Doping and Probing the Original Liquid

Krishna Rajagopal
MIT

30 Years of Heavy Ions: ... What Next?
CERN, November 9, 2016

30 Years of Heavy Ions: ...

What Next?

As of 2005, by recreating droplets of the matter that filled the microseconds-old universe in ultrarelativistic heavy ion collisions, our community had discovered a liquid that, as far as we now know, is:

- The first liquid that ever existed; the "original liquid" ...
- The liquid from which the protons and neutrons in today's universe formed, as the liquid fell apart into mist.
- At a few trillion degrees, the hottest liquid that has ever existed.
- The earliest complex form of matter.
- The most liquid liquid that has ever existed, with a specific viscosity $\eta/s \sim 0.1$.

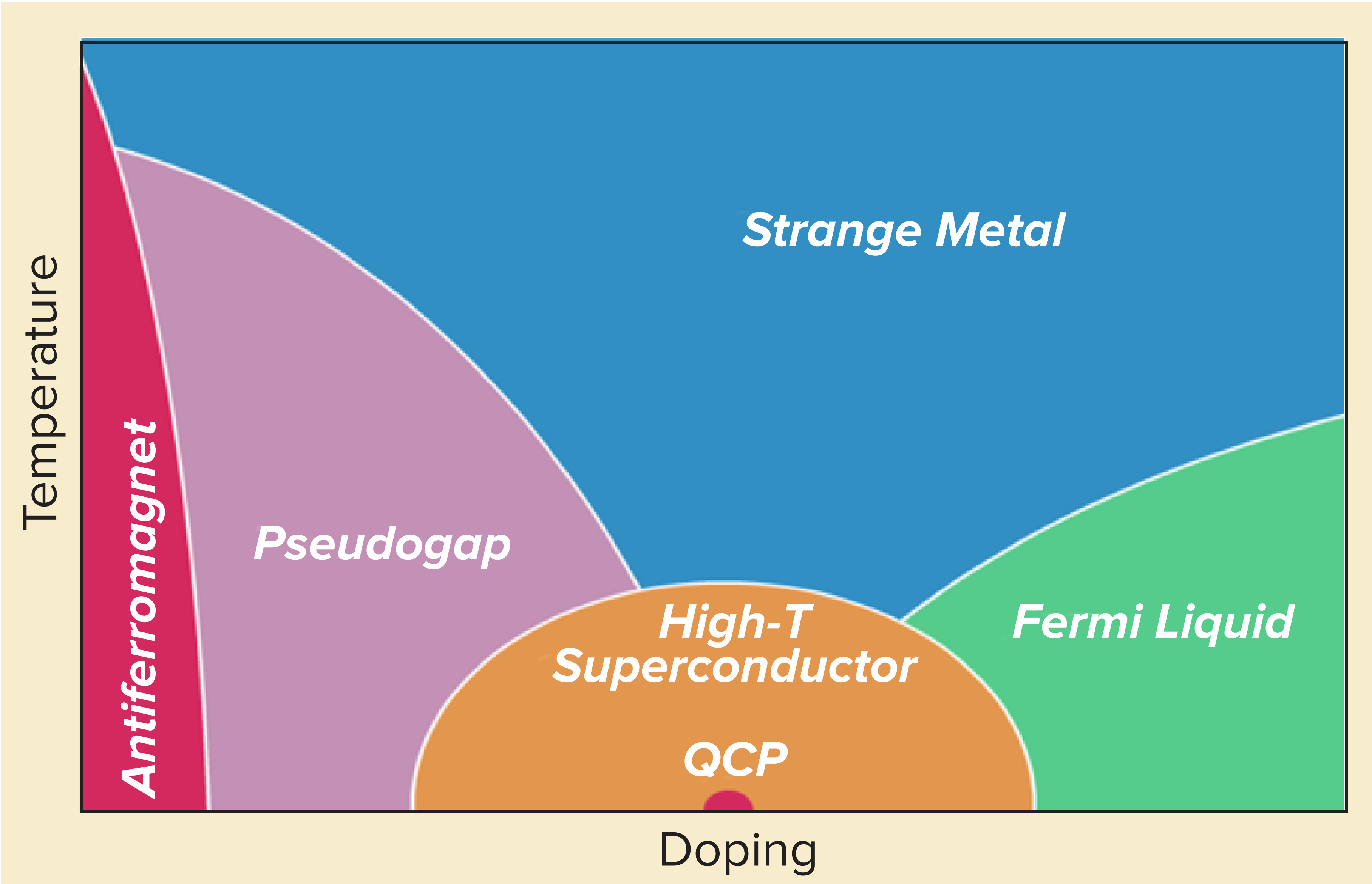
All great discoveries pose new challenges, and this one is no exception. My talk is about What Next?, namely the new challenges of the past decade as well as the decade to come.

What Next?

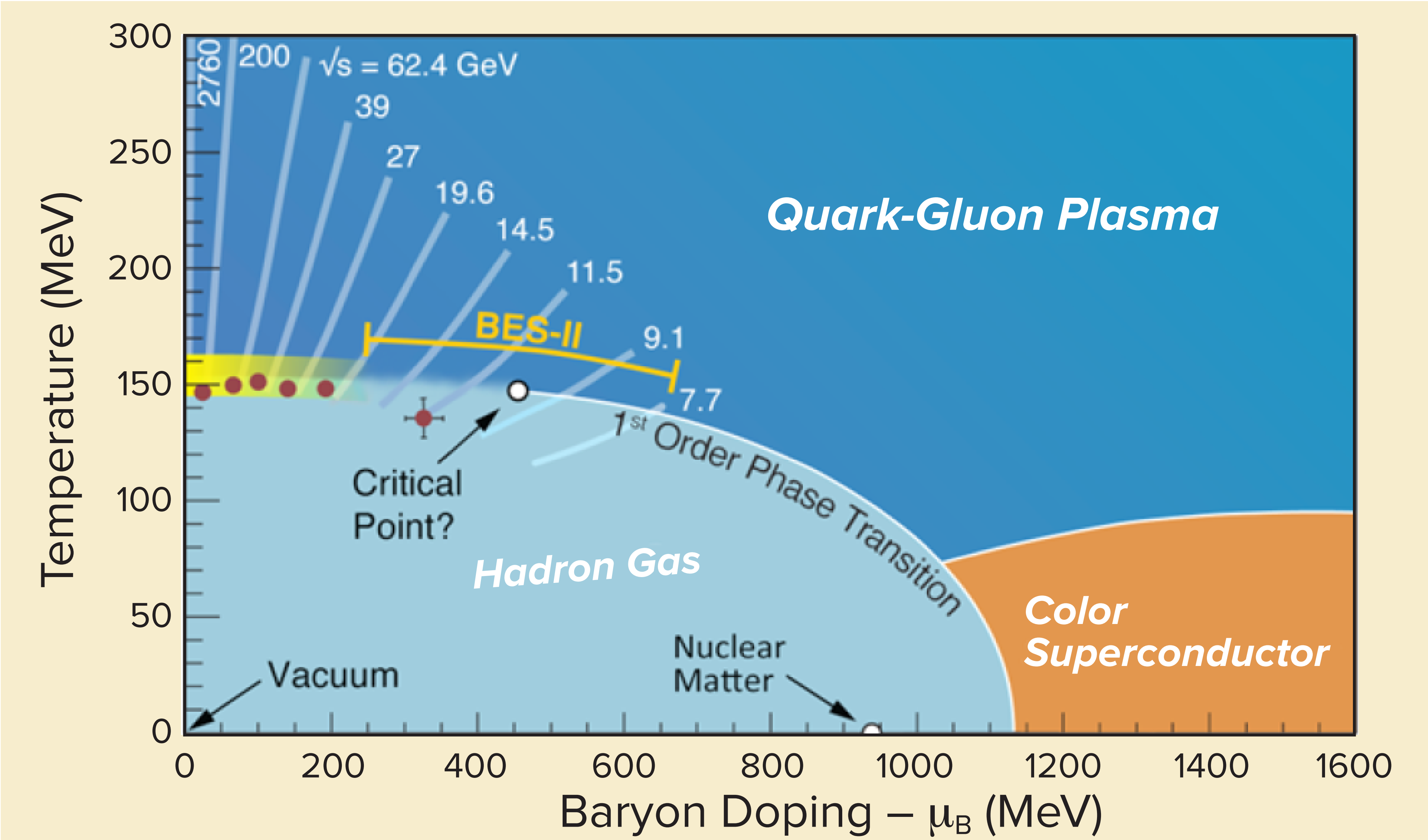
I will divide my talk into two kinds of What Next? questions...

- A question that one asks after the discovery of any new form of complex matter: What is its phase diagram? For high temperature superconductors, for example, phase diagram as a function of temperature and doping. Same here! For us, doping means excess of quarks over antiquarks, rather than an excess of holes over electrons.
- A question that we are privileged to have a chance to address, after the discovery of "our" new form of complex matter: 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 other contexts.

  When we get there, I will describe three different variants of this question...



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



300
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Temperature (MeV)
2760
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√s = 62.4 GeV
39
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11.5
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7.7
BES-II
Quark-Gluon Plasma
Critical
Point?
1st Order Phase Transition
Hadron Gas
Color
Superconductor
Vacuum
Nuclear
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Baryon Doping – μB (MeV)

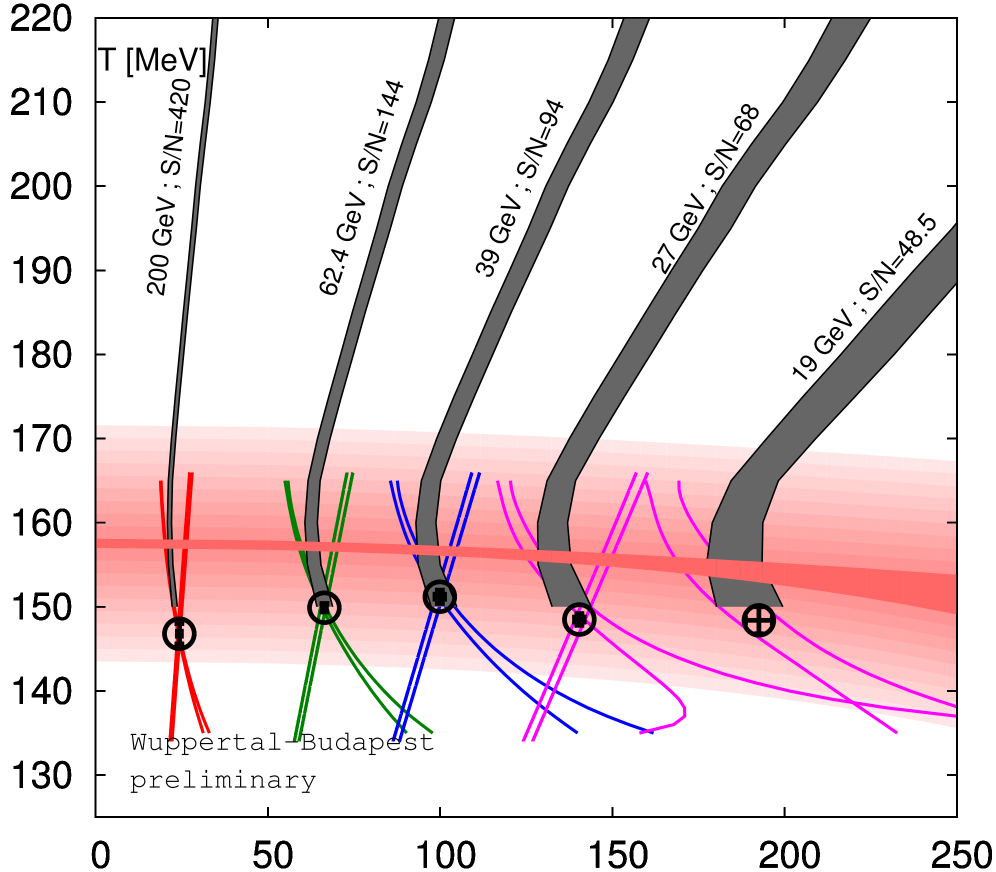
Mapping the QCD Phase Diagram

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

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

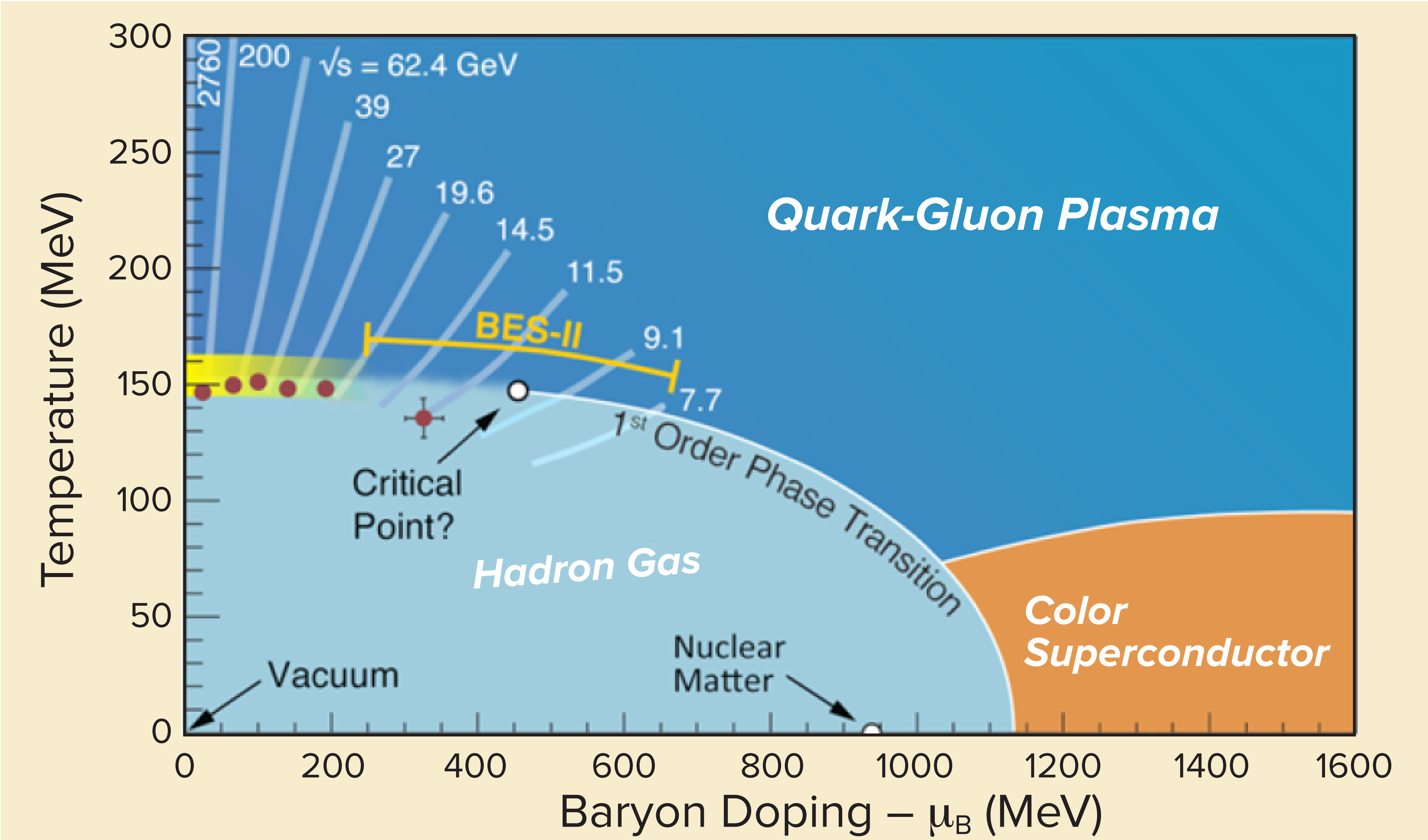
- Answering this question via theory will need further advances in lattice "technology". Impressive recent progress advancing established Taylor-expansion methods. New ideas also being evaluated. Nevertheless, at present theory is good at telling us what happens near a critical point or first order transition,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

Mapping the Crossover Region



Wuppertal-Budapest-Houston, 1601.00466

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



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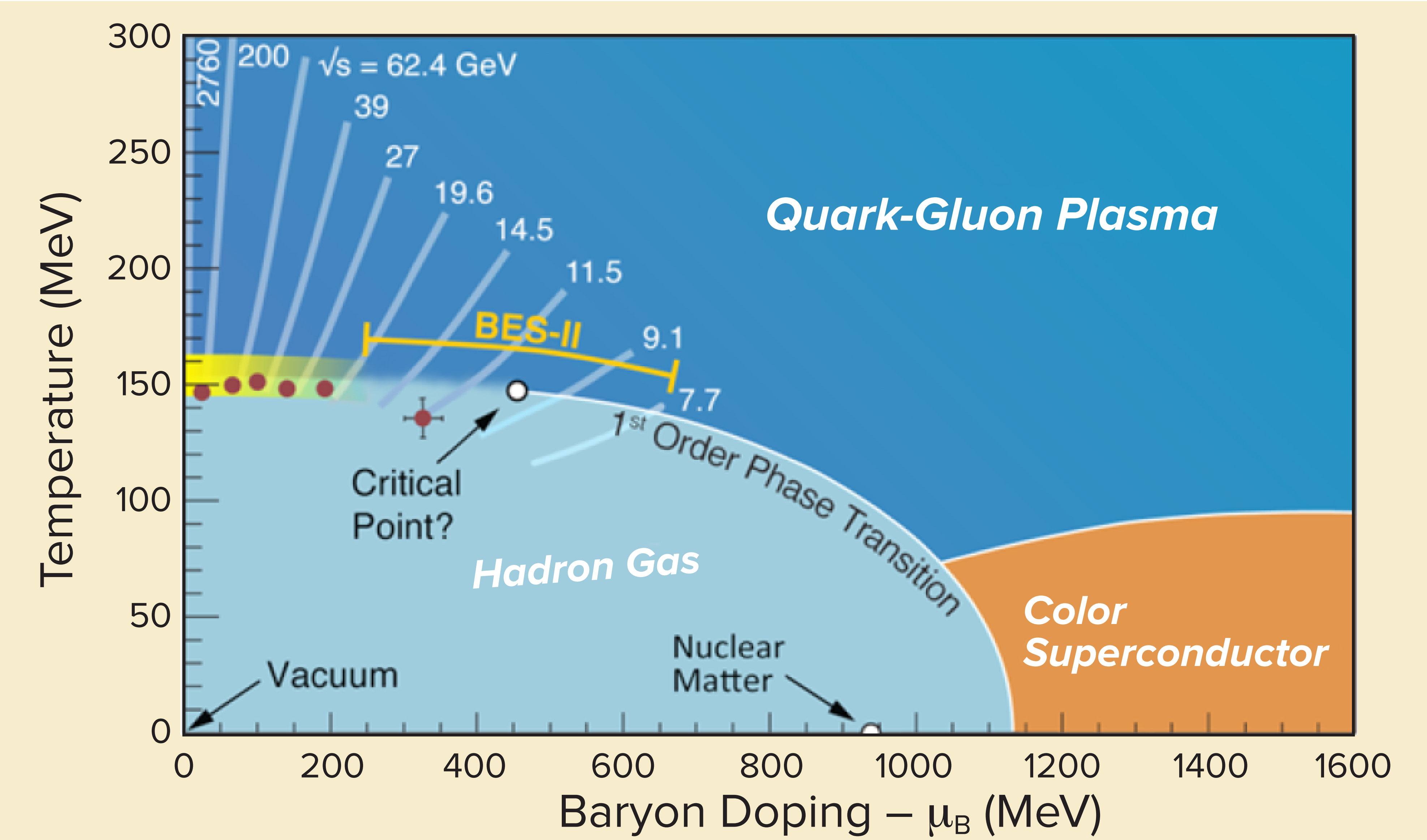

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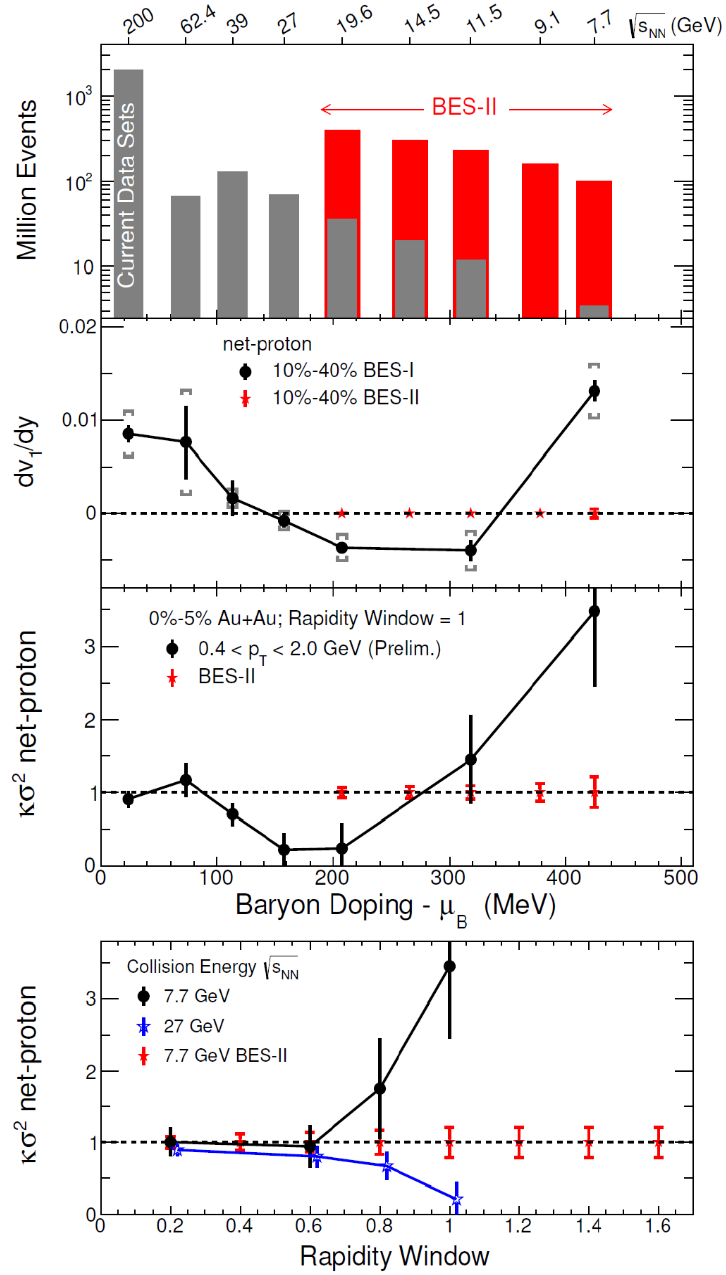
Mapping the QCD Phase Diagram

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

- BES-I results present an outstanding opportunity for theory. Aka a stiff challenge. Interpreting flow (and other) observables requires 3+1-D viscous hydrodynamic calculations at BES energies. And, hydro calculations at these lower energies present new challenges (j_B^μ in addition to $T^{\mu\nu}$) and must include state-of-the-art treatment of the hadrodynamics: relative importance of hadrodynamic effects on all observables grows. Also need baryon stopping and state-of-the-art initial state fluctuations. BES-I data demand that the sophistication that has been applied at top energies be deployed at BES energies.



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

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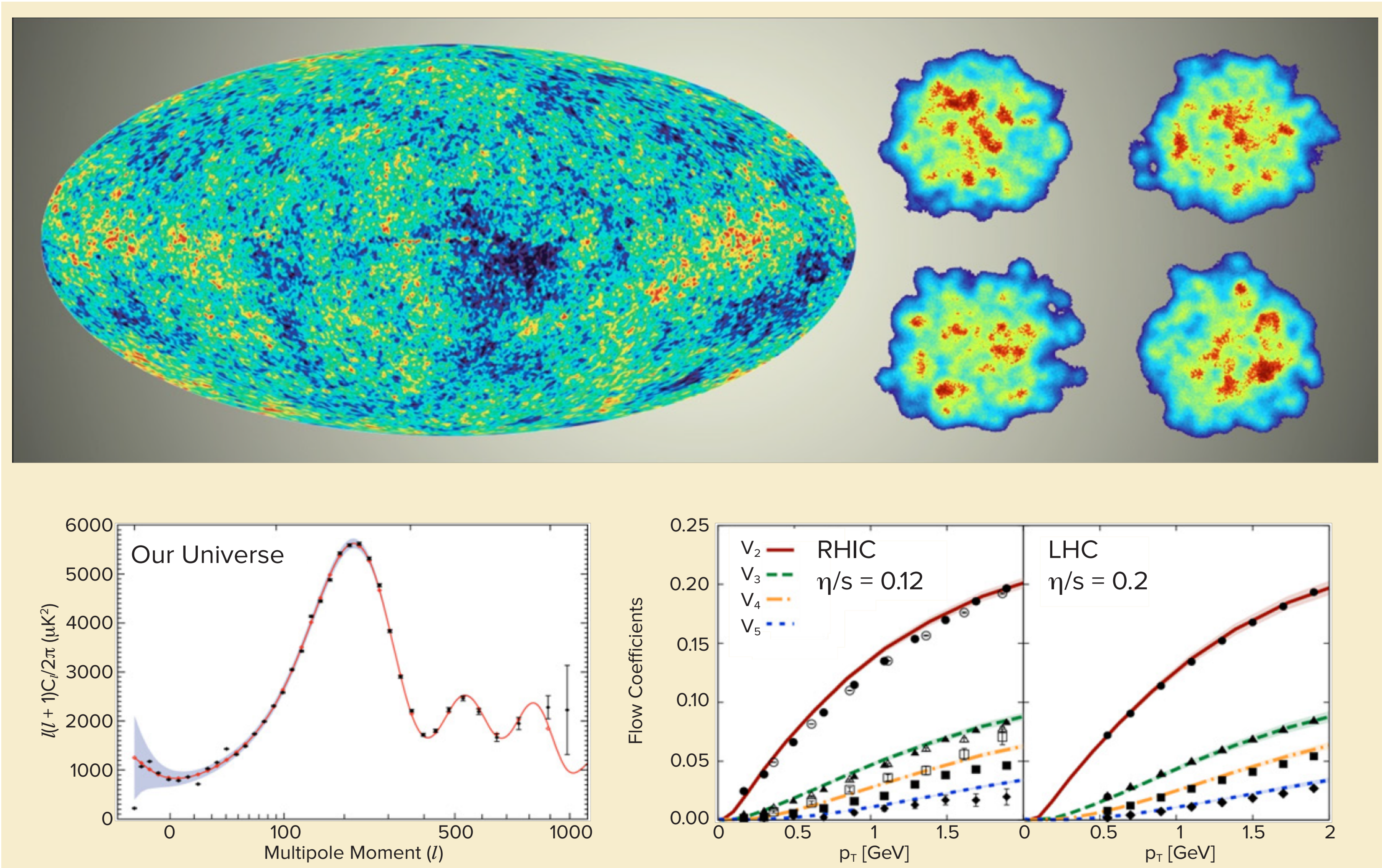
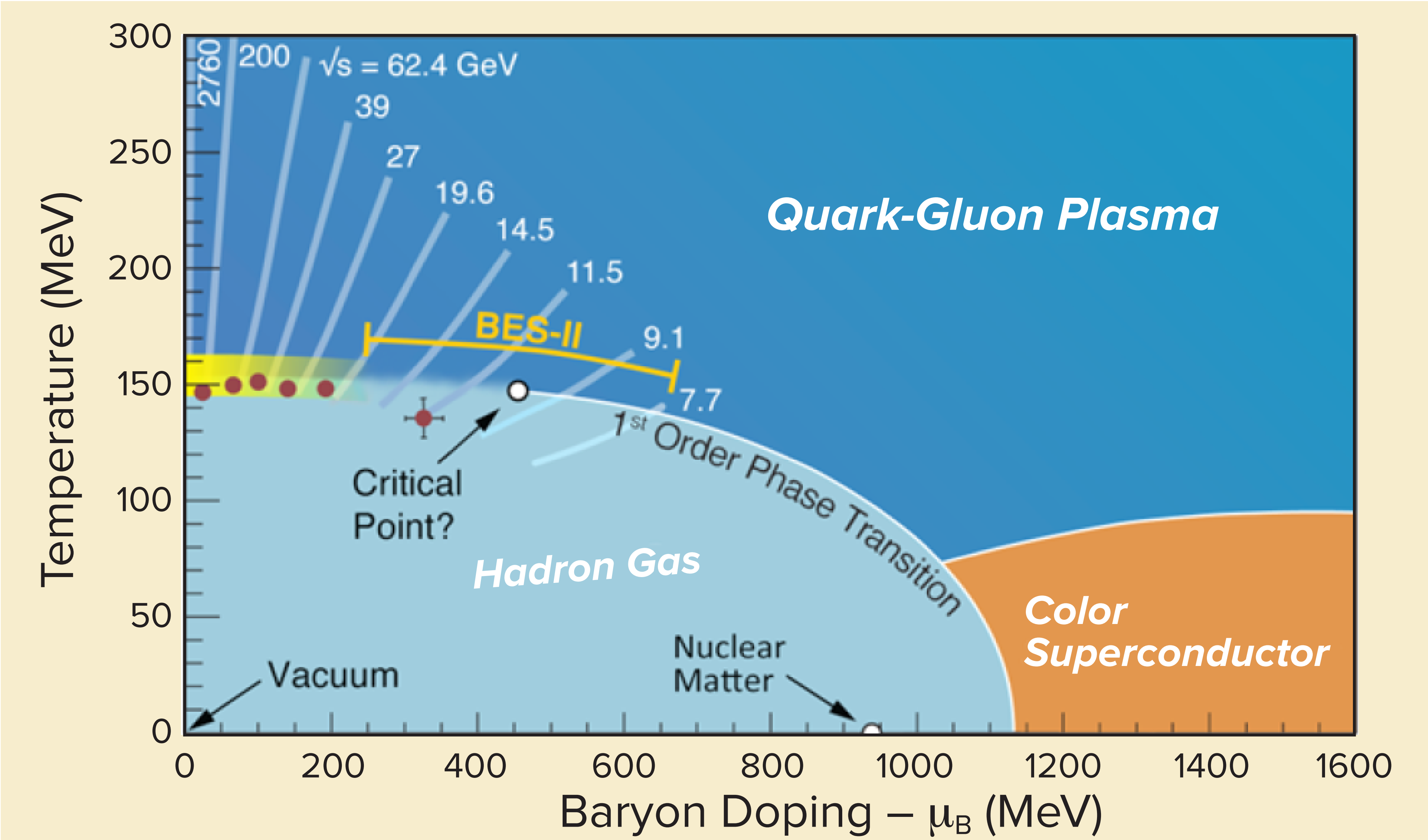


Our Universe
$l(l+1)C_l/2\pi$ (μK²)
6000
5000
4000
3000
2000
1000
0
0
100
500
1000
Multipole Moment (l)
Flow Coefficients
0.25
0.20
0.15
0.10
0.05
0.00
V_2
V_3
V_4
V_5
RHIC
η/s = 0.12
LHC
η/s = 0.2
0
0.5
1
1.5
2
p_T [GeV]
p_T [GeV]



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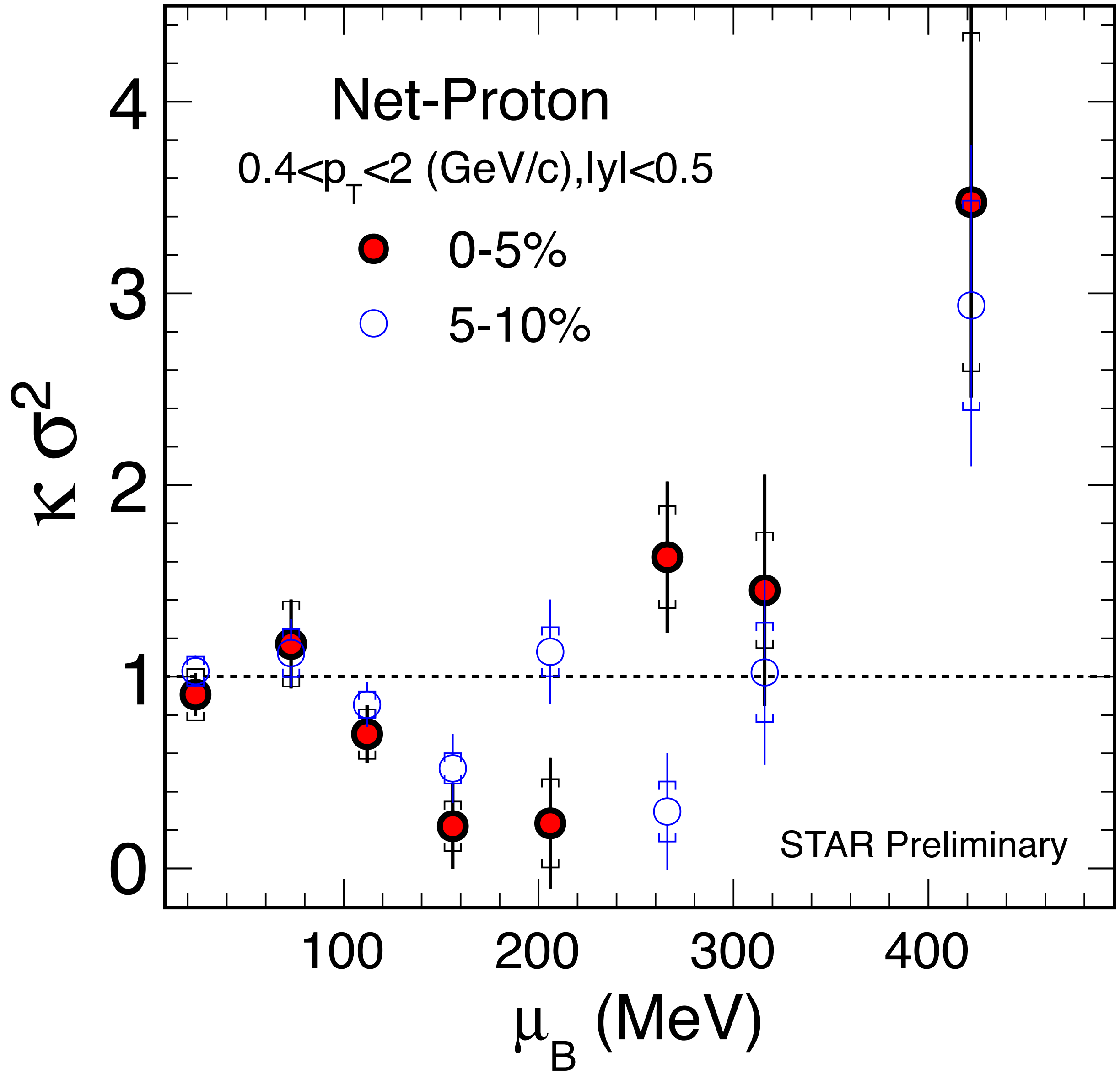
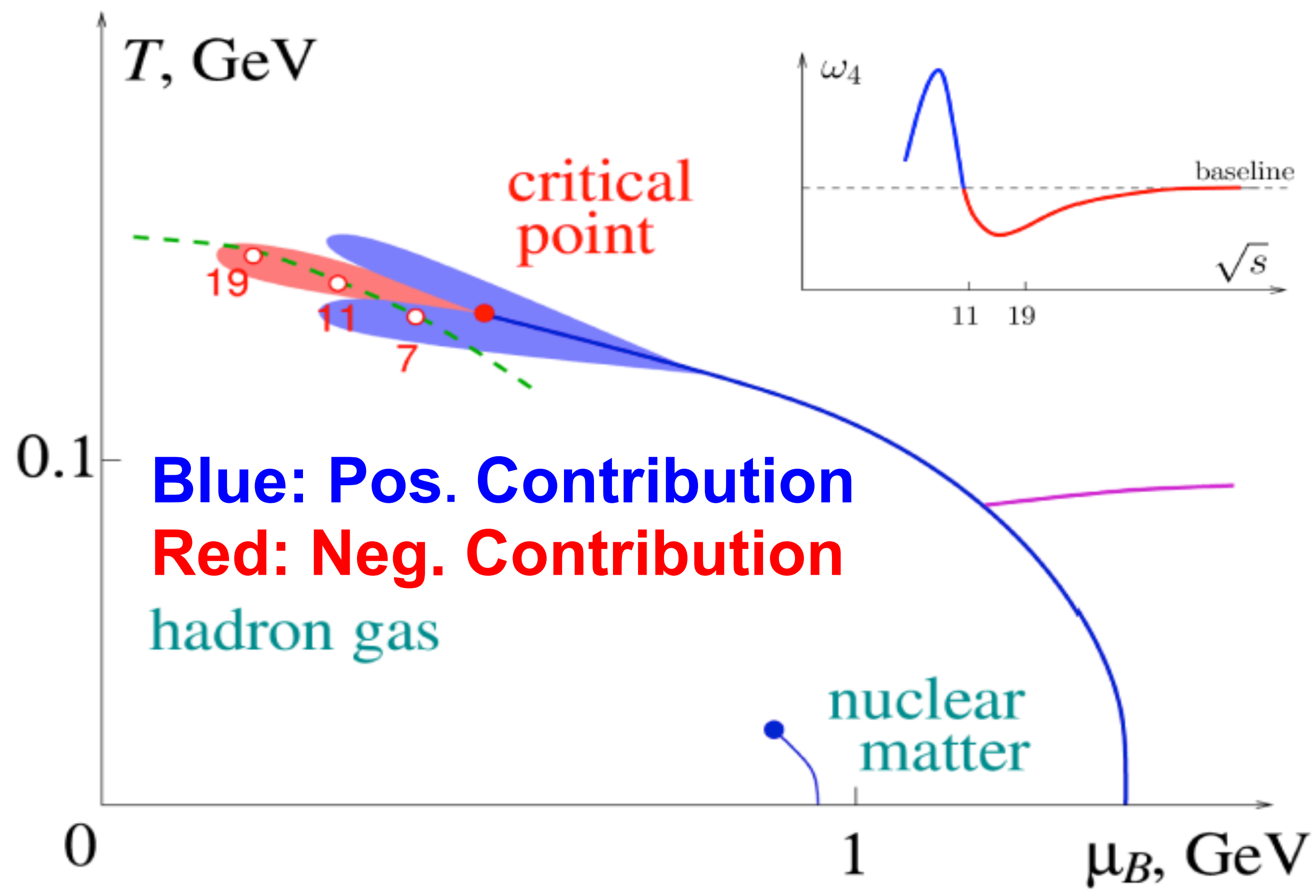
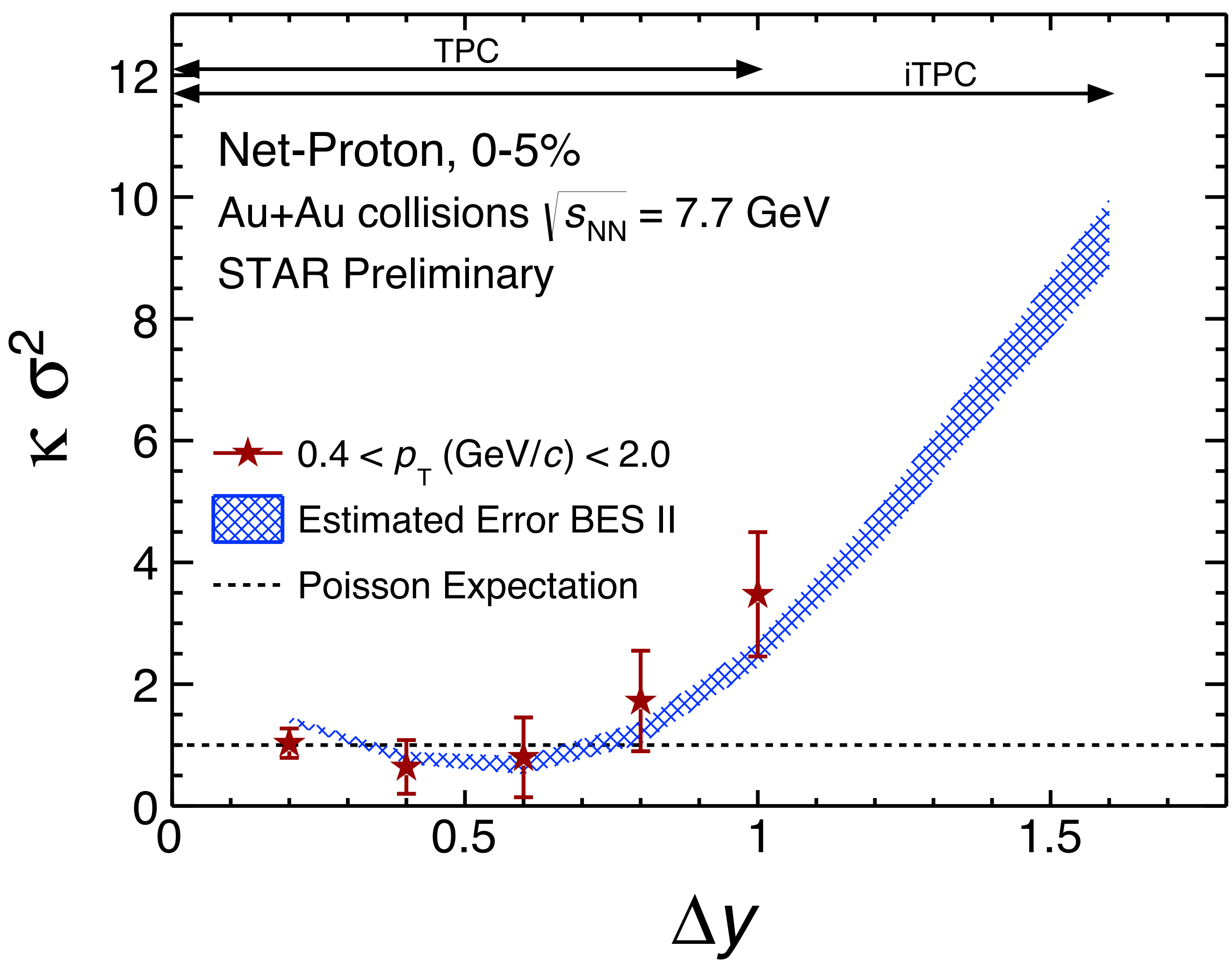


Net-Proton
0.4<p_T<2 (GeV/c),|y|<0.5
0-5%
5-10%
STAR Preliminary
κ σ²
μ_B (MeV)
0
1
2
3
4
100
200
300
400

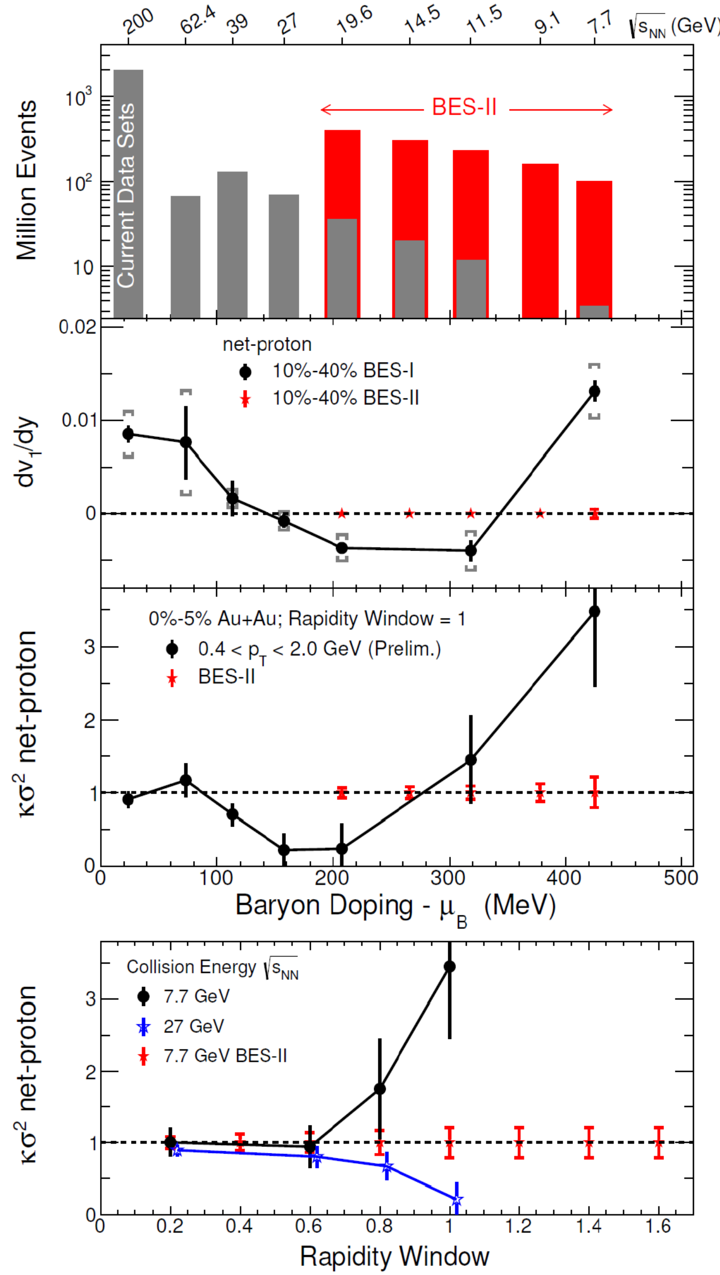

T, GeV
0.1
0
1
μB, GeV
critical point
19
11
7
ω4
baseline
√s
11
19
Blue: Pos. Contribution
Red: Neg. Contribution
hadron gas
nuclear matter

Mapping the QCD Phase Diagram

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



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



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$\kappa\sigma^2$ net-proton
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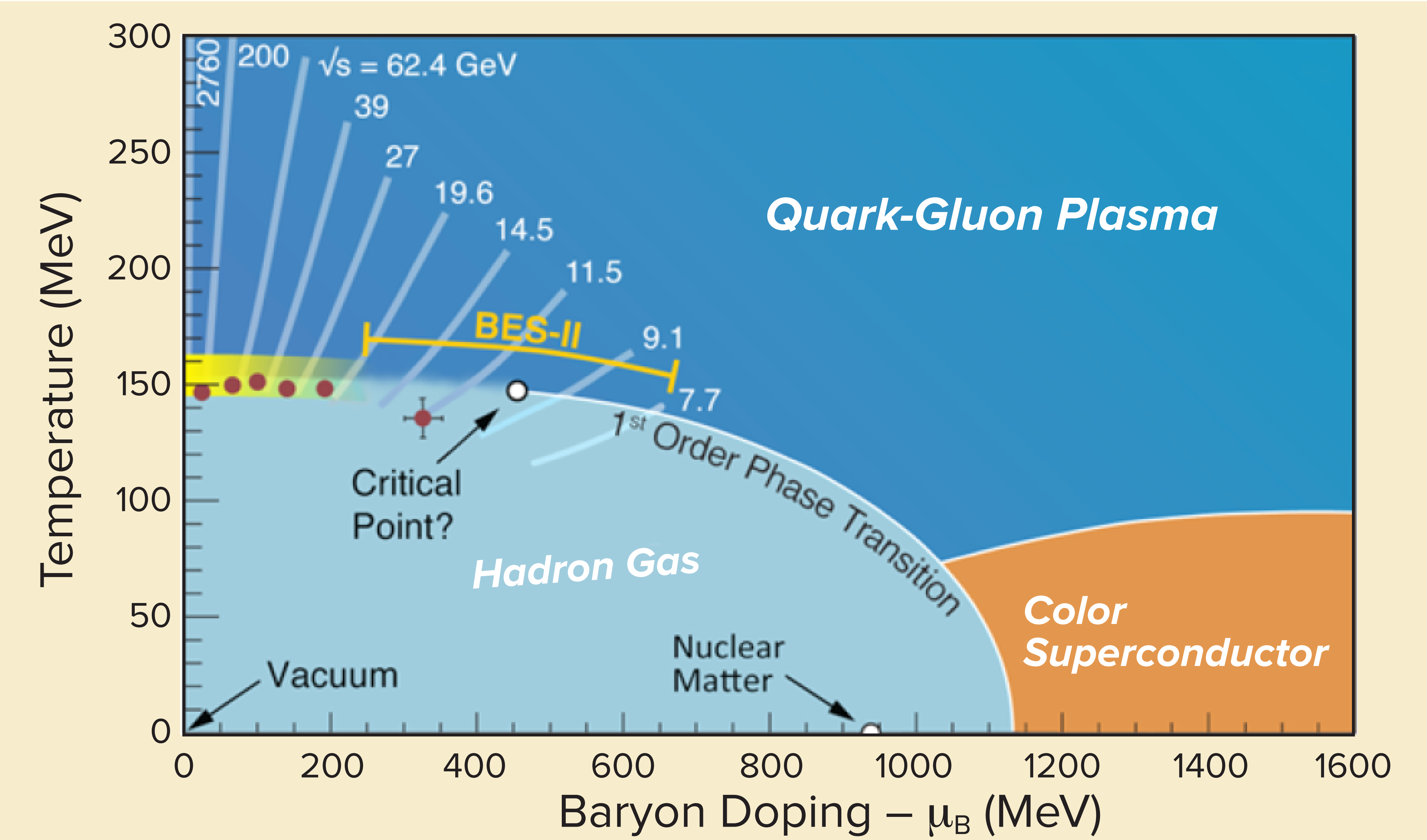
- **Theory needs to be ready in time for BES-II in 2019-20, when error bars will shrink and today's tantalizing hints, e.g. of non-monotonic behavior in dv_1/dy and in the kurtosis of the proton multiplicity distribution, will become ... ?**



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Baryon Doping – μB (MeV)

Probing the Original Liquid

The question **How does the strongly coupled liquid emerge from an asymptotically free gauge theory?** can be thought of in (at least) three different ways, corresponding to different meanings of the word "emerge".

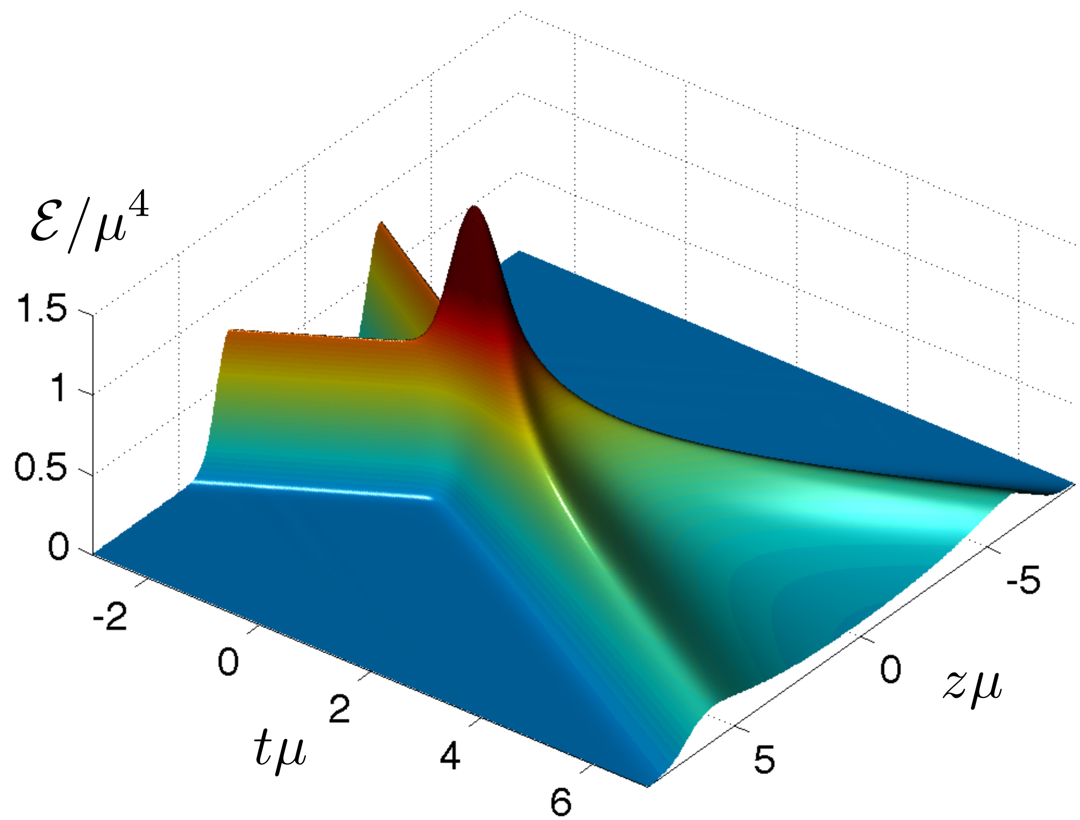
- What is the microscopic structure of the liquid? Since QCD is asymptotically free, when looked at with sufficiently resolution QGP must be made of weakly coupled quarks and gluons. How does the liquid emerge when you coarsen your resolution to length scales $\sim 1/T$?
- Physics at $t = 0$ in an ultrarelativistic heavy ion collision is weakly coupled. How does strongly coupled liquid form? How does it hydrodynamize?
- How does the liquid emerge as a function of increasing system size? What is the smallest possible droplet of the liquid?

Each, in a different way, requires stressing or probing the QGP.

Smallest possible droplet of liquid?

- **What is the smallest possible droplet of QGP that behaves hydrodynamically? Anyone doing holographic calculations at strong coupling, or anyone seeing effects of small lumps in the initial state visible in the final state, could have asked this question, but didn't. Question was asked by data: pPb collisions @LHC, then dAu and ^{3}HeAu data @RHIC.**
- **Subsequently, holographic calculations of a "proton" of radius R colliding with a sheet show hydrodynamic flow in the final state as long as the collision has enough energy such that $RT_{\rm hydrodynamization} \gtrsim 0.5$ to 1.**
- **Hydrodynamic behavior in small-big collisions at top RHIC energy and LHC energy. less surprising, *a posteriori*.**
- **"Stressing" the liquid by making the smallest droplets we can make (prior to eA collider) seems not to disturb its liquidness. So, lower $T_{\rm hydrodynamization}$ and try again: very interesting to look at dAu collisions at lower energies at RHIC, to see whether and how hydrodynamics turns off.**

Colliding Strongly Coupled Sheets of Energy

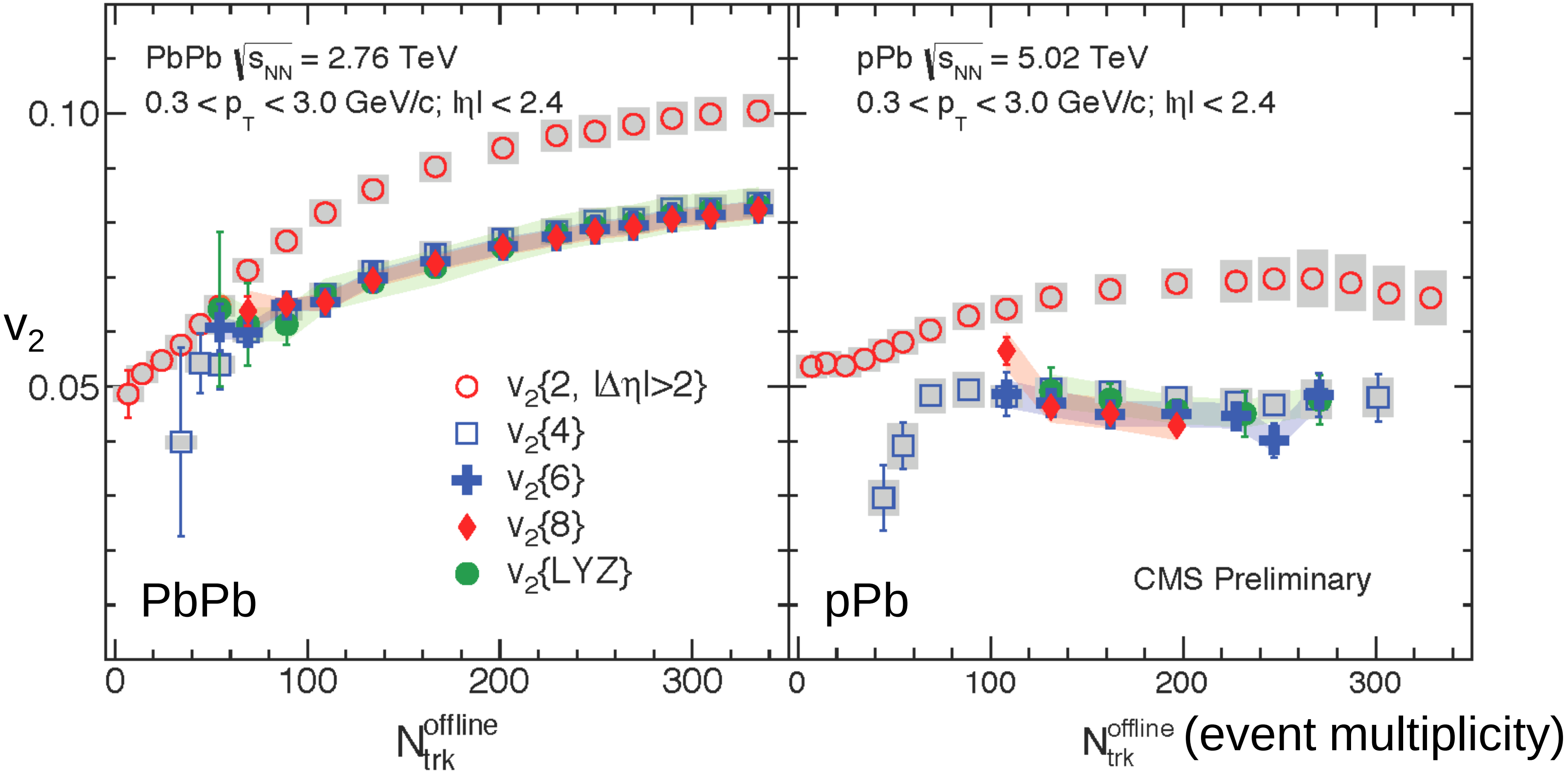


Hydrodynamics valid ~ 3 **sheet thicknesses after the collision, i.e.** ~ 0.35 **fm after a RHIC collision. Equilibration after** ~ 1 **fm need not be thought of as rapid.** Chesler, Yaffe 1011.3562; generalized in C-S,H,M,vdS 1305.4919; CY 1309.1439 **Similarly 'rapid' hydrodynamization times** ($\tau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

Multiparticle correlations

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

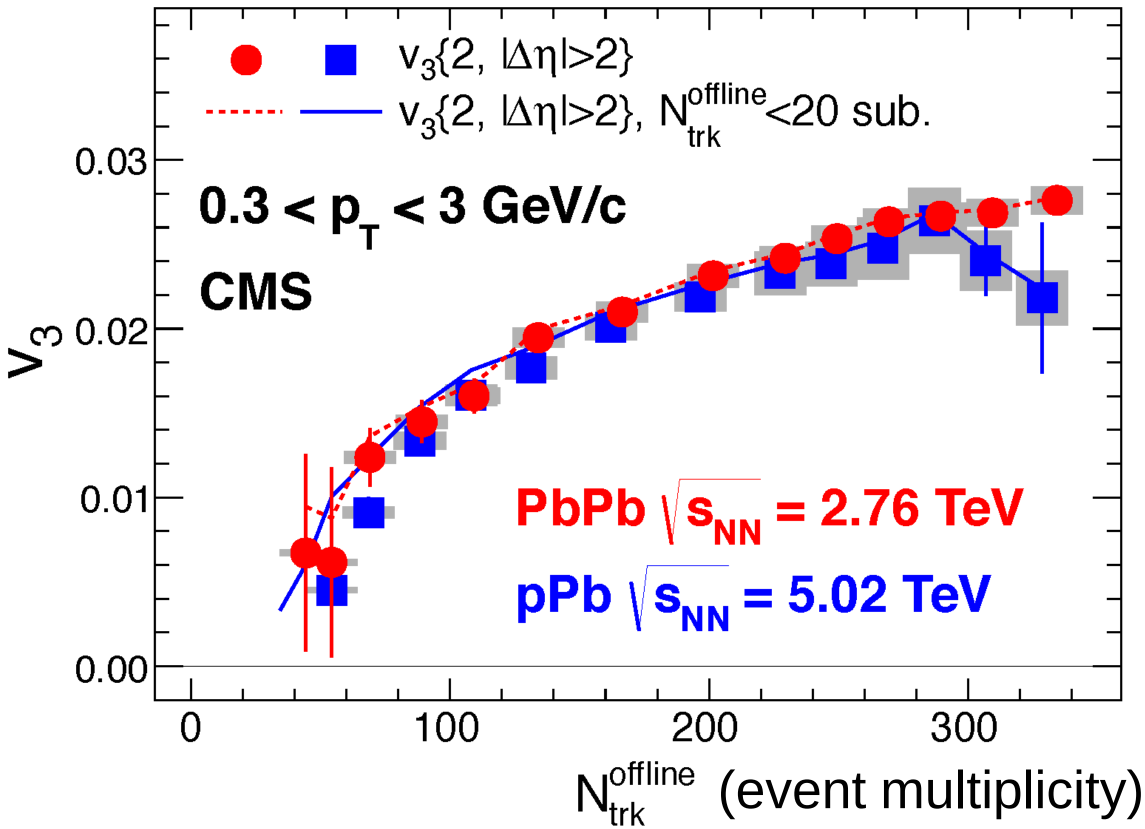
Talk by Wang
PAS-HIN-14-006

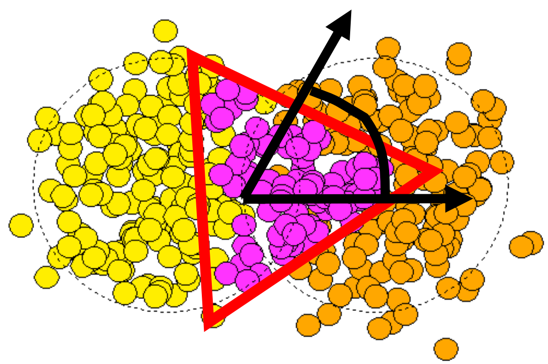


Triangular flow

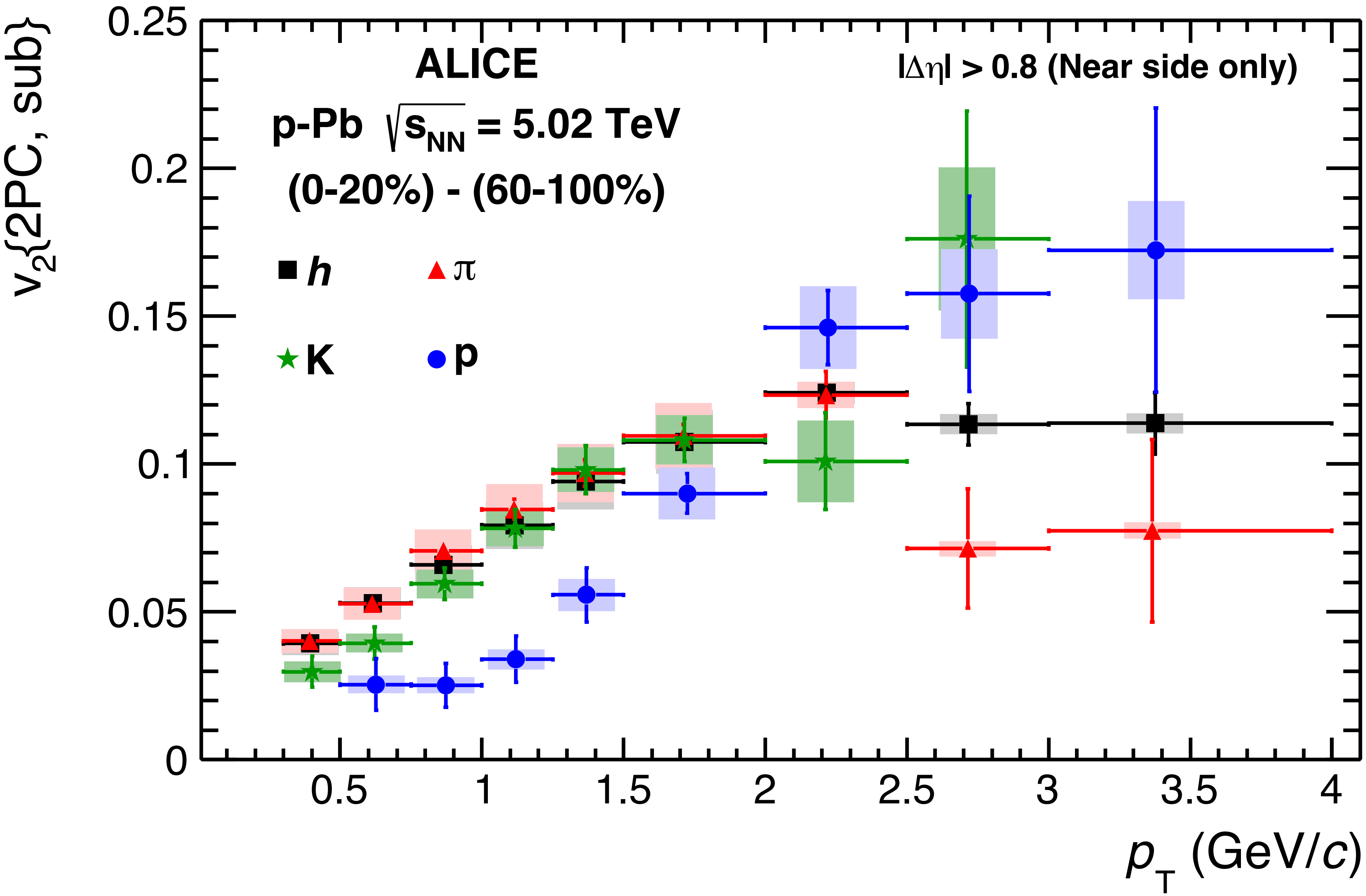
- Remarkable similarity in the v_3 signal as a function of multiplicity in pPb and PbPb

PLB724 (2013) 213





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

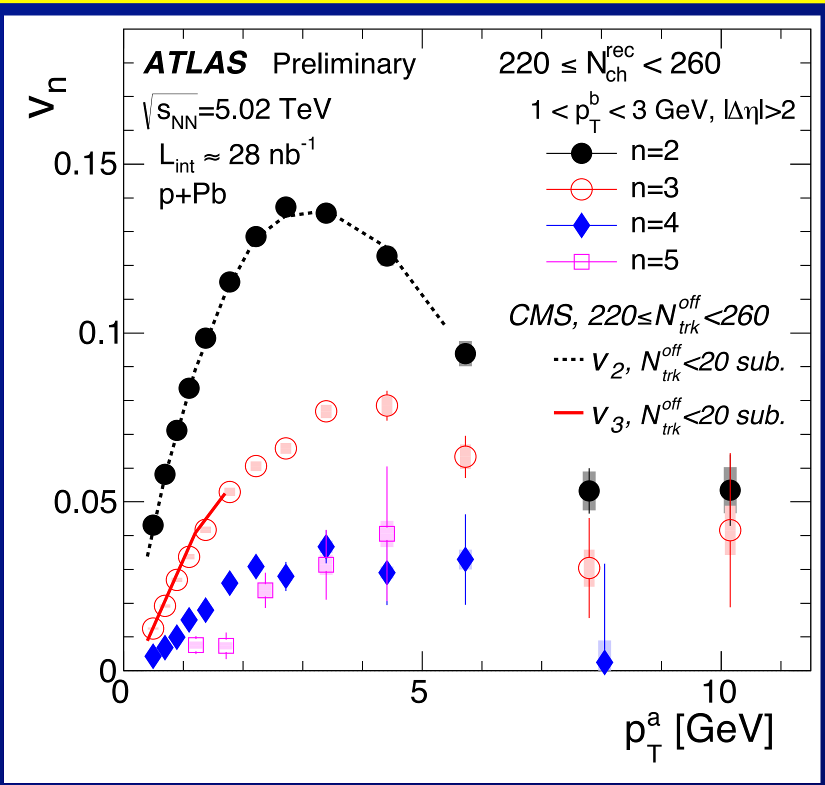


- $v_{2,\pi}$ similar to $v_{2,h}$
- hint of $v_{2,K}$ smaller than $v_{2,\pi}$ at low p_T
- $v_{2,p}$ smaller than $v_{2,\pi}$ below 2 GeV/c and larger above
- crossing at about 2 GeV/c

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

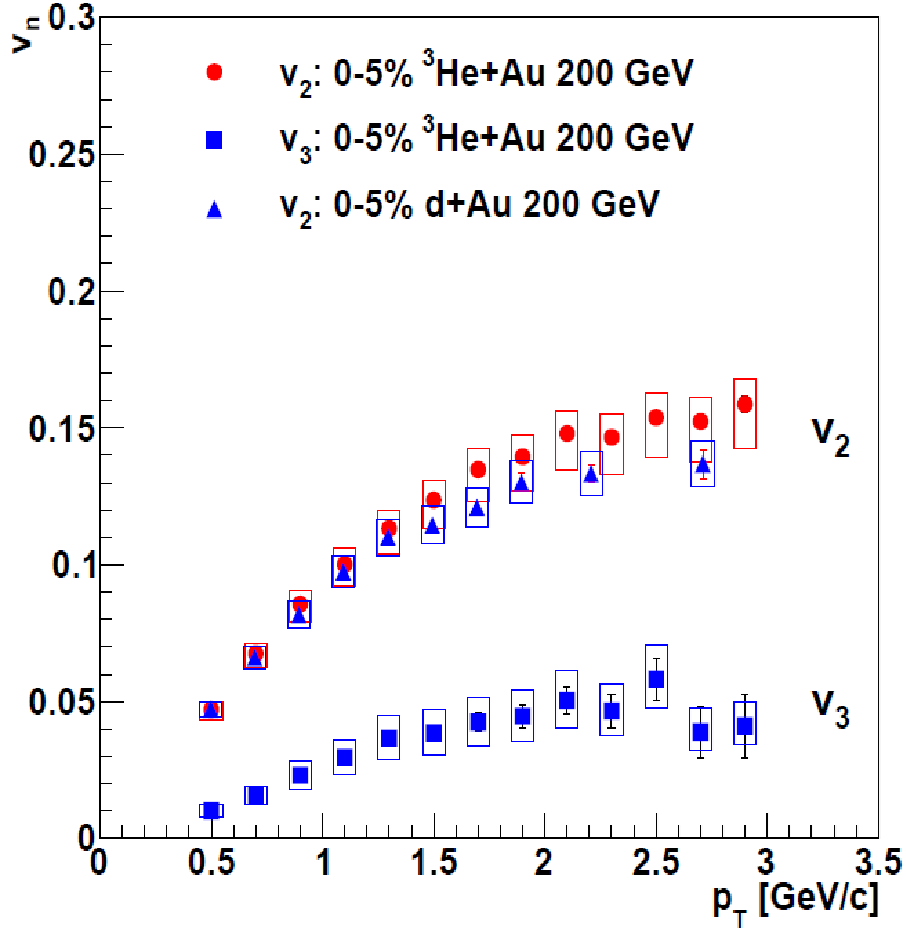
p+Pb 2-particle $v_n(p_T)$

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



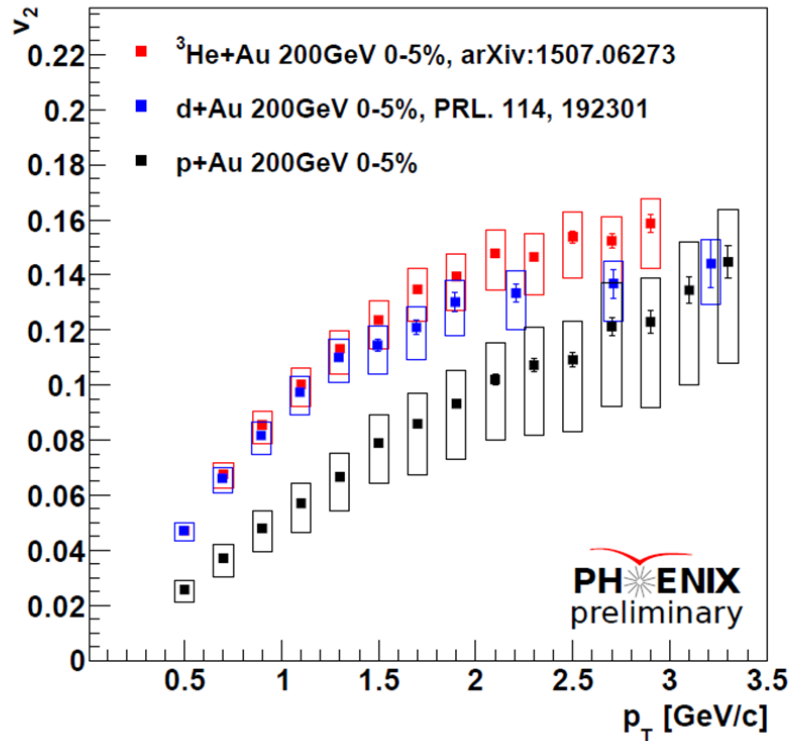
Flow in Small Systems at $\sqrt{s_{NN}}$ = 200 GeV

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



Top 5% in centrality

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



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

Stony Brook University

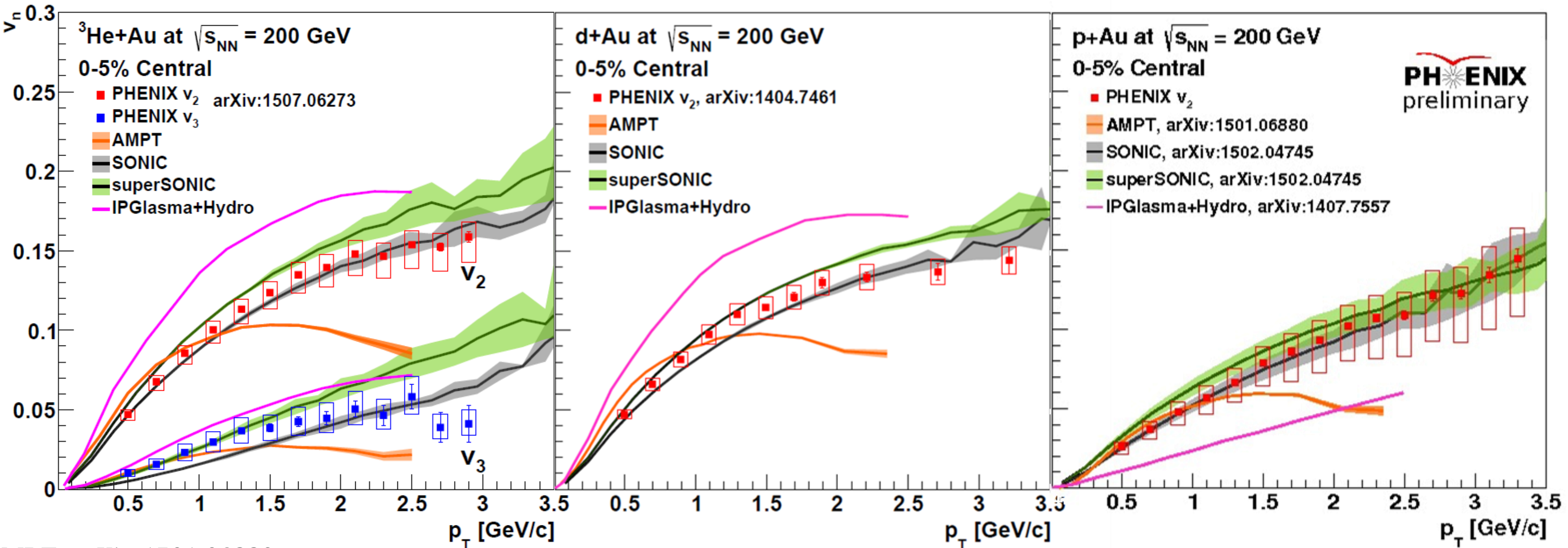
PHENIX

Comparison to Model Predictions

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

IPGlasma + hydrodynamic
AMPT parton + hadron cascade

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



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

Sensitivity to initial conditions and early time evolution

Stony Brook University

PHENIX

Smallest possible droplet of liquid?

- **What is the smallest possible droplet of QGP that behaves hydrodynamically? Anyone doing holographic calculations at strong coupling, or anyone seeing effects of small lumps in the initial state visible in the final state, could have asked this question, but didn't. Question was asked by data: pPb collisions @LHC, then dAu and ^{3}HeAu data @RHIC.**
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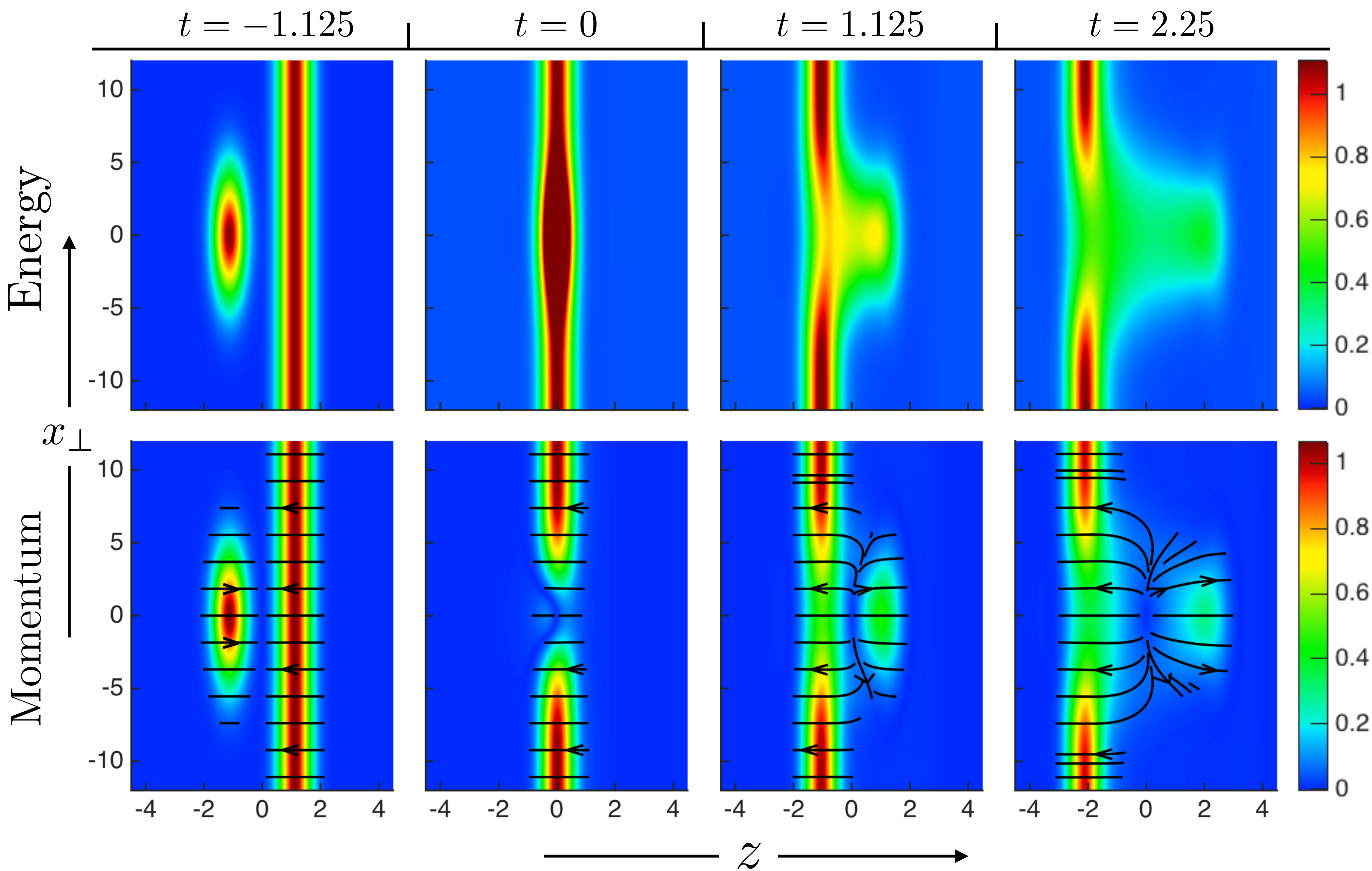
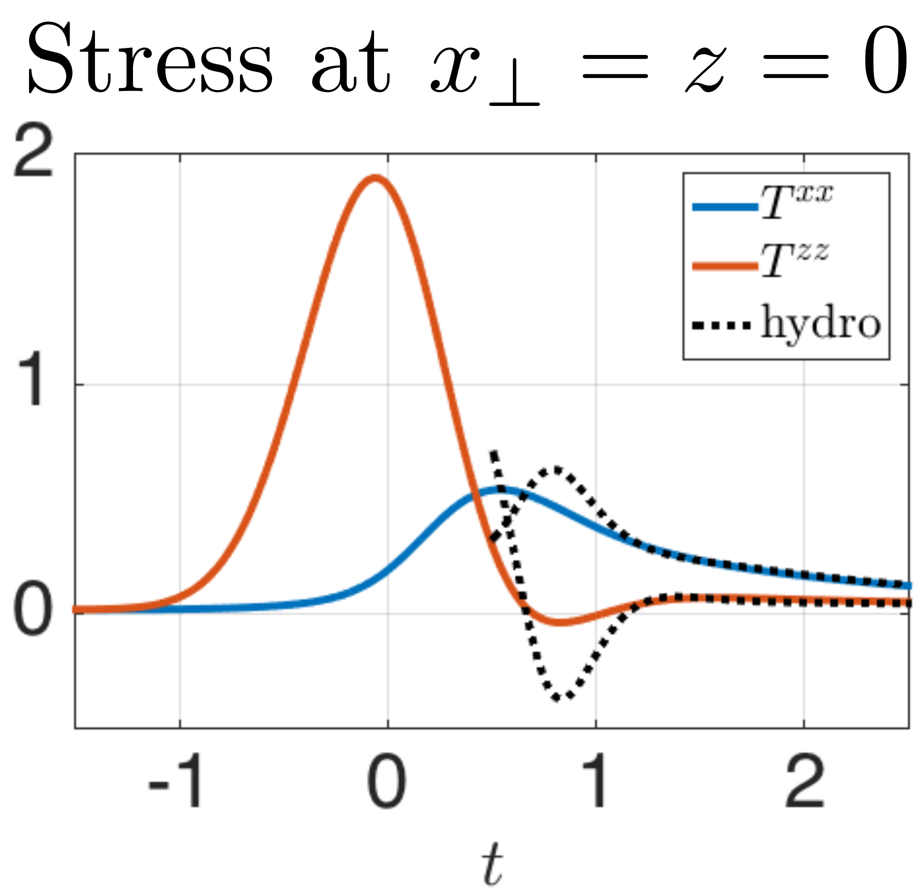
- **"Stressing" the liquid by making the smallest droplets we can make (prior to eA collider) seems not to disturb its liquidness. So, lower $T_{\text{hydrodynamization}}$ and try again: very interesting to look at dAu collisions at lower energies at RHIC, to see whether and how hydrodynamics turns off.**

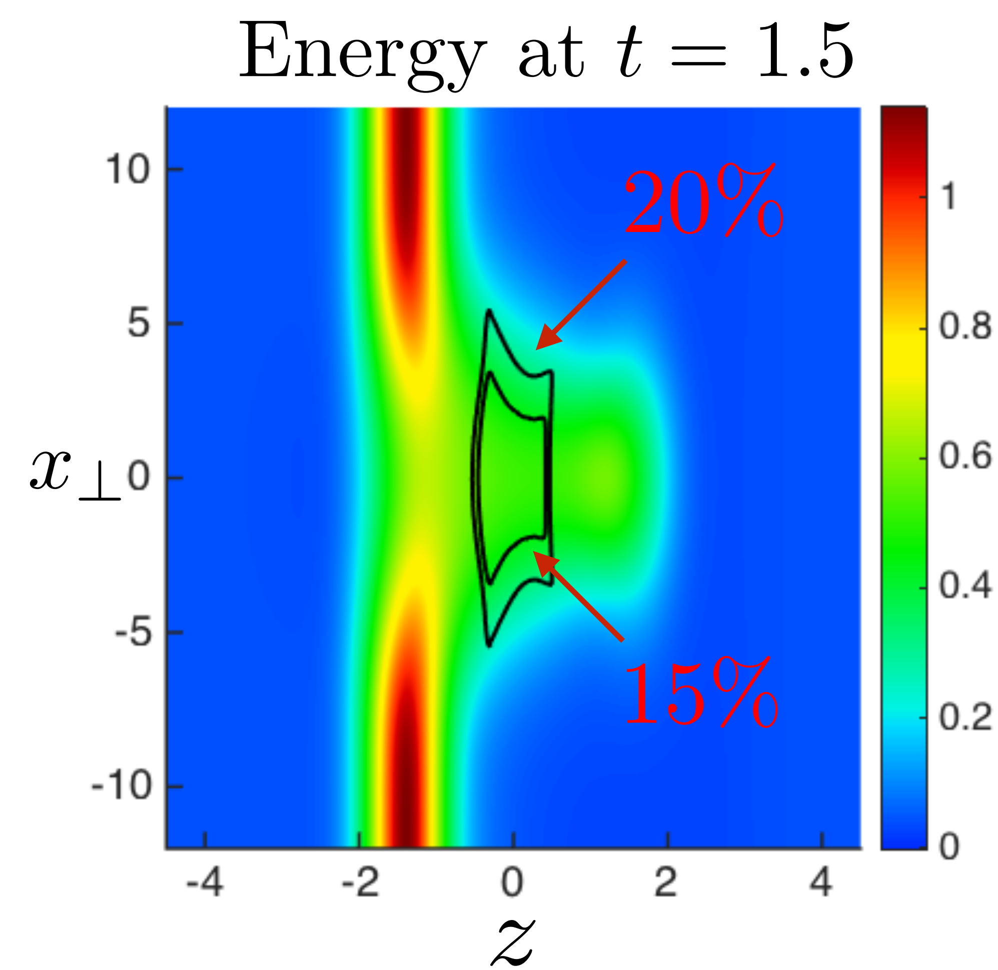
Results illustrated

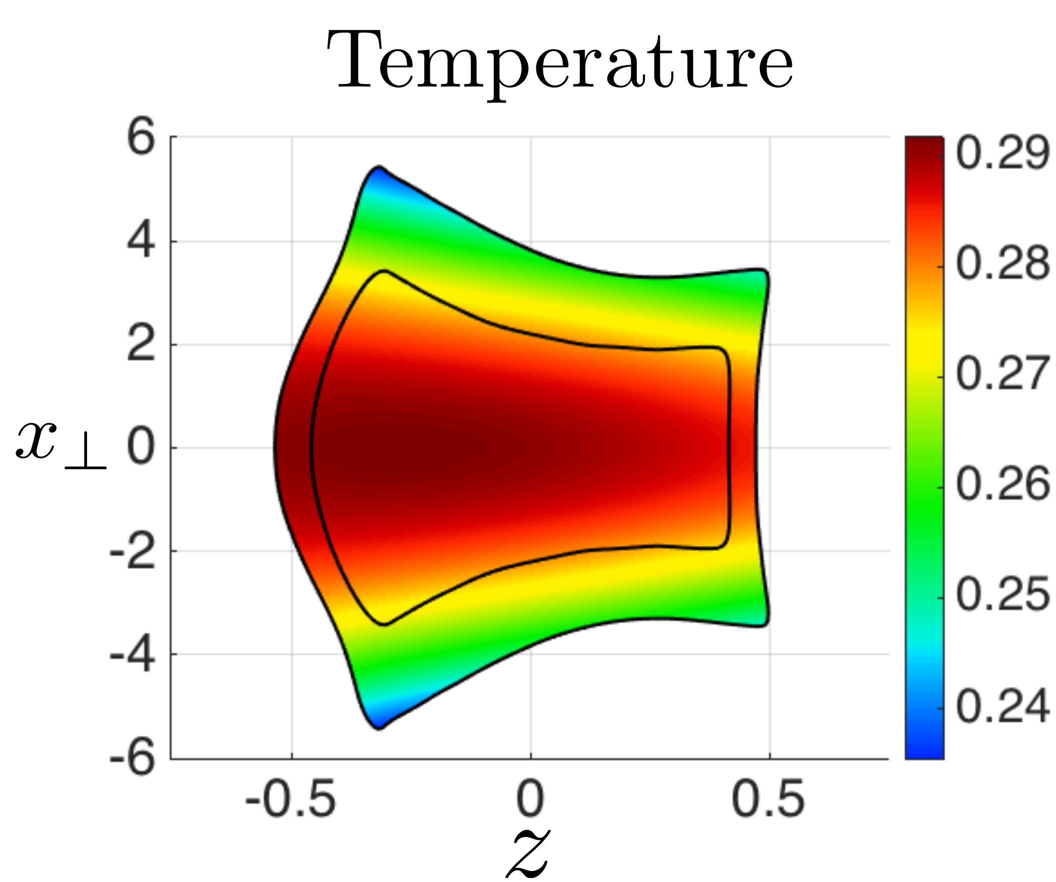
[PC: 1506.02209]



A tiny drop of liquid







How small of a droplet?

- Effective temperature

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

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

Rapid equilibration?

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

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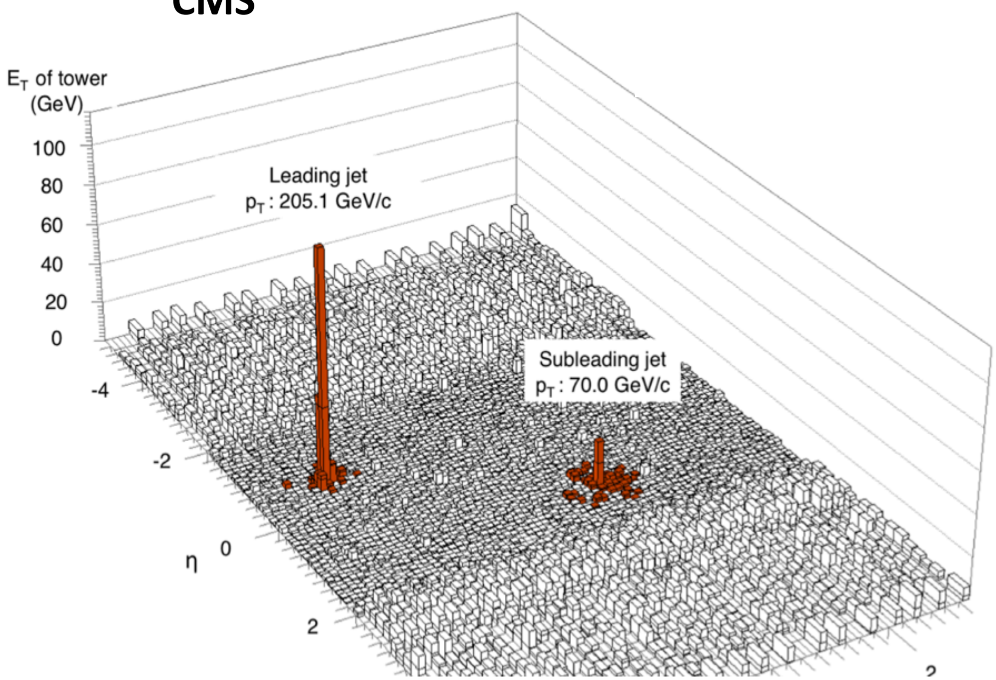
Jets as Probes of QGP

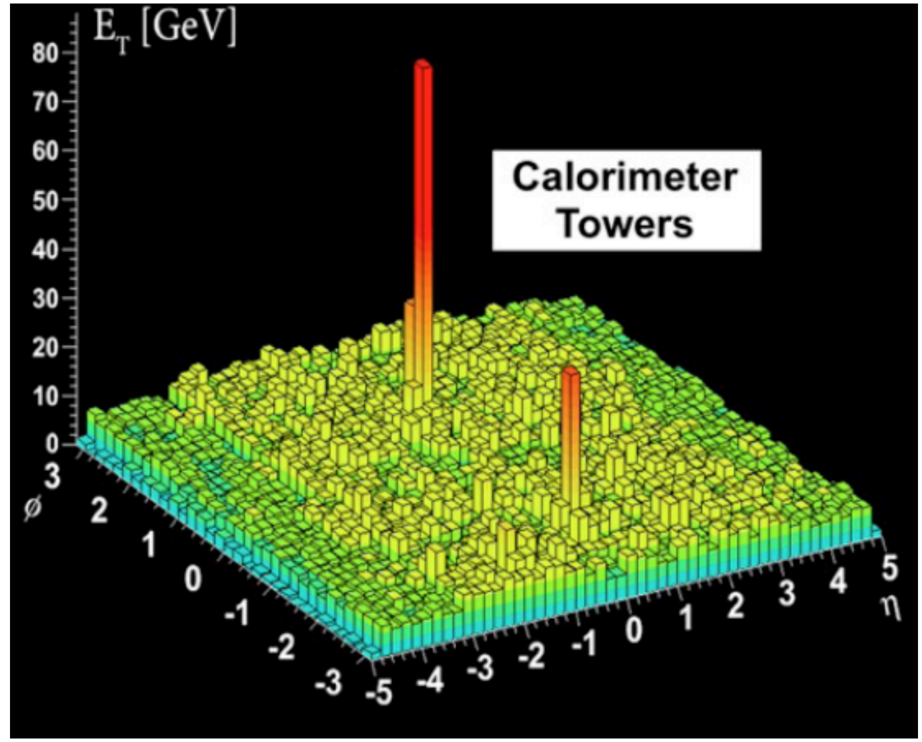
- Comparison between observed flow and hydrodynamic calculations can quantify the properties of Liquid QGP at its natural length scales $\sim 1/T$, where it has no quasiparticles.
- What is its microscopic structure? QCD is asymptotically free. When looked at with sufficient resolution, QGP must be made of weakly coupled quarks and gluons.
- How does the strongly coupled liquid emerge, at length scales $\sim 1/T$, 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.
- Need experimental evidence for point-like scatterers in QGP when QGP is probed with large momentum transfer. 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.

Jet Quenching at the LHC

CMS



ATLAS



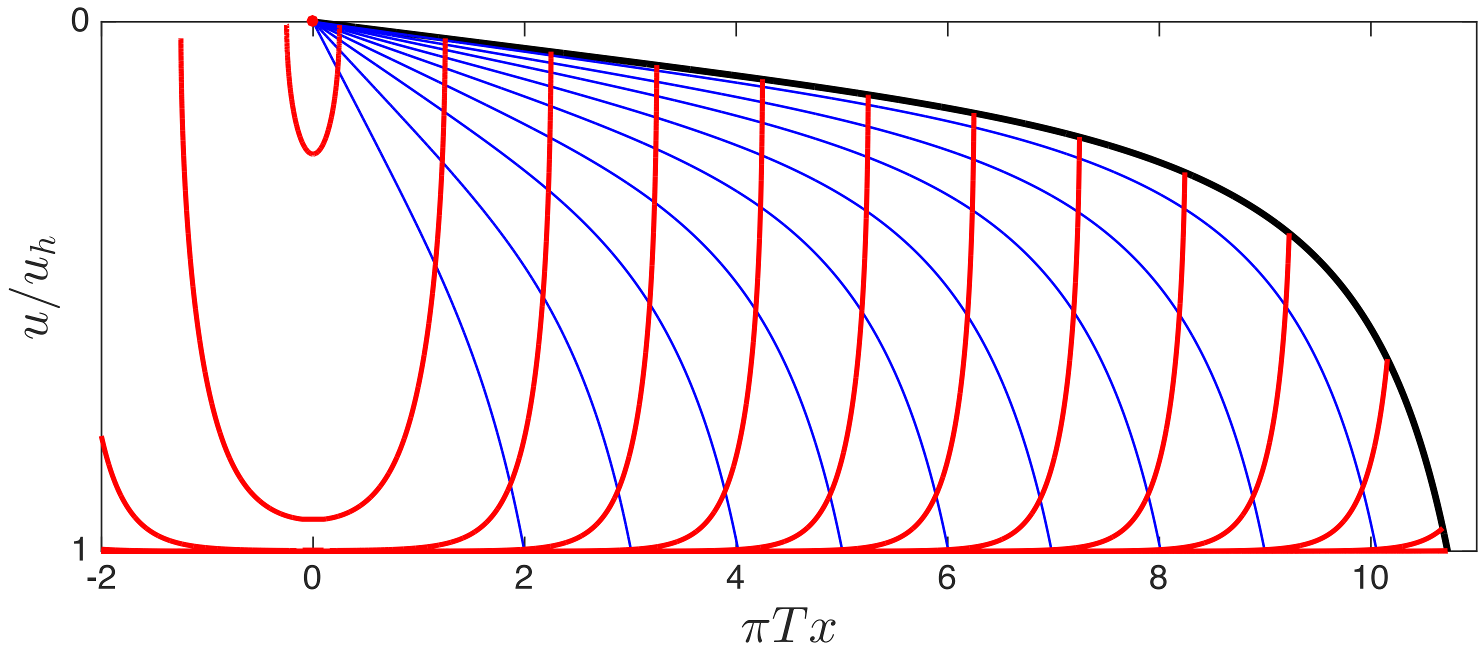
A large effect at the LHC. A strongly coupled plasma indeed.... Jet quenching was discovered at RHIC (via the associated diminution in the number of high-p_T hadrons) but here it is immediately apparent, and its effects (of many types) on reconstructed jets can be seen.

How to Do This?

- Addressing how a strongly coupled liquid emerges 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 I 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 a bit about holographic calculations by themselves, as a source of qualitative insight.

Quenching a Light Quark "Jet"

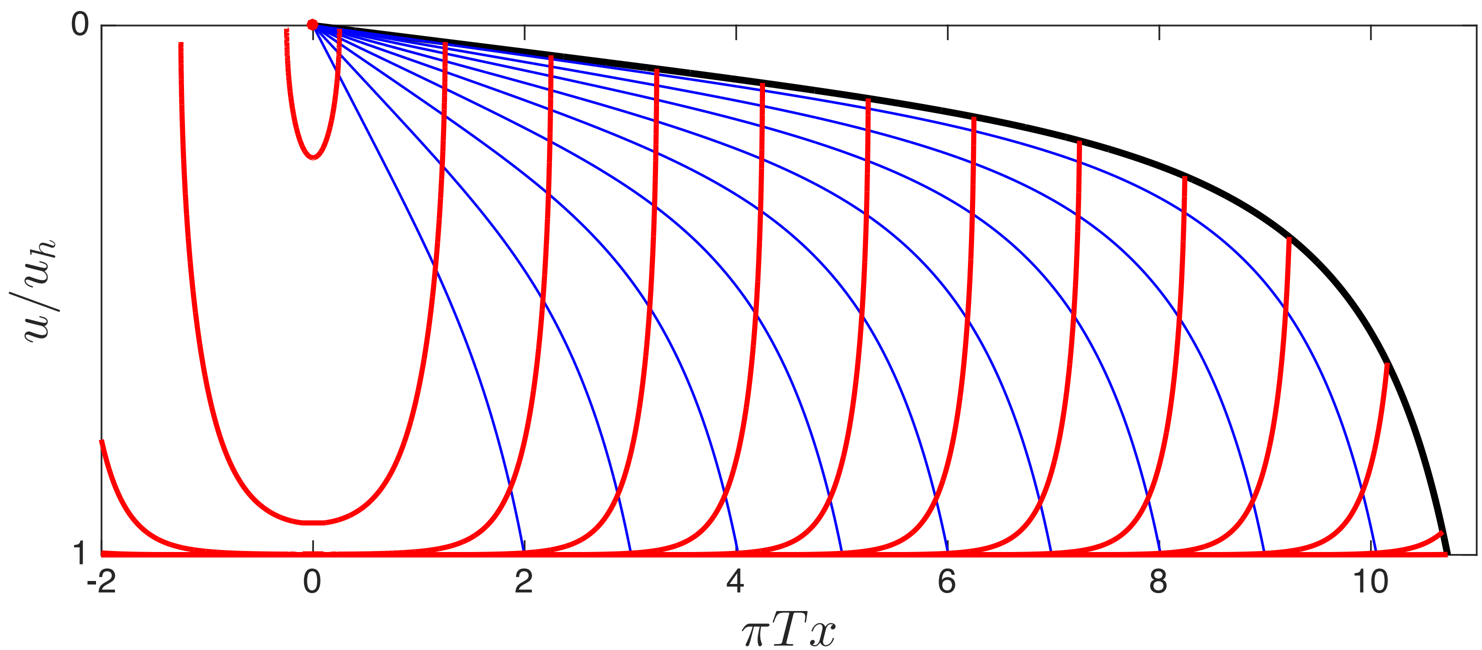
Chesler, Rajagopal, 1402.6756, 1511.07567



- 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”

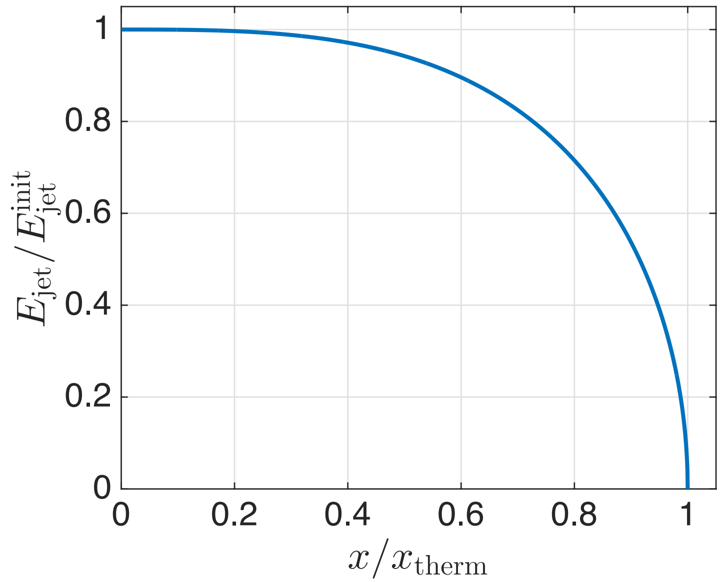
Chesler, Rajagopal, arXiv:1402.6756, 1511.07567



- **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.**

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756, 1511.07567



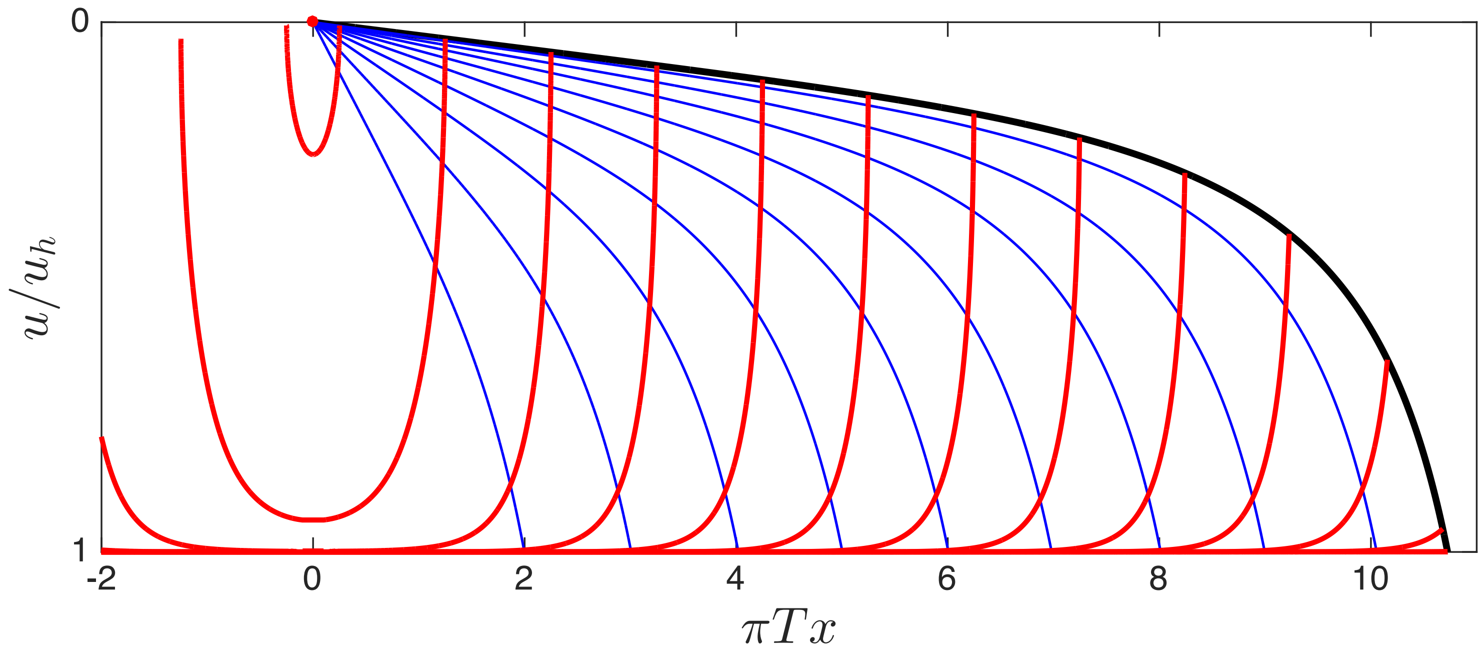
We compute E_{jet} analytically, by integrating the energy flowing into hydrodynamic modes, and showing its equivalence to that falling into the horizon. Geometric derivation of analytic expression for dE_{jet}/dx

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

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

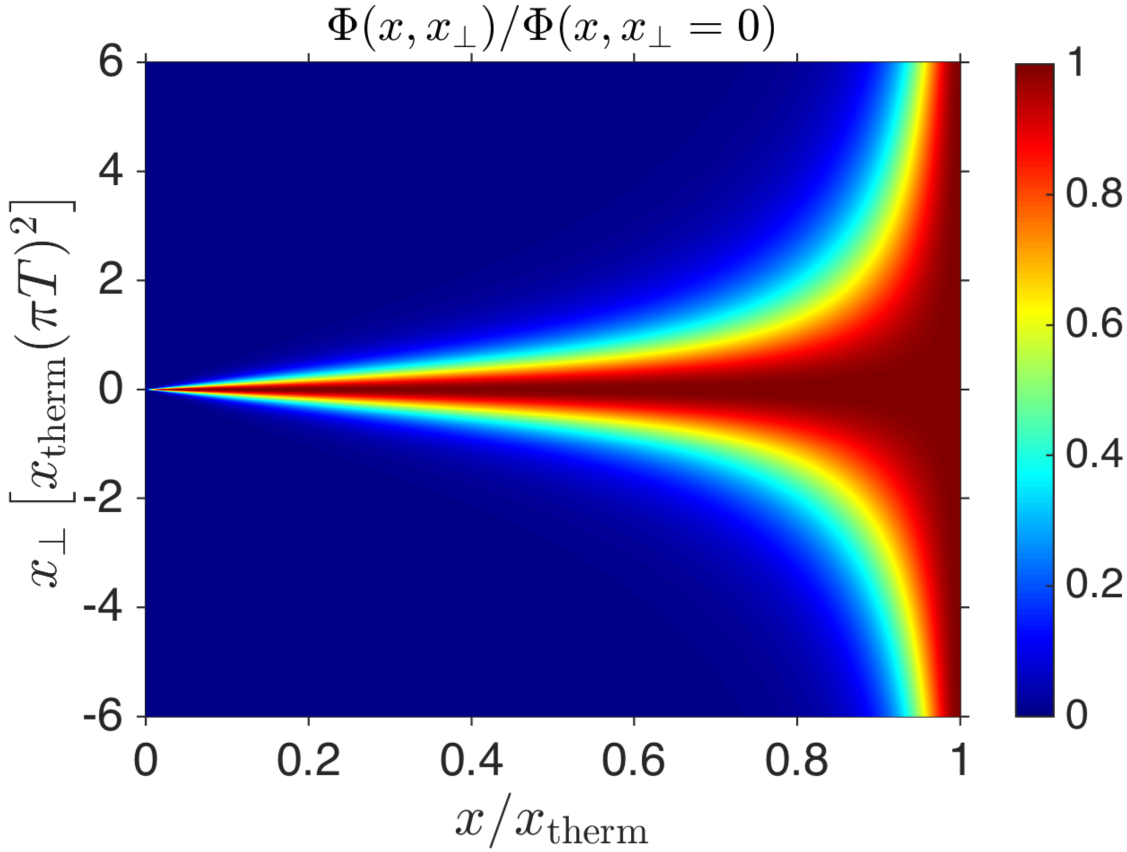


Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

- **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

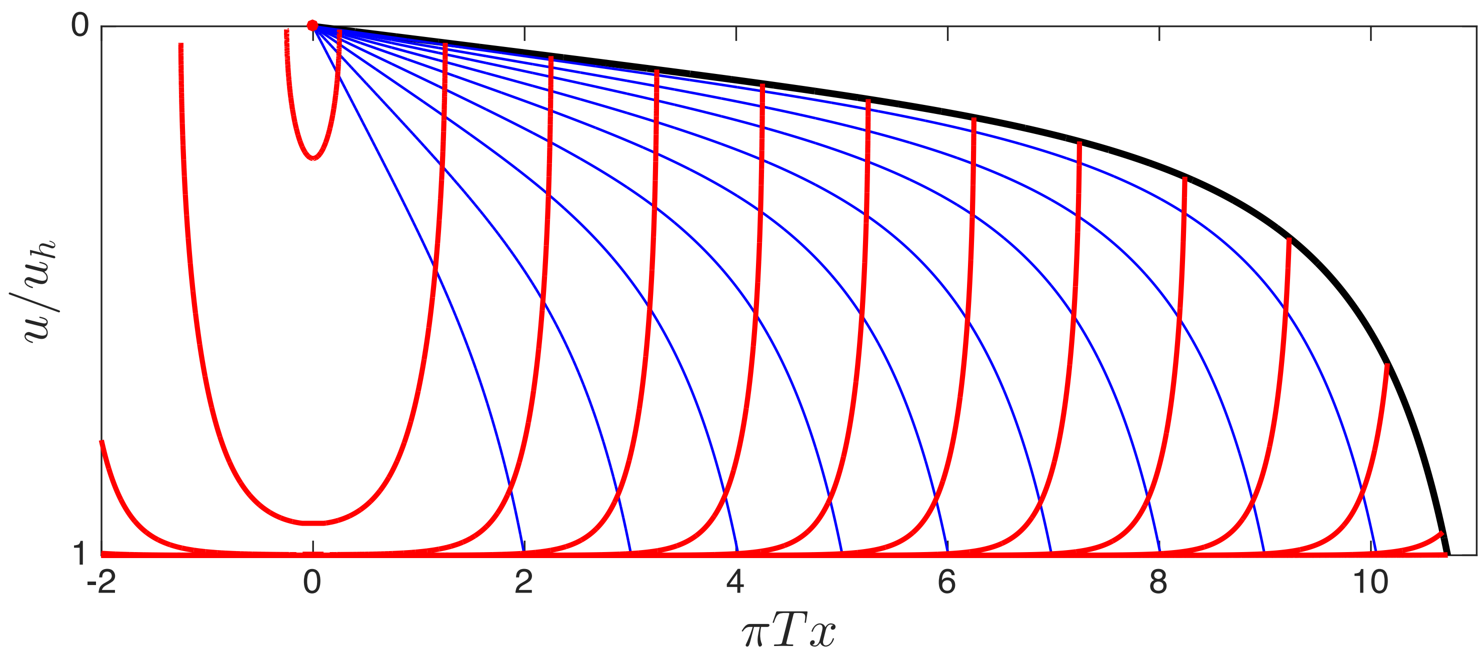
Chesler, Rajagopal, arXiv:1511.07567



- **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

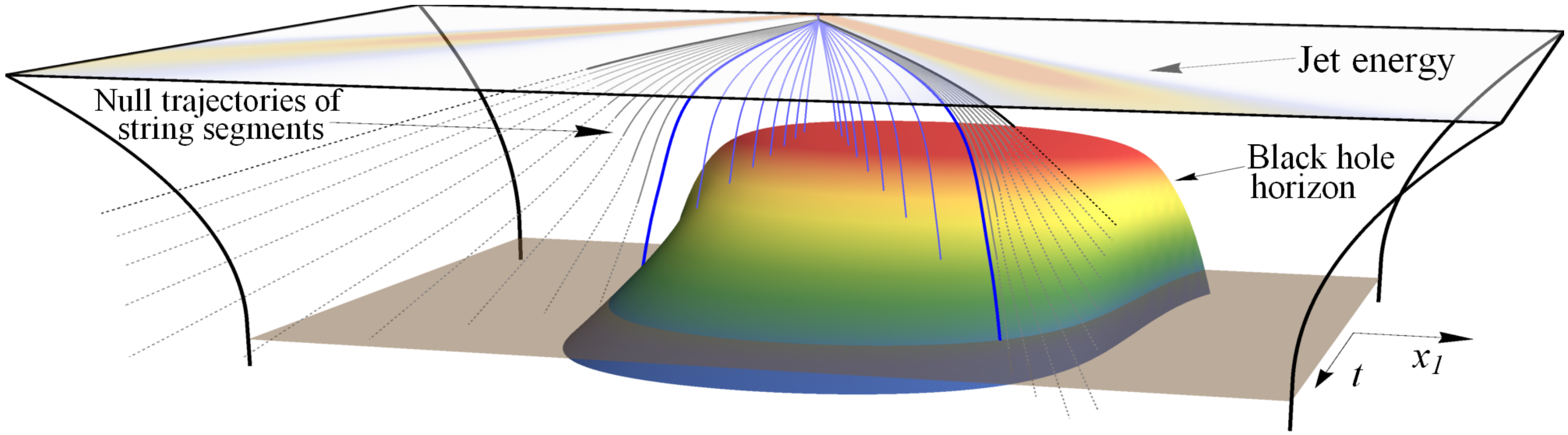


Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

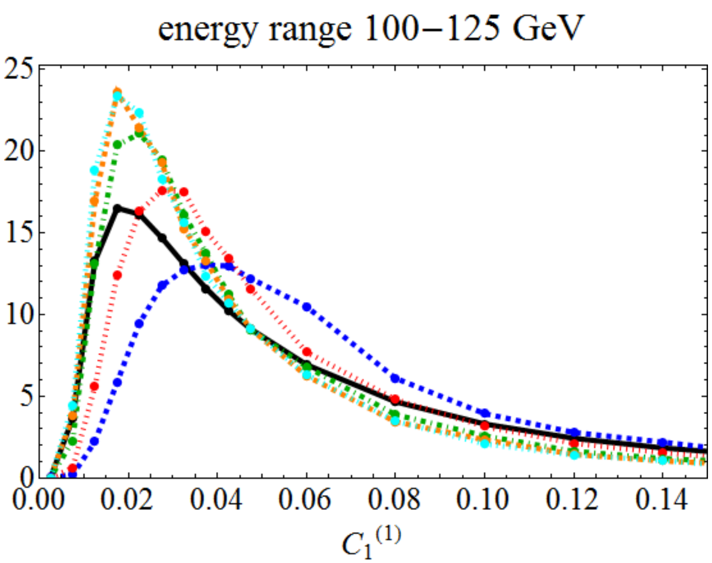
- **Second, jets with smaller initial $\theta_{\rm jet}^{\rm init}$ have a longer $x_{\rm therm}$. They lose their energy more slowly, over a longer distance. (In fact, $T x_{\rm therm} \propto 1/\sqrt{\theta_{\rm jet}^{\rm init}}$.)**
- **That is, for jets with the same $E_{\rm jet}^{\rm init}$ that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

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...**



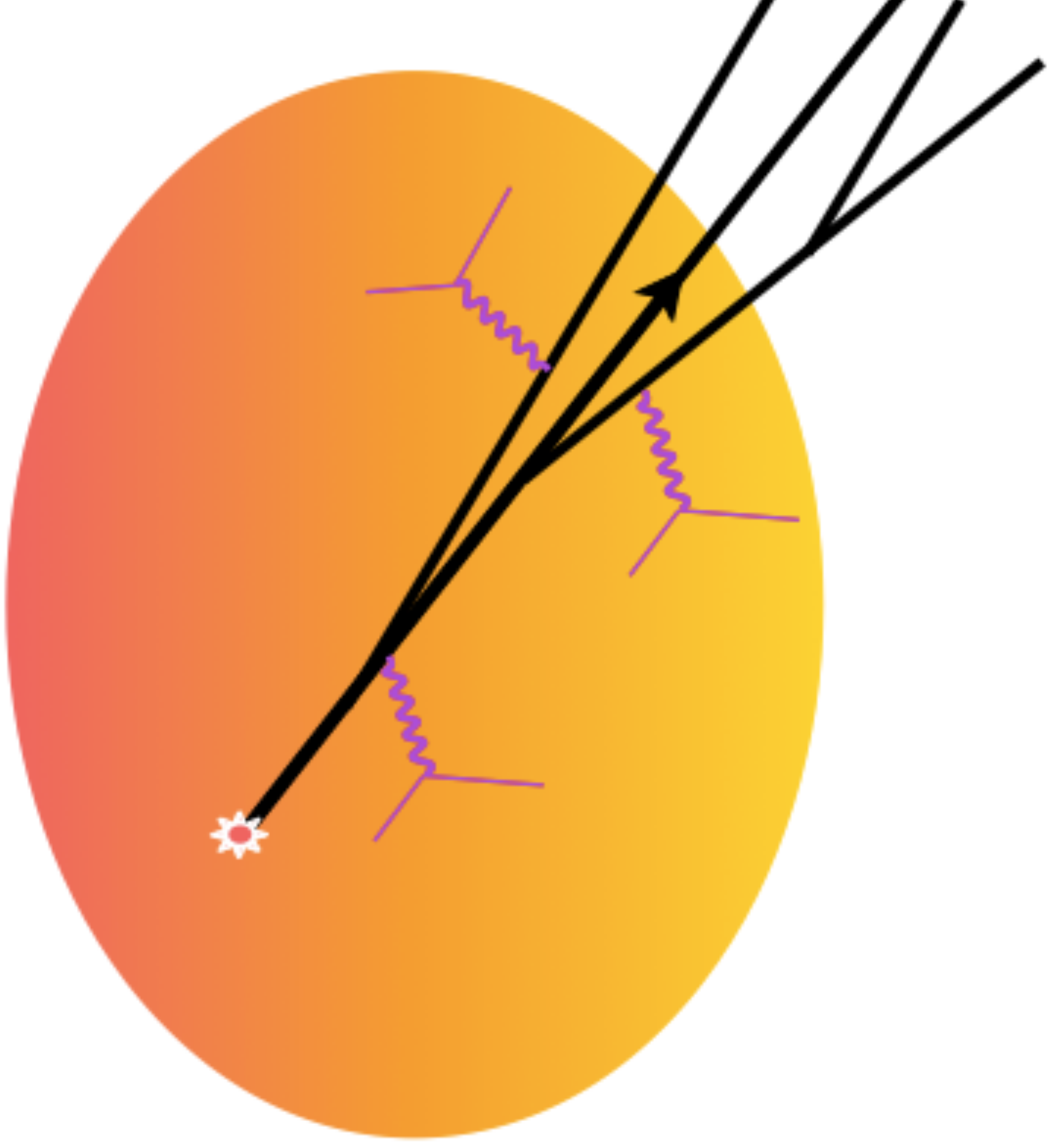
...but, at large opening angle the opening angle distribution for jets with specified E_{jet} is pushed ***down*****. (Because** ***wider jets lose much more energy*** **and drop out of the energy bin.)** ***Mean*** **opening angle easily pushed downward, as data indicate, even though opening angle of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

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: $x_{\rm therm}$ 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 and related observables.**

Monte Carlo Implementation



Jet production and evolution in PYTHIA

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

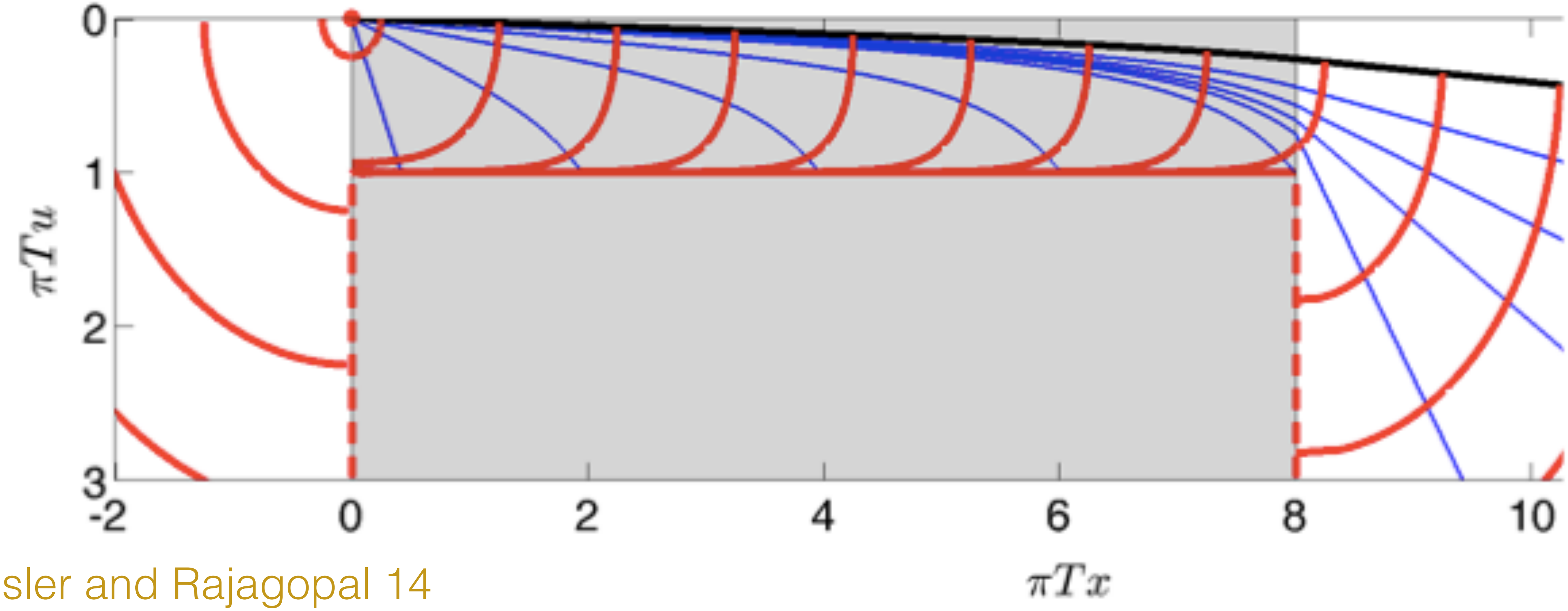
Embed the system into a hydrodynamic background (2+1 hydro code from Heinz and Shen)

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

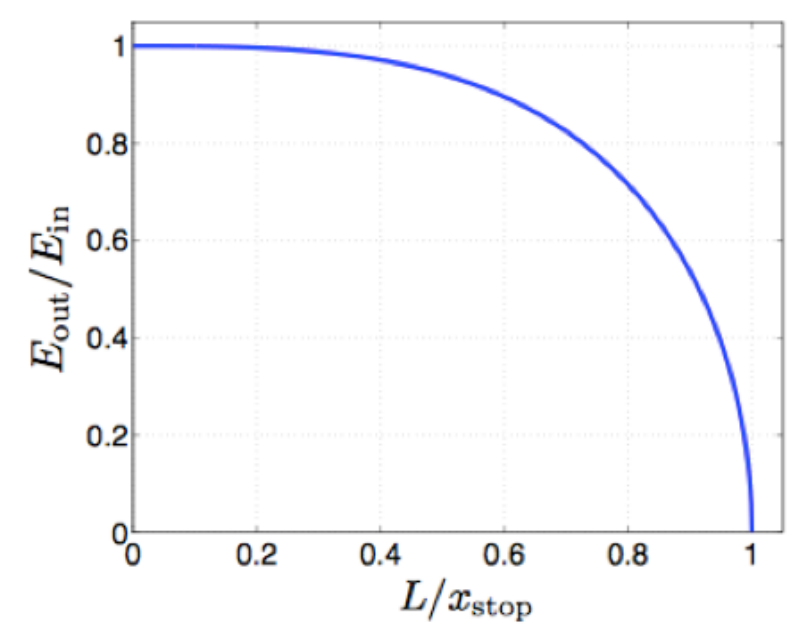
Strongly Coupled Energy Loss



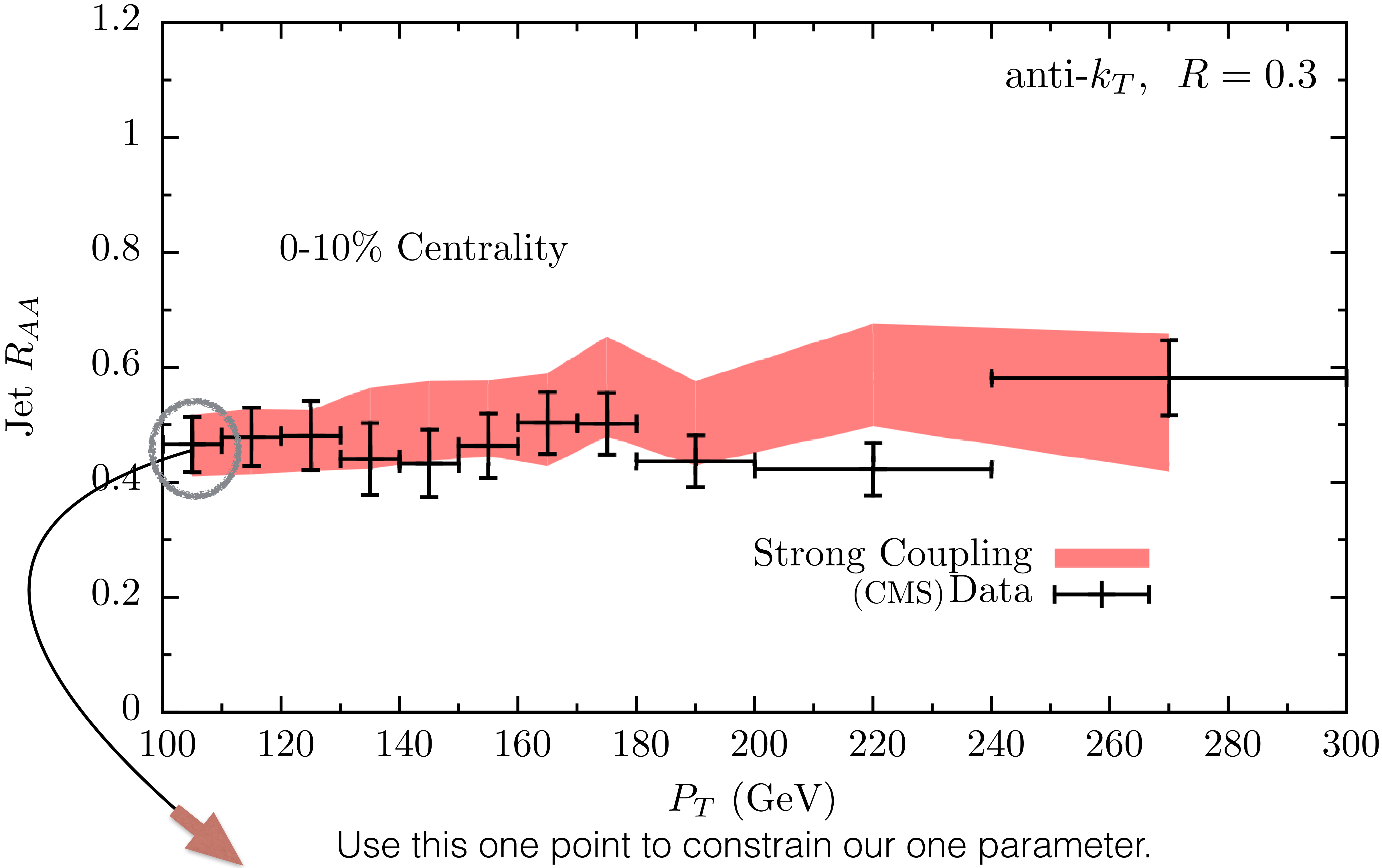
Chesler and Rajagopal 14

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

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



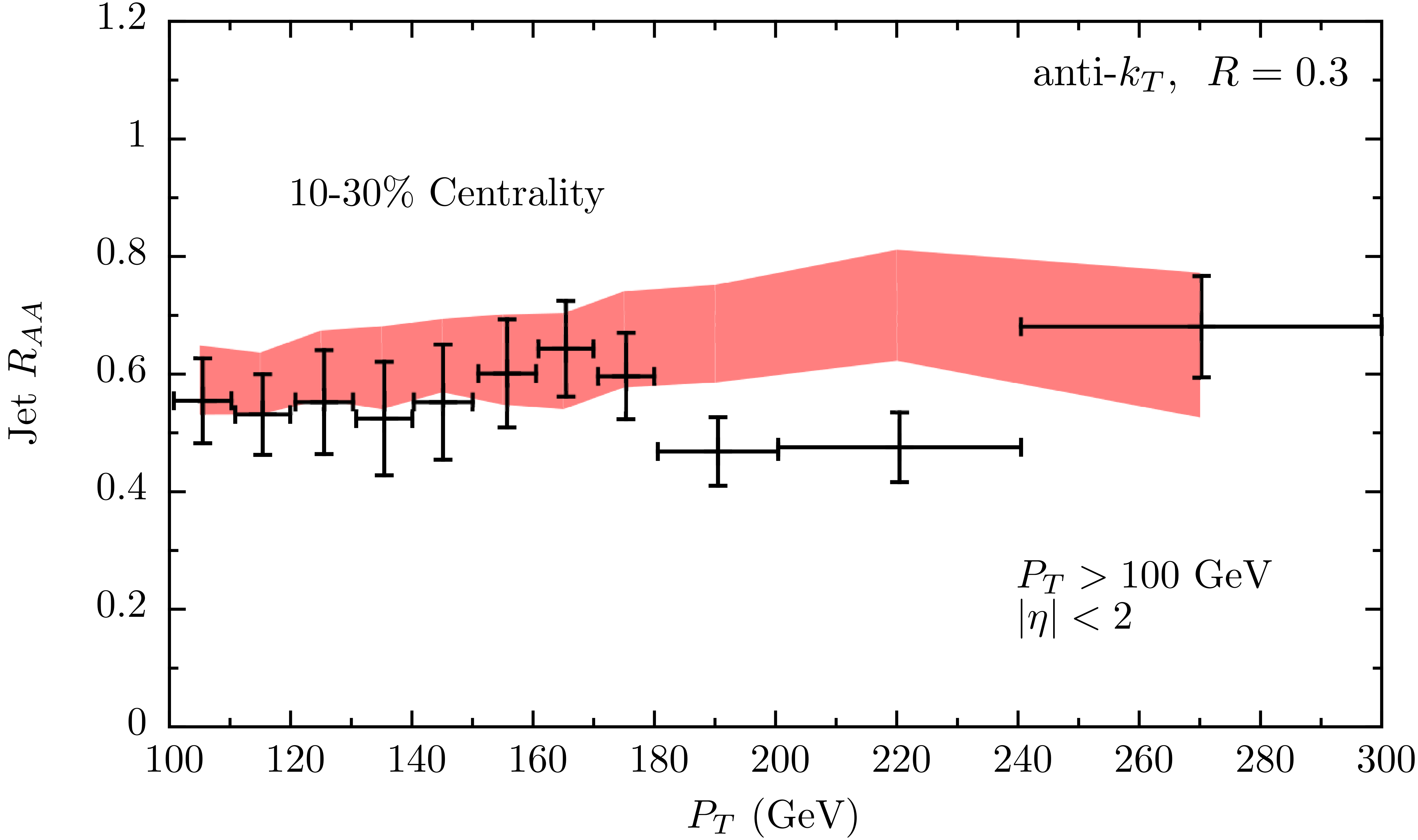
R_{AA}



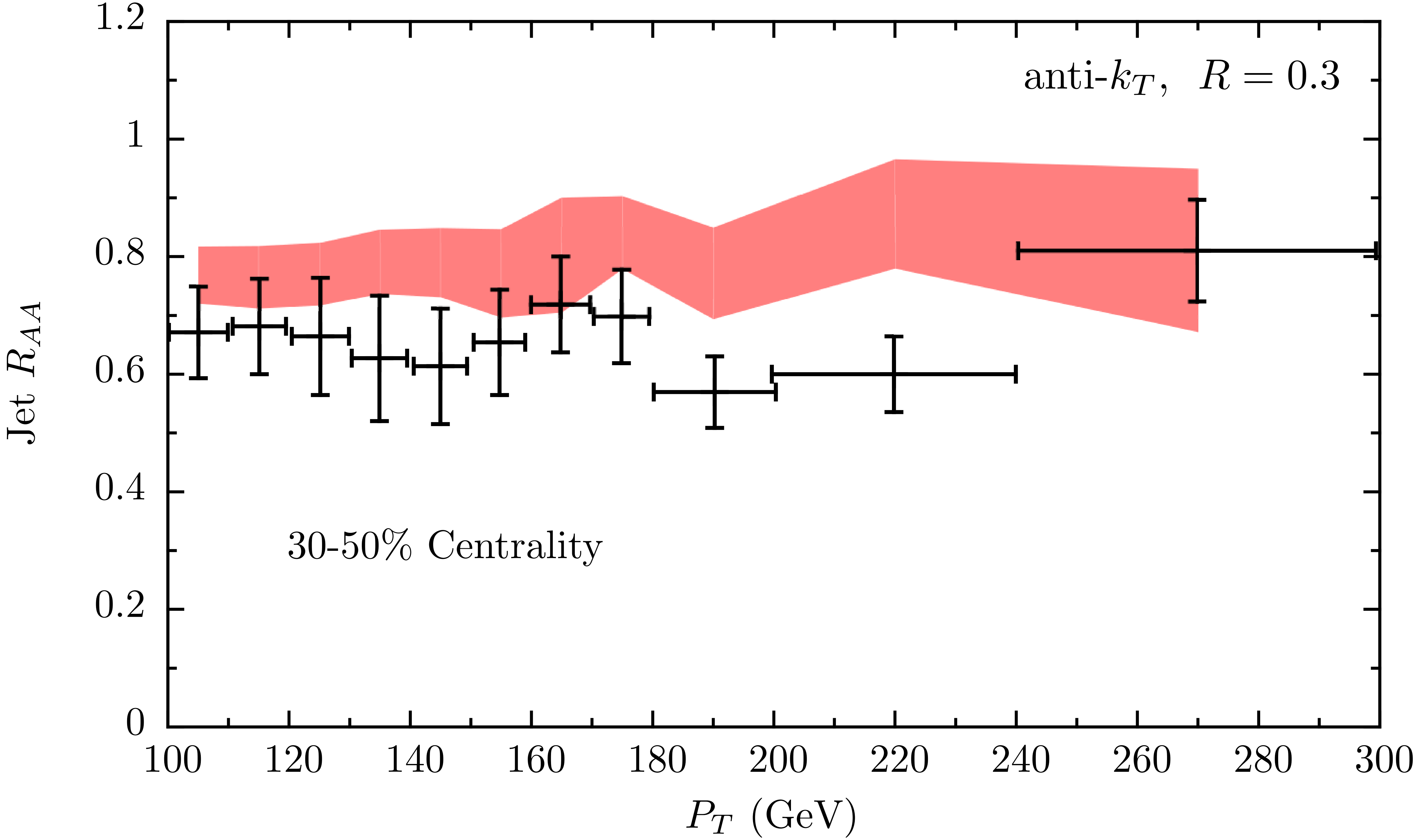
Use this one point to constrain our one parameter.

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

R_{AA}

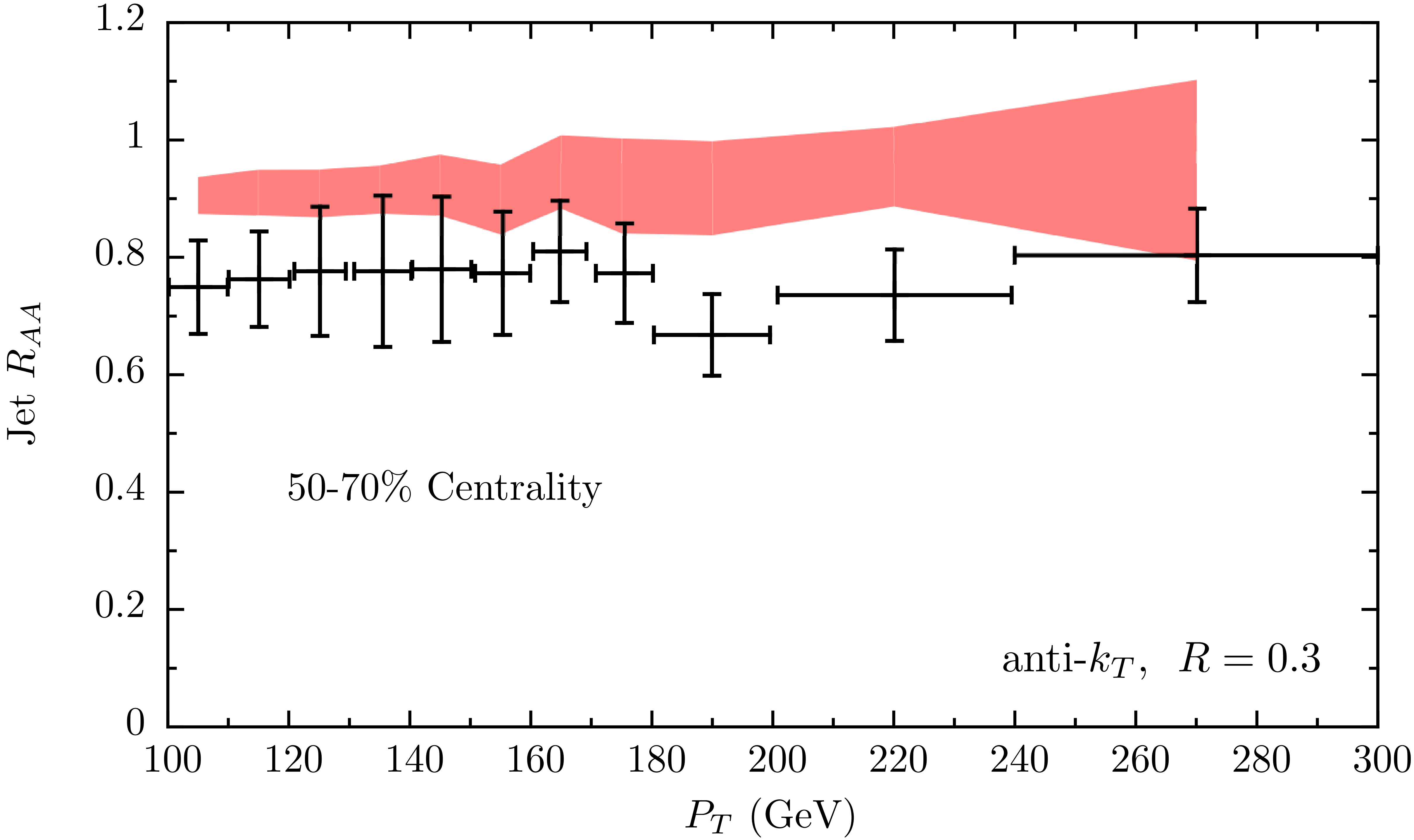

anti-k_T, $R = 0.3$
10-30% Centrality
$P_T > 100$ GeV
$|\eta| < 2$
Jet R_{AA}
P_T (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
100
120
140
160
180
200
220
240
260
280
300

R_{AA}



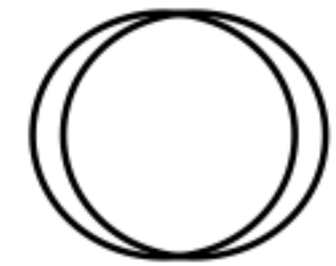
anti-k_T, $R = 0.3$
30-50% Centrality
Jet R_{AA}
P_T (GeV)
1.2
1
0.8
0.6
0.4
0.2
0
100
120
140
160
180
200
220
240
260
280
300

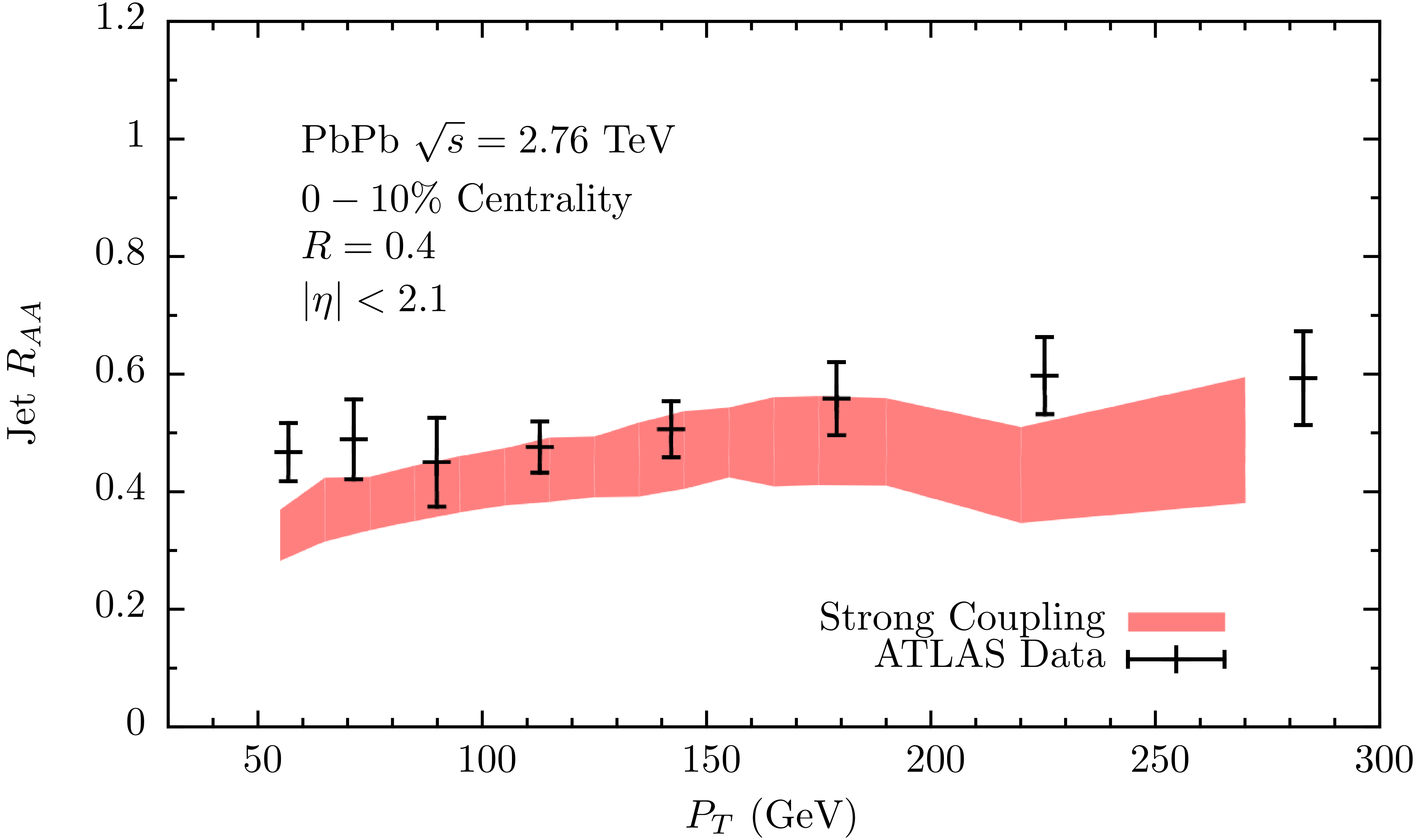
R_{AA}



We have only simulated the QGP phase

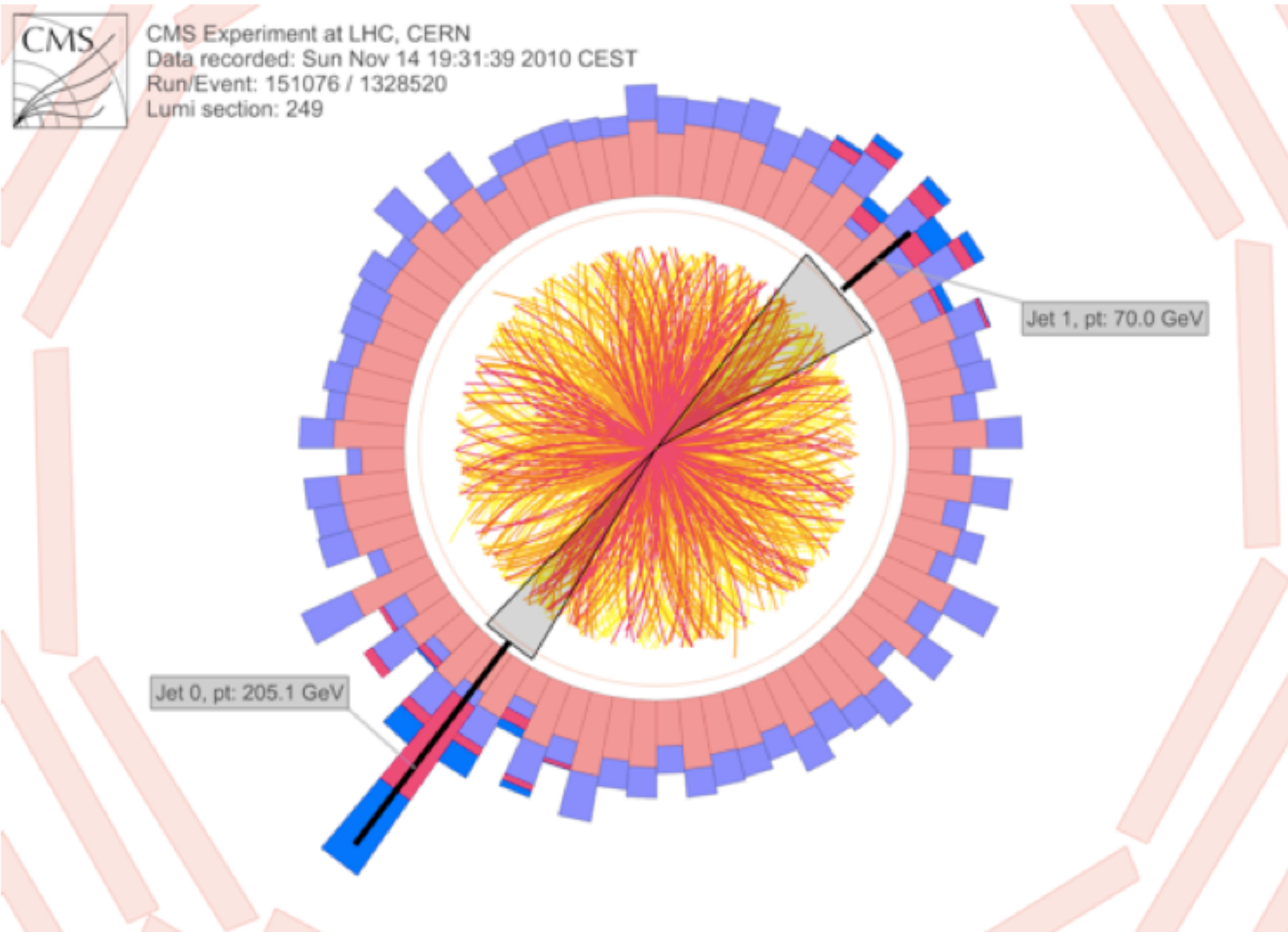
R_{AA}

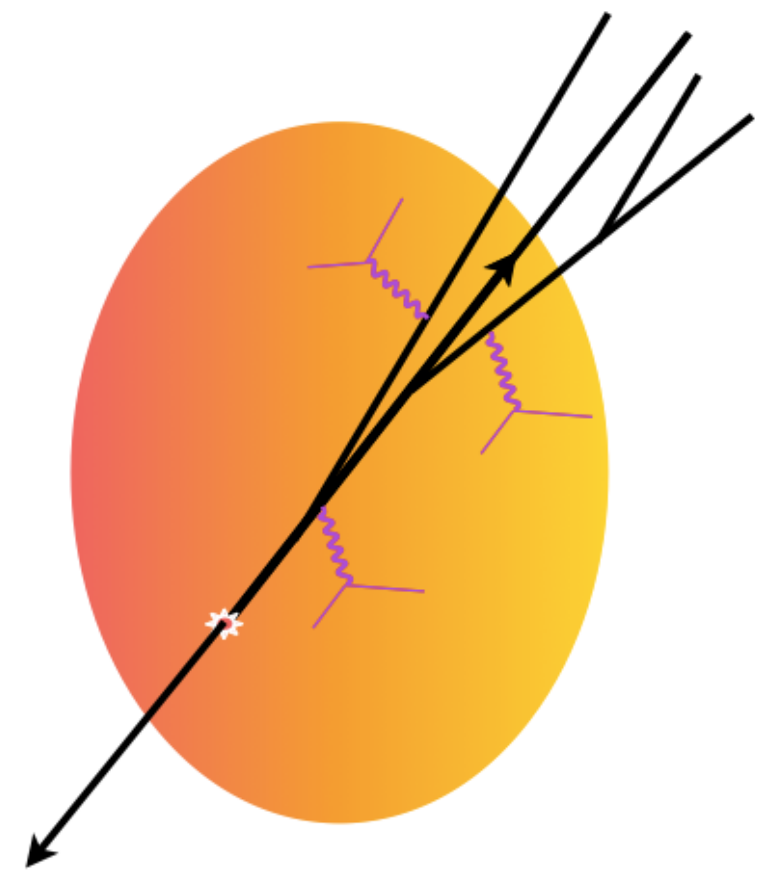




With current implementation, slightly more quenching for bigger jet radius

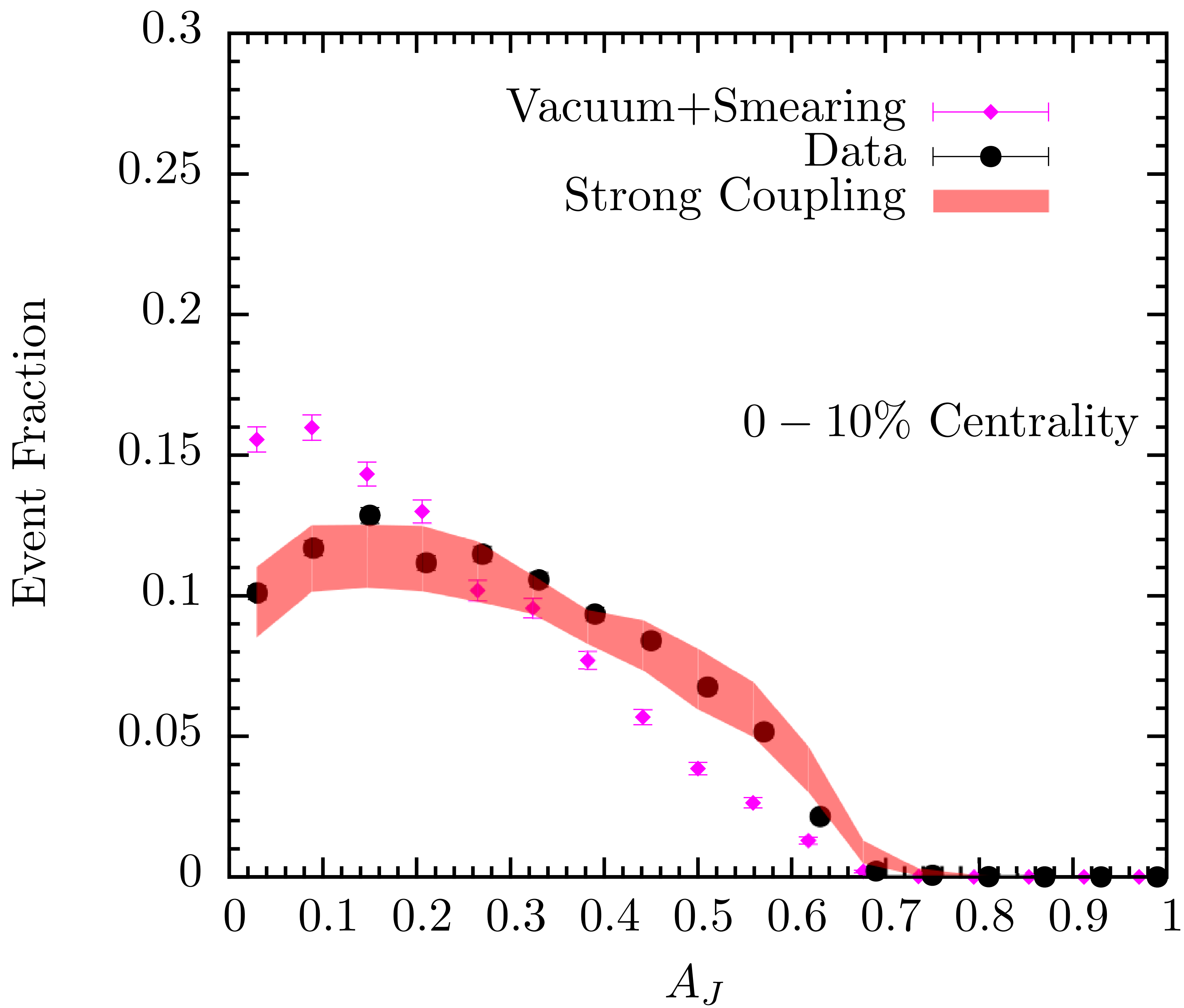
Dijets



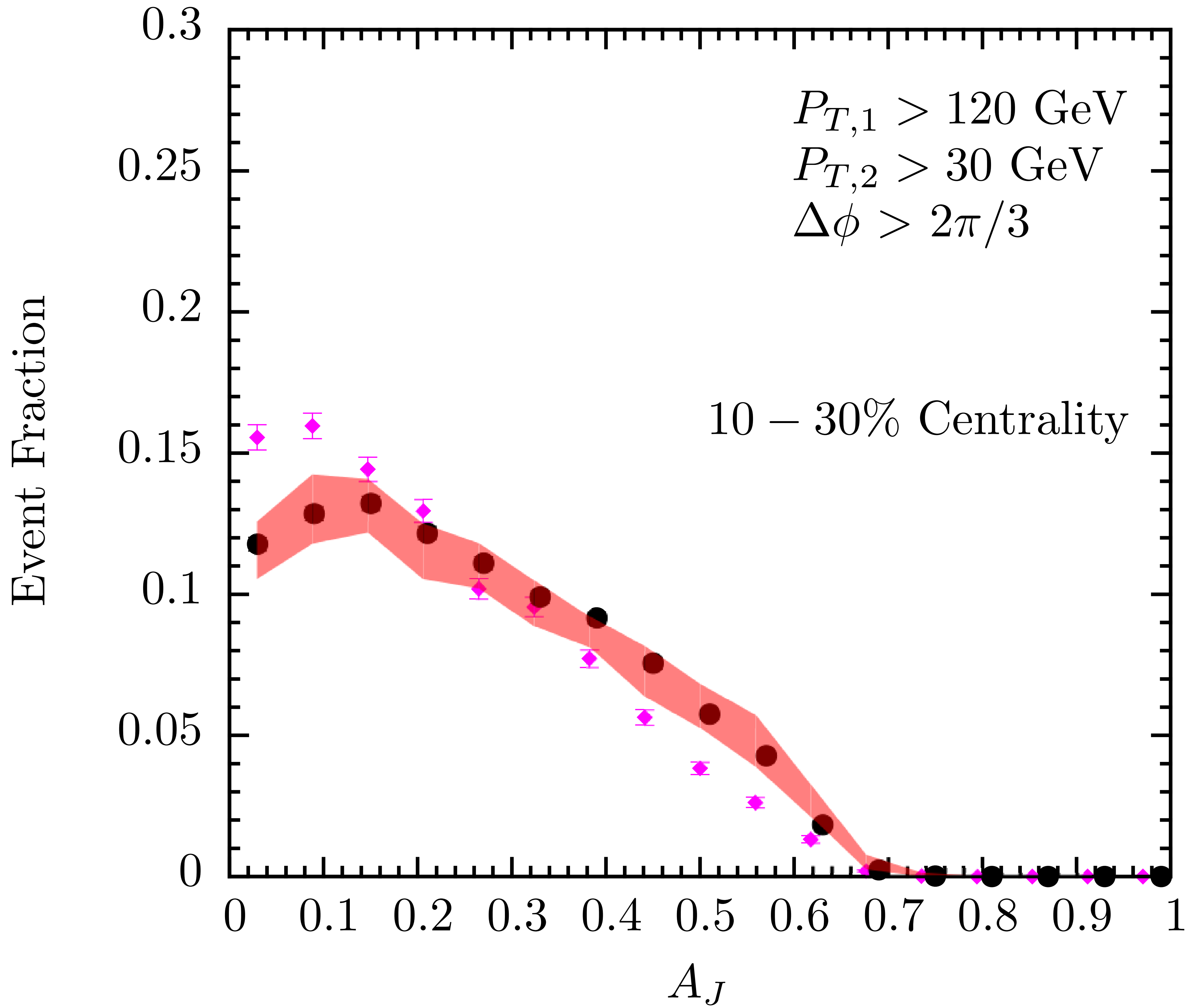


$$A_J = \frac{p_{T_1} - p_{T_2}}{p_{T_1} + p_{T_2}}$$

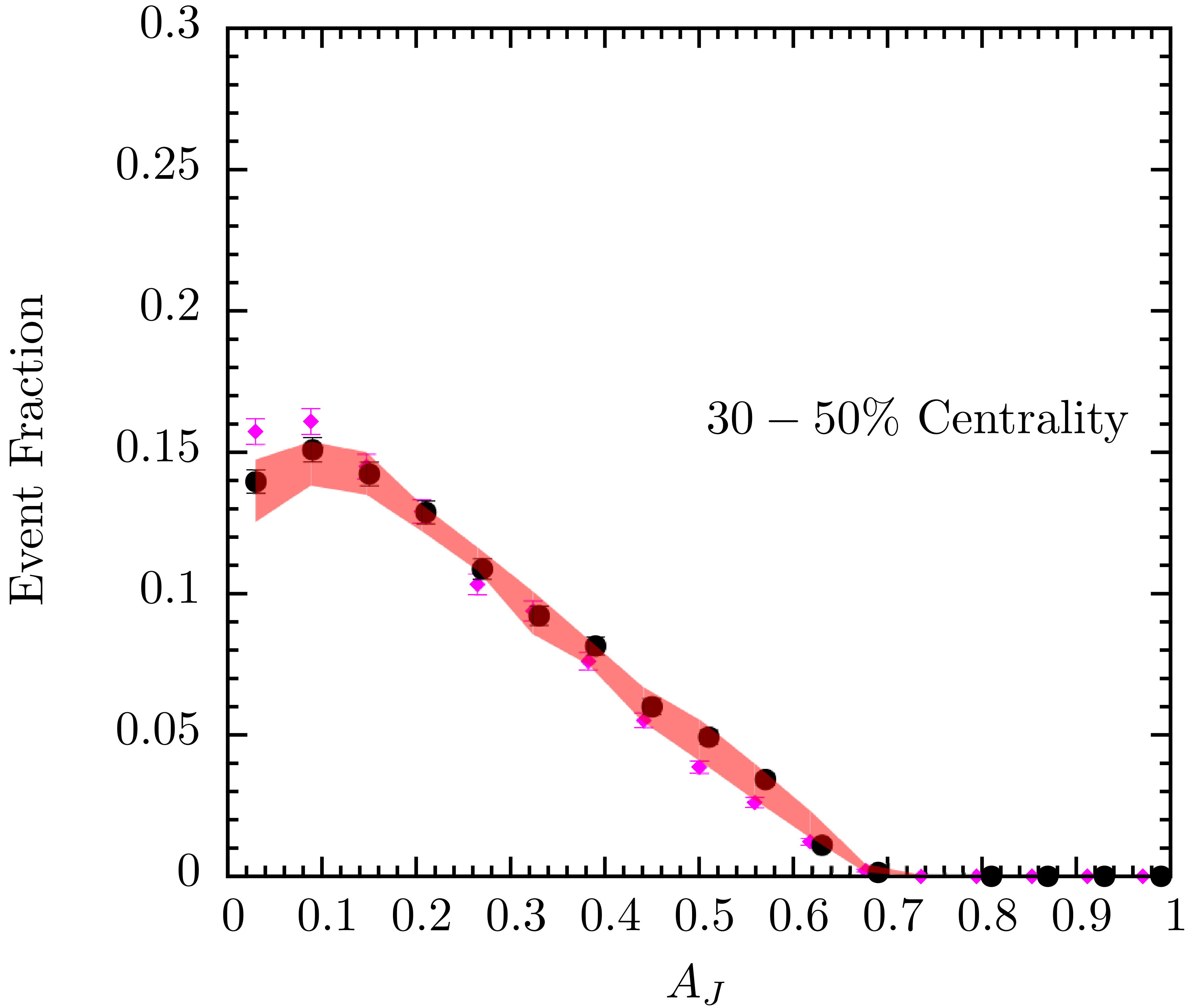
Imbalance


Vacuum+Smearing
Data
Strong Coupling
0 – 10% Centrality
Event Fraction
A_J
0
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

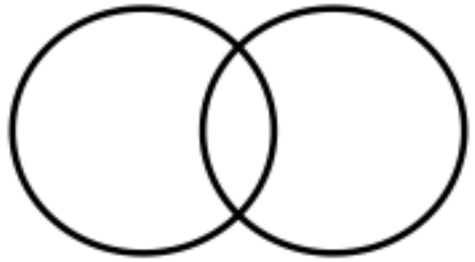

$P_{T,1} > 120$ GeV
$P_{T,2} > 30$ GeV
$\Delta\phi > 2\pi/3$
$10 - 30\%$ Centrality
Event Fraction
A_J
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

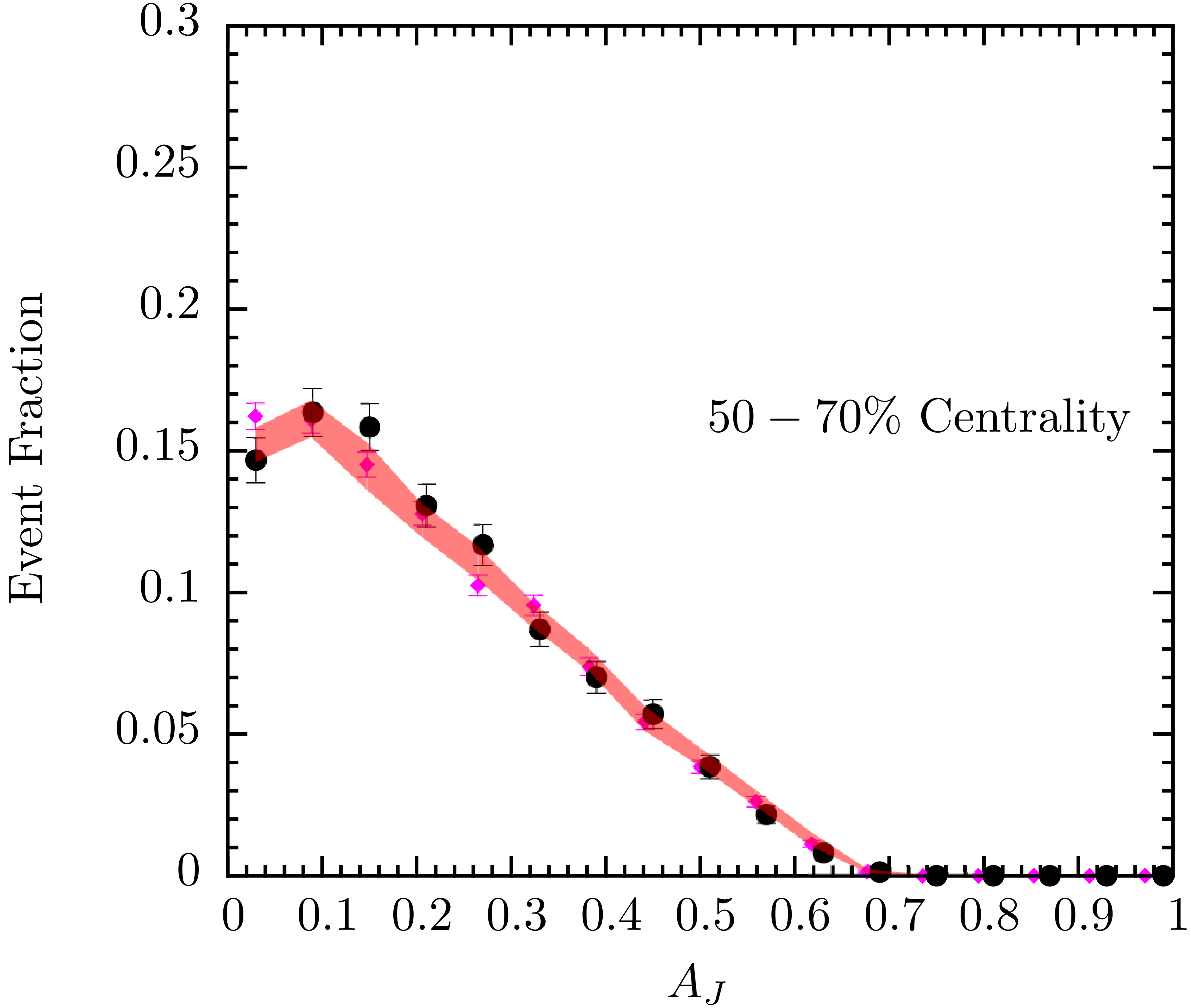
Imbalance



Event Fraction
0.3
0.25
0.2
0.15
0.1
0.05
0
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

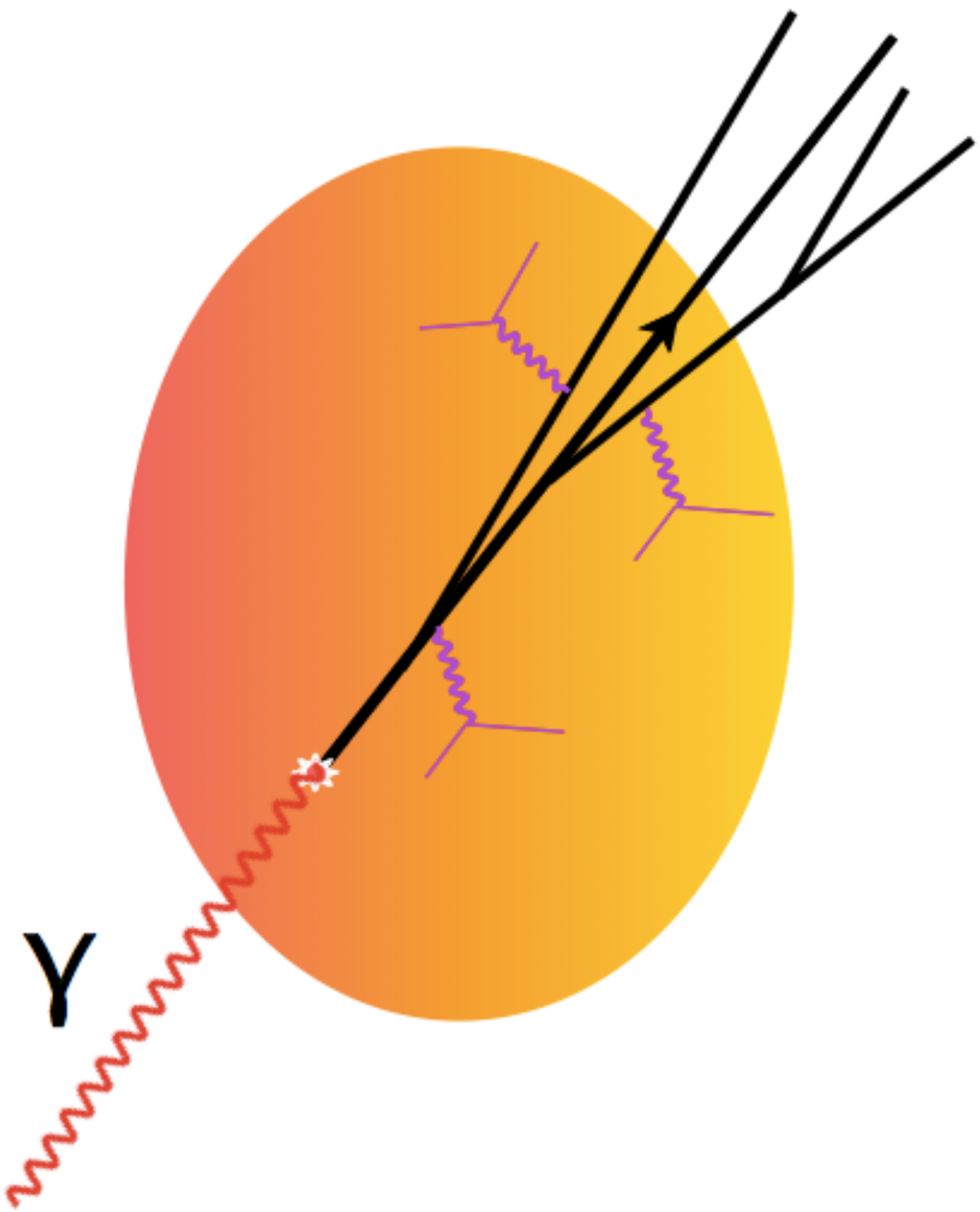
Imbalance





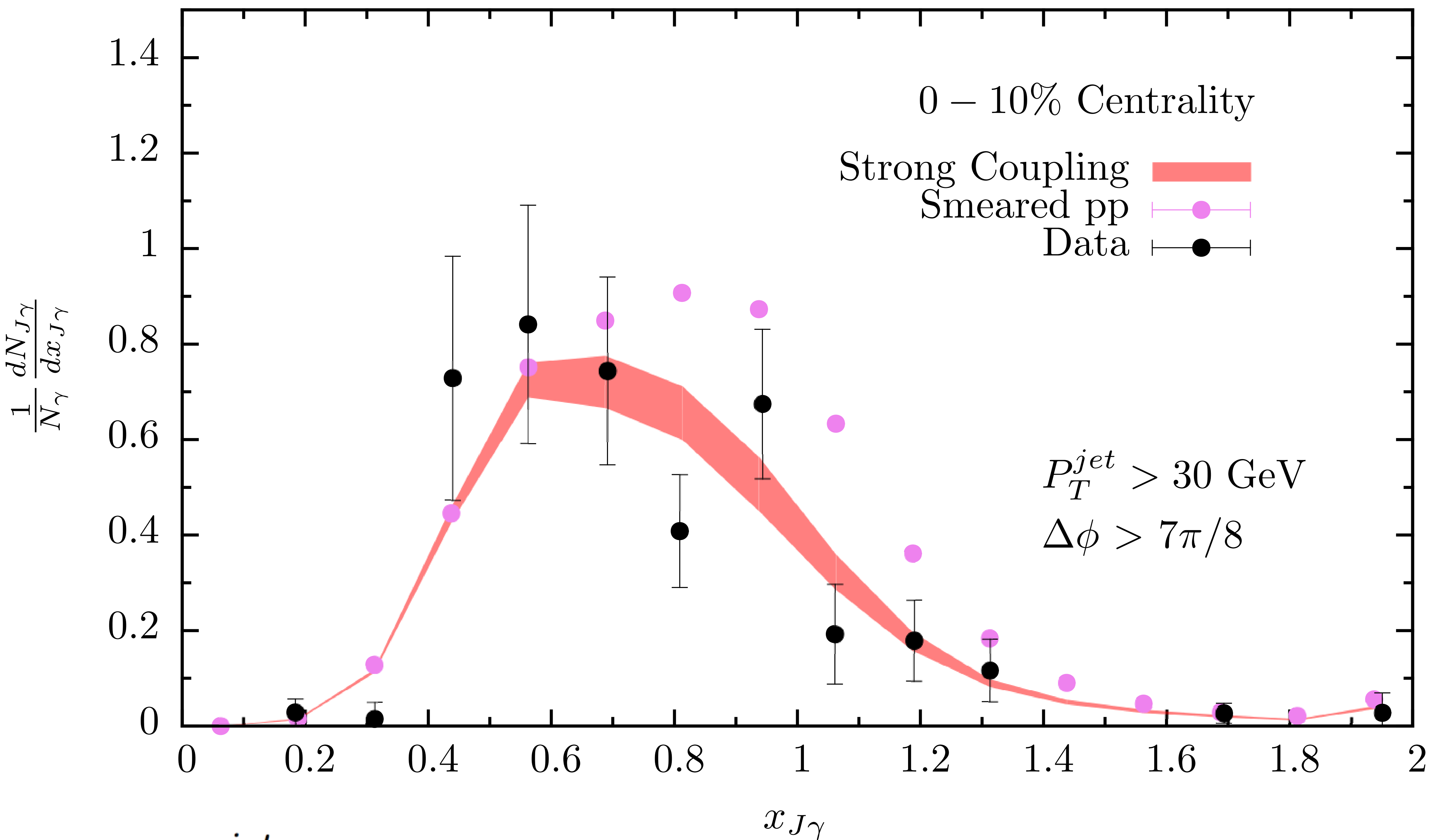
Event Fraction
A_J
50 − 70% Centrality
0
0.05
0.1
0.15
0.2
0.25
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Photon Jet



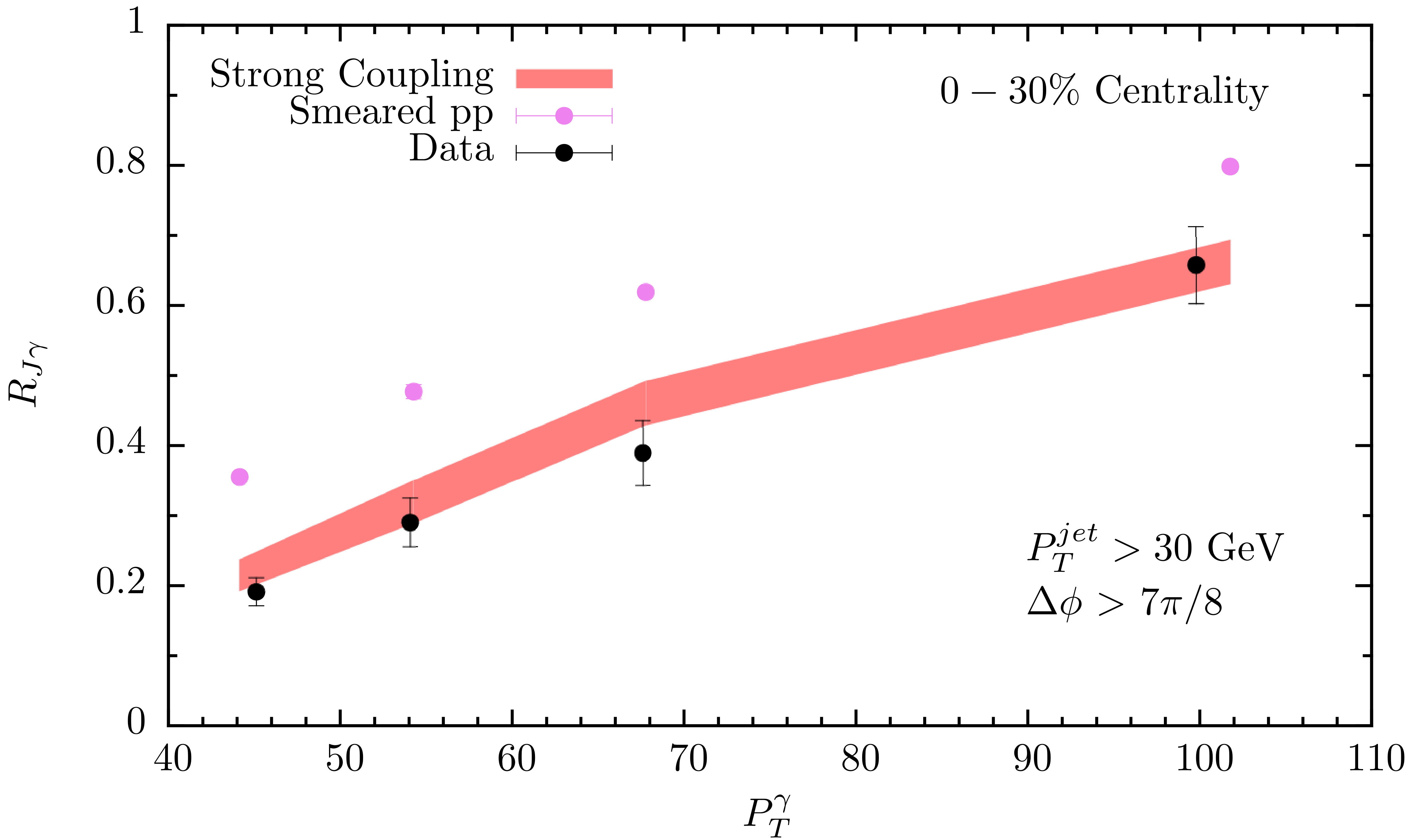
- Photons do not interact with plasma
- Look for associated jet
  - -Different geometric sampling
  - -Different species composition
  - -E_γ proxy for E_{jet}

Imbalance



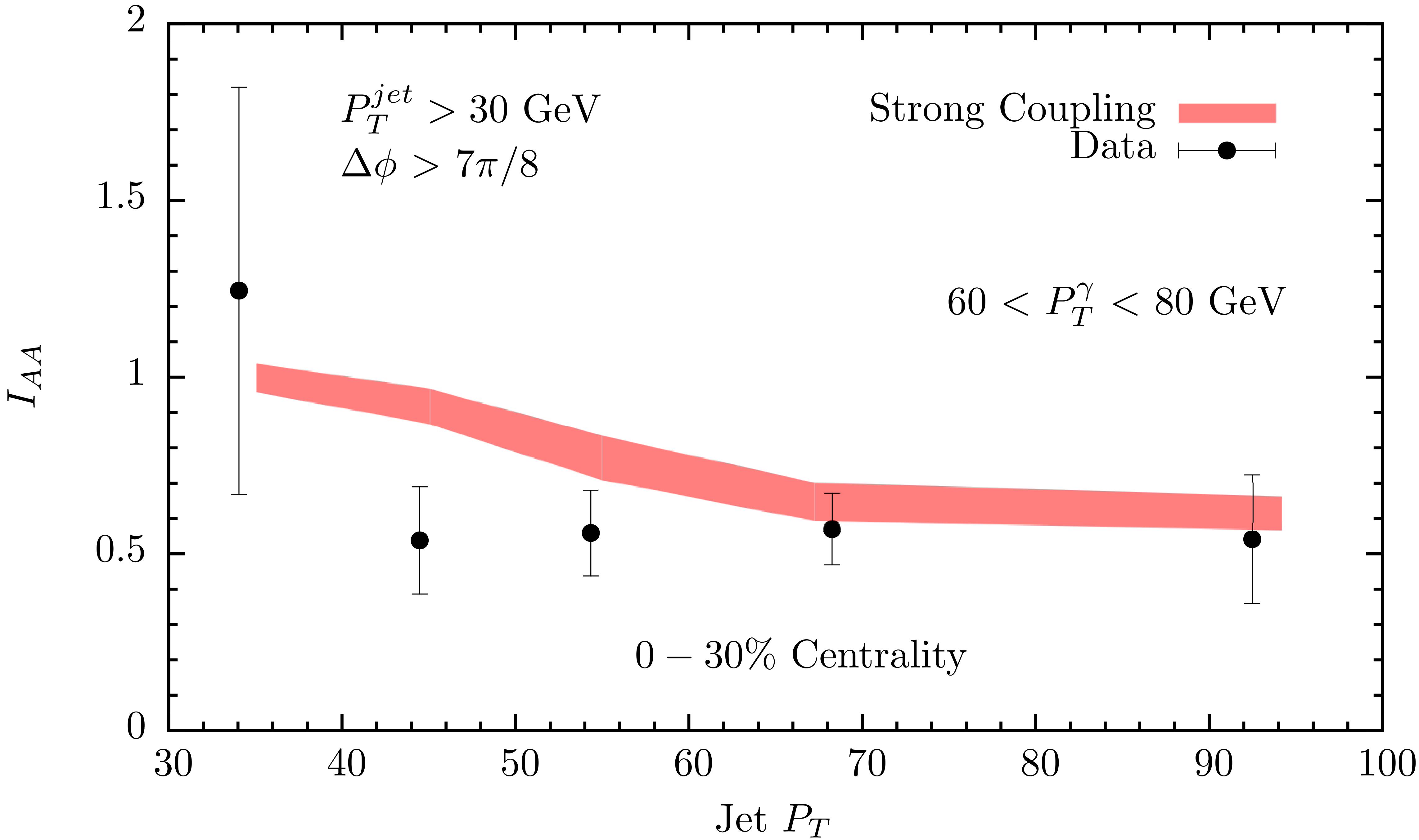
$$x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

Jet Suppression



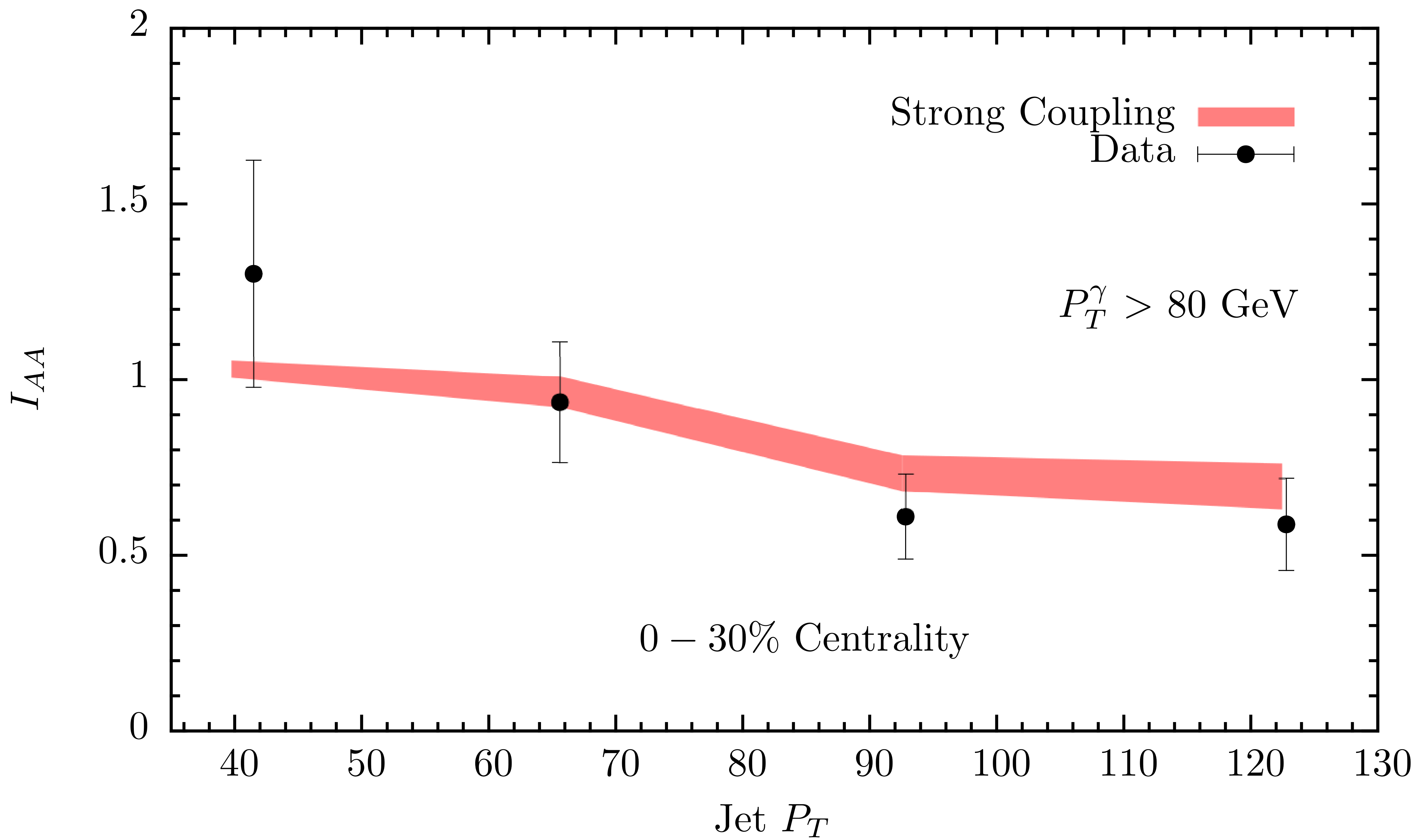
$$R_{J\gamma} = \frac{\text{Number of jets}}{\text{Number of photons}}$$

Spectrum

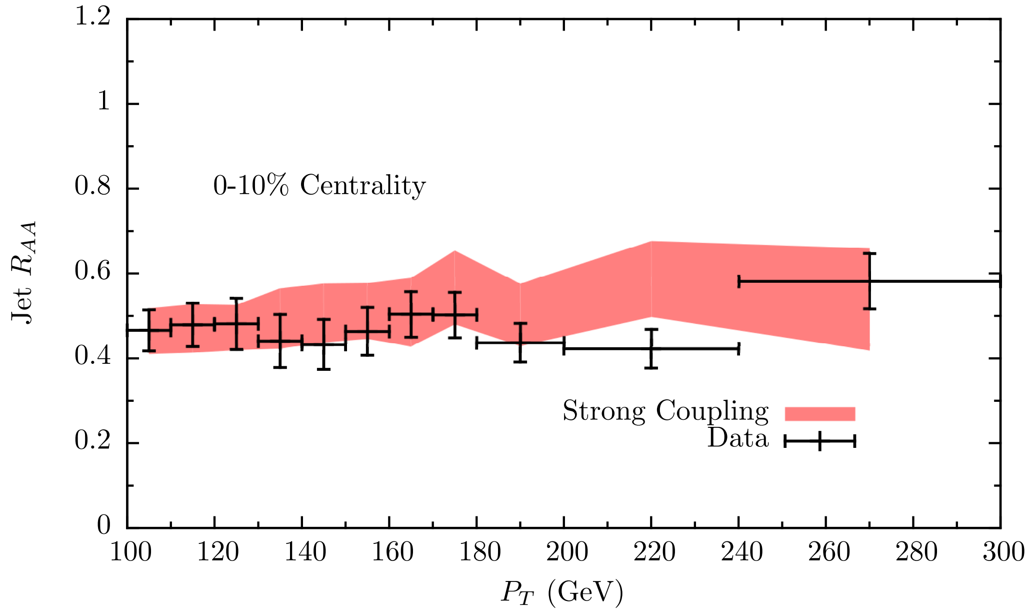


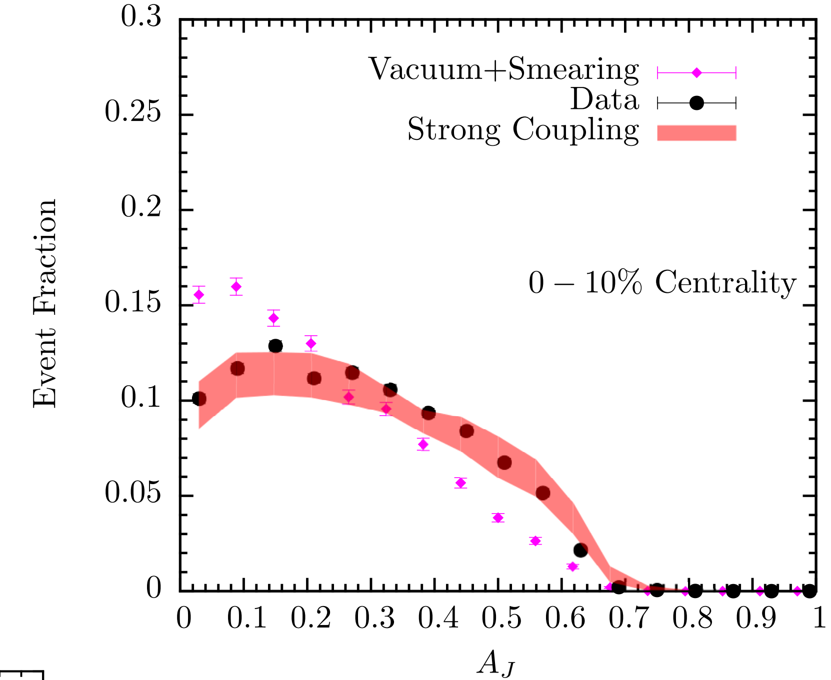
$$I_{AA} = \frac{\text{Number of associated jets in PbPb}}{\text{Number of associated jets in pp}}$$

Spectrum

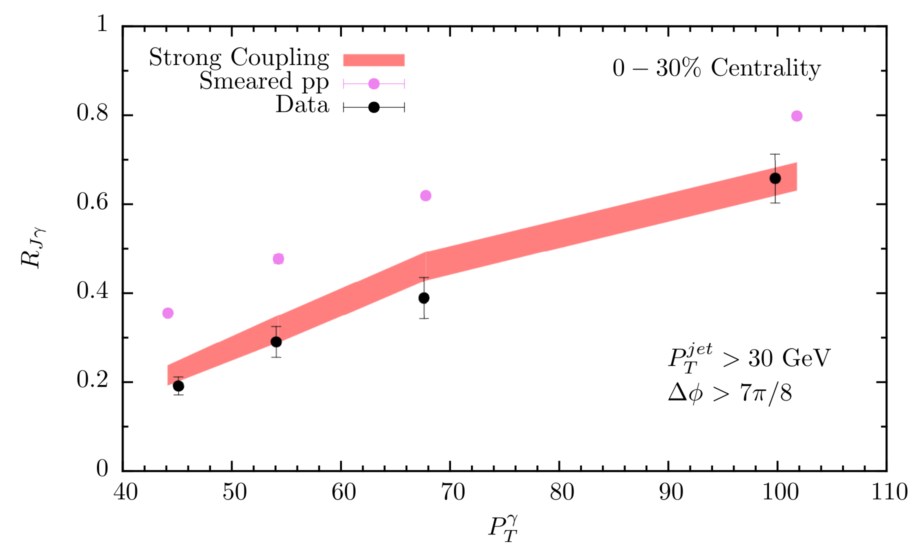


$$I_{AA} = \frac{\text{Number of associated jets in PbPb}}{\text{Number of associated jets in pp}}$$





5 observables
and centrality dependence
all described with
single parameter

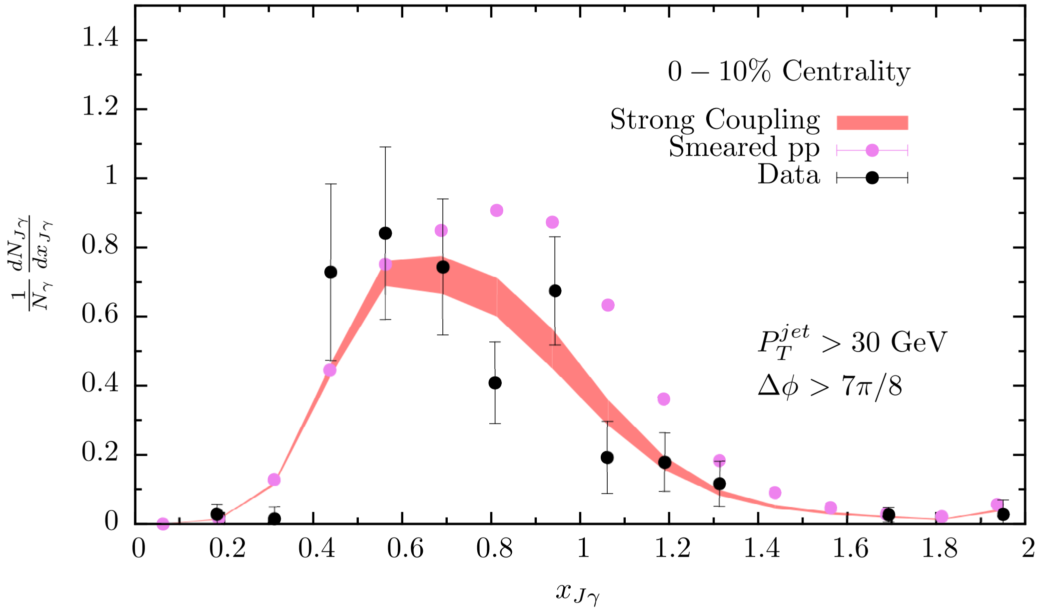


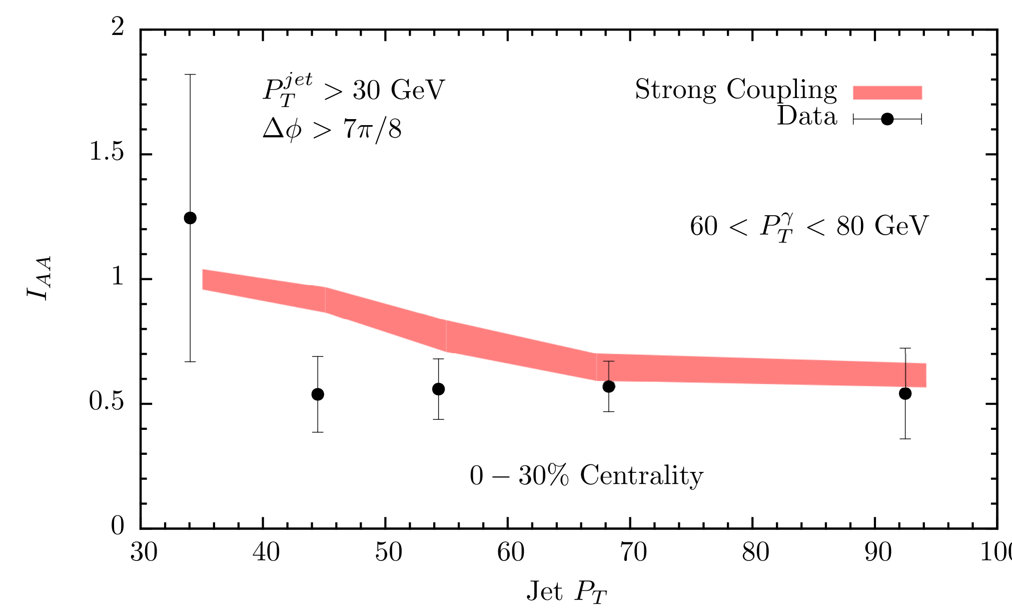
Bands in all plots correspond to

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

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

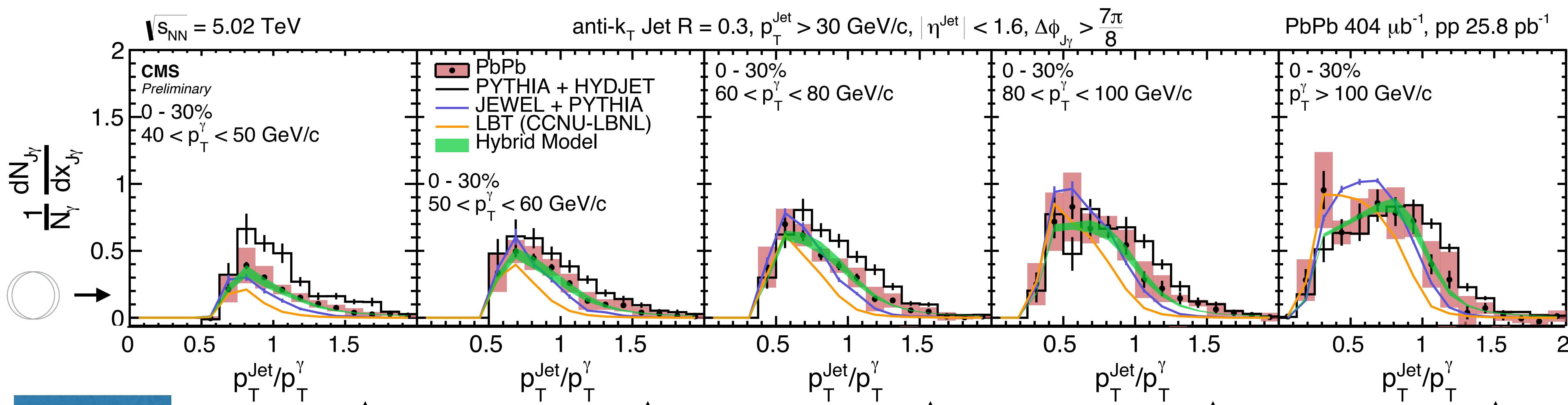
$$x^{QCD}_{stop} \sim (3-4)\, x^{\mathcal{N}=4}_{stop}$$





Predictions

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

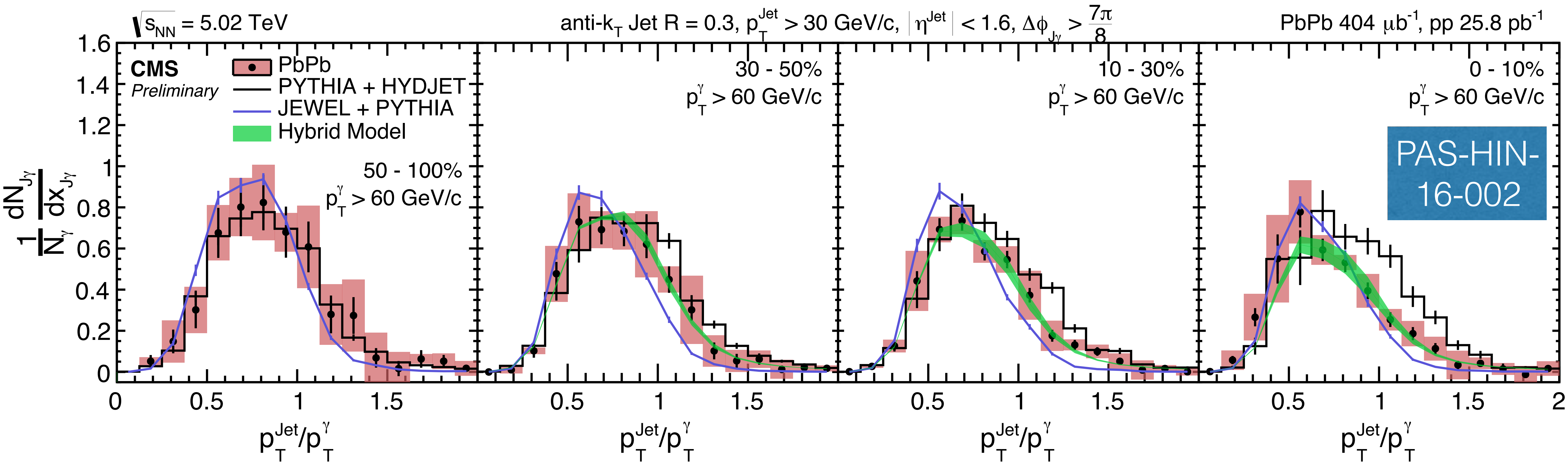


PAS-HIN-16-002

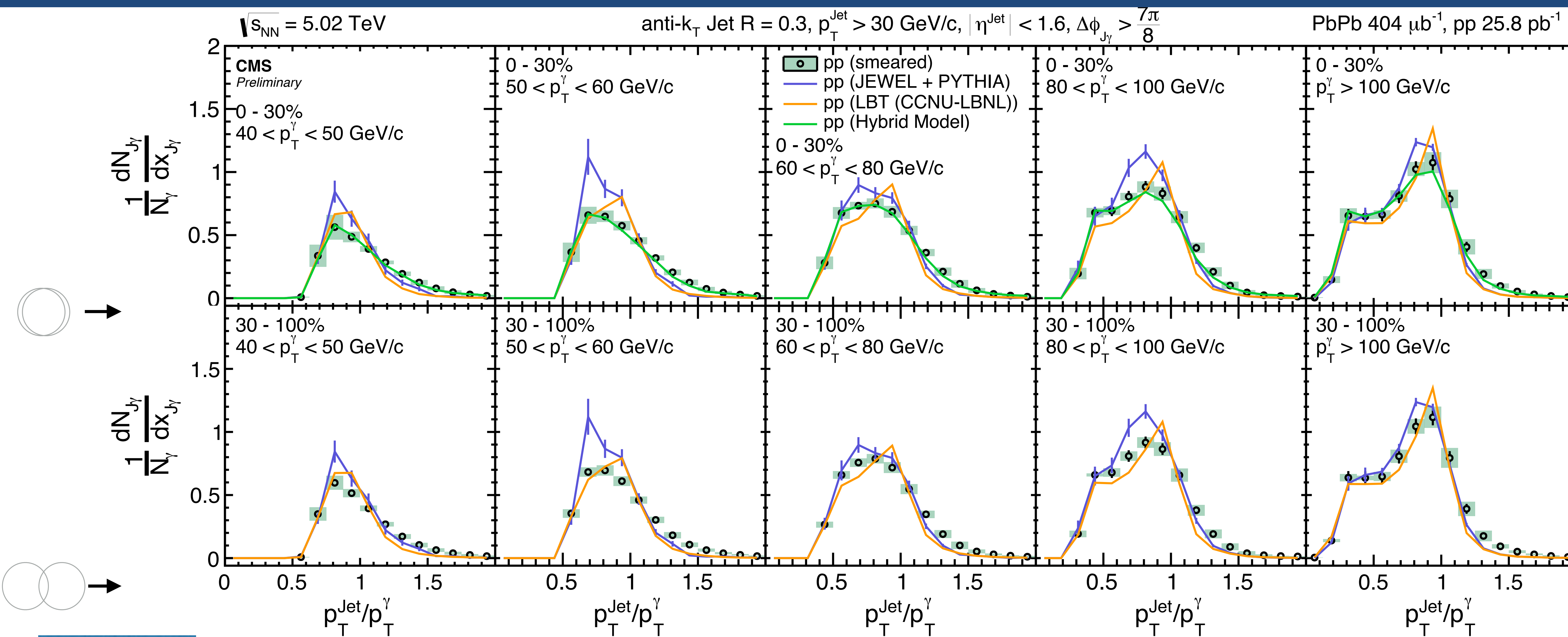
40 < p_T^{γ} < 50 **50 < p_T^{γ} < 60** **60 < p_T^{γ} < 80** **80 < p_T^{γ} < 100** **p_T^{γ} > 100**

- 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

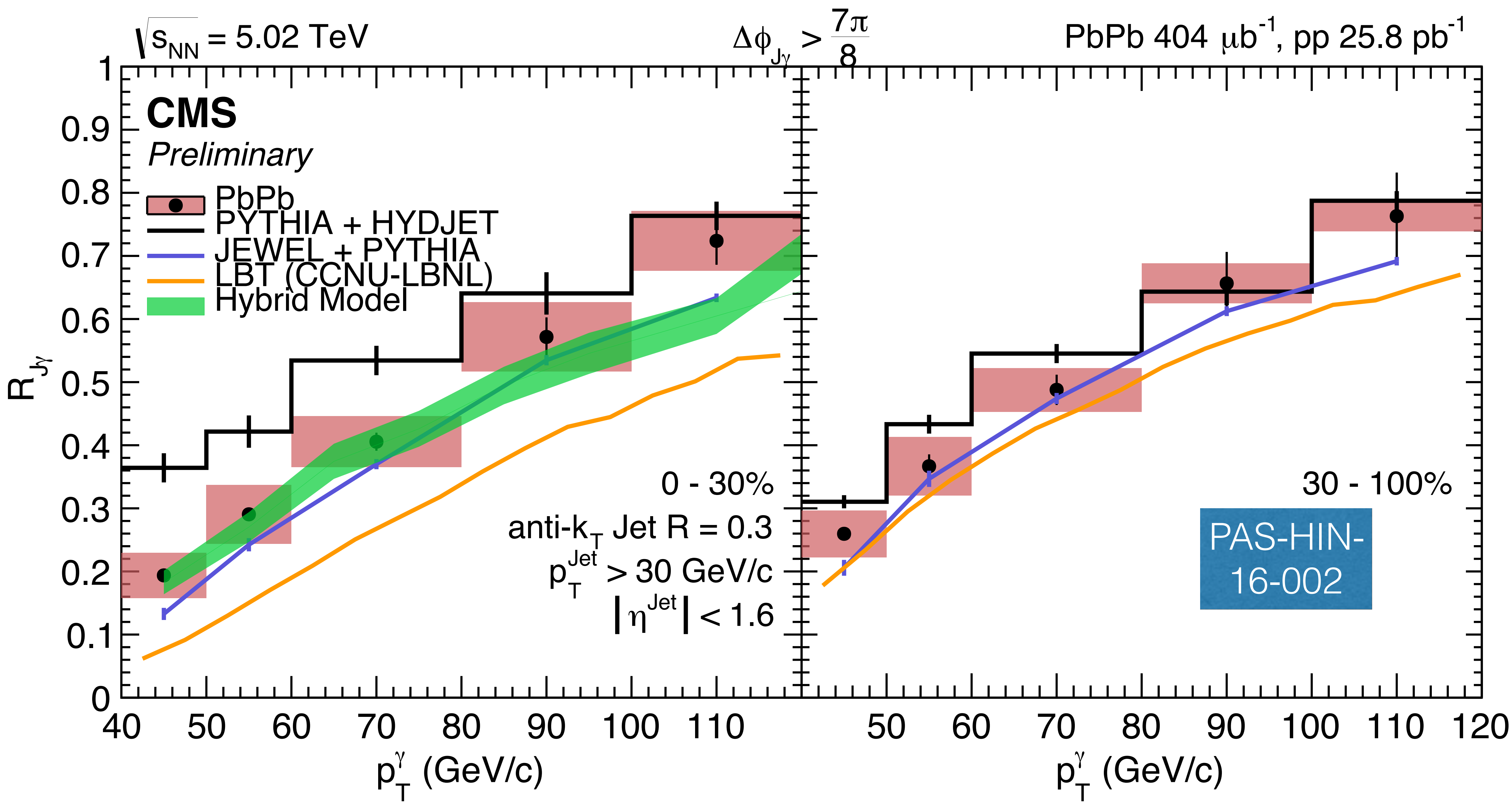


PAS-HIN-16-002

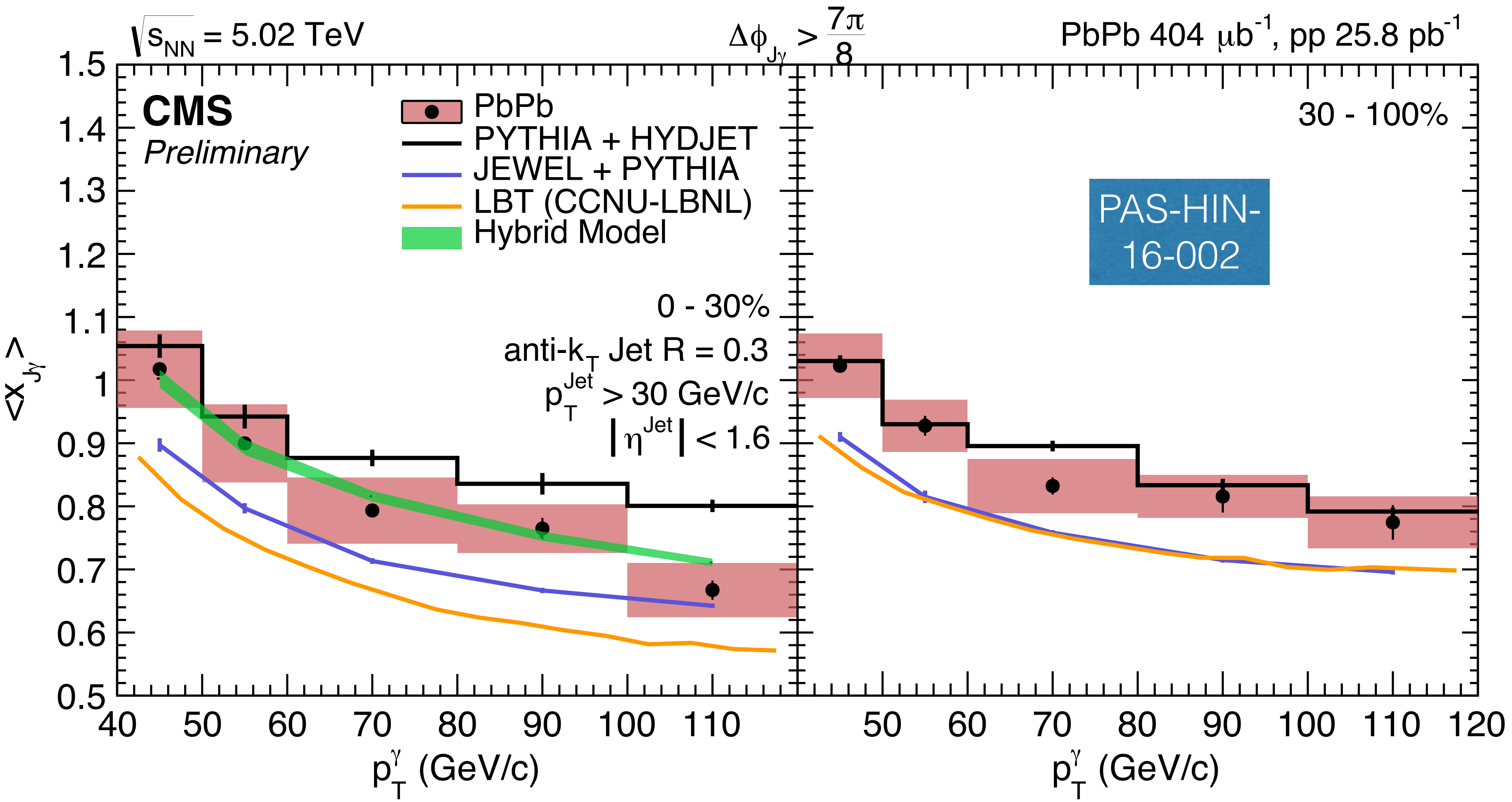
40 < p_T^γ < 50 **50 < p_T^γ < 60** **60 < p_T^γ < 80** **80 < p_T^γ < 100** **p_T^γ > 100**

- Overlaid PYTHIA, JEWEL, LBT and Hybrid Model

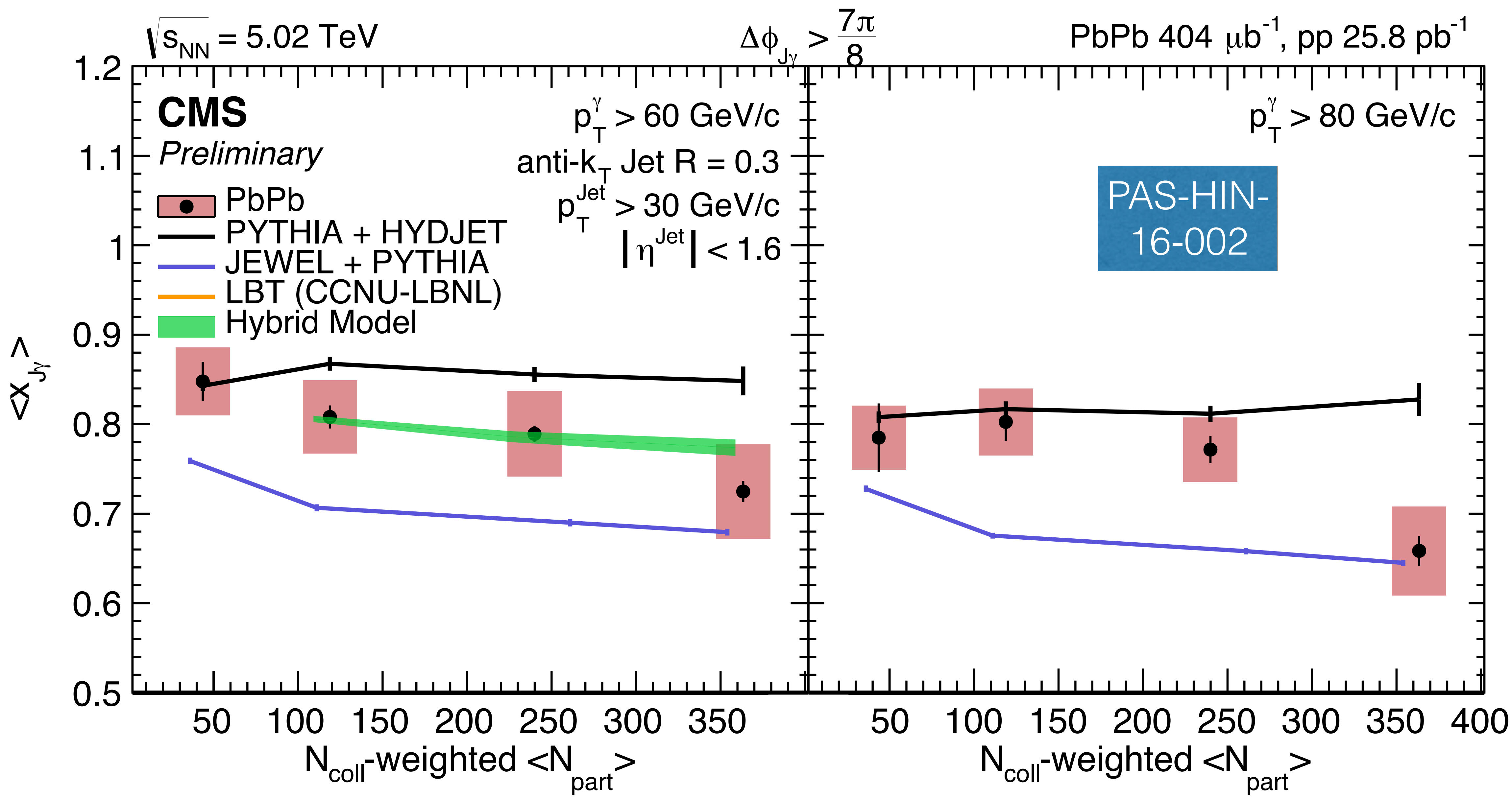
Theory Comparison: $R_{J\gamma}$ in PbPb



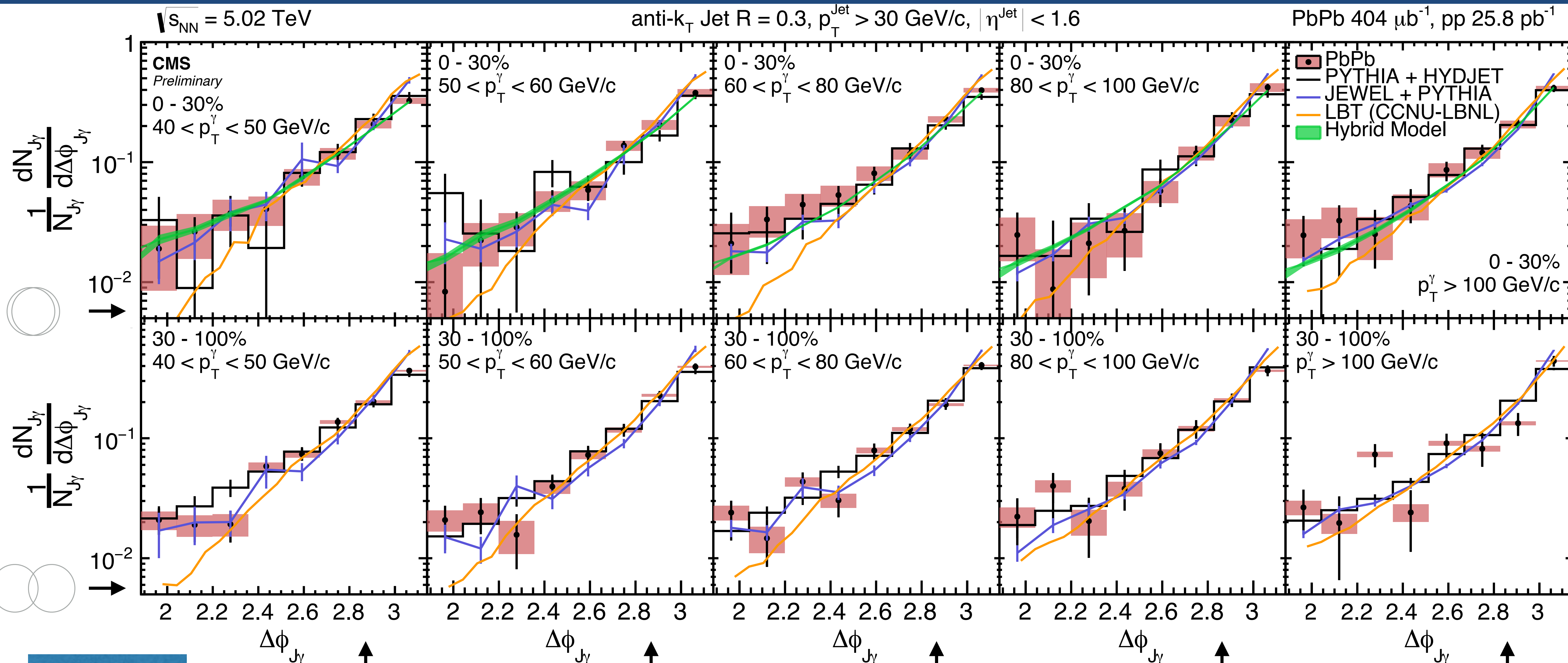
Theory Comparison: $x_{J\gamma}$ in PbPb



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



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



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+HYDJET, JEWEL, LBT and Hybrid Model

Coming soon

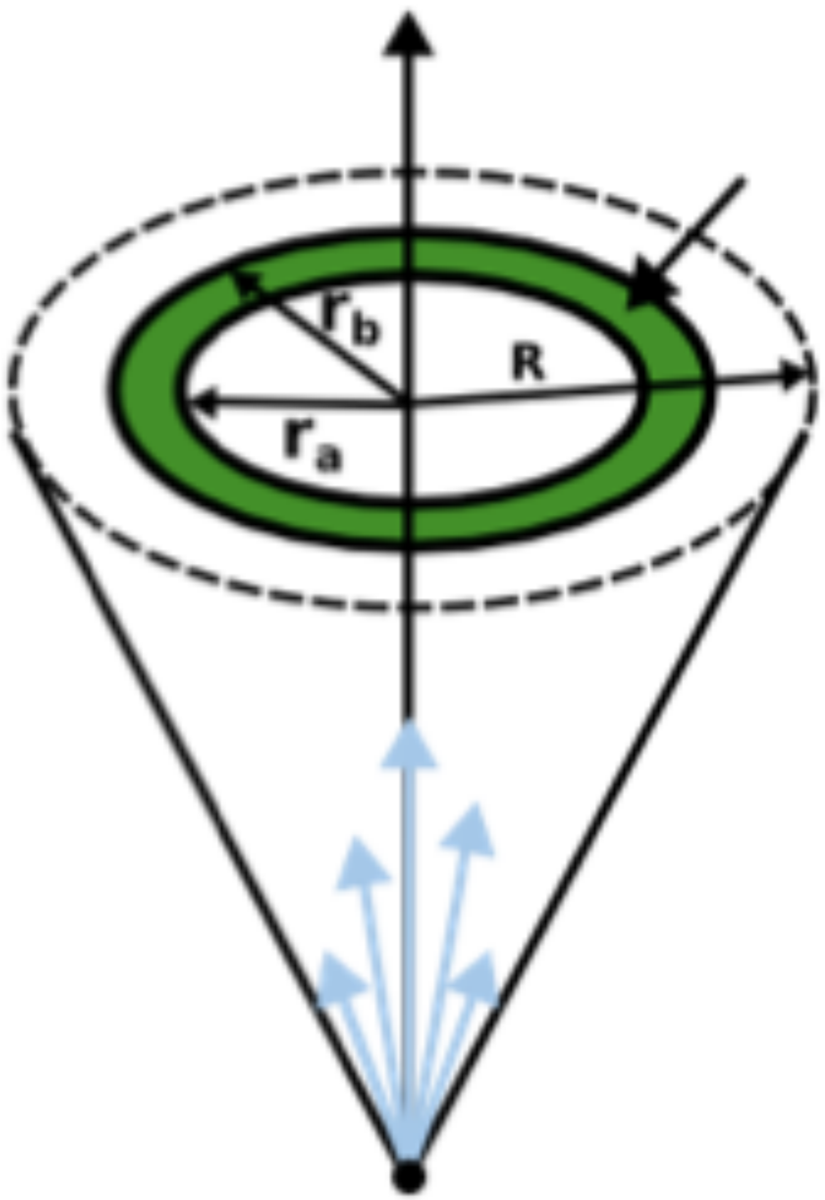
Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 2017

- Coming soon from the hybrid model: $R_{\rm AA}$ for hadrons, photon-jet acoplanarity, Z-jet acoplanarity, z_g, jet mass.
- Increasingly precise tests of the result that strongly coupled form for dE/dx, but with $x_{\rm therm}^{\rm QCD} \sim (3-4) x_{\rm therm}^{\mathcal{N}=4}$ describes jet observables sensitive to parton energy loss.
- 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 $dE/dx \propto T^3 x$.
- 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.

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 $K_{\mathrm{pert}} \simeq 5$.
- 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

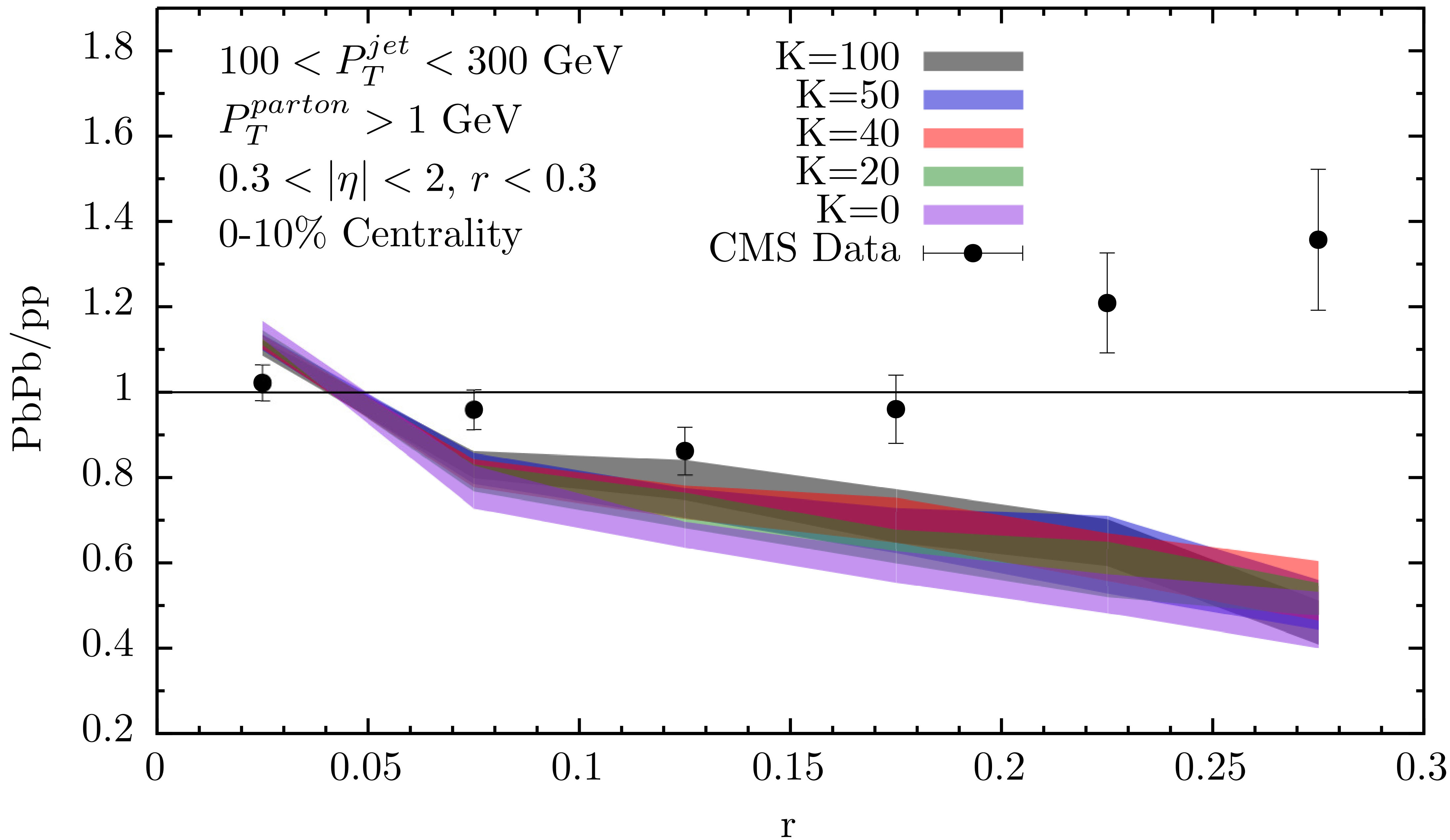


Transverse distribution of energy within the jet

Intra-jet observable robust to hadronization

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

Small sensitivity of standard jet shapes to broadening



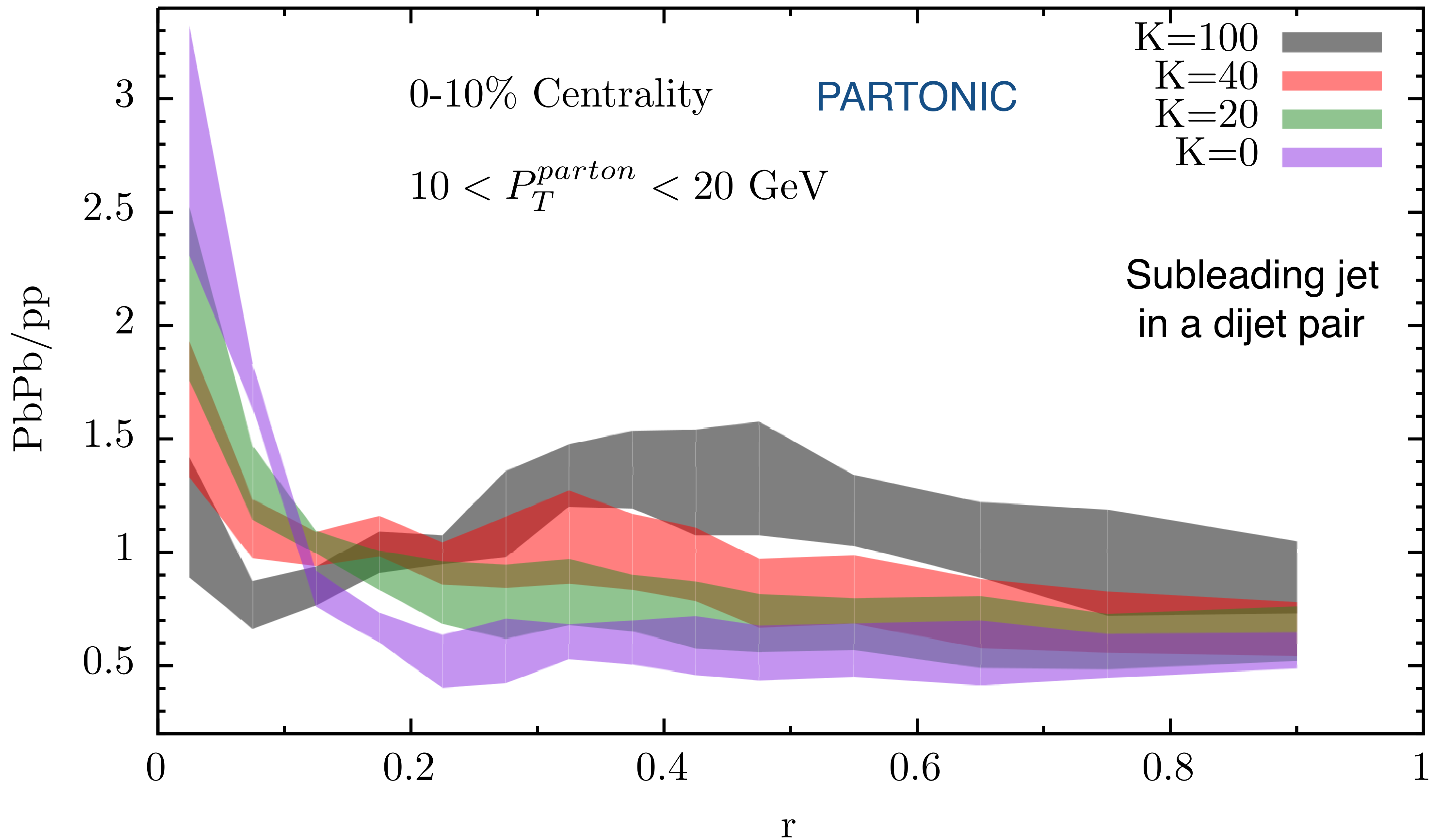
Small sensitivity of jet shapes to broadening:

- 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.)

A New Observable, Sensitive to Broadening

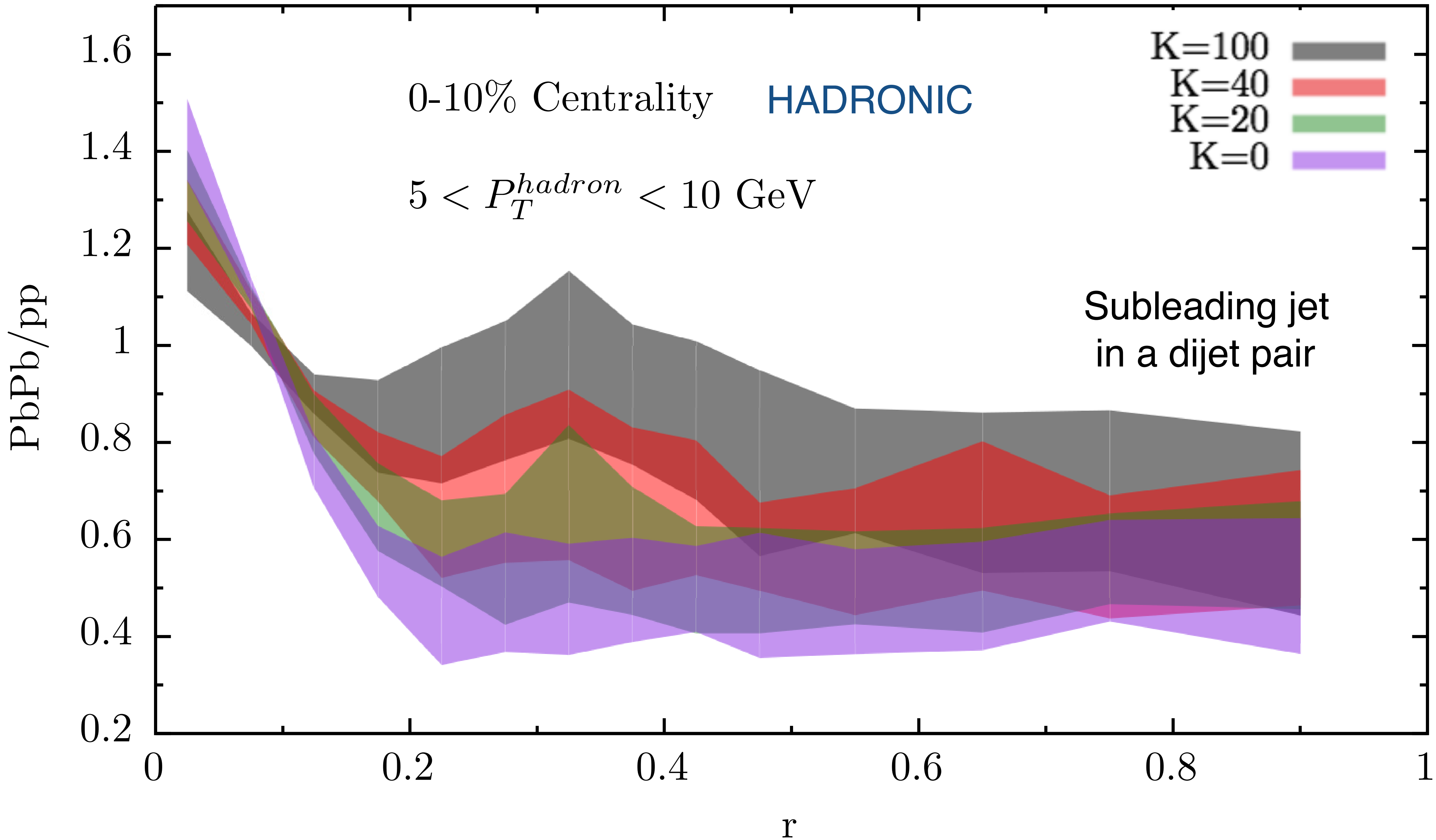


Kinematical cuts for partons chosen such that:

- 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

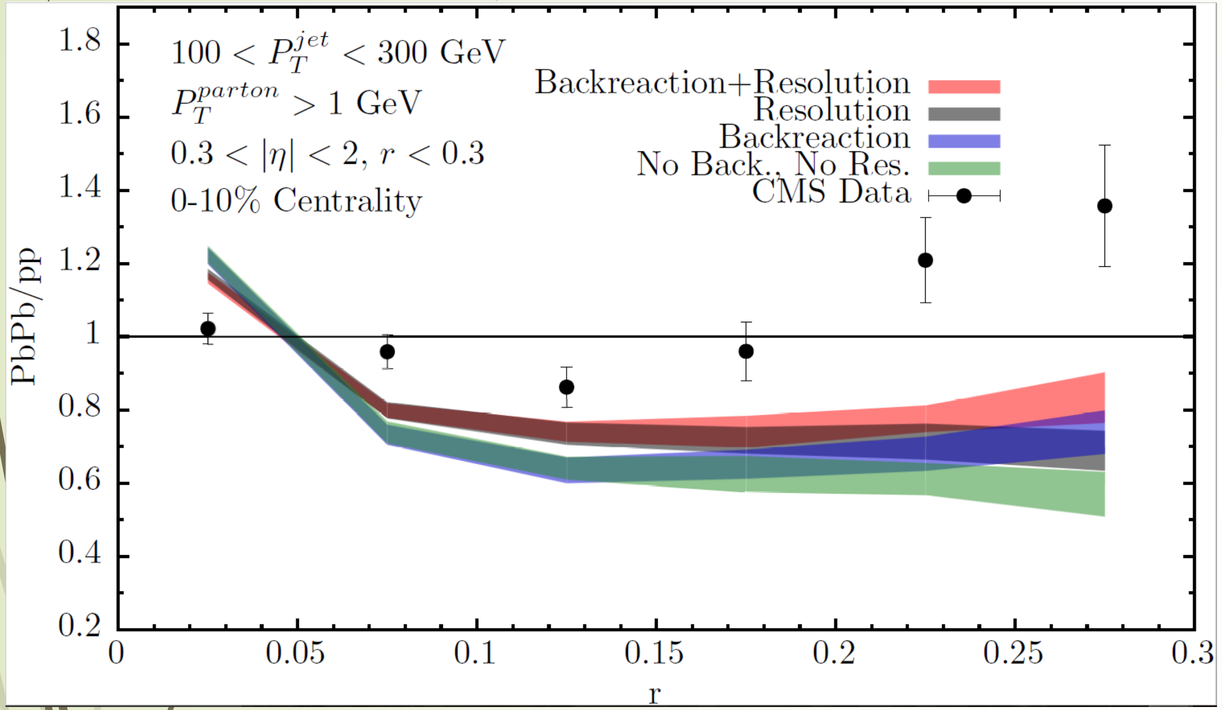
Looking Ahead to the 2020s

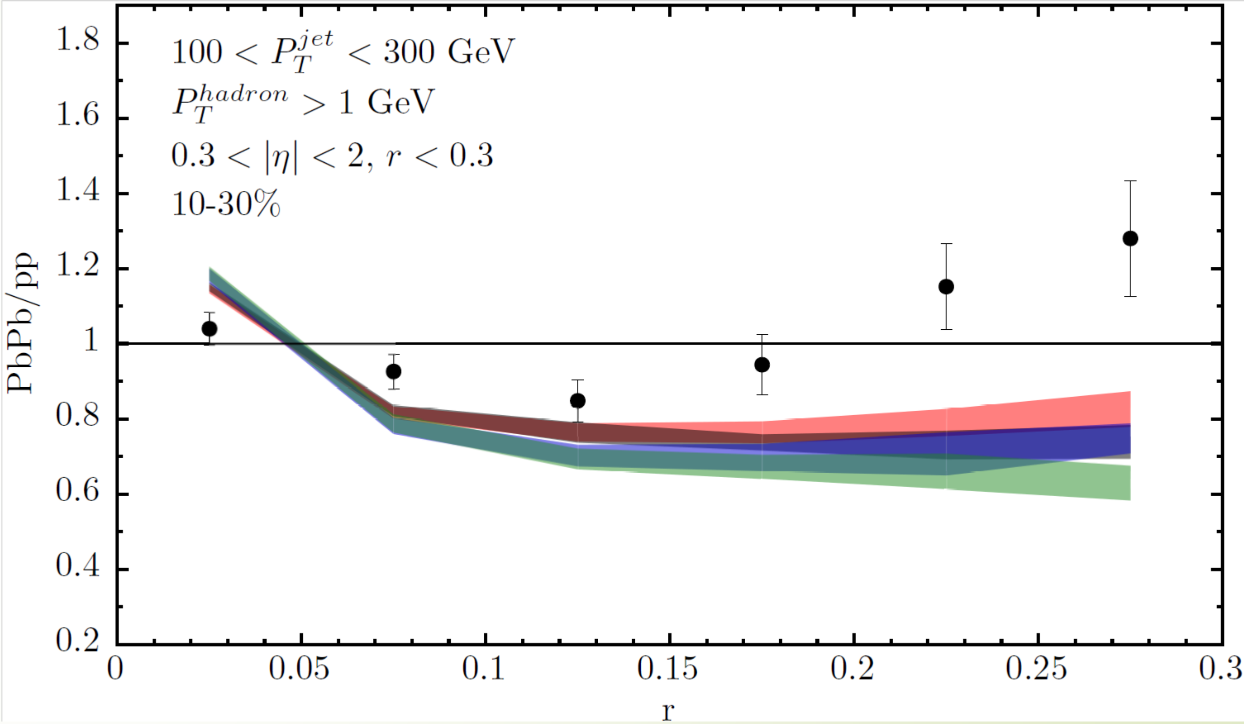
- Before then, via the use of differential jet shape ratios and similar observables that are sensitive to the angular distribution of 10-20 GeV partons in the jet it will be possible to constrain the value of K, the width of the Gaussian distribution of transverse momentum received. Can differential 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
- 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. Introducing this effect will reduce the quenching of soft particles.** Hulcher, Pablos, KR 2017

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



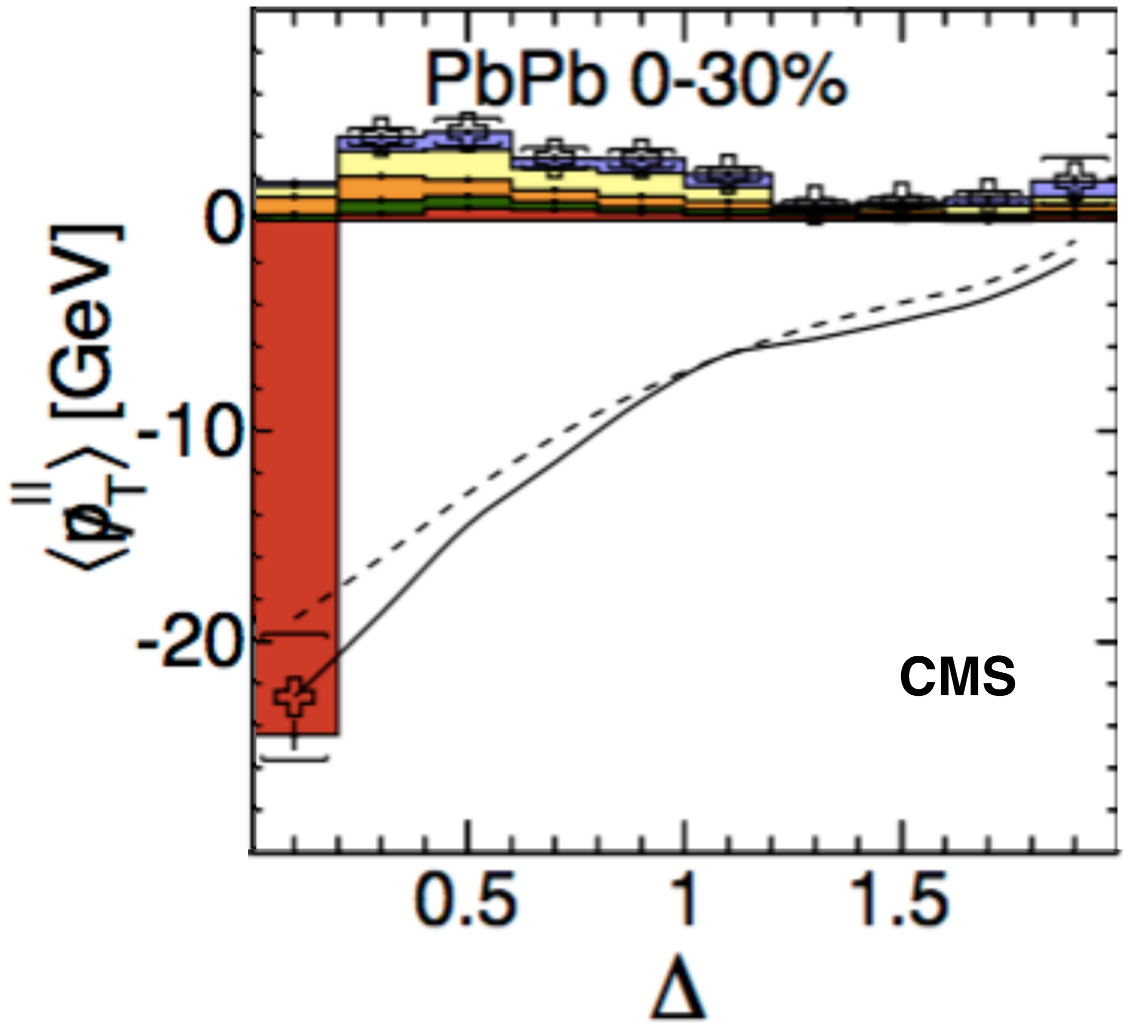


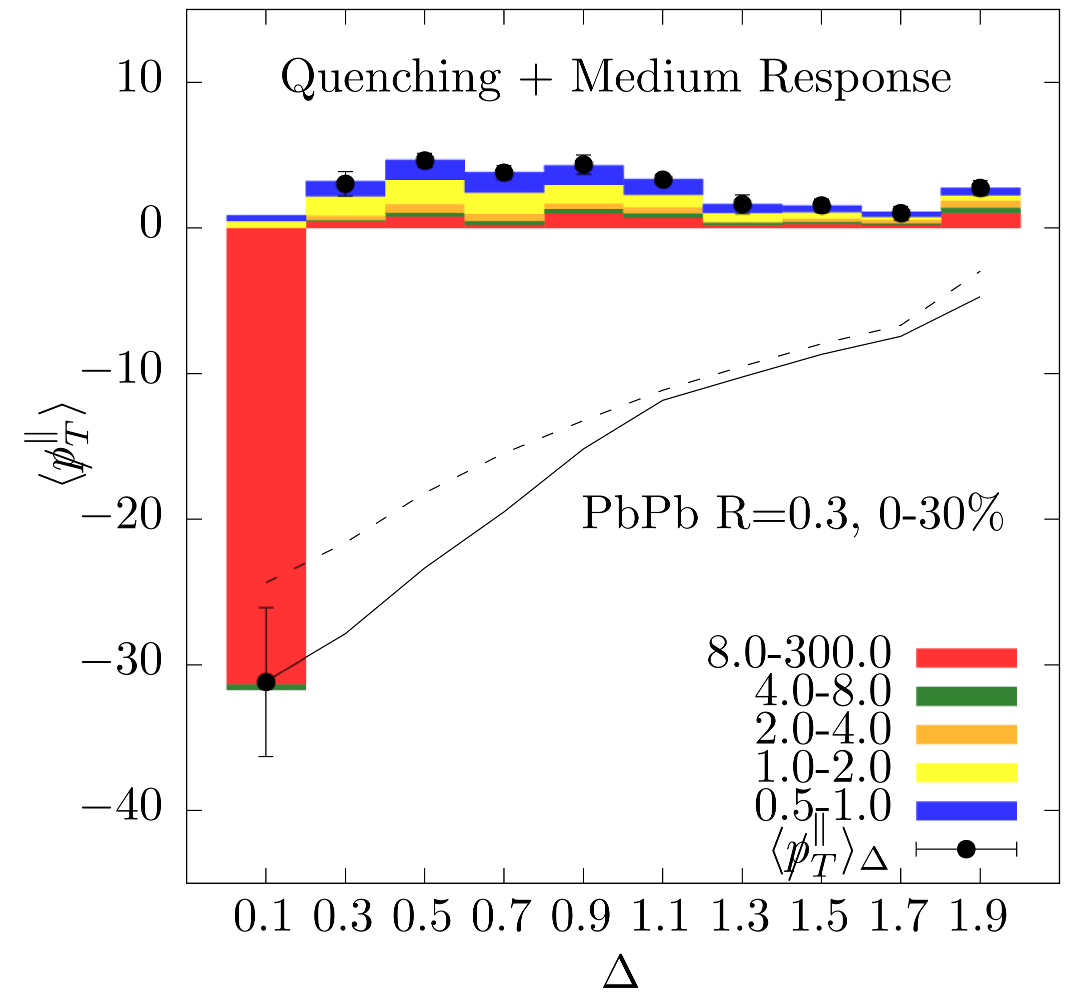
- Resolution effects for hadronized Jet Shapes shows the same behavior as for partonic Jet Shapes
- The middle of the curve lifts as the later softer particles at large angles are hidden and quenched for reduced periods of time
- The left part of the curve dips as the hard particles are relatively unchanged,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

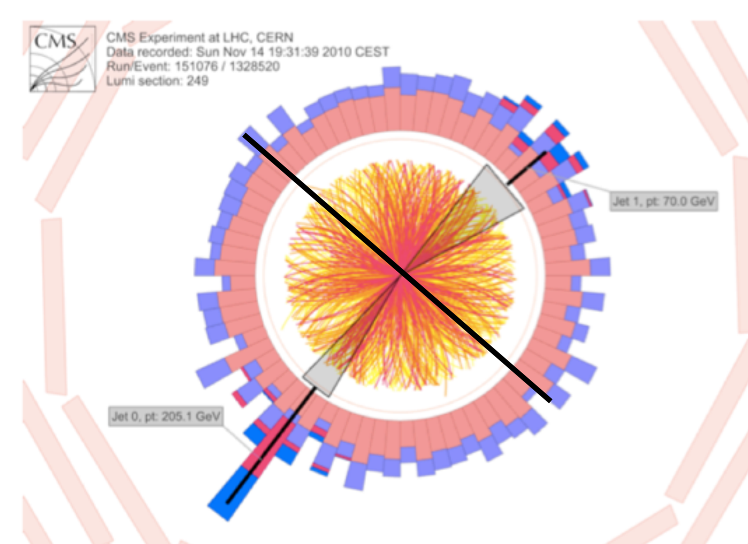
Recovering Lost Energy: Missing Pt



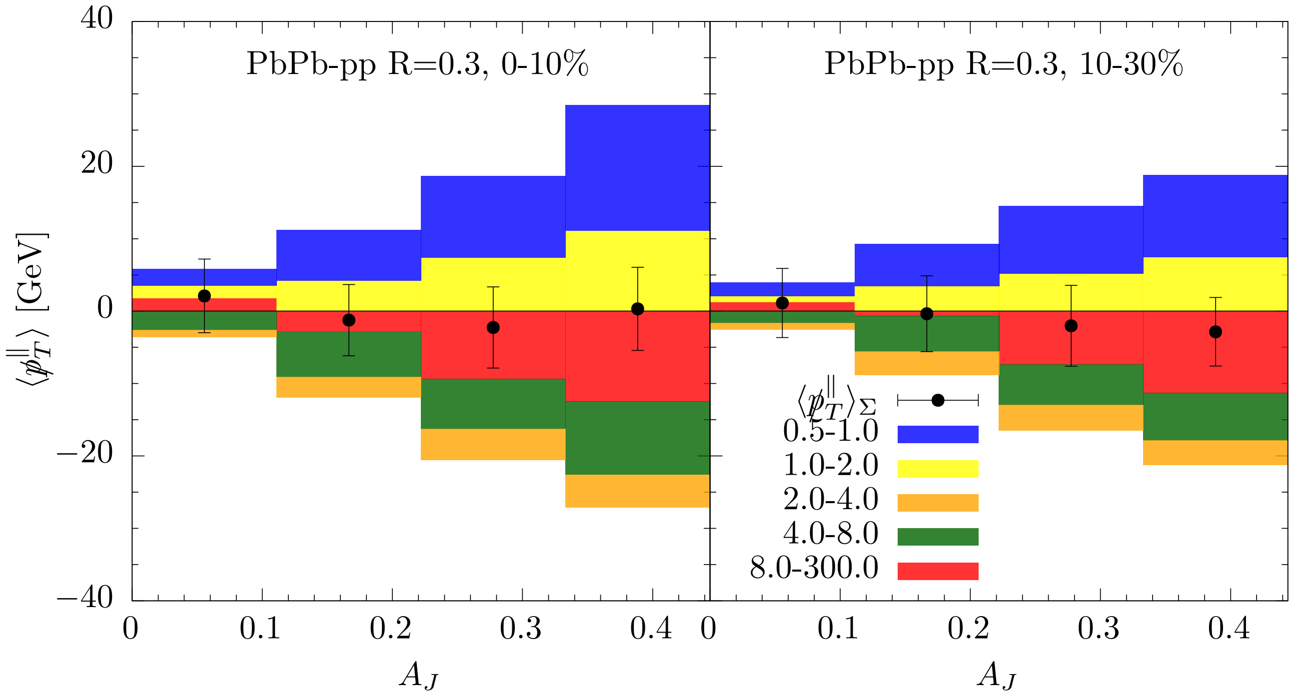


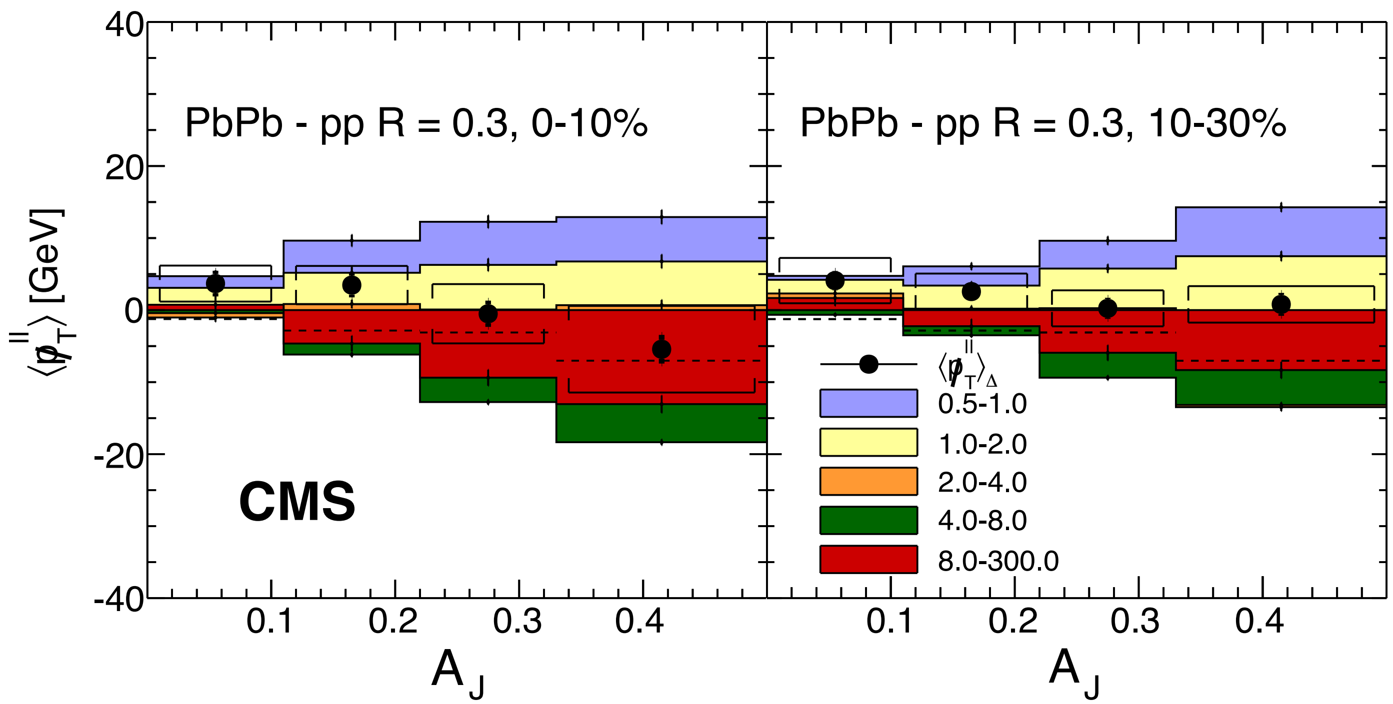
- Energy is recovered at large angles in the form of soft particles

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



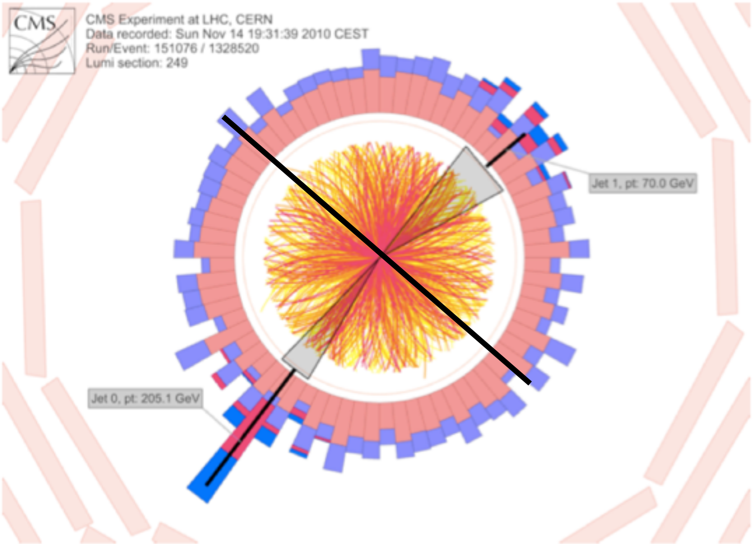
Recovering Lost Energy: Missing Pt



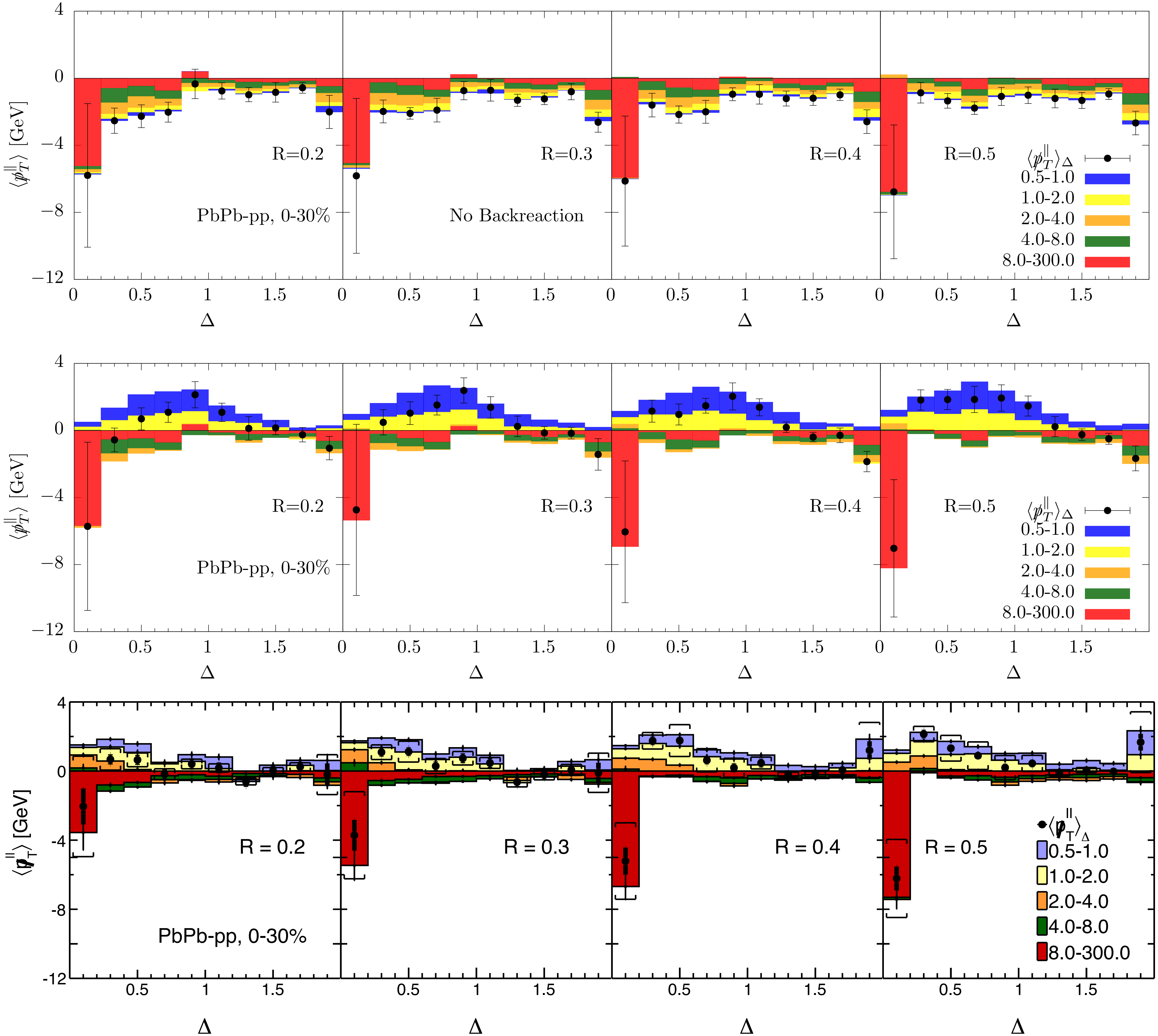


- In PbPb, more asymmetric dijet events are dominated by soft tracks in the subleading jet side

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

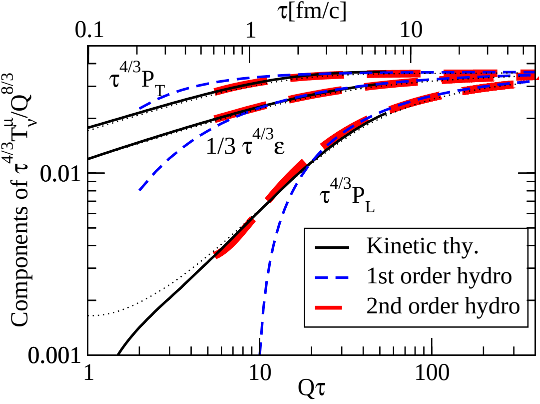


Jet radius dependence of Missing Pt



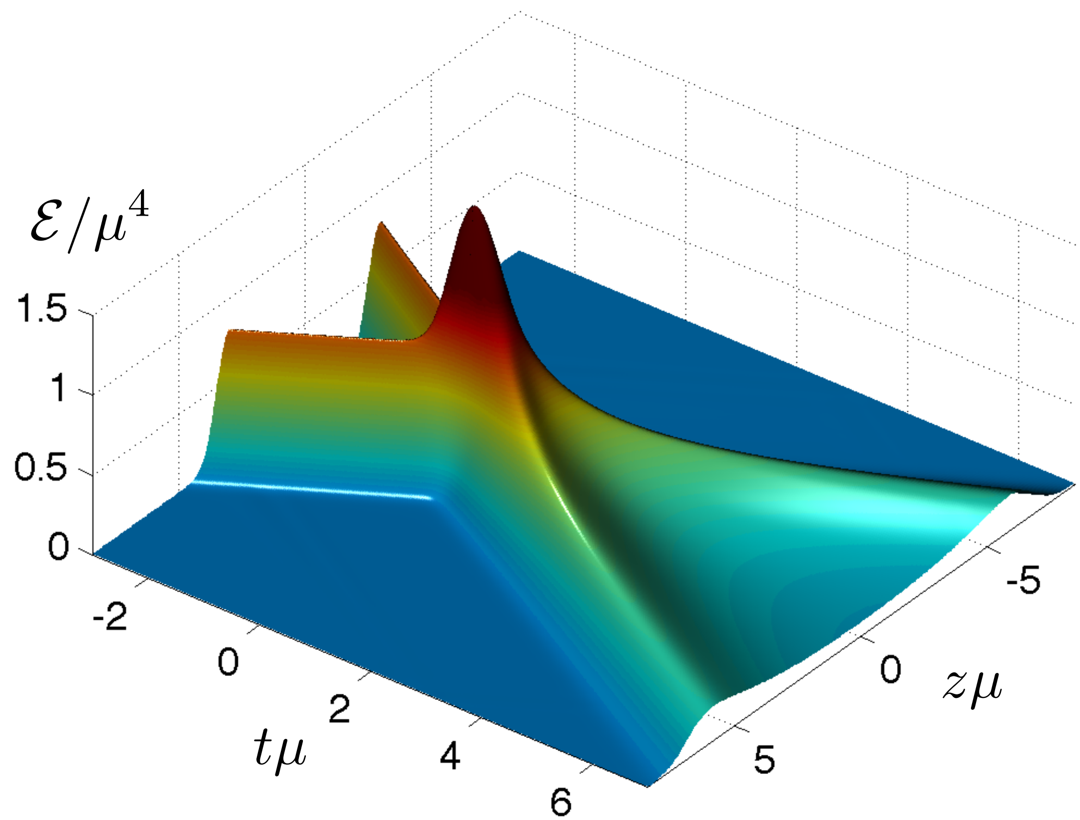
Missing p_T observables

- Our characterization of the wake is on 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.



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

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

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Probing the Liquid: What Next?

- 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 analyzing how our current baseline, which assumes a hydrodynamized wake, does not hit the nail fully on the head, we are learning about the degree to which 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?
- I hope that soon 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. (By using suitably differential jet shape observables.)

Probing the Liquid: What Next?

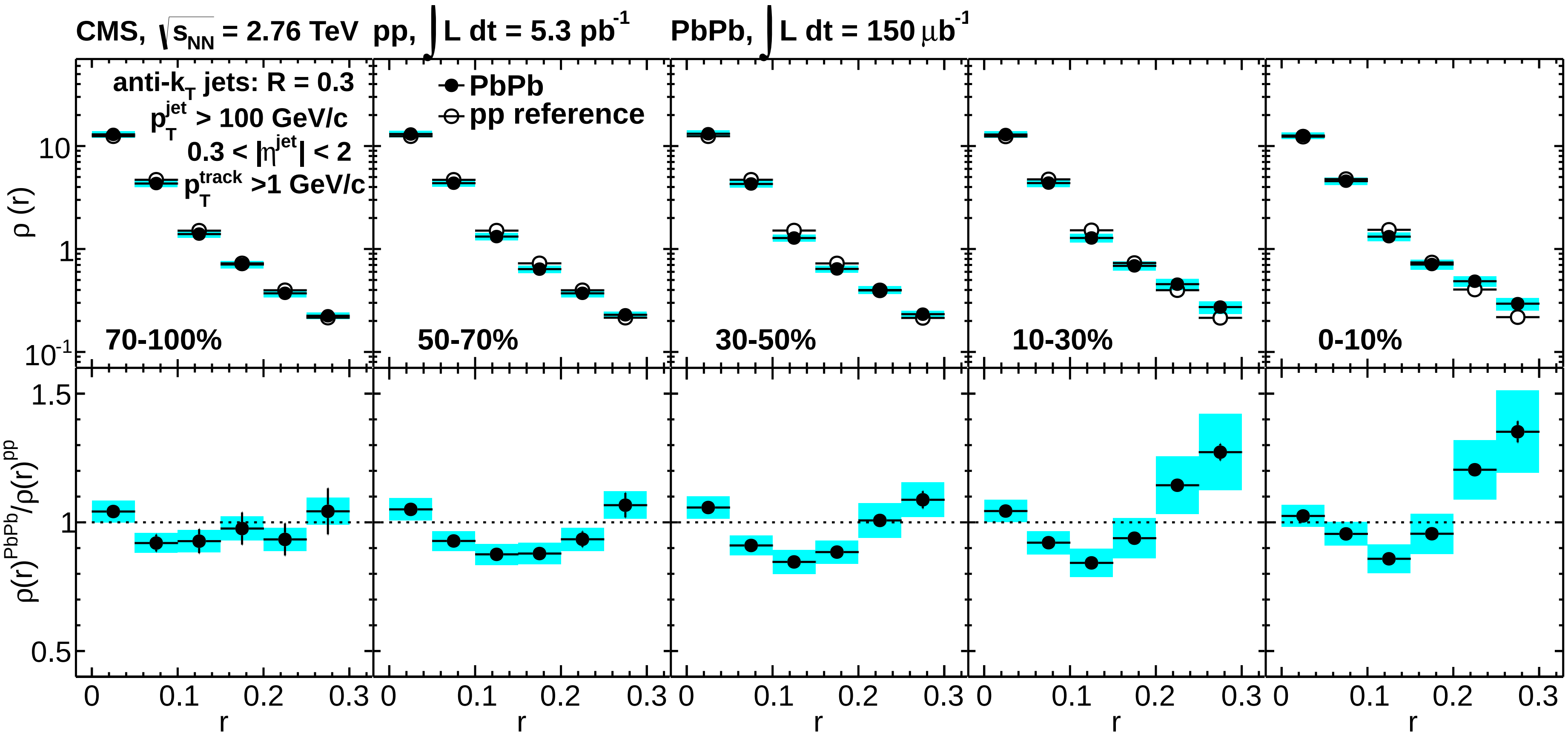
- I hope that in the early 2020s, with high statistics data from sPHENIX and the LHC on observables like the differential jet shape ratio, ideally in γ-jet events, we will be focused on the tail of this distribution corresponding to rare, but not Gaussianly rare, events in which the 10-20 GeV partons in the jet scatter off quasiparticles in the soup. $\rightarrow$ experimental access to the "microscopy variant" of the How does the strongly coupled liquid emerge from an asymptotically free gauge theory? question.
- And, for the What is the smallest possible droplet of the liquid? variant of the question, prior to an eA collider we won't be able to find a smaller droplet than in pA. So, most interesting path is to turn the collision energy down, since at lower collision energies the smallest possible droplet is larger. $\rightarrow$ looking forward to dA energy scan data.

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.**

Experimental Results

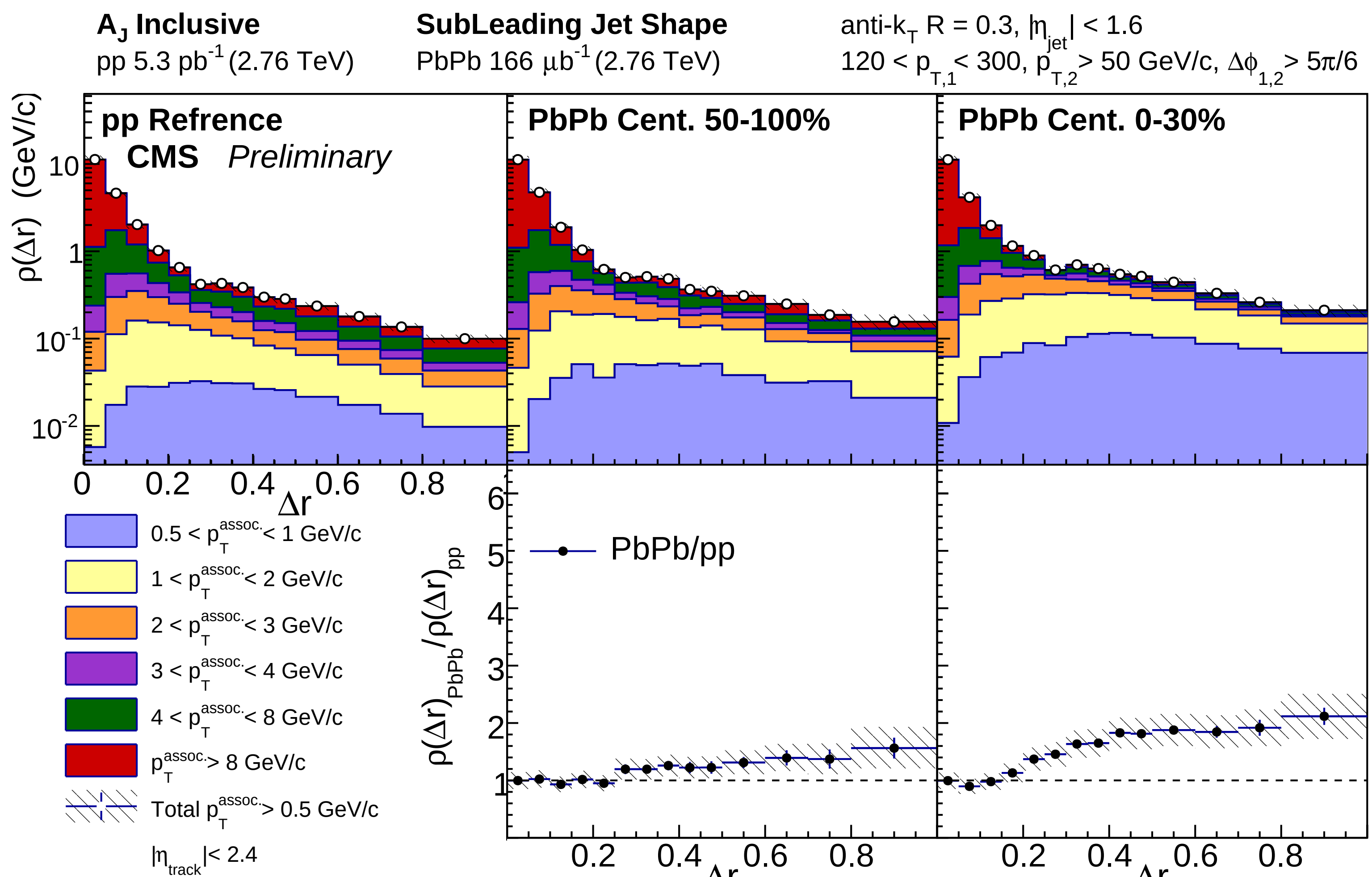
CMS, arxiv:1310.0878



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.