Inner Workings of the QGP: Where are We and Where are We Going?

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and Where are We Going?

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The title for my talk was given to me by the organizers...
And, I like it. For several reasons...

Inner Workings of the QGP:
Where are We
and Where are We Going?

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It ends in a question mark.
Good, since I don't know the answer to the implied question:

Inner Workings of the QGP: Where are We and Where are We Going?

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How are we actually going to use jets to discern the inner workings of QGP?

Inner Workings of the QGP:
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Since I do not know the answer, I am glad that the title I was given ends in a ?

Inner Workings of the QGP:
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I am also glad about the plural pronoun!
My plan: pose the question, my way, so WE can discuss...

Heavy Ion Collisions: What Next?

By recreating droplets of the matter that filled the microseconds-old universe in ultrarelativistic heavy ion collisions, we have discovered a liquid that, as far as we now know, is:

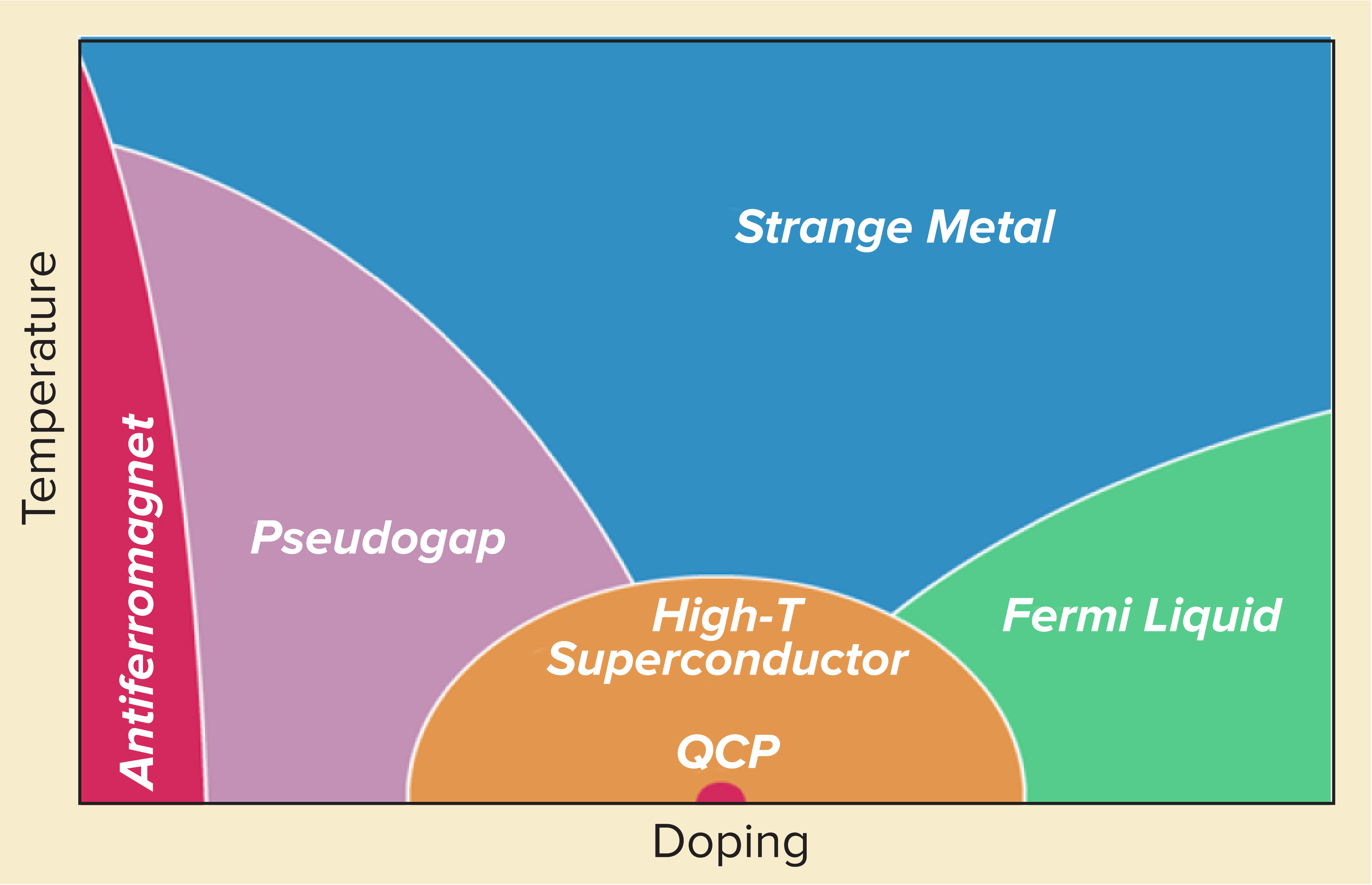
- The first liquid that ever existed; the "original liquid"…
- The liquid from which the protons and neutrons in today's universe formed, as the liquid fell apart into mist.
- At a few trillion degrees, the hottest liquid that has ever existed.
- The earliest complex form of matter.
- The most liquid liquid that has ever existed, with a specific viscosity $\eta/s \sim 0.1$.
- Perhaps in a sense the simplest form of complex matter, namely in the sense that it is "close" to the fundamental degrees of freedom of the standard model.

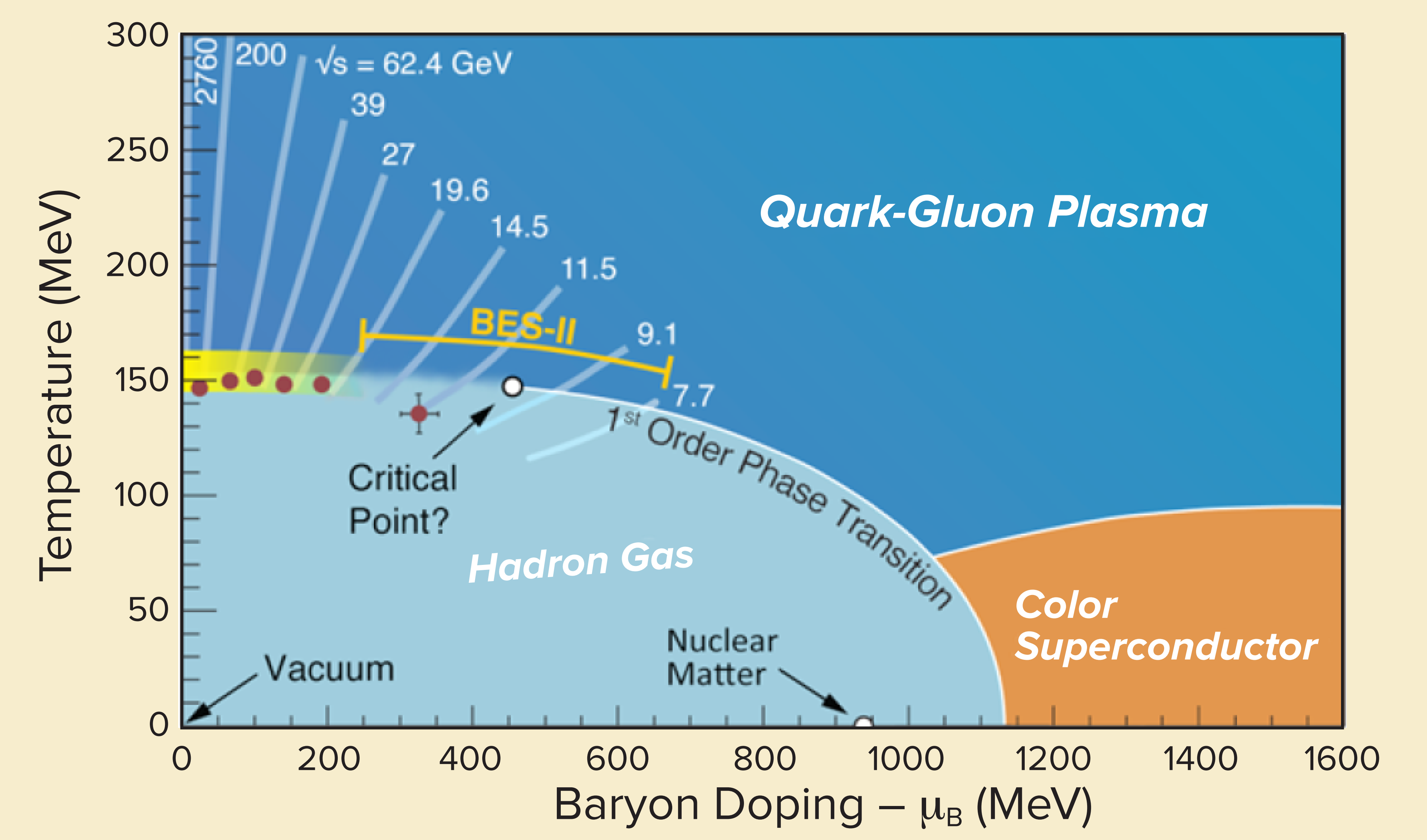
All great discoveries pose new challenges, and this is no exception. My talk is about What Next?, namely the new challenges for the decade to come.

What Next?

Two kinds of What Next? questions for the coming decade...

- 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 for another day, at another workshop.
- 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.
  Three different variants of this question...


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


Temperature (MeV)
300
250
200
150
100
50
0
Baryon Doping – μ_B (MeV)
0
200
400
600
800
1000
1200
1400
1600
2760
200
√s = 62.4 GeV
39
27
19.6
14.5
11.5
9.1
7.7
BES-II
Quark-Gluon Plasma
Critical Point?
1st Order Phase Transition
Hadron Gas
Color Superconductor
Vacuum
Nuclear Matter

What Next?

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  Three different variants of this question. . .

Probing the Original Liquid

The question How does the strongly coupled liquid emerge from an asymptotically free gauge theory? can be thought of in three different ways, corresponding to three meanings of the word "emerge": as a function of resolution, time, or size.

- How does the liquid emerge as a function of resolution scale? What is the microscopic structure of the liquid? Since QCD is asymptotically free, we know that when looked at with sufficient resolution QGP must be weakly coupled quarks and gluons. How does a liquid emerge when you coarsen your resolution length scale to $\sim 1/T$?
- 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. Each can tell us about its inner workings.

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 $RT_{\text{hydrodynamization}} \gtrsim 0.5$ to 1.**

- **Hydrodynamic behavior in small-big collisions at top RHIC energy and LHC energy less surprising,** *a posteriori*. **But still remarkable.**

- **And, it tells us that to see "inside" the liquid we will need probes which resolve short length scales...**

Why Jets?

- The remarkable utility of hydrodynamics, for pA collisions and in describing the dynamics of small lumps in the initial state in AA collisions, tells us that to see the inner workings of QGP, namely to see how the liquid is put together from quarks and gluons, we will need probes with much finer resolution. Need resolution scale that is $\ll$ size of a proton, $\ll$ size of lumps coming from the initial state that behave hydrodynamically, $\ll 1/T_{\text{hydrodynamization}}$.
- Nature gives us two multi-resolution-scale probes: Upsilons and jets.
- Upsilons tell us whether the QGP can screen color forces over length scales of order the size of the Υ(1S), Υ(2S), Υ(3S). LHC data indicate that the dissociation pattern of these quarkonia states depends on their binding energy, which is to say on their size, as long expected. More to come, for example as p_T-dependence is studied.

Why Jets?

- Upsilons can tell us about the screening length of the QGP, not about how it is put together. And, since the screening length is $\sim 1/T$ at strong coupling, and even longer at less strong coupling, the QGP is liquid-like at this resolution. And, if an Upsilon state is smaller than the screening length, it doesn't tell us anything beyond that fact. Bottom line: Upsilons are a three-scale probe that will tell us about screening but they do not see the inner workings.

Why Jets?

- Jets are multiscale probes. (Scales range from hard production scale, to scales associated with each splitting as the shower showers in medium, and wide range of scales of momentum transfer as jet partons interact with the medium and medium responds. So, from very hard to very soft.)
- They provide our best, and I would in fact argue only, chance of seeing the inner workings of the 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.
- But, precisely because they are multiscale probes, jets sure don't make it easy to decode the information about the nature of QGP at various length scales that are encoded in the modification of their energies, shapes, and structure.

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. Seeing them is not of itself interesting. But, it is a necessary precondition for addressing the question: 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. → Long-term goal of studying jets in QGP.

Jets as Probes of QGP

- But jets sure don't make it easy. That's why we need JETSCAPE. And, that is why we need 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. (The only route that I can see to seeing the inner workings of QGP. We need a scattering experiment, and this is the one that we get. You get what you get, and you don't get upset.)
- 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 mention some lessons that we (Casalderrey-Solana, Gulhan, Hulcher, Milhano, Pablos, KR) have drawn as we have wrestled with the challenge above in the context of the Hybrid Model. I will focus on lessons that are general.
- More on this tomorrow, in Pablos' talk.

A Hybrid Approach

Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1405.3864,1508.00815, 1609.05842; Hulcher, Pablos, KR, 1707.05245

- **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.**
- **Look at R_{AA} for jets and for hadrons, 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} (energetic parton thermalization distance) 3-4 times longer in QGP than in $\mathcal{N} = 4$ SYM plasma at same T.**
- **Most recently: adding momentum broadening and the wake in the plasma, adding resolution effects, looking at jet shapes, jet masses and related observables.**

Implementation of Hybrid Model

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

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

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

  where $x_{\rm therm} \equiv E_{\rm in}^{1/3}/(2\kappa_{\rm sc}T^{4/3})$ **with** $\kappa_{\rm sc}$ **one free parameter that to be fixed by fitting to one experimental data point. (**$\kappa_{\rm sc} \sim 1-1.5$ **in** $\mathcal{N}=4$ **SYM; smaller** $\kappa_{\rm sc}$ **means** $x_{\rm therm}$ **is longer in QGP than in** $\mathcal{N}=4$ **SYM plasma with same** T**.)**
- **Turn energy loss off when hydrodynamic plasma cools below a temperature that we vary between 145 and 170 MeV. (This, plus the experimental error bar on the one data point, becomes the uncertainty in our predictions.)**
- **Reconstruct jets using anti-**k_T**.**

Where are We?

- **Theorists need to use the data of today to build the baseline of understanding: one aspect is well underway.**
- **Parton energy loss is a dominant effect. Controls the modification of many jet observables, and as such can be parametrized and quantified via comparison between theory and data, today.**
- **Increasingly precise tests of the result that strongly coupled form for dE/dx, but with $x_{\mathrm{therm}}^{\mathrm{QCD}} \sim (3-4) x_{\mathrm{therm}}^{\mathcal{N}=4}$ describes** *jet observables sensitive to parton energy loss* **will come.**
- **Use of photon-jet data to compare hybrid model predictions with strongly coupled form for dE/dx to those with $dE/dx \propto T^2$ and $dE/dx \propto T^3 x$ will also come.**
- **This is all good. It is bringing us understanding of parton energy loss. 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 $K_{\text{pert}} \simeq 5$.
- 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 must be less than this.

Modifications to Shape of Jets?

- There must be a Gaussian distribution of transverse momentum kicks received by partons in jets. If the QGP were strongly coupled on all length scales, that would be the whole story.
- To see the inner workings of QGP need to start by seeing a fatter tail on top of this Gaussian distribution, coming from jet partons scattering off weakly coupled quarks and gluons resolved at high momentum transfer.
- Lets look at the jet shape, jet mass...
- BUT: if we want to constrain K by looking for jets getting wider in angle as all the partons in them are getting their Gaussian kicks, we have to first face two, much larger, confounding effects.

Where are we?

- **Jets with a given energy are *narrower* in PbPb collisions than in pp collisions. Why? Because of parton energy loss! Jets with a given energy come with a broad distribution of widths. Those that are wider lose more energy.**
  - **In hybrid model, and in fully weak coupling approaches like JEWEL, this happens because wider jets contain more partons. (CGMPR; Milhano, Zapp)**
  - **In fully strongly coupled models of jets, this is also true (Sadofyev, KR, van der Schee; Brewer, AS, KR, WvdS)**

  Consequently, even if individual jets get wider as they propagate through QGP as their partons receive kicks, in the ensemble of jets after quenching those that remain with a given energy are the ones that were the narrowest jets in the ensemble before quenching.
- **This narrowing seen in jet shapes when you look either only at small r, or only at hadrons with $p_T \gtrsim 4$ GeV.**
- **Aside: this effect also makes it obvious that triggering on high-p_T hadrons must yield less suppression (larger R_{AA}) than triggering on jets.**

Where are we?

- Jets are, at the same time, *wider* in PbPb collisions than in pp collisions. Why?
- The energy *and momentum* lost by the jet are not *lost*. The jet leaves behind a wake in the hydrodynamic plasma, and this wake has momentum. When the QGP hadronizes, this wake becomes soft particles distributed across a large range of angles relative to the jet direction − with net momentum in the jet direction.
- This can be seen in the data: “missing-p_T observables”.
- When experimentalists reconstruct a jet and subtract background, what they reconstruct and call a jet *must* include some soft particles coming from the hadronization of the plasma+wake, with momentum in the jet direction.
- This makes the reconstructed jets wider than in pp collisions, as seen in jet shapes when you look either at larger r, or at hadrons with $p_T \lesssim 4$ GeV.
- The two confounding effects can each be seen distinctly in jet shapes; in jet mass, they push in opposite directions making their effects hard to separate in that observable.

Where are we going?

- For today, an aside: By careful comparison of hybrid model calculations that assume that the wake thermalizes (subject to momentum conservation) to data on missing-p_T observables, we now know that the wake doesn't thermalize. Jet wakes contain more 2-4 GeV hadrons and fewer 0-2 GeV hadrons than they would if they had had time to thermalize. An experimental handle via which to study hydrodynamization...
- To constrain K by looking for jets getting wider in angle as all the partons in them are getting their Gaussian kicks is going to require careful choice of observable, and quantitative modeling.
- For example, jet shape ratio (PbPb/pp) for jet shapes constructed only from hadrons with p_T between 5 and 10 GeV. Or, any other observable designed to be sensitive to 10-20 GeV partons, and thus insensitive to the wake and to the hardest partons that are deflected least when kicked.

Where are we going?

- However, the dominant effect in any such differential jet shape ratio will still be the narrowing due to parton energy loss, which must therefore be reliably understood and modeled. (Can differential jet shape ratios be measured in photon-jet events?)
- Note that the narrowing of jets with a given energy due to parton energy loss also affects the comparison of dijet acoplanarity in PbPb to that in pp.
- What would be really cool is an observable (built using softdrop and substructure techniques?) that remembers the initial jet mass, i.e. what the jet mass or opening angle would have been in the absence of any parton energy loss or wake. If we could compare jets in pp and PbPb with the same value of such an observable, the differential jet shape ratio would then give direct access to transverse kicks, and K.

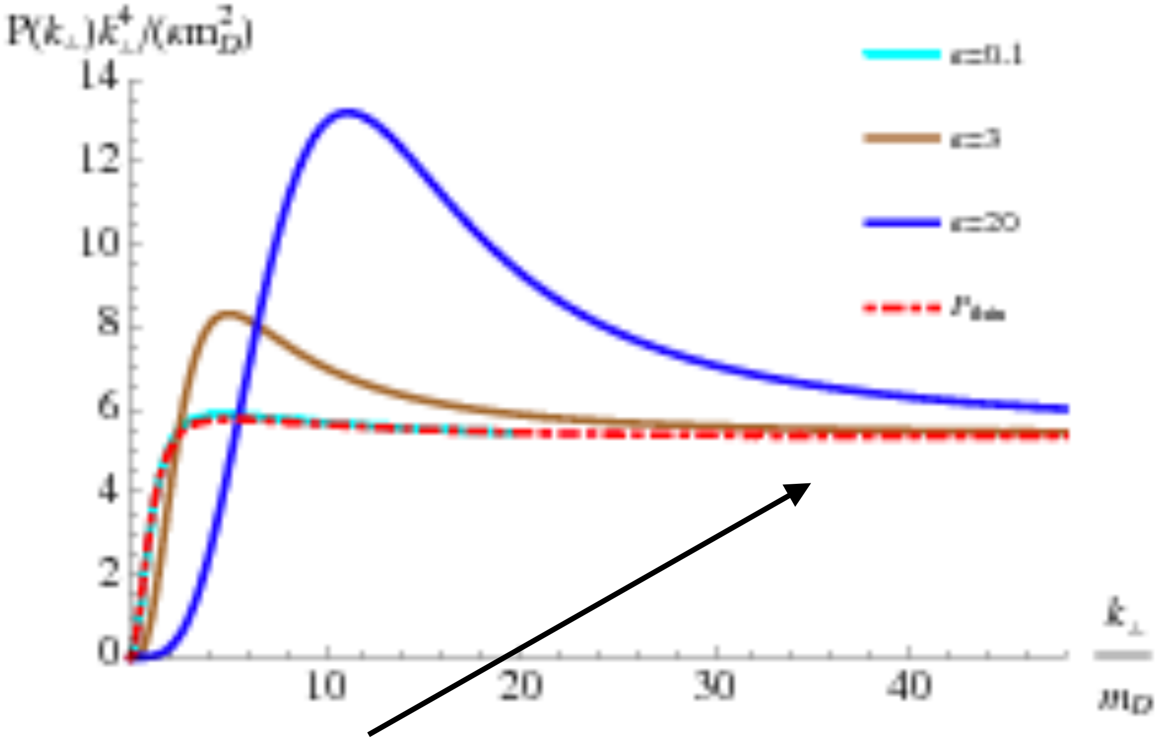
Where are we going?

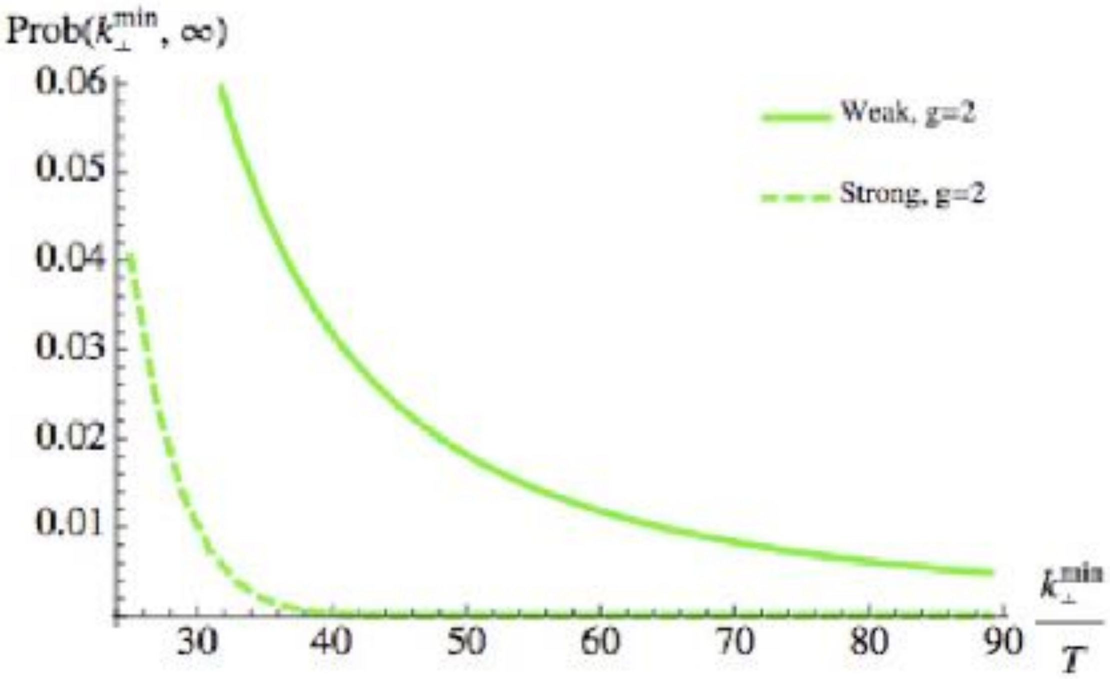
- A long road ahead. Two confounding (but interesting) effects, both large, to be understood first. Only then, see the Gaussian distribution of transverse kicks and constrain $\hat{K}$. And only then, see jet partons scattering off scatterers in the QGP.
- Goal for the 2020s: look for the rare (but only 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 resolved. D'Eramo, Lekaveckas, Liu, KR 1211.1922; Kurkela, Wiedemann, 1407.0293; D'Eramo, KR, Yin, 2018

Where are we going?

- How improbable are such Molière scatterings with a given angle?
- In 2011, computed the probability that an *infinite energy* parton receives a large kick in transverse momentum. Infinite energy means zero scattering angle. Also means only t-channel (Rutherford) scattering.
- FD'E, YY, KR are now remedying this. Brick of weakly coupled QGP, in equilibrium, with temperature T. Single scattering of a finite-incident-energy parton with some incident momentum p_i and a parton from the plasma. What is the probability that a parton emerges with a specified p_f at an angle θ relative to the incident parton's direction? ($p_i/T \neq \infty$ means $\theta \neq 0$; $p_f \neq p_i$ means not just t-channel.)
- This calculation won't have the Gaussian; add that by hand, for different values of K, and see where the tail from large angle scattering off a hard scatterer dominates the Gaussian.

Moliere scattering for a QGP brick





"Rutherford tail"

D'Eramo, Lekaveckas , Liu, Rajagopal, JHEP 12, (DLLR)

- Approaching "Rutherford tail" ~ $1/q^4$ for large transverse momentum.
- "Tail" is dominant over Gaussian and distinguish weakly coupled QGP from strongly coupled QGP.

Where are we going?

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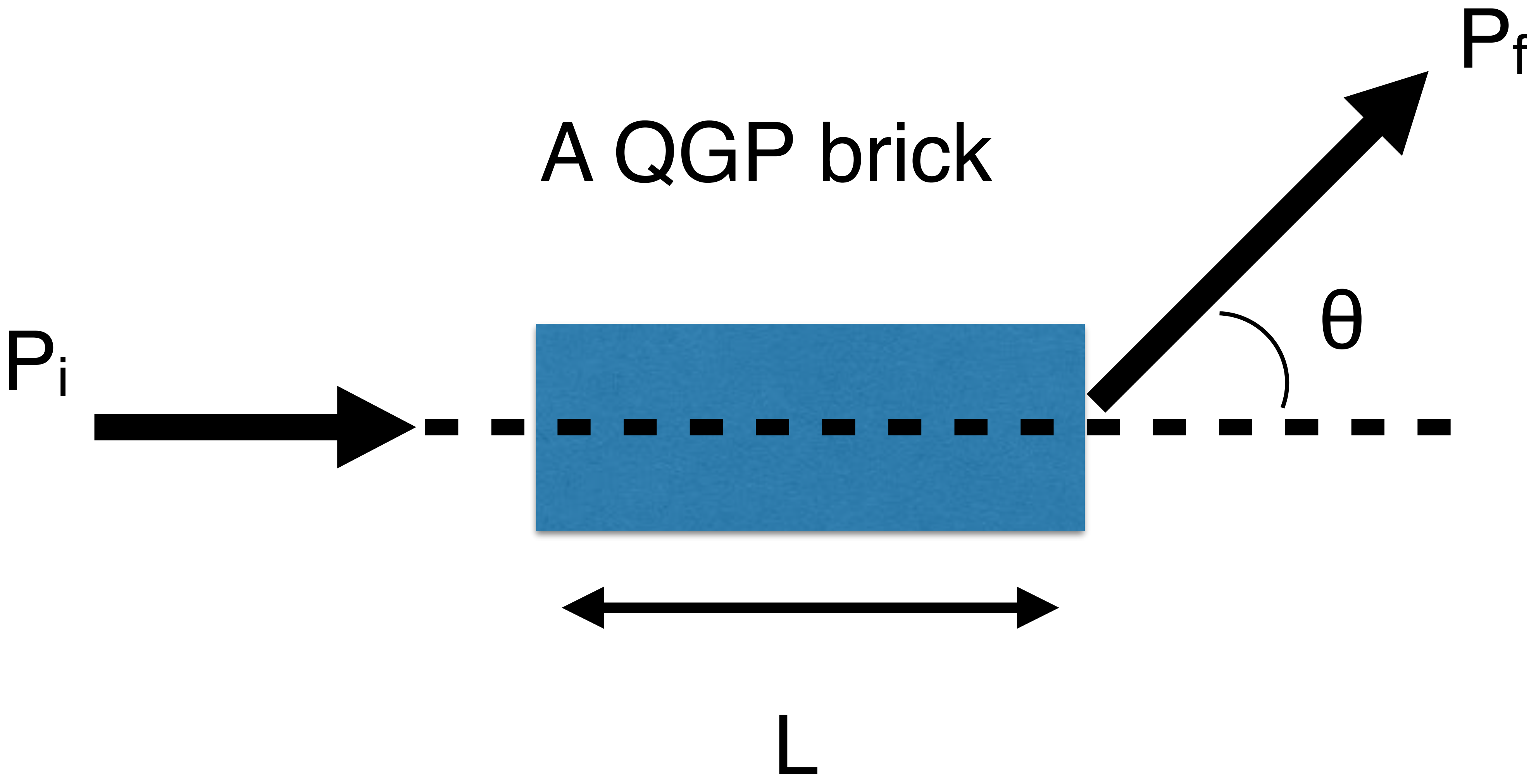
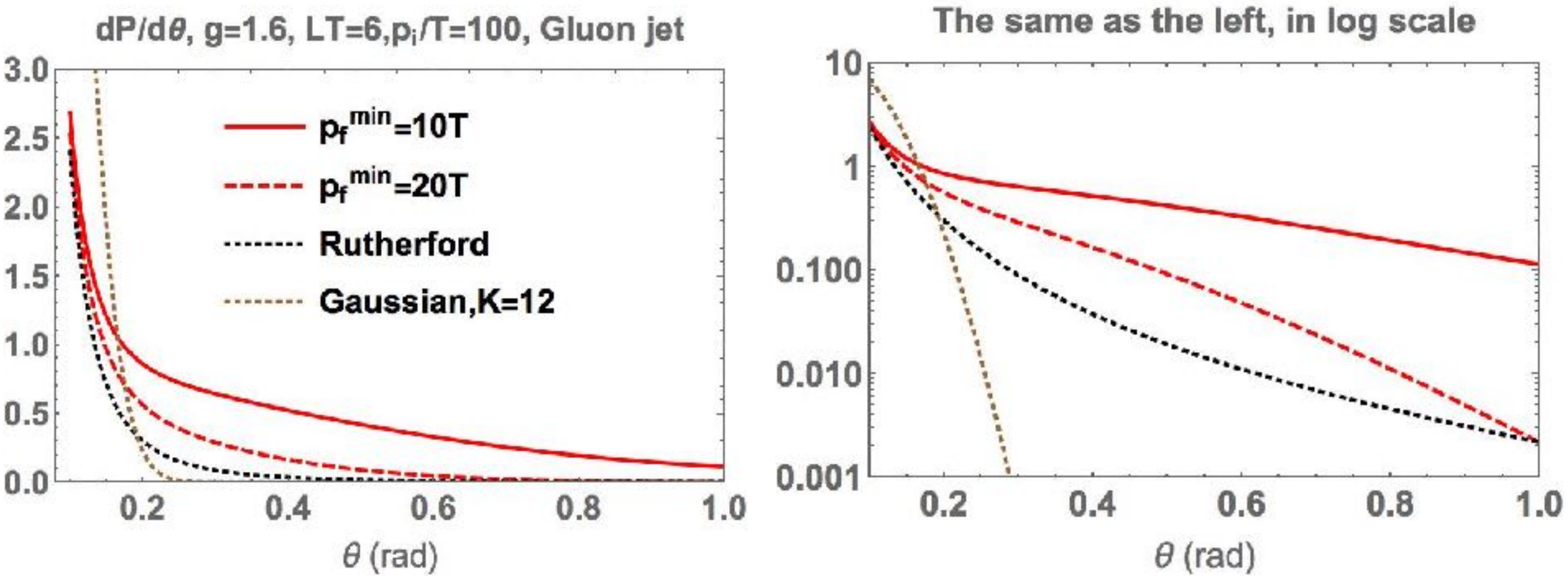
Shooting an energetic parton through a QGP Brick



Larger angle, larger momentum transfer.

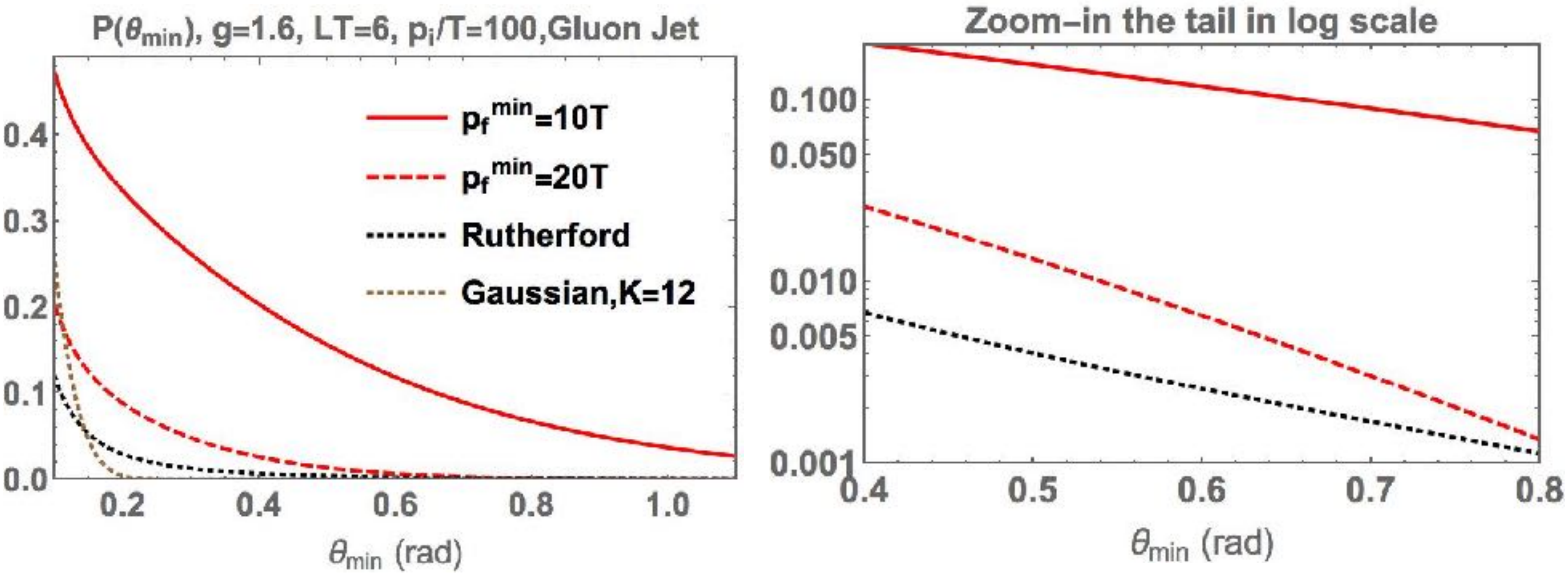
$P_i = 100\ T$



$$< q_\perp^2 >= K T^3 L$$ (K≈5 from Jet collaboration)

- Tail: a single scattering eventually wins over Gaussian.
- Fatter than “Rutherford tail” (more channels are included).

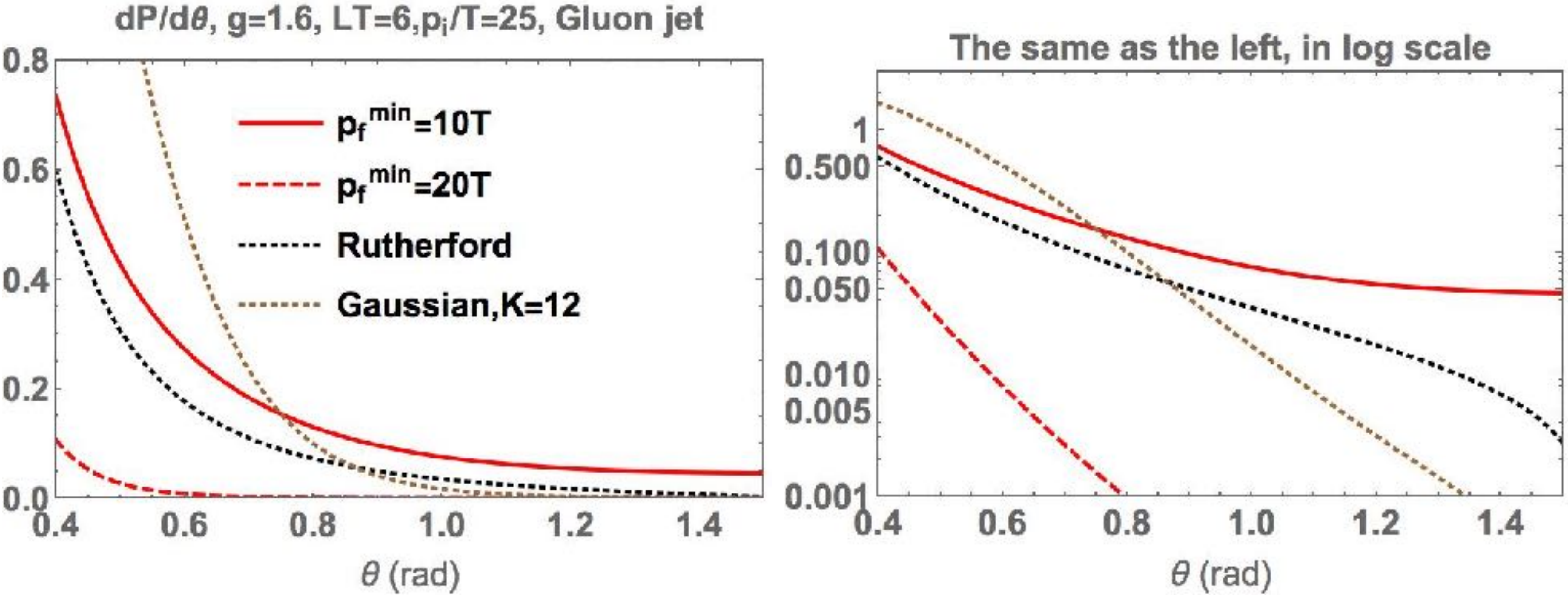
P_i =100 T



$$P(\theta_{\min}) = \int_{\theta_{\min}} d\theta \, \frac{dP}{d\theta}$$

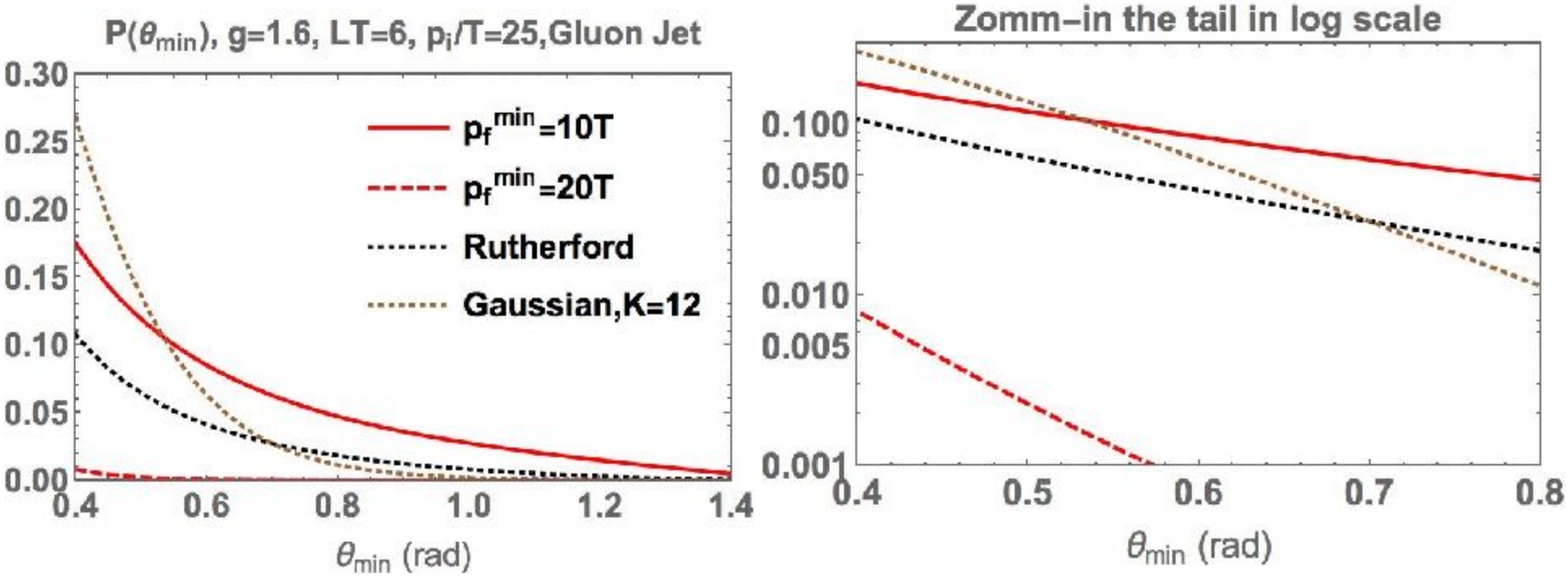
Rare but not too rare

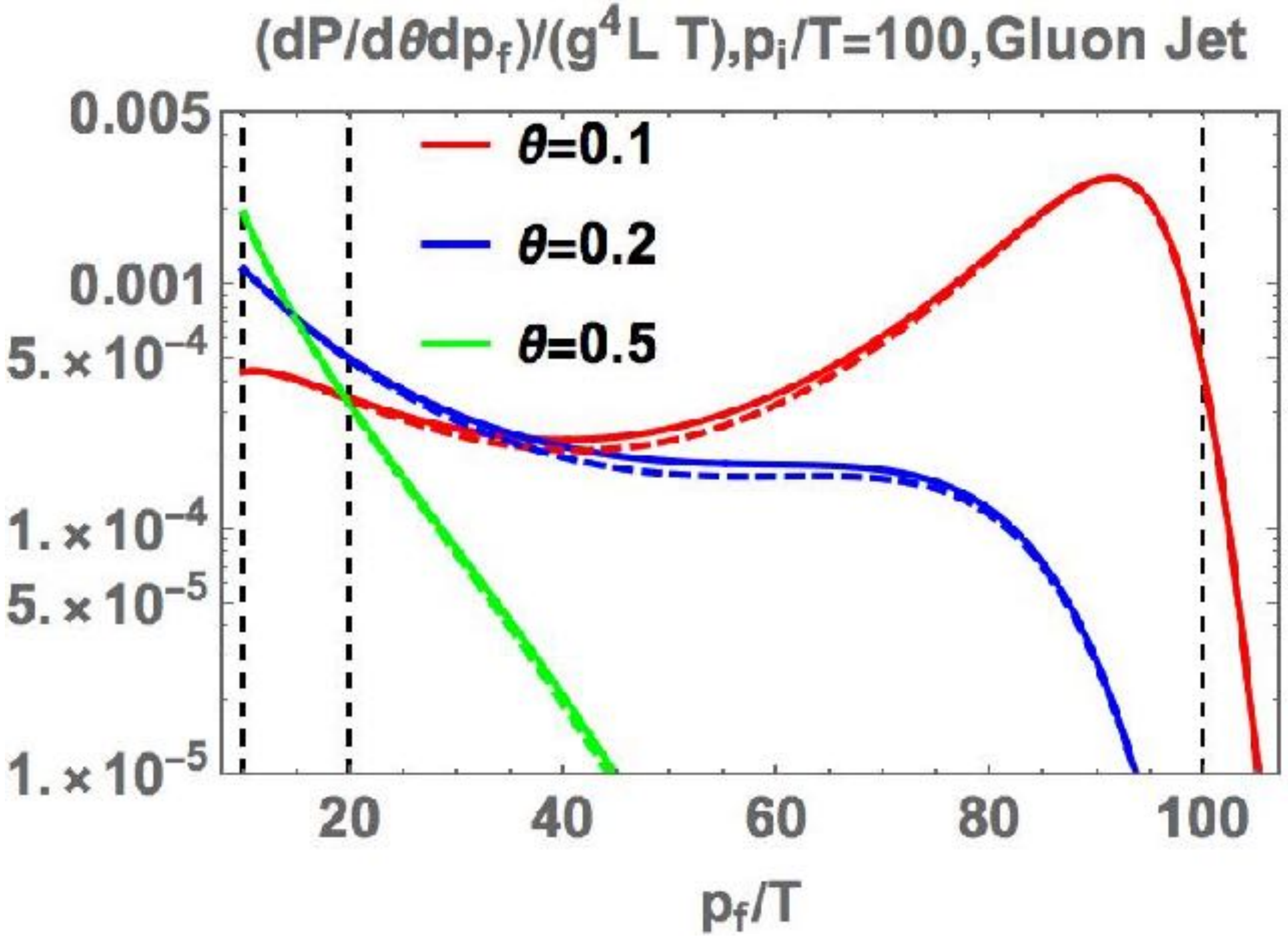
$P_i = 25$ T



- A jet parton with a smaller p_i is more sensitive to the kinematic cut.

P_i =25 T

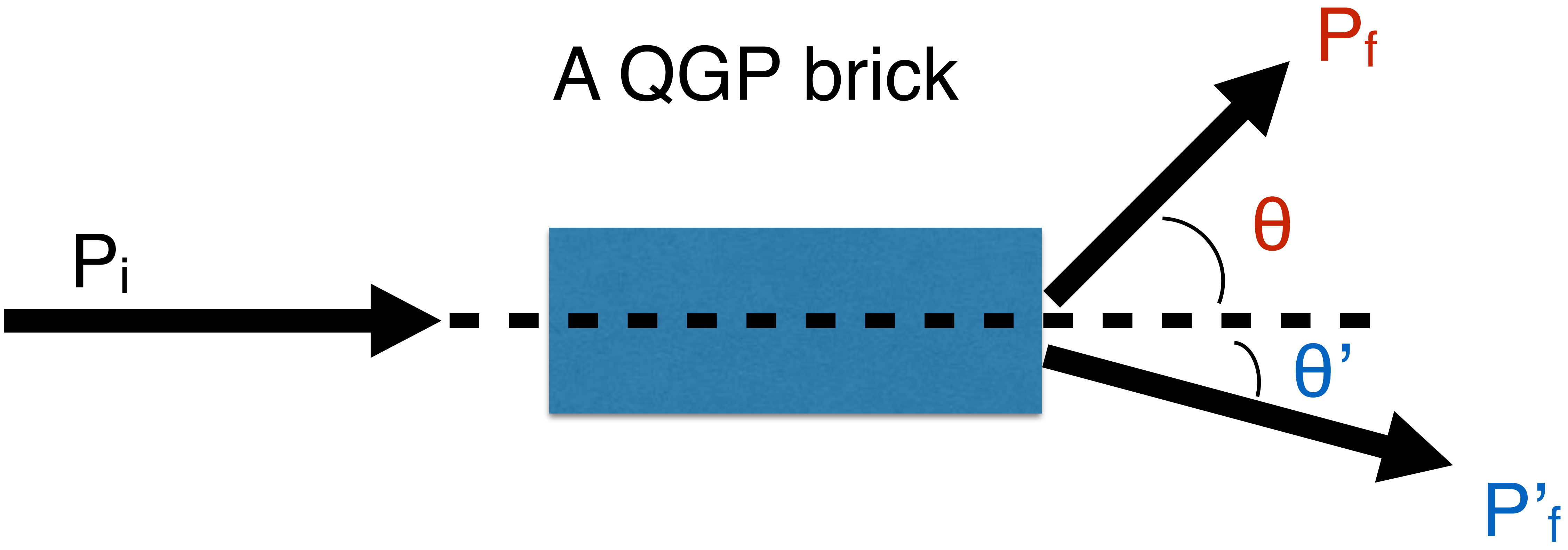

P(θmin), g=1.6, LT=6, pi/T=25,Gluon Jet
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.4
0.6
0.8
1.0
1.2
1.4
θmin (rad)
pfmin=10T
pfmin=20T
Rutherford
Gaussian,K=12
Zomm-in the tail in log scale
0.100
0.050
0.010
0.005
0.001
0.4
0.5
0.6
0.7
0.8
θmin (rad)



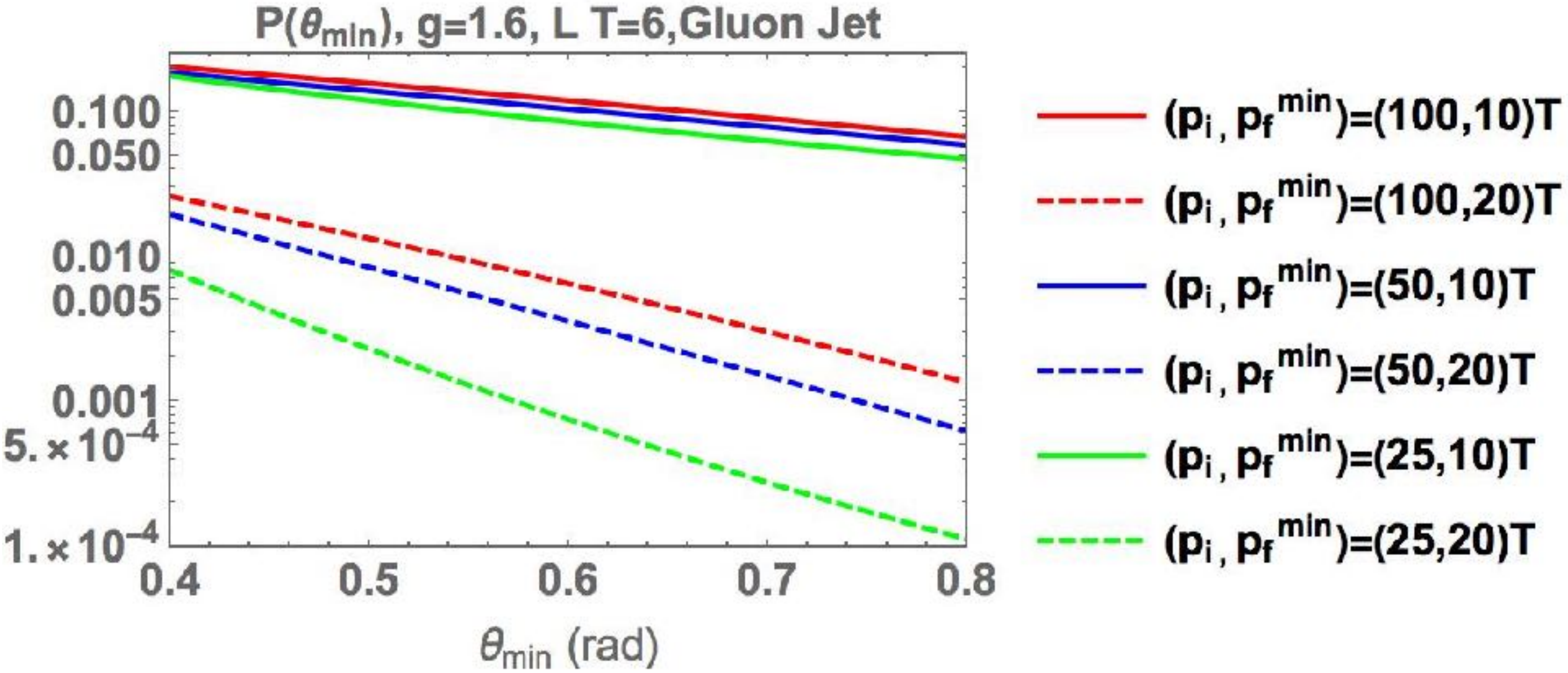
(4/9) quark rate (dashed) ≈ gluon rate.

Larger angle, more energy lost

A gift from momentum conservation



- E.g.: in a binary collision, a 40 GeV parton can "branch" into a 30 GeV parton and a 10 GeV parton. The one with the smaller p_f has the larger angle .



Different p_i , similar behavior

Where are we going?

- **This calculation is merely illustrative, to give a sense of what one might look for.**
- **E.g., thinking of T as 0.4 GeV and L as 3 fm, then if $p_i = 40$ GeV look for evidence of partons coming out with $p_f > 8$ GeV and $\theta > 0.3$ radians. And, $\theta = 0.8$ is only less probable than $\theta = 0.3$ by about a factor of 20.**
- **Or, if $p_i = 10$ GeV look for evidence of partons coming out with $p_f > 4$ GeV and $\theta > 0.9$ radians.**
- **To look at modification of differential jet shape and substructure observables, this analysis needs to be implemented within a jet Monte Carlo (e.g. JETSCAPE?).**
- **What about dijet acoplanarity? A more direct observable, but need a larger p_f, since p_f is now the momentum of a jet rather than of a parton within a jet, and this will push the probability down.**
- **We are open to suggestions for what choices of p_i/T, and what cuts on p_f/T, to use when we make our plots, to make them most illustrative.**

Where are we going?

- We are learning more and more, now and in the short and medium terms.
- Parton energy loss is of central interest, and we are constraining our understanding of it better and better.
- Ditto for how the medium responds, namely the wake.
- Modification to suitably differential jet shape observables, insensitive to the widening of the soft component of jets due to the wake and, either via modeling or maybe by construction, insensitive to the narrowing of the hard component of jets due to parton energy loss, will let us see the Gaussian component of transverse broadening.
- Those are all prerequisites to seeing the inner workings.
- Much work still to be done to go from illustrative calculations to defining, calculating, and measuring observables that focus on events in which a 10-20 GeV parton in the jet scatters off a quasiparticle in the soup.

The Long View

- The effects of the wake in the plasma are key to understanding full jet shape observables. By detailed comparison between a baseline which assumes a hydrodynamized wake and data we learn to what degree the wake does *and does not* thermalize. → experimental access to the "as a function of time" variant of How does the liquid emerge from weakly coupled degrees of freedom?
- Next: determine magnitude of K, the strength of the Gaussian distribution of transverse kicks felt by the partons in the jet. (Via suitably differential jet shape observables.)
- Early 2020s: use high statistics sPHENIX and LHC data, e.g. on gamma-jet acoplanarity, differential jet shape ratio in γ-jet events 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. → experimental access to the "microscopy variant" of How does the liquid emerge from an asymptotically free gauge theory?

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

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

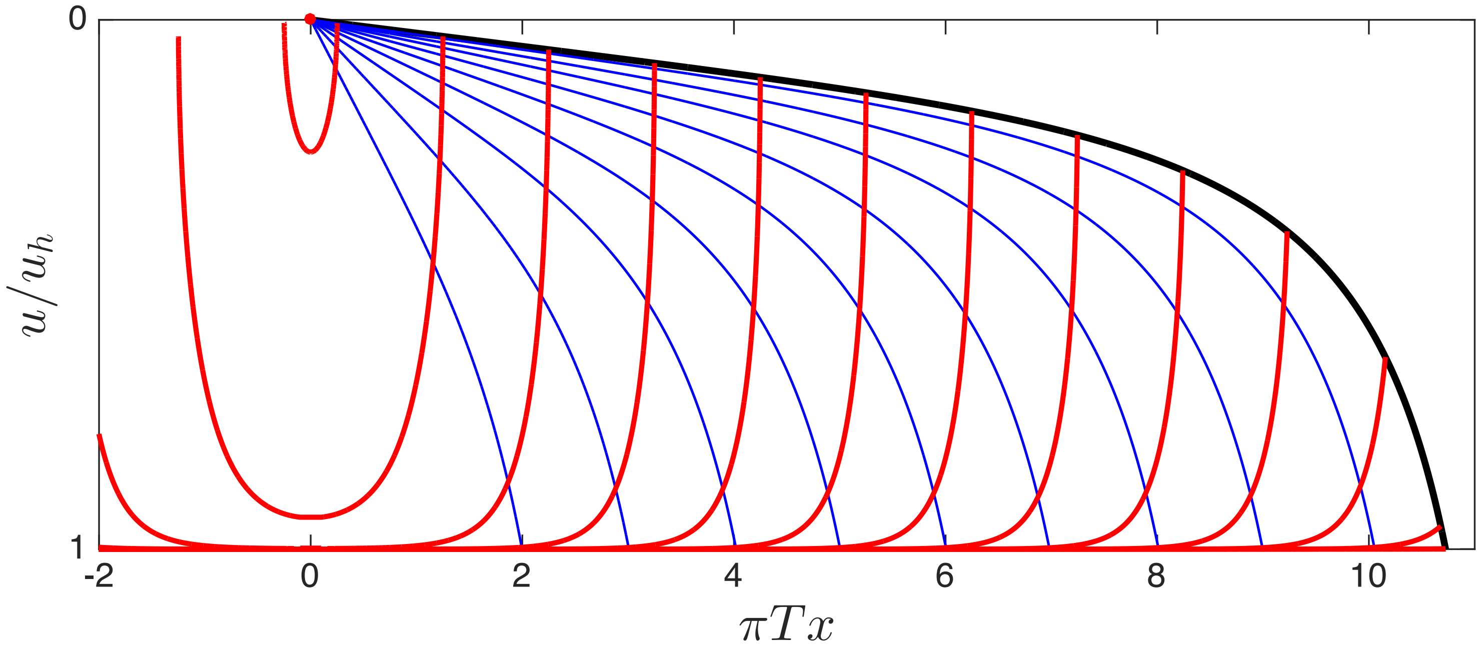
Canterbury Tales of Hot QFTs in the LHC Era
Oxford, UK, July 11, 2017

The Long View

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

Quenching a Light Quark "Jet"

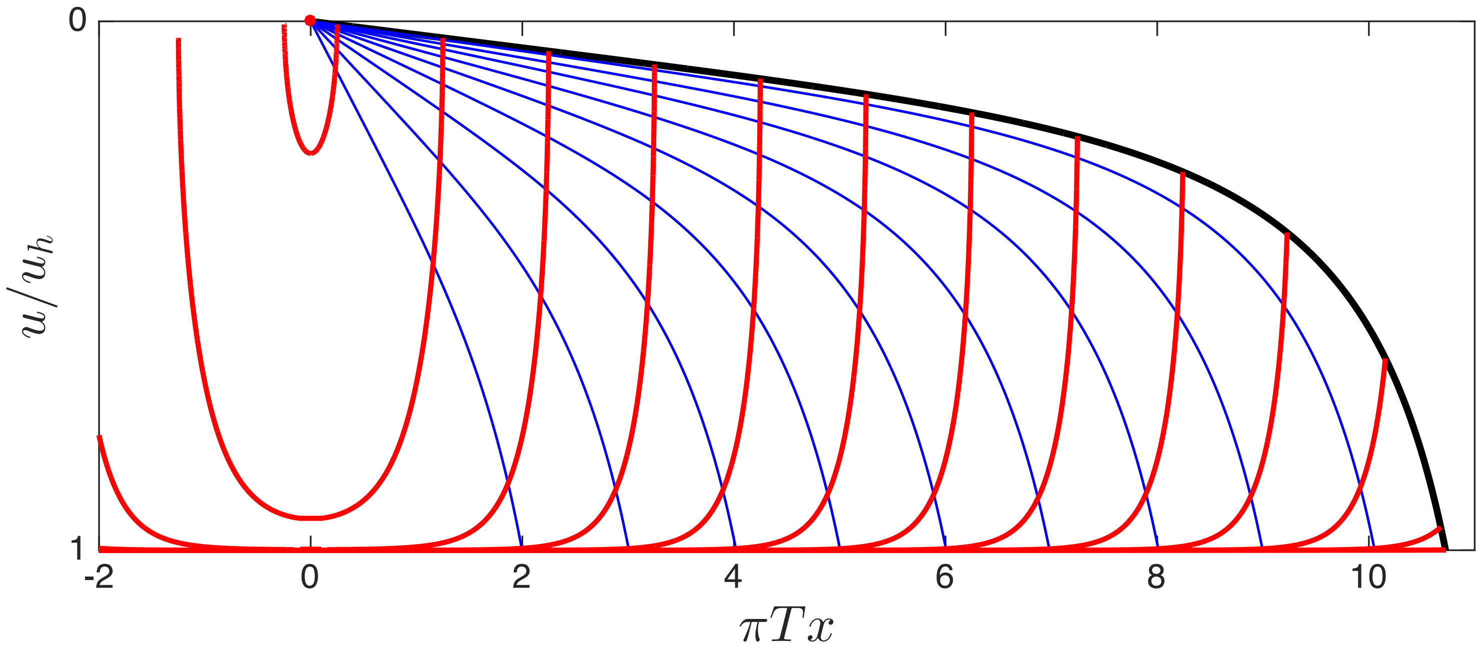
Chesler, Rajagopal, 1402.6756, 1511.07567



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

Quenching a Light Quark “Jet”

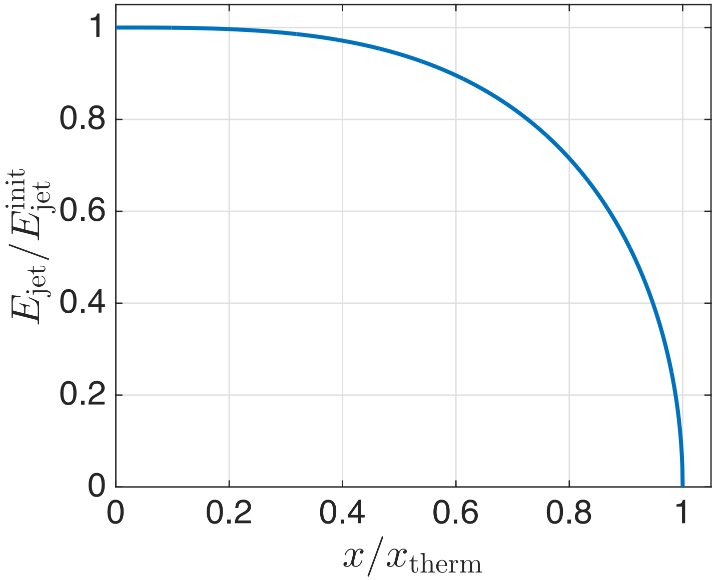
Chesler, Rajagopal, arXiv:1402.6756, 1511.07567



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

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756, 1511.07567



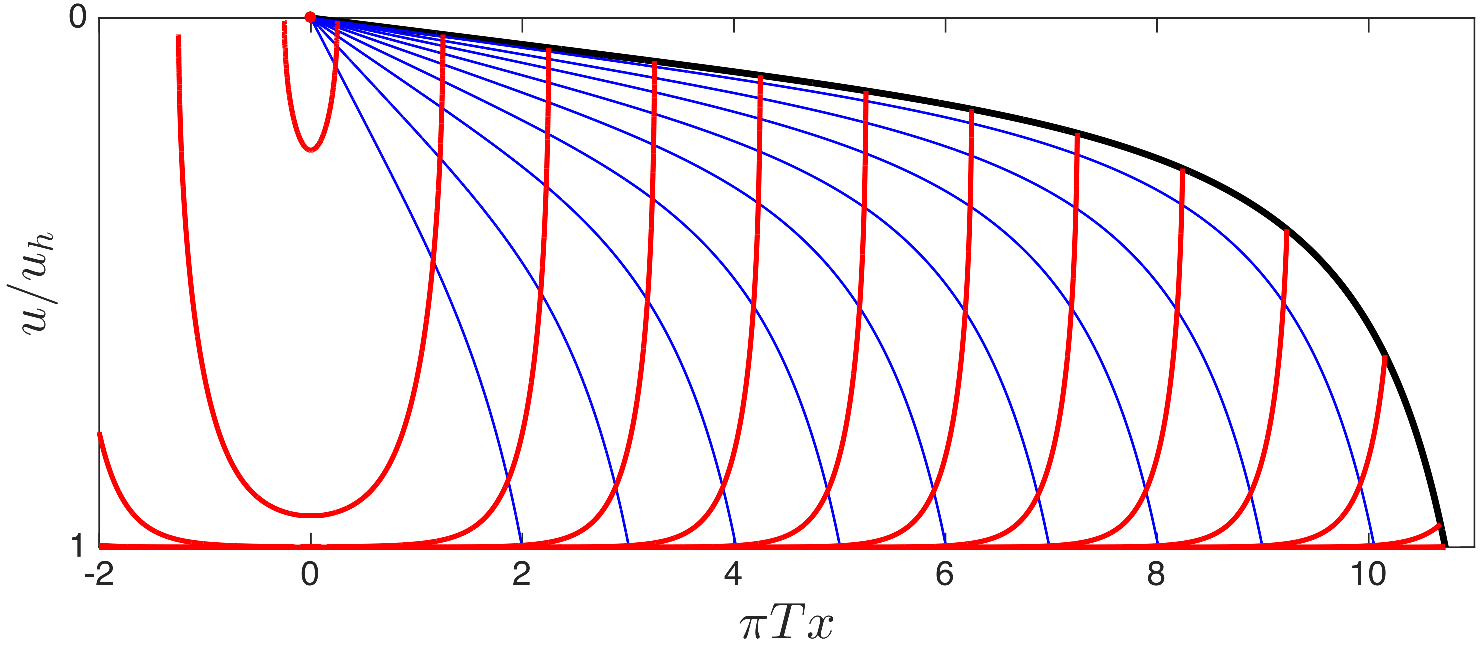
We compute E_{jet} analytically, by integrating the energy flowing into hydrodynamic modes, and showing its equivalence to that falling into the horizon. Geometric derivation of analytic expression for dE_{jet}/dx

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

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

Quenching a Holographic Jet

Chesler, Rajagopal, arXiv:1511.07567

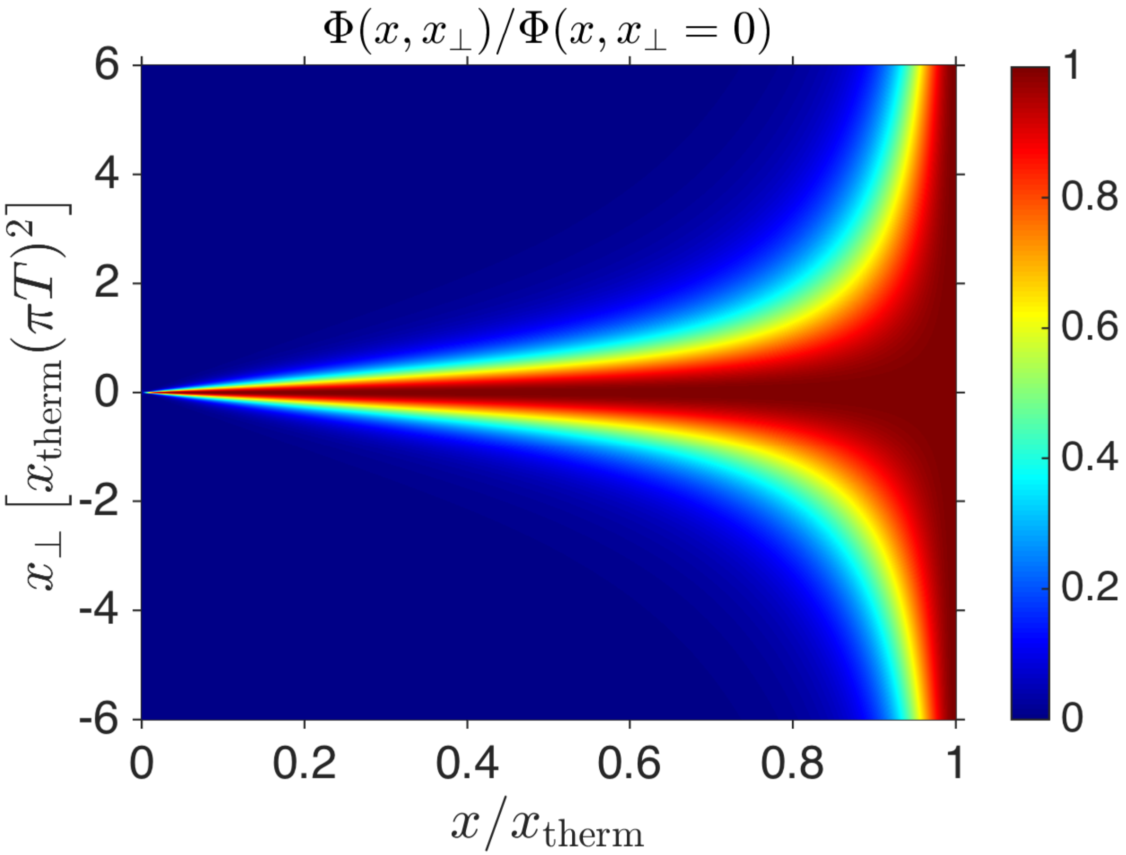


Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

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

Holographic “Jet” Energy Loss

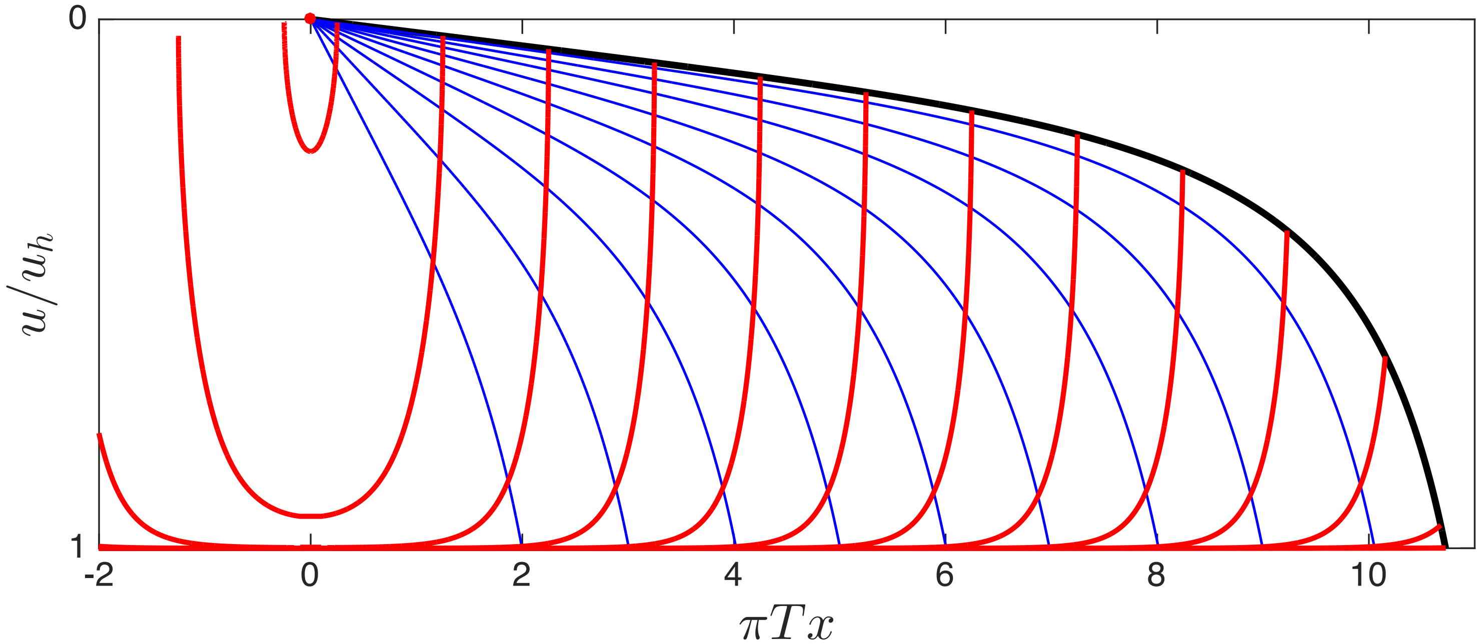
Chesler, Rajagopal, arXiv:1511.07567



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

Holographic “Jet” Energy Loss

Chesler, Rajagopal, arXiv:1511.07567



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

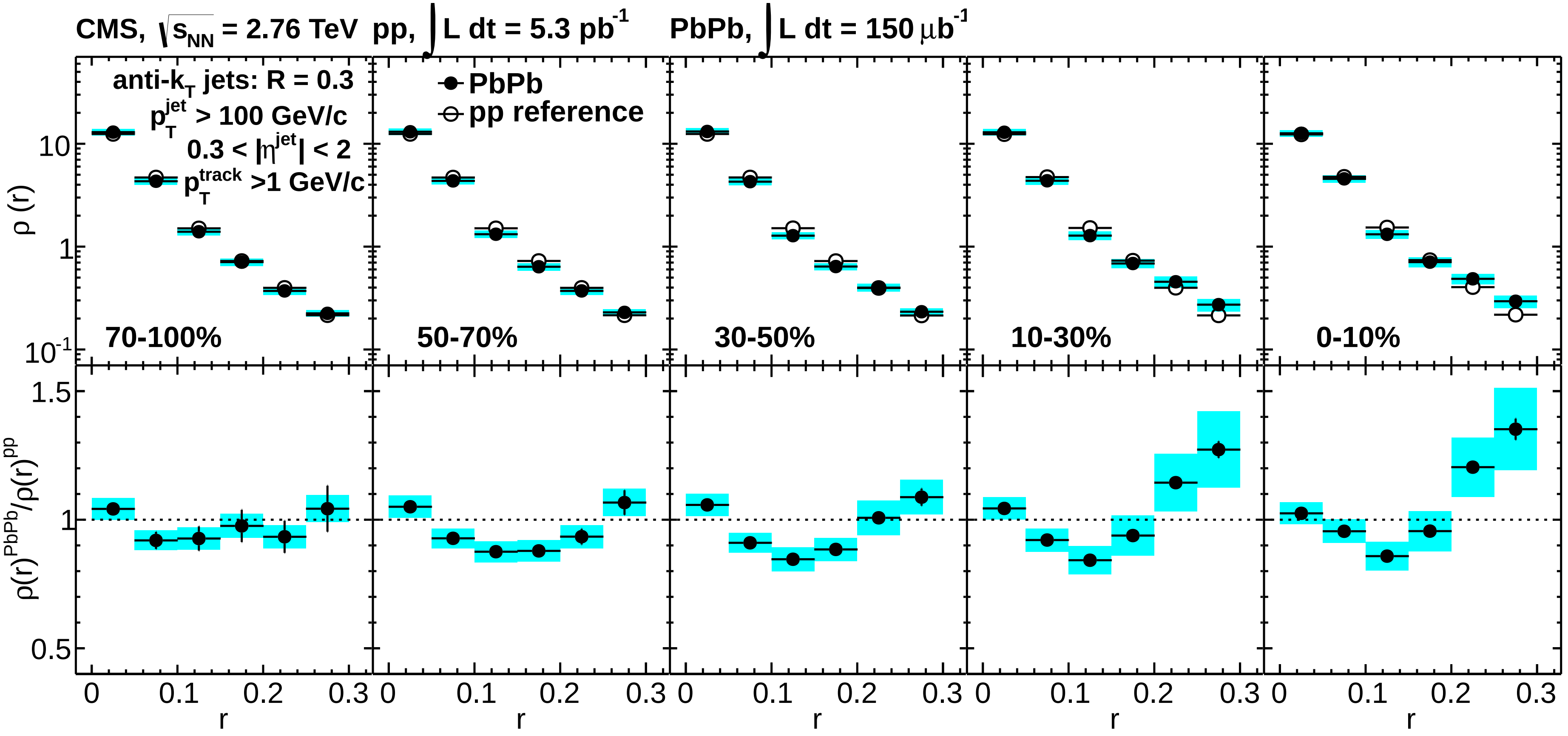
- Second, jets with smaller initial $\theta_{\rm jet}^{\rm init}$ have a longer $x_{\rm therm}$. They lose their energy more slowly, over a longer distance. (In fact, $T x_{\rm therm} \propto 1/\sqrt{\theta_{\rm jet}^{\rm init}}$.)
- That is, for jets with the same $E_{\rm jet}^{\rm init}$ that travel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

Two Approaches

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

Experimental Results

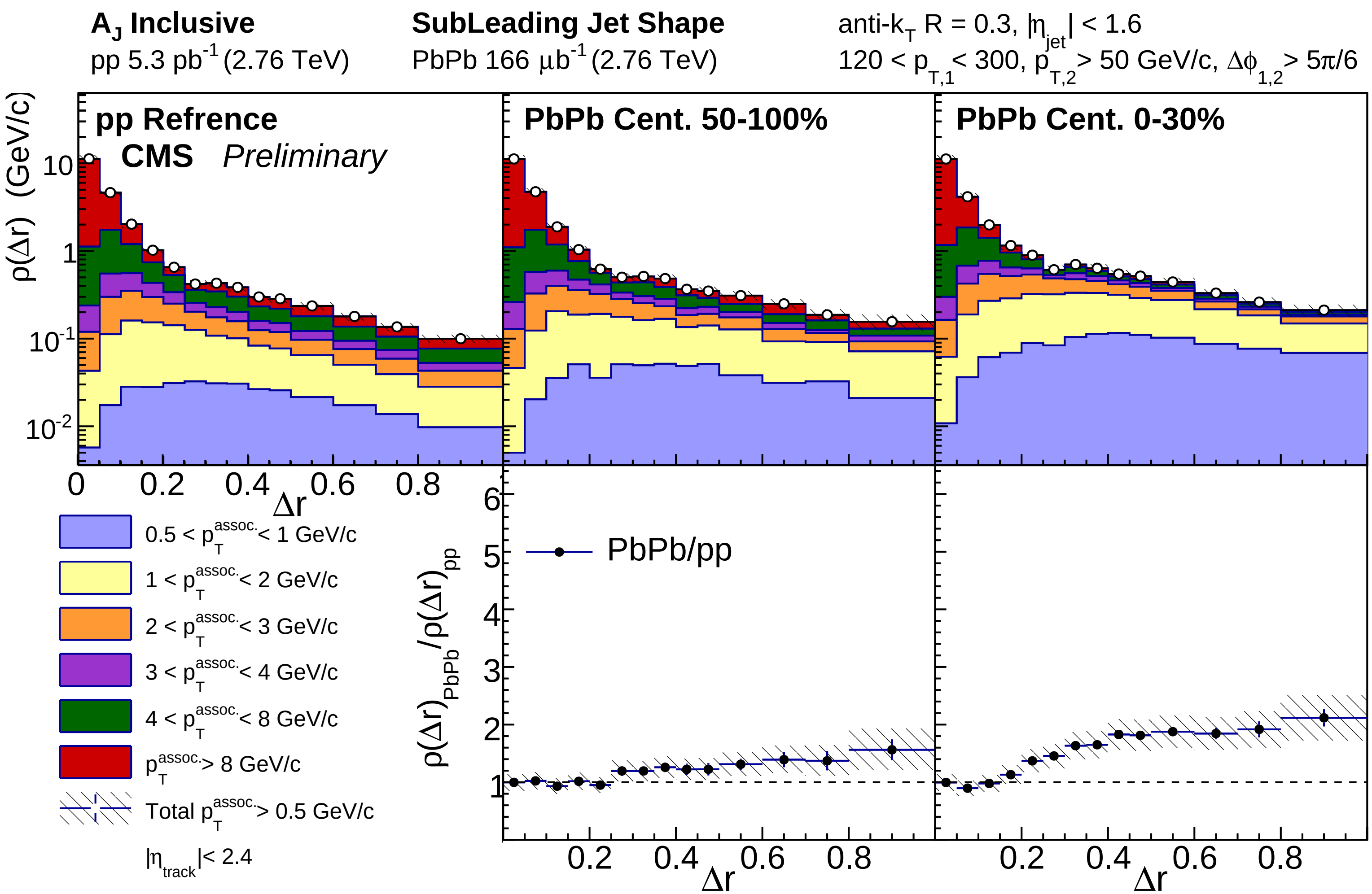
CMS, arxiv:1310.0878



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

Experimental Results

CMS, HIN-15-011



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

Experimental Results

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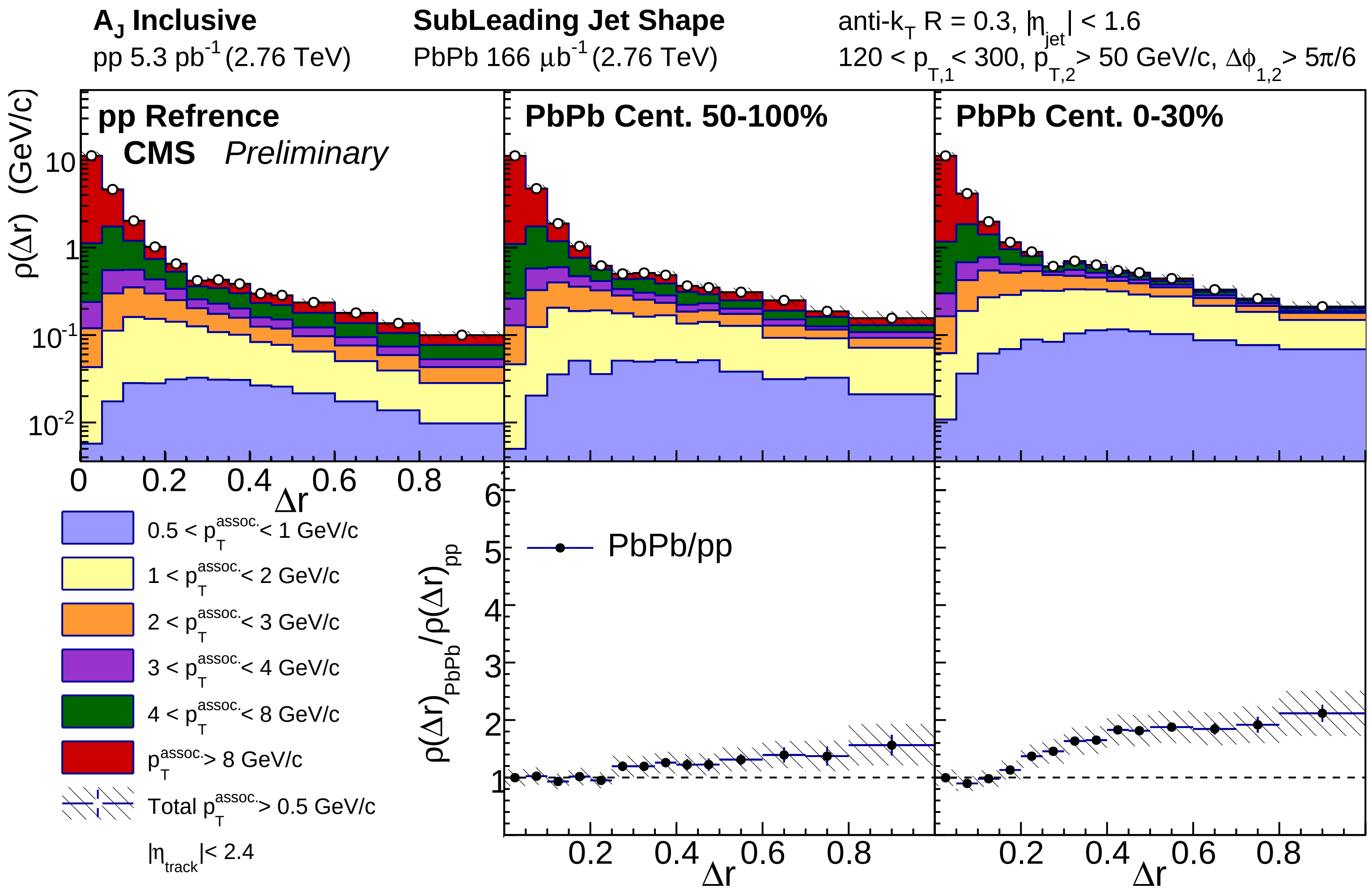


The narrowing at small angles comes from the hard component of the jet. The broadening at large, and very large, angles is in the softest particles, likely those coming from the wake in the plasma that are reconstructed as part of the jet.

A Contradiction?

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

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

Is this a contradiction? Not necessarily...

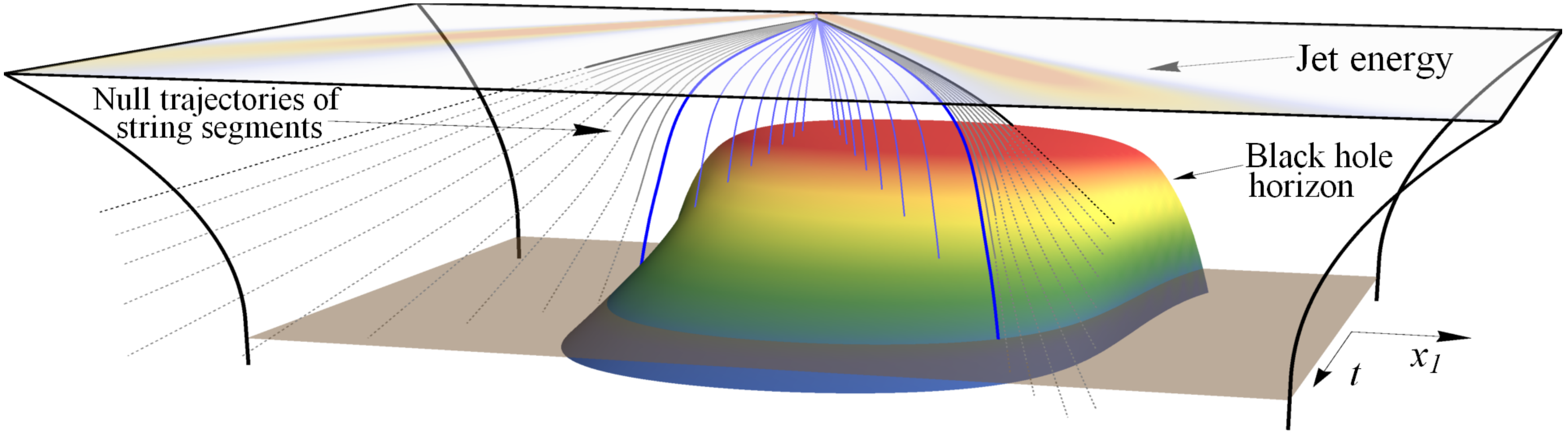
In order to compare quenched jets and unquenched jets with the same final energy, we need to follow what happens to an ensemble of jets.

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

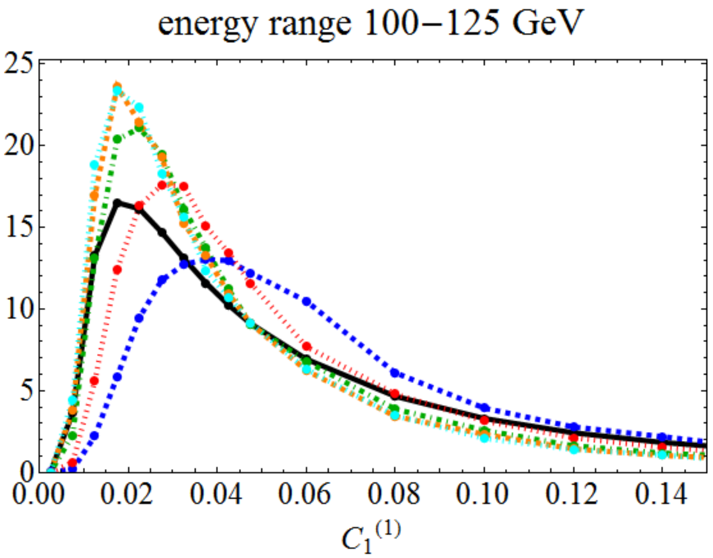
Our goal is to assess whether there is a blatant contradiction. And qualitative insight. So we will simplify many things...

Evolution of Jet Opening Angle Distribution

Rajagopal, Sadofyev, van der Schee, 1602.04187



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



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

Evolution of Jet Opening Angle Distribution

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

Choose an ensemble of holographic jets, distributed as follows:

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

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

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, $C_1^{(1)} = a\,\sigma_{\text{endpoint}}^{\text{init}}$. 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 $\sigma_{\text{endpoint}}^{\text{init}}$.)**

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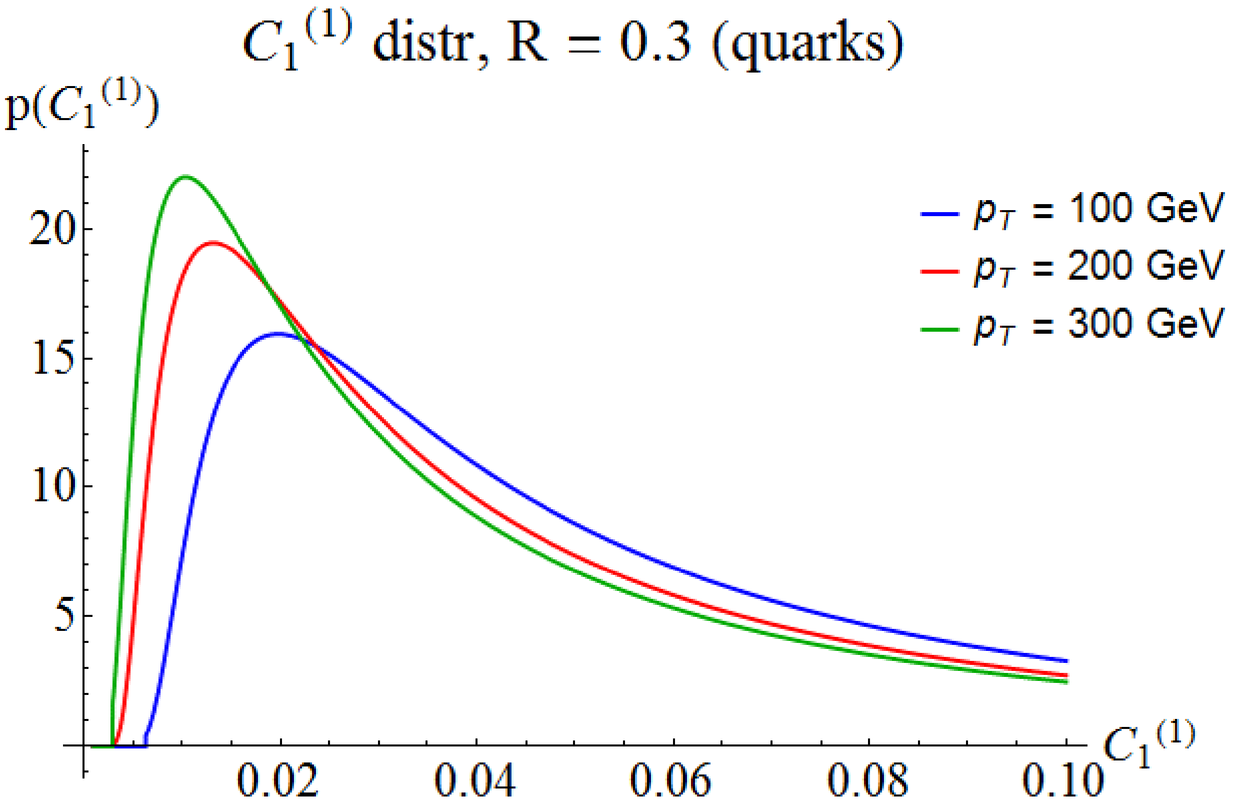

Larkoski, Marzani, Soyez, Thaler 1402.2657

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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:

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

where $r_{\textbf{bl}}(\tau) \equiv \sqrt{1 + (v_T \tau / R_{\rm Pb})^2}$, 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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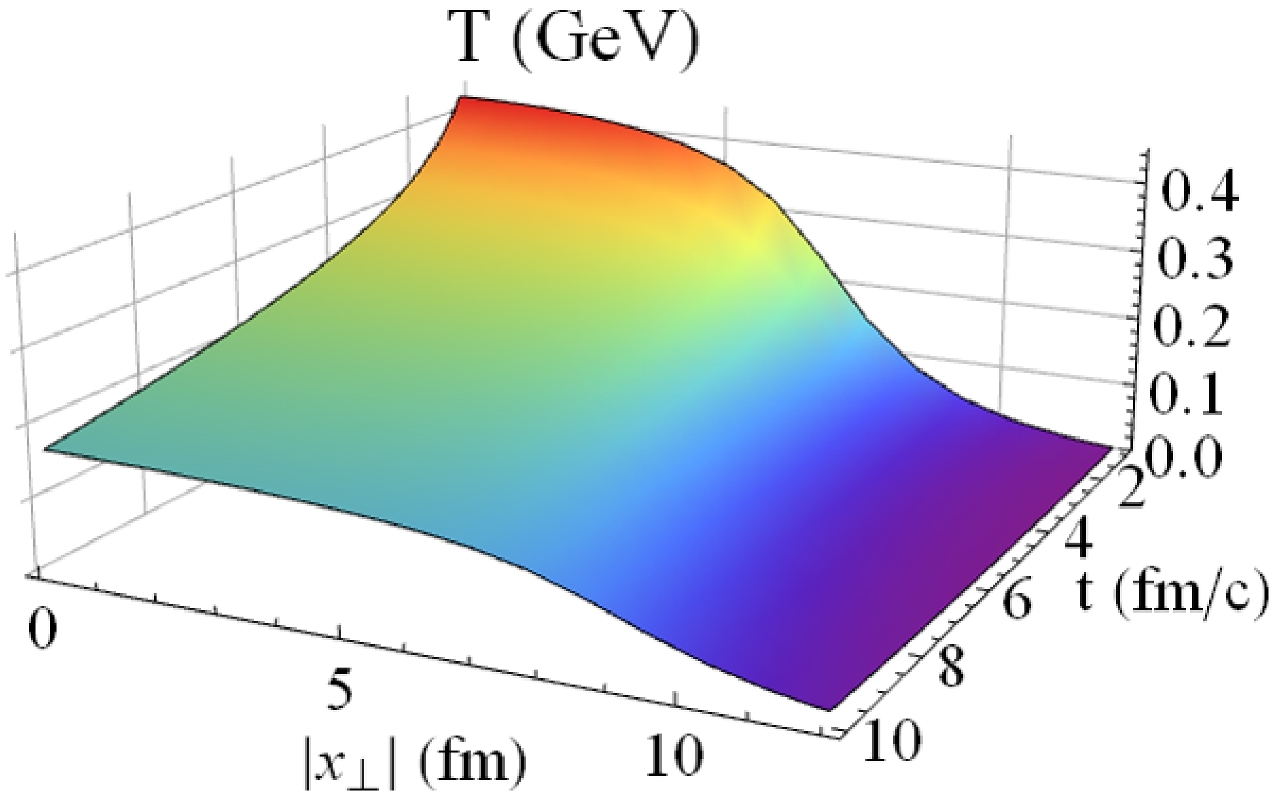

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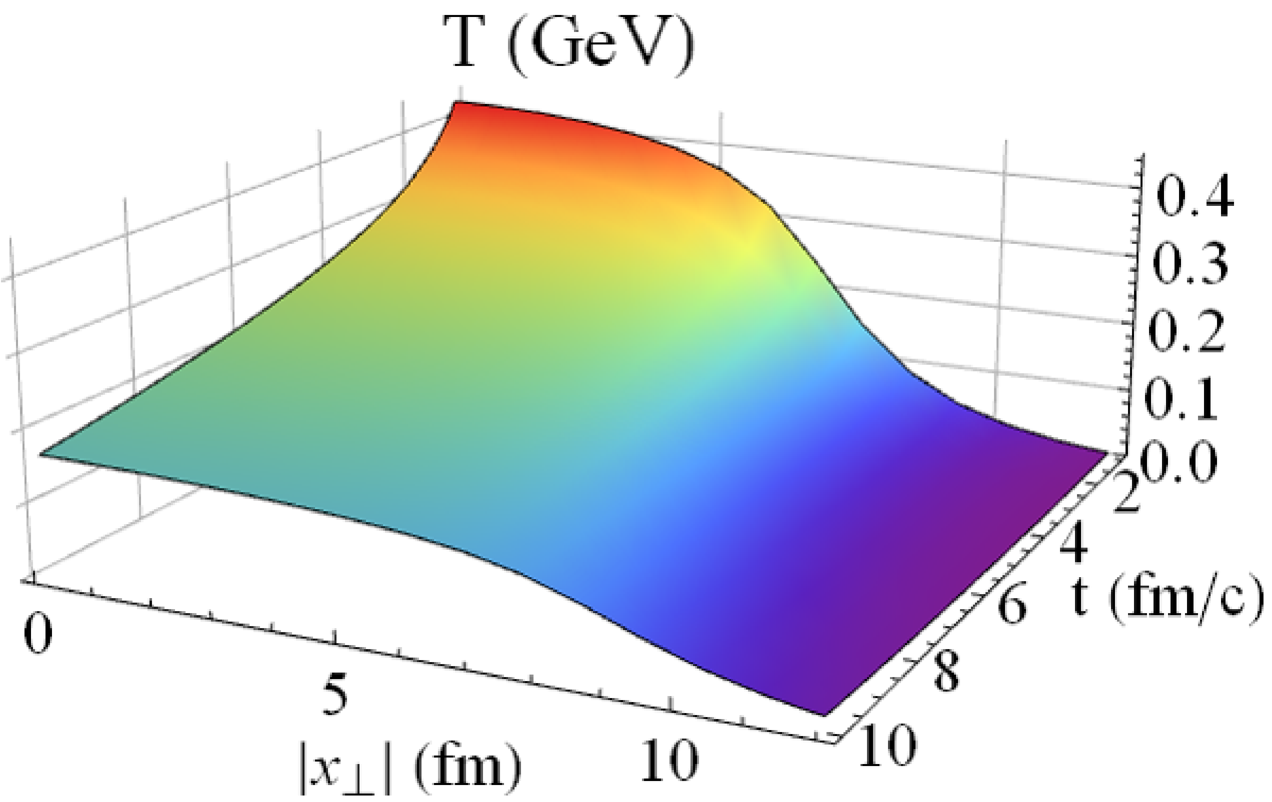


Evolution of Jet Opening Angle Distribution

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

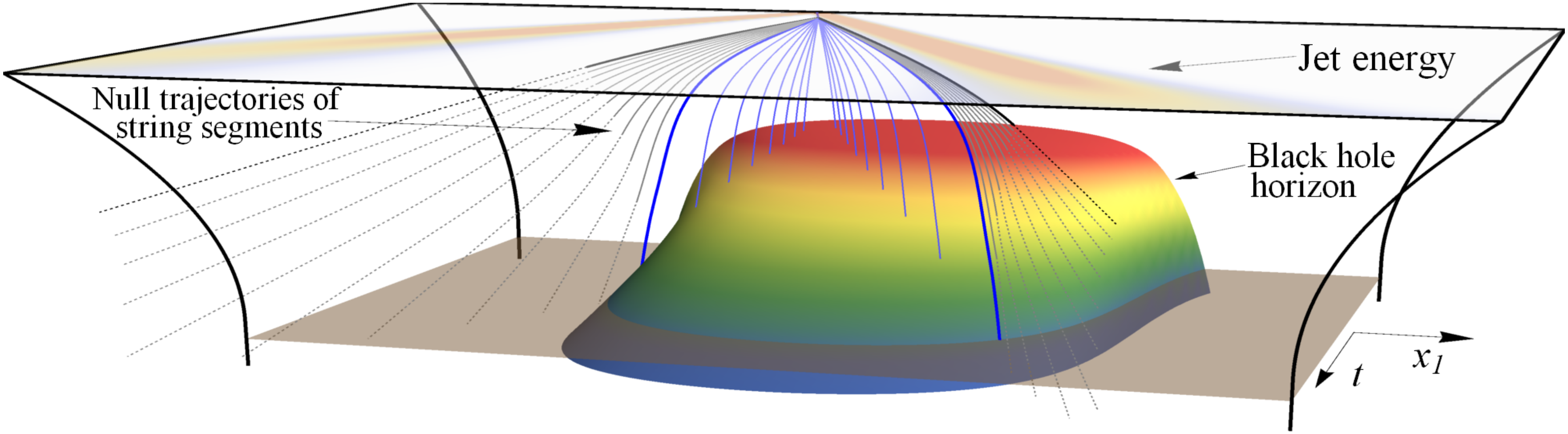
We initialize our simplified model for the expanding cooling droplet of plasma at $\tau = 1$ fm$/c$, and initialize our ensemble of jets at the same τ, choosing their initial transverse position $\propto \rho_{\text{part}}(\vec{x}_\perp)^2$ and choosing their transverse direction randomly. (Clearly, 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_{jet} and σ_{endpoint}, and extract the modified distribution of jet energies and opening angles.

Evolution of Jet Opening Angle Distribution

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



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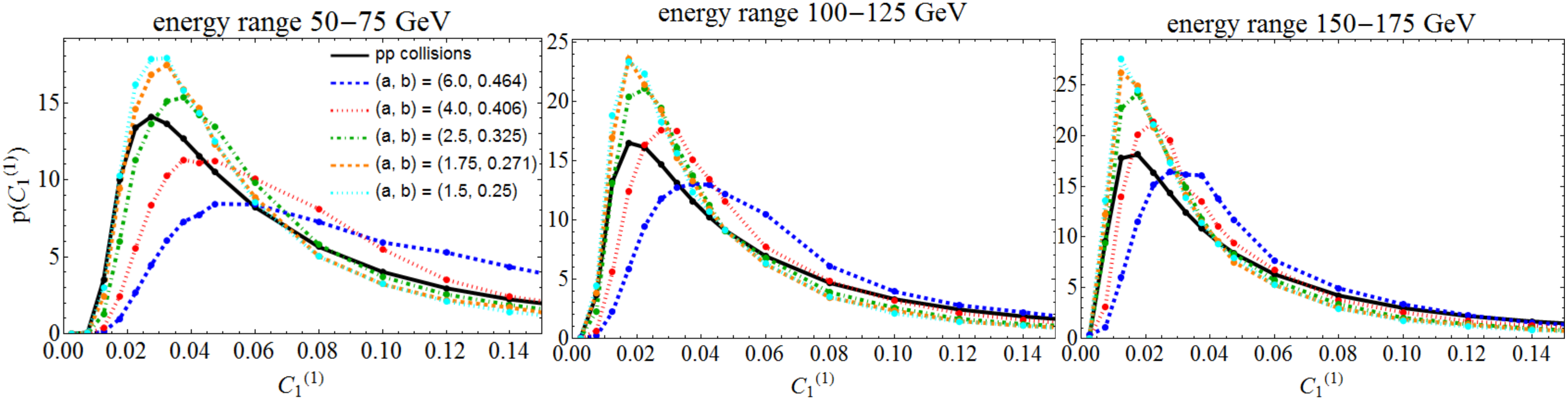
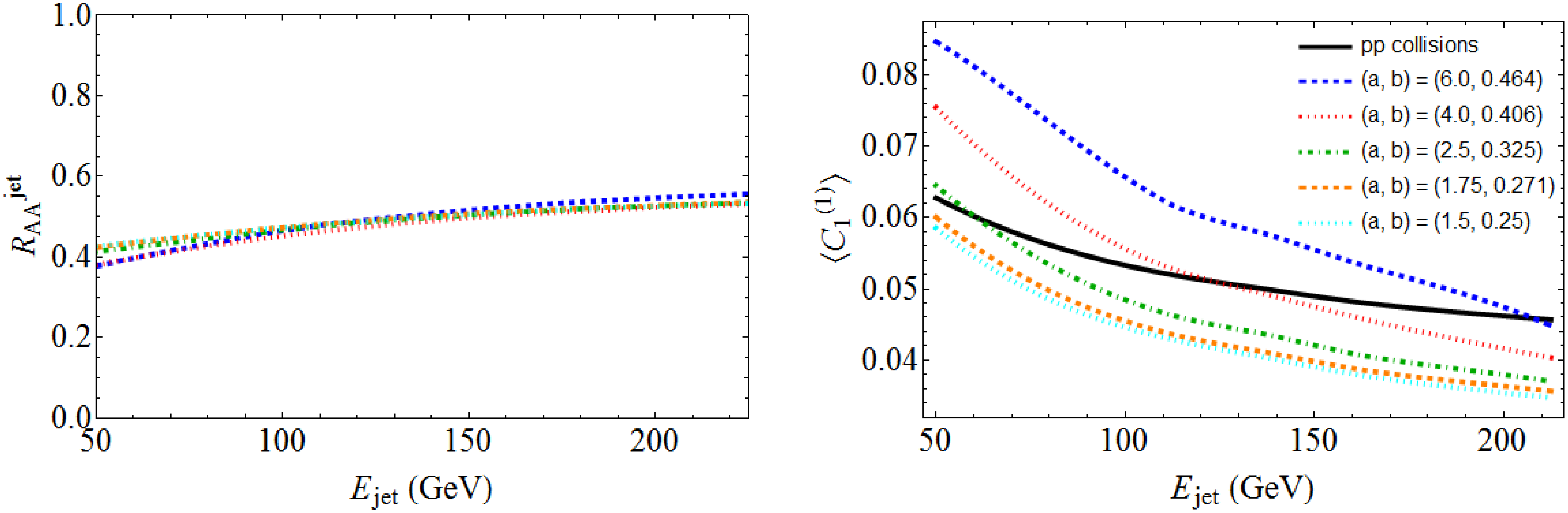


For small angles, opening angle distribution pushed toward larger angles. (Every jet gets wider as it propagates.)

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_{jet} relative to that number in the initial distribution.

The *mean* opening angle of the jets with a given E_{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

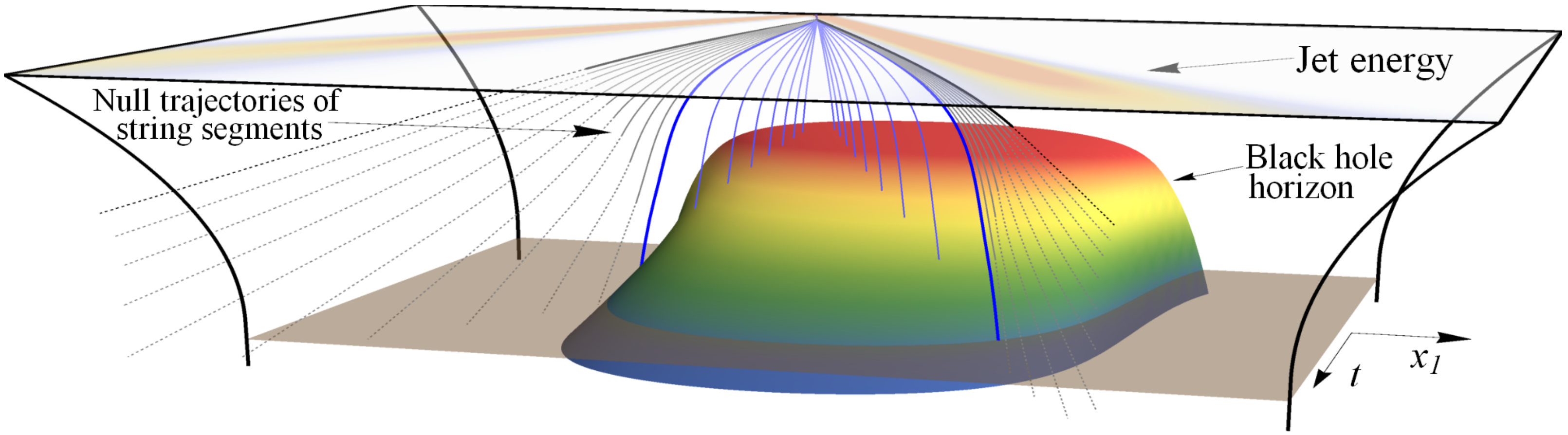
KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

There is no contradiction.

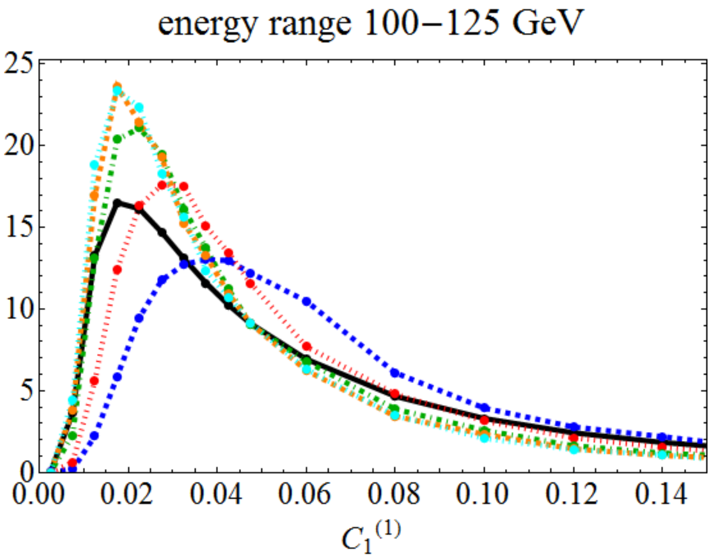
- **Because of inescapable qualitative fact # 2 (holographic jets that are initially wider lose more energy)**. . .
- . . . **and because of the steeply falling** $E_{\rm jet}$ **distribution**. . .
- . . . **there is no contradiction between inescapable qualitative fact #1 (every holographic jet broadens 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

Rajagopal, Sadofyev, van der Schee, 1602.04187



Holographic model for jet quenching. ***Ensemble*** **of $\sim$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. . .**


energy range 100–125 GeV

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

Evolution of Jet Opening Angle Distribution

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

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

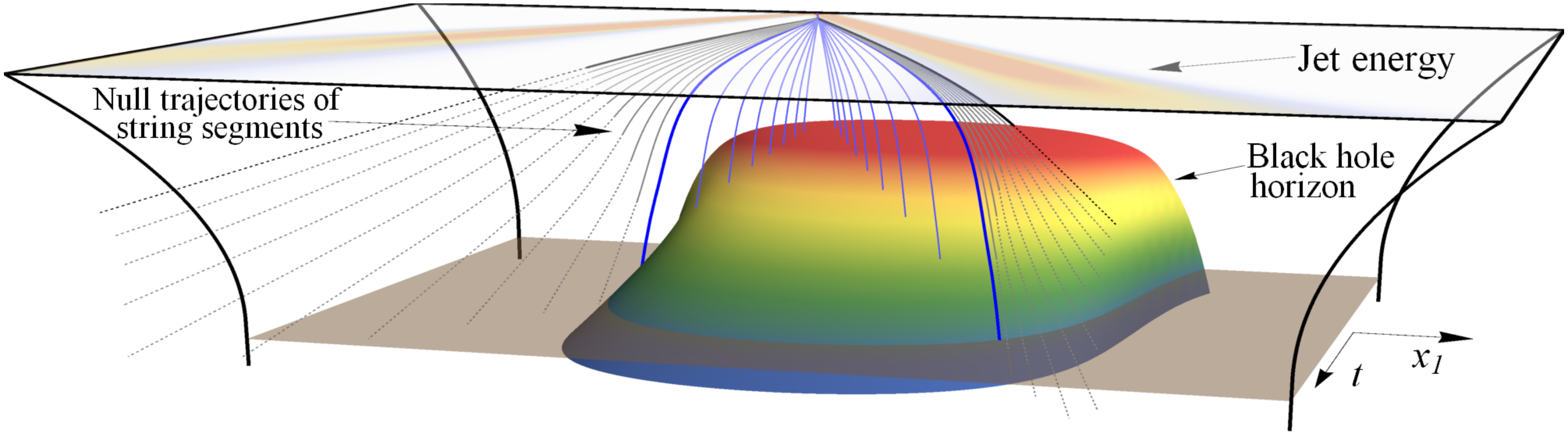
Same effect seen in an ensemble of weakly coupled jets in JEWEL (Milhano, Zapp 1512). At weak coupling, initially wider jets lose more energy than initially narrower ones because they contain more energy-losers (Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 1210). Similar conclusion also from weakly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

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

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

Evolution of Jet Opening Angle Distribution

Rajagopal, Sadofyev, van der Schee, 1602.04187



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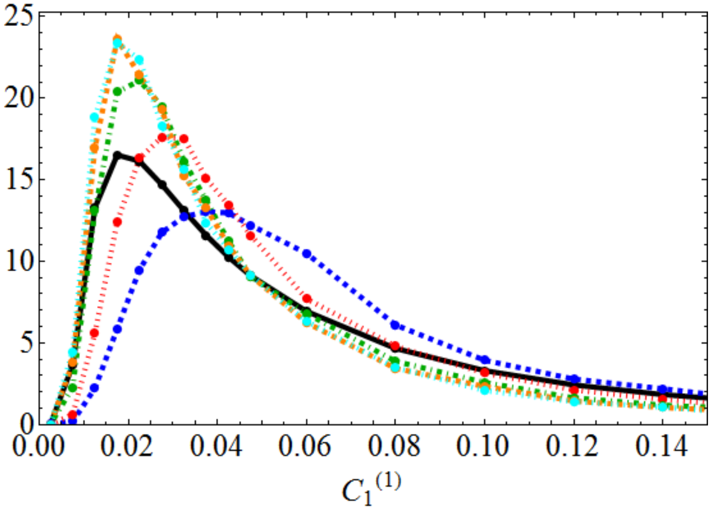

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Evolution of an Ensemble of Holographic (Di)jets

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

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

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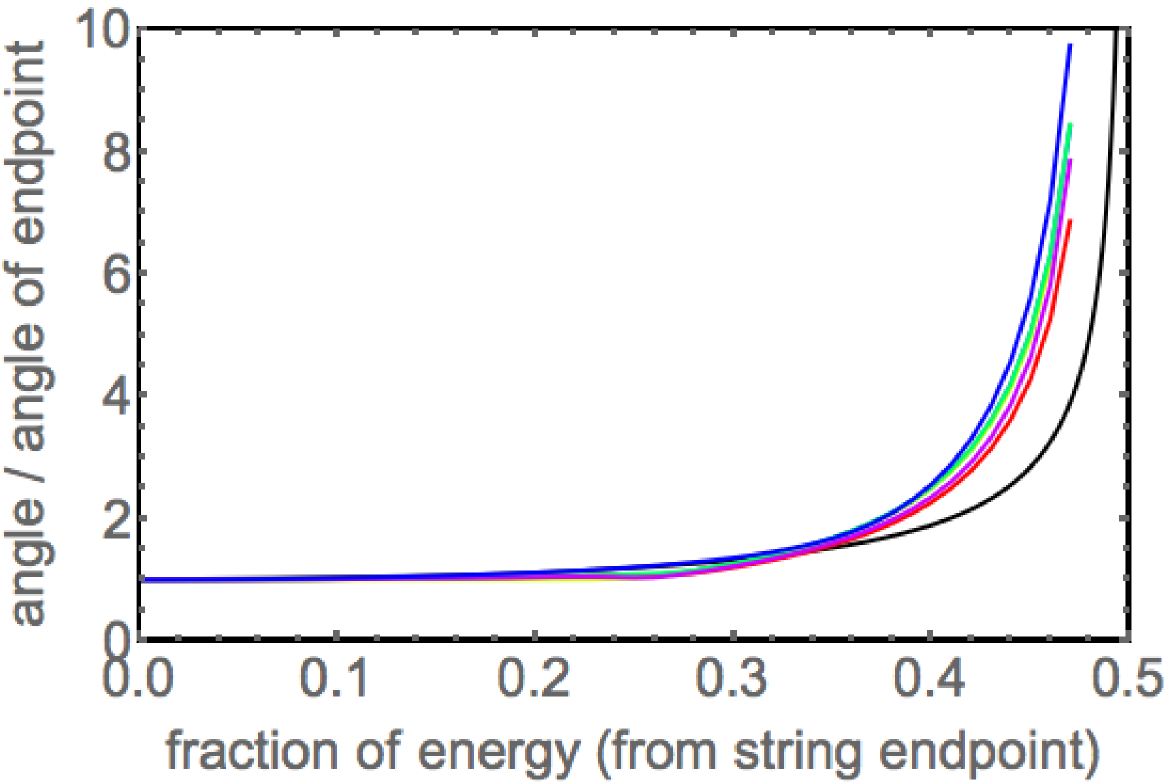

- **Full string dynamics "nullifies" and reproduces energy distribution along the string from near-endpoint approximation used by Chesler et al. (black curve). Colored curves are 6 different initial conditions for full string dynamics.**

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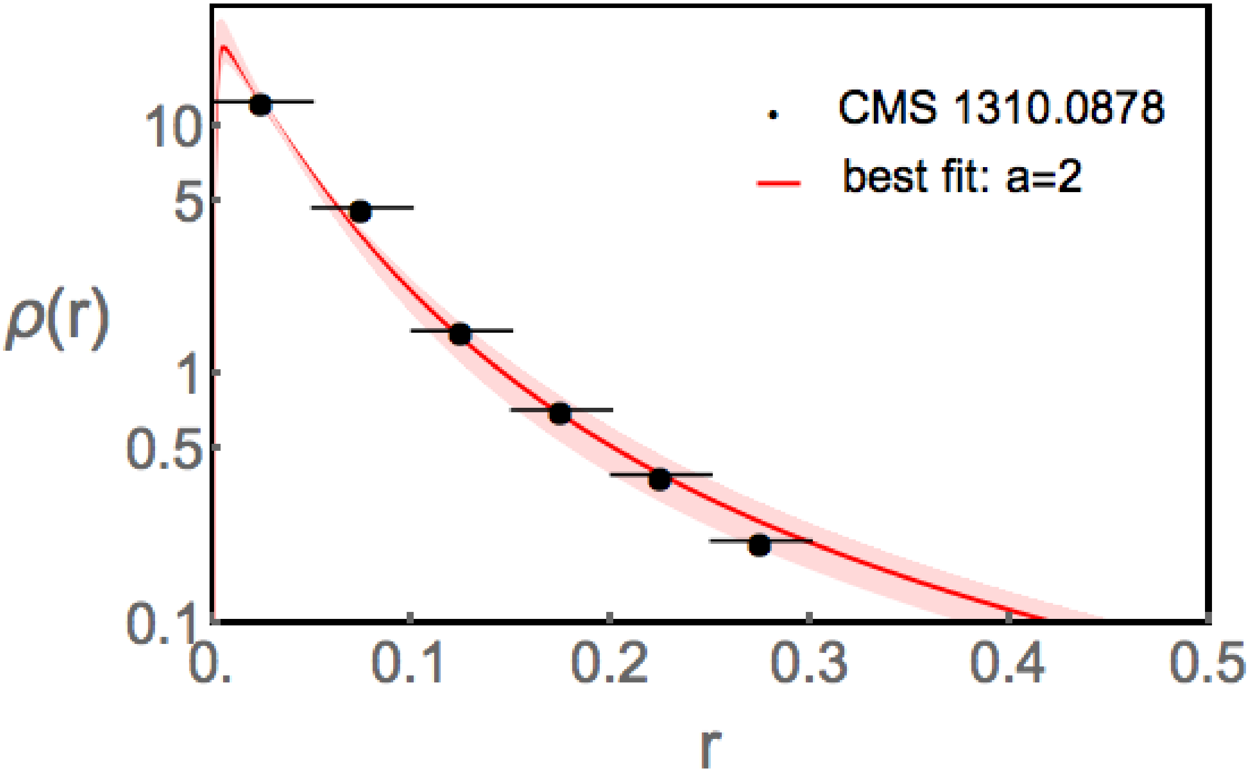

- Tailor an ensemble of holographic jets with $p_T > 100$ GeV to get initial jet shape is as in p-p collisions. Only tailoring needed is choice of parameter a: $1.8 < a < 2.5$. Data is from jets in p-p collisions. (Then choose b to get reasonable suppression in the number of jets in final ensemble.)

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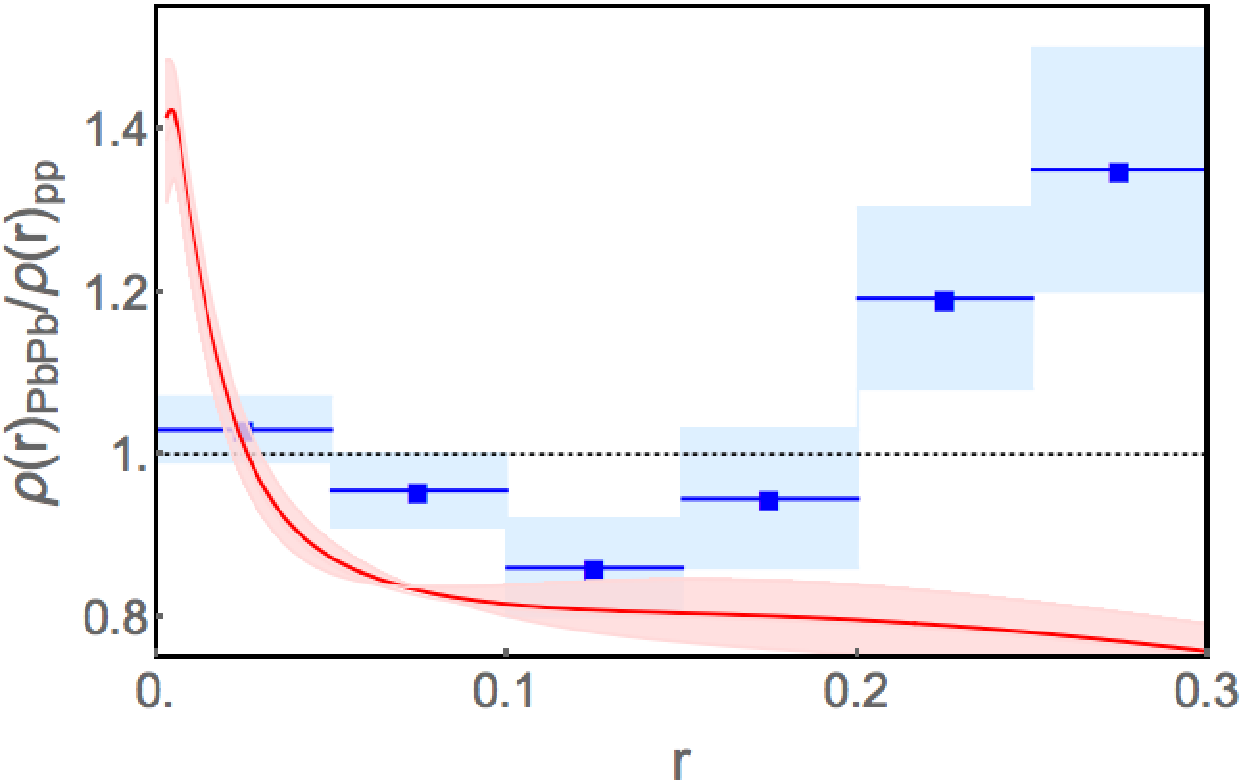

- **Analyze the modification of jet shape due to passage through plasma. Jet shape; not just width. Passage through plasma results in an ensemble of narrower jets (because wider jets lose more energy). Degree of narrowing qualitatively reproduces that seen in data.**

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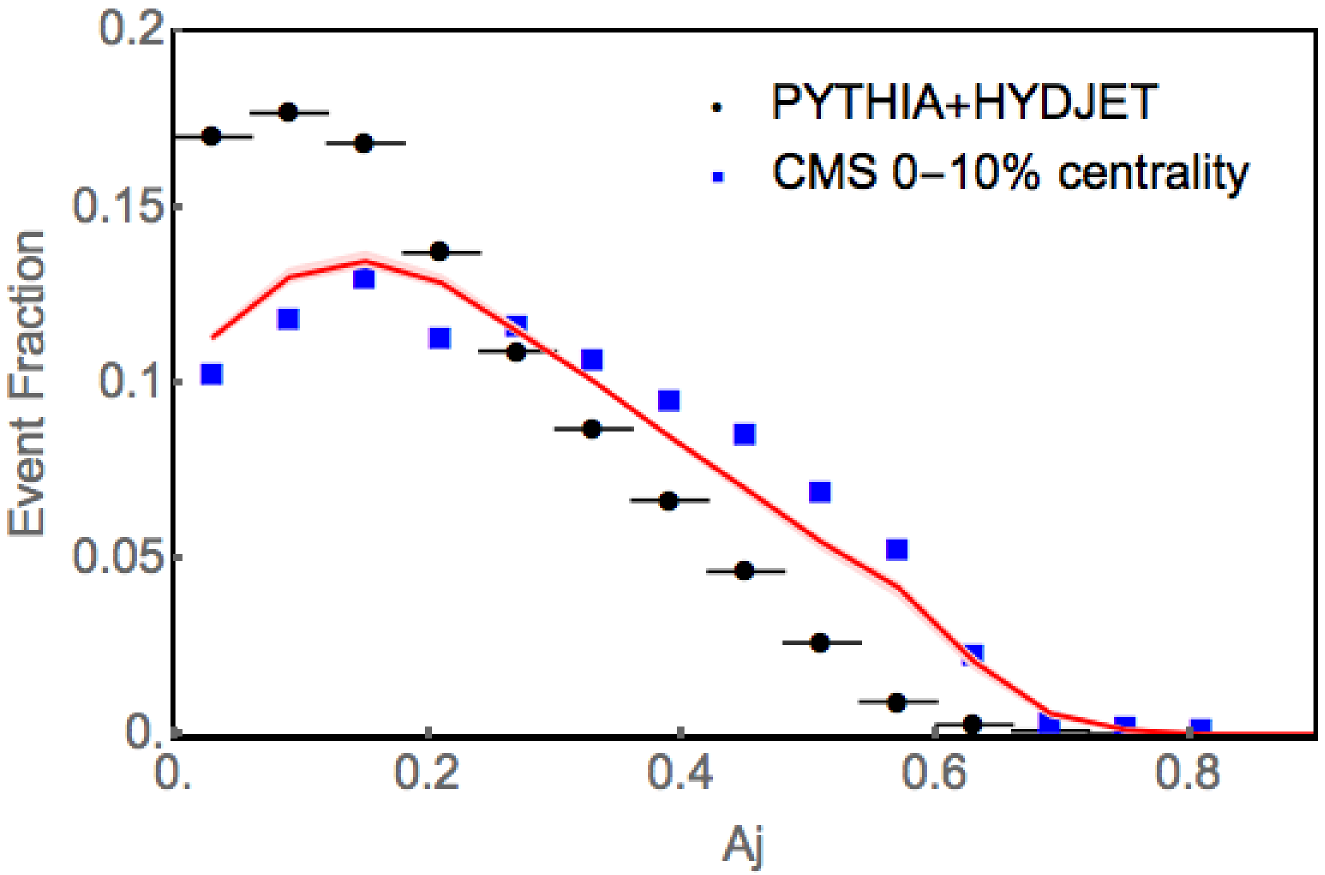
- Analysis of ensembles of holographic jets yield qualitative insights. For quantitative comparison to data...

Evolution of an Ensemble of Holographic (Di)jets

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



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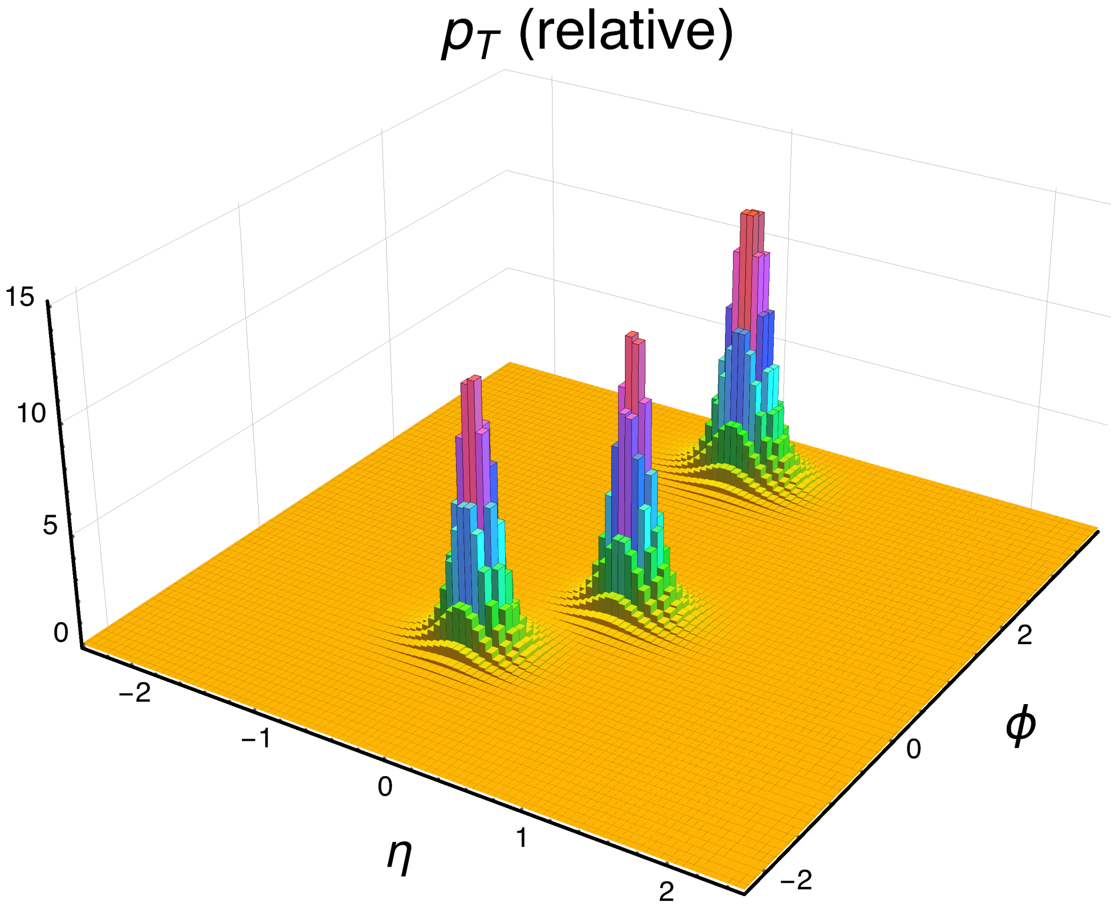

- **Construct an ensemble of dijet and trijet events, the latter constructed à la Casalderrey-Solana and Ficnar…**

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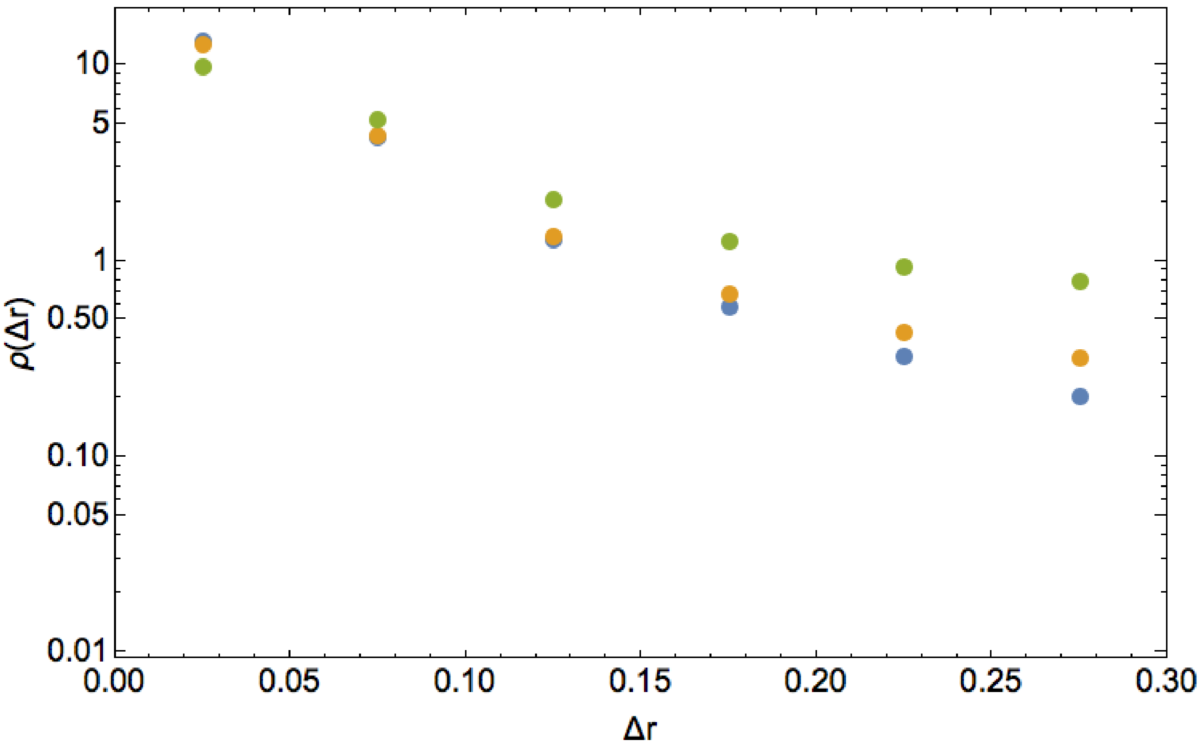

- The ensemble is still under construction, but here is a preliminary look at the jet shape for the leading, subleading, and third jets in an ensemble of three jet events, before quenching. Probablity distributions for all relevant angles and energies chosen from pQCD using MadGraph.

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A Hybrid Approach

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

- **Hard scattering and the fragmentation of a hard parton produced in a hard scattering are weakly coupled phenomena, well described by pQCD.**
- **The medium itself is a strongly coupled liquid, with no apparent weakly coupled description. And, the energy the jet loses seems to quickly become one with the medium.**
- **Try a hybrid approach. Think of each parton in a parton shower à la PYTHIA losing energy à la dE/dx for light quarks in strongly coupled liquid from a previous slide.**
- **We have looked at R_{AA}, dijet asymmetry, jet fragmentation function, photon-jet and Z-jet observables. Upon fitting one parameter, *lots* of data described well. Value of the fitted parameter is reasonable: x_{therm} in QGP is 3-4 times longer than in $\mathcal{N} = 4$ SYM plasma with same T.**
- **Most recently: adding momentum broadening and the wake in the plasma, adding resolution effects, looking at jet shapes, jet masses and related observables.**

Implementation of Hybrid Model

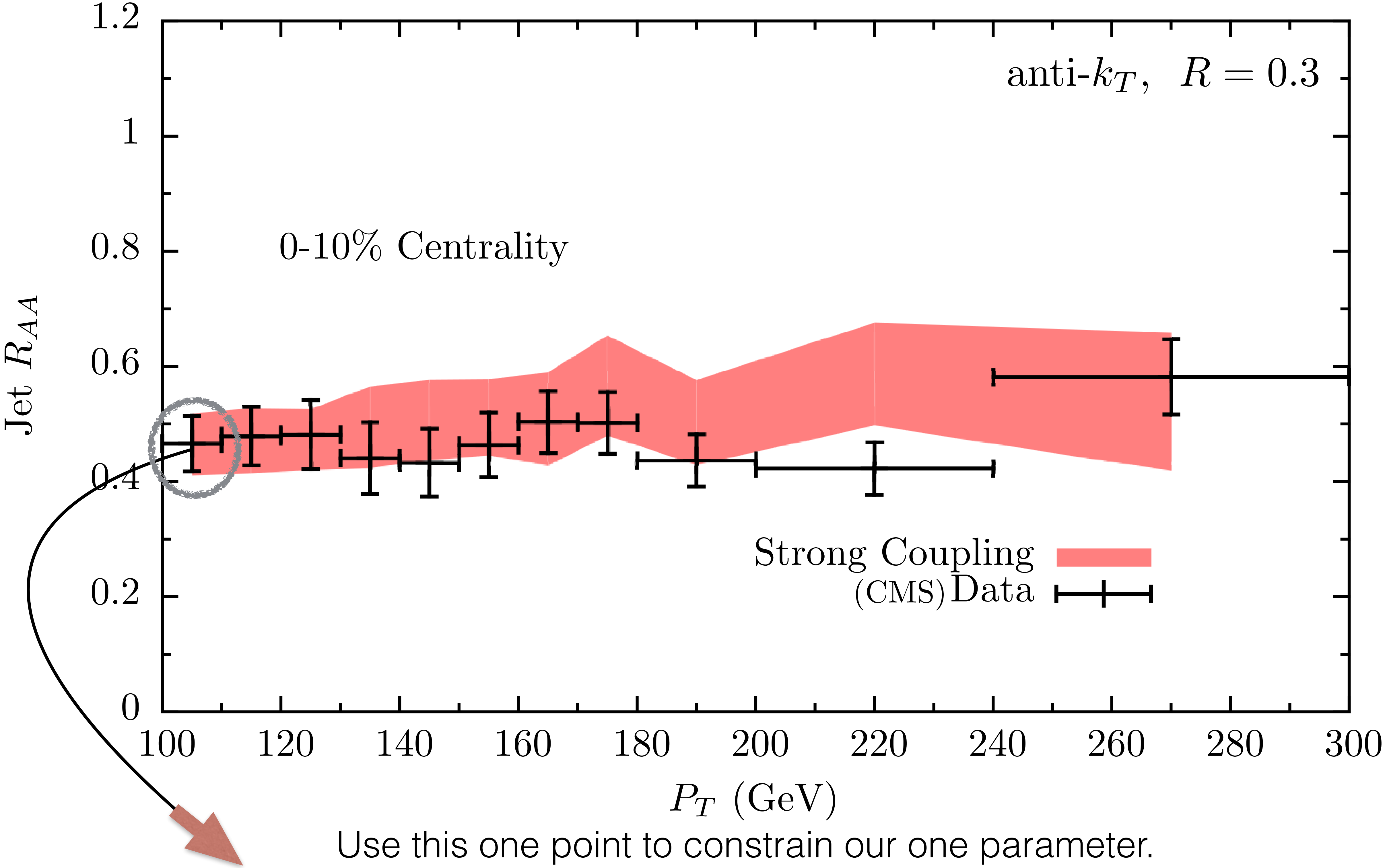
Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1405.3864,1508.00815

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

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

  where $x_{\text{therm}} \equiv E_{\text{in}}^{1/3}/(2\kappa_{\text{sc}} T^{4/3})$ **with** κ_{sc} **one free parameter that to be fixed by fitting to one experimental data point. (**$\kappa_{\text{sc}} \sim 1 - 1.5$ **in** $\mathcal{N} = 4$ **SYM; smaller** κ_{sc} **means** x_{therm} **is longer in QGP than in** $\mathcal{N} = 4$ **SYM plasma with same** T**.)**
- **Turn energy loss off when hydrodynamic plasma cools below a temperature that we vary between 145 and 170 MeV. (This, plus the experimental error bar on the one data point, becomes the uncertainty in our predictions.)**
- **Reconstruct jets using anti-**k_T**.**

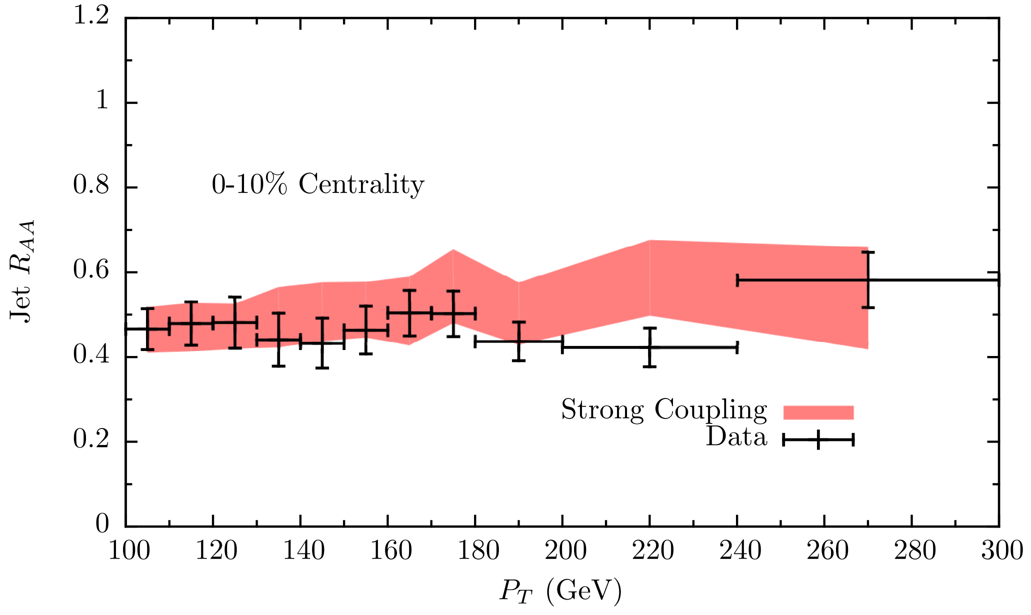
R_{AA}

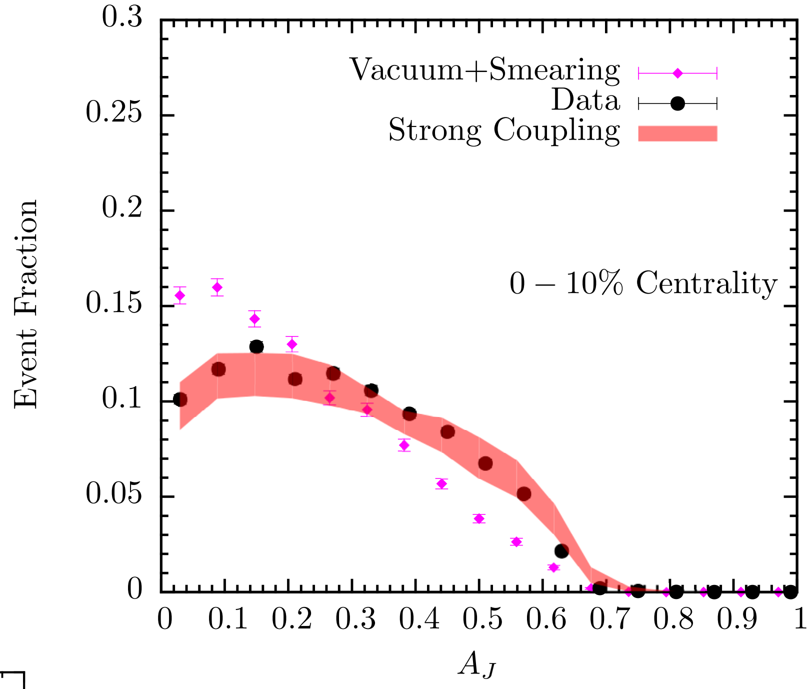


Use this one point to constrain our one parameter.

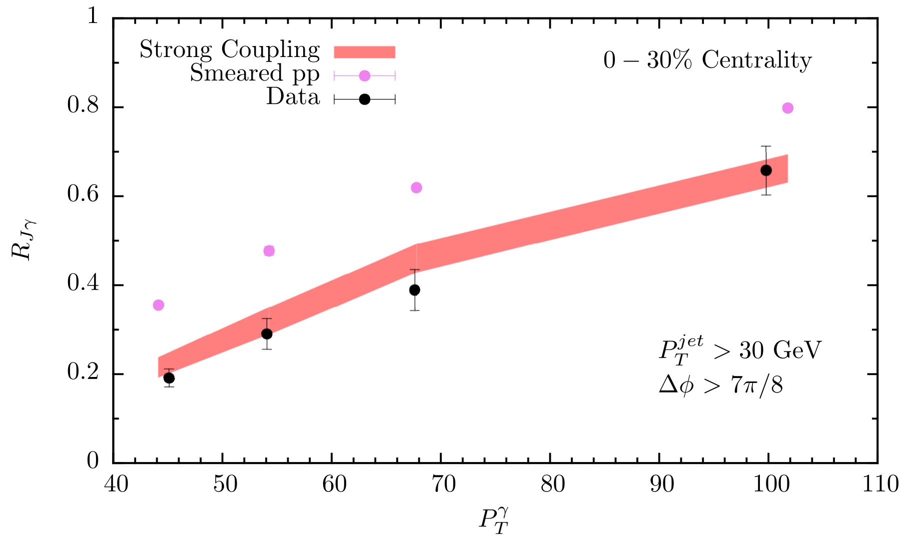
Bands come from experimental uncertainty on this point

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





5 observables
and centrality dependence
all described with
single parameter

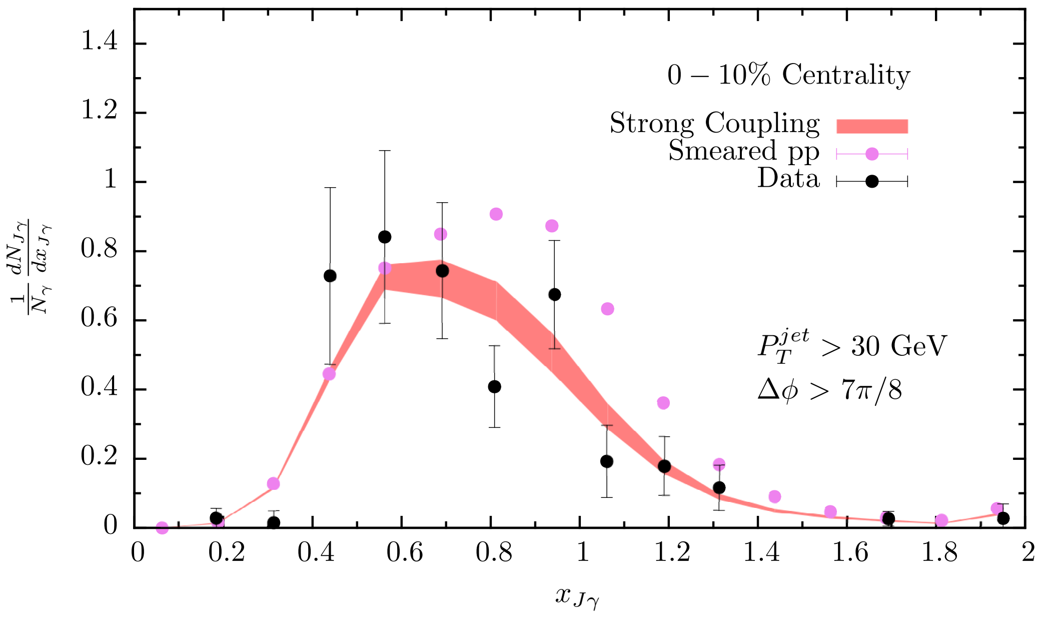


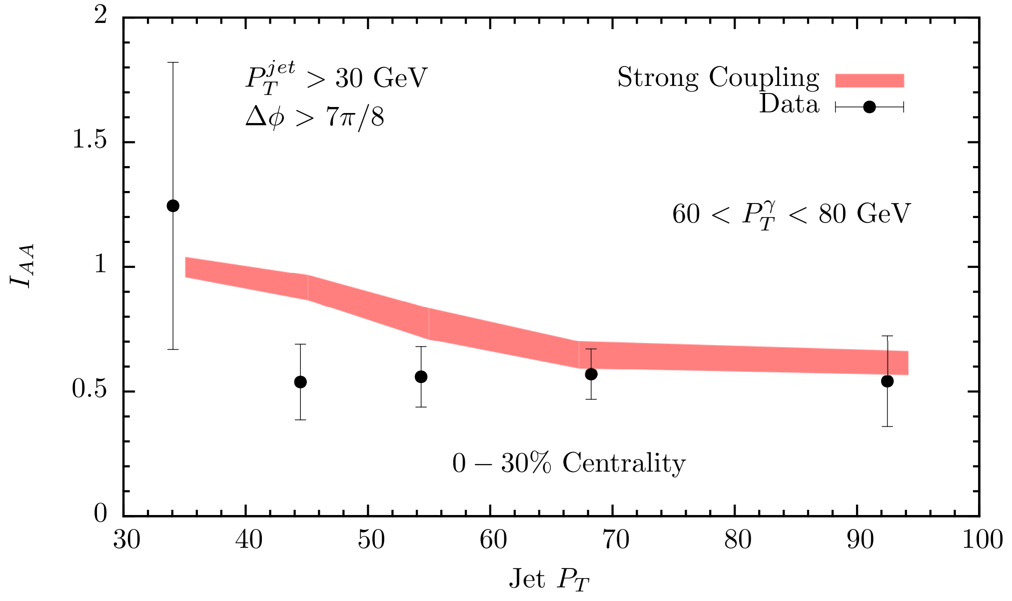
Bands in all plots correspond to

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

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

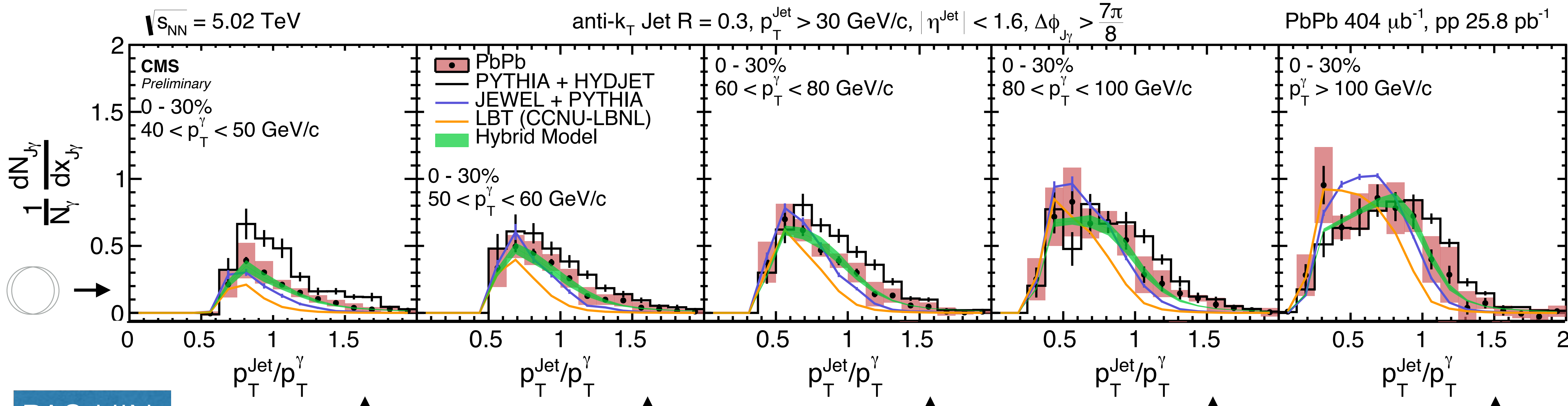
$$x_{stop}^{QCD} \sim (3-4)\, x_{stop}^{\mathcal{N}=4}$$





Predictions

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

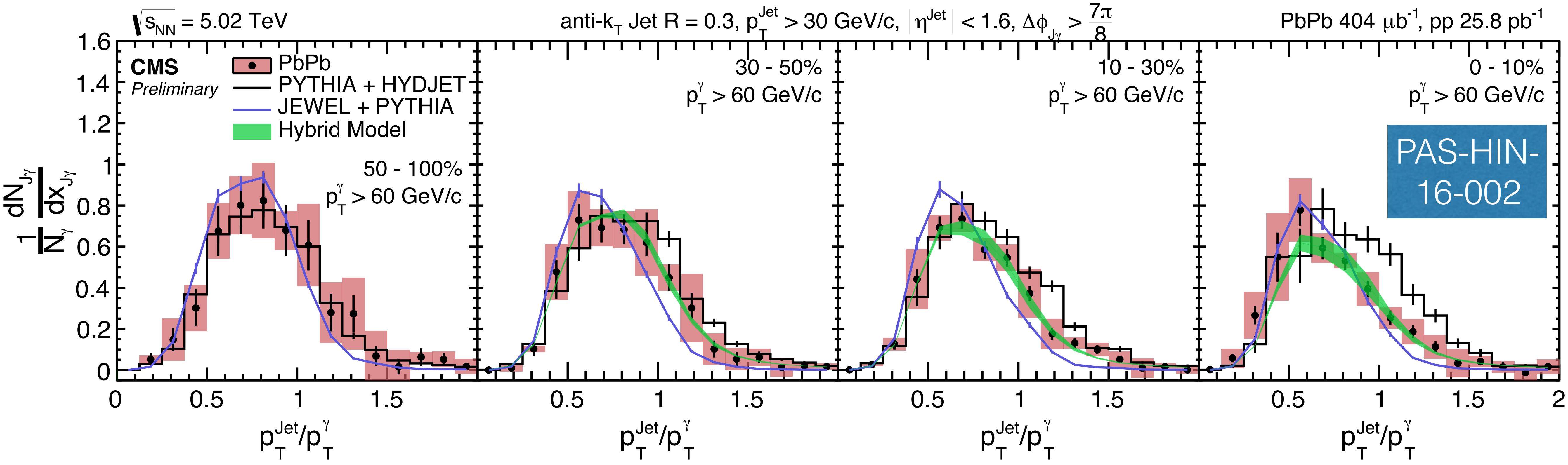


PAS-HIN-16-002

$40 < p_T^{\gamma} < 50$ **$50 < p_T^{\gamma} < 60$** **$60 < p_T^{\gamma} < 80$** **$80 < p_T^{\gamma} < 100$** **$p_T^{\gamma} > 100$**

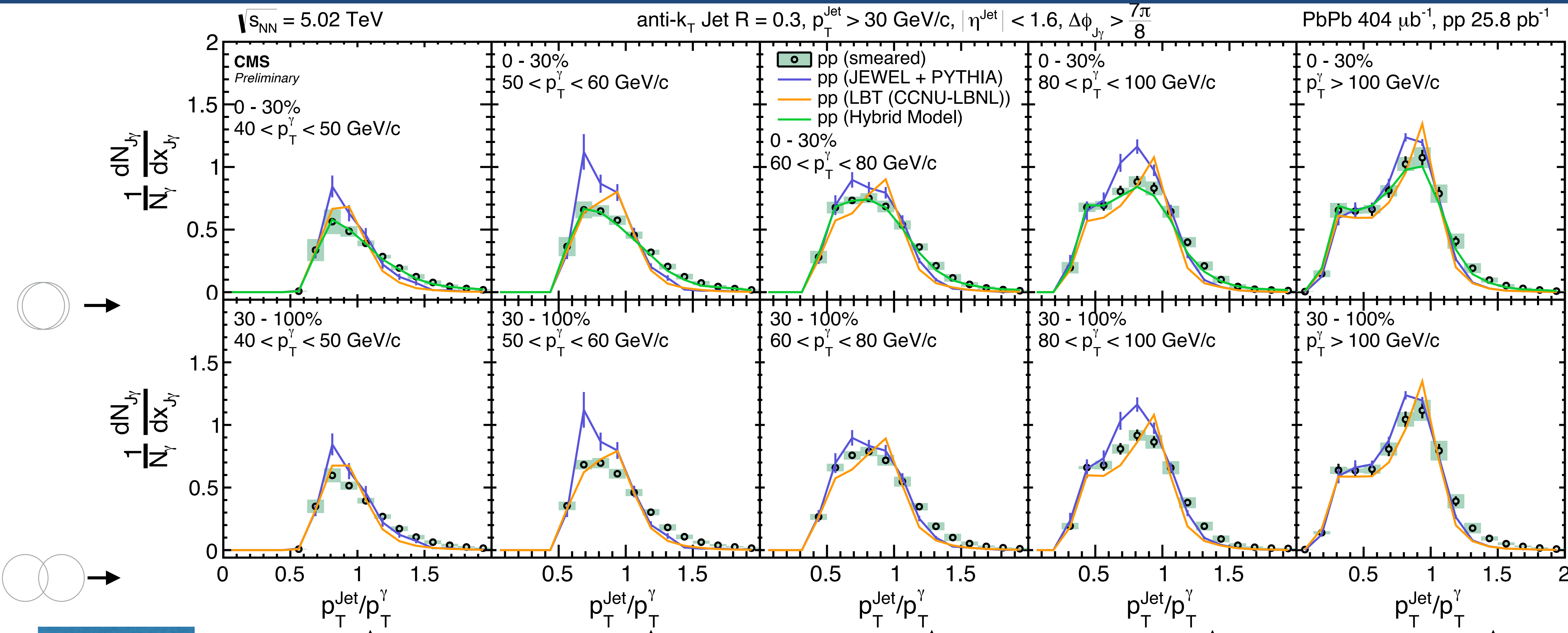
- In general, models appear to describe $x_{J\gamma}$
  - LBT has normalization issue relative to other curves
    - To be fixed in conjunction with analyzers
  - JEWEL and HYBRID comparable through all bins

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



PAS-HIN-16-002

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

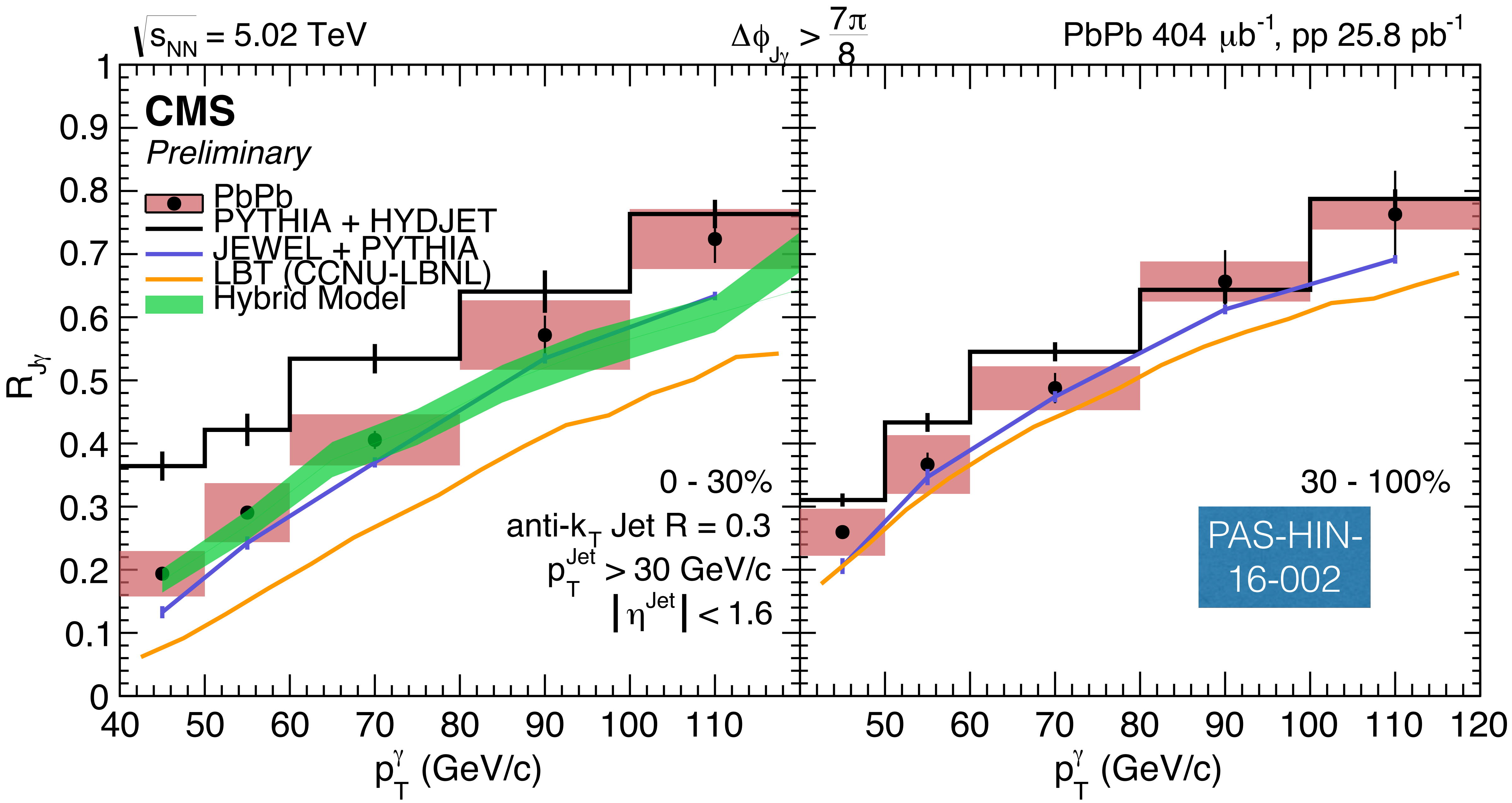
60 < p_T^γ < 80

80 < p_T^γ < 100

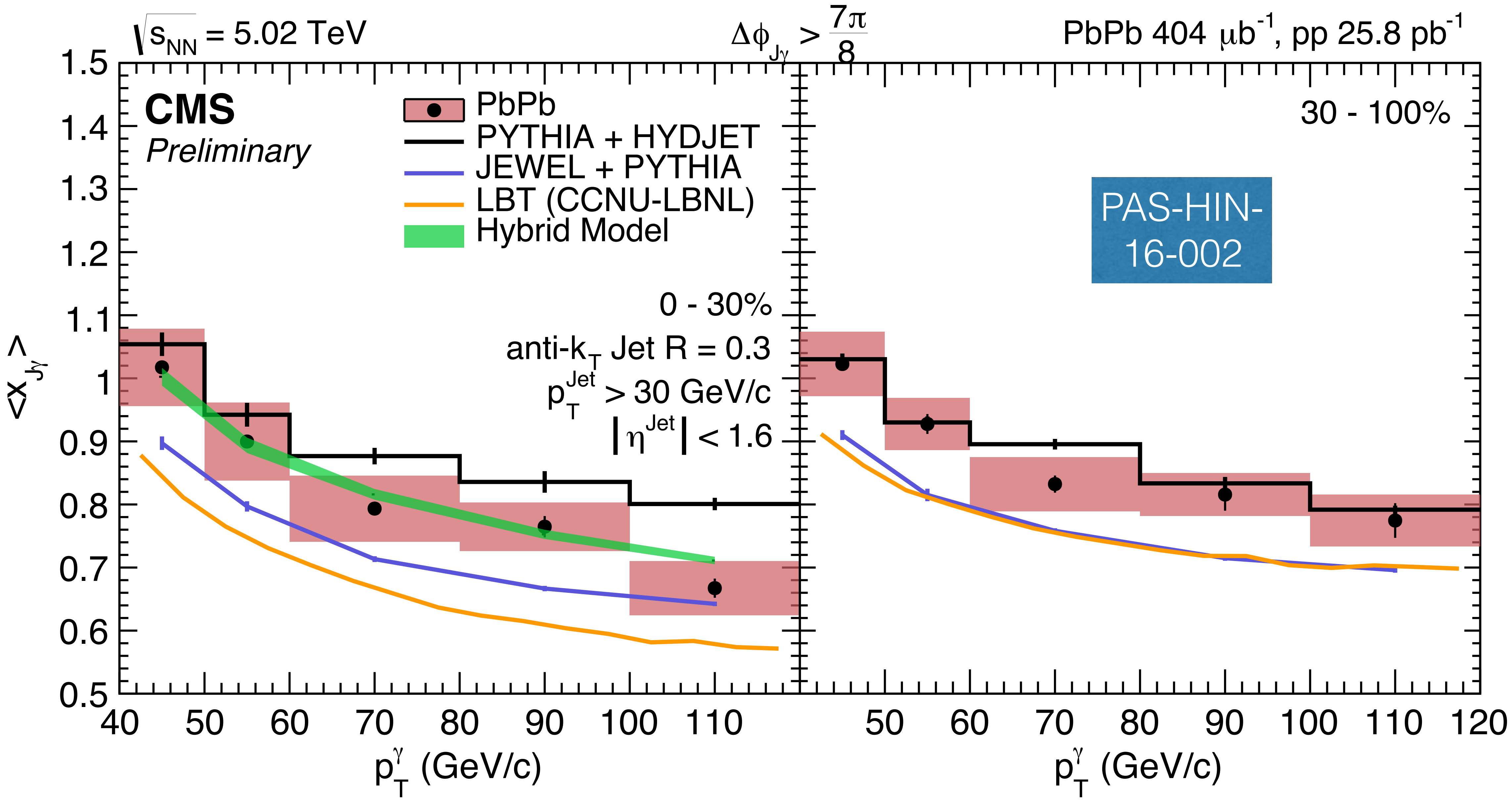
p_T^γ > 100

- Overlaid PYTHIA, JEWEL, LBT and Hybrid Model

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

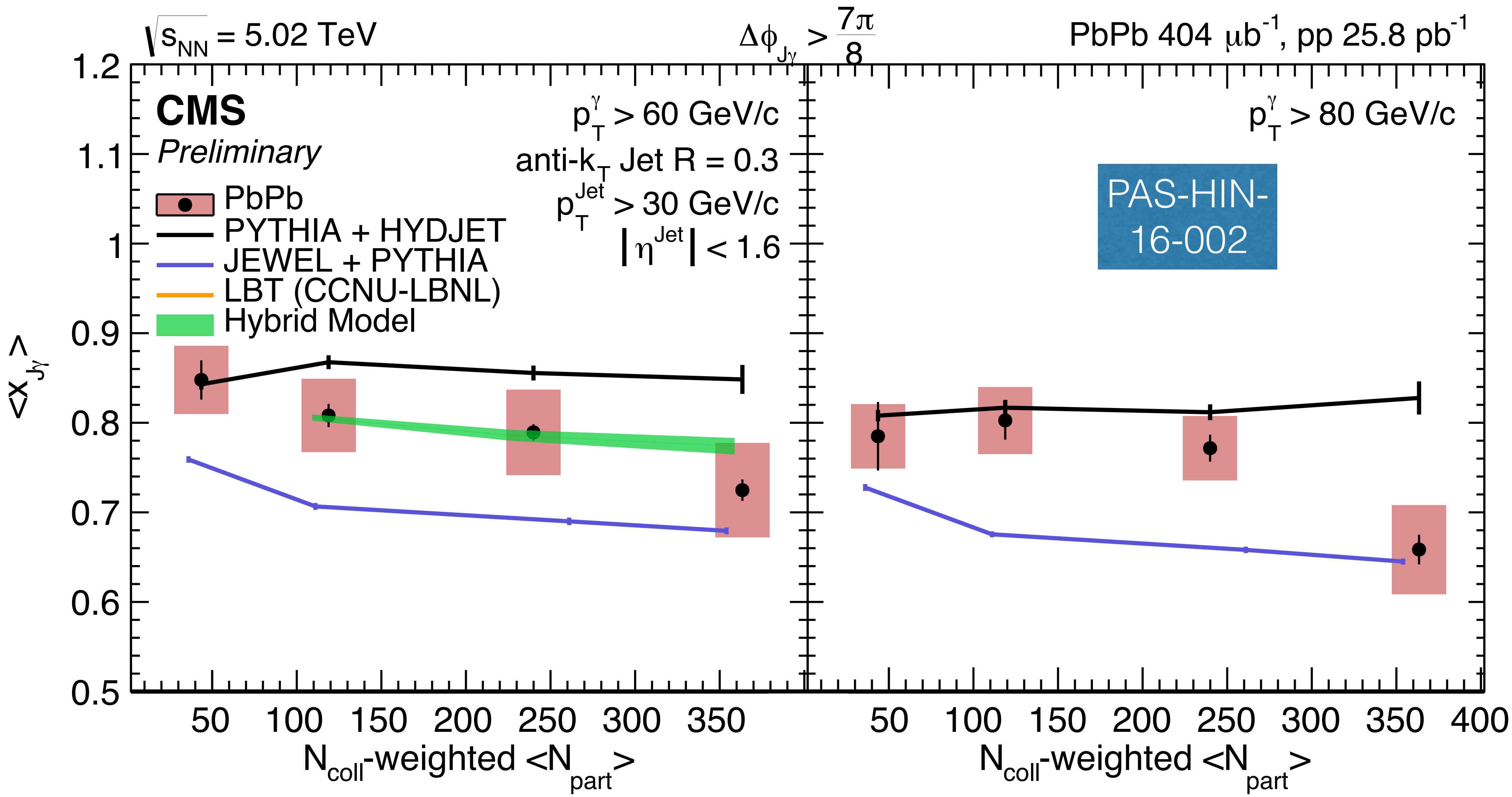


Theory Comparison: $x_{J\gamma}$ in PbPb

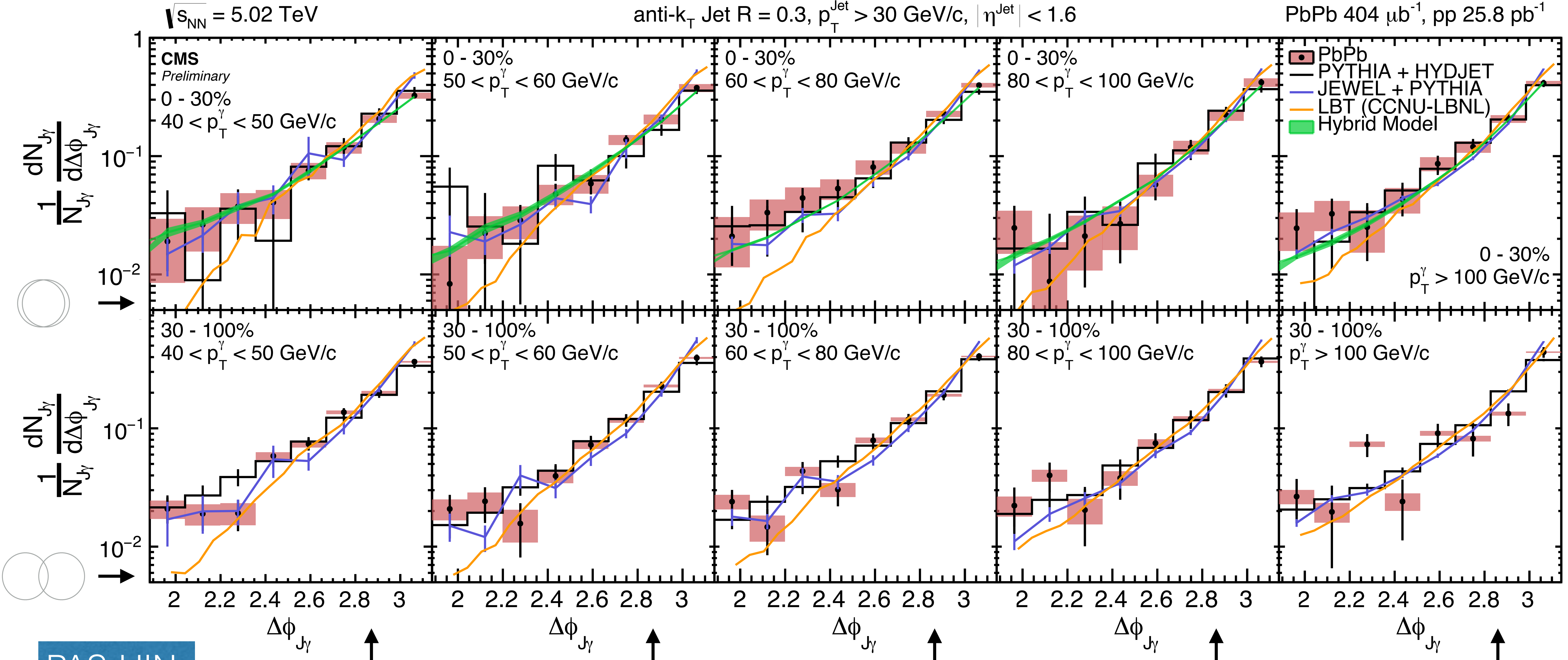


PAS-HIN-16-002

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



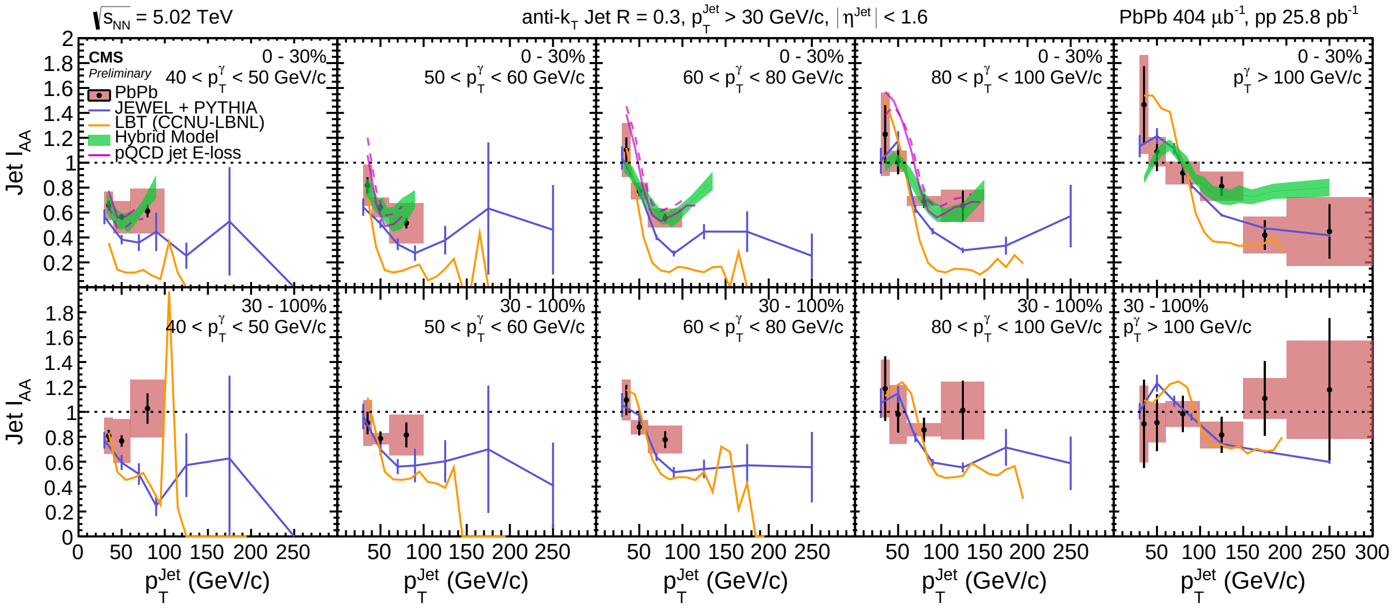
Theory Comparison: $\Delta\varphi_{J\gamma}$ in PbPb



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


$\sqrt{s_{NN}}$ = 5.02 TeV
anti-k_T Jet R = 0.3, p_T^{Jet} > 30 GeV/c, $|\eta^{Jet}|$ < 1.6
PbPb 404 μb^{-1}, pp 25.8 pb^{-1}
CMS
Preliminary
PbPb
JEWEL + PYTHIA
LBT (CCNU-LBNL)
Hybrid Model
pQCD jet E-loss
0 - 30%
40 < p_T^γ < 50 GeV/c
50 < p_T^γ < 60 GeV/c
60 < p_T^γ < 80 GeV/c
80 < p_T^γ < 100 GeV/c
p_T^γ > 100 GeV/c
30 - 100%
Jet I_{AA}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
50
100
150
200
250
300
p_T^{Jet} (GeV/c)

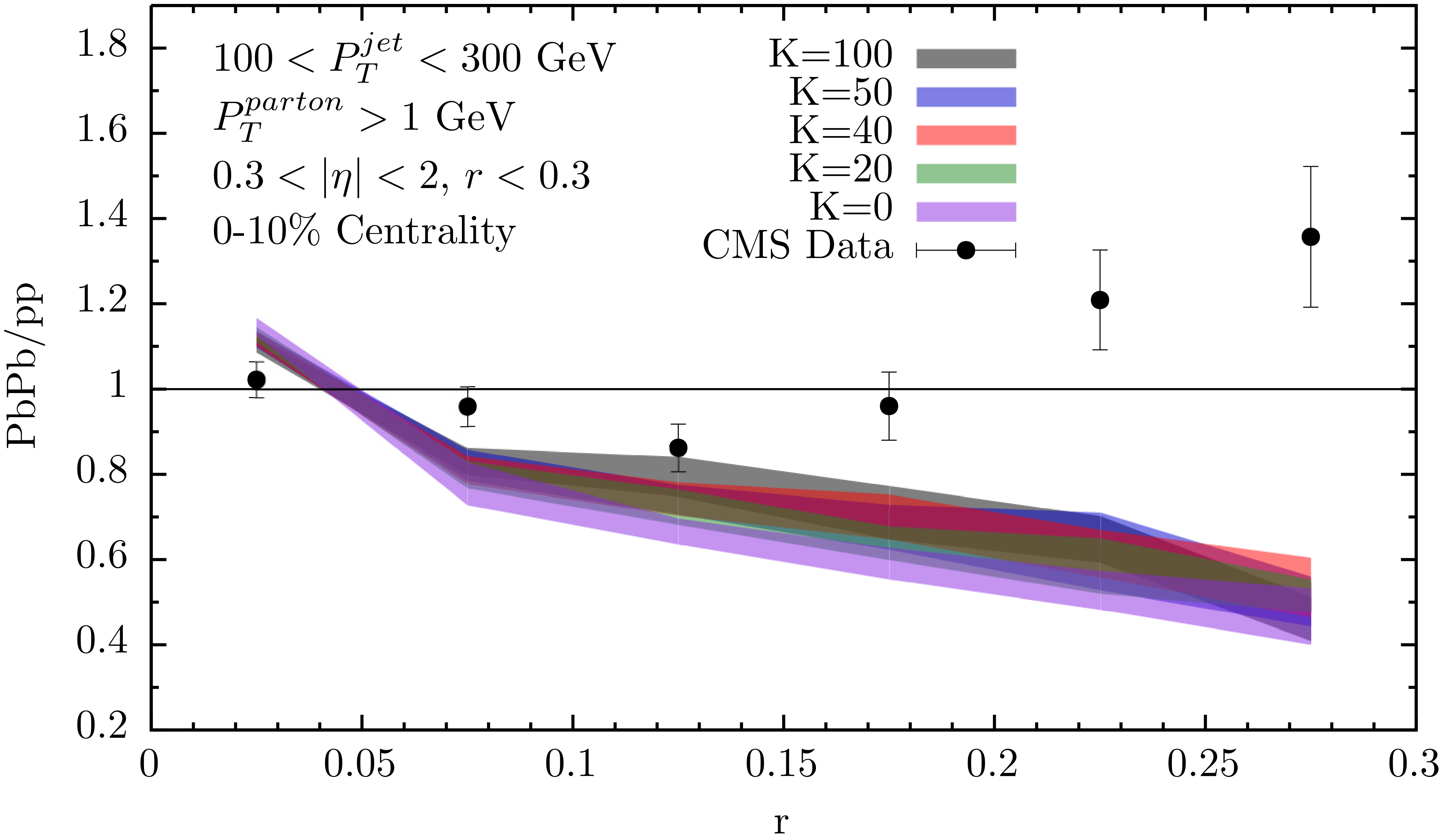
Desiderata

- **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*.**
- **Use of best-available photon-jet data to compare hybrid model predictions with strongly coupled form for dE/dx to those with $dE/dx \propto T^2$ and $dE/dx \propto T^3 x$.**
- **This is all good. It is bringing us understanding. But it does not get us to the goal of using jets to probe the microscopic structure of QGP. That has to come from looking at scattering of partons in the jet off (quasiparticles in) QGP. So we have to look at the modifications to the shape of jets.**
- **And, at this point, in order to learn something interesting we need to start seeing where the one parameter hybrid model described to this point fails to describe data.**

Modifications to Shape of Jets?

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

Small sensitivity of standard jet shapes to broadening



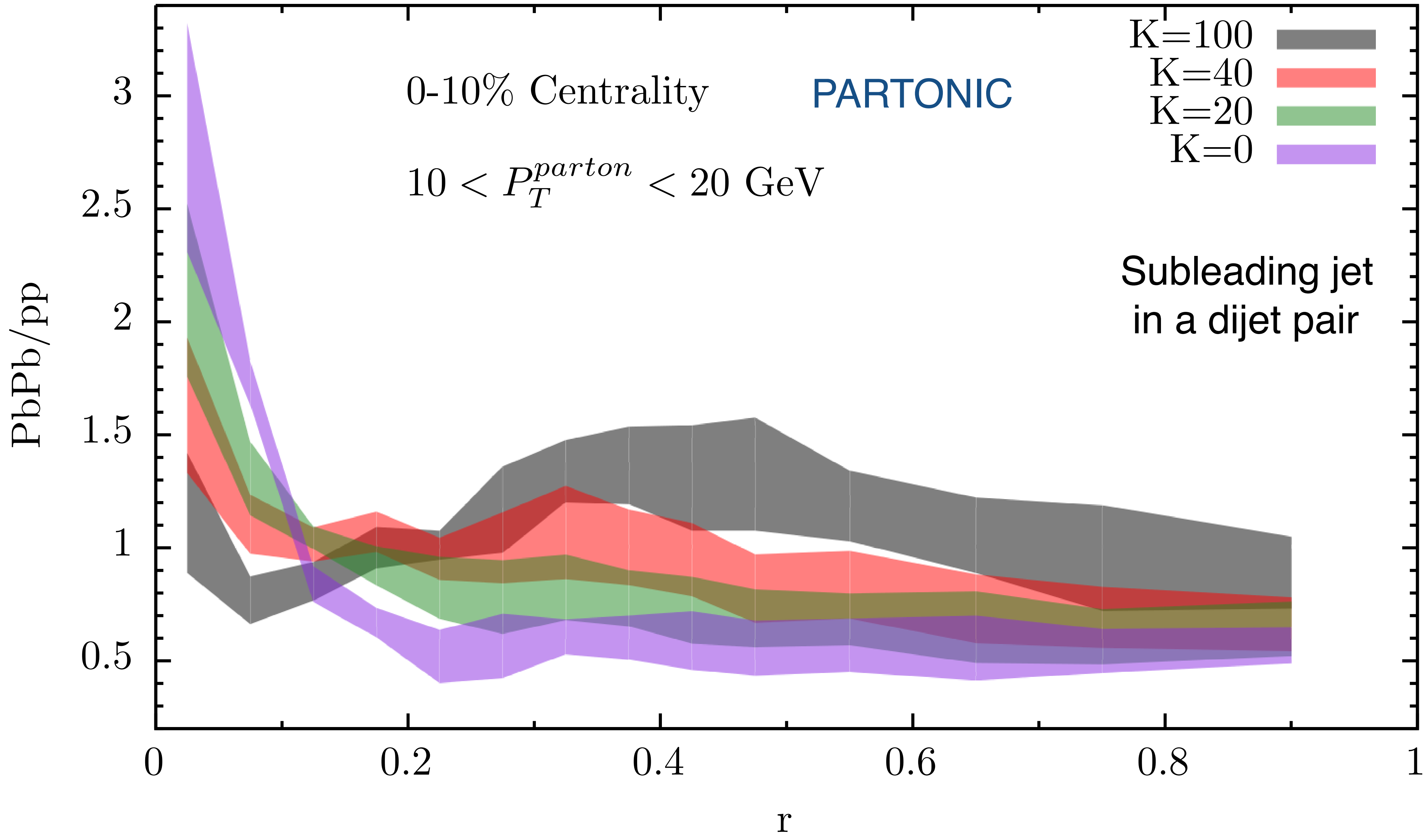
Small sensitivity of jet shapes to broadening:

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

Modifications to Shape of Jets?

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

A New Observable, Sensitive to Broadening

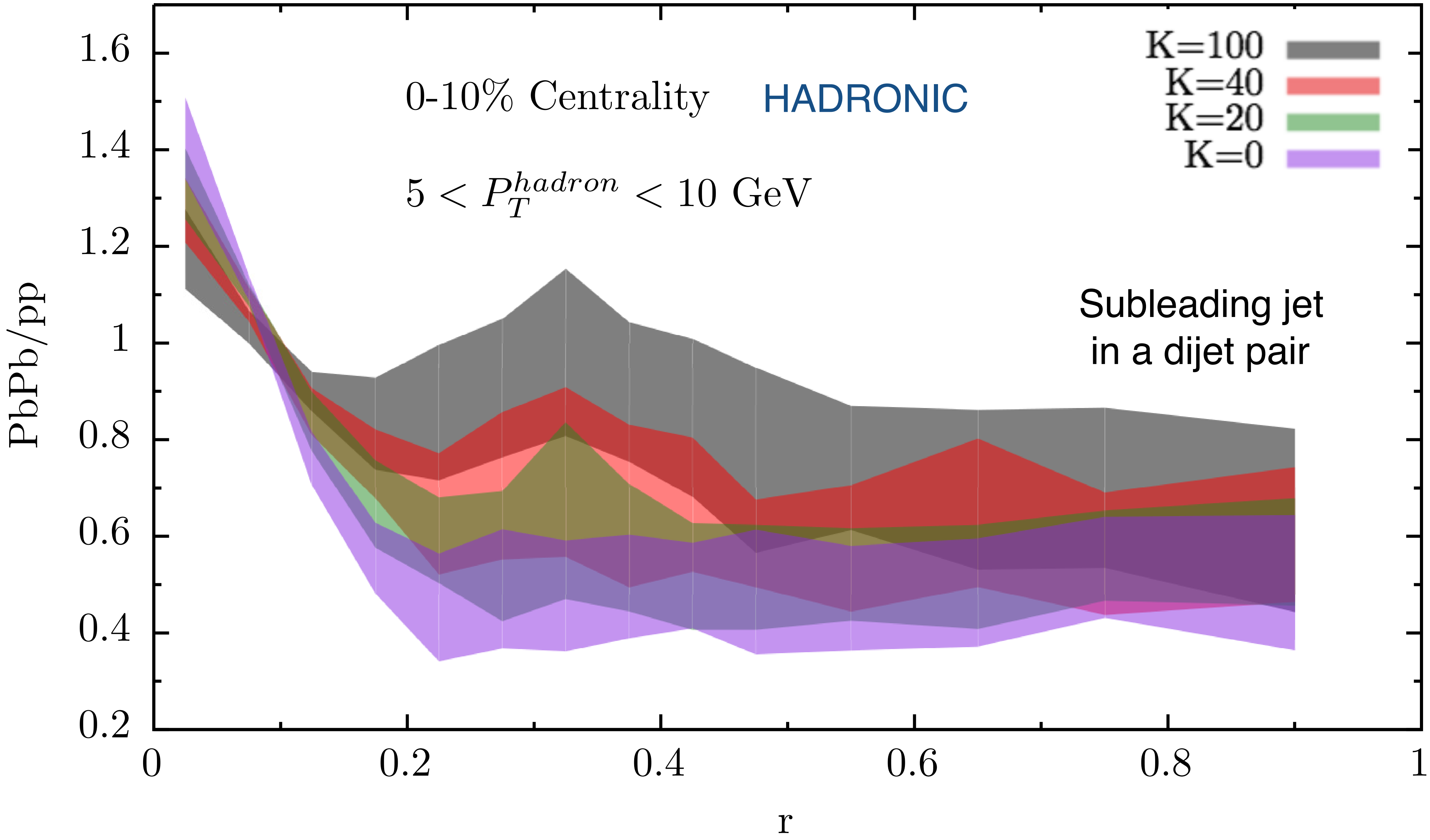


Kinematical cuts for partons chosen such that:

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

A New Observable, Sensitive to Broadening

motivated by CMS analysis CMS-HIN-15-011



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

Direct experimental determination of Gaussian broadening strength

Looking Ahead to the 2020s

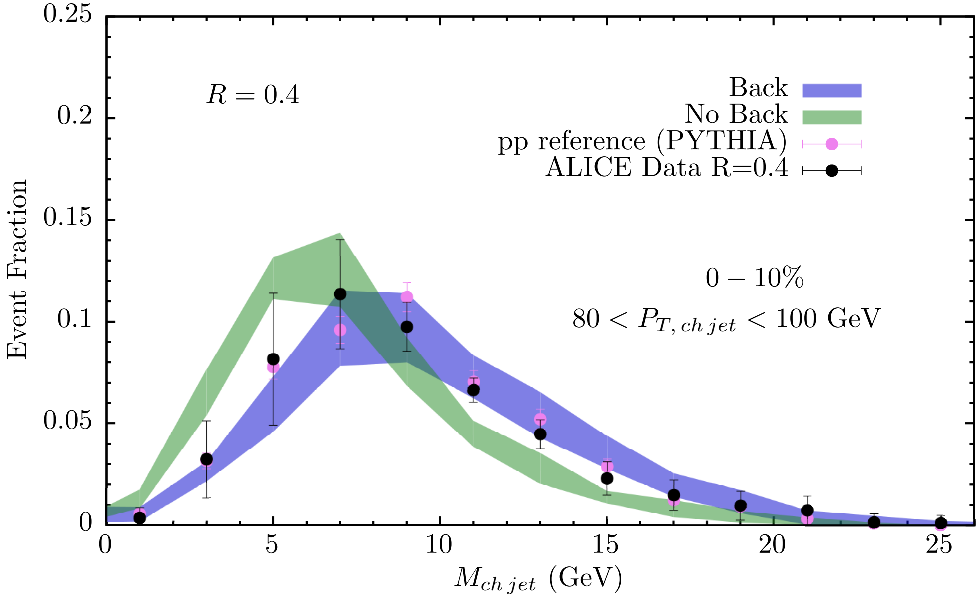
- Before then, via the use of differential jet shape ratios and similar observables that are sensitive to the angular distribution of 10-20 GeV partons in the jet it will be possible to constrain the value of K, the width of the Gaussian distribution of transverse momentum received. Can differential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

What is Missing?

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

Jet Mass

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



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

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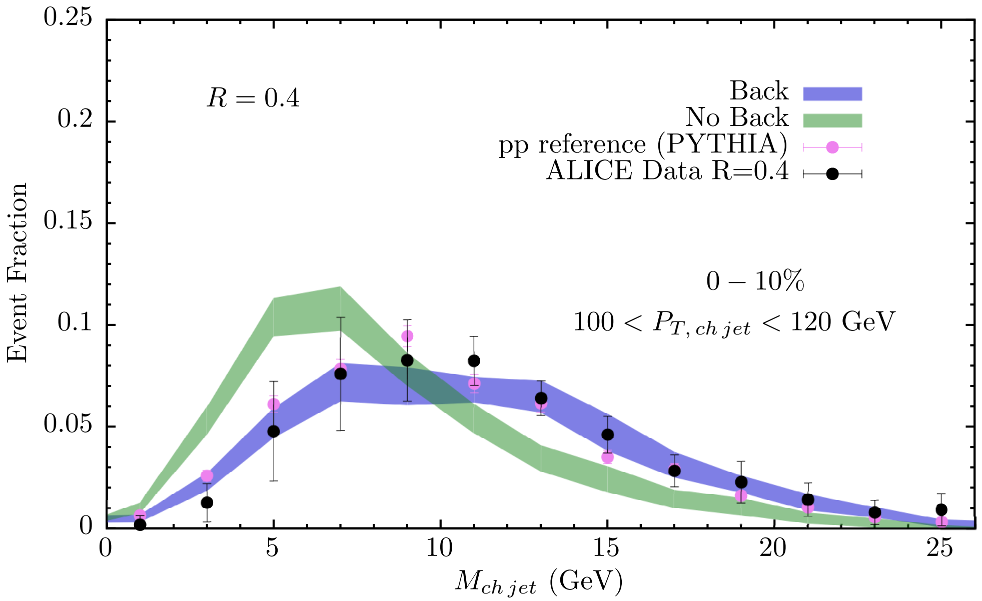
Casalderrey-Solana, Gulhan, Hulcher, Milhano, Pablos, KR, 2017



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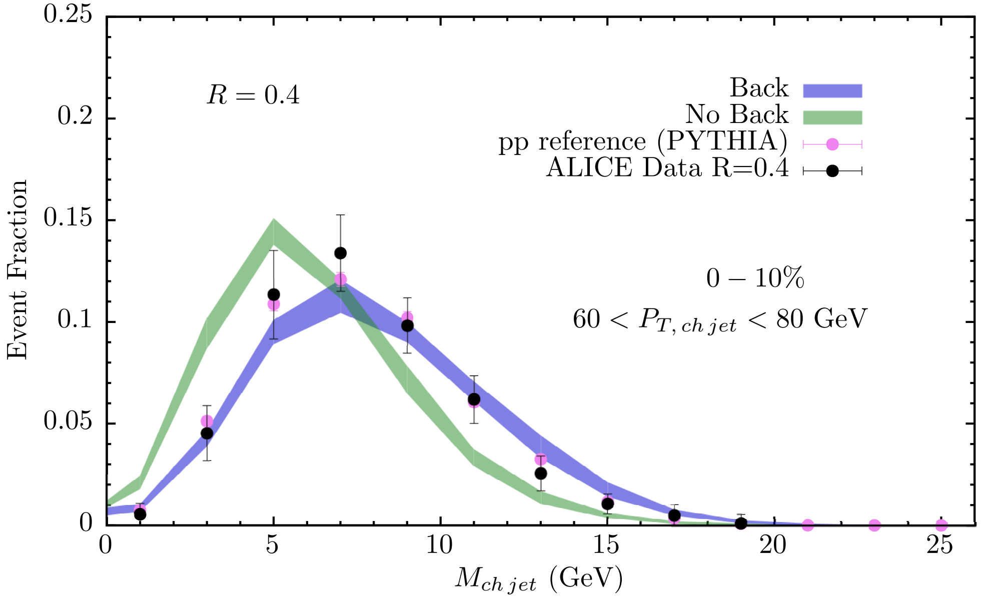

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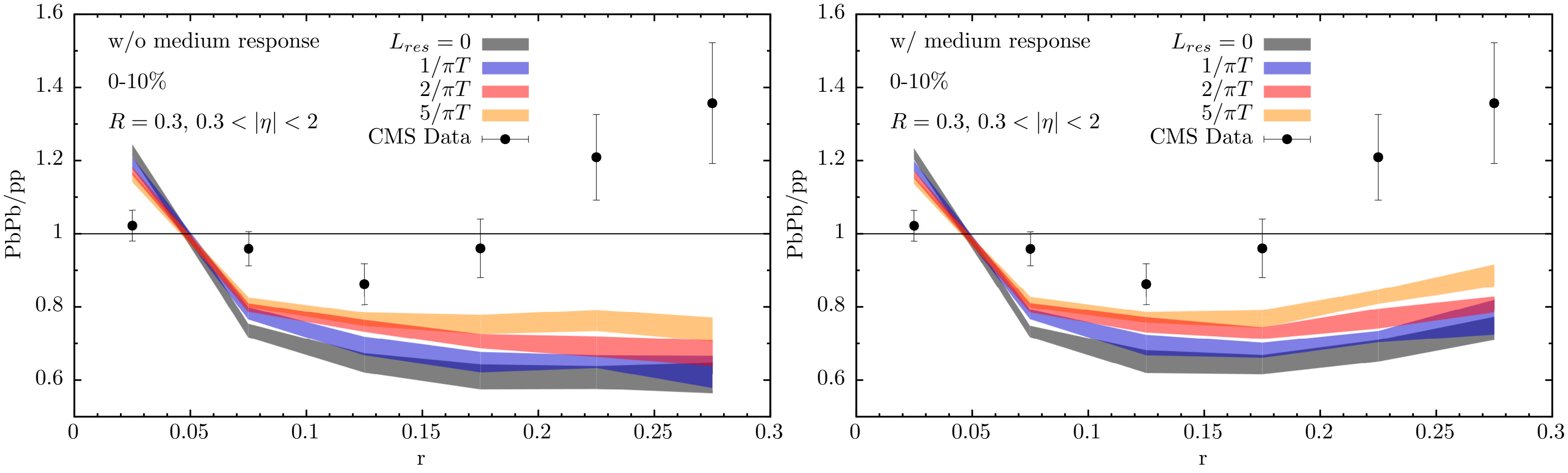
Jet Shape Ratio

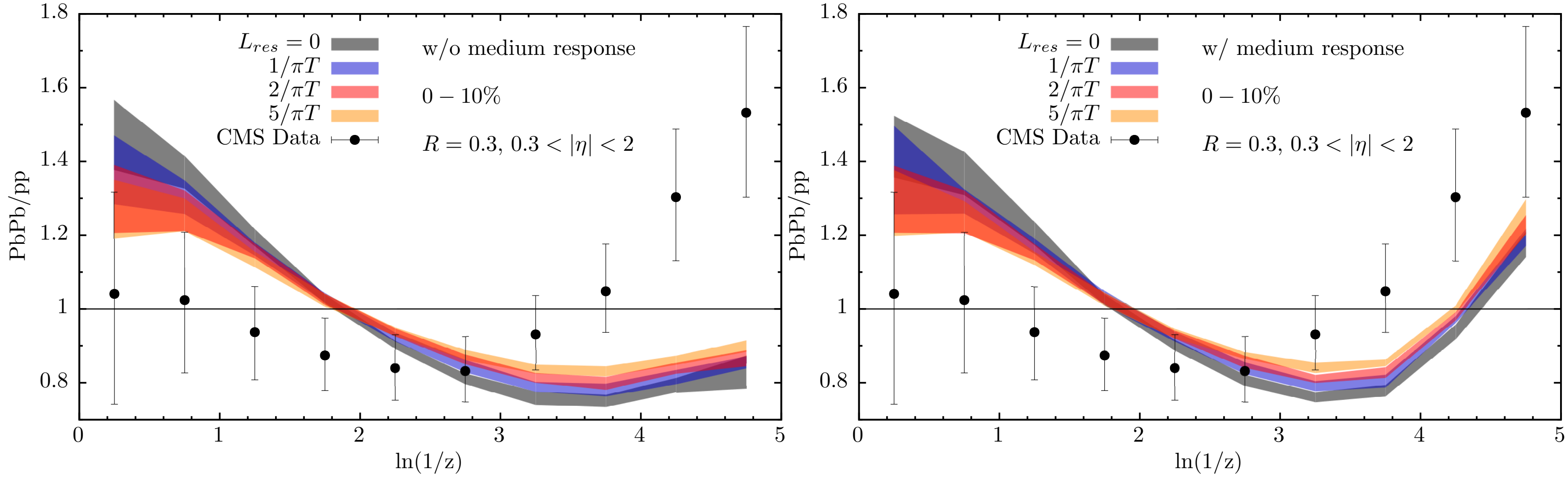
CGMPR 1609.05842; Hulcher, Pablos, KR, 2017



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

Fragmentation Function Ratio

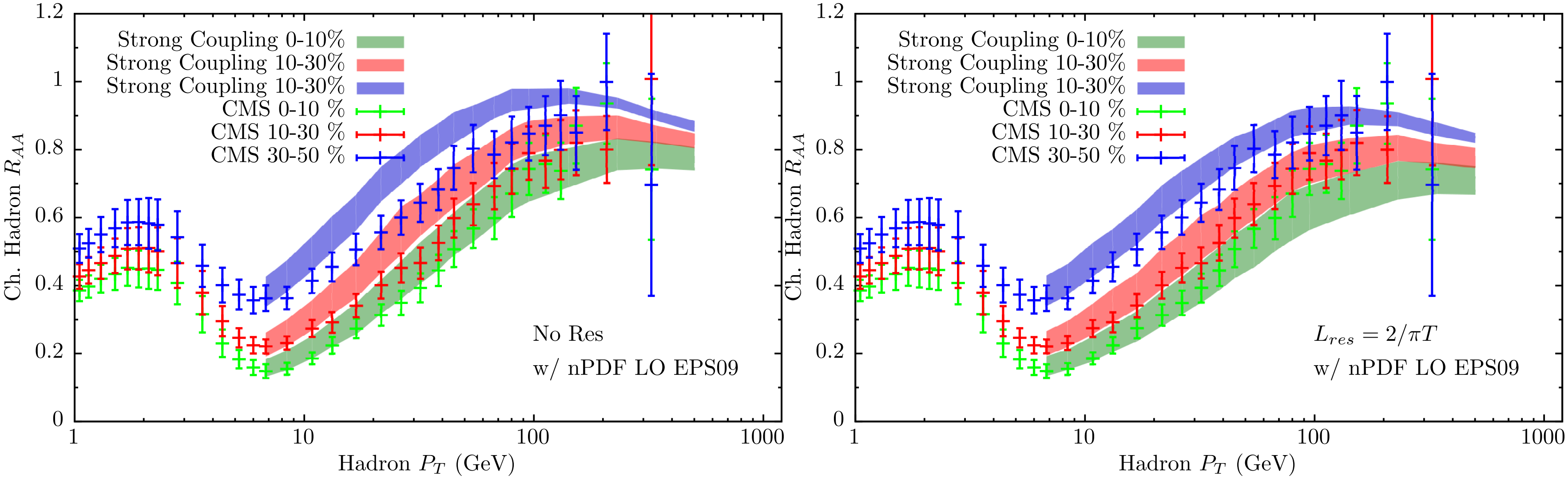
CGMPR 1609.05842; Hulcher, Pablos, KR, 2017



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

Hadron R_{AA}

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

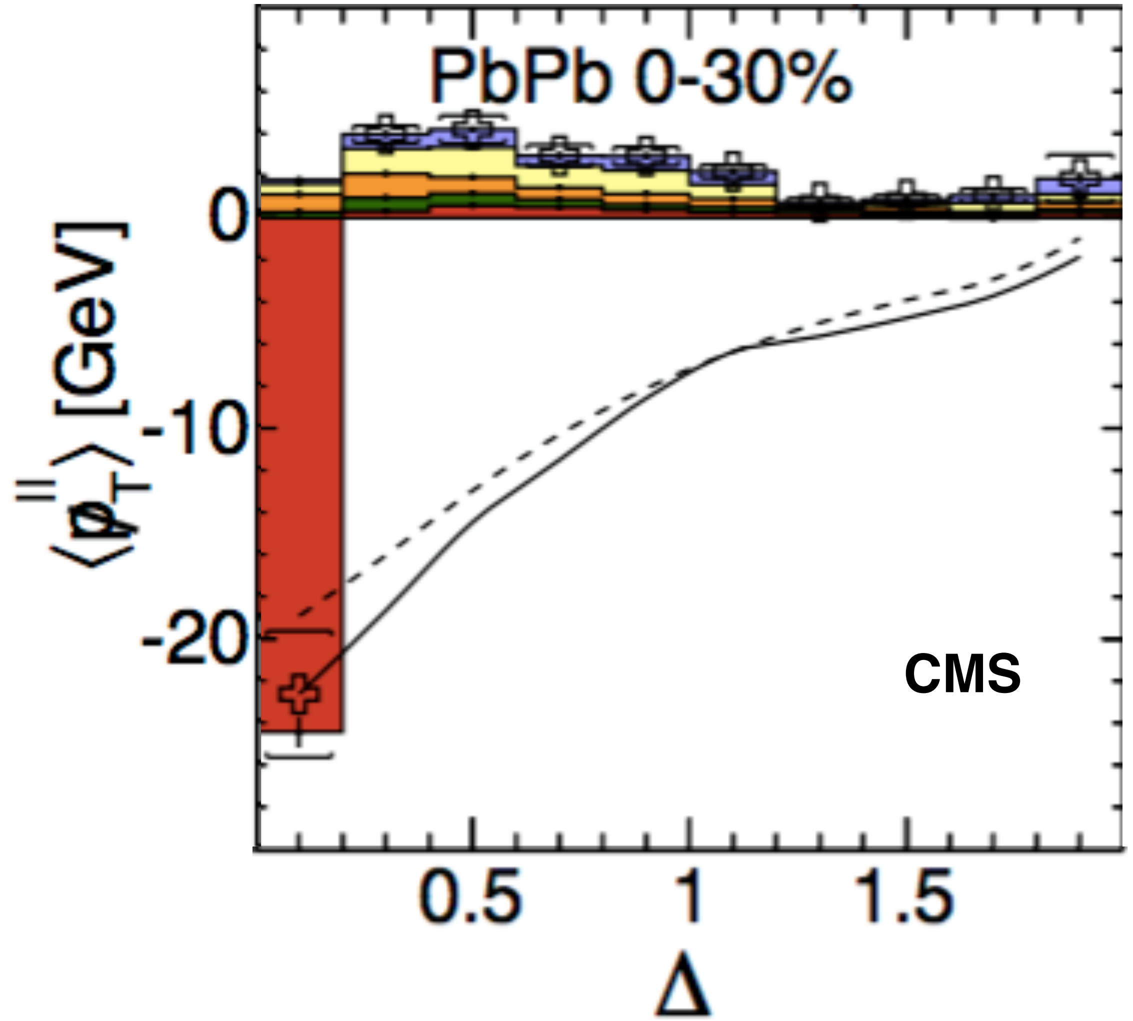


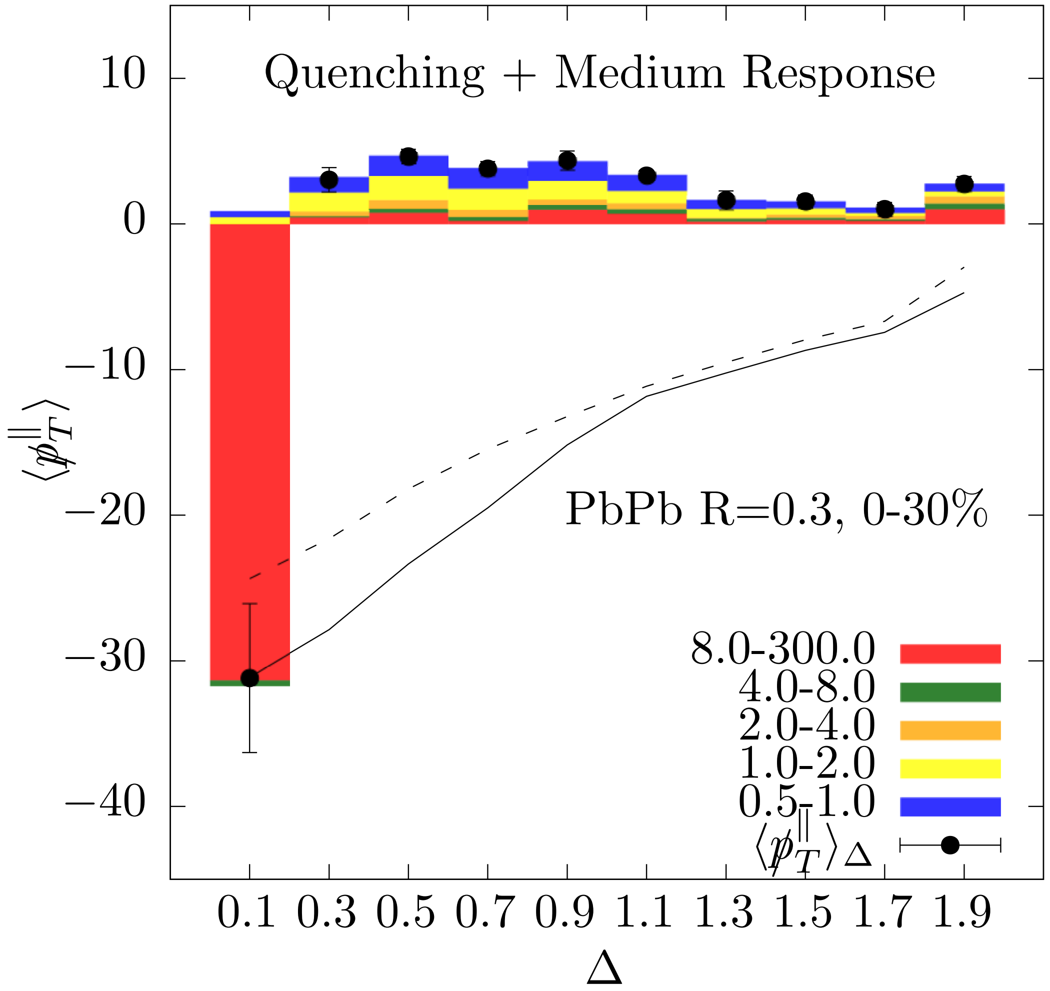
- **As an aside, note that with these extensions we can now also calculate R_{AA} for hadrons from our model, finding good agreement with data.**
- **R_{AA} for hadrons in the hybrid model with $L_{\text{res}} = 2/(\pi T)$ is in better agreement with data than if we take $L_{\text{res}} = 0$.**

Missing p_T observables

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

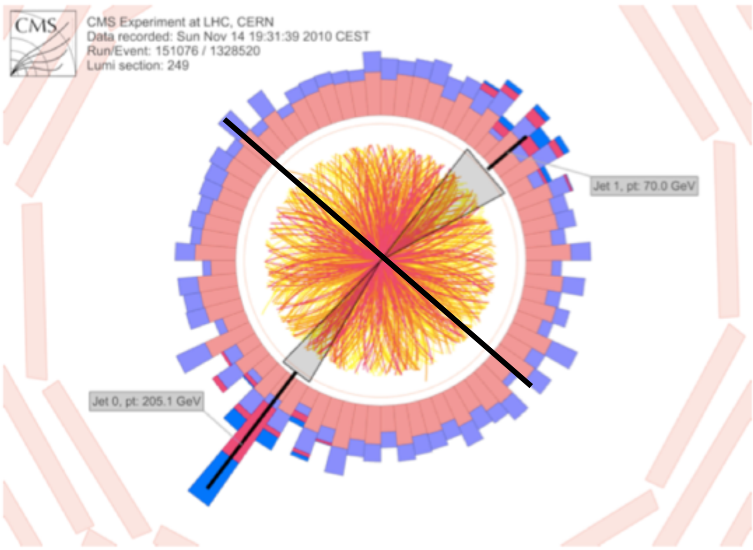
Recovering Lost Energy: Missing Pt



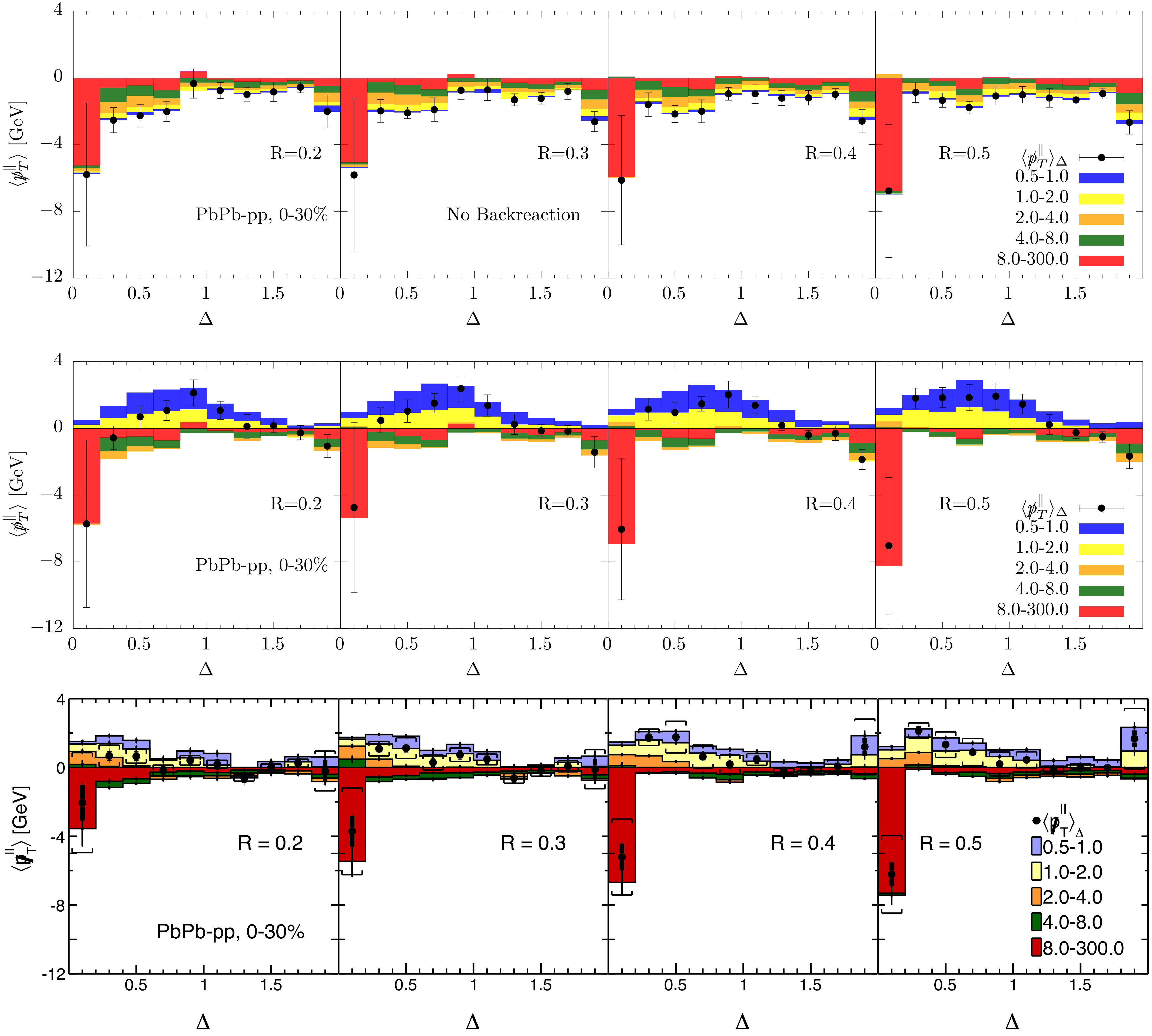


- Energy is recovered at large angles in the form of soft particles

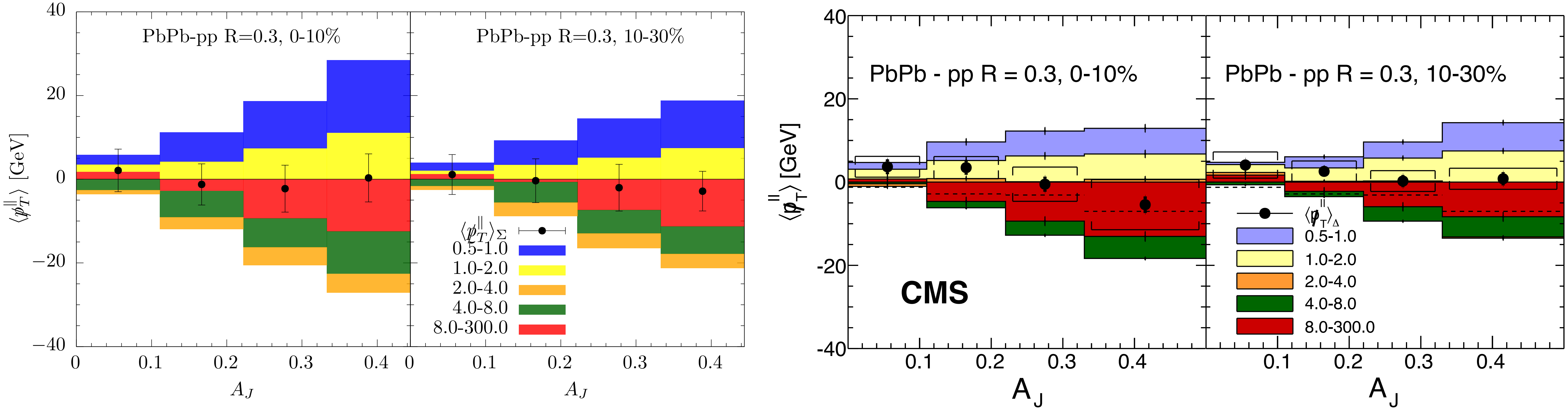
- Adding medium response is essential for a full understanding of jet quenching



Jet radius dependence of Missing Pt

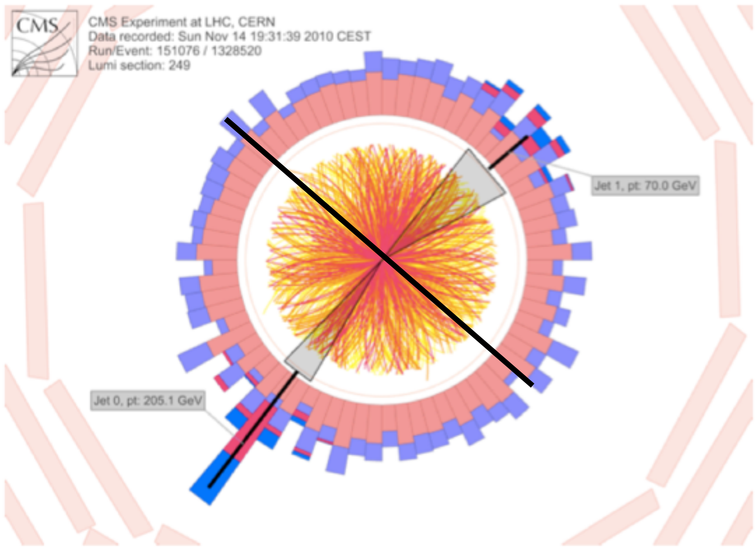


Recovering Lost Energy: Missing Pt



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

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

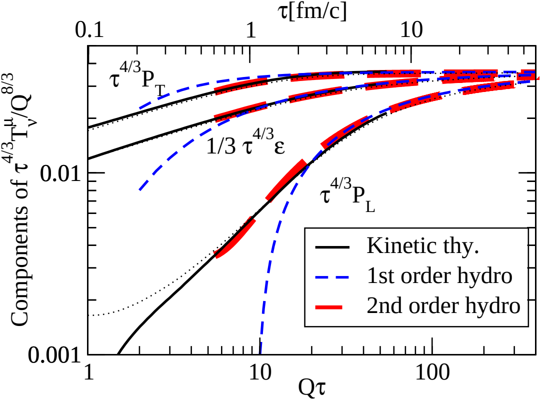


Missing p_T observables

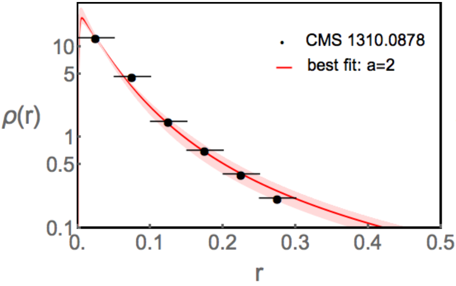
- Our characterization of the wake is on a good track. BUT:
- We have too many particles with 0.5 GeV$< p_T <$2 GeV.
- We have too few particles with 2 GeV$< p_T <$4 GeV.
- The energy and momentum given to the plasma by the jet does *not* fully thermalize. Further improving our model to describe the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

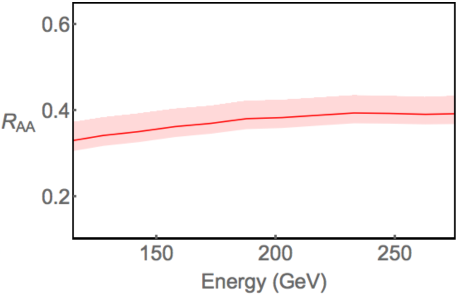
The Long View

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


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

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



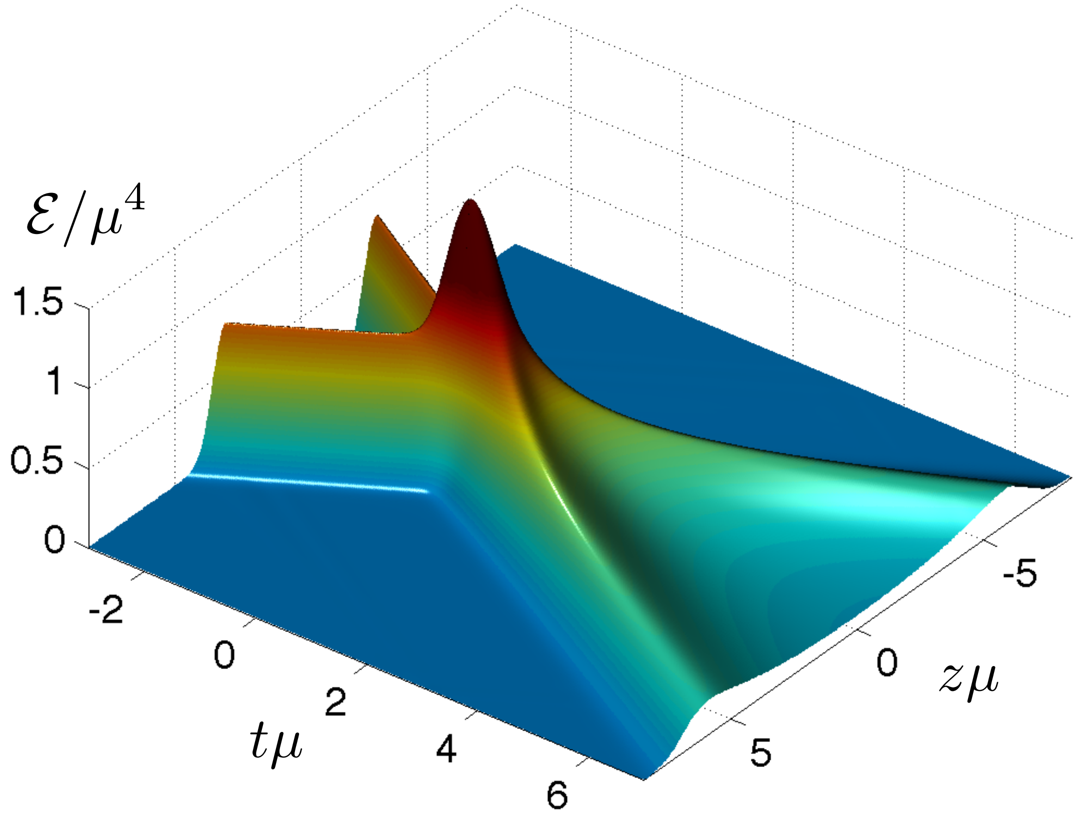


$$p_T > 100\text{GeV} \quad , \quad 0.3 < |\eta| < 2 \quad , \quad R = 0.3$$
$$a = 2 \quad , \quad b = 0.203$$

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

- **Two theories differ on various axes. But, their plasmas are *much* more similar than their vacua. Neither is supersymmetric. Neither confines or breaks chiral symmetry.**
- **$\mathcal{N} = 4$ SYM is conformal. QCD thermodynamics is reasonably conformal for $2T_c \lesssim T <$?. In model studies, adding the degree of nonconformality seen in QCD thermodynamics to $\mathcal{N} = 4$ SYM has *no* effect on η/s and little effect on observables like those this talk.**
- **The fact that the calculations in $\mathcal{N} = 4$ SYM are done at strong coupling is a feature, not a bug.**
- **But, the fact that strongly coupled $\mathcal{N} = 4$ SYM is strongly coupled at all scales, including short length scales, is a bug.**
- **$\mathcal{N} = 4$ SYM calculations done at $1/N_c^2 = 0$ rather than $1/9$.**
- **In QCD thermodynamics, fundamentals are as important as adjoints. No fundamentals in $\mathcal{N} = 4$ SYM, and so far they have only been added as perturbations.**
- **For the last three reasons, our goals must at present be limited to qualitative insights.**

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