

# Imaging the Wakes of Jets with Energy-Energy-Energy Correlators

Krishna Rajagopal

MIT

work in progress with

Hannah Bossi (MIT), Arjun Kudinoor (Cambridge),

Ian Moulton (Yale), Dani Pablos (Santiago),

Ananya Rai (Yale)

Energy Correlators at the Collider Frontier

MITP, Mainz, Germany; July 10, 2024

# Imaging the Wakes of Jets with Energy-Energy-Energy Correlators

Krishna Rajagopal  
MIT

First talk in a coordinated sequence of four...

This talk: intro to jet wakes and the Hybrid Model,  
& a complementary new observable

Energy Correlators at the Collider Frontier

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# Imaging the Wakes of Jets with Energy-Energy-Energy Correlators

Ananya Rai

Yale

Second talk in a coordinated sequence of four...

**Probing QCD Using Projected N-Point ECs**

ALICE pp measurements; E3C and E2C in HIC

Energy Correlators at the Collider Frontier

MITP, Mainz, Germany; July 10, 2024

# Imaging the Wakes of Jets with Energy-Energy-Energy Correlators

Hannah Bossi

MIT

Third talk in a coordinated sequence of four...

## First Investigations of Shape-Dependent Energy Correlators in HIC

Energy Correlators at the Collider Frontier

MITP, Mainz, Germany; July 10, 2024

# Imaging the Wakes of Jets with Energy-Energy-Energy Correlators

Arjun Kudinoor  
Cambridge & MIT

Fourth talk in a coordinated sequence of four...

**Coordinates for, and Explorations of,  
Jet Wakes in Energy-Energy-Energy Correlators**

Energy Correlators at the Collider Frontier

MITP, Mainz, Germany; July 10, 2024

# Liquid Quark-Gluon Plasma

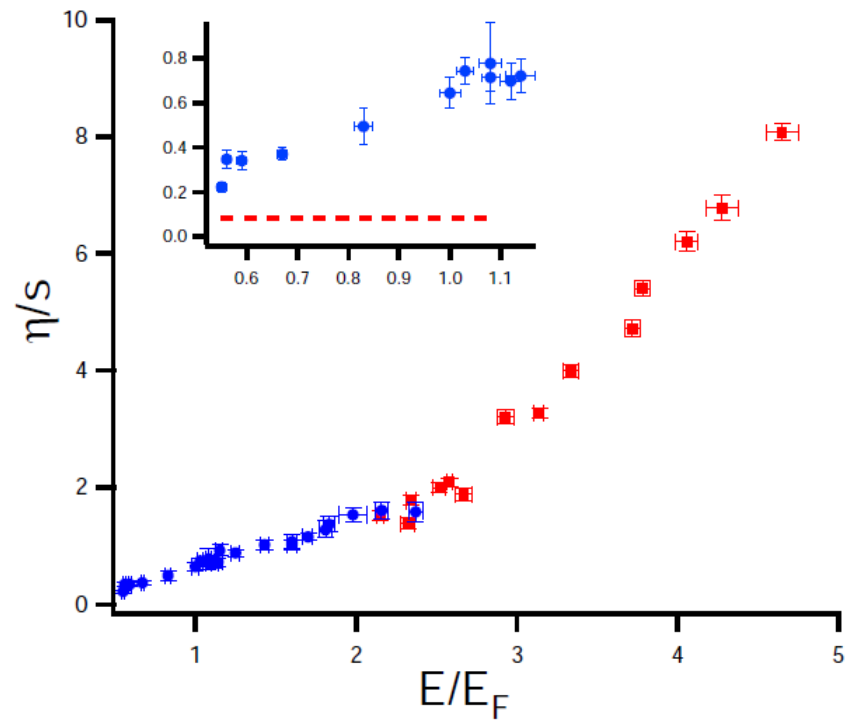
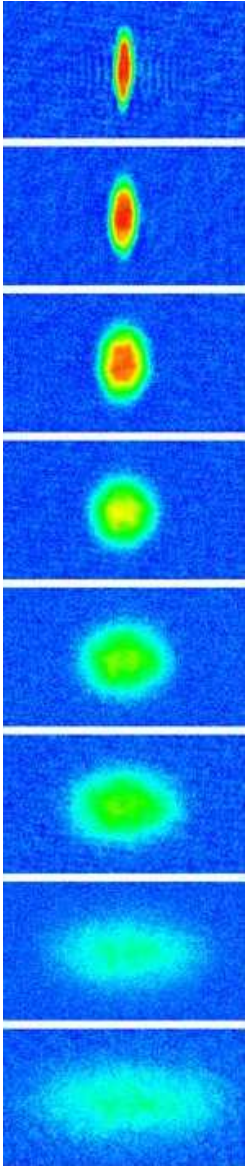
- Hydrodynamic analyses of RHIC and LHC data on how asymmetric blobs of Quark-Gluon Plasma expand (explode) taught us that QGP is a strongly coupled liquid, with  $(\eta/s)$  — the dimensionless characterization of how much dissipation occurs as a liquid flows — much smaller than that of all other known liquids except one.
- Quarks and gluons in QGP diffuse, without being confined in hadrons. QGP flows. Its energy density and coupling are so large that quarks and gluons are always bumping into each other. Far from noninteracting; mean free path hard to define; relaxation times  $\sim 1/T$ .
- Quarks and gluons in QGP are not confined — but also not free.
- 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  $\eta/s$  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  $\eta/s$  as a function of temperature...

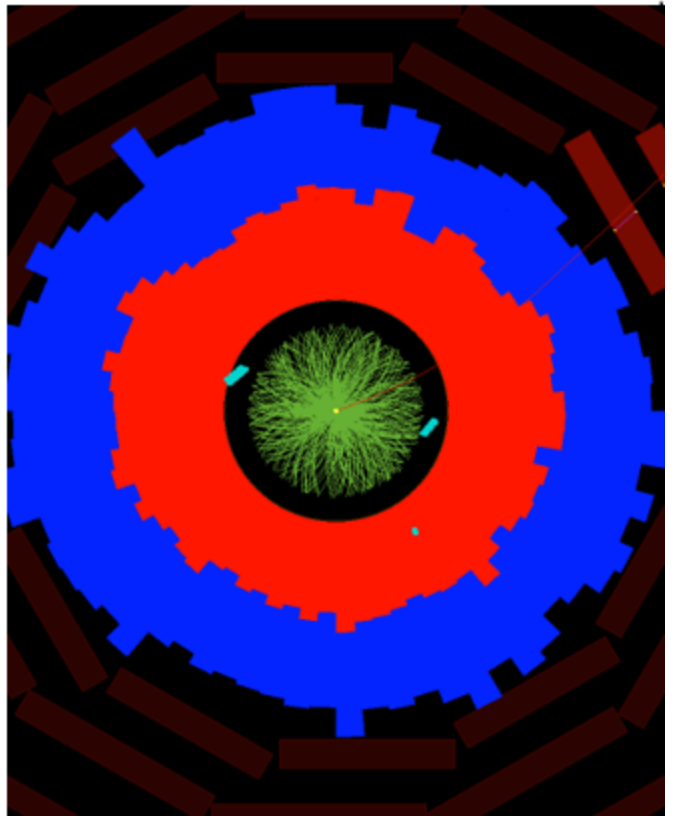
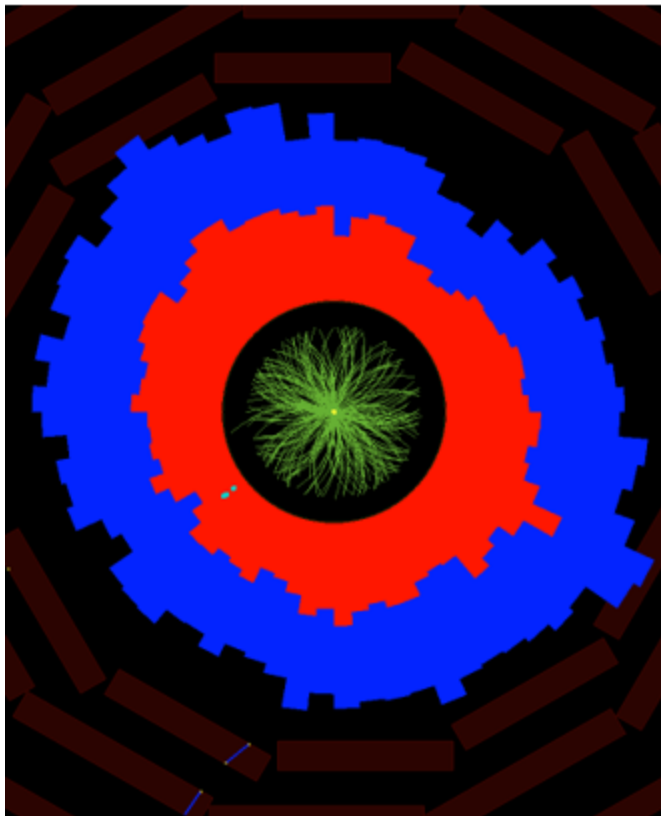
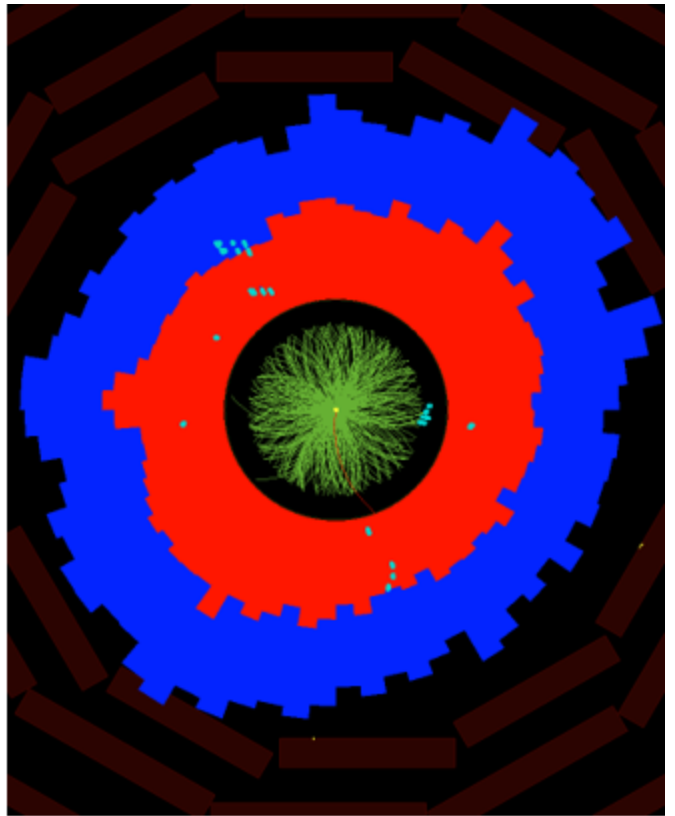
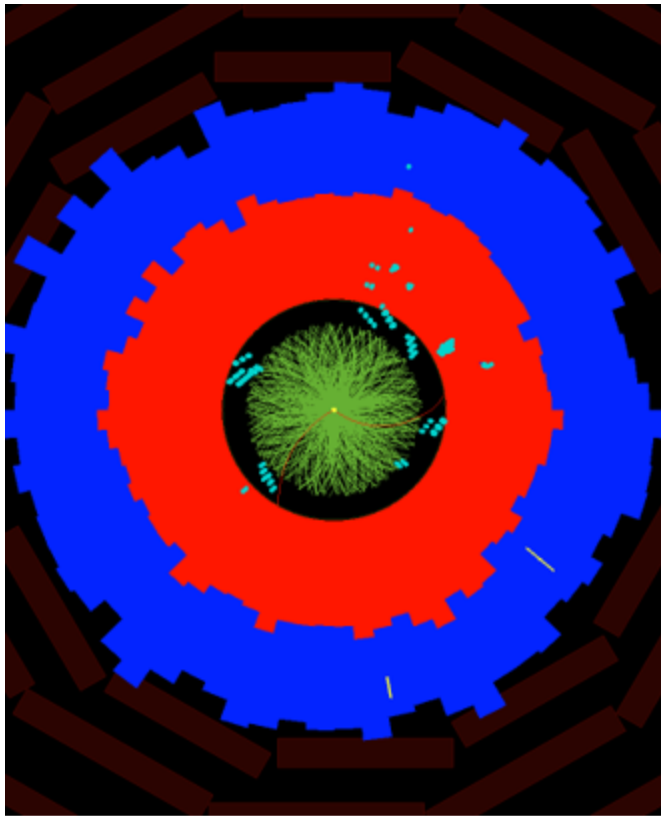
# Viscosity to entropy density ratio

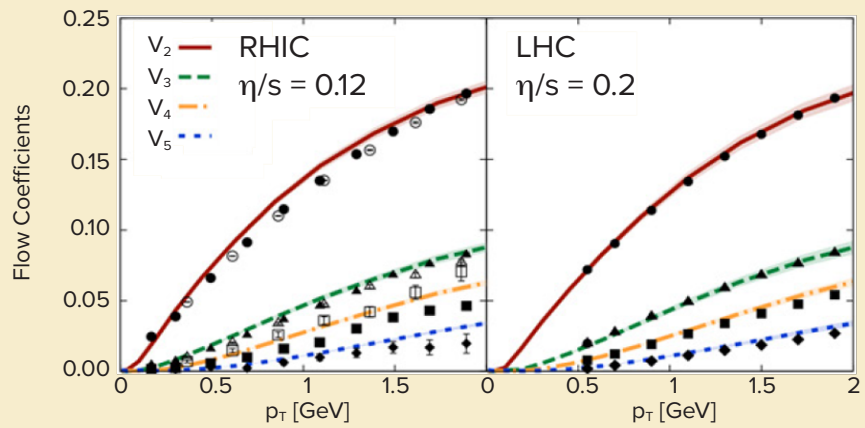
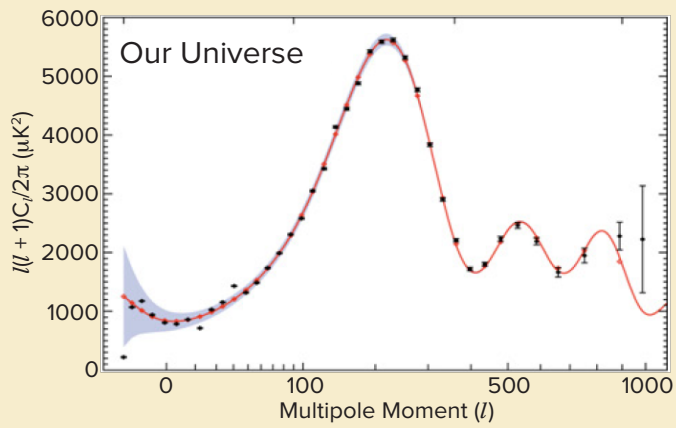
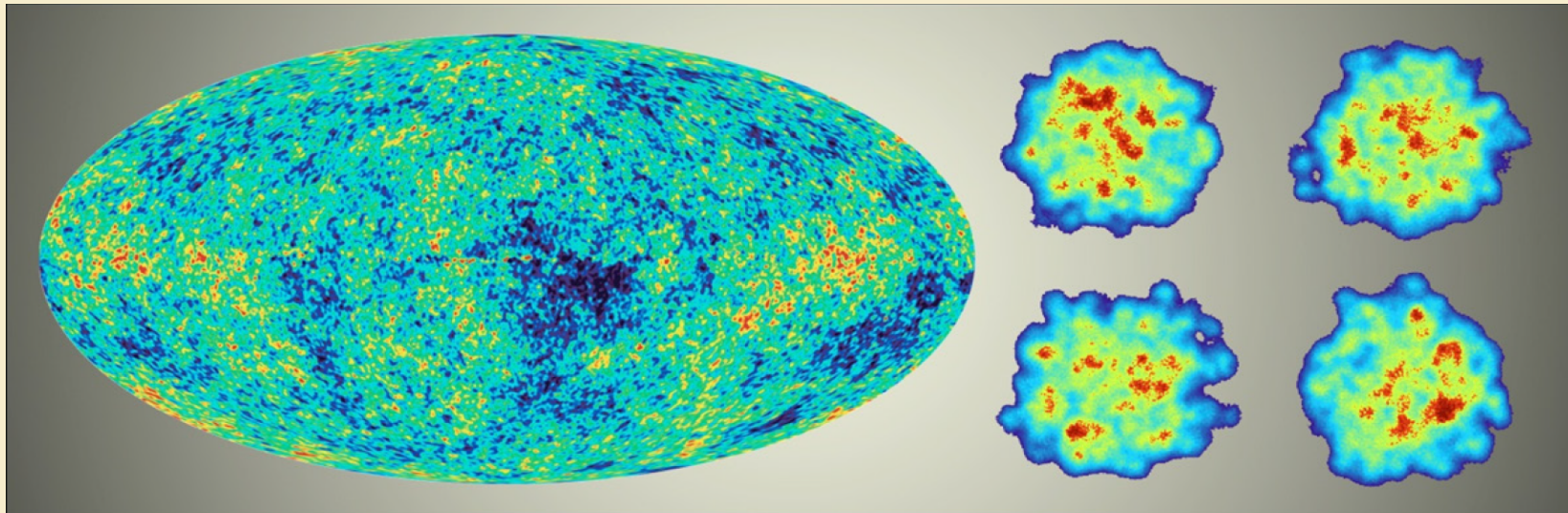
consider both collective modes (low T)  
and elliptic flow (high T)



Cao et al., Science (2010)

$$\eta/s \leq 0.4$$







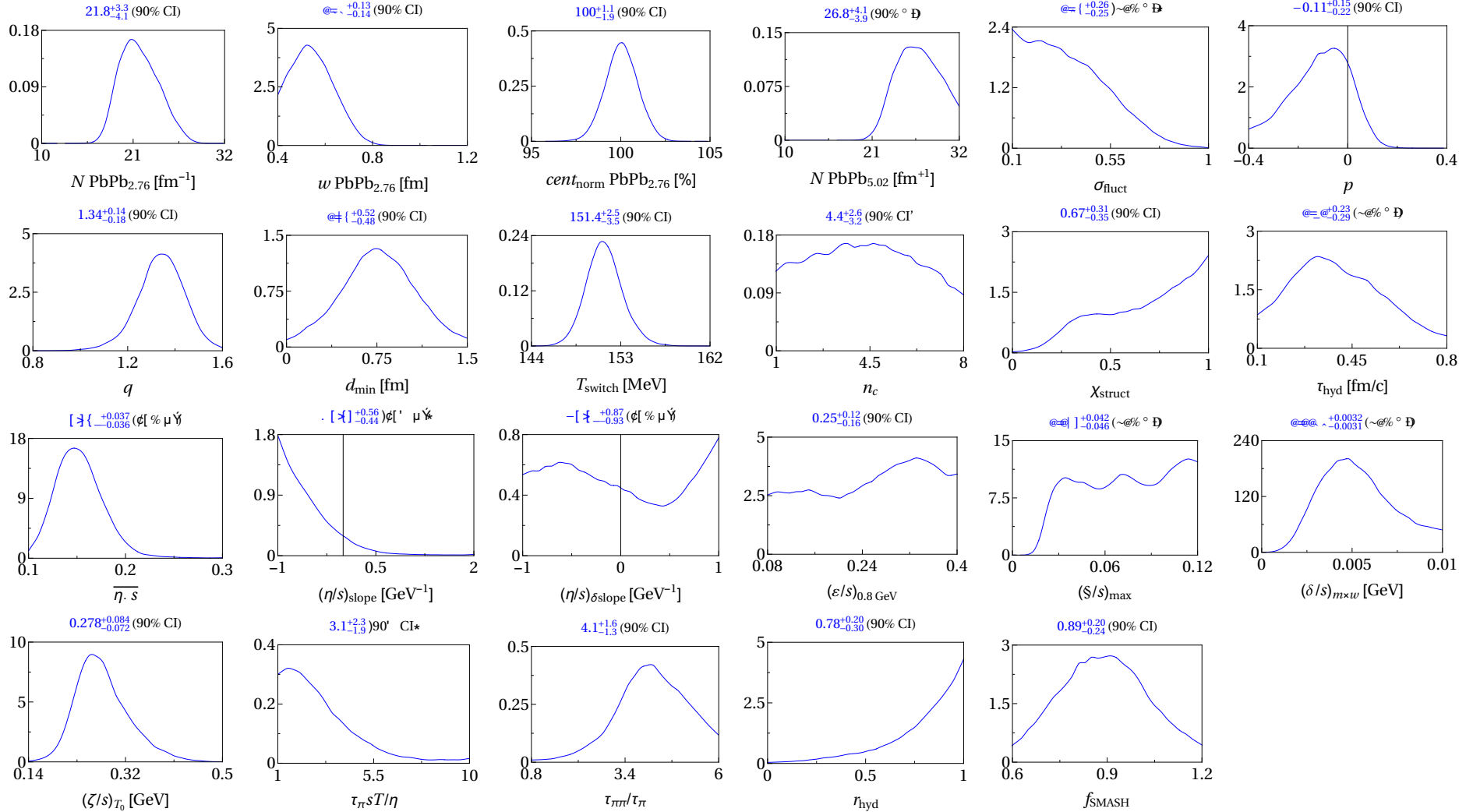
# QGP cf CMB

- In cosmology, initial-state quantum fluctuations, processed by hydrodynamics, appear in data as  $c_\ell$ 's. From the  $c_\ell$ '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  $\eta/s$ , ultimately its  $\eta/s(T)$  and  $\zeta/s$ .
- Cosmologists have a huge advantage in resolution:  $c_\ell$ '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...

# $\eta/s$ from RHIC and LHC data

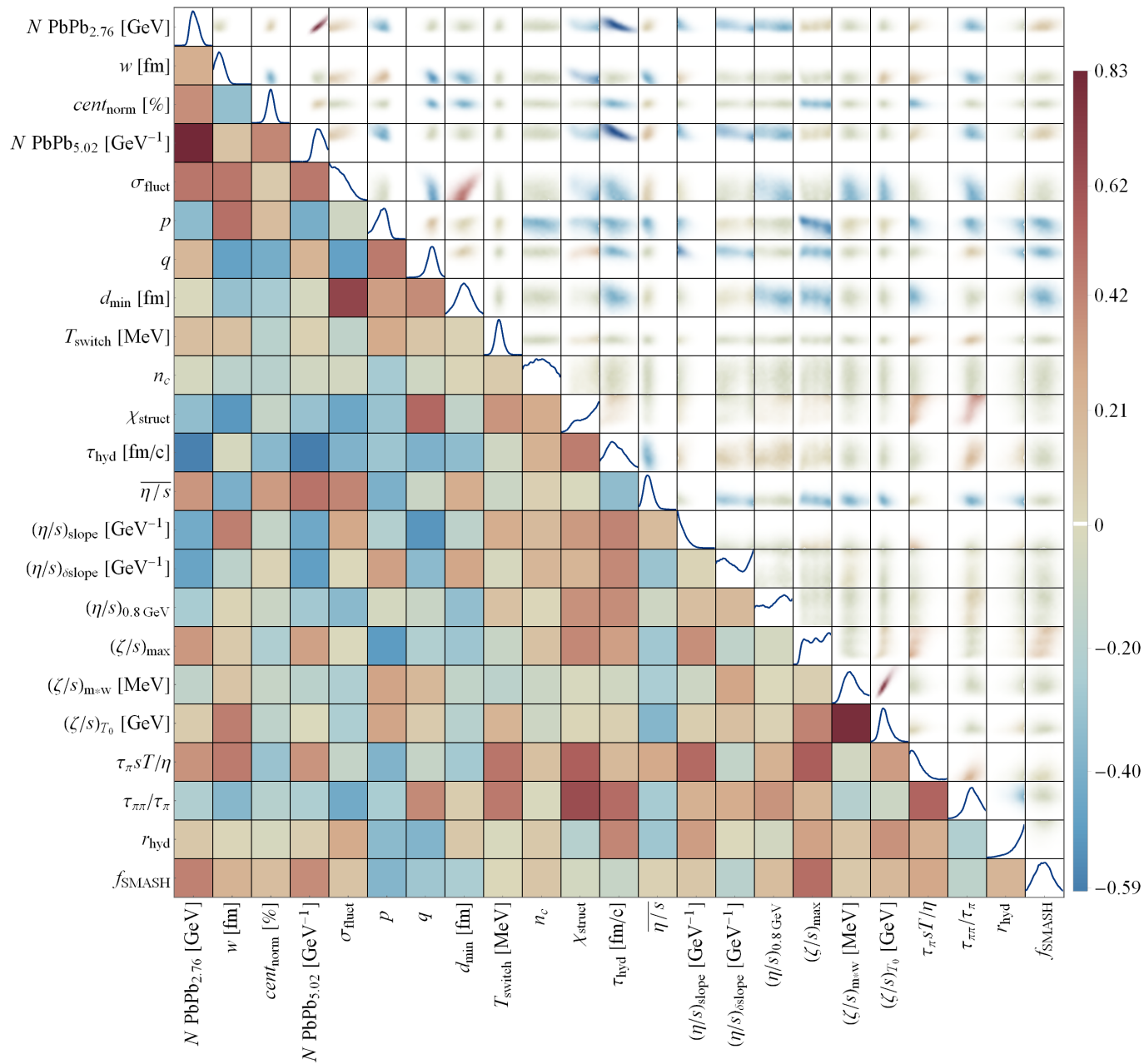
- I have given you the beginnings of a story that has played out over the past decade. I will now cut to the chase, leaving out many interesting chapters and oversimplifying.
- Using relativistic viscous hydrodynamics to describe expanding QGP, *produced in an initially lumpy heavy ion collision*, using microscopic transport to describe late-time hadronic rescattering, and using RHIC and LHC data on pion and proton spectra and  $v_2$  and  $v_3$  and  $v_4$  and  $v_5$  and  $v_6$  ... 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  $1 < 4\pi\eta/s < 3$ .  
**Nota bene: this was circa 2015.**
- $4\pi\eta/s \sim 10^4$  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.

# Eg. of Today's State of the Art



Trajectum (Gürsoy, Nijs, Snellings, van der Schee)  
 this fig: Nijs, van der Schee, arXiv:2304.06191

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Trajectory (Gürsoy, Nijs, Snellings, van der Schee)  
 this fig: Nijs, van der Schee, arXiv:2304.06191

# Determination of the neutron skin of $^{208}\text{Pb}$ from ultrarelativistic nuclear collisions

Govert Nijs

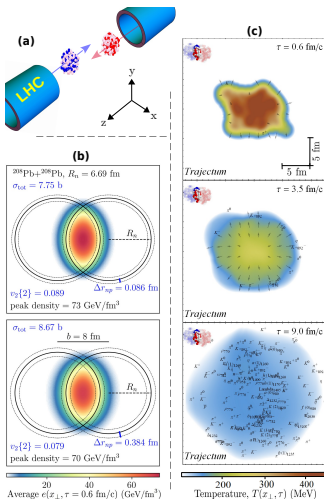
September 6, 2023

Based on:

- Giacalone, GN, van der Schee, 2305.00015



# How to measure neutron skin?

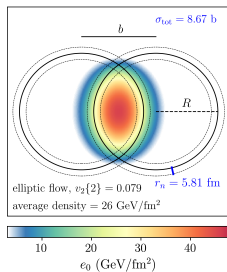
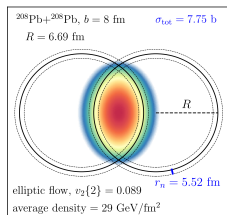


- To measure the neutron skin, we need the distributions of protons and neutrons inside the nucleus.
  - The proton distribution distribution is well-known from electron scattering.
- Several different methods are in use for the neutron distribution:
  - Polarized electron scattering off  $^{208}\text{Pb}$  (PREX).
  - Photon tomography of  $^{197}\text{Au}$  (STAR).
- Heavy ion collisions provide a completely orthogonal method.
  - Sensitive to the total matter distribution inside the nucleus.
  - Purely gluonic measurement.



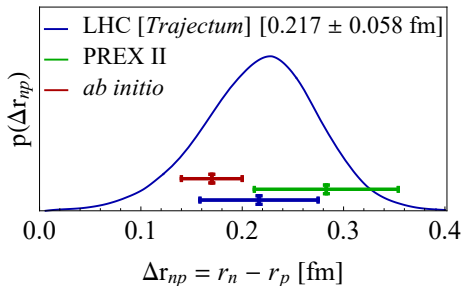
# Do we have observables sensitive to $a_n$ ?

- Initial geometry is sensitive to  $a_n$ .  
Larger nuclei lead to:
  - Larger hadronic PbPb cross-section,
  - Larger initial QGP size,
  - Smaller initial QGP eccentricity.
- Final state observables are in turn sensitive to initial geometry. Larger  $\Delta r_{np}$  leads to:
  - Larger hadronic PbPb cross-section,
  - Smaller charged particle yield,
  - Smaller mean transverse momentum,
  - Smaller elliptic flow.



# Bayesian analysis result using LHC data

- Resulting posterior for  $\Delta r_{np}$  is compatible with PREX II and *ab initio* nuclear theory.
- Slightly stronger constraint than PREX II ( $\Delta r_{np} = 0.283 \pm 0.071$ ).
- Result is in principle improvable with better Bayesian analyses.
  - May be hard to do in practice.
  - The current analysis already took 2M CPUh.





# 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, which is so close to the fundamentals: **How does the strongly coupled liquid emerge from laws governing quarks and gluons?** Maybe answering this question could help to understand how strongly coupled matter emerges in other contexts.

# Why Jets?

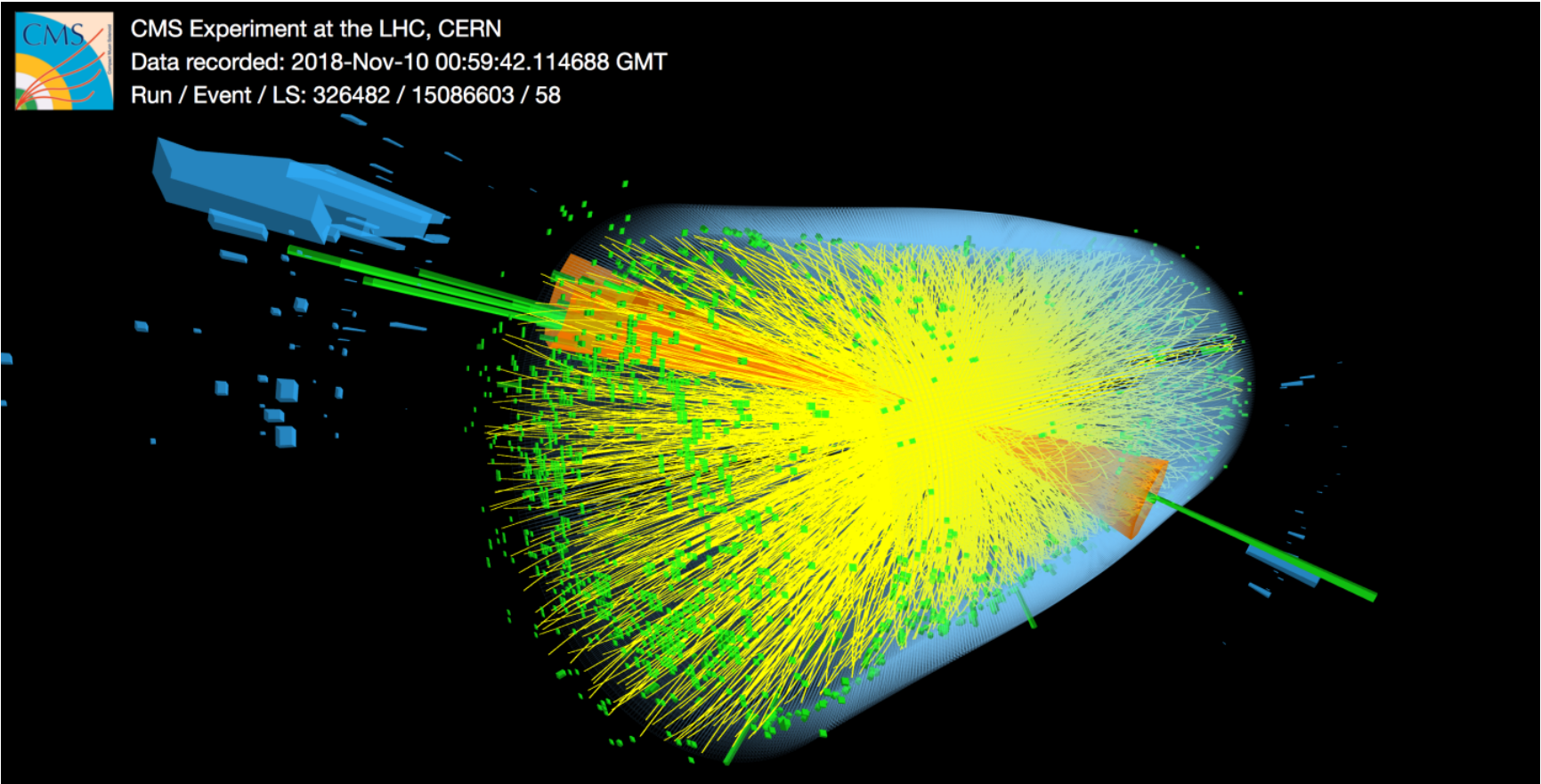
- The remarkable utility of hydrodynamics, eg. in describing the dynamics of small lumps in the initial state in heavy ion collisions, tells us that to see the inner workings of hot quark soup, namely to see how the liquid is put together from quarks and gluons, we will need probes with fine resolution.
- Jets in heavy ion collisions provide best chance for scattering off a droplet of hot Big Bang matter to see its inner workings à la Rutherford.
- Jets in heavy ion collisions *also* offer best chance of watching how the droplet responds. Jets leave a wake in the droplet of liquid. Can we see how this wake ripples and dissipates? Jets are our best shot at seeing this, too.
- → not easy to decode the wealth of info that jets contain! Need high statistics LHC and sPHENIX data; and need to use today's data to build baseline of understanding.

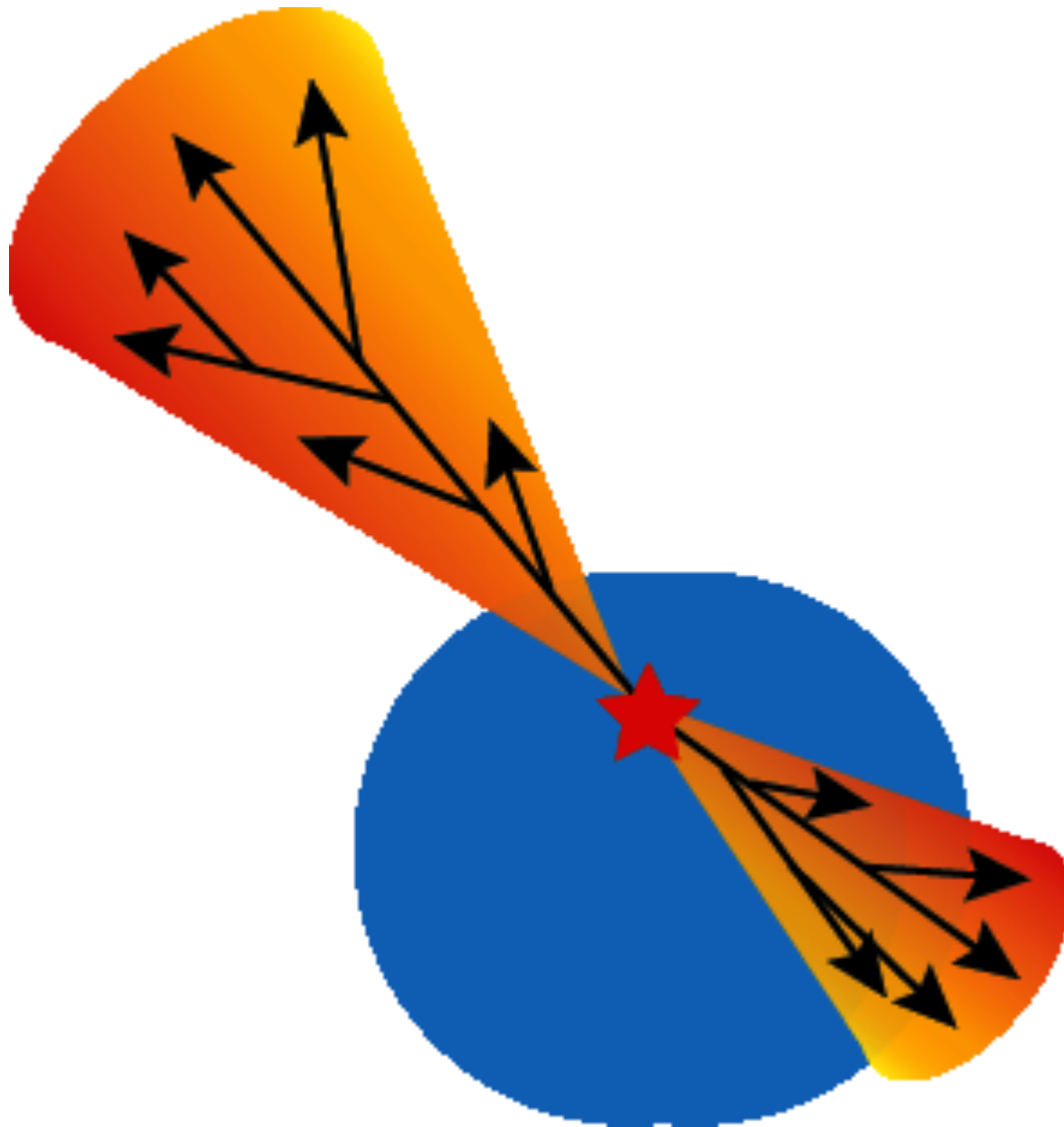


CMS Experiment at the LHC, CERN

Data recorded: 2018-Nov-10 00:59:42.114688 GMT

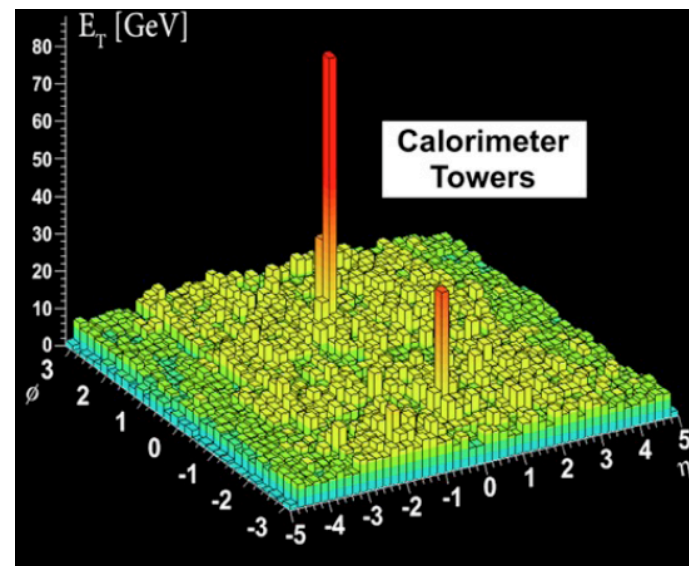
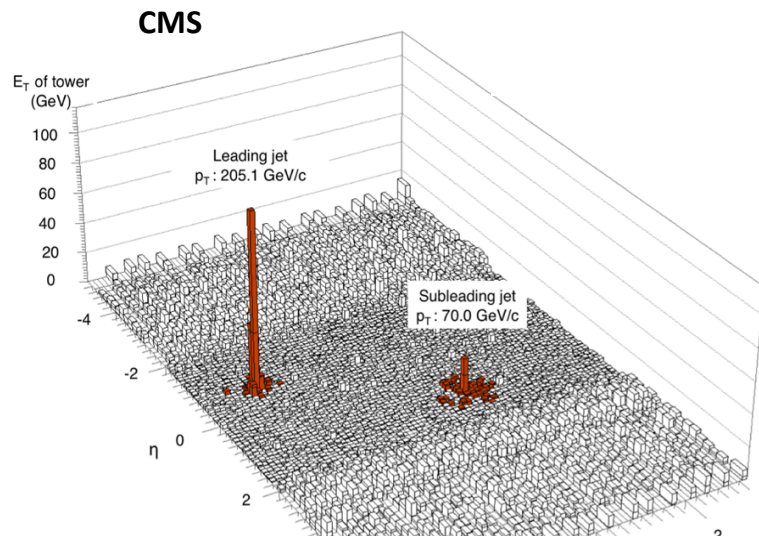
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# Jet Quenching, in brief

ATLAS



Jet quenching discovered @ RHIC; @ LHC, seen instantly!

- 200+ GeV jets lose many tens of GeV passing through the liquid QGP. This is well established.
- Lost energy turns into a wake, which becomes many soft particles, spread widely around the jet.
- To see the high energy quarks and gluons in a jet scatter off the quarks and gluons in the soup need more sophisticated measurements, now being defined, developed, planned.

# How you can learn from a model

- There are things you can do with a model (here, the Hybrid Model) that you cannot do with experimental data. (Eg, turn physical effects off and on) ...
- ... but that nevertheless teach us important lessons for how to look at, and learn from, experimental data.
- **TODAY'S EXAMPLE:** finding jet observables sensitive to, even dominated by, wakes that jets make in the soup.
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- After freezeout, momentum conservation means wake becomes soft hadrons with net momentum in jet direction.
- What an experimentalist reconstructs as a jet necessarily includes hadrons originating from the (modified) parton shower and from the wake in the droplet of QGP.
- In a model, though, the wake can be turned off and on.
- First, a *very* brief intro to the Hybrid Model...

# Jet Wake from Linearized Hydrodynamics

Jorge Casallerrey-Solana,<sup>1,\*</sup> José Guilherme Milhano,<sup>2,3,†</sup>

Daniel Pablos,<sup>4,‡</sup> Krishna Rajagopal,<sup>5,§</sup> and Xiaojun Yao<sup>5,¶</sup>

<sup>1</sup>*Departament de Física Quàntica i Astrofísica & Institut de Ciències del Cosmos (ICC),  
Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain*

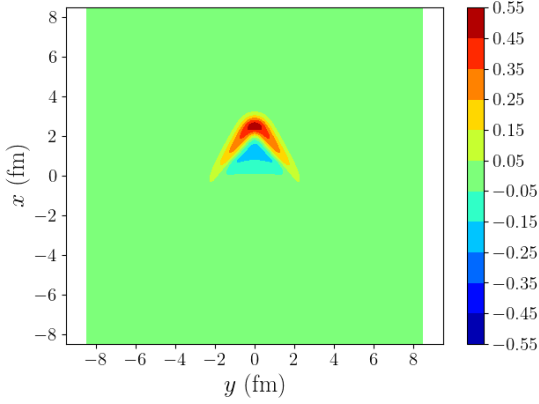
<sup>2</sup>*LIP, Av. Prof. Gama Pinto, 2, P-1649-003 Lisboa, Portugal*

<sup>3</sup>*Instituto Superior Técnico (IST), Universidade de Lisboa,  
Av. Rovisco Pais 1, 1049-001, Lisbon, Portugal*

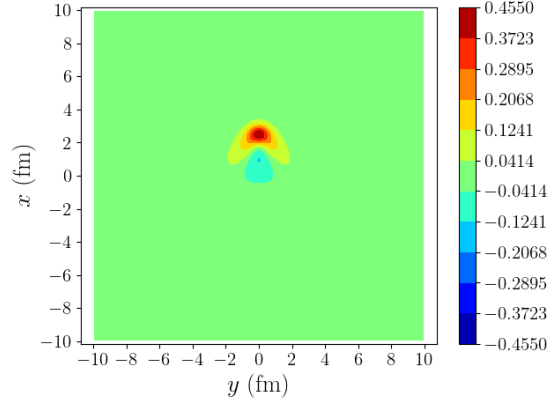
<sup>4</sup>*University of Bergen, Postboks 7803, 5020 Bergen, Norway*

<sup>5</sup>*Center for Theoretical Physics, Massachusetts  
Institute of Technology, Cambridge, MA 02139 USA*

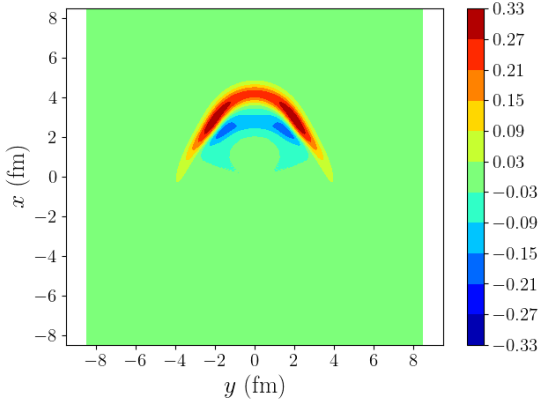
(Dated: June 1, 2021)



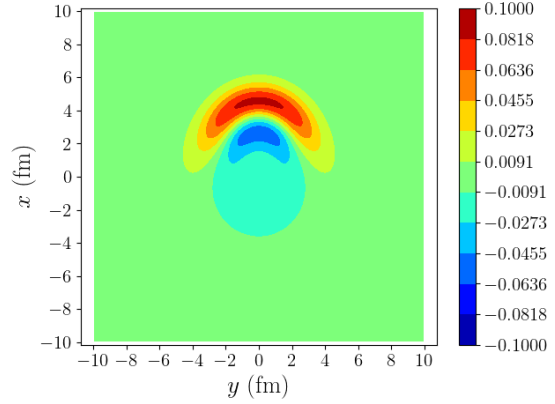
(a) Case 1 (ideal),  $\tau = 4.9$  fm/c.



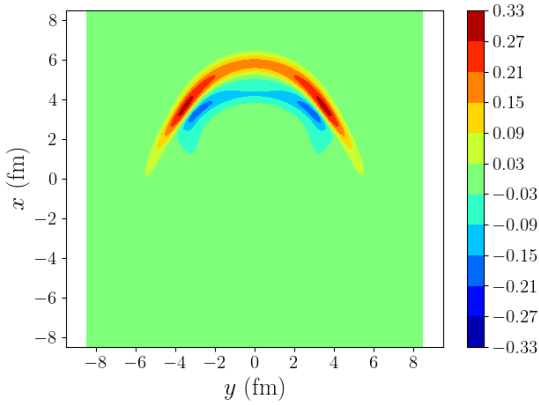
(b) Case 2 (viscous),  $\tau = 4.9$  fm/c.



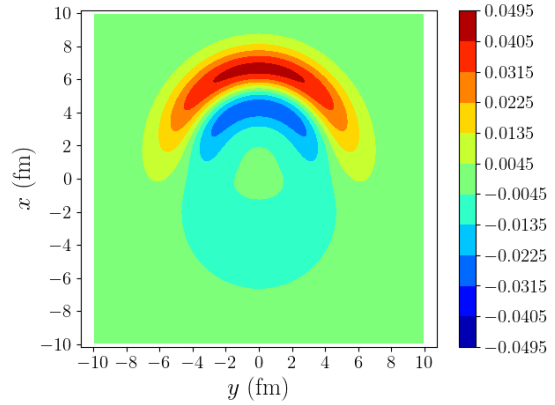
(c) Case 1 (ideal),  $\tau = 7.7$  fm/c.



(d) Case 2 (viscous),  $\tau = 8.3$  fm/c.



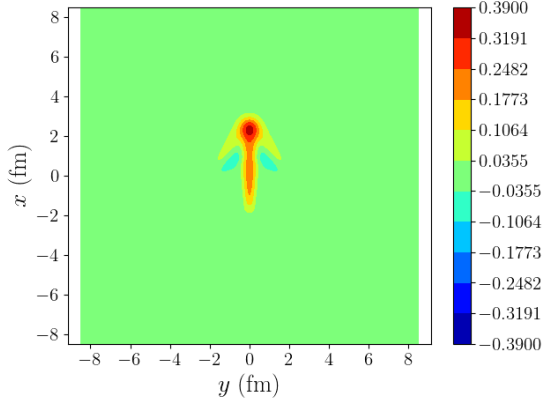
(e) Case 1 (ideal),  $\tau = 10.5$  fm/c.



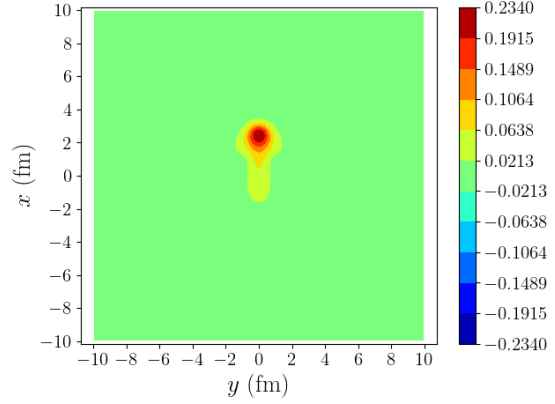
(f) Case 2 (viscous),  $\tau = 11.7$  fm/c.

FIG. 4: Plots of  $\frac{\delta\epsilon}{\epsilon_0}(\eta_s = 0)$  as functions of  $x$  and  $y$  at three different times  $\tau$  for Case 1 (ideal fluid; left panels) and 2 (viscous fluid; right panels). Note that we have used different color bars in different panels; assessing the strength of the perturbations (in this and the next two Figures also) requires looking at the color bars to see the magnitudes corresponding to the reddest and bluest colors.

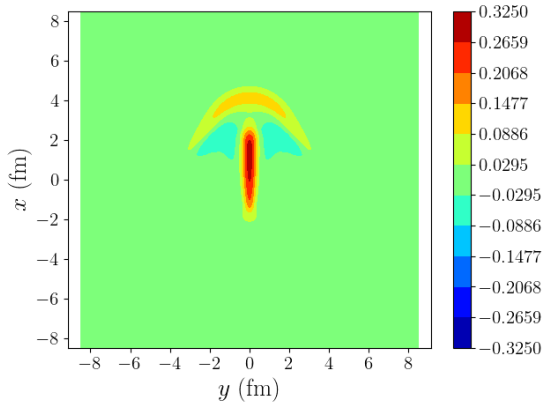




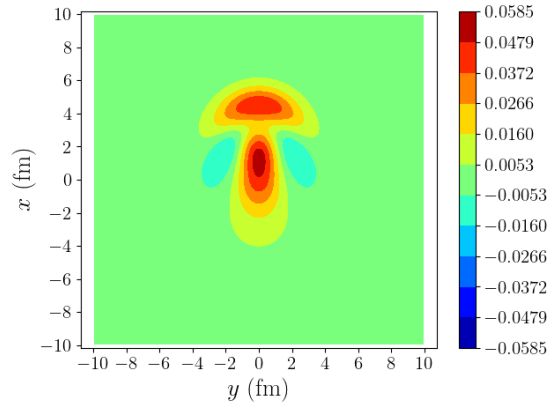
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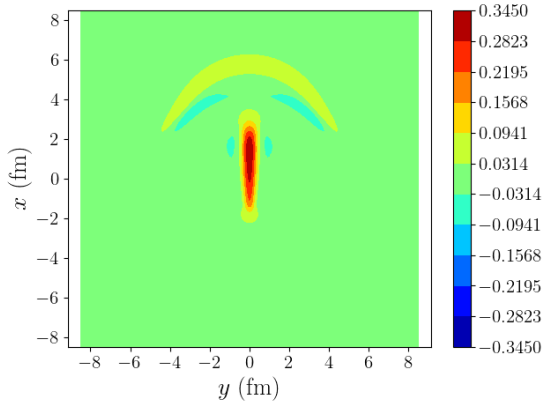
(b) Case 2 (viscous),  $\tau = 4.9$  fm/c.



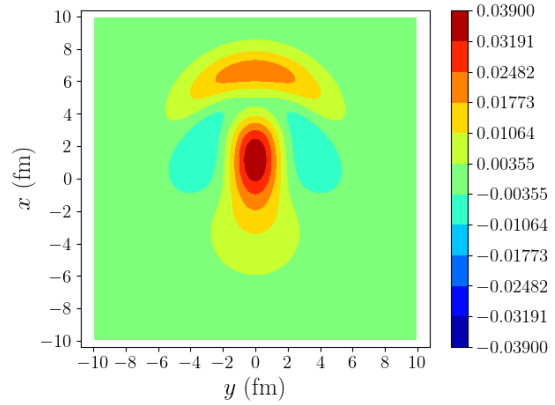
(c) Case 1 (ideal),  $\tau = 7.7$  fm/c.



(d) Case 2 (viscous),  $\tau = 8.3$  fm/c.



(e) Case 1 (ideal),  $\tau = 10.5$  fm/c.



(f) Case 2 (viscous),  $\tau = 11.7$  fm/c.

FIG. 5: Plots of  $\delta u^x(\eta_s = 0)$  as functions of  $x$  and  $y$  at three different times  $\tau$  for Case 1 (ideal fluid; left panels) and 2 (viscous fluid; right panels).

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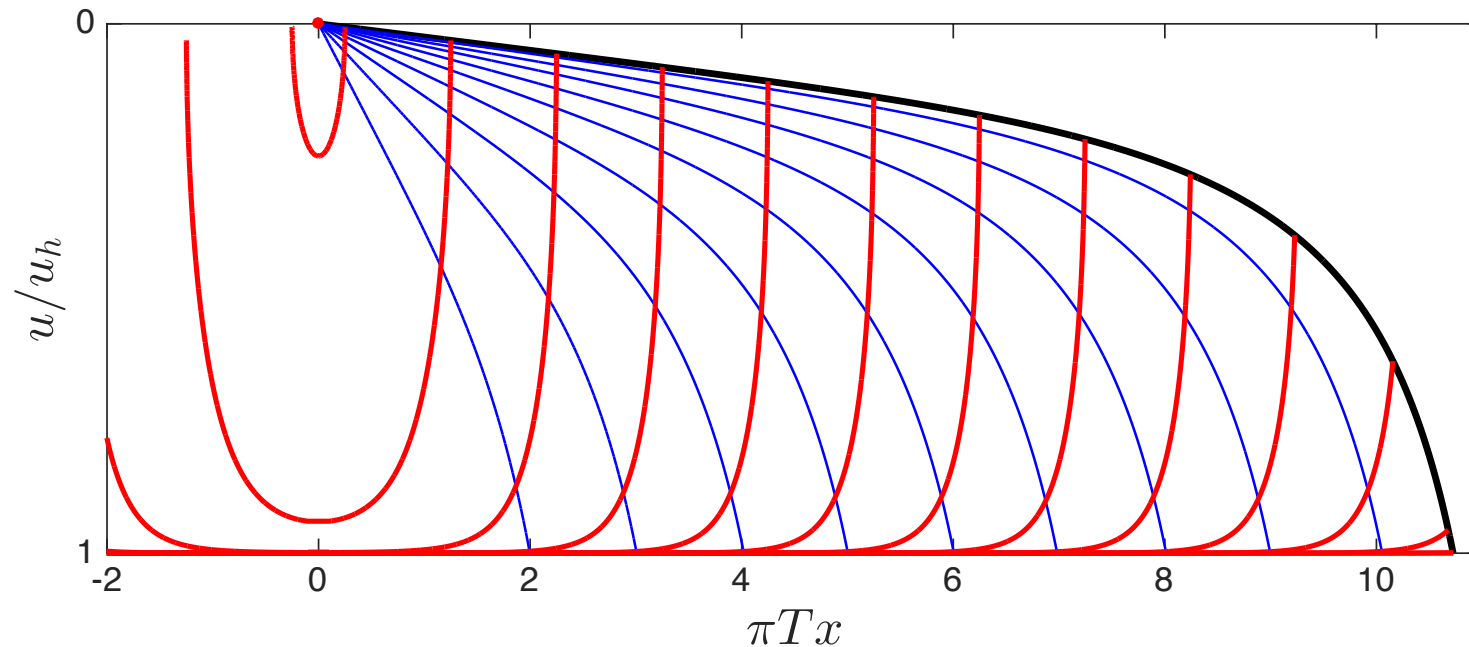
# A Hybrid Approach

Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 2014,15,16; Hulcher, DP,KR, '17; JCS,ZH,GM,DP,KR, '18; JCS,GM,DP,KR, '19; JCS,GM,DP,KR, Yao, '20

- **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:  $x_{\text{therm}}$  (energetic parton thermalization distance) 3-4 times longer in QGP than in  $\mathcal{N} = 4$  SYM plasma at same  $T$ .**
- **Then: add the wake in the plasma; add resolution effects; look at jet shapes, jet masses jet substructure observables; add Molière scattering...**

# 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

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

where  $x_{\text{therm}} \equiv E_{\text{in}}^{1/3} / (2\kappa_{\text{SC}} T^{4/3})$  with  $\kappa_{\text{SC}}$  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  $\kappa_{\text{SC}}$  means  $x_{\text{therm}}$  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- $k_T$ .

# Perturbative Shower ... Living in Strongly Coupled QGP

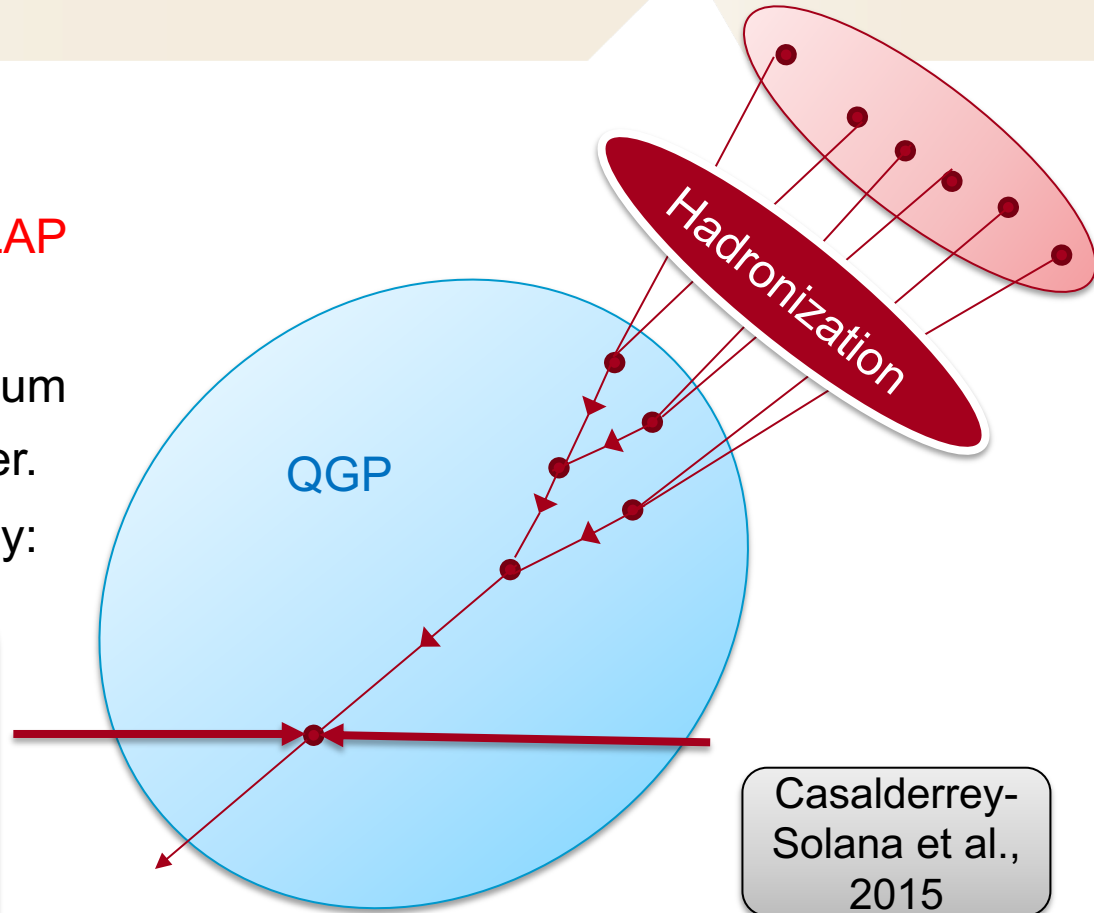
- High  $Q^2$  parton shower up until hadronization described by **DGLAP** evolution (PYTHIA).
- For QGP with  $T \sim \Lambda_{QCD}$ , the medium interacts strongly with the shower.
  - Energy loss from holography:

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

$O(1)$  fit const.

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

$$\tau = \frac{2E}{Q^2}$$



Casalderrey-Solana et al., 2015

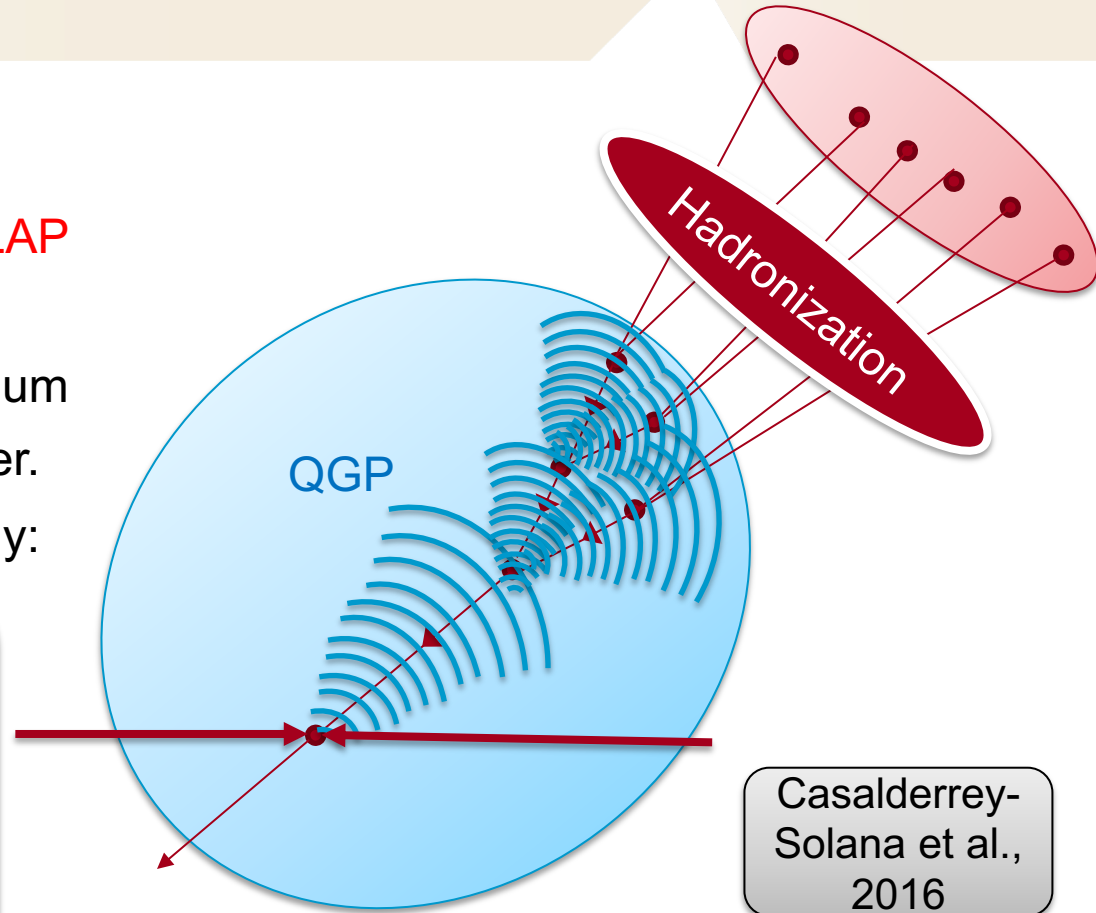
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$x_{stop} = \frac{1}{2\kappa_{sc}} \frac{E_{in}^{\frac{3}{4}}}{T^{\frac{3}{4}}}$	$\tau = \frac{2E}{Q^2}$
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Energy and momentum conservation  $\longrightarrow$  deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3} \int \tau dx dy d\eta_s m_T \cosh(y - \eta_s) \left[ f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right) \right]$$

# An Estimate of Backreaction

Perturbations on top of a Bjorken flow

$$\Delta P_{\perp}^i = w\tau \int d\eta d^2x_{\perp} \delta u_{\perp}^i \quad \Delta S = \tau c_s^{-2} s \int d\eta d^2x_{\perp} \frac{\delta T}{T}$$
$$\Delta P^{\eta} = 0 \quad c_s^2 = \frac{s}{T} \frac{dT}{ds}$$

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

One body distribution

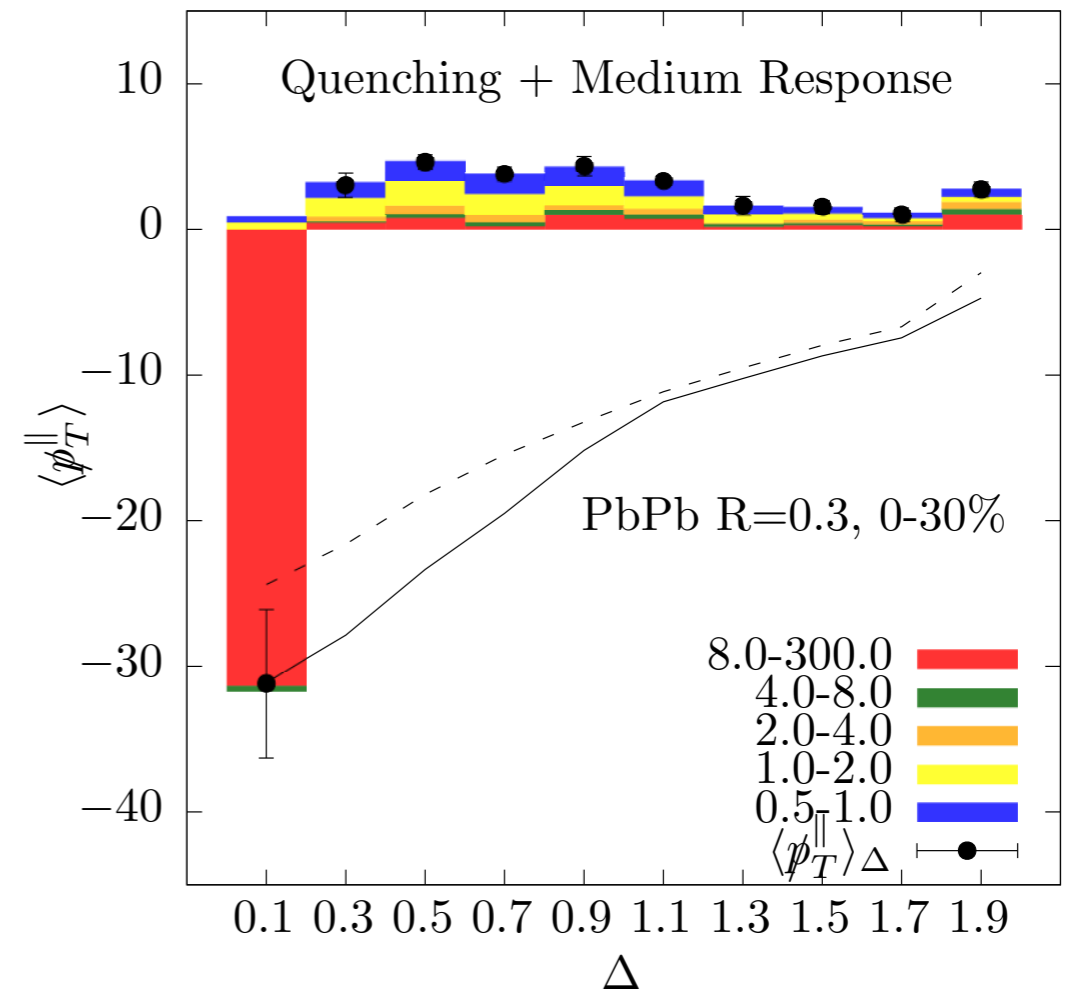
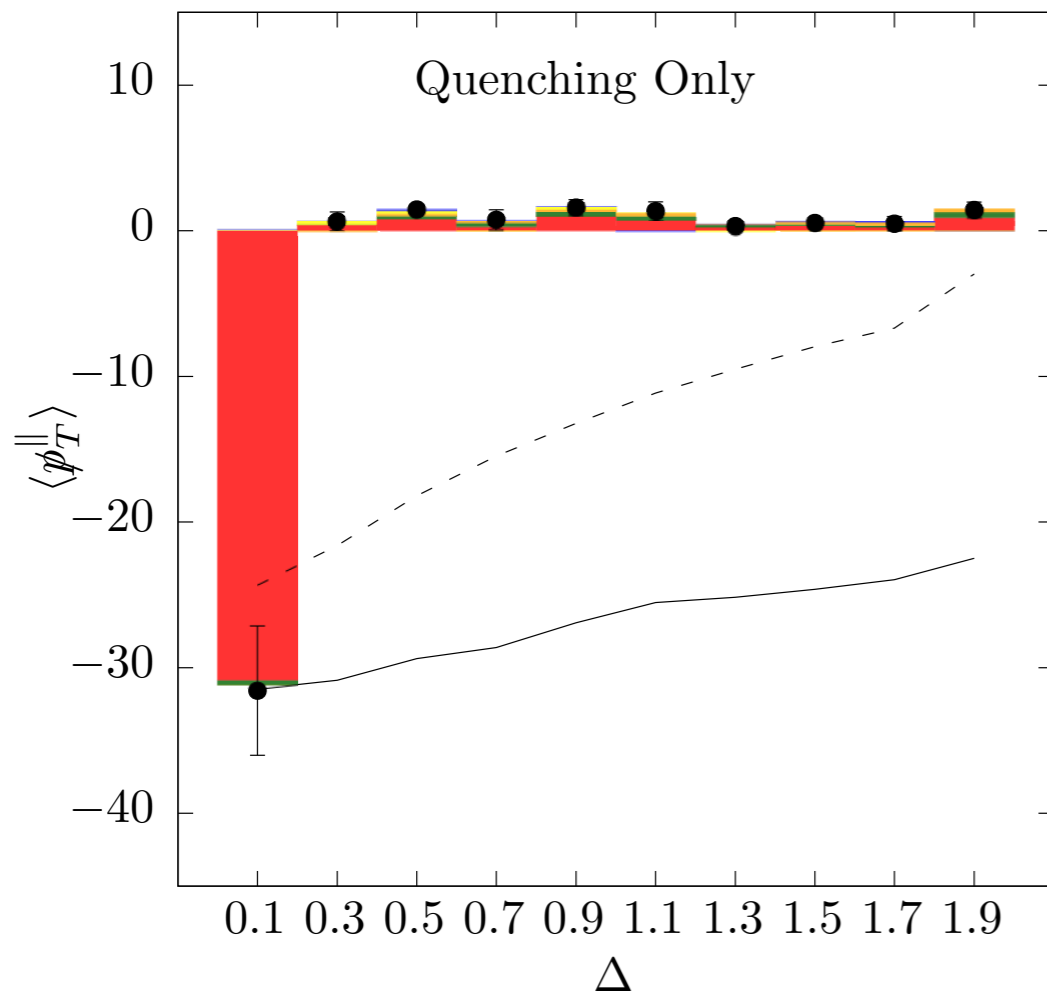
$$E \frac{dN}{d^3p} = \frac{1}{32\pi} \frac{m_T}{T^5} \cosh(y - y_j) e^{-\frac{m_T}{T} \cosh(y - y_j)}$$
$$\left[ p_T \Delta P_T \cos(\phi - \phi_j) + \frac{1}{3} m_T \Delta M_T \cosh(y - y_j) \right]$$



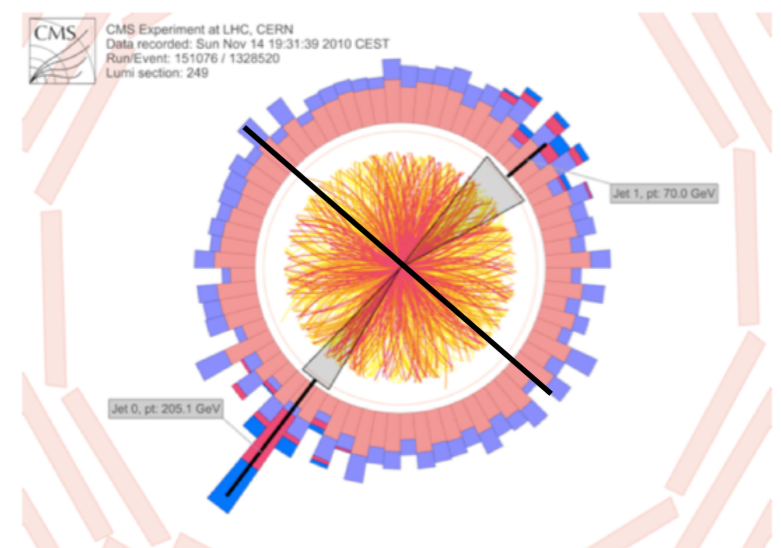
# Missing $p_T$ observables – 2016

- Adding the soft particles from the wake is necessary if we aim to describe data. It also seems that our treatment of the wake does not fully capture what the data calls for.
- If goal is seeing larger angle scattering of partons in the jet, ignore the wake, look at observables sensitive to 5-20 GeV partons; groomed jet substructure observables.
- Lets focus on wake: what was key oversimplification?
- We *assumed* that the wake rapidly equilibrates, and 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. This is natural at strong coupling.
- We assumed the perturbations to the final state spectra due to the wake are small at all  $p_T$ . Need not be so at intermediate  $p_T$ .
- To diagnose how well these approximations are justified in reality we need more sophisticated observables...

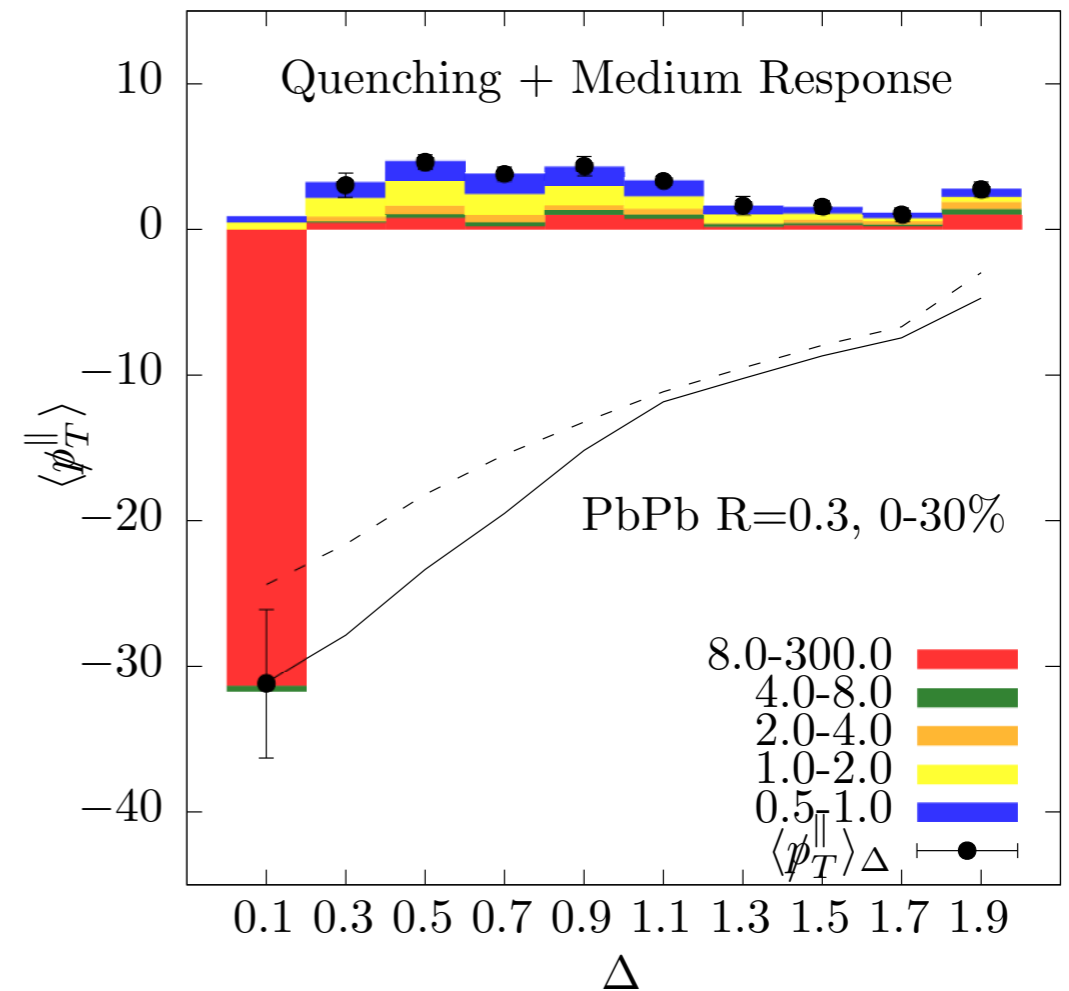
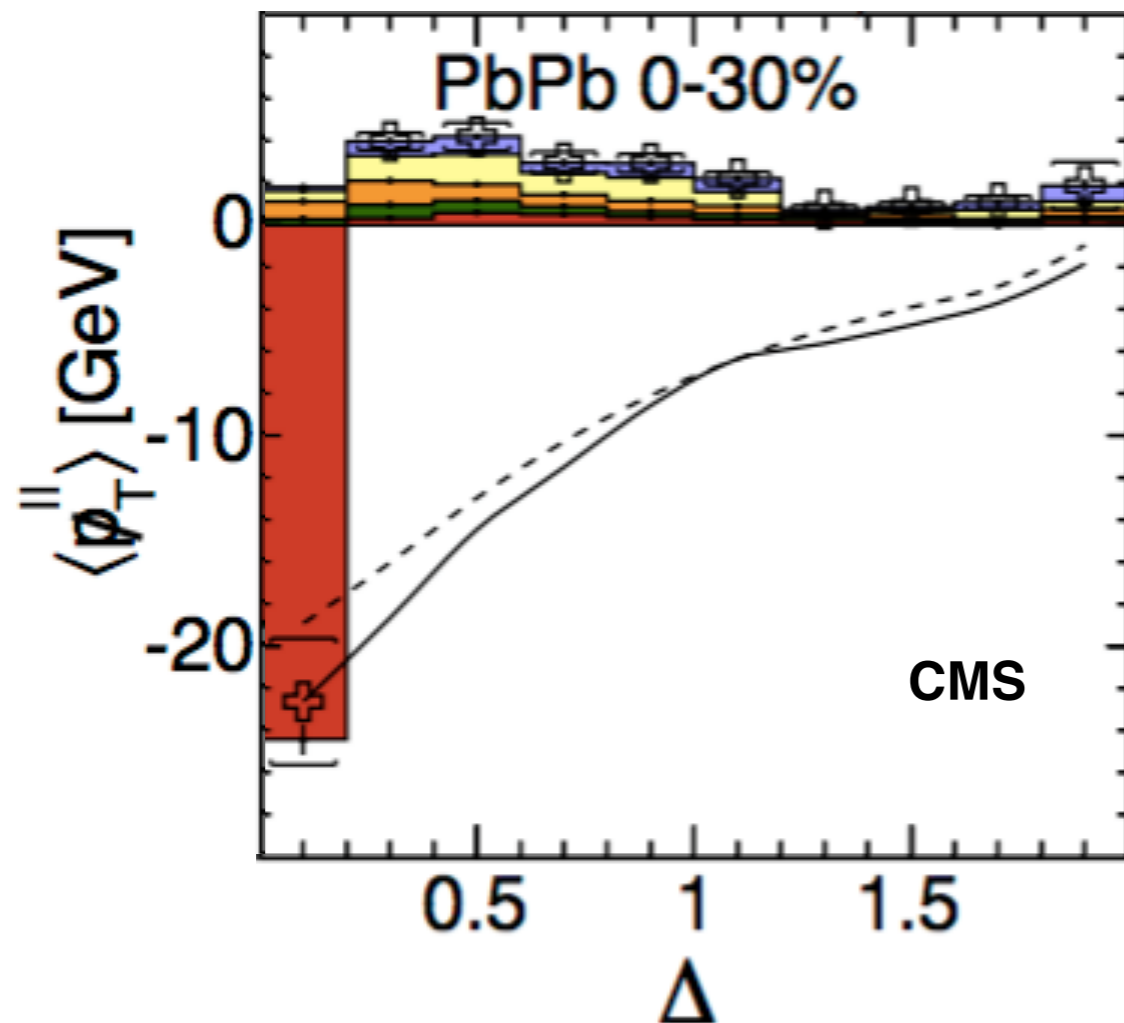
# Recovering Lost Energy: Missing Pt



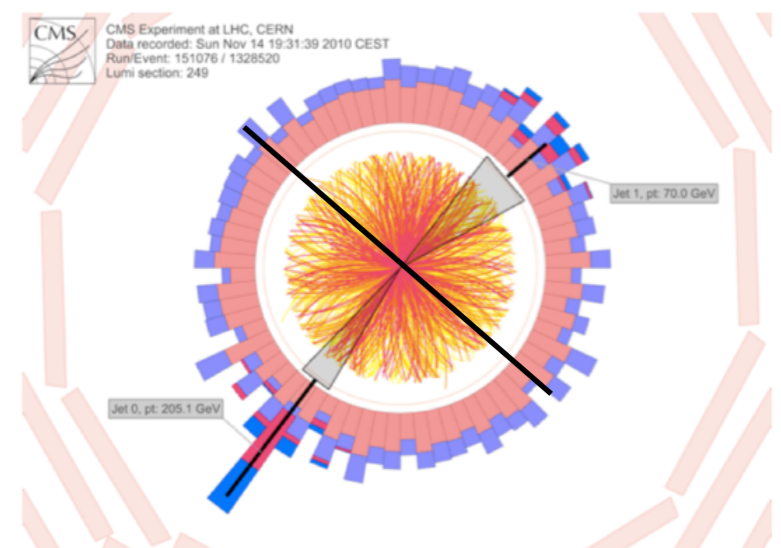
- Energy is recovered at large angles in the form of soft particles
- Adding medium response is essential for a full understanding of jet quenching



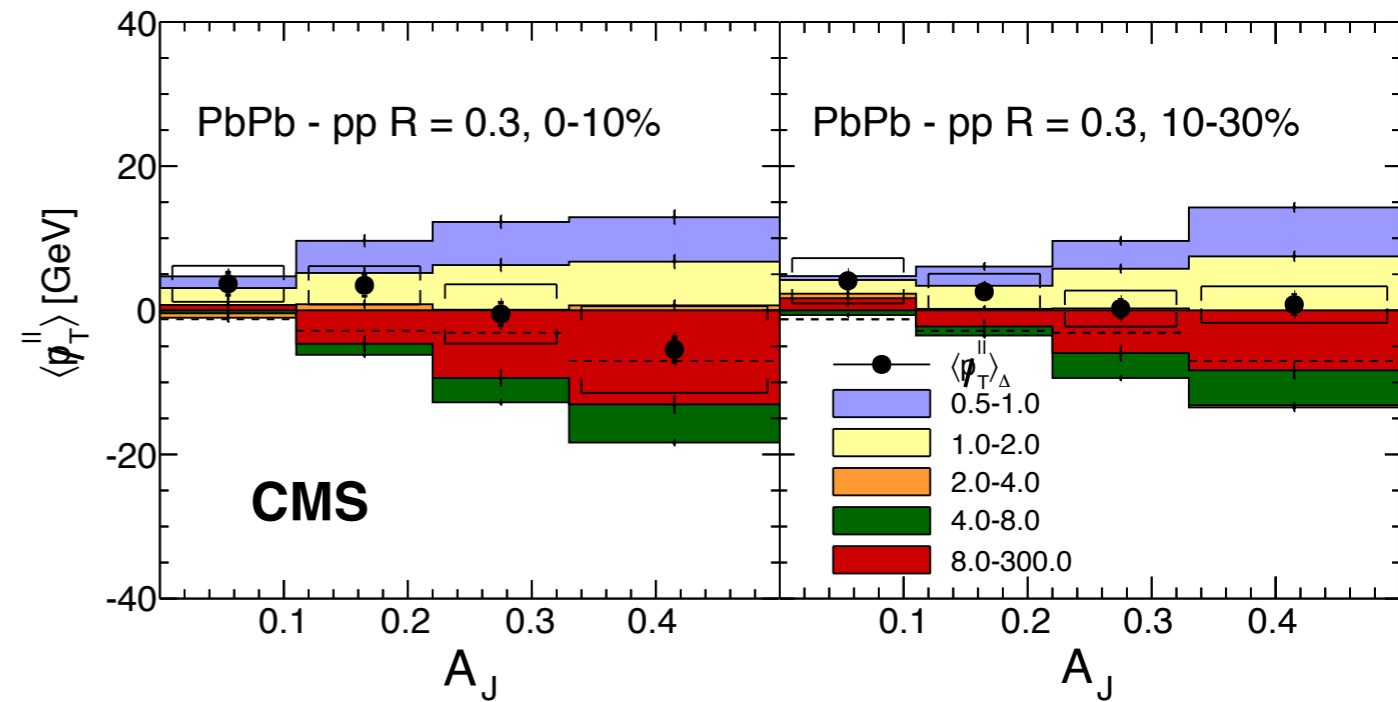
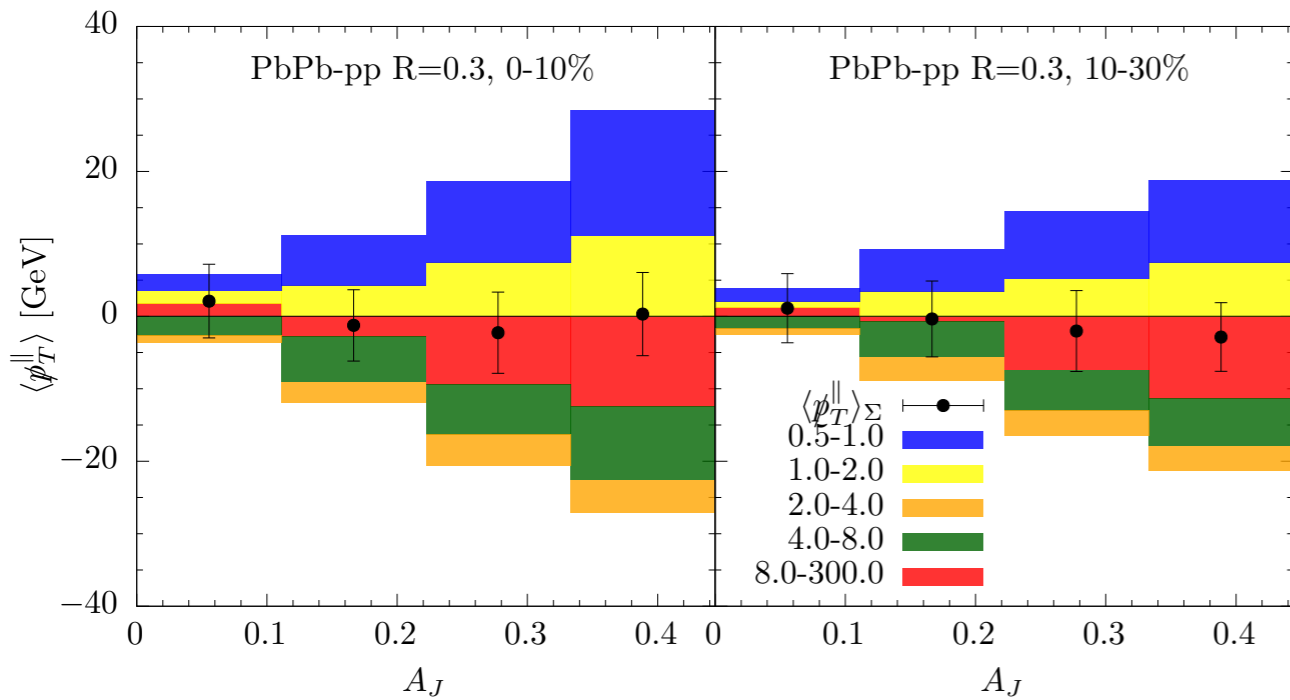
# Recovering Lost Energy: Missing Pt



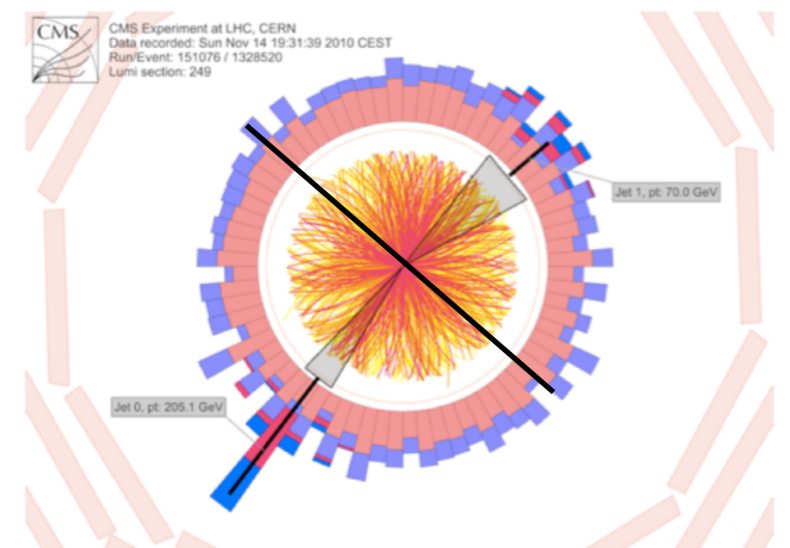
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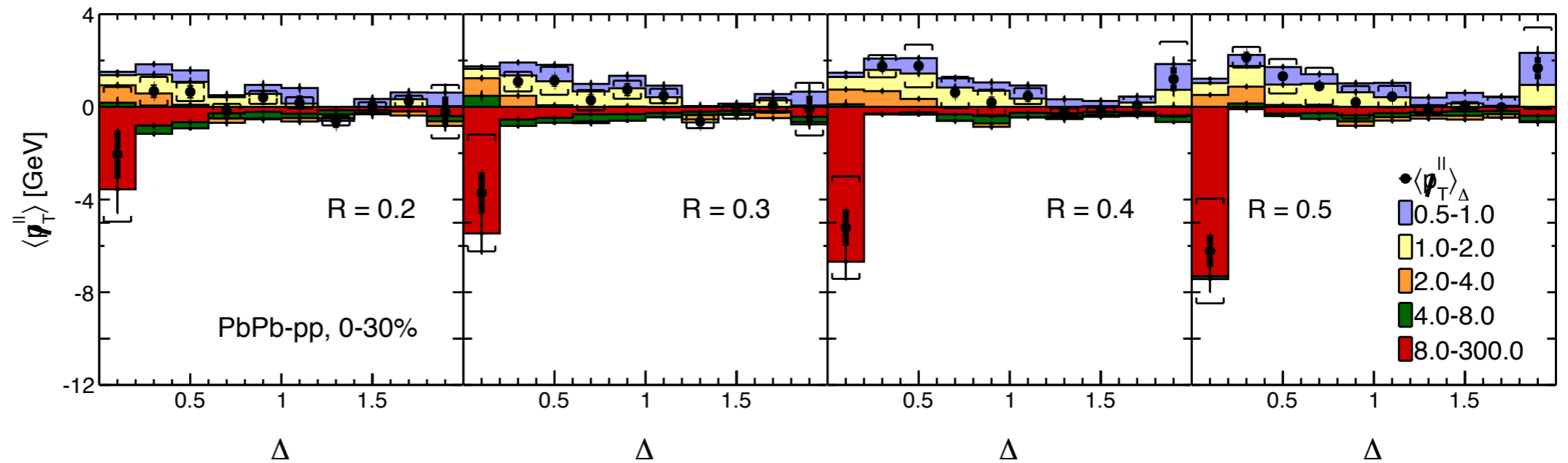
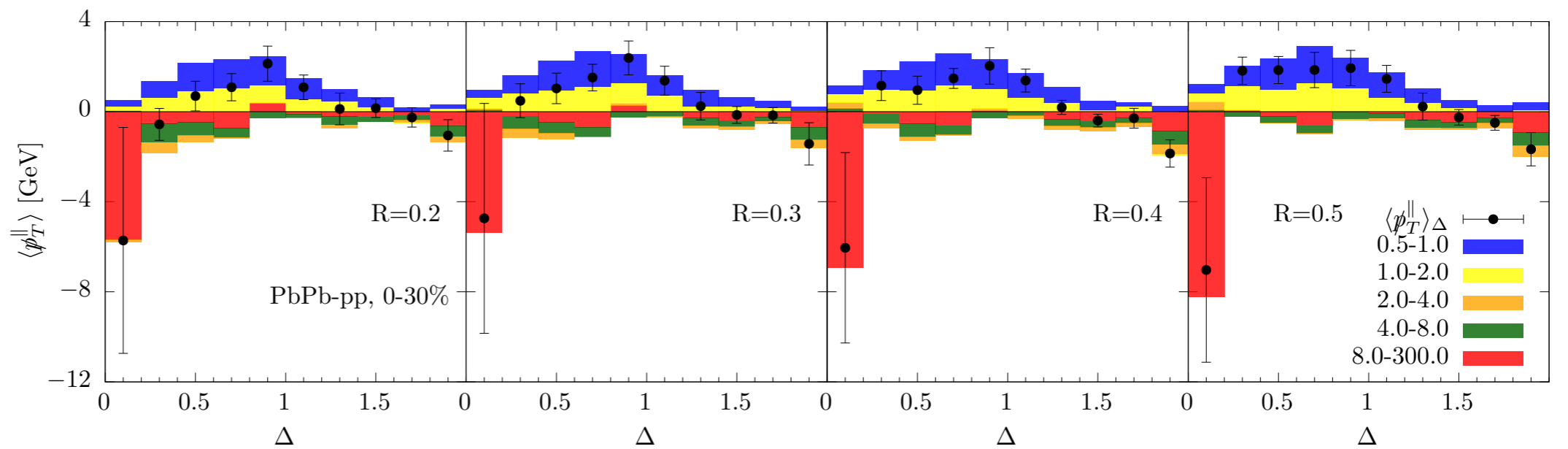
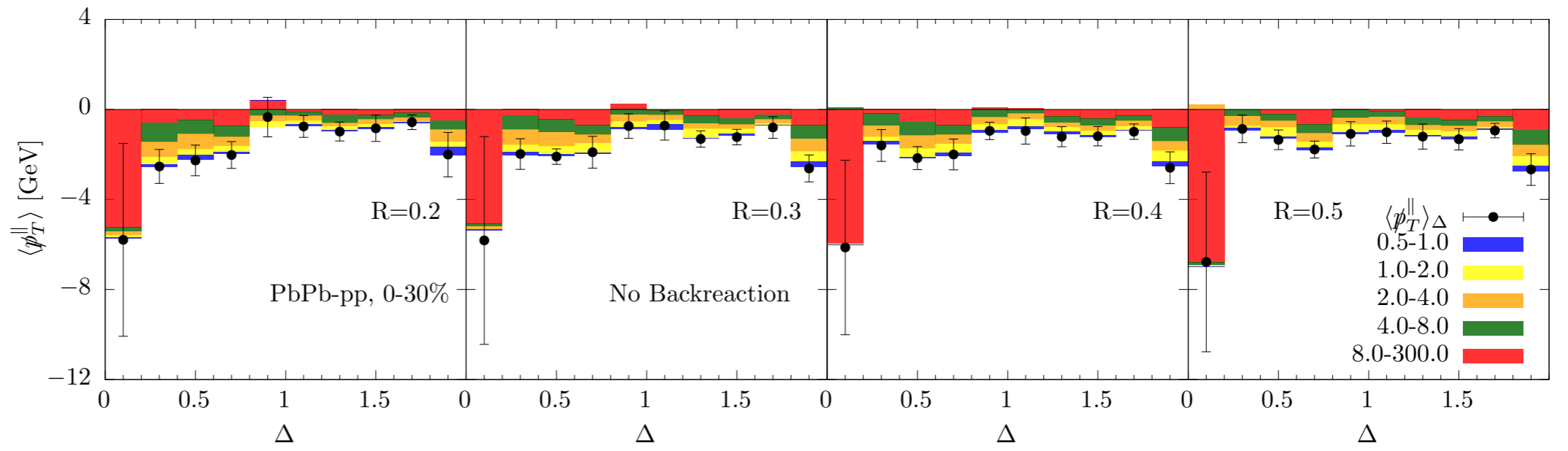
# Recovering Lost Energy: Missing Pt



- In PbPb, more asymmetric dijet events are dominated by soft tracks in the subleading jet side
- Discrepancies w.r.t. data in the semi-hard regime motivate improvements to our model



Jet radius dependence of Missing Pt



# Missing $p_T$ observables – 2016

- Our characterization of the wake is on the right track. BUT:
- We have too many particles with  $0.5 \text{ GeV} < p_T < 2 \text{ GeV}$ .
- We have too few particles with  $2 \text{ GeV} < p_T < 4 \text{ GeV}$ .
- The energy and momentum given to the plasma by the jet may 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.
- Others, using other calculational frameworks, should add background, include the wake, subtract background, and compare to data on Missing- $p_T$  observables. Can we determine whether the energy lost by the jet — namely the wake in the plasma — does not fully thermalize, remembering more than just its energy and momentum?

# Jets as Probes of QGP

- Theorists taking key steps...
- Disentangling jet modification from jet selection.
- Showing that hot quark soup (QGP) *can* resolve structure within jet shower.
- Calculations of the dynamics of jet wakes in droplets of QGP, identification of new experimental observables, and predictions that will enable experimental measurements to “see” the particles coming from these wakes.
- Identifying those jet substructure observables that *are* sensitive to scattering of jet quarks/gluons off QGP quarks/gluons, “seeing” the latter à la Rutherford, and are *not* sensitive to particles coming from the wake.
- Next several years will be the golden age of jet physics: sPHENIX, LHC runs 3 and 4, new substructure observables. *Many* theory advances, and analyses of today’s data, whet our appetite for the feast to come.
- We shall learn about the microscopic structure of QGP, and the dynamics of rippling QGP.

# Jets as Probes of QGP

- Jet wakes in droplets of QGP.
  - Momentum/energy “lost” by parton shower → wake in the fluid → spray of soft hadrons, many in the jet. Jets in HIC are not just the parton shower hadronized.
  - To use jets as probes, must calculate, or understand+avoid, wake. Wake also interesting: study equilibration.
  - Crude calculation of particles in jet originating from wake has been a part of the Hybrid Model since 2016, it’s weaknesses and strengths known...
  - Full hydrodynamic calculation of wake due to every parton in every jet in a sample of 100,000 jets is unfeasible. Jet wake from *linearized* hydrodynamics will suffice, and will modify Hybrid Model predictions for soft particles in jets in the direction indicated by data: 2010.01140 Casalderrey-Solana, Milhano, Pablos, KR, Yao
  - Use the linearity of linearized hydro to speed up calculation of wake by  $\sim 10,000$  and of its hadronization by  $\sim 100$  (in progress).



# A New Angle on Visualizing Jet and Wake Substructure

Krishna Rajagopal

MIT

work in progress with

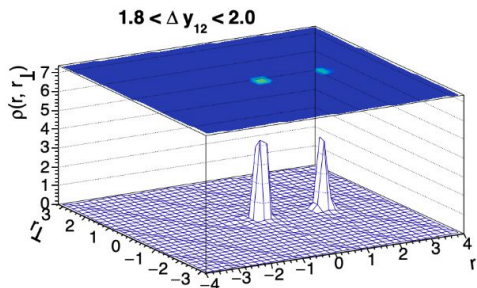
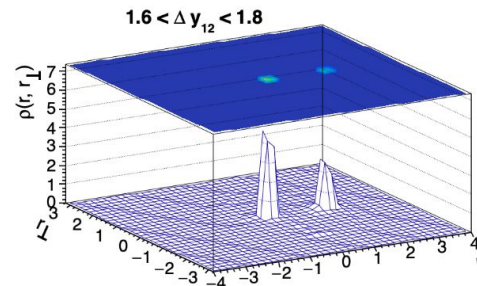
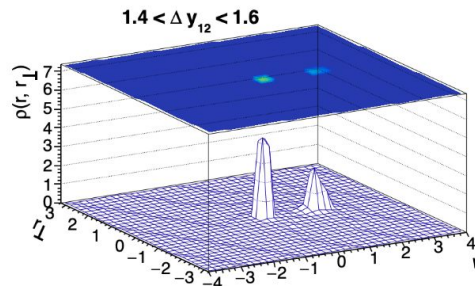
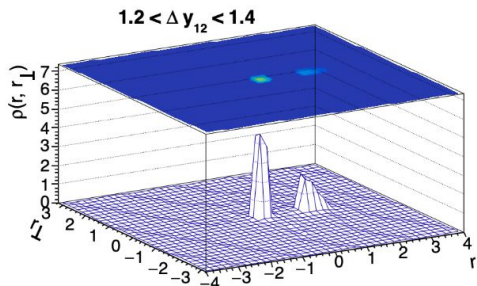
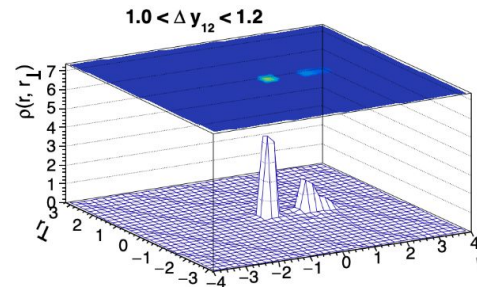
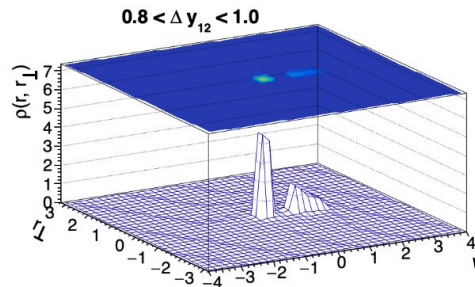
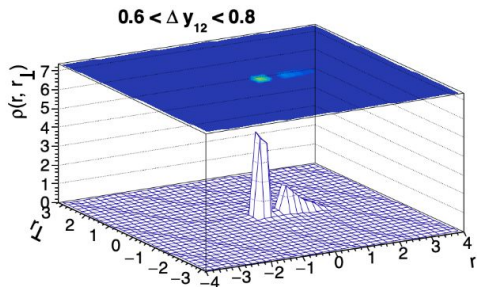
Arjun Kudinoor (Cambridge University)

Dani Pablos (Universidad de Santiago de Compostela)

# Do Subjets Have Separate Wakes?

- A question prompted by an interesting observable, introduced by ATLAS at QM19. See 2301.05606.
- First reconstruct anti- $k_t$ - $R = 0.2$  jets, call them subjets, with  $p_T^{\text{subjet}} > 35$  GeV; then reconstruct anti- $k_t$ - $R = 1.0$  jets from these objects.
- ATLAS finds  $R_{AA}$  for  $R = 1.0$  jets with 1 ( $\geq 2$ ) subjets is less (more) suppressed. For jets with 2 subjets, look at angular separation and splitting parameter.
- Another perspective: a way to find events with two skinny  $R = 0.2$  (sub)jets with a specified separation  $\Delta R_{12}$ . Then, look at all the particles in such events and ask about the shape of the wake of this two-pronged object.
- In a model, we can turn the wake off and on. Use this ability to learn how to use this observable, this tool, to learn something interesting from data.
- For today an aside: Moliere scattering effects are small in magnitude; motivates repeating this study with lower- $p_T$  subjets.

# JET SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS



**Pb+Pb (No Elastic), 5.02 TeV, 0-5%**

**Reclustered  $R = 2.0$  jets with up to 2 subjets**

**$|y| < 2.0$   $50 < p_T < 1000$  GeV**

**All particles within  $R = 2.0$  radius of reclustered jet axis**

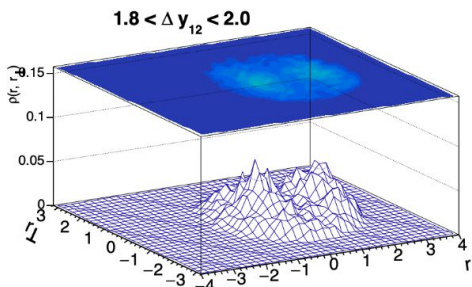
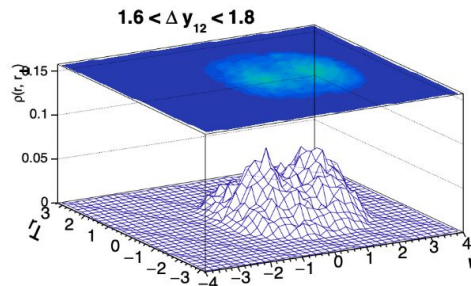
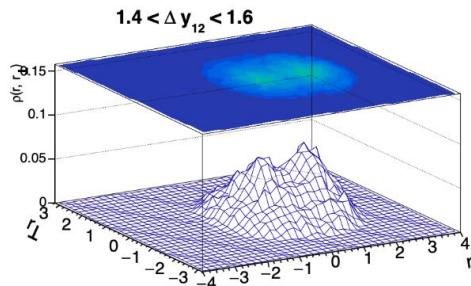
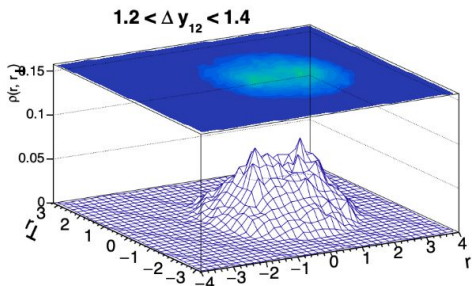
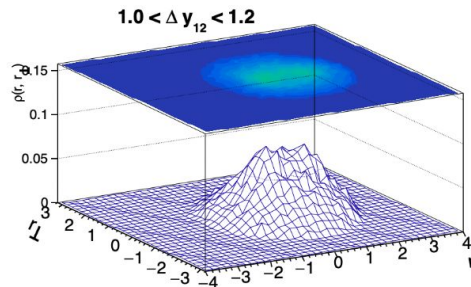
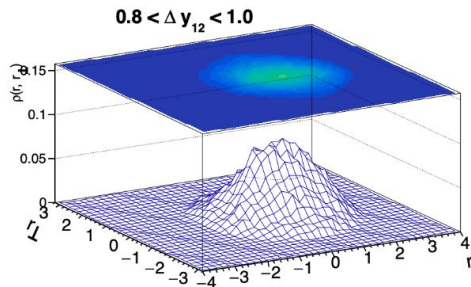
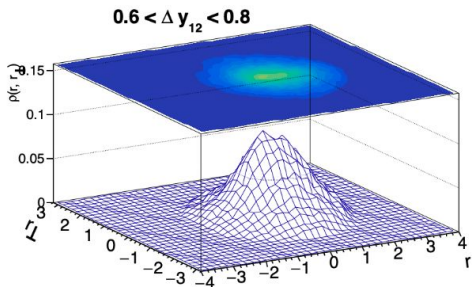
**Photon selection and isolation criteria:**

**$p_T^\gamma > 100$  GeV  $|\eta^\gamma| < 1.44$**

**Around  $R = 0.4$  of  $\gamma$ ,  $\Sigma E_T < 5.0$  GeV**

**$\Delta\phi(\gamma, \text{jet}) > 2\pi/3$**

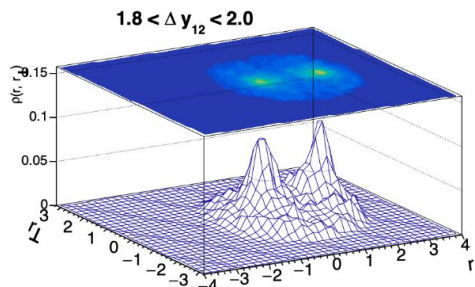
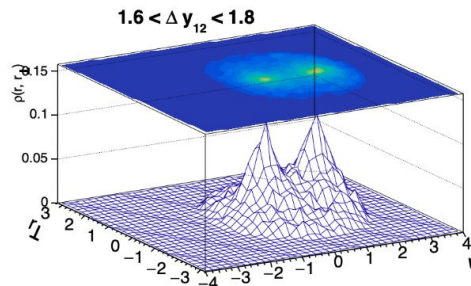
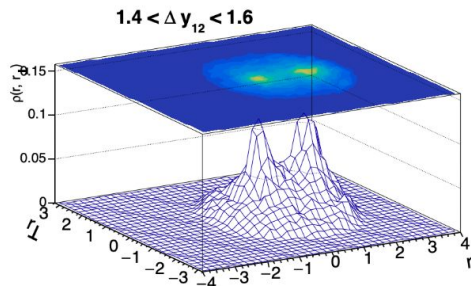
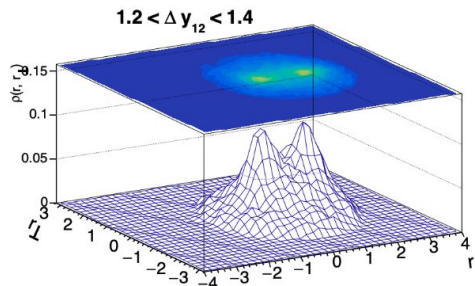
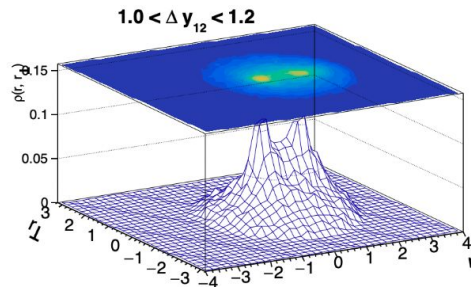
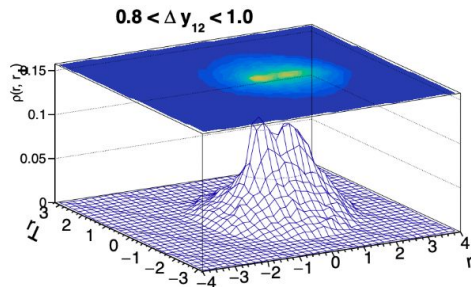
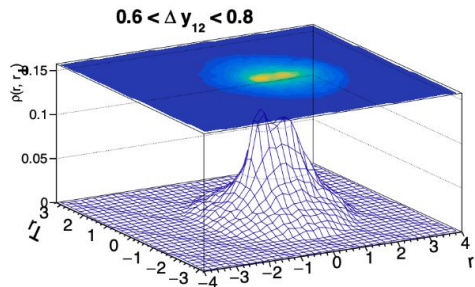
# WAKE SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS



Even when subjects are separated by  $\Delta y_{12} < 1.0$ , there is a single wake produced by 2 hard structures (the subjects). **Two distinct sub-wakes are visibly produced only when the subjects are quite far-separated (around  $\Delta y_{12} > 1.4$ )!**

How can we see this in experiments?

# SHAPE OF PARTICLES WITH $p_T < 1.5$ GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

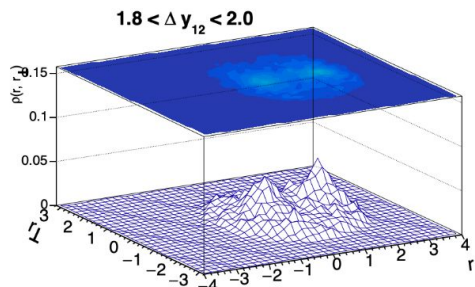
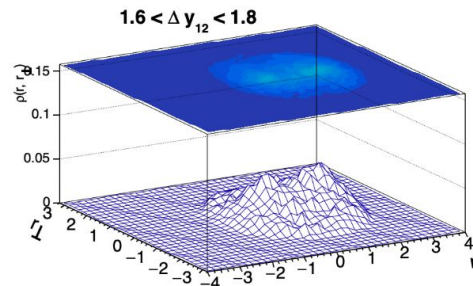
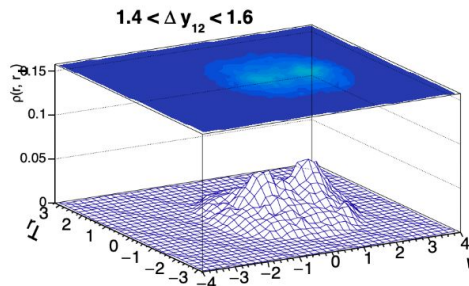
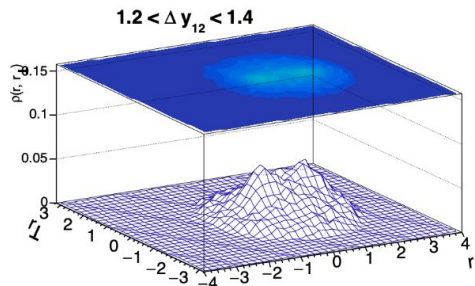
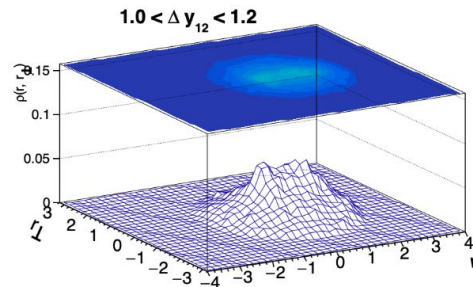
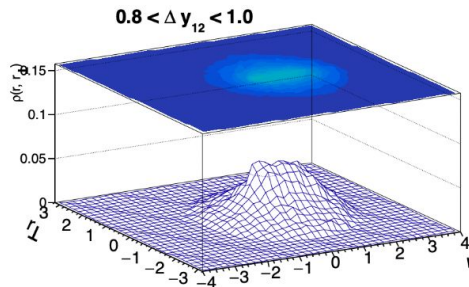
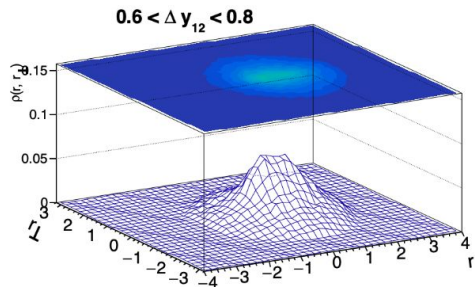


Experimentalists look for the wake by restricting to observing particles with low- $p_T$ .

If we restrict to calculating the jet shape for particles with  $p_T < 1.5$  GeV, then **it begins to resemble the shape of the wake.**

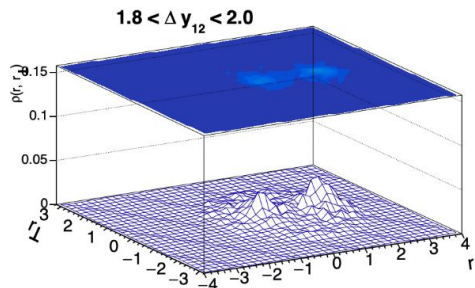
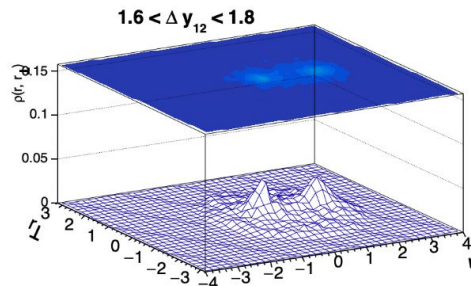
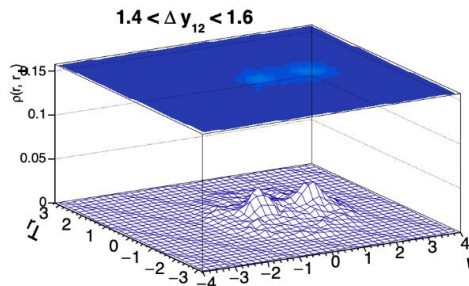
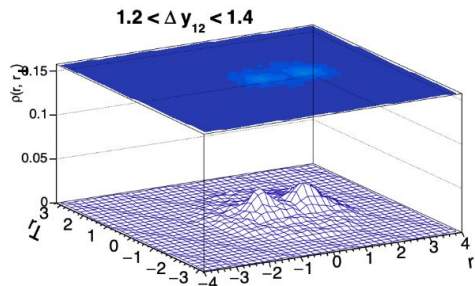
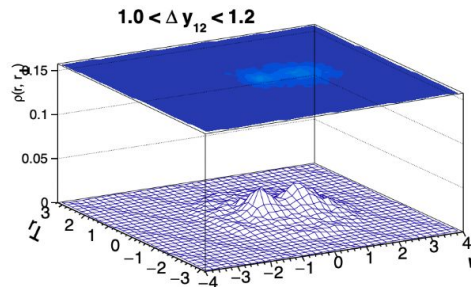
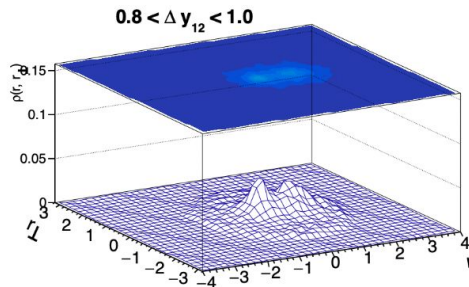
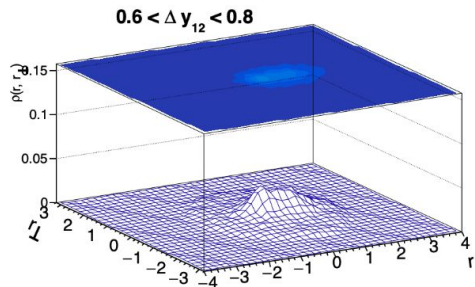


# SHAPE OF PARTICLES WITH $p_T < 1.0$ GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS



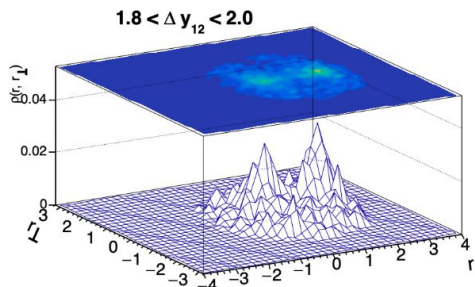
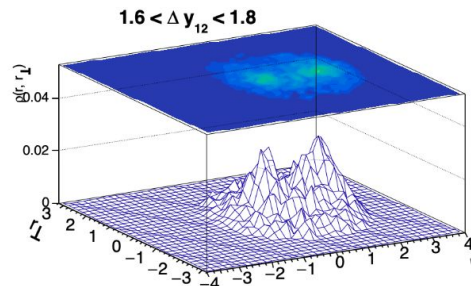
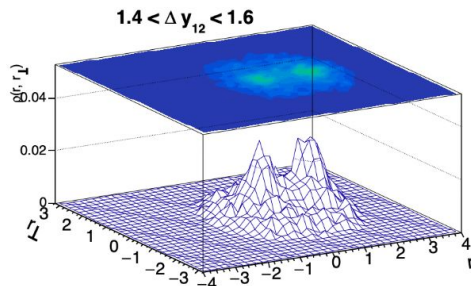
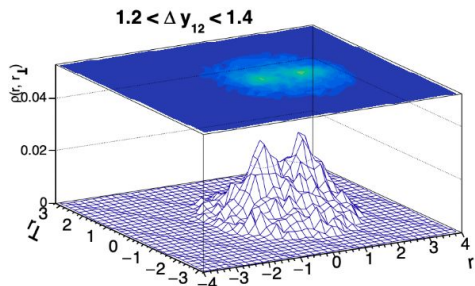
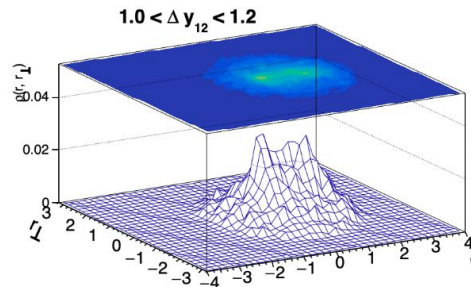
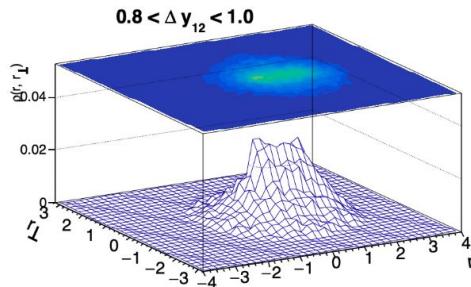
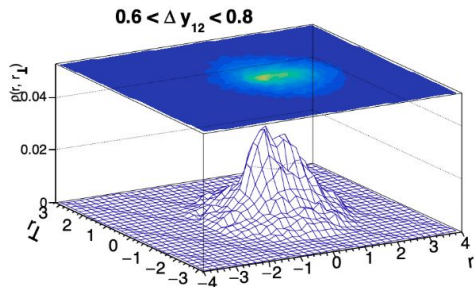
When restricting to particles with  $p_T < 1.0$  GeV, the jet shape looks quite similar to the wake. In particular, a single broad soft structure is observed when  $\Delta y_{12} < 1.0$ , and two distinct soft structures are visible when  $\Delta y_{12} > 1.4$ .

# SHAPE OF PARTICLES WITH $p_T < 1.0$ GeV IN GAMMA-JETS IN pp COLLISIONS WITH 2 SUBJETS



At very low  $p_T$  of less than 1.0 GeV, there are still two distinct peaks in the vacuum (pp) case... even when the subjects are closely-separated!

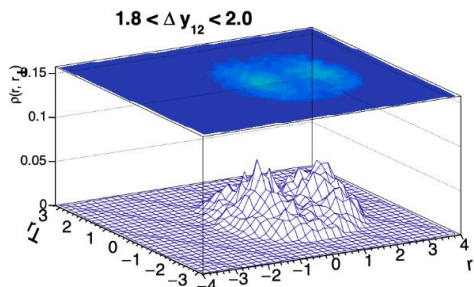
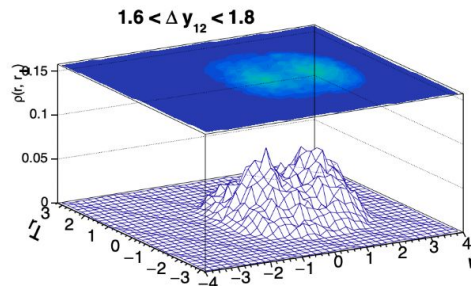
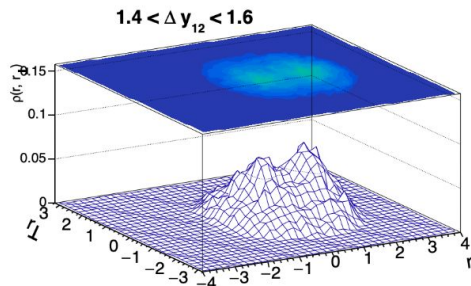
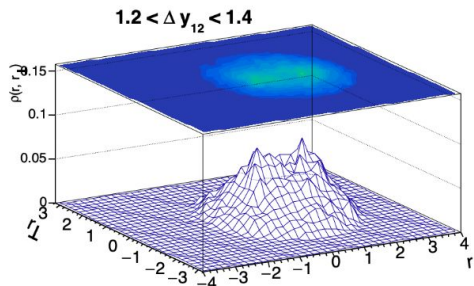
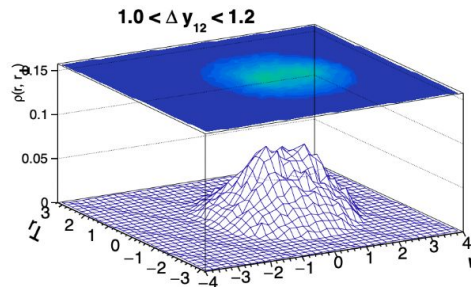
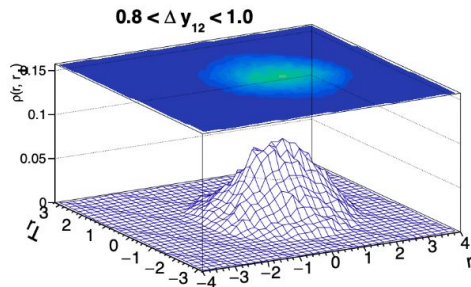
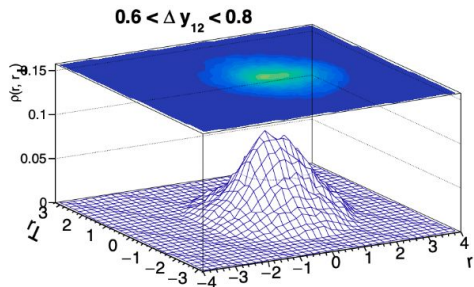
# SHAPE OF PARTICLES WITH $0.7 < p_T < 1.0$ GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS



When restricting to particles with  $0.7 < p_T < 1.0$  GeV, the feature of sub-wake emergence only at large  $\Delta y_{12}$  survives! So, this feature of wake substructure could survive experimental background subtraction.



# WAKE SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS



Even when subjects are separated by  $\Delta y_{12} < 1.0$ , there is a single wake produced by 2 hard structures (the subjects). **Two distinct sub-wakes are visibly produced only when the subjects are quite far-separated (around  $\Delta y_{12} > 1.4$ )!**

How can we see this in experiments?

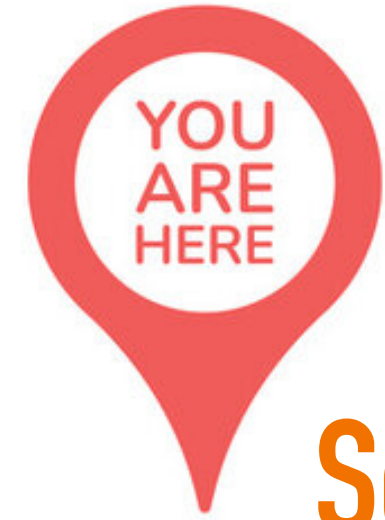
# Do Subjets Have Separate Wakes?

- Only when they are far apart!
- With the crude hybrid model wake: for  $\Delta y > 1.4$ , two separated wakes; for  $\Delta y < 1.0$ , the two skinny subjets (each has  $R = 0.2$ ; well-separated?) have a common wake.
- Particles with  $p_T < 1$  GeV, or with  $0.7 < p_T < 1$  GeV, are good proxies for the wake;  $p_T < 1.5$  GeV is reasonable.
- Note: in pp, the skinny subjets are separate even in these low  $p_T$  bins. Seeing two subjets  $\Delta y \sim 0.8$  apart merge at low  $p_T$  in heavy ion collisions  $\rightarrow$  wake!
- Seeing the wake separate into two subwakes when  $\Delta y$  is large enough visualizes the size of the wake.
- We can further optimize this study, in conversation with experimentalists, to find the best practical ways to use two-skinny-subjet events as a new angle with which to visualize the shape of the (sub)wake(s)!
- The current hybrid model implementation of the wake is crude, and is too wide and too soft. We will improve it. The real point, today, is that we have identified a tool with which experimentalists can visualize (sub)wake(s)!

# Lessons for Energy Correlators

- Hadrons coming from the response of the medium to the parton shower *are* a component of what is reconstructed as a jet in heavy ion collisions. But to date it has been difficult to find and measure jet observables that are unambiguously dominated by this component.
- Beautiful physics of energy correlators in jets in vacuum will be modified in heavy ion collisions, as parton shower is modified. In some kinematic regimes, this beautiful physics will be obscured by particles coming from the wake.
- Examples in Ananya's talk. Qualitatively, consider the effect of what you have just seen on the four-point correlator examples from Ian Mout's talk.
- If the wake can obscure, perhaps in some kinematic regimes it can dominate! → Imaging the shape of the wake via energy-energy-energy correlators!
- Long term: use event selection and correlator engineering to see how wake evolves/dissipates by comparing smaller/larger collisions, smaller/larger path length.

# Imaging the Wakes of Jets with EEECs: Roadmap



**See Ananya's talk next!**

How can projected correlators be used to probe QCD?



**Hannah!**

What new things can the shape-dependent energy-energy-energy correlator add?

**Arjun!**

How do these results depend on coordinate choices and the superposition of wakes?

What are wakes and what is the hybrid model?

# Imaging the Wakes of Jets with Energy-Energy-Energy Correlators

Krishna Rajagopal

MIT

work in progress with

Hannah Bossi (MIT), Arjun Kudinoor (Cambridge),

Ian Moulton (Yale), Dani Pablos (Santiago),

Ananya Rai (Yale)

**BACKUP SLIDES**

# How you can learn from a model

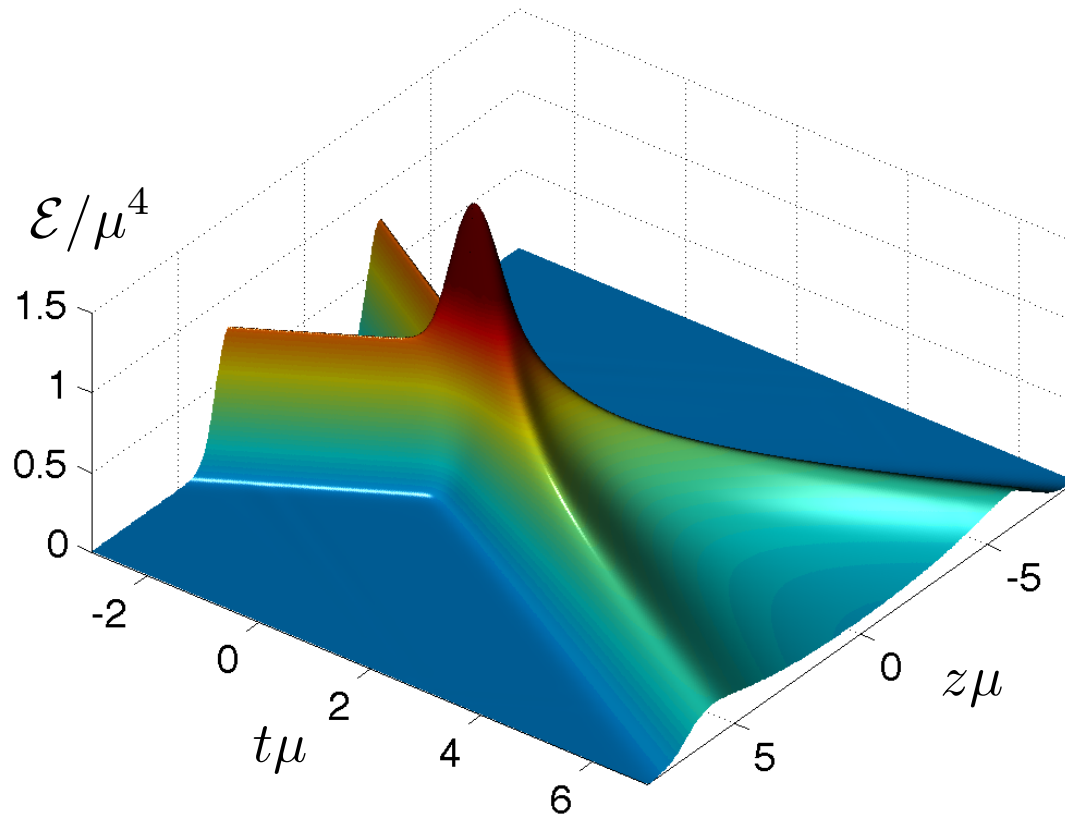
- There are things you can do with a model (here, the Hybrid Model) that you cannot do with experimental data. (Eg, turn physical effects off and on) ...
- ... but that nevertheless teach us important lessons for how to look at, and learn from, experimental data.
- TODAY'S EXAMPLE: identifying which jet observables are more sensitive to the presence of quasiparticles — scatterers — in the QGP-soup. And, which are more sensitive to the wakes that jets make in the soup.
- Disentangling effects of jet modification from effects of jet selection. In simulations; in  $Z+\text{jet}$  or  $\gamma+\text{jet}$  data. 2110.13159 Brewer, Brodsky, KR
- Using jet substructure modification to probe QGP resolution length. Can QGP “see” partons within a jet shower (rather than losing energy coherently)? 1707.05245 ZH, DP, KR; 1907.11248 Casalderrey-Solana, Milhano, DP, KR. (Apparent answer: yes. Eg., 2303.13347 ALICE)
- But first, a *very* brief intro to the Hybrid Model...

# Rapid Equilibration?

- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large  $\eta/s$ ) 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?

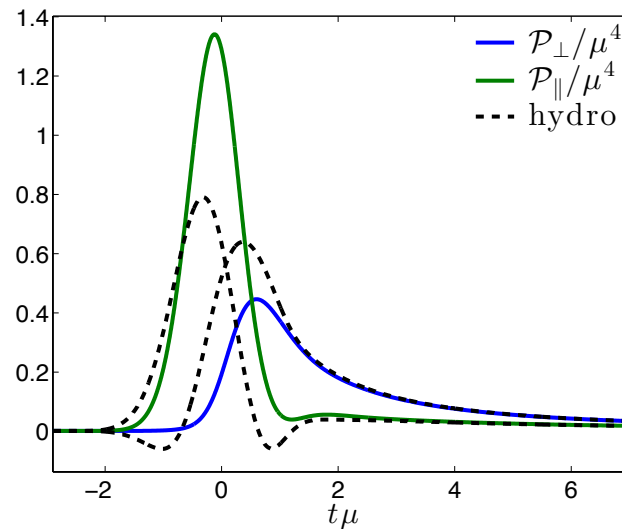


# Colliding Strongly Coupled Sheets of Energy



Hydrodynamics valid  $\sim 3$  sheet thicknesses after the collision, i.e.  $\sim 0.35$  fm after a RHIC collision. Equilibration after  $\sim 1$  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 initial conditions. 1103.3452, 1202.0981, 1203.0755, 1304.5172. **This was the best answer we had circa 2015.**

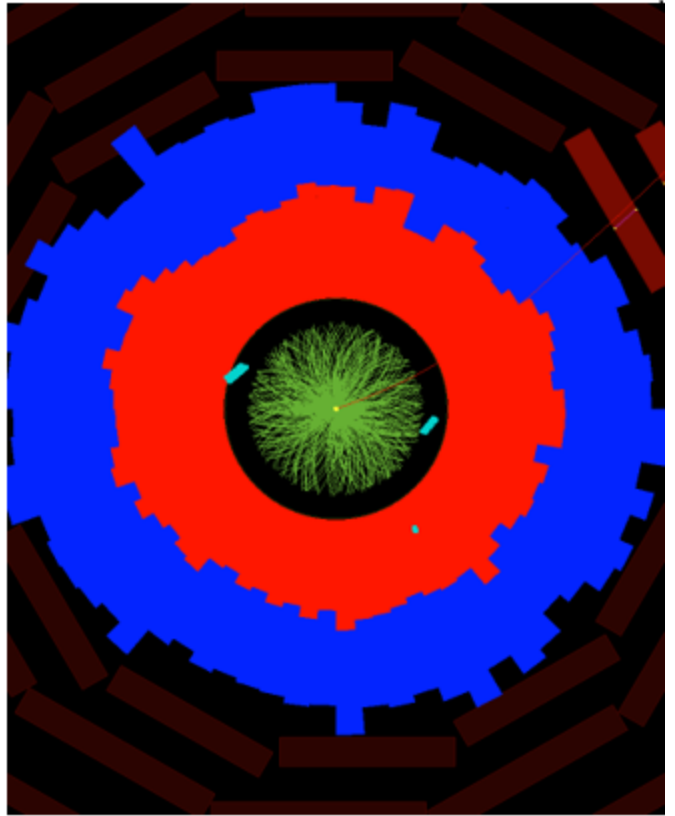
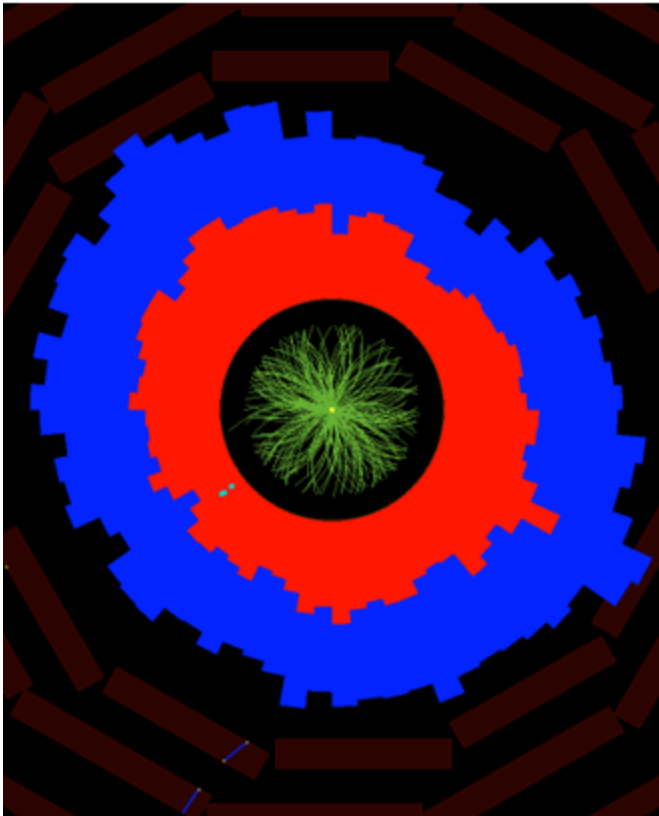
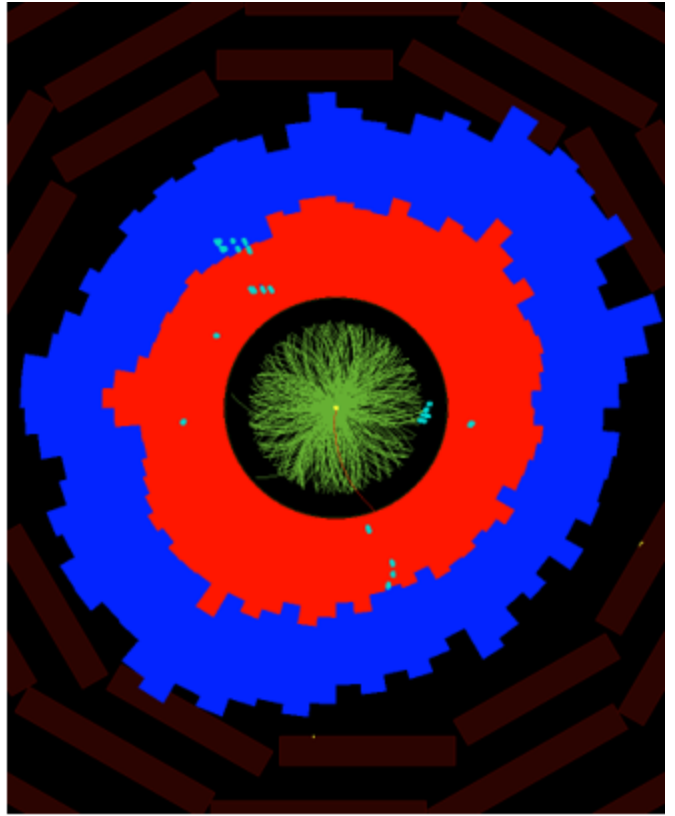
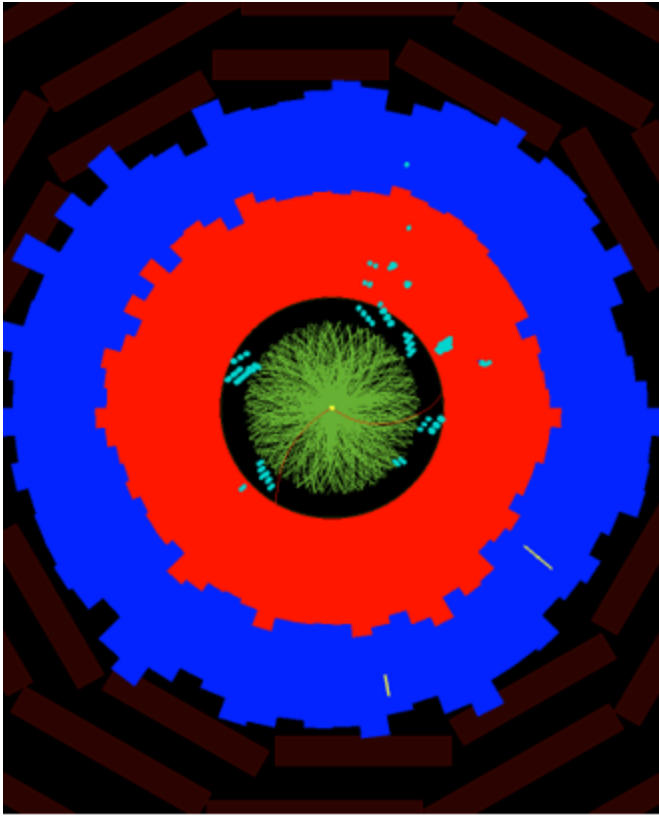
# Anisotropic Viscous Hydrodynamics



Hydrodynamics valid so early that the hydrodynamic fluid is not yet isotropic. ‘Hydrodynamization before isotropization.’ An epoch when first order effects (spatial gradients, anisotropy, viscosity, dissipation) important. Hydrodynamics with entropy production.

This has now been seen in very many strongly coupled analyses of hydrodynamization. Janik et al., Chesler et al., Heller et al., ...

Could have been anticipated as a possibility without holography. But, it wasn’t — because in a weakly coupled context isotropization happens first.



# 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  $\eta/s$  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  $\tau_{qp} \sim (5\eta/s)(1/T) \gg 1/T$ .]
- 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 will turn...  
**But first, what from 2015 Intro must be updated in 2024? Many improvements, but big picture was solid in 2015! I will highlight two ways in which it has been consolidated.**

# 2024 Updates to 2015 Intro

- Much more complete understanding now of how hydrodynamization happens in kinetic theory. A weakly coupled picture, applied at intermediate coupling. Hydrodynamization in  $1 \text{ fm}/c$  is no longer surprising in kinetic theory. Berges, Heller, Kurkela, Mazeliauskas, Paquet, Schlichting, Spalinski, Strickland, Teaney, Zhu...
- We had a qualitative, intuitive, understanding of how it can happen on this timescale at strong coupling in 2015. Now we have a qualitative, intuitive, understanding in kinetic theory also: *adiabatic hydrodynamization*. Brewer, Yan, Yin; Brewer, Scheihing-Hitschfeld, Yin; KR, Scheihing-Hitschfeld, Steinhorst...
- **Quantification! including uncertainty quantification.** Via work of *many* experimentalists and theorists, we now have more, and more precise, experimental data that, together with improved theoretical modeling, are driving Bayesian determinations, by multiple groups, of the “shape” of the fluid at the time of hydrodynamization, and key properties of QGP and their temperature dependence.

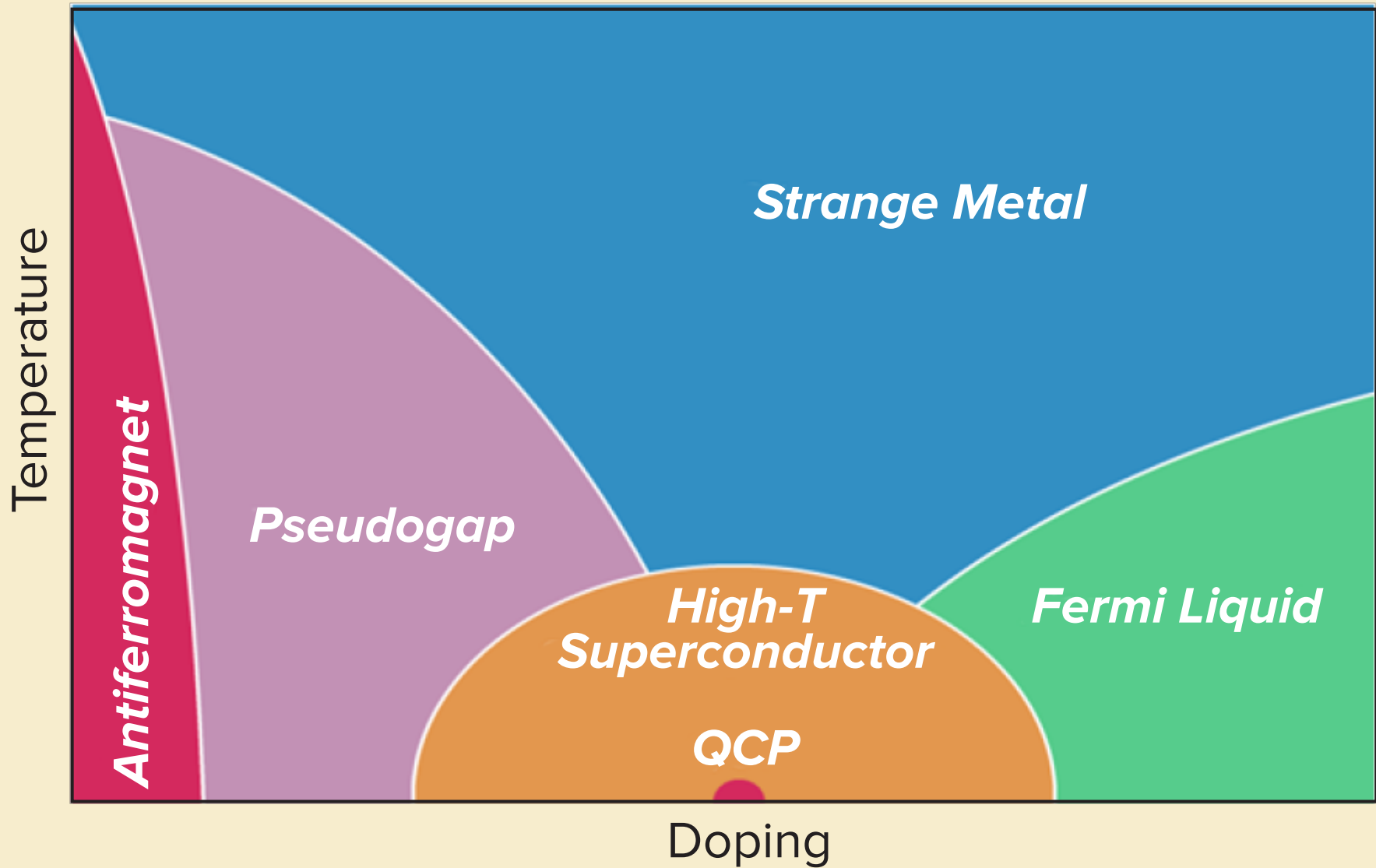
# $\eta/s$ from RHIC and LHC data

- 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 and LHC data on pion and proton spectra and  $v_2$  and  $v_3$  and  $v_4$  and  $v_5$  and  $v_6$  ... 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  $1 < 4\pi\eta/s < 3$ .  
**Nota bene: this was circa 2015.**
- $4\pi\eta/s \sim 10^4$  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.

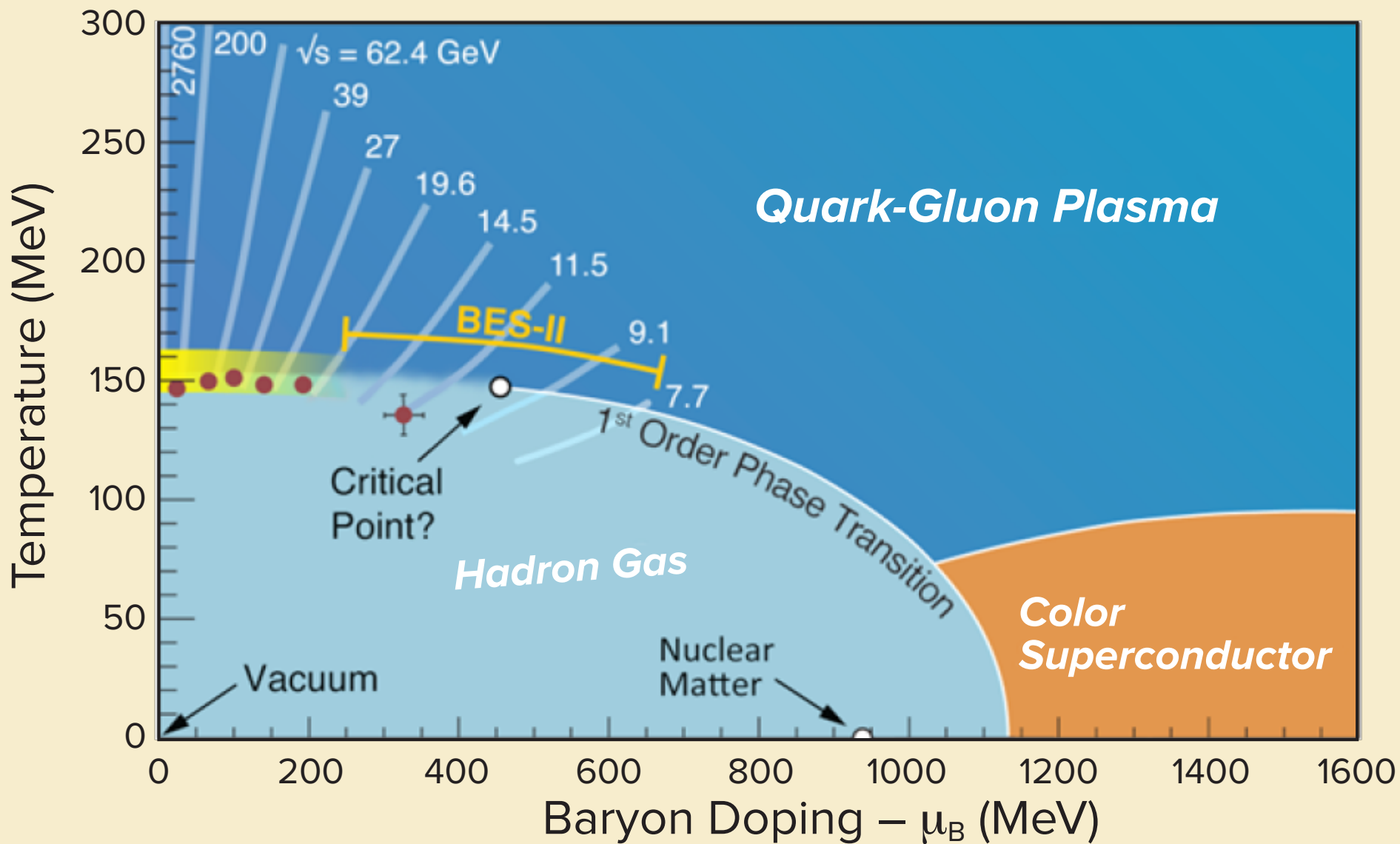
# What Next?

Two kinds of What Next? questions ...

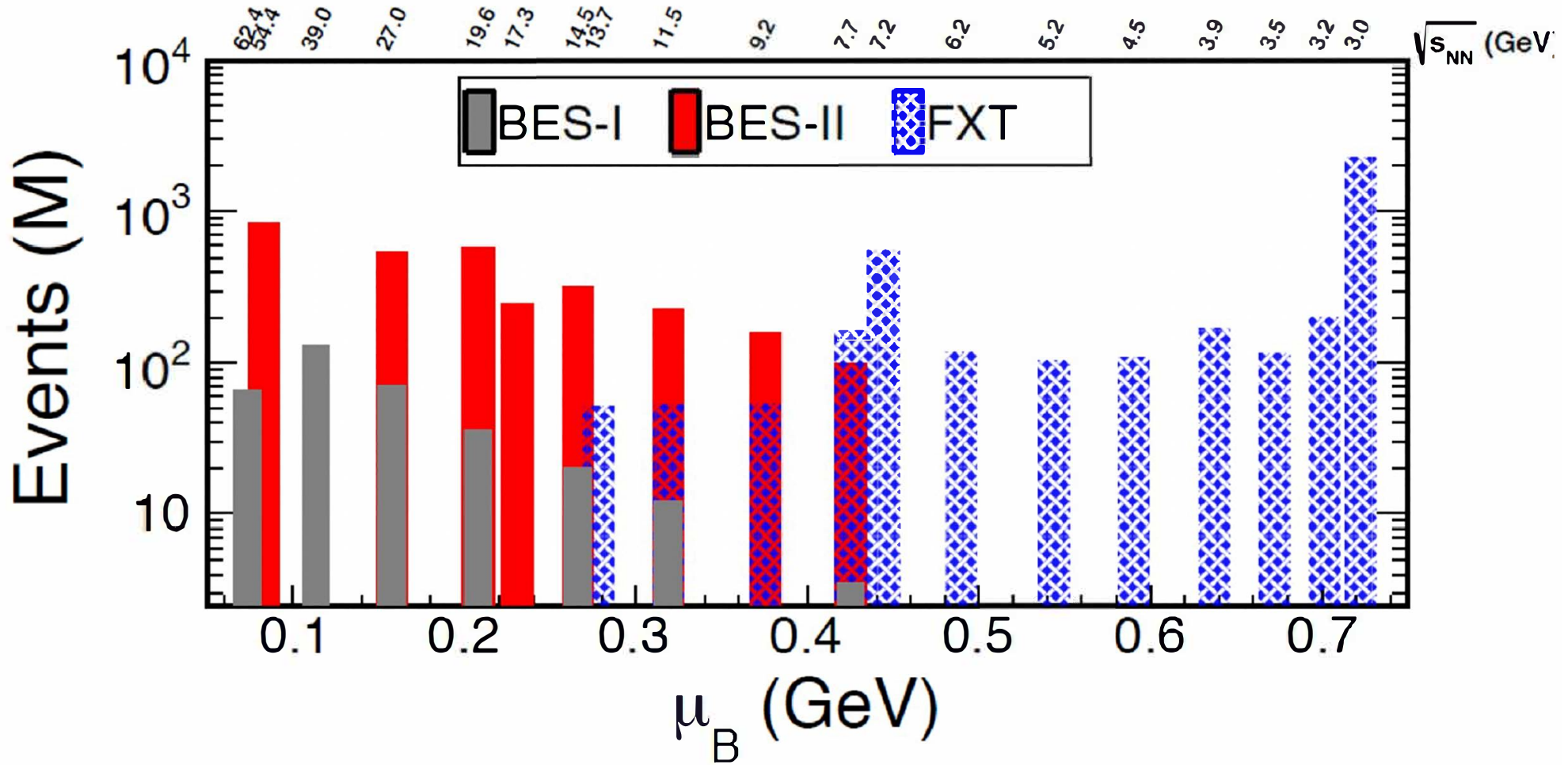
- A question that one asks after the discovery of any new form of complex matter: **What is its phase diagram?** For high temperature superconductors, for example, phase diagram as a function of temperature and doping. Same here! For us, doping means excess of quarks over anti-quarks, rather than an 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.

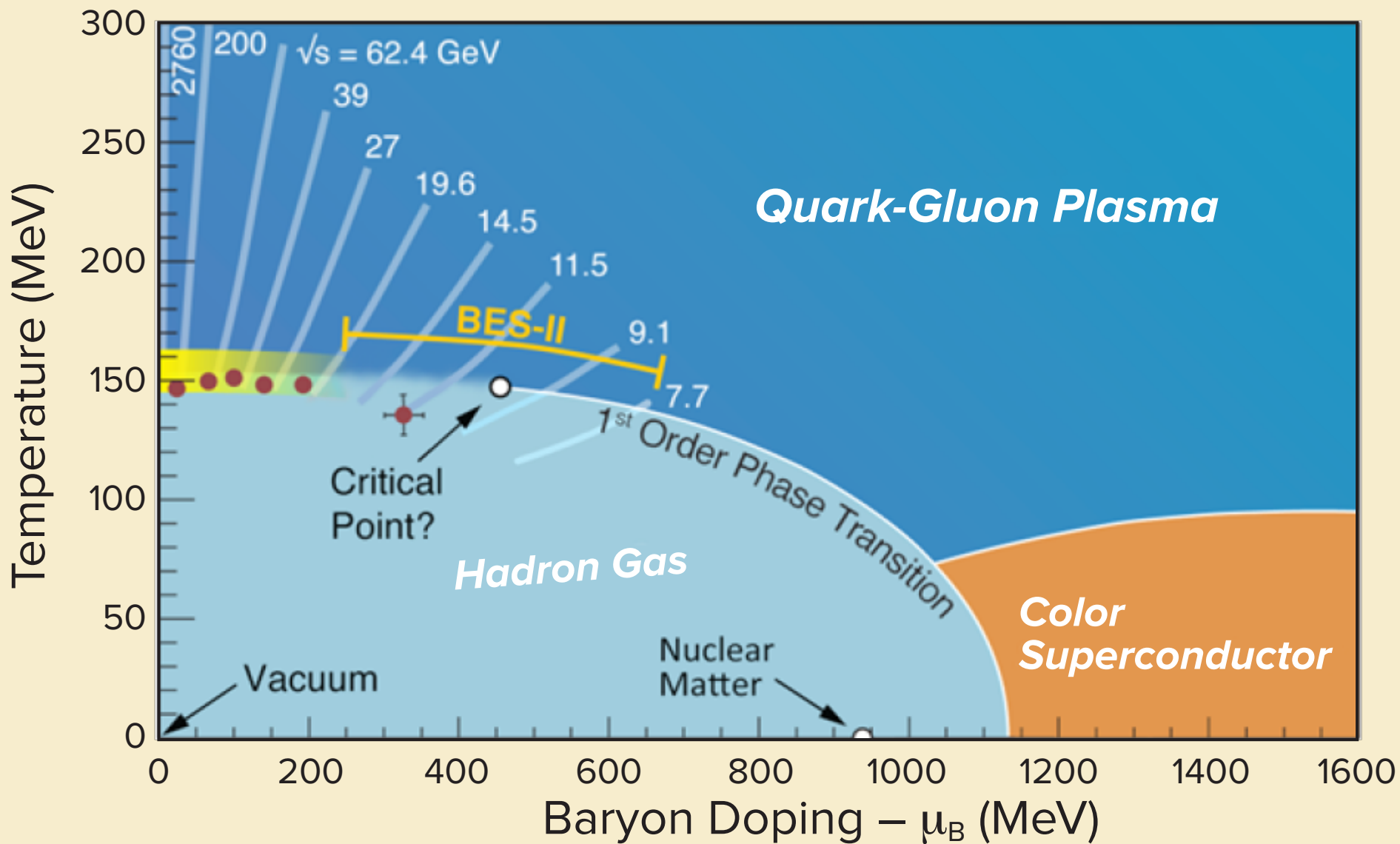




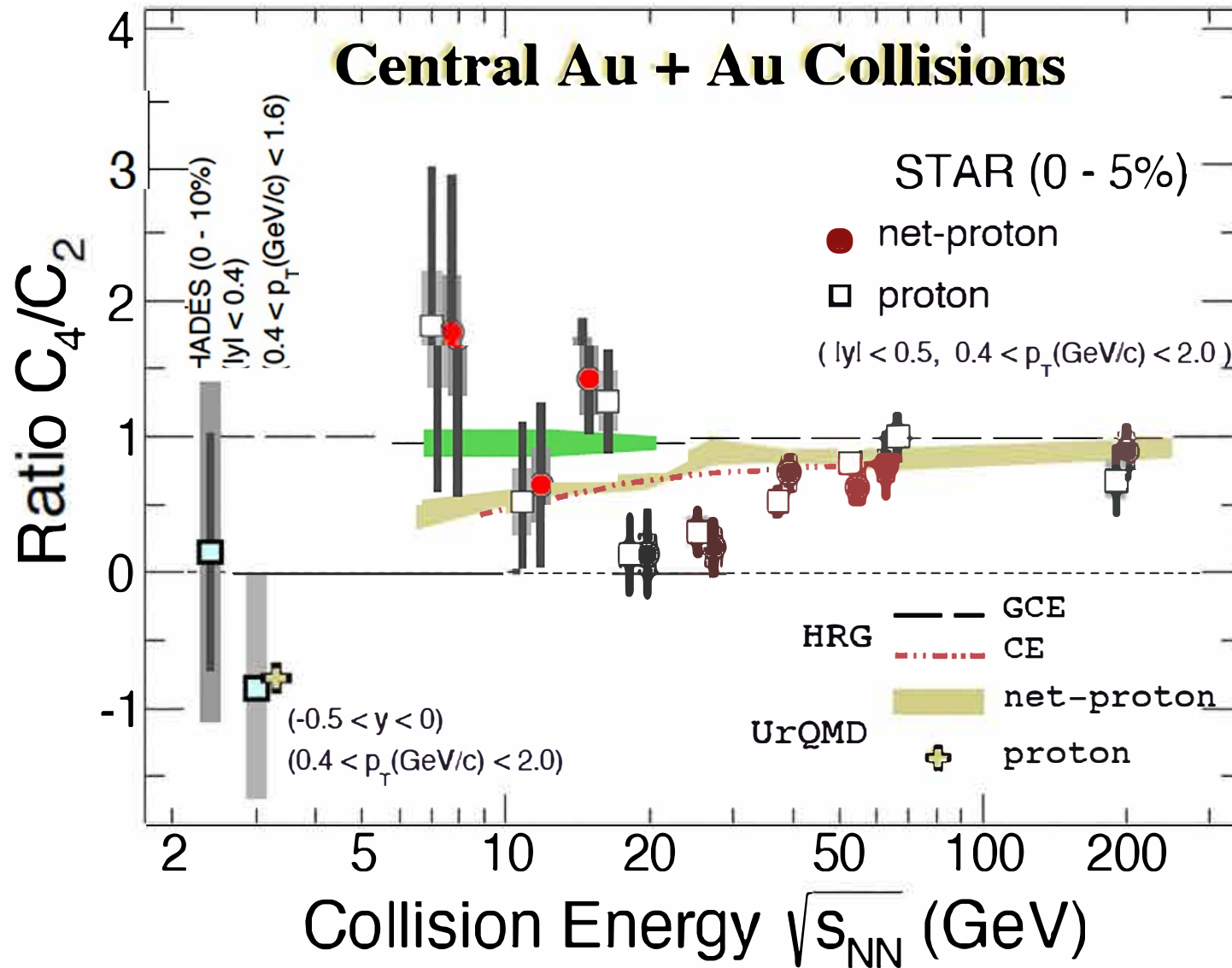


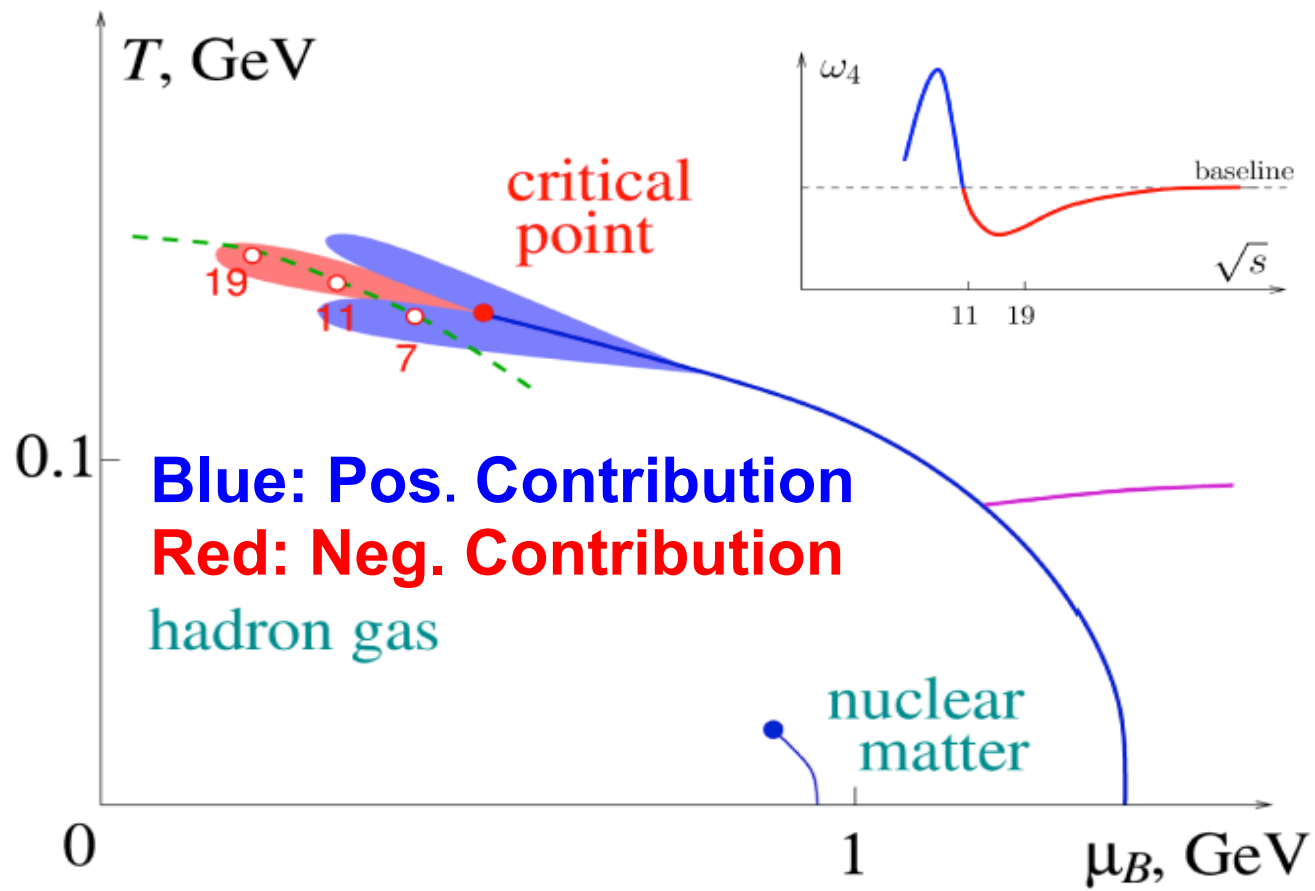
# RHIC BES II Data Taken...



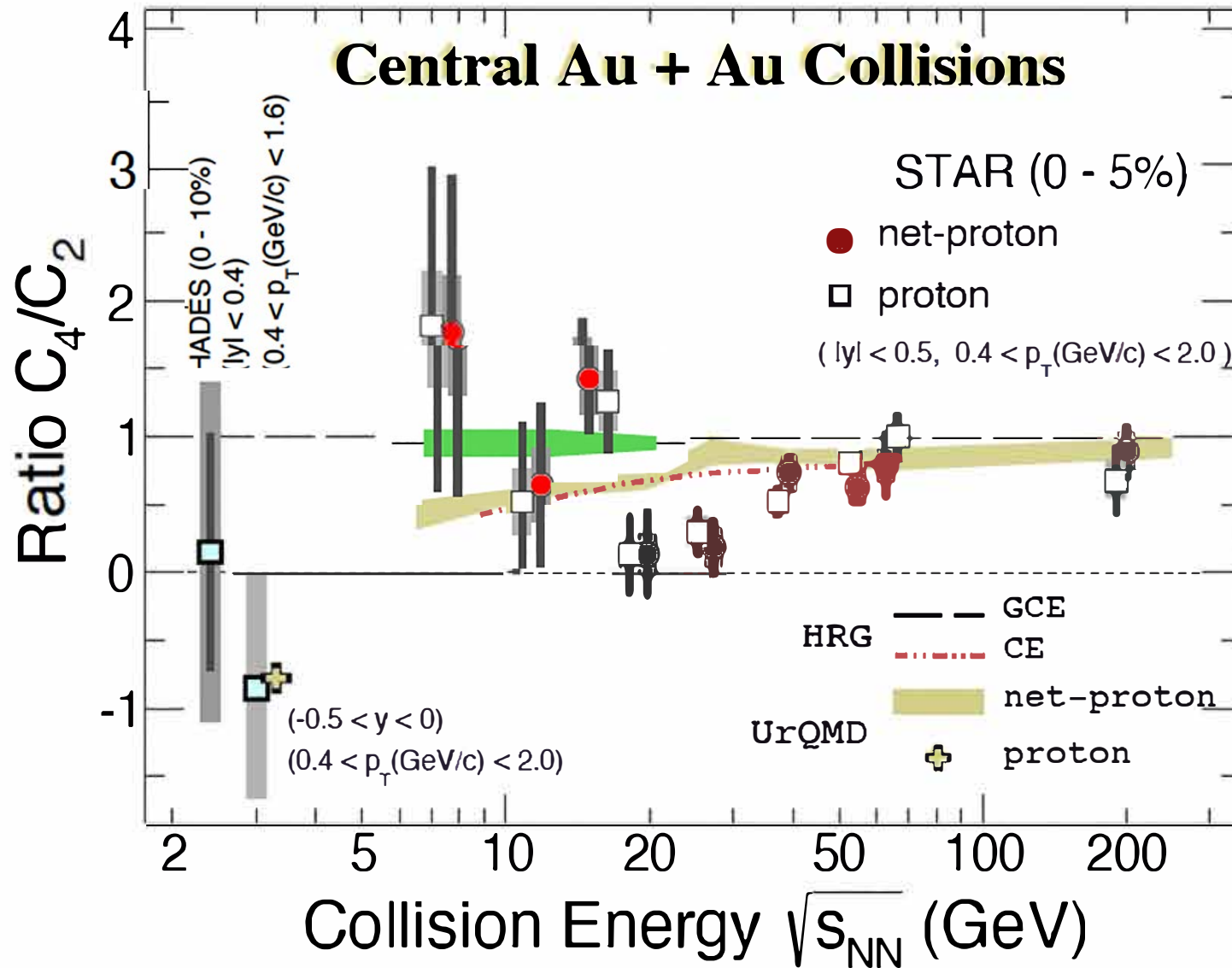


# Proton Kurtosis, before BES II





# Proton Kurtosis, before BES II





# PRECISION MEASUREMENT OF NET-PROTON NUMBER FLUCTUATIONS IN Au+Au COLLISIONS AT RHIC

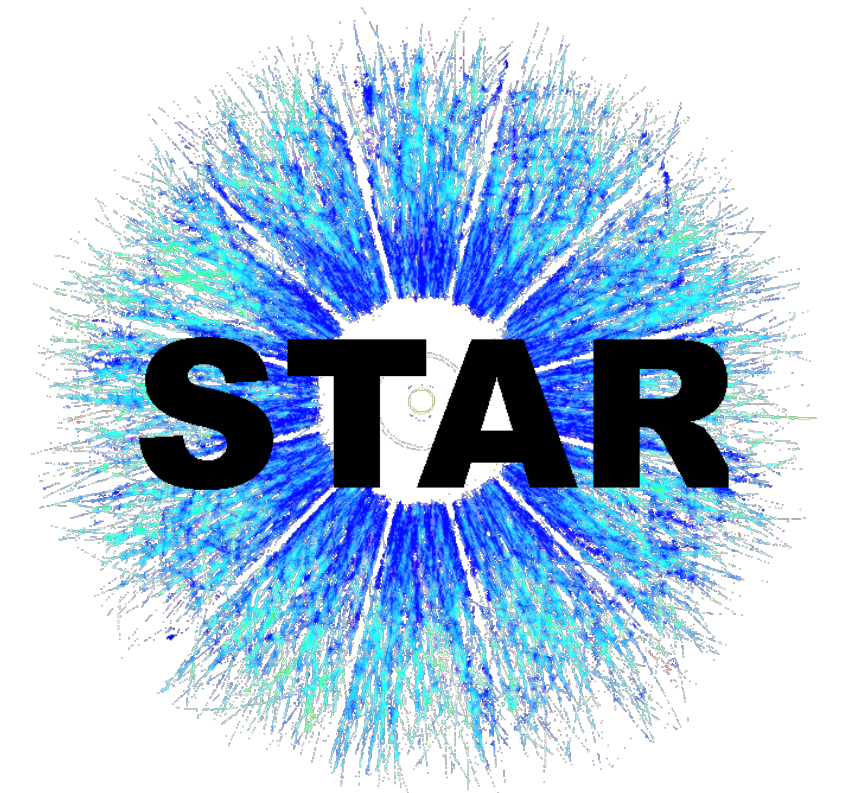
Ashish Pandav for STAR Collaboration  
Lawrence Berkeley National Laboratory  
May 21, 2024

**CPOD2024**  
Berkeley, CA  
May 20 - 24, 2024



## Outline

1. Introduction
2. Experimental analysis
3. Results
4. Summary



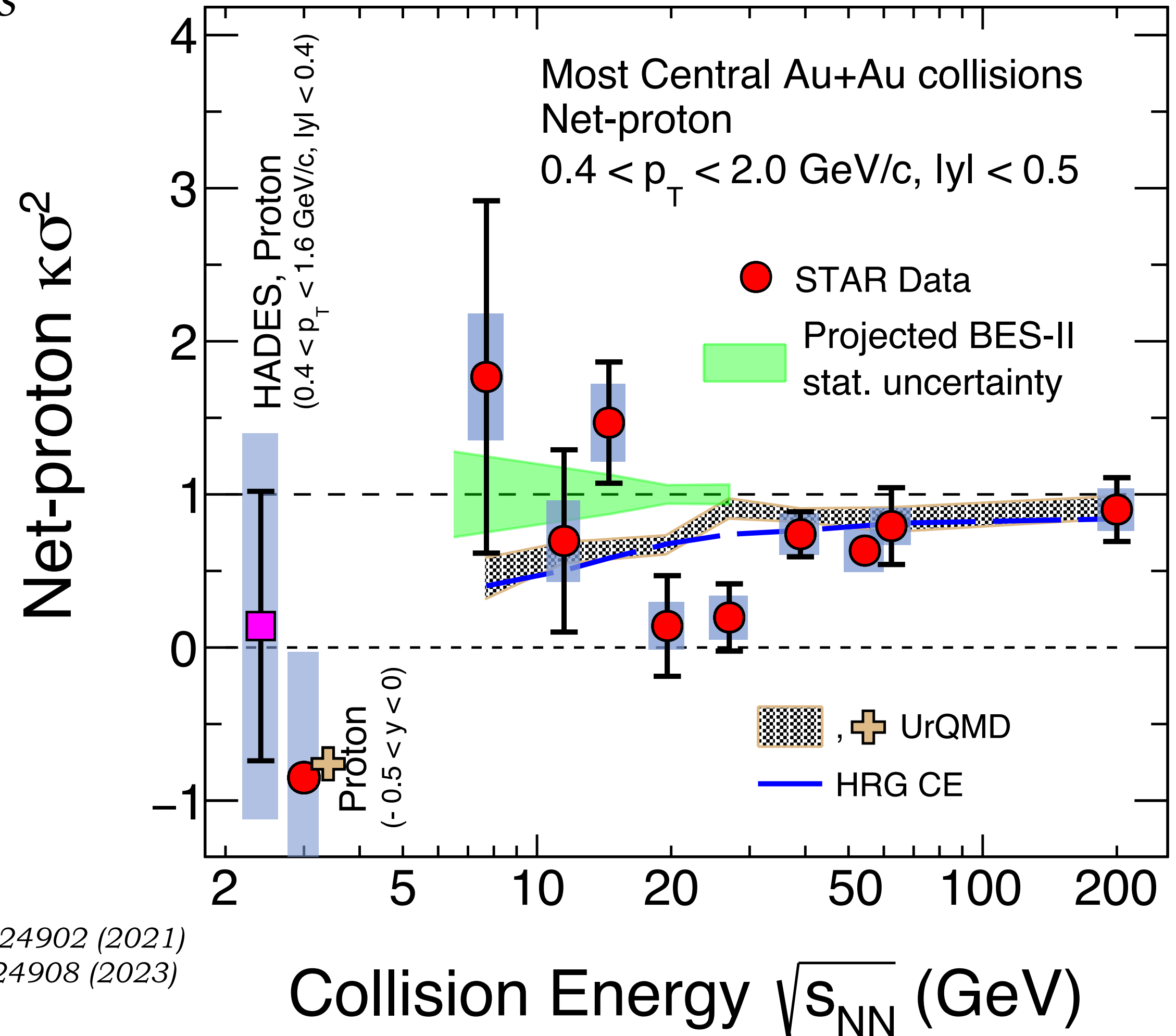
# EXPERIMENTAL SEARCH FOR CP: BES SCAN AT STAR-RHIC

## Phase I of BES program (BES-I): Au+Au collisions

*J. Cleymans, et. al, PRC. 73, 034905 (2006)*

$\sqrt{s_{NN}}$ (GeV)	Events ( $10^6$ )	$\mu_B$ (MeV)
200	220	25
62.4	43	75
54.4	550	85
39	92	112
27	31	156
19.6	14	206
14.5	14	262
11.5	7	316
7.7	2.2	420
3.0	140	750

STAR : PRL 127, 262301 (2021), PRC 104, 24902 (2021)  
 : PRL 128, 202302 (2022), PRC 107, 24908 (2023)  
 HADES: PRC 102, 024914 (2020)



Observed hint of non-monotonic trend in BES-I ( $3 \sigma$ ): consistent with model expectation with a CP  
 Robust conclusion require confirmation from precision measurement from BES-II.  
 Extend reach to even lower collision energies with FXT energies



# STAR BES-II PROGRAM: PRECISION MEASUREMENTS

## Au+Au Collisions at RHIC

### Collider Runs

### Fixed-Target Runs

Events used for net-proton fluctuation studies (Collider runs)

### BES-II vs BES-I

$\sqrt{s_{NN}}$ (GeV)	Events BES-I (10 <sup>6</sup> )	Events BES-II (10 <sup>6</sup> )
7.7	3	<b>45</b>
<b>9.2</b>	-	<b>78</b>
11.5	7	<b>110</b>
14.5	20	<b>178</b>
<b>17.3</b>	-	<b>116</b>
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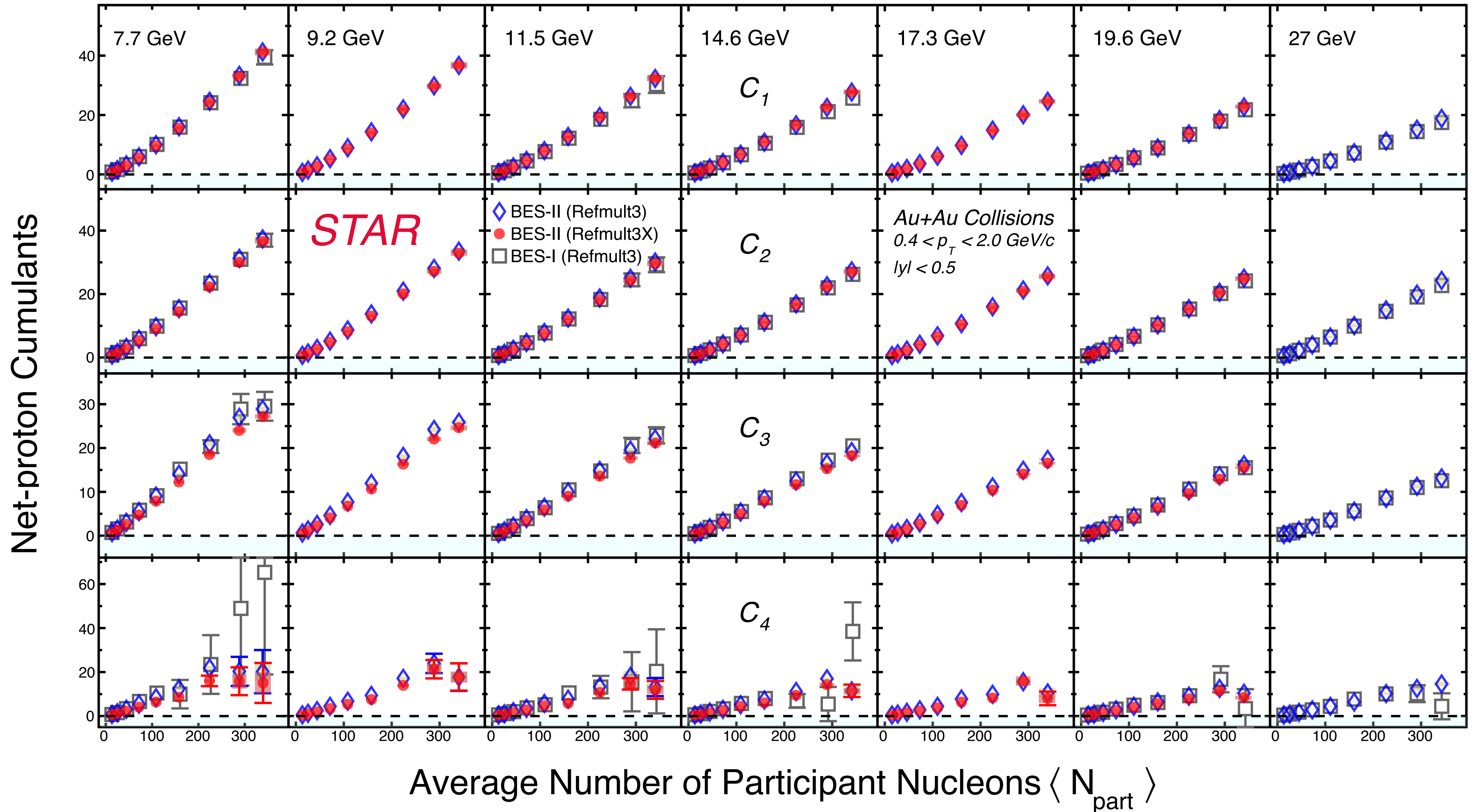
**~10-18 fold improvement in statistics**  
**9.2 and 17.3 GeV added to energy scan**

Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	$\mu_B$ (MeV)	Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	$\mu_B$ (MeV)
1	<b>200</b>	<b>380</b>	<b>25</b>	1	13.7 (100)	50	280
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3	54.4	1200	85	3	9.2 (44.5)	50	372
4	39	86	112	4	7.7 (31.2)	260	420
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10	9.2	160	372	10	3.5 (5.75)	120	670
11	7.7	104	420	11	3.2 (4.59)	200	699
	<b>BES-II collider results ready</b>			12	<b>3.0 (3.85)</b>	<b>260 + 2000</b>	<b>750</b>

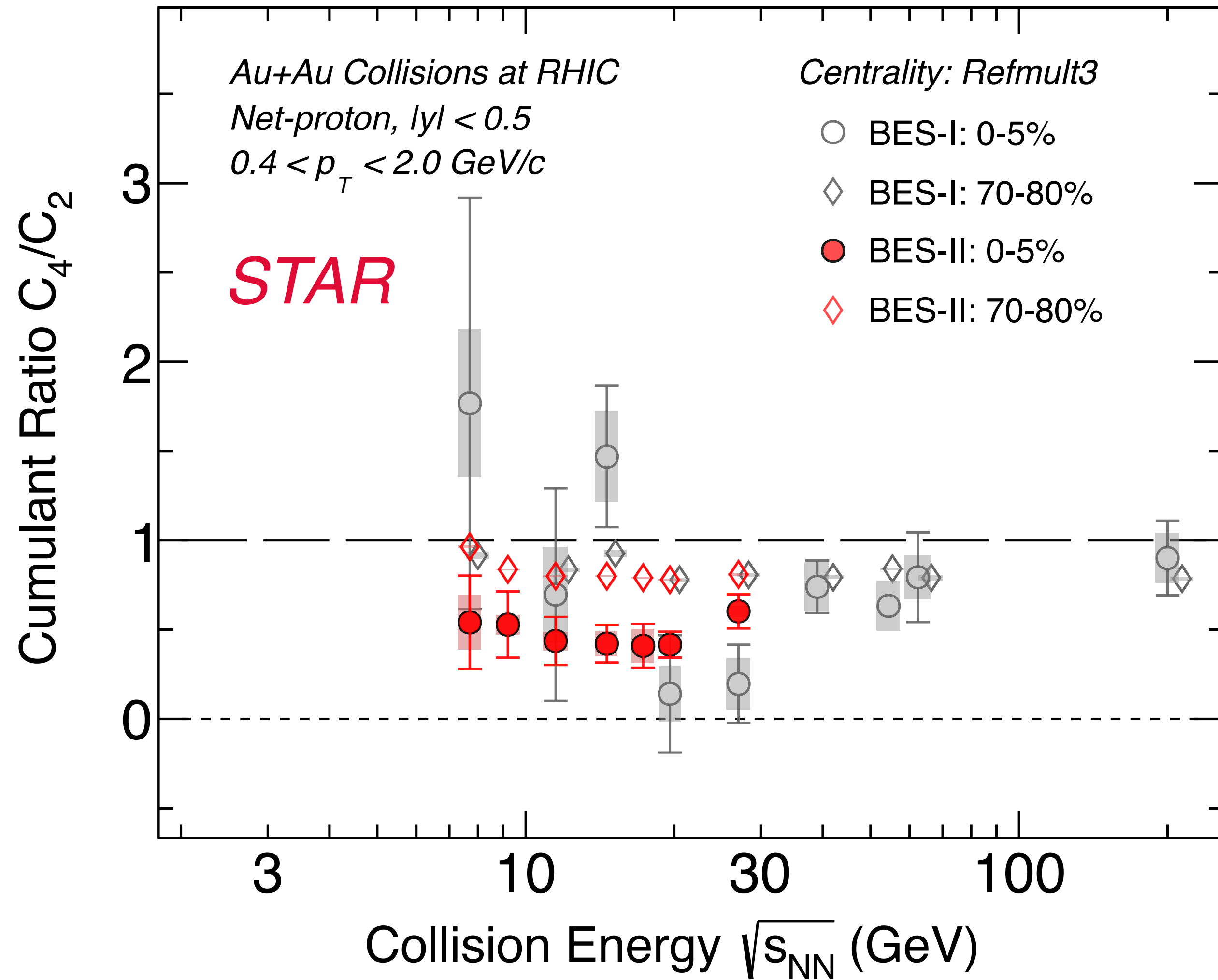
$$3 \leq \sqrt{s_{NN}} \text{ (GeV)} \leq 200 \rightarrow 750 \geq \mu_B \text{ (MeV)} \geq 25$$

High precision, widest  $\mu_B$  coverage to date

# CENTRALITY DEPENDENCE AND COMPARISON WITH BES-I



# ENERGY DEPENDENCE OF $C_4/C_2$ : COMPARISON WITH BES-I

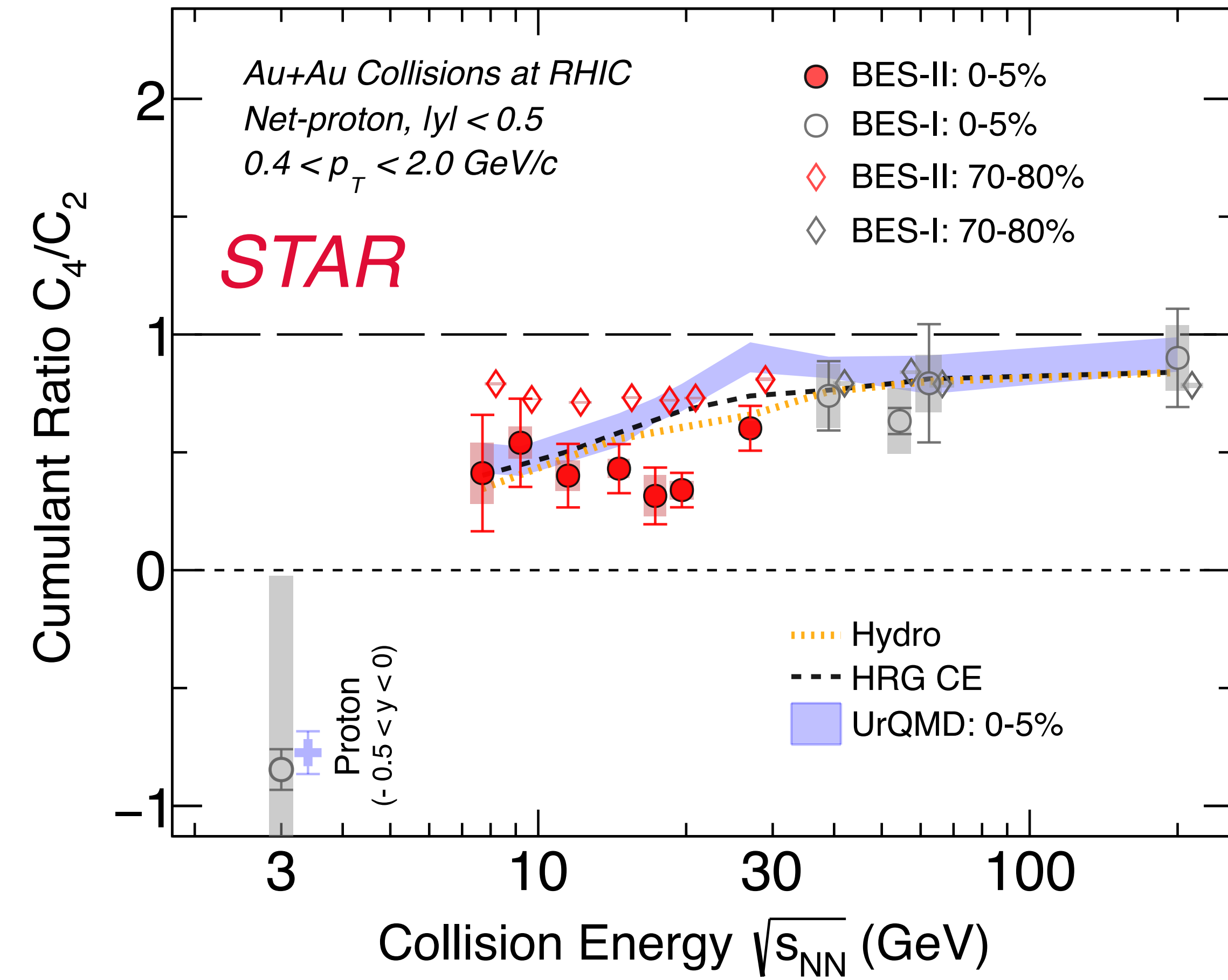


Deviation between BES-II and BES-I data

$\sqrt{s_{NN}}$ (GeV)	0-5%	70-80%
7.7	$1.0\sigma$	$0.9\sigma$
11.5	$0.4\sigma$	$1.3\sigma$
14.6	$2.2\sigma$	$2.5\sigma$
19.6	$0.7\sigma$	$0.0\sigma$
27	$1.4\sigma$	$0.2\sigma$

- BES-II results consistent with BES-I within uncertainties.

# ENERGY DEPENDENCE OF $C_4/C_2$ : QUANTIFYING DEVIATION



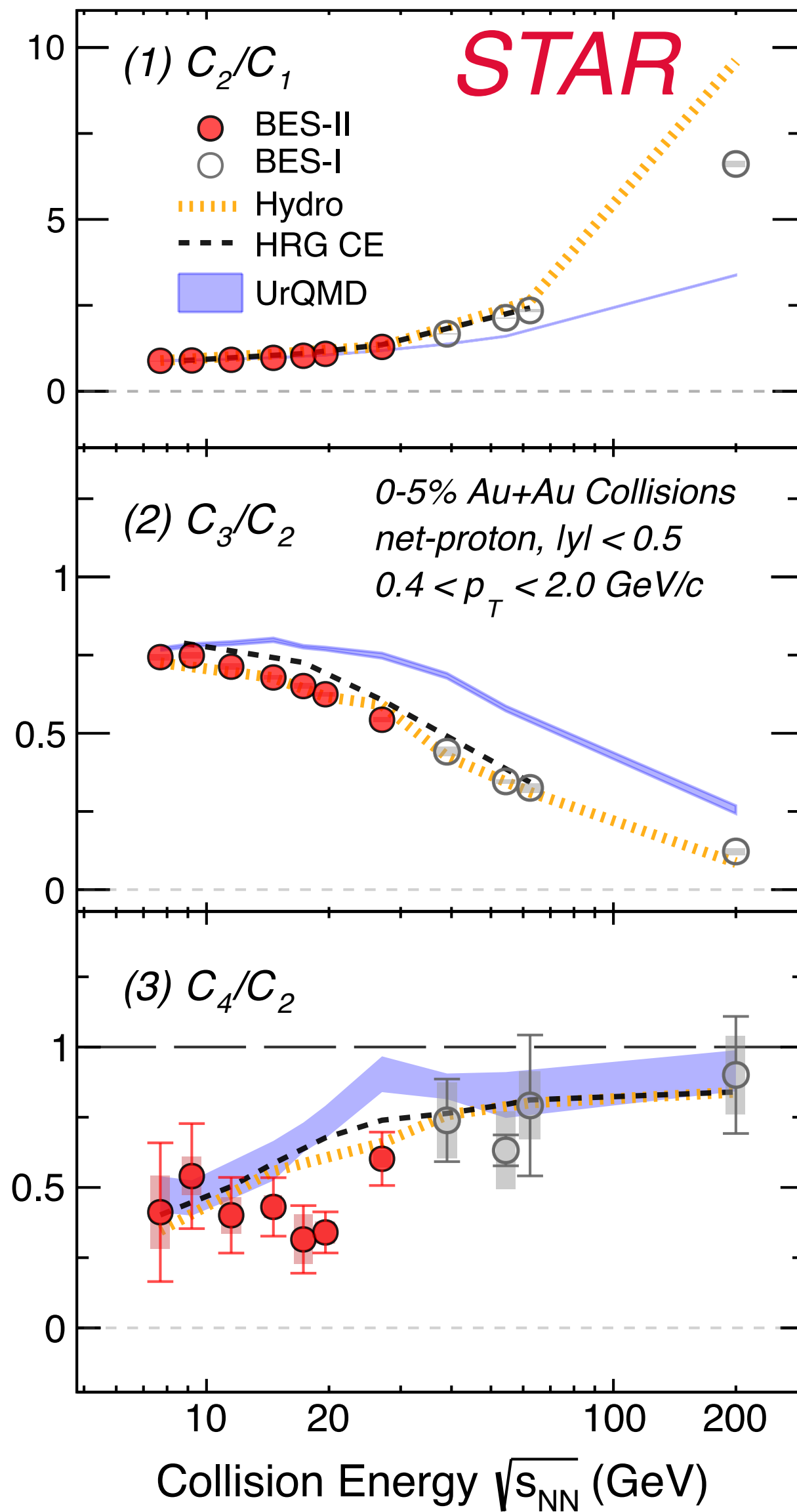
# Mapping the QCD Phase Diagram

- STAR and RHIC have done as promised. High statistics data, mapping the  $\mu_B \leq 420$  MeV region.
- No evidence for a critical point in this region of the phase diagram. A significant experimental result.
- Theorists with parametrized equations of state will use new STAR data to constrain parameters.
- STAR Fixed Target (FXT) data coming soon. Measurements of these observables from  $\sqrt{s} = 3$  GeV up to 4.5 GeV. STAR FXT acceptance limited above  $\sqrt{s} = 4.5$  GeV.
- For discussion, but not today:
  - STAR collider data motivate exploring  $420 \text{ MeV} < \mu_B \lesssim 600 \text{ MeV}$ , meaning  $7.7 \text{ GeV} > \sqrt{s} \gtrsim 4 \text{ GeV}$ .
  - Several recent lattice-based theoretical explorations point to this region also.
  - STAR FXT will give us a good look at fluctuations in  $4.5 \text{ GeV} > \sqrt{s} > 3 \text{ GeV}$  collisions, but what is the best option for  $7.7 \text{ GeV} > \sqrt{s} > 4.5 \text{ GeV}$  collisions?



# ENERGY DEPENDENCE: MODEL COMPARISON

## Net-proton cumulant ratios



1. Smooth variation vs  $\sqrt{s_{NN}}$  in  $C_2/C_1$  and  $C_3/C_2$  observed.  $C_4/C_2$  decreases with decreasing  $\sqrt{s_{NN}}$ .

2. Non-CP models used for comparison:

A. Hydro: Hydrodynamical model

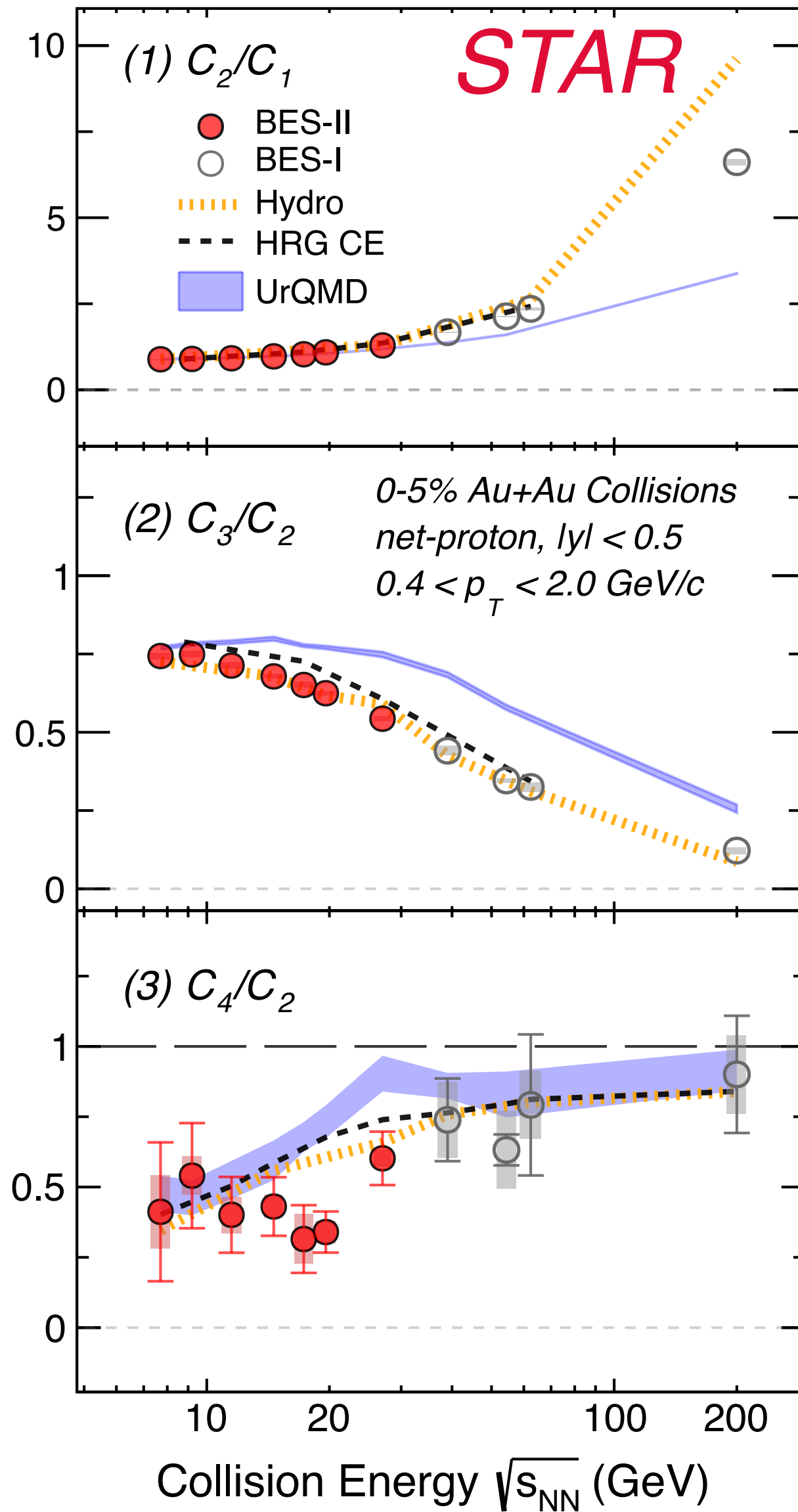
B. HRG CE: Thermal model with canonical treatment of baryon charge

C. UrQMD: Hadronic transport model

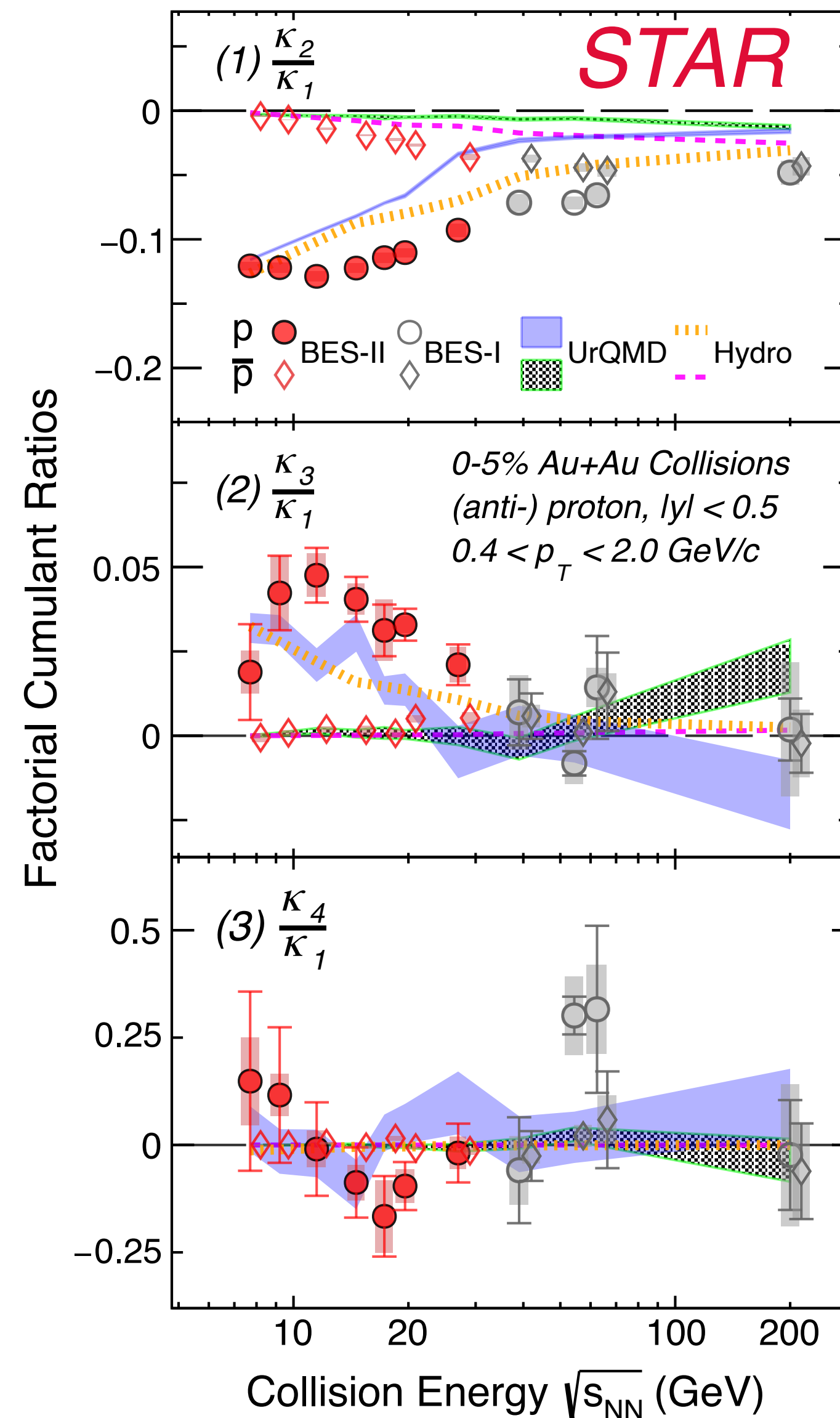
(All models include baryon number conservation)

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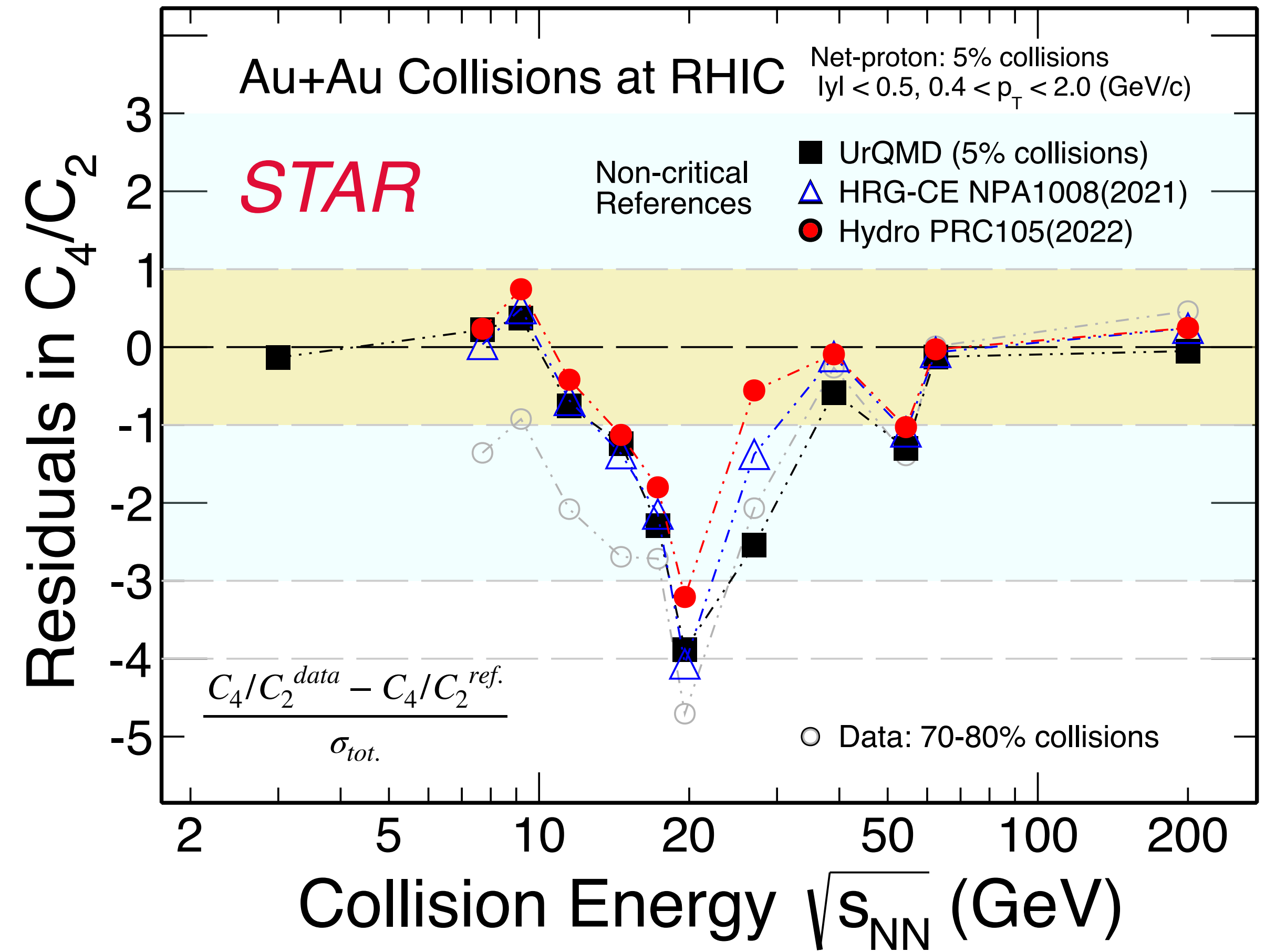
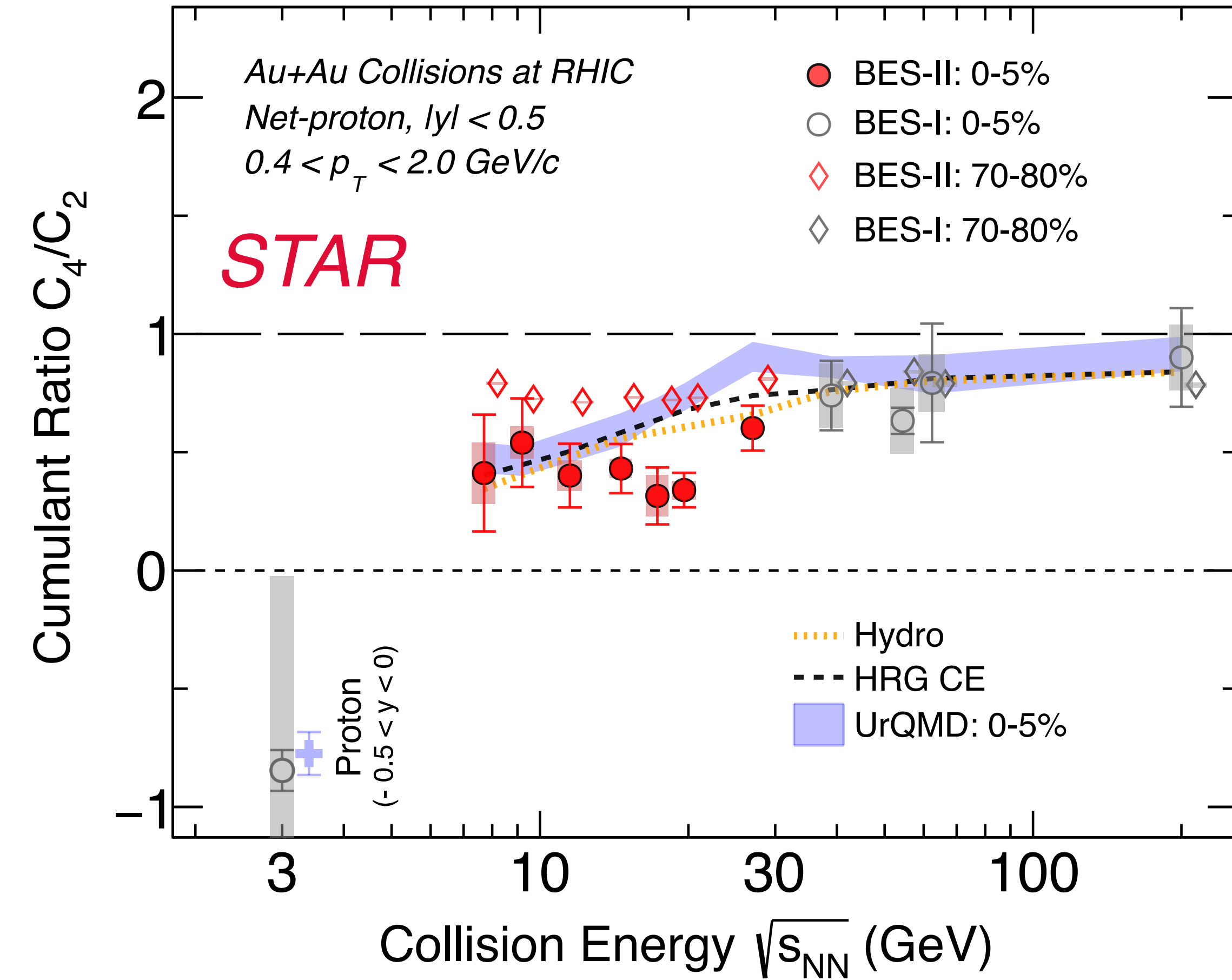


## Proton/antiproton factorial cumulant ratios



1. Smooth variation vs  $\sqrt{s_{NN}}$  in  $C_2/C_1$  and  $C_3/C_2$  observed.  $C_4/C_2$  decreases with decreasing  $\sqrt{s_{NN}}$ .
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  - A. Hydro: Hydrodynamical model
  - B. HRG CE: Thermal model with canonical treatment of baryon charge
  - C. UrQMD: Hadronic transport model
 (All models include baryon number conservation)
3. Proton factorial cumulant ratios deviates from poisson baseline at 0. Antiproton  $\kappa_3/\kappa_1, \kappa_4/\kappa_1$  closer to 0.
4. Qualitative trend described by model. Quantitative differences exist b/w data and non-CP model.

# ENERGY DEPENDENCE OF $C_4/C_2$ : QUANTIFYING DEVIATION



$C_4/C_2$  shows minimum around  $\sim 20$  GeV comparing to non-CP models, 70-80% data

1. Maximum deviation:  $3.2 - 4.7\sigma$  at  $\sqrt{s_{NN}} = 20$  GeV ( $1.3 - 2\sigma$  at BES-I)

2. Overall deviation from  $\sqrt{s_{NN}} = 7.7 - 27$  GeV:  $1.9 - 5.4\sigma$  ( $1.4 - 2.2\sigma$  at BES-I)



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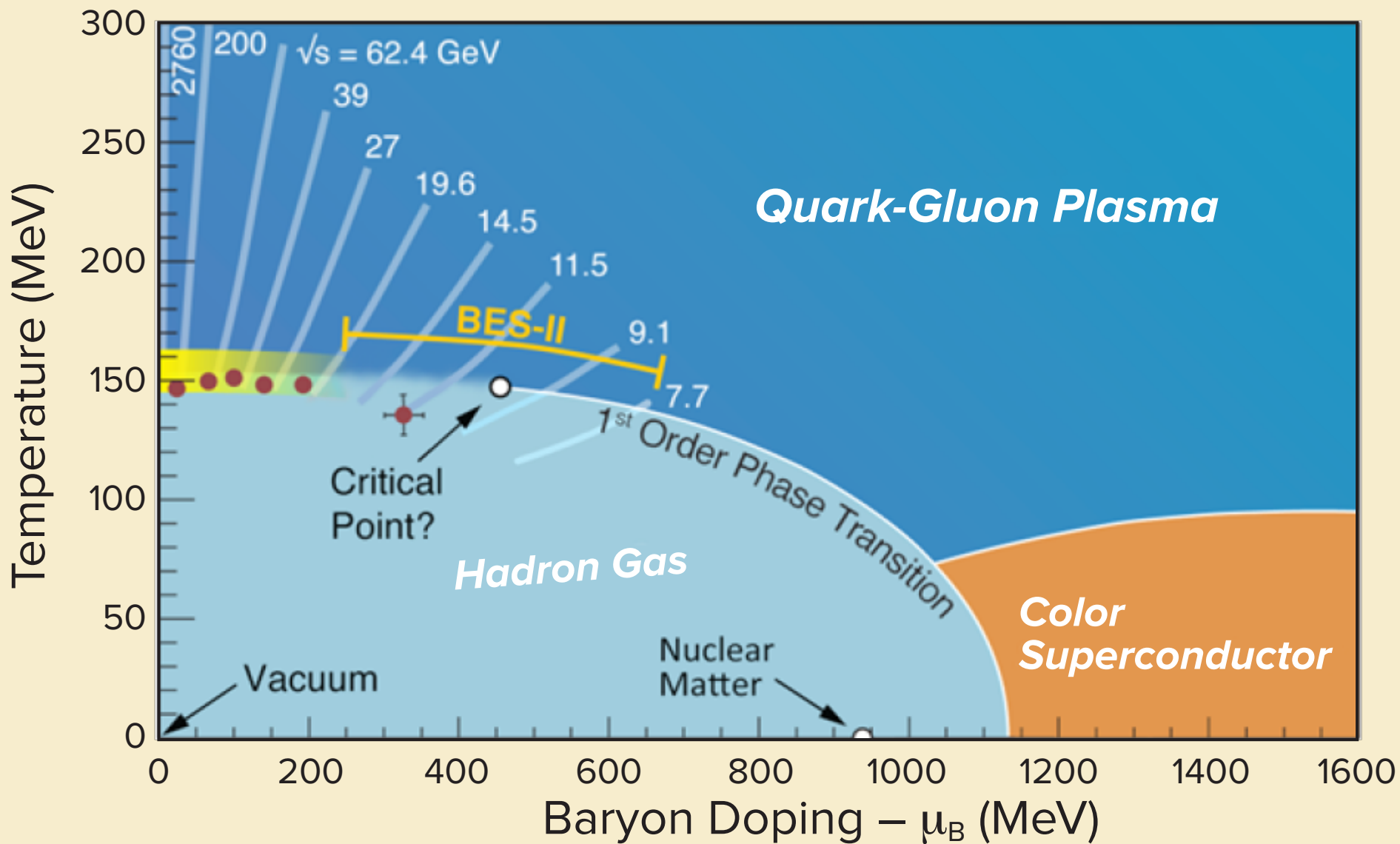
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High precision, widest  $\mu_B$  coverage to date



# What Next?

Two kinds of What Next? questions ...

- A question that one asks after the discovery of any new form of complex matter: **What is its phase diagram?** For high temperature superconductors, for example, phase diagram as a function of temperature and doping. Same here! For us, doping means excess of quarks over 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.

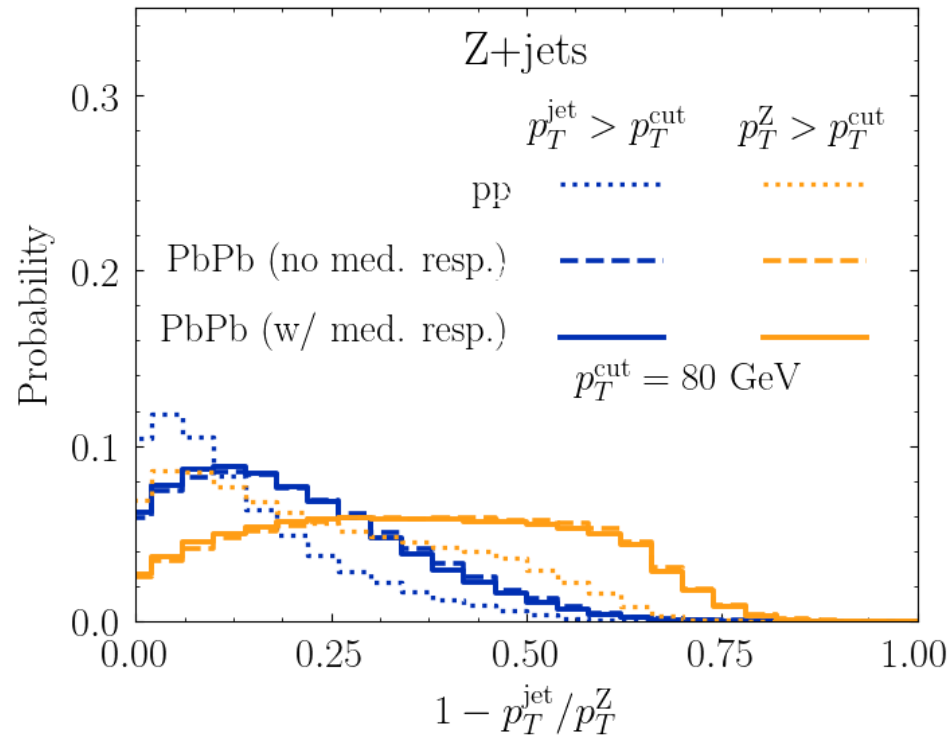
# Probing the Original Liquid

- The question **How does the strongly coupled liquid emerge from the fundamental laws governing quarks and gluons?** is one of today's most active research frontiers.
- Seeing the inner workings of hot quark soup.
- First step to seeing what they are doing is we need to “see” the individual quarks and gluons that make up the liquid. Need a high-resolution, fast shutter-speed, look at one quark or gluon at one moment.
- Need to do for hot quark soup what Rutherford did for atoms and Friedman, Kendall and Taylor did for protons.
- Need to probe the liquid, see how the liquid responds, *and watch how the probe scatters.*
- Can't bring a drop of Big Bang matter from Geneva to Stanford to image it with an electron beam; it only lives for  $10^{-22}$  seconds! Have to use a probe made in the same collision that makes the drop of hot quark soup. Jets!

# Jets as Probes of QGP

- Theorists taking key steps...
- Disentangling jet modification from jet selection.
- Showing that hot quark soup (QGP) *can* resolve structure within jet shower.
- Calculations of the dynamics of jet wakes in droplets of QGP, identification of new experimental observables, and predictions that will enable experimental measurements to “see” the particles coming from these wakes.
- Identifying those jet substructure observables that *are* sensitive to scattering of jet quarks/gluons off QGP quarks/gluons, “seeing” the latter à la Rutherford, and are *not* sensitive to particles coming from the wake.
- Next several years will be the golden age of jet physics: sPHENIX, LHC runs 3 and 4, new substructure observables. *Many* theory advances, and analyses of today’s data, whet our appetite for the feast to come.
- We shall learn about the microscopic structure of QGP, and the dynamics of rippling QGP.

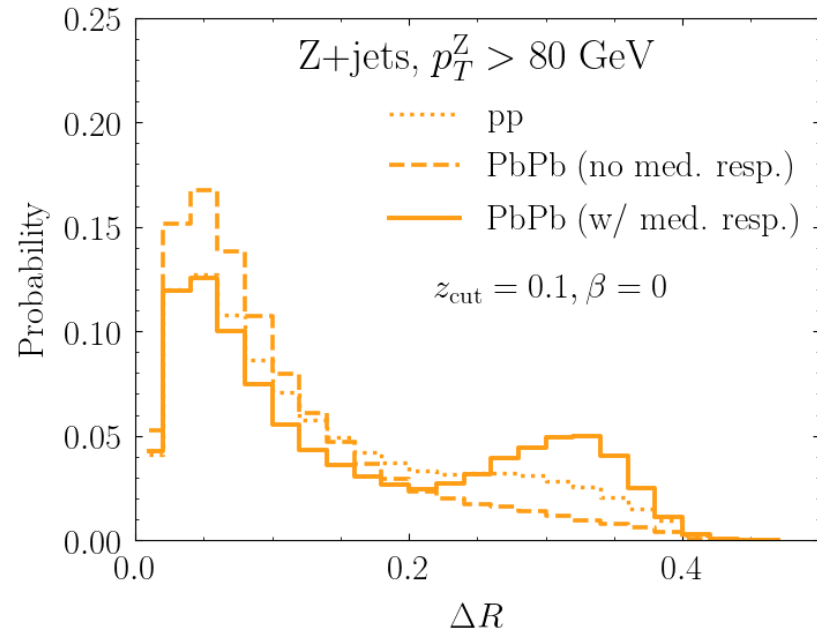
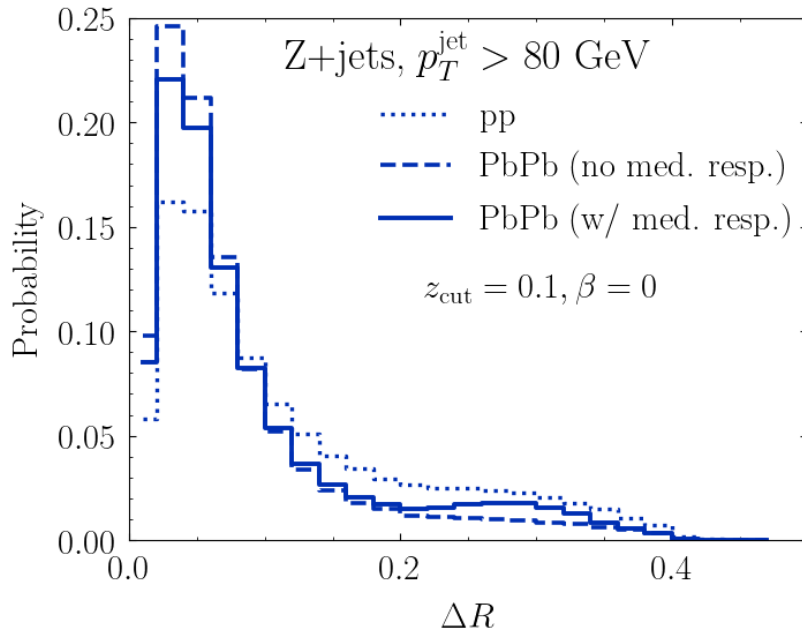
# Disentangling Jet Modification from Selection



**Orange:**  $p_T^Z > 80 \text{ GeV}$ ;  $p_T^{\text{jet}} > 30 \text{ GeV}$

**Blue:**  $p_T^{\text{jet}} > 80 \text{ GeV}$ ;  $p_T^Z > 30 \text{ GeV}$  — jet selection biases toward those jets that lose less energy

# Disentangling Jet Modification from Selection



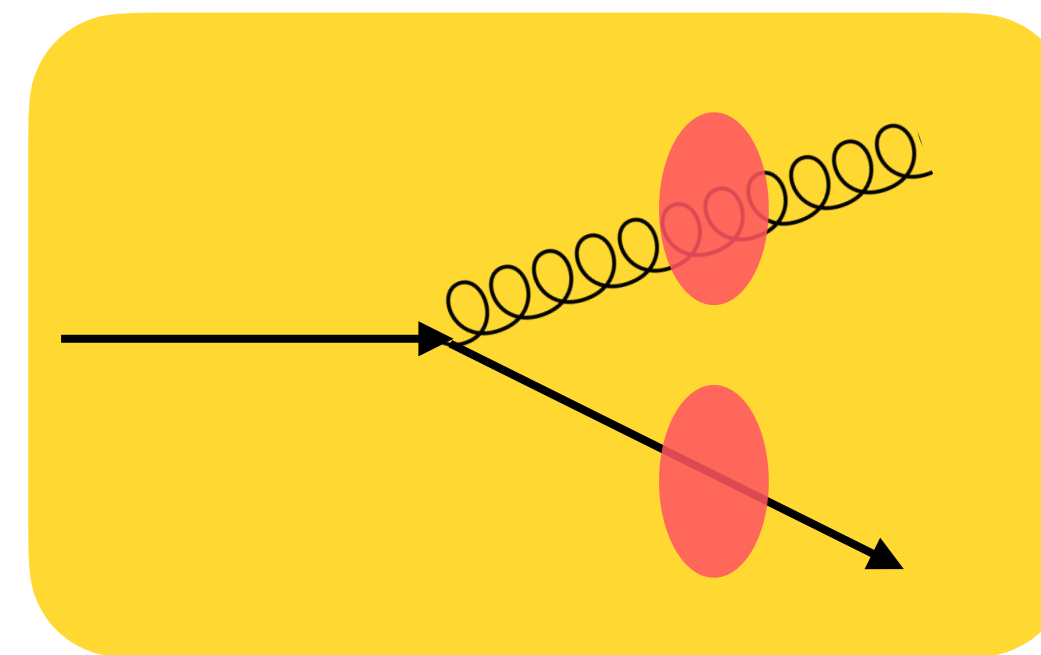
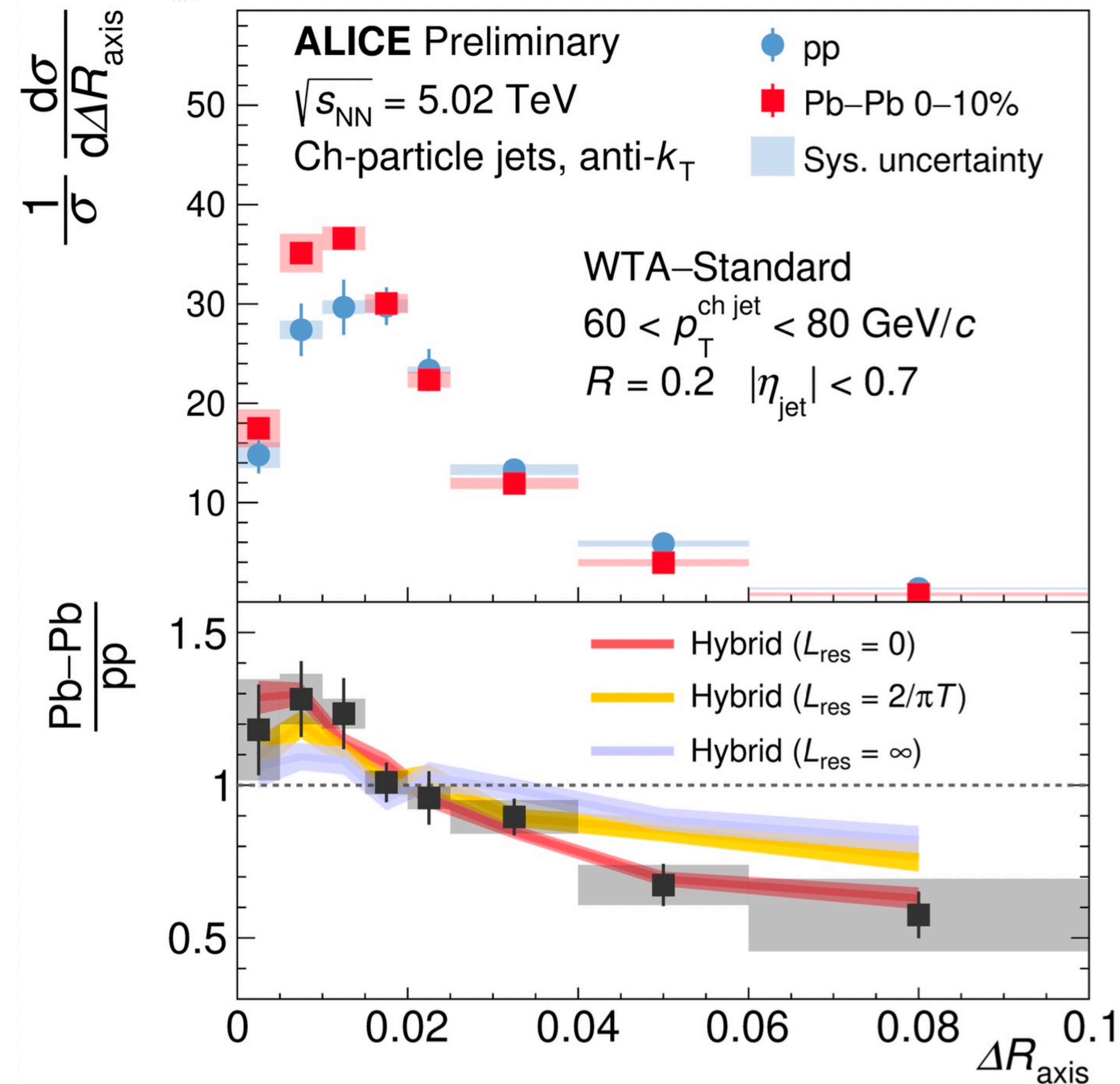
**Orange:**  $p_T^Z > 80$  GeV;  $p_T^{\text{jet}} > 30$  GeV. See jet modification.

**Blue:**  $p_T^{\text{jet}} > 80$  GeV;  $p_T^Z > 30$  GeV — jet selection biases toward those jets that lose less energy. These jets are skinnier. And the bias is toward less jet modification.

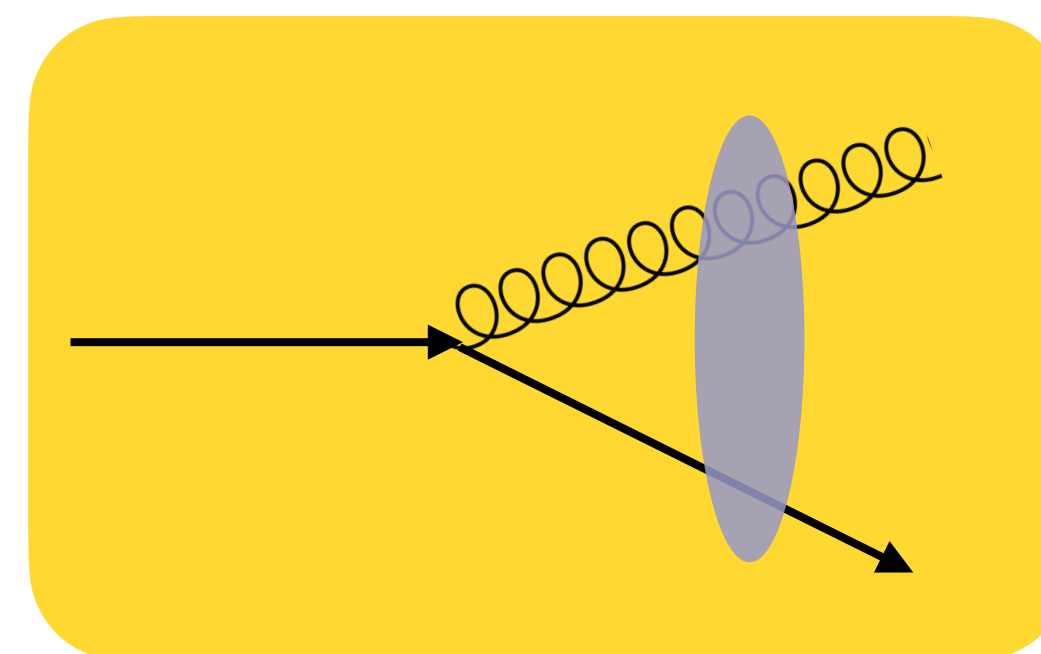




# Medium resolution length, $L_{res}$



$L_{res} = 0$ : medium resolves splitting immediately after parton fragments.  
Fully-incoherent energy loss



$L_{res} = \infty$ : medium does not resolve splitting.  
Fully-coherent energy loss

Data favors mechanisms of incoherent energy loss in the QGP

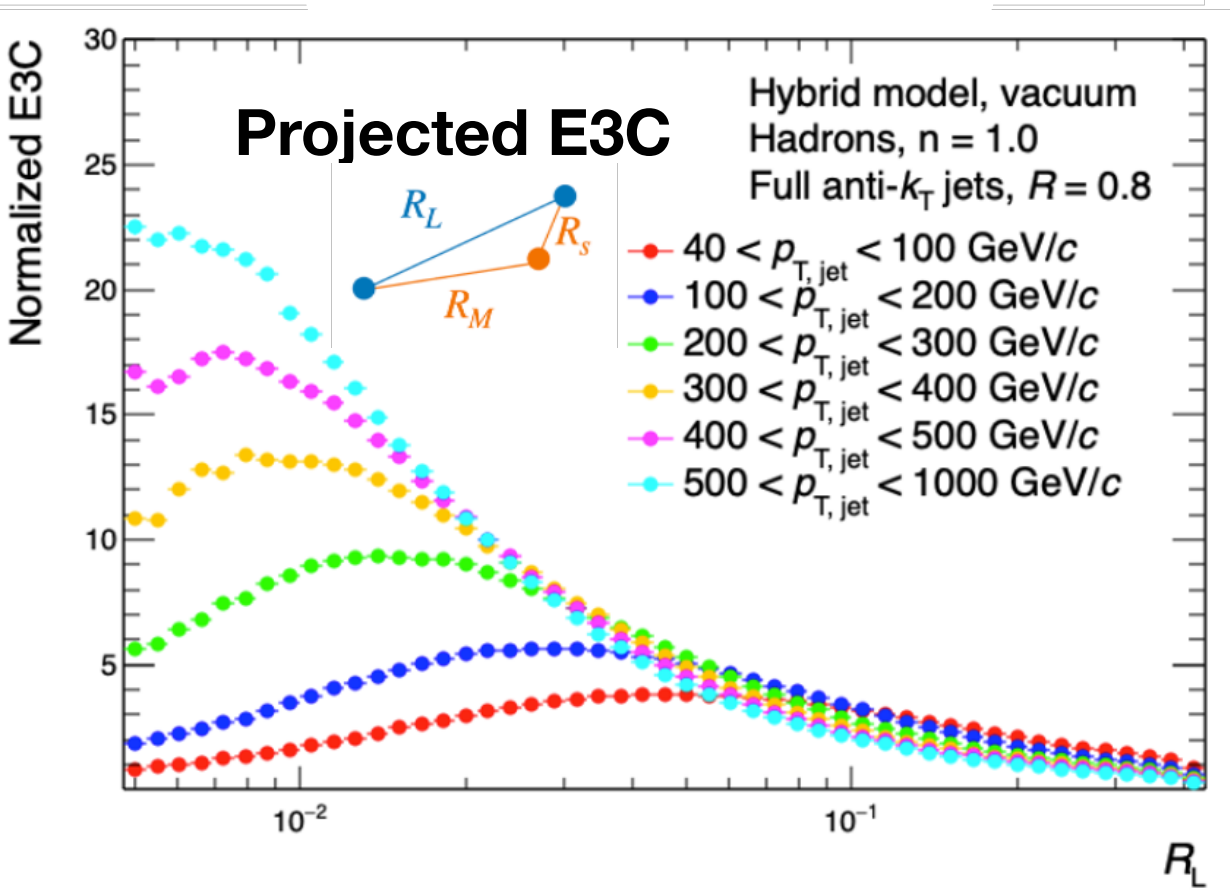
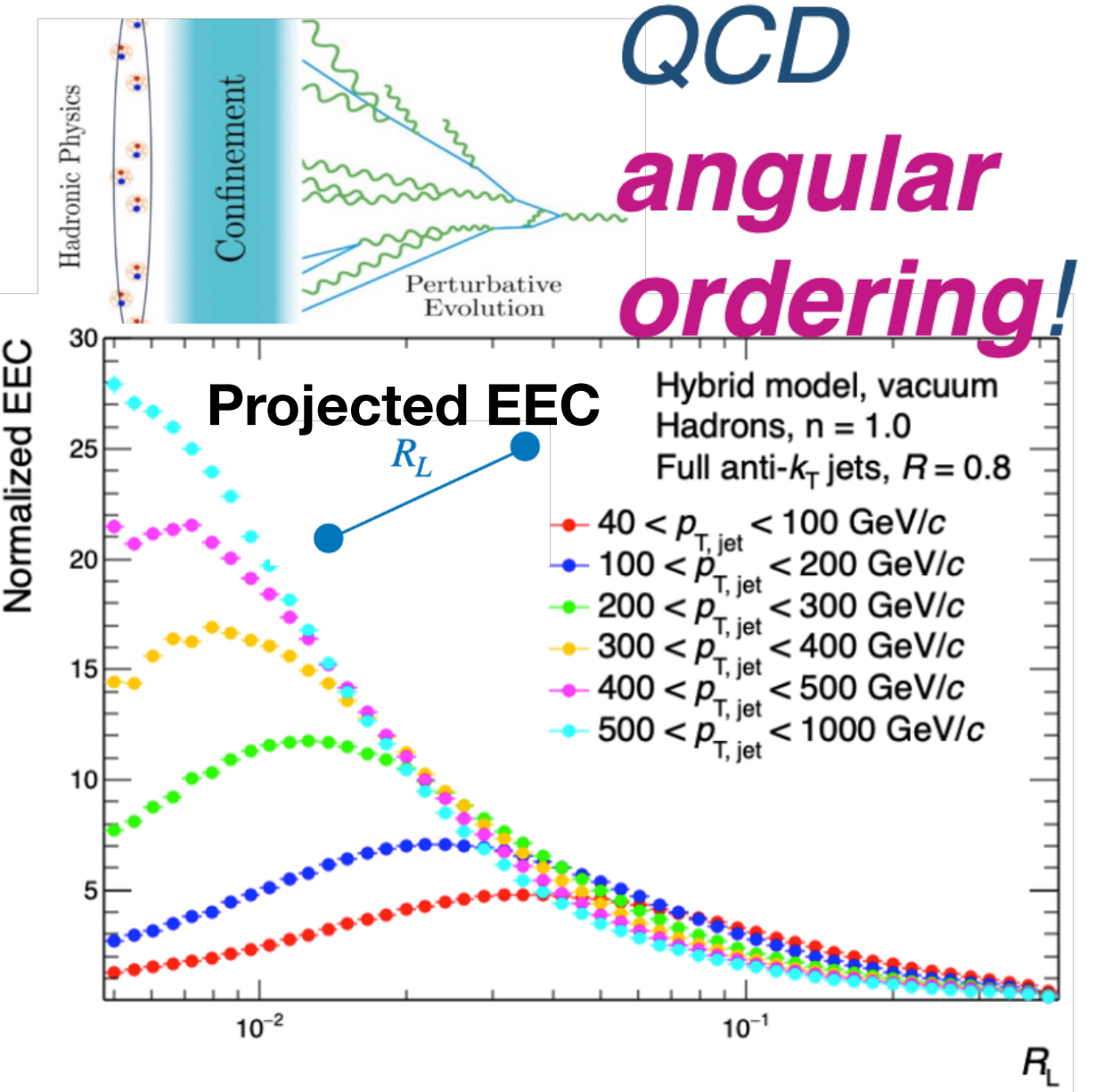


# Energy Correlators in Vacuum

$$\text{ENC}(R_L) = \left( \prod_{k=1}^N \int d\Omega_{\vec{n}_k} \right) \delta(R_L - \Delta \hat{R}_L) \cdot \frac{1}{(E_{\text{jet}})^N} \langle \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \dots \mathcal{E}(\vec{n}_N) \rangle$$

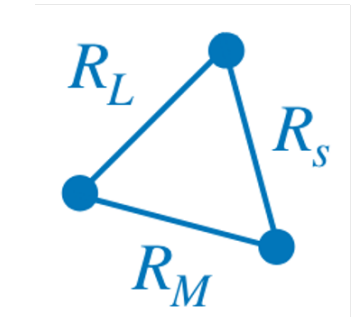
## Projected Correlators

**QCD**  
**angular ordering!**

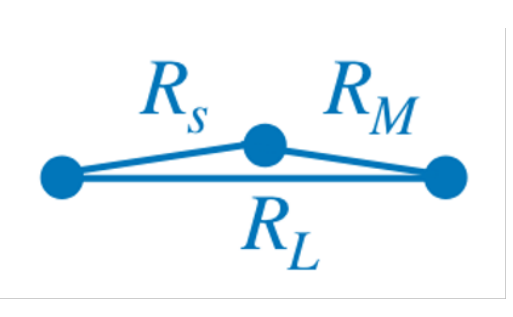


## 3-point correlator (EEEC)

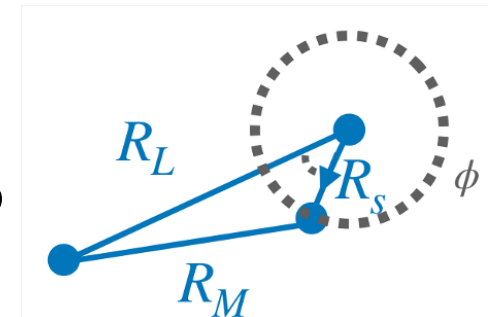
Configurations: Equilateral



Flat

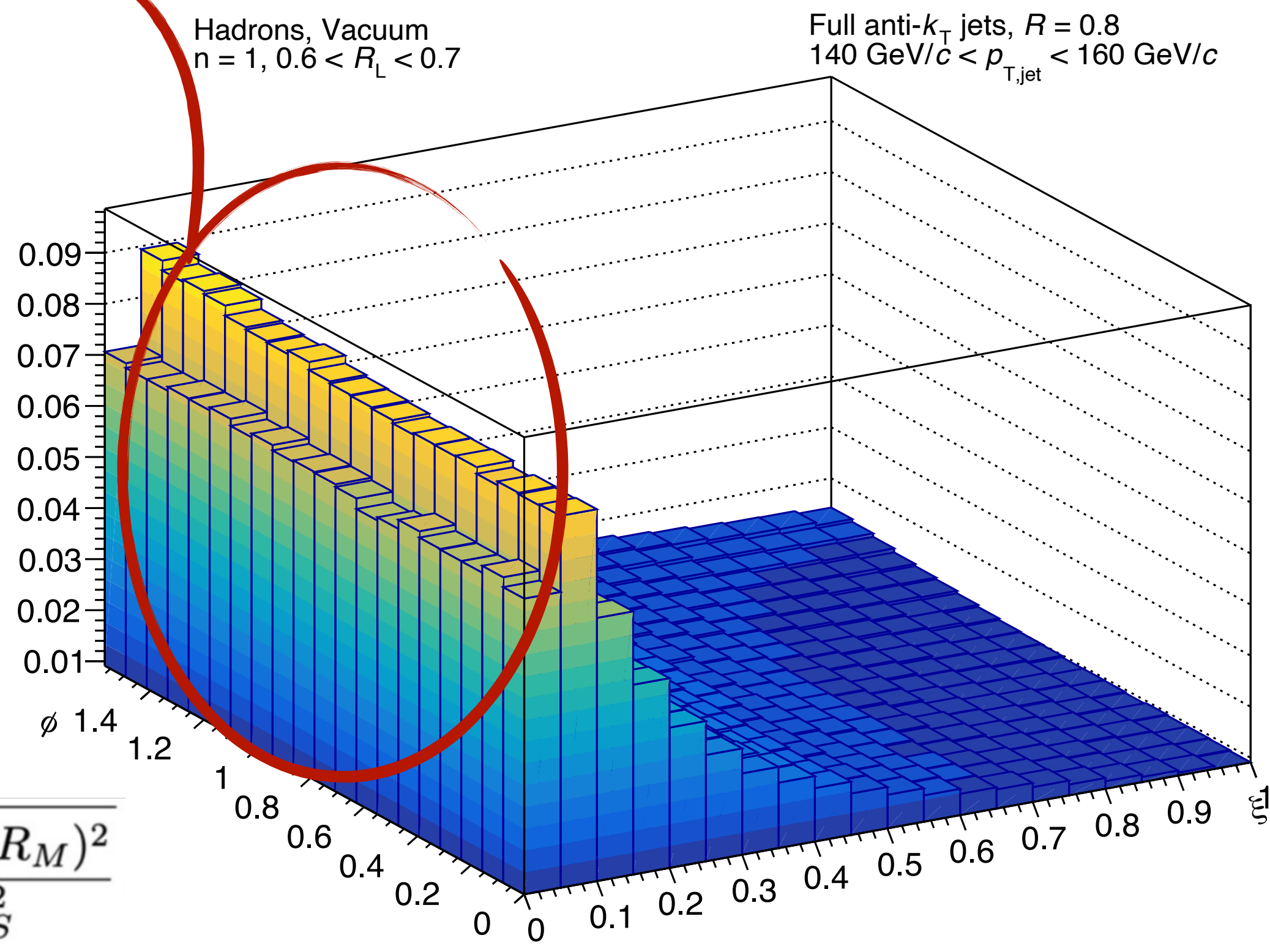
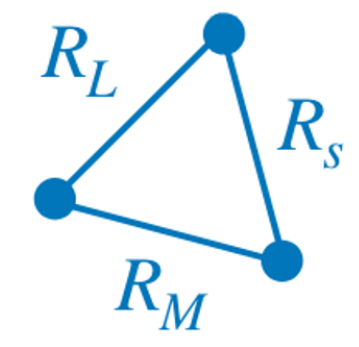


Isosceles



**Collinear singularity of vacuum QCD!**

Collinear Singularity



$$\phi = \arcsin \sqrt{1 - \frac{(R_L - R_M)^2}{R_S^2}}$$

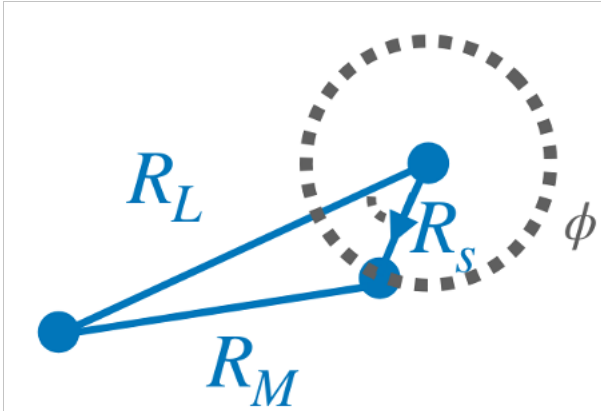
$$\xi = \frac{R_S}{R_M}$$

# EEEC sensitivity to the Wake

## Pb-Pb/Vacuum

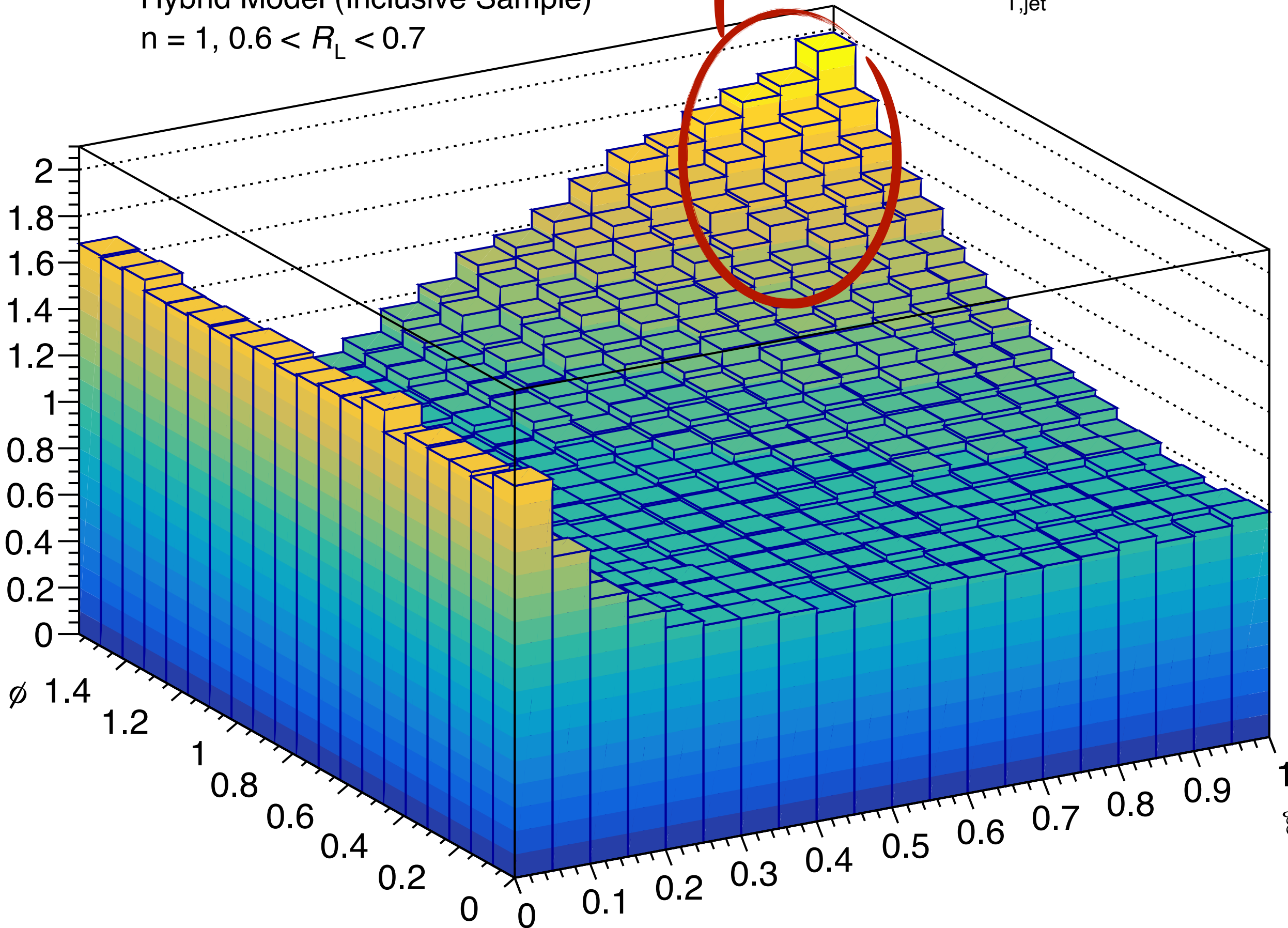
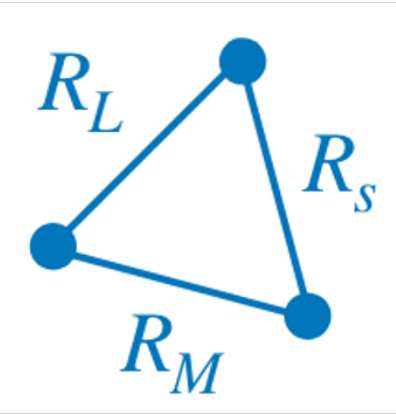
$$\sqrt{s_{NN}} = 5.02 \text{ TeV}$$

Jet Radius = 0.8

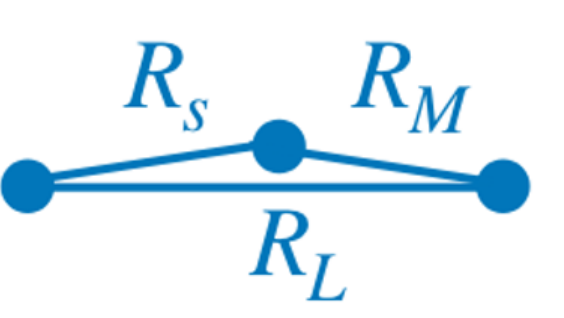


Hadrons,  $\text{Jet}_{\text{Wake=On}}^{\text{Med}} / \text{Jet}^{\text{Vac}}$   
Hybrid Model (Inclusive Sample)  
 $n = 1, 0.6 < R_L < 0.7$

Full anti- $k_T$  jets,  $R = 0.8$   
 $140 \text{ GeV}/c < p_{T,\text{jet}} < 160 \text{ GeV}/c$



Ratio with vacuum shows **significant** enhancement in the **equilateral region** - effect of the **wake!**





# EEEC sensitivity to the Wake

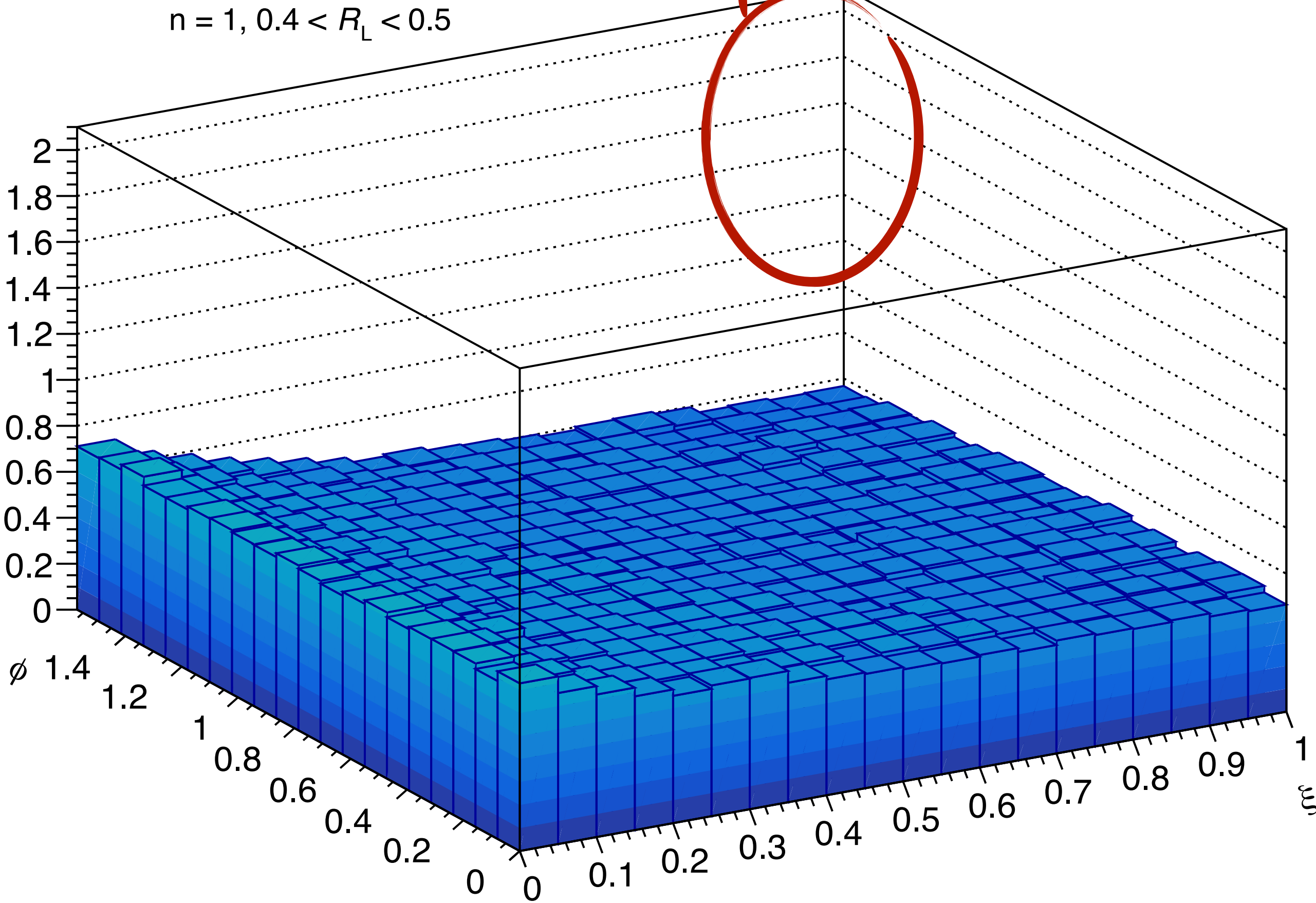
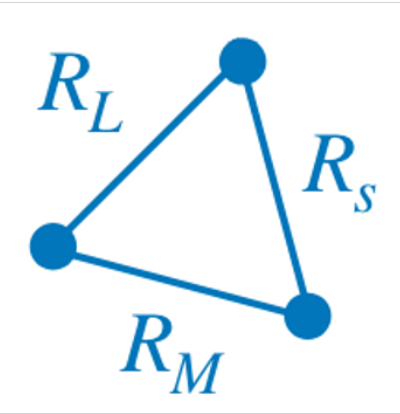
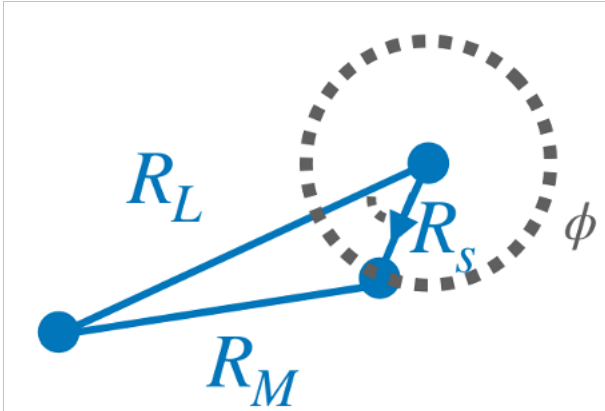
## Pb-Pb-without-wake/Vacuum

$\sqrt{s_{NN}} = 5.02 \text{ TeV}$

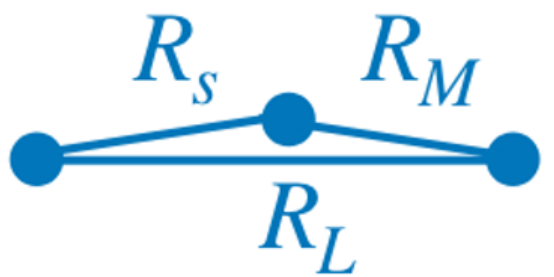
Jet Radius = 0.8

Hadrons,  $\text{Jet}_{\text{Wake=Off}}^{\text{Med}} / \text{Jet}^{\text{Vac}}$   
 Hybrid Model (Inclusive Sample)  
 $n = 1, 0.4 < R_L < 0.5$

Full anti- $k_T$  jets,  $R = 0.8$   
 $140 \text{ GeV}/c < p_{T,\text{jet}} < 160 \text{ GeV}/c$

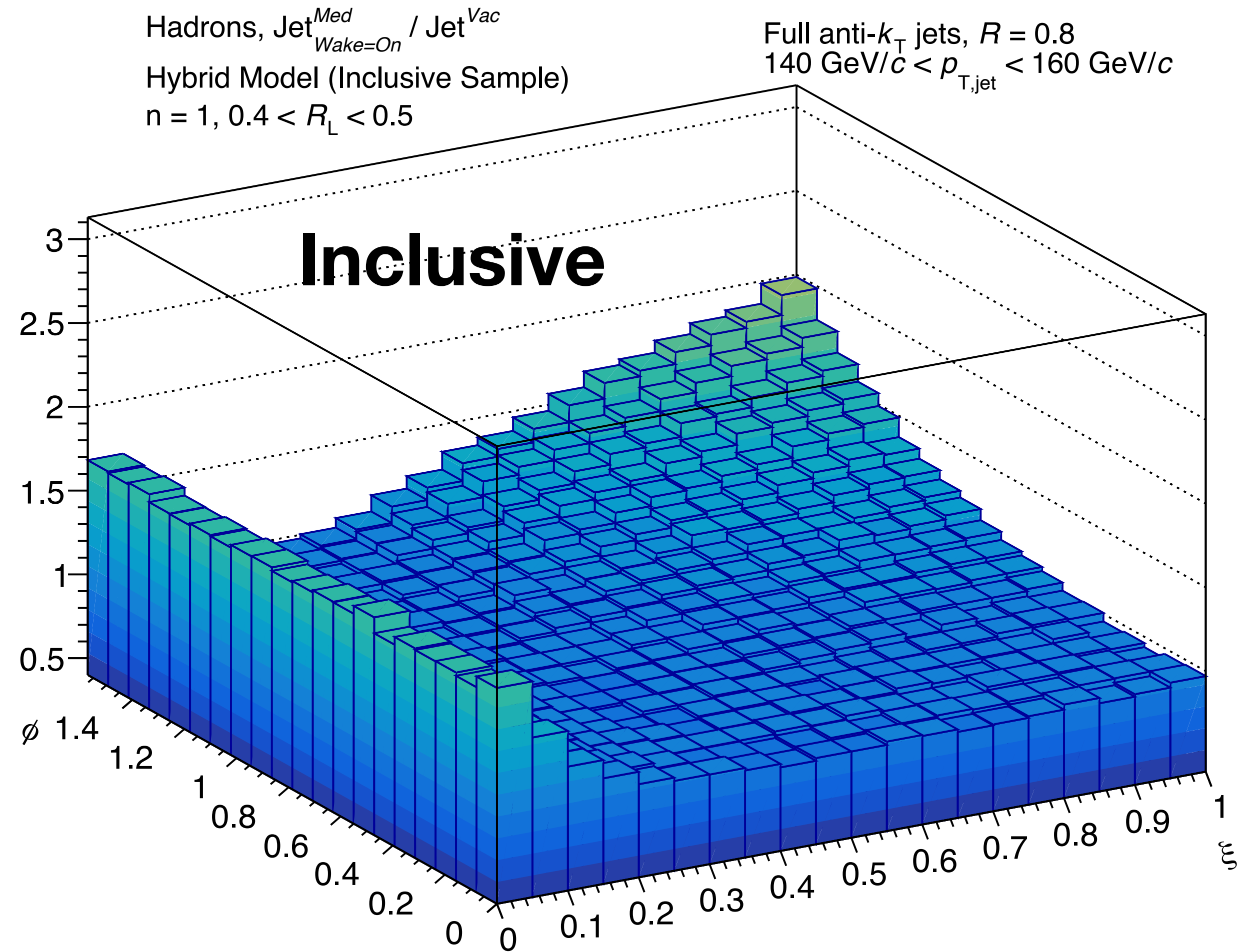
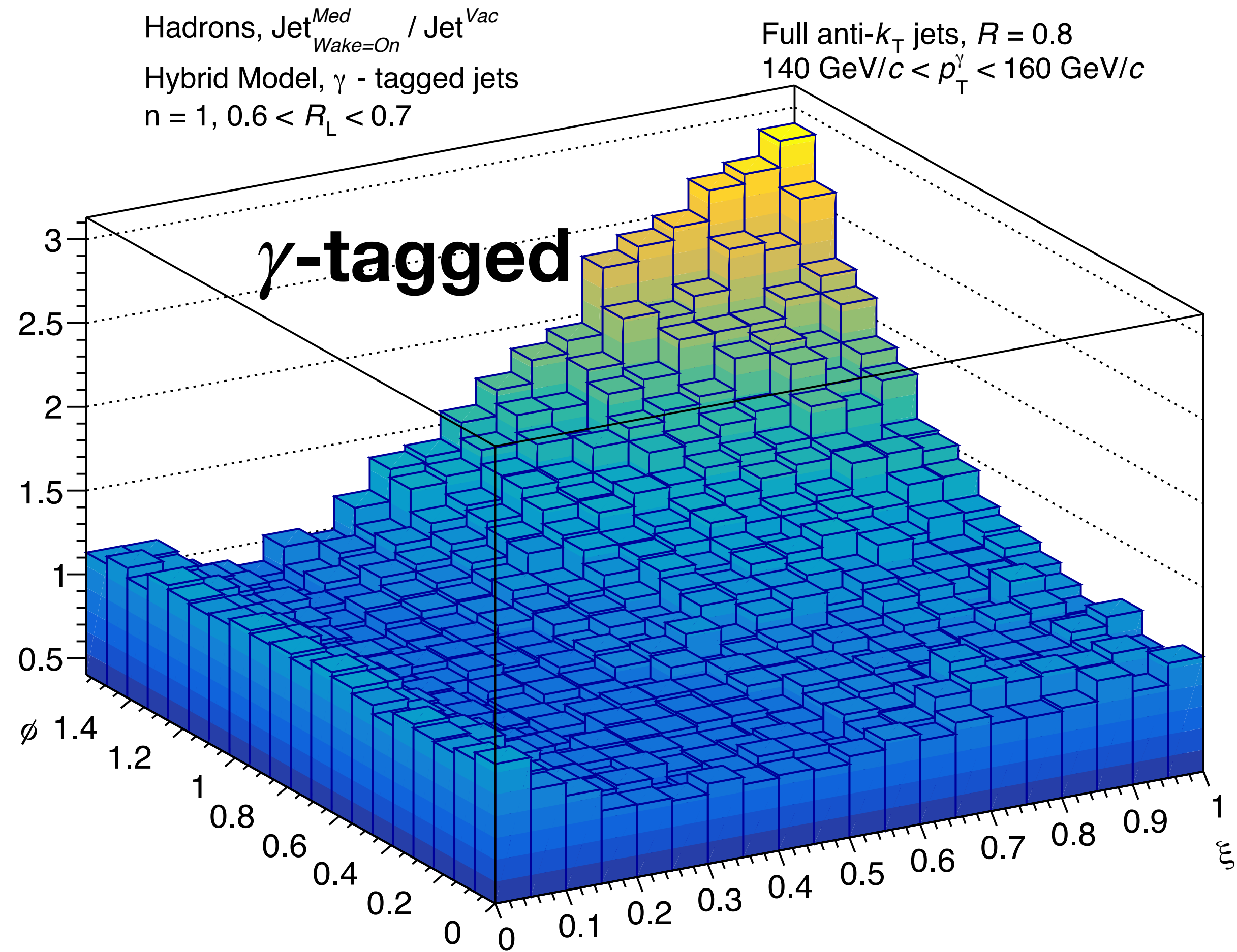


Ratio with vacuum shows **no enhancement in the equilateral region!**



# Pb-Pb/Vacuum Ratio: $\gamma$ -tagged vs Inclusive

*The effect of the wake is more pronounced in  $\gamma$ -tagged jets!*

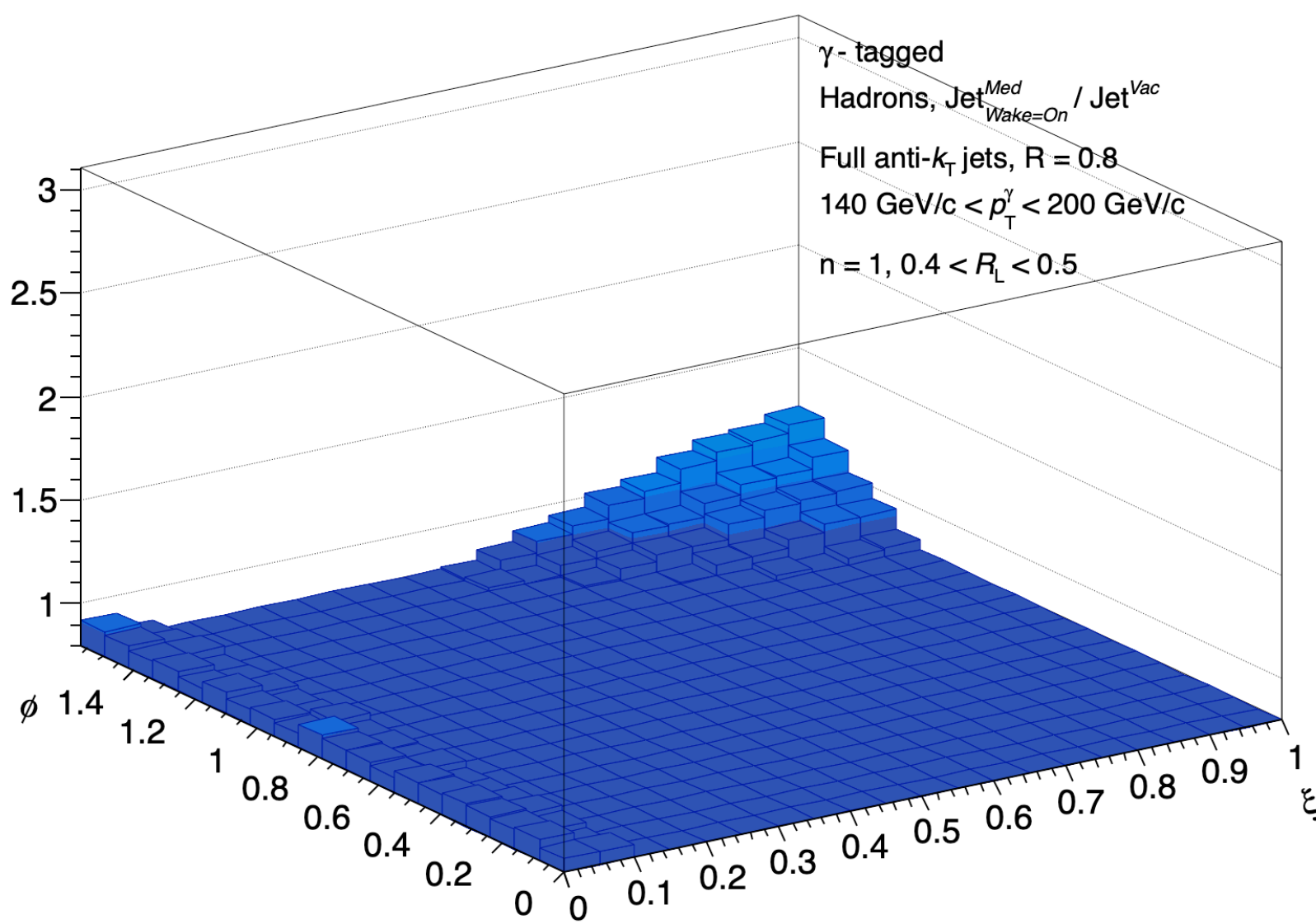


$p_{T,\text{min}}^{\text{jet}} > 40 \text{ GeV}/c$

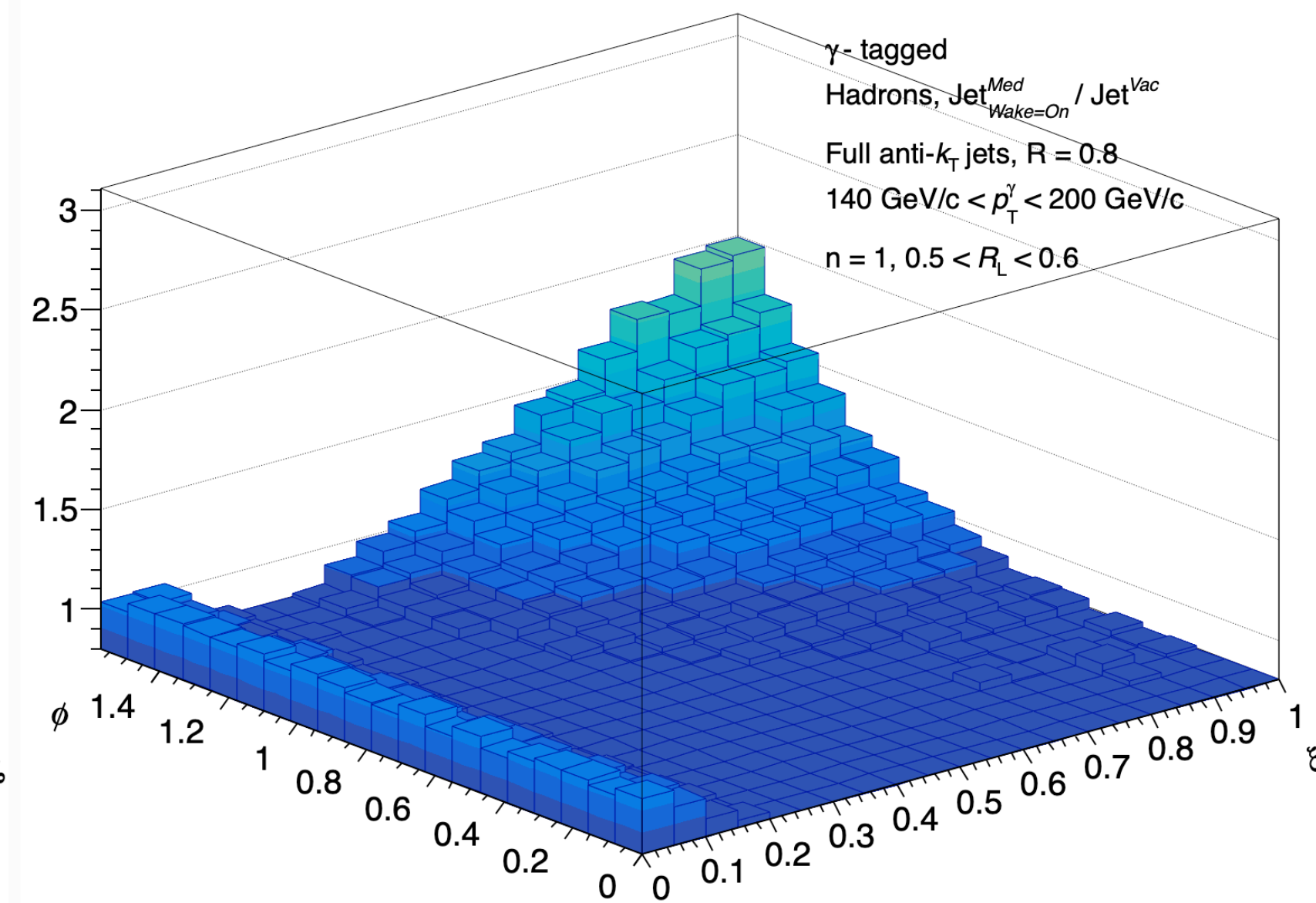


# $R_L$ dependence, $\gamma$ -tagged

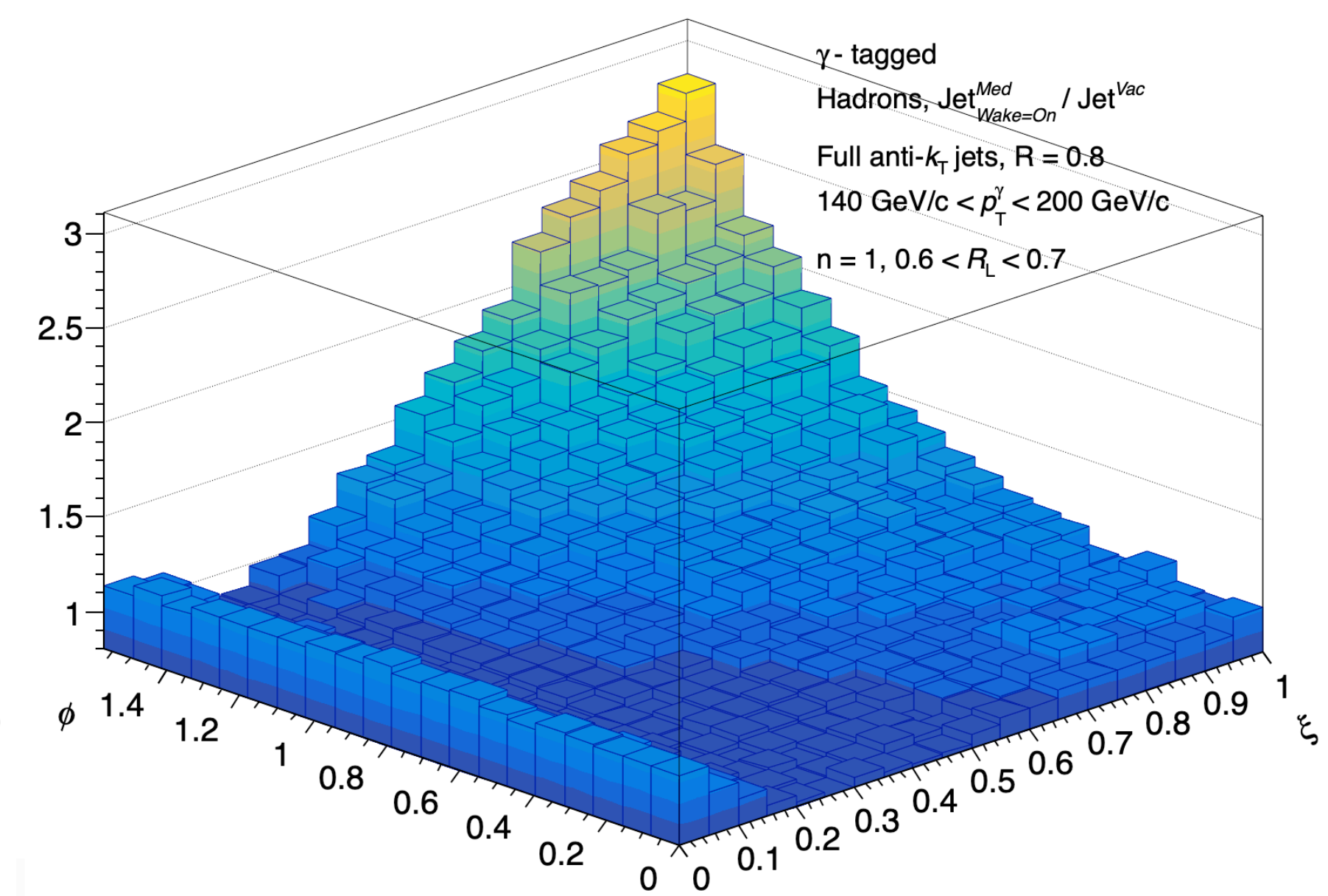
$0.4 < R_L < 0.5$



$0.5 < R_L < 0.6$



$0.6 < R_L < 0.7$



$140 \text{ GeV}/c < p_T^\gamma < 200 \text{ GeV}/c$

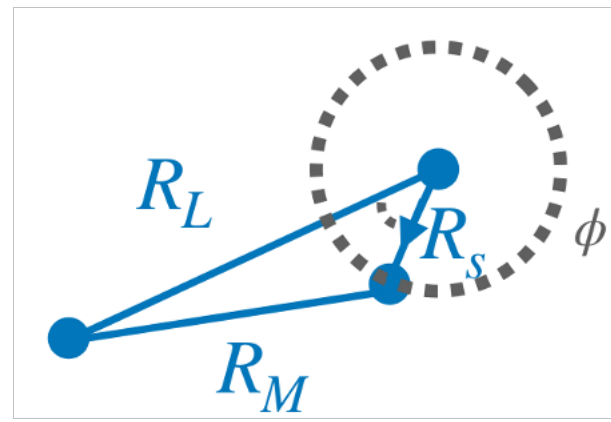
$p_{T,\text{min}}^{\text{jet}} > 40 \text{ GeV}/c$

# EEEC sensitivity to the Wake

## Pb-Pb/Vacuum

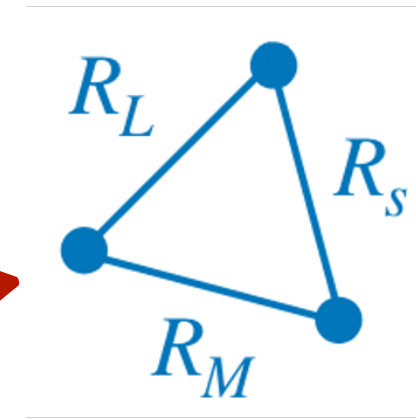
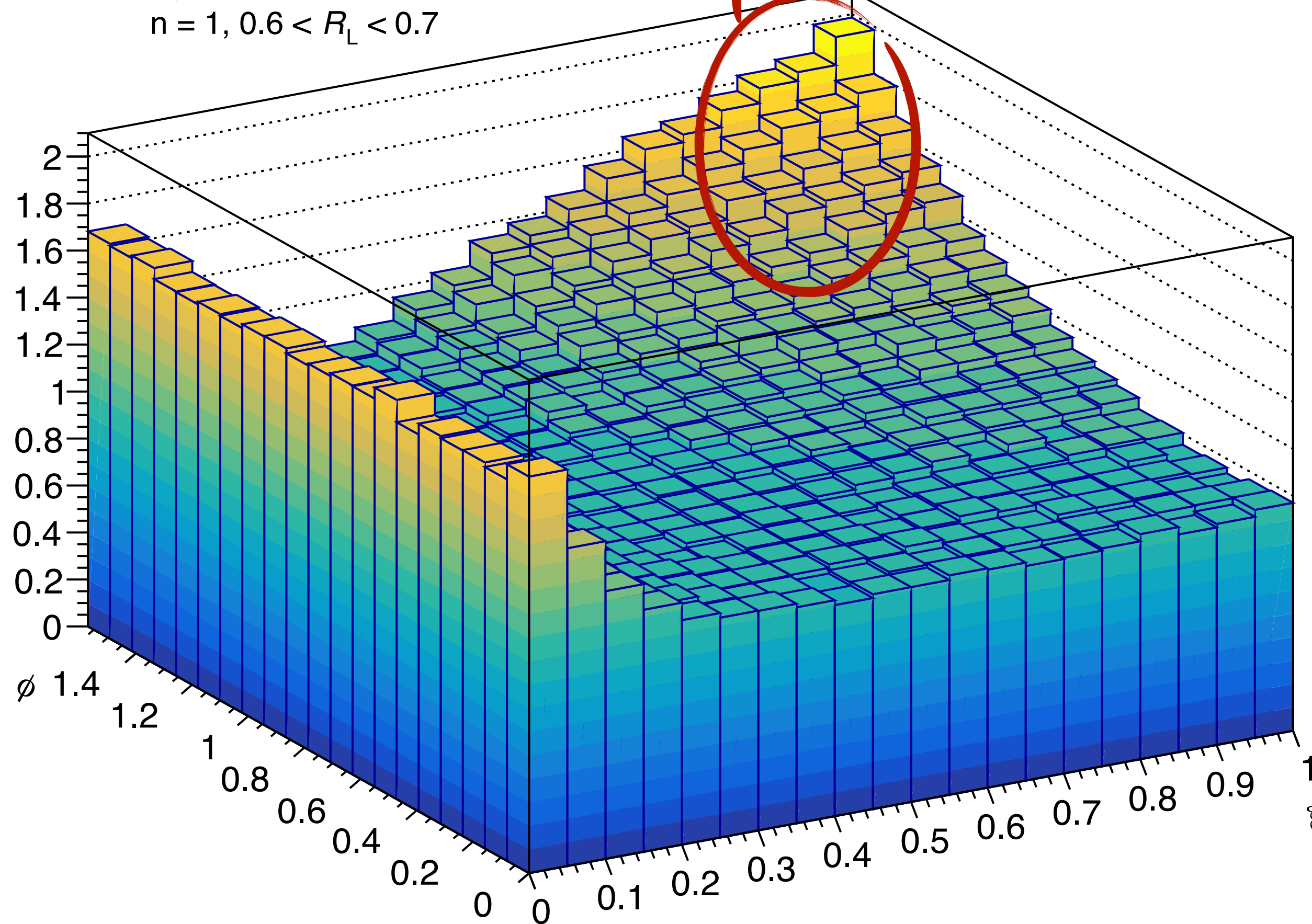
$$\sqrt{s_{NN}} = 5.02 \text{ TeV}$$

Jet Radius = 0.8



Hadrons,  $\text{Jet}_{\text{Wake=On}}^{\text{Med}} / \text{Jet}^{\text{Vac}}$   
 Hybrid Model (Inclusive Sample)  
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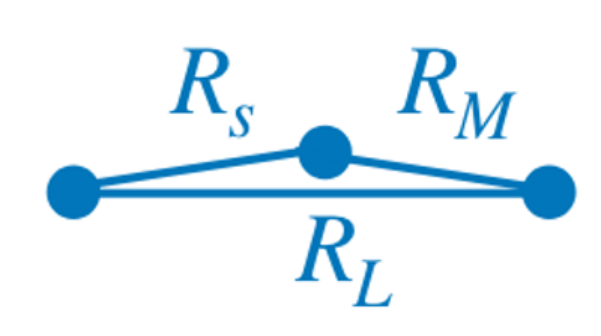
Full anti- $k_T$  jets,  $R = 0.8$   
 $140 \text{ GeV}/c < p_{T,\text{jet}} < 160 \text{ GeV}/c$



Ratio with vacuum shows **significant** enhancement in the **equilateral region** - effect of the **wake!**

**Wake leaves clear signatures in comparison to jets in vacuum.**

“Shape” of medium response is encoded in these ratios.





# Jets as Probes of QGP

- Theorists taking key steps...
- Disentangling jet modification from jet selection.
- Showing that hot quark soup (QGP) *can* resolve structure within jet shower.
- Calculations of the dynamics of jet wakes in droplets of QGP, identification of new experimental observables, and predictions that will enable experimental measurements to “see” the particles coming from these wakes.
- Identifying those jet substructure observables that *are* sensitive to scattering of jet quarks/gluons off QGP quarks/gluons, “seeing” the latter à la Rutherford, and are *not* sensitive to particles coming from the wake.
- Next several years will be the golden age of jet physics: sPHENIX, LHC runs 3 and 4, new substructure observables. *Many* theory advances, and analyses of today’s data, whet our appetite for the feast to come.
- We shall learn about the microscopic structure of QGP, and the dynamics of rippling QGP.



# Identifying Jet Observables with which to “See” the Short-Scale Structure of QGP

Krishna Rajagopal

MIT

with

Zach Hulcher (Stanford)

Dani Pablos (INFN Torino)

# Why Molière scattering?

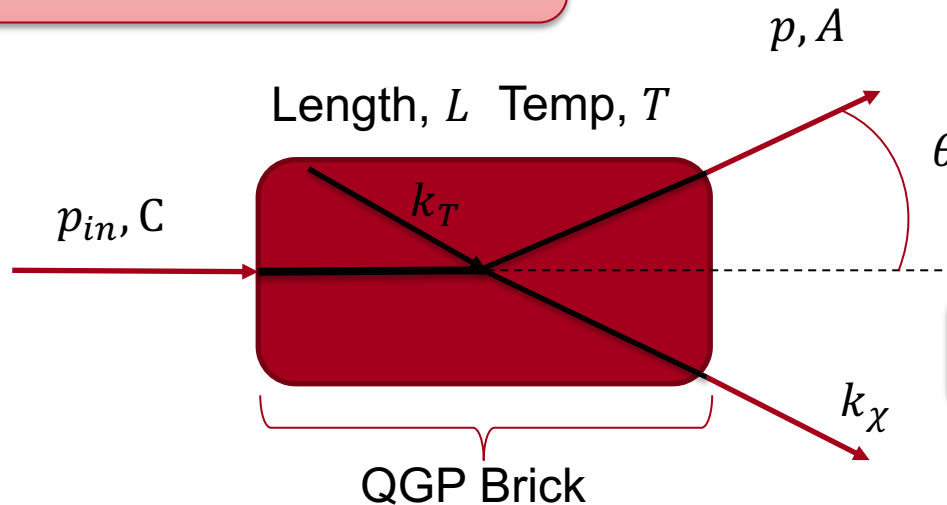
## Why add to Hybrid Model?

- QGP, at length scales  $\mathcal{O}(1/T)$ , is a strongly coupled liquid. Flow, and jet observables sensitive to parton energy loss, are well-described (eg in hybrid model) in such a fluid, without quasiparticles.
- At shorter length scales, probed via large momentum-exchange, asymptotic freedom  $\rightarrow$  quasiparticles matter.
- High energy partons in jet showers *can* probe particulate nature of QGP. Eg via power-law-rare, high-momentum-transfer, large-angle, Molière scattering
- “Seeing” such scattering is first step to probing microscopic structure of QGP.
- What jet observables are sensitive to effects of high-momentum-transfer scattering? To answer, need to turn it off/on.
- Start from Hybrid Model – in which any particulate effects are definitively off! Add Molière, and look at effects...

# Moliere Scattering in a brick of QGP (D'Eramo, KR, Yin, 2019)

Power-law-rare medium kicks which can probe particle constituents of QGP

In JEWEL, LBT, MARTINI, harder to turn off



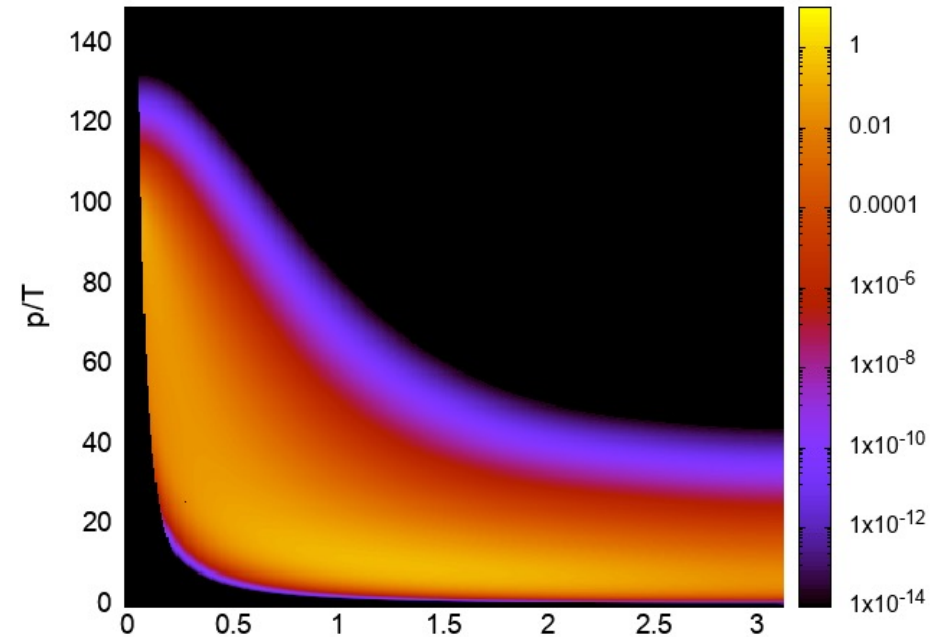
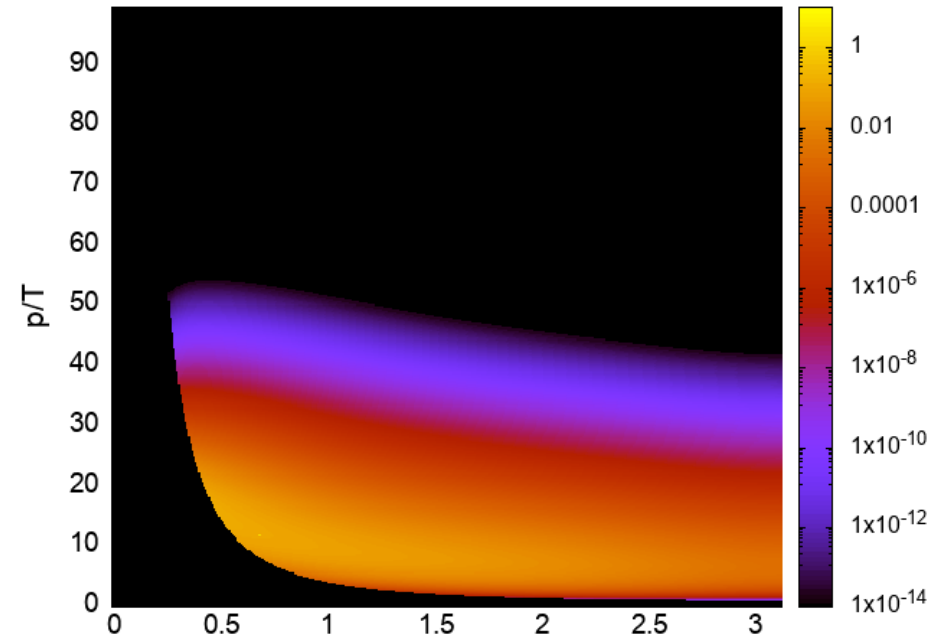
D'Eramo et al., 2019

- Sufficiently hard scattering should be perturbative.
- High  $p_T$  particle can be deflected, changing its energy and direction.
- Recoiling particle,  $k_\chi$ , a new particle to be quenched
- Thermal particle,  $k_T$ , from BE/FD distribution, removed from medium.

Tree-Level 2-2 massless scattering amplitudes

$$F^{C \rightarrow A}(p, \theta; p_{in}) = \sum_{nDB} \frac{c_{DBn}^{C \rightarrow A}}{2(4\pi)^3} \left( \frac{p \sin(\theta)}{p_{in} |\mathbf{p} - \mathbf{p}_{in}| T} \right) \int_{k_{min}}^{\infty} dk_T n_D(k_T) [1 \pm n_B(k_\chi)] \int_0^{2\pi} \frac{d\phi}{2\pi} \frac{|M^{(n)}|^2}{g_s^4}$$

## Results (for a QGP brick)



Incoming gluon,  $p_{in} = 20T$ ,  $L = 15/T$

Incoming gluon,  $p_{in} = 100T$ ,  $L = 15/T$

- Excluding  $\tilde{u} > 10 m_D^2$  not a simple curve on this plot, but effects visible
- Restricting to  $\tilde{u}, \tilde{t} > 10 m_D^2$  excludes soft scatterings; justifies assumptions made in amplitudes; avoids double counting. Can vary where to set this cut...
- Analytical results  $\rightarrow$  fast to sample
- Apply at every time step, to every rung, in every shower, in Hybrid Model Monte Carlo....  
And, if a scattering happens, two subsequent partons then lose energy a la Hybrid

# Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum  $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

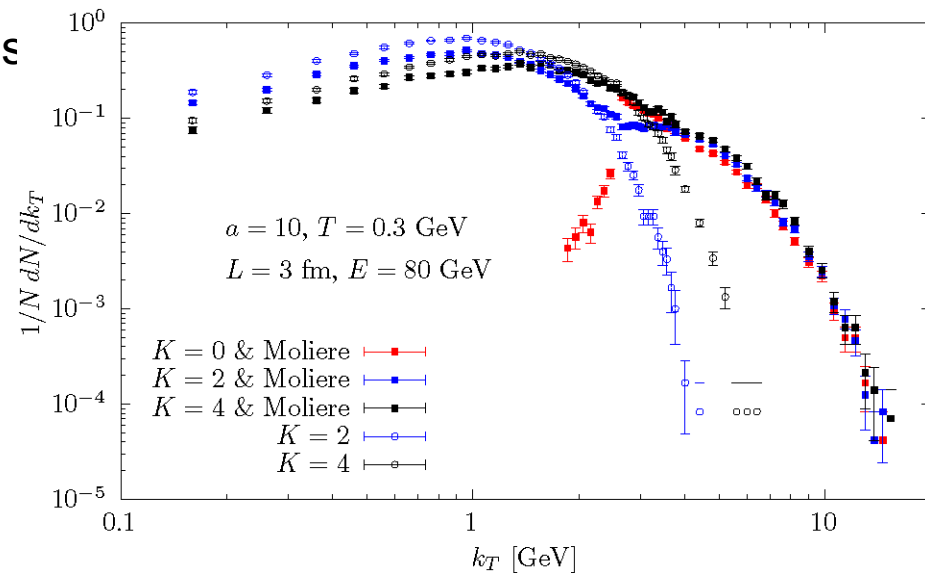
At strong coupling, holography predicts Gaussian broadening **without quasi-particles** (eg: N=4 SYM)

$$P(k_{\perp}) \sim \exp\left(-\frac{\sqrt{2}k_{\perp}^2}{\hat{q}L^-}\right) \quad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma(\frac{3}{4})}{\Gamma(\frac{5}{4})}\sqrt{\lambda}T^3$$

Adding this in hybrid model (C-S et al 2016) yielded little effect on jet observables.

Today, Bayesian inference from hadron  $R_{AA}$  data indicates  $P(k_{\perp}) \sim K T^3$  with  $K \sim 2 - 4$ . This need not have anything to do with quasiparticles.

- Add Moliere scattering with momentum exchanges  $> m_D$ ; here,  $a = 10$  and 80 GeV incident jet parton



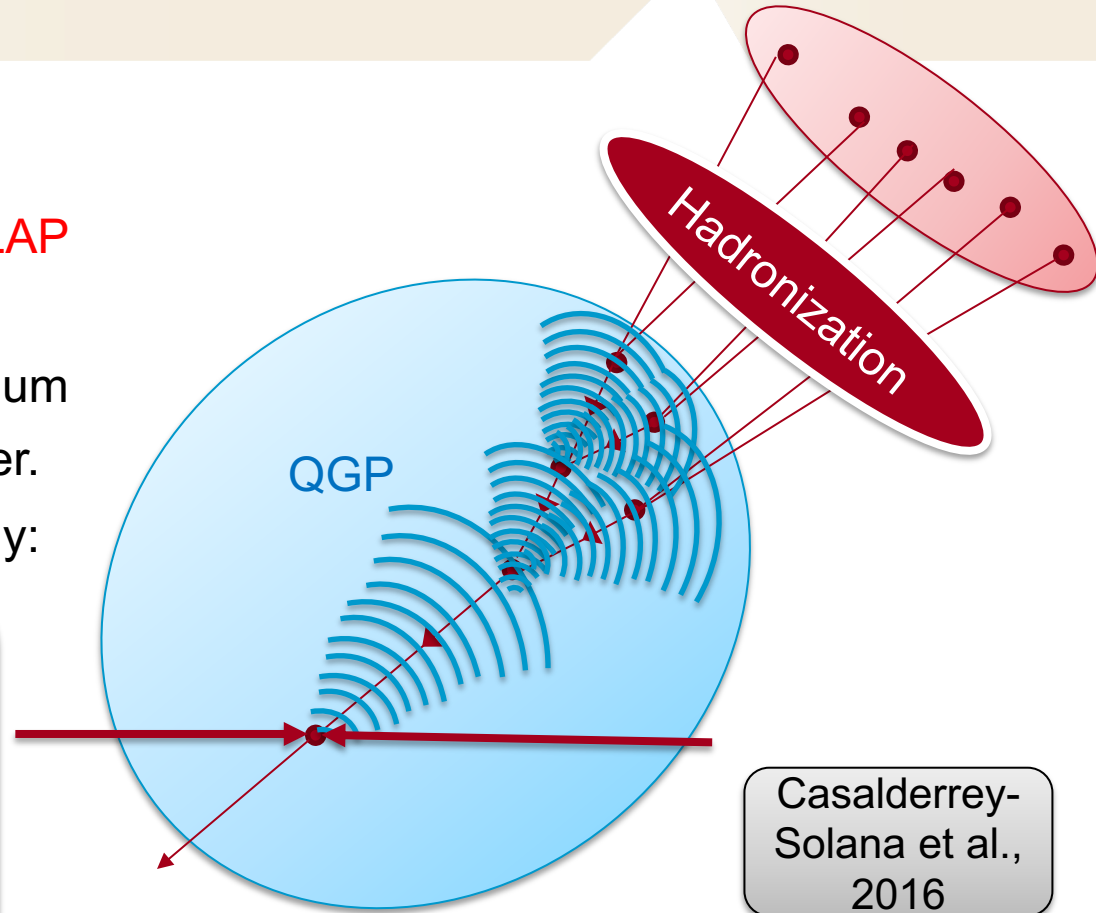
# Perturbative Shower ... Living in Strongly Coupled QGP

- High  $Q^2$  parton shower up until hadronization described by **DGLAP** evolution (PYTHIA).
- For QGP with  $T \sim \Lambda_{QCD}$ , the medium interacts strongly with the shower.
  - Energy loss from holography:

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

$O(1)$  fit const.

$x_{stop} = \frac{1}{2\kappa_{sc}} \frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}}$	$\tau = \frac{2E}{Q^2}$
--	-------------------------

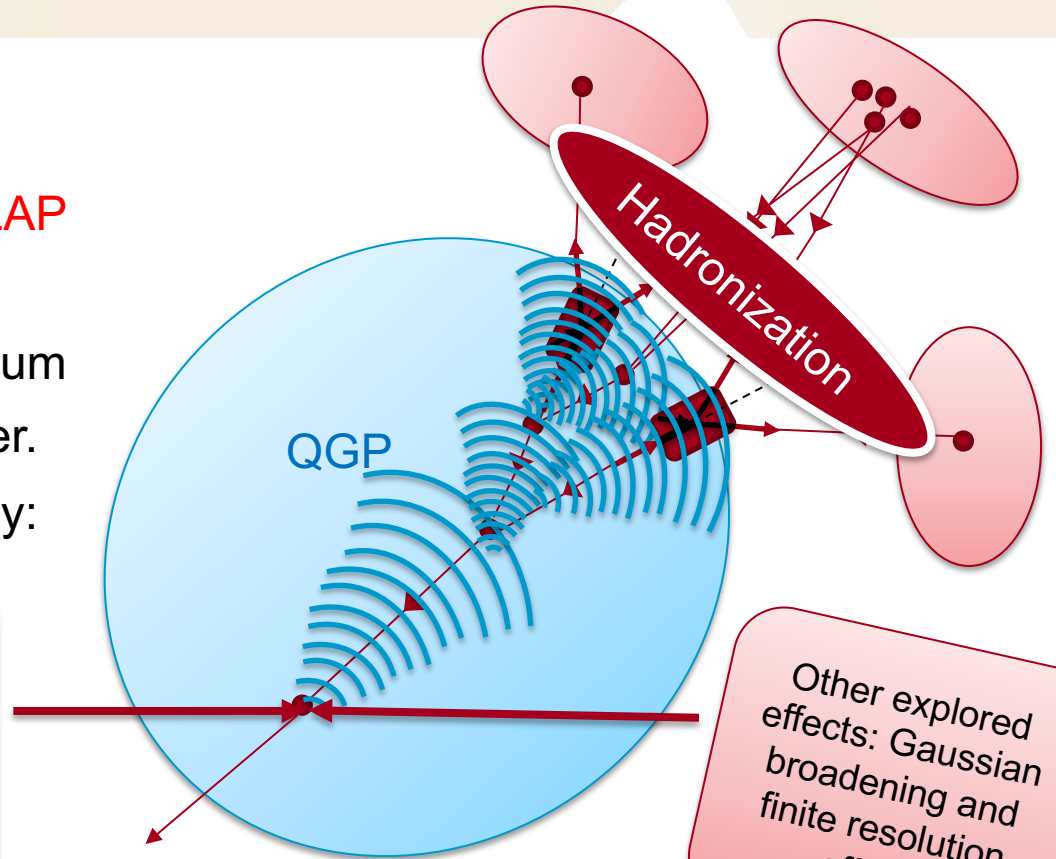


Energy and momentum conservation  $\longrightarrow$  deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3} \int \tau dx dy d\eta_s m_T \cosh(y - \eta_s) \left[ f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right) \right]$$

# Adding Moliere Scattering to Hybrid Model

- High  $Q^2$  parton shower up until hadronization described by **DGLAP** evolution (PYTHIA).
- For QGP with  $T \sim \Lambda_{QCD}$ , the medium interacts strongly with the shower.
  - Energy loss from holography:



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

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

$$\tau = \frac{2E}{Q^2}$$

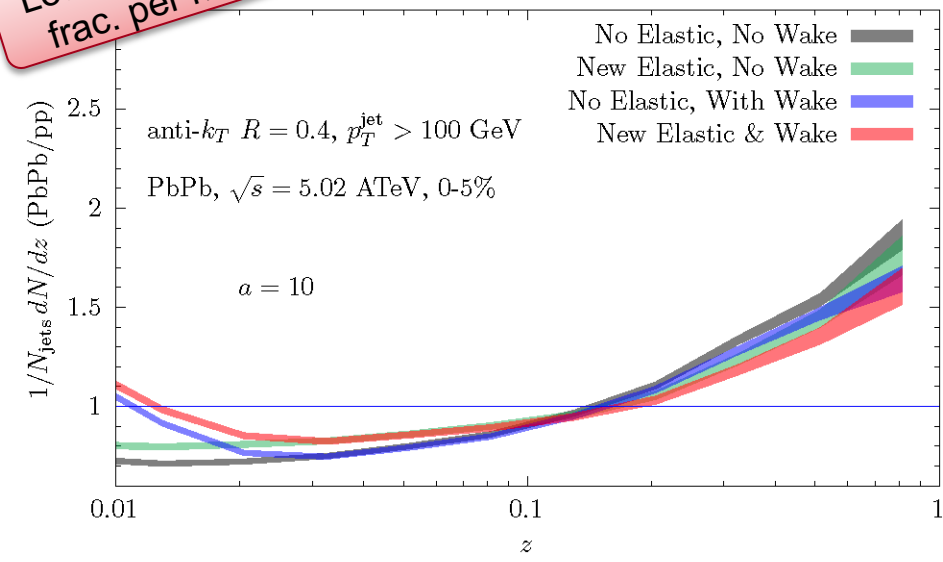
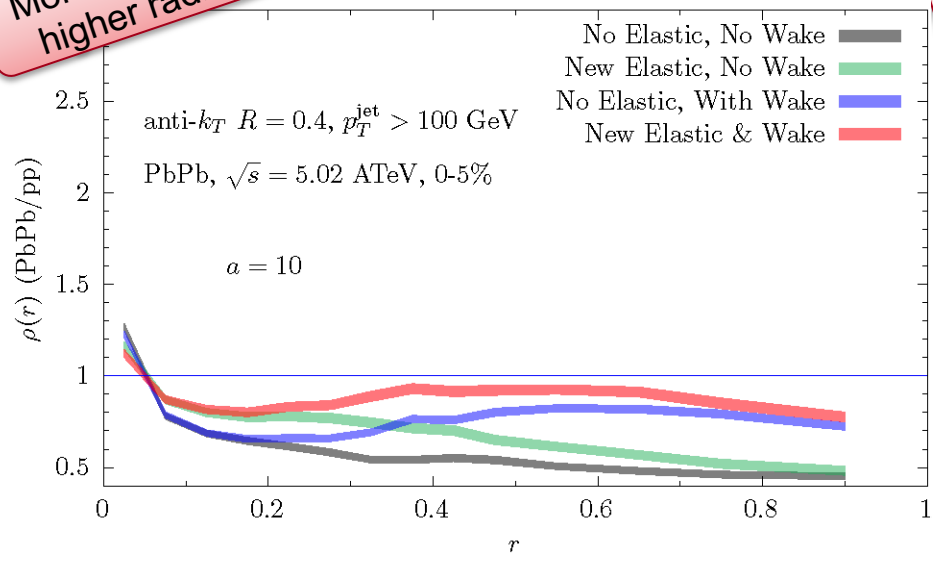
Energy and momentum conservation  $\longrightarrow$  activate hydrodynamic modes of plasma

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3} \int \tau dx dy d\eta_s m_T \cosh(y - \eta_s) \left[ f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right) \right]$$

# Jet Shapes and Fragmentation Functions

More energy at higher radius

Lower momentum frac. per hadron



→ Elastic scattering effects look very similar to wake effects, but smaller.

- Moliere scattering transfers jet energy to high angle and lower momentum fraction particles. So does energy loss to wake in fluid.
- In **these observables**, effect of Moliere looks like just a bit more wake.
- In principle sensitive to Moliere, but in practice not: more sensitive to wake.
- Moliere effects are even slightly smaller if  $\tilde{u}, \tilde{t} > a m_D^2$  with  $a=10$ .
- What if we look at groomed observables? Less sensitive to wake...



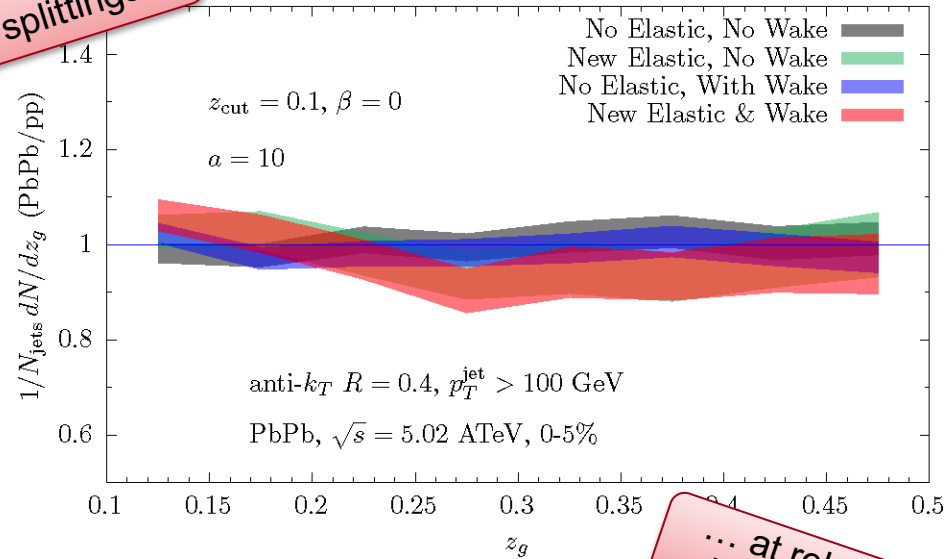
# Groomed $z_g$ and $R_g$

## Soft Drop ( $\beta = 0$ )

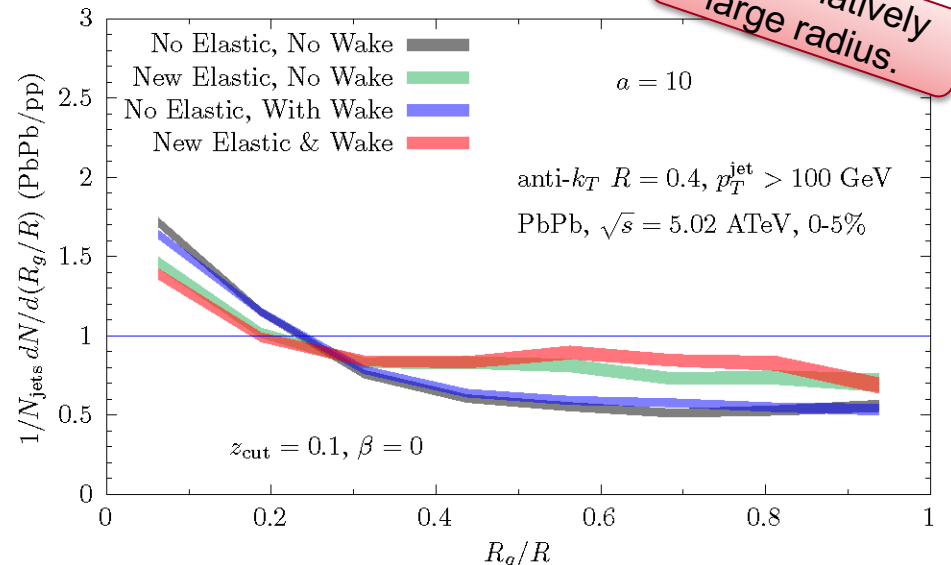
1. Reconstruct jet with anti- $k_T$
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2, separated by angle  $R_g$
4. If  $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \equiv z_g > z_{cut}$ , then original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and repeat

Much less sensitivity to wake;  
Moliere scattering shows up;  
effects of Moliere and wake are again similar in shape, but here effects of Moliere on  $R_g$  are dominant, with  $a=4$  or 10.

Enhancement of softer splittings...



... at relatively large radius.



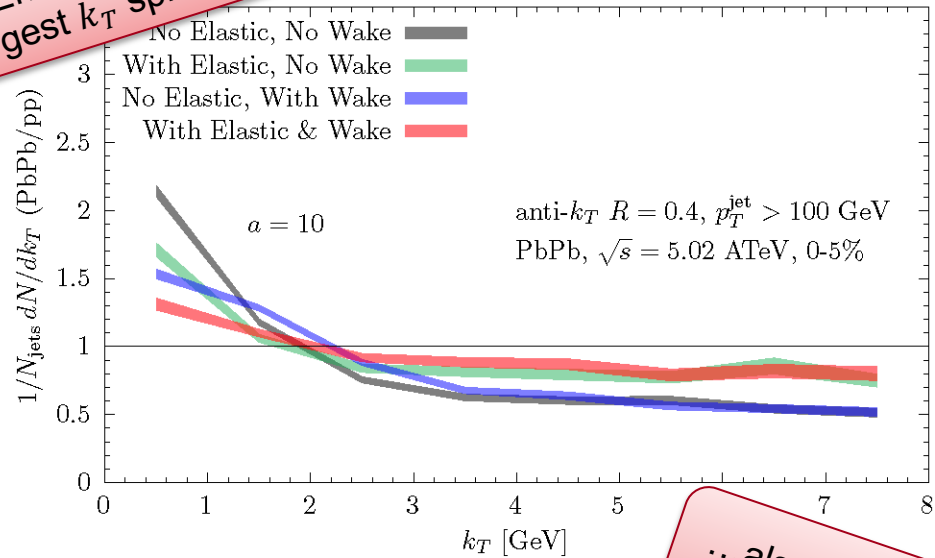
# Leading $k_T$

1. Reconstruct jet with anti- $k_T$
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2
4. Note  $k_T$  of splitting
5. Follow primary branch until the end.
6. Record largest  $k_T$

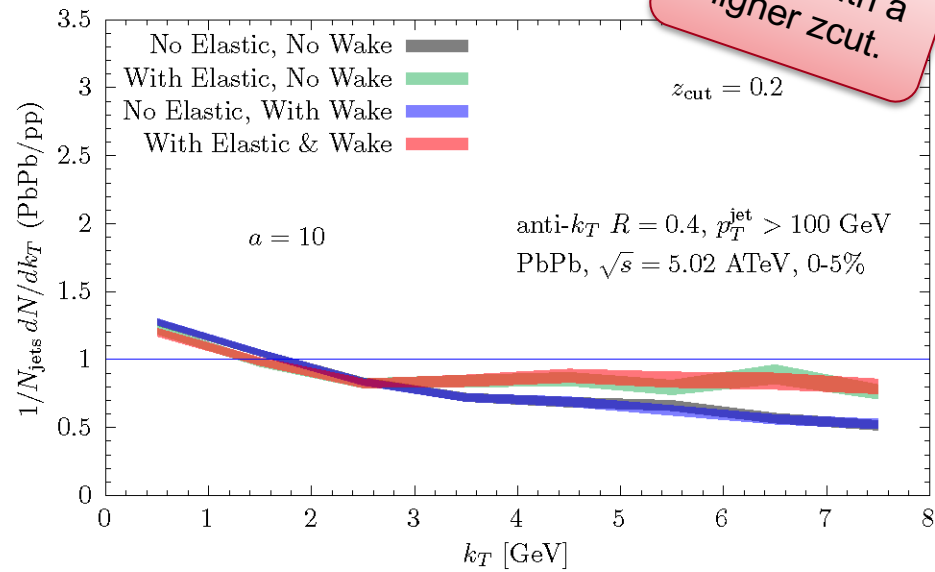
$$k_T = \min(p_{T1}, p_{T2}) \sin(R_g)$$

Similar message also for this groomed observable: **Moliere scattering effects show up; much larger than wake effects.**

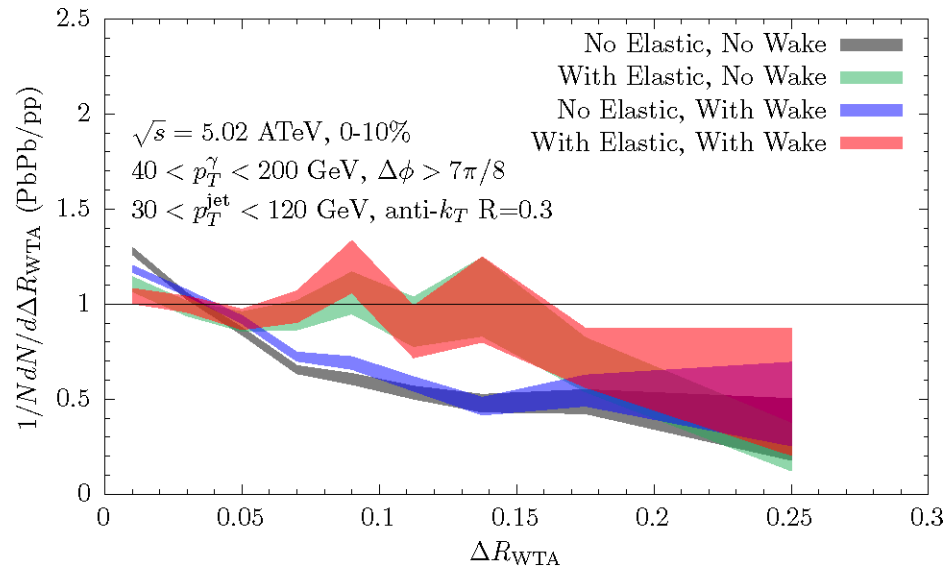
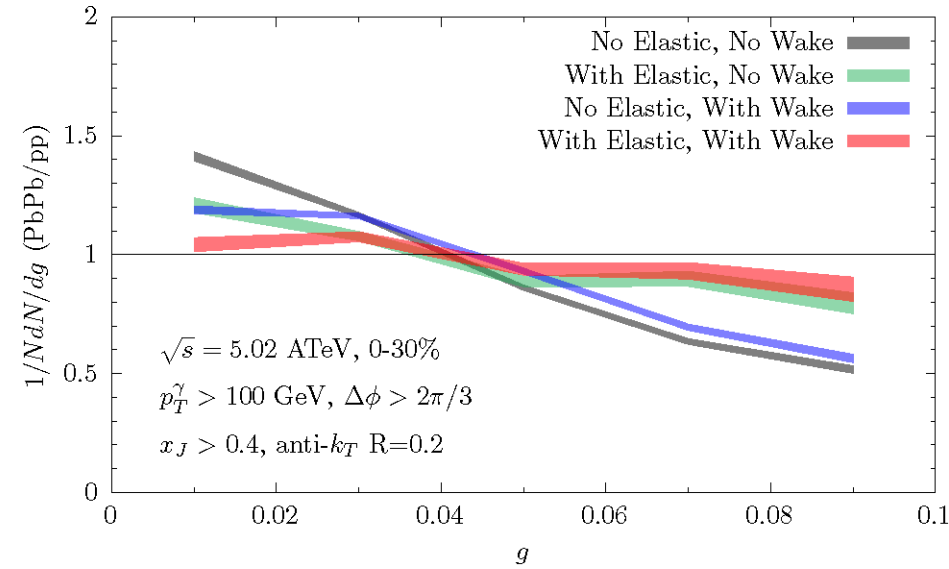
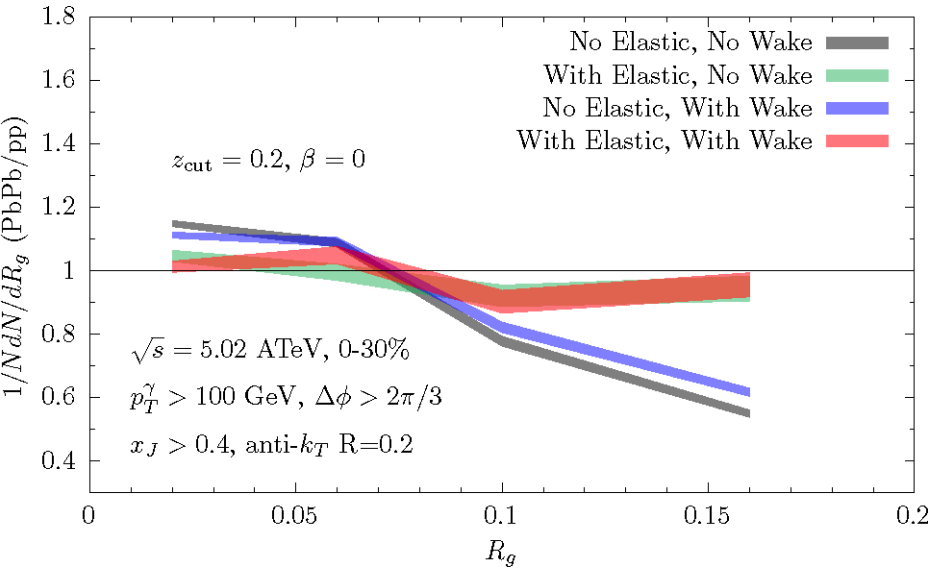
Enhancement of largest  $k_T$  splittings...



...also with a higher  $z_{\text{cut}}$ .

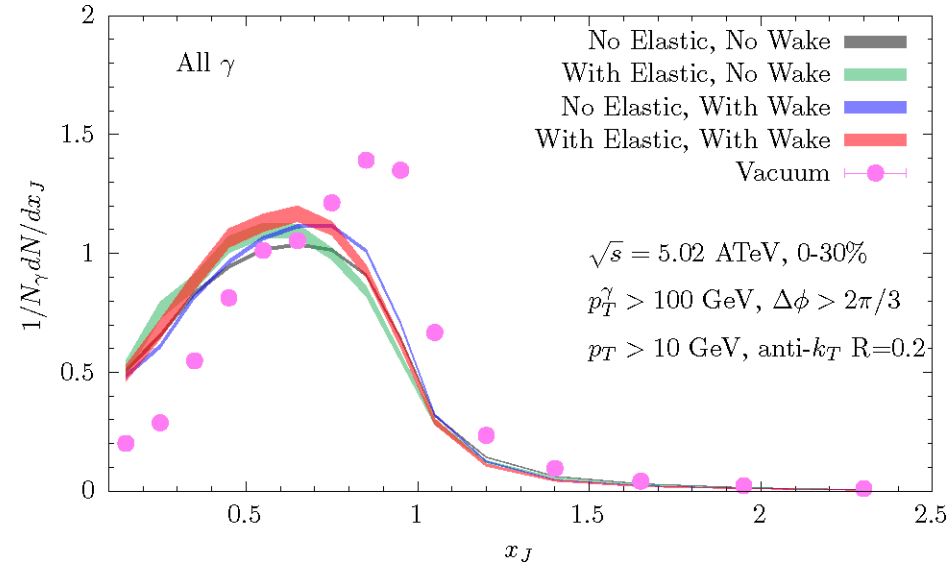
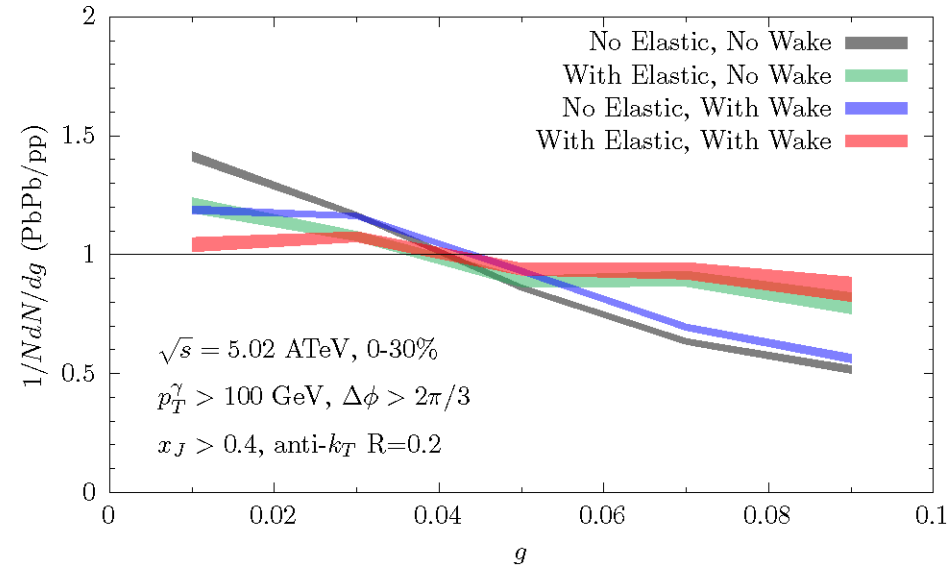
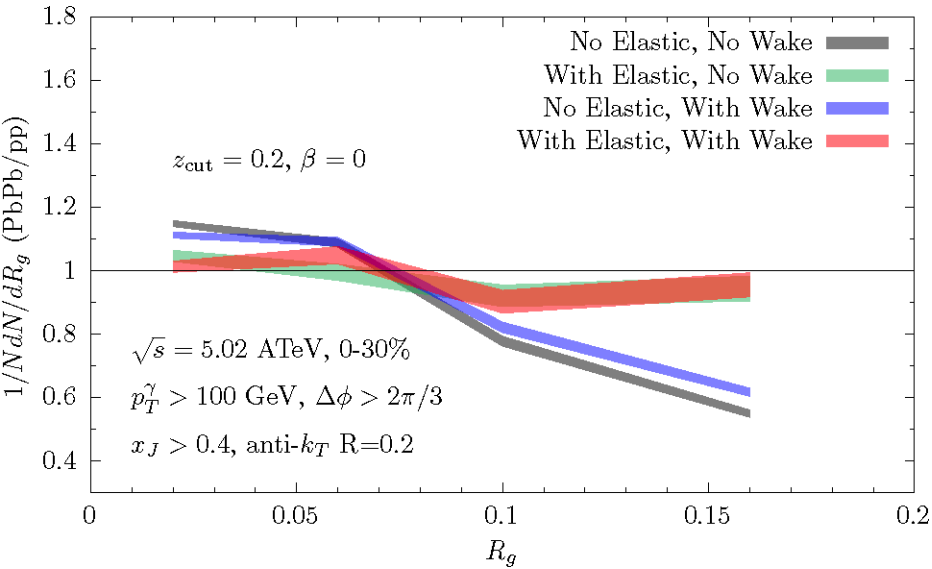


# Three “groomed” gamma-Jet Observables: $R_g$ , Girth, and angle between standard and WTA axes



All show much less sensitivity to wake: R=0.2; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere are very much dominant.

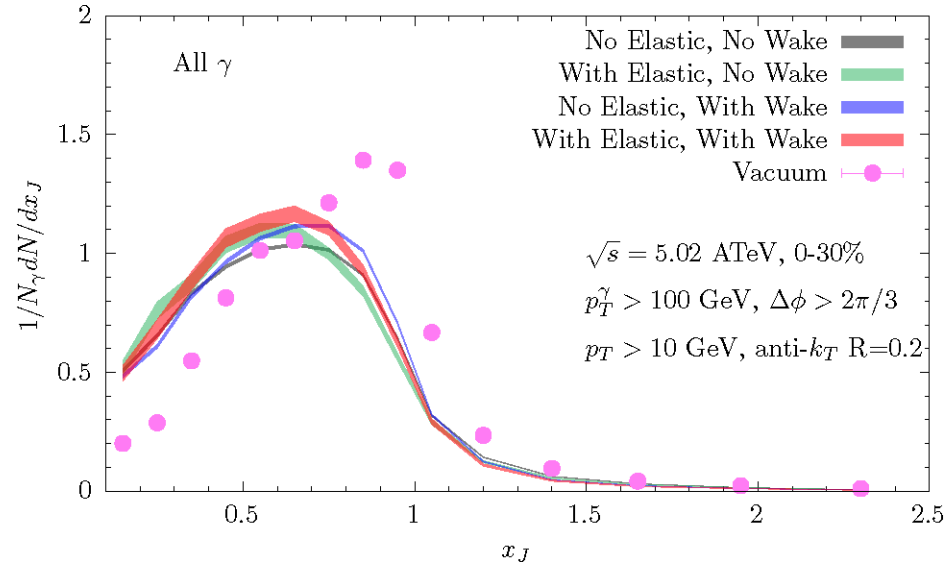
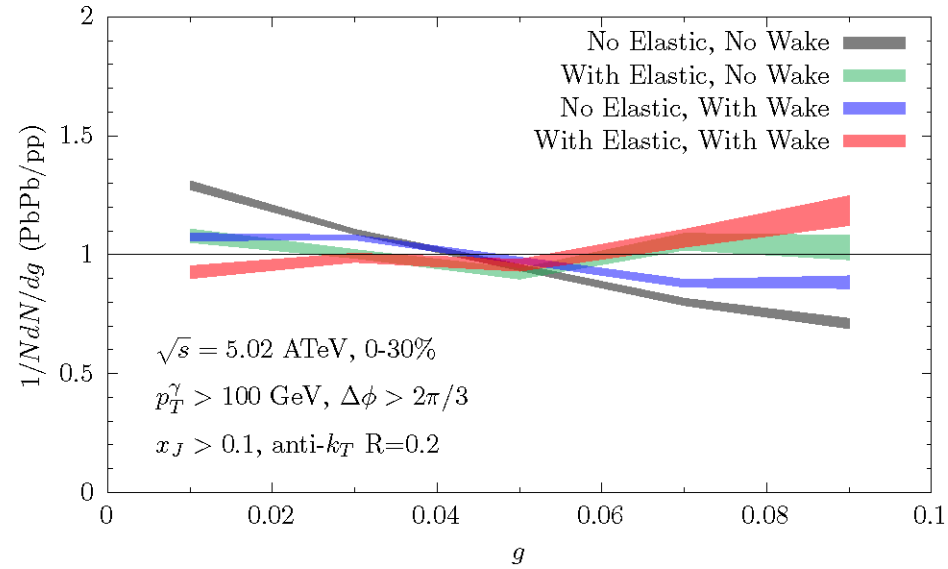
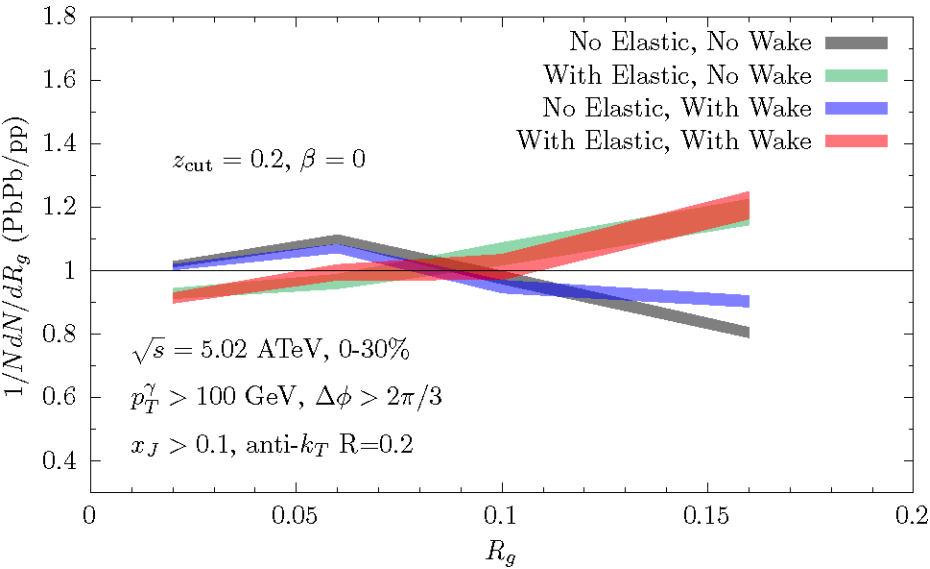
# Gamma-Jet Observables: $R_g$ and Girth



All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

But why is  $R_{AA}$  below 1? Selection bias! With  $x_J > 0.4$  selection, missing too many of the most modified jets.

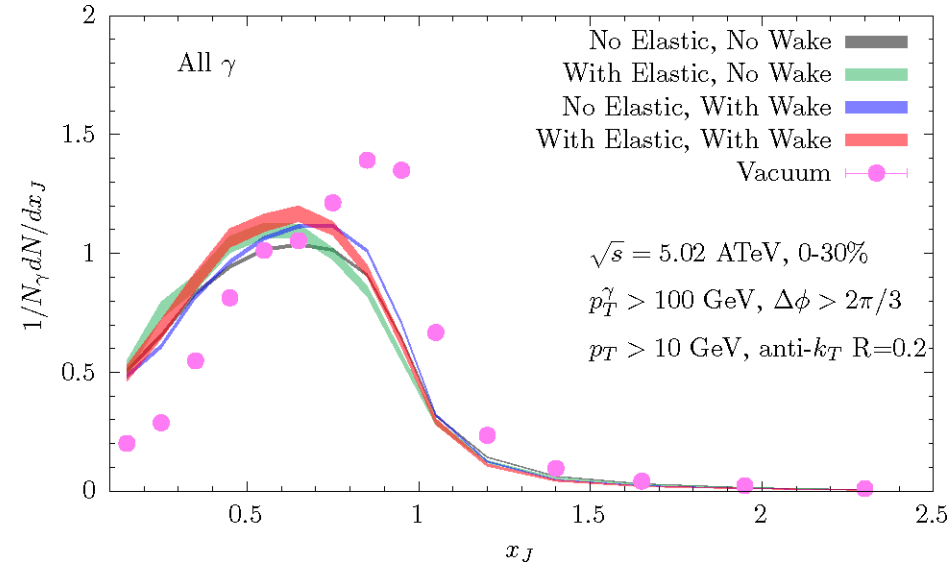
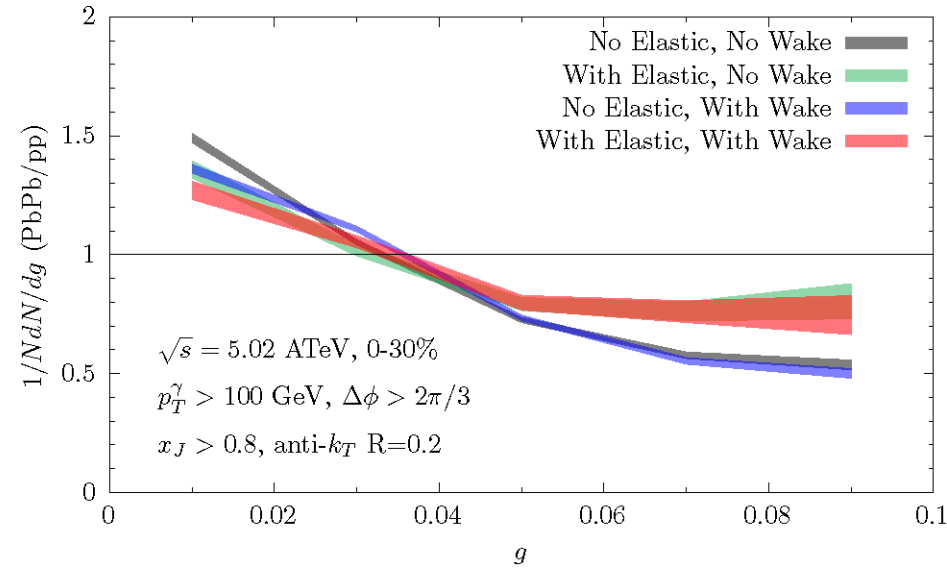
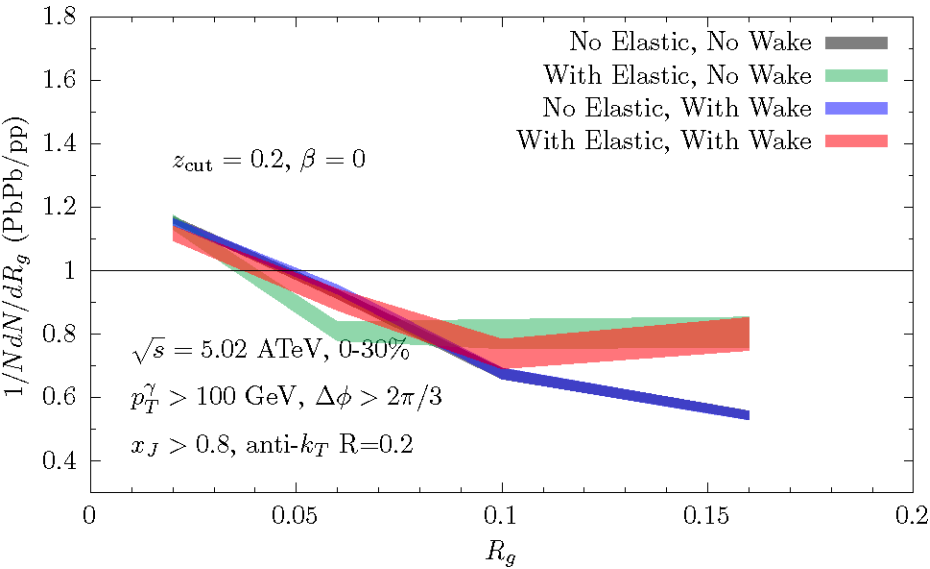
# Gamma-Jet Observables: $R_g$ and Girth, with $x_J > 0.1$



On previous slides,  $R_g$  and Girth with  $x_J > 0.4$ : missing the most modified jets. Here,  $x_J > 0.1$ . Moliere scattering important, and causes  $R_{AA} > 1$ .

Selection bias reduced (cf Brewer+Brodsky+KR); some effects of wake visible.

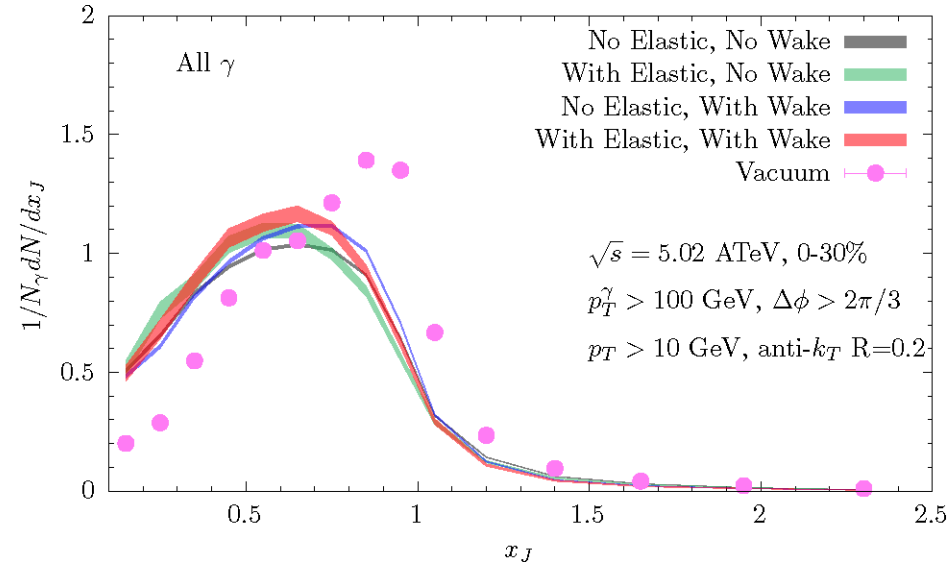
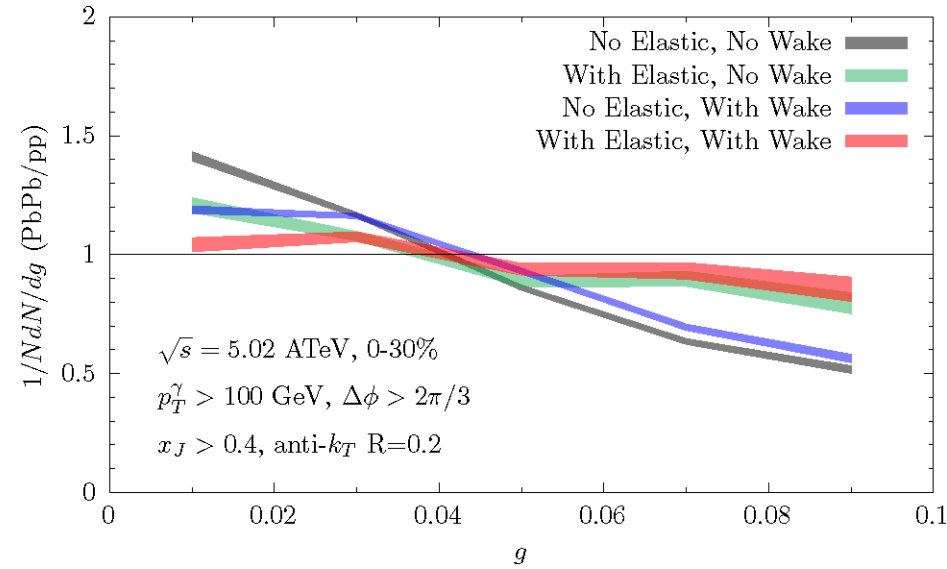
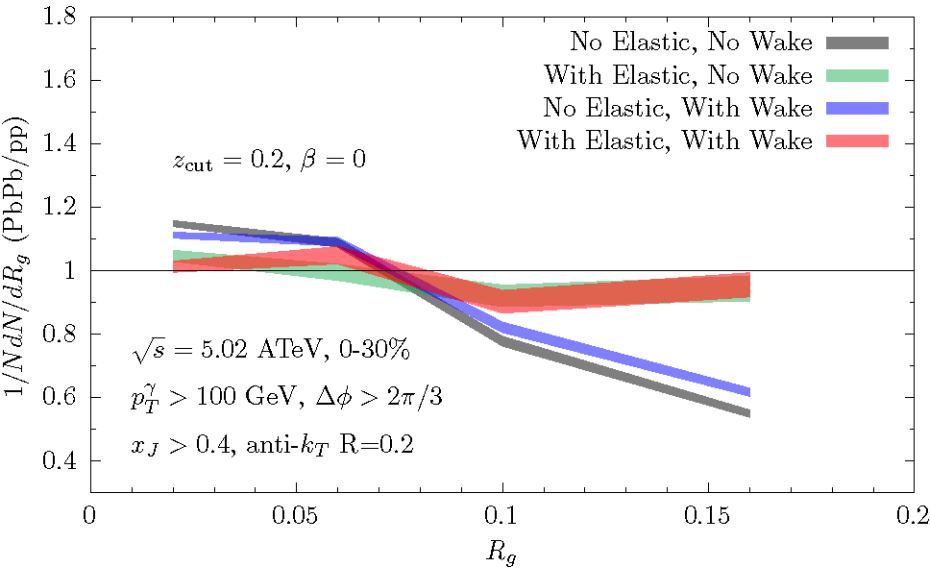
# Gamma-Jet Observables: $R_g$ and Girth, with $x_J > 0.8$



On previous slides,  $R_g$  and Girth with  $x_J > 0.4$ : missing the most modified jets. Here,  $x_J > 0.8$ . Selection bias increased.

Moliere scattering still important, and but selection bias so strong that it does not yield  $R_{AA} > 1$ .

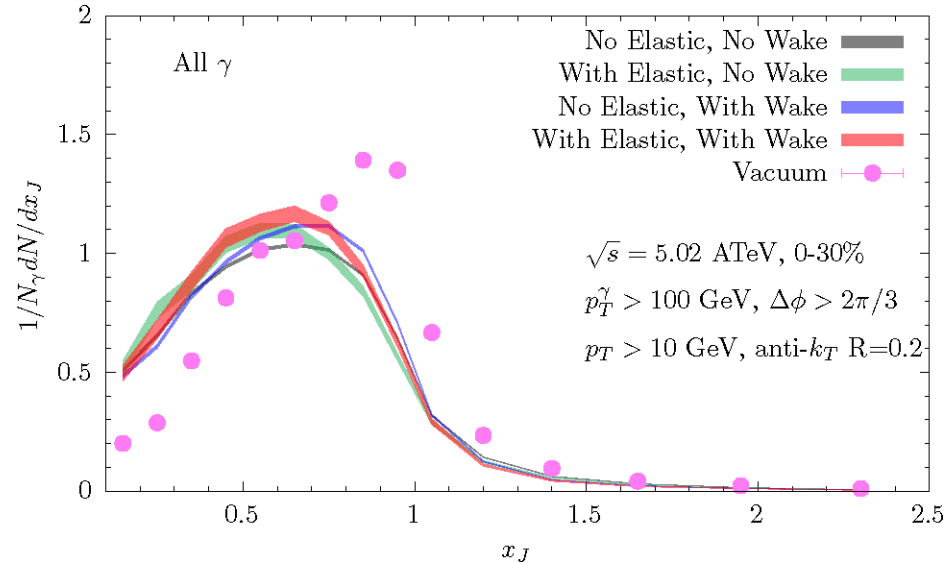
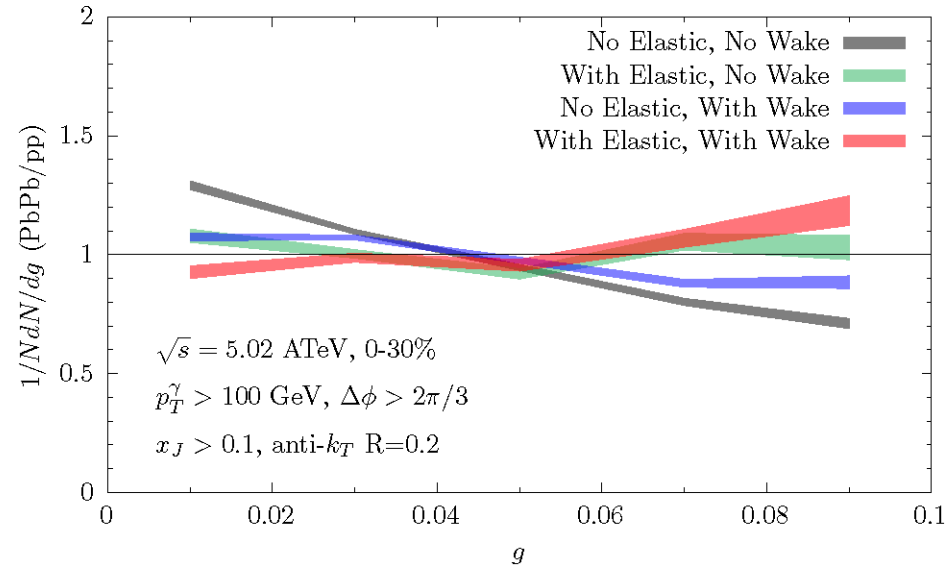
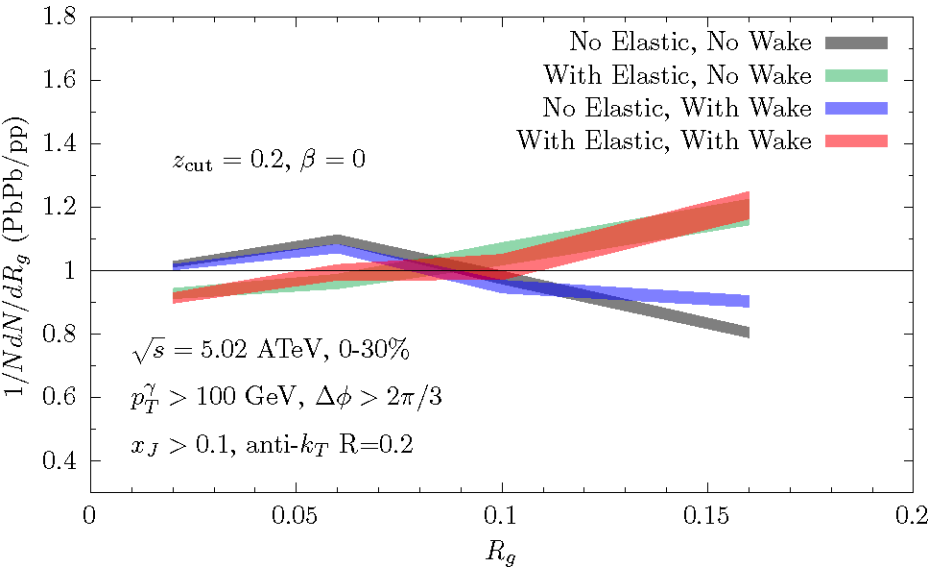
# Gamma-Jet Observables: $R_g$ and Girth, with $x_J > 0.4$



All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

But why is  $R_{AA}$  below 1? Selection bias! With  $x_J > 0.4$  selection, missing too many of the most modified jets.

# Gamma-Jet Observables: $R_g$ and Girth, with $x_J > 0.1$



On previous slides,  $R_g$  and Girth with  $x_J > 0.4$ : missing the most modified jets. Here,  $x_J > 0.1$ . Moliere scattering important, and causes  $R_{AA} > 1$ .

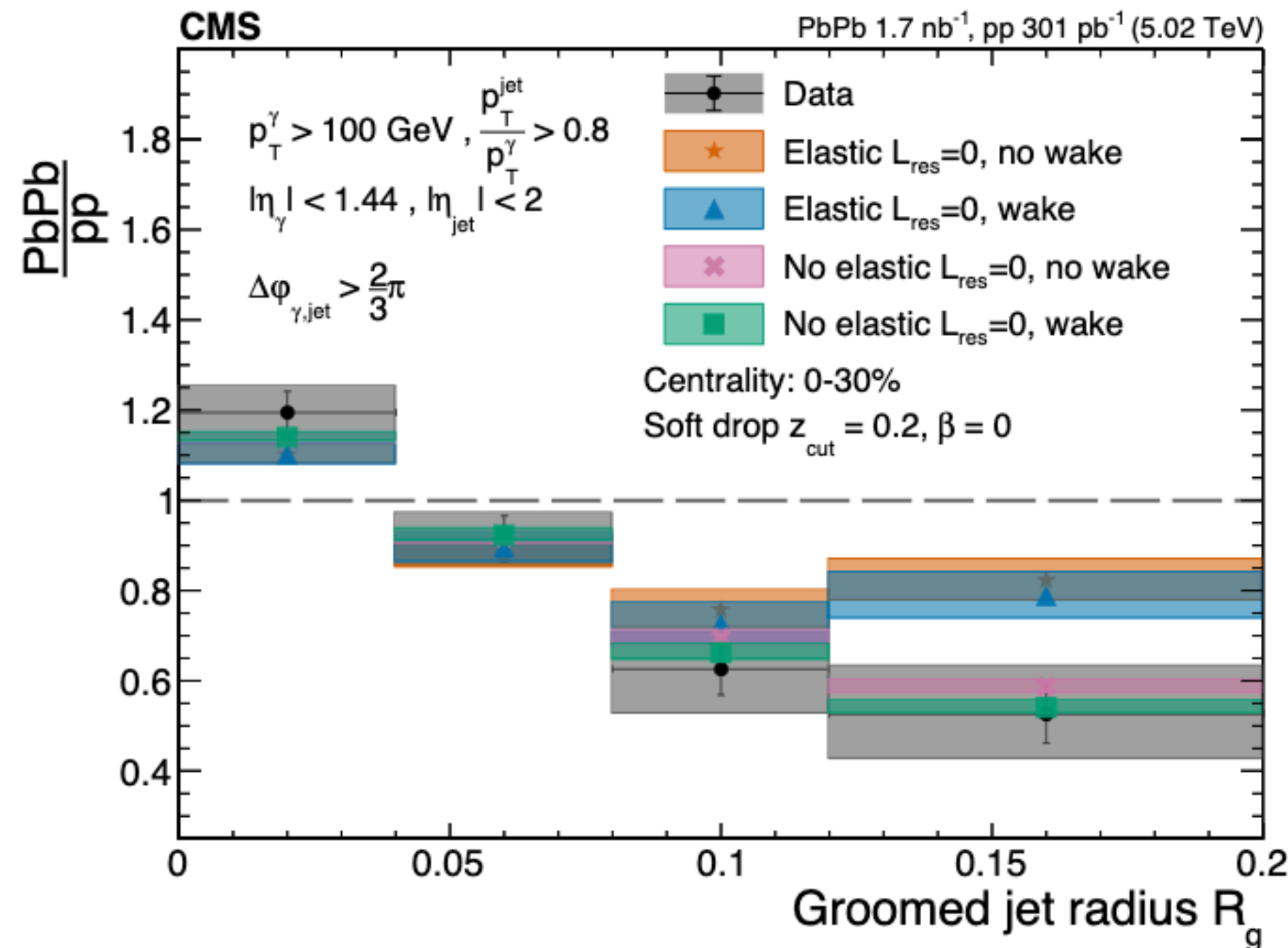
Selection bias reduced (cf Brewer+Brodsky+KR); some effects of wake visible.



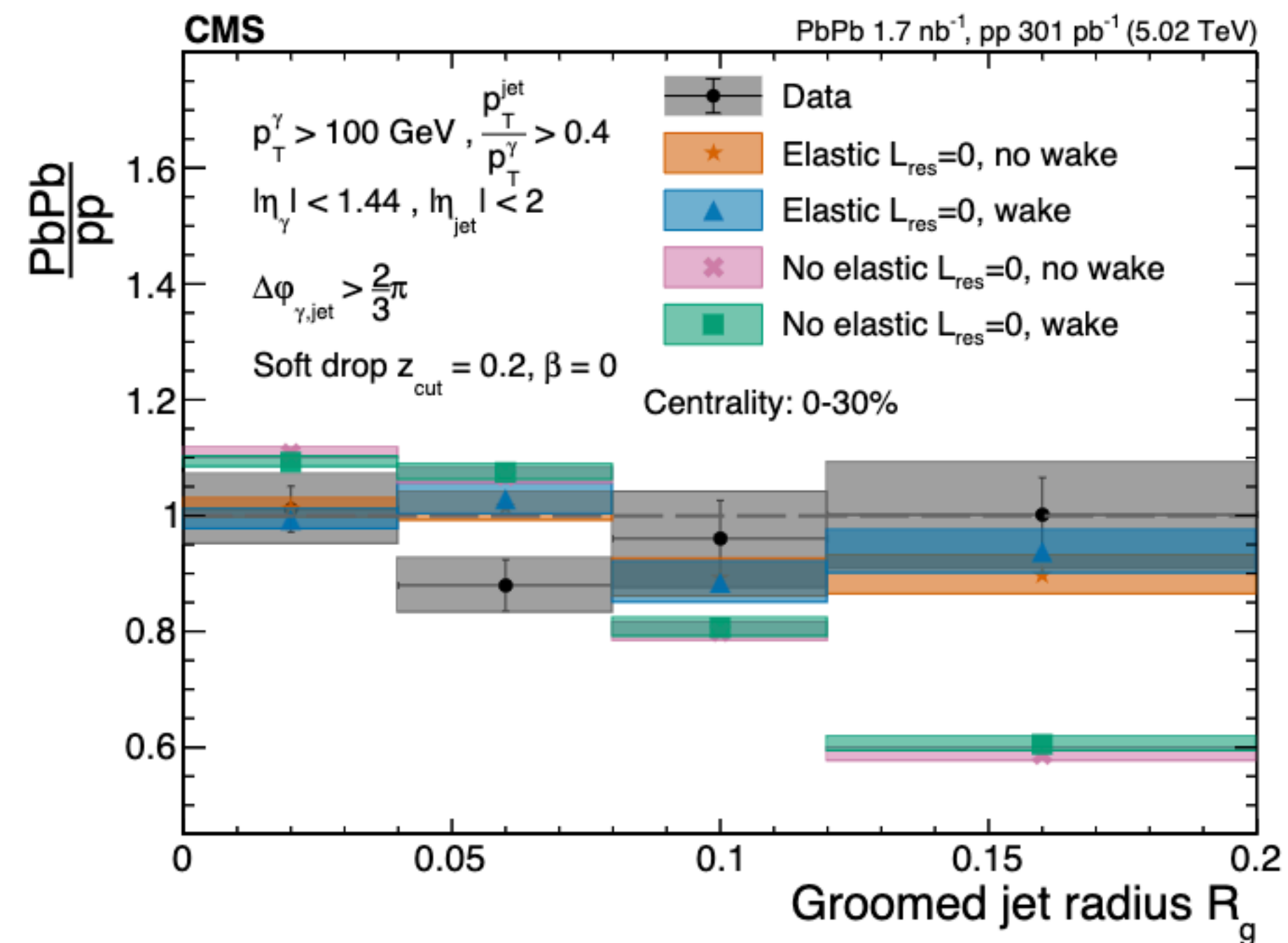
# $\gamma$ -jet substructure: suppression of the survivor bias

PbPb

less quenched  $x_J > 0.8$



more quenched  $x_J > 0.4$



## Comparison to the Hybrid model ([Rajagopal et al, JHEP 10 \(2014\) 019](#))

Factorized by construction

Interplay of several mechanisms:

Energy loss

Elastic hard interactions (interaction with free q/g within QGP)

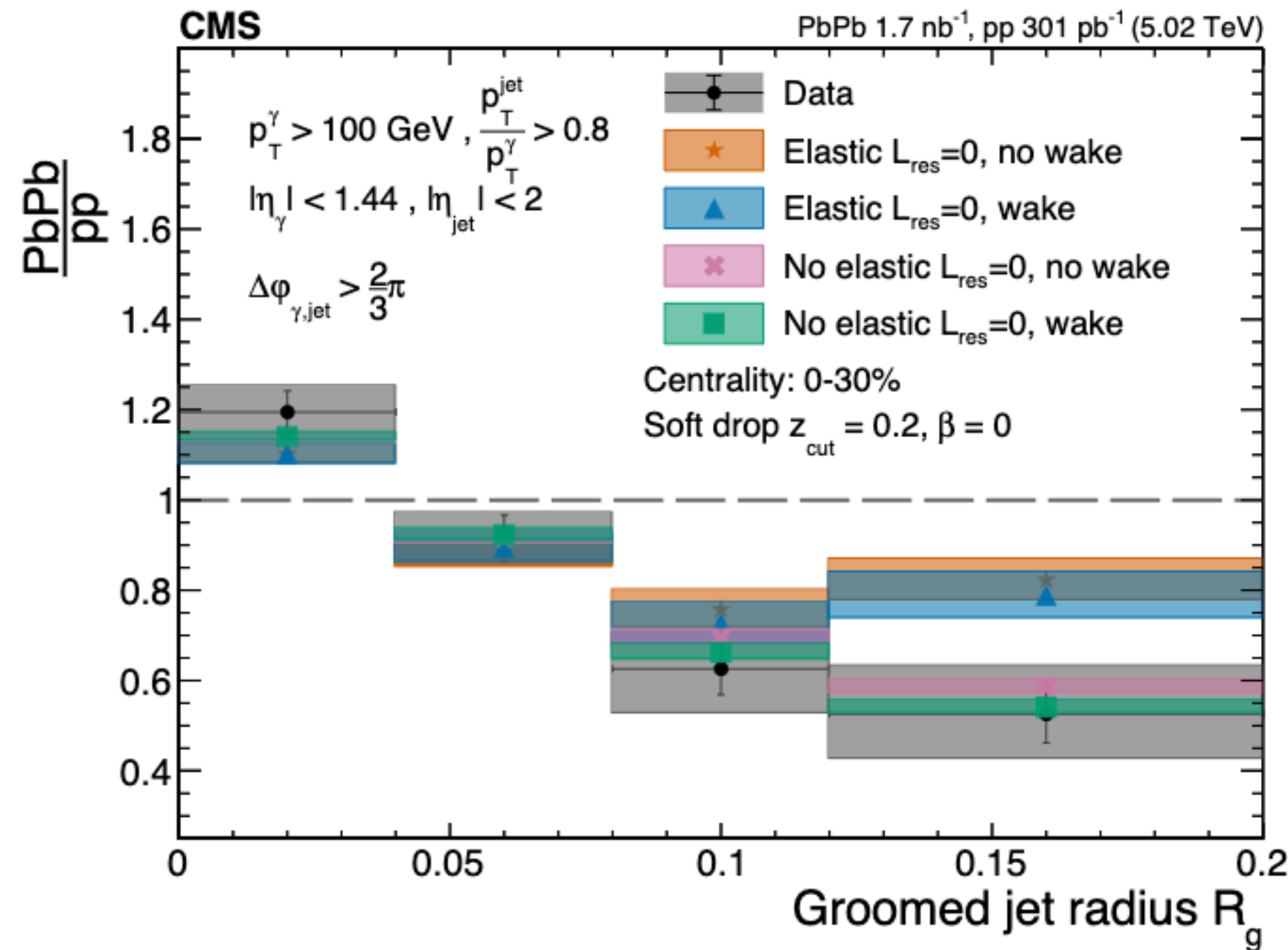
Resolution length

small-R suppresses nonperturbative effects like the wake!

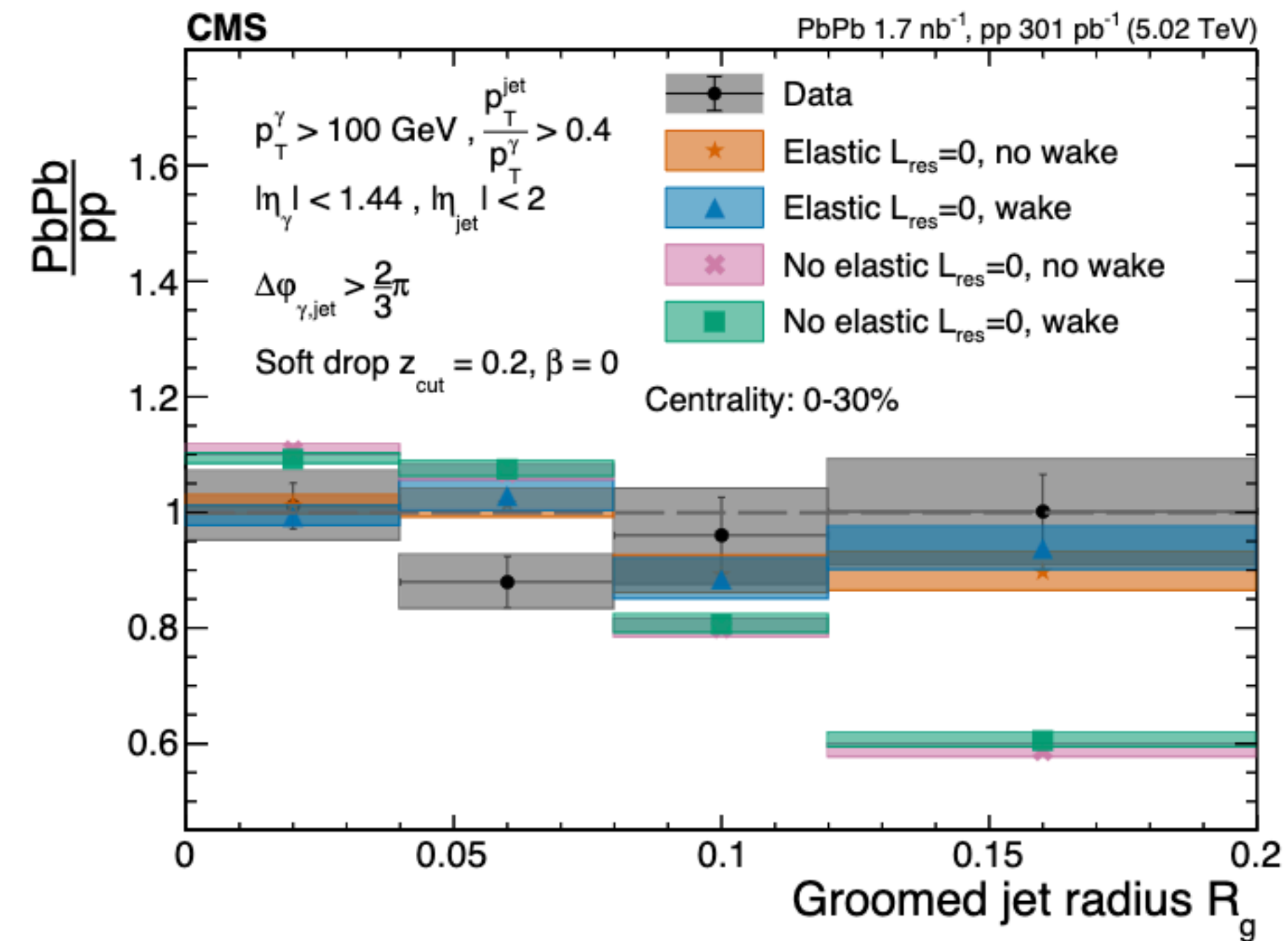
# $\gamma$ -jet substructure: suppression of the survivor bias

PbPb

less quenched  $x_J > 0.8$



more quenched  $x_J > 0.4$



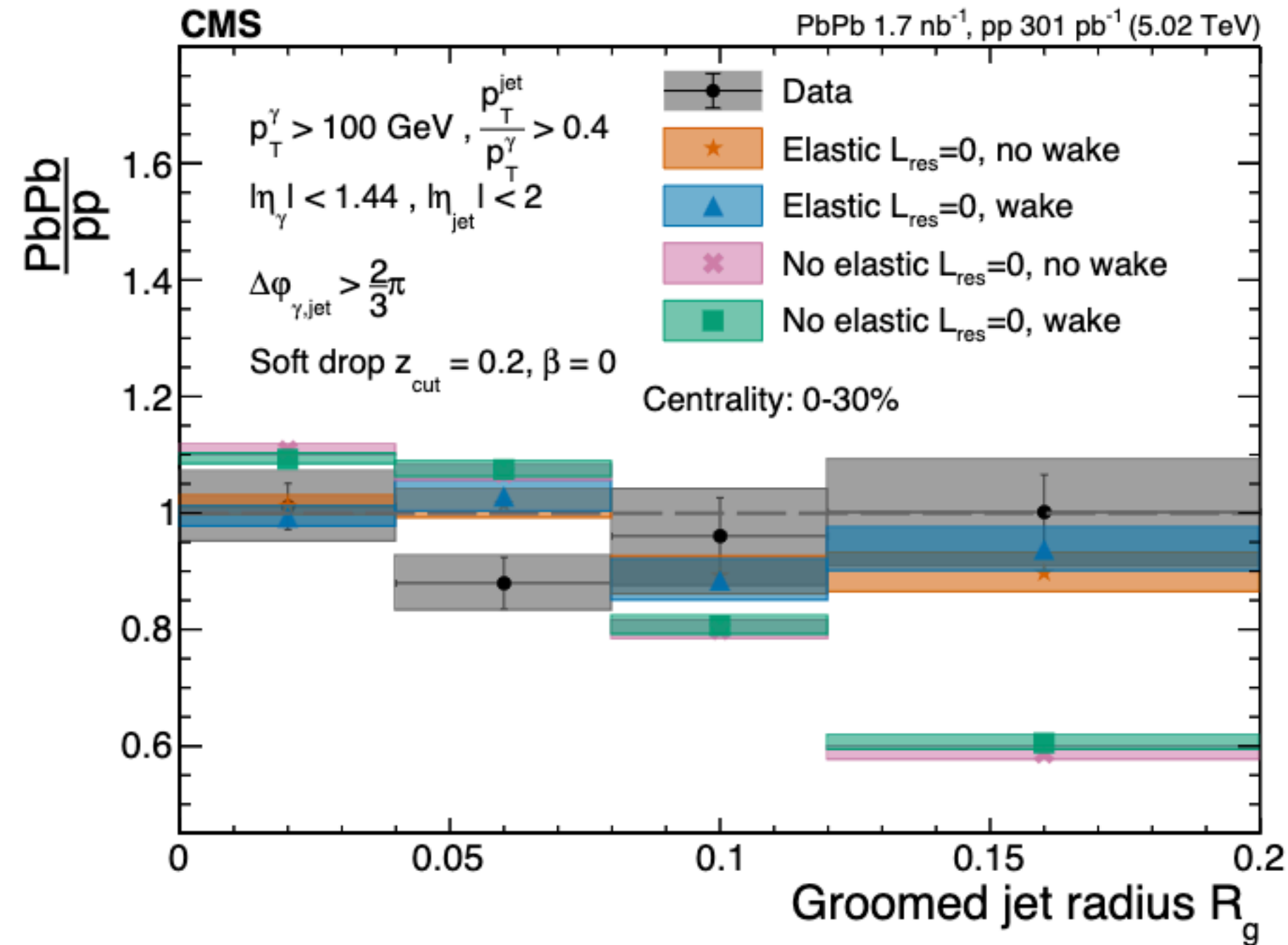
## Comparison to the Hybrid model ([Rajagopal et al, JHEP 10 \(2014\) 019](#))

Not a single set of parameters describes the differential data consistently  
Great constraining power of the data

small- $R$  suppresses nonperturbative effects like the wake!

# $\gamma$ -jet substructure, prospects

$x_J > 0.4$

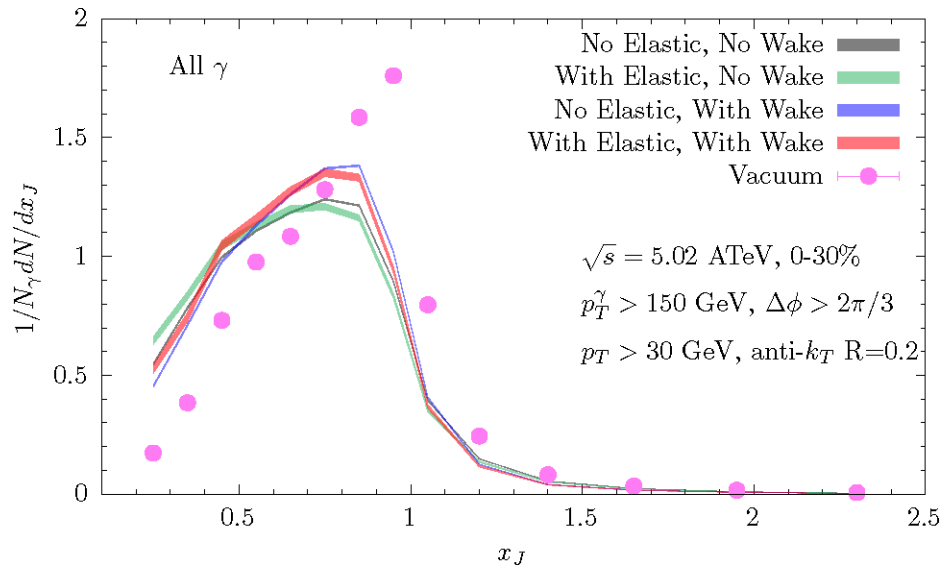
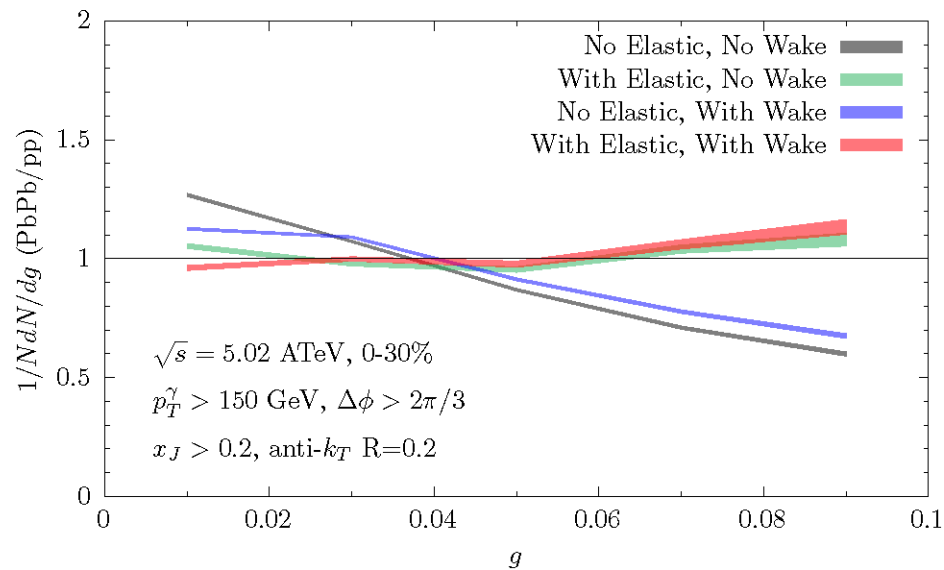
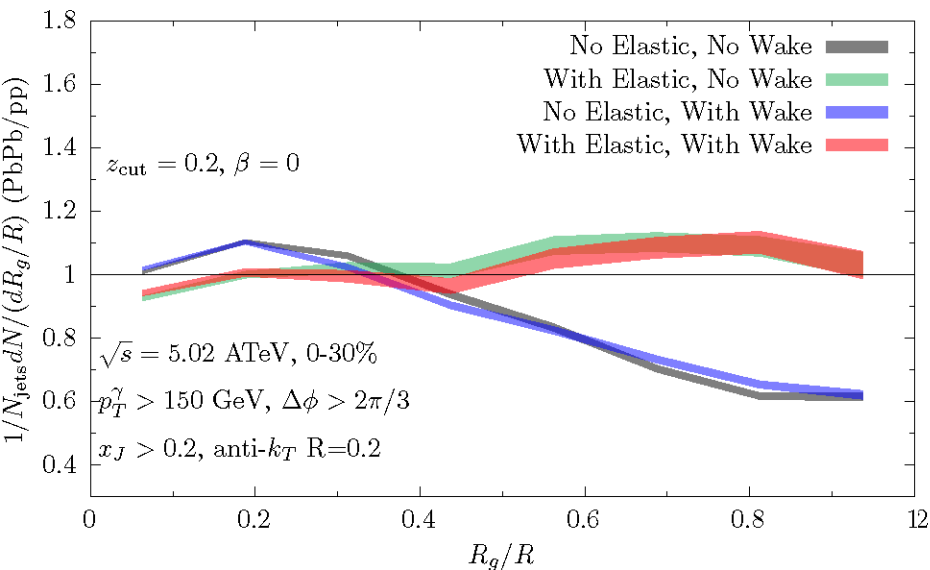


The survivor bias can be fully suppressed when  $x_J \rightarrow 0$   
 (the model has a strong survivor bias down to  $x_J=0.1$ )

Since low jet  $p_T$  is limited by detector effects, such zero bias limit can be achieved by increasing the energy of the photons

Ideally, **simultaneous measurement of  $x_J$  and substructure**, current results are statistically limited

# Gamma-Jet Observables with $p_T^\gamma > 150$ GeV: $R_g$ and Girth, with $x_J > 0.2$

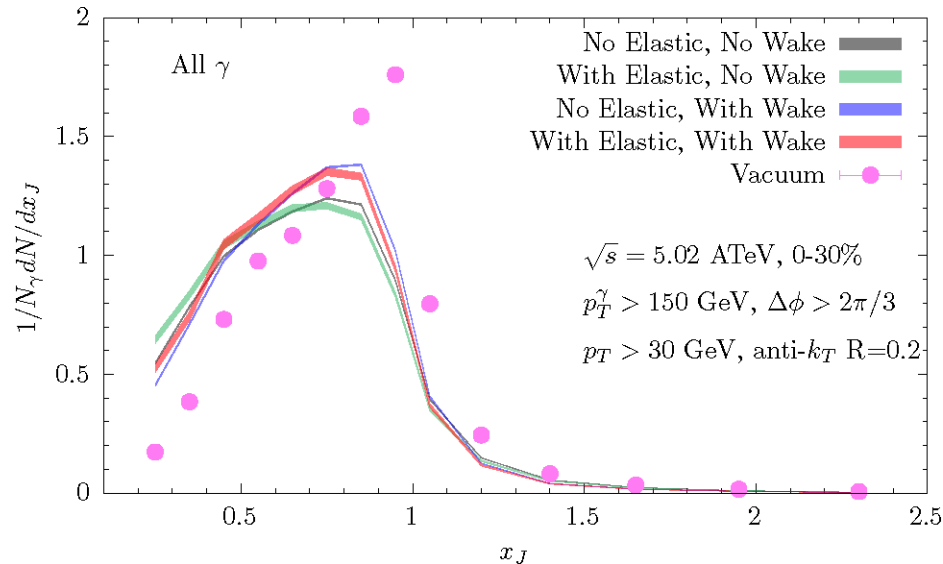
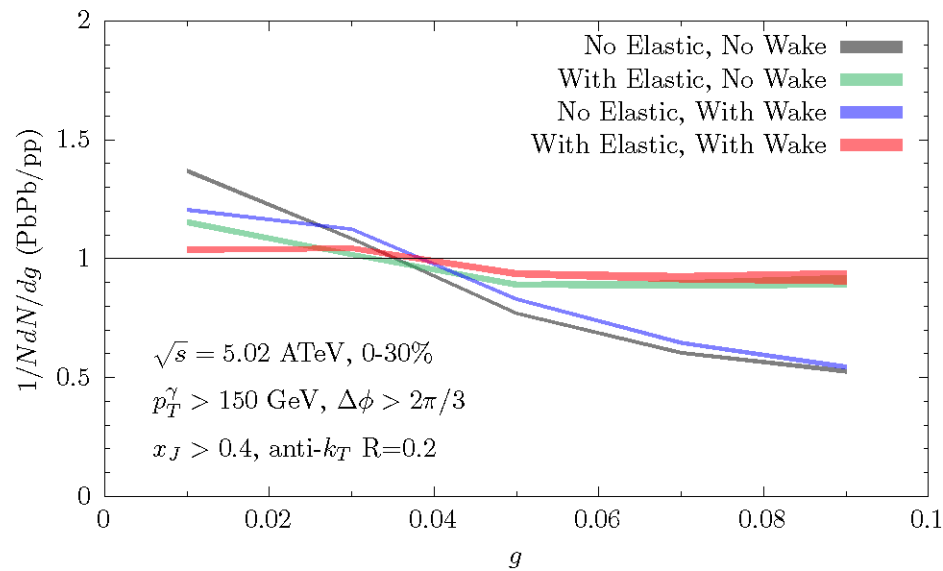
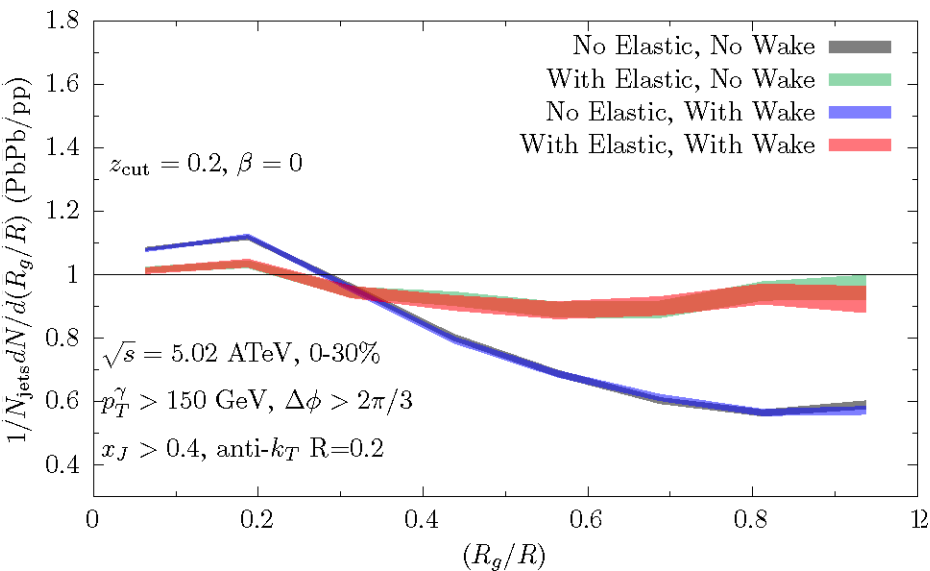


On previous slides,  $p_T^\gamma > 100$  GeV;  
 here,  $p_T^\gamma > 150$  GeV.

Means  $x_J > 0.2$  corresponds to  
 $p_T^{\text{jet}} > 30$  GeV. And, no need to go  
 down to  $x_J > 0.1$ .

Moliere effects substantial;  
 selection bias reduced; wake  
 effects negligible.

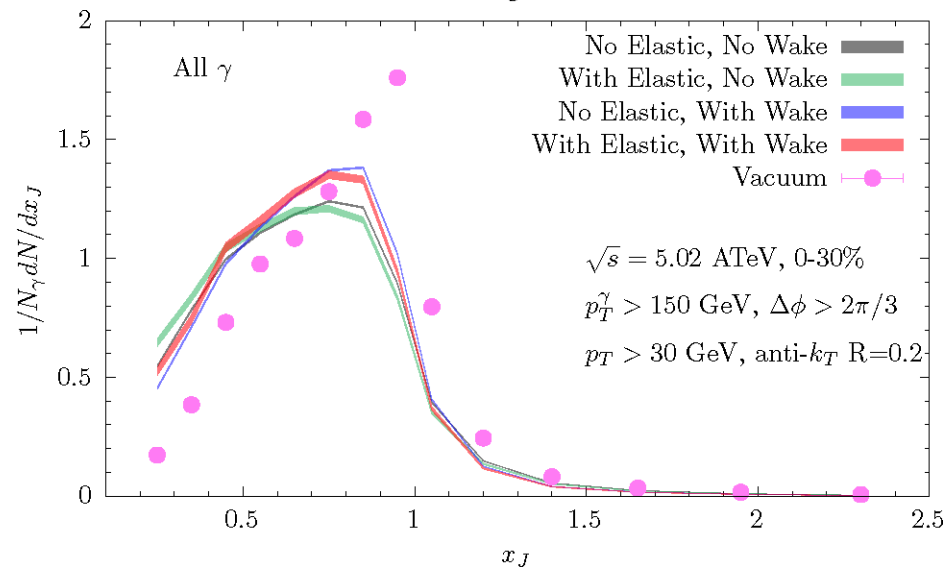
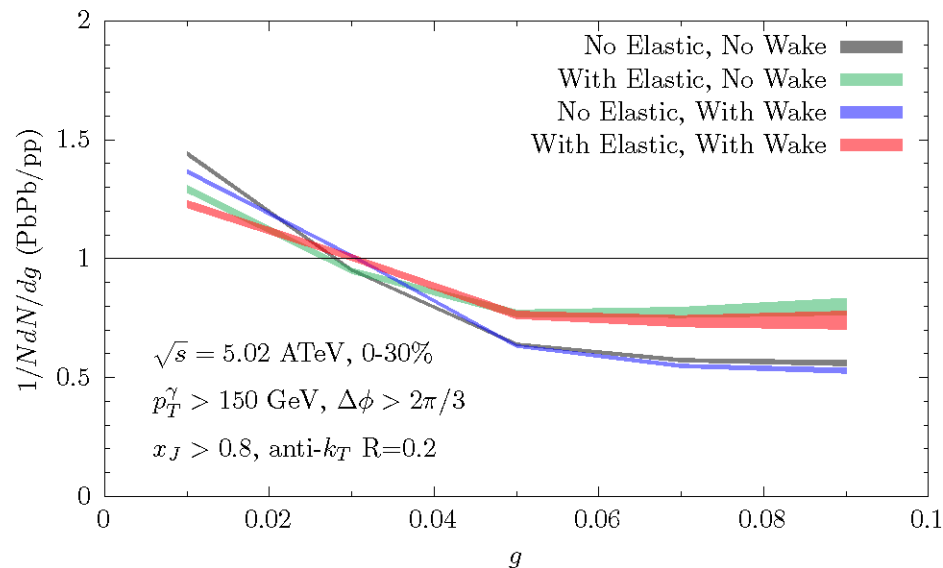
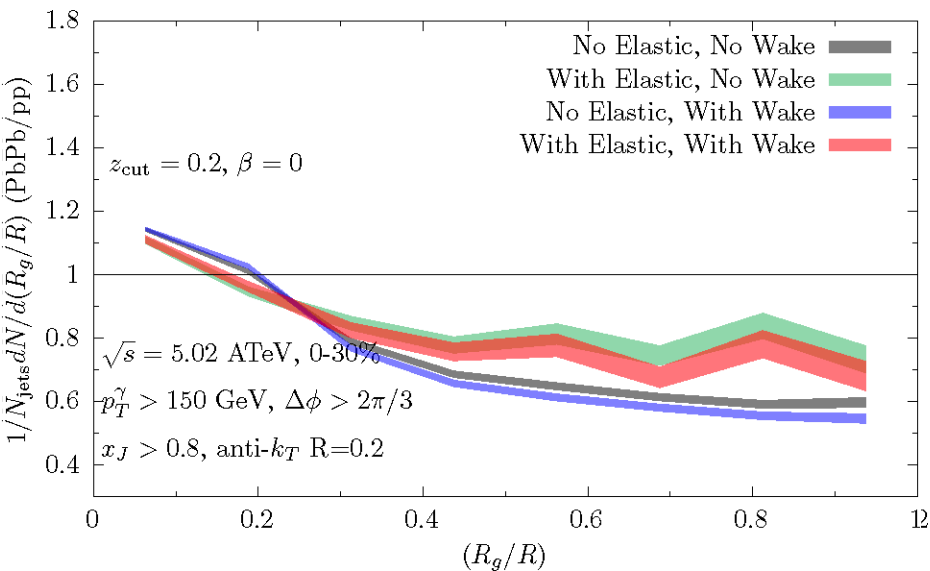
# Gamma-Jet Observables with $p_T^\gamma > 150$ GeV: $R_g$ and Girth, with $x_J > 0.4$



On previous slides,  $p_T^\gamma > 100$  GeV;  
 here,  $p_T^\gamma > 150$  GeV.  
 Means  $x_J > 0.4$  corresponds to  
 $p_T^{\text{jet}} > 60$  GeV.

Moliere effects substantial;  
 selection bias significant; wake  
 effects negligible.

# Gamma-Jet Observables with $p_T^\gamma > 150$ GeV: $R_g$ and Girth, with $x_J > 0.8$

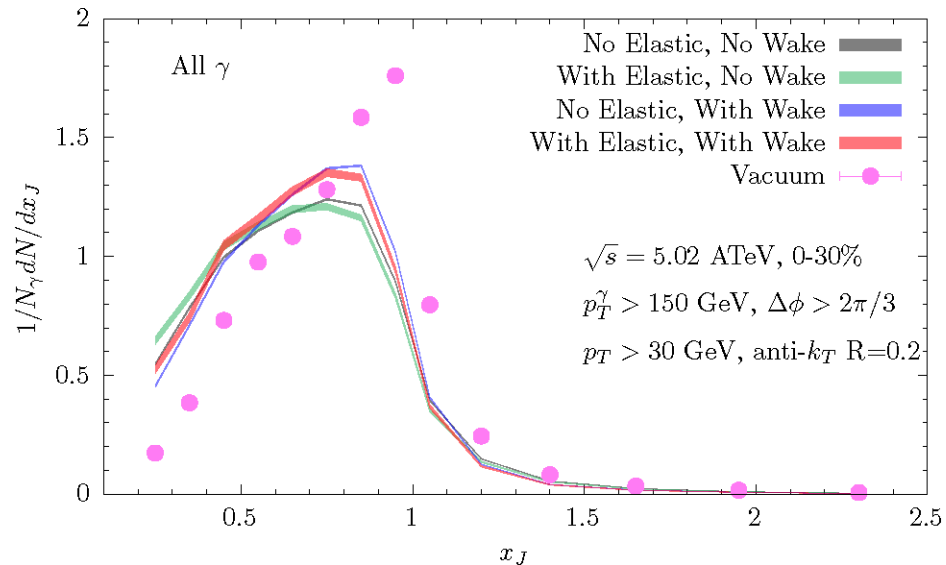
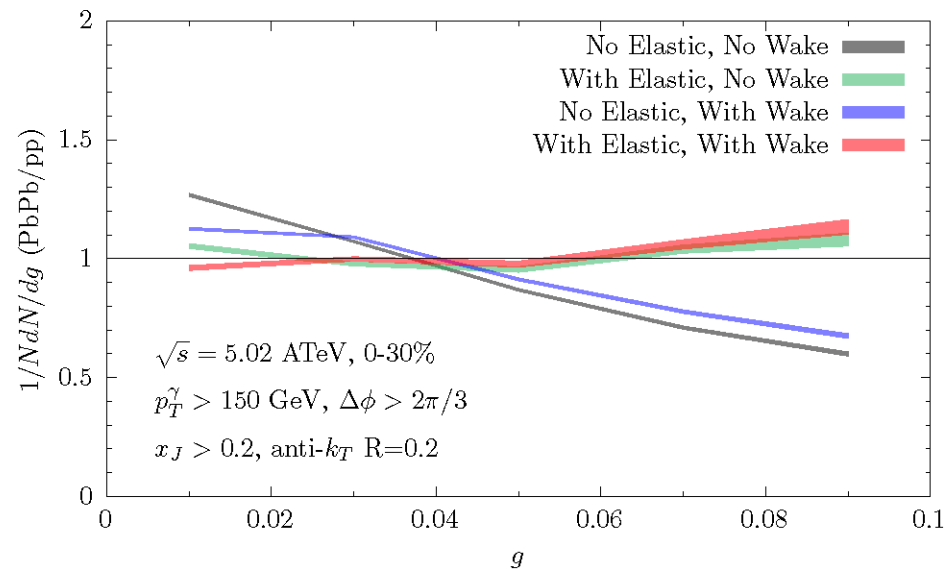
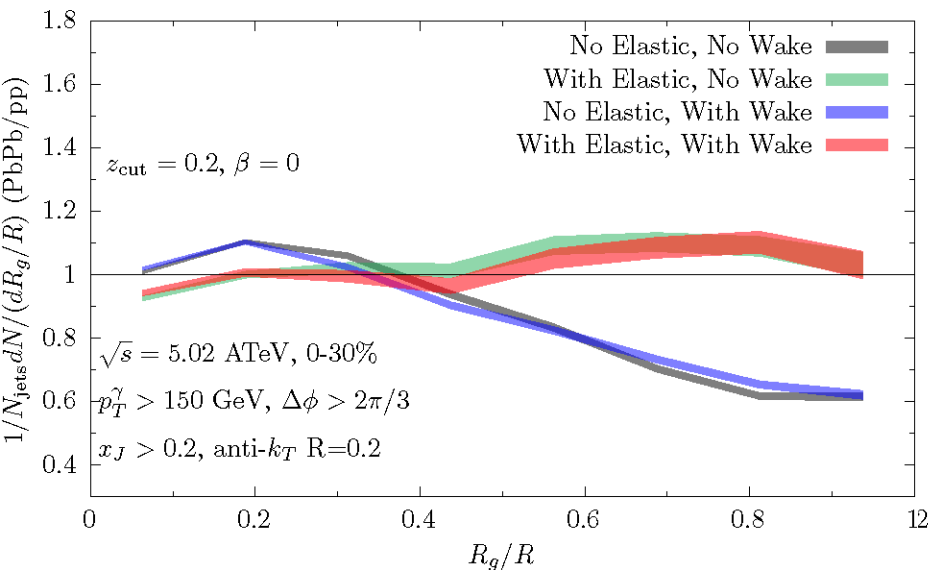


On previous slides,  $p_T^\gamma > 100$  GeV;  
 here,  $p_T^\gamma > 150$  GeV.  
 Means  $x_J > 0.8$  corresponds to  
 $p_T^{\text{jet}} > 120$  GeV.

Moliere effects substantial;  
 selection bias dominant; wake  
 effects negligible.



# Gamma-Jet Observables with $p_T^\gamma > 150$ GeV: $R_g$ and Girth, with $x_J > 0.2$



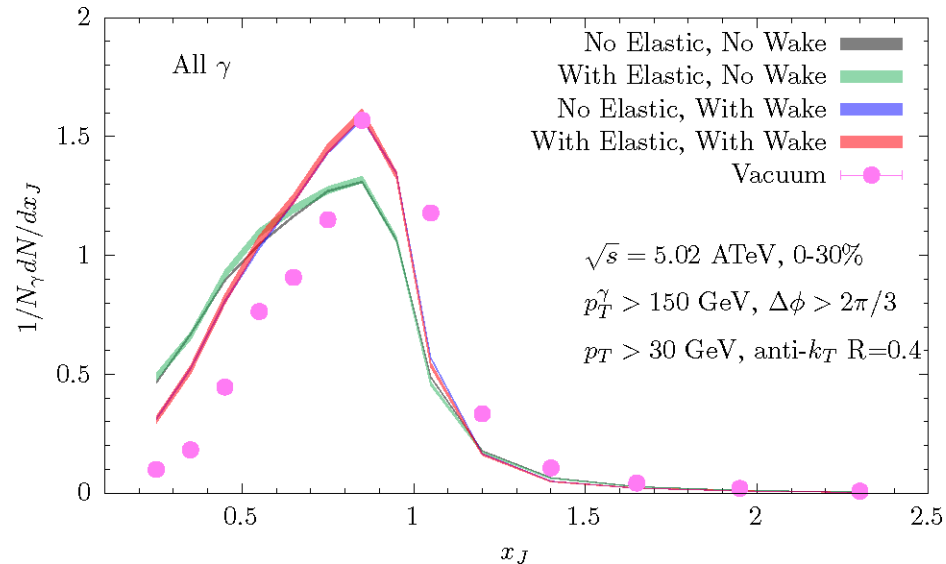
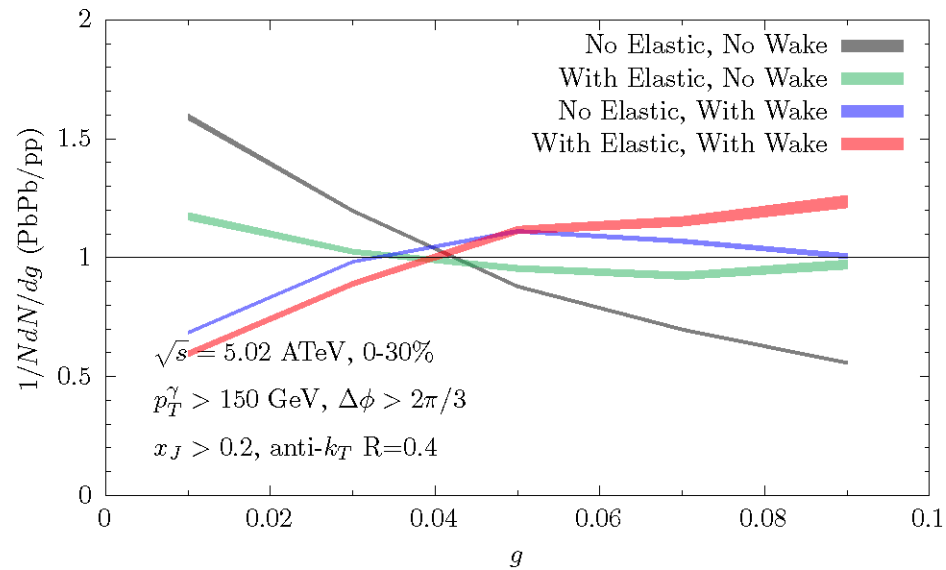
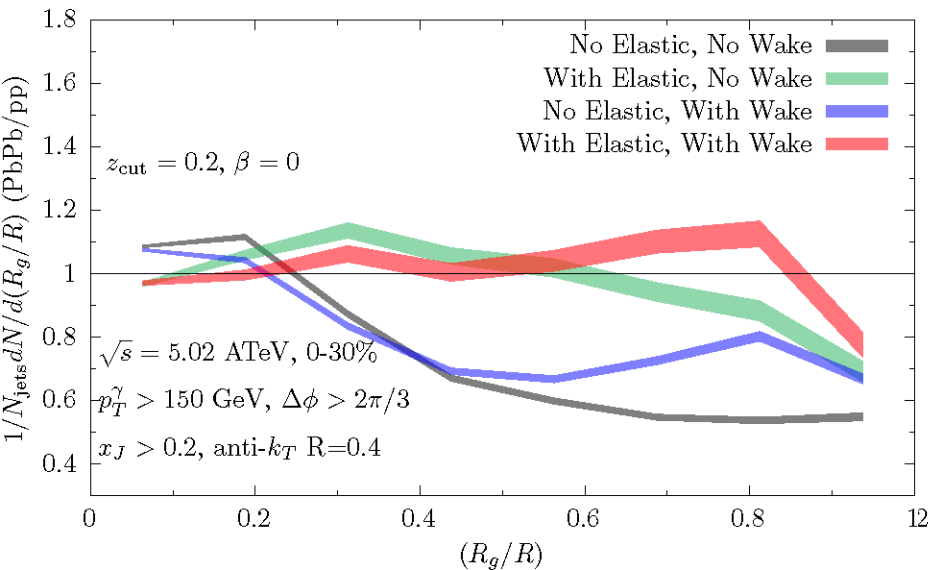
On previous slides,  $p_T^\gamma > 100$  GeV;  
 here,  $p_T^\gamma > 150$  GeV.

Means  $x_J > 0.2$  corresponds to  
 $p_T^{\text{jet}} > 30$  GeV. And, no need to go  
 down to  $x_J > 0.1$ .

Moliere effects substantial;  
 selection bias reduced; wake  
 effects negligible.



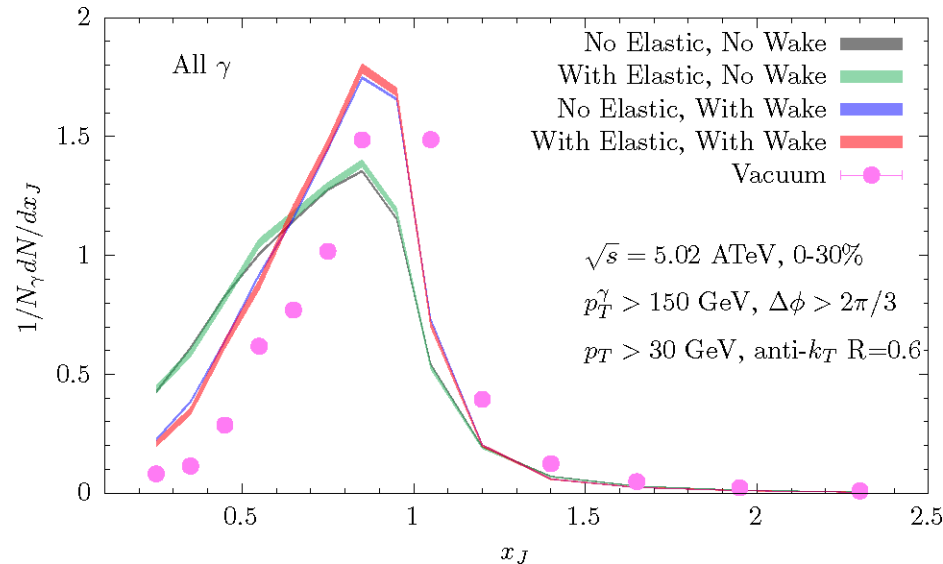
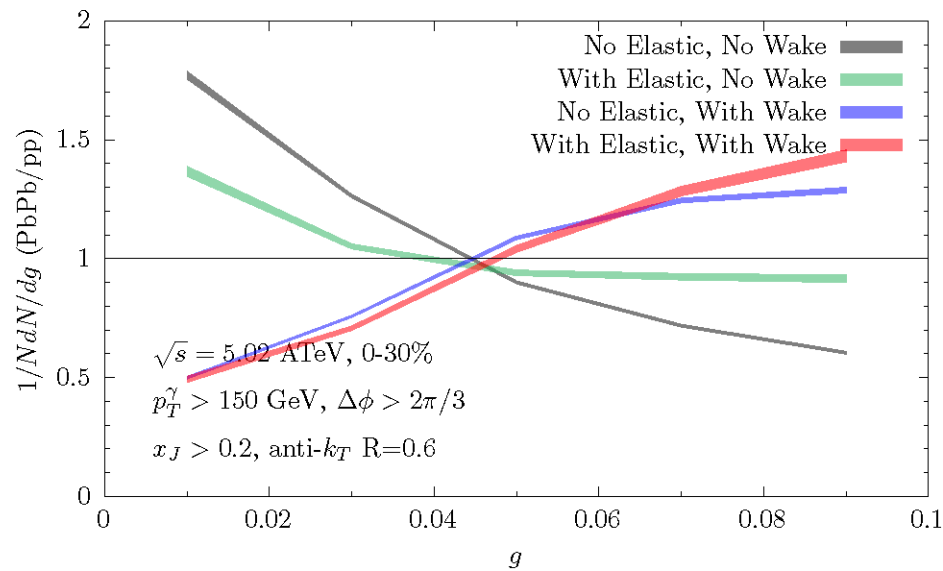
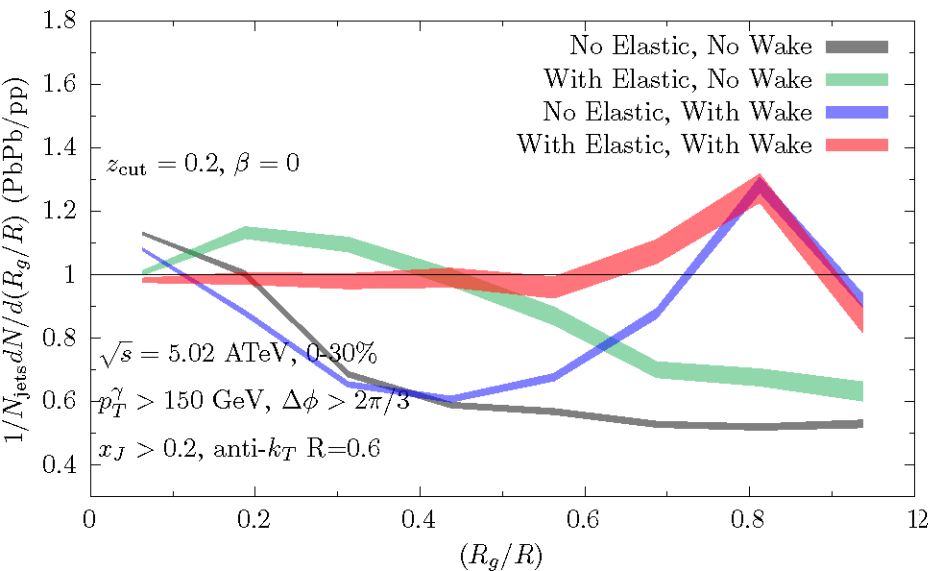
# Gamma-Jet Observables with $p_T^\gamma > 150$ GeV and $R=0.4$ : $R_g$ and Girth, with $x_J > 0.2$



On previous slides,  $p_T^\gamma > 150$  GeV with  $R=0.2$ . Here,  $R=0.4$ , so that we can “catch” more wake, with little selection bias.

Moliere effects substantial; selection bias reduced; wake effects significant.

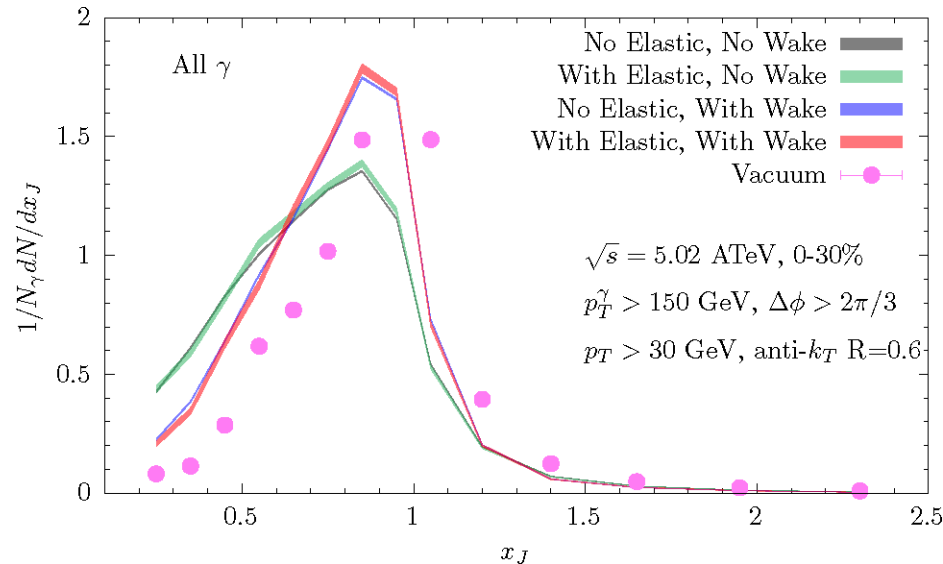
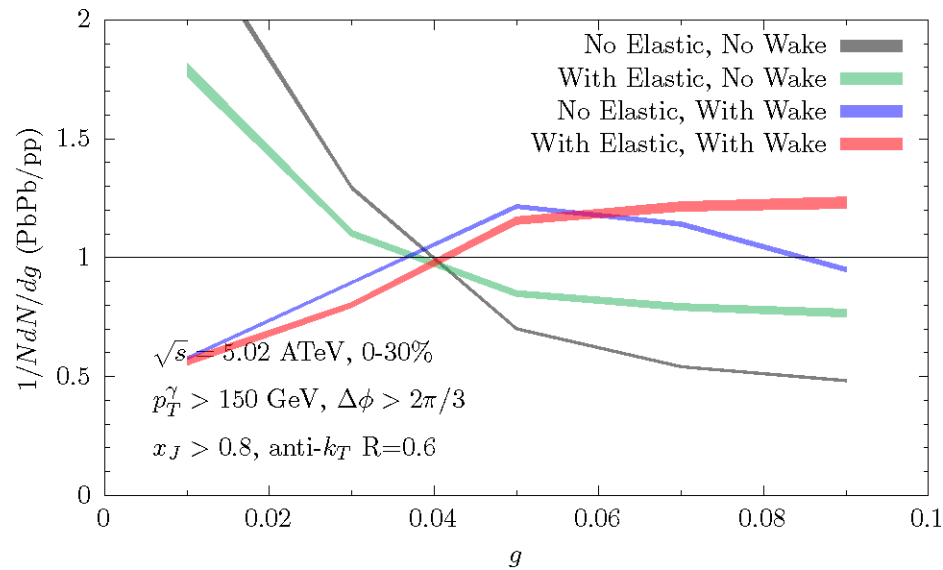
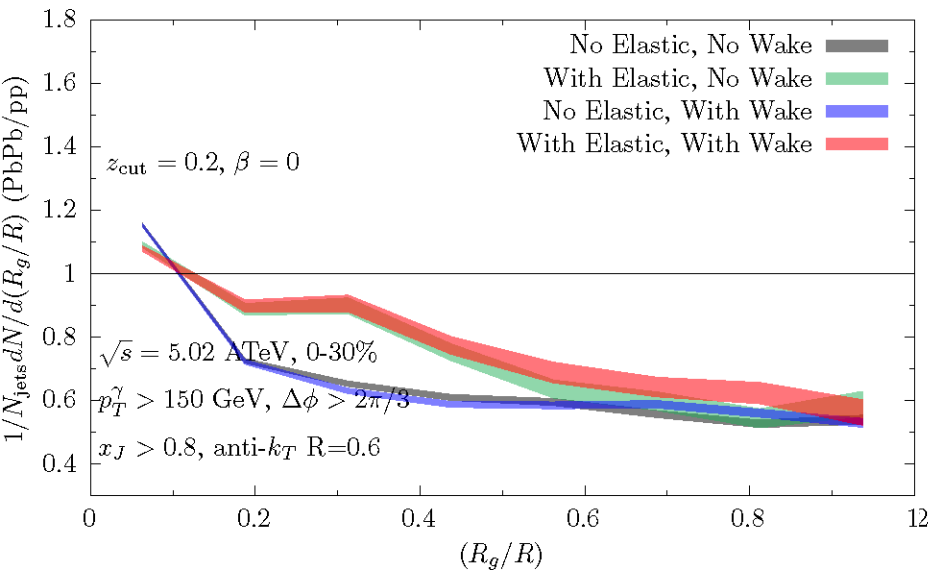
# Gamma-Jet Observables with $p_T^\gamma > 150$ GeV and $R=0.6$ : $R_g$ and Girth, with $x_J > 0.2$



On previous slides,  $p_T^\gamma > 150$  GeV with  $R=0.2$ . Here,  $R=0.6$ , so that we can “catch” *even more* wake, with little selection bias.

Moliere effects substantial; selection bias reduced; wake effects enormous, and as in Brewer+Brodsky+KR.

# Gamma-Jet Observables with $p_T^\gamma > 150$ GeV and $R=0.6$ : $R_g$ and Girth, with $x_J > 0.8$

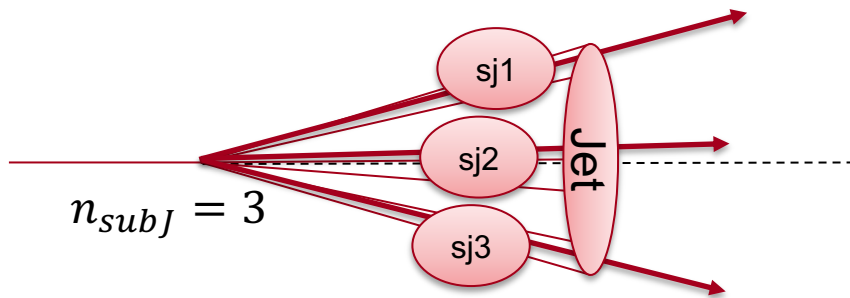


On previous slides,  $p_T^\gamma > 150$  GeV with  $R=0.2$ . Here,  $R=0.6$ . But, we've turned the selection bias back ON.

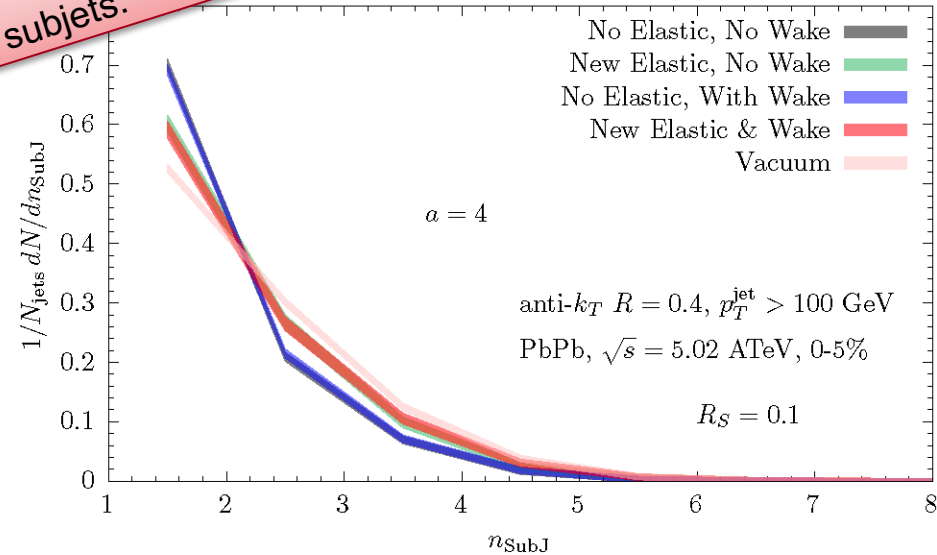
Moliere effects still substantial; selection bias dominant; wake effects *greatly reduced*, as in Brewer+Brodsky+KR.

# Inclusive Jets within Inclusive Jets: Inclusive Subjets

1. Reconstruct jet with  $R=0.6$
2. Recluster each jet's particle content into subjets with  $R=0.15$



Increase in number of subjets.



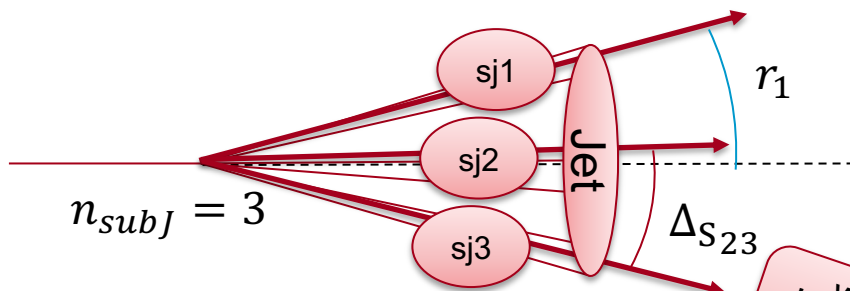
Moliere scattering visible as increase in number of subjets; no such effect coming from wake at all.

Moliere scattering also yields more separated subjets...

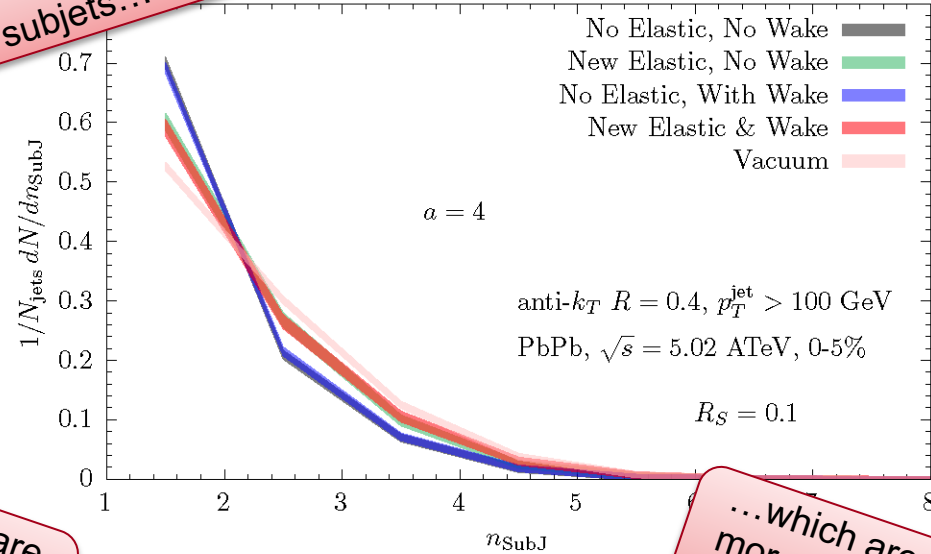
These observables are directly sensitive to “sprouting a new subjet” the intrinsic feature of Moliere scattering which makes it NOT just a bit more wake.

# Inclusive Subjects

1. Reconstruct jet with  $R=0.4$
2. Recluster each jet's particle content into subjects with  $R=0.1$

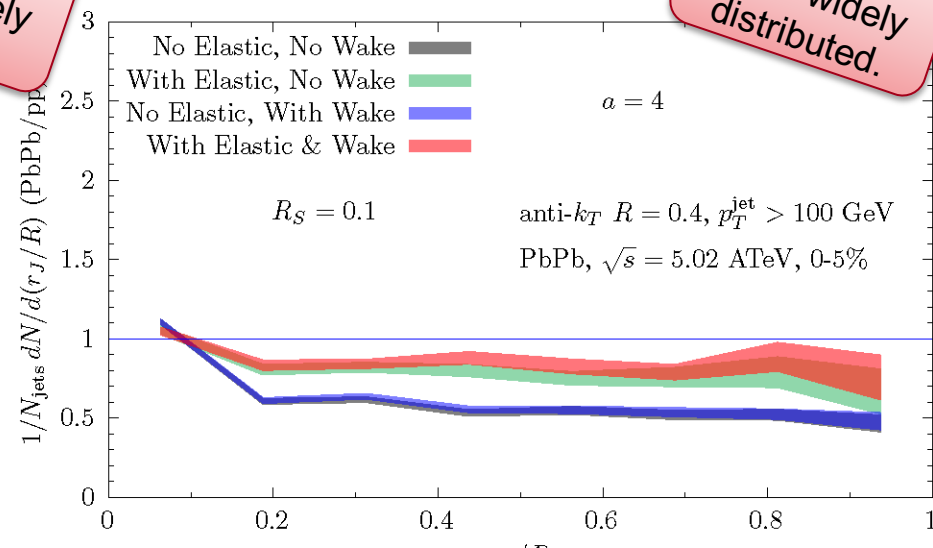
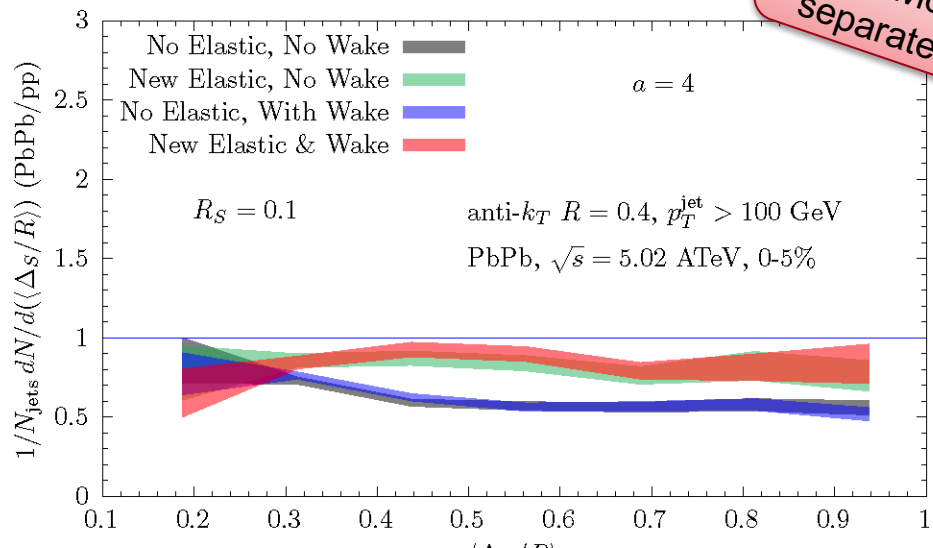


Increase in number of subjects...



... which are more widely distributed.

... which are more widely separated.



# Conclusions

- Studied the effect of elastic Moliere scattering of jet partons off medium partons on jet observables in the perturbative regime.
- For “overall shape observables” (jet shapes; FF) effects of Moliere scattering are similar to, and smaller than, effects of wake.
- Grooming helps, by grooming away the soft particles from the wake. Effects of Moliere scattering dominate the modification of several groomed observables ( $R_g$ , Leading  $k_T$ , Girth, WTA axis angle.)
- $R_g$  and girth observables in  $\gamma$ +jet events can be “engineered” to reduce (or enhance) selection bias by selecting with  $x_J >$  a low (or high) threshold. When selection bias is reduced, Moliere scattering yields  $R_{AA} > 1$ .
- $R_g$  and girth observables in  $\gamma$ +jet events can be “engineered” to remove (or highlight) effects of the wake by choosing small  $R$  (or large  $R$  with  $x_J >$  a low threshold).
- Modification of inclusive subjet observables (number, and angular spread, of subjets) are especially sensitive to the presence of Moliere scatterings. These observables are unaffected by the wake. They reflect what it is that makes the effects of scattering different from those of the wake.
- Subjet and  $\gamma$ +jet observables may also be influenced by other ways in which jet shower partons “see” particulate aspects of the QGP. That’s great!
- Acoplanarity observables that we have investigated to date show little sensitivity to Moliere scattering; significant sensitivity to the wake in many cases.

# Jets as Probes of QGP

- Theorists taking key steps...
- Disentangling jet modification from jet selection.
- Showing that hot quark soup (QGP) *can* resolve structure within jet shower.
- Calculations of the dynamics of jet wakes in droplets of QGP, identification of new experimental observables, and predictions that will enable experimental measurements to “see” the particles coming from these wakes.
- Identifying those jet substructure observables that *are* sensitive to scattering of jet quarks/gluons off QGP quarks/gluons, “seeing” the latter à la Rutherford, and are *not* sensitive to particles coming from the wake.
- Next several years will be the golden age of jet physics: sPHENIX, LHC runs 3 and 4, new substructure observables. *Many* theory advances, and analyses of today’s data, whet our appetite for the feast to come.
- We shall learn about the microscopic structure of QGP, and the dynamics of rippling QGP.



# 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.

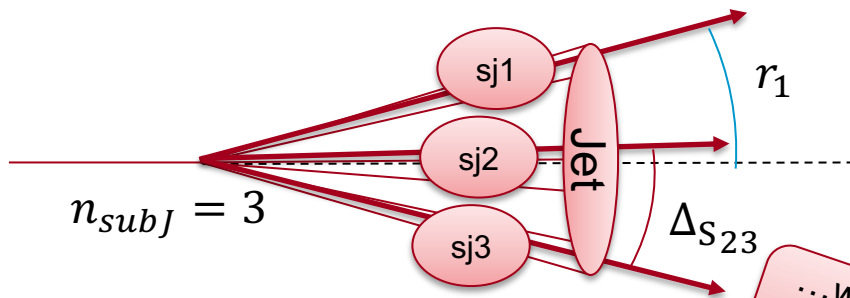
# What Next?

Two kinds of What Next? questions ...

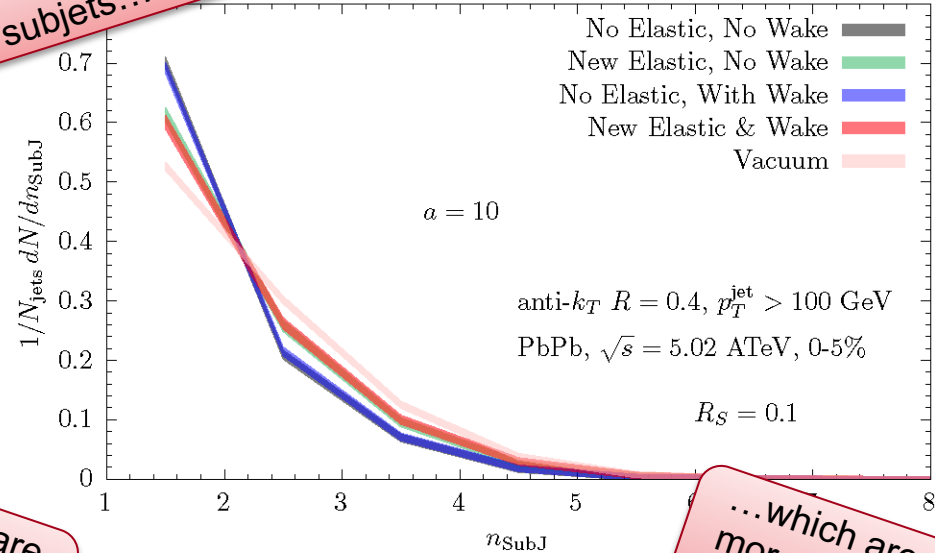
- A question that one asks after the discovery of any new form of complex matter: **What is its phase diagram?** For high temperature superconductors, for example, phase diagram as a function of temperature and doping. Same here! For us, doping means excess of quarks over anti-quarks, rather than an 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.

# Inclusive Subjects

1. Reconstruct jet with  $R=0.4$
2. Recluster each jet's particle content into subjects with  $R=0.1$

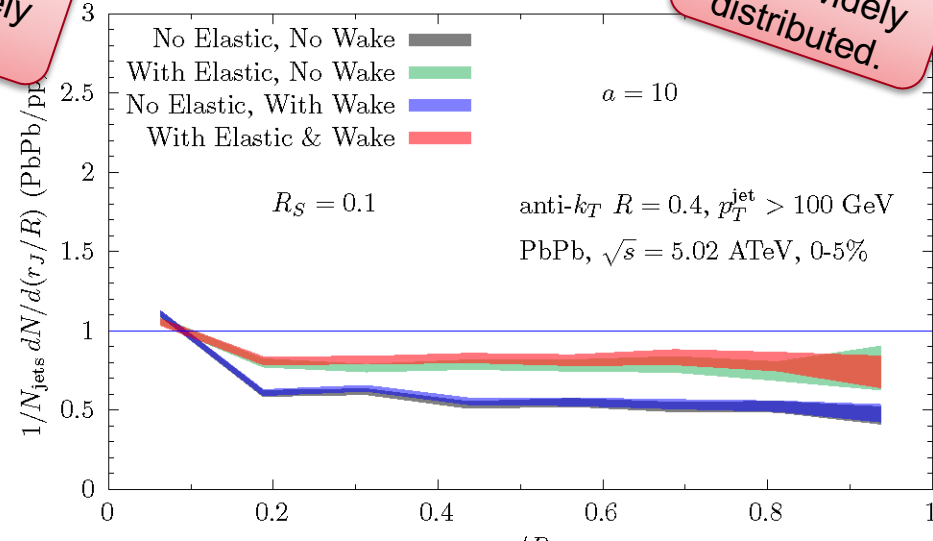
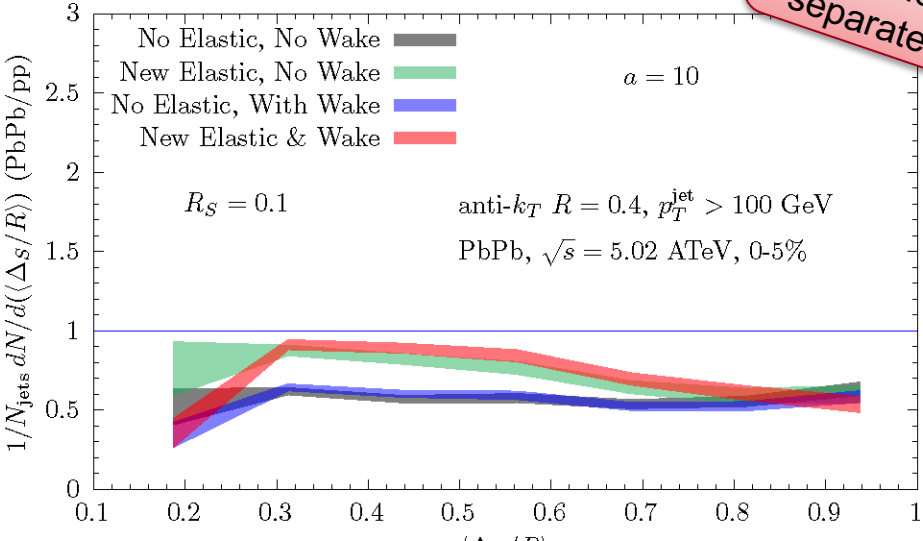


Increase in number of subjects...



... which are more widely separated.

... which are more widely distributed.



# Analysis procedure

1. **Select events** based on the **presence of a high- $p_T$  ‘trigger’ hadron**
2. **Do jet reconstruction** on these events
3. **Count jets recoiling from the trigger hadron** as function of:
  - opening angle ( $\Delta\varphi$ ) of jet relative to trigger axis
  - transverse momentum ( $p_{T,jet}$ ) of recoil jet

#### 4. Define observable:

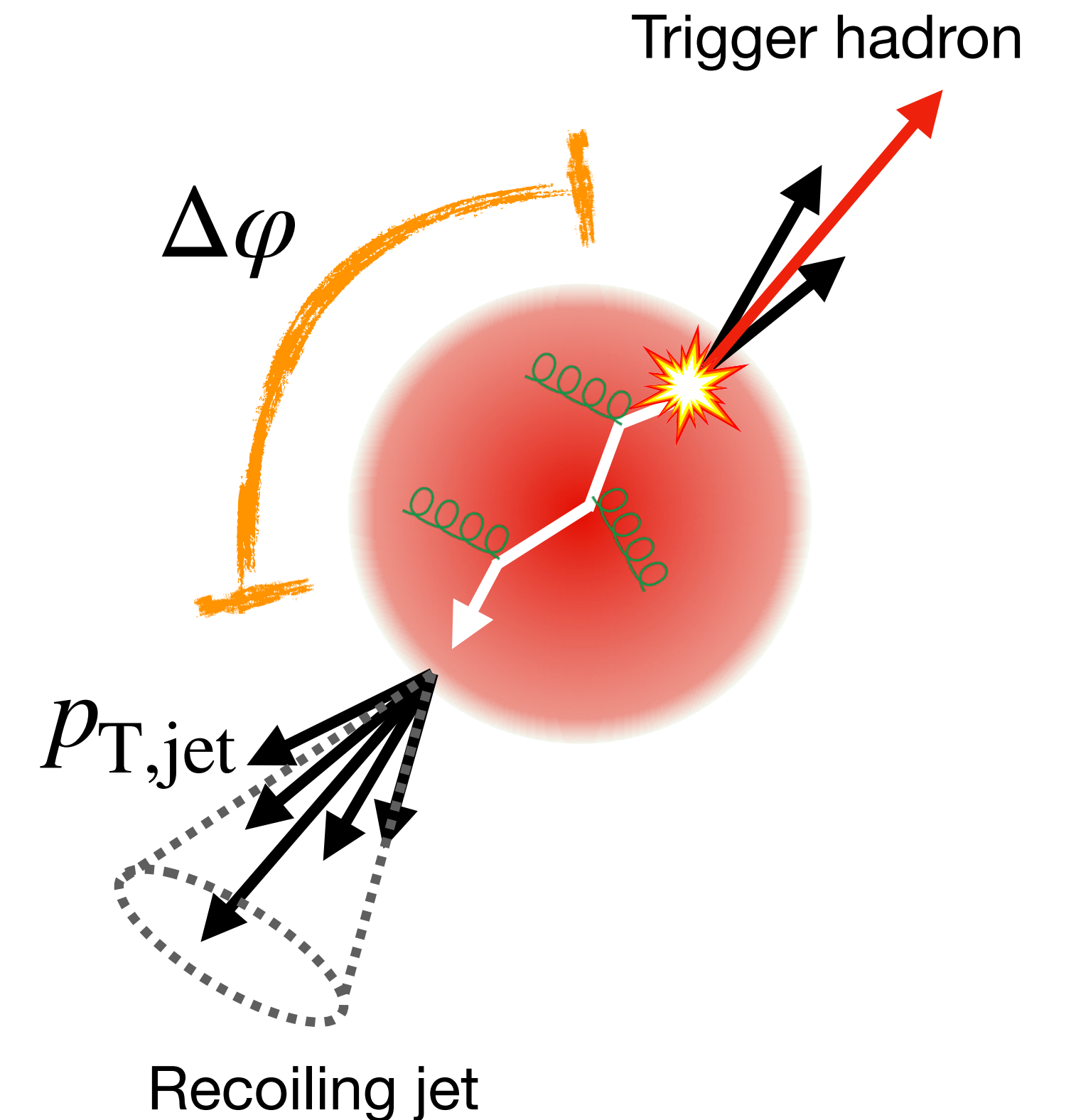
$$\frac{1}{N_{trig}^{AA}} \frac{d^3 N_{jet}^{AA}}{dp_{T,jet}^{ch} d\Delta\varphi d\eta_{jet}} \Bigg|_{p_{T,h} \in TT} = \left( \frac{1}{\sigma^{AA \rightarrow h+X}} \cdot \frac{d^3 \sigma^{AA \rightarrow h+jet+X}}{dp_{T,jet}^{ch} d\Delta\varphi d\eta} \right) \Bigg|_{p_{T,h} \in TT}$$

- **Perturbatively calculable**

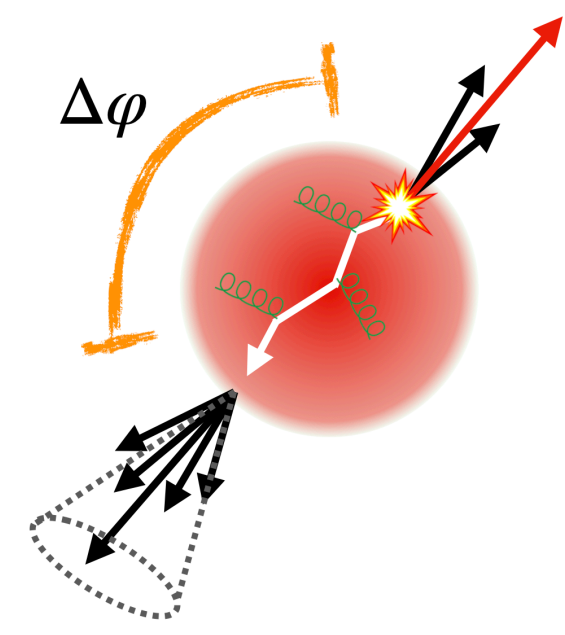
Ratio between high- $p_T$  hadron and jet production cross sections

- **Semi-inclusive**

events selected based on presence of trigger  $\rightarrow$  count all recoil jets in defined acceptance

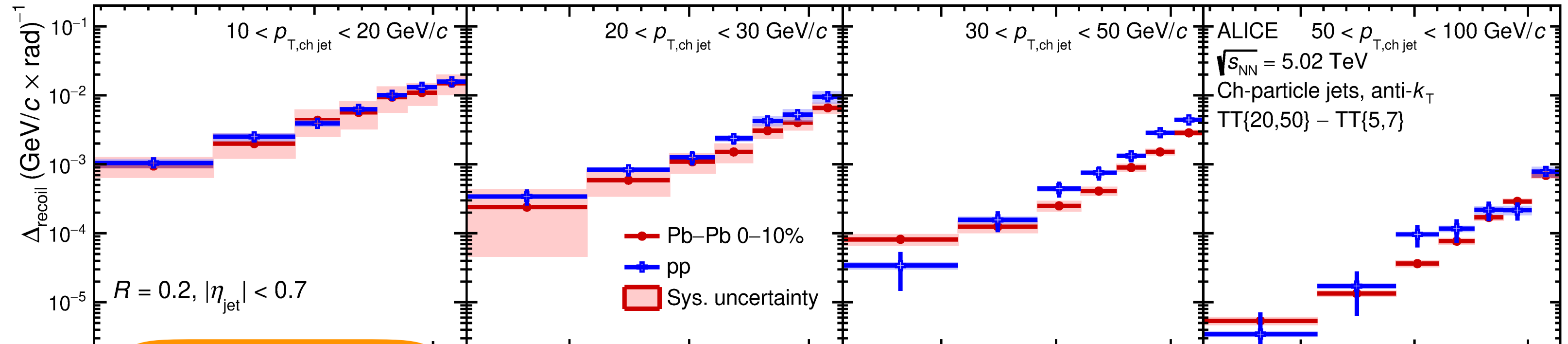


# $\Delta_{\text{recoil}}(\Delta\varphi)$ distributions in pp and Pb-Pb collisions

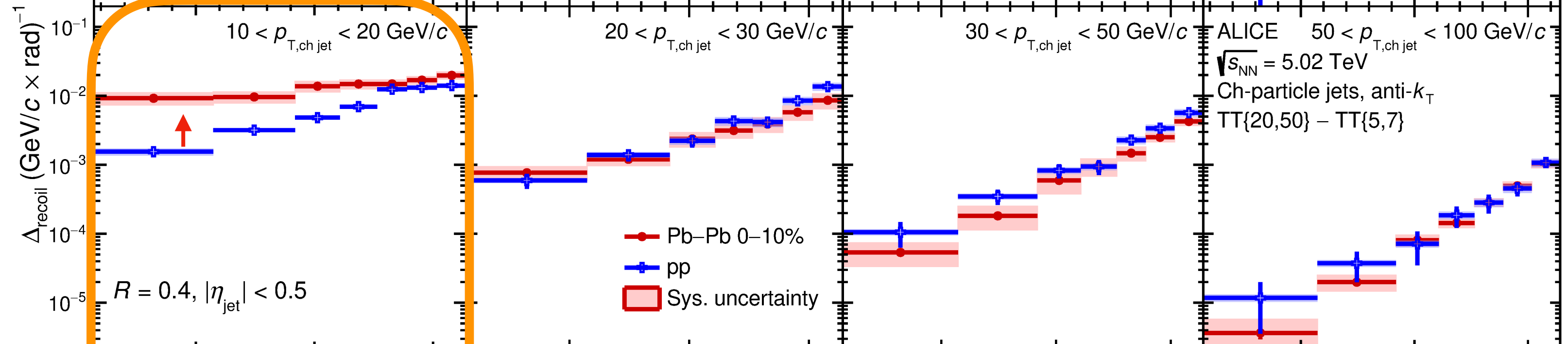


$p_{T,\text{ch jet}}$ : **[10,20] GeV/c**      [20,30] GeV/c      [30,50] GeV/c      [50,100] GeV/c

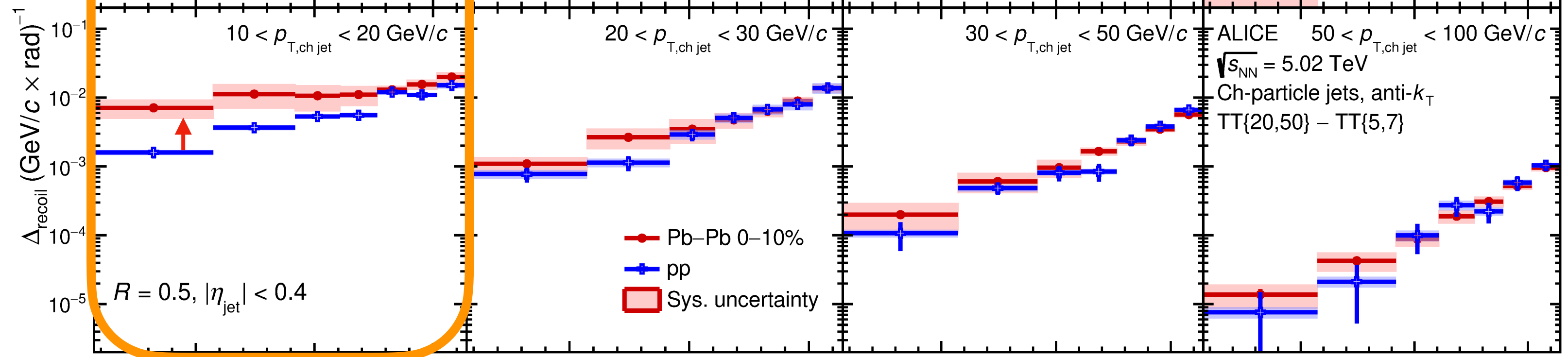
$R=0.2$



$R=0.4$



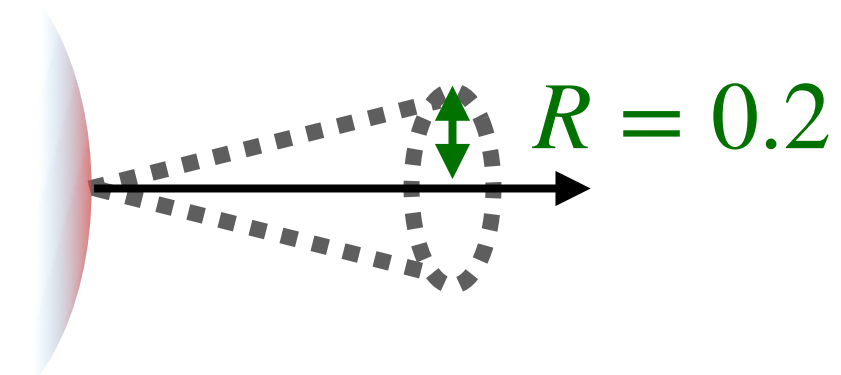
$R=0.5$



- **Significant azimuthal broadening** for  $R=0.4$  and  $R=0.5$  at low  $p_{T,\text{ch jet}}$

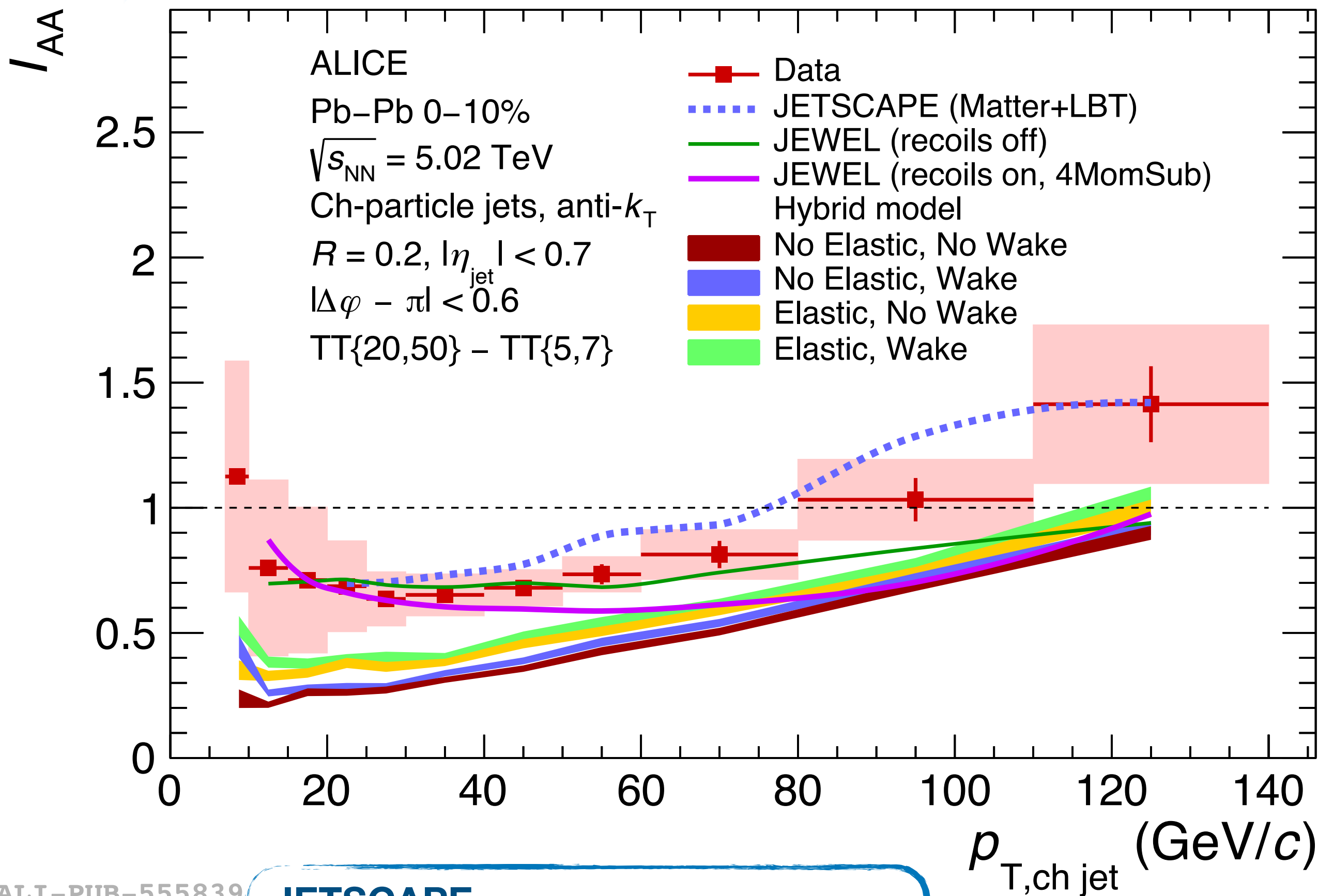
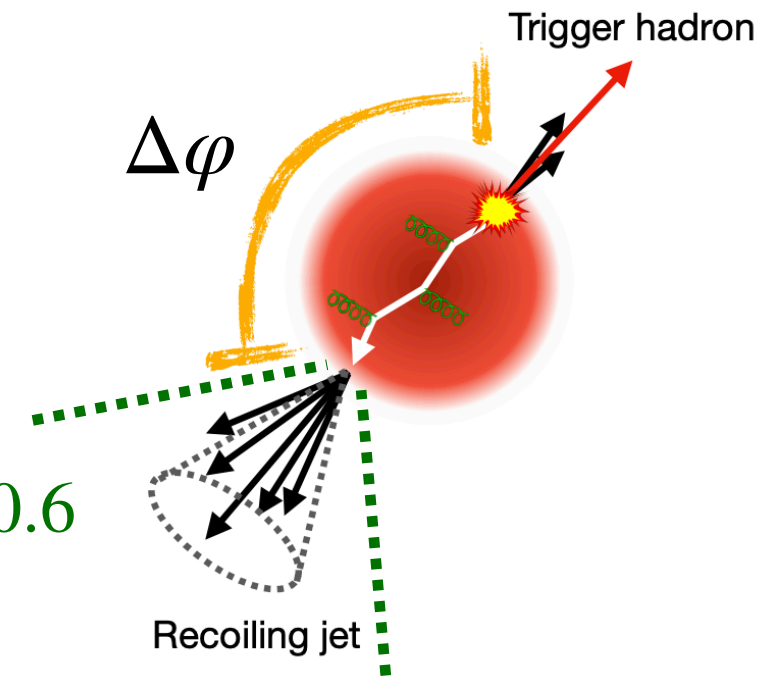


# $I_{AA}(p_{T, \text{ch jet}})$ - recoil jet yield modification in Pb-Pb collisions



$$I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$

$$|\Delta\phi - \pi| < 0.6$$



- **Suppression** at  $20 < p_{T, \text{ch jet}} < 80 \text{ GeV}/c$   
→ jet energy loss
- **Rising trend with  $p_{T, \text{ch jet}}$**   
→ interplay between hadron and jet energy loss?  
Less trigger surface bias when  $p_{T, \text{jet}} \gg p_{T, \text{trig}}$ ?
- Models (Hybrid, JETSCAPE) capture rising trend
- JEWEL describes low- $p_{T, \text{jet}}$   $I_{AA}$

ALI-PUB-555839

## JETSCAPE

Energy loss based on MATTER (high virtuality) and LBT (low virtuality)

JETSCAPE, Phys. Rev. C 107, 034911

## JEWEL

Medium response effects via treatment of 'recoils'

K. Zapp, EPJ C, Volume 74, Issue 2, 2014  
R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141

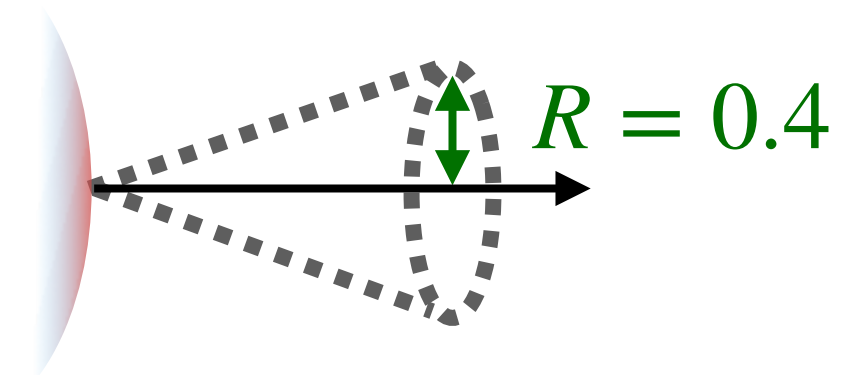
## Hybrid model

Elastic (Molière) scatterings and wake (medium response) included

F. d'Eramo, K. Rajagopal, Y. Yin, JHEP 01 (2019) 172  
Z. Hulcher, D. Pablos, K. Rajagopal, 2208.13593 (QM22)

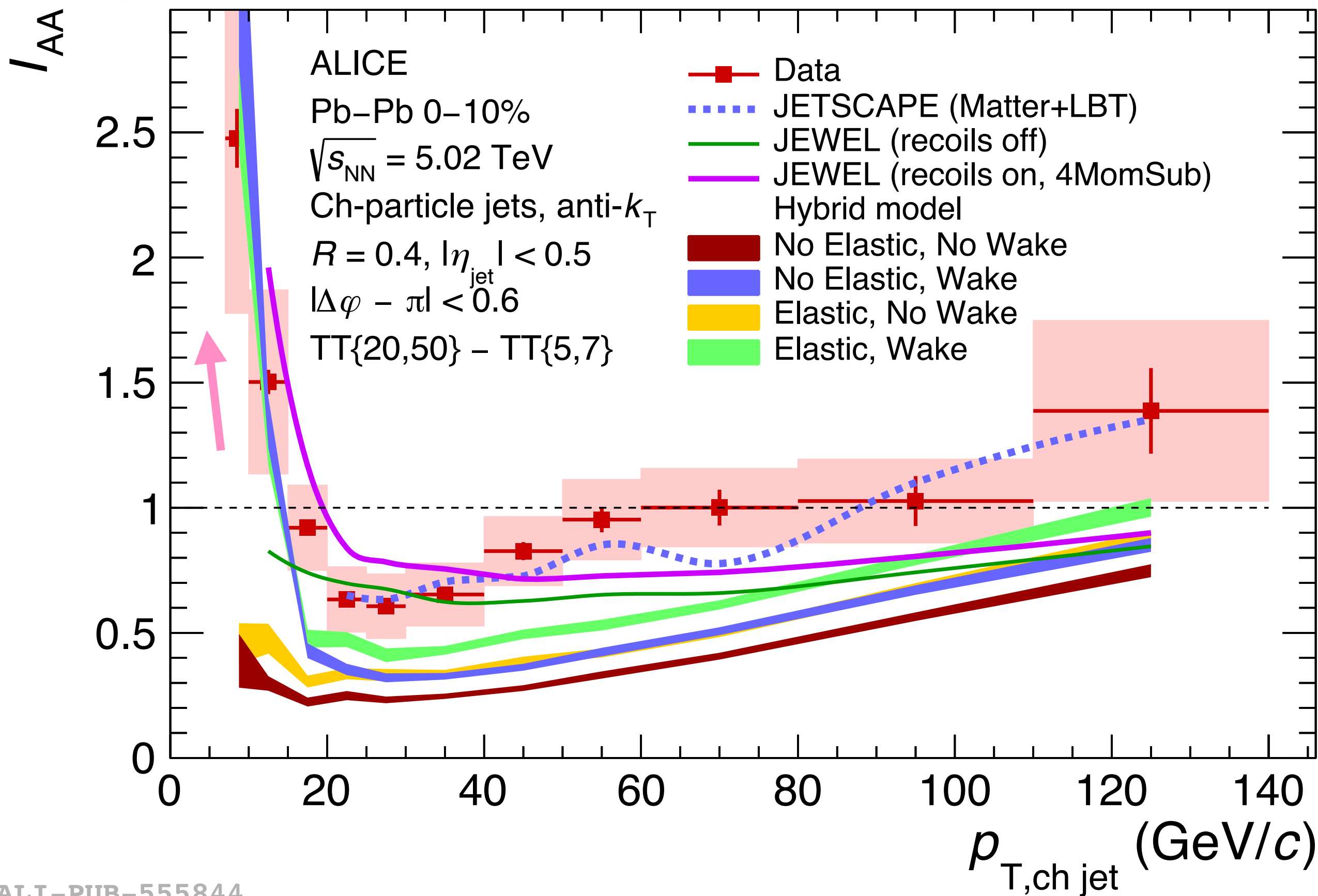
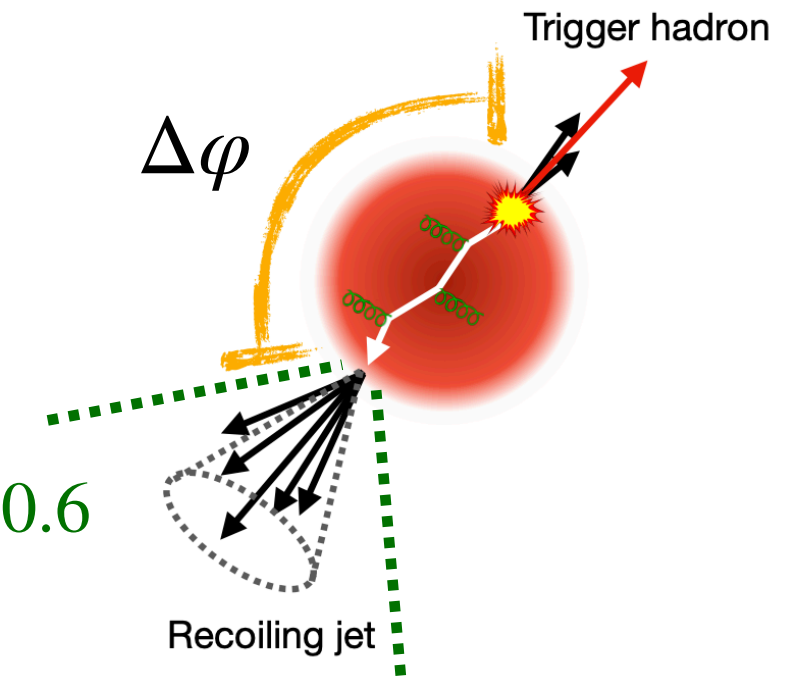


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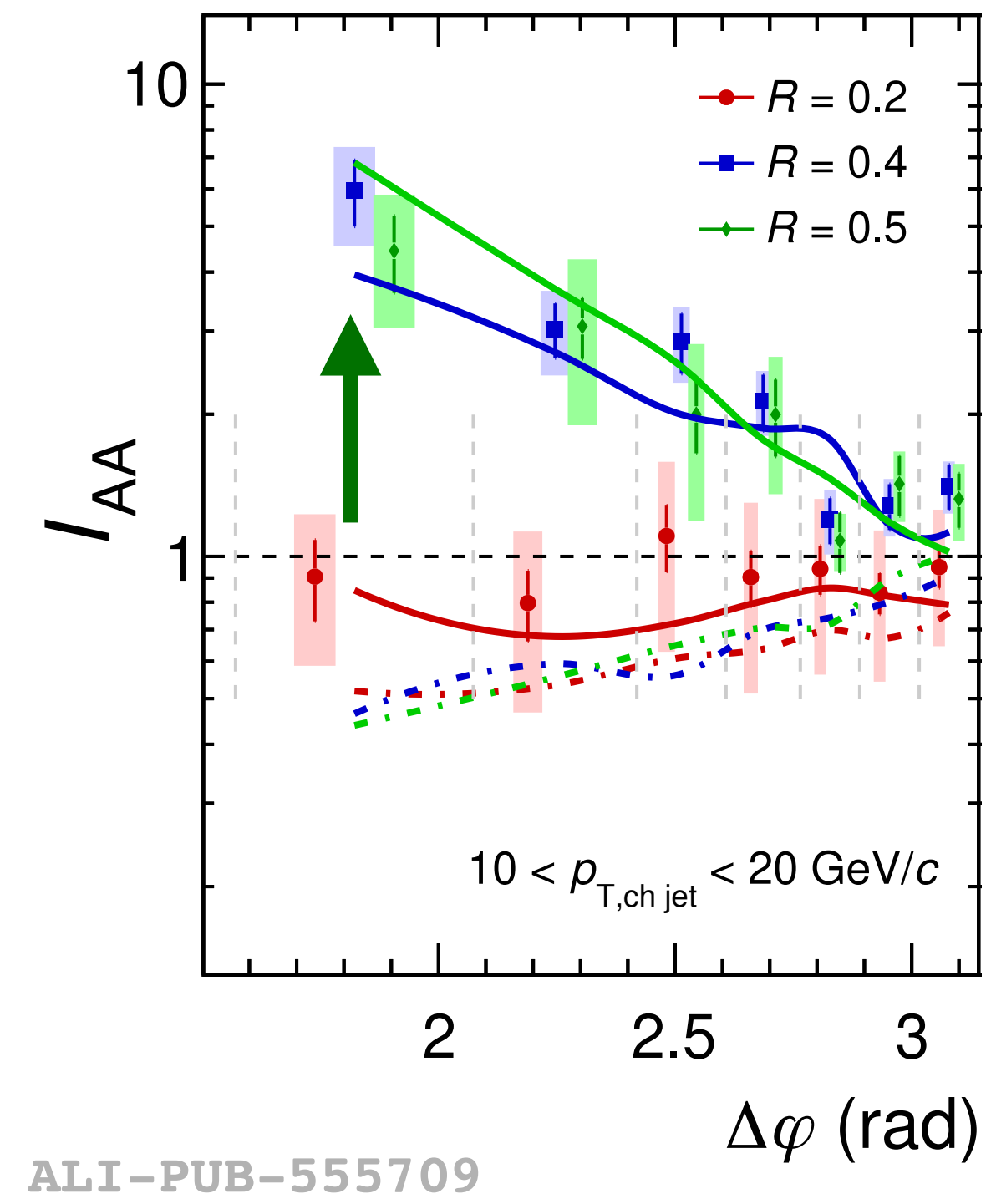
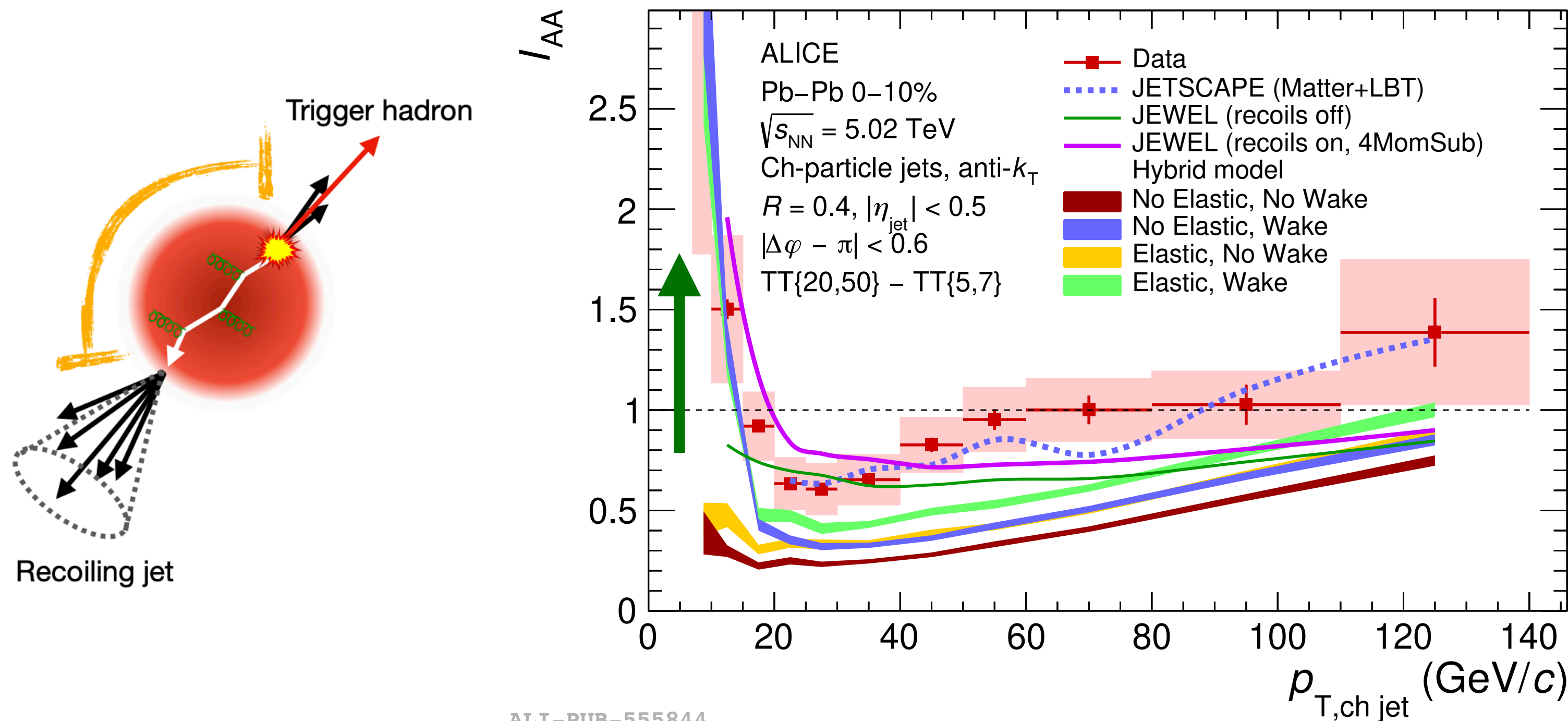
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 → interplay between hadron and jet energy loss?  
 Less trigger surface bias when  $p_{T, \text{jet}} \gg p_{T, \text{trig}}$ ?
- **Rise at low  $p_{T, \text{ch jet}}$**   
 → Energy recovery? Reproduced by models including medium response

ALI-PUB-555844

# Summary and outlook

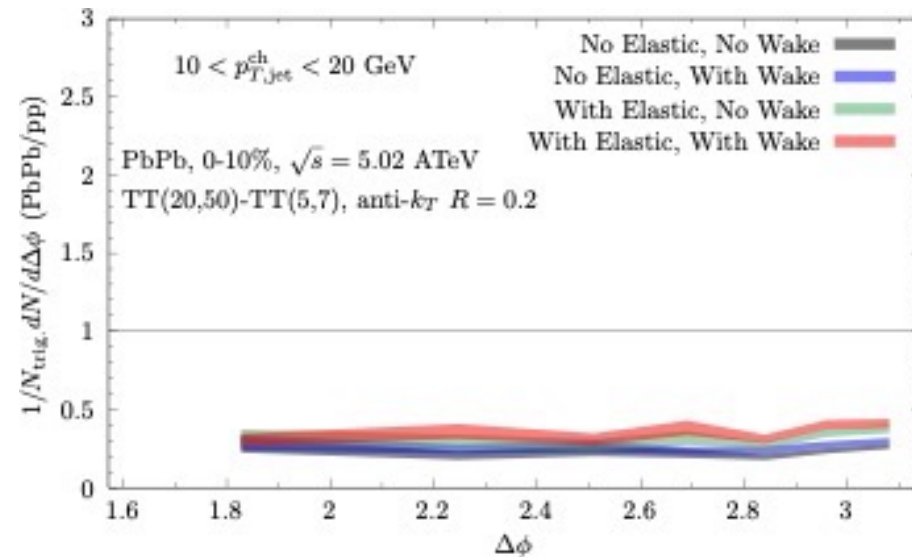
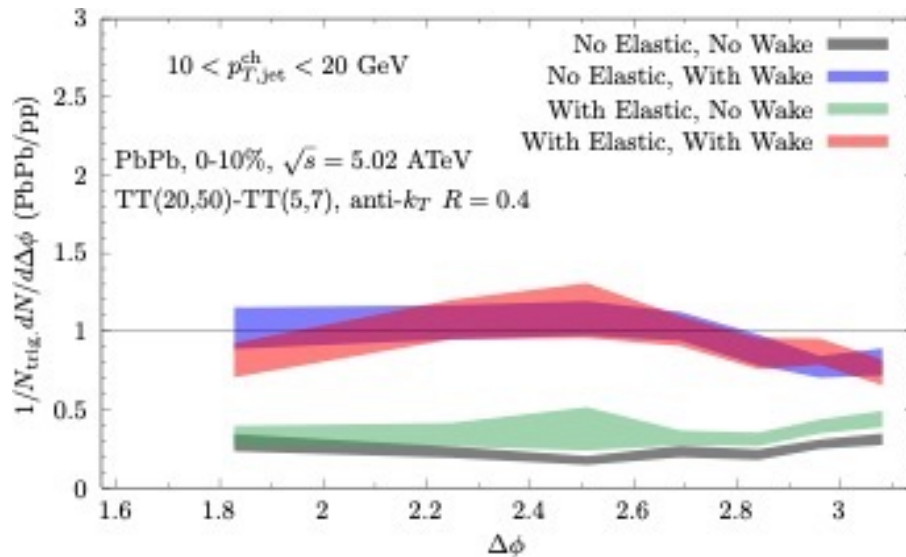


- **First observation of significant low- $p_{T, jet}$  jet yield and large-angle enhancement in Pb-Pb collisions with ALICE!**
- Medium response or medium-induced soft radiation favoured as cause for both measured effects
- Looking forward to further studies with Run 3 data with ALICE after significant upgrade programme

[arXiv:2308.16128](https://arxiv.org/abs/2308.16128)  
[arXiv:2308.16131](https://arxiv.org/abs/2308.16131)

# Hadron--Charge-Jet Acoplanarity, LHC energy

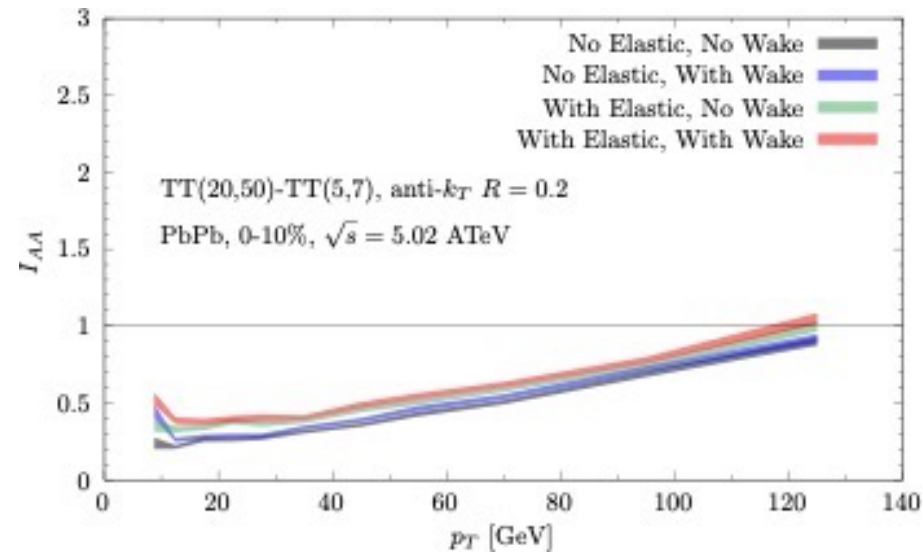
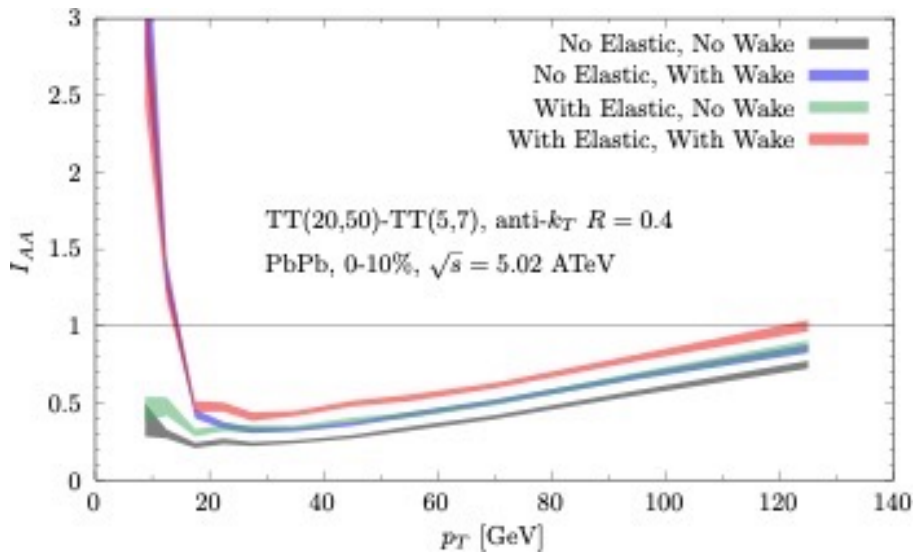
Preliminary



- Study acoplanarity in hadron - charged jet system.
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Preliminary

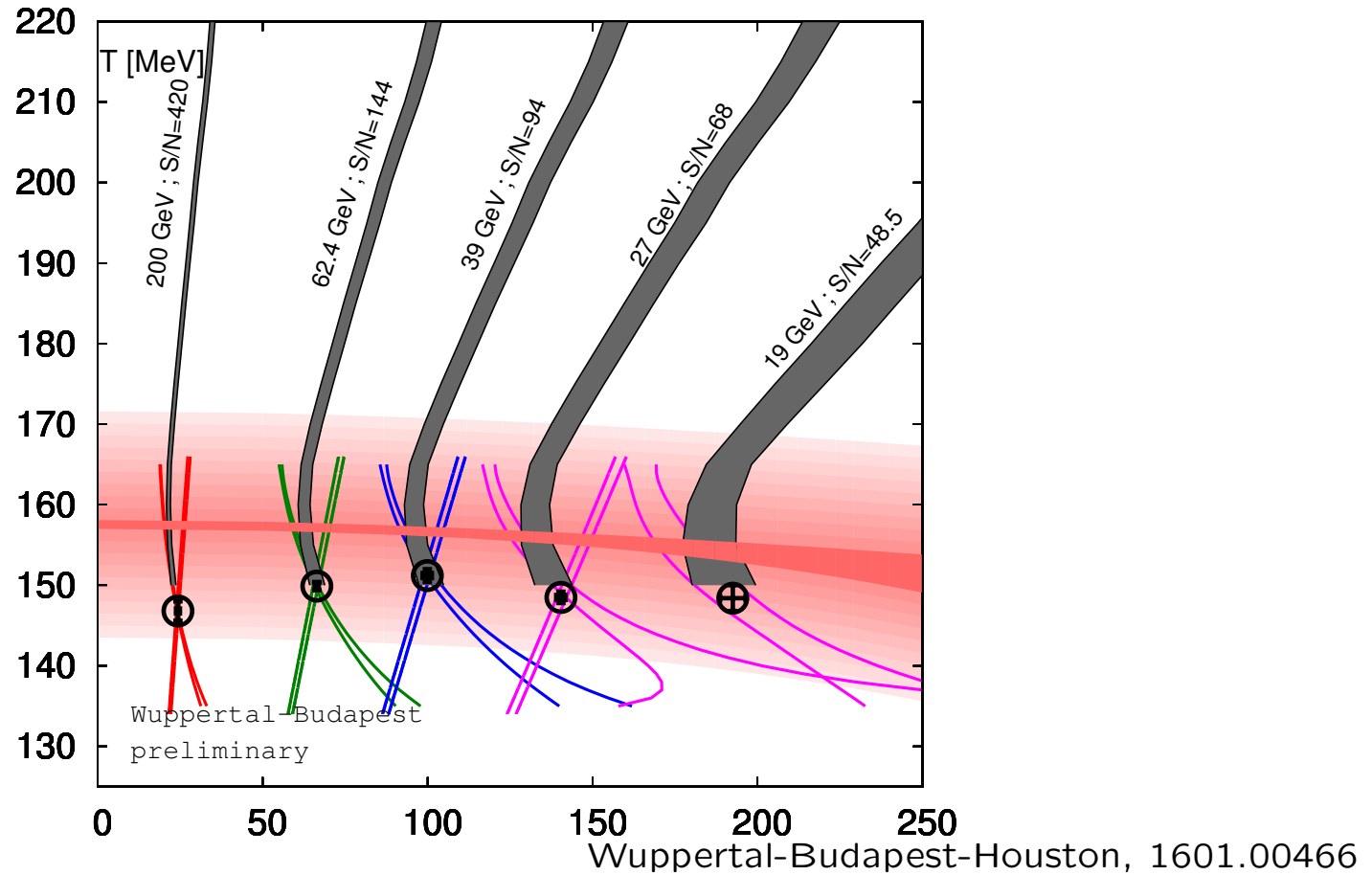


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# Mapping the QCD Phase Diagram

- **How does QGP change as you “dope” it with a larger and larger excess of quarks over antiquarks, i.e. larger and larger  $\mu_B$ ? 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



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



# 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  $\mu_B$ ? Signs of an upturn at larger  $\mu_B$  are inconclusive. Higher statistics data needed. As are substantial advances on the theory side...
- Once you have a validated hydrodynamic 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.

# Mapping the QCD Phase Diagram

- Finding, or excluding, a critical point requires theory and modeling, with ingredients including:
- Energy and baryon number in initial stages.
- **Equation of State (EoS)**
  - Known (lattice QCD) at  $\mu_B = 0$ ; universal features known near a critical point. Putting these together into a model EoS with non-universal parameters to be fixed via comparison to data: Parotto, ..., KR, et al, 1805.05249. Now referred to as the “BEST EoS”.
  - Implementing strangeness conservation and neutrality (2110.00622) into BEST EoS
  - Extending BEST EoS to describe first order phase transition (Karthein, Koch, Ratti, in progress)
- Hydrodynamics. Critical fluctuations.
- Freezeout of critical fluctuations.

# Mapping the QCD Phase Diagram

- Energy and baryon number in initial stages.
- Equation of State (EoS)
- **Hydrodynamics. Critical fluctuations.**
  - Critical fluctuations develop in those collisions that pass near a critical point as they cool
  - Critical slowing down  $\rightarrow$  fluctuations cannot stay in equilibrium (Berdnikov+KR, 1999). Must describe out-of-equilibrium critical fluctuations and hydrodynamics self-consistently. Two formalisms developed; we use Hydro+ (Stephanov, Yin, 2017)
  - First use of Hydro+ to model fluctuation dynamics near a QCD critical point (KR, Ridgway, Weller, Yin, 2019; Du, Heinz, 2020; Pradeep, KR, Stephanov, Yin, 2022)
  - Cooling+critical slowing down  $\rightarrow$  growth of critical fluctuations “lags” what it would be in equilibrium, fluctuations also persist longer than they would; expansion, radial flow  $\rightarrow$  critical fluctuations advected outward; back-reaction on hydrodynamics turns out to be small.
- Freezeout of critical fluctuations.

# Mapping the QCD Phase Diagram

- Finding, or excluding, a critical point requires theory and modeling, with ingredients including:
- Energy and baryon number in initial stages.
- Equation of State (EoS)
- Hydrodynamics. Critical fluctuations.
- **Freezeout of critical fluctuations**
  - Freezing out Hydro+ so as to faithfully turn the critical fluctuations described via Hydro+ into fluctuations of observed proton multiplicities: 2204.00639 Pradeep, KR, Stephanov, Yin
  - ... faithfully turn the *higher moments of the critical fluctuations into the skewness and kurtosis of observed proton multiplicities (in progress)* Kartheim, Pradeep, KR, Stephanov, Yin
- Phase diagram mapping theory+modeling tools vastly better than in 2015; being completed; data coming soon!

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# 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; pAu, dAu and  $^3\text{HeAu}$  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  $RT_{\text{hydrodynamization}} \gtrsim 1$ . (Chesler, 2015)
- Many recent theoretical advances. Hydrodynamic behavior in small-big collisions at top RHIC energy and LHC energy less surprising, *a posteriori*. But still remarkable.
- Not our focus today. For today, tells us that to see “inside” the liquid we will need probes which resolve short length scales...

# Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum  $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

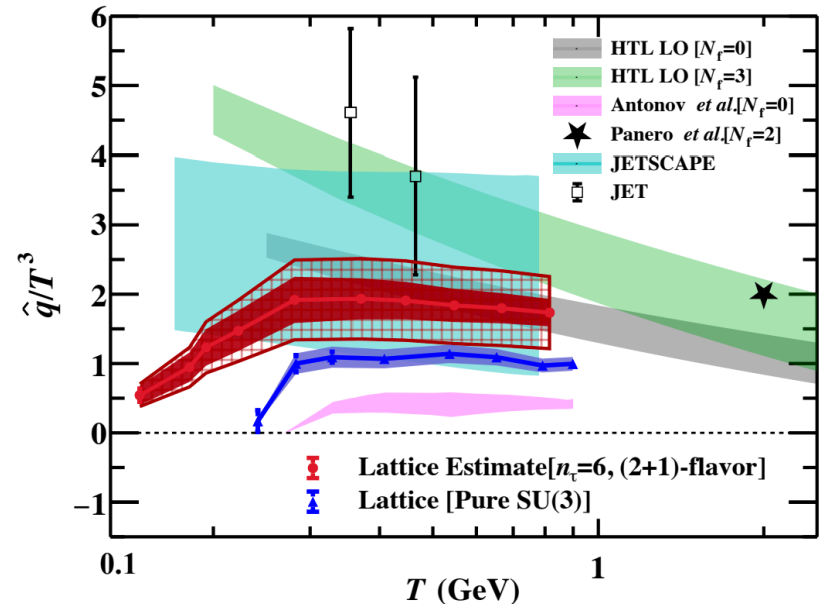
At strong coupling, holography predicts Gaussian broadening **without quasi-particles** (eg: N=4 SYM)

$$P(k_{\perp}) \sim \exp\left(-\frac{\sqrt{2}k_{\perp}^2}{\hat{q}L^-}\right) \quad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma(\frac{3}{4})}{\Gamma(\frac{5}{4})}\sqrt{\lambda}T^3$$

Adding this in hybrid model (C-S et al 2016) yielded little effect on jet observables.

Today, Bayesian inference from hadron  $R_{AA}$  data indicates  $P(k_{\perp}) \sim K T^3$  with  $K \sim 2 - 4$ . This need not have anything to do with quasiparticles.

- Add Moliere scattering with momentum exchanges  $> m_D$ ; focus on perturbative regime



From Weber's HP2023 talk

D'Eramo et al., 2011, 2018  
+  
Mehtar-Tani et al., PRD 2021

# Gaussian Broadening vs Large Angle Scattering

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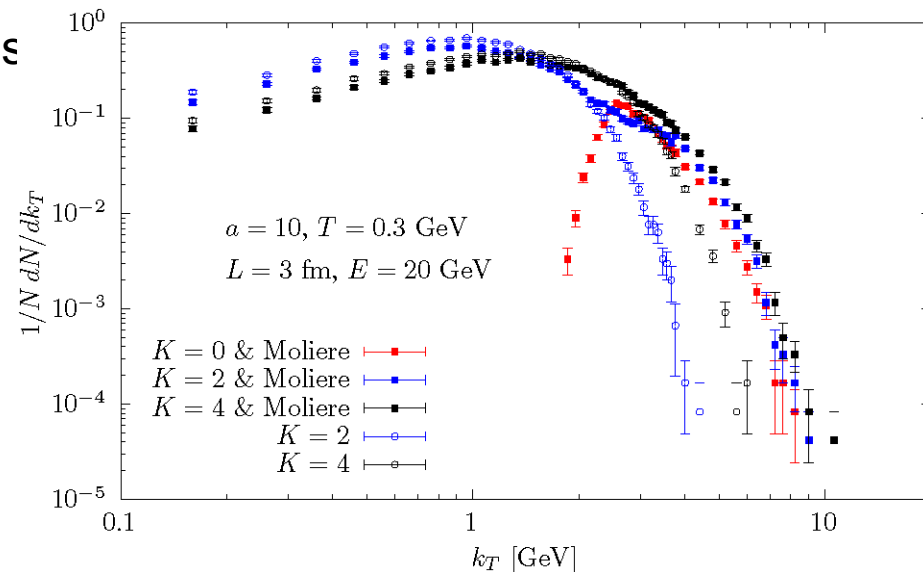
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- Add Moliere scattering with momentum exchanges  $> m_D$ ; here,  $a = 10$



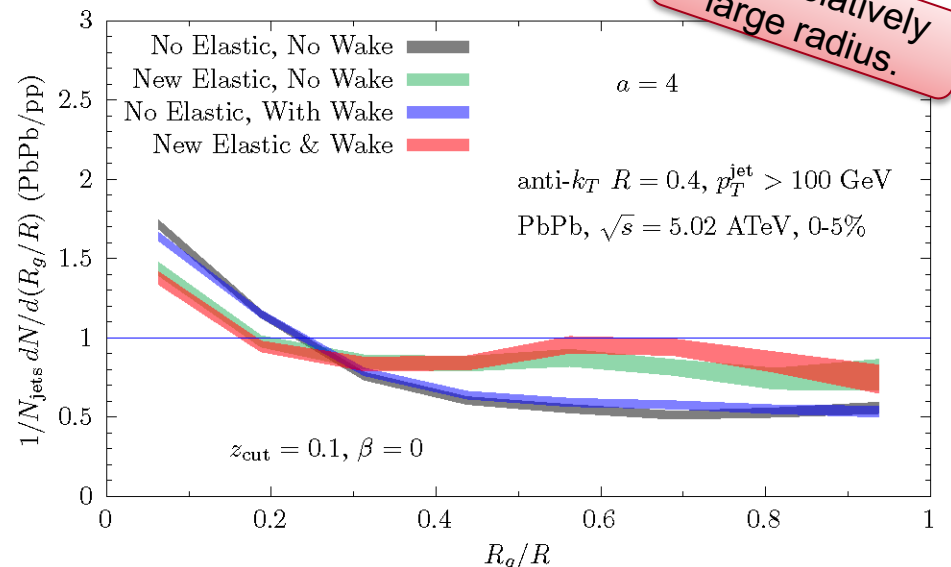
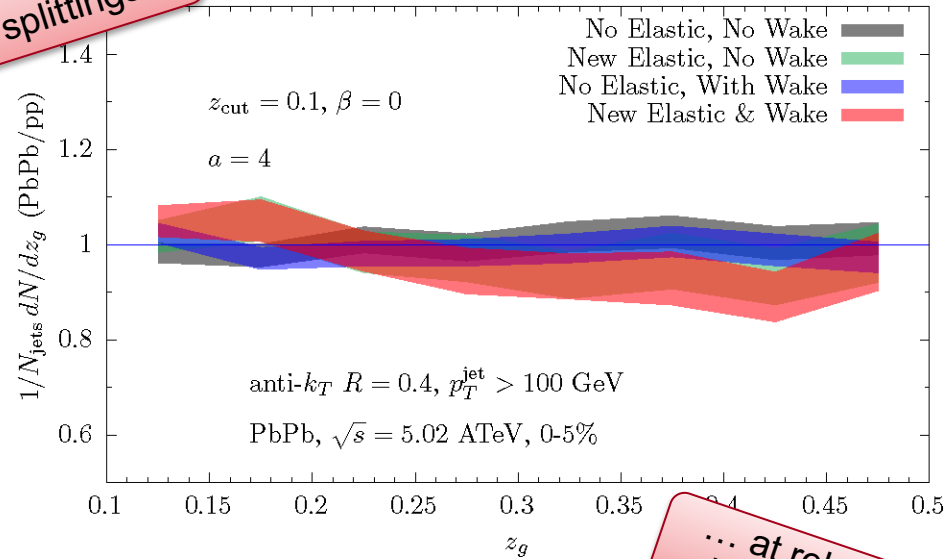
# Groomed $z_g$ and $R_g$

## Soft Drop ( $\beta = 0$ )

1. Reconstruct jet with anti- $k_T$
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2, separated by angle  $R_g$
4. If  $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \equiv z_g > z_{cut}$ , then original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and repeat

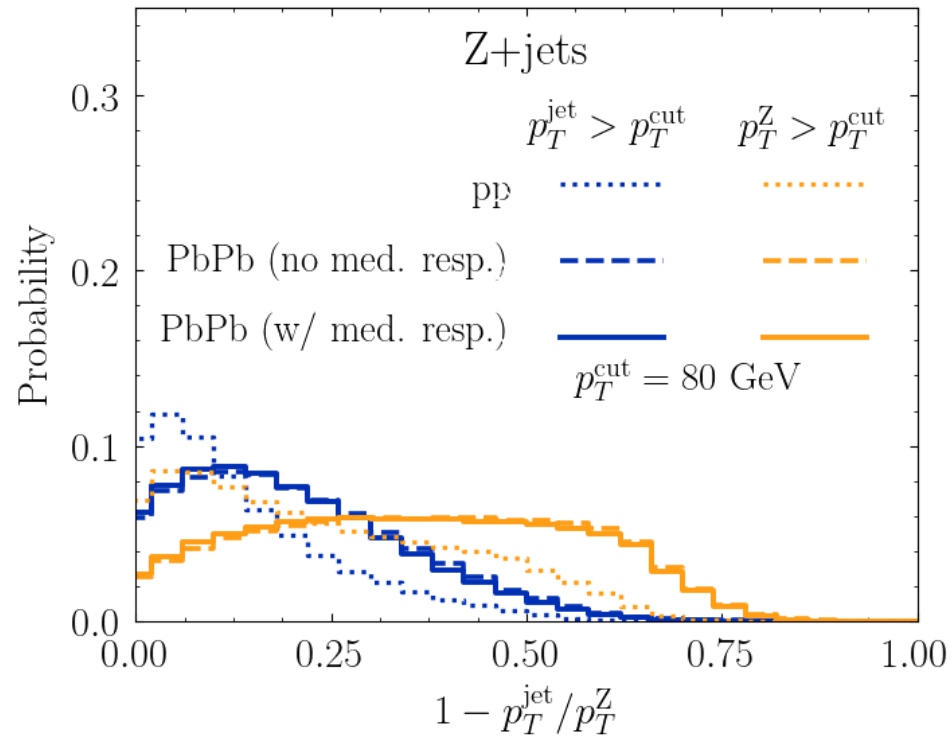
Much less sensitivity to wake;  
Moliere scattering shows up;  
effects of Moliere and wake are again similar in shape, but here effects of Moliere on  $R_g$  are dominant, with  $a=4$  or 10.

Enhancement of softer splittings...



... at relatively large radius.

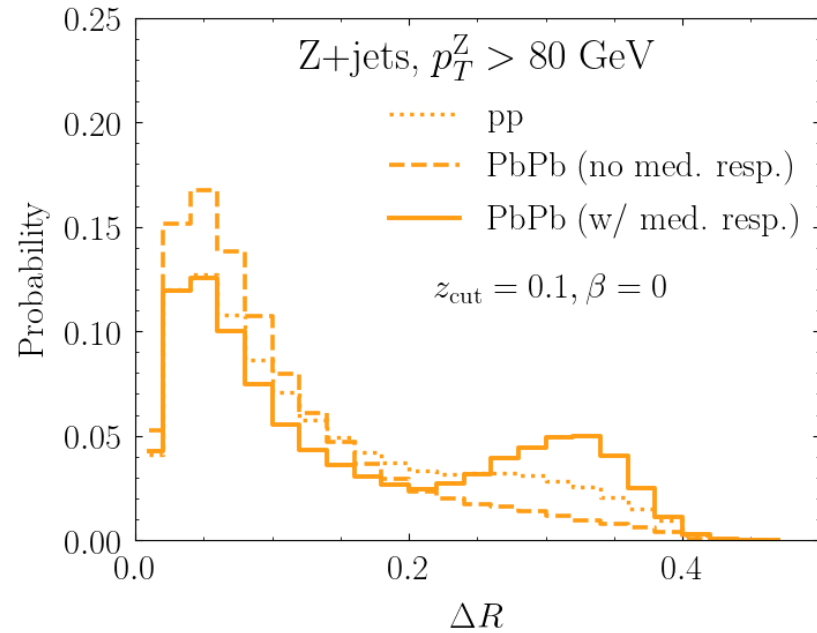
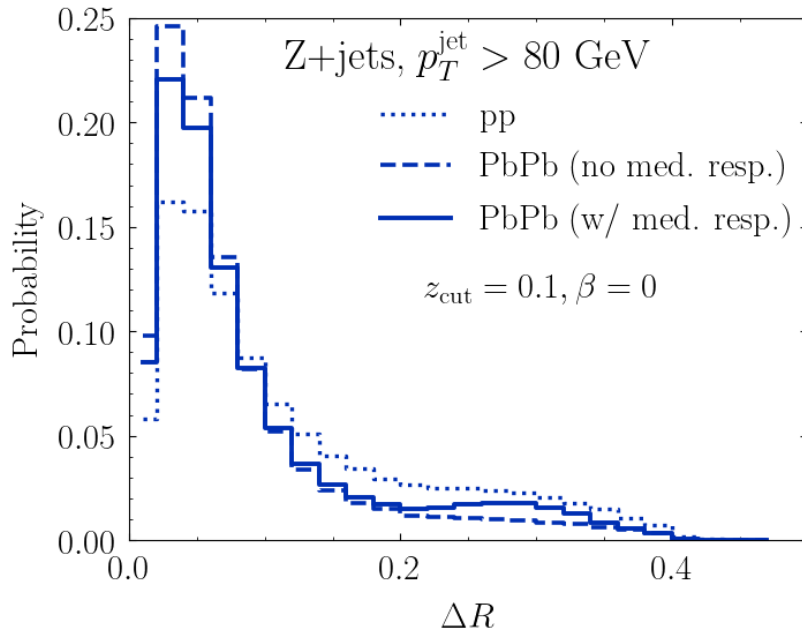
# Disentangling Jet Modification from Selection



**Orange:**  $p_T^Z > 80 \text{ GeV}$ ;  $p_T^{\text{jet}} > 30 \text{ GeV}$

**Blue:**  $p_T^{\text{jet}} > 80 \text{ GeV}$ ;  $p_T^Z > 30 \text{ GeV}$  — jet selection biases toward those jets that lose less energy

# Disentangling Jet Modification from Selection



**Orange:**  $p_T^Z > 80 \text{ GeV}$ ;  $p_T^{\text{jet}} > 30 \text{ GeV}$ . See jet modification.

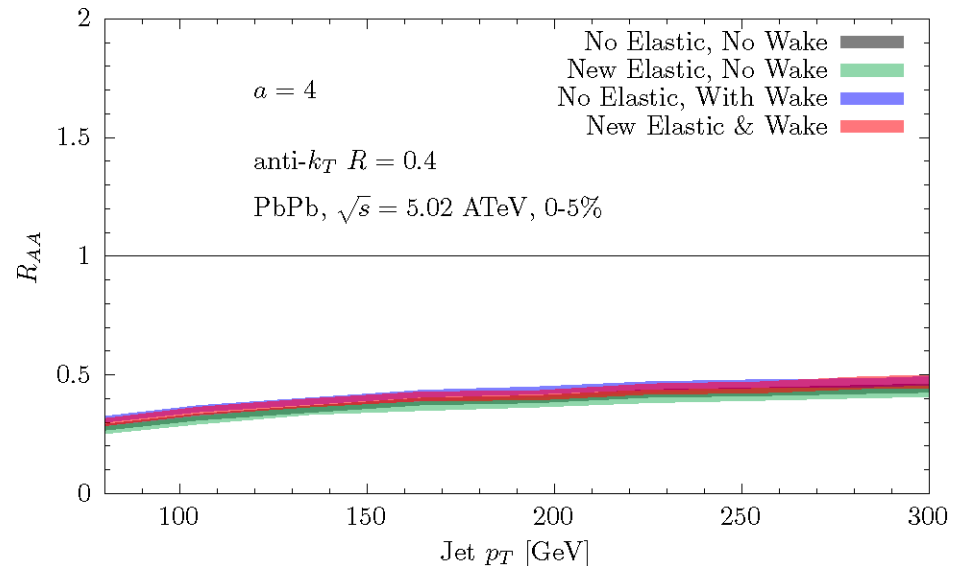
**Blue:**  $p_T^{\text{jet}} > 80 \text{ GeV}$ ;  $p_T^Z > 30 \text{ GeV}$  — jet selection biases toward those jets that lose less energy. These jets are skinnier. And the bias is toward less jet modification.



# Jet $R_{AA}$

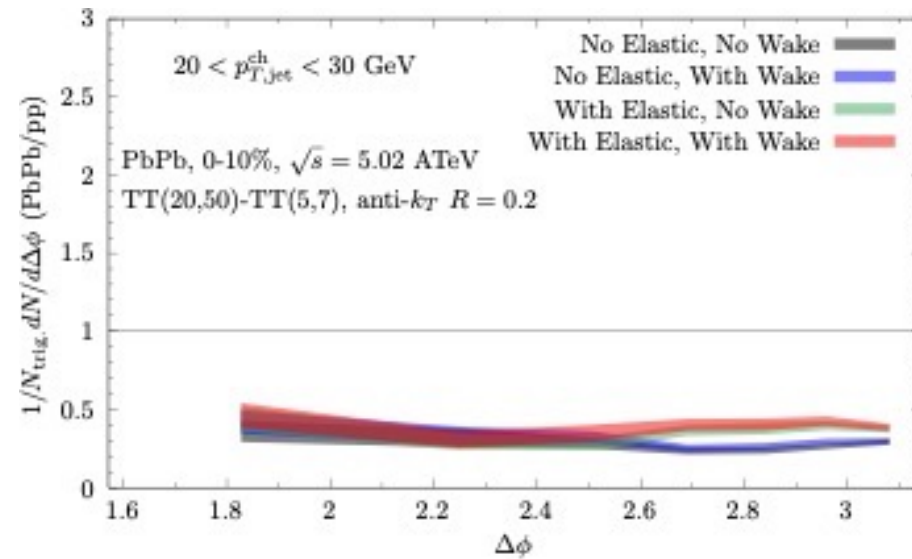
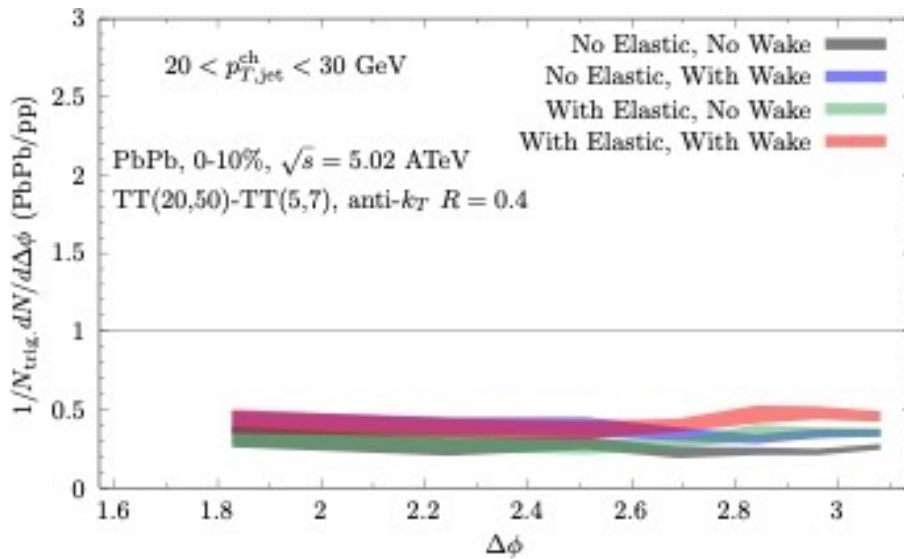
Casalderrey  
-Solana et  
al. 2019

- $\kappa_{SC}$  previously fit with jet and hadron suppression data from ATLAS+CMS at 2.76+5.02 TeV
- Elastic scatterings lead to slight additional suppression; refit  $\kappa_{SC}$ . That means red is on top of blue in this plot by construction. (Addition of the elastic scatterings yields only small change to value of  $\kappa_{SC}$ .)
- Adding the hadrons from the wake allows the recovery of part of the energy within the jet cone; blue and green slightly below red and blue.



# Hadron--Charge-Jet Acoplanarity, LHC energy

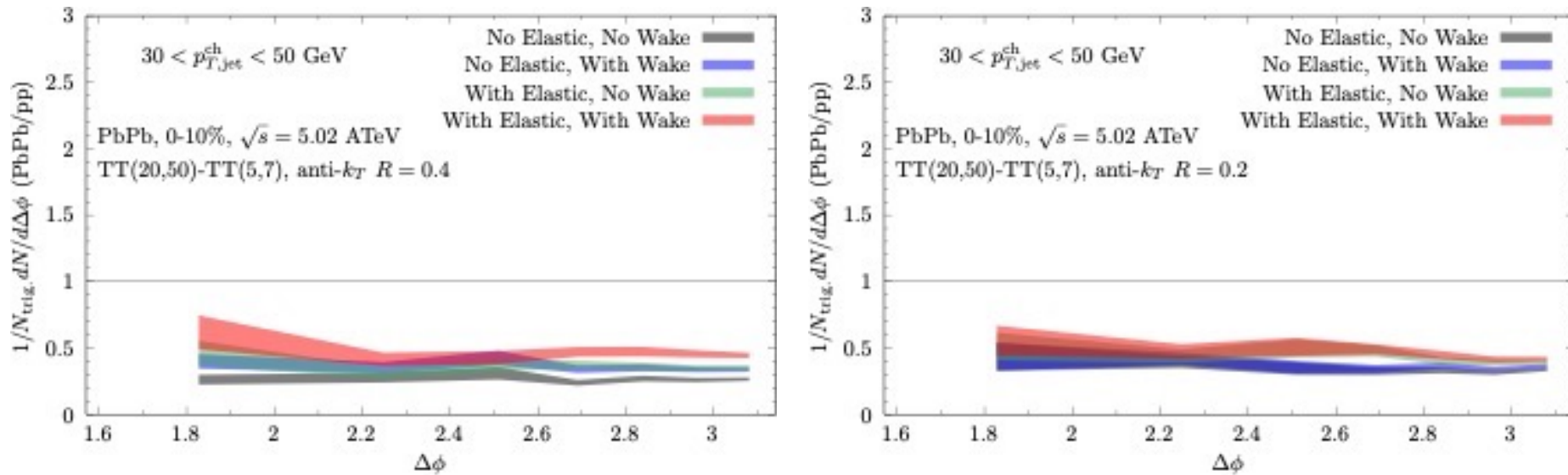
Preliminary



- Study acoplanarity in hadron - charged jet system.
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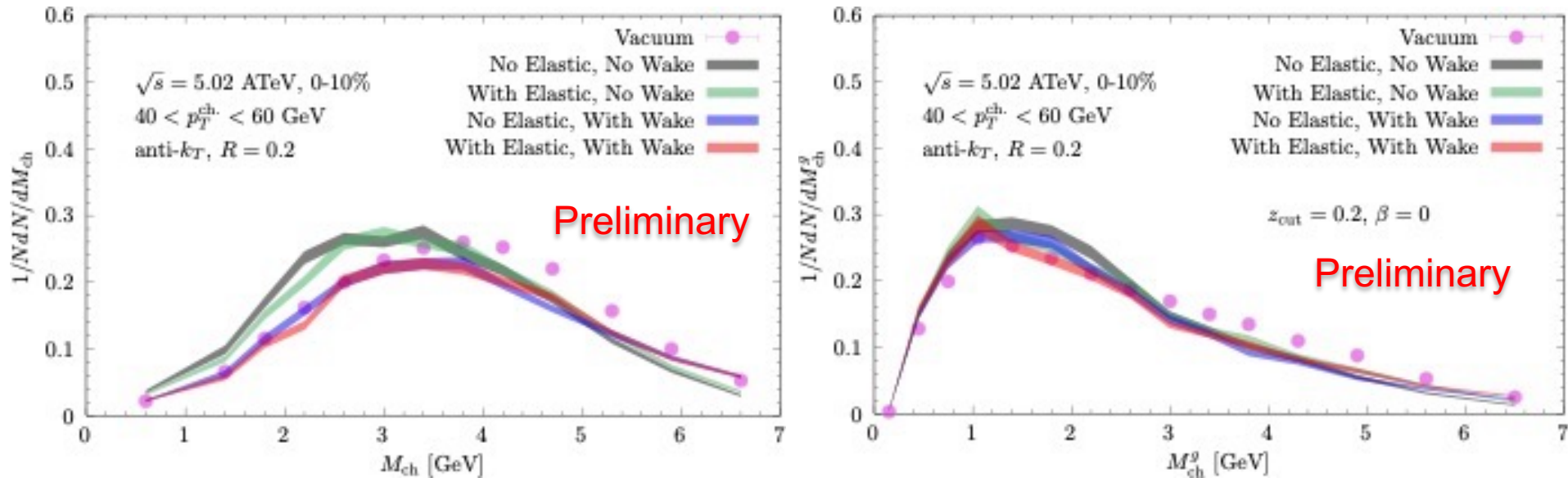
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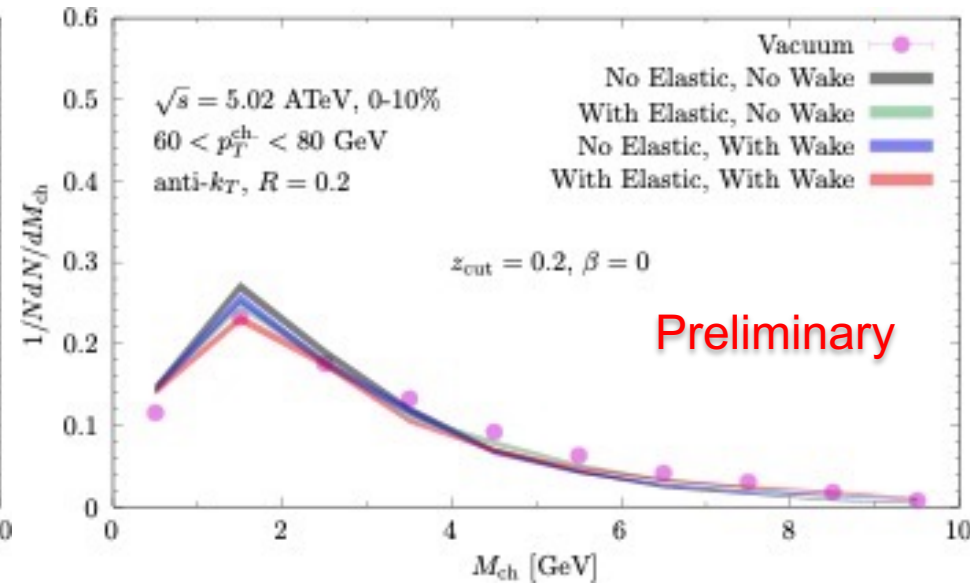
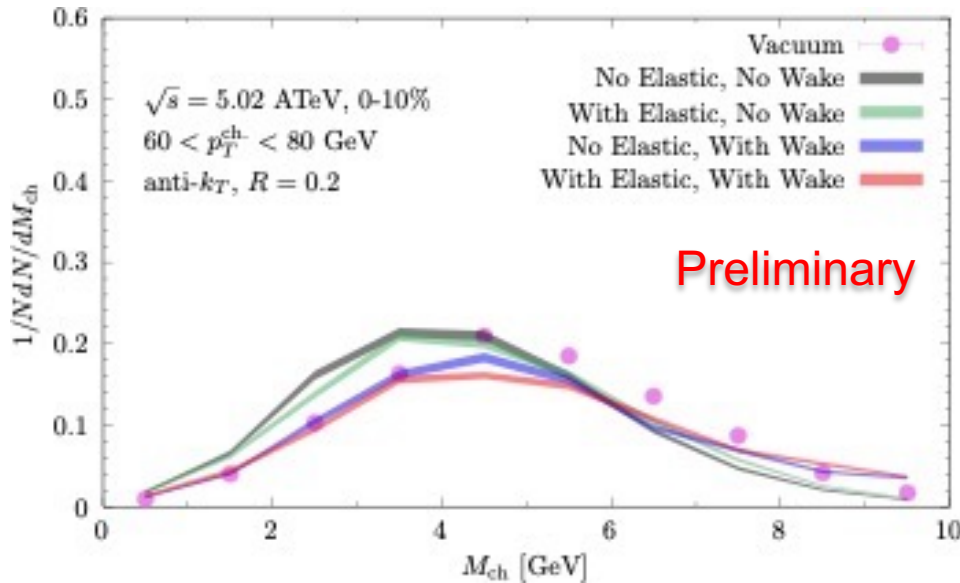
# Jet Mass, and Groomed Jet Mass



→ Ungroomed observable is sensitive to the wake; not to Moliere scattering.  
 Grooming removes wake, but still little sensitivity to Moliere scattering.

- What if we look at groomed observables? Less sensitive to wake...
- Yes, but not every groomed observable is sensitive to hard scattering...

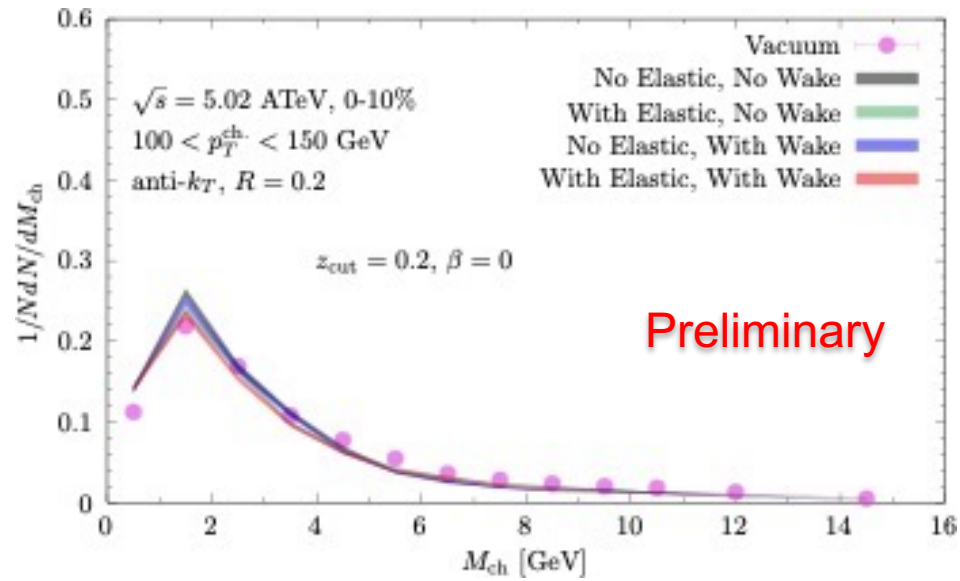
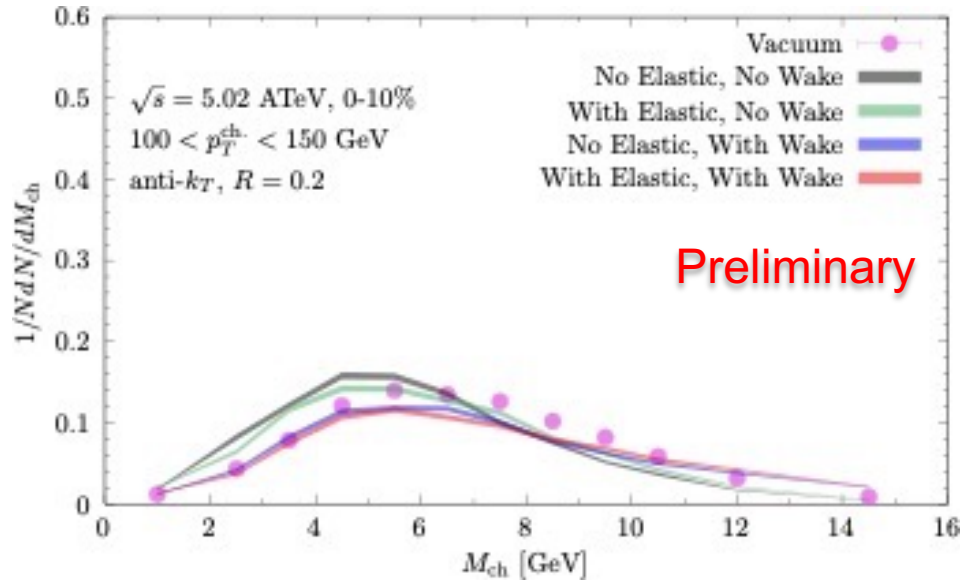
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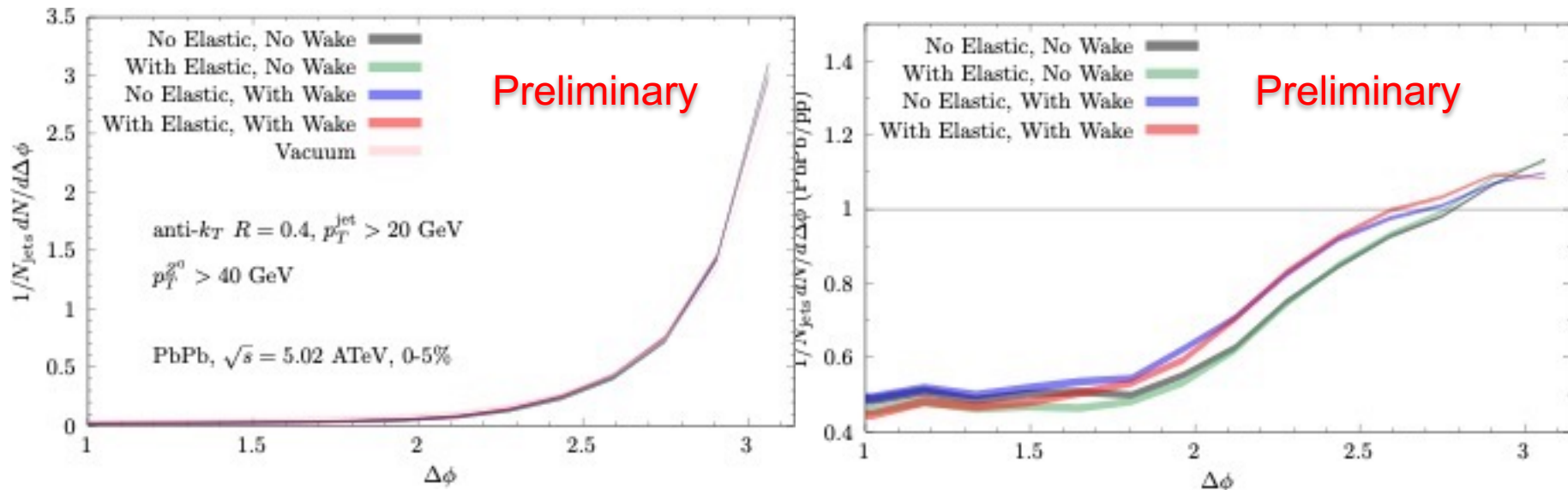
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# Z-Jet Acoplanarity

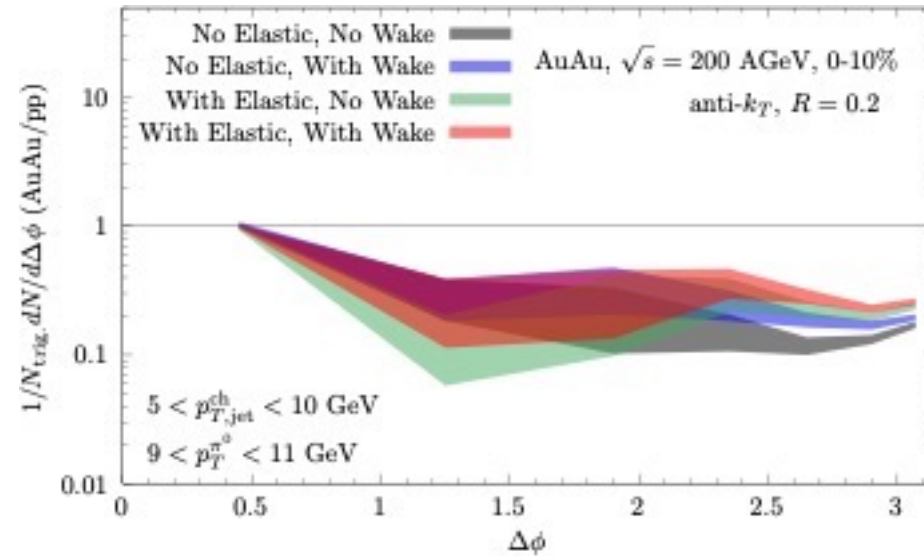
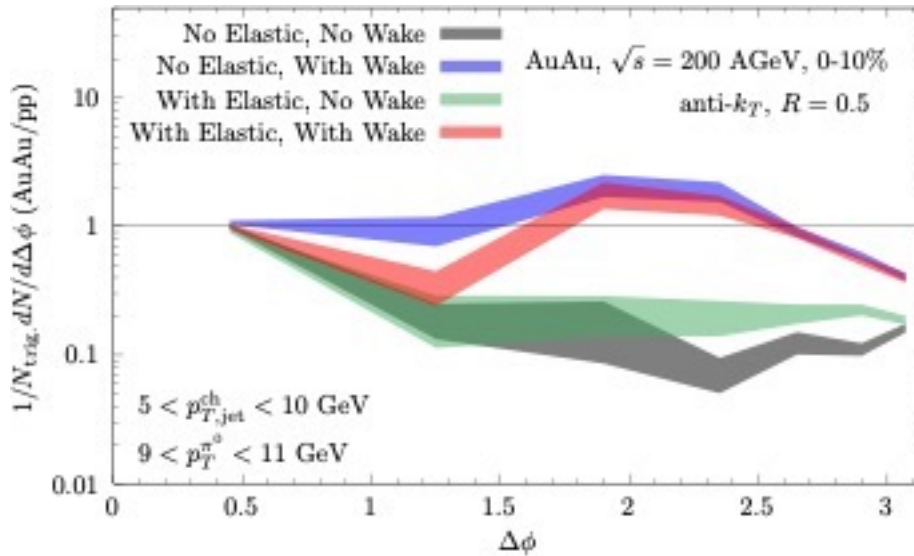


- Study acoplanarity in boson-jet system: Z-jet.
- **Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.**
- Similar conclusions for acoplanarities at even lower  $p_T$ , via hadron—charged-jet correlations. Should look also Gamma-D,  $D\bar{D}$  correlations....
- Groomed  $z_g$  and  $R_g$ , leading  $k_T$ , and in particular inclusive subjet observables all more sensitive to Moliere scattering.
- Moliere scattering: jet sprouts added prongs, not much overall deflection



# Hadron--Charge-Jet Acoplanarity, RHIC energy

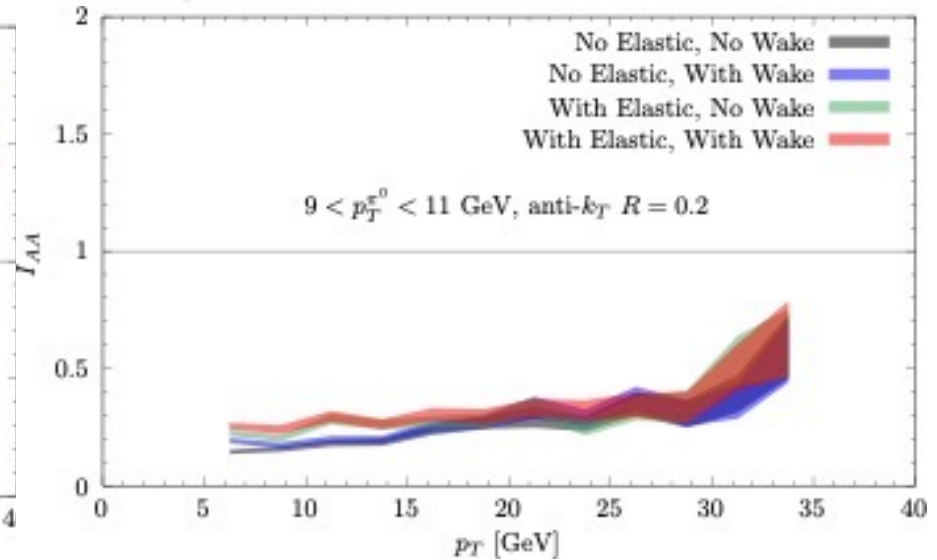
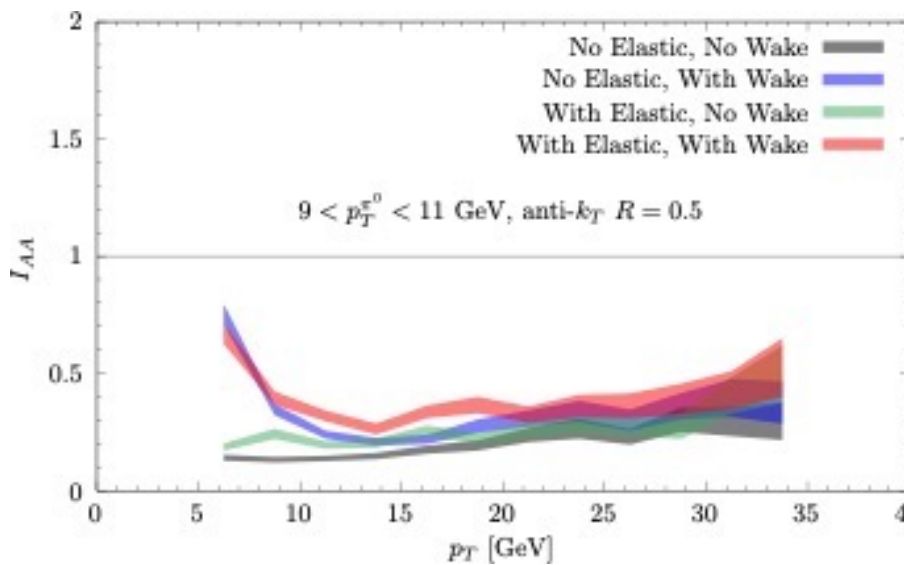
Preliminary



- Study acoplanarity in pi0 - charged jet system.
- Parameters similar to but not same as STAR
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# Hadron--Charge-Jet Acoplanarity, RHIC energy

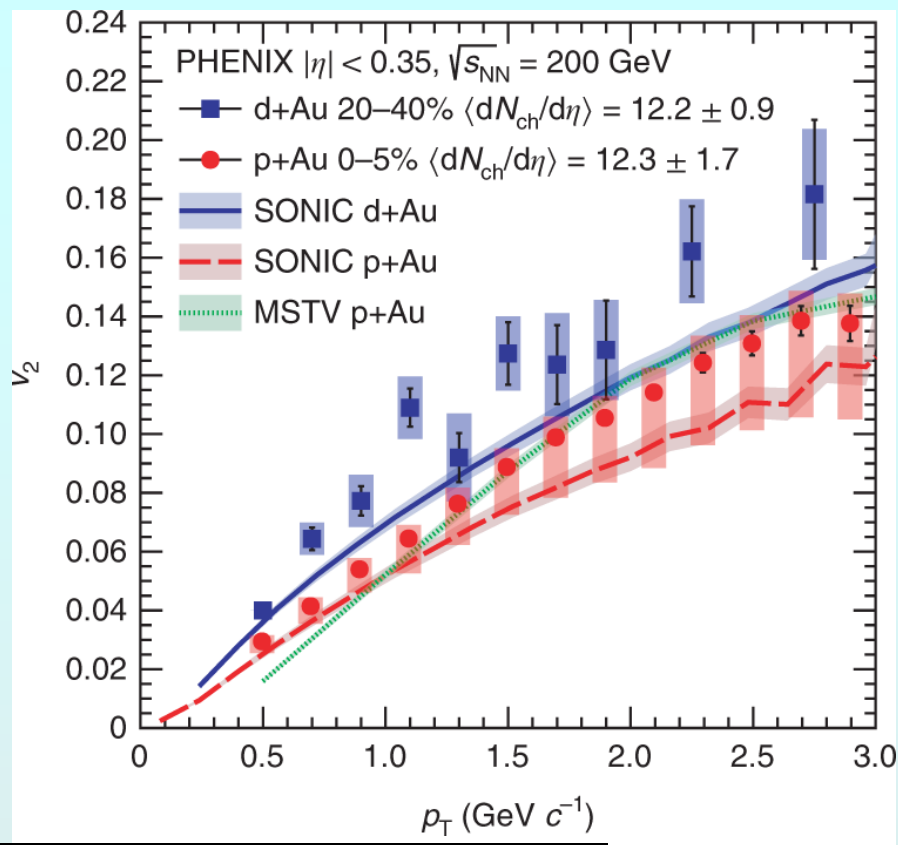
Preliminary



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# Eek! Hydrodynamics in small systems!

PHENIX  
Collaboration  
Nature Physics  
(2018)

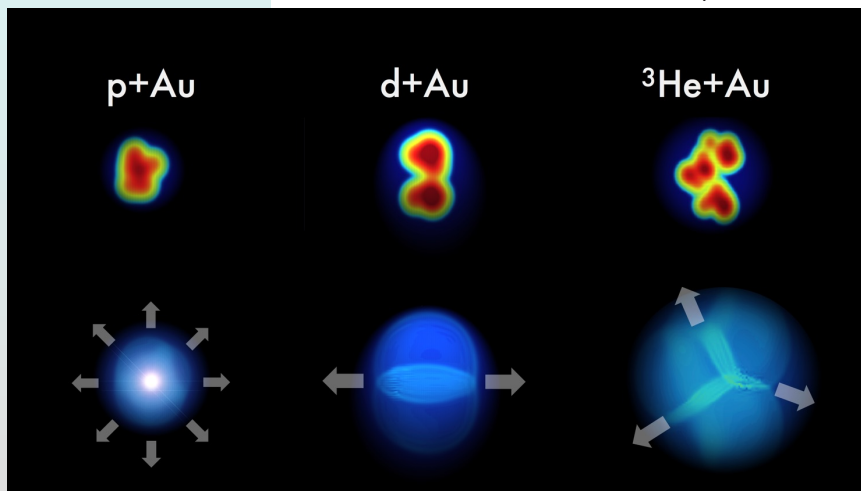


*Not big & dense*

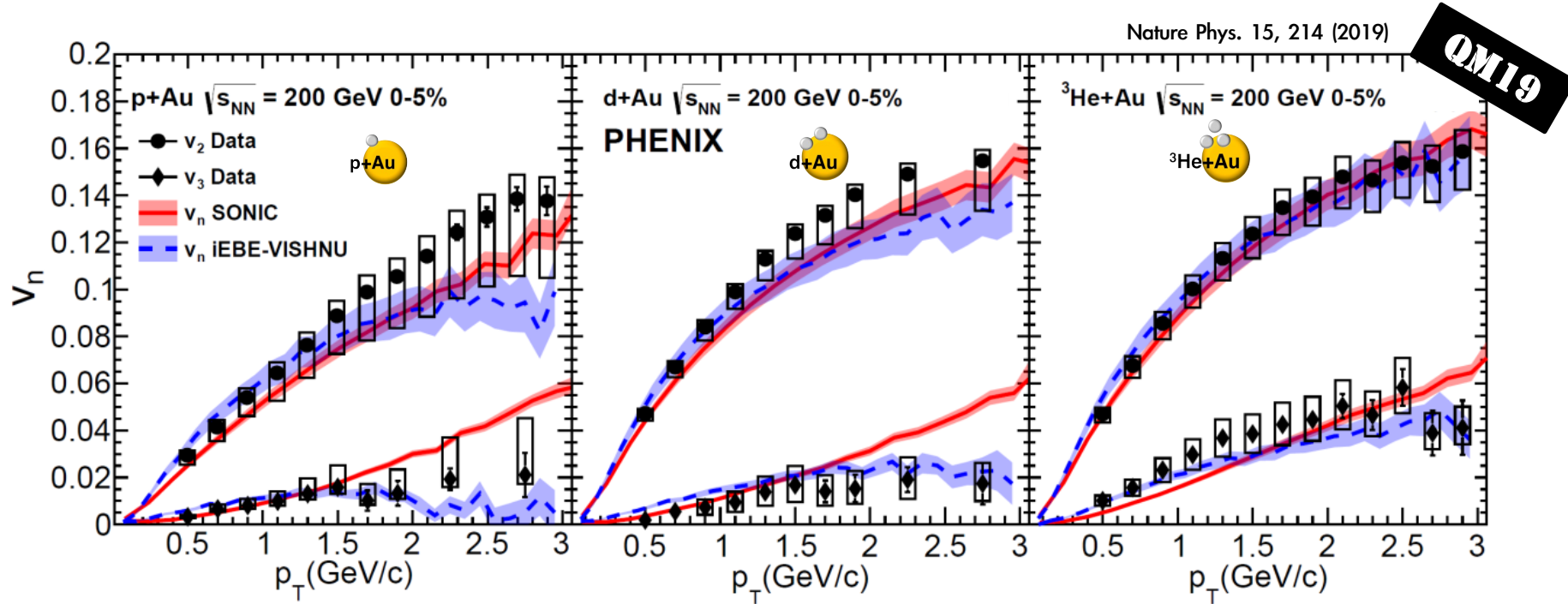
*But, we see collective flow!*

*Seeded by the initial geometry*

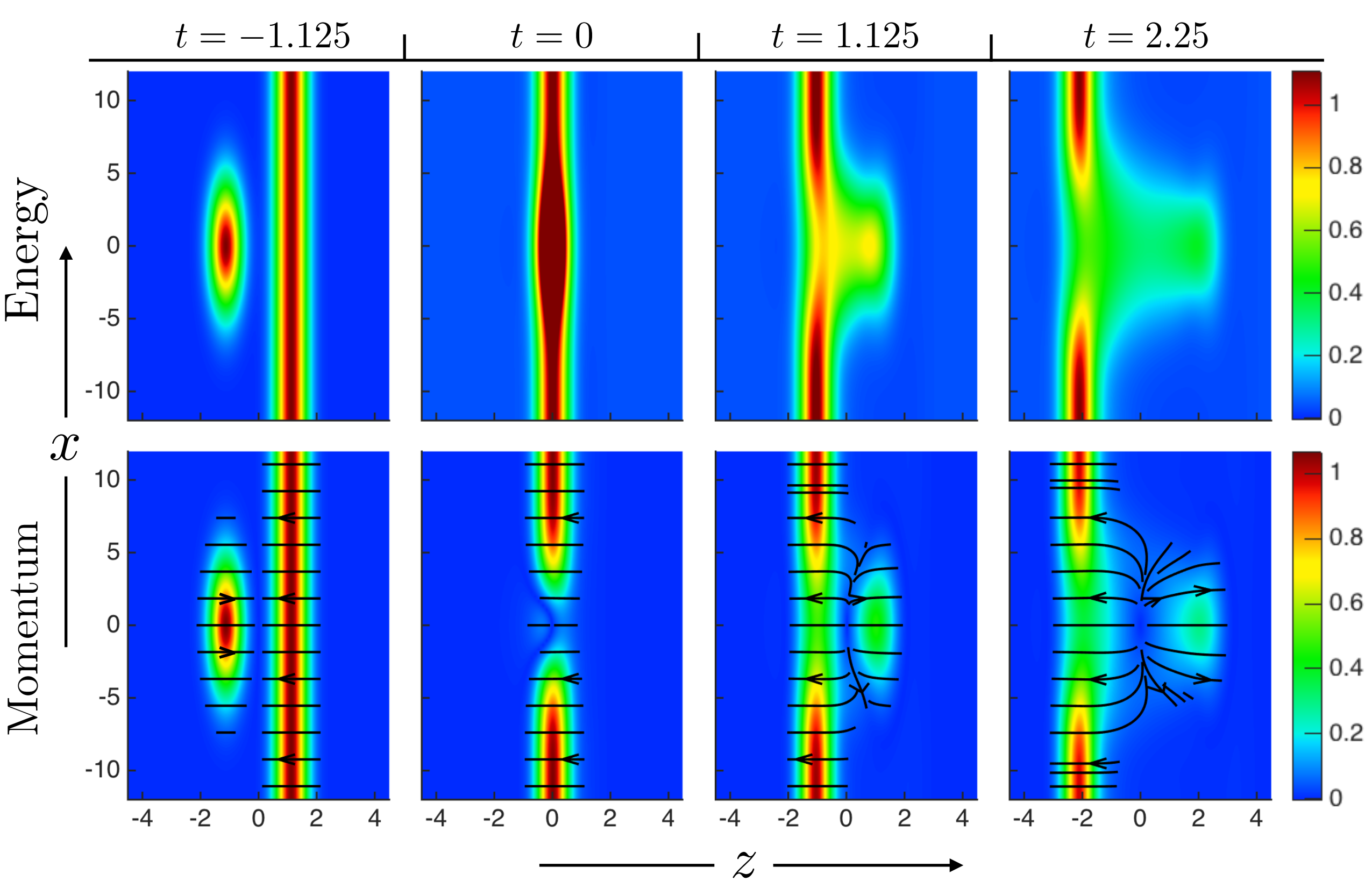
*A small droplet of QGP?!*



# Collectivity in small systems



- Evidence of QGP droplets in small collision systems
- Smaller  $v_2$  in p+Au and larger  $v_3$  in  $^3\text{He}+\text{Au}$



# 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; pAu, dAu and  $^3\text{HeAu}$  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  $1$ .
- Many recent theoretical advances. Hydrodynamic behavior in small-big collisions at top RHIC energy and LHC energy less surprising, *a posteriori*. But still remarkable.
- Not our focus today. For today, tells us that to see “inside” the liquid we will need probes which resolve short length scales...

# How to Calculate Properties of Strongly Coupled QGP Liquid?

- **Lattice QCD.** Perfect for THERMODYNAMICS. Calculation of  $\eta$ , heavy quark diffusion coefficient, other transport coefficients, beginning. Hydrodynamization, jet quenching and other dynamical processes not in sight.
- **Perturbative QCD.** The right theory, but the wrong approximation.
- Calculate properties, transport coefficients, hydrodynamization, dynamical processes for hot strongly coupled liquid in other gauge theories that, via **holography**, *are* analyzable at strong coupling. Right approximation, wrong theory.

Are some dynamical properties similar across strongly coupled liquid phases in many theories? How can we use holographic calculations to gain intuition re dynamical questions? Examples have arisen in the first Intro, and will arise again in last lecture. So, a second Intro...



# $N=4$ SUPERSYMMETRIC YANG MILLS

- A gauge theory specified by two parameters:  $N_c$  and  $g^2 N_c \equiv \lambda$ .
- Conformal. ( $\lambda$  does not run.)
- If we choose  $\lambda$  large, at  $T \neq 0$  we have a strongly coupled plasma.
- This 3+1 dimensional gauge theory is equivalent to a particular string theory in a particular spacetime:  $\underbrace{\text{AdS}_5}_{4+1 \text{ "big" dimensions}} \times \underbrace{S^5}_{5 \text{ "curled up" dim.}}$
- In the  $N_c \rightarrow \infty$ ,  $\lambda \rightarrow \infty$  limit, the string theory reduces to classical gravity.  $\therefore$  calculations easy at strong coupling.

# Thermodynamics at Strong Coupling

- In the  $N_c \rightarrow \infty$  and  $\lambda \rightarrow \infty$  limit, the thermodynamics of strongly coupled  $\mathcal{N} = 4$  SYM plasma are:

$$\frac{\varepsilon_{\lambda=\infty}}{\varepsilon_{\lambda=0}} = \frac{P_{\lambda=\infty}}{P_{\lambda=0}} = \frac{s_{\lambda=\infty}}{s_{\lambda=0}} = \frac{3}{4}$$

- Teaches us that thermodynamics of very weakly coupled plasmas and very strongly coupled plasmas can be very similar.
- Reminds us that (approximate) conformality above  $T_c$  need not mean weak coupling.
- But we don't "need" this, in the sense that we have reliable lattice calculations of the thermodynamics of QGP in QCD.

# $\eta/s$ and Holography

- $4\pi\eta/s = 1$  for any (of the very many) known strongly coupled large- $N_c$  gauge theory plasmas that are the “hologram” of a (4+1)-dimensional gravitational theory “heated by” a (3+1)-dimensional black-hole horizon.
- Examples of theories in which this result holds are known which are: conformal or not; confining at  $T = 0$  or not; have fundamentals or not; supersymmetric or not.
- cf.  $1 < 4\pi\eta/s < 3$  for QGP at RHIC and LHC.
- Suggests a new kind of universality, not yet well understood, applying to dynamical aspects of strongly coupled liquids. To which liquids? Unitary Fermi ‘gas’?

# $\eta/s$ and Holography

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- Geometric intuition for dynamical phenomena at strong coupling. Hydrodynamization = horizon formation. Nontrivial hydrodynamic flow pattern = nontrivial undulation of black-hole metric. Dissipation due to shear viscosity = gravitational waves falling into the horizon.
- Conformal examples show that hydrodynamics need not emerge from an underlying kinetic theory of particles. A liquid can just be a liquid.

# AdS/CFT

We now know of infinite classes of different gauge theories whose quark-gluon plasmas:

- are all equivalent to string theories in higher dimensional spacetimes that contain a black hole

- all have

$$\frac{E}{T^4} = \frac{3}{4} \left( \frac{E}{T^4} \right)_0$$

Gubser Klebanov  
Tseytlin Peet...

$$\eta/s = \frac{1}{4\pi}$$

Son Poliacastro Starinets  
Kovtun Buchel Liu...

in the limit of strong coupling and large number of colors.

⌈ Not known whether QCD in this class. ⌋



# Why care about the value of $\eta/s$ ?

- Here is a theorist's answer...
- Any gauge theory with a holographic dual has  $\eta/s = 1/4\pi$  in the large- $N_c$ , strong coupling, limit. In that limit, the dual is a classical gravitational theory and  $\eta/s$  is related to the absorption cross section for stuff falling into a black hole. If QCD has a dual, since  $N_c = 3$  it must be a string theory. Determining  $(\eta/s) - (1/4\pi)$  would then be telling us about string corrections to black hole physics, in whatever the dual theory is.

- For fun, quantum corrections in dual of  $\mathcal{N} = 4$  SYM give:

$$\frac{\eta}{s} = \frac{1}{4\pi} \left( 1 + \frac{15 \zeta(3)}{(g^2 N_c)^{3/2}} + \frac{5 (g^2 N_c)^{1/2}}{16 N_c^2} + \dots \right) \quad \text{Myers, Paulos, Sinha}$$

with  $1/N_c^2$  and  $N_f/N_c$  corrections yet unknown. Plug in  $N_c = 3$  and  $\alpha = 1/3$ , i.e.  $g^2 N_c = 12.6$ , and get  $\eta/s \sim 1.73/4\pi$ . And,  $s/s_{SB} \sim 0.81$ , near QCD result at  $T \sim 2 - 3T_c$ .

- A more serious answer...

# 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  $\eta/s$  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  $\tau_{qp} \sim (5\eta/s)(1/T) \gg 1/T.$ ]
- 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;...
- Emerging hints of how to look at matter in which quasiparticles have disappeared and quantum entanglement is enhanced: “many-body physics through a gravitational lens.” Black hole descriptions of liquid QGP and strange metals are continuously related! But, this lens is at present still somewhat cloudy...



# 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  $\eta/s$  and little effect on many other observables.
- The fact that the calculations in  $\mathcal{N} = 4$  SYM are done at strong coupling is a feature, not a bug.
- The fact that strongly coupled  $\mathcal{N} = 4$  SYM is strongly coupled at all scales, including short length scales, is a bug.  $\rightarrow$  Wednesday.
- $\mathcal{N} = 4$  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.
- Our goals are, and must be, limited to qualitative insights.

# A Grand Challenge

- How can we clarify the understanding of fluids without quasiparticles, whose nature is a central mystery in so many areas of science?
- We have two big advantages: (i) direct experimental access to the fluid of interest without extraneous degrees of freedom; (ii) weakly-coupled quark and gluon quasiparticles at short distances.
- We can quantify the properties and dynamics of Liquid QGP at its natural length scales.
- Can we probe, quantify and understand Liquid QGP at *short distance scales*, where it is made of quark and gluon quasiparticles? See *how* the strongly coupled fluid emerges from well-understood quasiparticles at short distances.
- The LHC and newly upgraded RHIC offer new probes and open new frontiers.

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

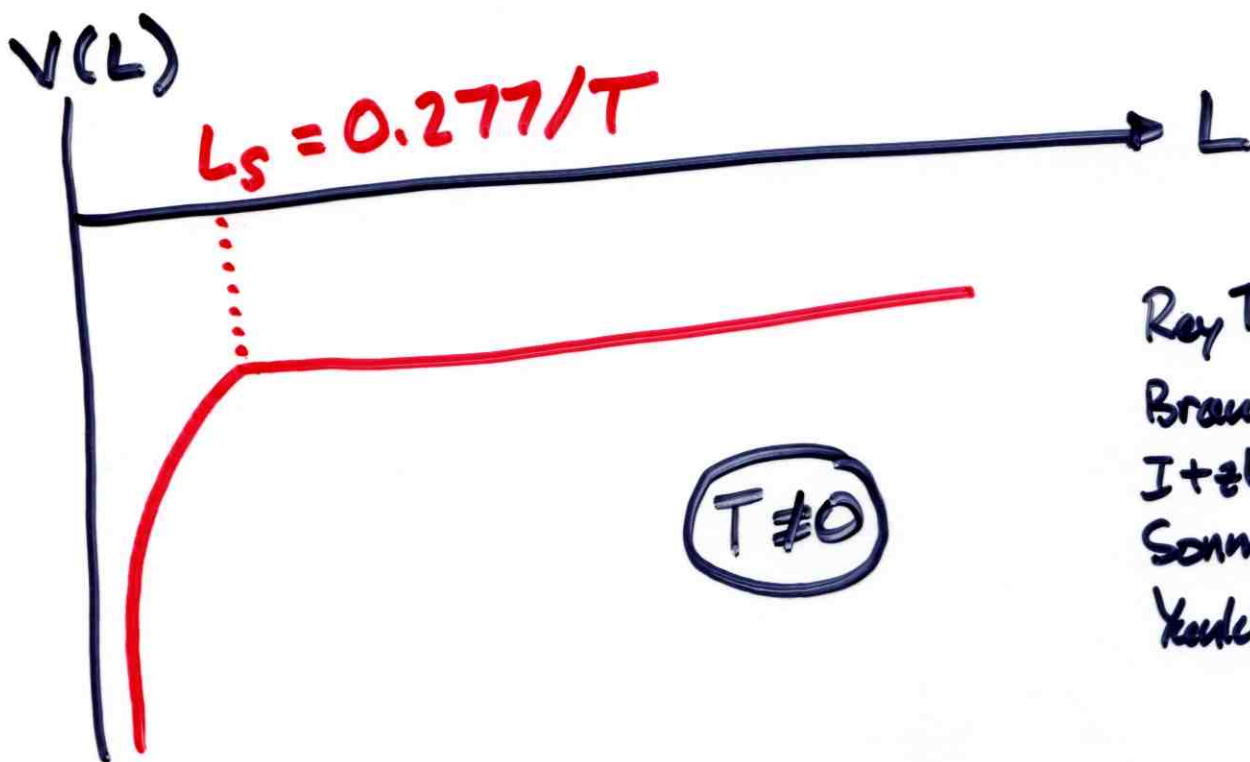
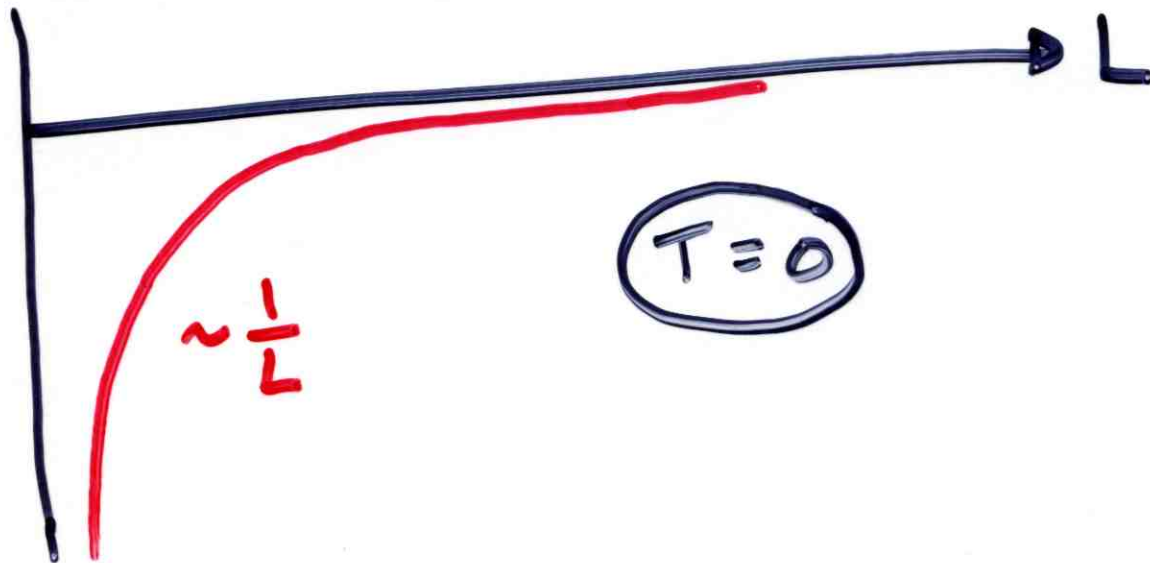
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# SCREENING IN $N=4$

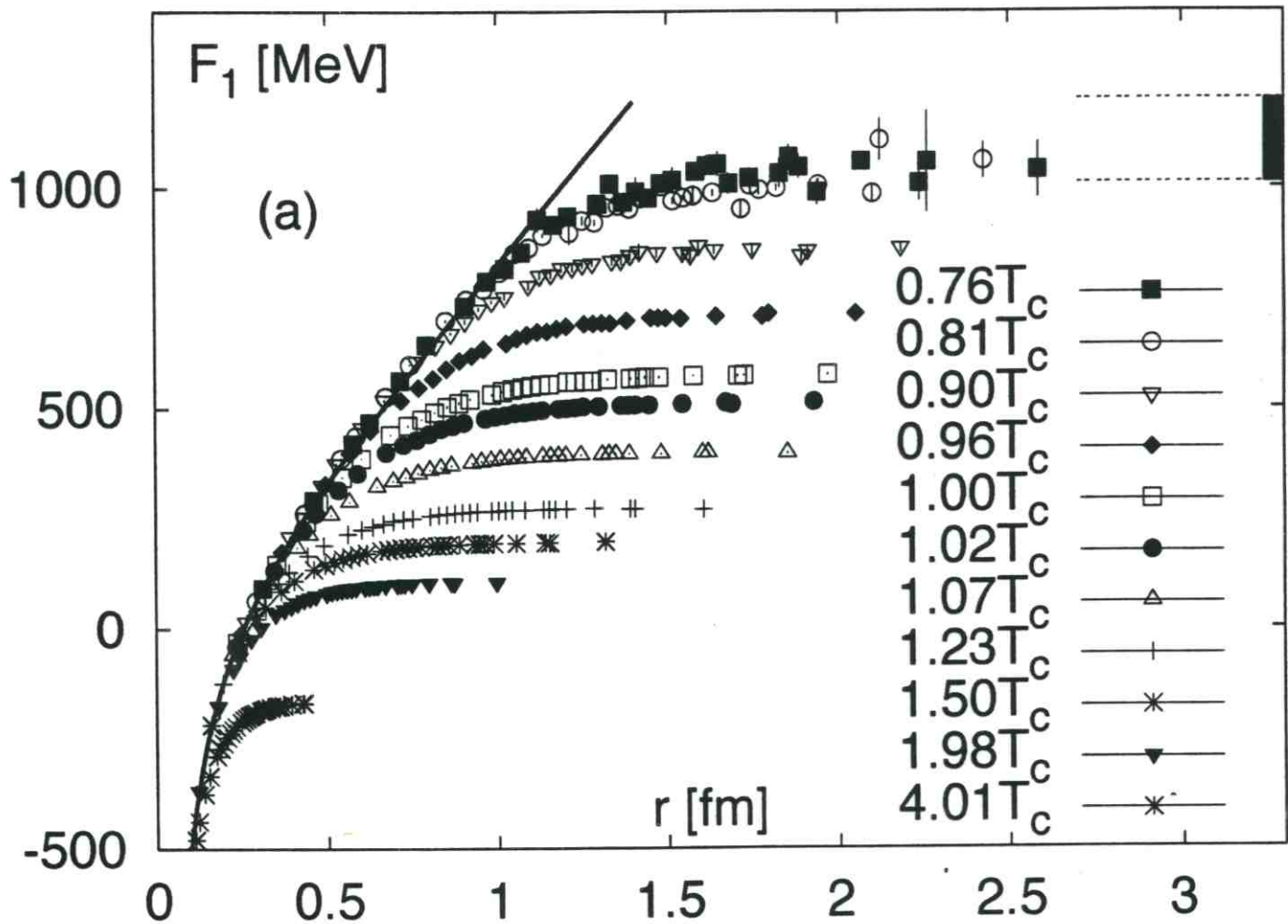
$V(L)$  = potential between static  $Q \leftrightarrow \bar{Q}$



Rey Theisen Yee,  
Brandhuber  
Itzhaki  
Sonnenschein  
Yuditskoye

Similar to screening in QCD above  
QCD's  $T_c$ ....

# SCREENING IN QCD



Kaczmarek, Zantow

lattice QCD calculation

[Unquenched.  $N_f = 2$ ]

Upon defining an  $L_s$ , the authors find  $L_s \sim 0.5/T$



# AdS/CFT

Malda cerna ; Witten ; Gubser  
Klebanov Polyakov, ....

$N=4$  SYM is equivalent to Type IIB

String theory on  $AdS_5 \times S^5$

4+1 "big" dimensions      5 curled up dimension

Translation Dictionary:

$N=4$  SYM gauge theory  
in 3+1 dim

String theory in  
4+1(+5) dim

$$\frac{g^2 N_c}{4\pi N_c}$$

=

$g_{\text{string}}$

$N_c \rightarrow \infty$  at fixed  $g^2 N_c$

means  $g_{\text{string}} \rightarrow 0$

$$\sqrt{g^2 N_c}$$

$$= R^2 / \alpha'$$

$R$ : AdS curvature

$\frac{1}{2\pi\alpha'}$ : string tension

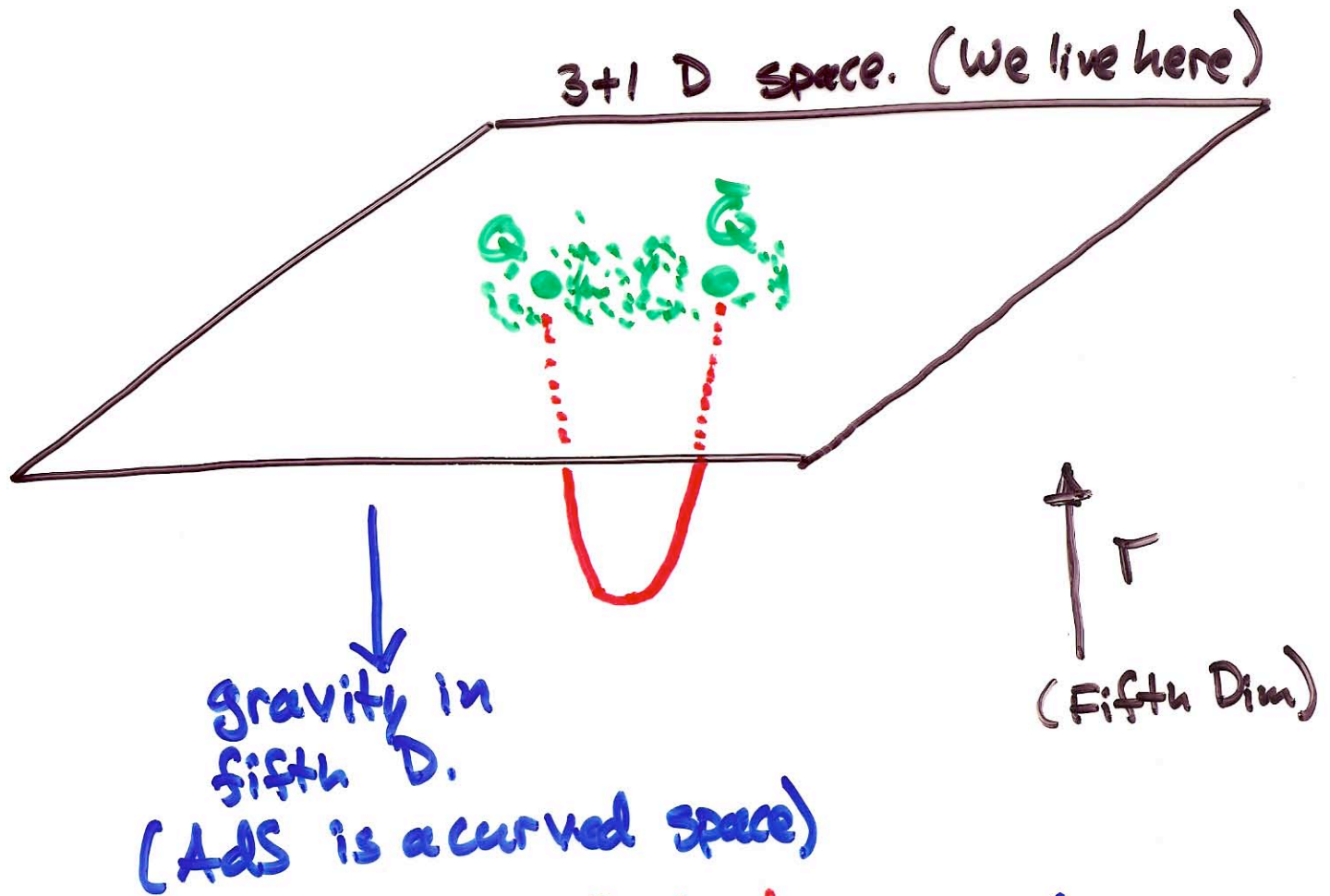
Heat the gauge  
theory to a  
temperature  $T$ .

$$= T_H = r_0 / \pi R^2$$

$r_0$ : location of BH  
horizon in fifth dim.

horizon in fifth dim.

How can strings in 5D describe, say, force between  $Q$  and  $\bar{Q}$  in a 4D gauge theory?

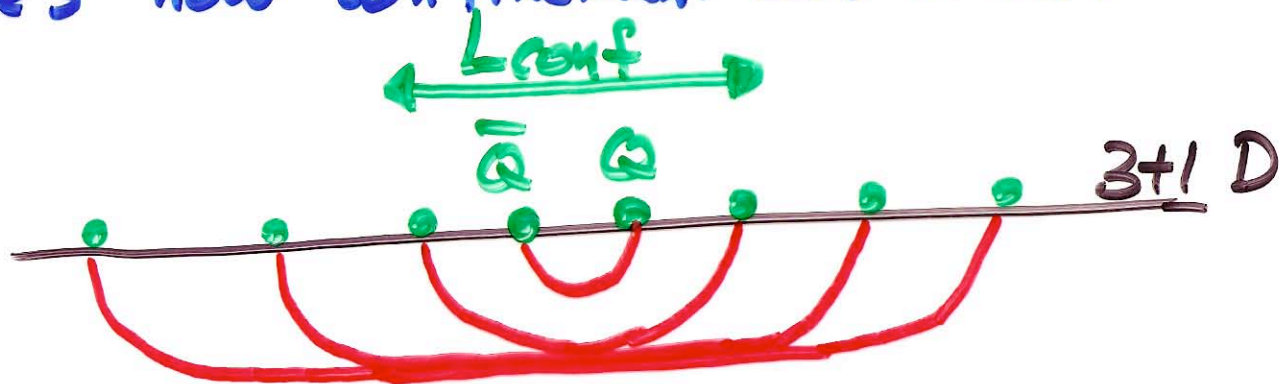


- Extremize energy of  $U$  string. (Like catenary problem, in unused gravitational field.)
  - Large  $g^2 N_c \rightarrow$  Large tension  $\rightarrow$  no fluctuation
  - Large  $N_c \rightarrow$  small  $g_{\text{string}} \rightarrow$  no loops break off.
- Force between  $Q$  and  $\bar{Q}$  =  $\frac{d}{d \text{ separation}}$  (Energy of string)



# CONFINEMENT?

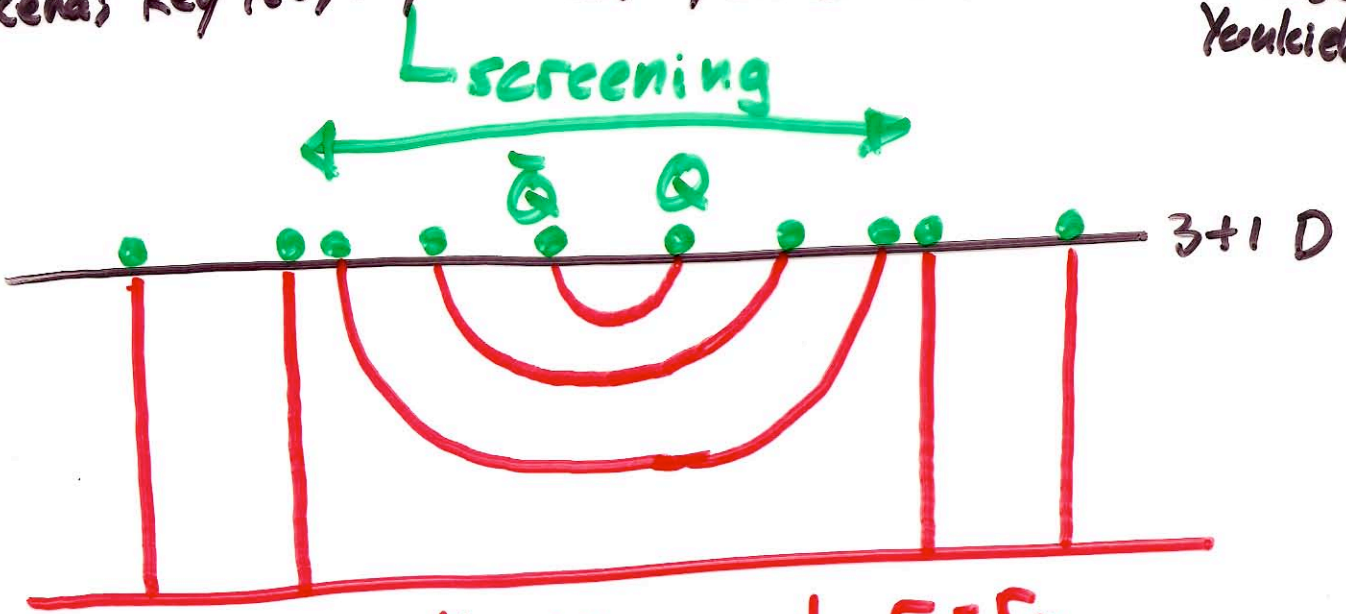
Here's how confinement can arise ....



- This does not happen in  $N=4$ 
  - shape of string stays same as  $L$  increases. ( $N=4$  is conformal)
- Confining gauge theories with dual descriptions like this are known.
- QCD not known to have a description like this.
- Don't use  $N=4$  as a guide to QCD at  $T=0$ .

# DECONFINEMENT AT $T \neq 0$

Maldacena; Rey Yee; Rey Theisen Yee; Brandhuber Itzhakei Sonnenschein Yonkei elang



Black Hole Horizon at  $r = r_0$

- For  $L < L_s$ , force between  $Q$  &  $\bar{Q}$ .
- For  $L > L_s$ , force is screened.  $Q$  &  $\bar{Q}$  deconfined.
- In  $N=4$  SUSY QCD,
 
$$L_s = \frac{0.277}{T}$$
- In QCD, force between static  $Q$  &  $\bar{Q}$  in QGP can be calculated. (Lattice QCD)
 

Can define  $L_s$ , though it is not a sharp boundary. Find:  $L_s \sim \frac{0.5}{T} \rightarrow \frac{0.7}{T}$  Kaczmarek, Karsch, Zantow, Petreczky
- $N=4$  gets this feature of the QCD strongly interacting QGP to within factor of 2!

# Dragging a Heavy Quark through Strongly Coupled Plasma

HKKKY, G, 2006

- One of the first holographic calculations related to *probing* strongly coupled plasma.
- To drag a heavy quark,  $M \rightarrow \infty$ , with constant velocity  $\vec{\beta}$  through the **static, homogeneous, equilibrium** strongly coupled plasma with temperature  $T$  of  $\mathcal{N} = 4$  SYM theory requires exerting a *drag force*:

$$\vec{f} = \frac{\sqrt{\lambda}}{2\pi} (\pi T)^2 \gamma \vec{\beta} \propto \frac{\vec{p}}{M}$$

with  $\lambda \equiv g^2 N_c$  the 't Hooft coupling.

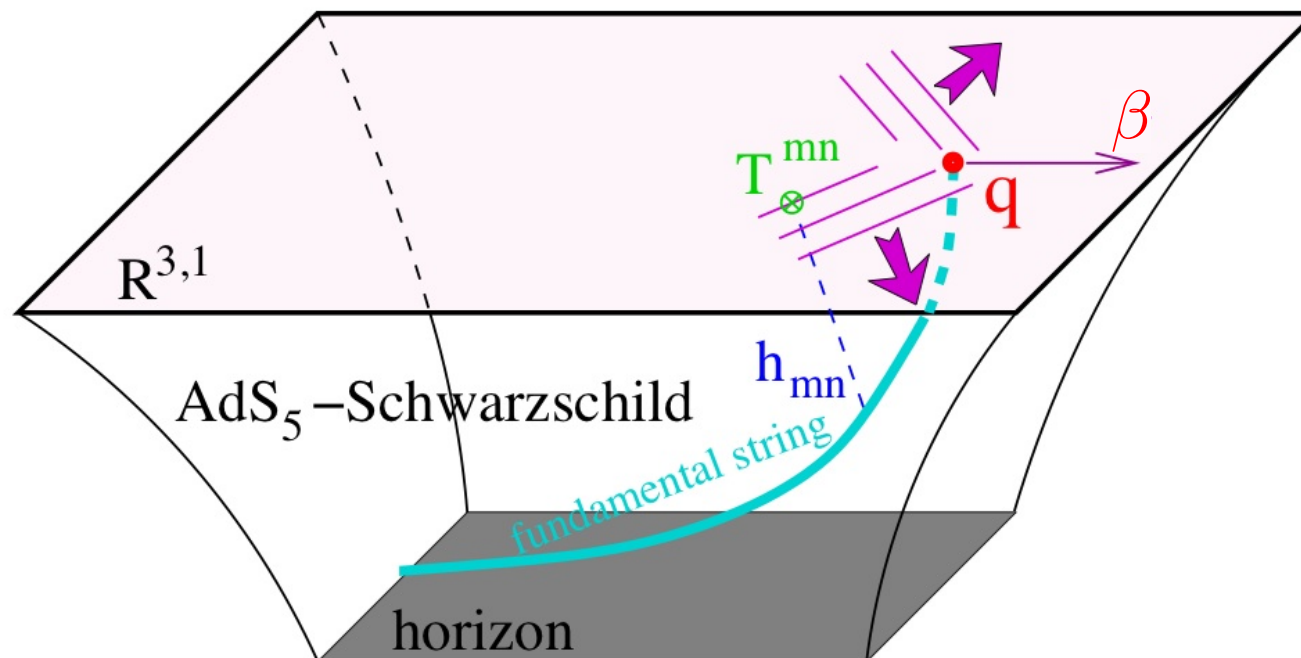
- *Caveat emptor*: At finite  $M$ , this picture only applies for

$$\sqrt{\gamma} \ll \frac{M}{T\sqrt{\lambda}} .$$

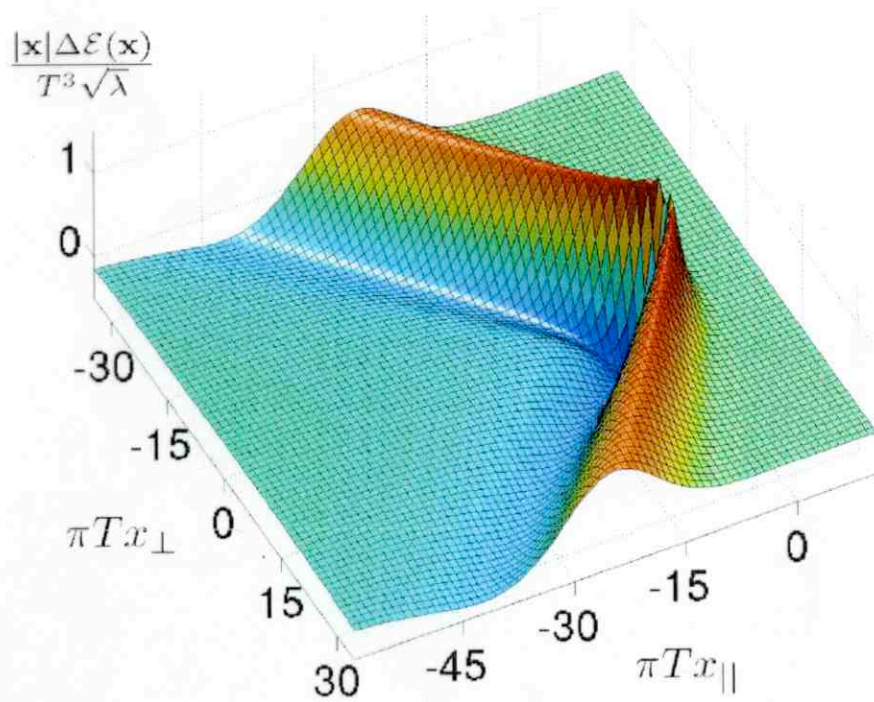
Eg for  $b$  quarks at the LHC validity is  $p_T \lesssim 20 - 40$  GeV.  
Higher  $p_T$  heavy quarks behave like light quarks.

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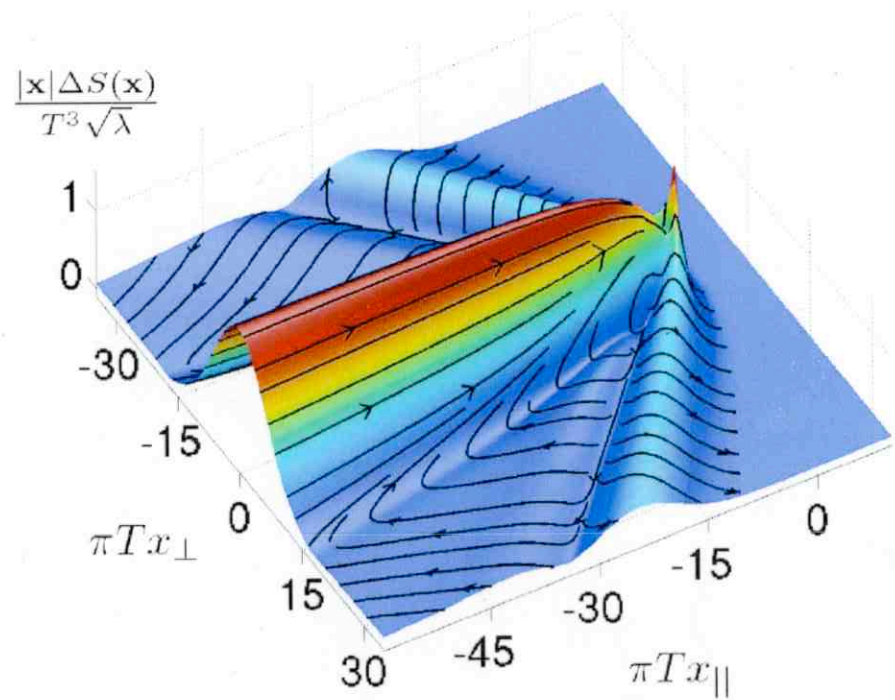
HKKKY, G, 2006







Energy density.  
 Nb: Specific heat  $\propto Nc^2$  amplifies effect of heat over motion in  $\mathcal{E}$ .  
 So, this plot tells you where there is heating. I.e. compression.  
 I.e. SOUND.



Momentum flow.  
 Mach cone and wake.

Chesler + Yaffe



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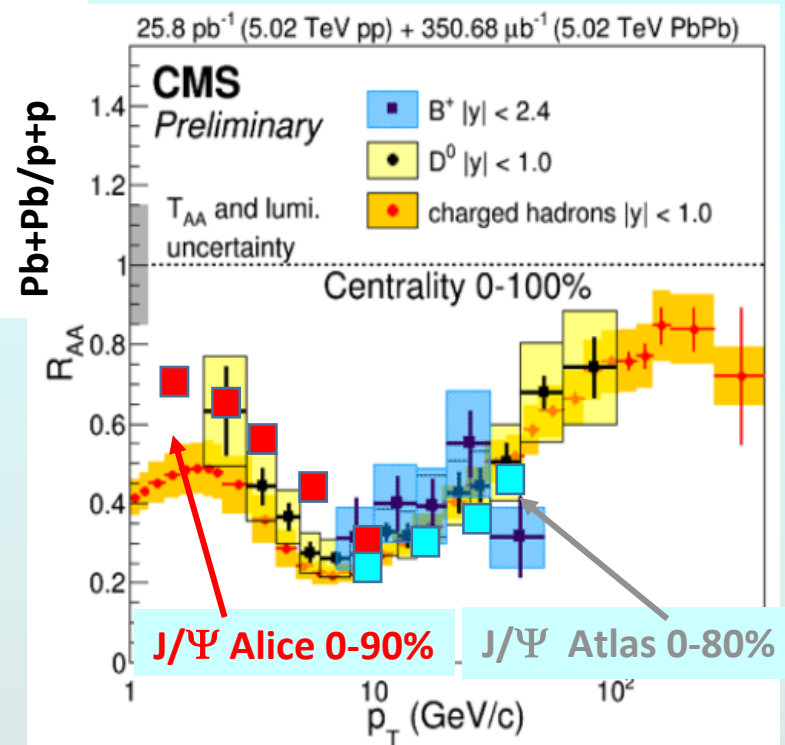
Eg for  $b$  quarks at the LHC validity is  $p_T \lesssim 20 - 40$  GeV.  
Higher  $p_T$  heavy quarks behave like light quarks.

# An astounding result!

Even more surprising  
than you might think...



Even  $b$  quarks  
lose energy!



# Heavy Quark Drag and Diffusion in Strongly Coupled Plasma

HKKKY, G, C-Y&T 2006

- Under the same conditions as on the previous slide, heavy quark in strongly coupled plasma satisfies:

$$\frac{dp}{dt} = -\eta_{\text{drag}} p + \xi(t) \quad \langle \xi(t), \xi(t') \rangle = \kappa \delta(t - t')$$

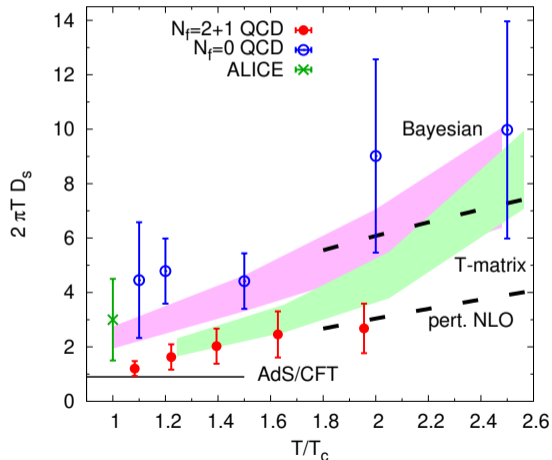
where

$$\eta_{\text{drag}} = \frac{\pi \sqrt{\lambda} T^2}{2M} \quad D \equiv \frac{2T^2}{\kappa} = \frac{4}{\sqrt{\lambda}} \frac{1}{2\pi T} \quad \kappa = 2MT\eta_{\text{drag}}$$

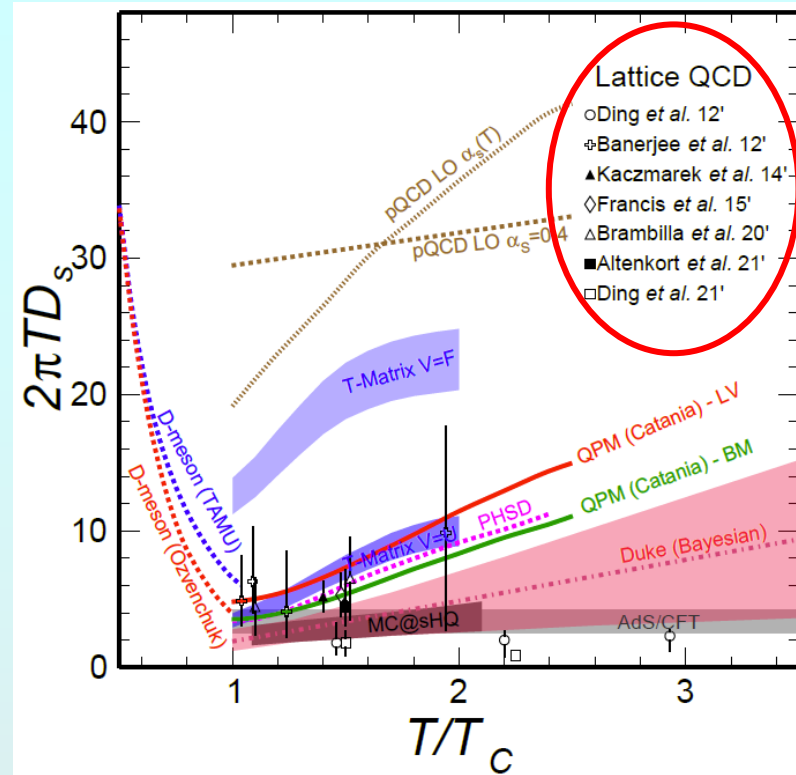
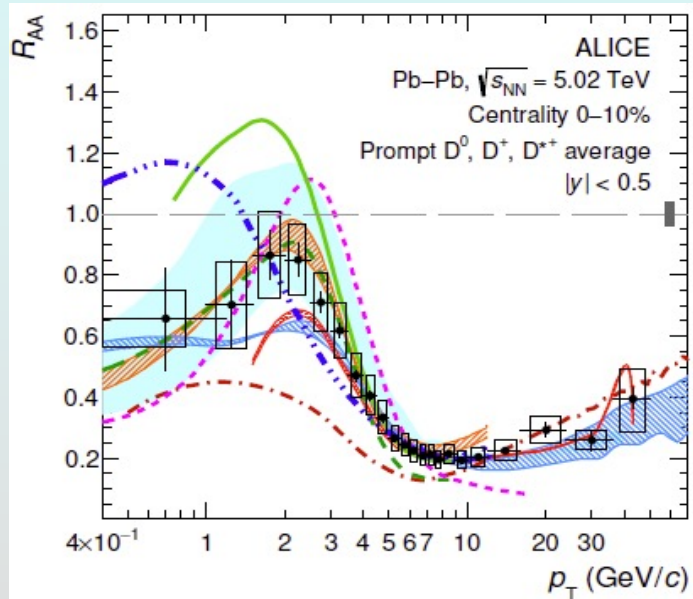
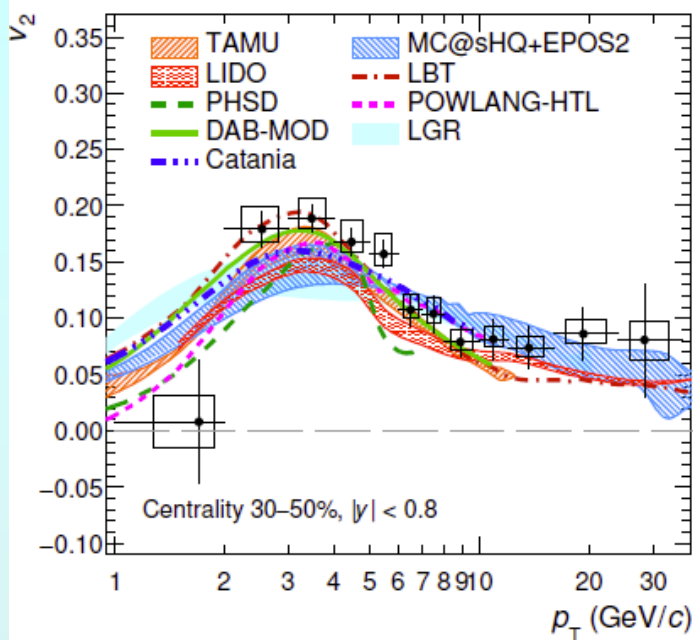
- So, the calculation of the drag force is at the same time a calculation of the heavy quark diffusion constant  $D$ . And, for  $\lambda \simeq 12.6$  (the value we used several slides ago) the diffusion constant in strongly coupled plasma is  $D \simeq 1.1/(2\pi T)$ .
- This fifteen year old result agrees *surprisingly well* with contemporary lattice calculations of  $D$  in QGP. The extraction of  $D$  from heavy ion collision data, see Barbara's lectures, is broadly consistent with this also.

- Results for  $D_s = 2T^2/\kappa$  shows lower than quenched behavior

- $6D_s$  is the mean distance squared traveled by unit time
- T-Matrix results updated compared to figure in paper, R. Rapp et al. [arxiv:1612.09318][arxiv:1711.03282]



# Heavy quark diffusion from D meson $v_2$ and $R_{AA}$



Again use data + models together:  
radiation, collisions, medium evolution

$$D_s(2\pi T) = 1.5 - 4.5 \text{ near } T_c$$

per models with  $\chi^2/\text{DOF} < 5$  (2)

for  $R_{AA}(v_2)$

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HKKKY, G, C-Y&T 2006

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where

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- Perhaps best to focus on a striking qualitative feature:

$$\frac{dp}{dt} \propto \frac{p}{M}$$

which is inevitable at strong coupling, and not the case at weak coupling. Energy loss of a 20 (or 10 or 5) GeV bottom quark same as energy loss of 6 (or 3 or 1.5) GeV charm quark. This qualitative feature has not been tested against data, and should be...



# $\hat{q}$ in $\mathcal{N} = 4$ SYM Plasma

Liu, KR, Wiedemann 2006

- The jet quenching parameter, featured in Barbara's lectures, can also be calculated exactly in holographic theories, in the  $N_c^2 \rightarrow \infty$ ,  $\lambda \rightarrow \infty$  limit. (The calculation involves computing the expectation value of a certain Wilson loop with two light-like sides.) The result is:

$$\hat{q} = \frac{\pi^{3/2} \Gamma(5/4)}{\Gamma(3/4)} \sqrt{\lambda} T^3 = 4.12 \sqrt{\lambda} T^3$$

- If we again take  $\lambda \approx 12.6$  this yields  $\hat{q} \approx 14.6 T^3$ . This fifteen year old result is about three times larger than that estimated for QGP in QCD – not unreasonable.
- $\hat{q}$  is *not* proportional to  $s$  or to the number density of scatterers, as at weak coupling. Such quantities are  $\propto N_c^2 T^3$ , and  $\hat{q} \propto \sqrt{\lambda} T^3$  in strongly coupled plasma.
- Reminds us that strongly coupled holographic liquids have no well-defined quasiparticles, so  $\hat{q}$  cannot count the density of such.

# INSIGHTS I DESCRIBED / SKETCHED

- ① Thermodynamics within 15-25% of that at zero coupling arises at strong coupling.
- ②  $\eta/s = 1/4\pi$ , in  $N_c^2 \rightarrow \infty, \lambda \rightarrow \infty$  limit, for plasma of any gauge theory with a gravity dual.  
 $\eta/s$  in QCD plasma (lattice; RHIC) and for unitary cold atom gas seems comparable.
- ③  $\hat{q} \propto \sqrt{\frac{s}{N_c^2 T^3}} \sqrt{\lambda} T^3$  for an infinite class of strongly coupled plasmas. Jet quenching does not count gluons; all multiple gluon correlations equally important.  
 $\hat{q} \sim 3-5 \text{ GeV}^2/\text{fm}$  at  $T=300 \text{ MeV}$ .  $\frac{\hat{q}_{\text{LHC}}}{\hat{q}_{\text{RHIC}}} \sim \frac{(dN/d\eta)_{\text{LHC}}}{(dN/d\eta)_{\text{RHIC}}}$
- ④ In a strongly coupled plasma, heavy POINT-LIKE quarks drag, diffuse, and excite a Mach cone.
- ⑤ Heavy quarkonia mesons, bound above  $T_c$ , dissociate at lower temperatures when moving.  $T_{\text{diss}}(v) \approx T_{\text{diss}}(0) (1-v^2)^{1/4}$   
Also for heavy quark baryons.



# WHAT ARE WE LEARNING?

- Qualitative, and semi-quantitative, insights and predictions regarding properties of strongly interacting quark-gluon plasma
- String theory useful as a source of new calculational techniques, opening previously intractable regimes.
- Perhaps QGP in QCD at  $T \sim \text{few } T_c$  is "close to", or maybe even is, equivalent to a string theory in a curved 4+1 dimensional spacetime containing a black hole. Is there a precise sense of universality here?
- Could successes of this approach to RHIC data hint that QCD is equivalent to a string theory????