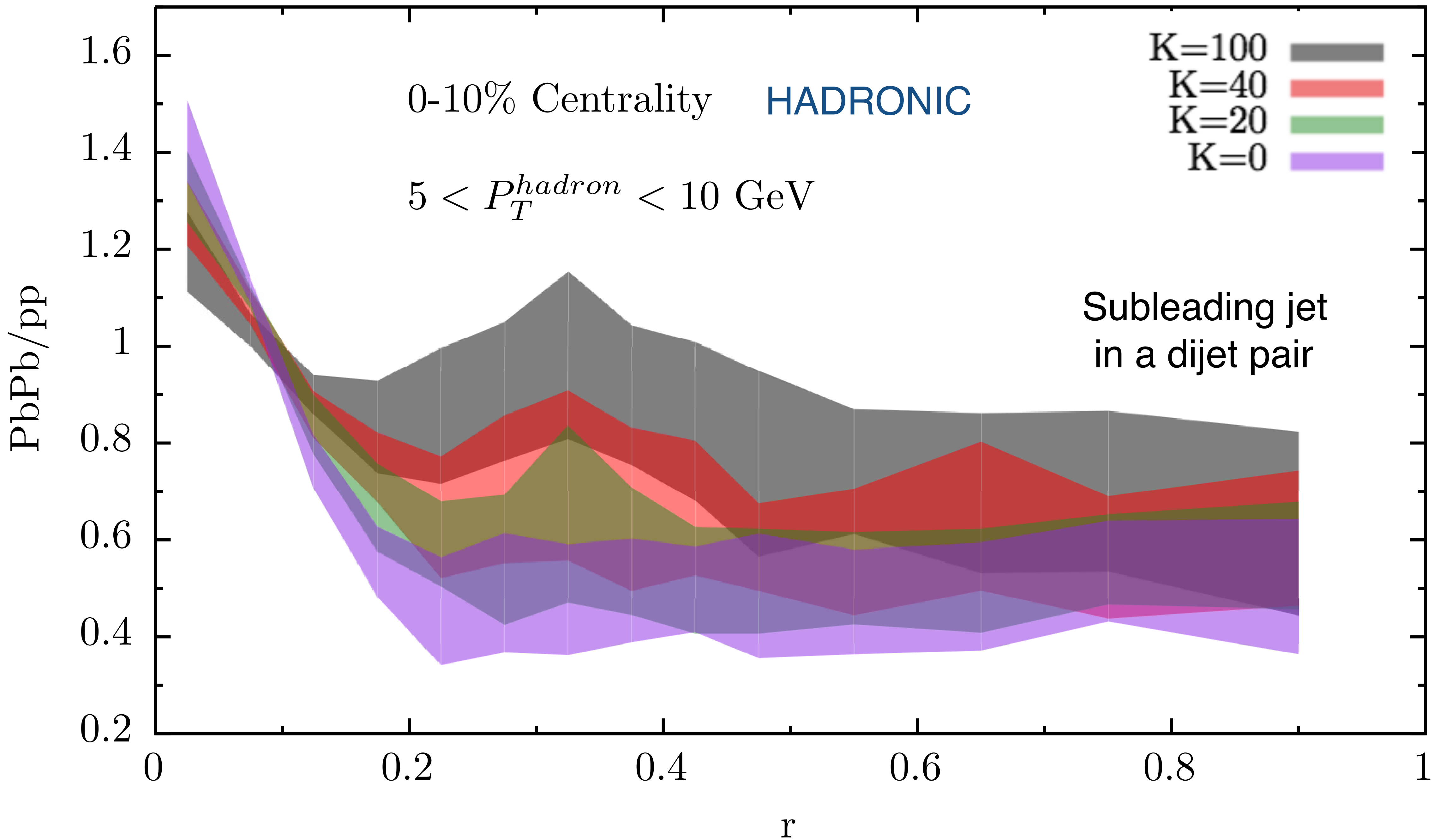


Kinematical cuts for partons chosen such that:

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

A New Observable, Sensitive to Broadening

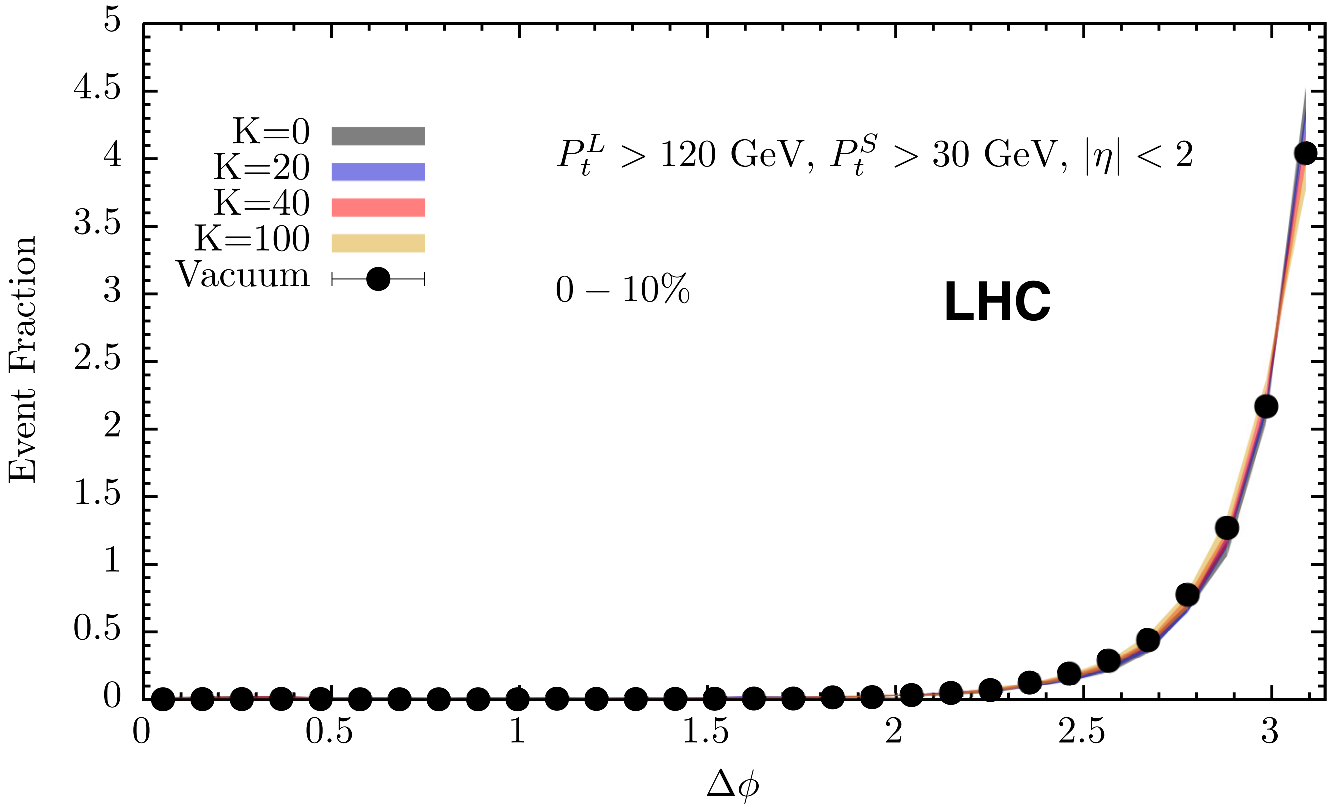
motivated by CMS analysis CMS-HIN-15-011

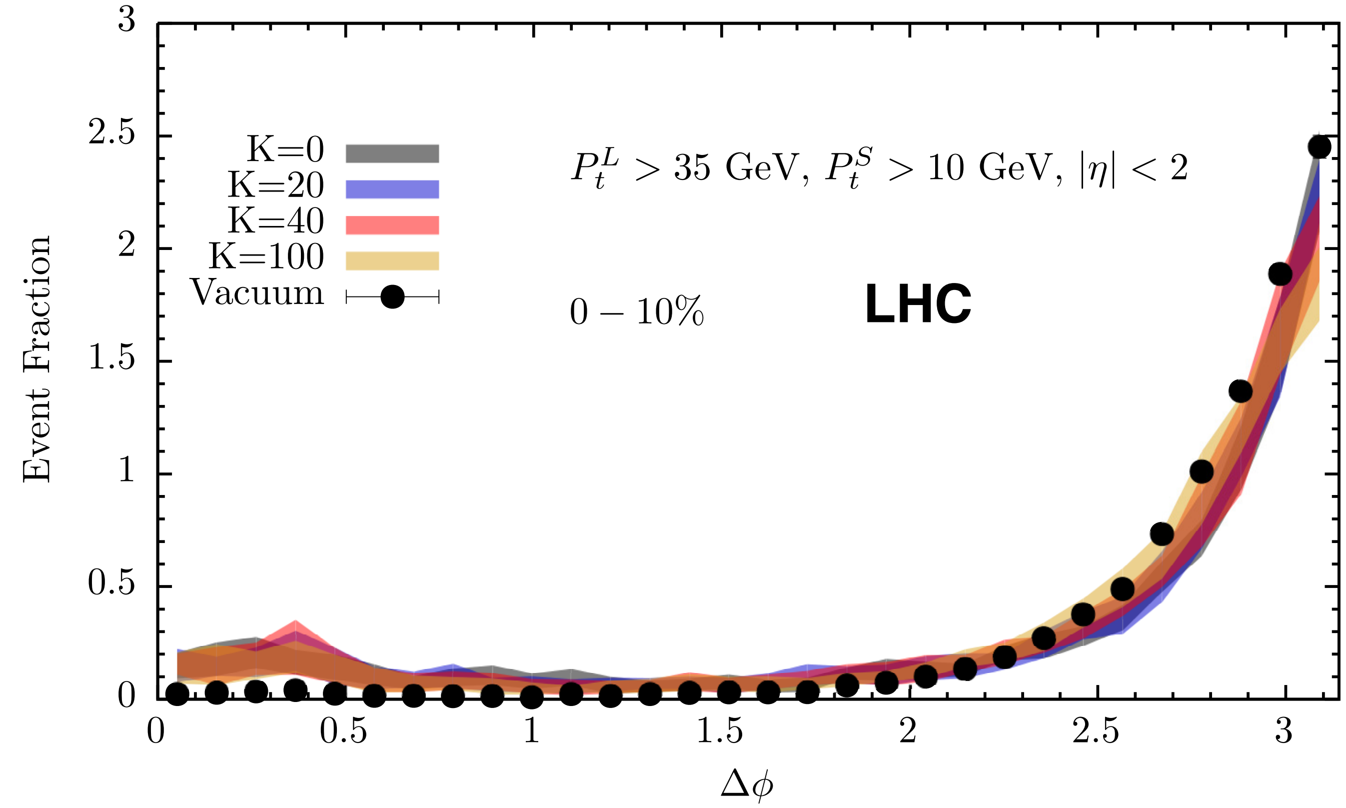


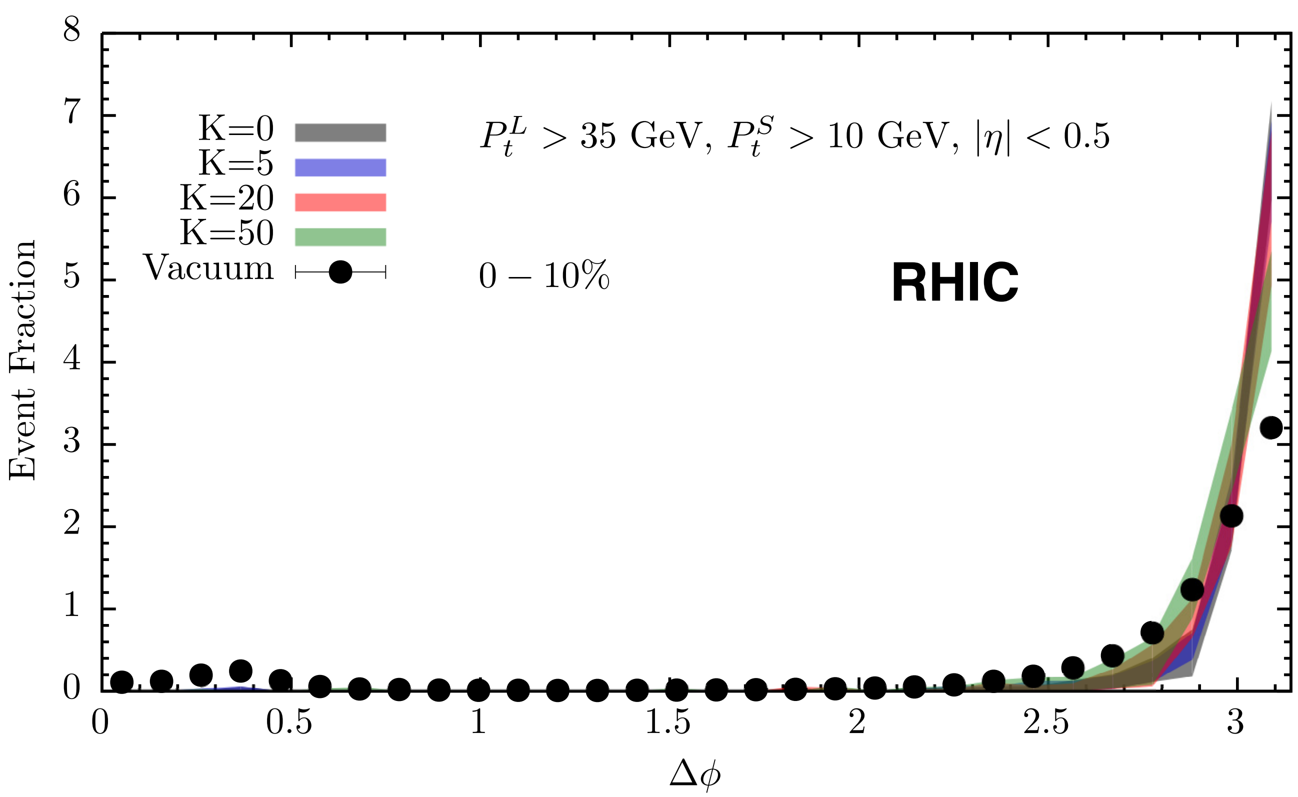
Hadrons with a given range of momenta
originate from partons with a wider range of momenta

Direct experimental determination of Gaussian broadening strength

Dijet Acoplanarities







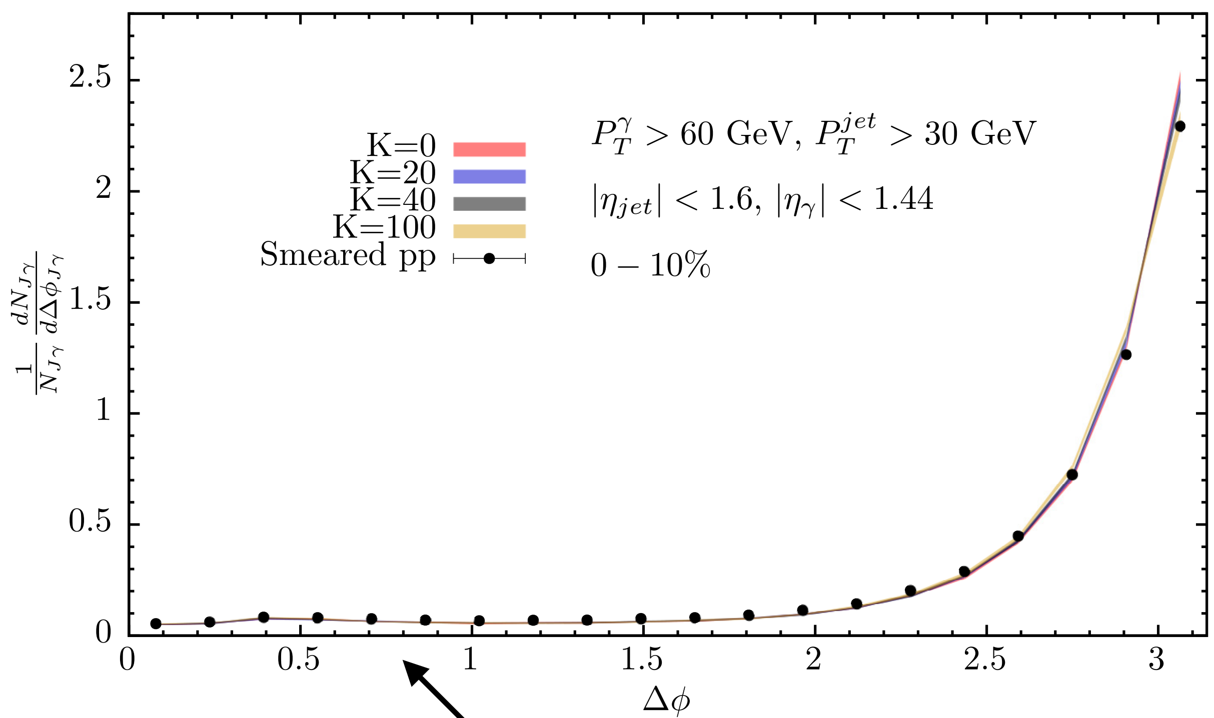
Higher energy jets are narrower: less acoplanar

Energy loss narrows the distributions, while broadening widens them back

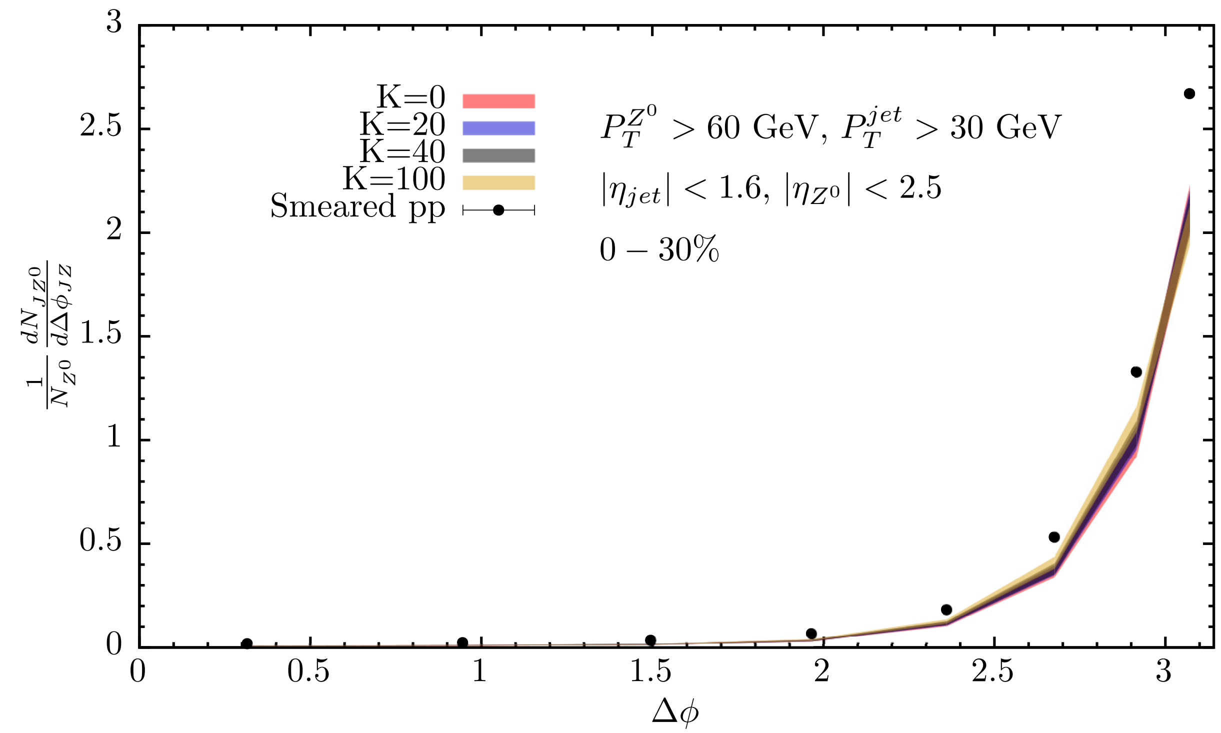
Effects strongest for lower energies due to more steeply falling spectrum

Boson Jet Acoplanarities

Photon Jet



Z Jet



frag. photon contamination

different normalisation

Photon Jet: over the number of photon jet pairs

Z Jet: over the number of Zs

more on Boson Jet observables in the Backup

Where will we be soon?

- Coming soon from the hybrid model: dijet and photon-jet acoplanarities (further evidence that energy loss yields narrower jets); jet mass (ditto, and more); z_g.
- Although it will clearly be a challenge, it seems plausible that 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?
- Am I being optimistic in thinking this a goal for $t < 2020$?

And, the 2020s?

- **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
- **In the 2020s, what will be interesting will be rare. In a sense event-by-event jet physics, although need not be literally so.**
- **In the 2020s, what will be interesting is deviations from the descendant of the hybrid model.**
- **So, what is the model missing that is important at larger r? The wake of the jet... And, resolution effects... In this regime, it is *already* the case that what is interesting is deviations from the hybrid model – at least as I have described it to this point. Need to add more physics...**

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. Introducing this effect will reduce the quenching of soft particles.** Hulcher, Pablos, KR 161n.nnnnn

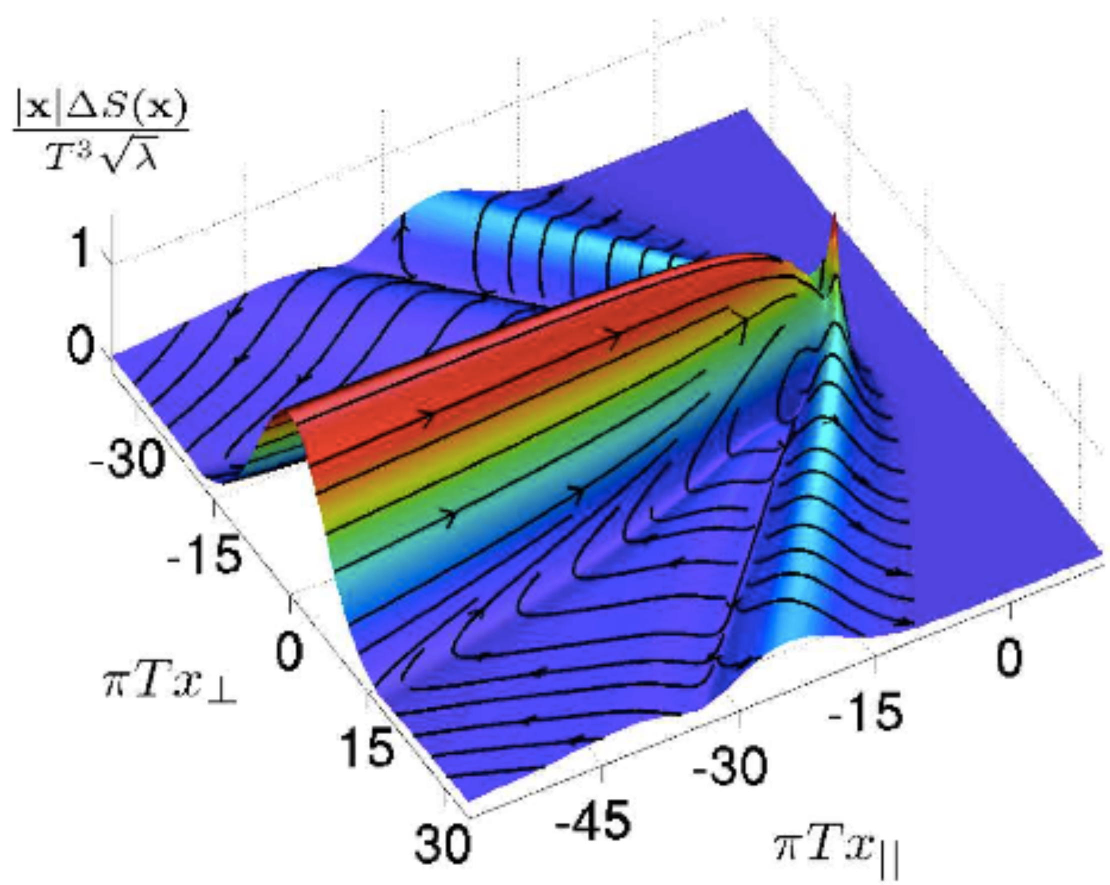
An Estimate of Backreaction

Hydro response to jet passage:

Assumption: small perturbation of hydro

Consequence:

- no details on the perturbation are needed
- distribution fully constrained by **energy-momentum conservation**
- no additional parameters



Chester and Yaffe 0712.0050

An Estimate of Backreaction

Perturbations on top of a Bjorken flow

$$\Delta P_{\perp}^{i} = w\tau \int d\eta \, d^2 x_{\perp} \, \delta u_{\perp}^{i}$$

$$\Delta P^{\eta} = 0$$

$$\Delta S = \tau c_s^{-2} s \int d\eta \, d^2 x_{\perp} \, \frac{\delta T}{T}$$

$$c_s^2 = \frac{s}{T} \frac{dT}{ds}$$

Cooper-Frye $$E\frac{dN}{d^3p} = \frac{1}{(2\pi)^3} \int d\sigma^{\mu} p_{\mu} f(u^{\mu} p_{\mu})$$

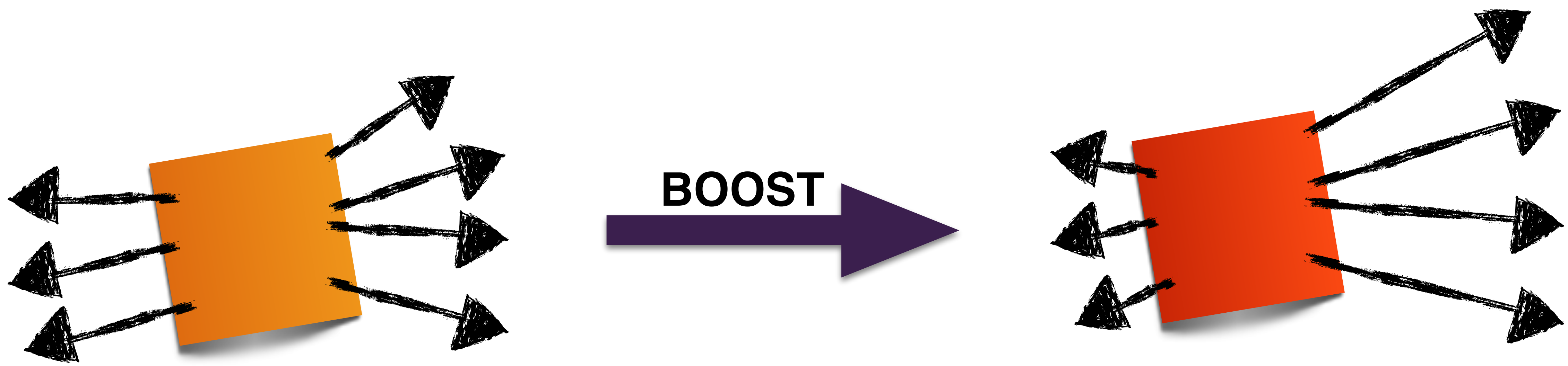
One body distribution

$$E\frac{dN}{d^3p} = \frac{1}{32\pi} \frac{m_T}{T^5} \cosh(y - y_j) e^{-\frac{m_T}{T}\cosh(y-y_j)}$$

$$\left[p_T \Delta P_T \cos(\phi - \phi_j) + \frac{1}{3} m_T \Delta M_T \cosh(y - y_j)\right]$$

An Estimate of Backreaction

One body distribution has negative contributions at large azimuthal separation



Background diminished w.r.t unperturbed hydro for that region in space

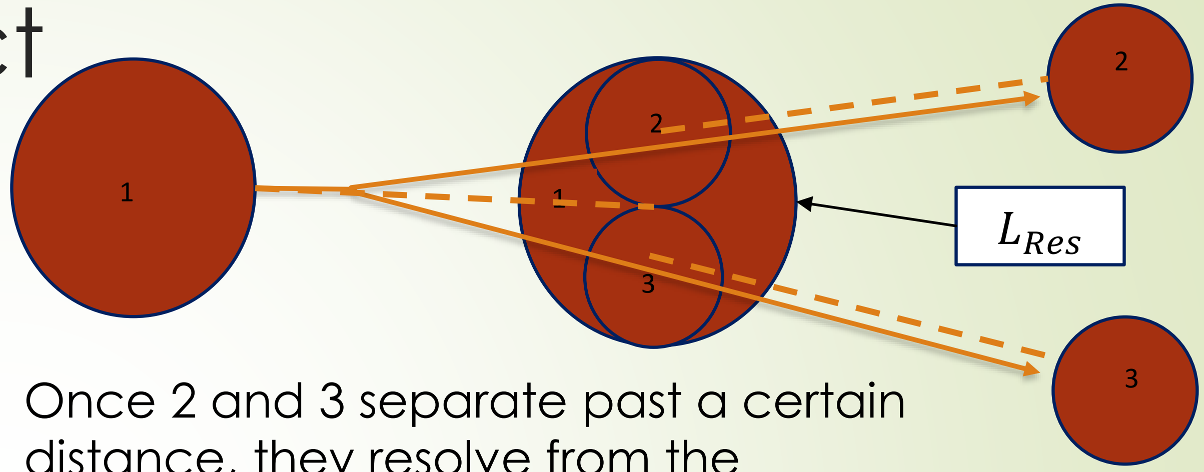
Need to emulate experimental background subtraction

Add background,
embed jets,
subtract background

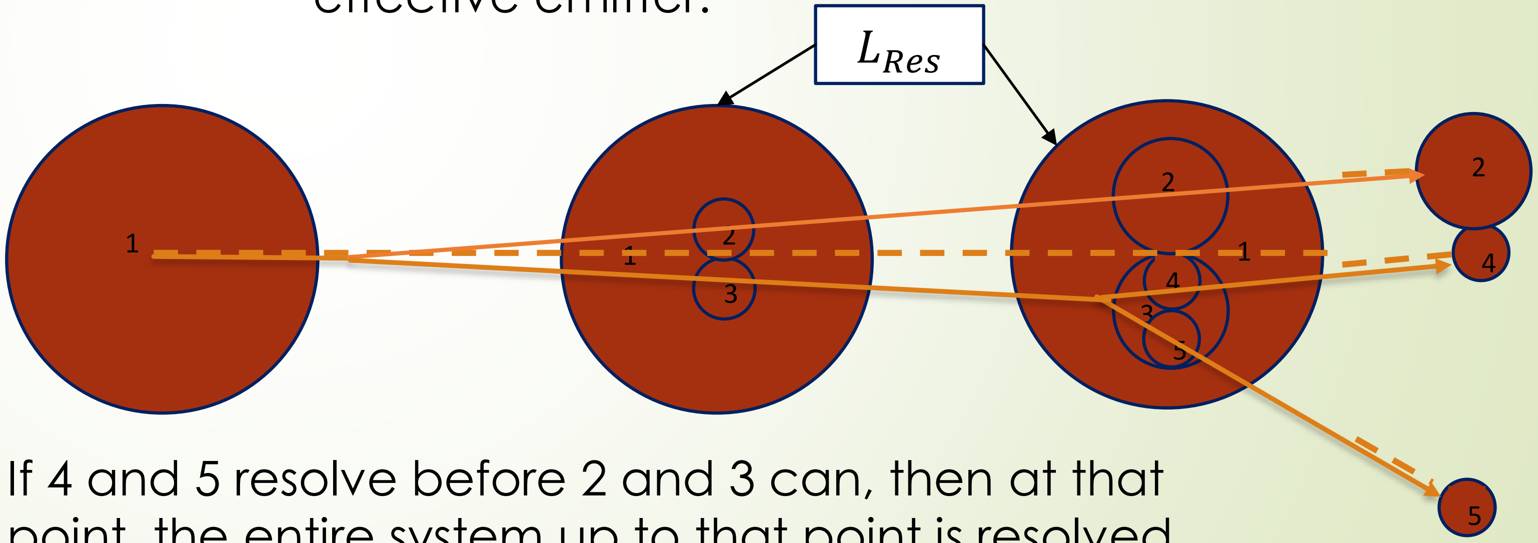
Event by event, determine the extra particles distribution enforcing energy/momentum conservation via Metropolis algorithm

Resolution Effect

- The Quark Gluon Plasma cannot resolve sister partons from their mother until they are separated by a certain distance, L_{Res}.
- If any of the daughters or granddaughters etc. of a particle resolve before that particle, that particle must resolve at that time.



Once 2 and 3 separate past a certain distance, they resolve from the effective emitter.



If 4 and 5 resolve before 2 and 3 can, then at that point, the entire system up to that point is resolved.

Resolution Distance, L_{Res}

- We expect L_{Res} in a certain region to be comparable to the Debye length or the screening length for charges at that part of the plasma.

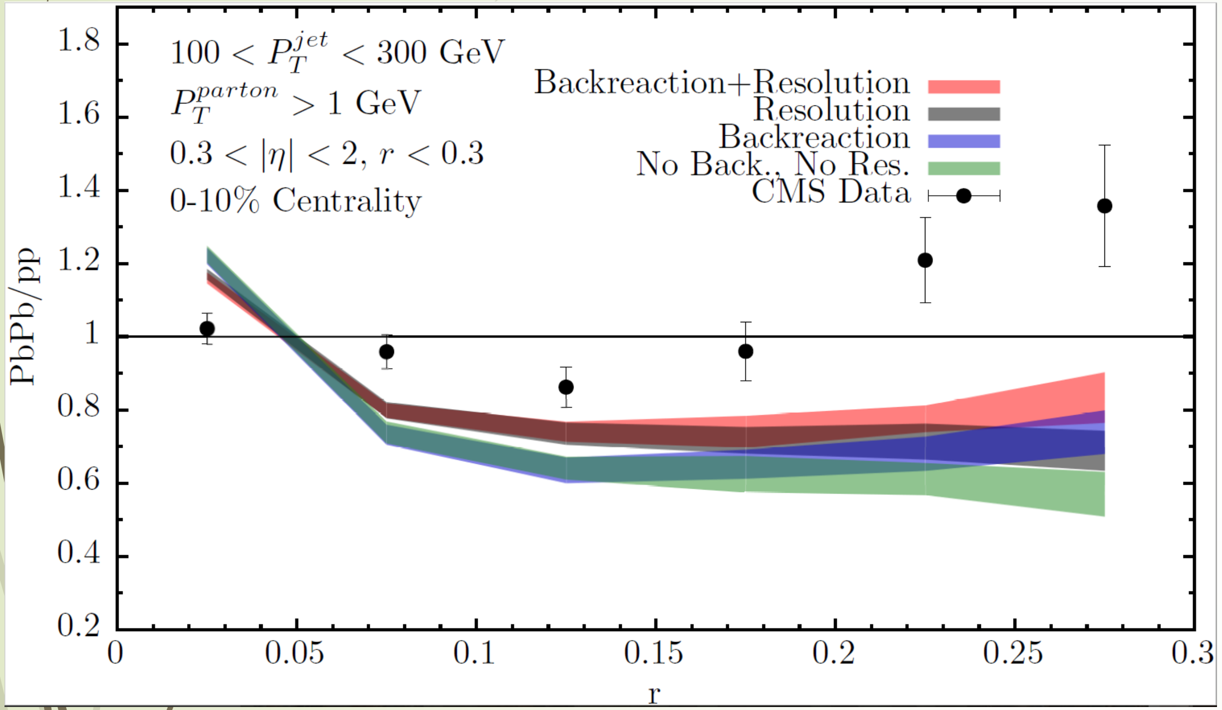
$$L_{Res} \approx \lambda_D$$

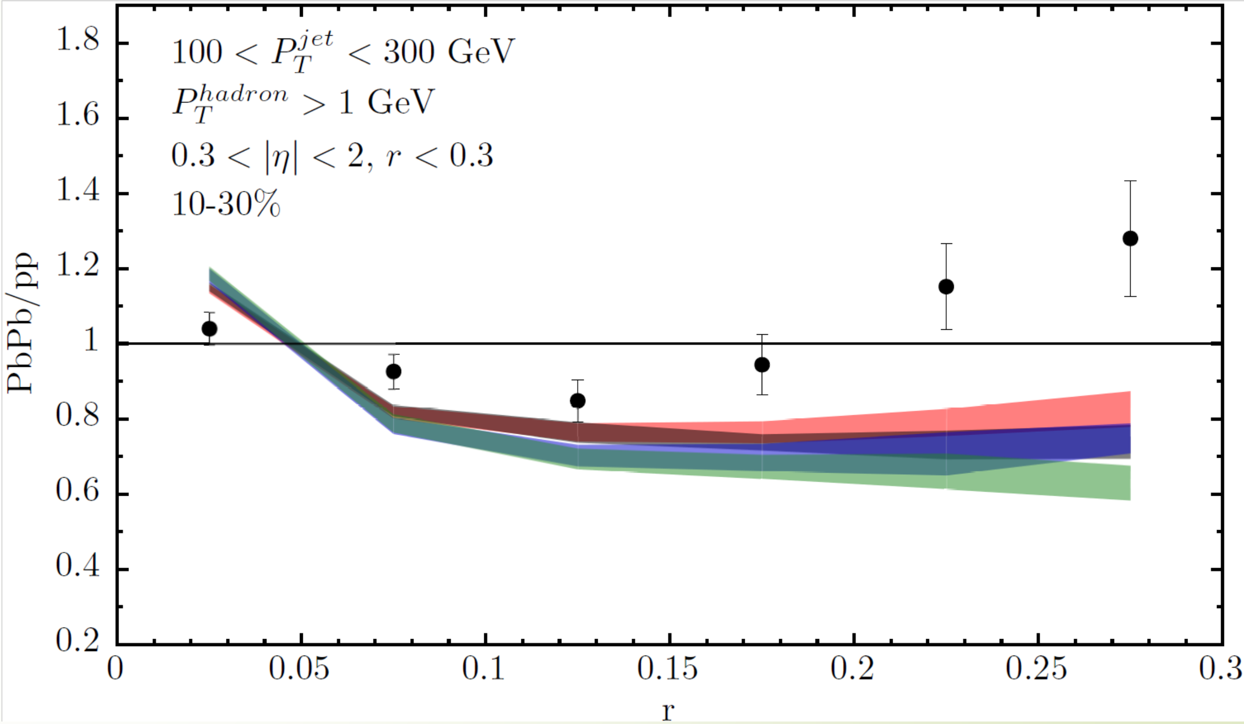
- We can use estimates of λ_D in the strong and weak coupling limits.

- In the weak coupling regime, $\lambda_D \approx \frac{2.6}{g\pi T}$, and $\alpha_{QCD} \approx \frac{1}{3} \Rightarrow g \approx 2$
- With strong coupling, AdS/CFT calculations in [Bak, Karch, Yaffe 2007] yield that $\lambda_D \approx \frac{.3}{\pi T}$, but correcting for extra degrees of freedom, λ_D in QCD at strong coupling must be larger than this.

- We chose $\lambda_D \approx \frac{1}{\pi T}$ as a start, with $\lambda_D \approx \frac{1}{2\pi T}$ and $\lambda_D \approx \frac{2}{\pi T}$ as further exploratory values.

Hadronic Shapes at $L_{Res} = \frac{1}{\pi T}$



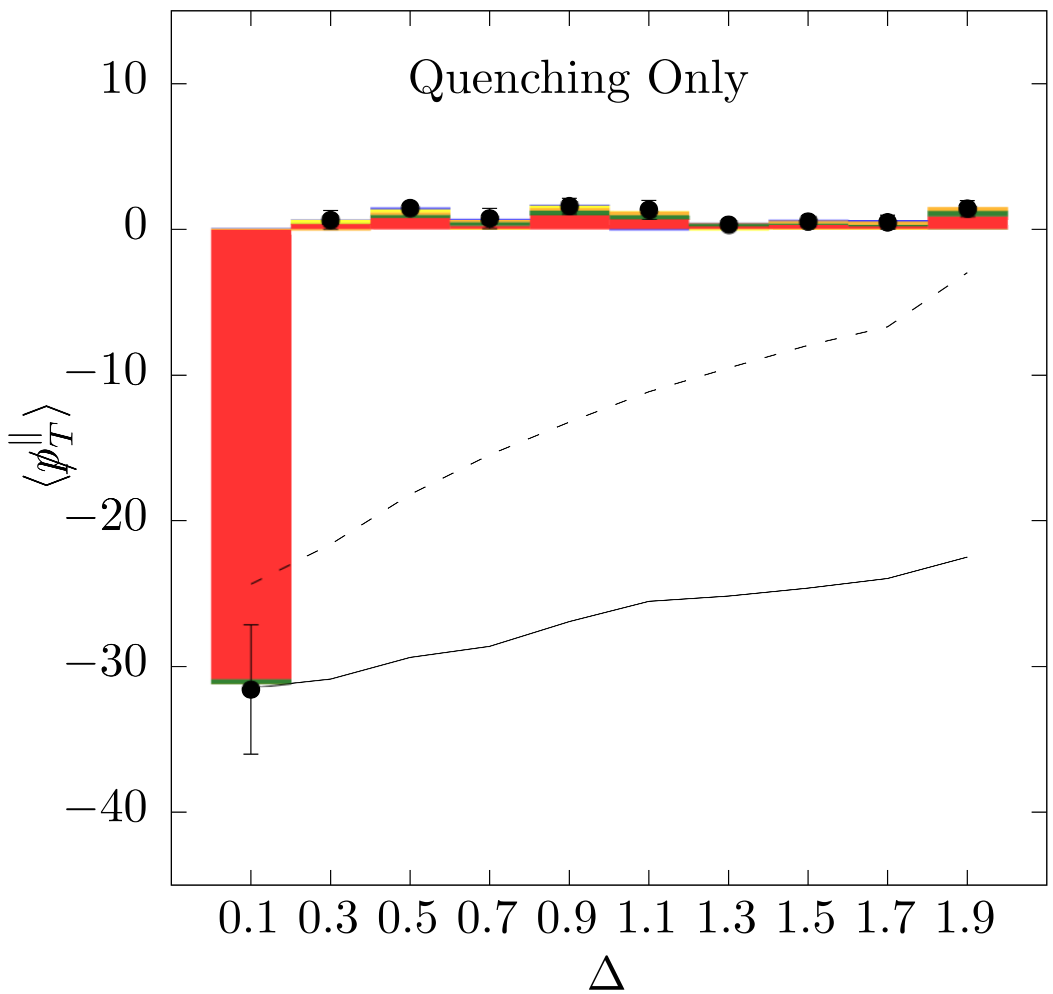


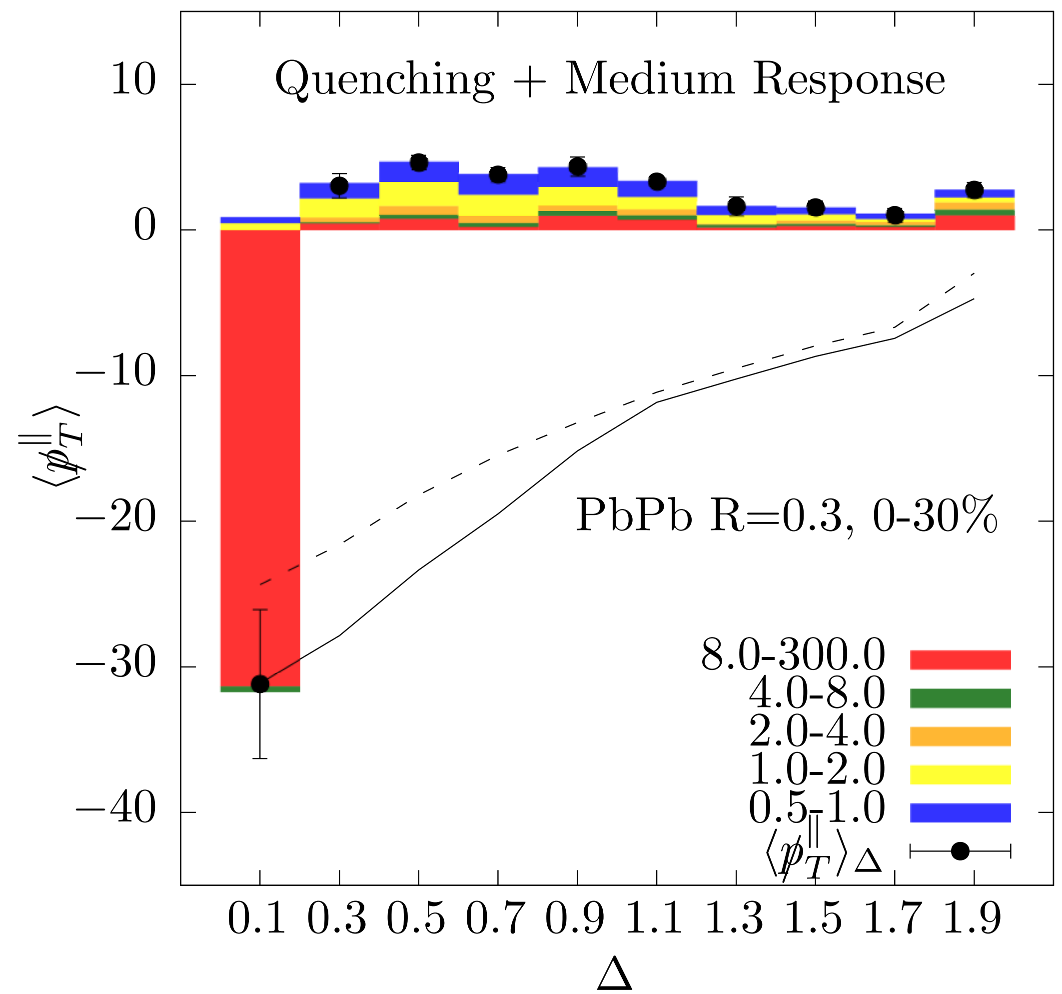
- Resolution effects for hadronized Jet Shapes shows the same behavior as for partonic Jet Shapes
- The middle of the curve lifts as the later softer particles at large angles are hidden and quenched for reduced periods of time
- The left part of the curve dips as the hard particles are relatively unchanged, but they make up less of the energy fraction of the jet

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...

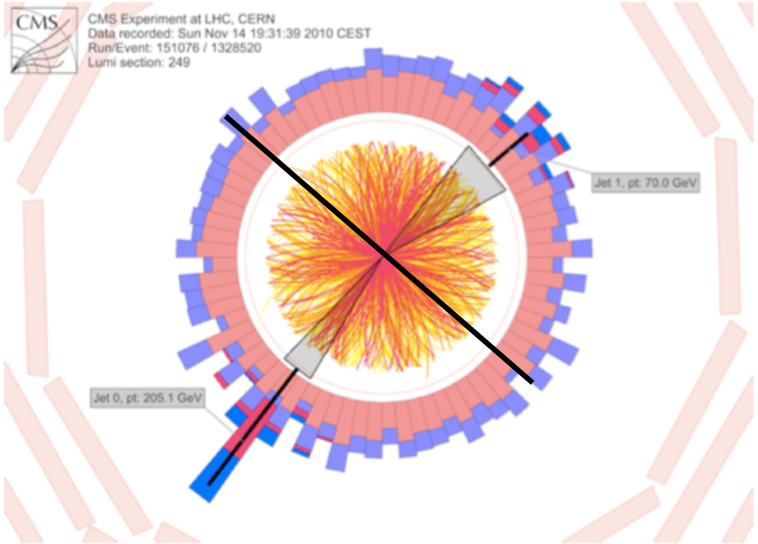
Recovering Lost Energy: Missing Pt





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

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



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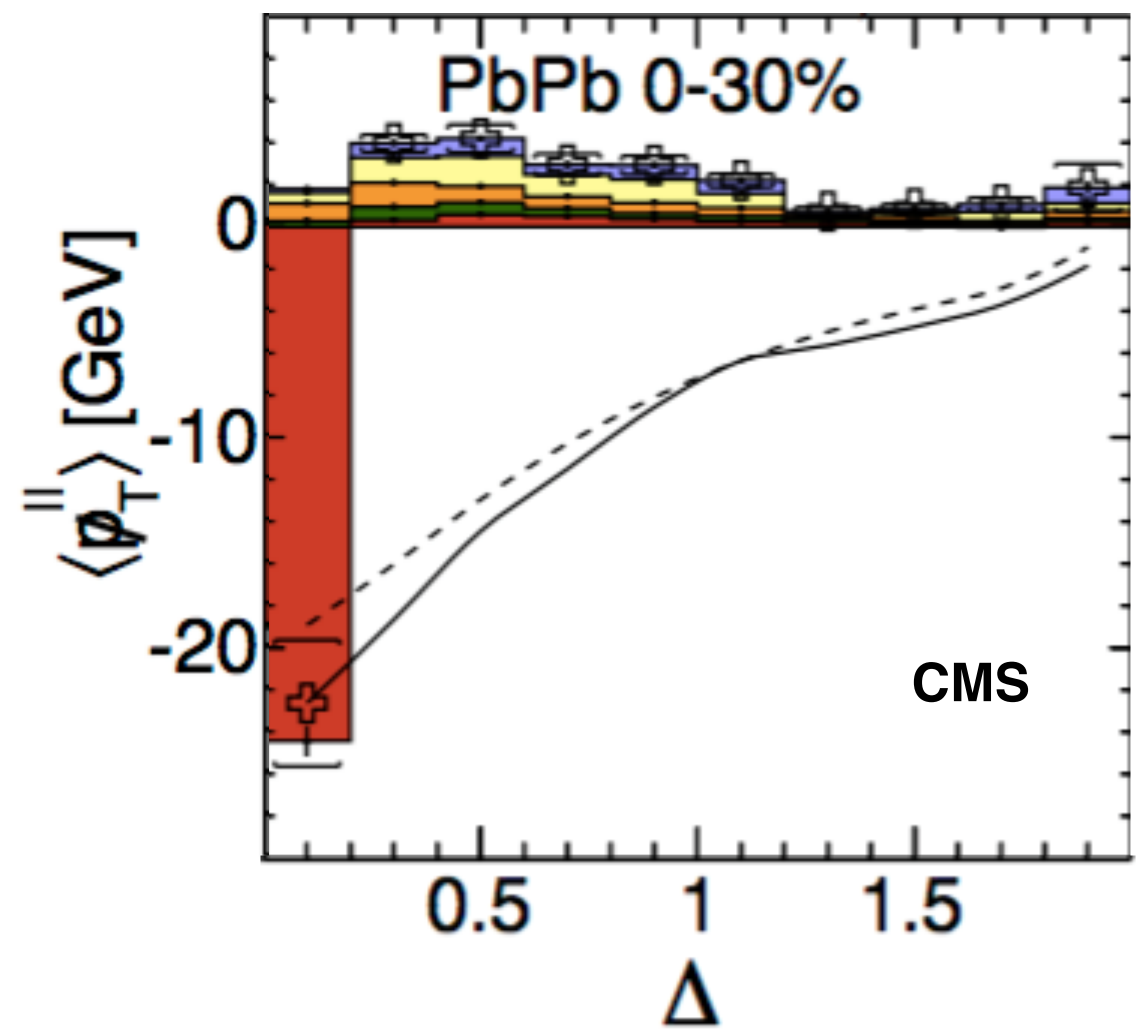

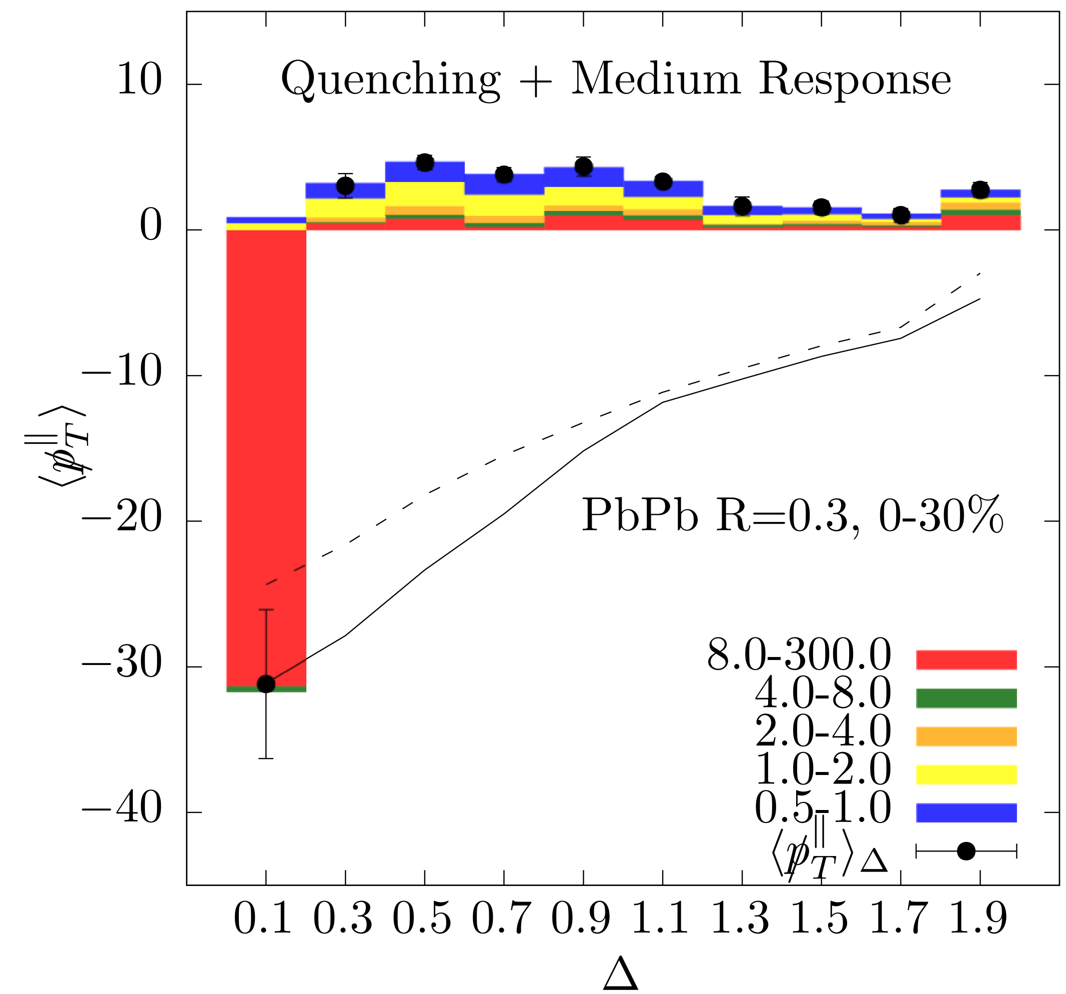

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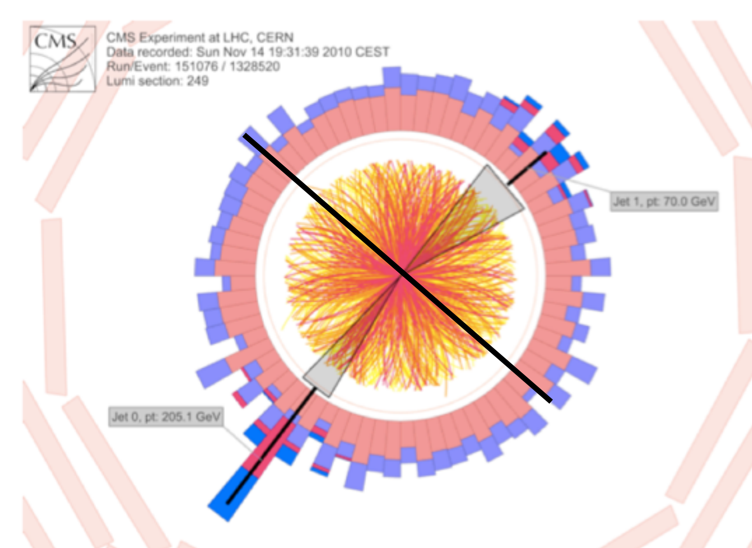
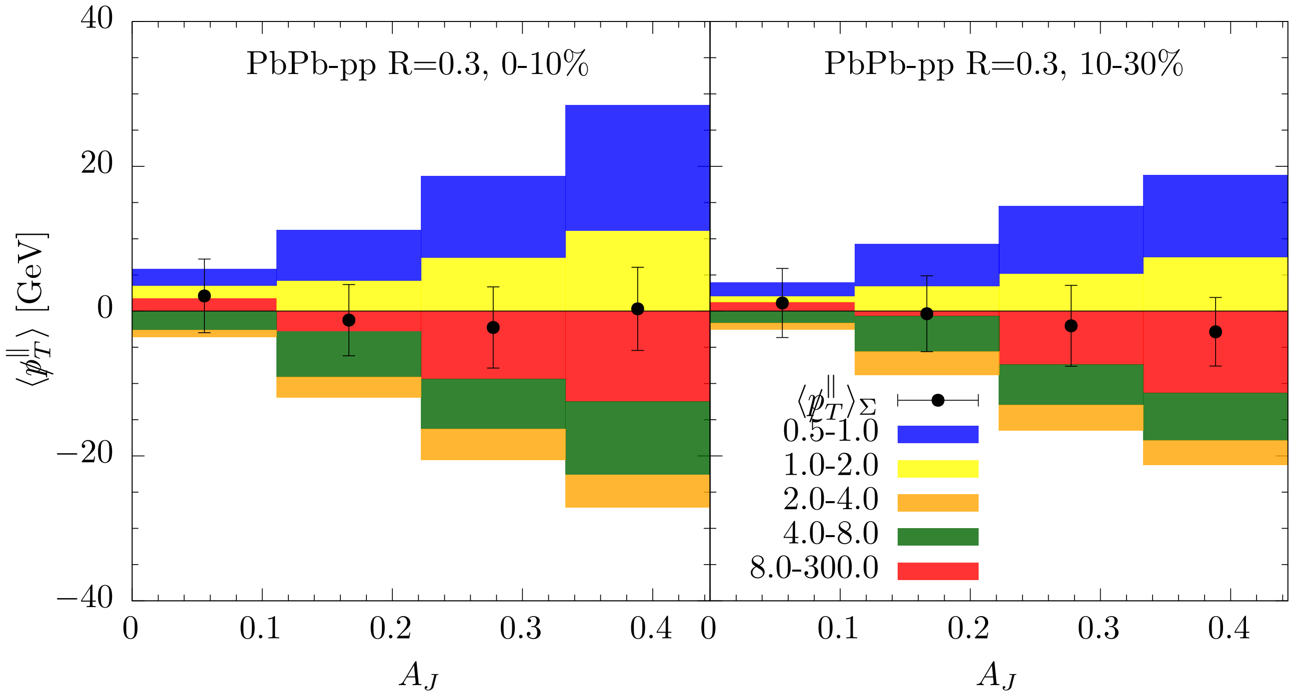
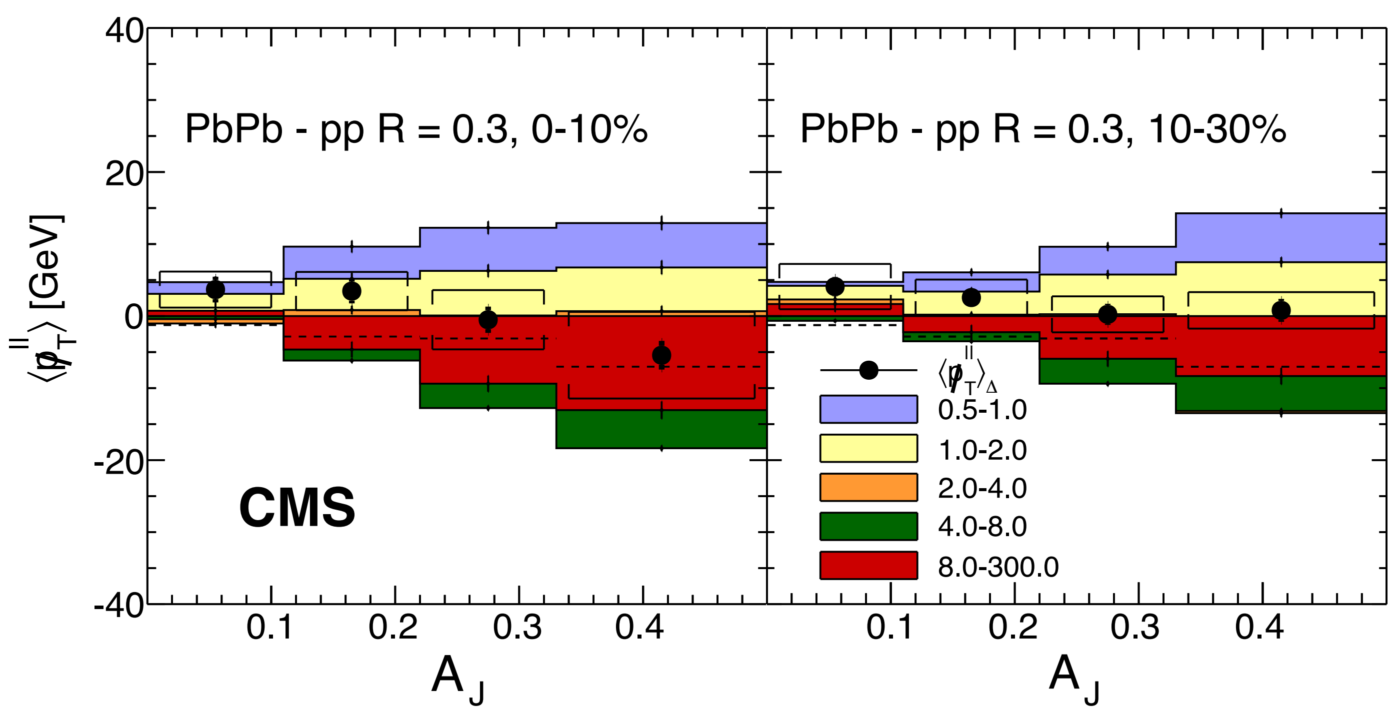


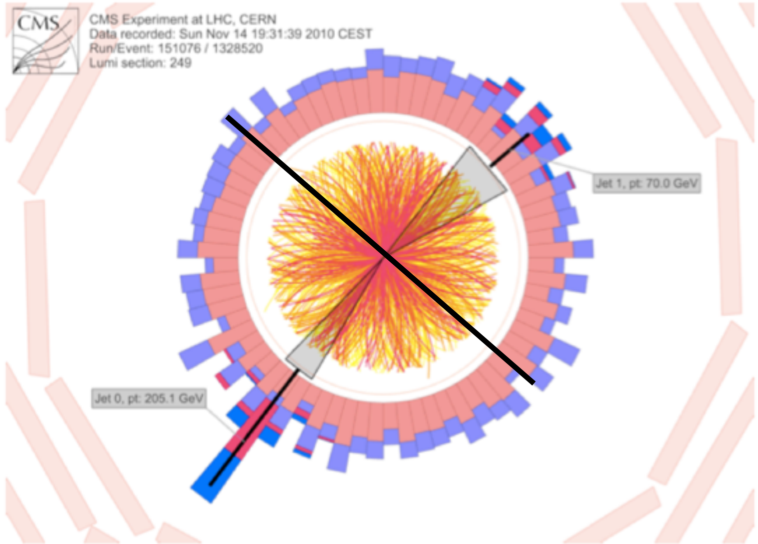
Recovering Lost Energy: Missing Pt



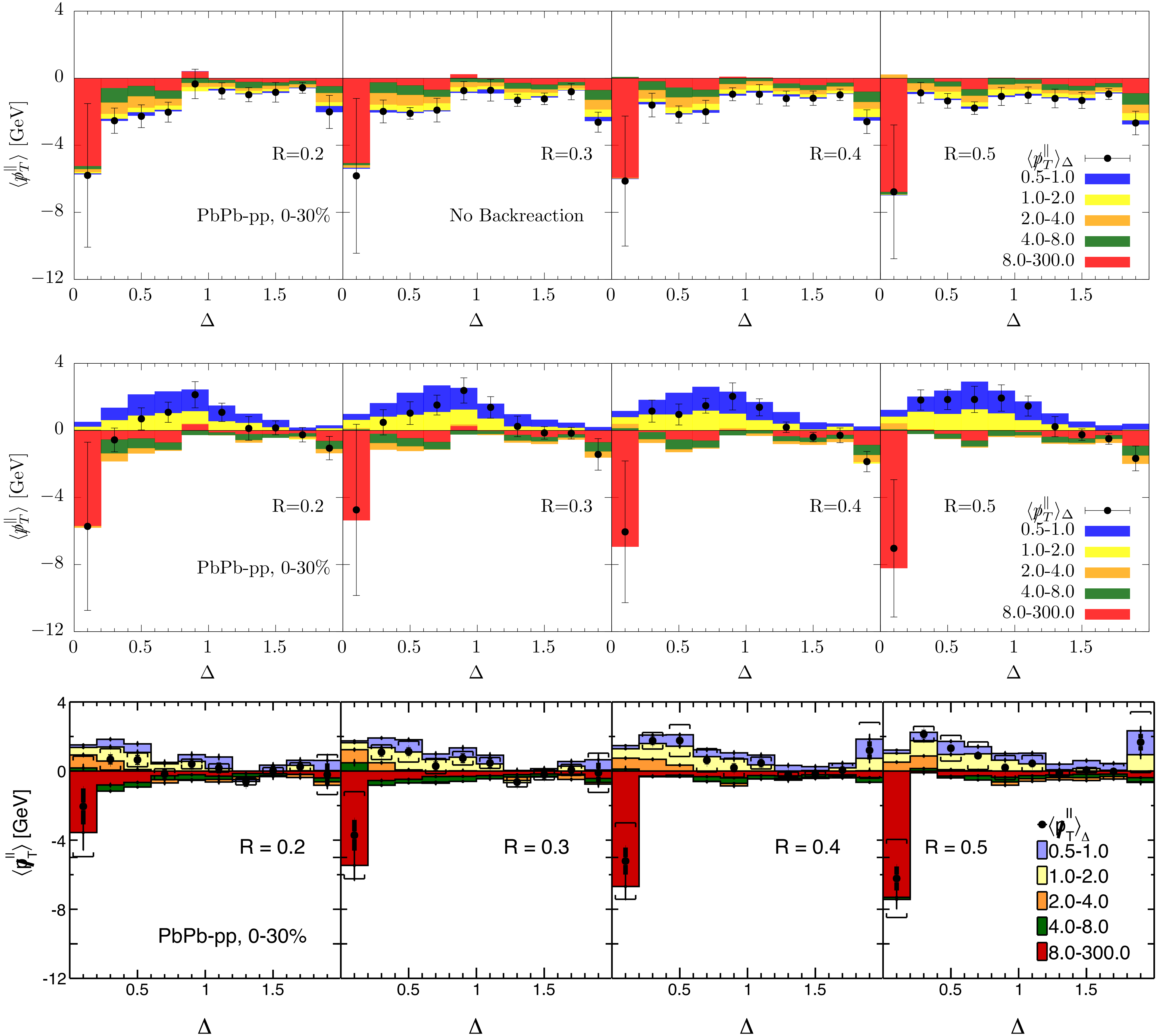


- In PbPb, more asymmetric dijet events are dominated by soft tracks in the subleading jet side

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



Jet radius dependence of Missing Pt



Missing p_T observables

- Our characterization of the wake is on the right 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 understanding broadening, and then looking for rare large angle scattering.)
- Others, using other calculational frameworks, should add background, include the wake, subtract background, and compare to data on Missing-p_T observables, to see whether they too conclude that the energy lost by the jet — namely the wake in the plasma — does not fully thermalize, remembering more than just its energy and momentum.

From now to the 2020s

- Our characterization of the wake is on the right track. And, we are learning something interesting from the way in which it does not hit the nail fully on the head. We are learning about the wake in the plasma, and about the degree to which it does and does not thermalize.
- I hope that before the 2020s we will have nailed down the magnitude of K, the strength of the Gaussian distribution of transverse kicks felt by the partons in the jet.
- I hope that in the 2020s, with high statistics data on observables like the differential jet shape ratio that focus on 10-20 GeV partons in the jet, and so are insensitive to the wake, we will see the quasiparticles in the soup by analyzing rare, but not Gaussianly rare, events that the descendants of the hybrid model don't get right.
- It would also be good to have completely different observables that give us access to the microscopic structure of QGP. Could z_g be the beginnings of such an observable? (Guilherme's talk.)

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

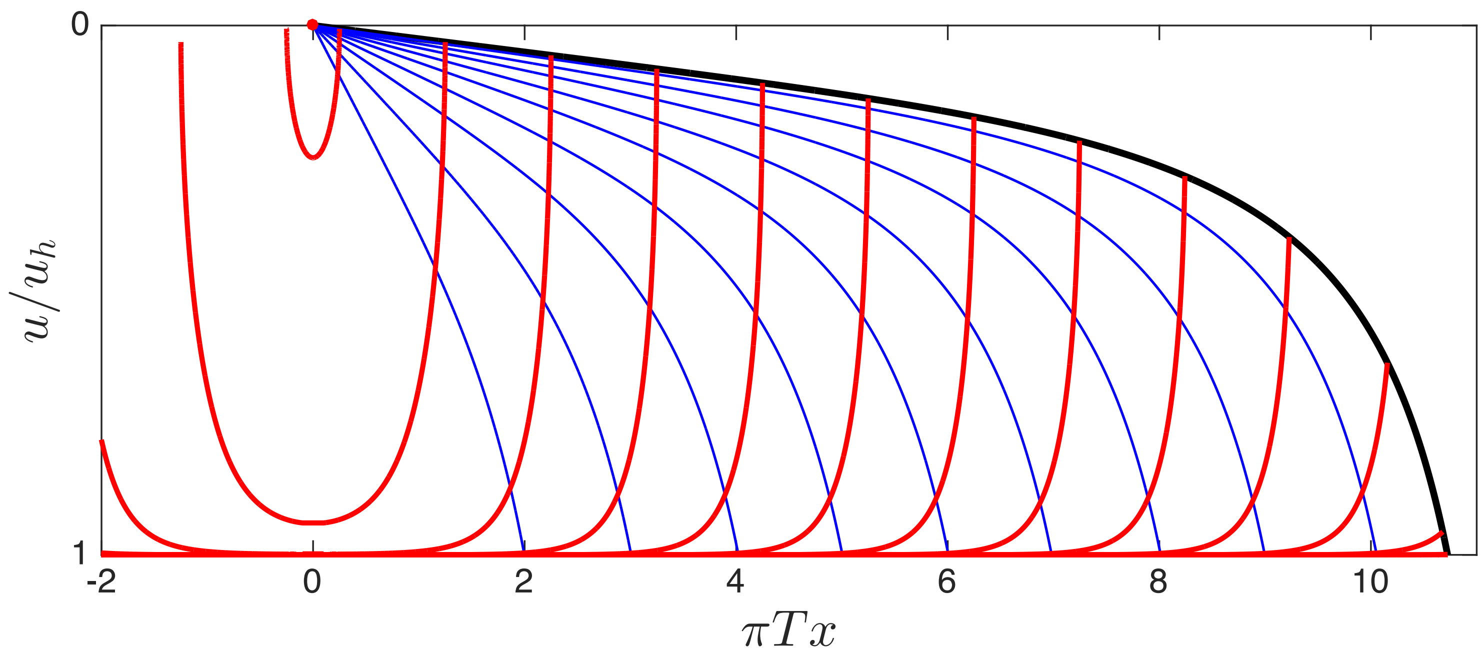
- Two theories differ on various axes. But, their plasmas are *much* more similar than their vacua. Neither is supersymmetric. Neither confines or breaks chiral symmetry.
- $\mathcal{N} = 4$ SYM is conformal. QCD thermodynamics is reasonably conformal for $2T_c \lesssim T <$?. In model studies, adding 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.

What if We Try a Bolder Approach?

- The hybrid approach takes insights from AdS/CFT calculations of parton energy loss and uses them to model the quenching of pQCD jets in a way that can be confronted with jet observables.
- What if we try to be non-hybrid? By which I mean what if we try to compare the AdS/CFT calculations directly with the phenomenology of jets in heavy ion collisions?
- This bolder approach starts off well, but then seems to be contradicted in a qualitative way by data...

Holographic “Jet” Energy Loss

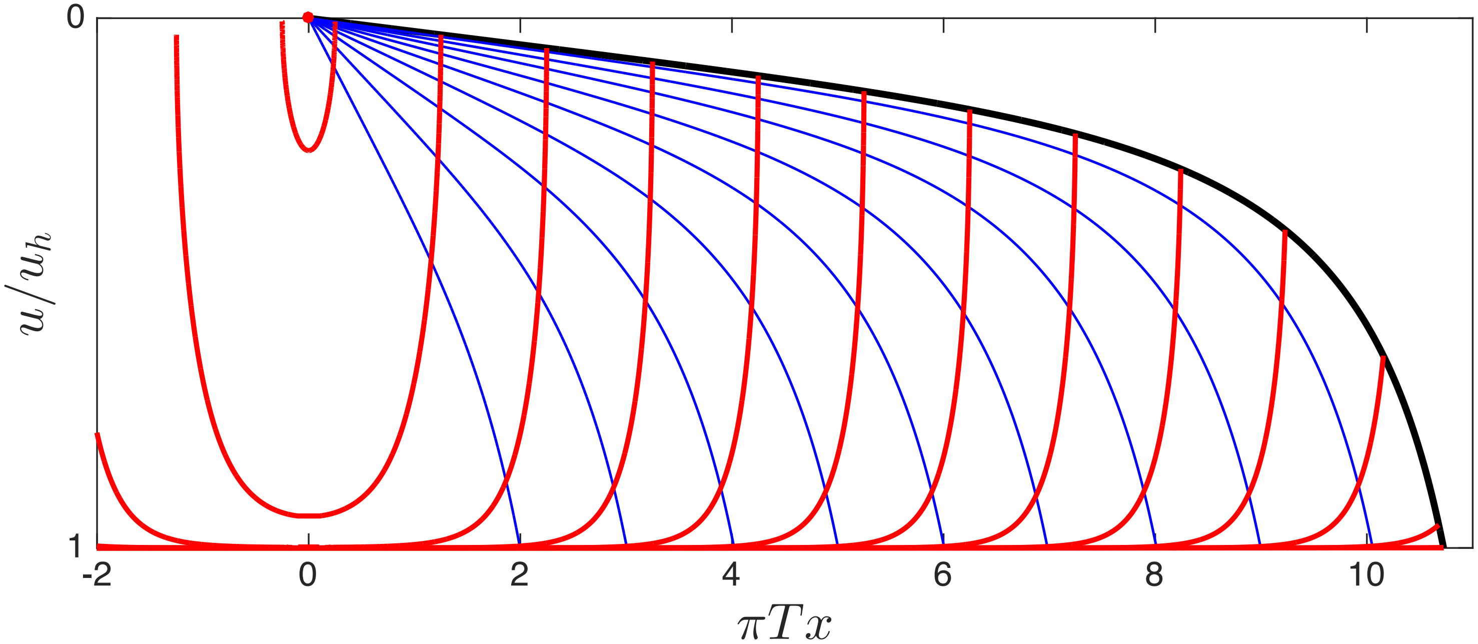
Chesler, Rajagopal, arXiv:1402.6756, 1511.07567



- **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.**
- **Since energy density is largest close to the string endpoint, for intuition focus on the endpoint trajectory.**
- **This calculation describes a “jet” with some initial $\theta_{\text{jet}}^{\text{init}} \propto$ initial downward angle of the endpoint.**

Holographic “Jet” Energy Loss

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

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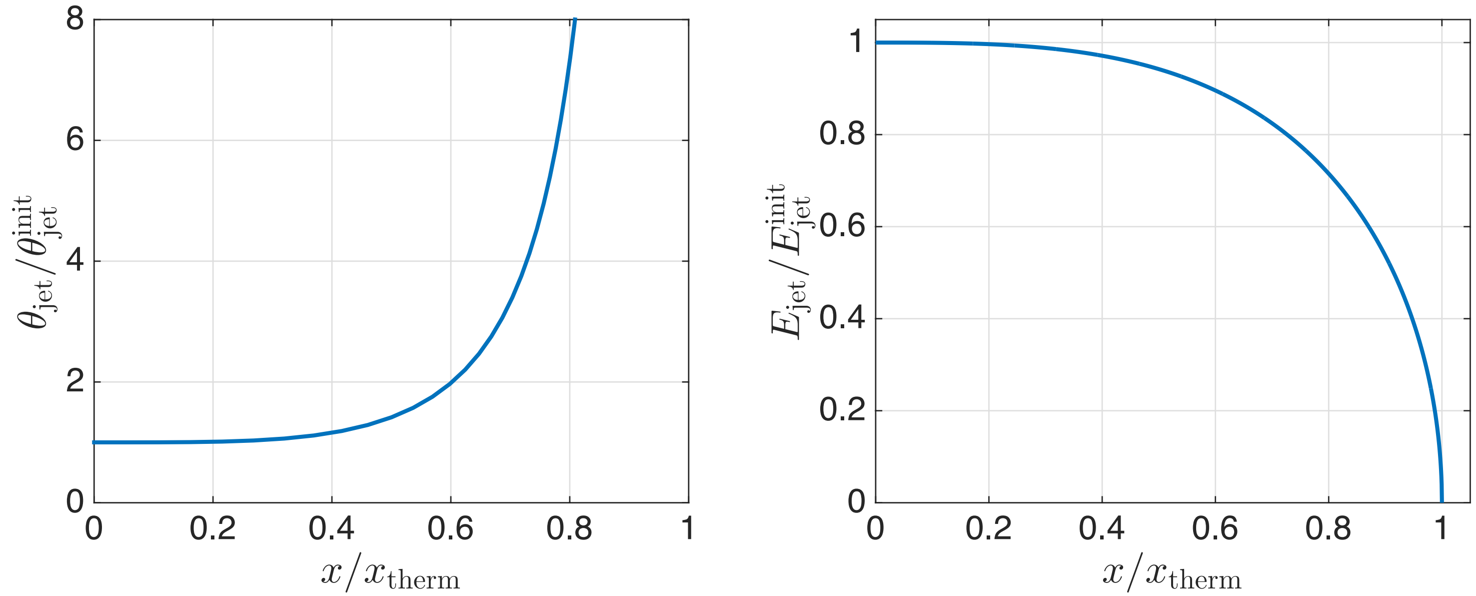
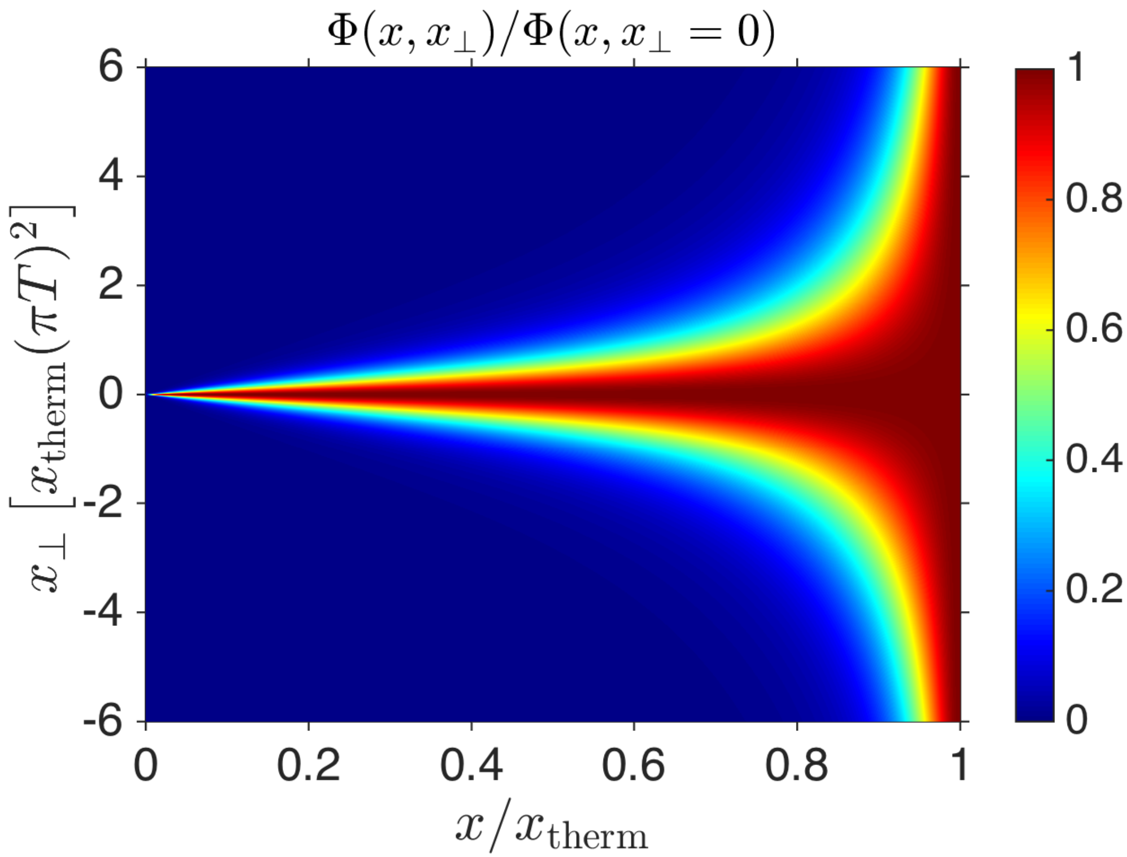


Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

- **First, every jet broadens in angle as it propagates through the strongly coupled plasma. $\theta_{\rm jet}$ increases as $E_{\rm jet}$ decreases. (The result plotted for $\theta_{\rm jet}/\theta_{\rm jet}^{\rm init}$ is in the limit of small $\theta_{\rm jet}^{\rm init}$, meaning large $x_{\rm therm}T$. See the paper for results away from this limit.)**

Holographic "Jet" Energy Loss

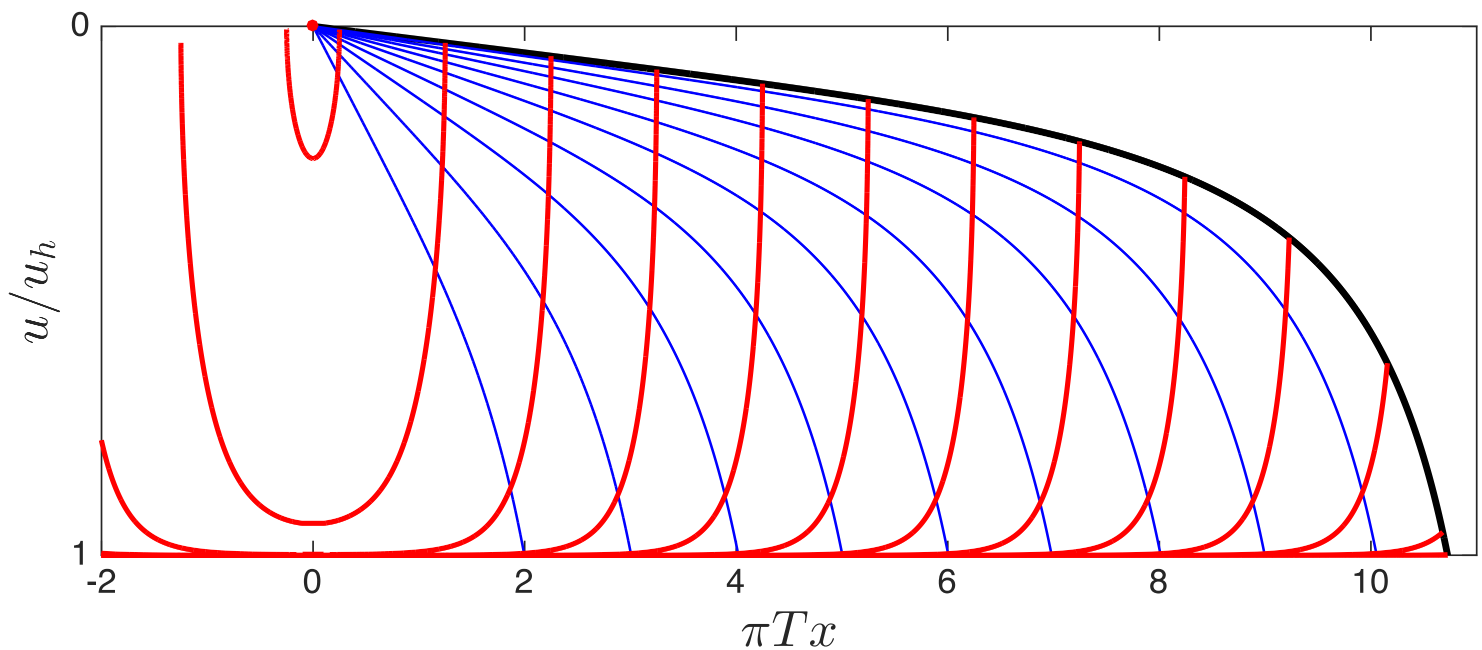
Chesler, Rajagopal, arXiv:1511.07567



- **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

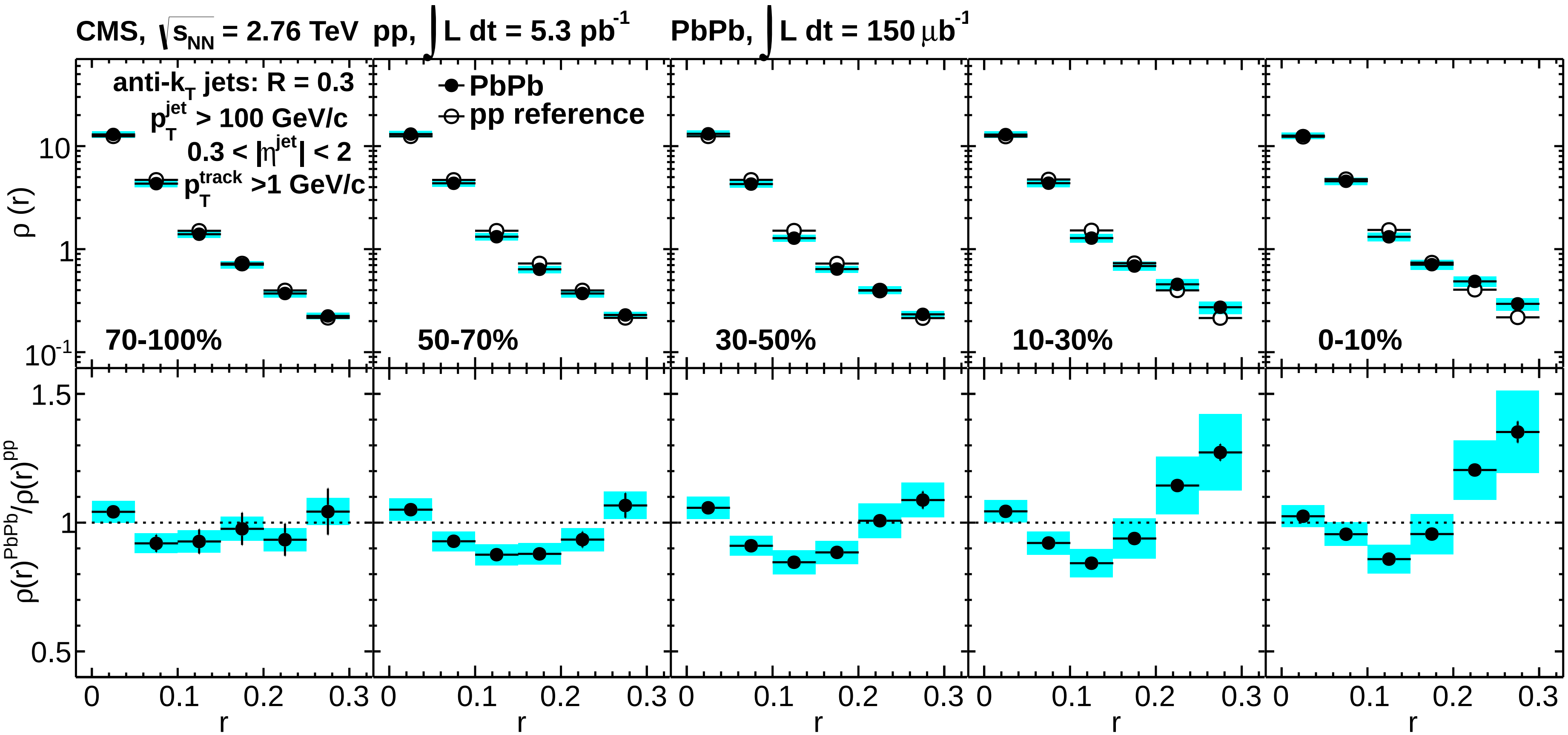


Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

- **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.**

Experimental Results

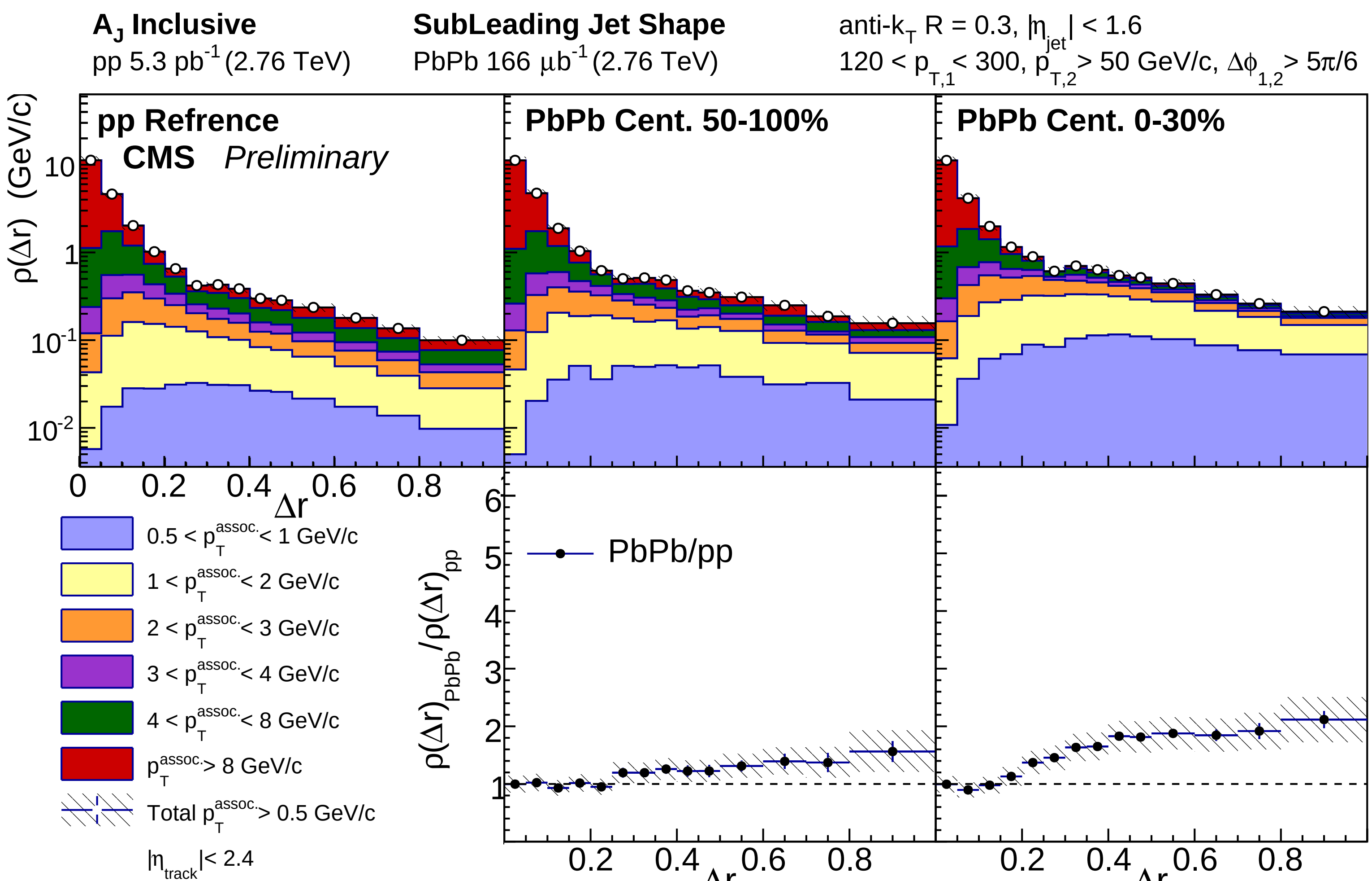
CMS, arxiv:1310.0878



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 only to assess whether there is a blatant contradiction. So we will simplify many things. . .

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 $\sigma_{\rm endpoint}^{\rm init}$.)**

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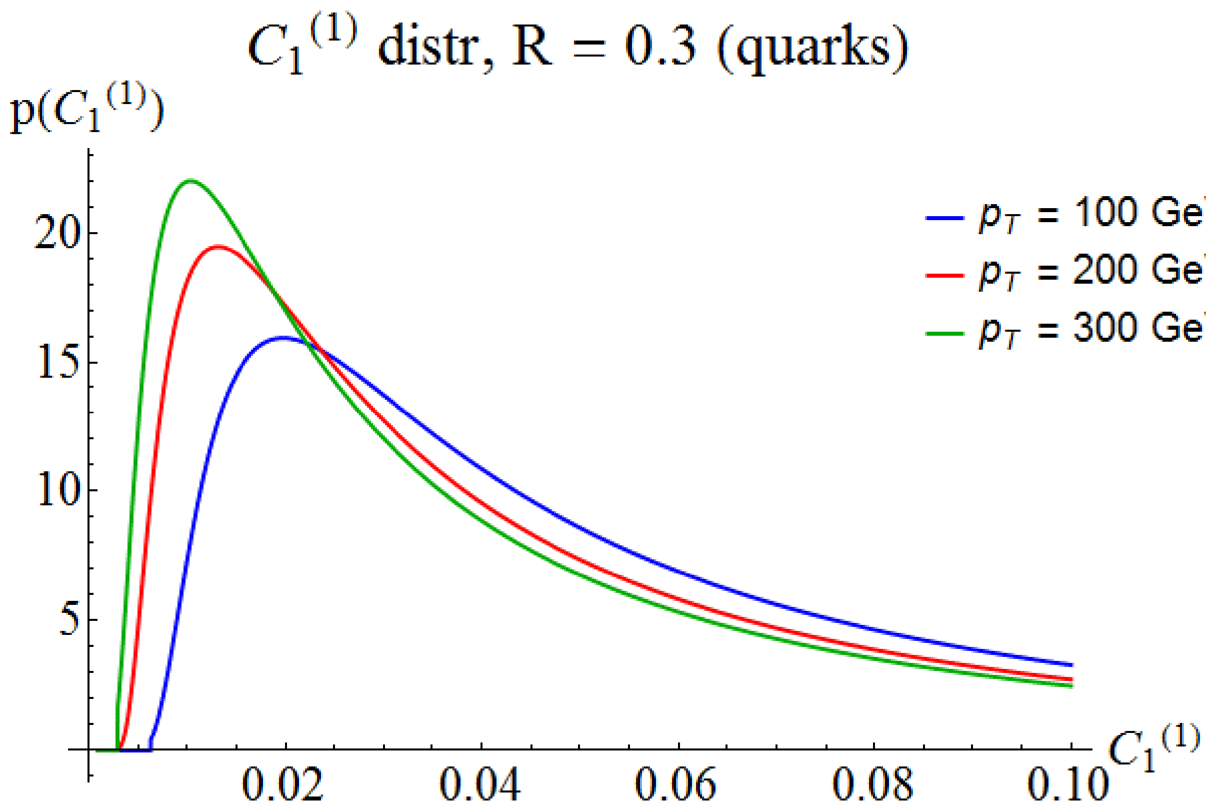

Larkoski, Marzani, Soyez, Thaler 1402.2657

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. . . 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.

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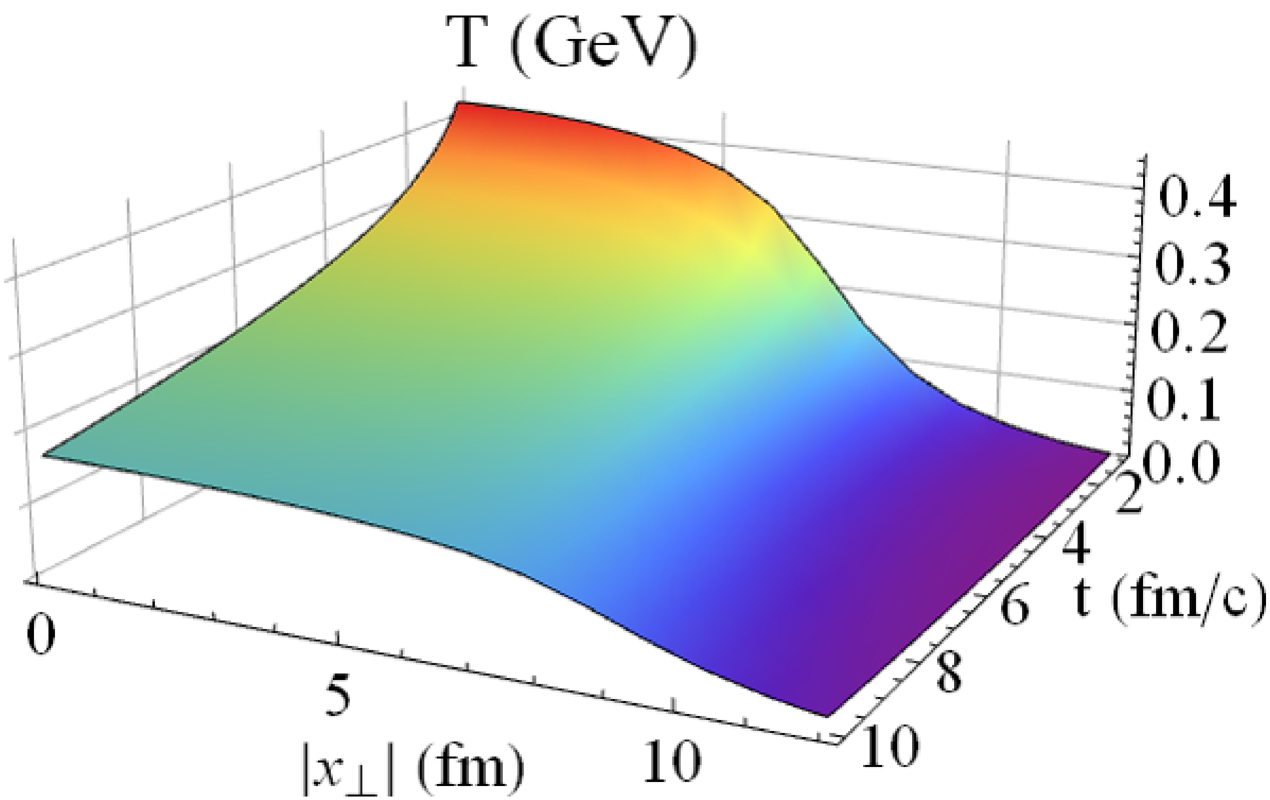

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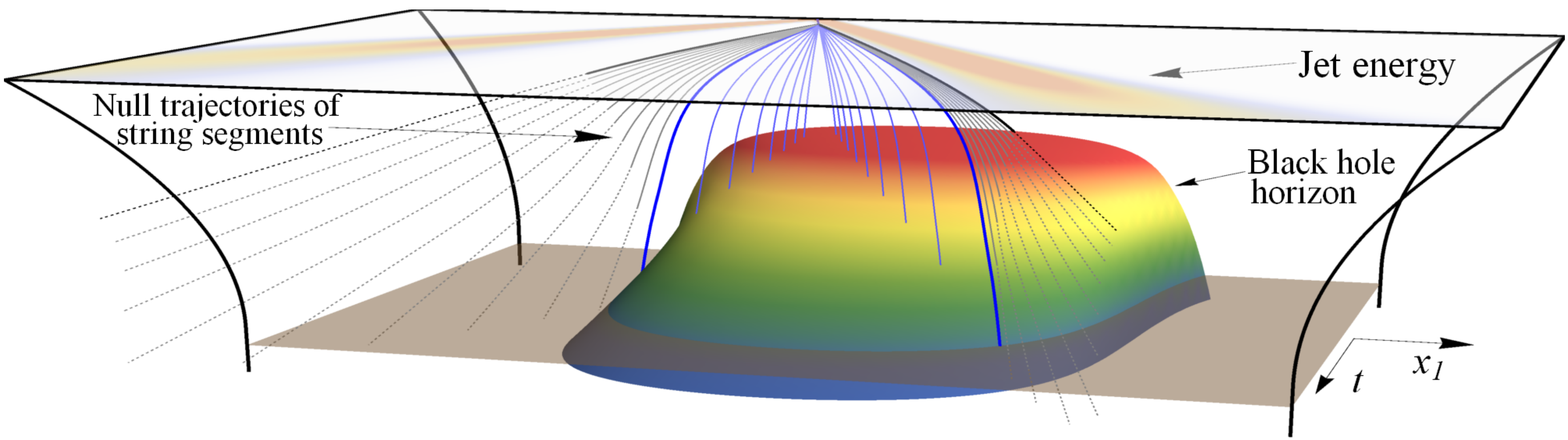

Evolution of Jet Opening Angle Distribution

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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.

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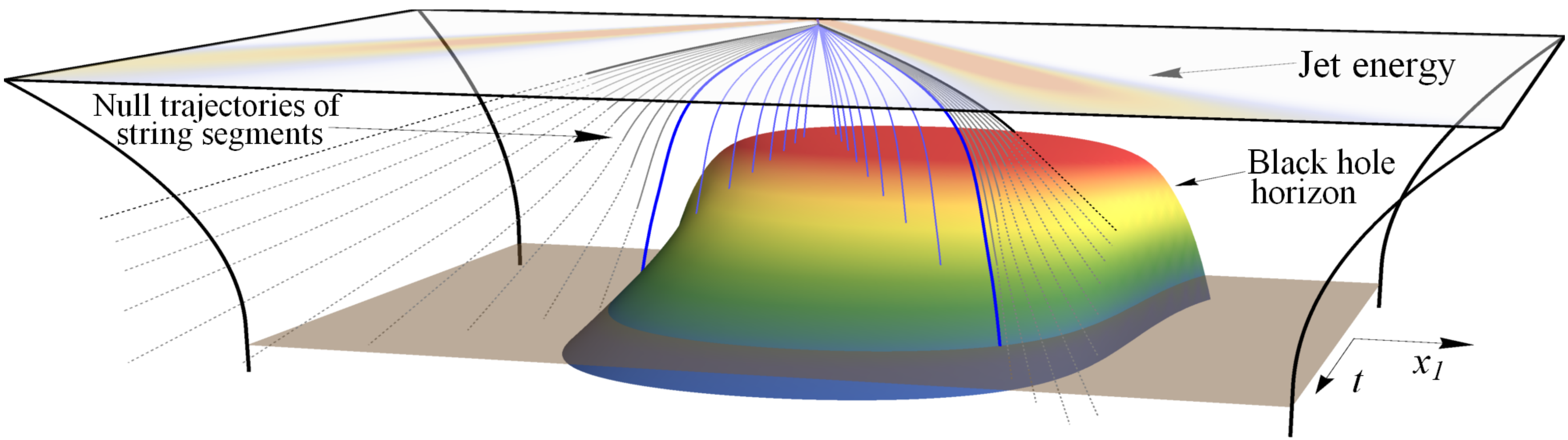

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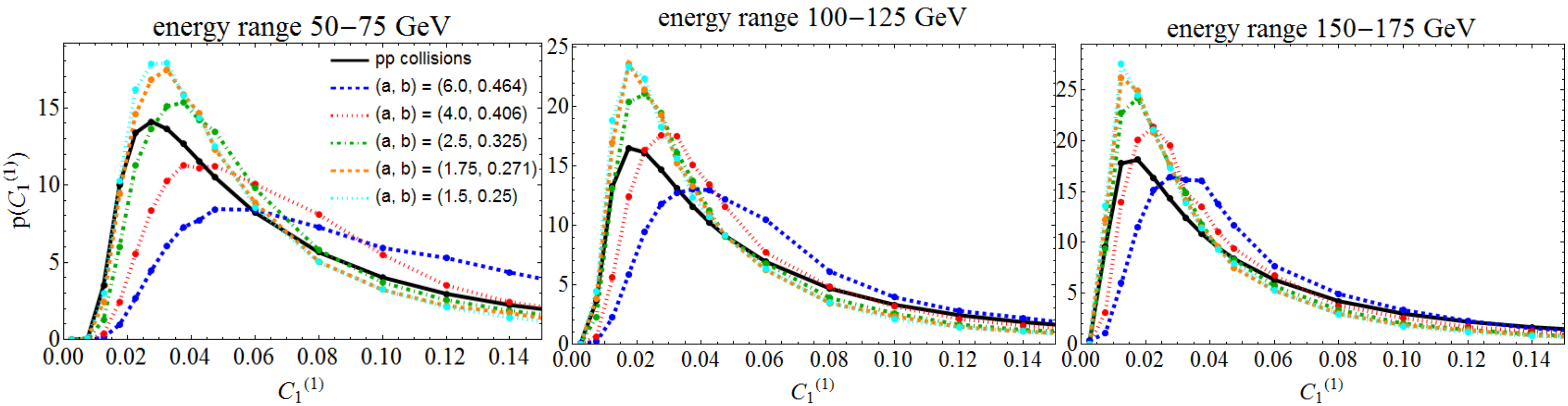
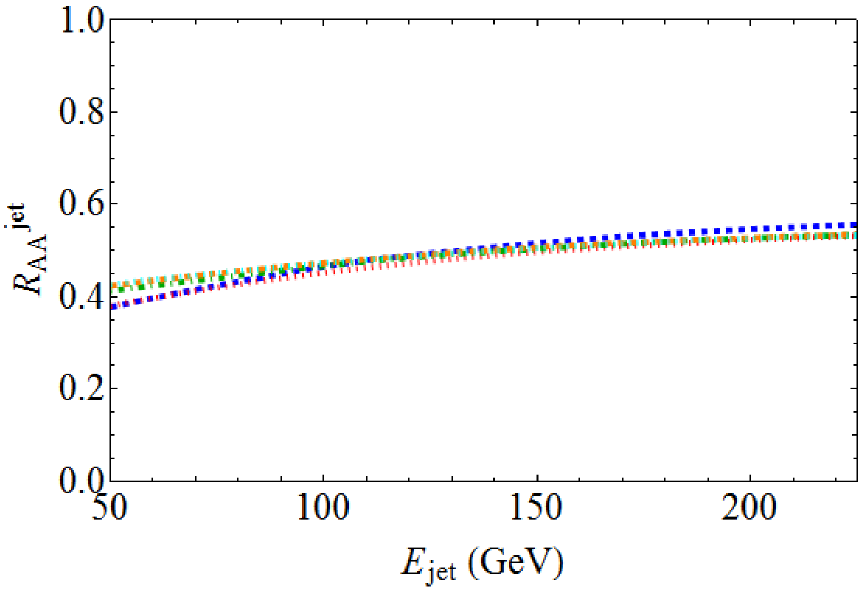


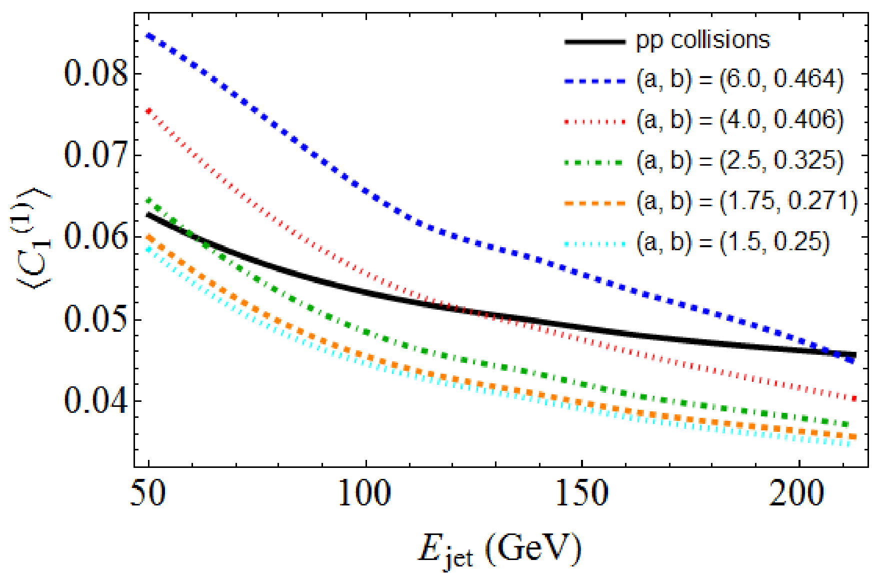
For small angles, opening angle distribution pushed toward larger angles. (Every jet gets wider as it propagates.)

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).

Same effect seen in hybrid model also (Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 160n).

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

Evolution of Jet Opening Angle Distribution

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

The "bolder approach" (comparing holographic jets directly to data) is at present less well developed than the hybrid model, vis-a-vis comparison to jet observables. We (Brewer, KR, Sadofyev, van der Schee) are working on improving various aspects of the simplified analysis I have presented. . . .

Before we get to look for rare largish angle scatterings of partons in jets off the QGP, probing its microscopic structure, we'll need to: (i) see and quantify the "typical" Gaussian distribution of transverse momentum broadening; (ii) understand and avoid the wake — whose equilibration is of interest in its own right, though; (iii) have a quantitative understanding of the evolution of the shape of jets in QGP.

The fact that jets with a given energy can get narrower even as every individual jet gets wider is an object lesson re the challenges ahead.