Doping and Probing the Original Liquid

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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.

Quark-Gluon Plasma

- The $T \to \infty$ phase of QCD. Entropy wins over order; symmetries of this phase are those of the QCD Lagrangian.

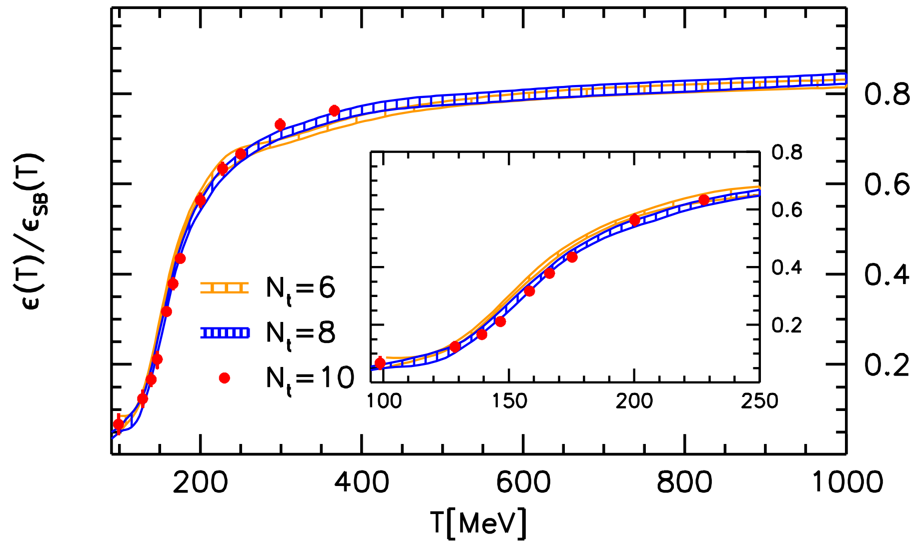
- Asymptotic freedom tells us that, for $T \to \infty$, QGP must be weakly coupled quark and gluon quasiparticles.

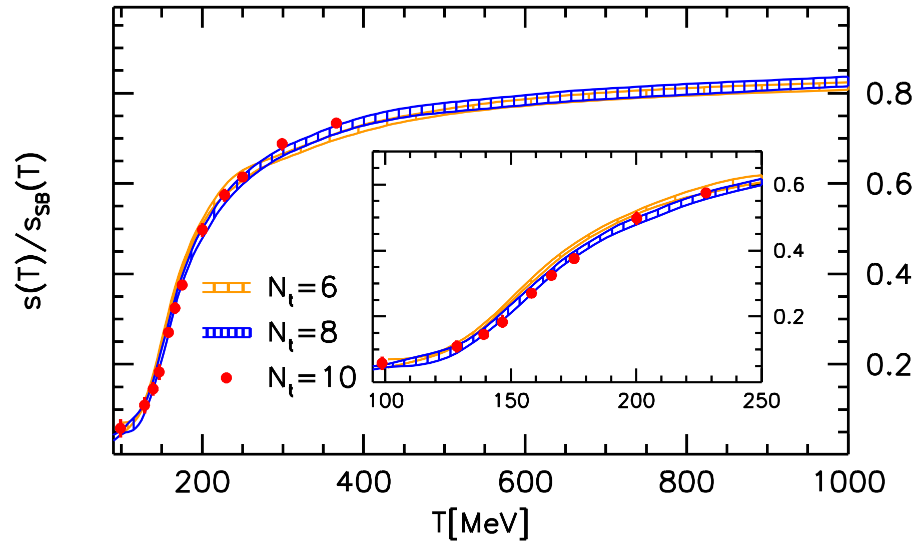
- Lattice calculations of QCD thermodynamics reveal a smooth crossover, like the ionization of a gas, occurring in a narrow range of temperatures centered at a $T_c \simeq 150$ MeV $\simeq 2$ trillion °C ~ 20 μs after big bang. At this temperature, the QGP that filled the universe broke apart into hadrons and the symmetry-breaking order that characterizes the QCD vacuum developed.

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

QGP Thermodynamics on the Lattice

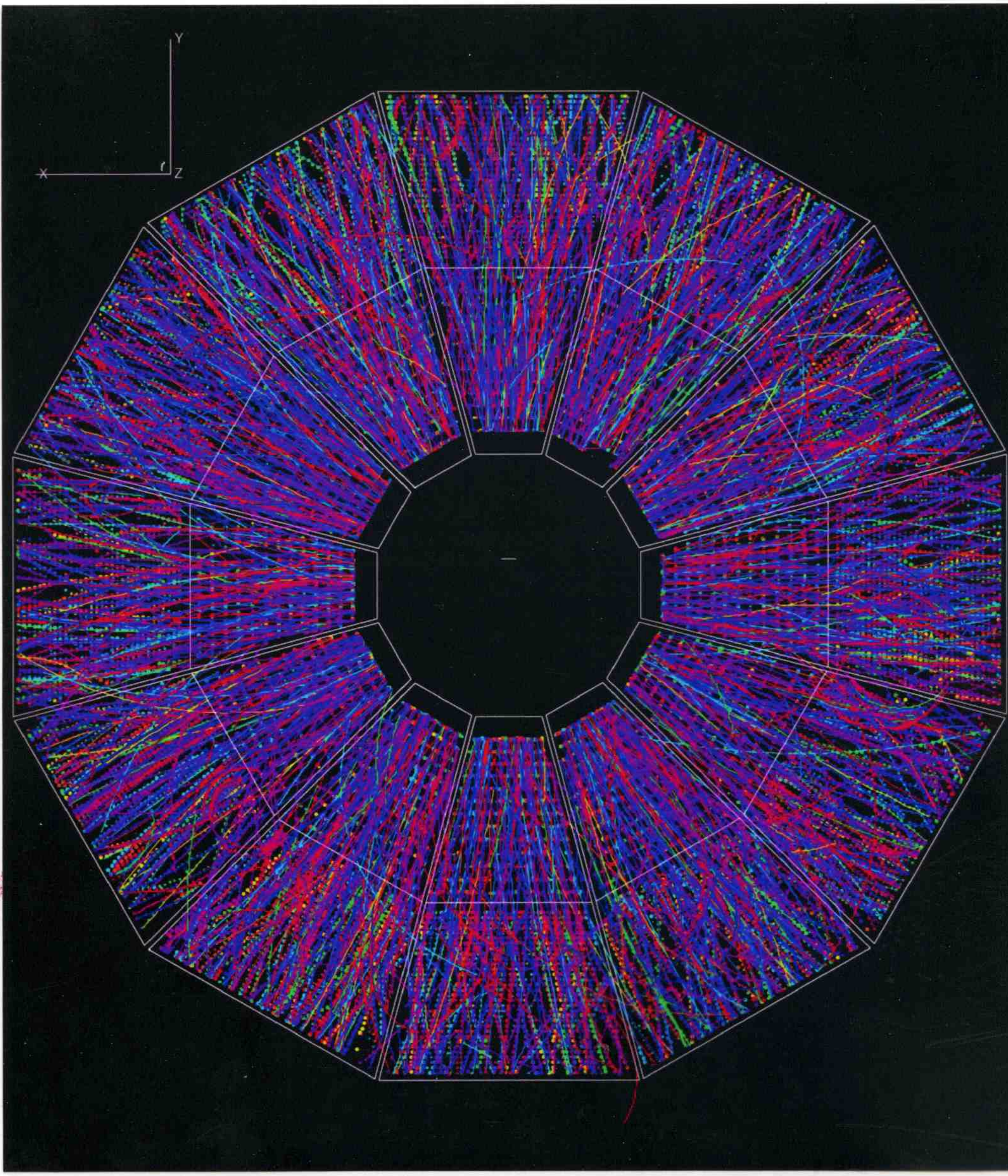
Endrodi et al, 2010





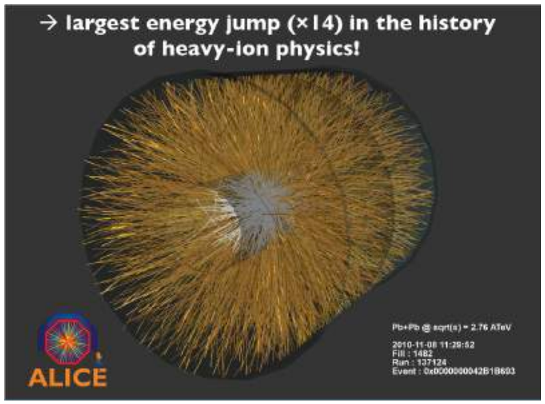
Above $T_{\text{crossover}} \sim$ 150-200 MeV, QCD = QGP. QGP static properties can be studied on the lattice.

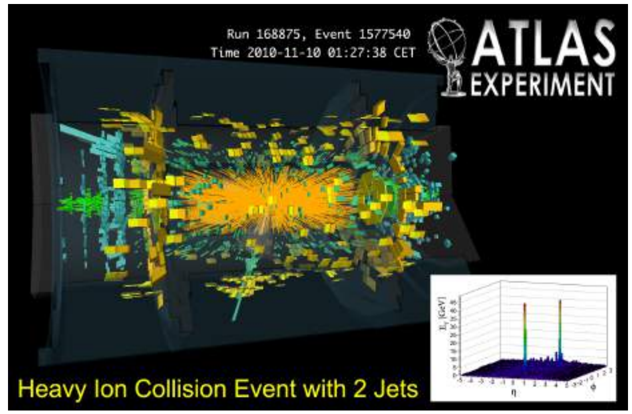
Lesson of the past decade: don't try to infer dynamic properties from static ones. Although its thermodynamics is almost that of ideal-noninteracting-gas-QGP, this stuff is very different in its dynamical properties. [Lesson from experiment+hydrodynamics. But, also from the large class of gauge theories with holographic duals whose plasmas have ε and s at infinite coupling 75% that at zero coupling.]



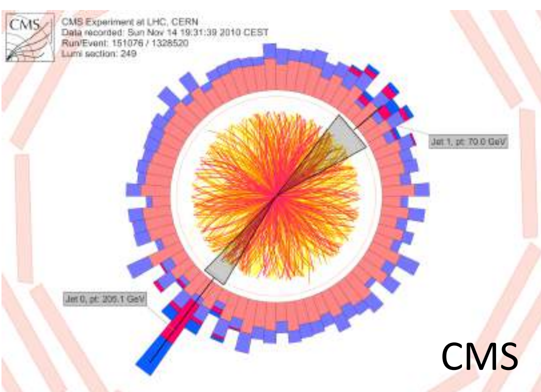
STAR

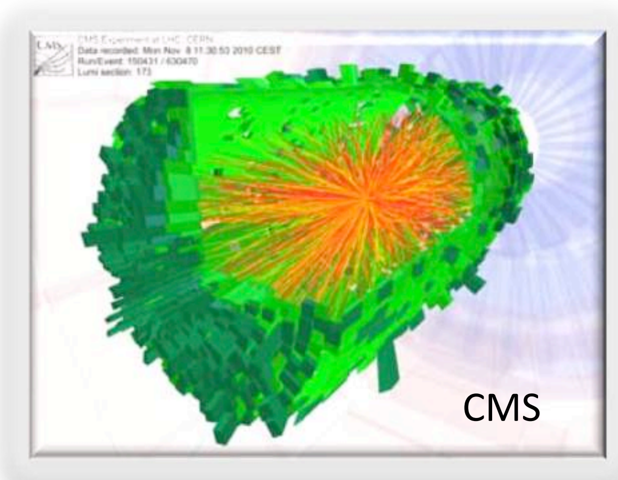
Nov 2010 first LHC Pb+Pb collisions





$\sqrt{s_{NN}}$ = 2760 GeV





Integrated Luminosity = 10 μb^{-1}

Liquid Quark-Gluon Plasma

- Hydrodynamic analyses of RHIC data on how asymmetric blobs of Quark-Gluon Plasma expand (explode) have taught us that QGP is a strongly coupled liquid, with (η/s) — the dimensionless characterization of how much dissipation occurs as a liquid flows — much smaller than that of all other known liquids except one.

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

Ultracold Fermionic Atom Fluid

- The one terrestrial fluid with η/s comparably small to that of QGP.

- NanoKelvin temperatures, instead of TeraKelvin.

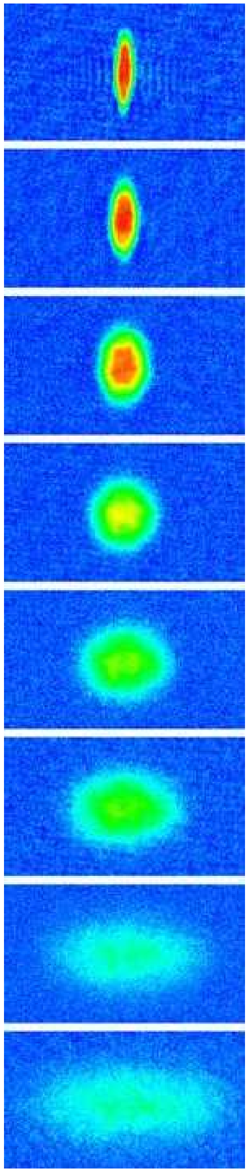
- Ultracold cloud of trapped fermionic atoms, with their two-body scattering cross-section tuned to be infinite. A strongly coupled liquid indeed. (Even though it's conventionally called the "unitary Fermi gas".)

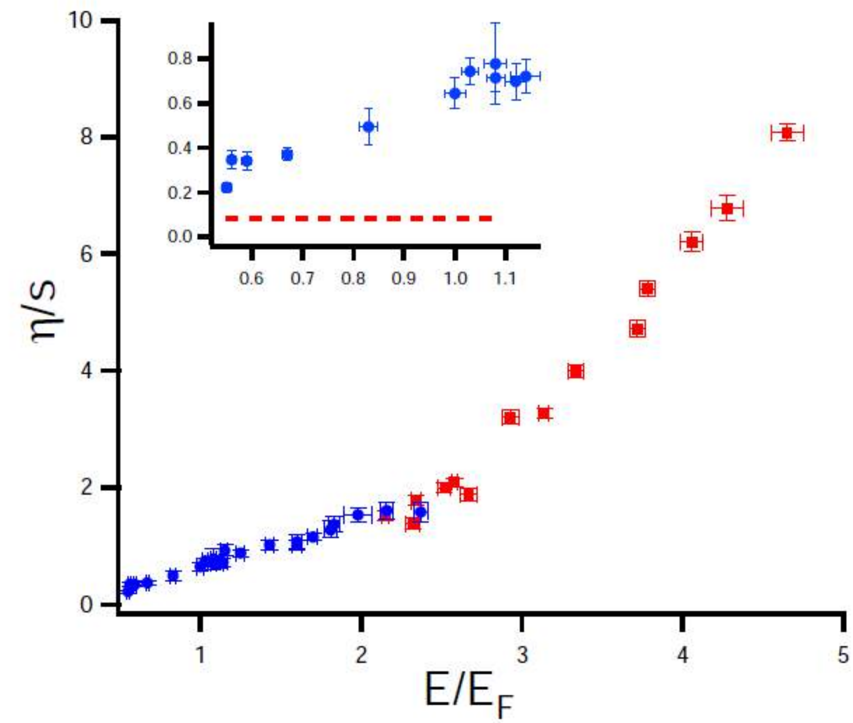
- Data on elliptic flow (and other hydrodynamic flow patterns that can be excited) used to extract η/s as a function of temperature...

Viscosity to entropy density ratio

consider both collective modes (low T)

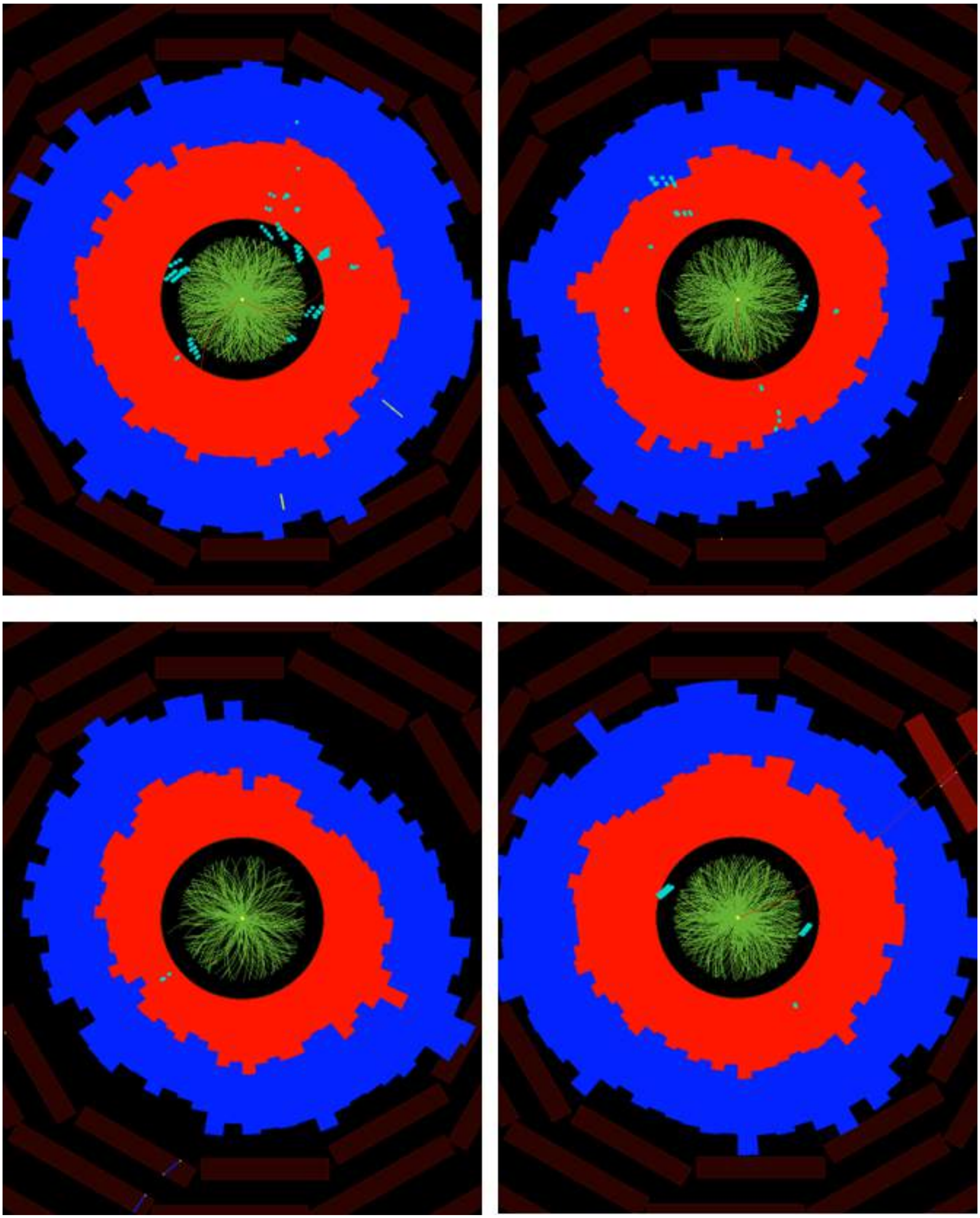
and elliptic flow (high T)





Cao et al., Science (2010)

$$\eta/s \leq 0.4$$



Rapid Equilibration?

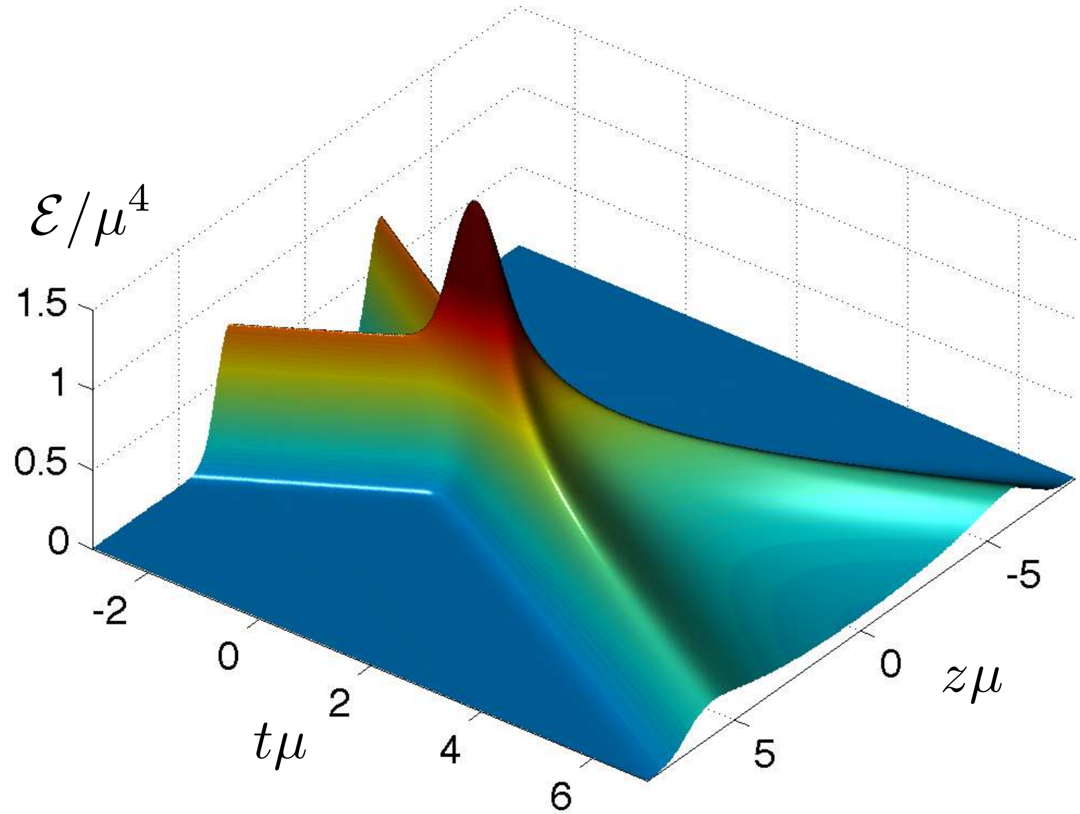
- **Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.**

- **Long-standing estimate is that a hydrodynamic description must already be valid only 1 fm/c after the collision.**

- **This is the time it takes light to cross a proton, and was long seen as** *rapid equilibration*.

- **But, is it really? How rapidly does equilibration occur in a strongly coupled theory?**

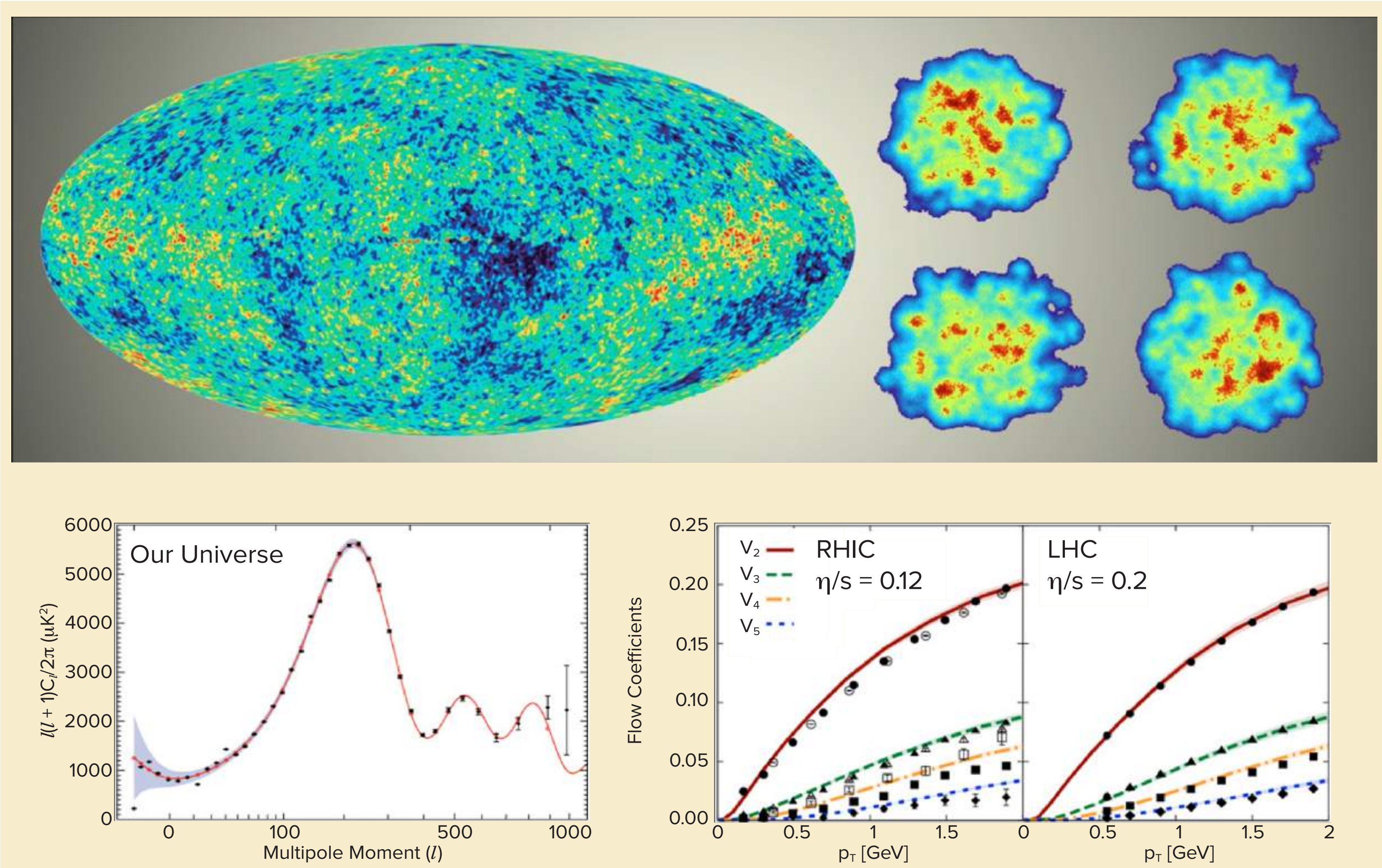
Colliding Strongly Coupled Sheets of Energy



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

η/s from RHIC and LHC data

- **I have given you the beginnings of a story that has played out over the past decade. I will now cut to the chase, leaving out many interesting chapters and oversimplifying.**
- **Using relativistic viscous hydrodynamics to describe expanding QGP,** *produced in an initially lumpy heavy ion collision*, **using microscopic transport to describe late-time hadronic rescattering, and using RHIC data on pion and proton spectra and** v_2 *and* v_3 *and* v_4 *and* v_5 *and* v_6 $\ldots$ **as functions of** p_T **and impact parameter**. . .
- **QGP@RHIC, with** $T_c < T \lesssim 2T_c$**, has** $1 < 4\pi\eta/s < 2$ **and QGP@LHC with** $T_c < T \lesssim 3T_c$ **has** $1 < 4\pi\eta/s < 3$**.**
- $4\pi\eta/s \sim 10^4$ **for typical terrestrial gases, and** 10 **to** 100 **for all known terrestrial liquids except one. Hydrodynamics works much better for QGP@RHIC than for water.**
- $4\pi\eta/s = 1$ **for any (of the by now very many) known strongly coupled gauge theory plasmas that are the "hologram" of a (4+1)-dimensional gravitational theory "heated by" a (3+1)-dimensional black-hole horizon.**



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

QGP cf CMB

- In cosmology, initial-state quantum fluctuations, processed by hydrodynamics, appear in data as c_ℓ's. From the c_ℓ's, learn about initial fluctuations, and about the "fluid" — eg its baryon content.

- In heavy ion collisions, initial state quantum fluctuations, processed by hydrodynamics, appear in data as v_n's. From v_n's, learn about initial fluctuations, and about the QGP — eg its η/s, ultimately its $\eta/s(T)$ and ζ/s.

- Cosmologists have a huge advantage in resolution: c_ℓ's up to $\ell \sim$ thousands. But, they have only one "event"!

- Heavy ion collisions only up to v_6 at present. But they have billions of events. And, they can do controlled variations of the initial conditions, to understand systematics...

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Beyond Quasiparticles

- QGP at RHIC & LHC, unitary Fermi "gas", gauge theory plasmas with holographic descriptions are all strongly coupled fluids with no apparent quasiparticles.

- In QGP, with η/s as small as it is, there can be no 'transport peak', meaning no self-consistent description in terms of quark- and gluon-quasiparticles. [Q.p. description self consistent if $\tau_{\rm qp} \sim (5\eta/s)(1/T) \gg 1/T$.]

- Other "fluids" with no quasiparticle description include: the "strange metals" (including high-T_c superconductors above T_c); quantum spin liquids; matter at quantum critical points;... Among the grand challenges at the frontiers of condensed matter physics today.

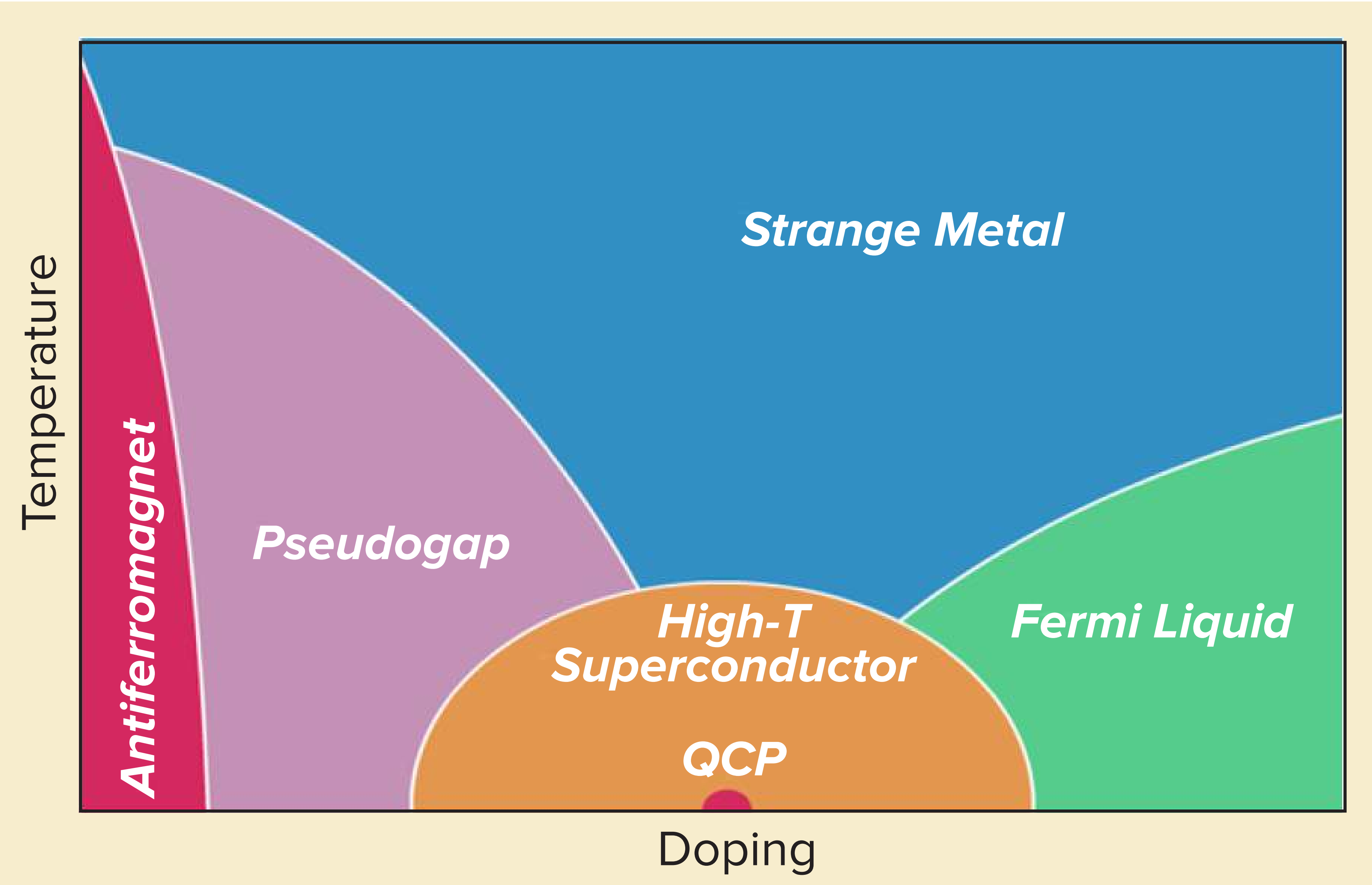
- In all these cases, after discovery two of the central strategies toward gaining understanding are *probing* and *doping*. To which we now turn...

What Next?

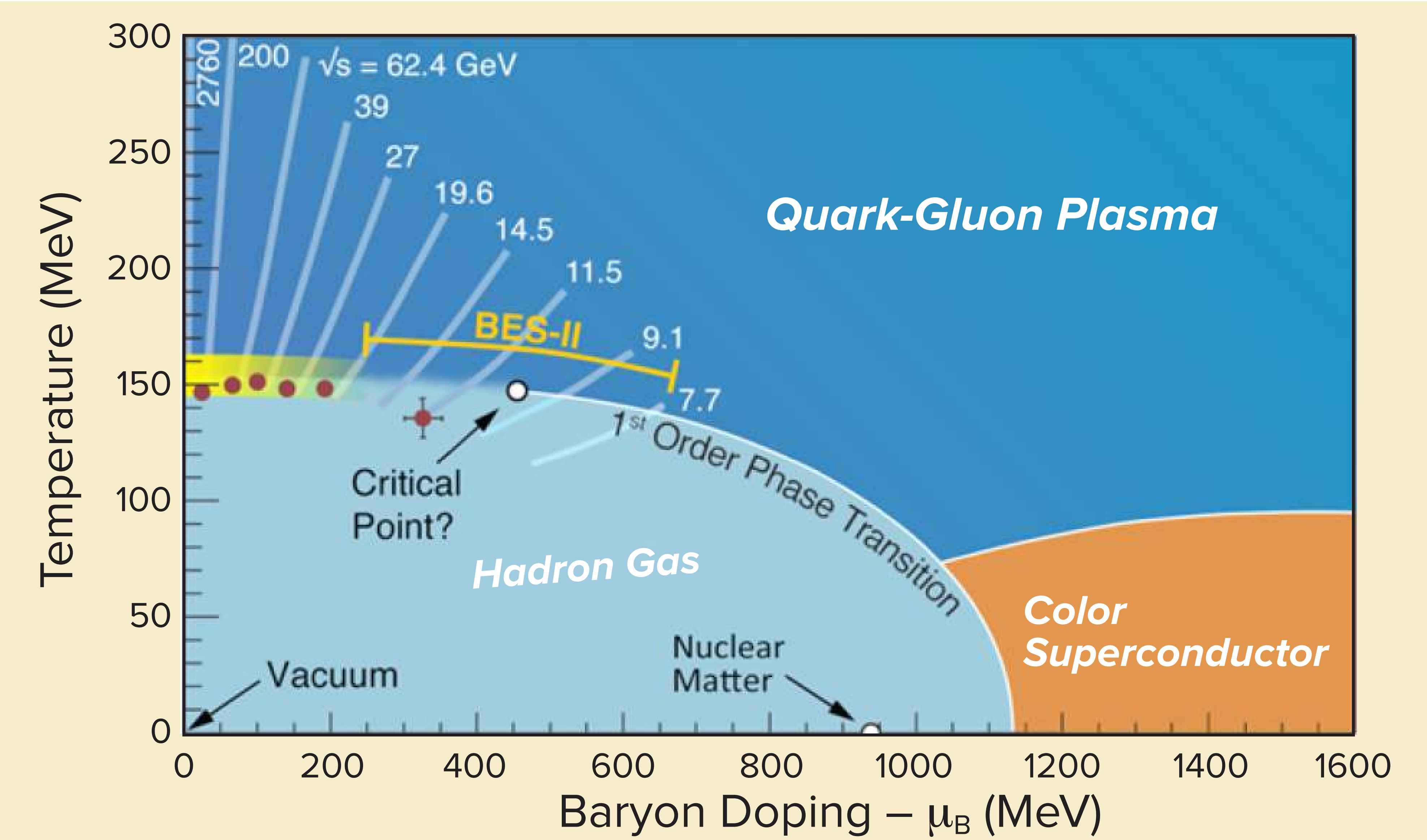
Two kinds of What Next? questions for the coming decade...

- 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 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...



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


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

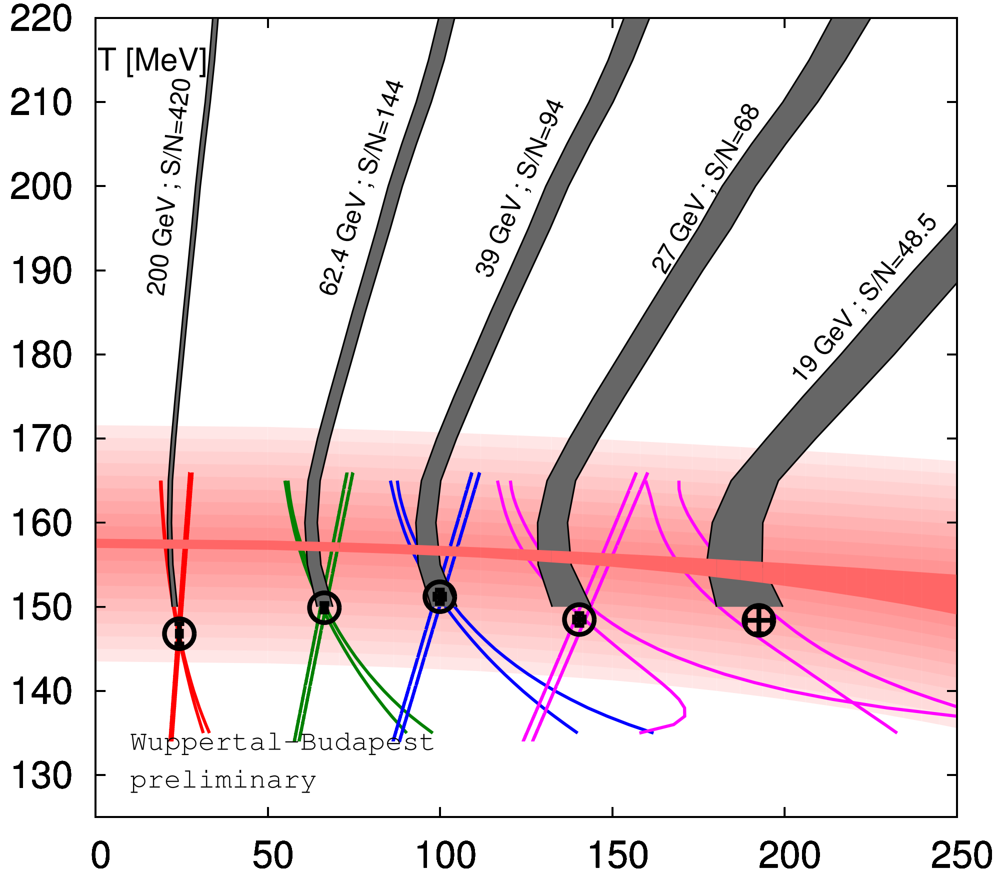
Mapping the QCD Phase Diagram

- 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?

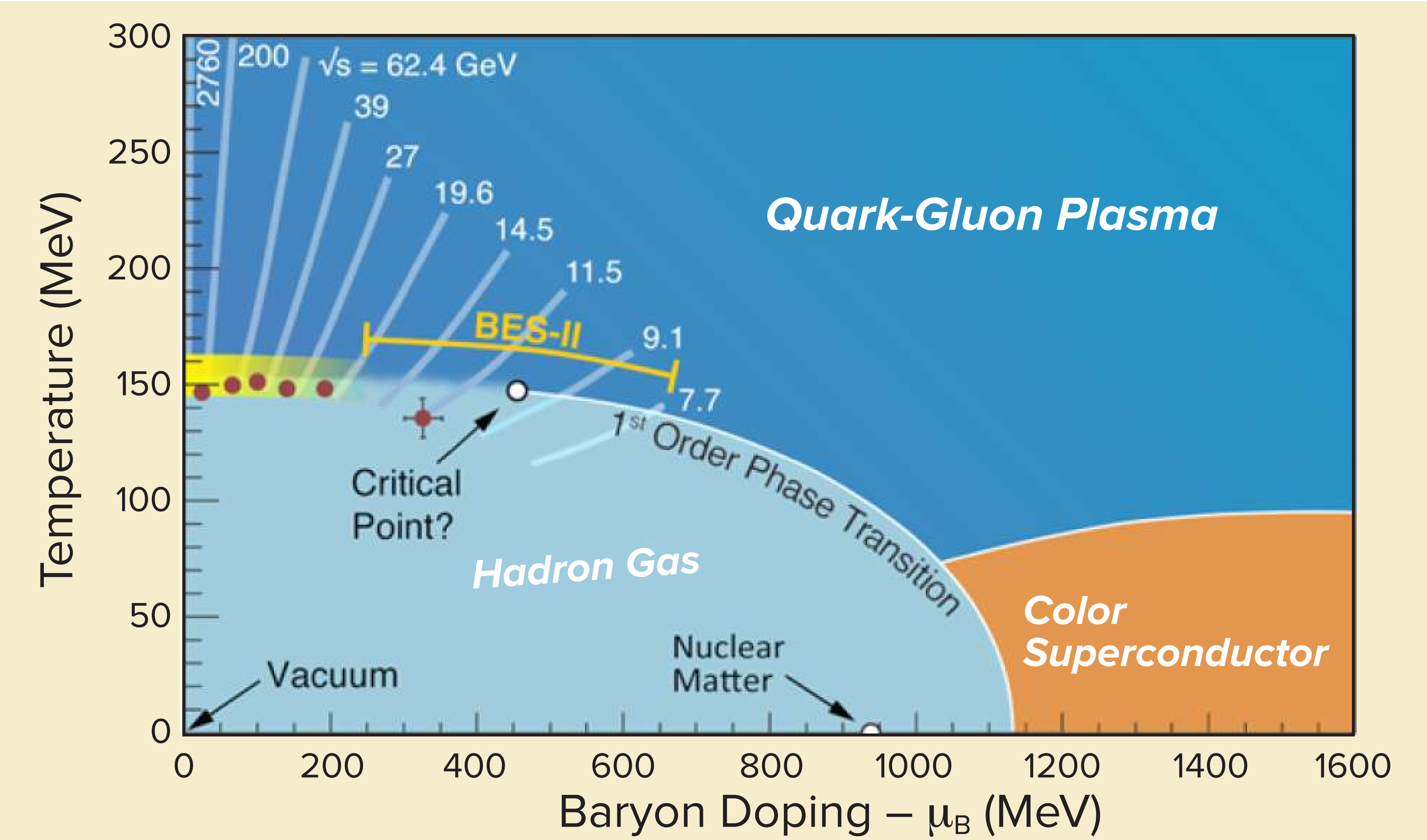
- Answering this question via theory will need further advances in lattice "technology". Impressive recent progress advancing established Taylor-expansion methods. New ideas also being evaluated. Nevertheless, at present theory is good at telling us what happens near a critical point or first order transition, 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.



Temperature (MeV)
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Baryon Doping – μ_B (MeV)
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BES-II
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1st Order Phase Transition
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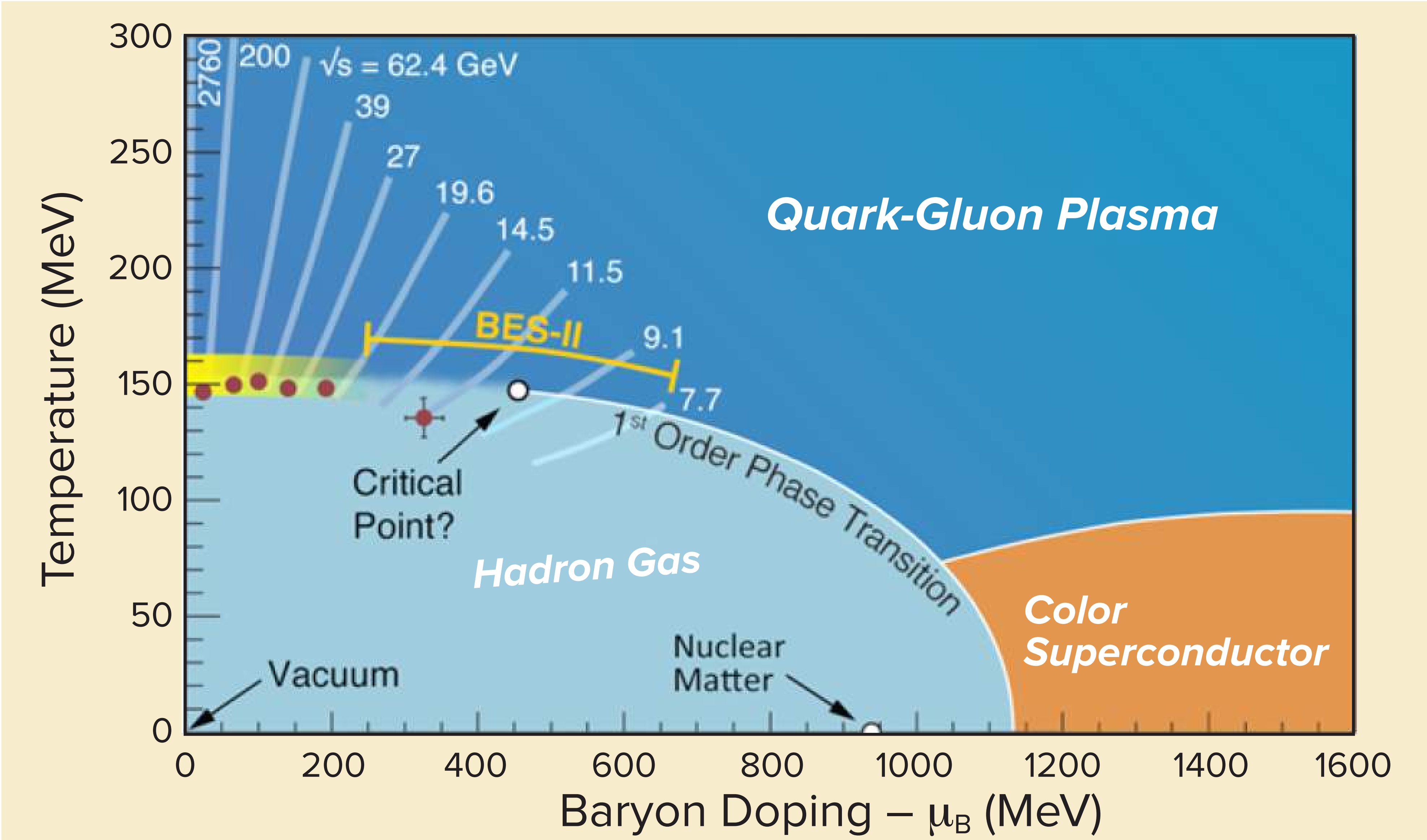

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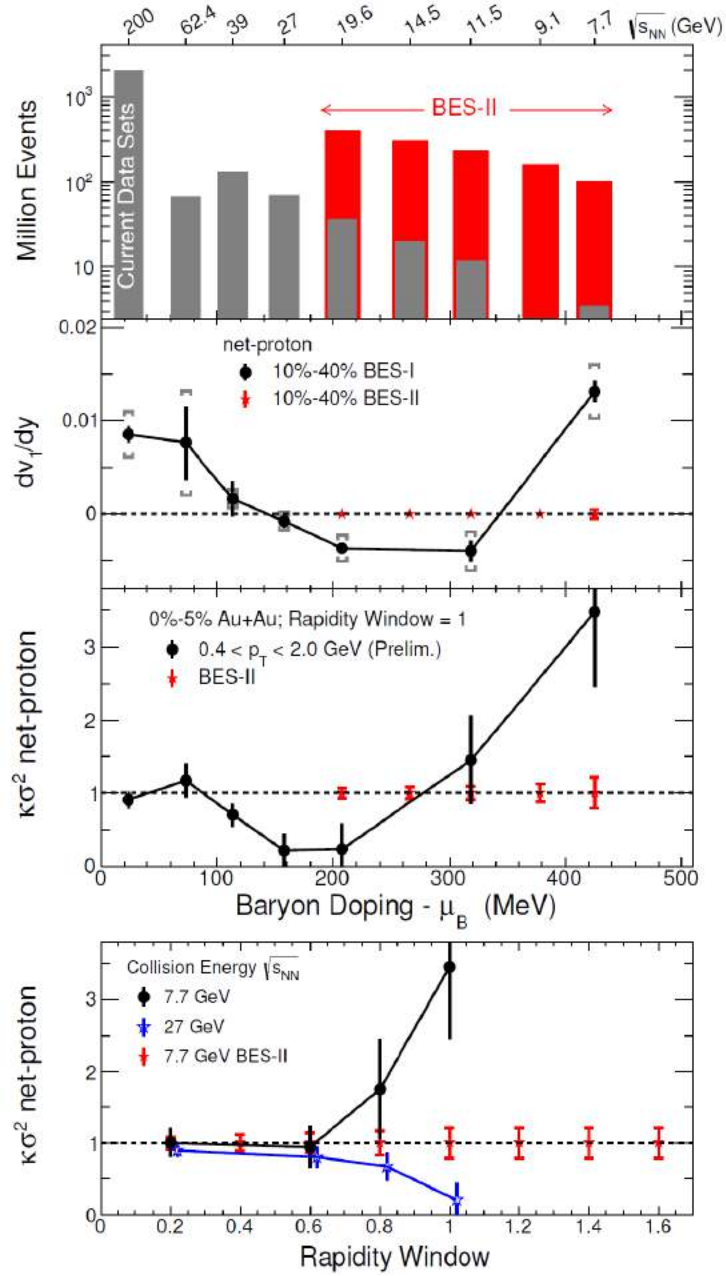
Mapping the QCD Phase Diagram

- 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
62.4
39
27
19.6
14.5
11.5
9.1
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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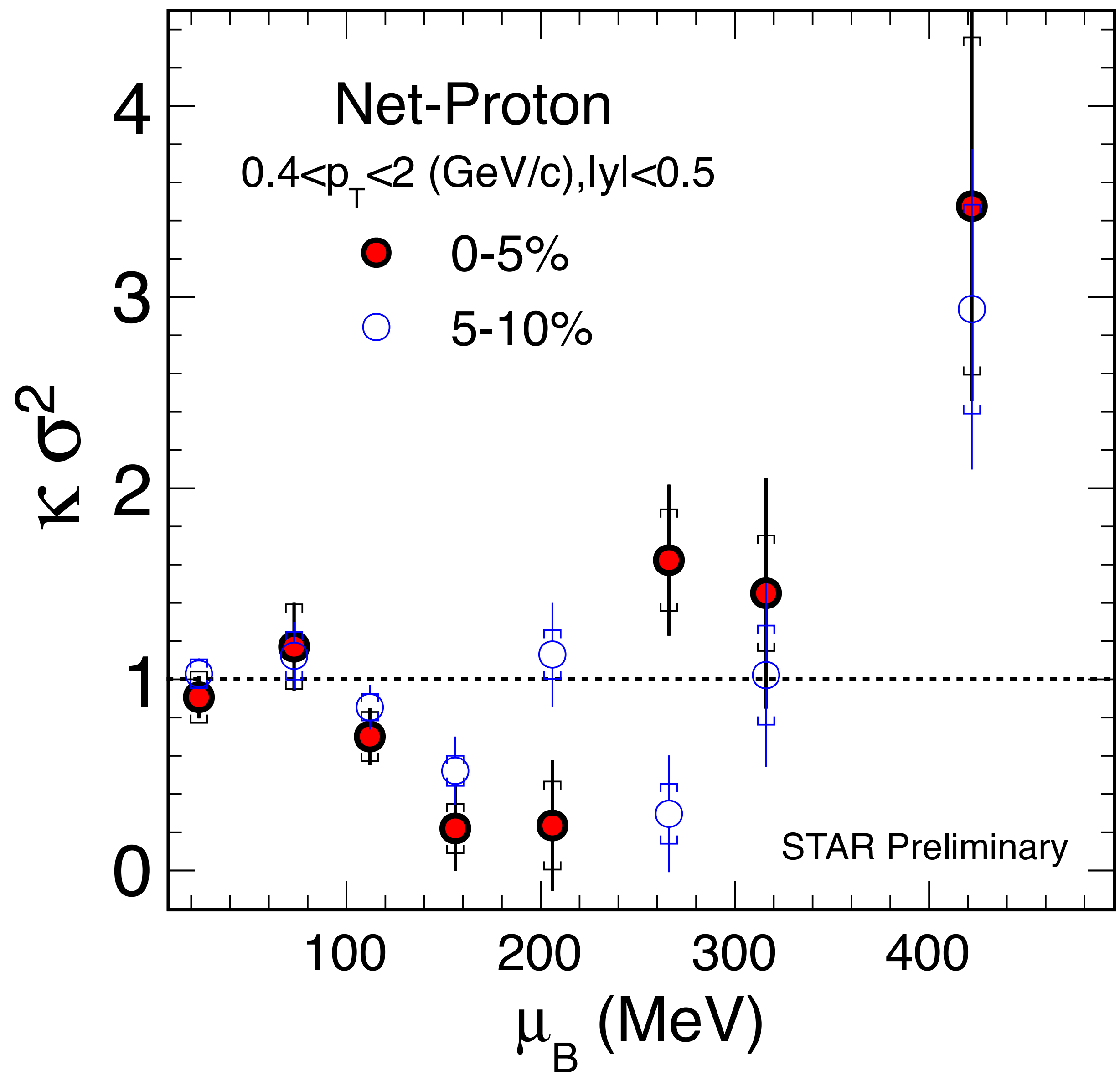
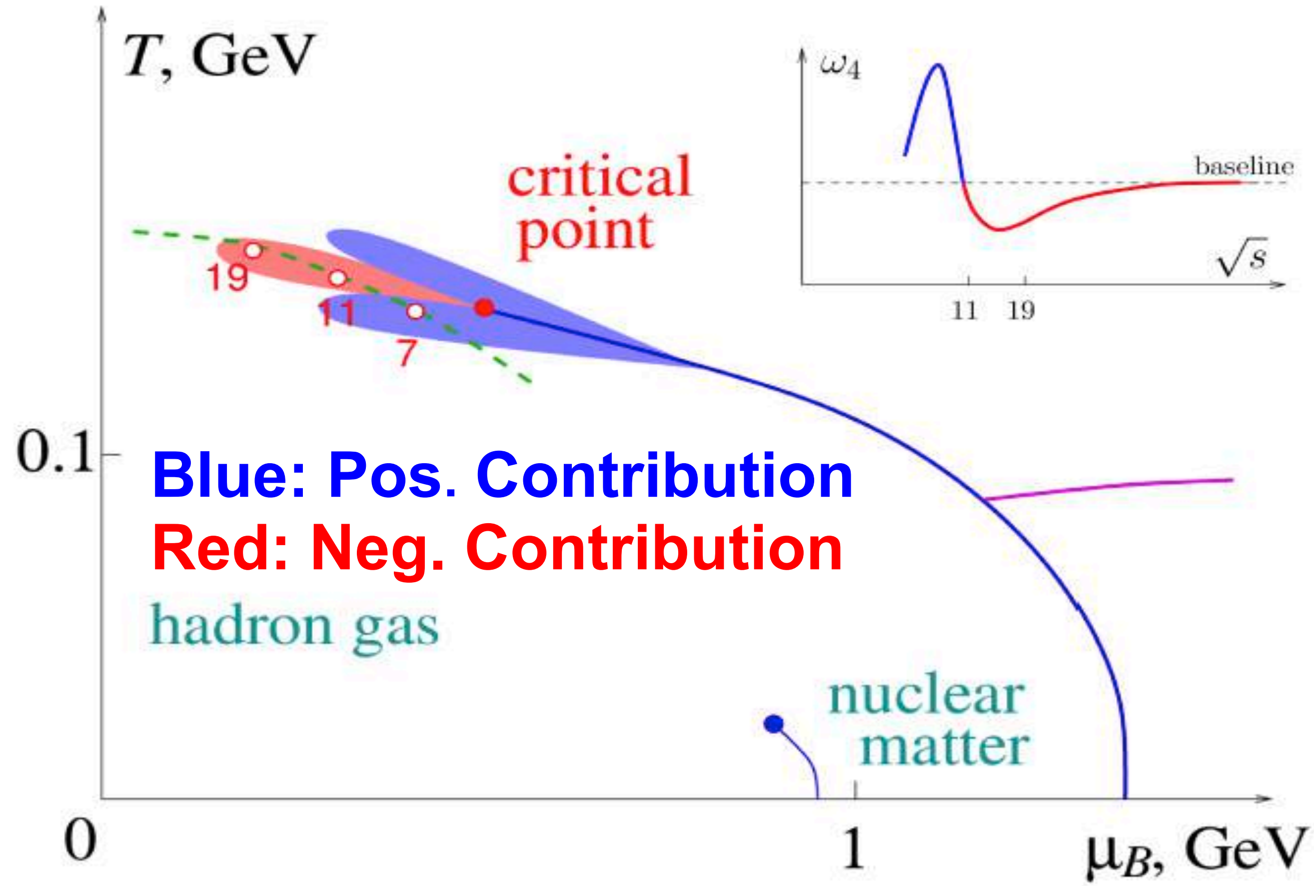
7.7 GeV BES-II
$\kappa\sigma^2$ net-proton
Rapidity Window


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



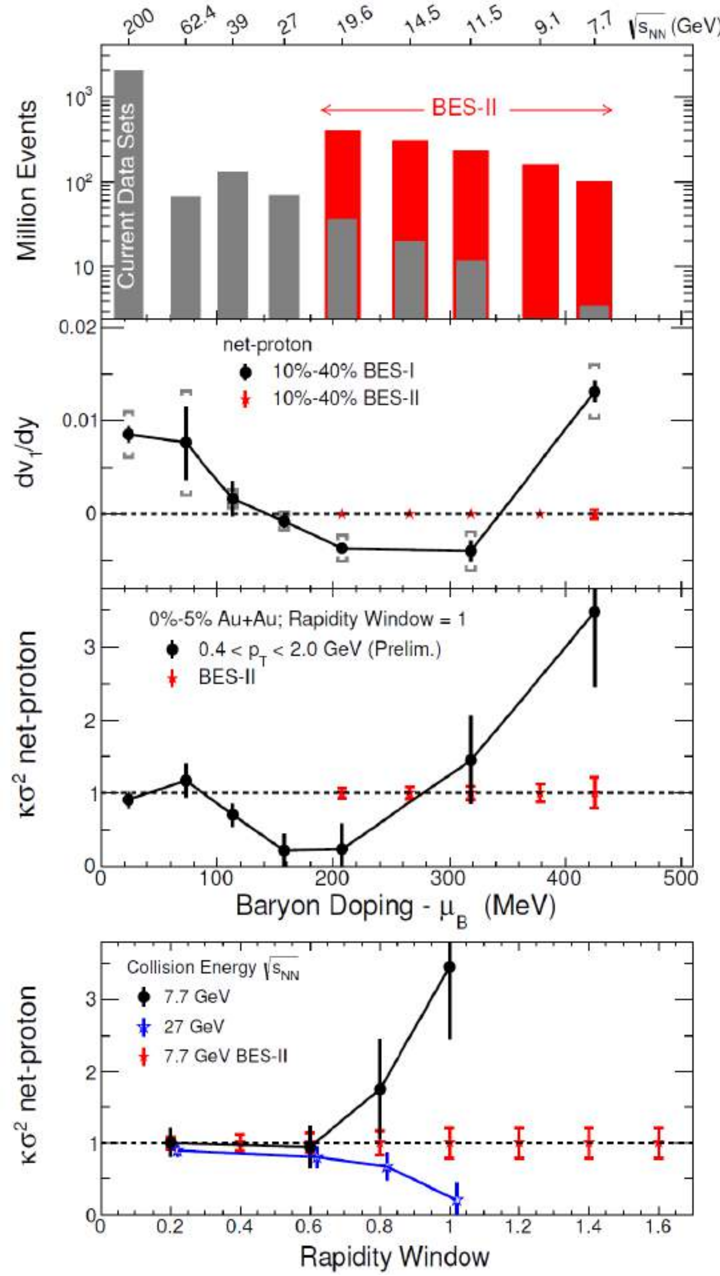
T, GeV
0.1
0
1
μB, GeV
critical
point
19
11
7
ω4
baseline
√s
11
19
Blue: Pos. Contribution
Red: Neg. Contribution
hadron gas
nuclear
matter

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. Higher statistics data 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 self-consistent treatment: fluctuations can't stay in eqbm because of finite-time limitation on growth of the correlation length, how do the fluctuations evolve? feedback on hydro? Only then can quantify the signatures of, a possible critical point. This is goal of BEST Collaboration.



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Collision Energy $\sqrt{s_{NN}}$
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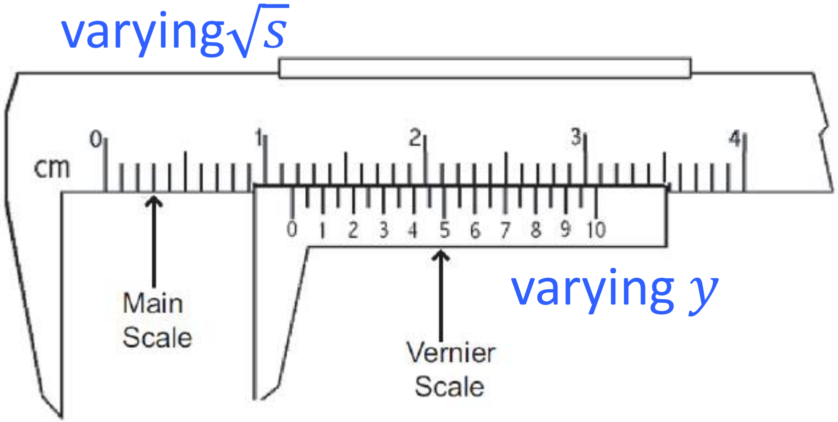
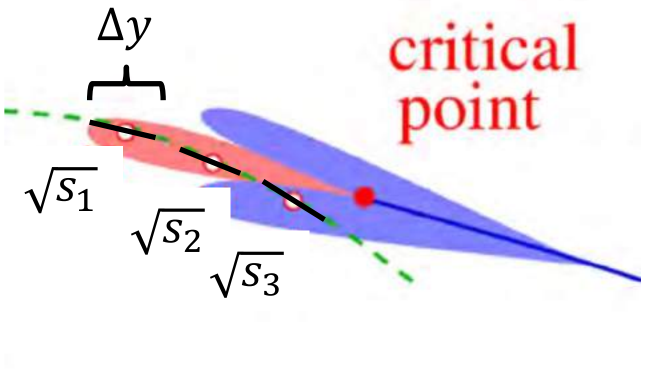
27 GeV
7.7 GeV BES-II
$\kappa\sigma^2$ net-proton
Rapidity Window

Rapidity is a finer-resolution probe of the critical regime than $\sqrt{s}$

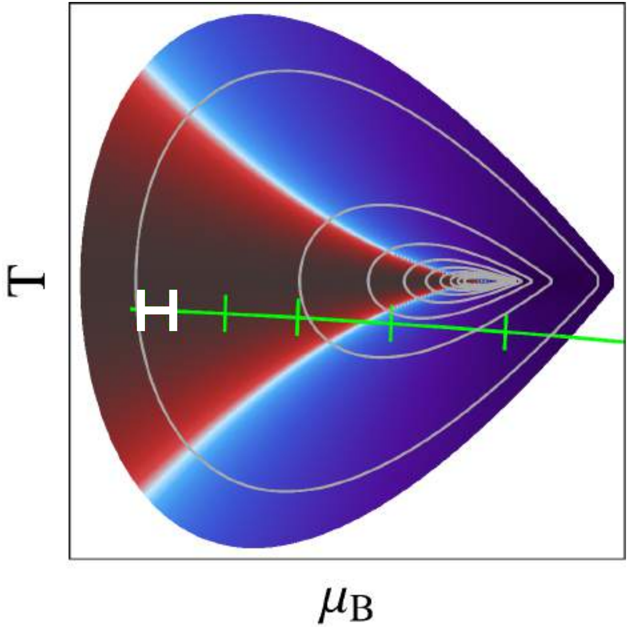




"mini-scan" in y can be used to give additional signatures of a CP

There are several different ways to look at the rapidity dependence

Total rapidity acceptance



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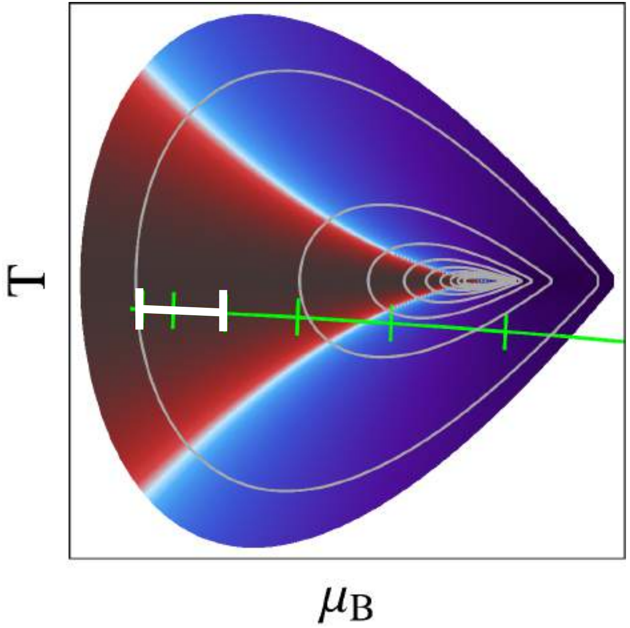

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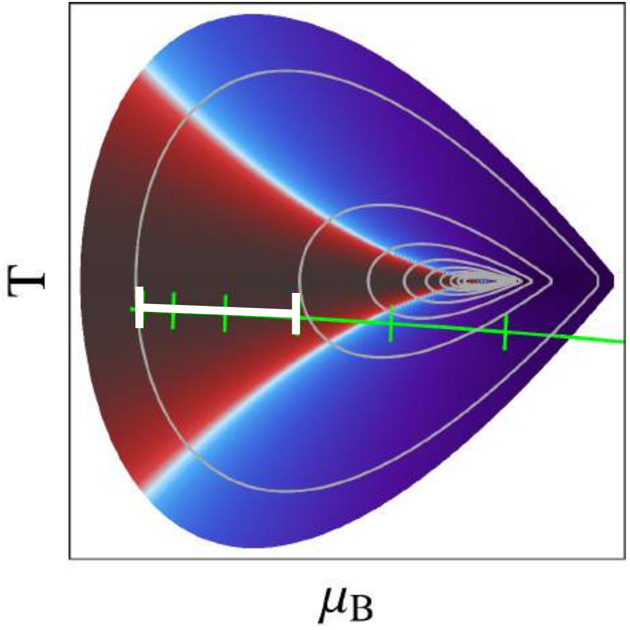

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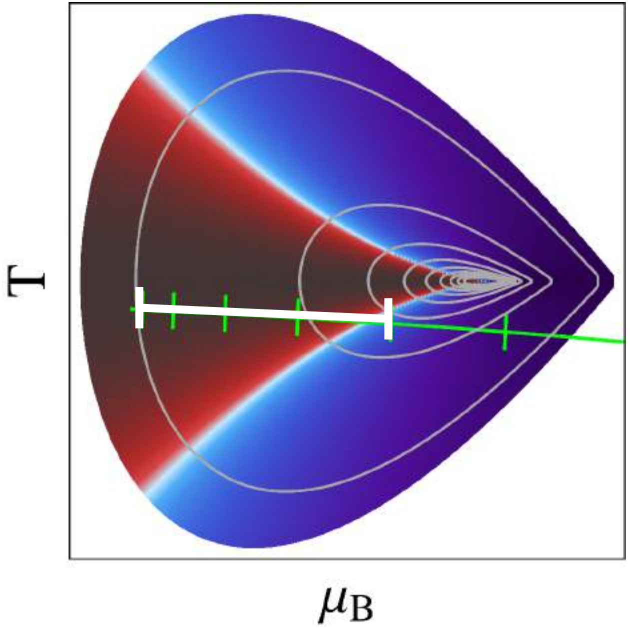

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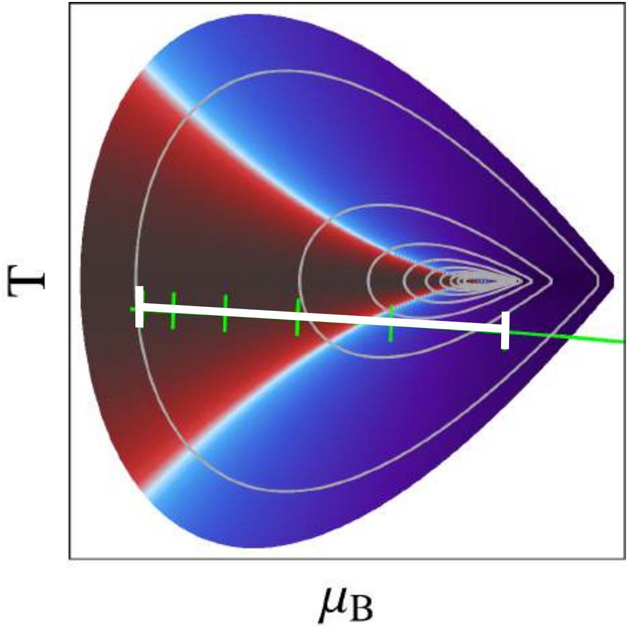

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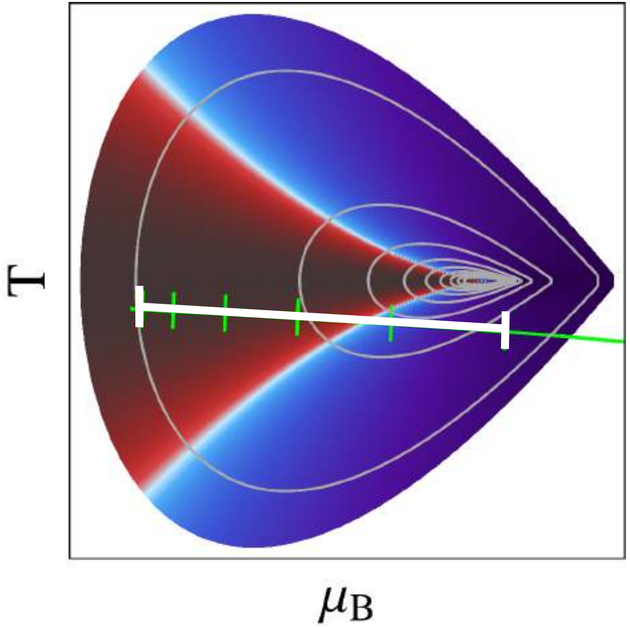
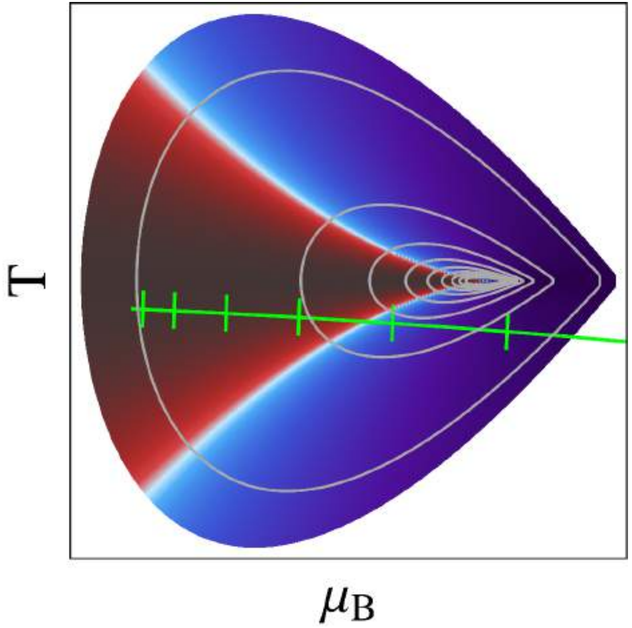


Binning in rapidity



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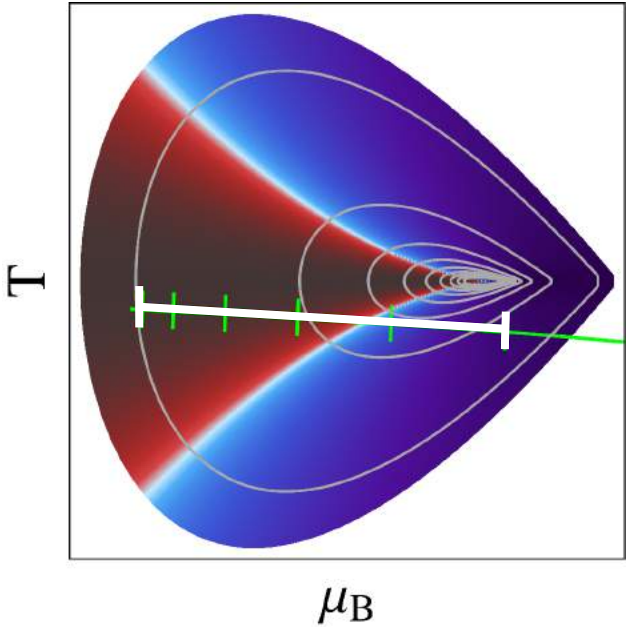
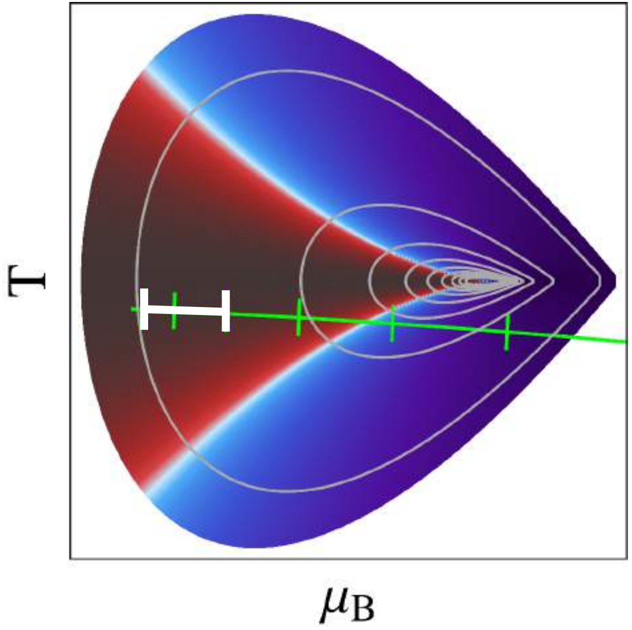
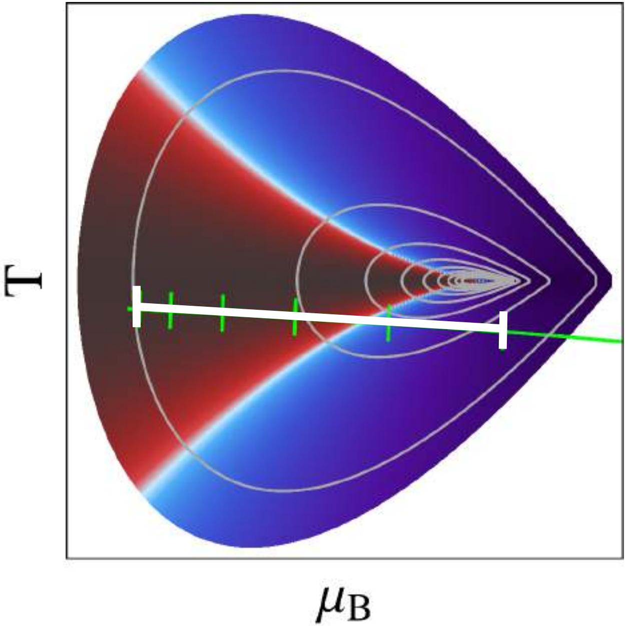


Binning in rapidity

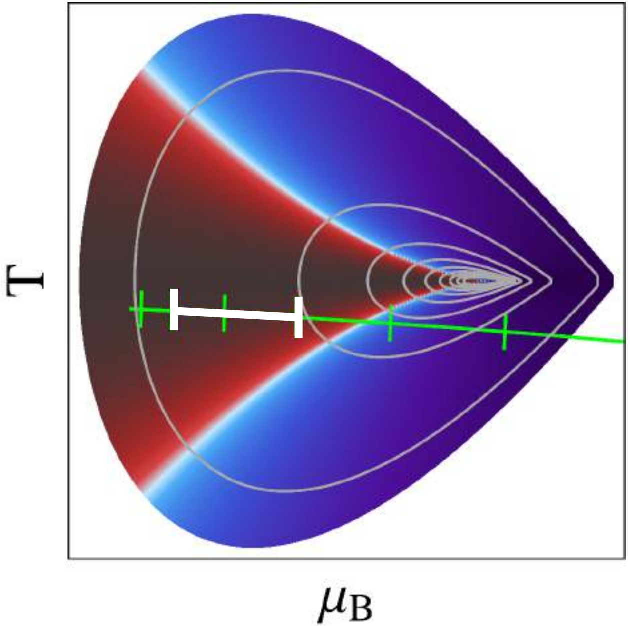


There are several different ways to look at the rapidity dependence

Total rapidity acceptance

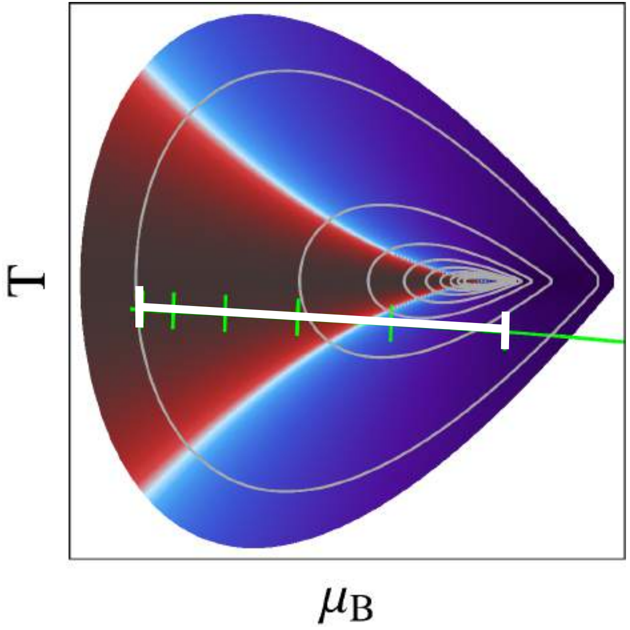


Binning in rapidity

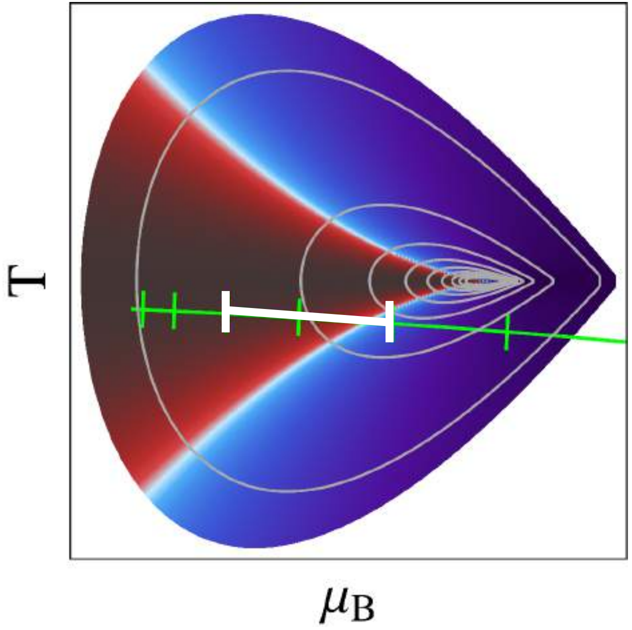


There are several different ways to look at the rapidity dependence

Total rapidity acceptance

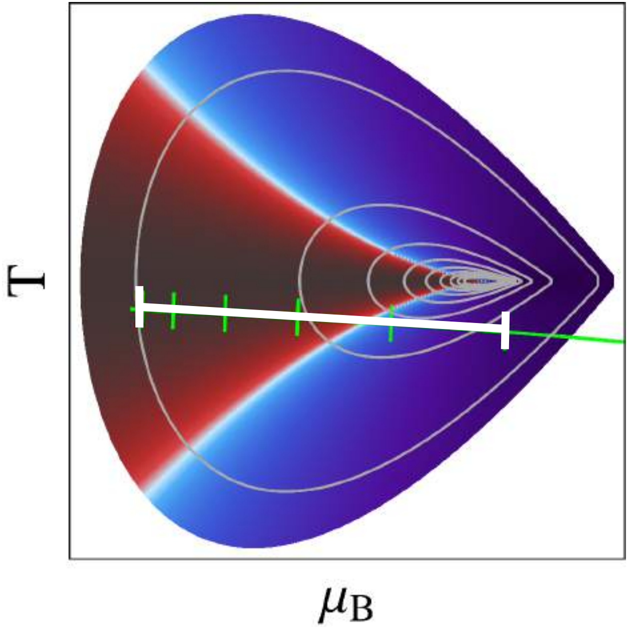


Binning in rapidity

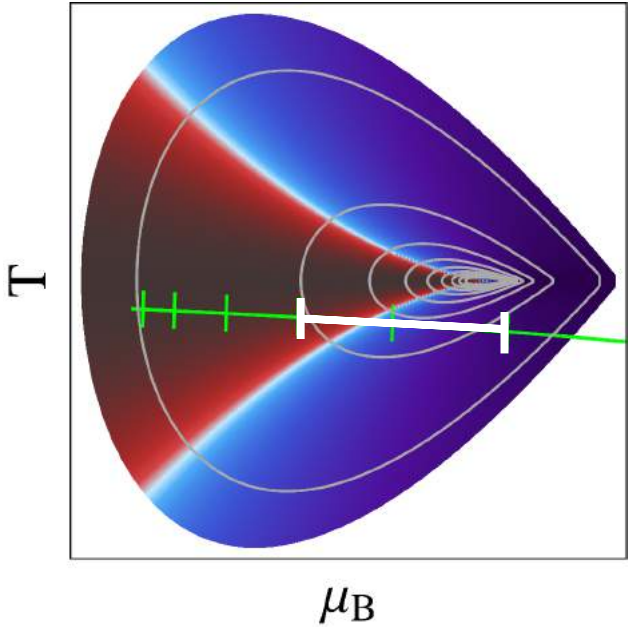


There are several different ways to look at the rapidity dependence

Total rapidity acceptance

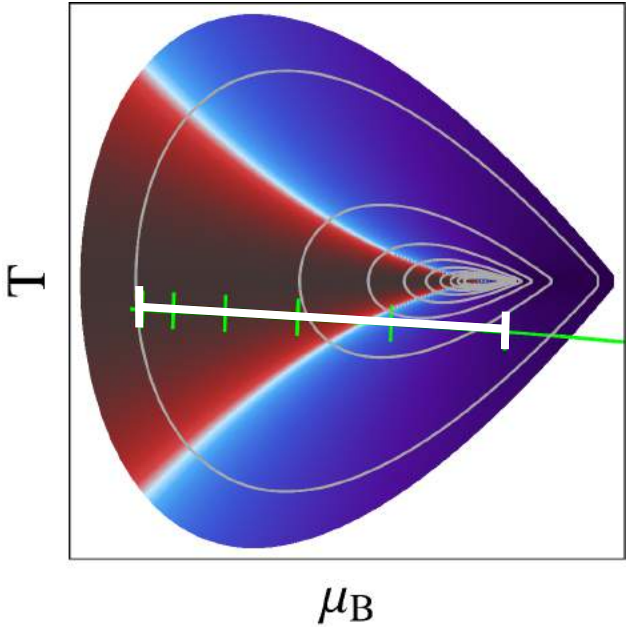


Binning in rapidity

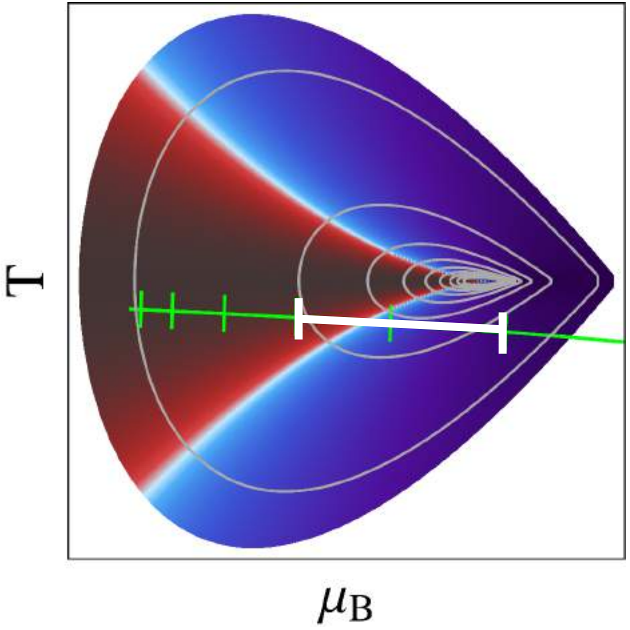


There are several different ways to look at the rapidity dependence

Total rapidity acceptance

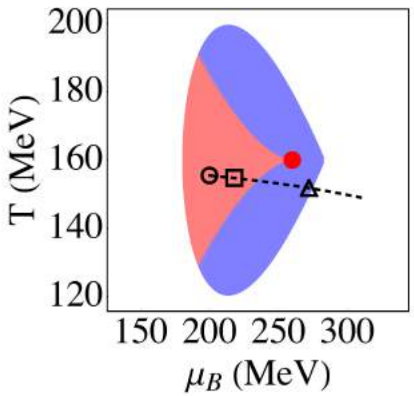


Binning in rapidity



More crisp picture of the critical region

Consider a hypothetical heavy ion collision which freezes out near a hypothetical critical point:



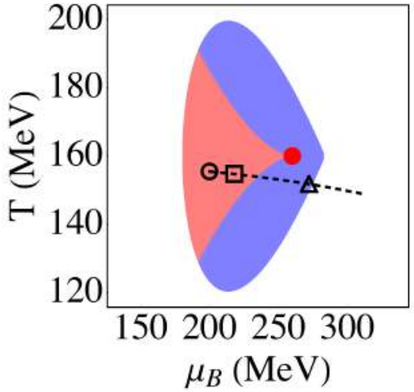
freezeout curve is extended in the critical regime due to

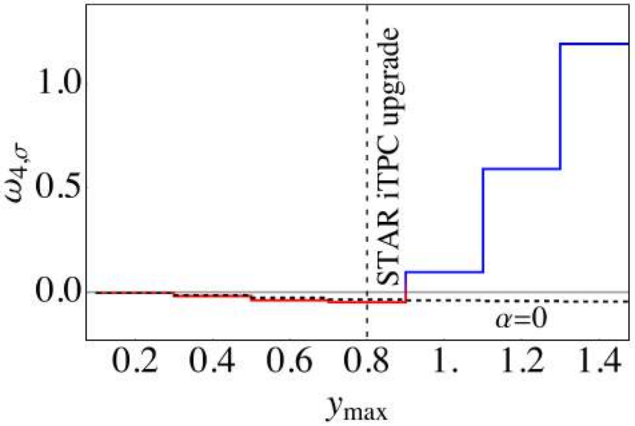
$$\mu_B = \mu_B(y_s) = \mu_{B,0} + \alpha\, y_s^2$$

○ □ △ $\rightarrow y_s = 0, 0.6, 1.2$

$\alpha = 50\ MeV$

Distinctive signatures of criticality arise in the dependence of the kurtosis on the total rapidity acceptance

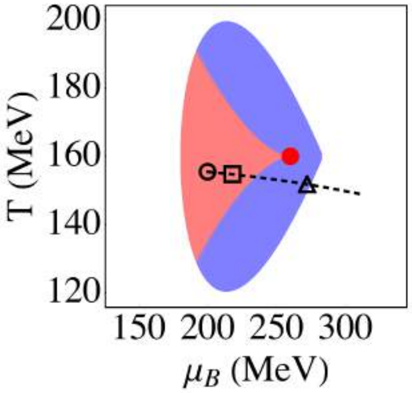


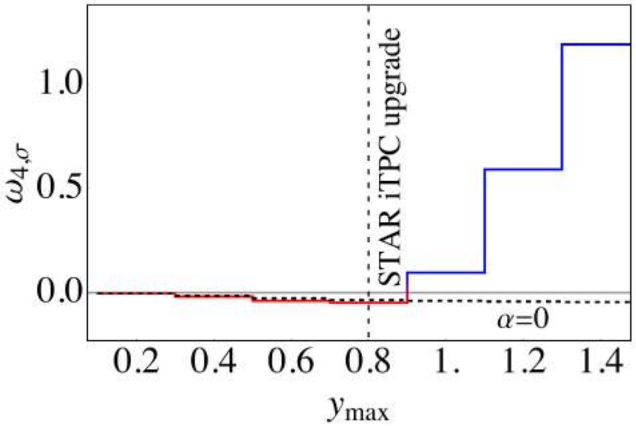


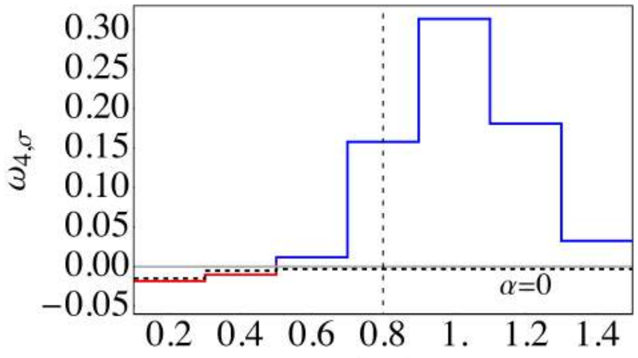
Including contributions from total rapidity acceptance $|y| < y_{max}$ averages over details of the critical regime

○ □ △ $\rightarrow y_s = 0, 0.6, 1.2$

Binning in rapidity gives a more sensitive probe of the critical region





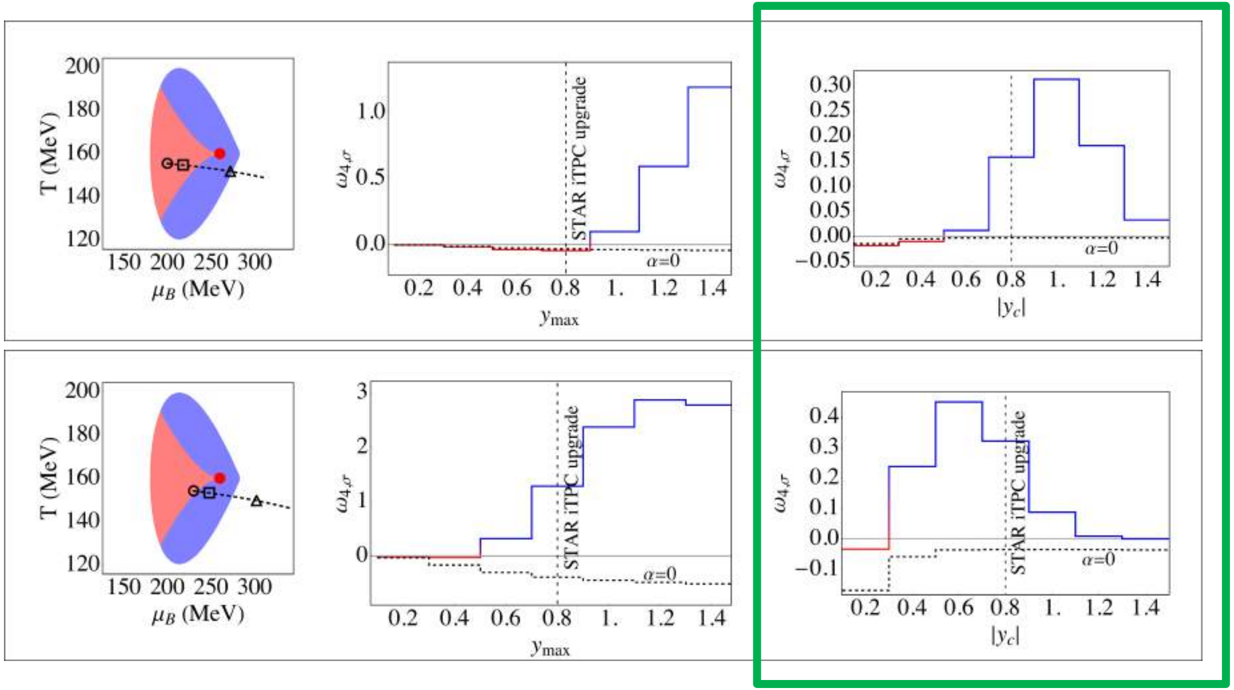


binning in y

Sign change at lower rapidity

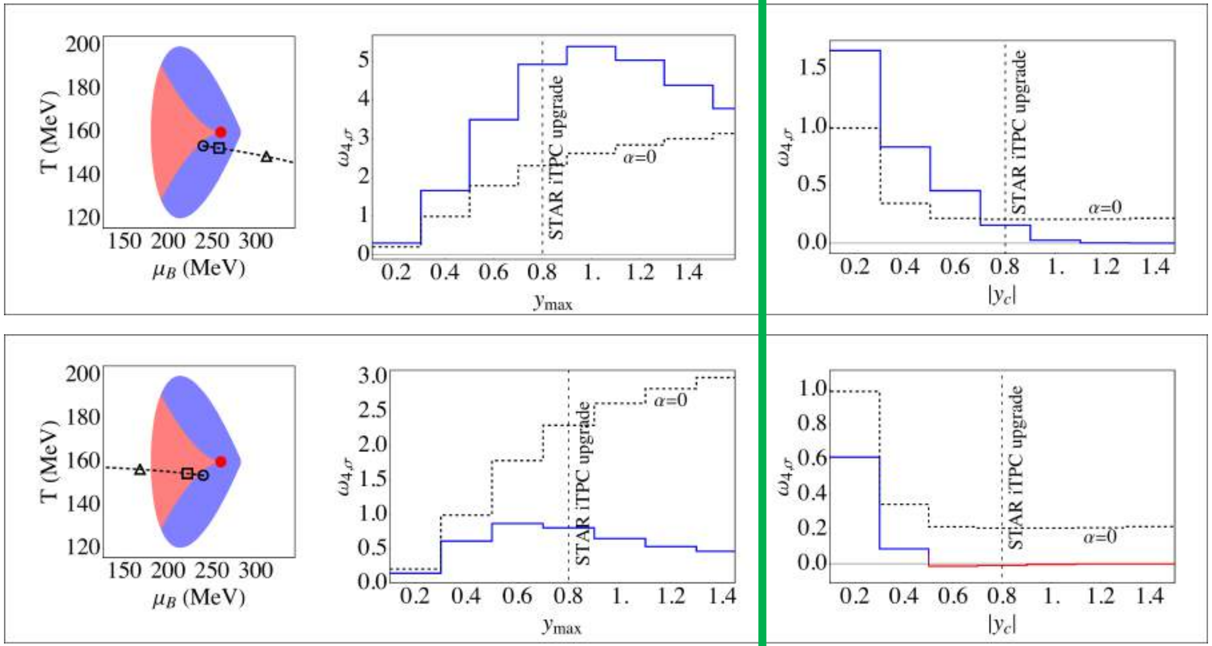
Critical signatures easier to detect at lower rapidity

Decreasing $\sqrt{s}$ to approach a critical point, binned cumulants increase with rapidity



Increasing with rapidity near mid-rapidity

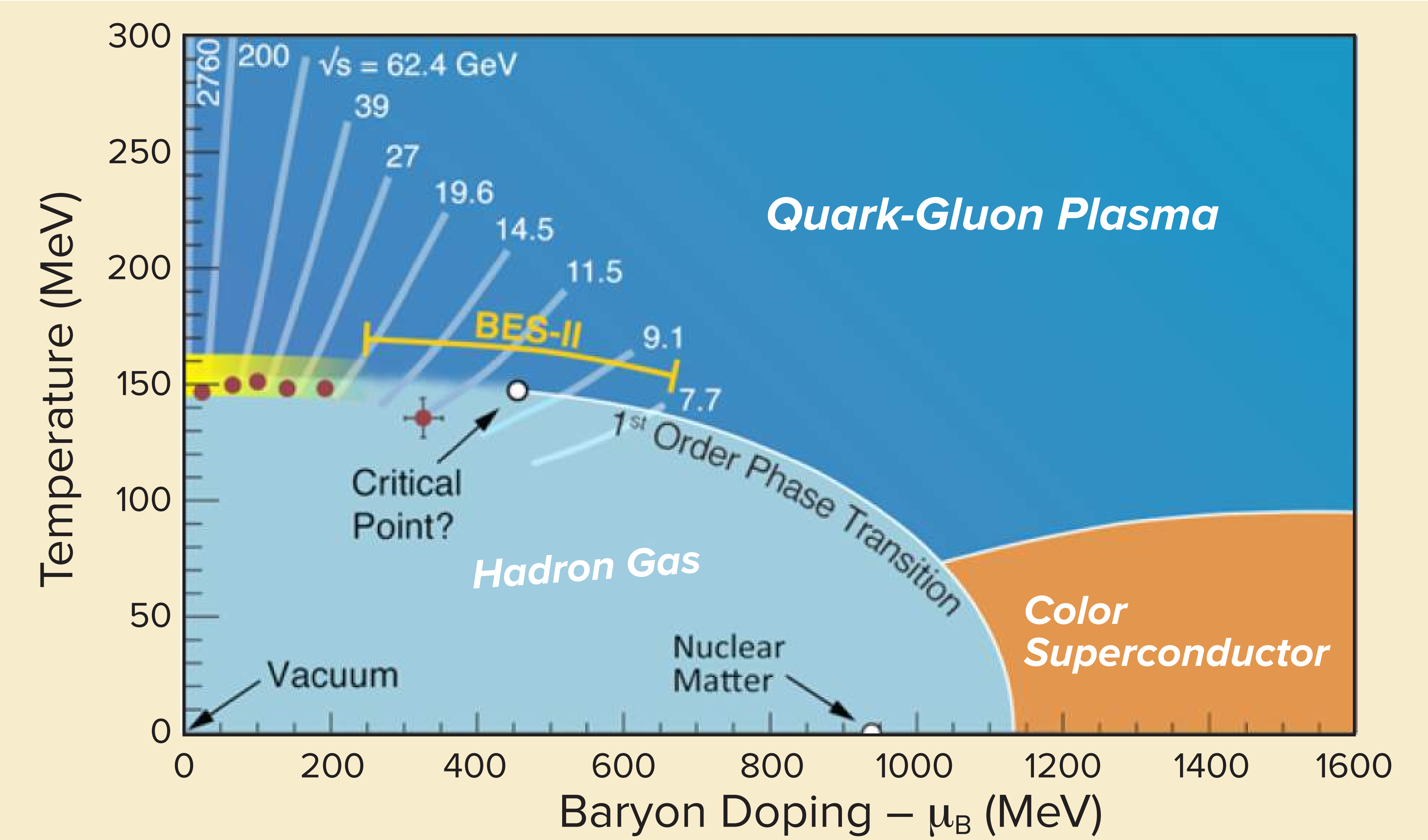
If a critical point is passed, binned cumulants switch to decreasing with rapidity



Decreasing with rapidity near mid-rapidity

Mapping the QCD Phase Diagram

- 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. Higher statistics data are needed. As is a substantial advance on the theory side...
- Once you have a validated hydro model at BES energies, then you can add critical fluctuations of the chiral order parameter. Need to source them, evolve them, and describe their consequences at freezeout. Need self-consistent treatment: fluctuations can't stay in eqbm because of finite-time limitation on growth of the correlation length, how do the fluctuations evolve? feedback on hydro? Only then can quantify the signatures of, a possible critical point. This is goal of BEST Collaboration.
- Theory needs to be ready in time for BES-II in 2019-21, 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 ... ?



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

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 anti-quarks, 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.

  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, $\ll 1/T_{\rm hydrodynamization}$.
- 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. $\rightarrow$ Long-term goal of studying jets in QGP.

Jets as Probes of QGP

- But jets sure don't make it easy. 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.

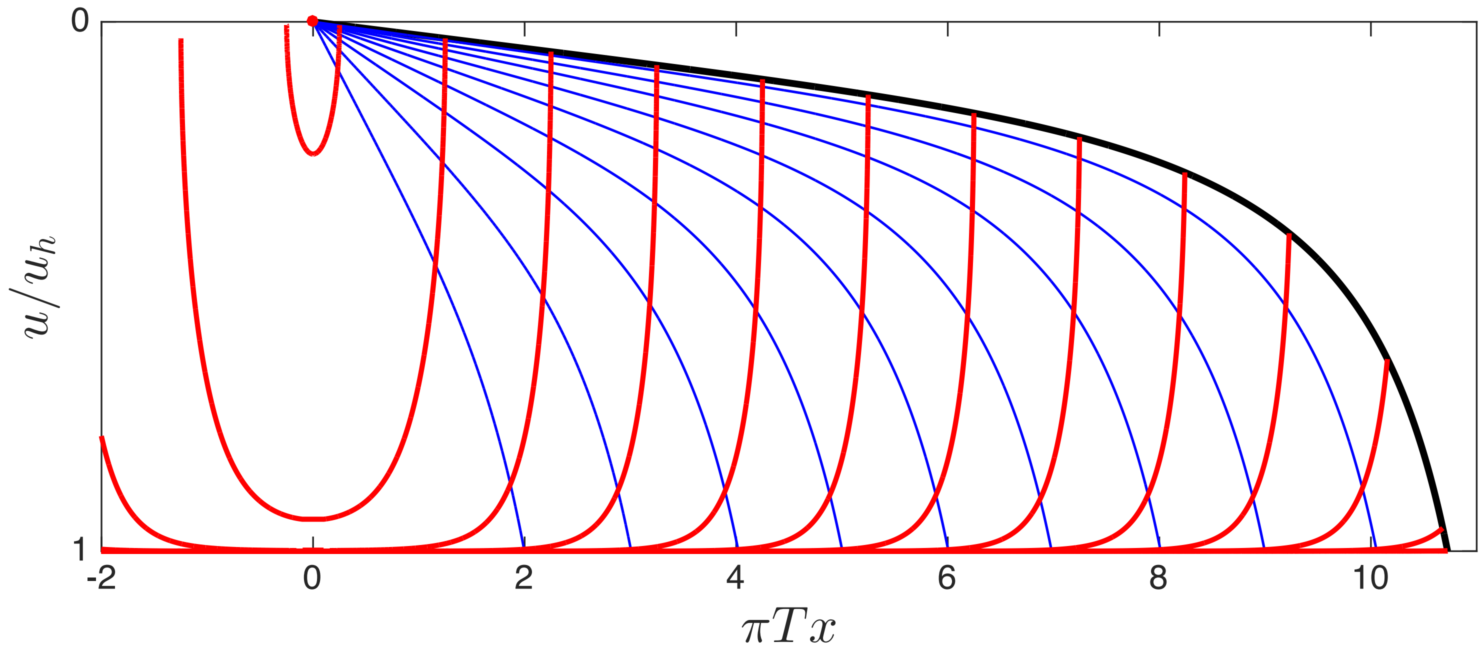
A Hybrid Approach

Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1405.3864,1508.00815, 1609.05842; Hulcher, DP, KR, 1707.05245; JCS, ZH, GM, DP, KR 1808.07386

- **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.**
- **More recently: adding momentum broadening and the wake in the plasma, adding resolution effects, looking at jet shapes, jet masses and related observables.**

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.

Implementation of Hybrid Model

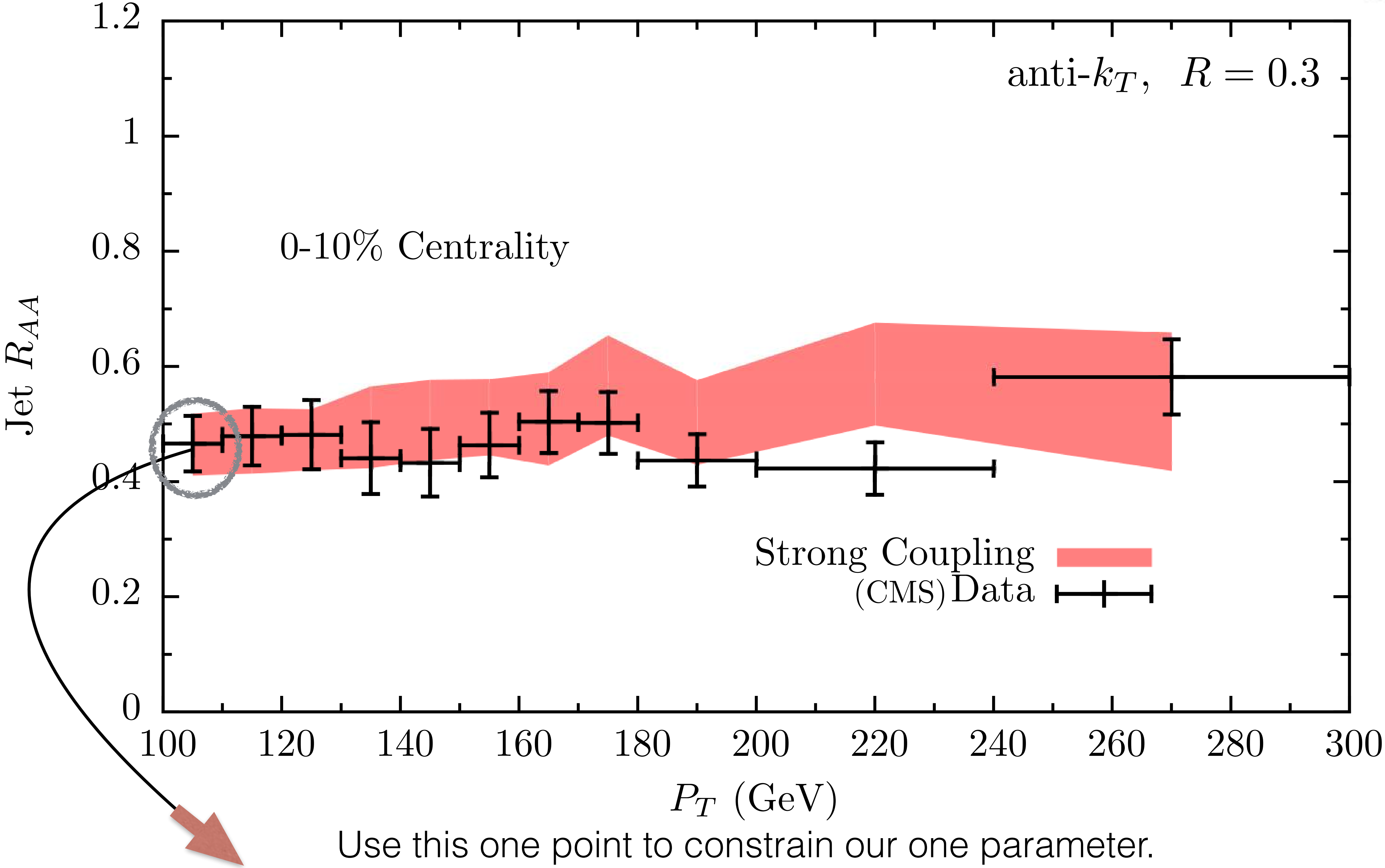
Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1405.3864,1508.00815

- **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**

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

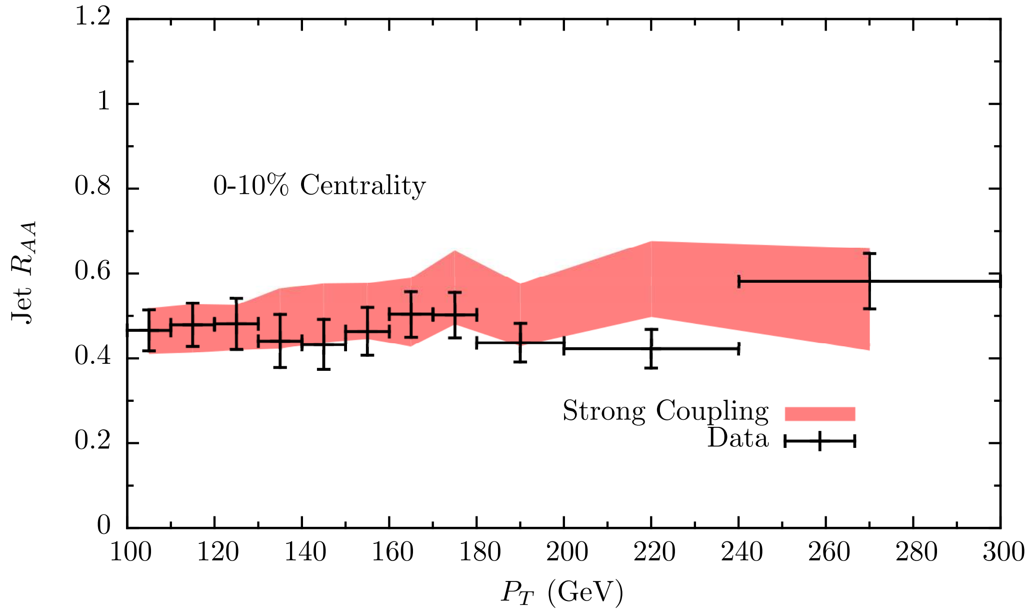
  where $x_{\rm therm} \equiv E_{\rm in}^{1/3}/(2\kappa_{\rm sc}T^{4/3})$ **with** $\kappa_{\rm sc}$ **one free parameter that to be fixed by fitting to one experimental data point. (**$\kappa_{\rm sc} \sim 1 - 1.5$ **in** $\mathcal{N} = 4$ **SYM; smaller** $\kappa_{\rm sc}$ **means** $x_{\rm therm}$ **is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

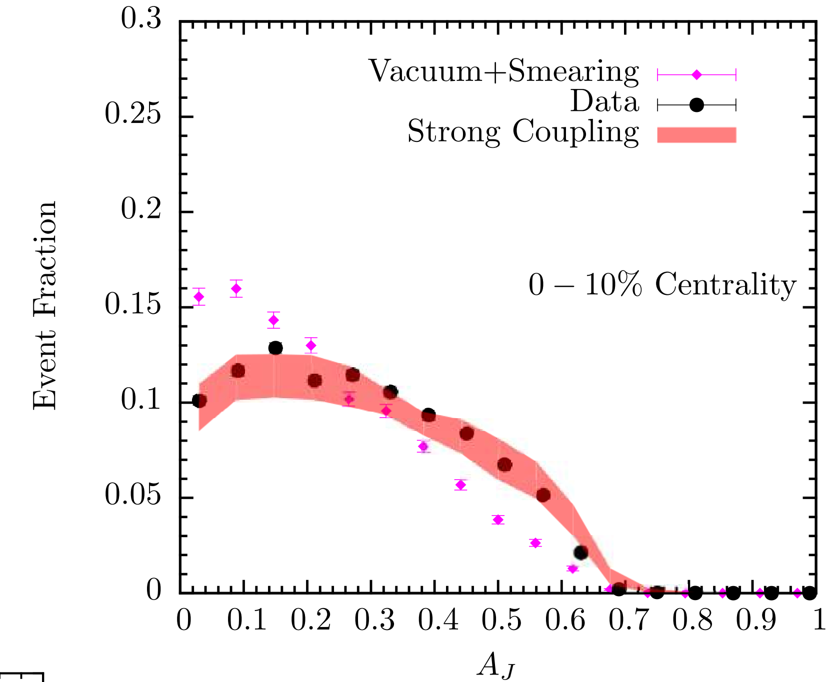
R_{AA}



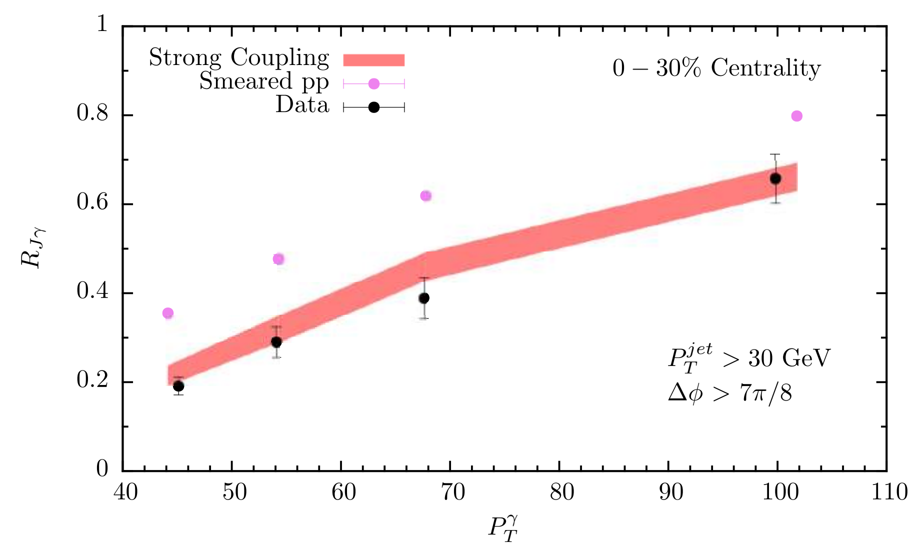
Use this one point to constrain our one parameter.

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





5 observables
and centrality dependence
all described with
single parameter

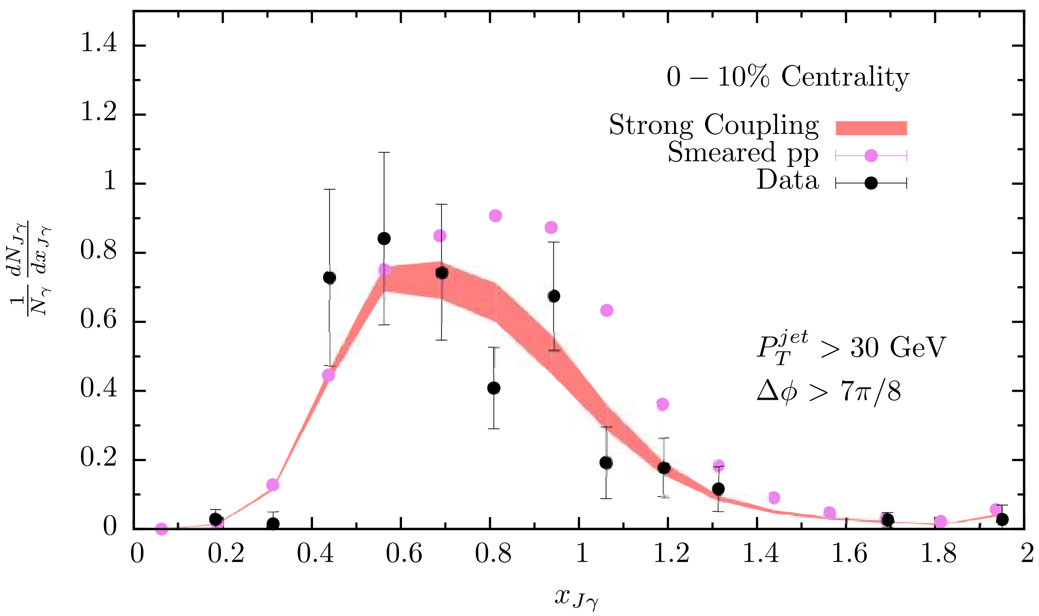


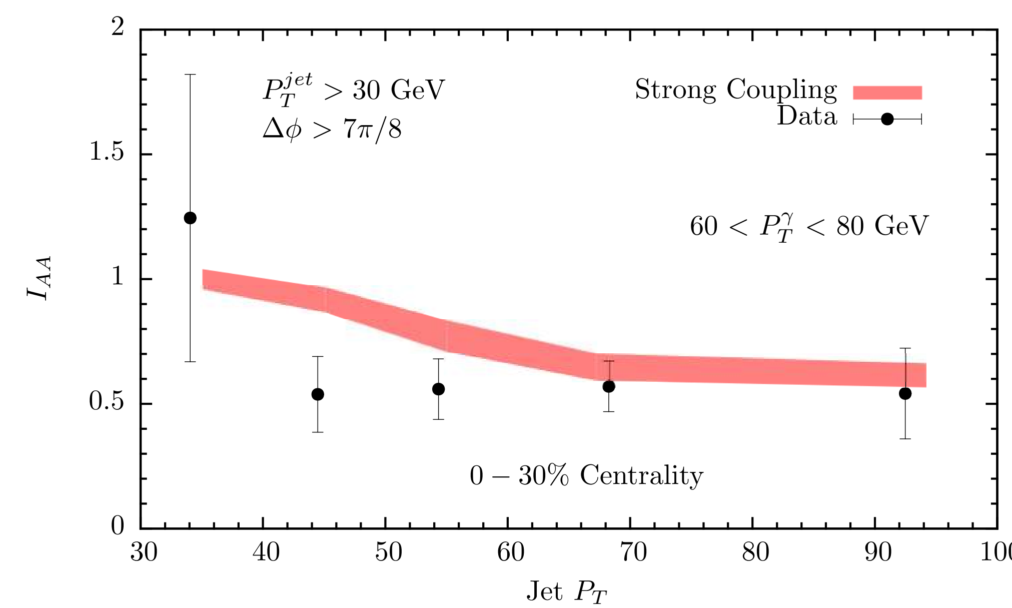
Bands in all plots correspond to

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

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

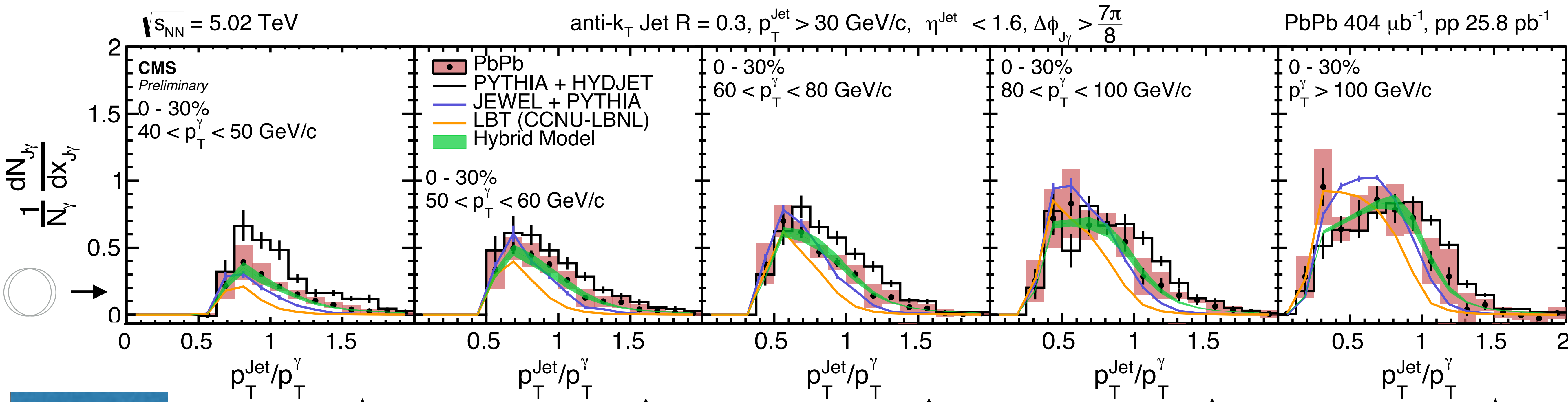
$$x_{stop}^{QCD} \sim (3-4)\, x_{stop}^{\mathcal{N}=4}$$





Predictions

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

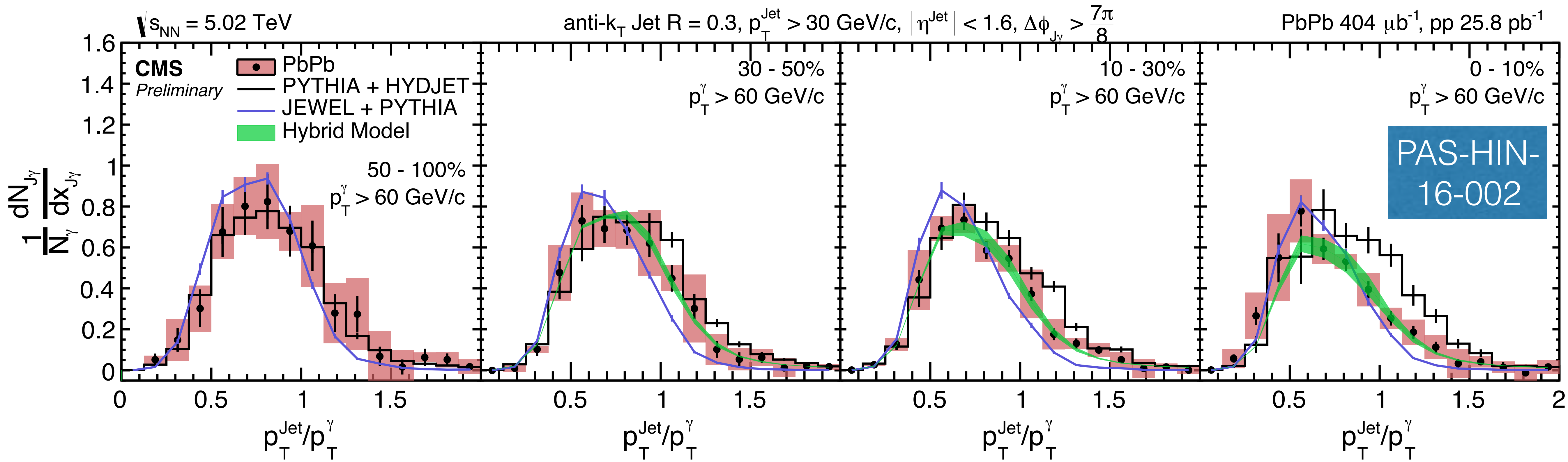


PAS-HIN-16-002

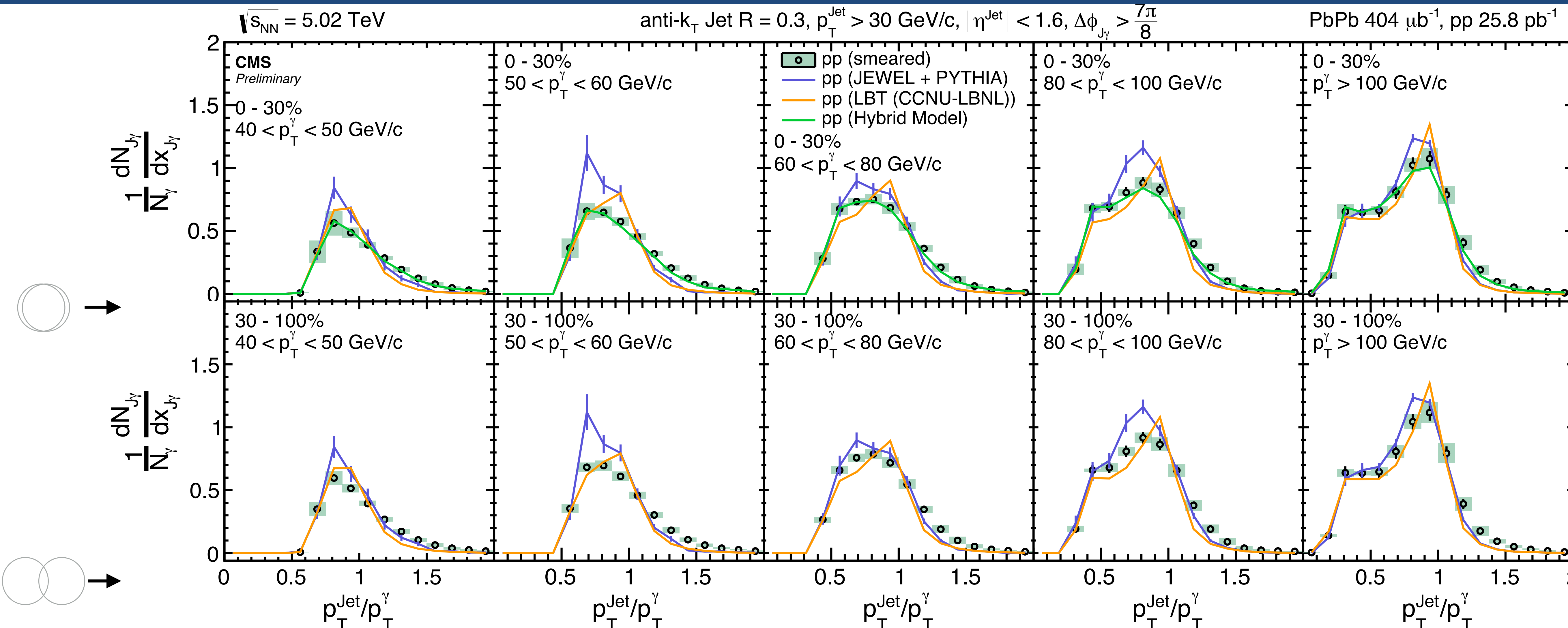
40 < p_T^γ < 50 | 50 < p_T^γ < 60 | 60 < p_T^γ < 80 | 80 < p_T^γ < 100 | p_T^γ > 100

- 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

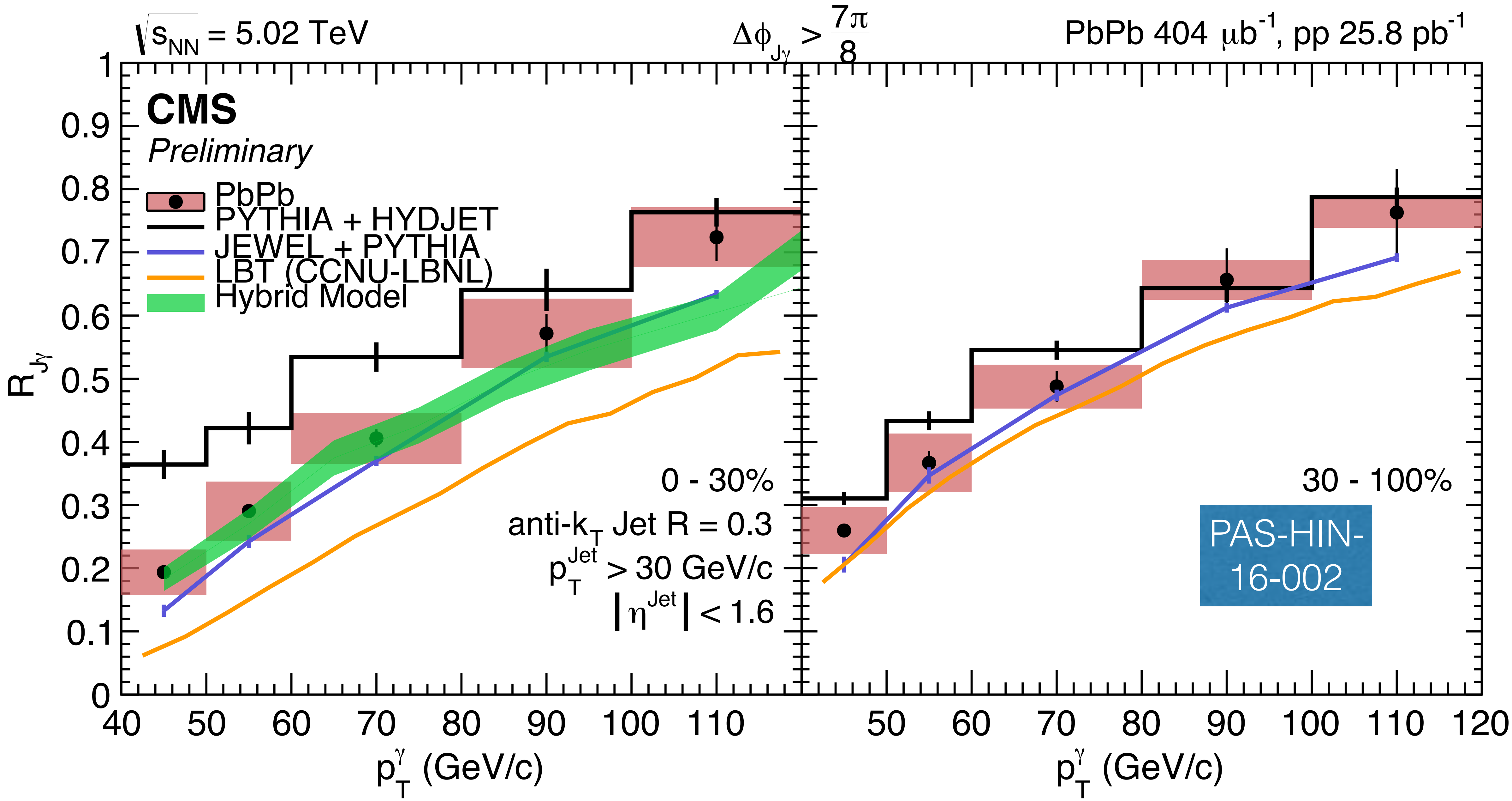


PAS-HIN-16-002

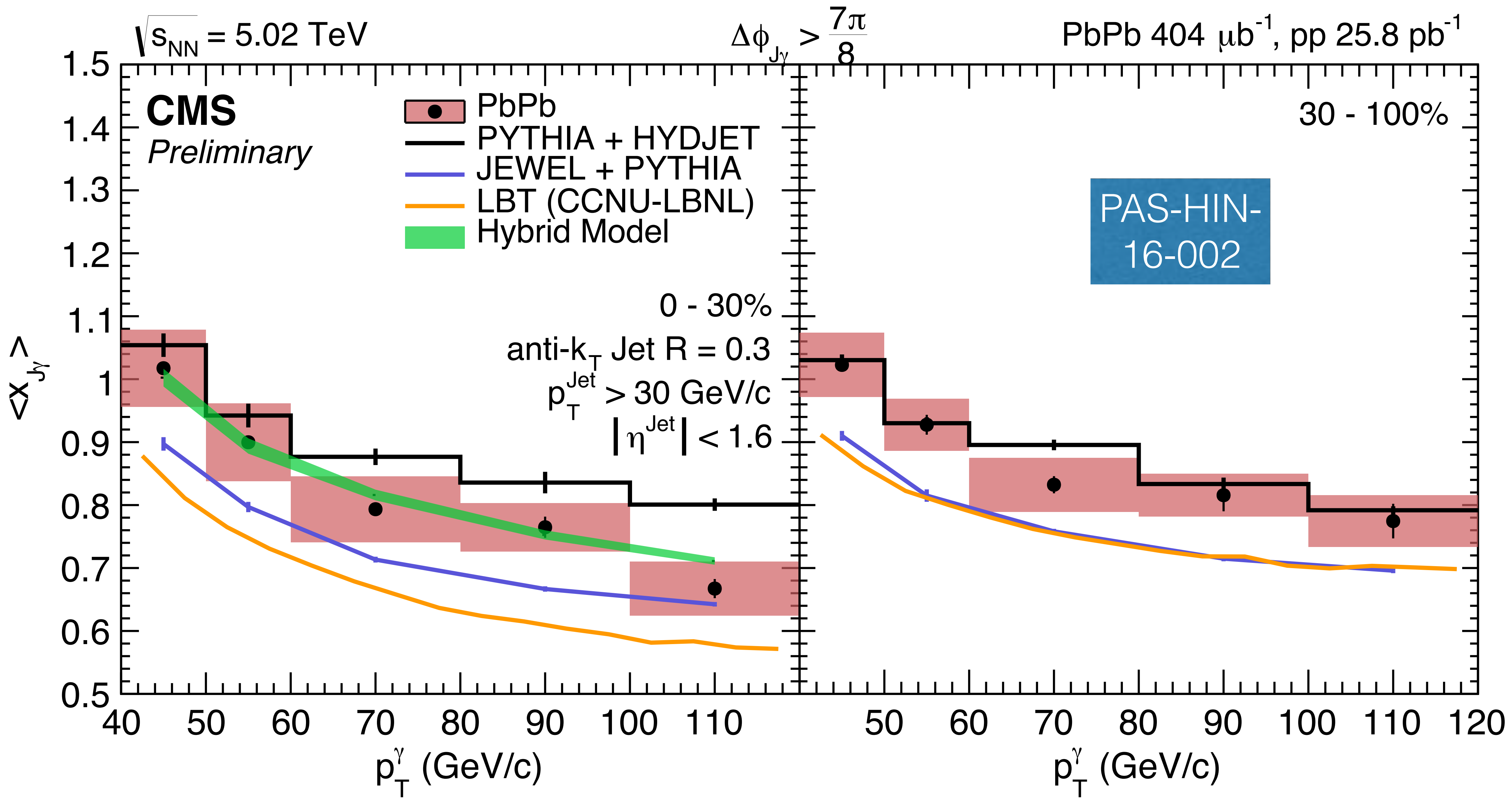
40 < p_T^γ < 50 **50 < p_T^γ < 60** **60 < p_T^γ < 80** **80 < p_T^γ < 100** **p_T^γ > 100**

- Overlaid PYTHIA, JEWEL, LBT and Hybrid Model

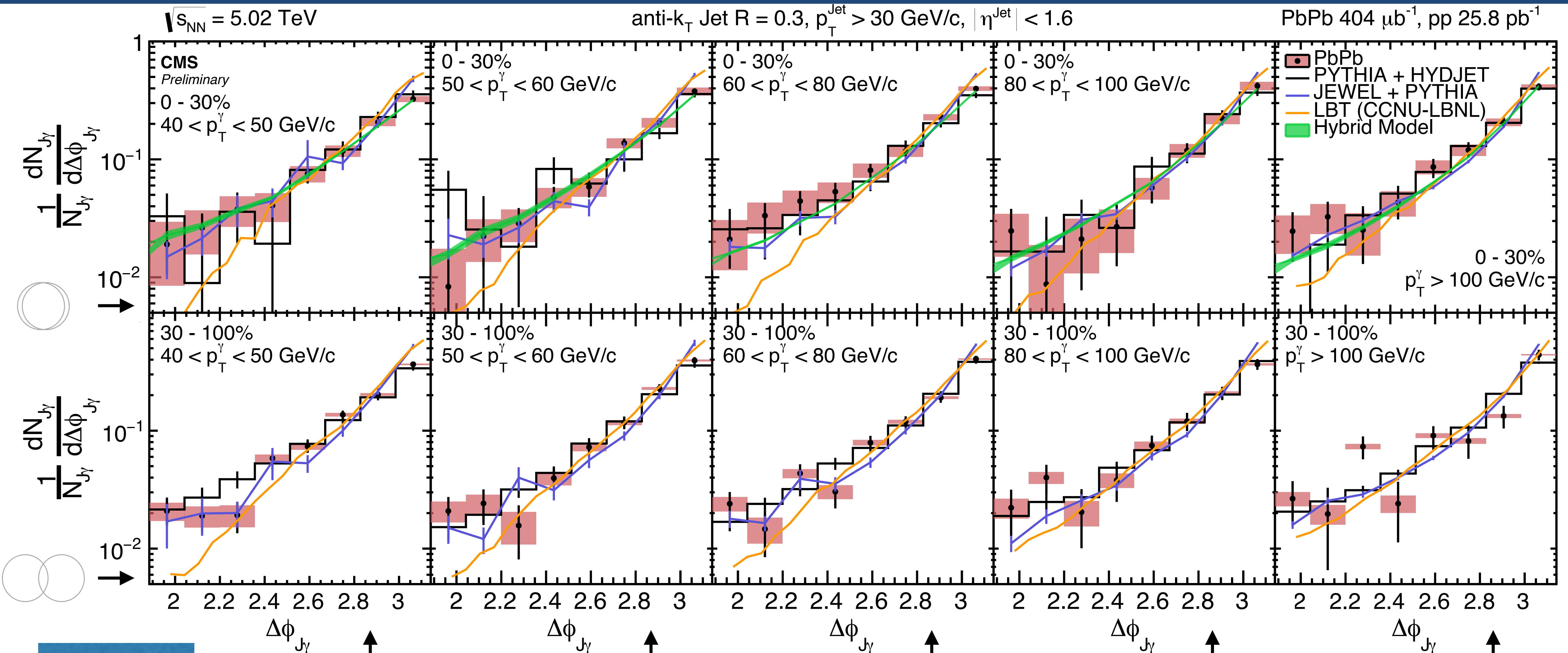
Theory Comparison: $R_{J\gamma}$ in PbPb



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



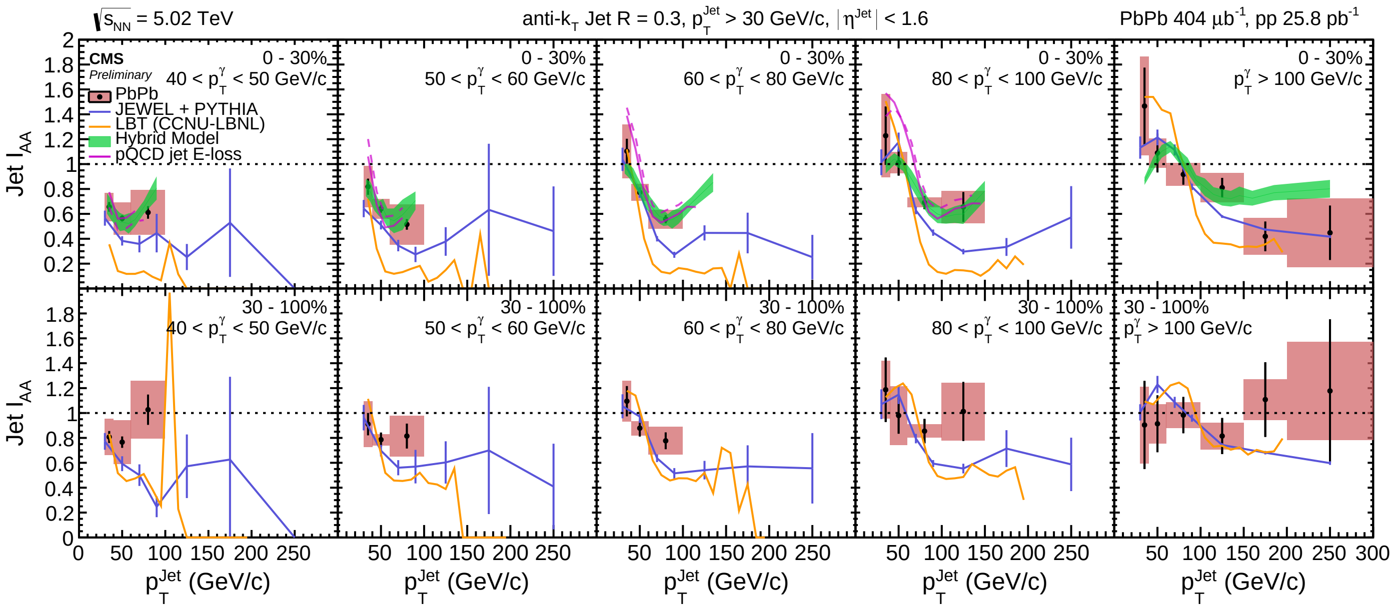
Theory Comparison: $\Delta\phi_{J\gamma}$ in PbPb



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



$\sqrt{s_{NN}}$ = 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%
30 - 100%
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
Jet I_{AA}
p_T^{Jet} (GeV/c)

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 $x_{\rm therm}^{\rm QCD} \sim (3-4)x_{\rm therm}^{\mathcal{N}=4}$ 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 $K_{\rm pert} \simeq 5$.
- 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?

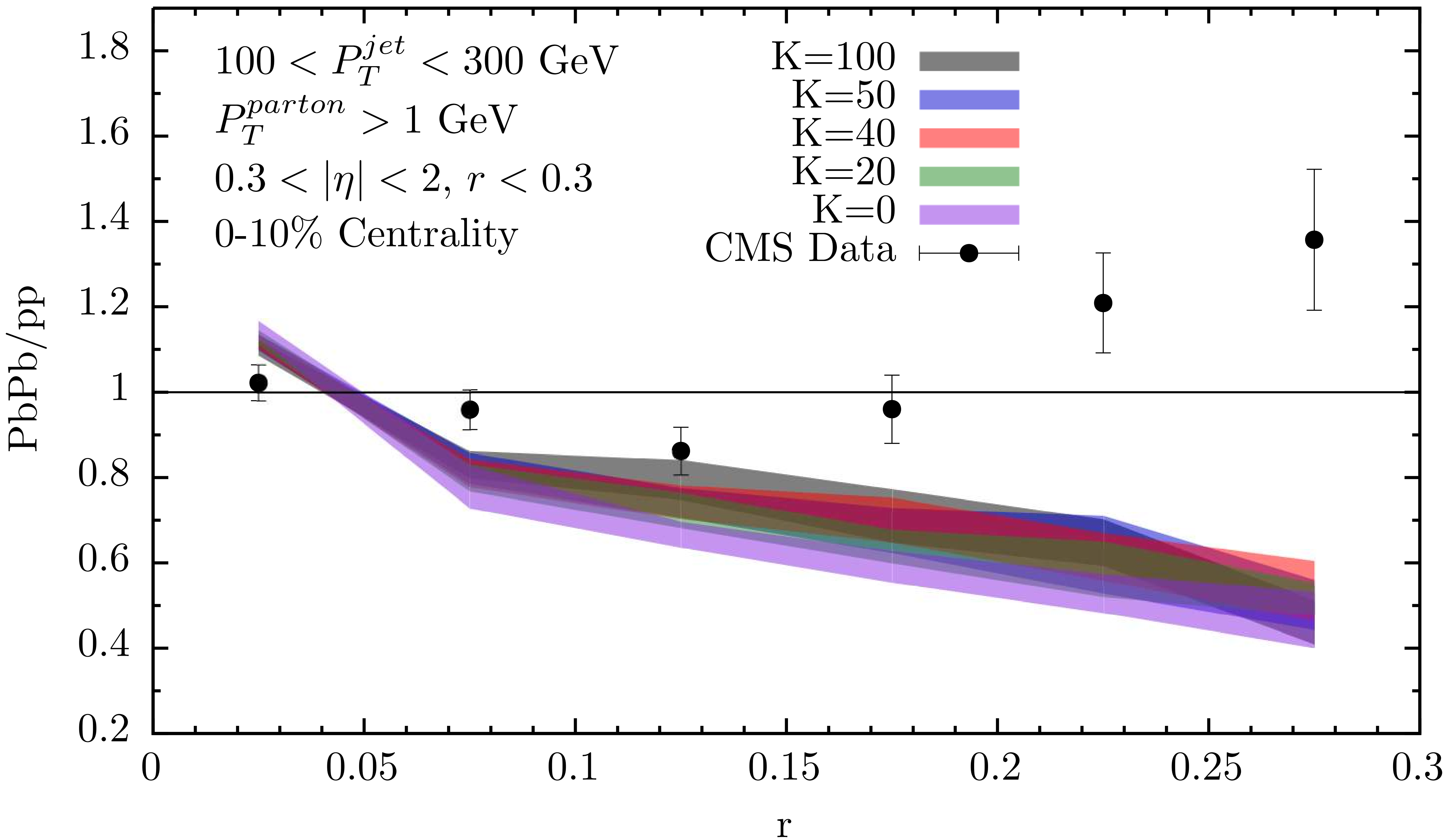
- There must be a Gaussian distribution of transverse momentum kicks received by partons in jets. If the QGP were strongly coupled on all length scales, that would be the whole story.
- To see the inner workings of QGP need to start by seeing a fatter tail on top of this Gaussian distribution, coming from jet partons scattering off weakly coupled quarks and gluons resolved at high momentum transfer, à la Rutherford.
- Lets start by looking at the jet shape, jet mass, and start by seeking to constrain K ...
- 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, as seen in data.**

Small sensitivity of standard jet shapes to broadening



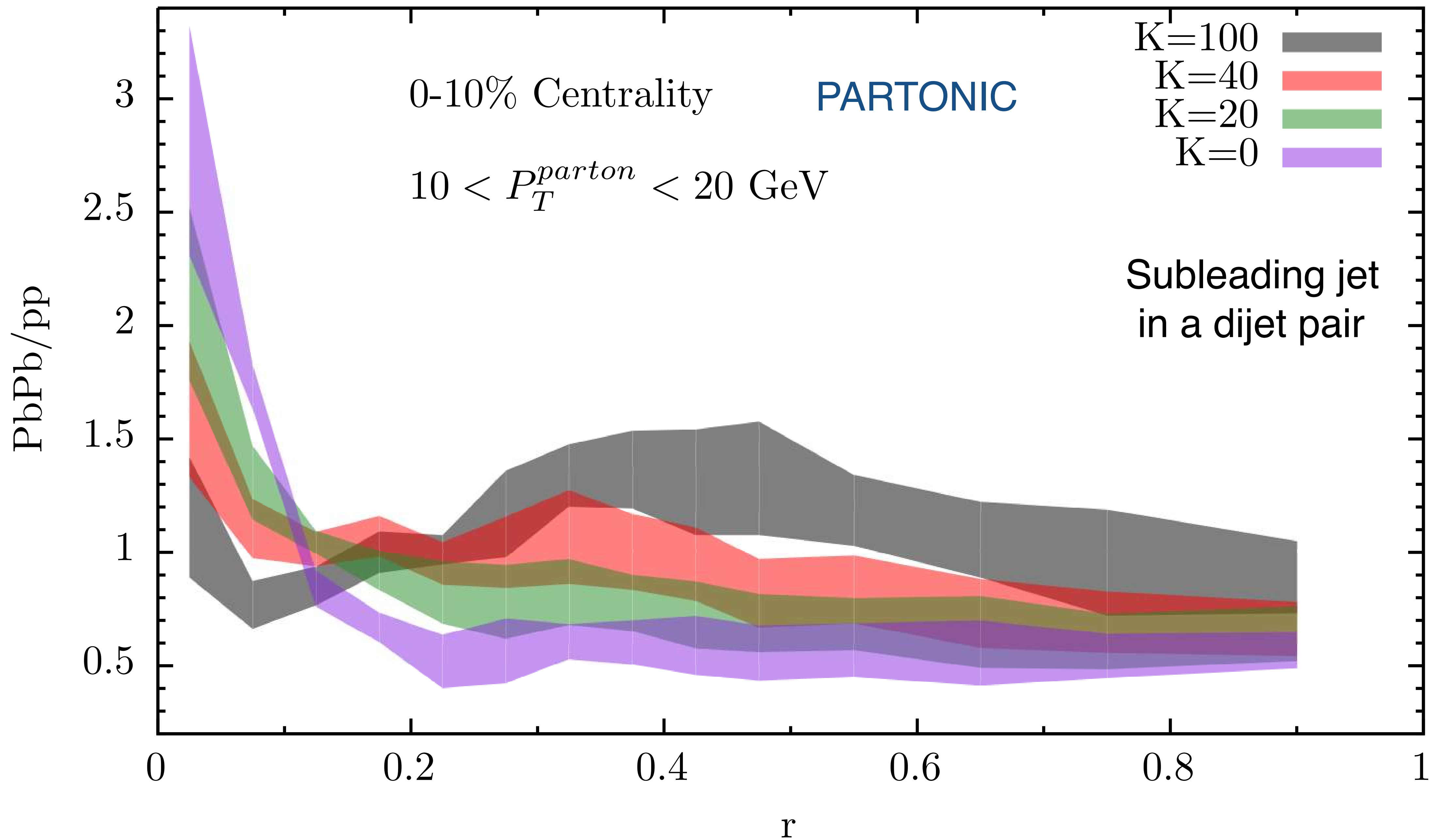
Small sensitivity of jet shapes to broadening:

- 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

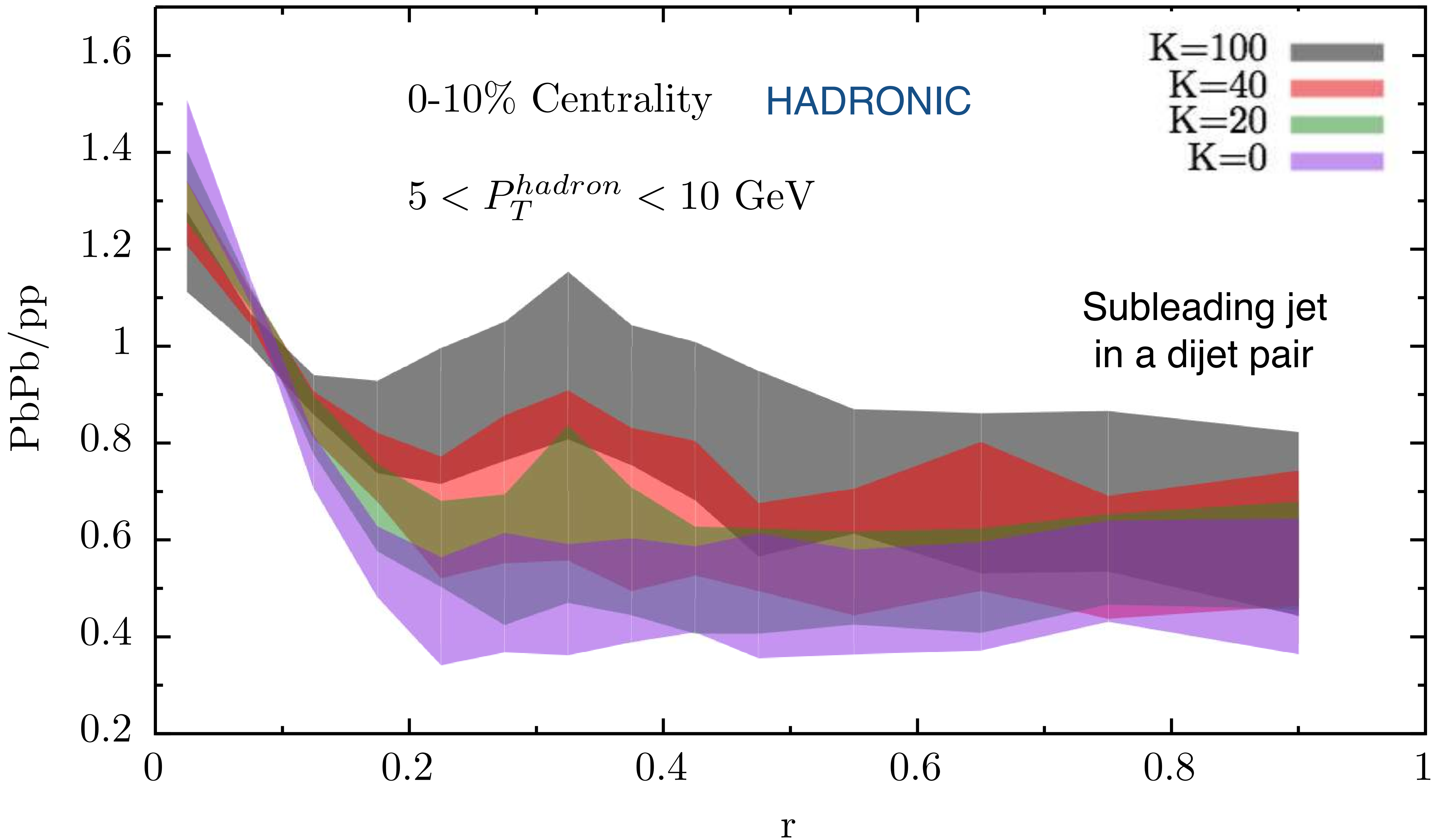


Kinematical cuts for partons chosen such that:

- 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

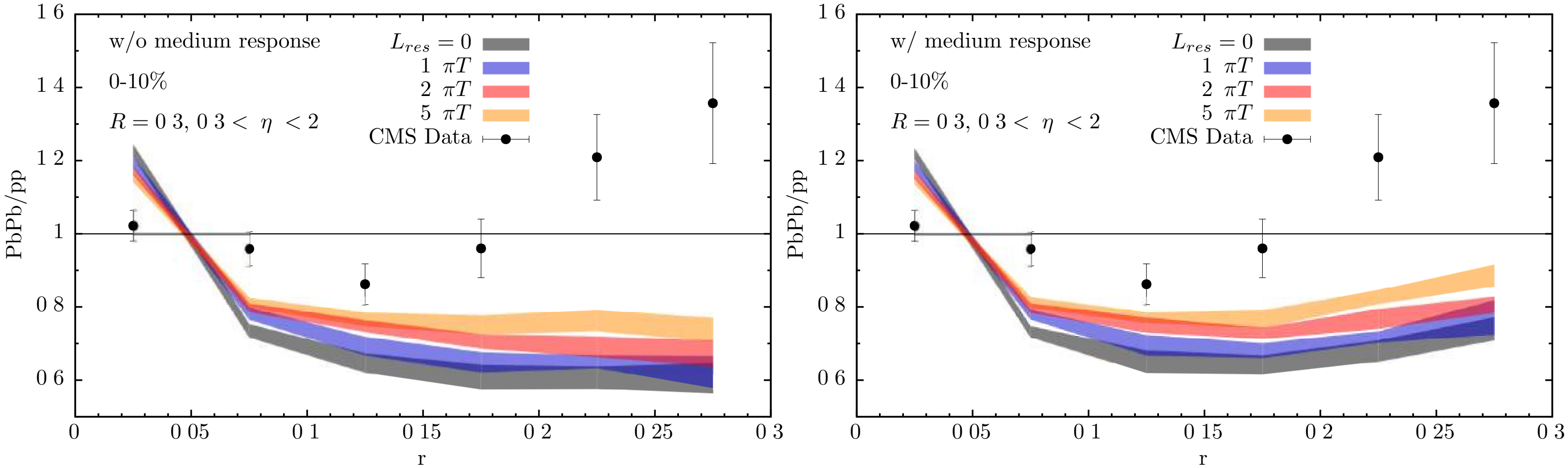
Direct experimental determination of Gaussian broadening strength

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.**

Jet Shape Ratio

CGMPR 1609.05842; Hulcher, Pablos, KR, 2017

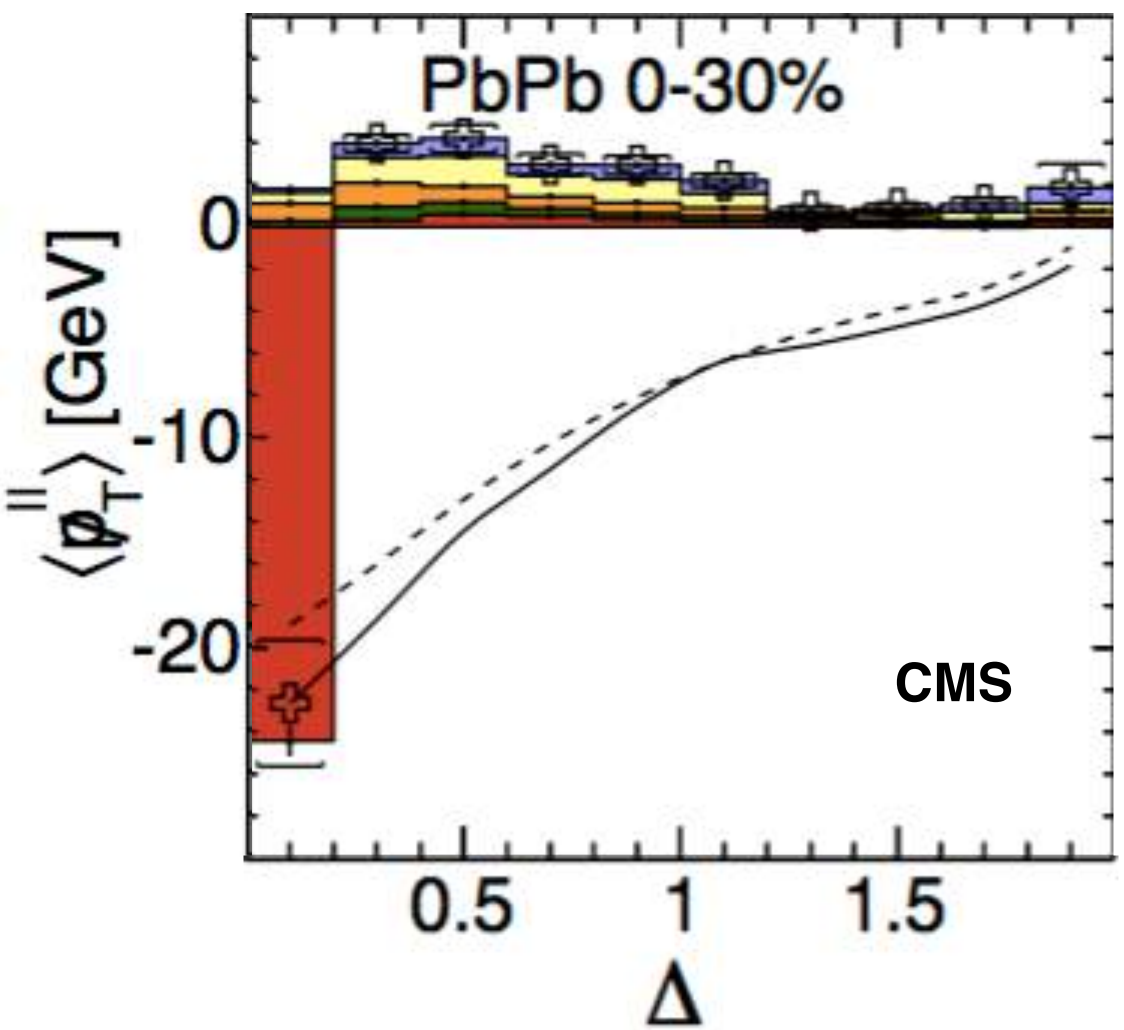


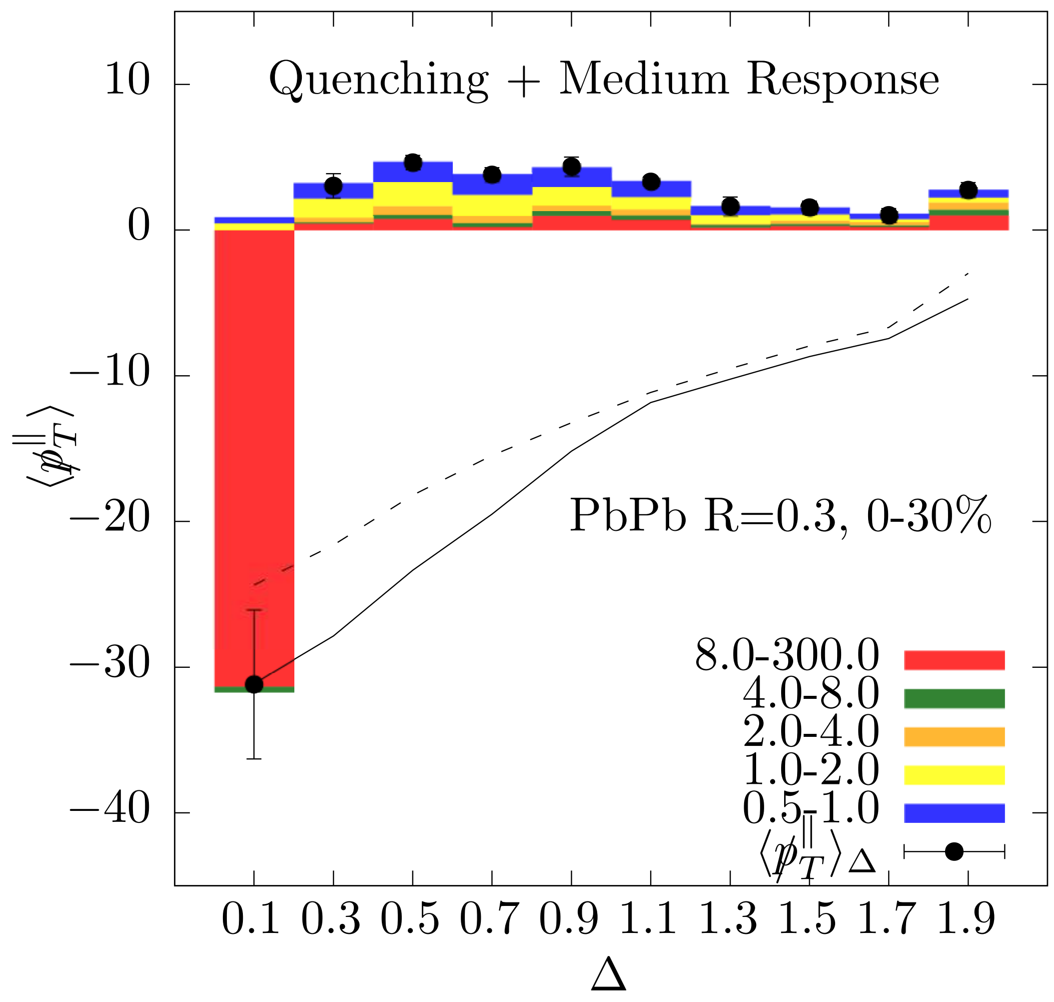
- **Introducing a resolution length of $L_{\rm res} = 1/(\pi T)$ or $L_{\rm res} = 2/(\pi T)$ pushes the jet shape ratio up at intermediate and large r.**
- **Introducing the soft particles from the wake in the plasma created by the jet pushes the jet shape ratio up at large r, but not as much as in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

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...

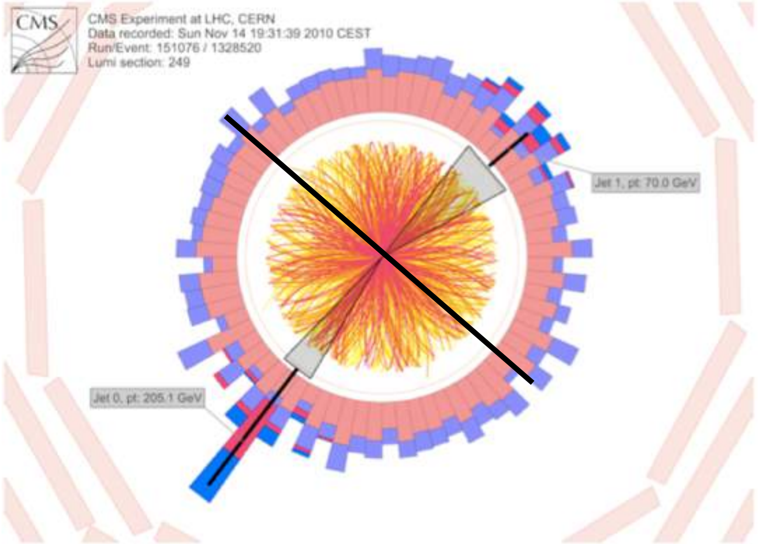
Recovering Lost Energy: Missing Pt



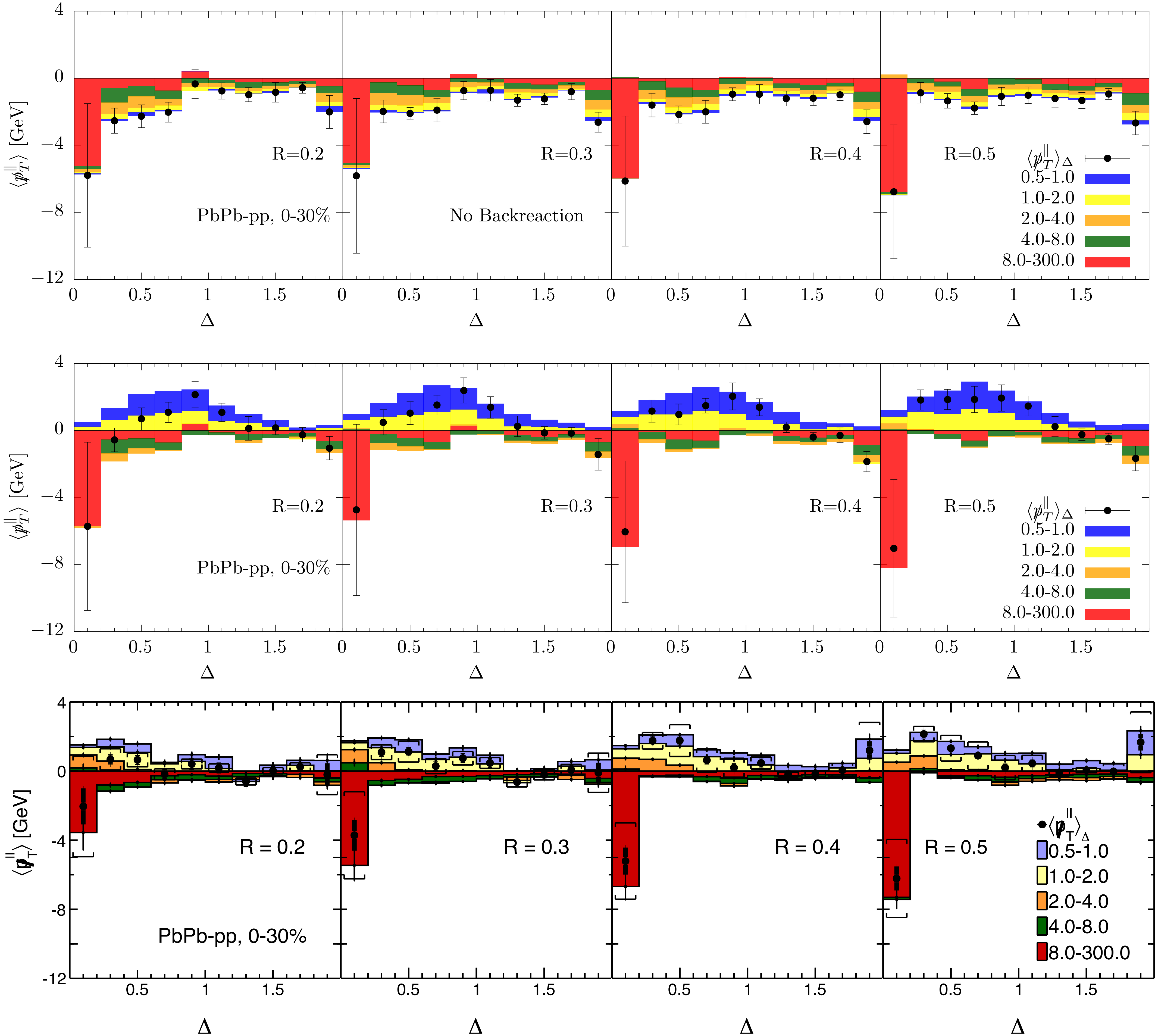


- Energy is recovered at large angles in the form of soft particles

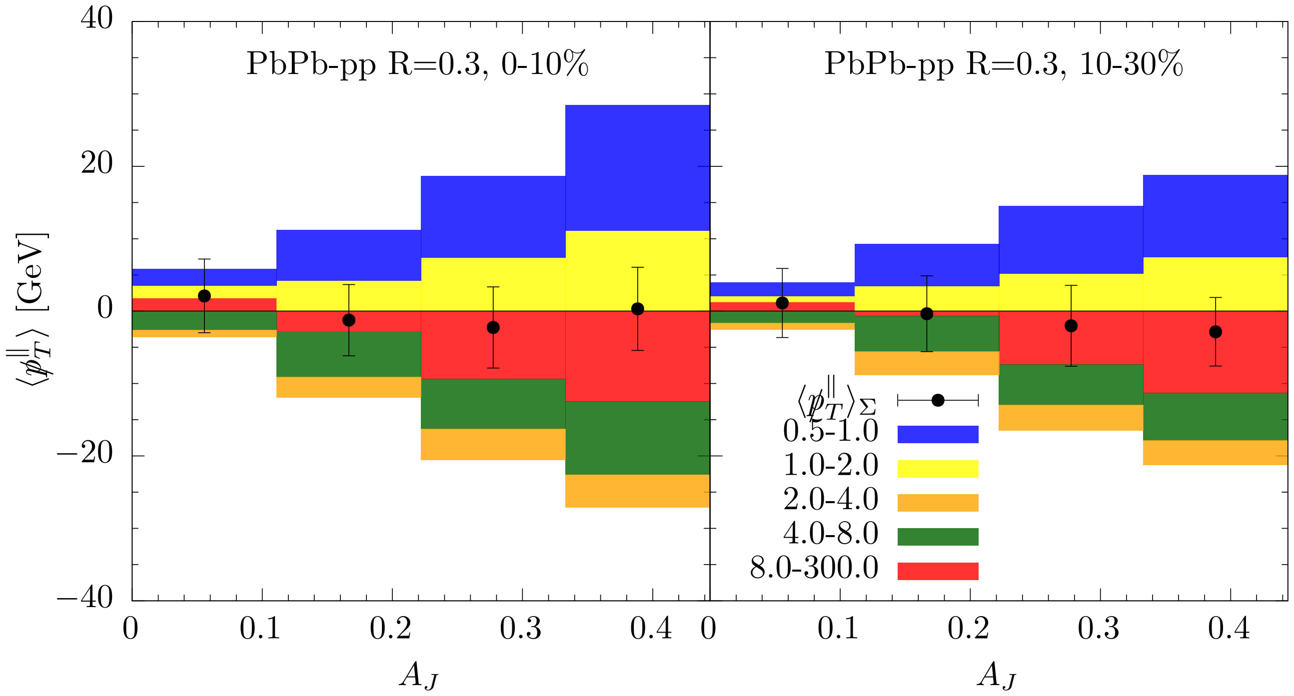
- Adding medium response is essential for a full understanding of jet quenching

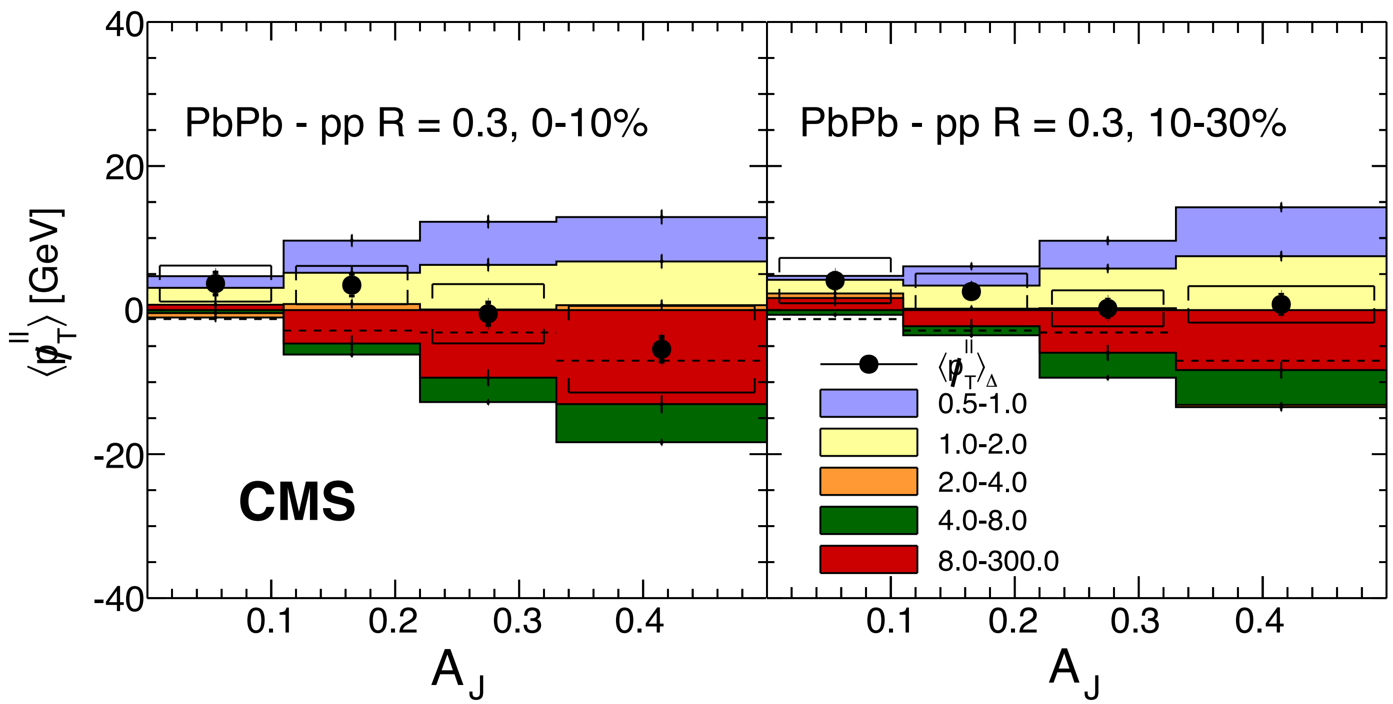


Jet radius dependence of Missing Pt



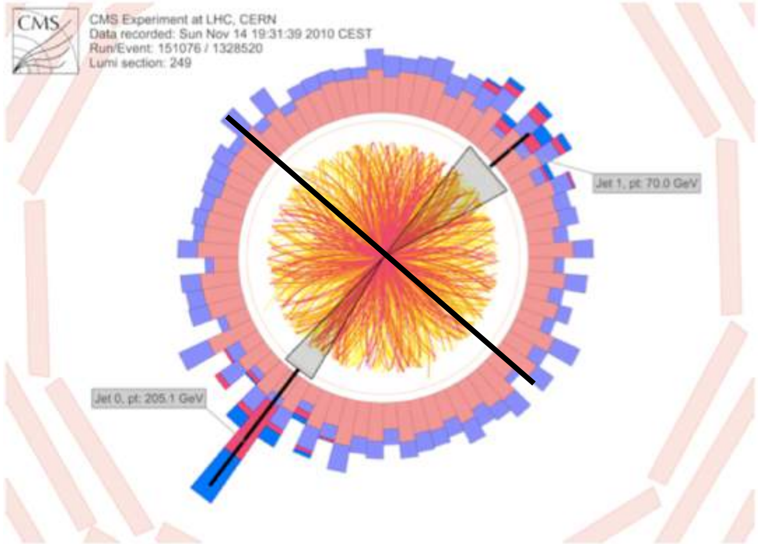
Recovering Lost Energy: Missing Pt





- 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.

Where are we going?

- 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?

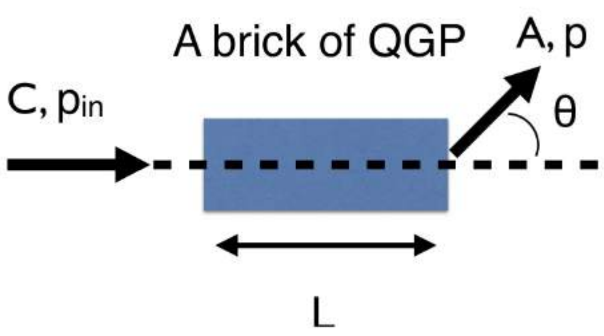
- **A long road ahead. Two confounding (but interesting) effects, both large, to be understood first. Only then, see the Gaussian distribution of transverse kicks and constrain K. And only then, see jet partons scattering off scatterers in the QGP.**
- **Goal for the 2020s: look for the rare (but only 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, 1808.03250

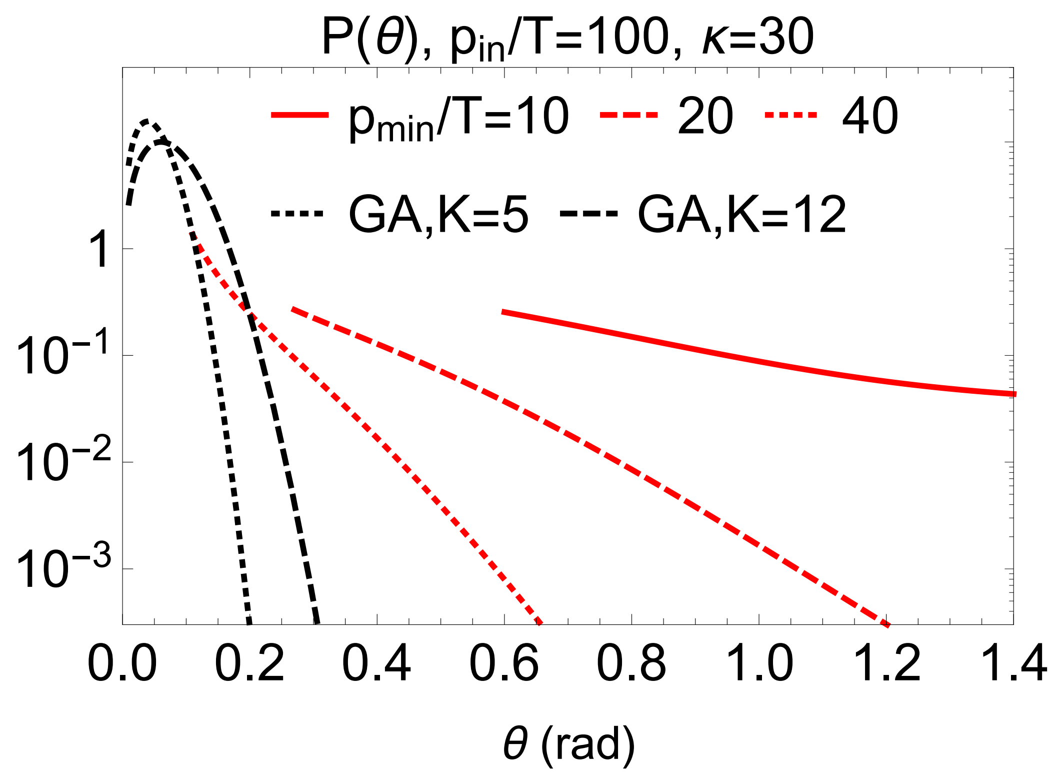
Where are we going?

- How improbable are such Molière scatterings?
- 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 have now remedied 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 Rutherford-channel. The parton that you detect at angle θ might be a parton from the medium.)
- 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.

Finding Scatterers in the Soup

D'Eramo, KR, Yin, 1808.03250

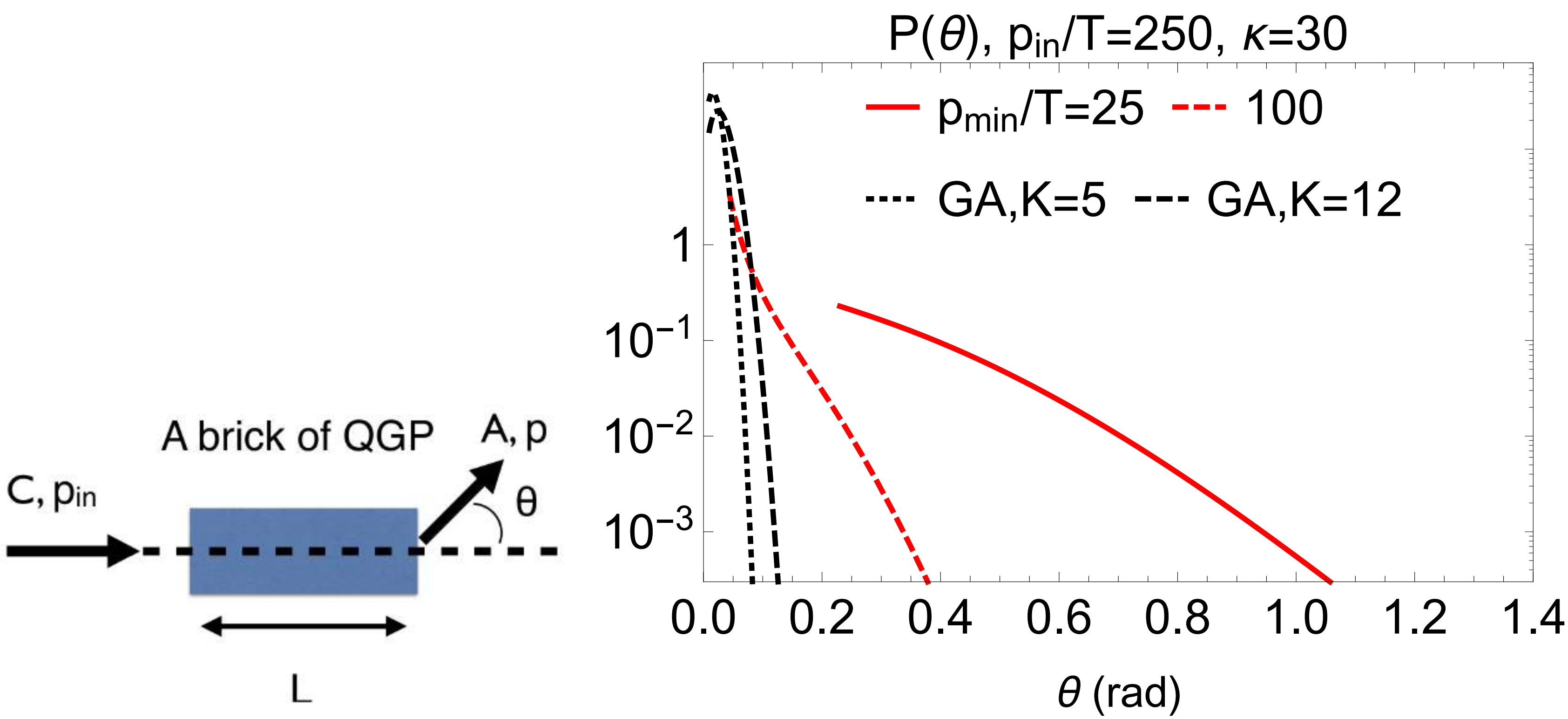




Compare Gaussian distribution of kicks (no scatterers, just liquid) with perturbative tail (point-like scatterers).
Large kicks are rare but certainly not exponentially so, in particular since the parton you see can be either the kickee or the kicker. (Red curves can be for: $C =$ gluon, $A =$ parton, $T = 0.4$ GeV, $L = 3$ fm, $p_{\rm in} = 40$ GeV, $p > 16, 8, 4$ GeV.)

Finding Scatterers in the Soup

D'Eramo, KR, Yin, 1808.03250



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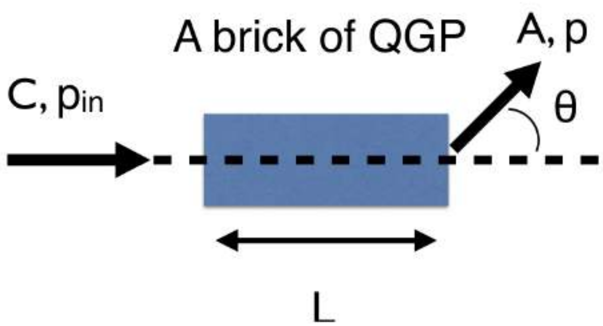
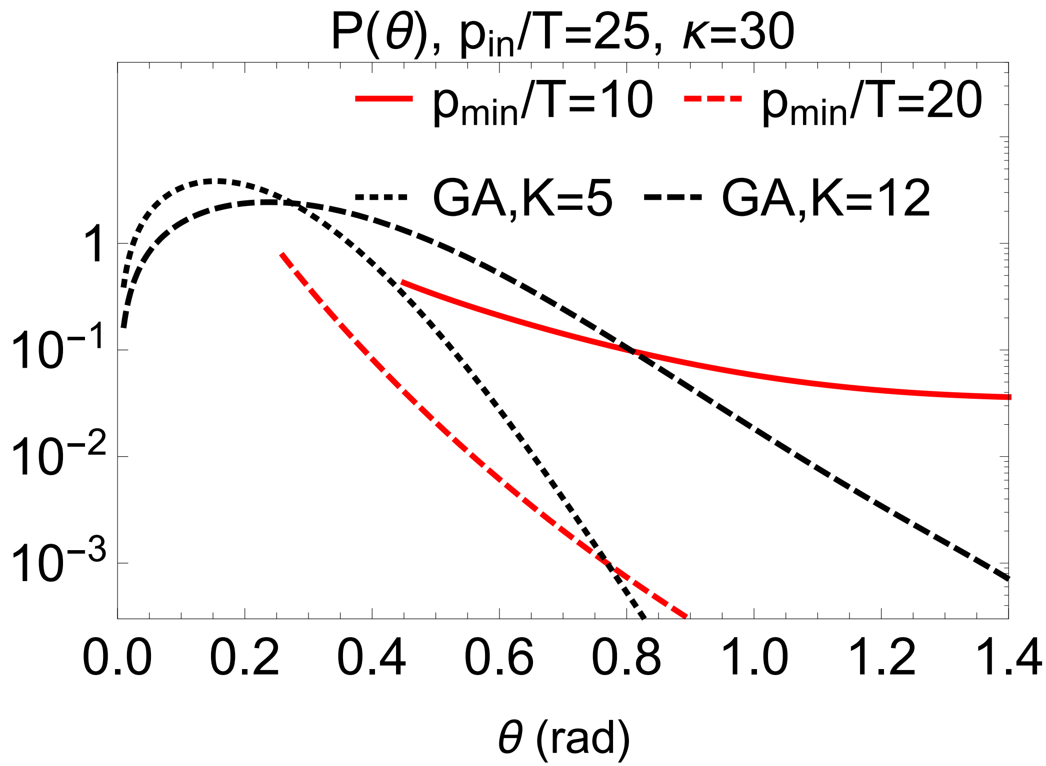
Finding Scatterers in the Soup

D'Eramo, KR, Yin, 1808.03250





Compare Gaussian distribution of kicks (no scatterers, just liquid) with perturbative tail (point-like scatterers).
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Where are we going?

- This calculation is merely illustrative, to give a sense of what one might look for.
- To look at modification of substructure observables due to scattering of partons within a jet, this analysis needs to be implemented within a jet Monte Carlo.
- WIll want to look at modification of substructure observables that tell you the probability for a jet to "sprout an extra prong" due to propagation through QGP, for example because a 40 GeV parton in the jet kicks a 16 GeV parton out to $\theta > 0.4$ (or kicks an 8 GeV parton out to $\theta > 0.8$) with probability 10^{-3}. Not easy, and will require high statistics.
- What about dijet (or γ-jet) 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 pushes the probability down.

Where are we going?

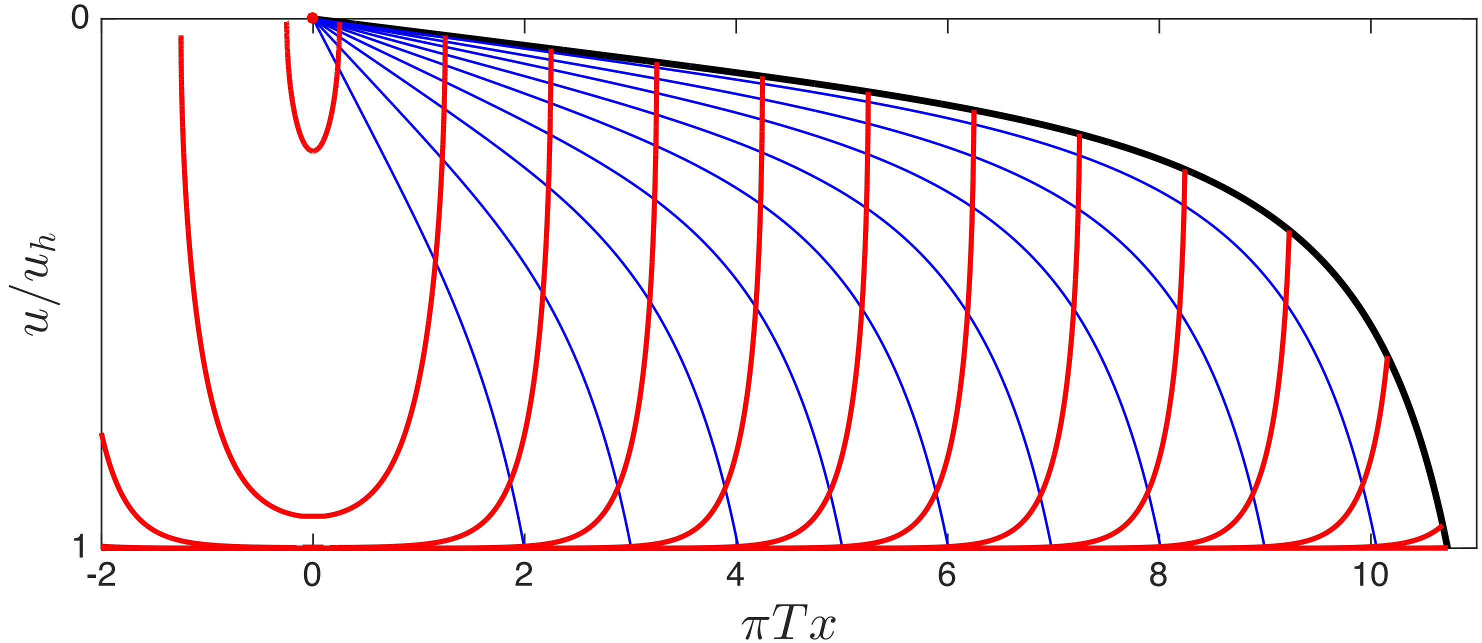
- We are learning more and more, now and in the short and medium terms.
- Parton energy loss is of central interest, and we are constraining our understanding of it better and better.
- Ditto for how the medium responds, namely the wake.
- Modification to suitably differential jet shape observables, 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 20-40 GeV parton in the jet scatters off a quasiparticle in the soup.

The Long View

- Dope the QGP with quarks; map the QCD phase diagram; perhaps find a critical point.
- 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. $\rightarrow$ experimental access to the “as a function of time” variant of How does the liquid emerge from weakly coupled degrees of freedom?
- 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. $\rightarrow$ experimental access to the “microscopy variant” of How does the liquid emerge from an asymptotically free gauge theory?

Quenching a Light Quark "Jet"

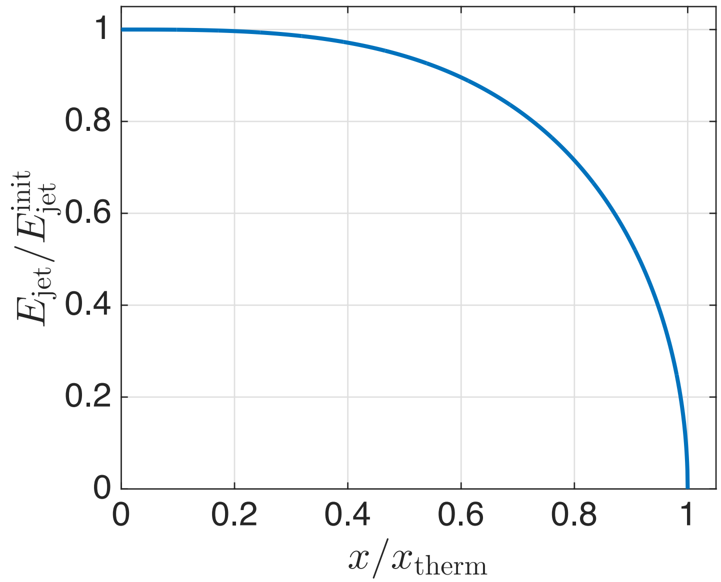
Chesler, Rajagopal, arXiv:1402.6756, 1511.07567



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

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756, 1511.07567



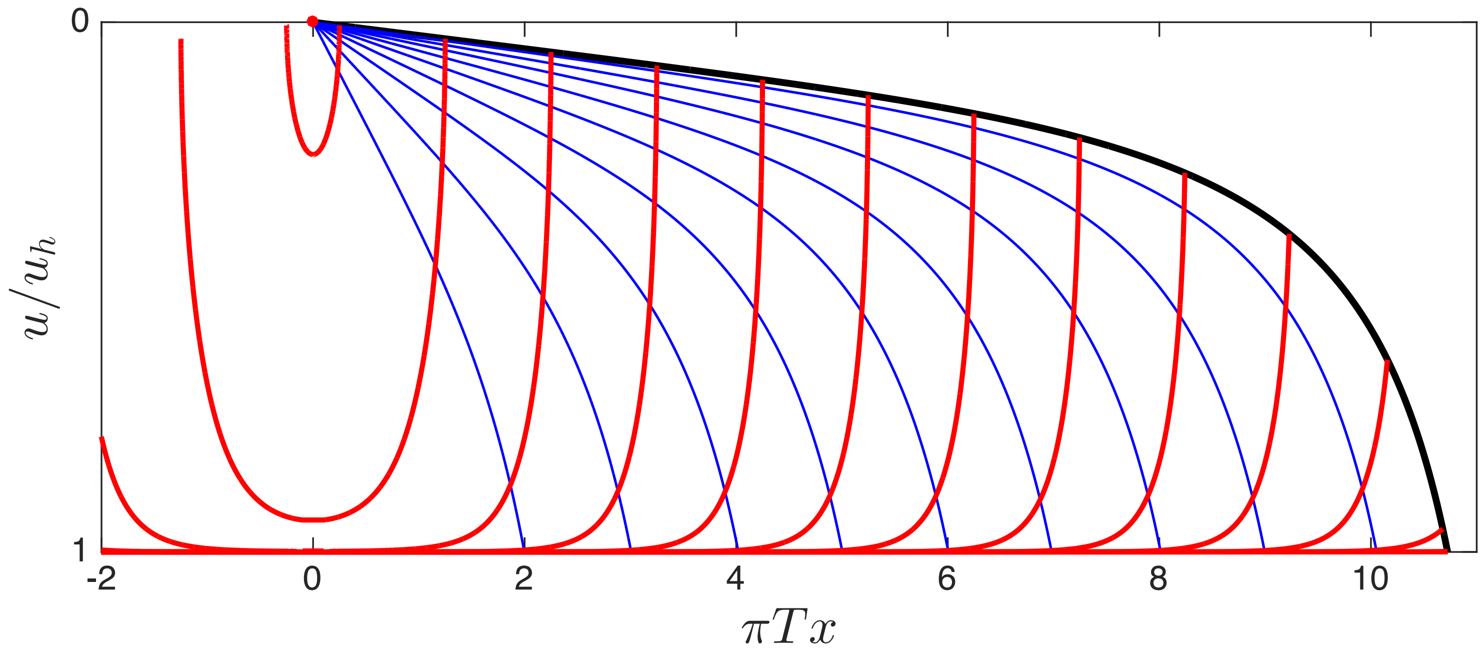
We compute E_{jet} analytically, by integrating the energy flowing into hydrodynamic modes, and showing its equivalence to that falling into the horizon. Geometric derivation of analytic expression for dE_{jet}/dx

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

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

Quenching a Holographic Jet

Chesler, Rajagopal, arXiv:1511.07567

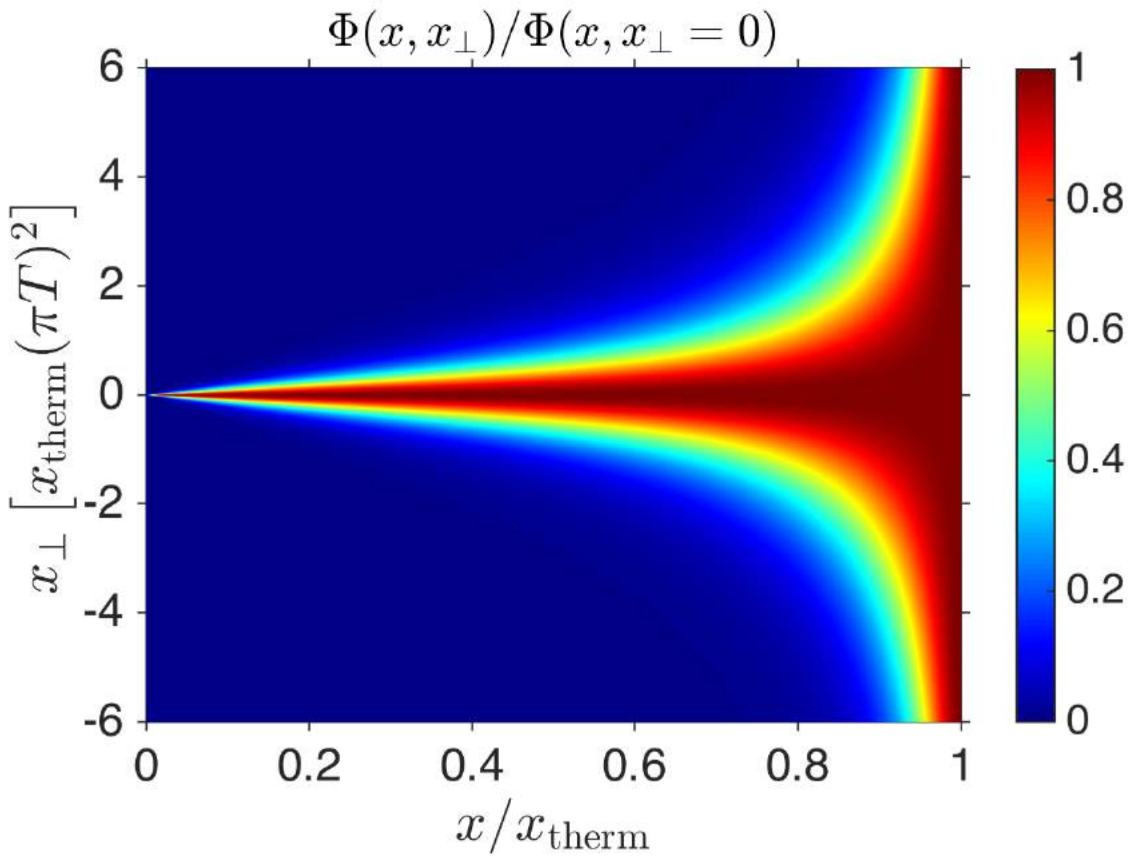


Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

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

Holographic “Jet” Energy Loss

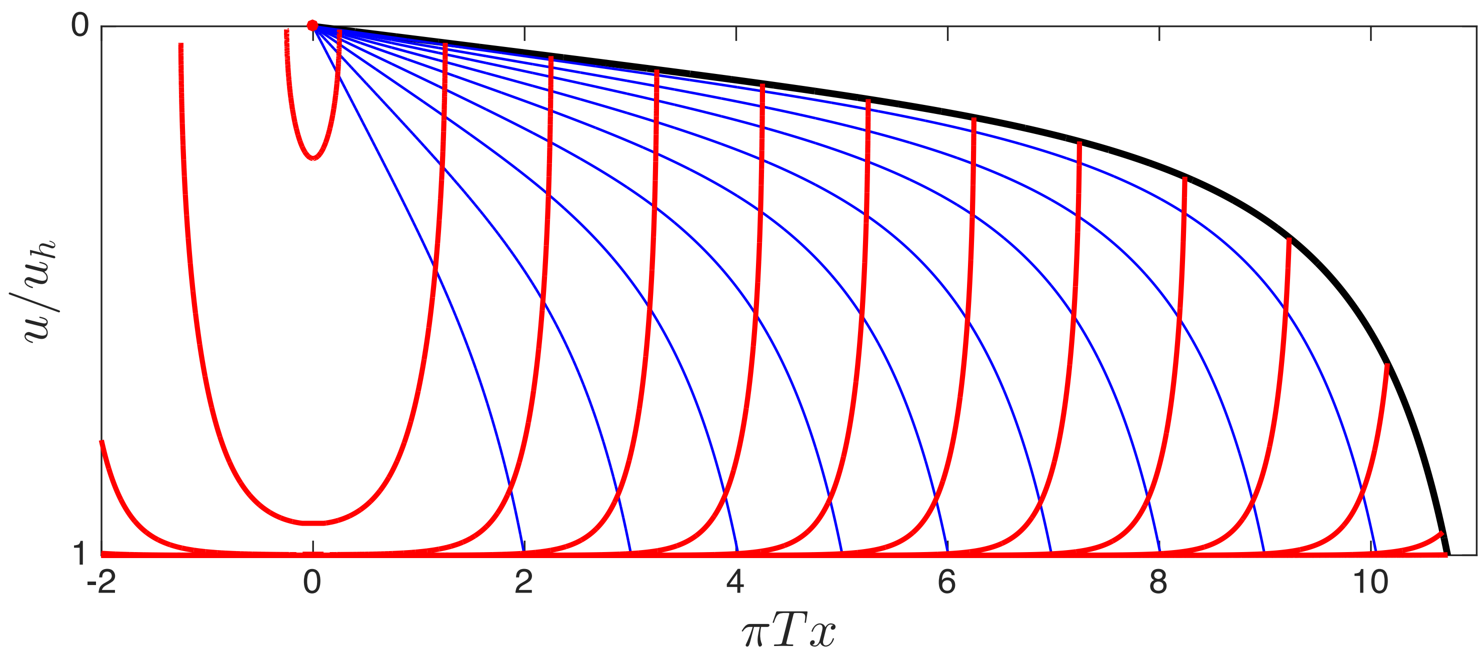
Chesler, Rajagopal, arXiv:1511.07567



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

Holographic "Jet" Energy Loss

Chesler, Rajagopal, arXiv:1511.07567



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

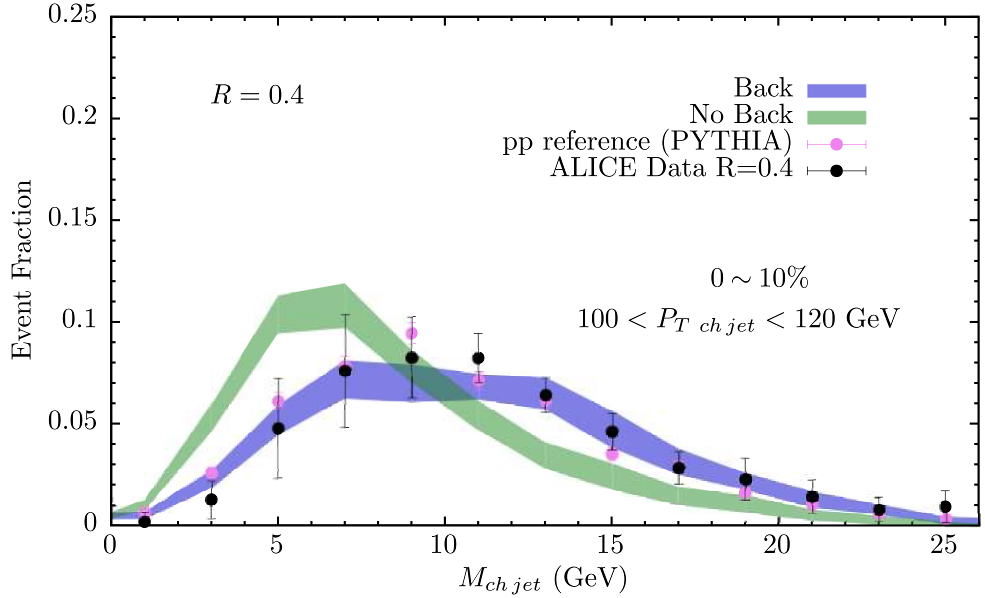
- **Second, jets with smaller initial $\theta_{\text{jet}}^{\text{init}}$ have a longer x_{therm}. They lose their energy more slowly, over a longer distance. (In fact, $T x_{\text{therm}} \propto 1/\sqrt{\theta_{\text{jet}}^{\text{init}}}$.)**
- **That is, for jets with the same $E_{\text{jet}}^{\text{init}}$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

Jet Mass

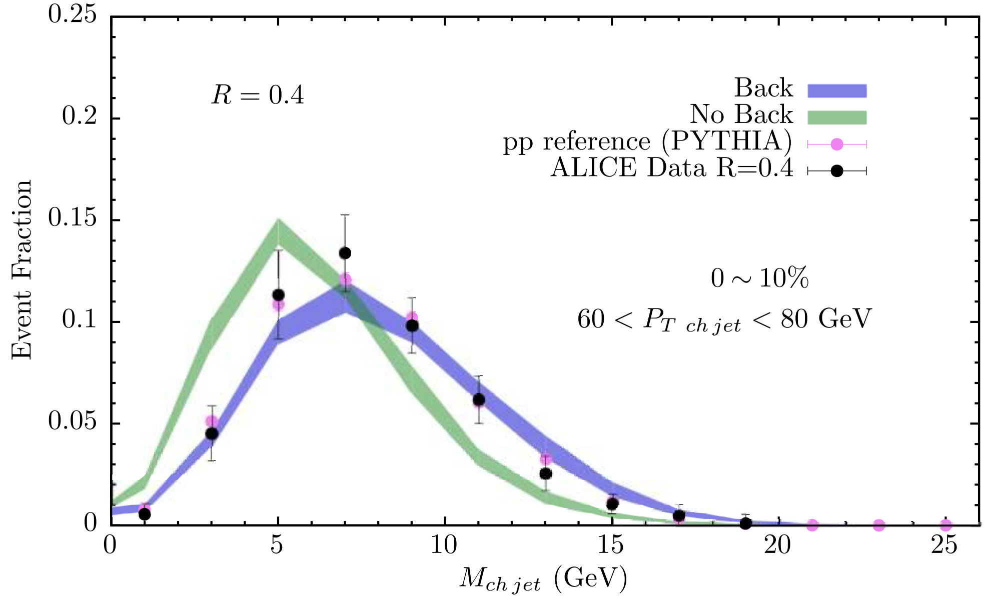
Casalderrey-Solana, Gulhan, Hulcher, Milhano, Pablos, KR, 2017



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

Jet Mass

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



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Jet Mass

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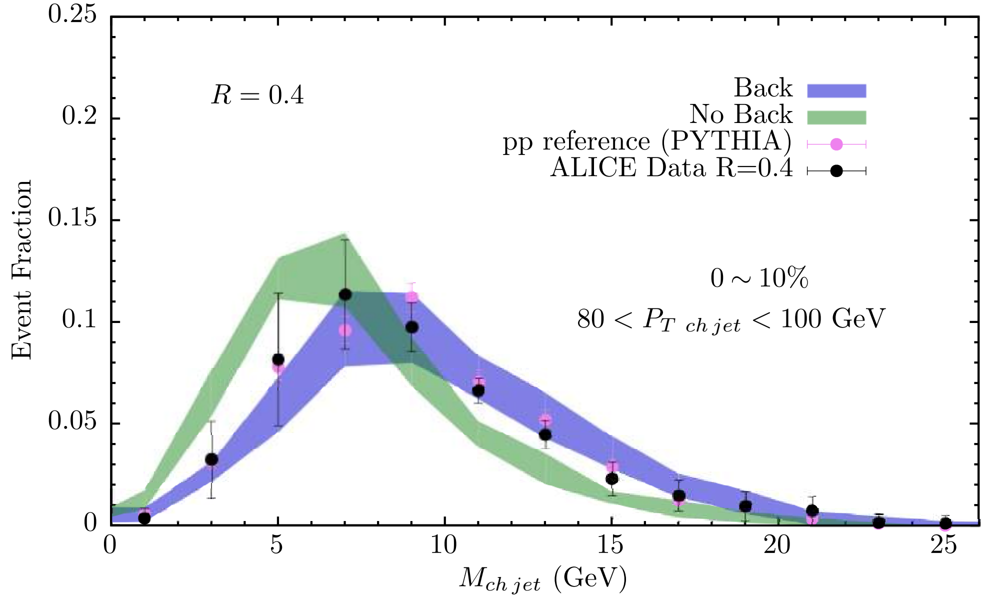

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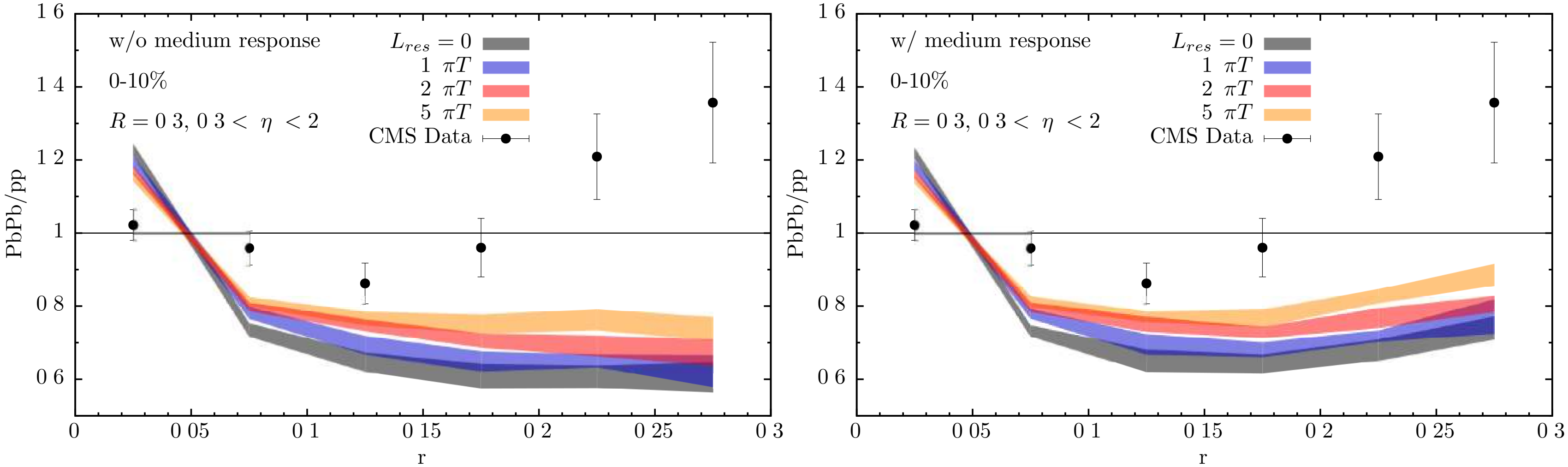
Jet Shape Ratio

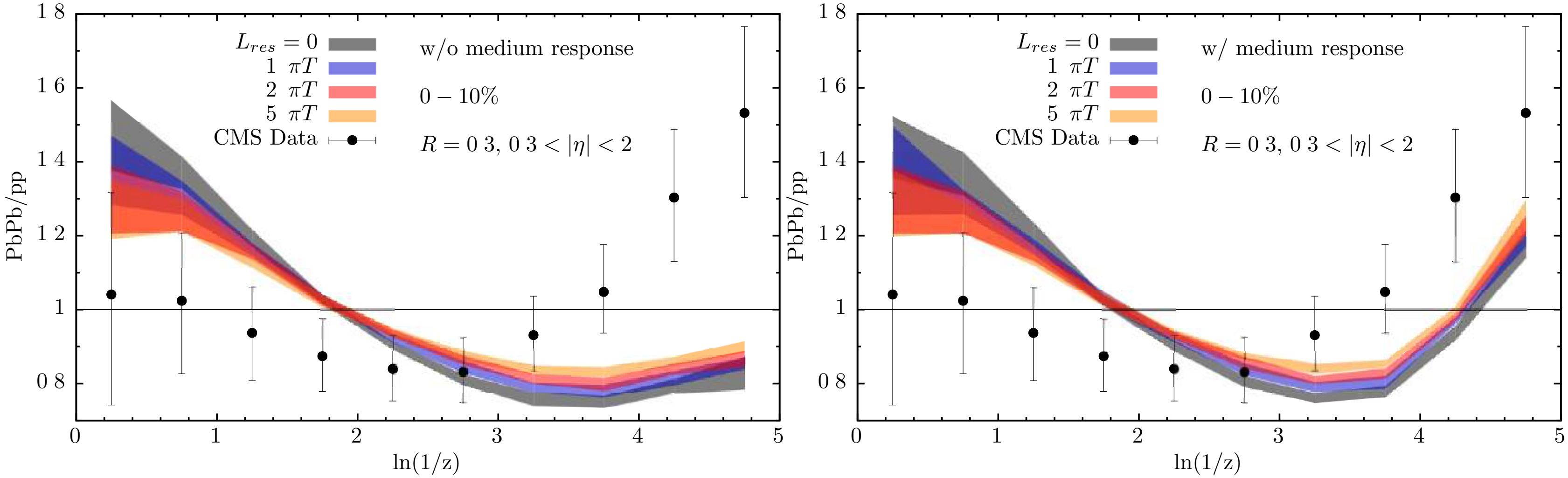
CGMPR 1609.05842; Hulcher, Pablos, KR, 2017



- **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

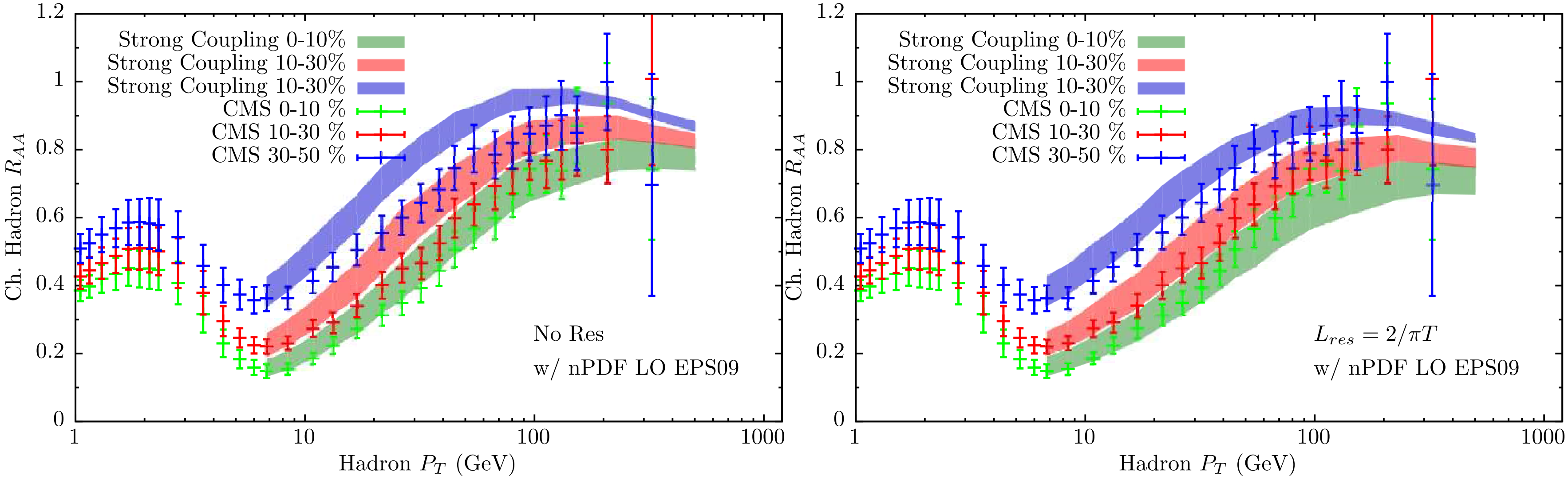
CGMPR 1609.05842; Hulcher, Pablos, KR, 2017



- **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 $L_{res} = 2/(\pi T)$ is in better agreement with data than if we take $L_{res} = 0$.**