Novel Probes of the Primordial Liquid

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CERN TH Colloquium

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Heavy Ion Collisions. . .

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

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

All great discoveries pose new challenges. This talk will be about some recent advances and the challenges for the decade to come., But first, the Intro to the talk will be vintage 2015. . .

Quark-Gluon Plasma

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

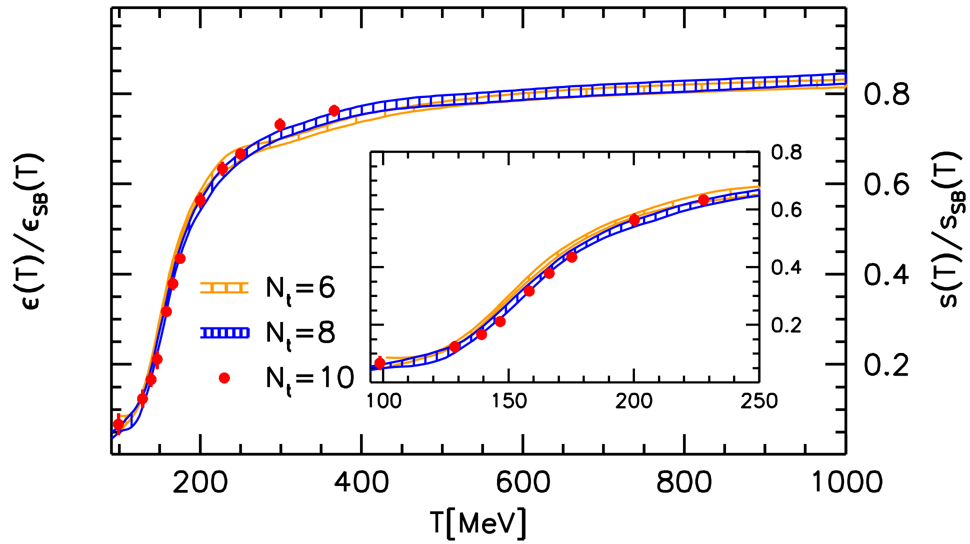
- Asymptotic freedom tells us that, for $T \to \infty$, QGP must be weakly coupled quark and gluon quasiparticles.

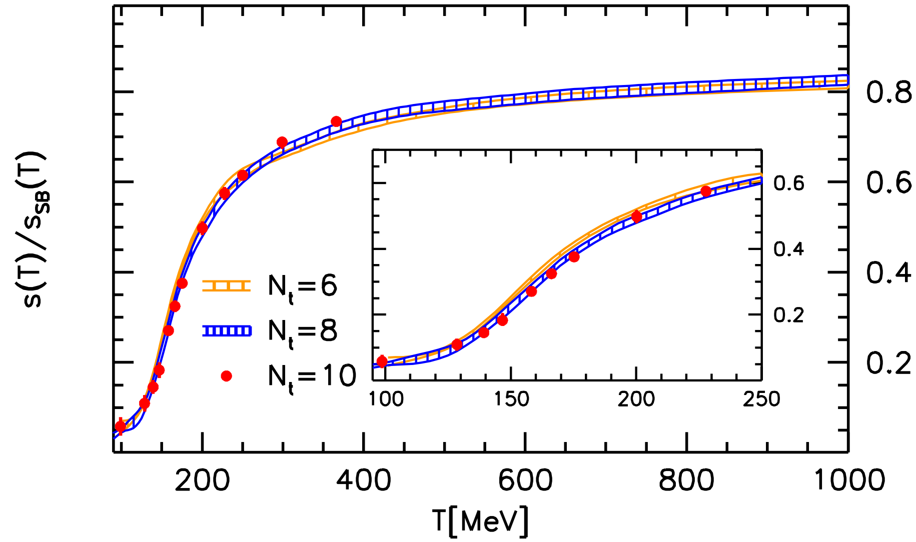
- Lattice calculations of QCD thermodynamics reveal a smooth crossover, like the ionization of a gas, occurring in a narrow range of temperatures centered at a $T_c \simeq 150$ MeV $\simeq 2$ trillion °C $\sim$ 20 μs after big bang. At this temperature, the QGP that filled the universe broke apart into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

- Heavy ion collisions produce droplets of QGP at temperatures several times T_c, reproducing the stuff that filled the few-microseconds-old universe.

QGP Thermodynamics on the Lattice

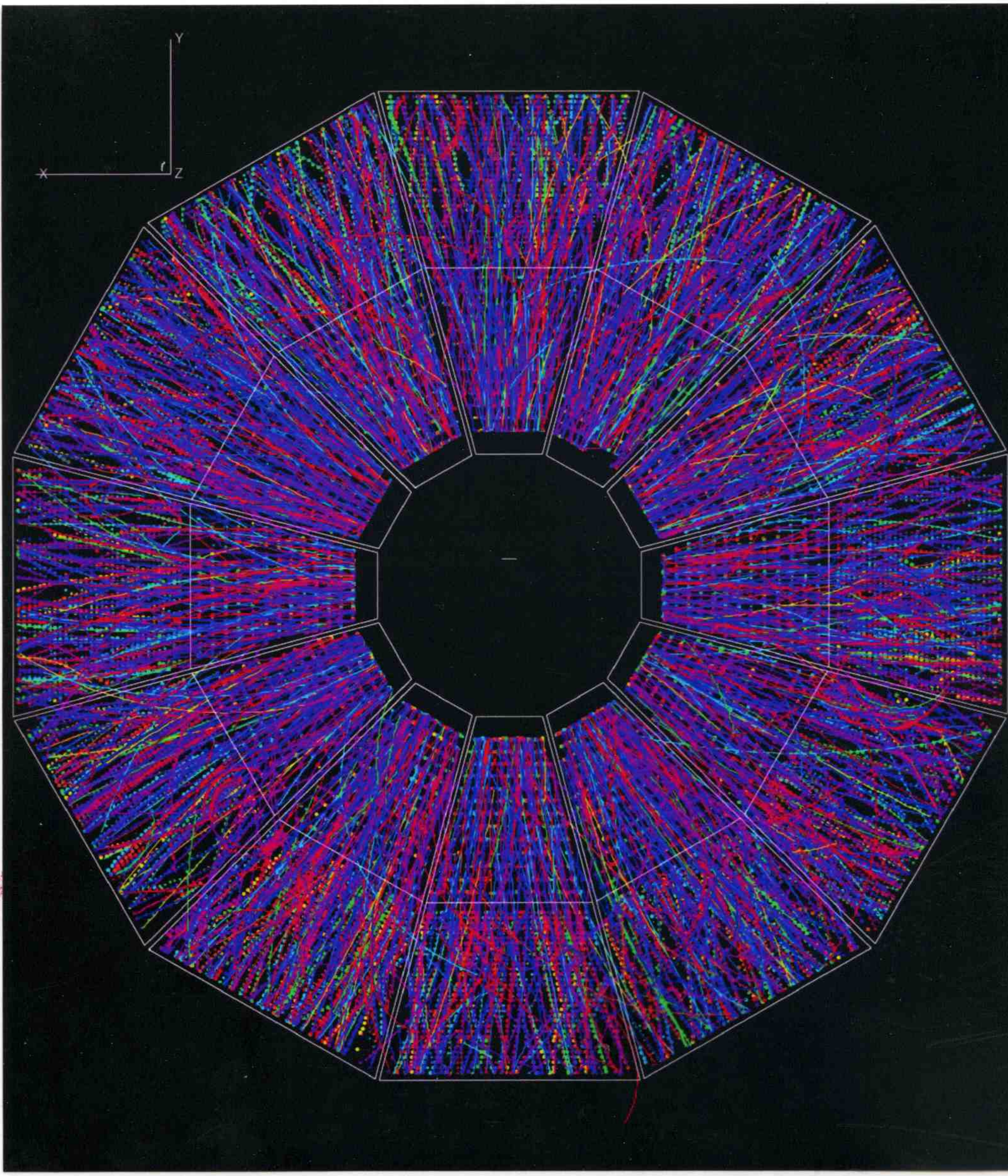
Endrodi et al, 2010





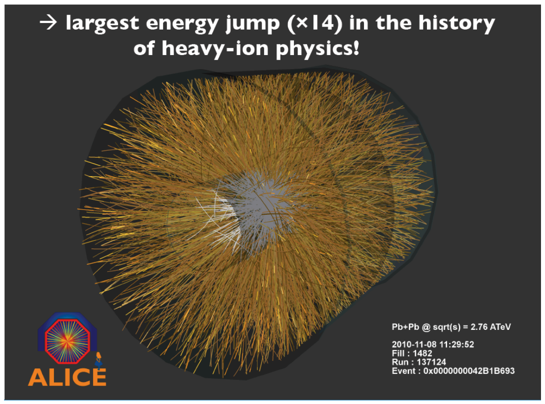
Above $T_{\text{crossover}} \sim$ 150-200 MeV, QCD = QGP. QGP static properties can be studied on the lattice.

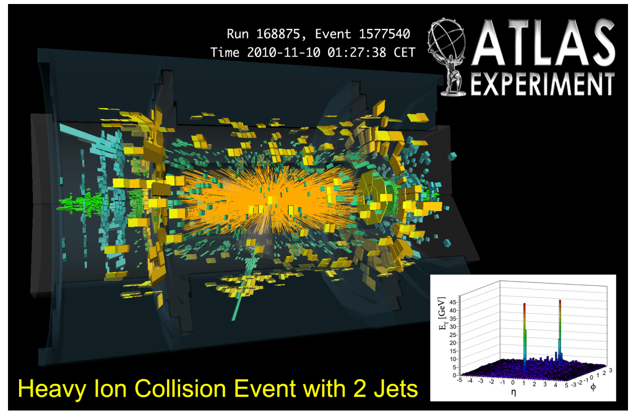
BUT: don't try to infer dynamic properties from static ones! Although its thermodynamics is almost that of ideal, noninteracting gas, QGP, this stuff is very different in its dynamical properties. [Lesson from experiment+hydrodynamics. But, also from the large class of gauge theories with holographic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



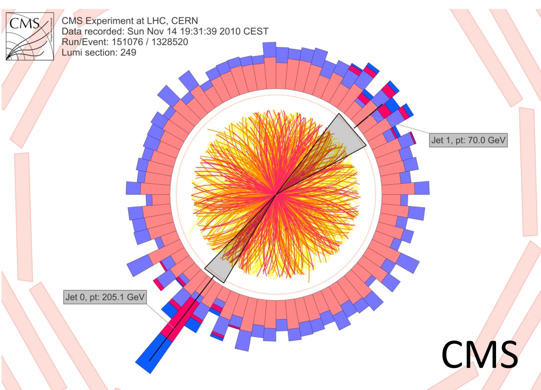
STAR

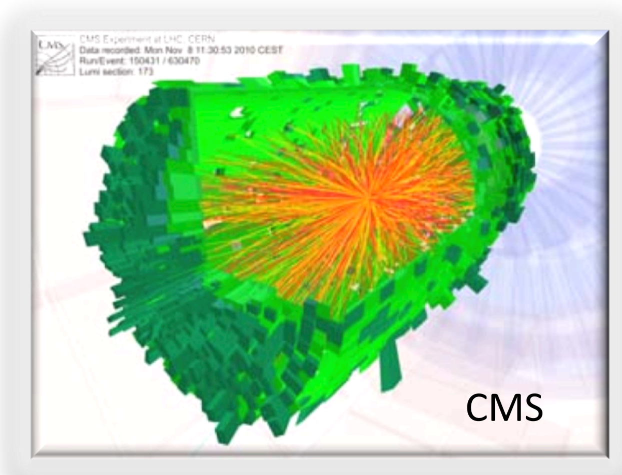
Nov 2010 first LHC Pb+Pb collisions





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





Integrated Luminosity = 10 μb^{-1}

Liquid Quark-Gluon Plasma

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

- 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 η/s comparably small to that of QGP.

- NanoKelvin temperatures, instead of TeraKelvin.

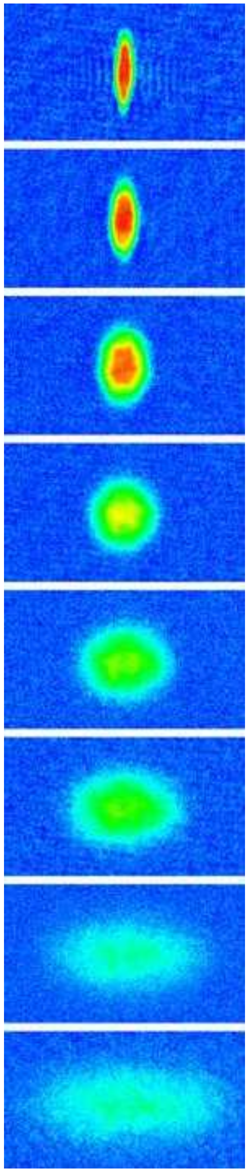
- Ultracold cloud of trapped fermionic atoms, with their two-body scattering cross-section tuned to be infinite. A strongly coupled liquid indeed. (Even though it's conventionally called the "unitary Fermi gas".)

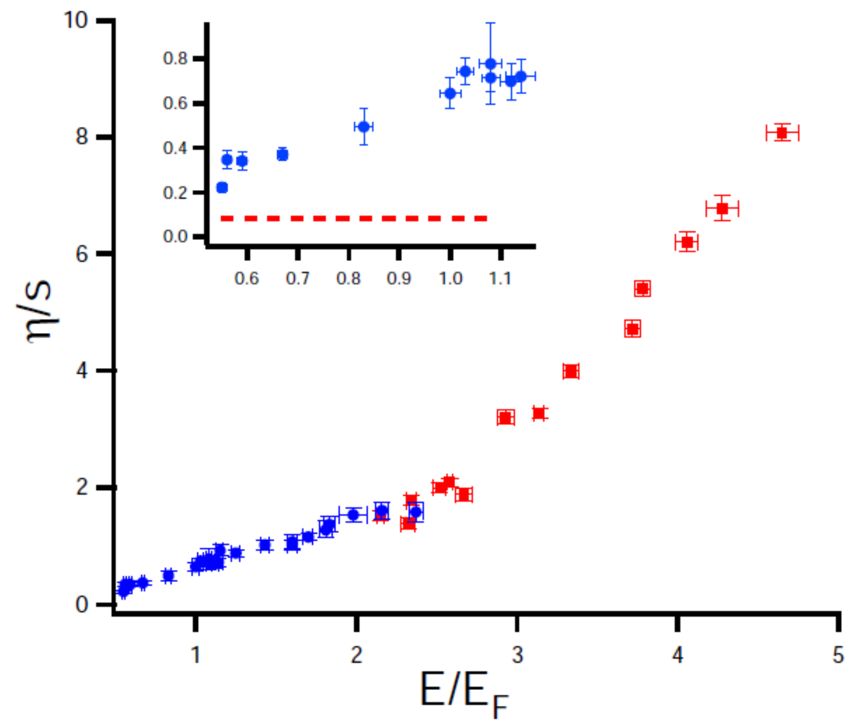
- Data on elliptic flow (and other hydrodynamic flow patterns that can be excited) used to extract η/s as a function of temperature...

Viscosity to entropy density ratio

consider both collective modes (low T)

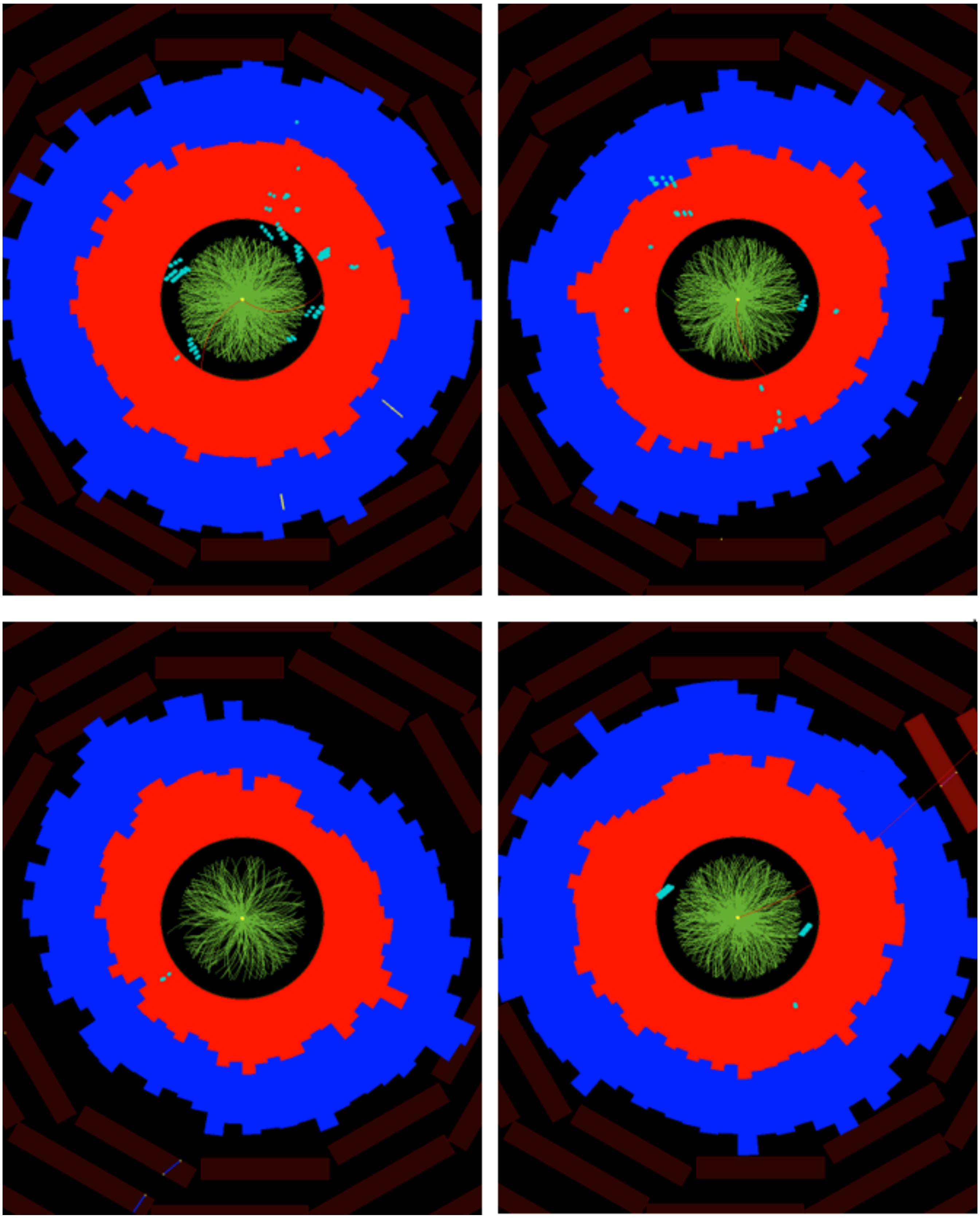
and elliptic flow (high T)





Cao et al., Science (2010)

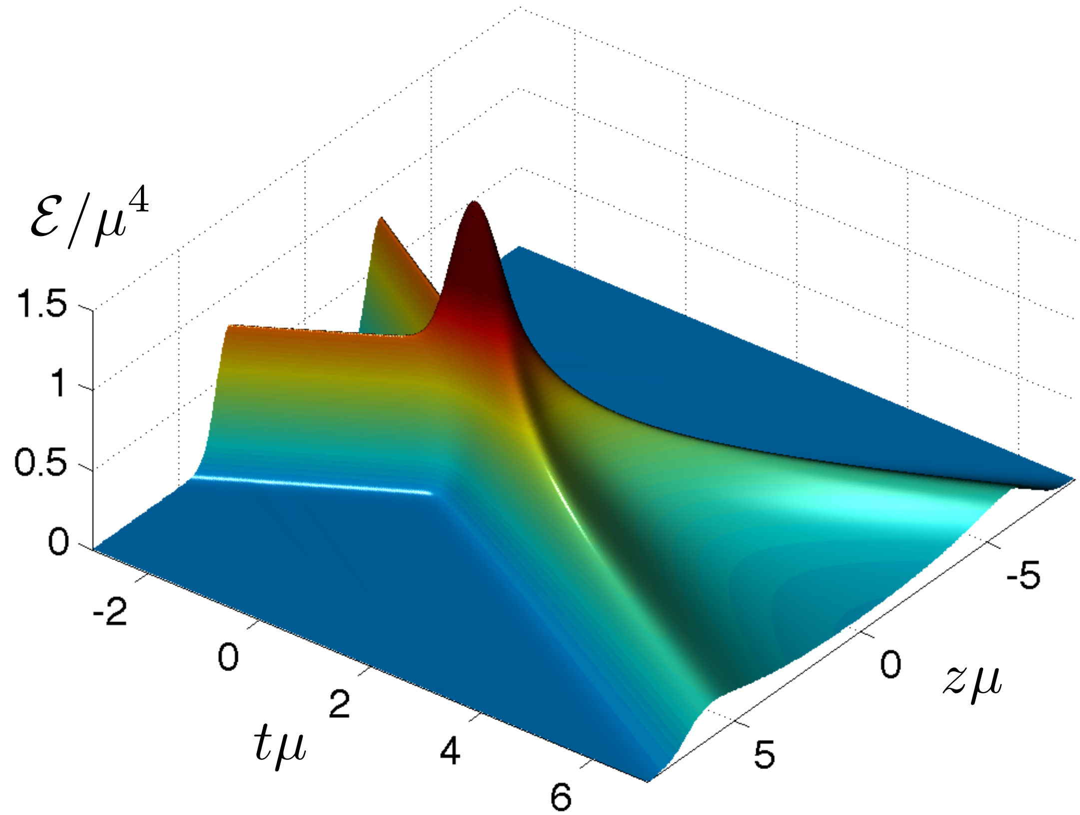
$$\eta/s \leq 0.4$$



Rapid Equilibration?

- **Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.**
- **Long-standing estimate is that a hydrodynamic description must already be valid only 1 fm/c after the collision.**
- **This is the time it takes light to cross a proton, and was long seen as** *rapid equilibration*.
- **But, is it really? How rapidly does equilibration occur in a strongly coupled theory?**

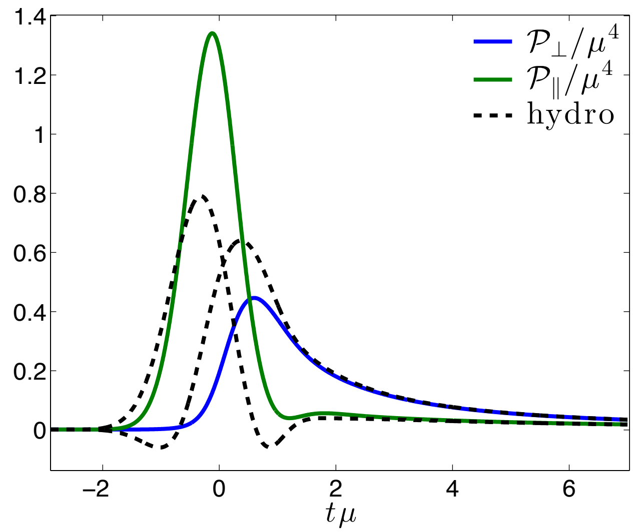
Colliding Strongly Coupled Sheets of Energy



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

This was the best answer we had circa 2015.

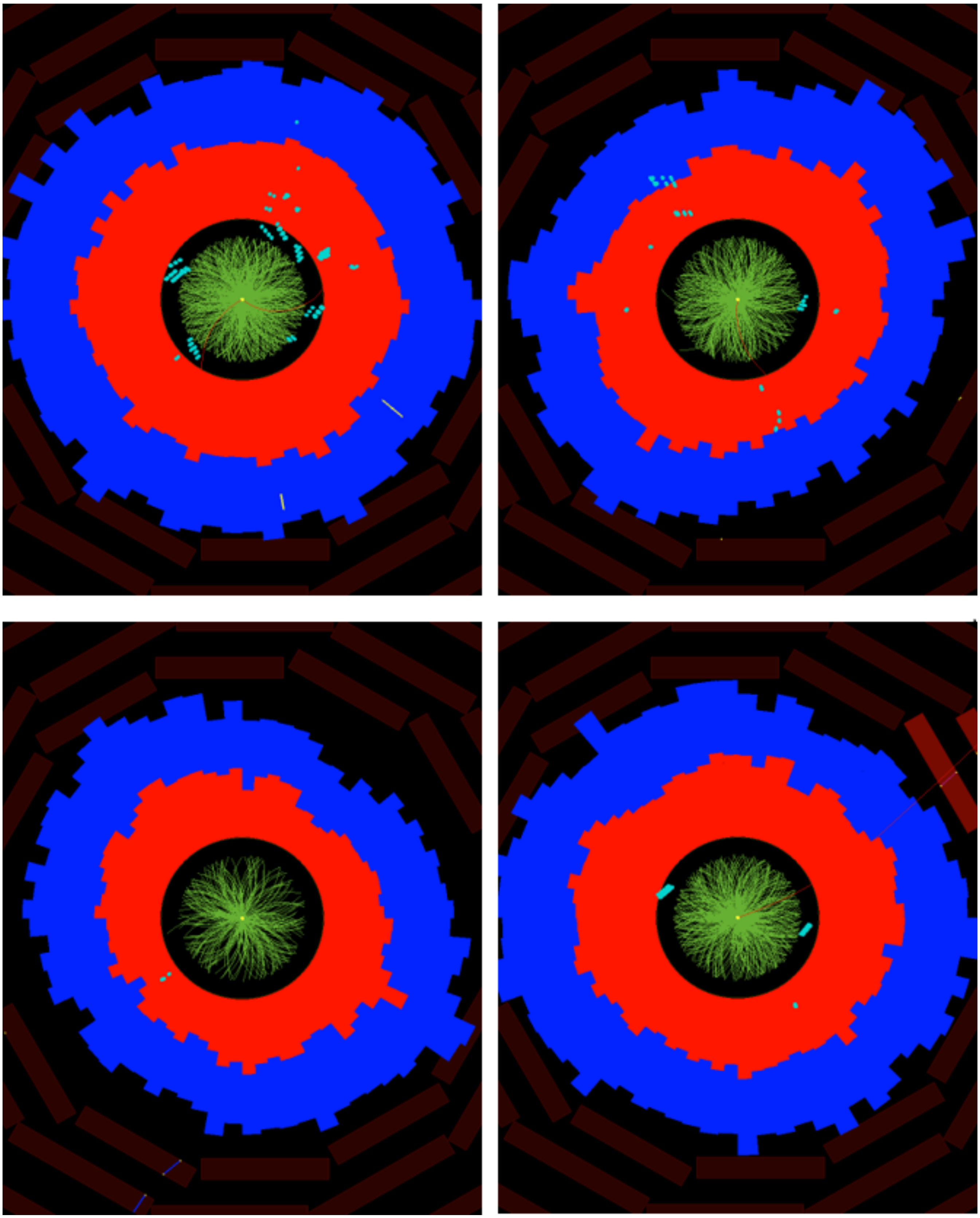
Anisotropic Viscous Hydrodynamics



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.

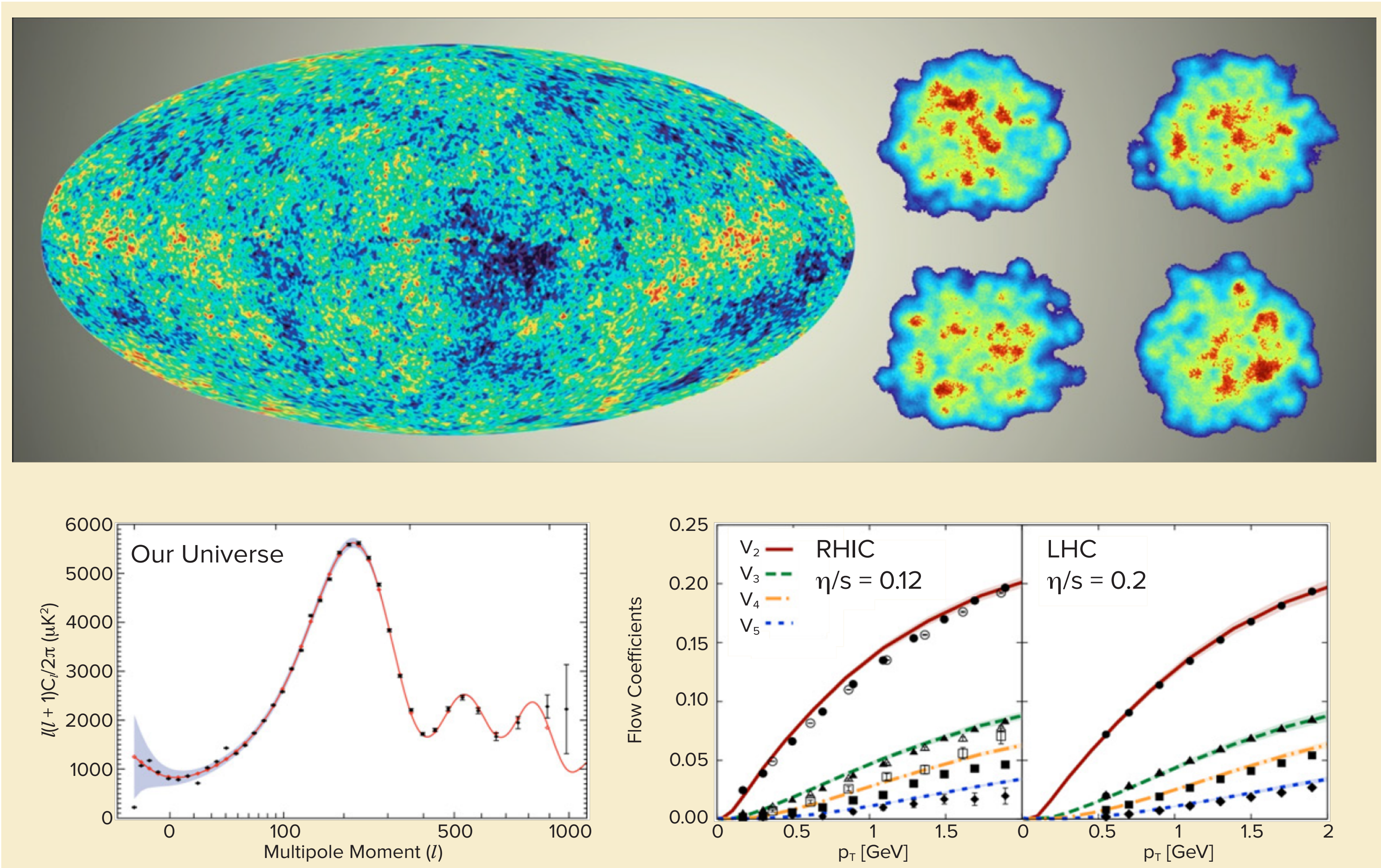
This has now been seen in very many strongly coupled analyses of hydrodynamization. Janik et al., Chesler et al., Heller et al., ...

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



η/s from RHIC and LHC data

- **I have given you the beginnings of a story that has played out over the past decade. I will now cut to the chase, leaving out many interesting chapters and oversimplifying.**
- **Using relativistic viscous hydrodynamics to describe expanding QGP,** *produced in an initially lumpy heavy ion collision*, **using microscopic transport to describe late-time hadronic rescattering, and using RHIC and LHC data on pion and proton spectra and** v_2 *and* v_3 *and* v_4 *and* v_5 *and* v_6 $\ldots$ **as functions of** p_T **and impact parameter...**
- **QGP@RHIC, with** $T_c < T \lesssim 2T_c$**, has** $1 < 4\pi\eta/s < 2$ **and QGP@LHC, with** $T_c < T \lesssim 3T_c$ **has** $1 < 4\pi\eta/s < 3$**.**
  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.**



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

QGP cf CMB

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

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

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

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

Beyond Quasiparticles

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

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

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

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

η/s from RHIC and LHC data

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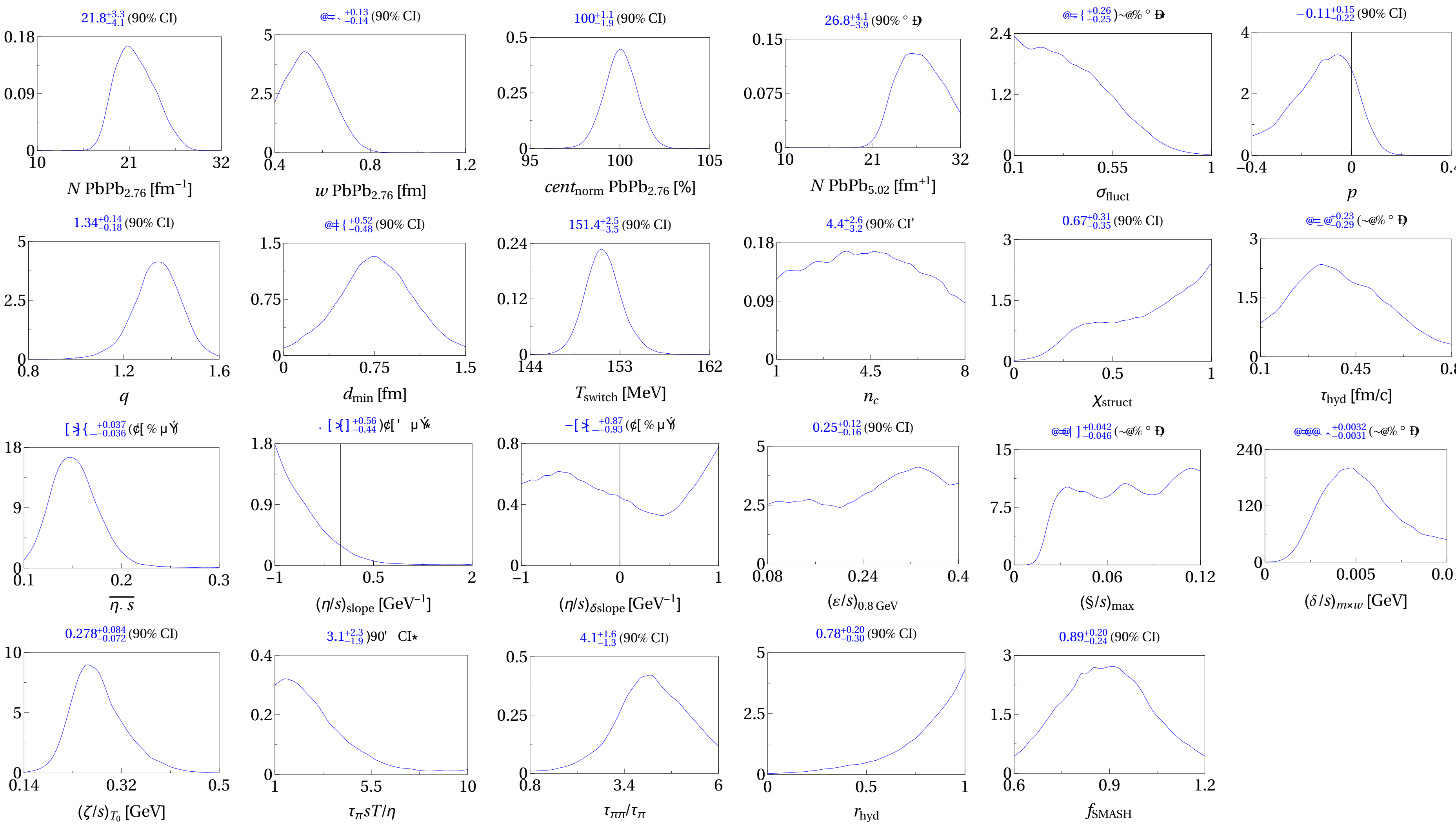
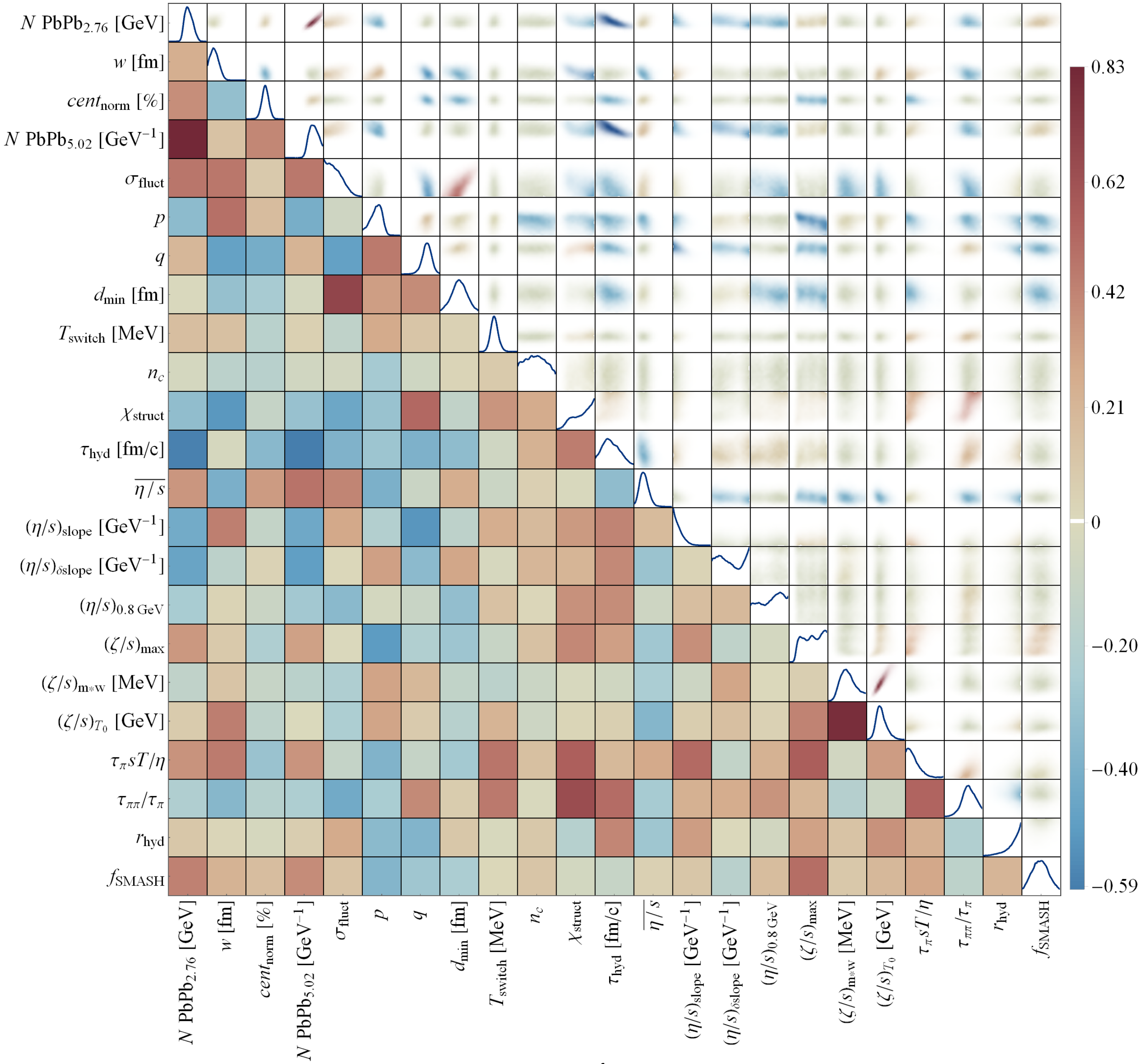
Eg. of Today’s State of the Art



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

Eg. of Today's State of the Art



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

Determination of the neutron skin of ^{208}Pb from ultrarelativistic nuclear collisions

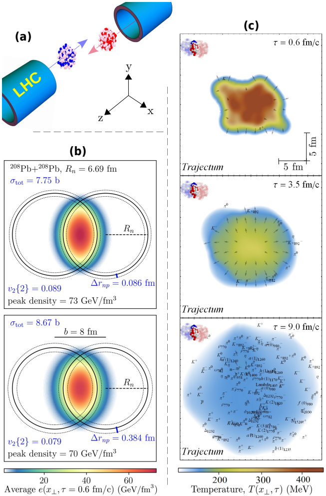
Govert Nijs

September 6, 2023

Based on:

- Giacalone, GN, van der Schee, 2305.00015

How to measure neutron skin?

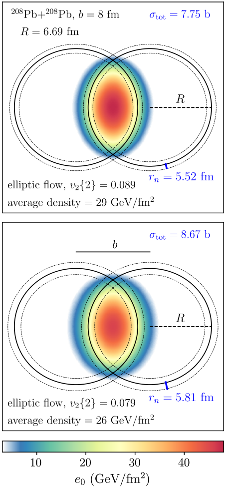


- To measure the neutron skin, we need the distributions of protons and neutrons inside the nucleus.
  - The proton distribution distribution is well-known from electron scattering.
- Several different methods are in use for the neutron distribution:
  - Polarized electron scattering off ^{208}Pb (PREX).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

CERN

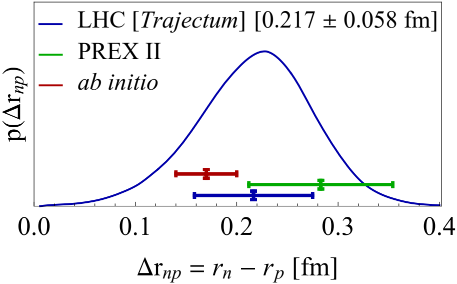
Do we have observables sensitive to a_n?

- 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 Δr_{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

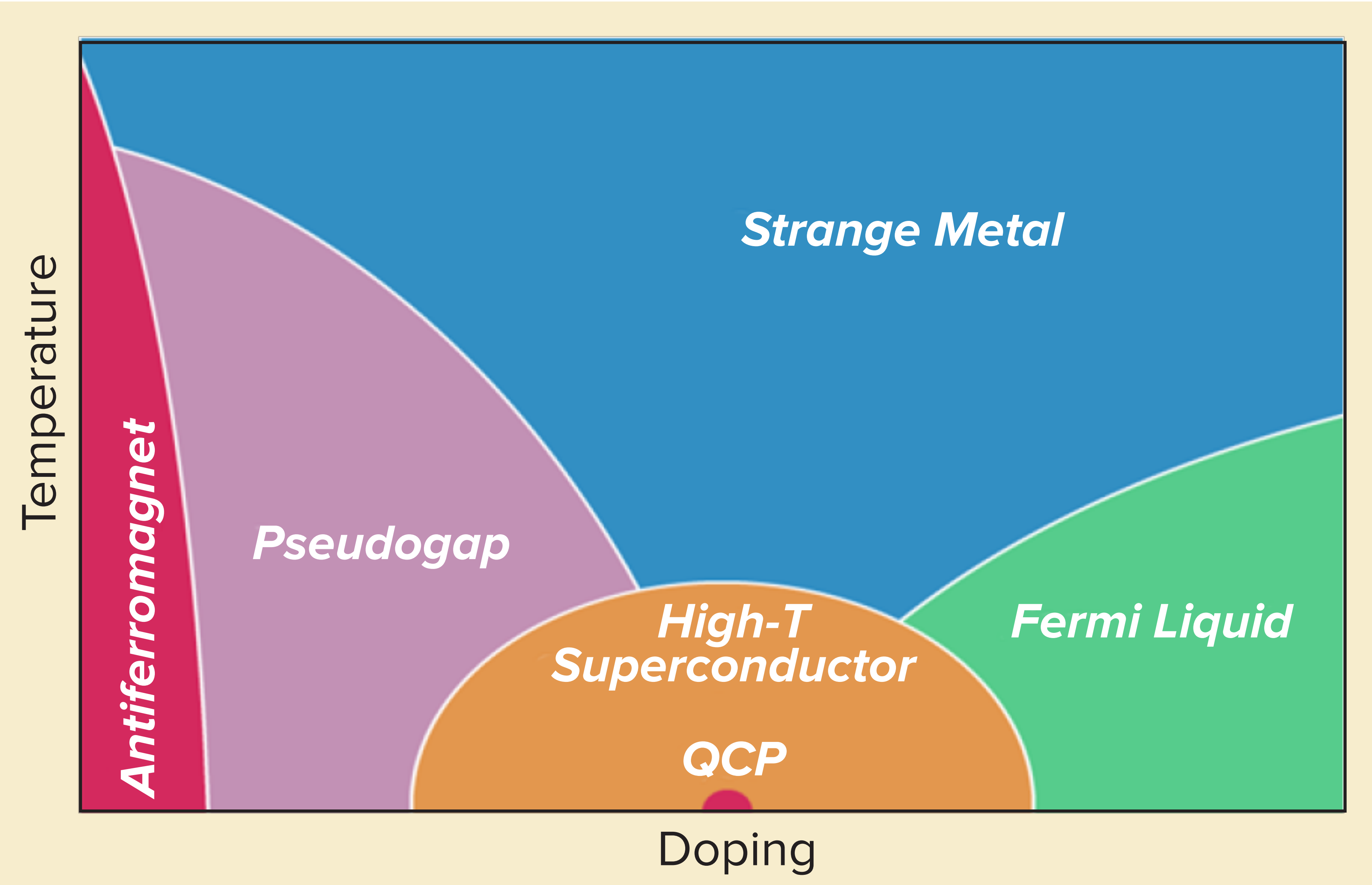
- Resulting posterior for Δr_{np} is compatible with PREX II and ab initio nuclear theory.
- Slightly stronger constraint than PREX II ($\Delta r_{np} = 0.283 \pm 0.071$).
- Result is in principle improvable with better Bayesian analyses.
  - May be hard to do in practice.
  - The current analysis already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

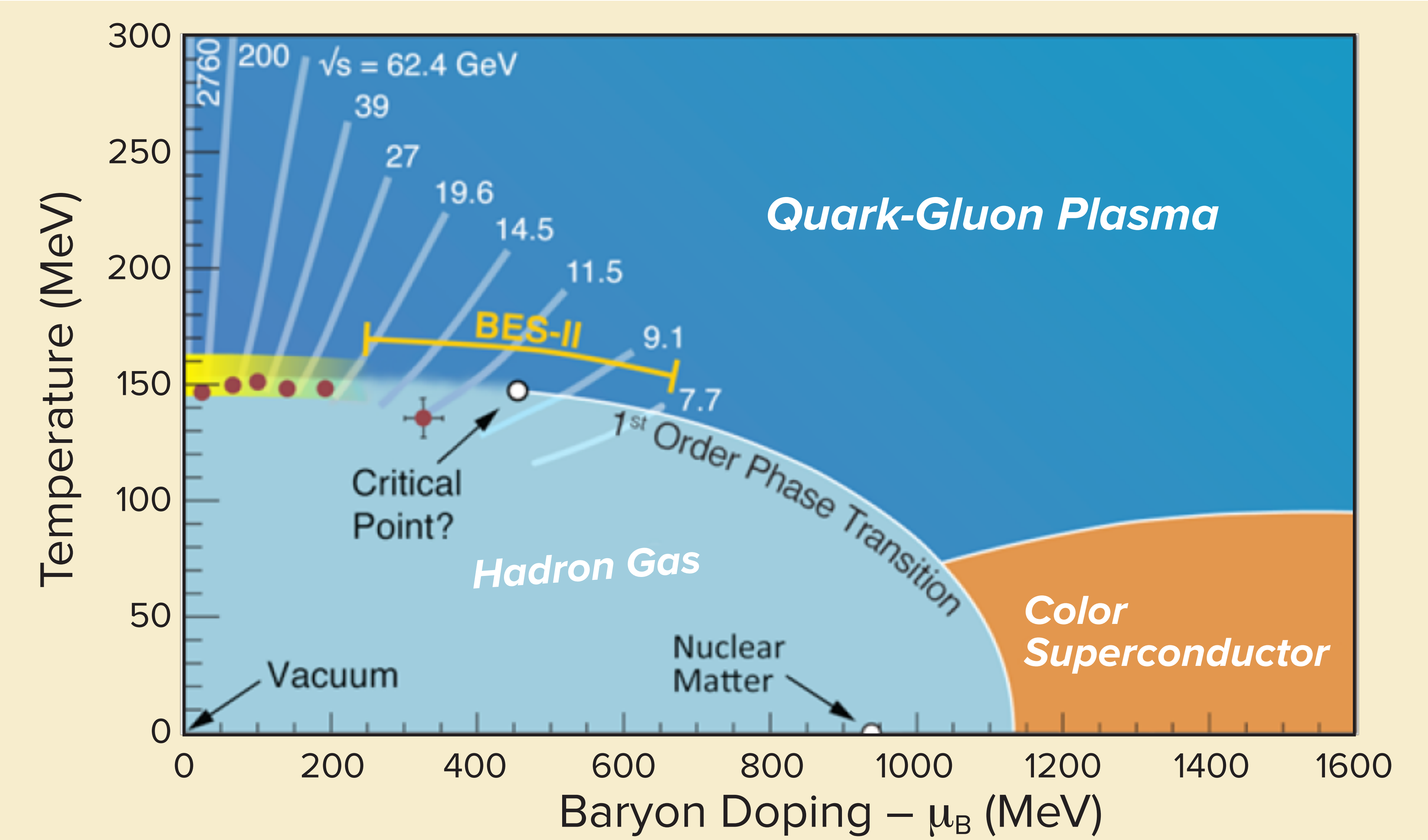


What Next?

Two kinds of What Next? questions . . .

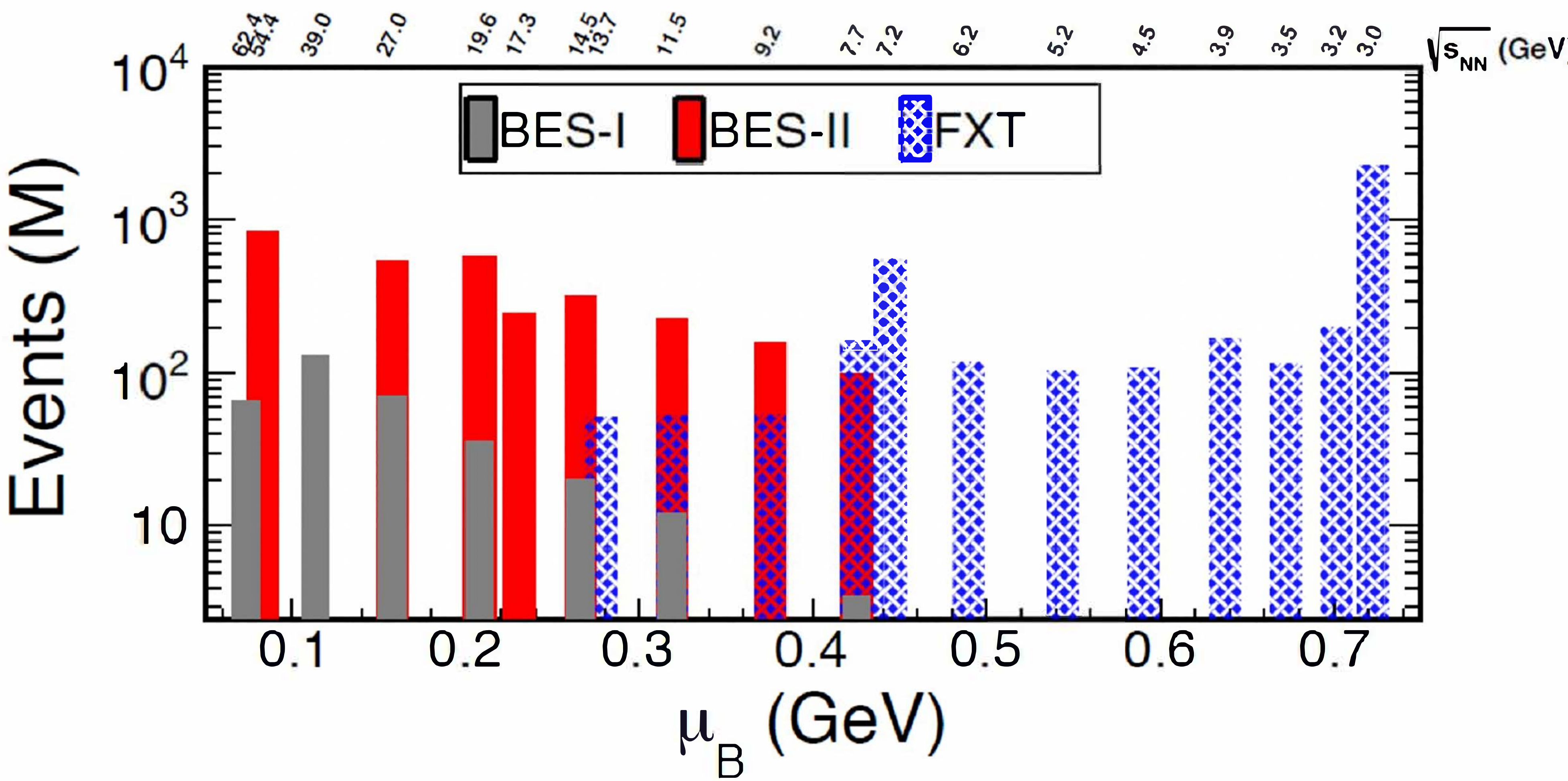
- A question that one asks after the discovery of any new form of complex matter: What is its phase diagram? For high temperature superconductors, for example, phase diagram as a function of temperature and doping. Same here! For us, doping means excess of quarks over antiquarks, rather than an excess of holes over electrons.
- A question that we are privileged to have a chance to address, after the discovery of "our" new form of complex matter: How does the strongly coupled liquid emerge from an asymptotically free gauge theory? Maybe answering this question could help to understand how strongly coupled matter emerges in other contexts.

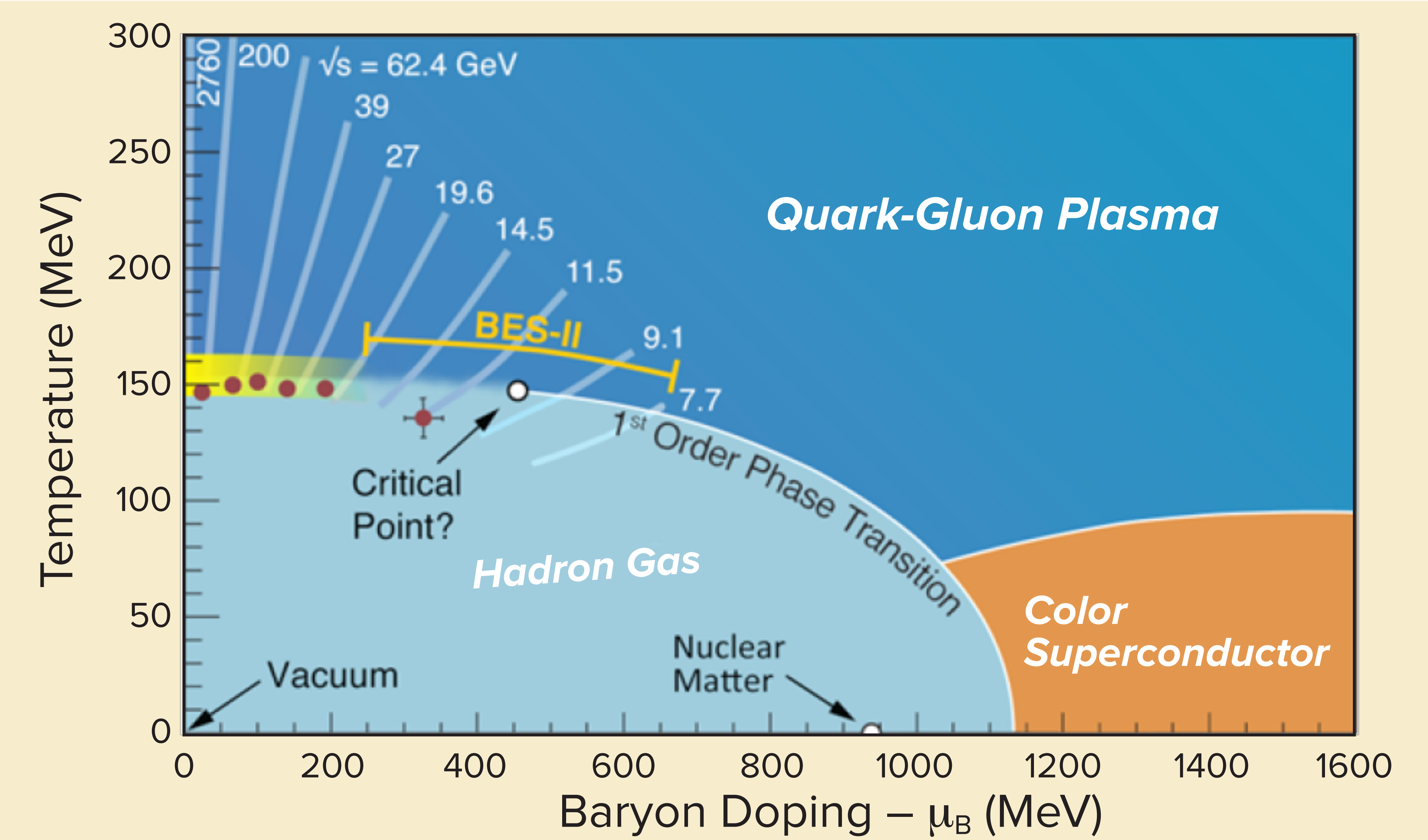

Strange Metal
Pseudogap
Antiferromagnet
High-T
Superconductor
QCP
Fermi Liquid
Temperature
Doping



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

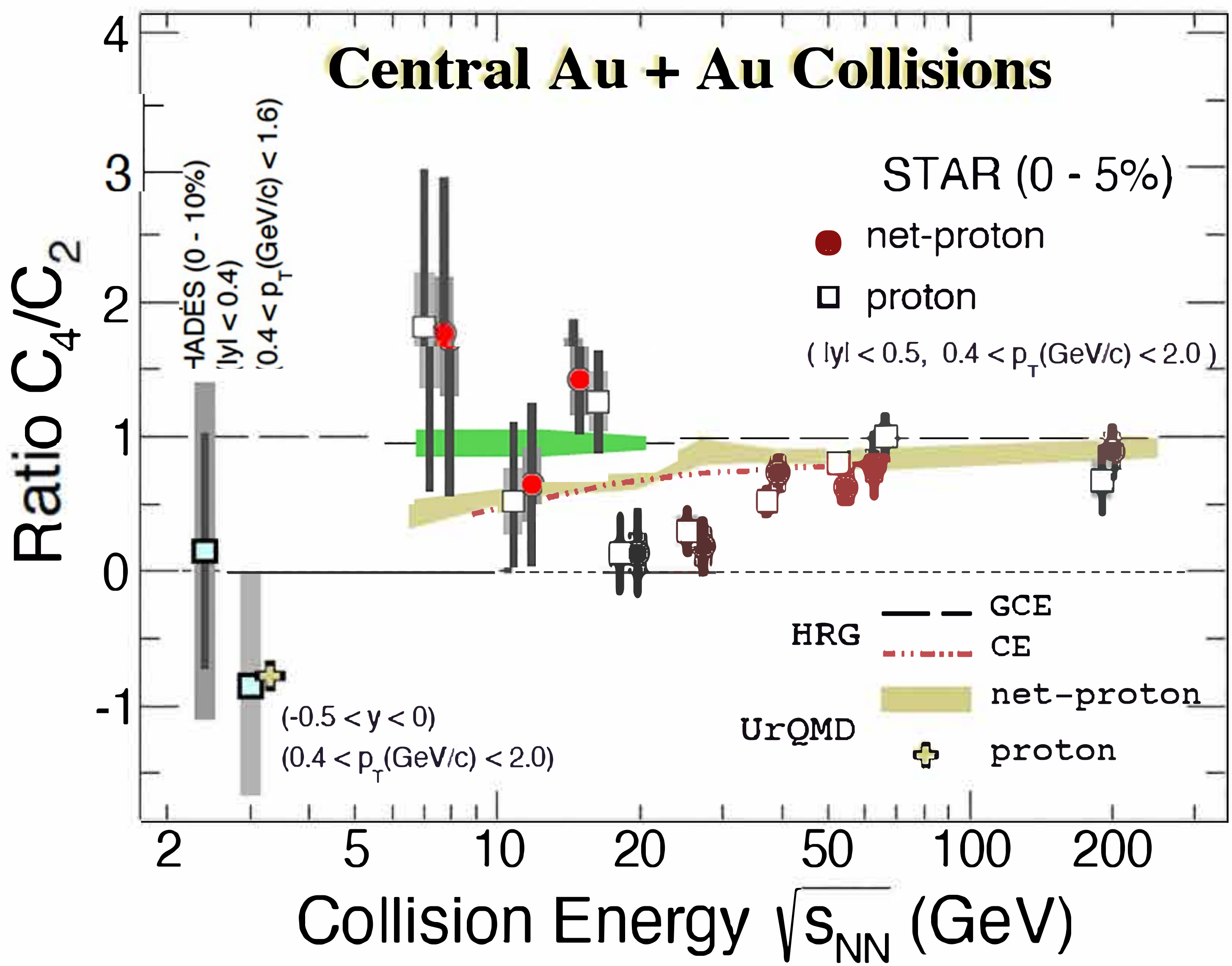
RHIC BES II Data Taken...

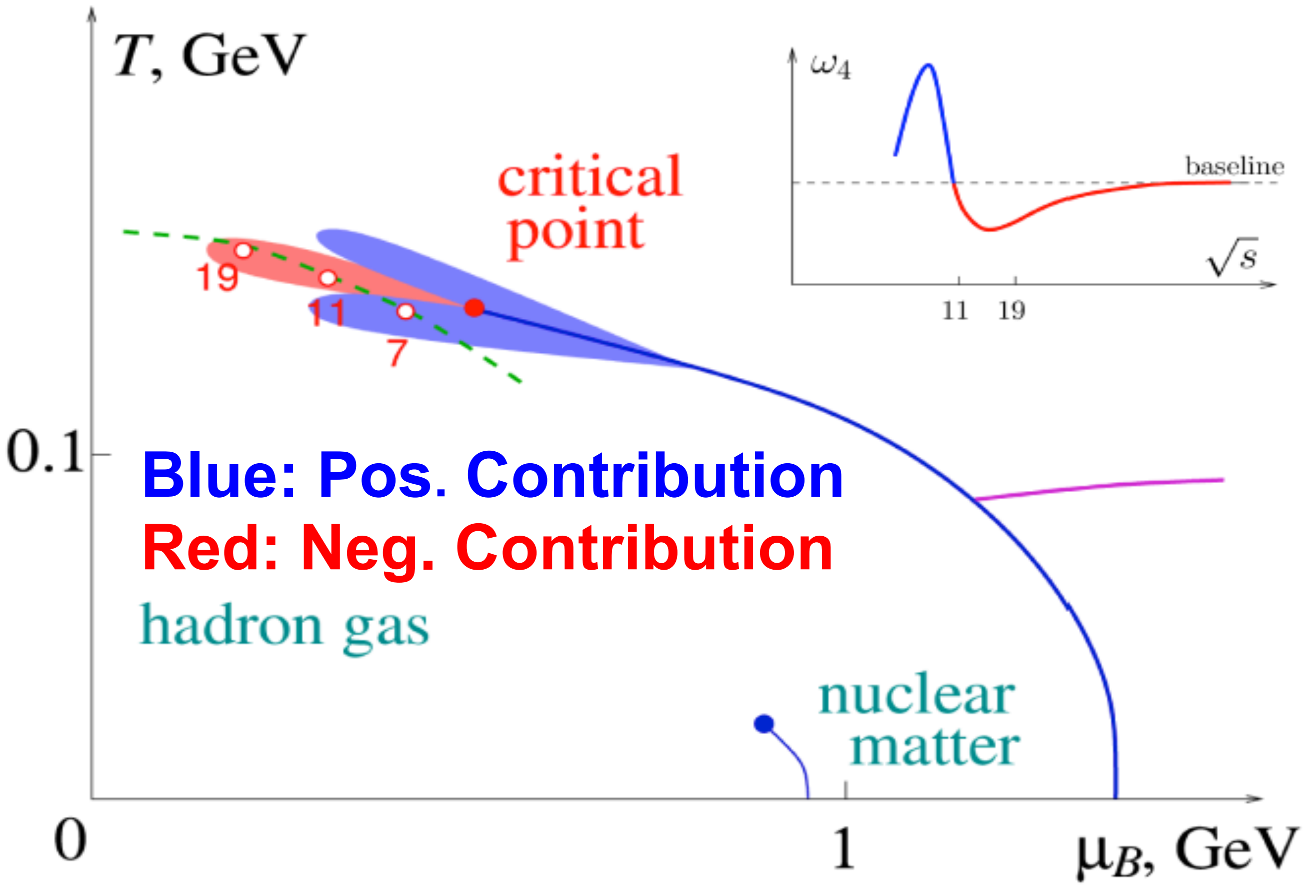




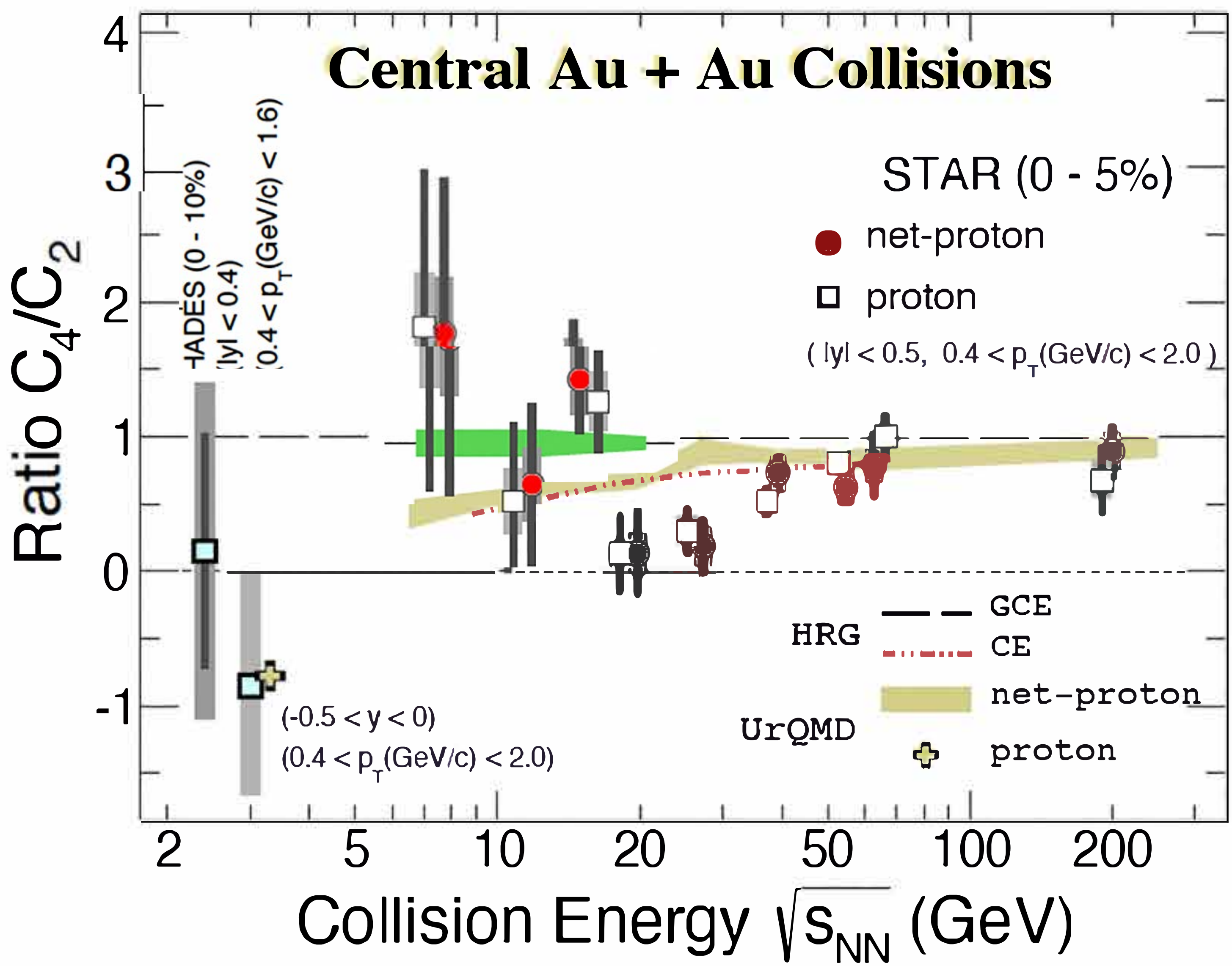
Temperature (MeV)
Baryon Doping – μ_B (MeV)
300
250
200
150
100
50
0
200
400
600
800
1000
1200
1400
1600
2760
200
√s = 62.4 GeV
39
27
19.6
14.5
11.5
9.1
7.7
BES-II
Quark-Gluon Plasma
Critical
Point?
1st Order Phase Transition
Hadron Gas
Color
Superconductor
Nuclear
Matter
Vacuum

Proton Kurtosis, before BES II




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

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

BERKELEY LAB

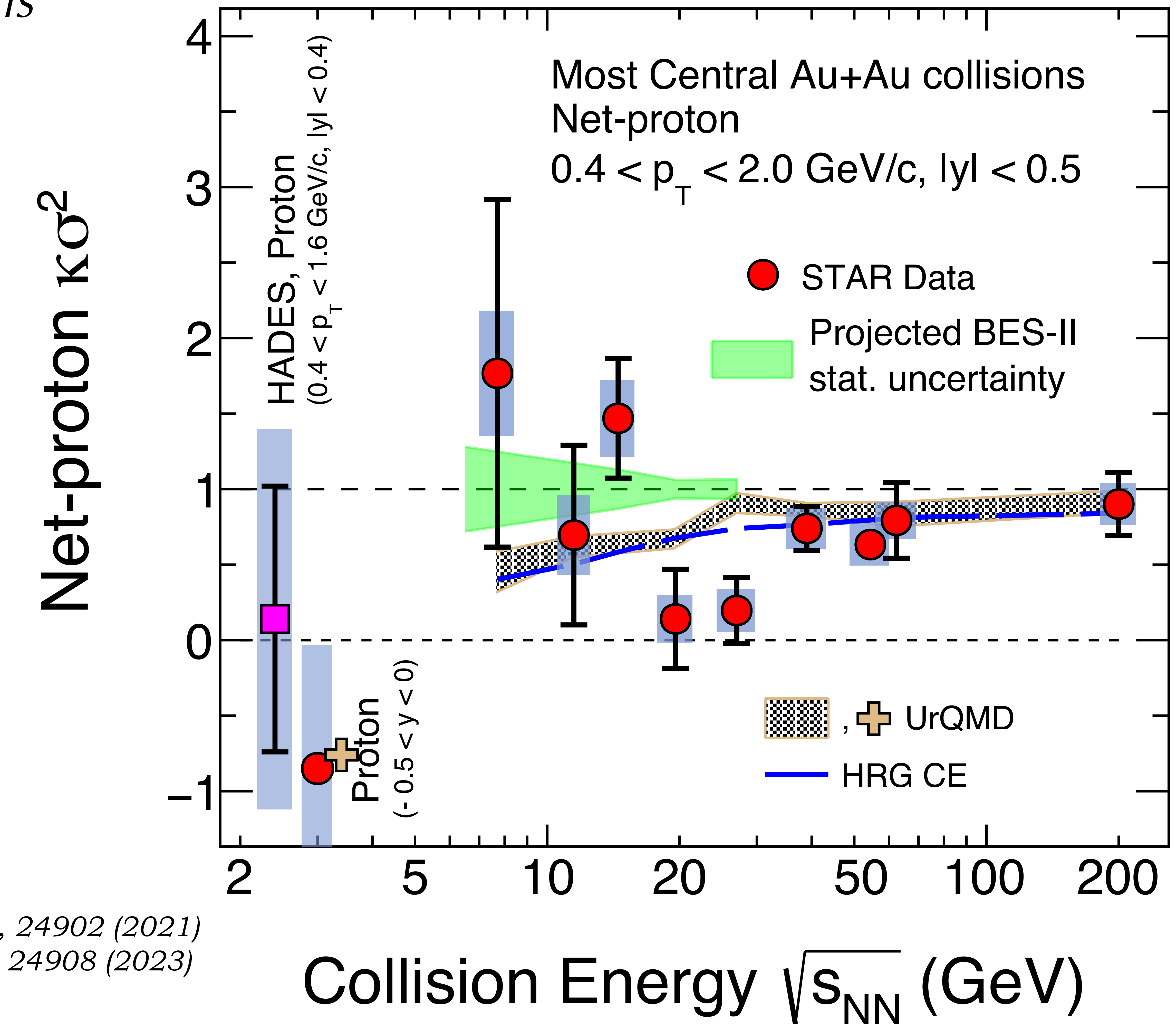
STAR

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)	μ_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 σ): 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			
Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	μ_B (MeV)	Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	μ_B (MeV)
1	**200**	380	**25**	1	13.7 (100)	50	280
2	62.4	46	75	2	11.5 (70)	50	316
3	54.4	1200	85	3	9.2 (44.5)	50	372
4	39	86	112	4	7.7 (31.2)	260	420
5	27	585	156	5	7.2 (26.5)	470	440
6	19.6	595	206	6	6.2 (19.5)	120	490
7	17.3	256	230	7	5.2 (13.5)	100	540
8	14.6	340	262	8	4.5 (9.8)	110	590
9	11.5	257	316	9	3.9 (7.3)	120	633
10	9.2	160	372	10	3.5 (5.75)	120	670
11	7.7	104	420	11	3.2 (4.59)	200	699
	BES-II collider results ready			12	**3.0** (3.85)	**260** + 2000	**750**

Events used for net-proton fluctuation studies (Collider runs) BES-II vs BES-I

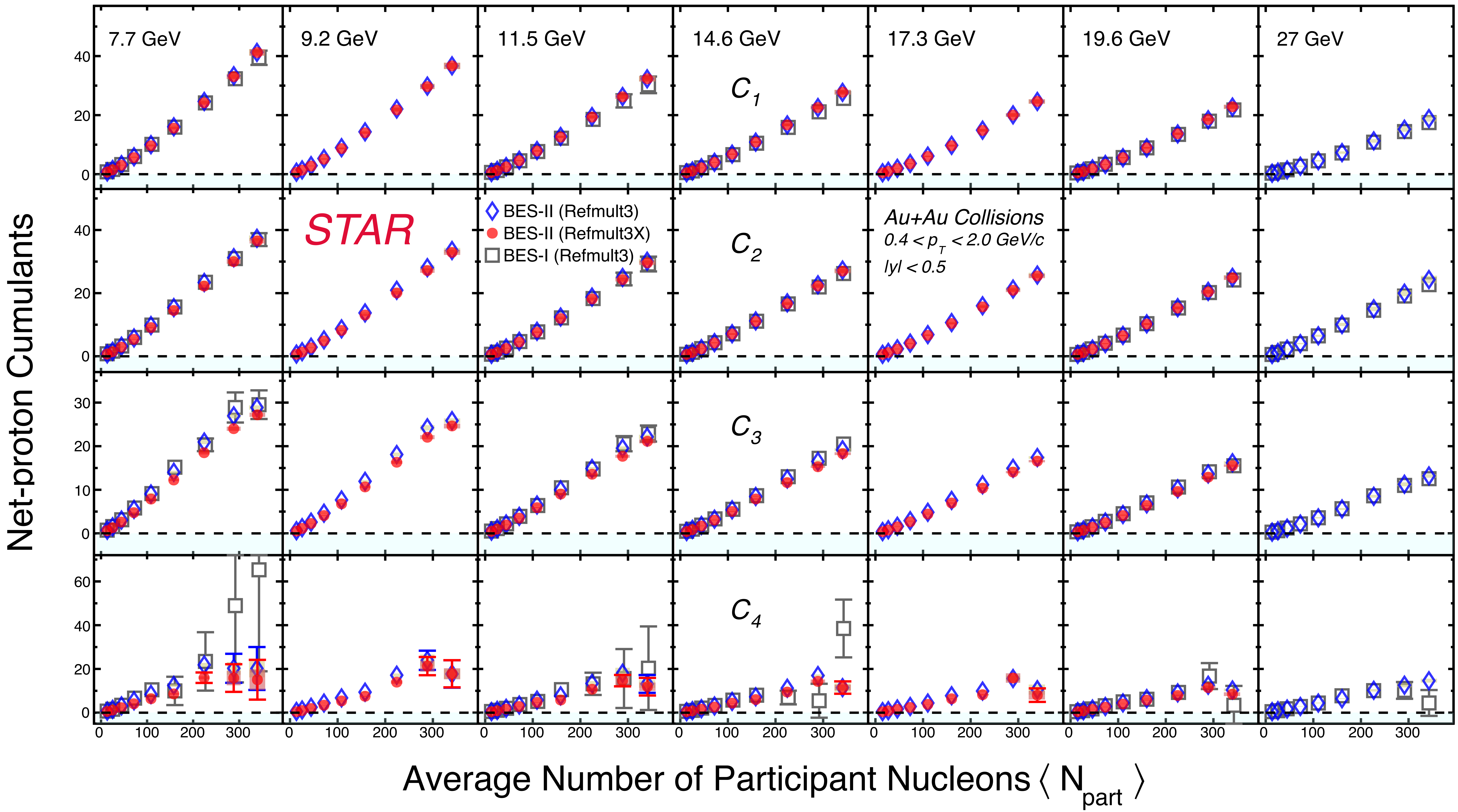
$\sqrt{s_{NN}}$ (GeV)	Events BES-I (10^6)	Events BES-II (10^6)
7.7	3	**45**
9.2	-	**78**
11.5	7	**110**
14.5	20	**178**
17.3	-	**116**
19.6	15	**270**
27	30	**220**

~10-18 fold improvement in statistics
9.2 and 17.3 GeV added to energy scan

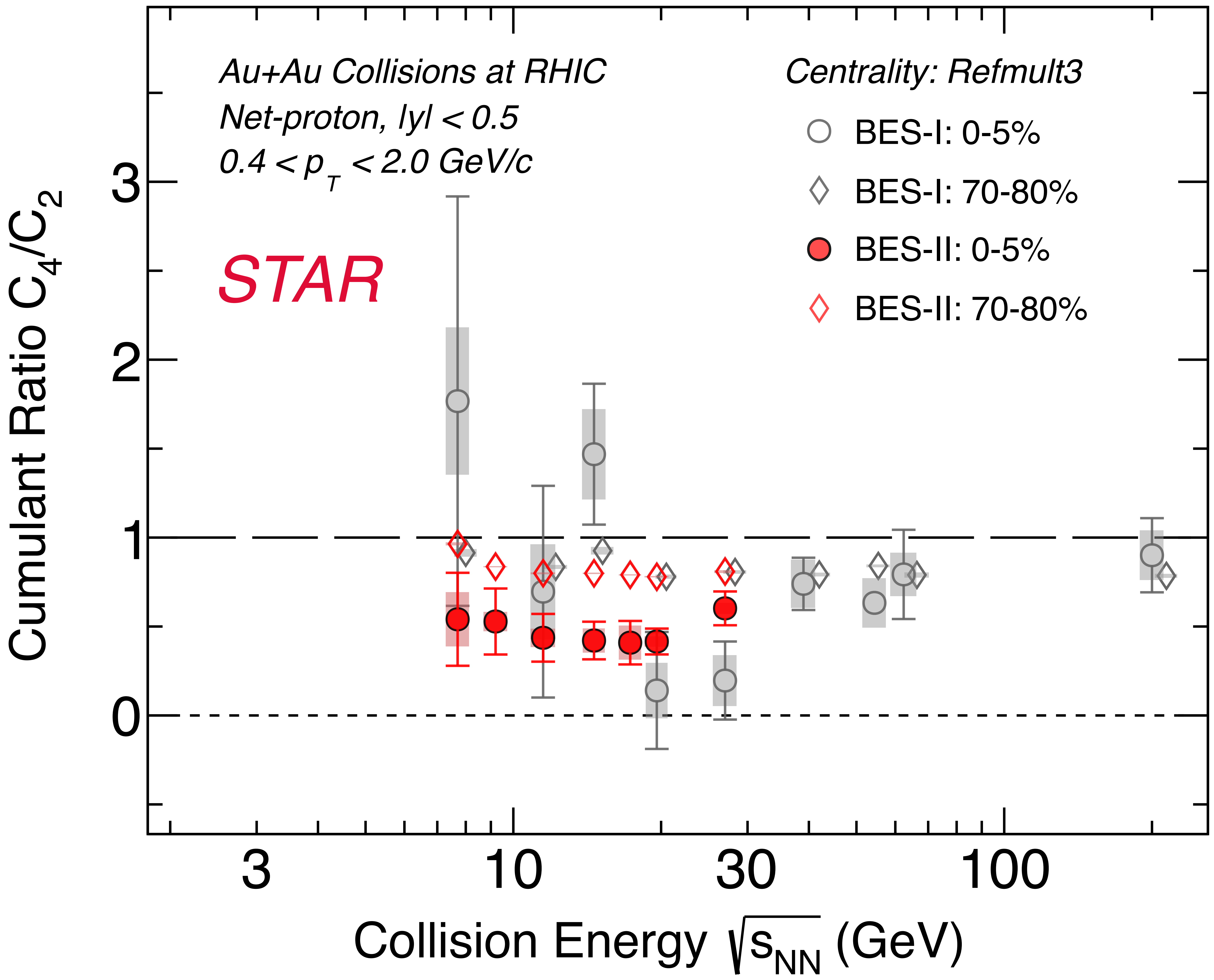
$$3 \leq \sqrt{s_{NN}}\ (GeV) \leq 200 \ \rightarrow 750 \geq \mu_B\ (MeV) \geq 25$$

High precision, widest μ_B coverage to date

Centrality Dependence and comparison with BES-I



Energy Dependence of C_4/C_2: Comparison with BES-I

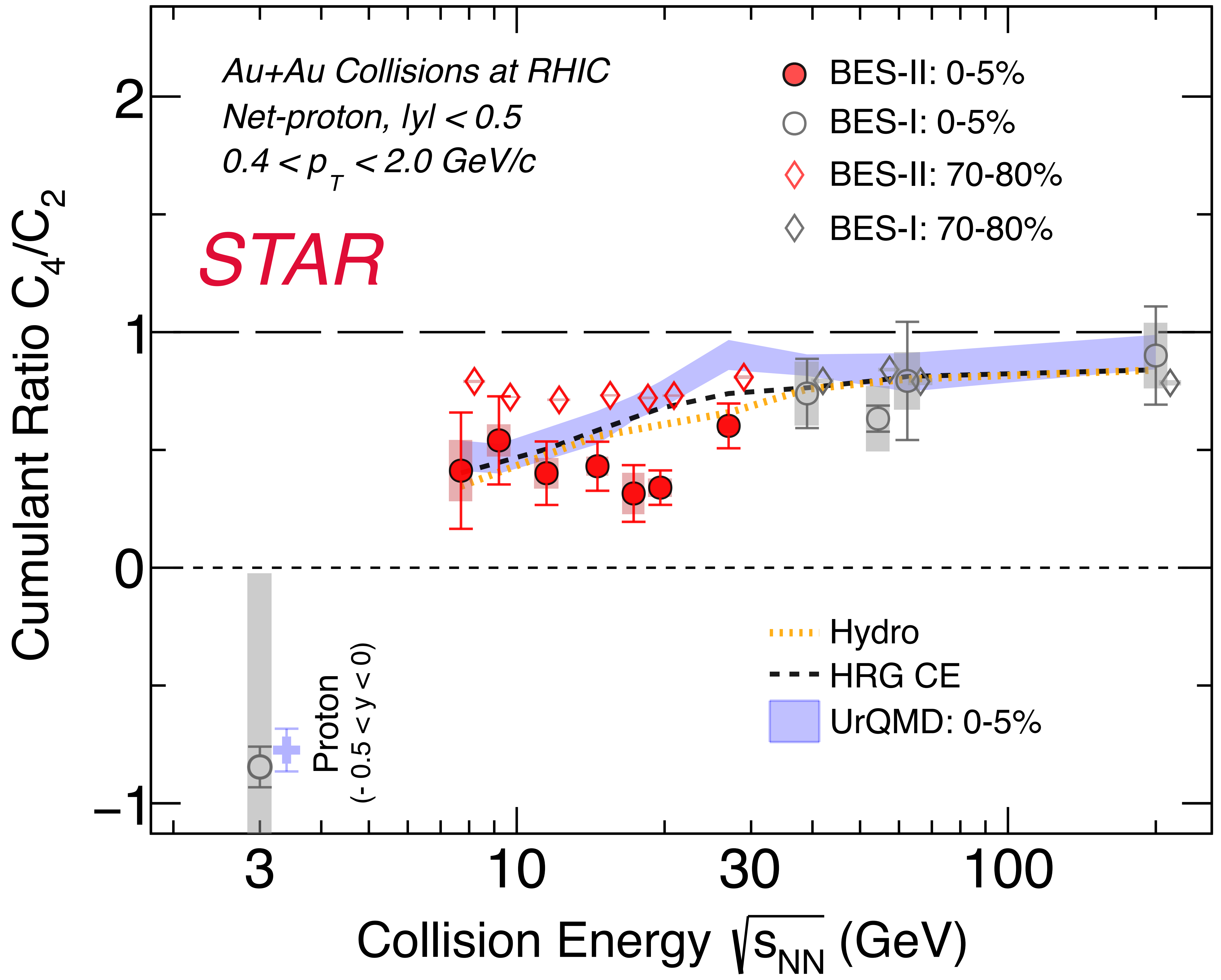


Deviation between BES-II and BES-I data

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

- 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.**
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  - **STAR collider data motivate exploring** $420 \text{ MeV} < \mu_B \lesssim 600$ **MeV, meaning** $7.7 \text{ GeV} > \sqrt{s} \gtrsim 4$ **GeV.**
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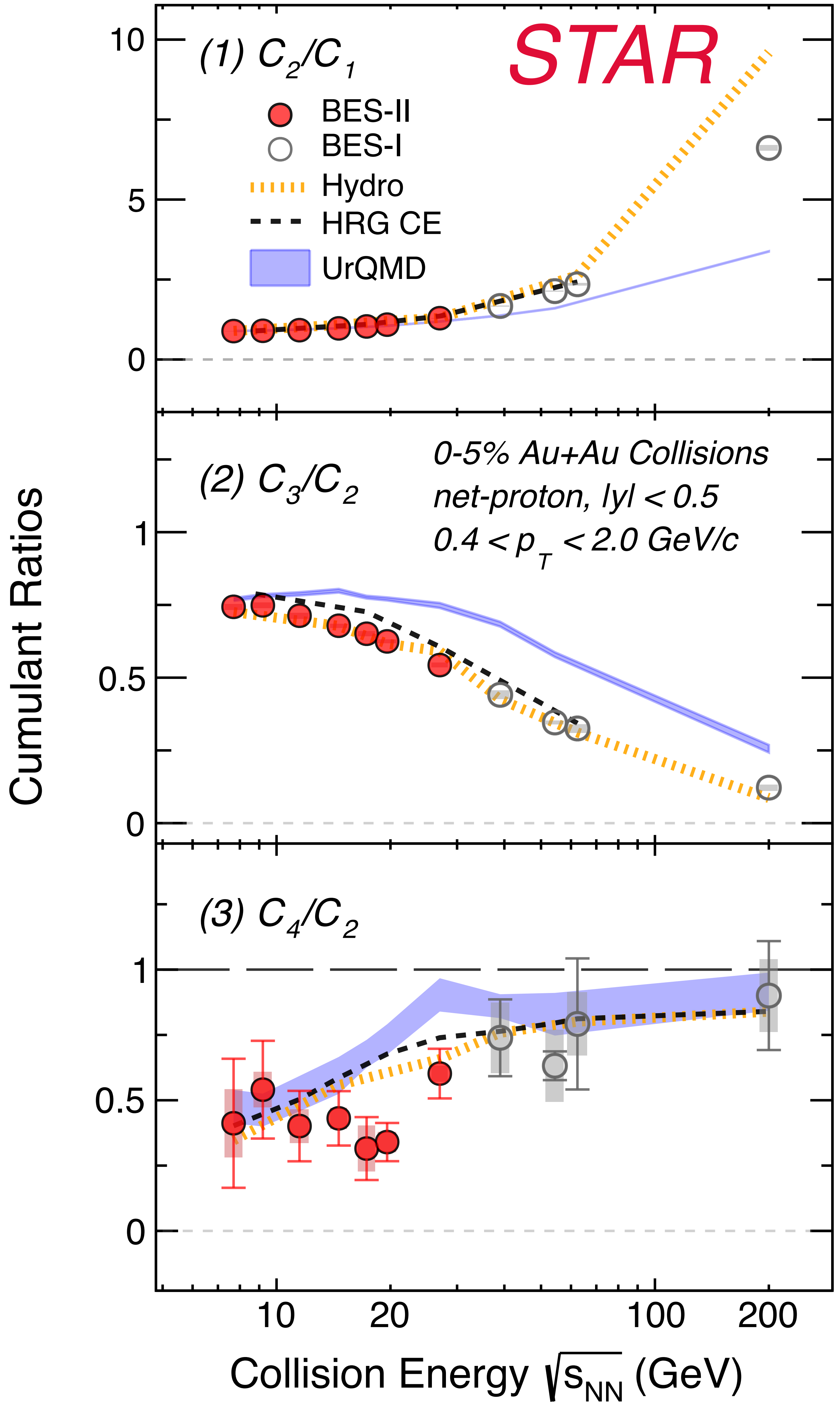
  - **STAR FXT will give us a good look at fluctuations in** $4.5 \text{ GeV} > \sqrt{s} > 3 \text{ GeV}$ **collisions, but what is the best option for** $7.7 \text{ GeV} > \sqrt{s} > 4.5 \text{ GeV}$ **collisions?**

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 baron charge
   C. UrQMD: Hadronic transport model
   (All models include baryon number conservation)

HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
Hydro: V. Vovchenko et al, PRC 105, 014904 (2022)

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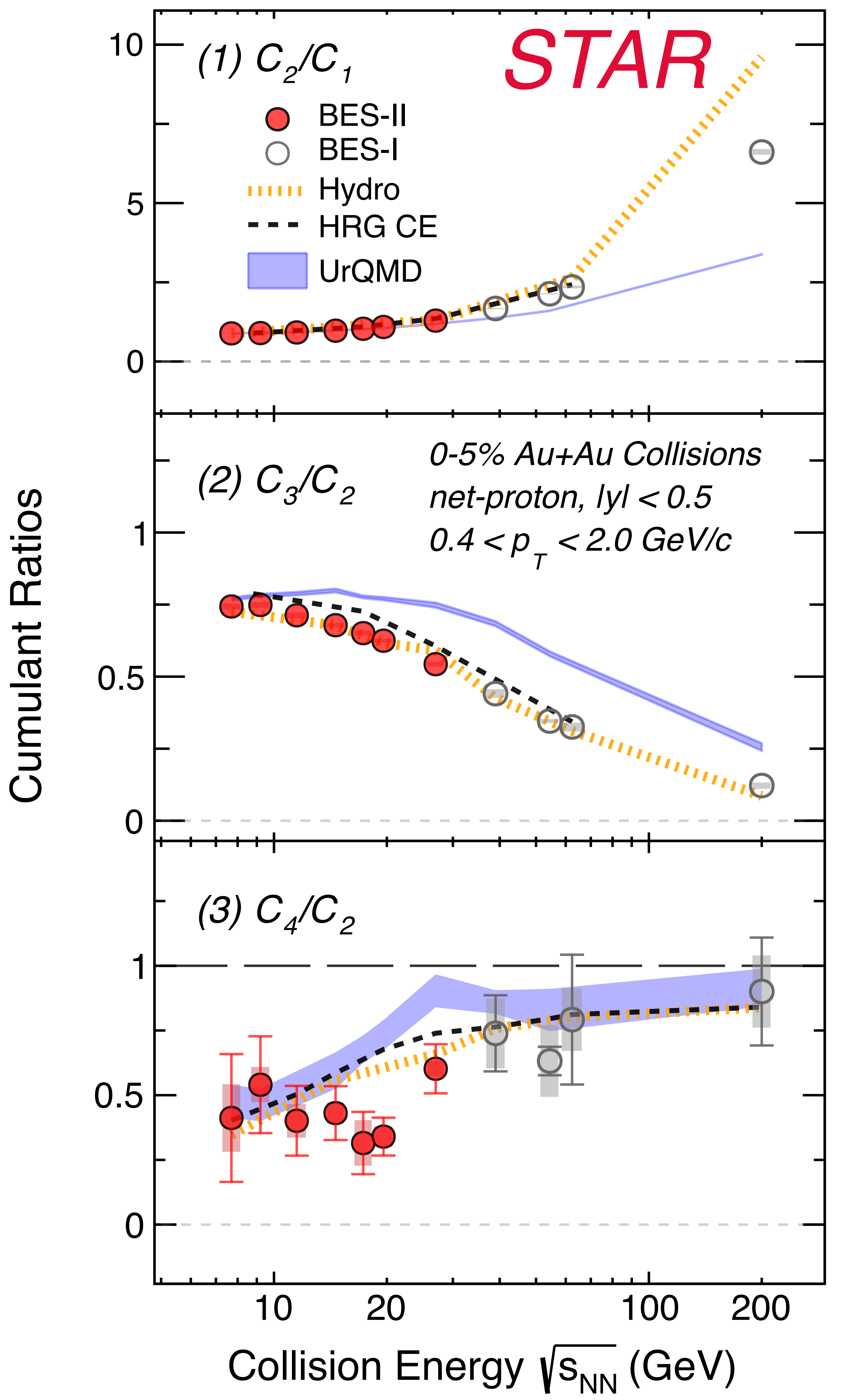
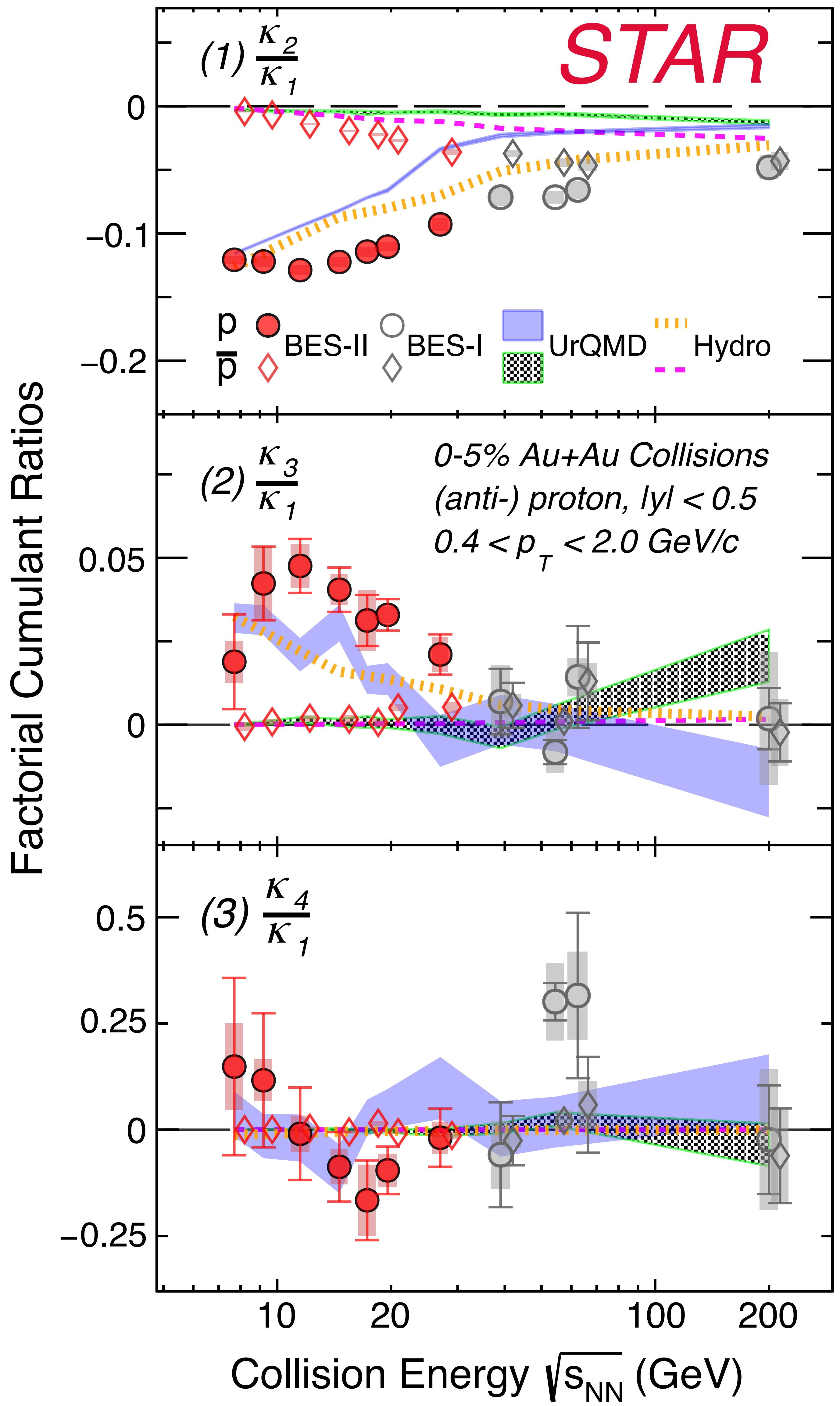


Proton/antiproton factorial cumulant ratios



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   C. UrQMD: Hadronic transport model
   (All models include baryon number conservation)
3. Proton factorial cumulant ratios deviates from poisson baseline at 0. Antiproton κ_3/κ_1, κ_4/κ_1 closer to 0.
4. Qualitative trend described by model. Quantitative differences exist b/w data and non-CP model.

HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
Hydro: V. Vovchenko et al, PRC 105, 014904 (2022)

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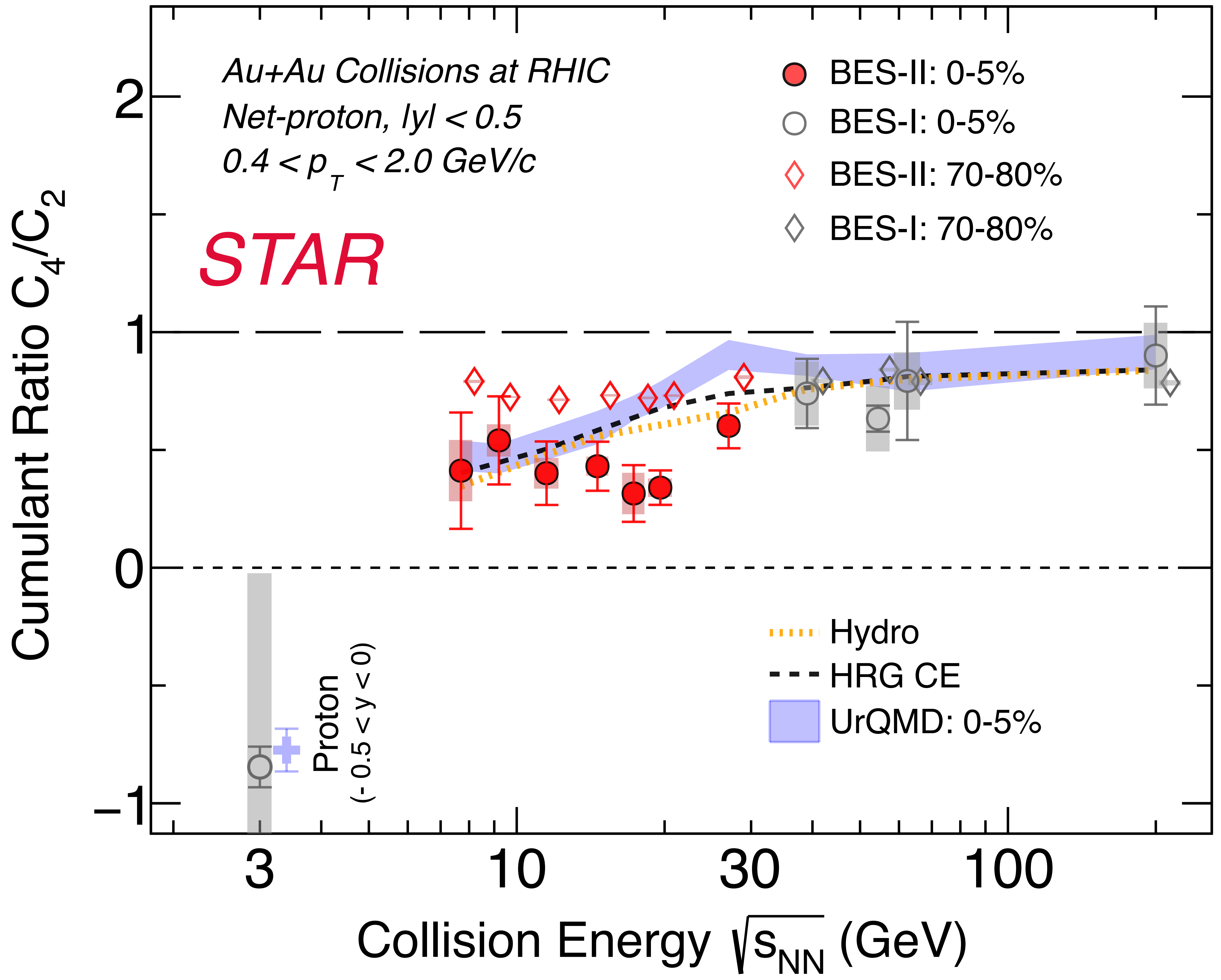

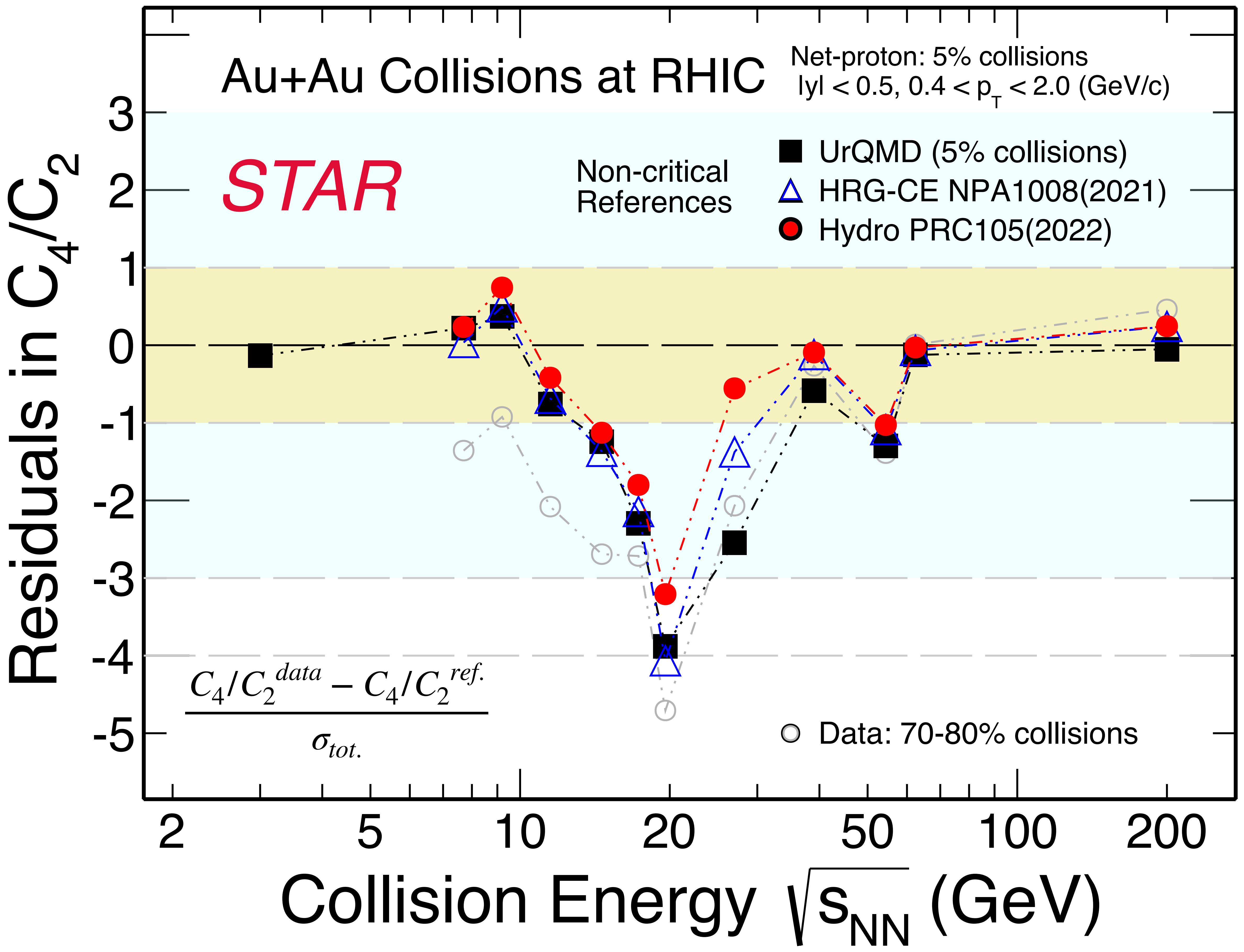

C_4/C_2 shows minimum around ~20 GeV comparing to non-CP models, 70-80% data

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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STAR BES-II Program: Precision Measurements

Au+Au Collisions at RHIC							
Collider Runs				**Fixed-Target Runs**			
Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	μ_B (MeV)	Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	μ_B (MeV)
1	**200**	380	**25**	1	13.7 (100)	50	280
2	62.4	46	75	2	11.5 (70)	50	316
3	54.4	1200	85	3	9.2 (44.5)	50	372
4	39	86	112	4	7.7 (31.2)	260	420
5	27	585	156	5	7.2 (26.5)	470	440
6	19.6	595	206	6	6.2 (19.5)	120	490
7	17.3	256	230	7	5.2 (13.5)	100	540
8	14.6	340	262	8	4.5 (9.8)	110	590
9	11.5	257	316	9	3.9 (7.3)	120	633
10	9.2	160	372	10	3.5 (5.75)	120	670
11	7.7	104	420	11	3.2 (4.59)	200	699
	BES-II collider results ready			12	**3.0** (3.85)	**260** + 2000	**750**

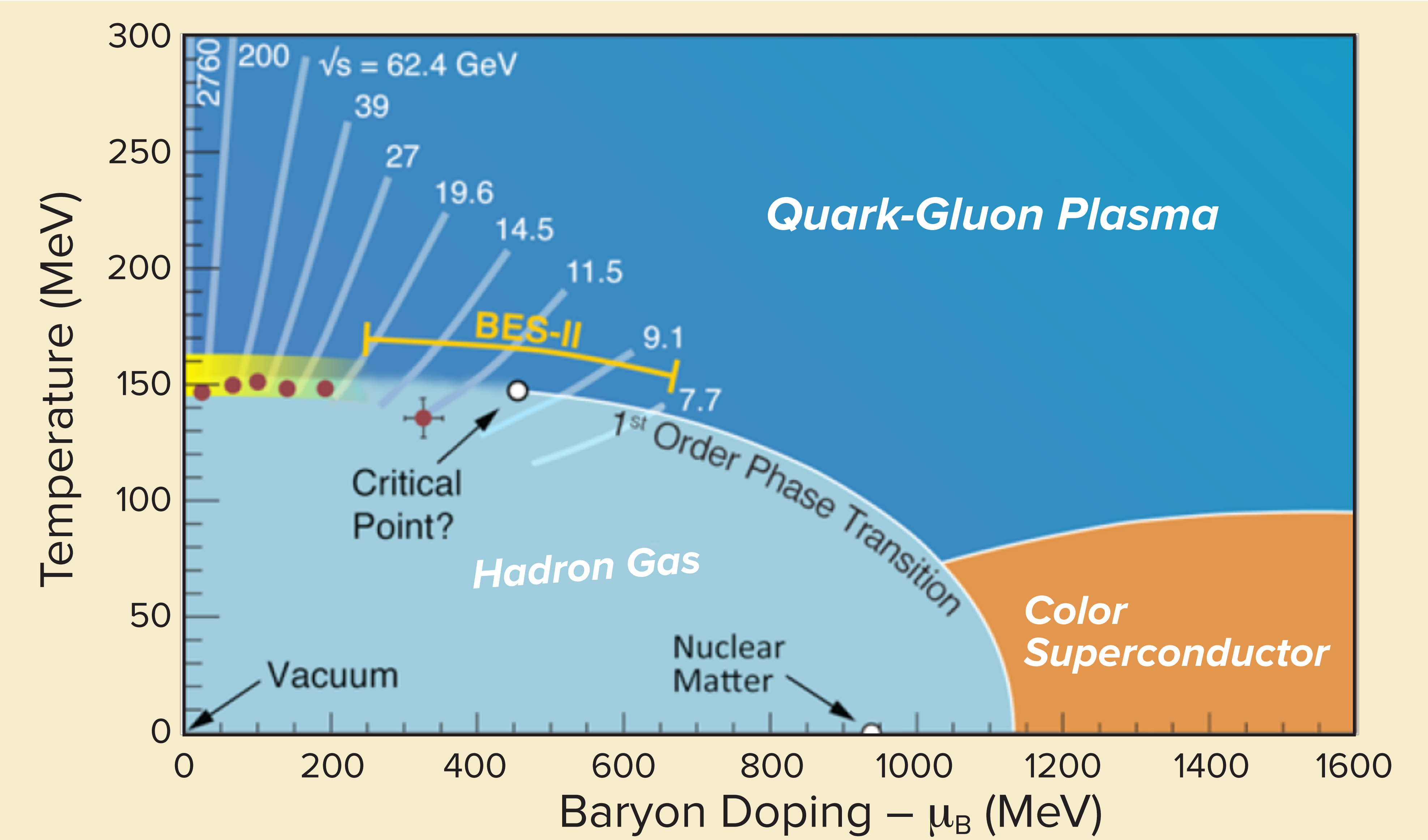
Events used for net-proton fluctuation studies (Collider runs) BES-II vs BES-I

$\sqrt{s_{NN}}$ (GeV)	Events BES-I (10^6)	Events BES-II (10^6)
7.7	3	**45**
9.2	-	**78**
11.5	7	**110**
14.5	20	**178**
17.3	-	**116**
19.6	15	**270**
27	30	**220**

~10-18 fold improvement in statistics
9.2 and 17.3 GeV added to energy scan

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

High precision, widest μ_B coverage to date



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

What Next?

Two kinds of What Next? questions ...

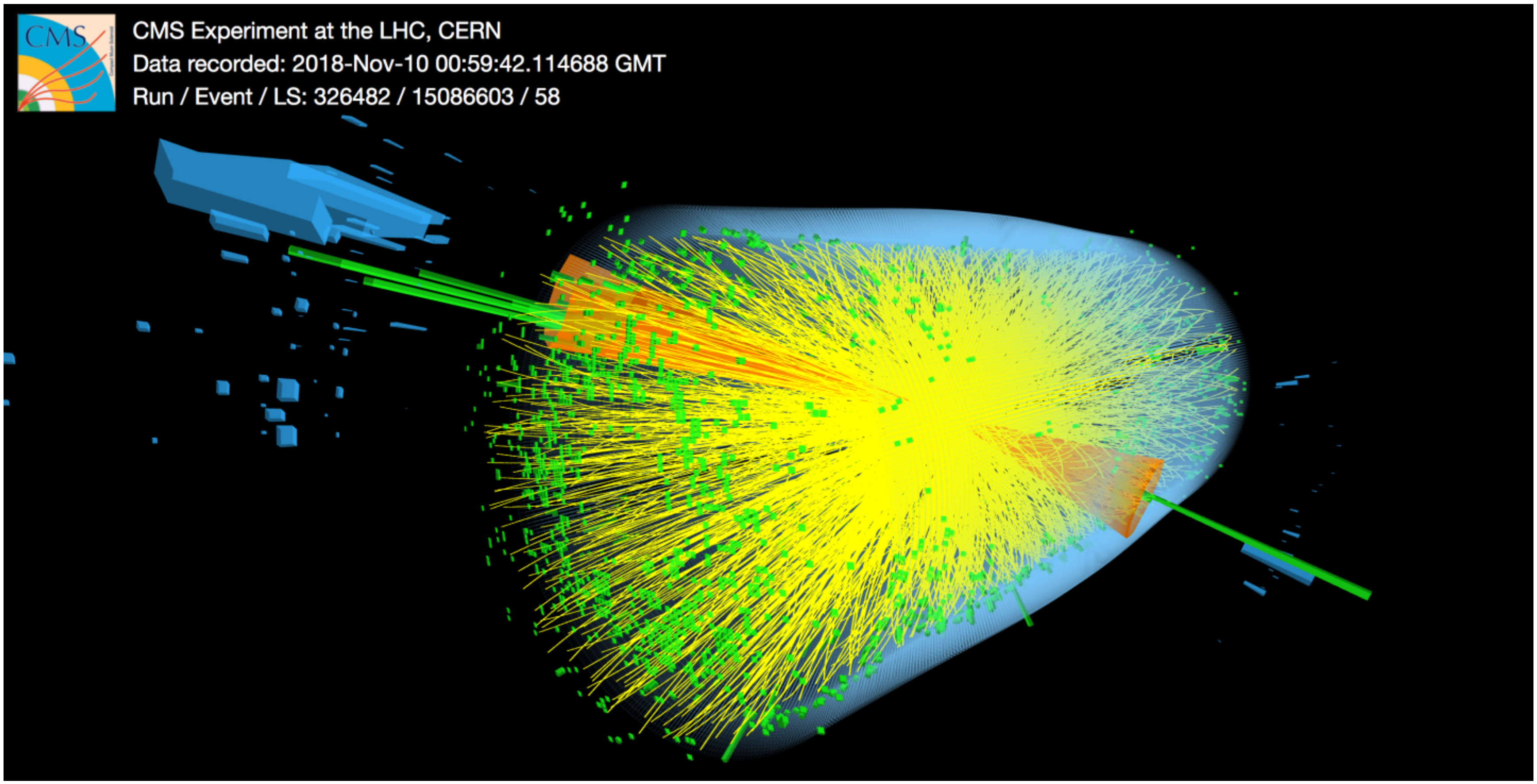
- A question that one asks after the discovery of any new form of complex matter: What is its phase diagram? For high temperature superconductors, for example, phase diagram as a function of temperature and doping. Same here! For us, doping means excess of quarks over antiquarks, rather than an excess of holes over electrons.
- A question that we are privileged to have a chance to address, after the discovery of "our" new form of complex matter: How does the strongly coupled liquid emerge from an asymptotically free gauge theory? Maybe answering this question could help to understand how strongly coupled matter emerges in other contexts.

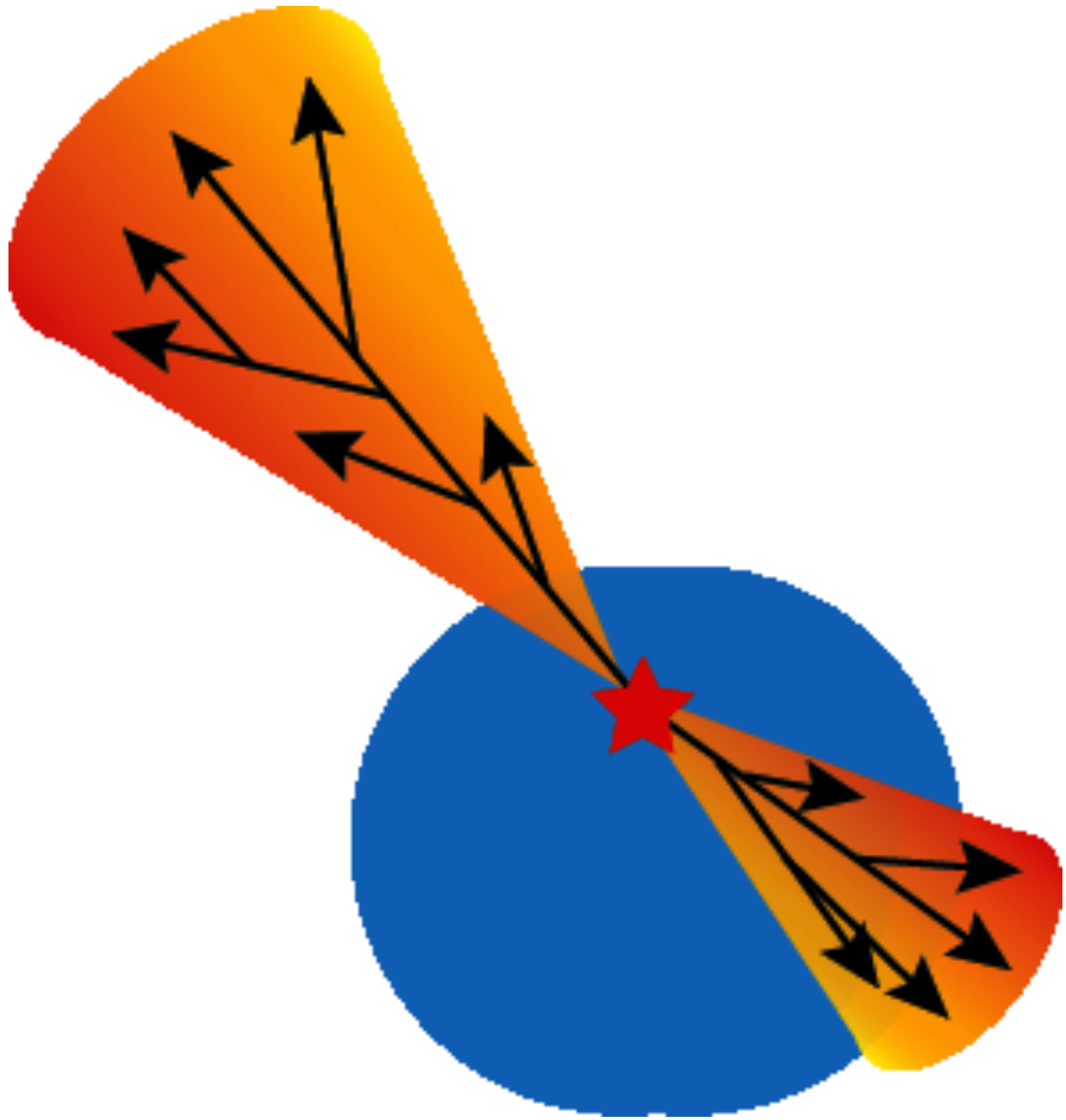
Probing the Original Liquid

- 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!

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.
- $\rightarrow$ 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
Run / Event / LS: 326482 / 15086603 / 58



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+jet or γ+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. . .

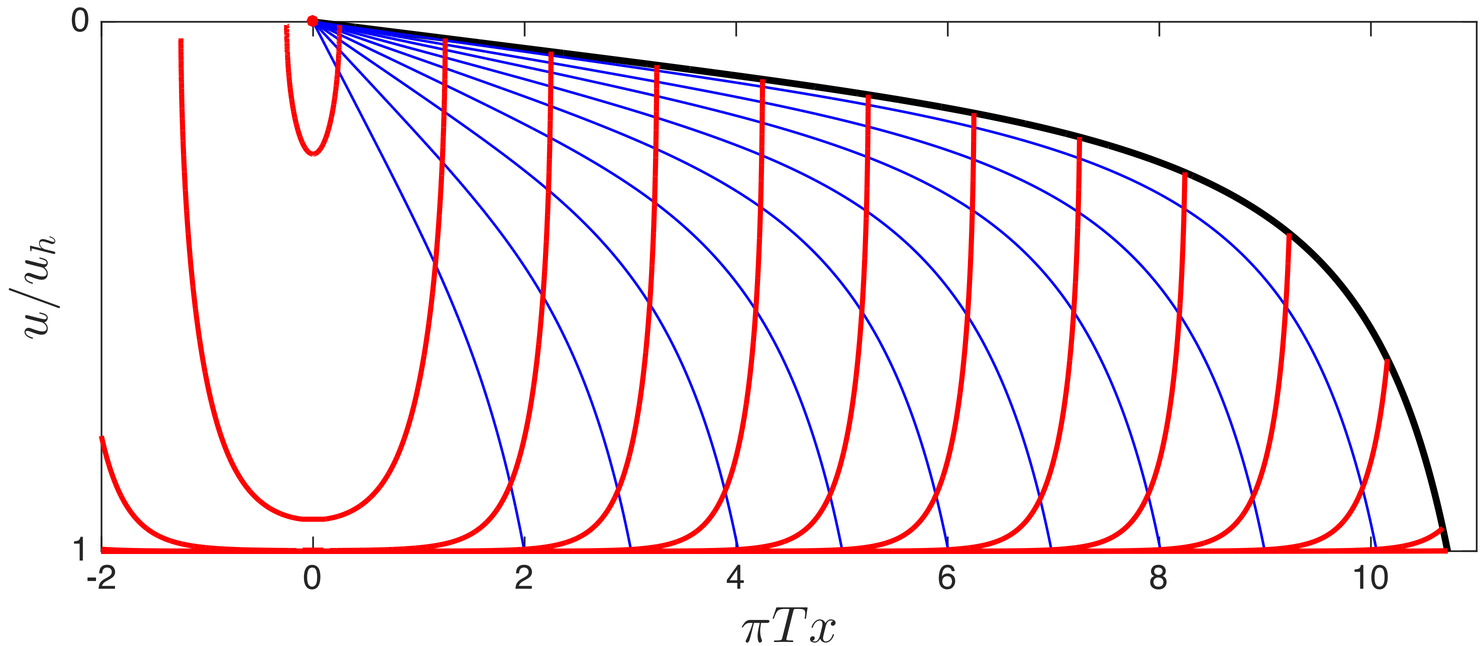
A Hybrid Approach

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_{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

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

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

Perturbative Shower … Living in Strongly Coupled QGP

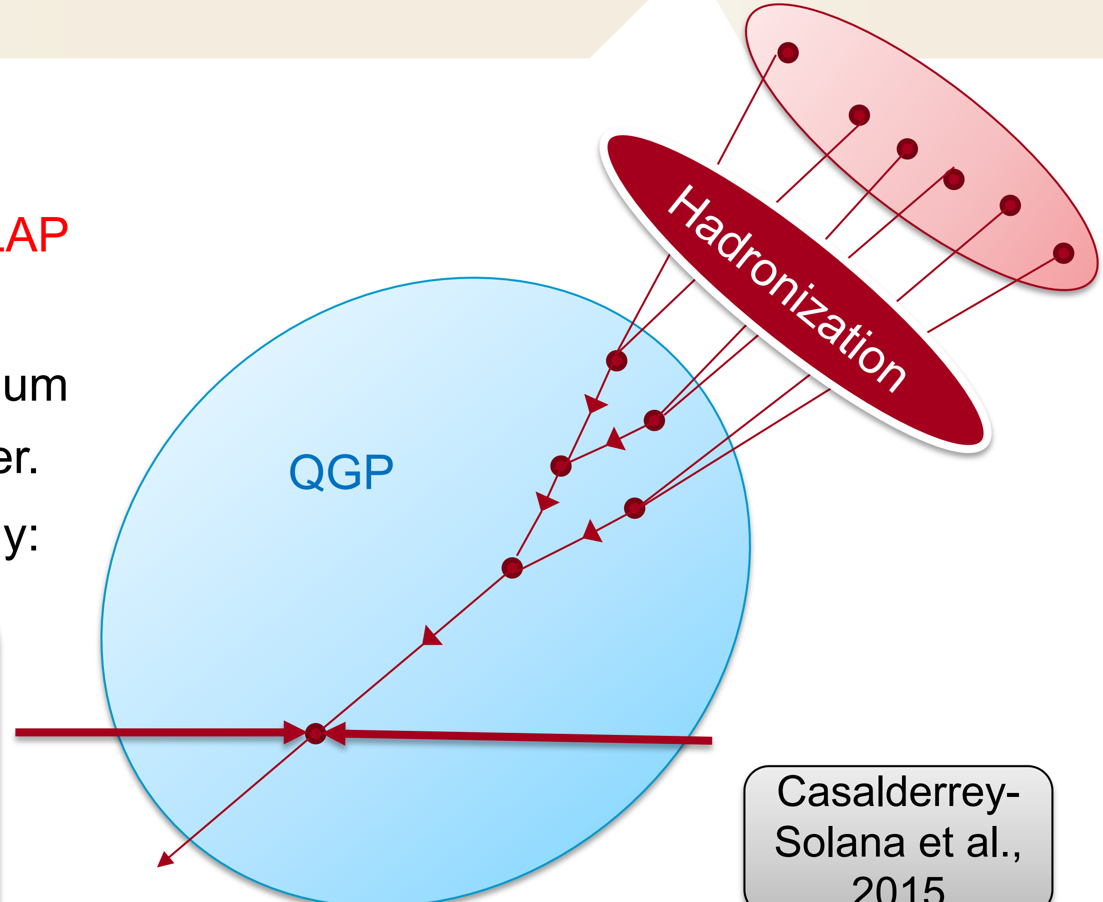
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

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

O(1) fit const.

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

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



Casalderrey-Solana et al., 2015

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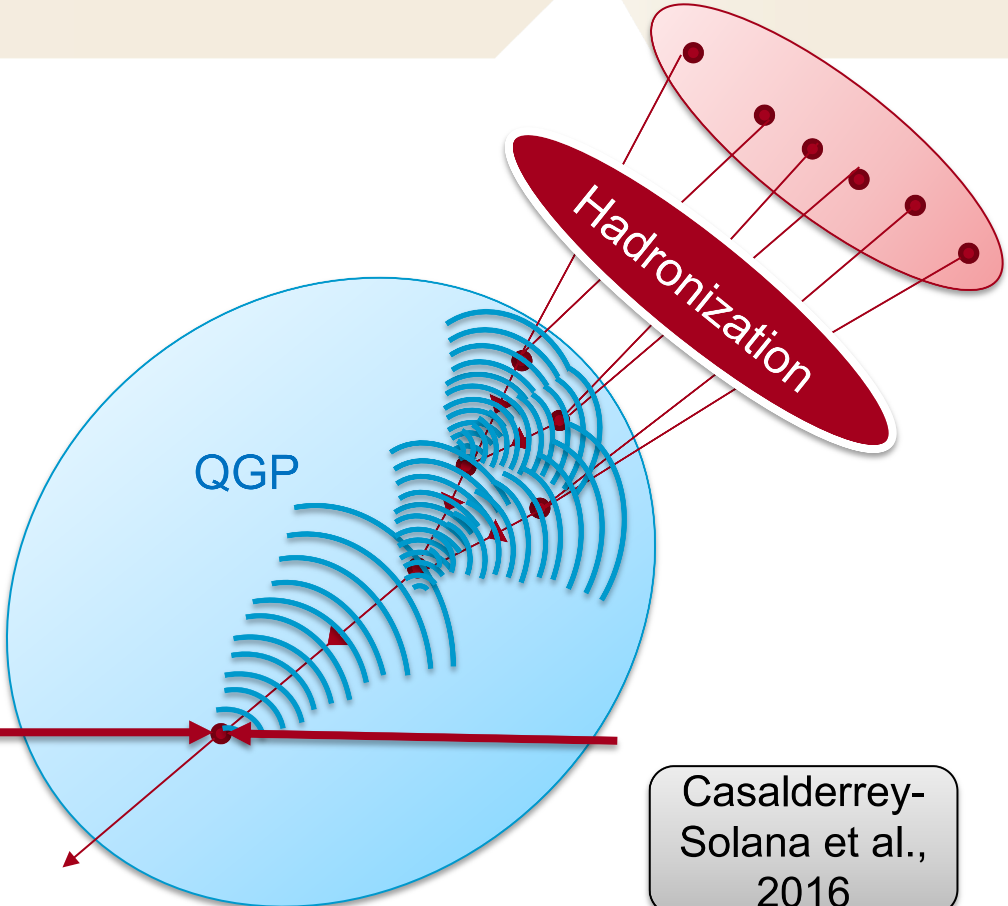


Casalderrey-Solana et al., 2016

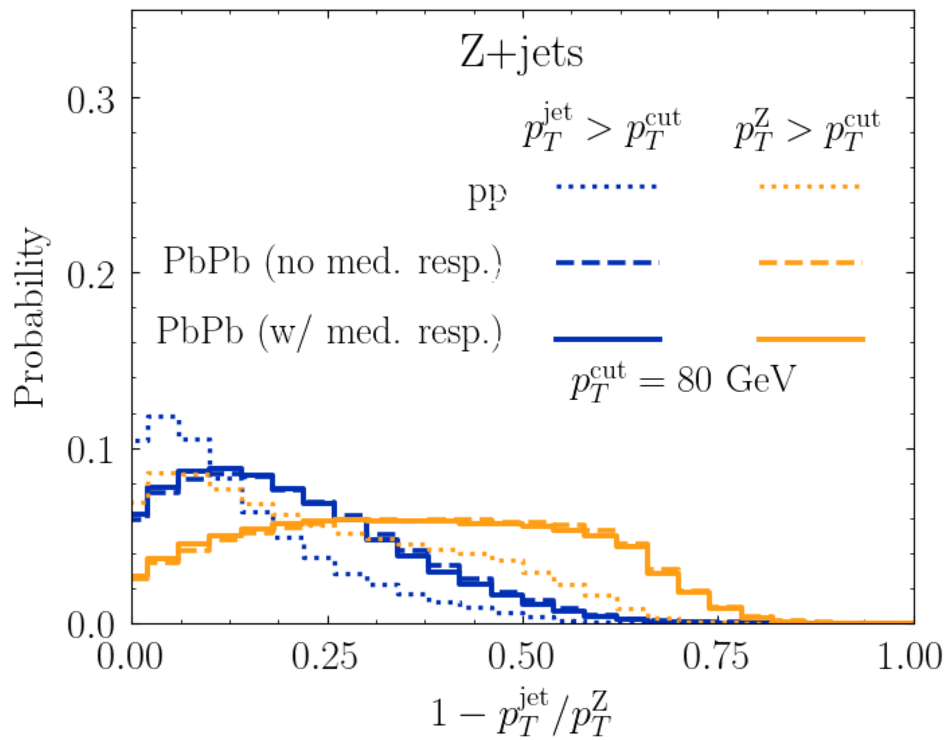
Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

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

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

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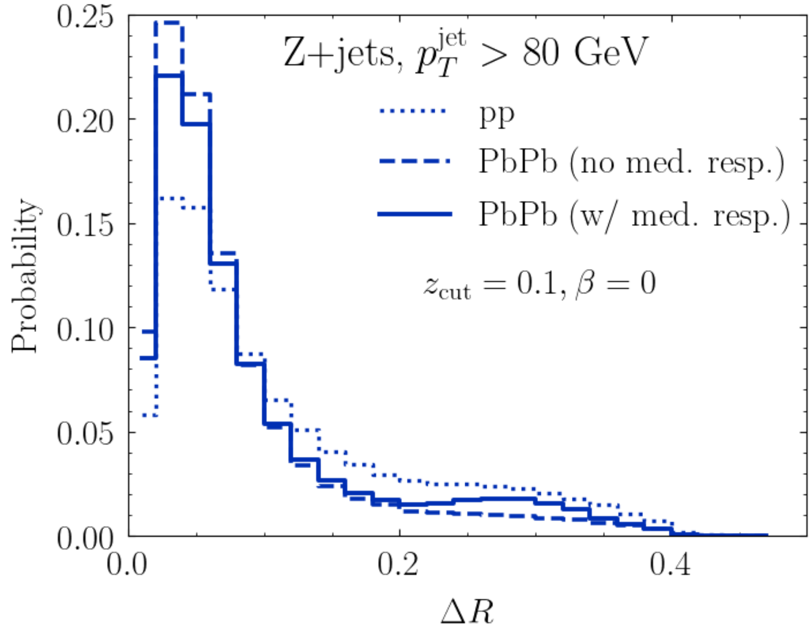
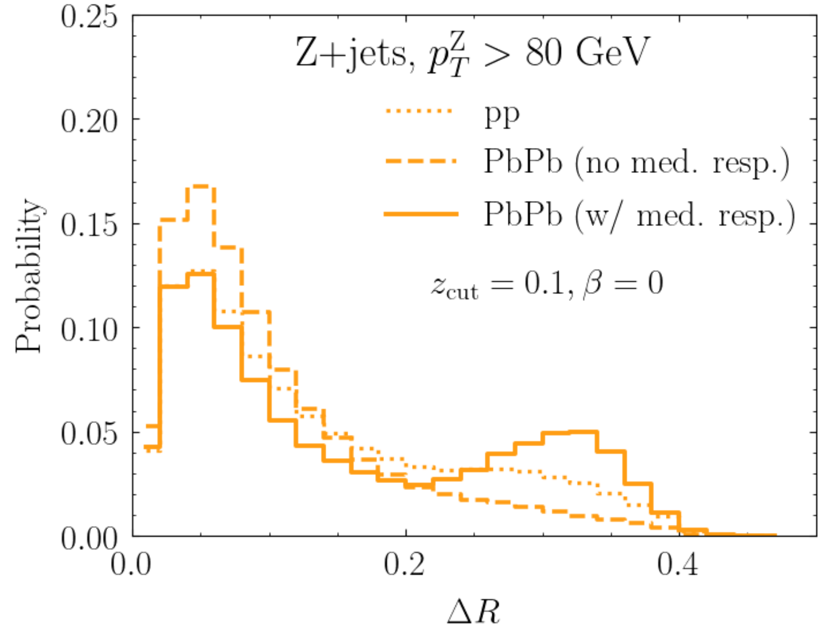
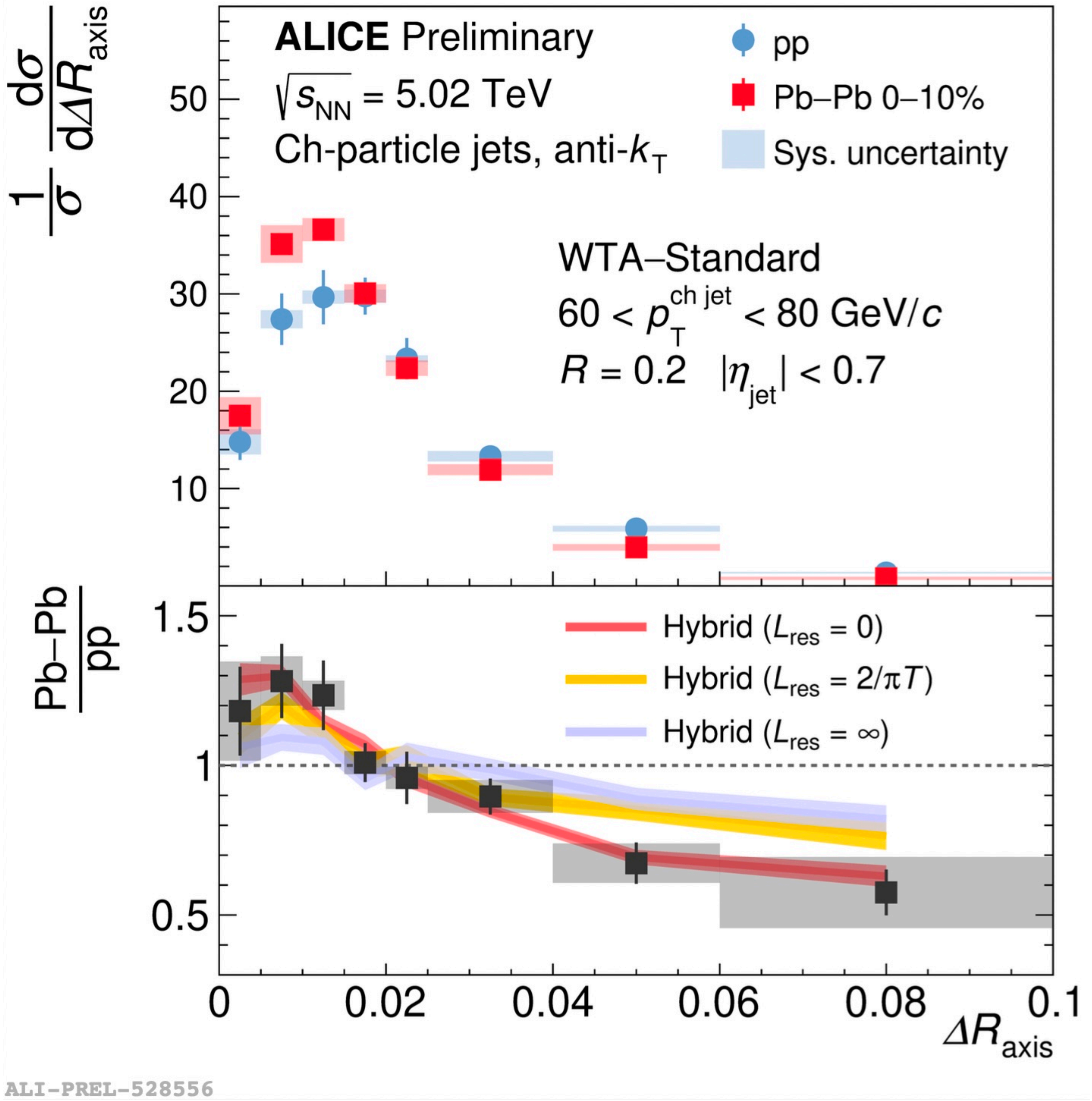


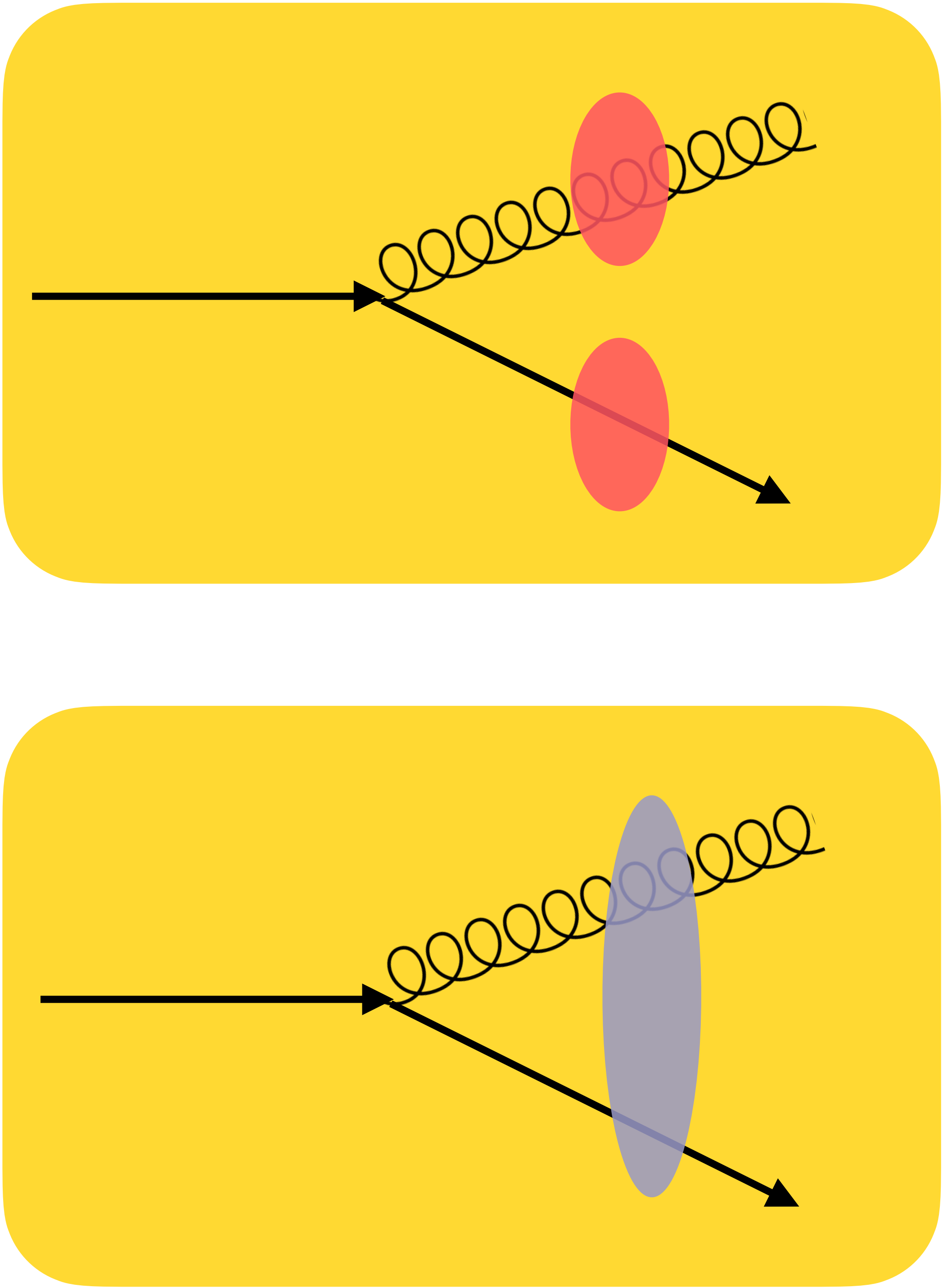


Orange: $p_T^Z > 80$ GeV; $p_T^{\text{jet}} > 30$ GeV. See jet modification.

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} = ∞: medium does not resolve splitting.
Fully-coherent energy loss

Data favors mechanisms of incoherent energy loss in the QGP

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Jets as Probes of QGP

- Jet wakes in droplets of QGP.
  - Momentum/energy "lost" by parton shower $\rightarrow$ wake in the fluid $\rightarrow$ 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 ~ 100 (in progress).

A New Angle on Visualizing Jet and Wake Substructure

Krishna Rajagopal

MIT

work in progress with

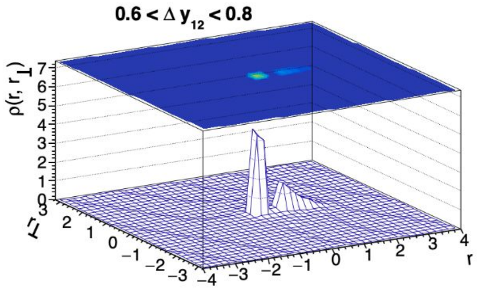
Arjun Kudinoor (Cambridge University)

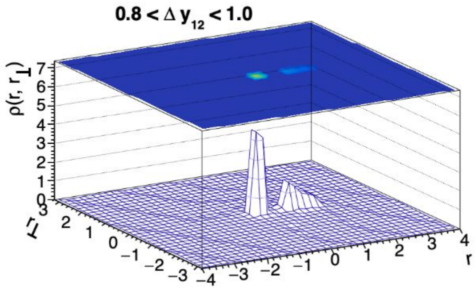
Dani Pablos (Universidad de Santiago de Compostela)

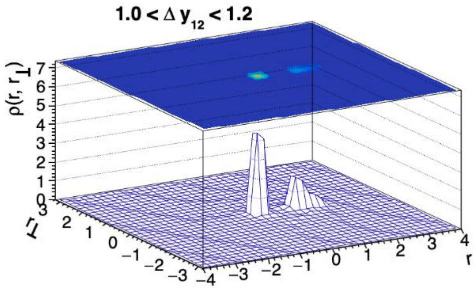
Do Subjets Have Separate Wakes?

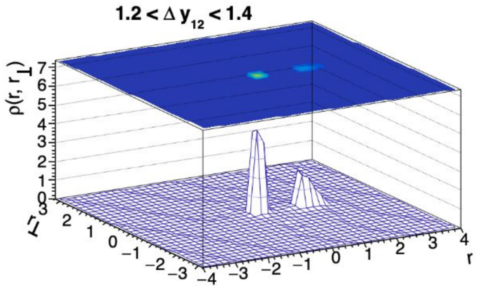
- A question prompted by an interesting observable, introduced by ATLAS at QM19. See 2301.05606.
- First reconstruct anti-k_t-$R = 0.2$ jets, call them subjets, with $p_T^{\text{subjet}} > 35$ GeV; then reconstruct anti-k_t-$R = 1.0$ jets from these objects.
- ATLAS finds R_{AA} for $R = 1.0$ jets with 1 (≥ 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 ΔR_{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.

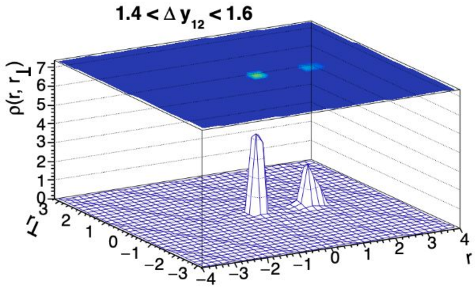
JET SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

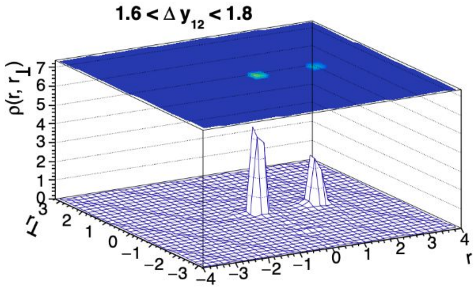


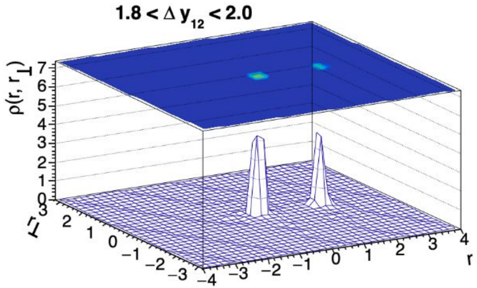








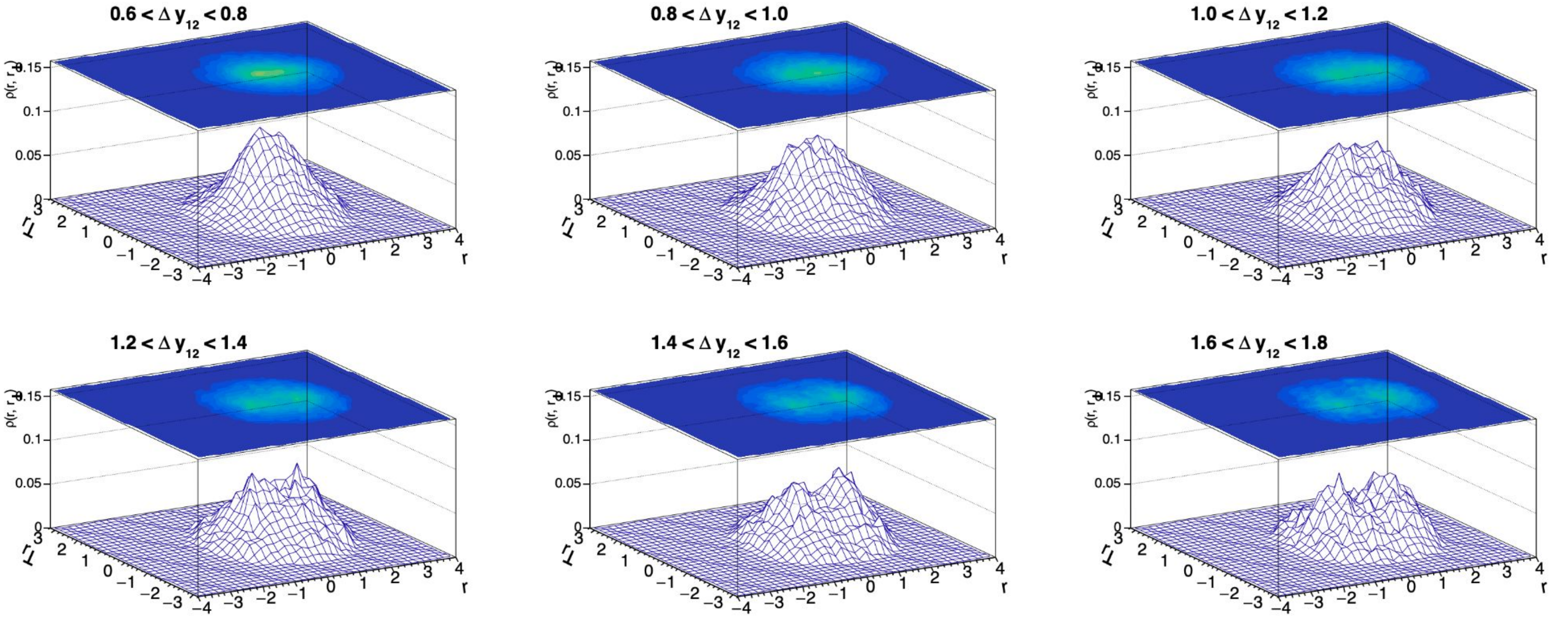


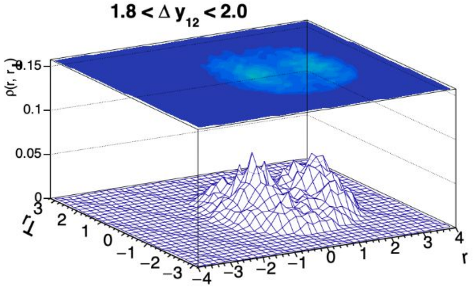


Pb+Pb (No Elastic), 5.02 TeV, 0-5%
Reclustered R = 2.0 jets with up to 2 subjets
$|y| < 2.0$ $50 < p_T < 1000$ GeV
All particles within R = 2.0 radius of reclustered jet axis

Photon selection and isolation criteria:
$p_T^\gamma > 100$ GeV $|\eta^\gamma| < 1.44$
Around R = 0.4 of γ, $\Sigma E_T < 5.0$ GeV
$\Delta\phi(\gamma, \text{jet}) > 2\pi/3$

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

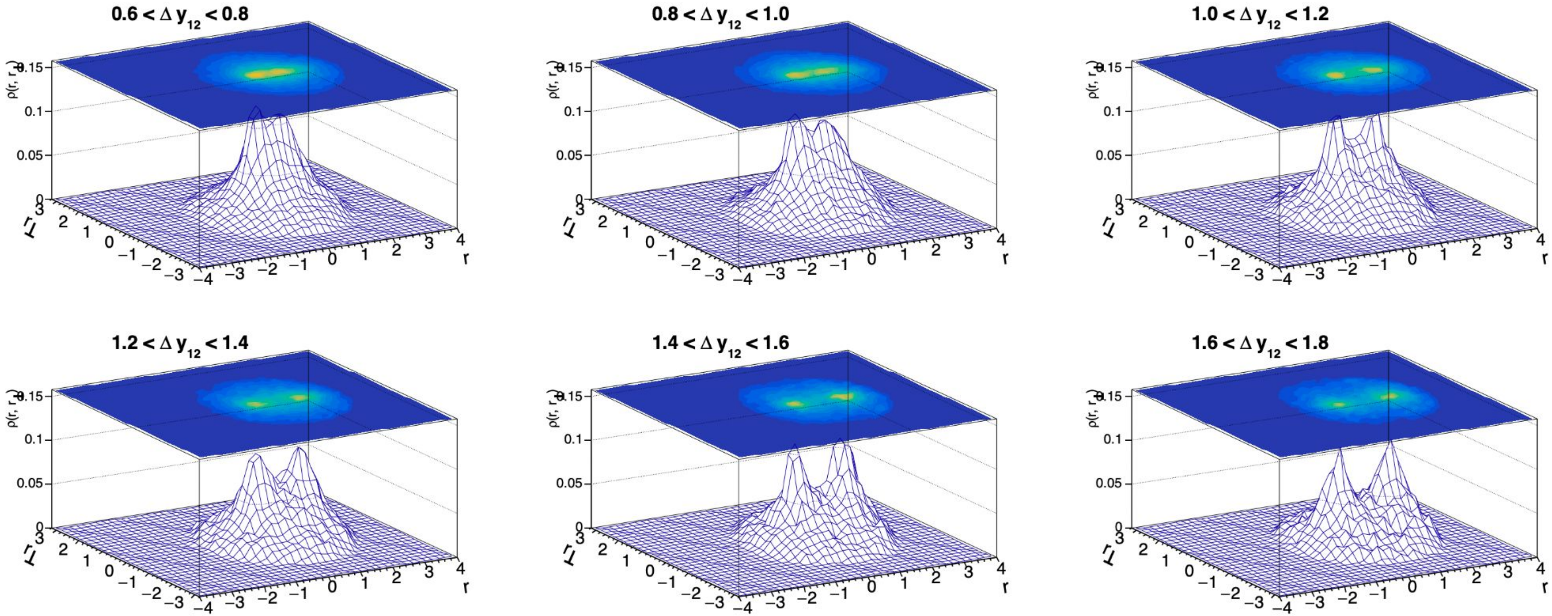


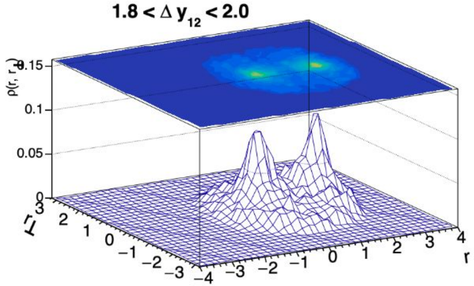


Even when subjets are separated by $\Delta y_{12} < 1.0$, there is a single wake produced by 2 hard structures (the subjets). **Two distinct sub-wakes are visibly produced only when the subjets are quite far-separated** (around $\Delta y_{12} > 1.4$)!

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

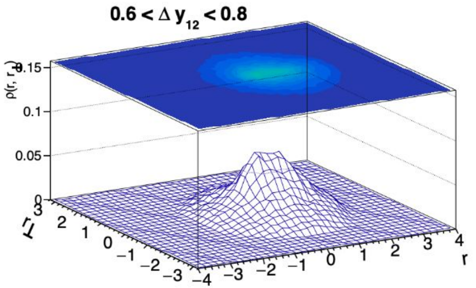


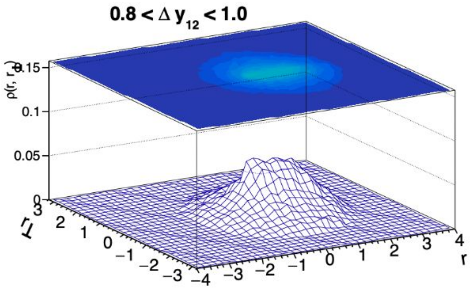


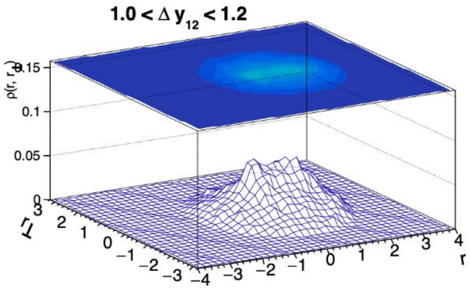
Experimentalists look for the wake by restricting to observing particles with low-p_T.

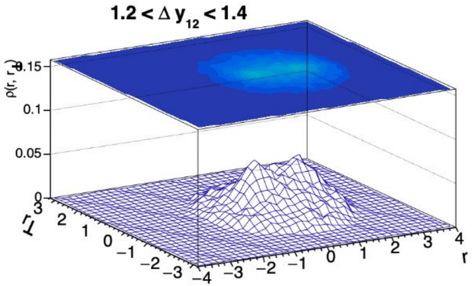
If we restrict to calculating the jet shape for particles with p_T < 1.5 GeV, then it begins to resemble the shape of the wake.

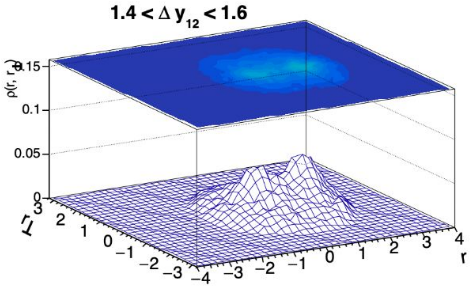
SHAPE OF PARTICLES WITH P_T < 1.0 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

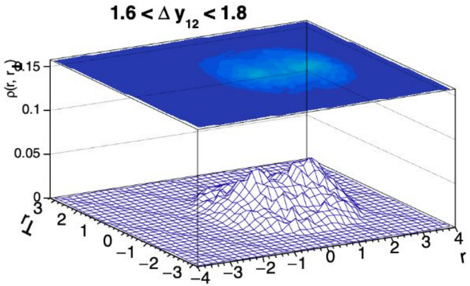


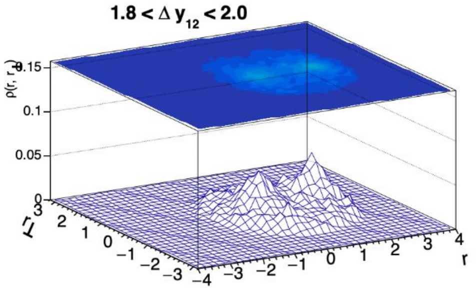






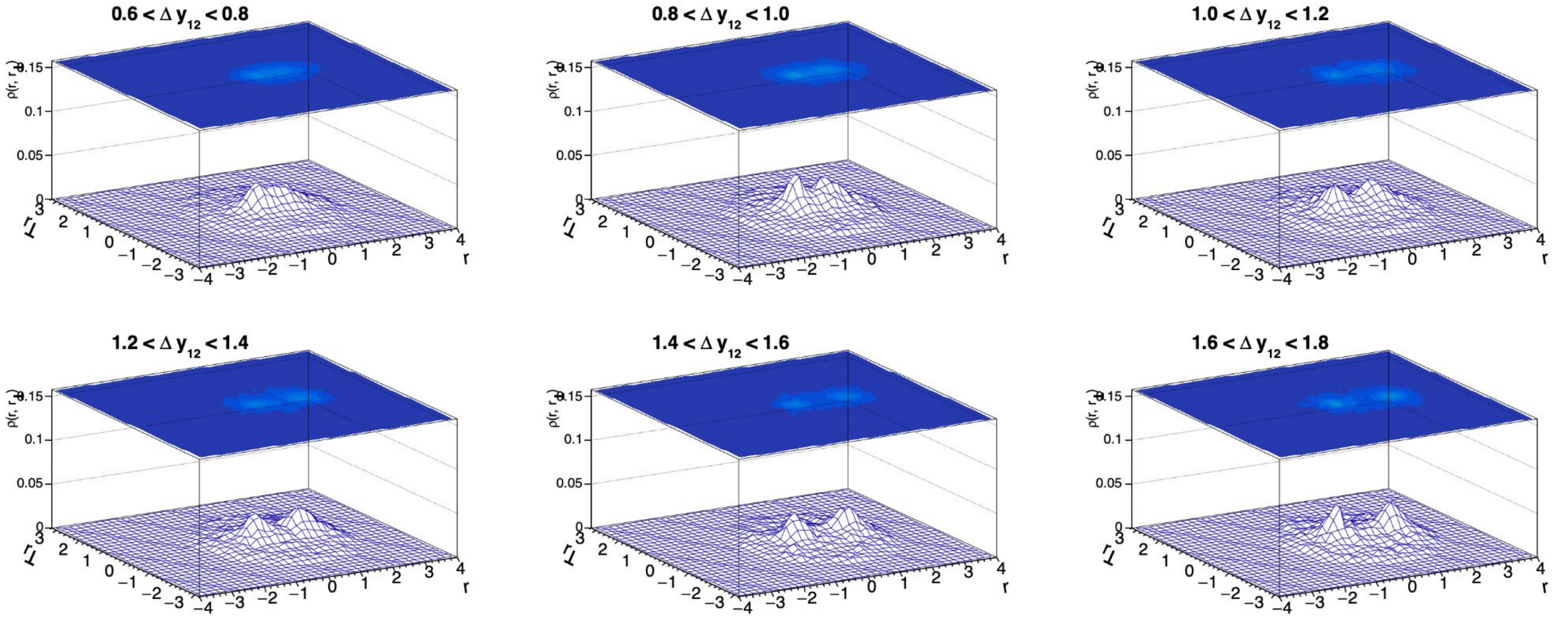


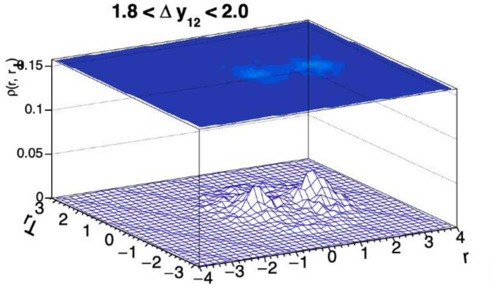




When restricting to particles with p_T < 1.0 GeV, the jet shape looks quite similar to the wake. In particular, a single broad soft structure is observed when $\Delta y_{12} < 1.0$, and two distinct soft structures are visible when $\Delta y_{12} > 1.4$.

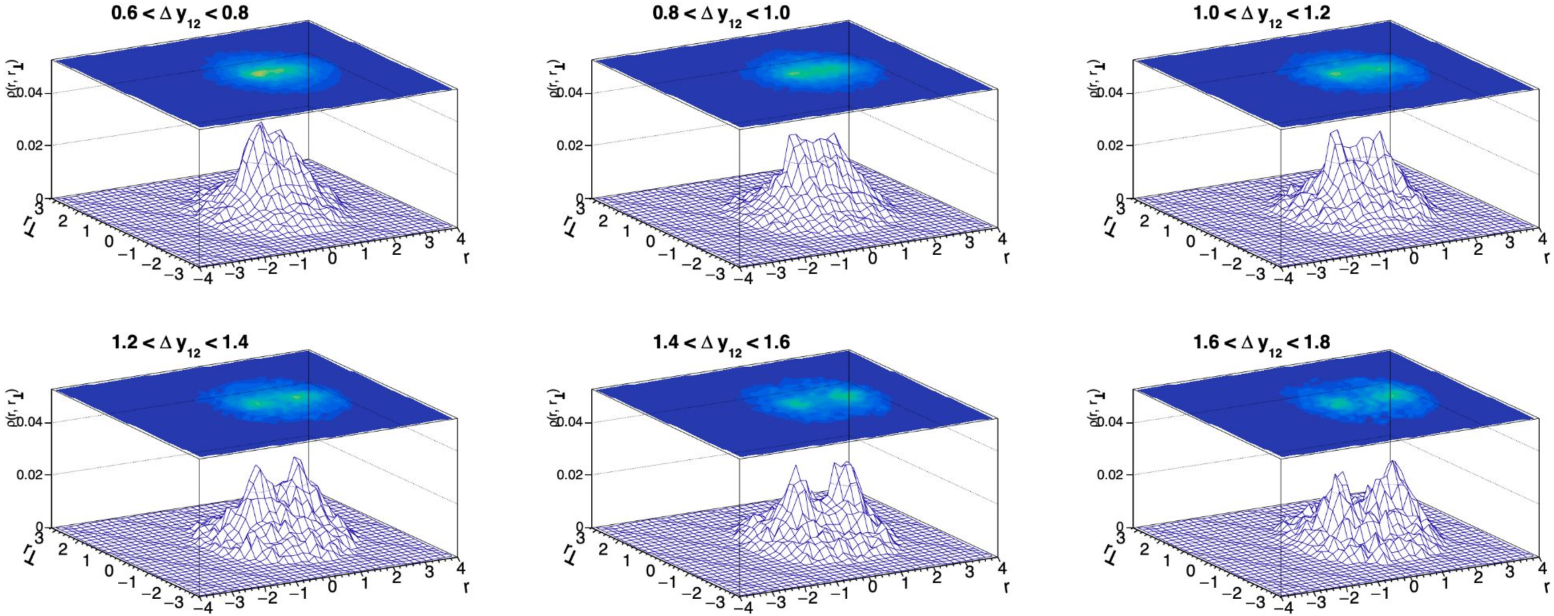
SHAPE OF PARTICLES WITH P_T < 1.0 GeV IN GAMMA-JETS IN pp COLLISIONS WITH 2 SUBJETS

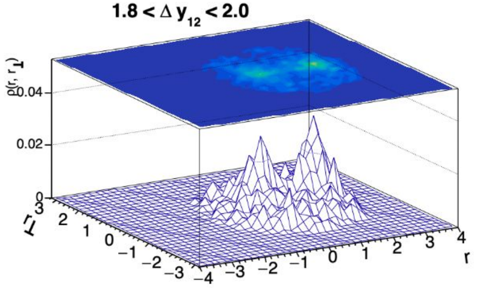




At very low p_T of less than 1.0 GeV, there are still two distinct peaks in the vacuum (pp) case… even when the subjets are closely-separated!

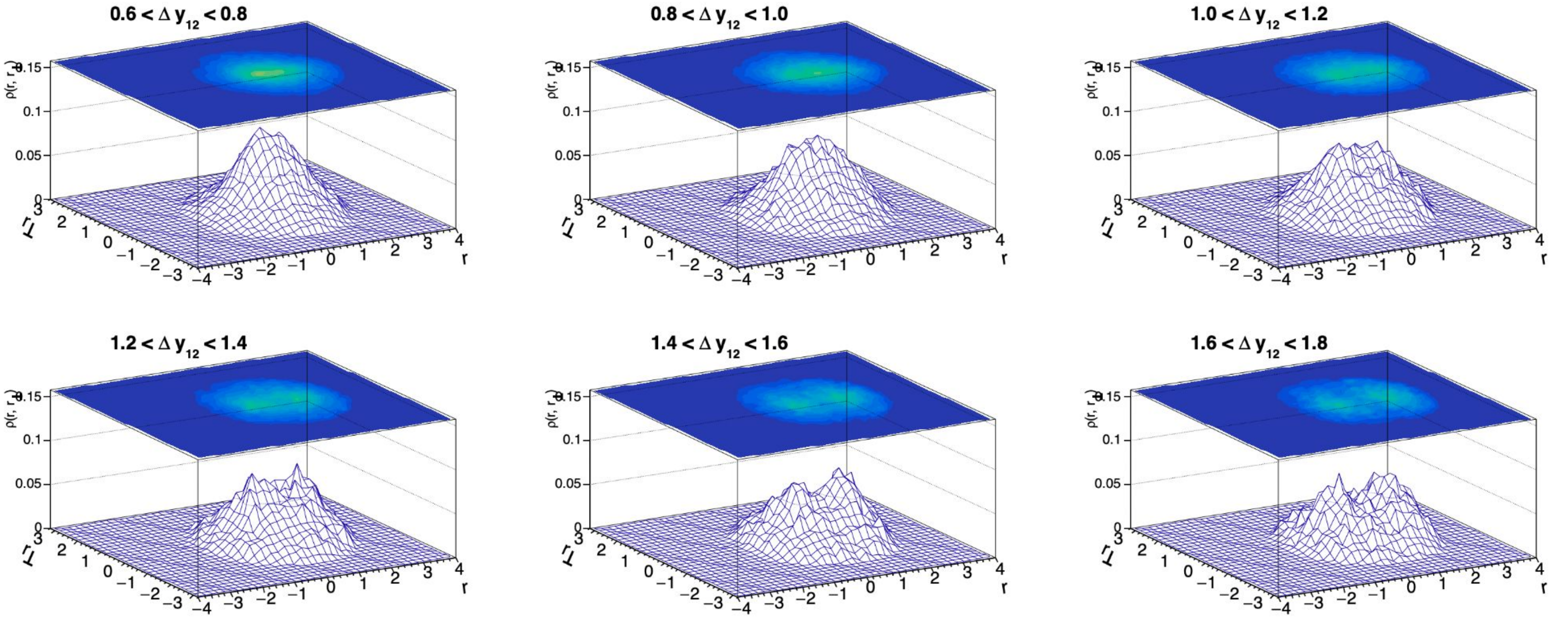
SHAPE OF PARTICLES WITH 0.7 < P_T < 1.0 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

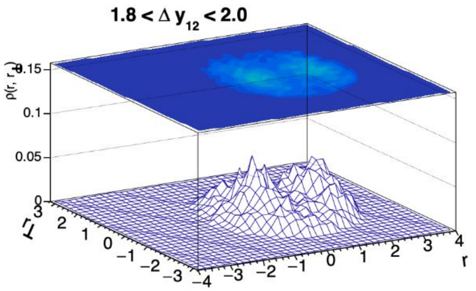




When restricting to particles with 0.7 < p_T < 1.0 GeV, the feature of sub-wake emergence only at large Δy_{12} survives! So, this feature of wake substructure could survive experimental background subtraction.

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





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

How can we see this in experiments?

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

Krishna Rajagopal

MIT

work in progress with

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

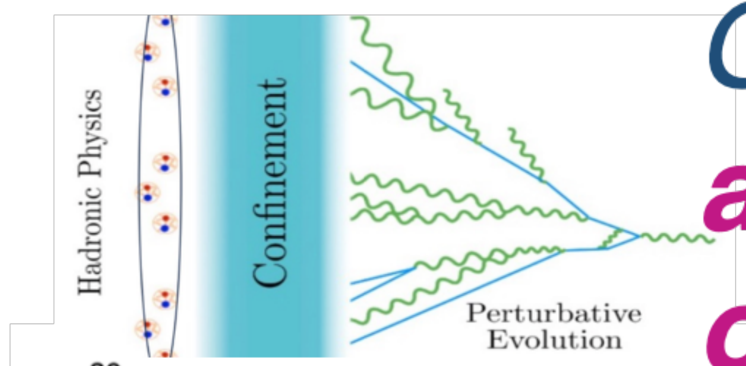
Ian Moult (Yale), Dani Pablos (Santiago),

Ananya Rai (Yale)

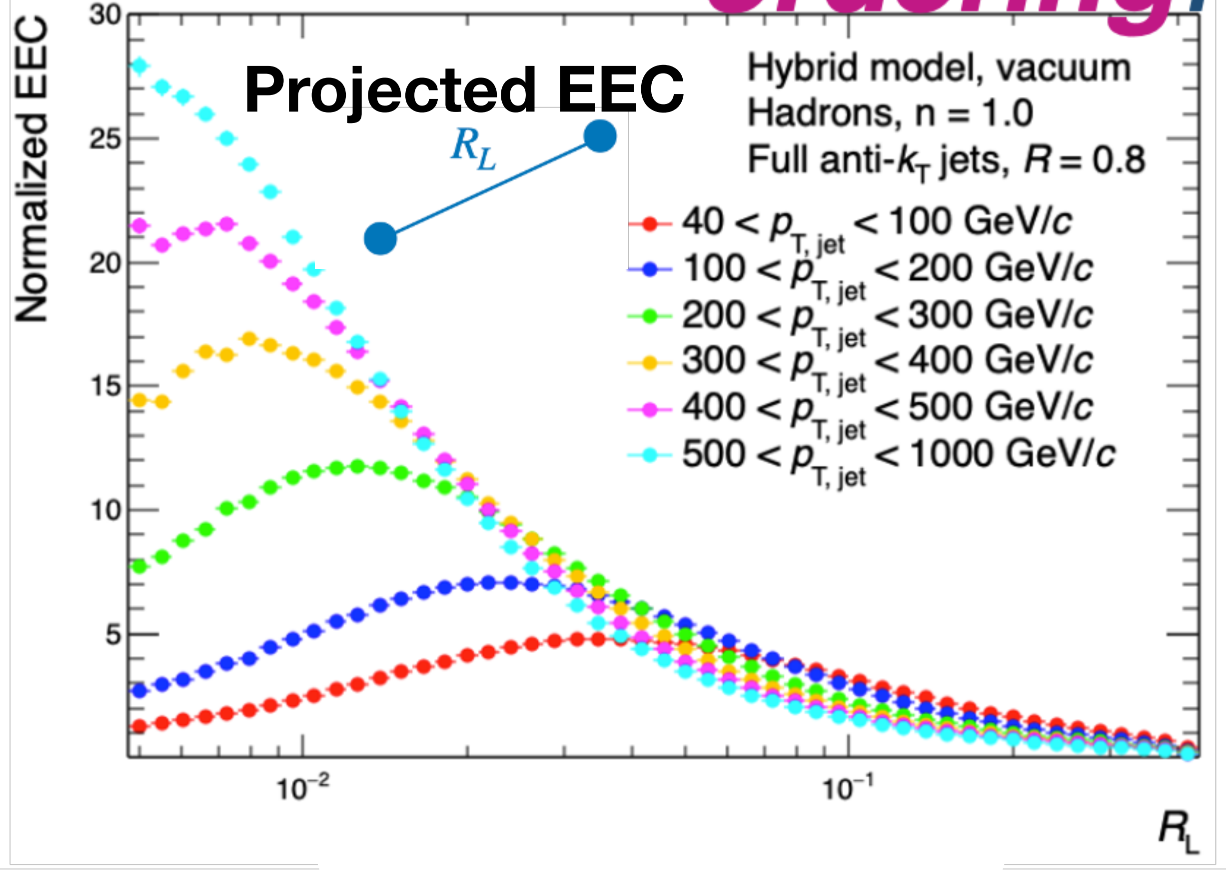
Energy Correlators in Vacuum

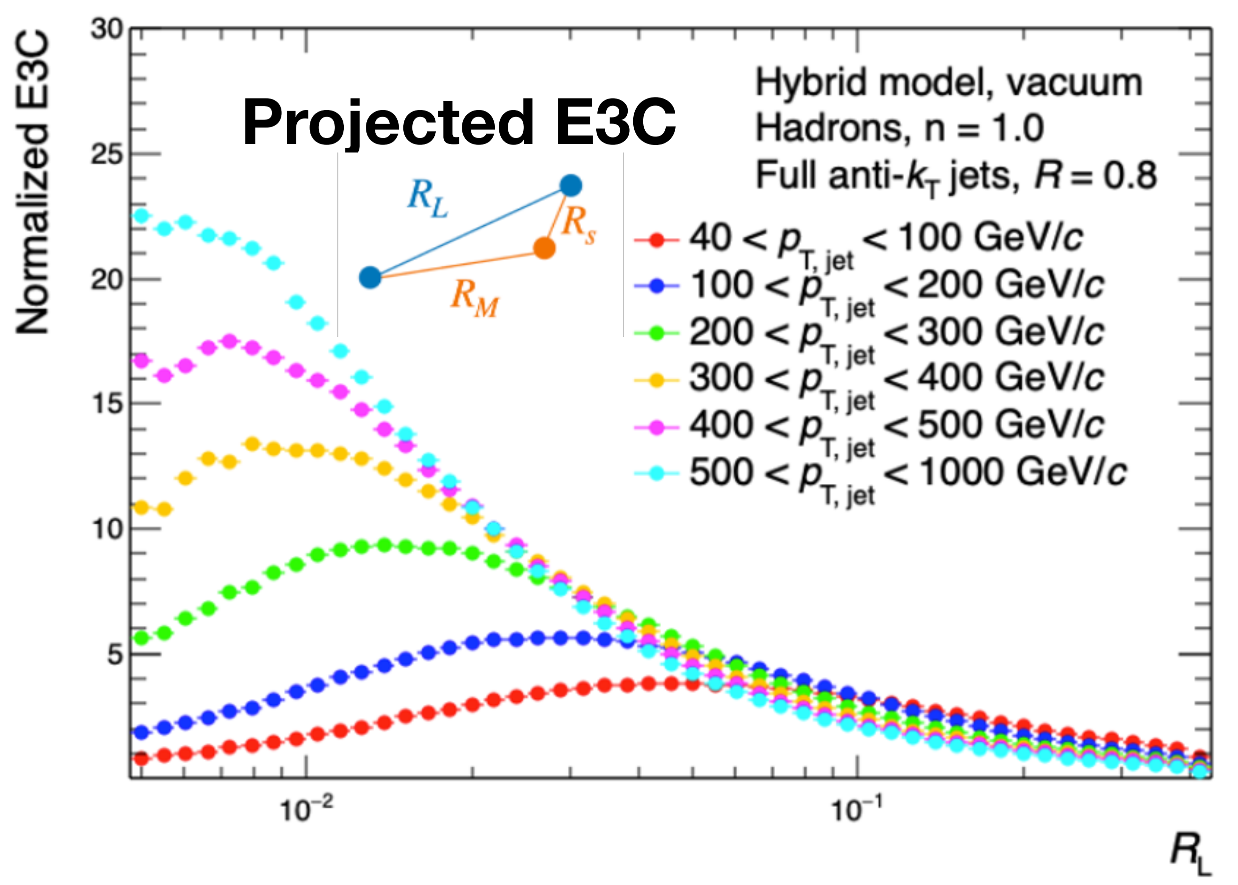
$$\mathrm{ENC}(R_L) = \left(\prod_{k=1}^{N} \int d\Omega_{\vec{n}_k} \right) \delta(R_L - \Delta\hat{R}_L) \cdot \frac{1}{(E_{\mathrm{jet}})^N} \langle \mathscr{E}(\vec{n}_1)\mathscr{E}(\vec{n}_2)\cdots\mathscr{E}(\vec{n}_N) \rangle$$

Projected Correlators



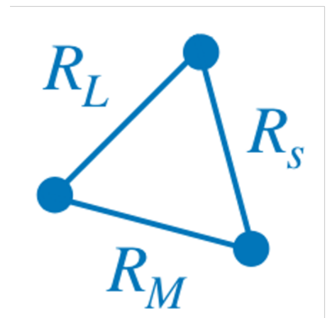
QCD ***angular ordering!***



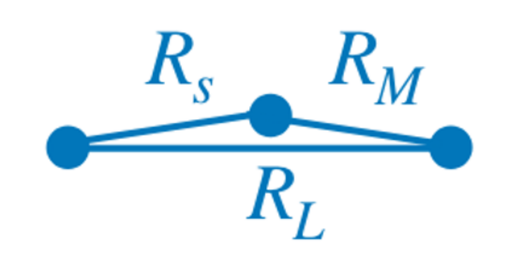


3-point correlator (EEEC)

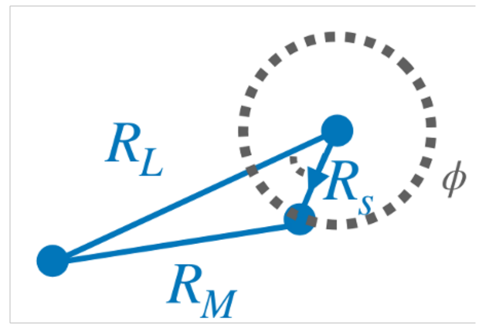
Configurations: Equilateral



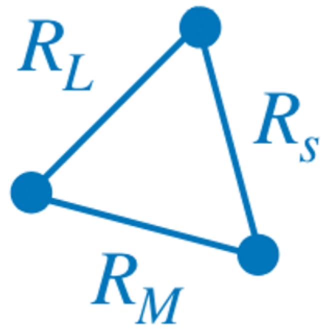
Flat



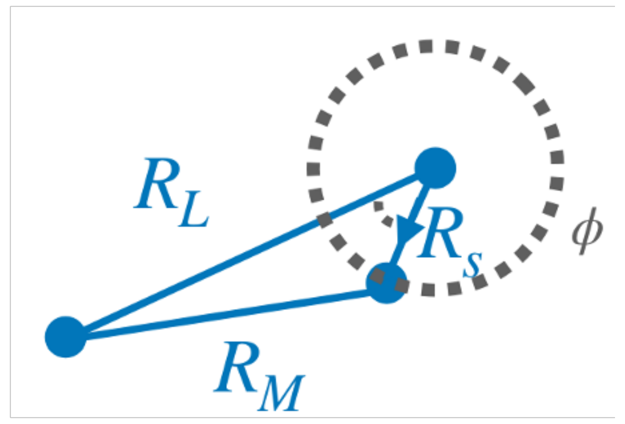
Isosceles

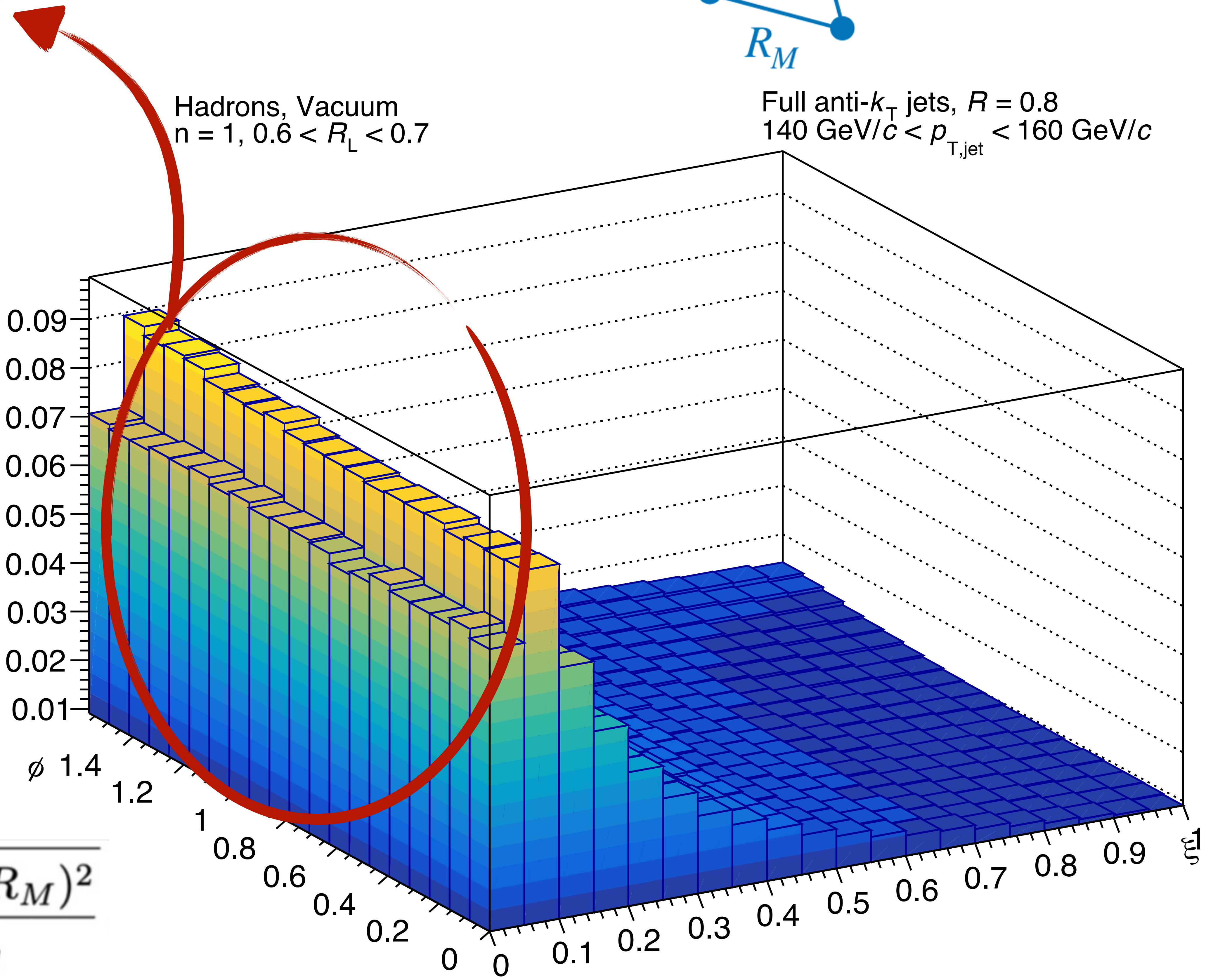


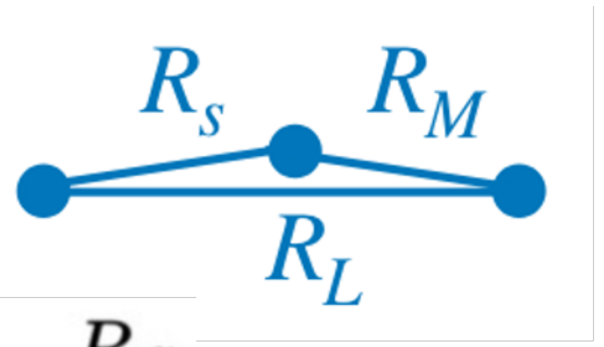
Collinear *singularity of vacuum QCD!*



Collinear Singularity







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

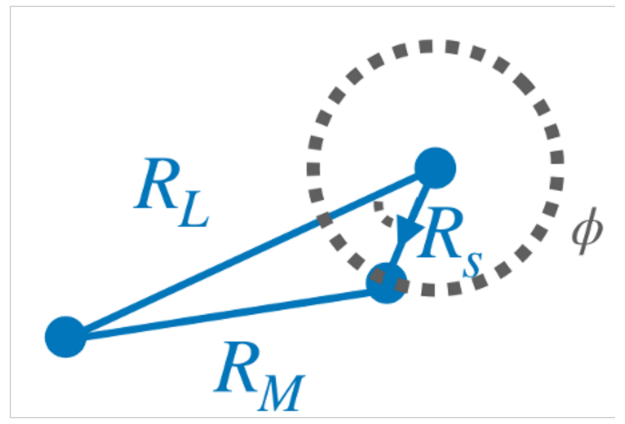
$$\xi = \frac{R_S}{R_M}$$

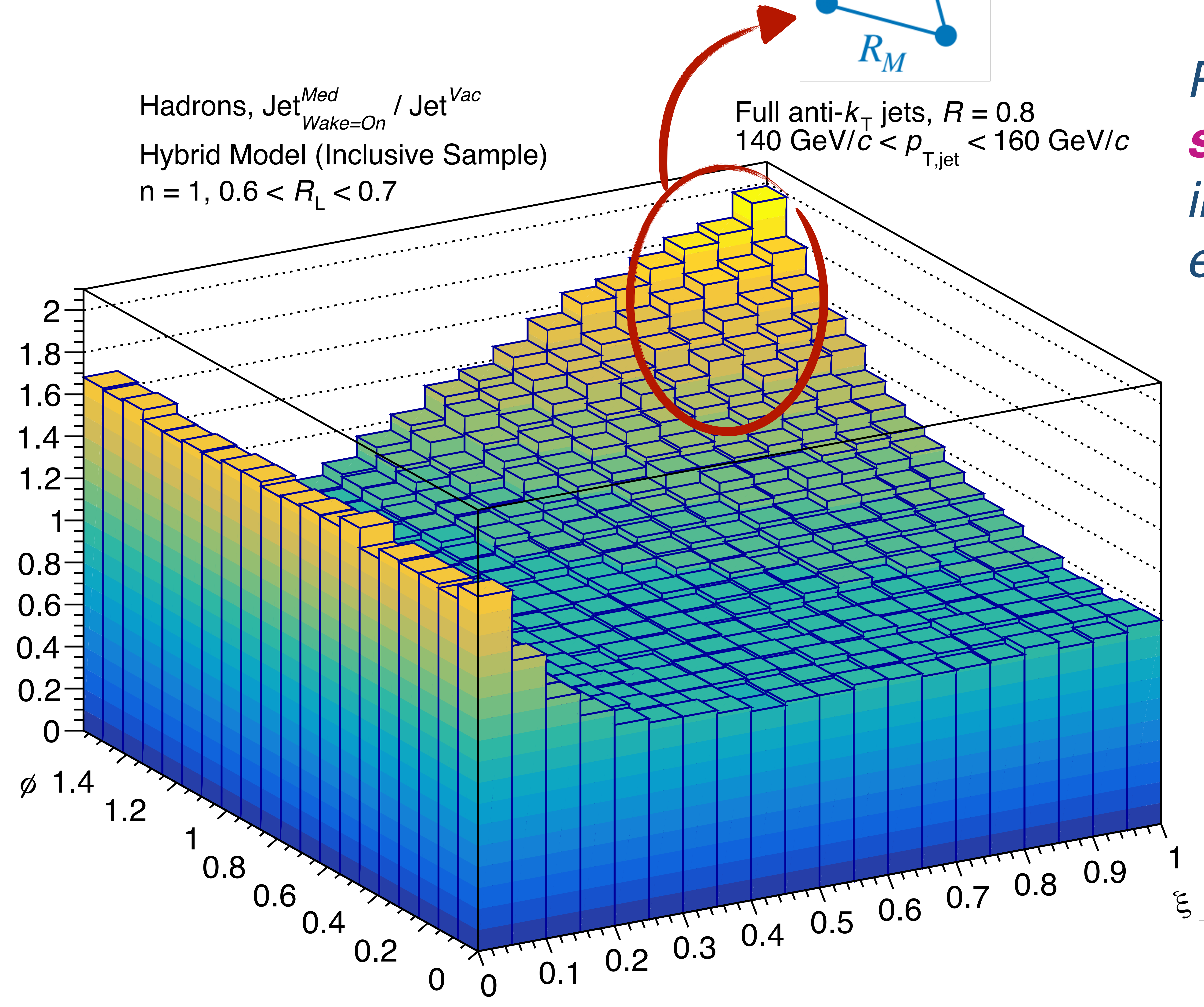
EEEC sensitivity to the Wake

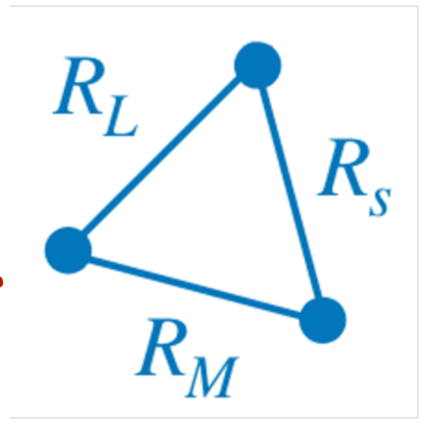
Pb-Pb/Vacuum

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

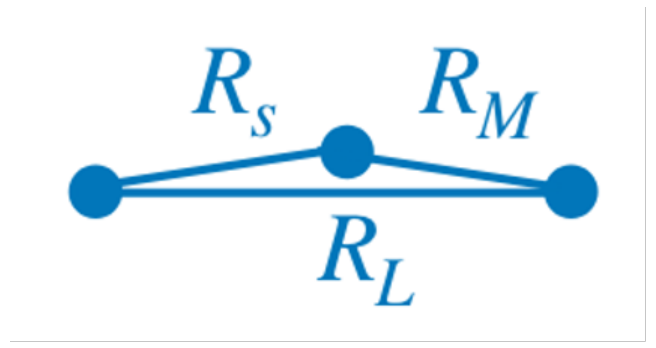
Jet Radius = 0.8







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

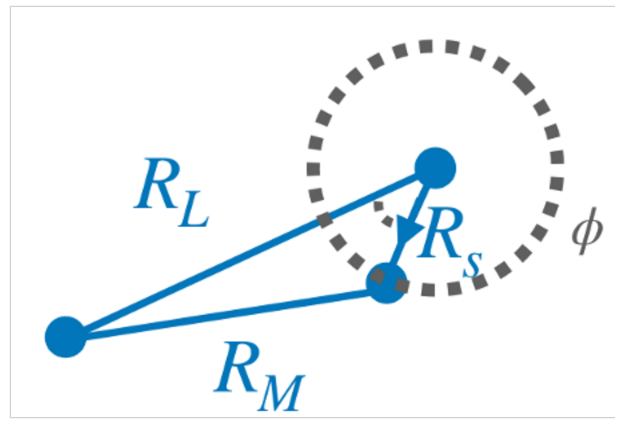


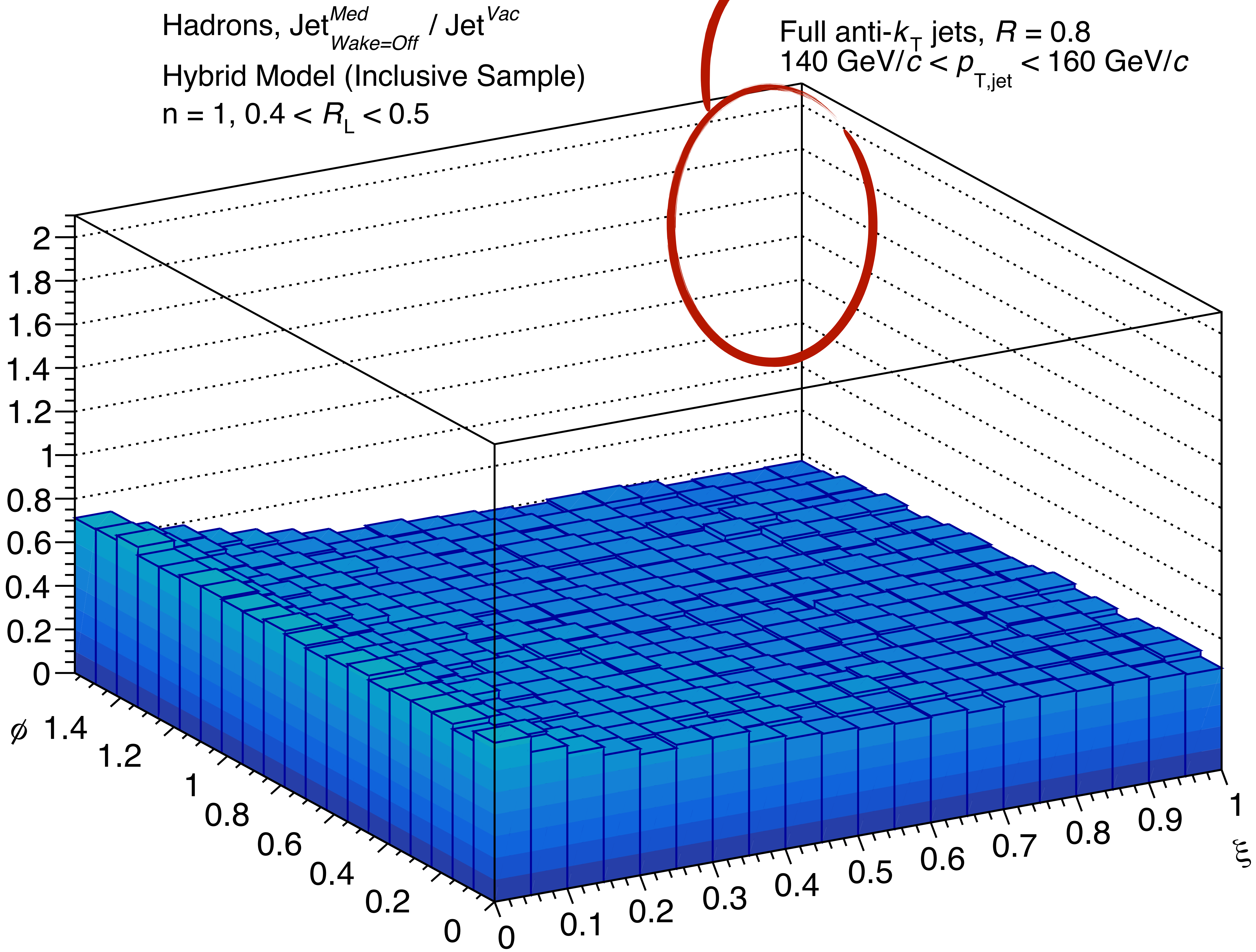
EEEC sensitivity to the Wake

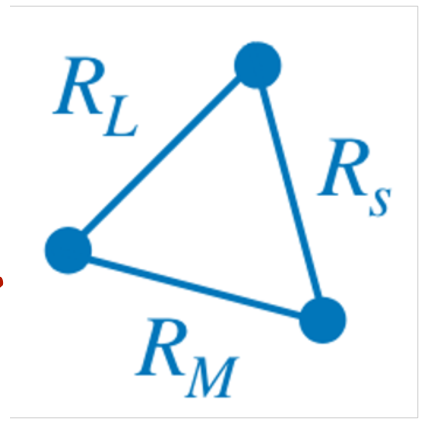
Pb-Pb-without-wake/Vacuum

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

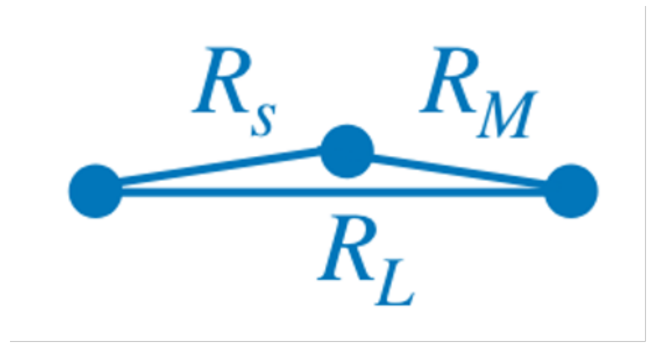
Jet Radius = 0.8





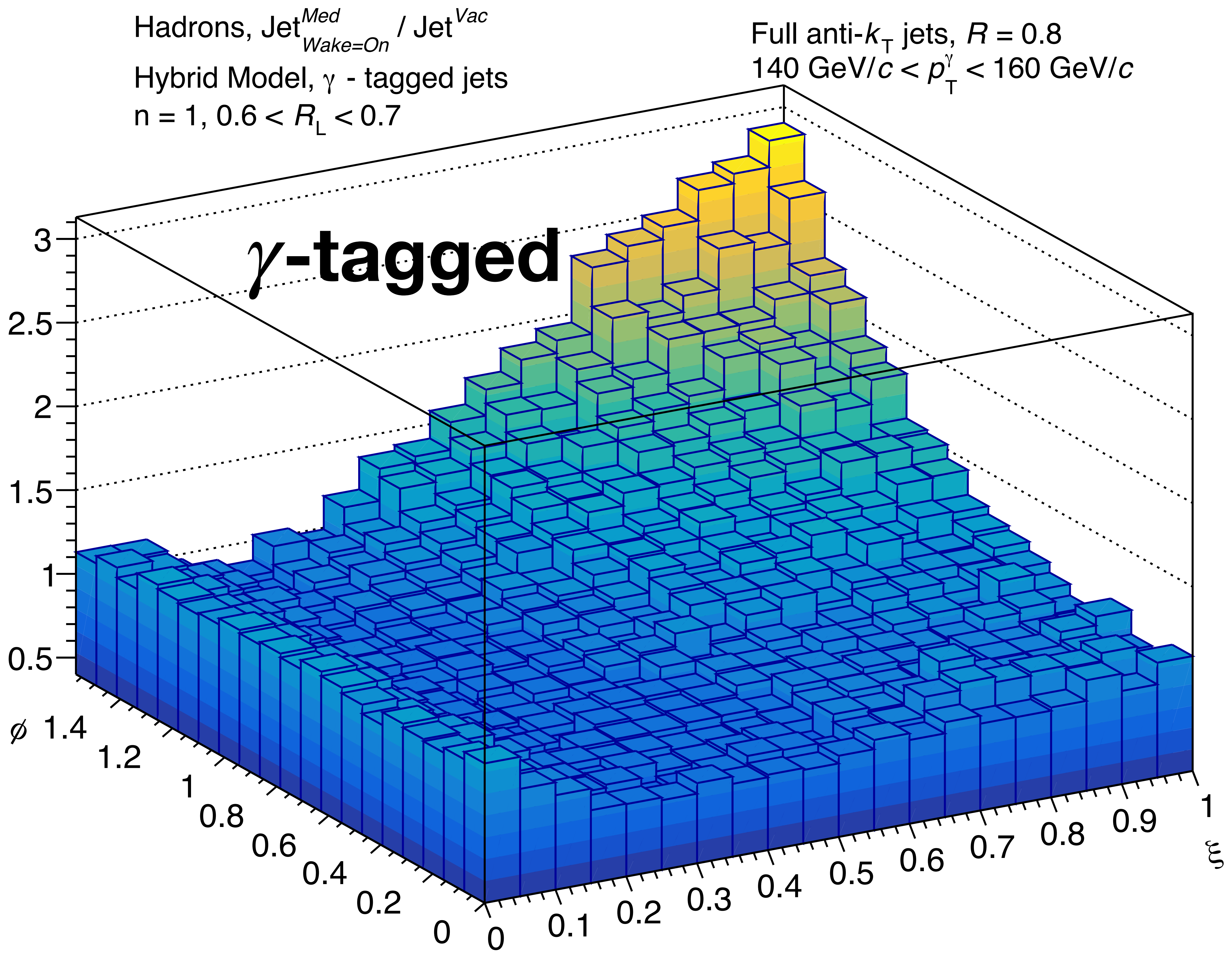


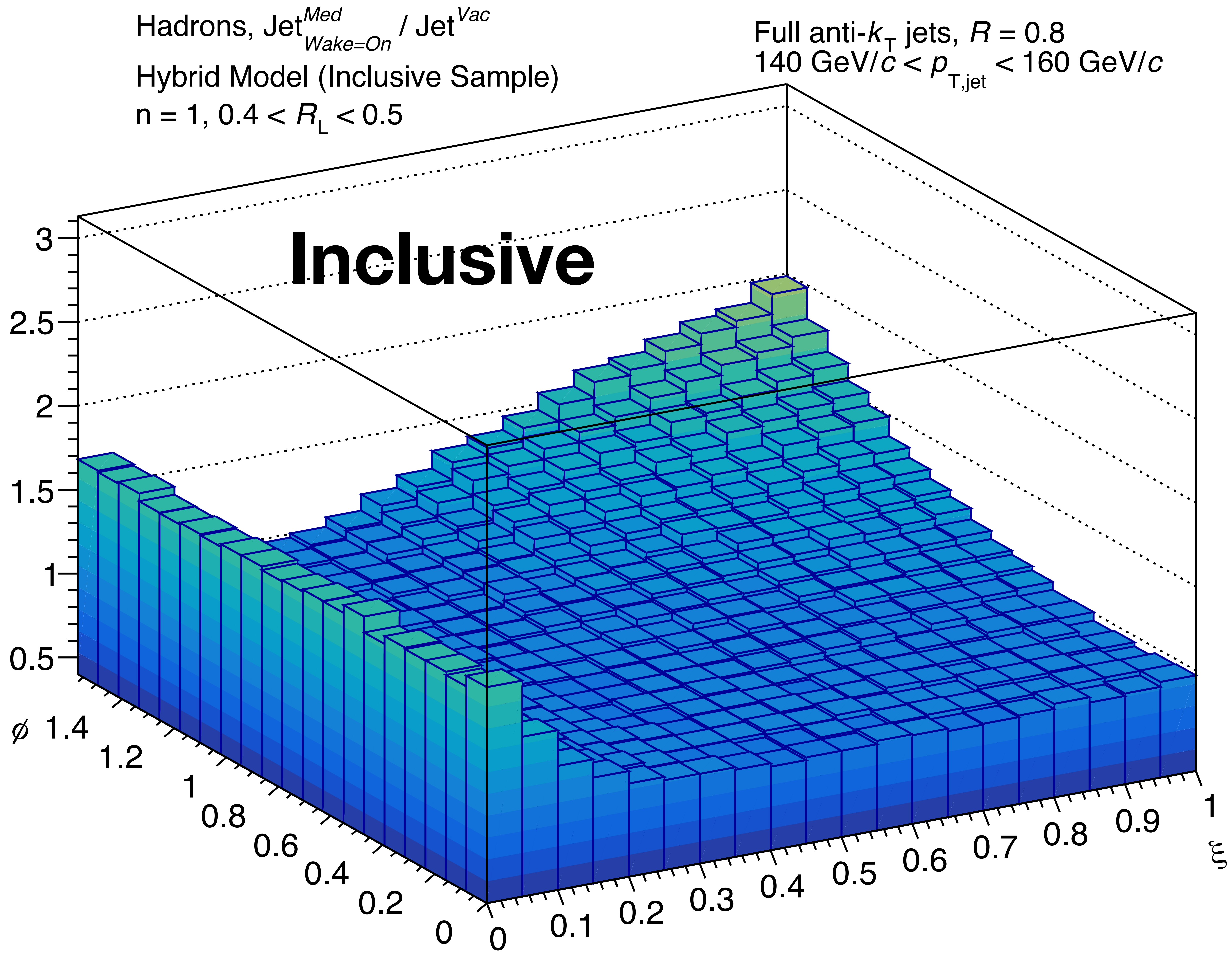
Ratio with vacuum shows ***no*** *enhancement in the* ***equilateral region****!*



Pb-Pb/Vacuum Ratio: γ-tagged vs Inclusive

The effect of the wake is more pronounced in γ-tagged jets!

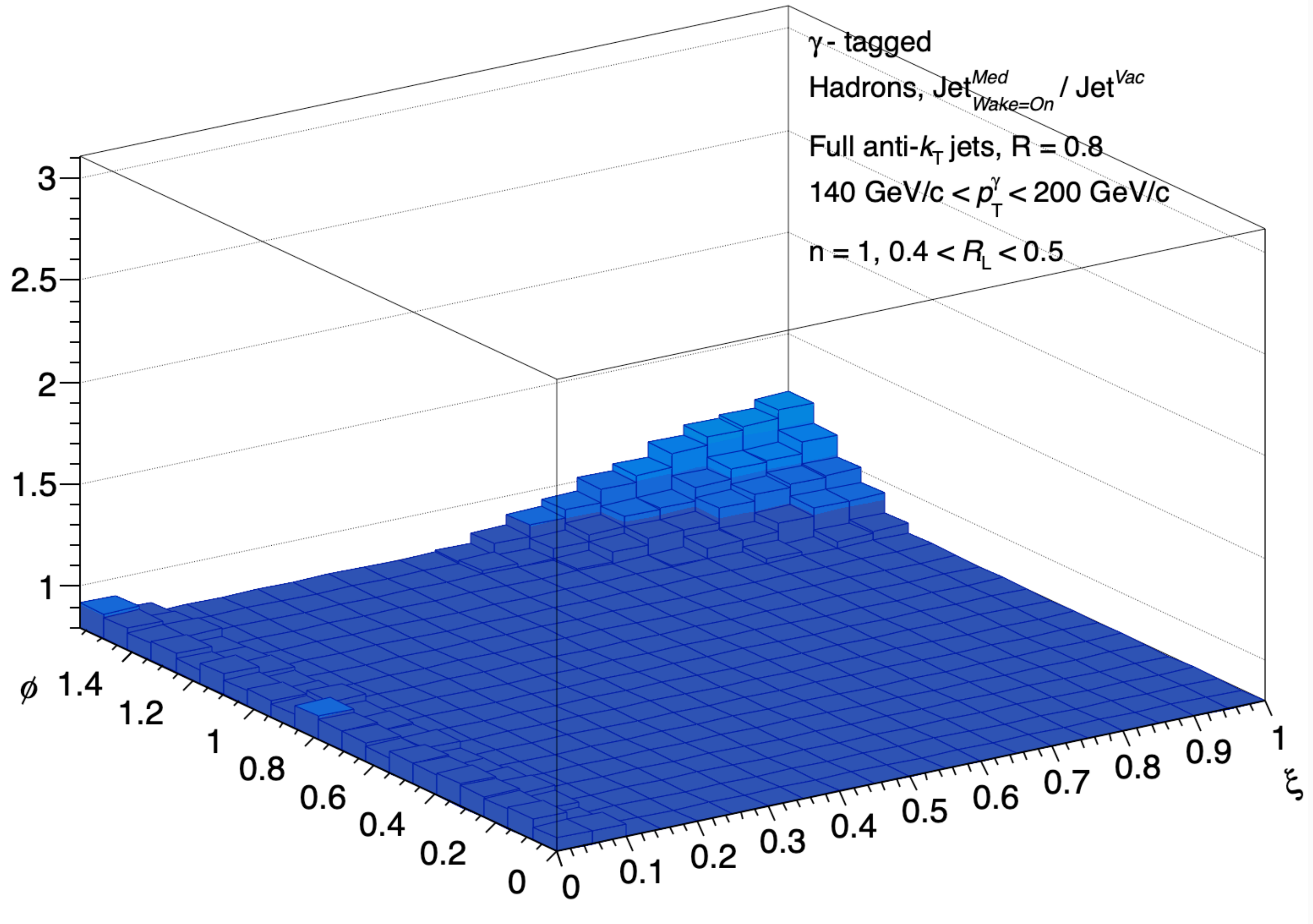




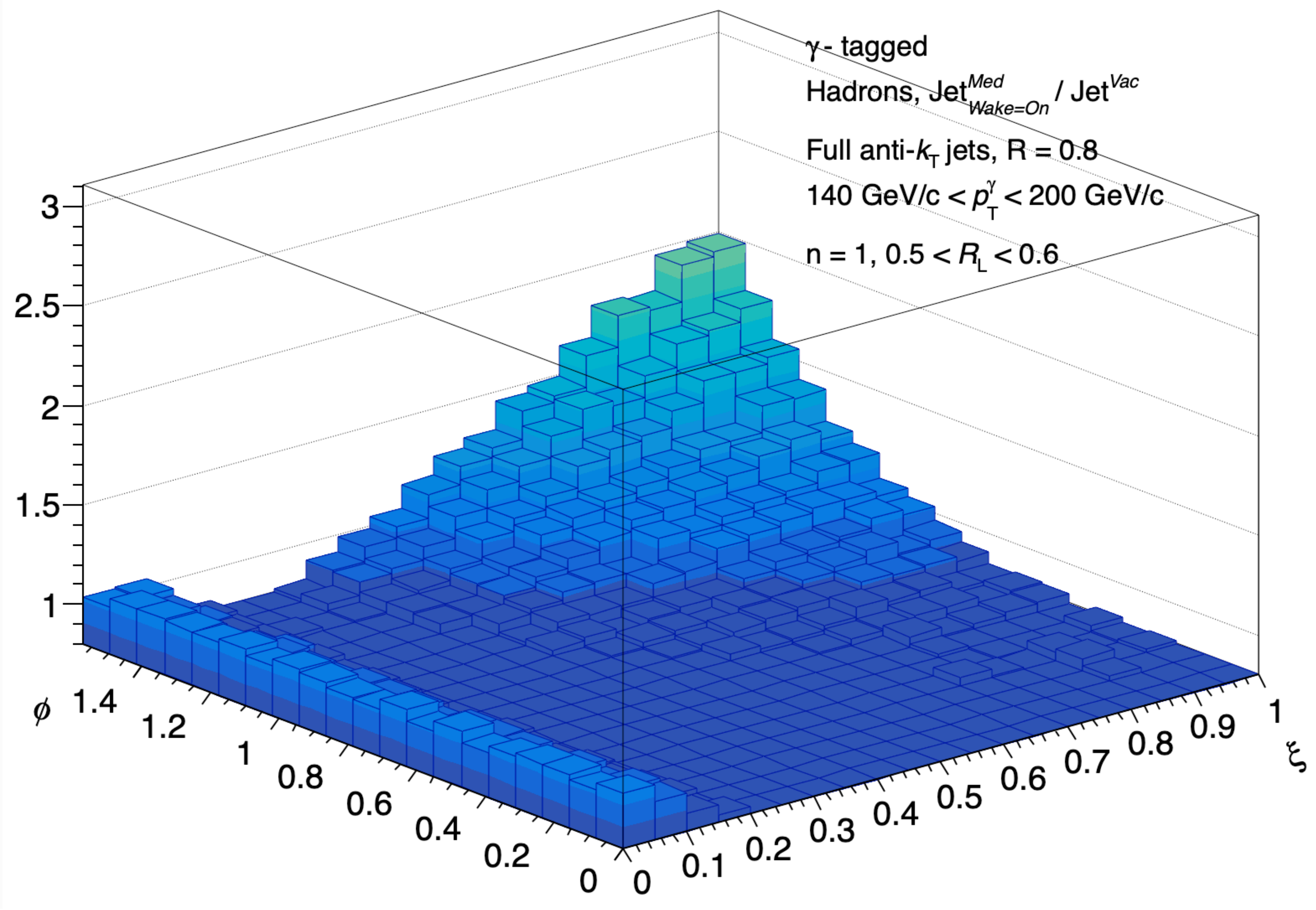
$p^{jet}_{T,min} > 40\ GeV/C$

R_L dependence, γ-tagged

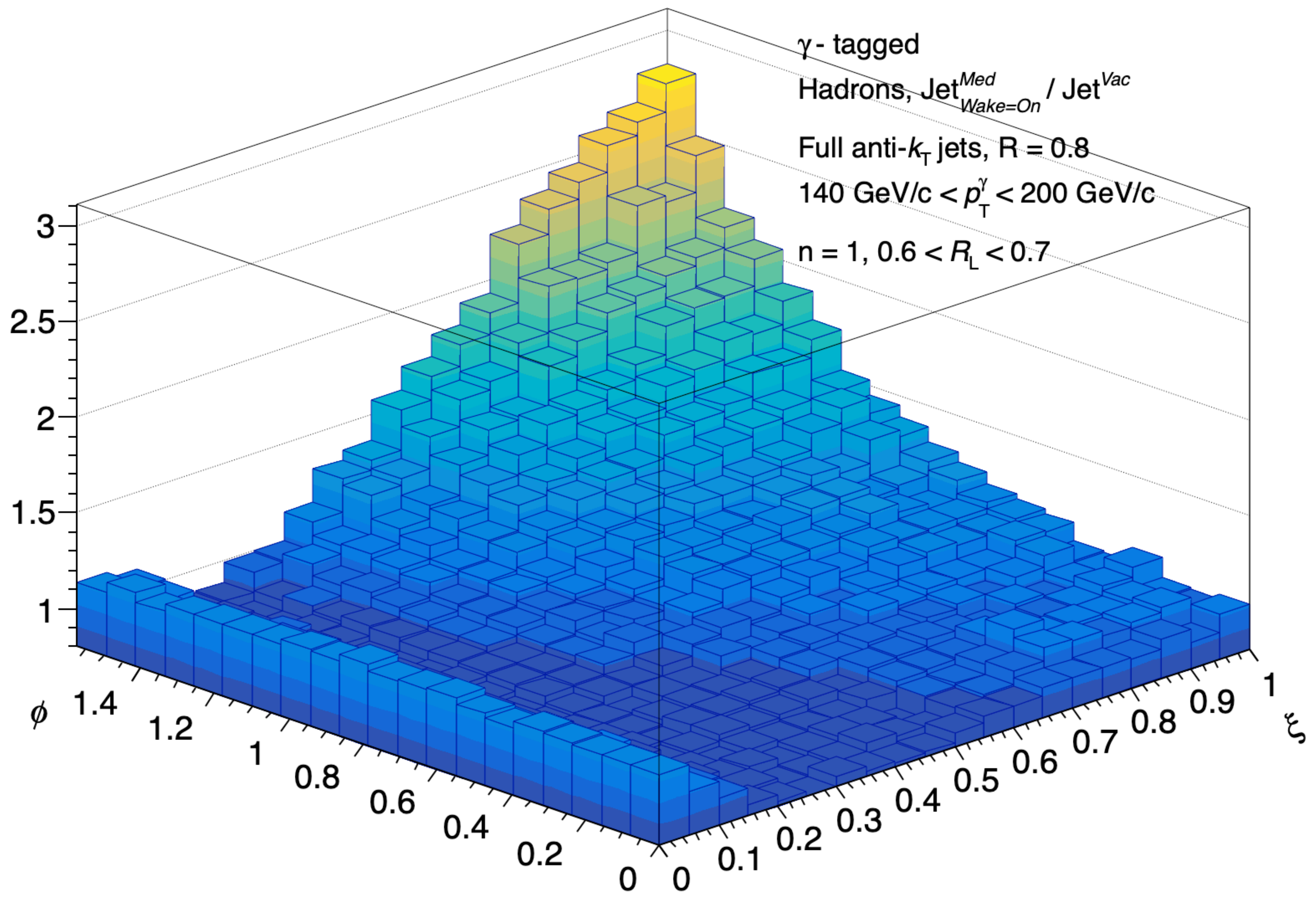
$0.4 < R_L < 0.5$



$0.5 < R_L < 0.6$



$0.6 < R_L < 0.7$



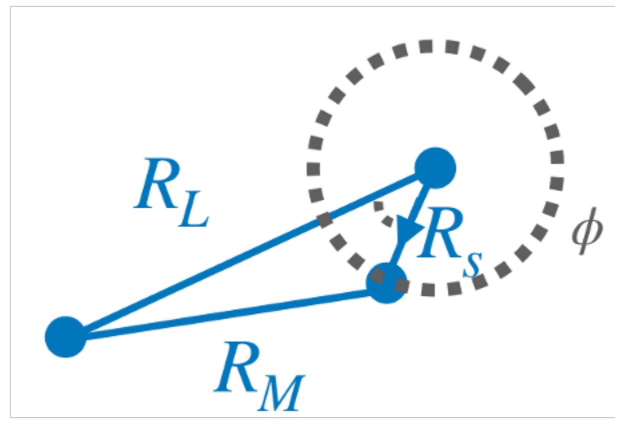
$140\ GeV/c < p_T^{\gamma} < 200\ GeV/c$ $\quad$ $p_{T,min}^{jet} > 40\ GeV/C$

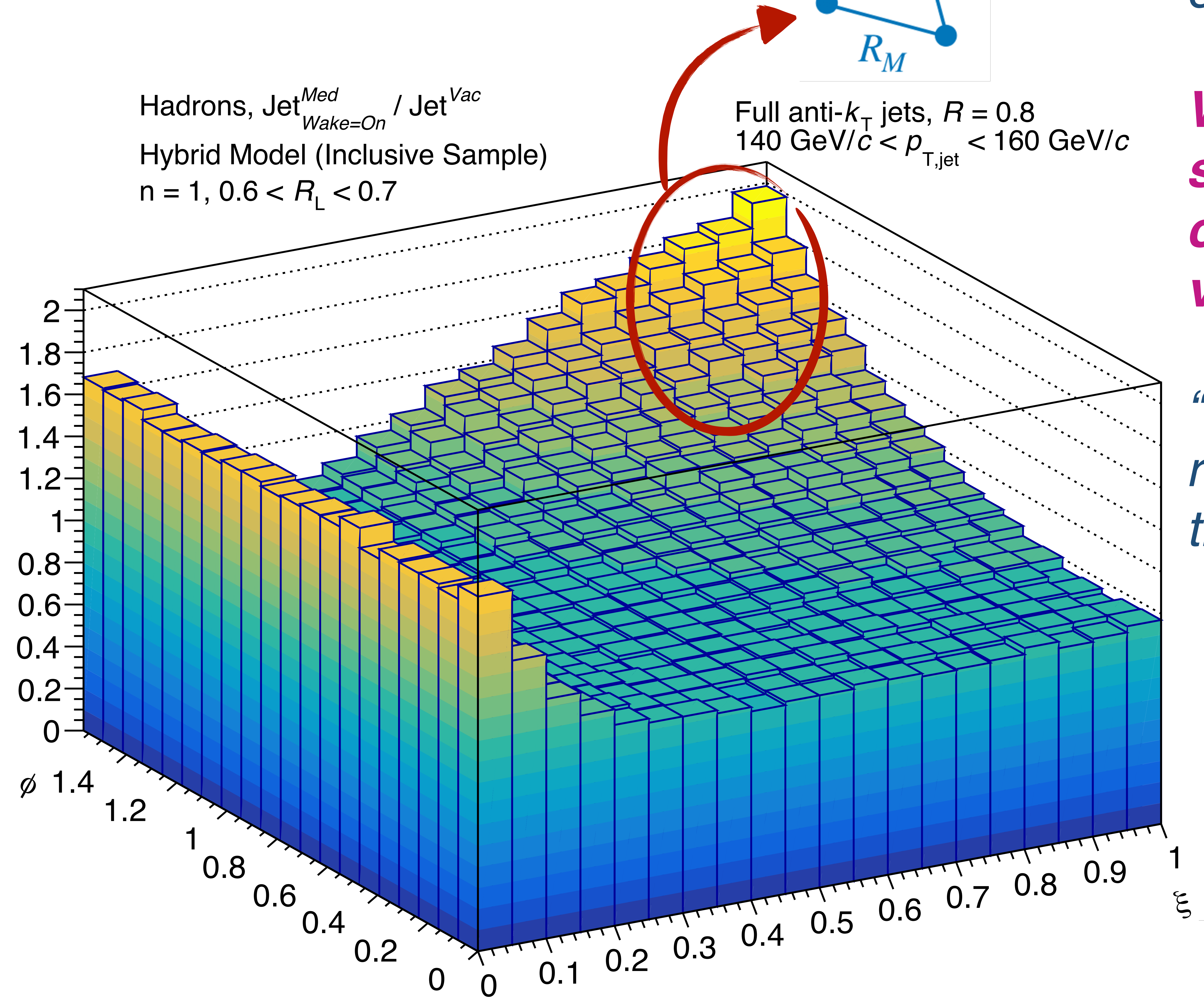
EEEC sensitivity to the Wake

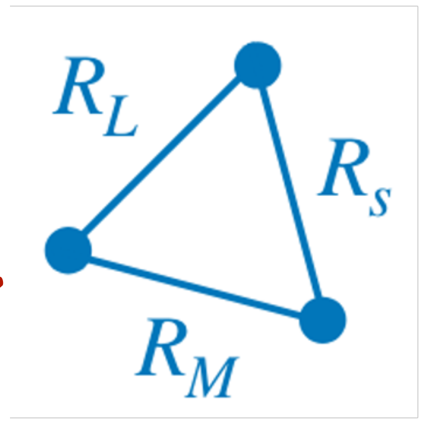
Pb-Pb/Vacuum

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

Jet Radius = 0.8



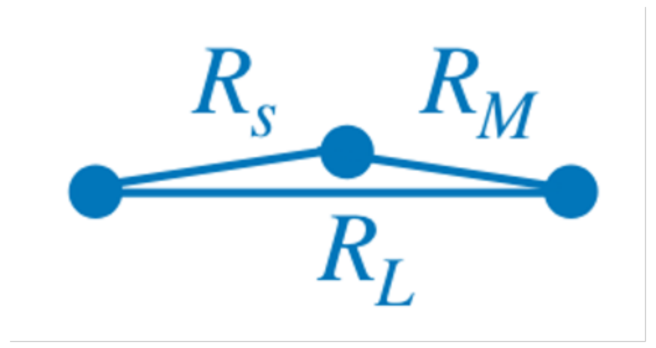




*Ratio with vacuum shows **significant** enhancement in the **equilateral region** - effect of the **wake!***

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)

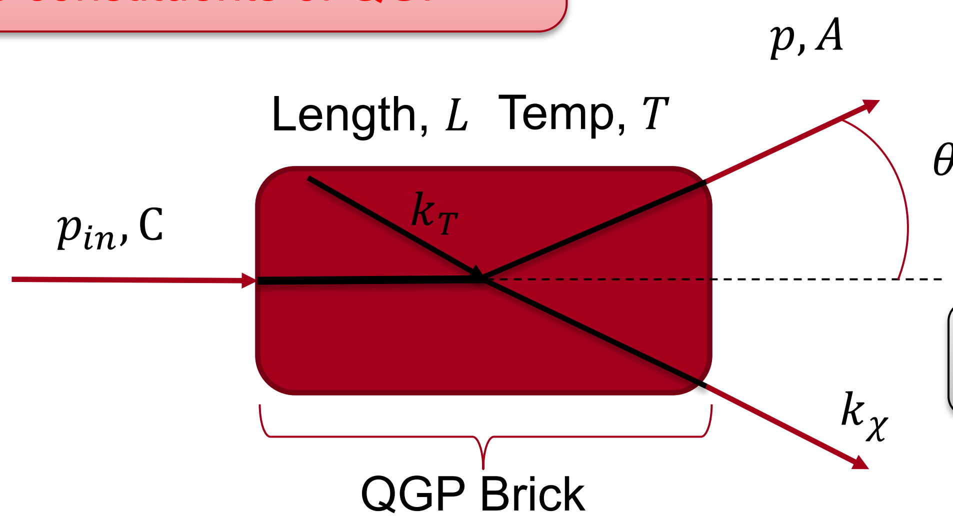
Why Molière scattering?
Why add to Hybrid Model?

- 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



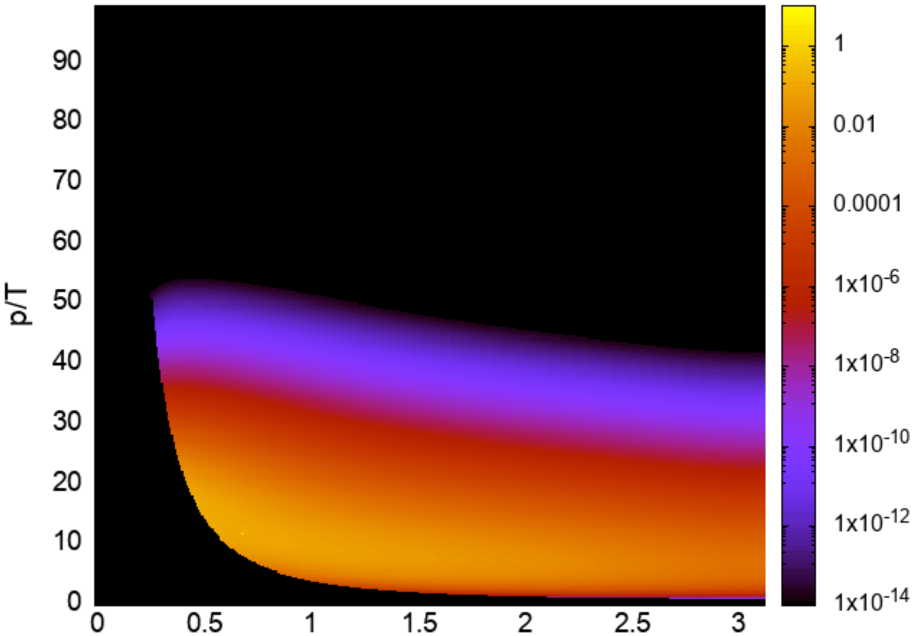
D'Eramo et al., 2019

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

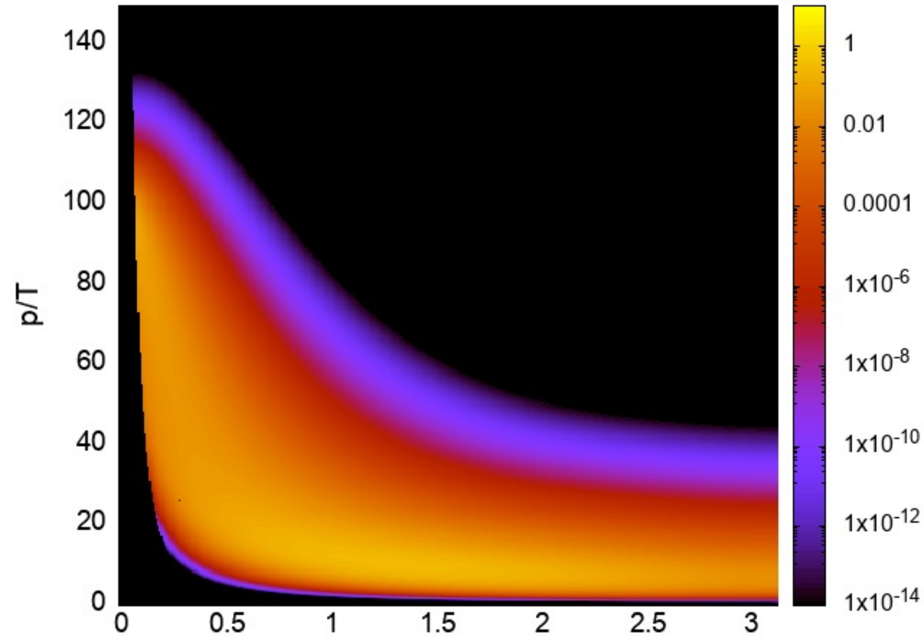
Tree-Level 2-2 massless scattering amplitudes

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

Results (for a QGP brick)



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



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

- 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 → 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

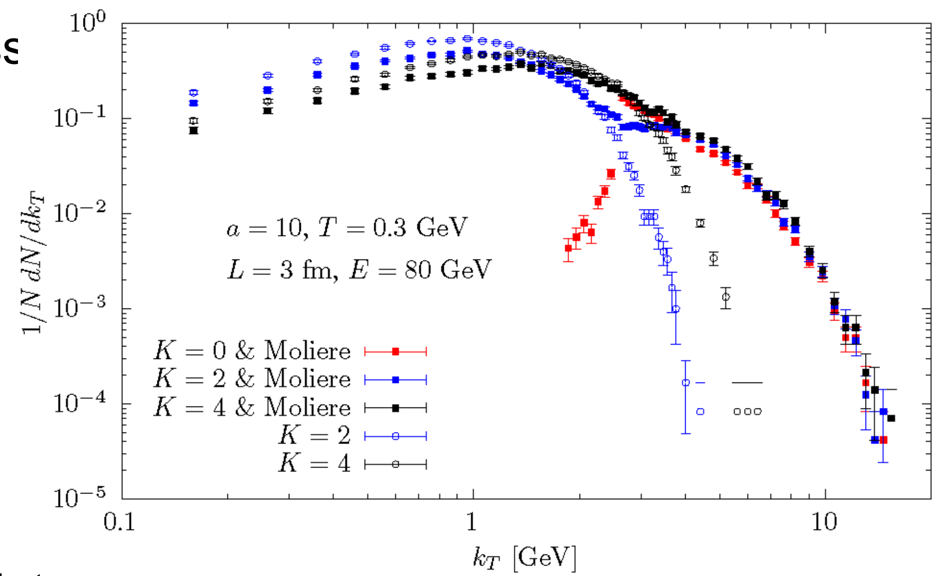
At strong coupling, holography predicts Gauss broadening without quasi-particles (eg: N=4 SYM)

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

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

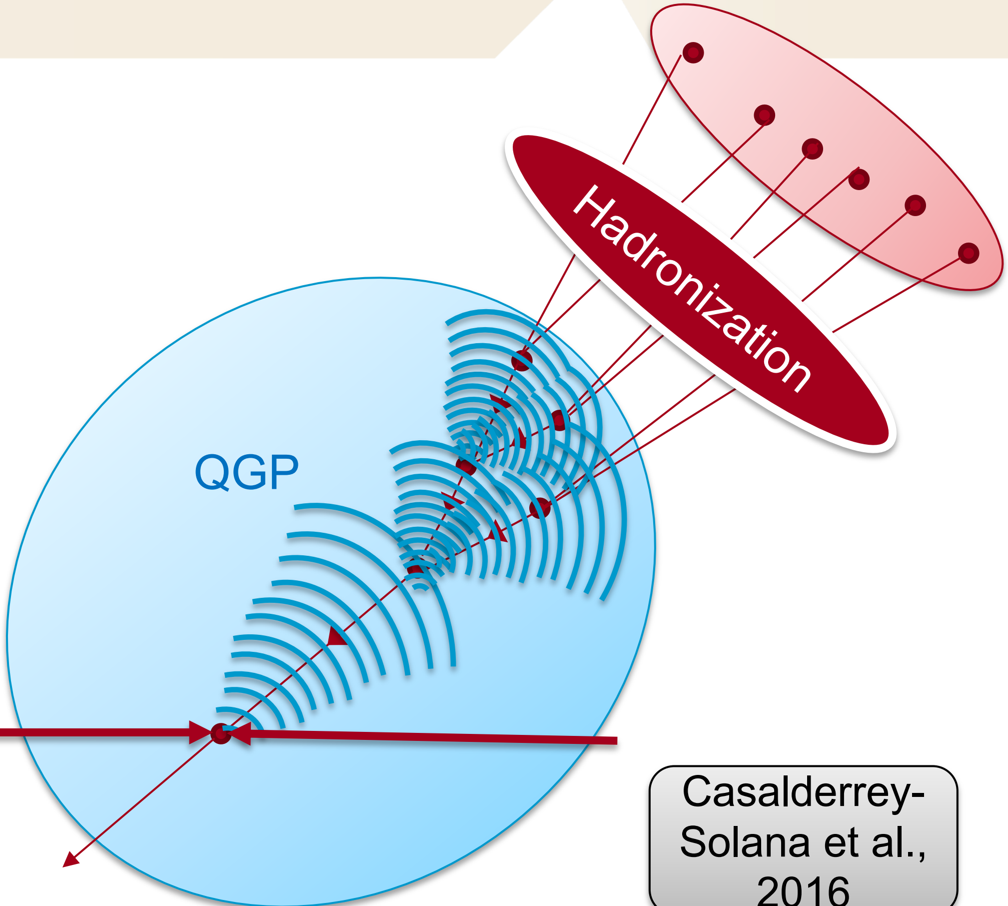
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

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

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

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

O(1) fit const.



Casalderrey-Solana et al., 2016

Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

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

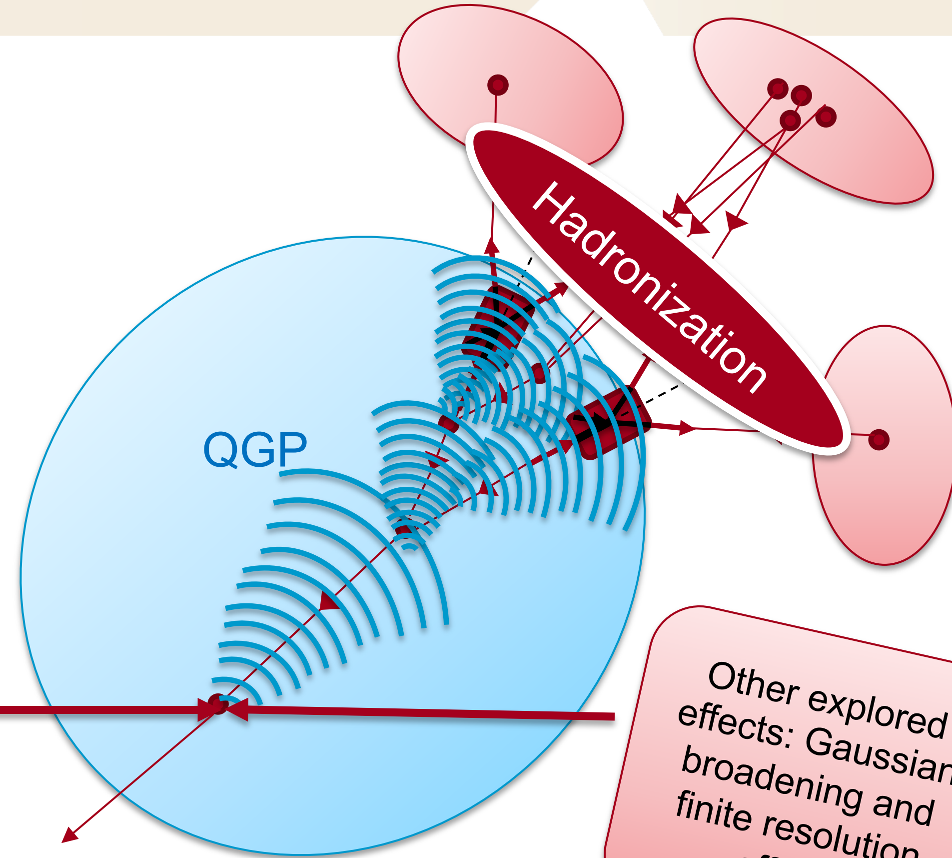
Adding Moliere Scattering to Hybrid Model

- 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:

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

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

O(1) fit const.

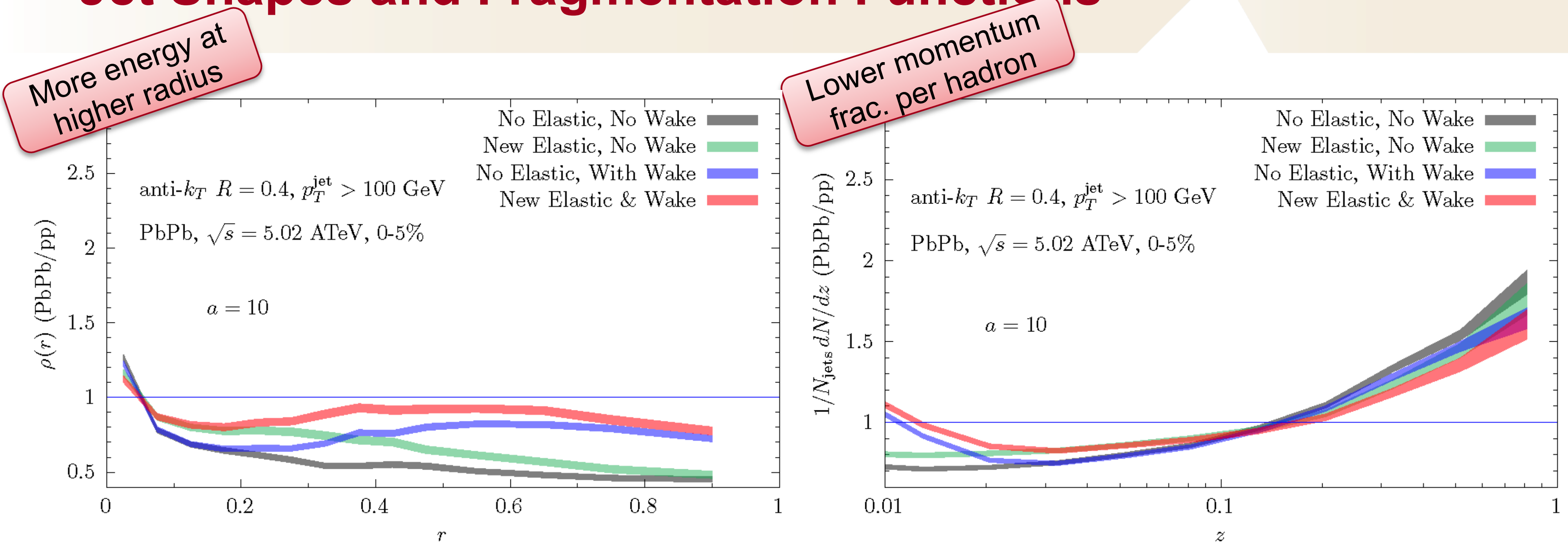


Other explored effects: Gaussian broadening and finite resolution effects

Energy and momentum conservation → activate hydrodynamic modes of plasma

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y - \eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

Jet Shapes and Fragmentation Functions



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

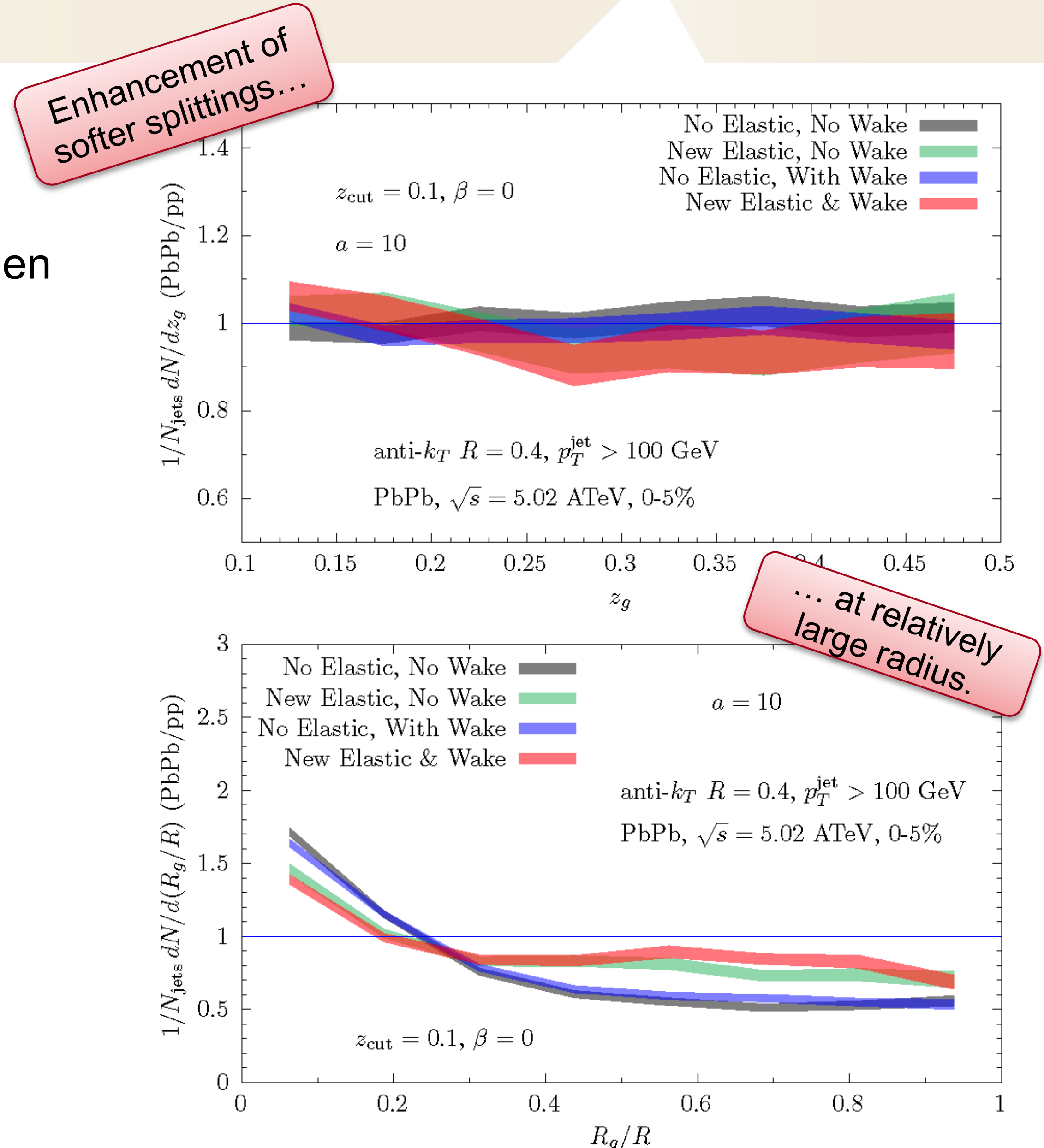
- Moliere scattering transfers jet energy to high angle and lower momentum fraction particles. So does energy loss to wake in fluid.
- In **these observables**, effect of Moliere looks like just a bit more wake.
- In principle sensitive to Moliere, but in practice not: more sensitive to wake.
- Moliere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



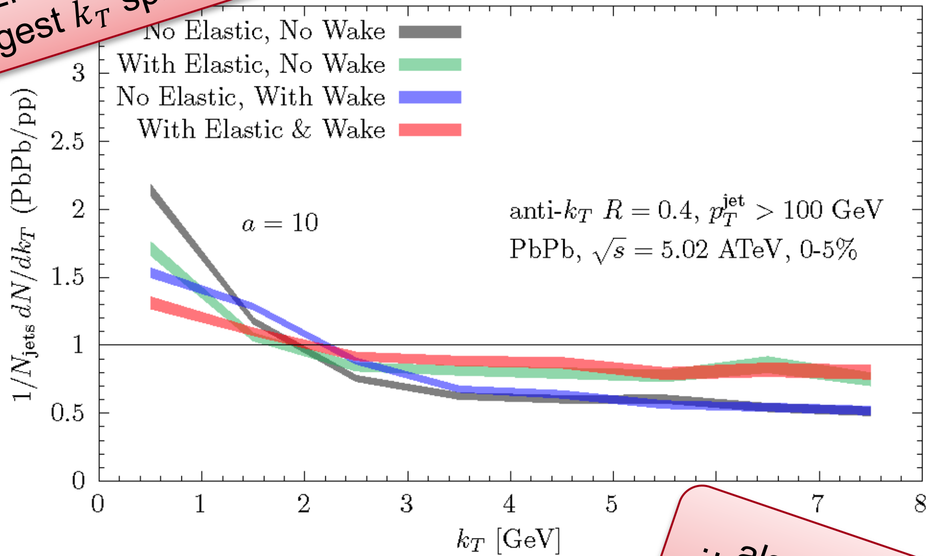
Leading k_T

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

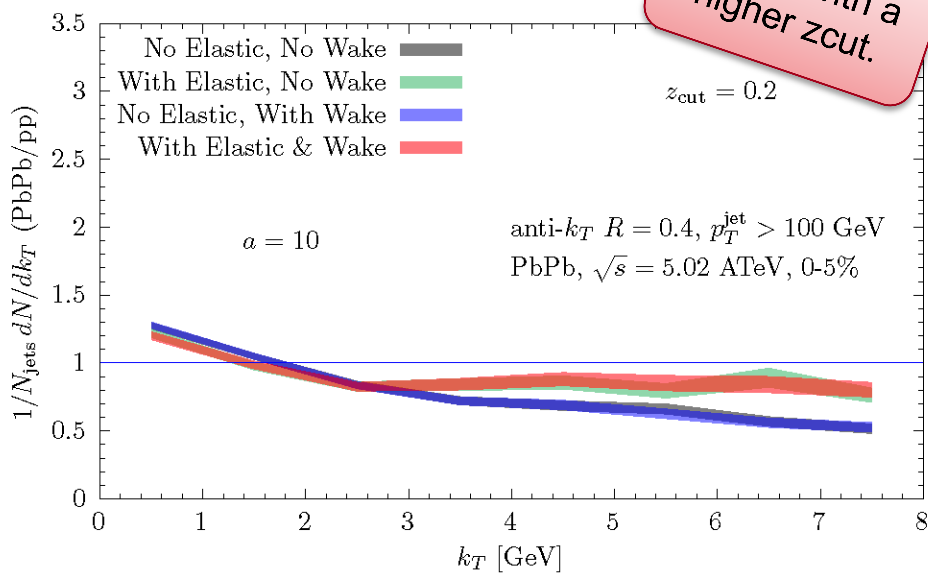
$$k_T = \min(p_{T1}, p_{T2})\sin(R_g)$$

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

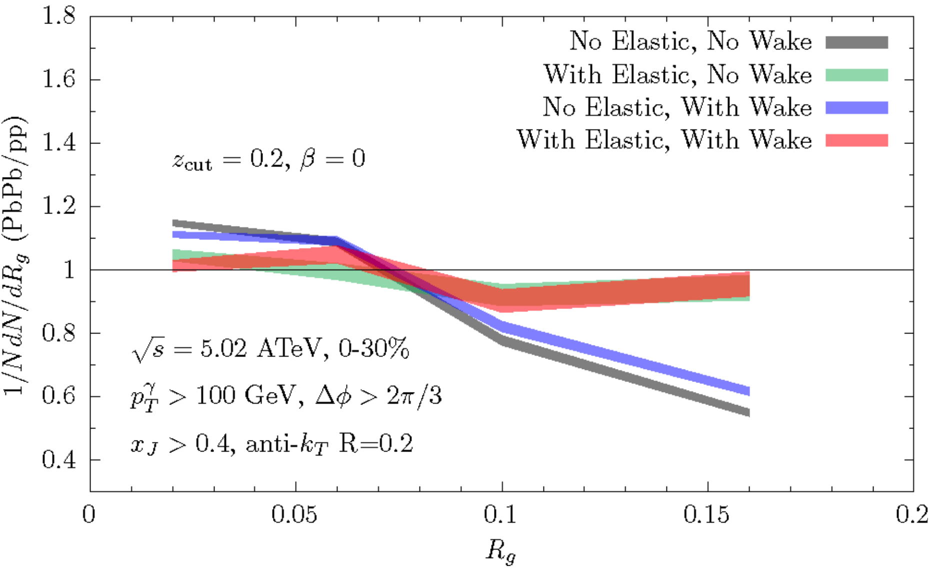
Enhancement of largest k_T splittings…

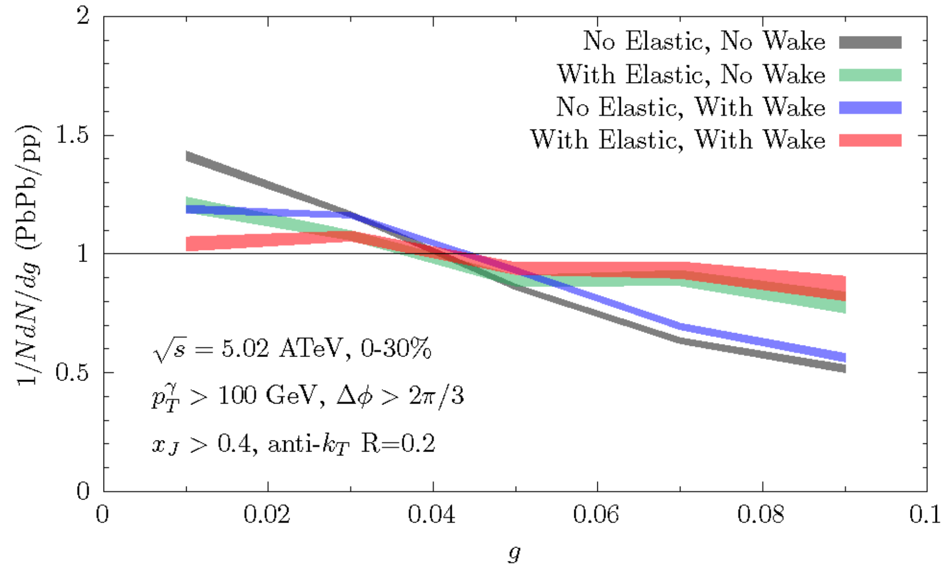


…also with a higher zcut.

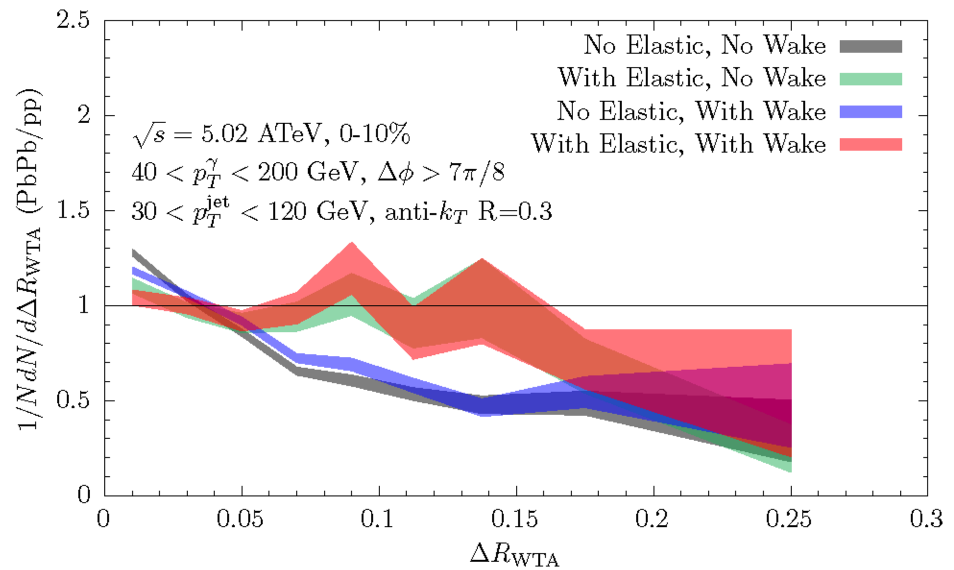


Three "groomed" gamma-Jet Observables: R_g , Girth, and angle between standard and WTA axes

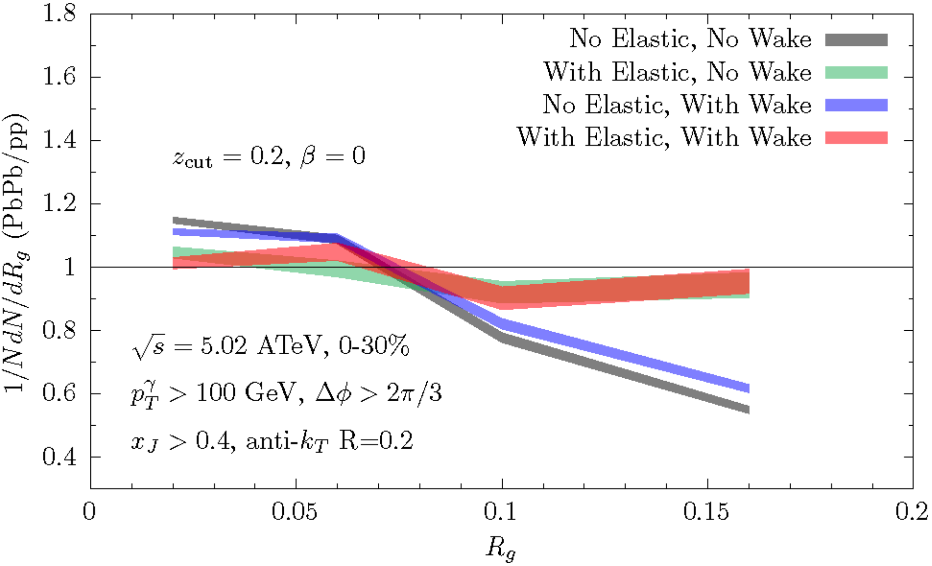


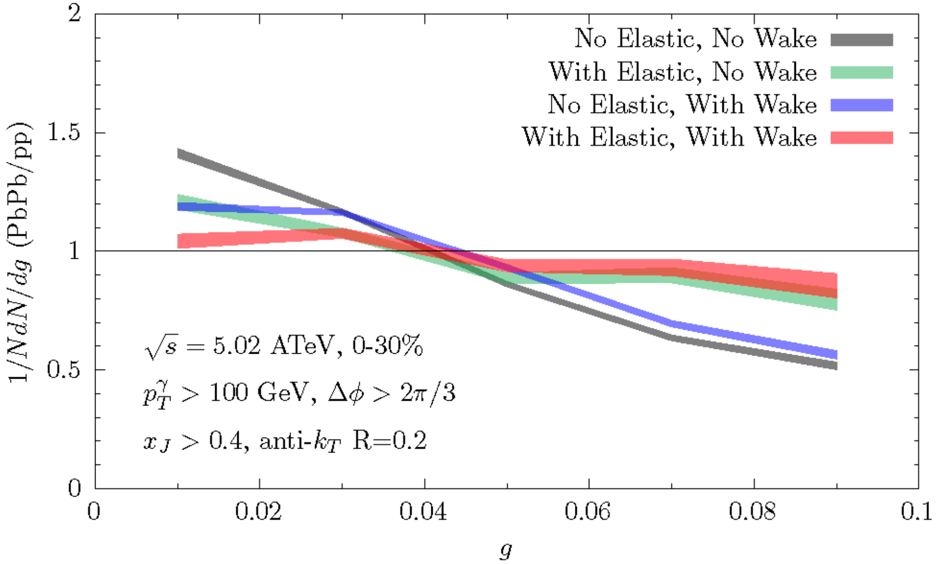


All show much less sensitivity to wake: R=0.2; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere are very much dominant.



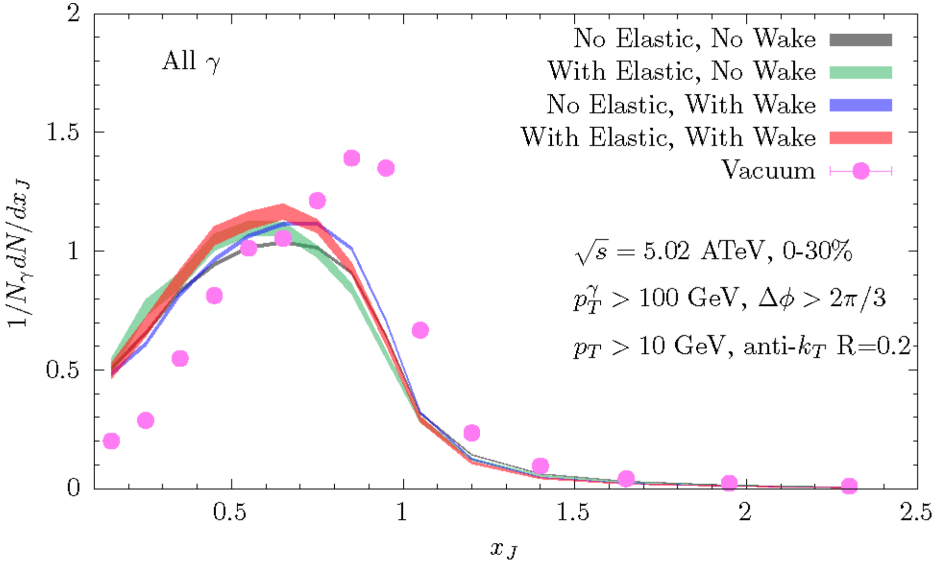
Gamma-Jet Observables: R_g and Girth



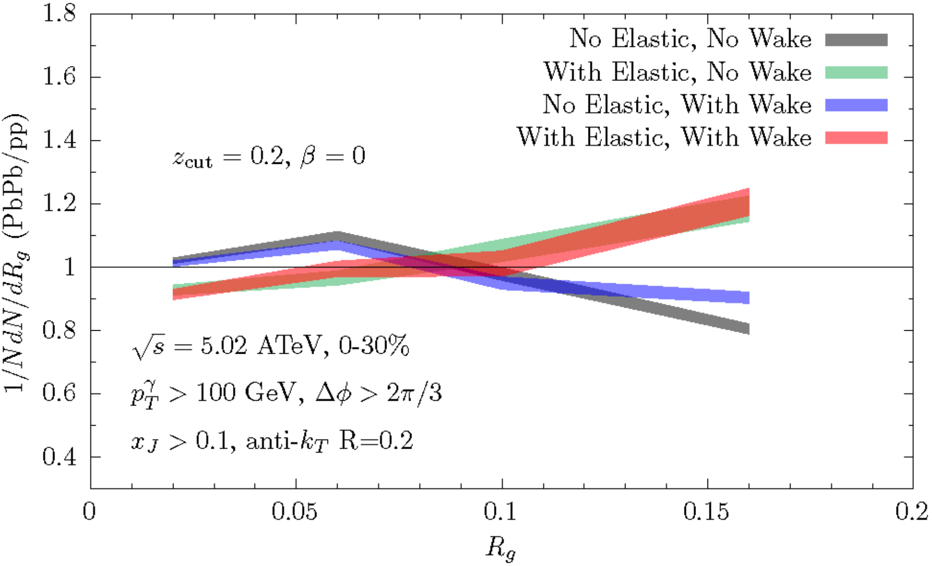


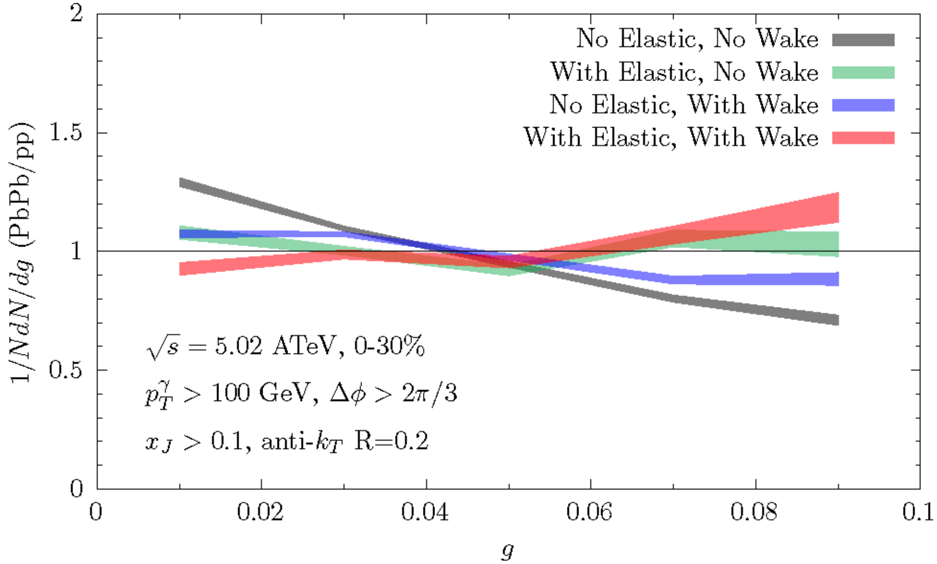
All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

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



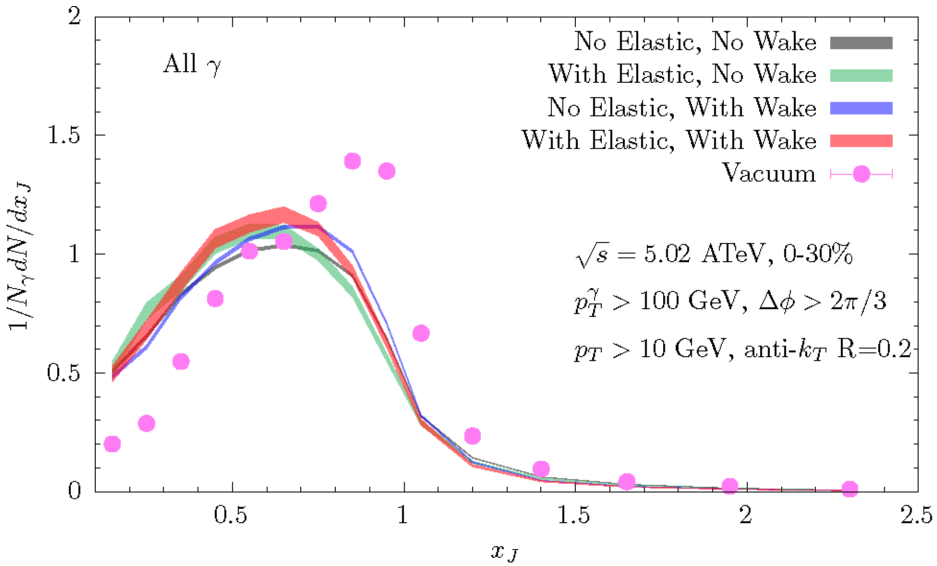
Gamma-Jet Observables: R_g and Girth, with x_J>0.1



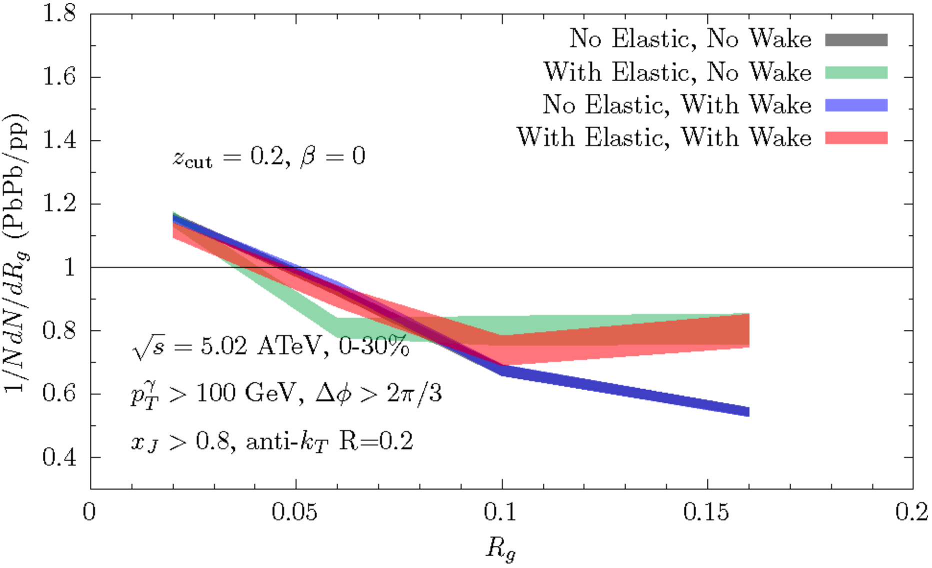


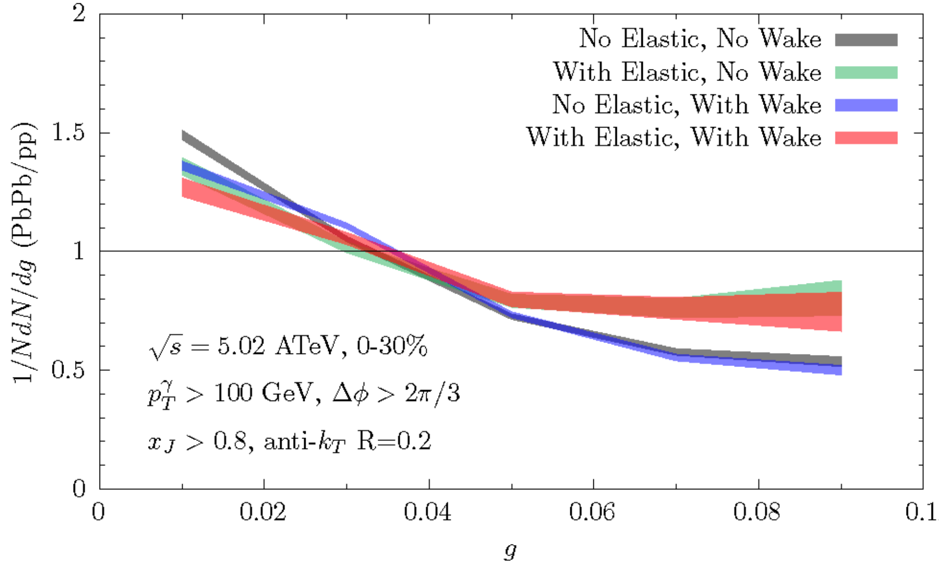
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.1. Moliere scattering important, and causes R_{AA} >1.

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



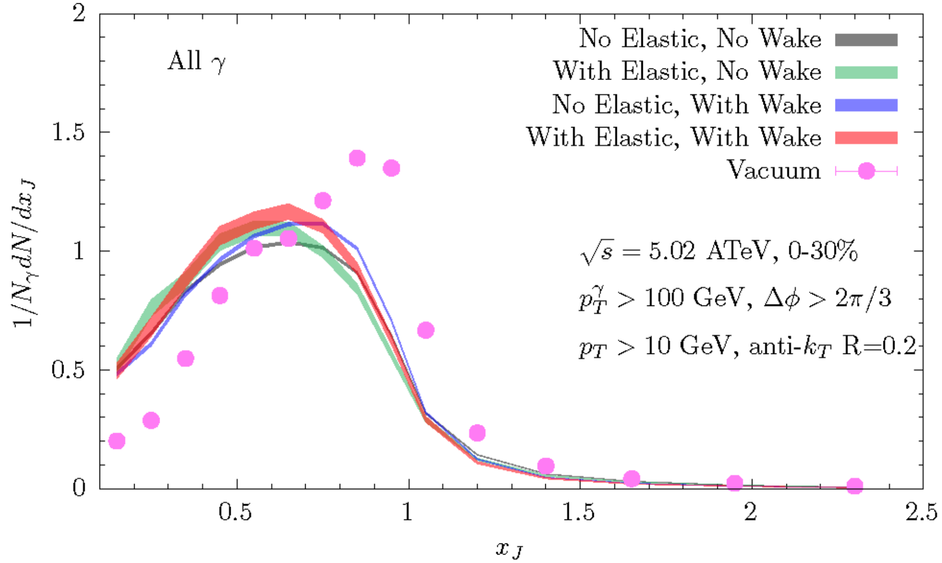
Gamma-Jet Observables: R_g and Girth, with x_J>0.8



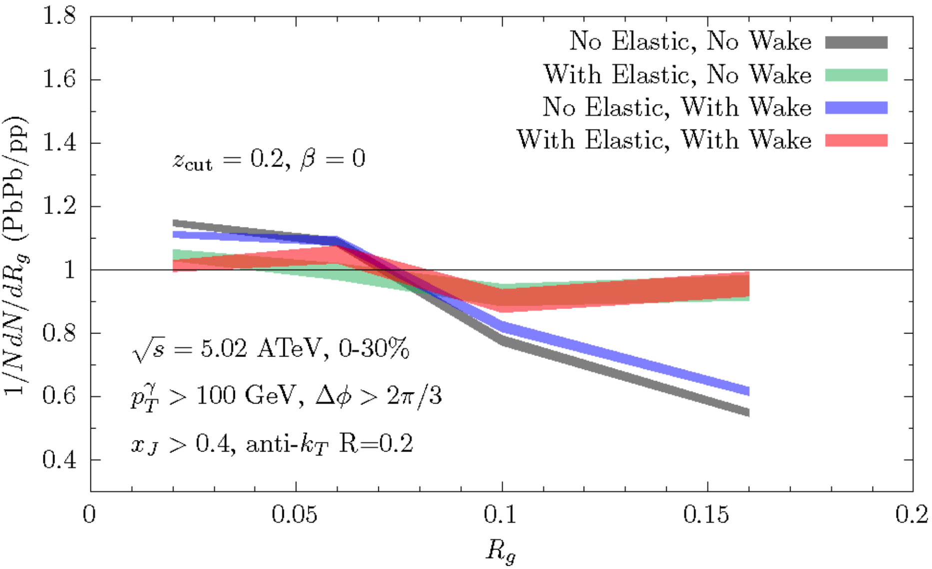


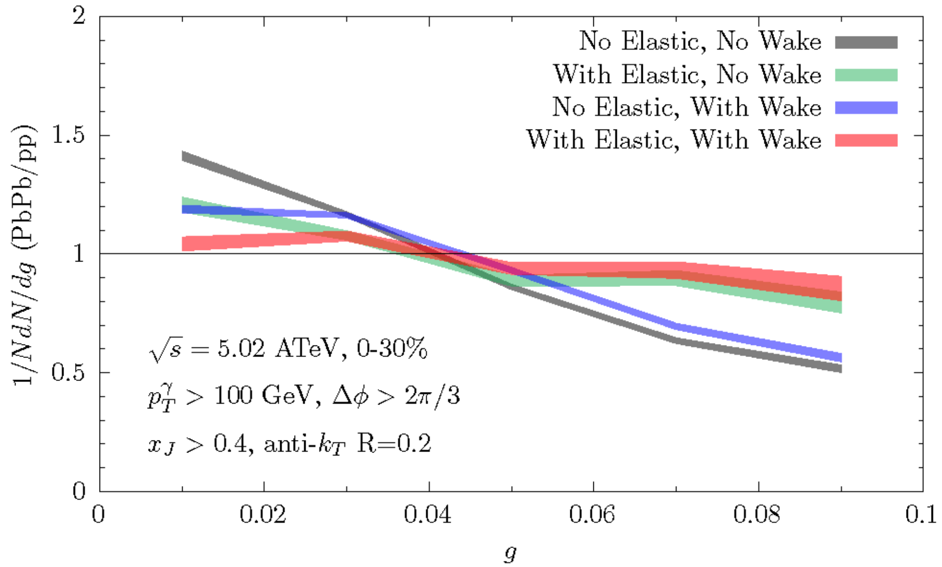
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.8. Selection bias increased.

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



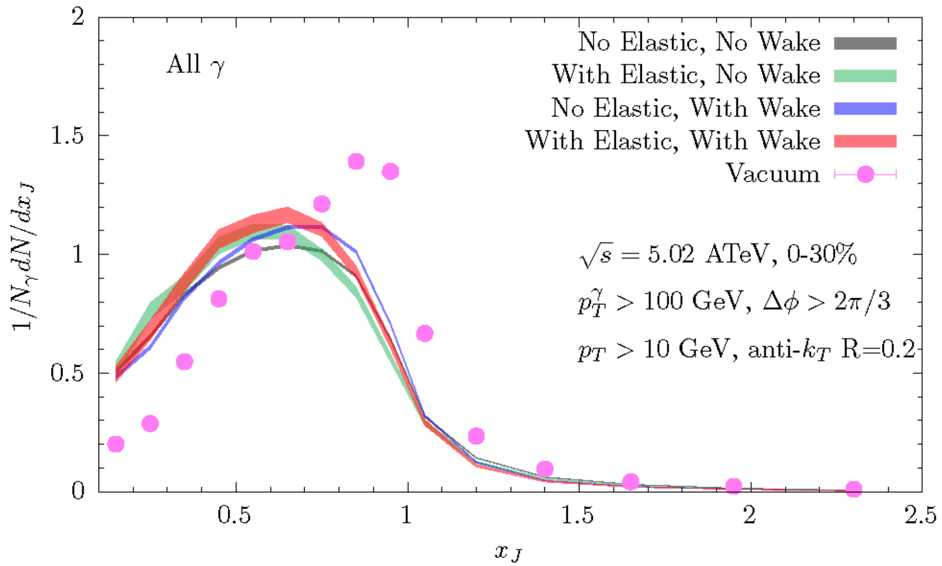
Gamma-Jet Observables: R_g and Girth, with x_J>0.4



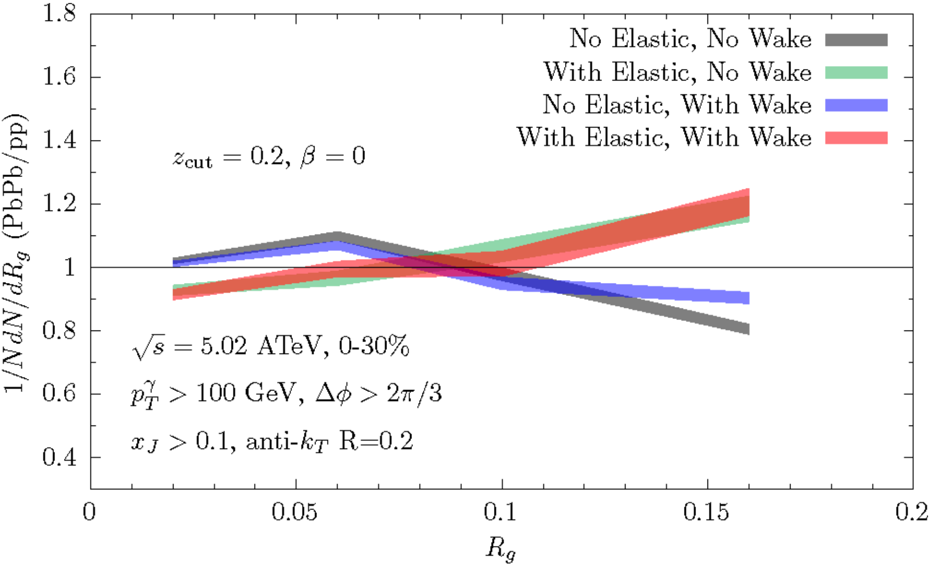


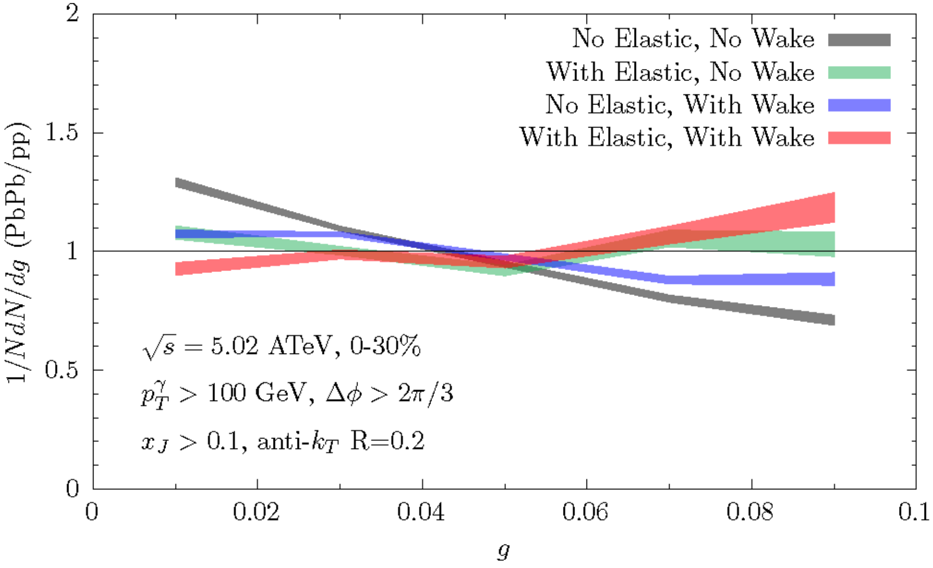
All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

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





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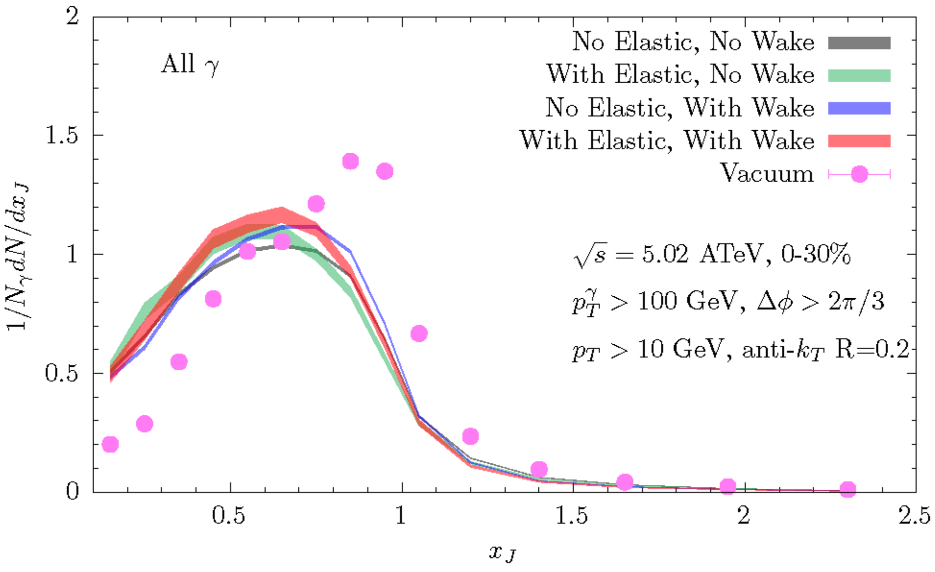
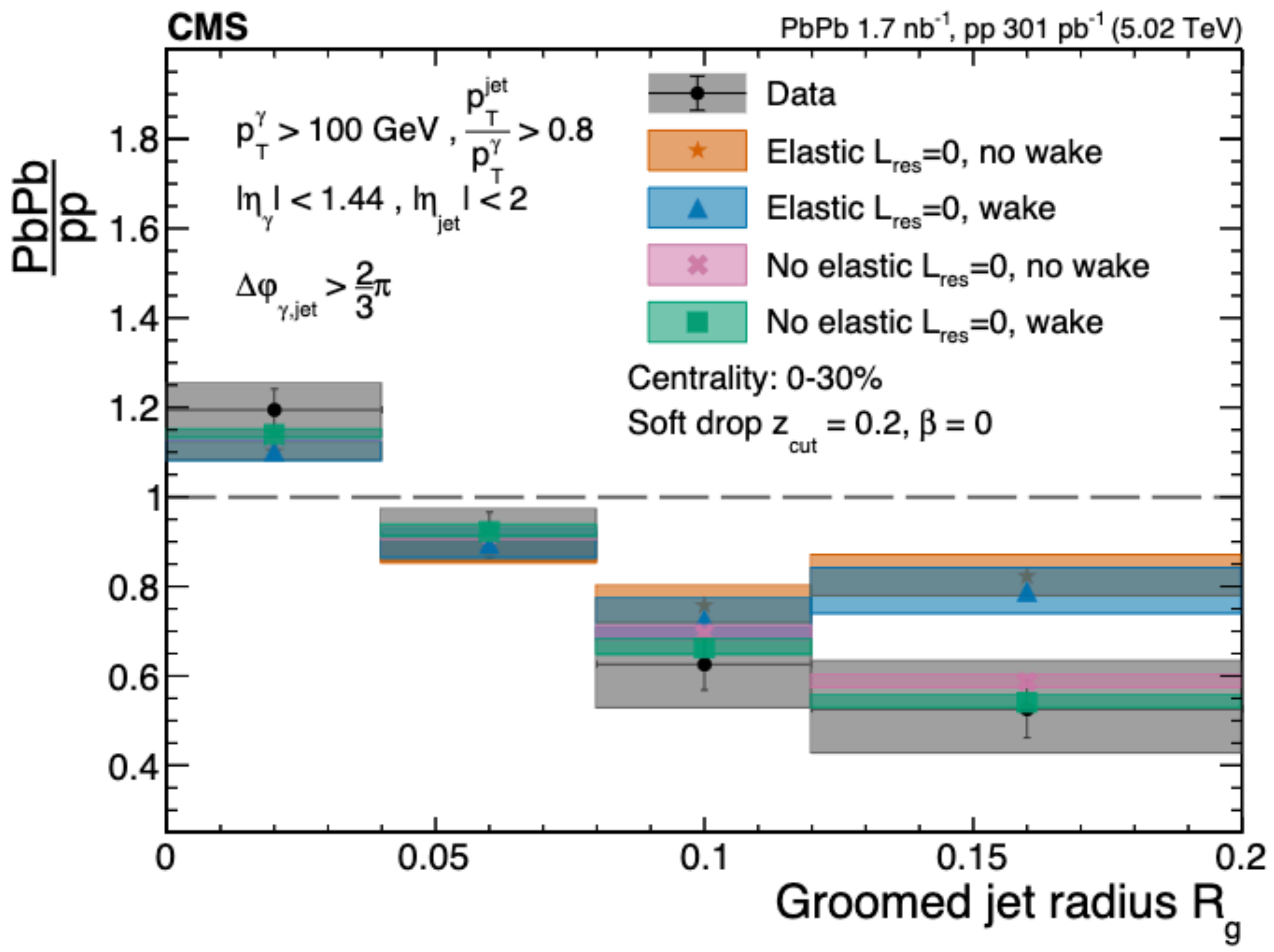


lesson 4: it seems all we see is survivor bias

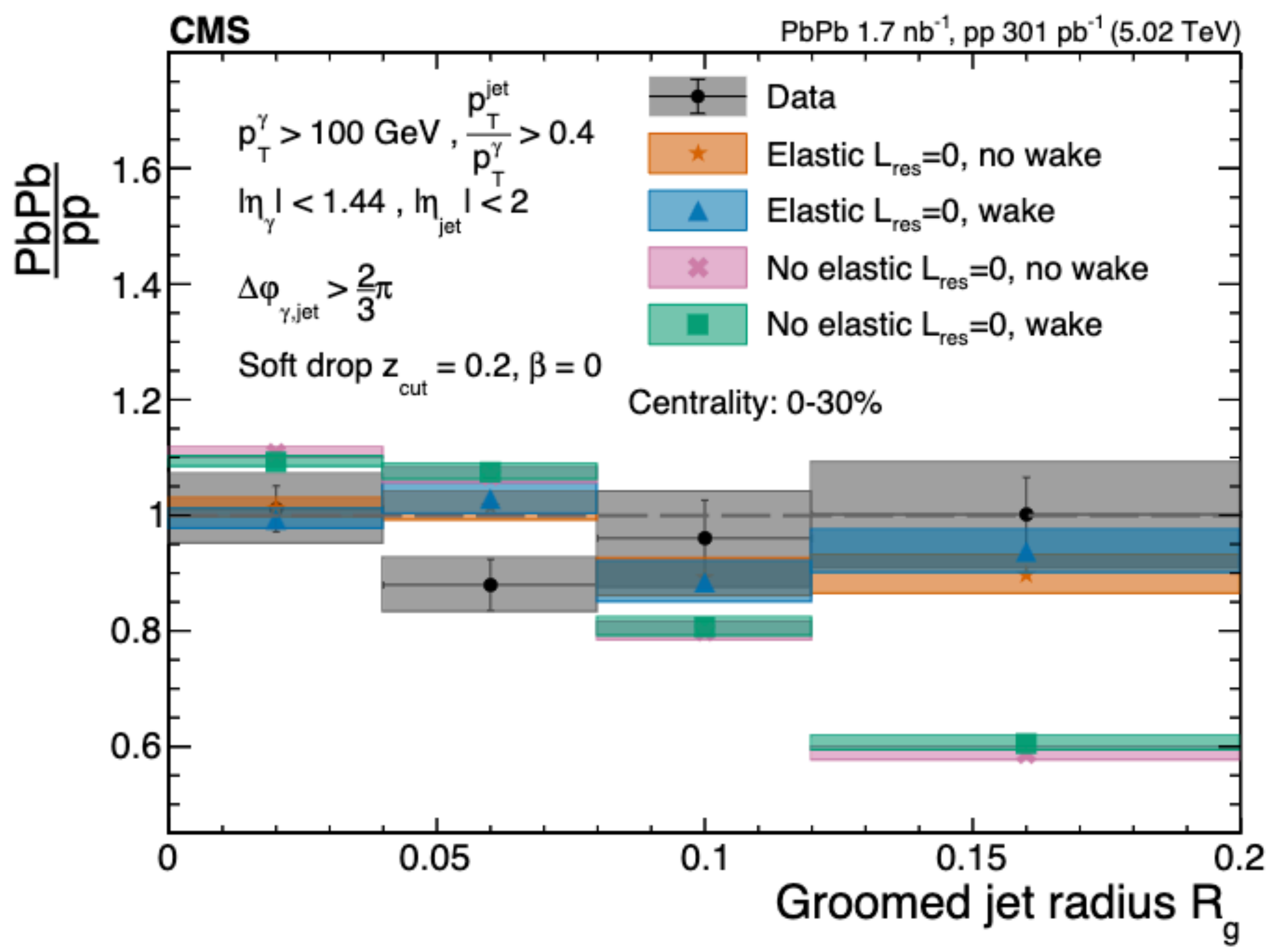
γ-jet substructure: suppression of the survivor bias

PbPb

less quenched xJ>0.8



more quenched xJ>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

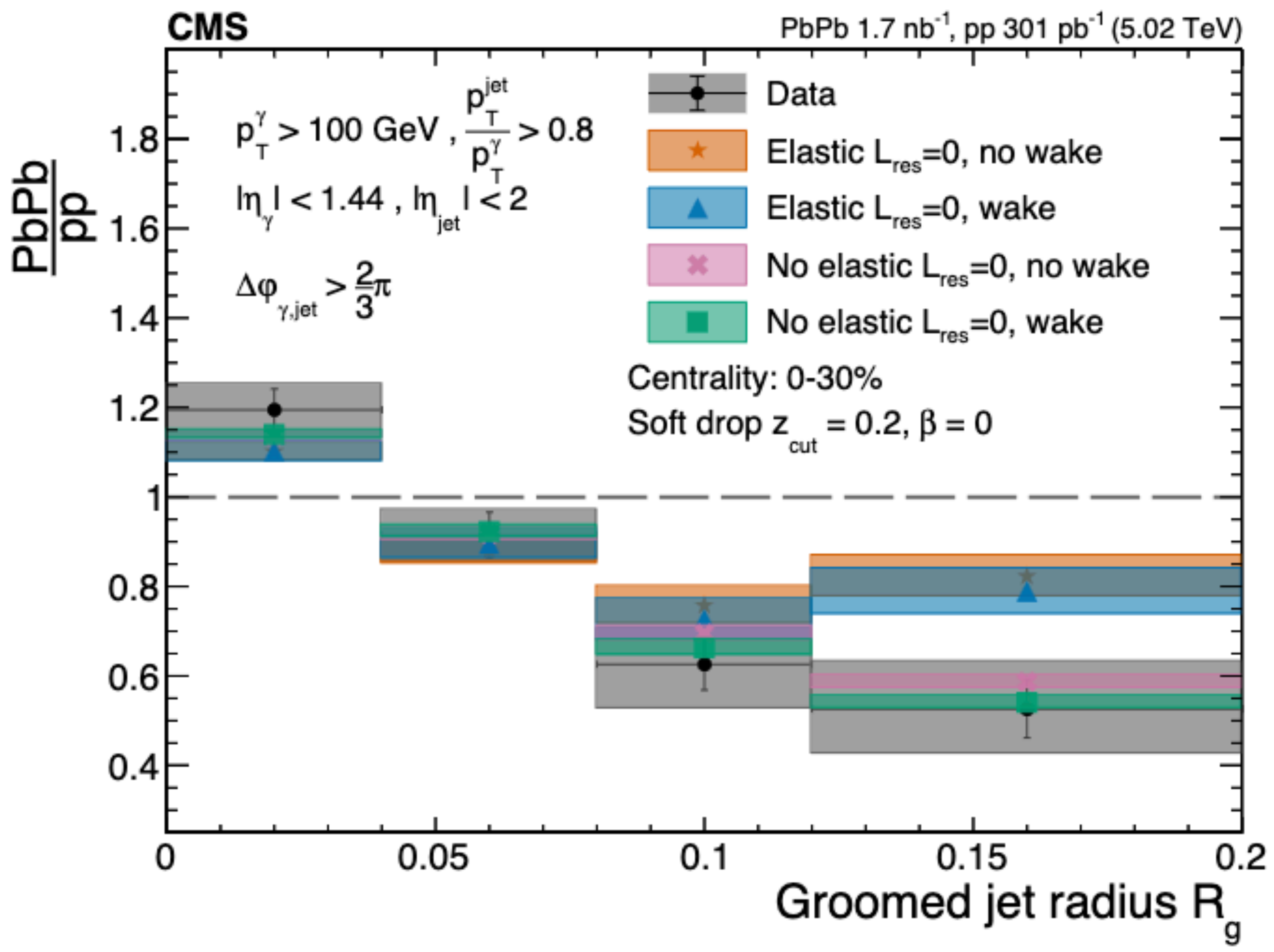
small-R suppresses nonperturbative effects like the wake!

CMS-PAS-HIN-23-001

γ-jet substructure: suppression of the survivor bias

PbPb

less quenched xJ>0.8



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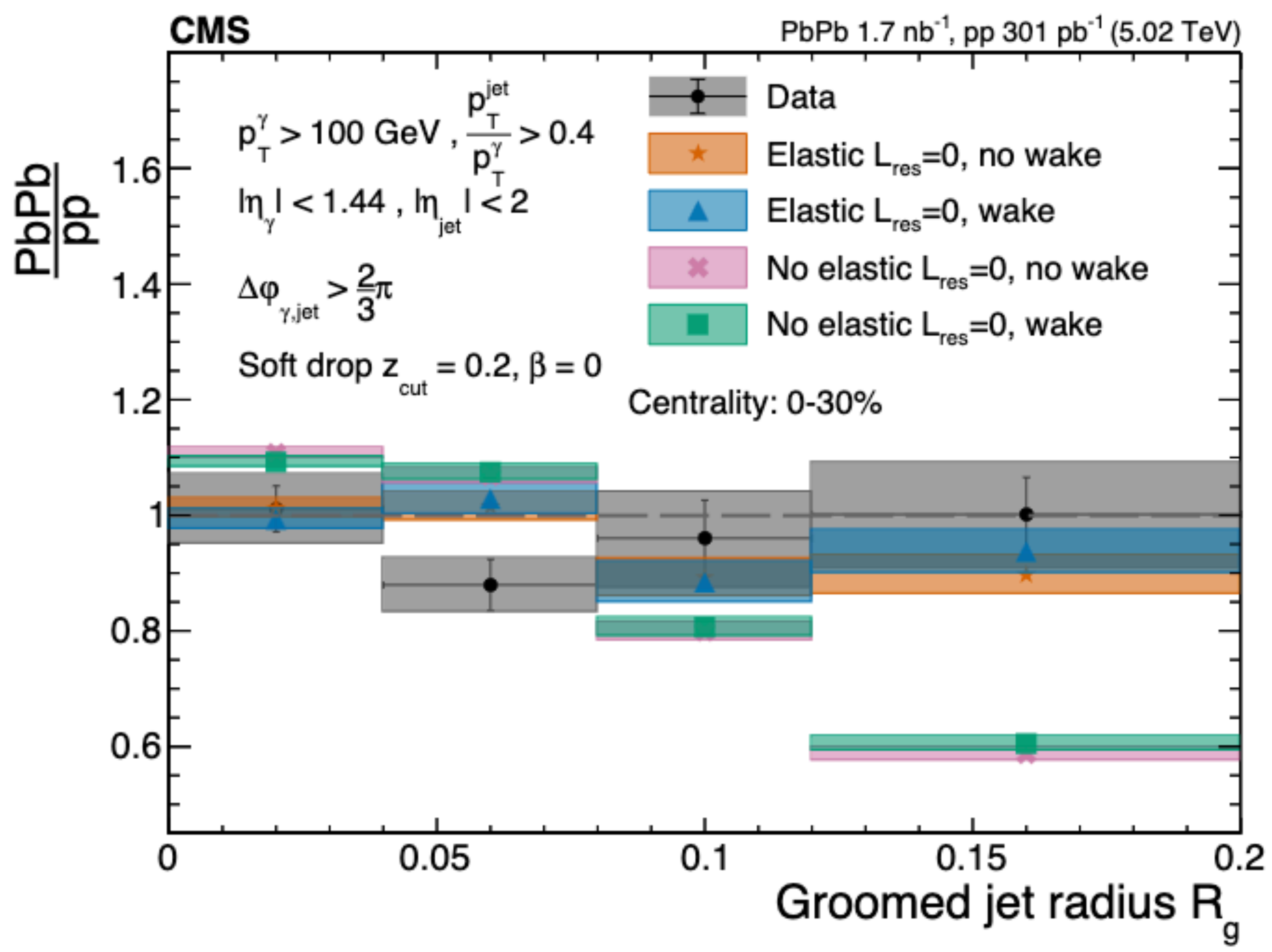


Comparison to the Hybrid model (*Rajagopal et al, JHEP 10 (2014) 019)*

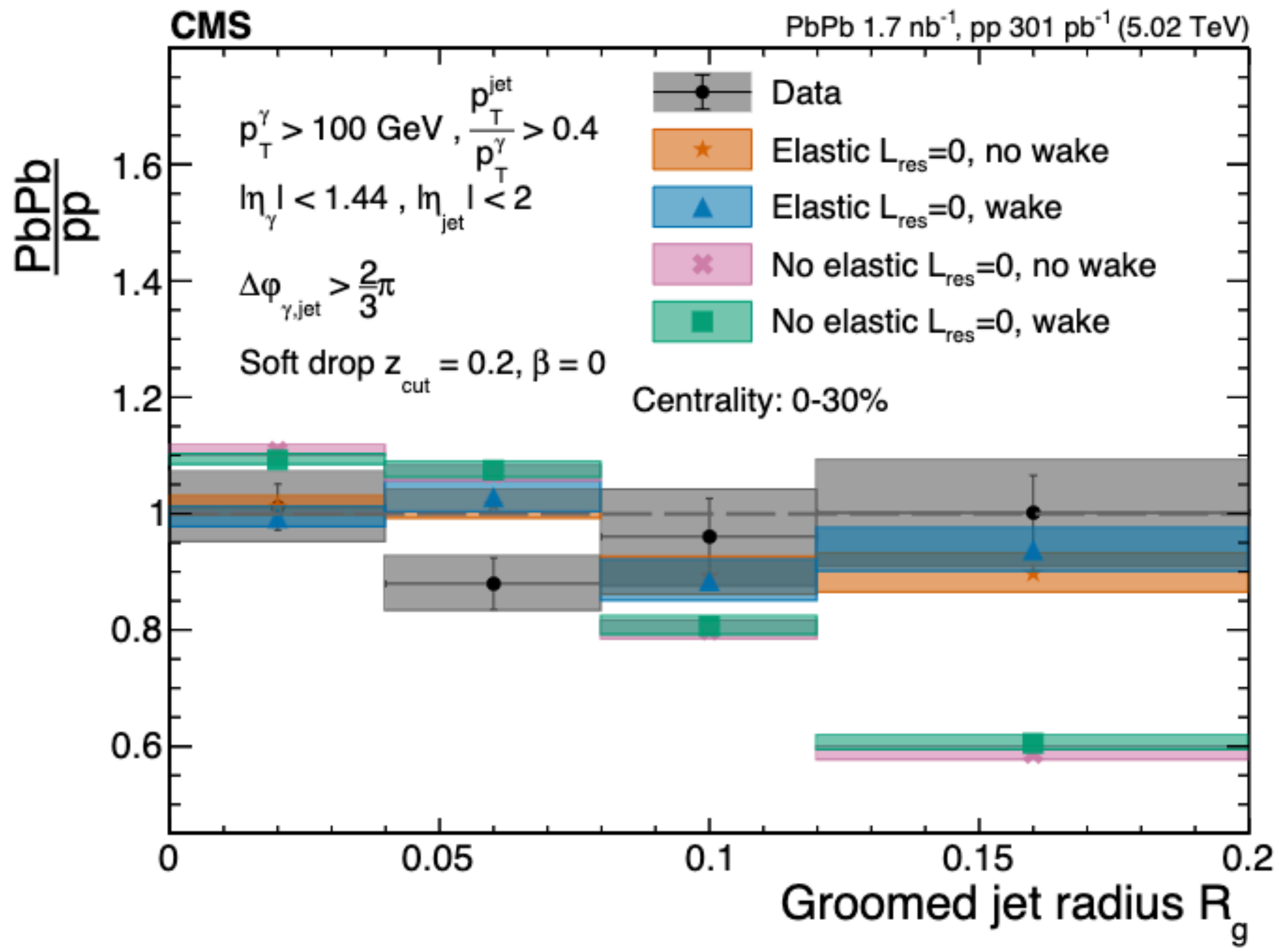
Not a single set of parameters describes the differential data consistently
Great constraining power of the data

small-R suppresses nonperturbative effects like the wake!

CMS-PAS-HIN-23-001

γ-jet substructure, prospects

xJ>0.4



The survivor bias can be fully suppressed when $x_J \to 0$

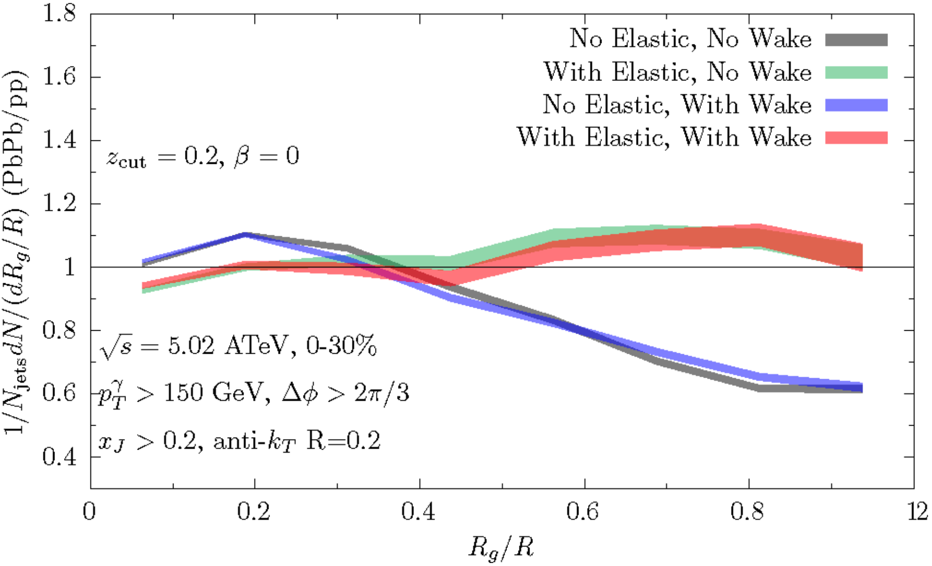
(the model has a strong survivor bias down to xJ=0.1)

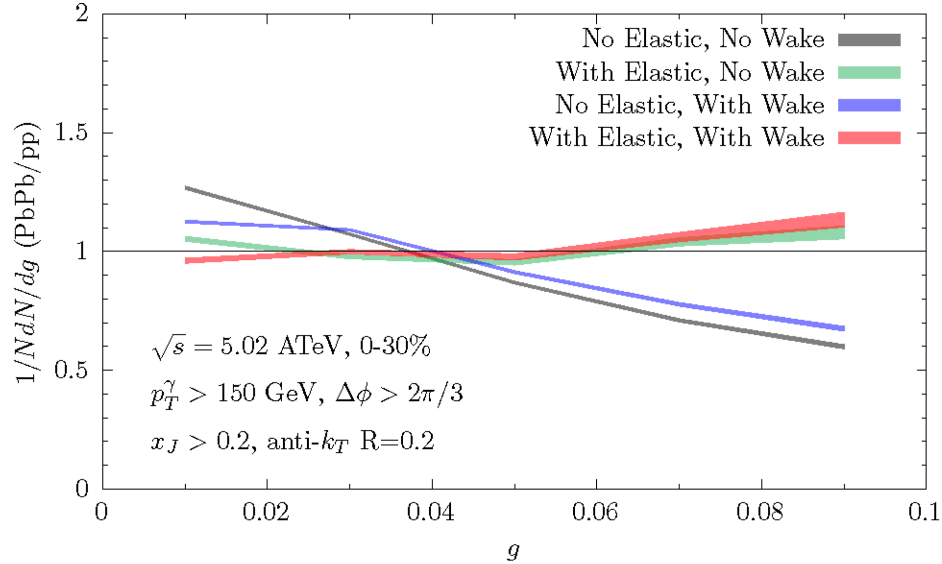
Since low jet p_T is limited by detector effects, such zero bias limit can be achieved by increasing the energy of the photons

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

CMS-PAS-HIN-23-001

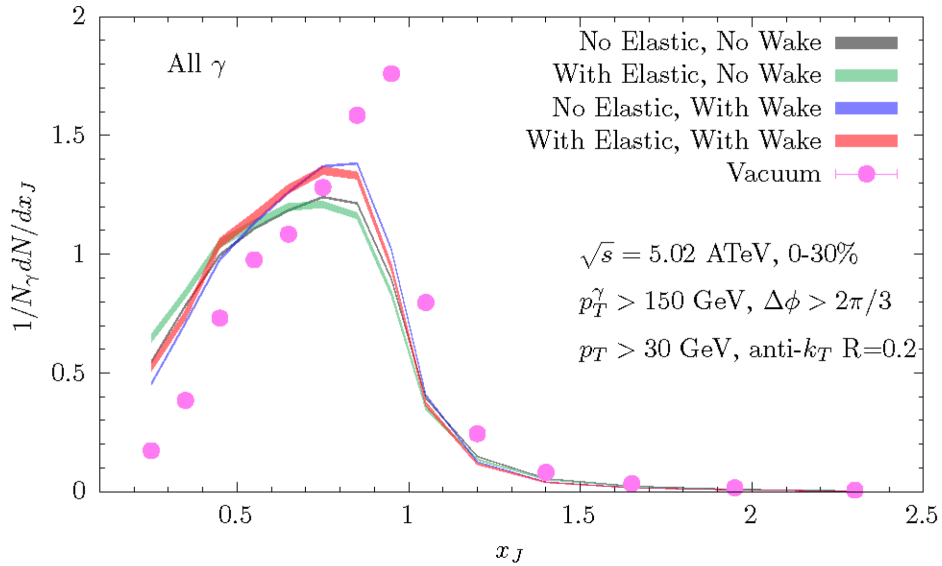
Gamma-Jet Observables with p_T^{γ} >150 GeV: R_g and Girth, with x_J>0.2



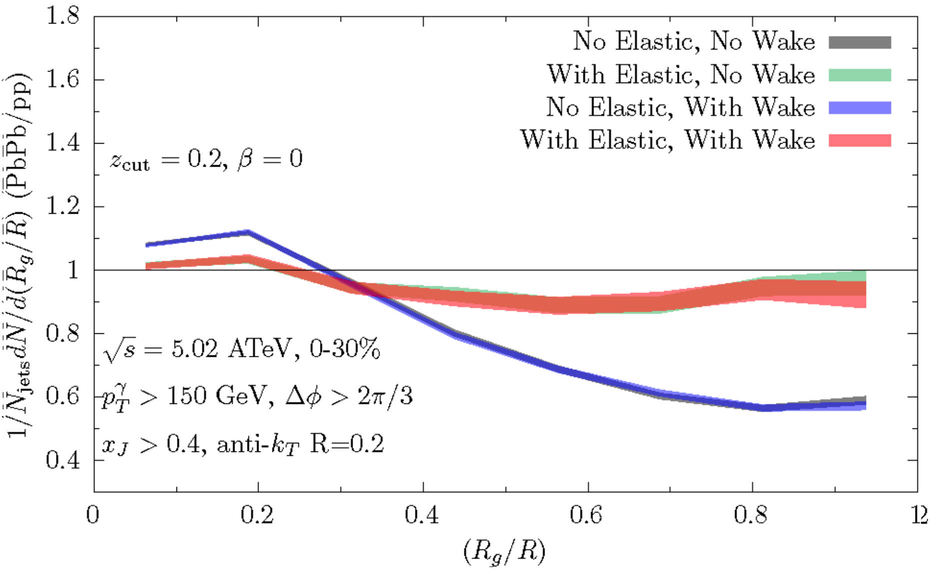


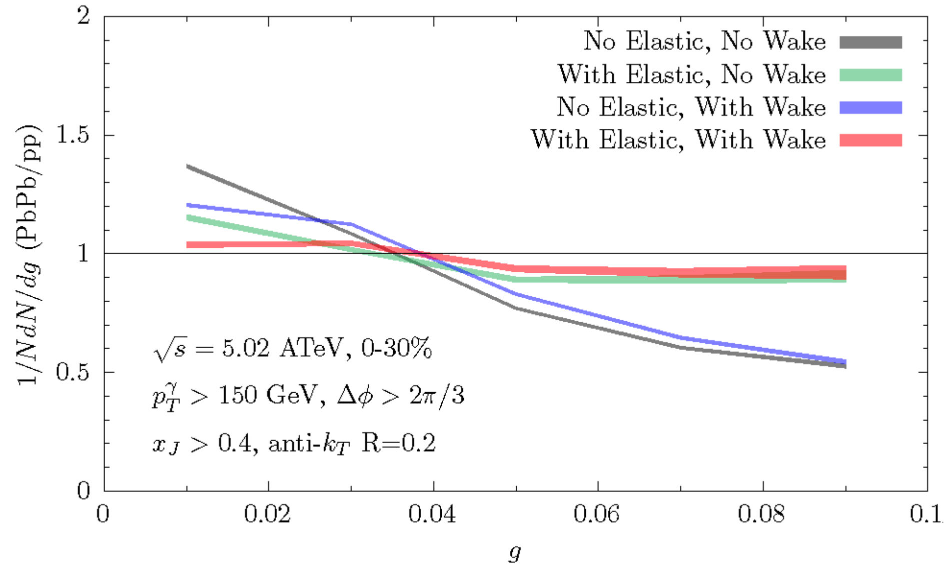
On previous slides, p_T^{γ} >100 GeV; here, p_T^{γ} >150 GeV.
Means x_J>0.2 corresponds to p_T^{jet}>30 GeV. And, no need to go down to x_J>0.1.

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



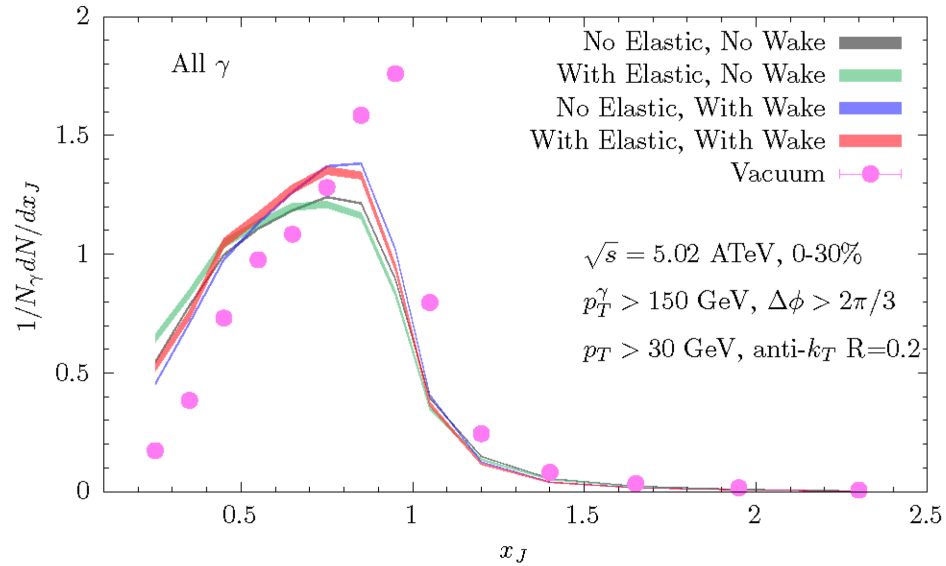
Gamma-Jet Observables with p_T^{γ} >150 GeV: R_g and Girth, with x_J>0.4



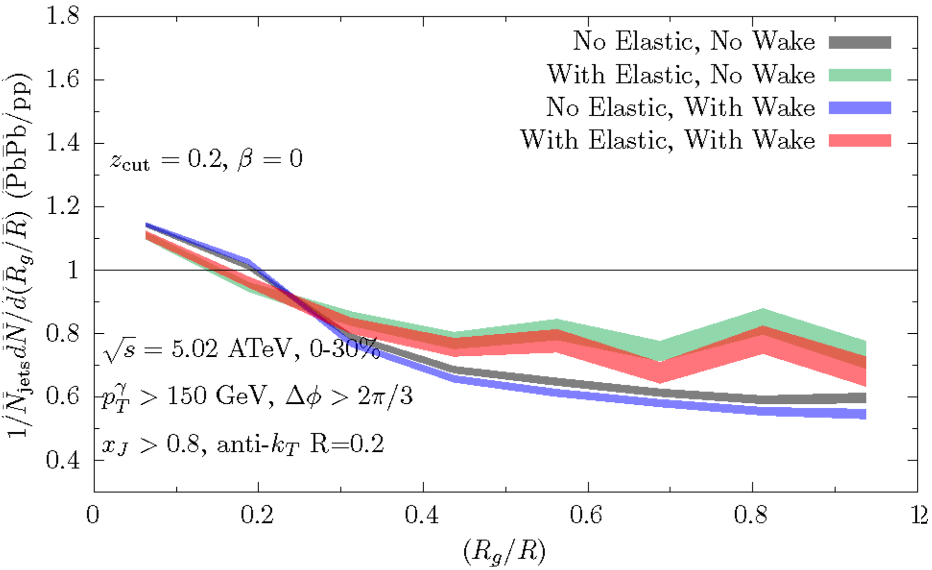


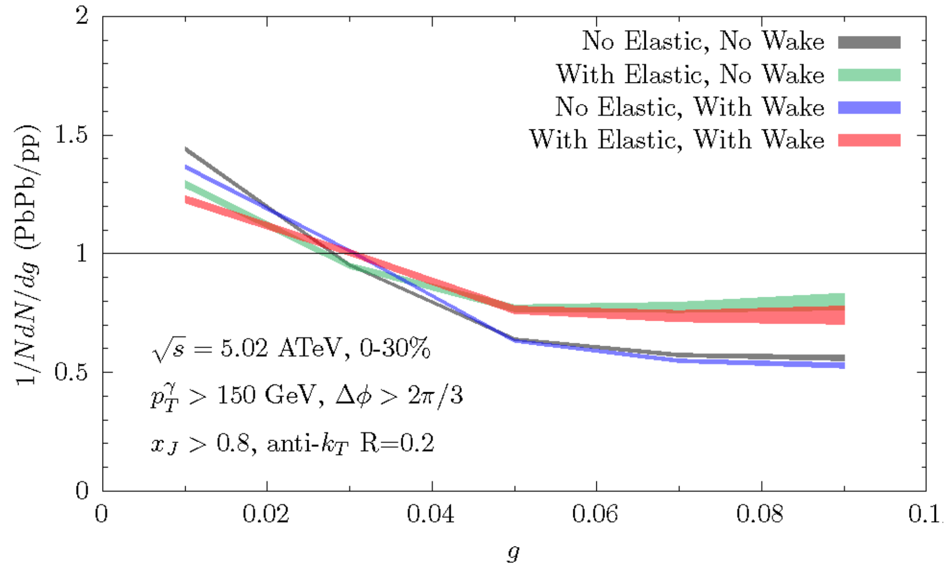
On previous slides, p_T^{γ} >100 GeV; here, p_T^{γ} >150 GeV.
Means x_J>0.4 corresponds to p_T^{jet}>60 GeV.

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



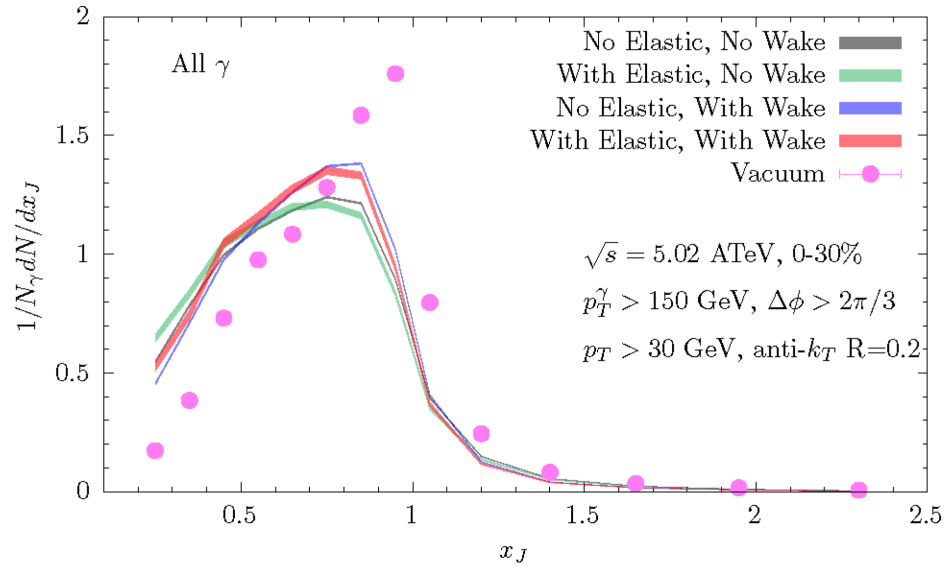
Gamma-Jet Observables with p_T^γ >150 GeV: R_g and Girth, with x_J>0.8



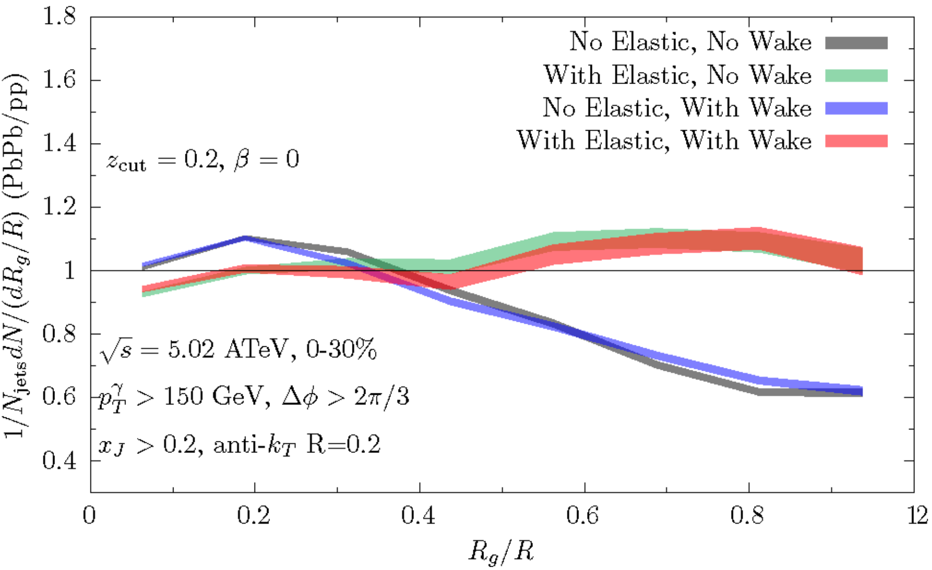


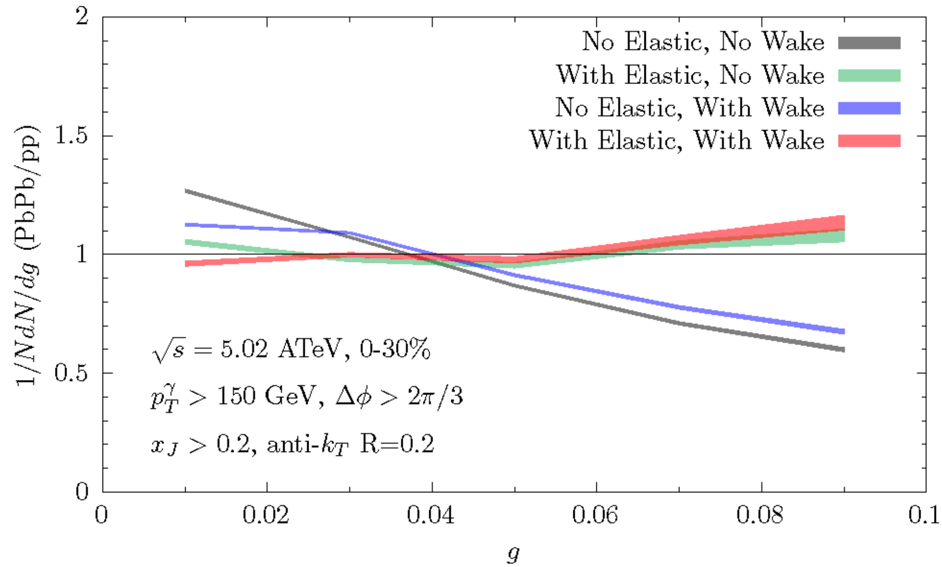
On previous slides, p_T^γ >100 GeV; here, p_T^γ >150 GeV.
Means x_J>0.8 corresponds to p_T^{jet}>120 GeV.

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



Gamma-Jet Observables with p_T^{γ} >150 GeV: R_g and Girth, with x_J>0.2





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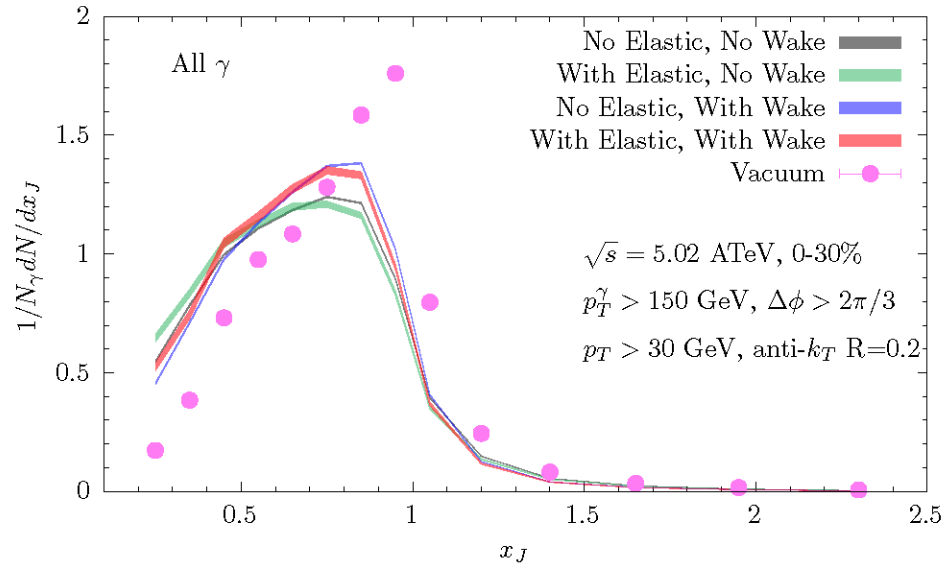
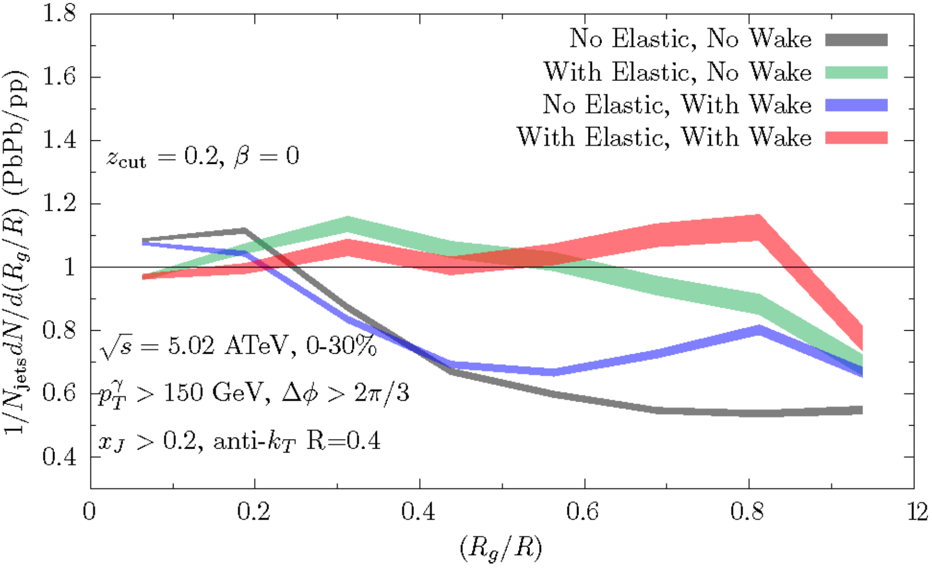
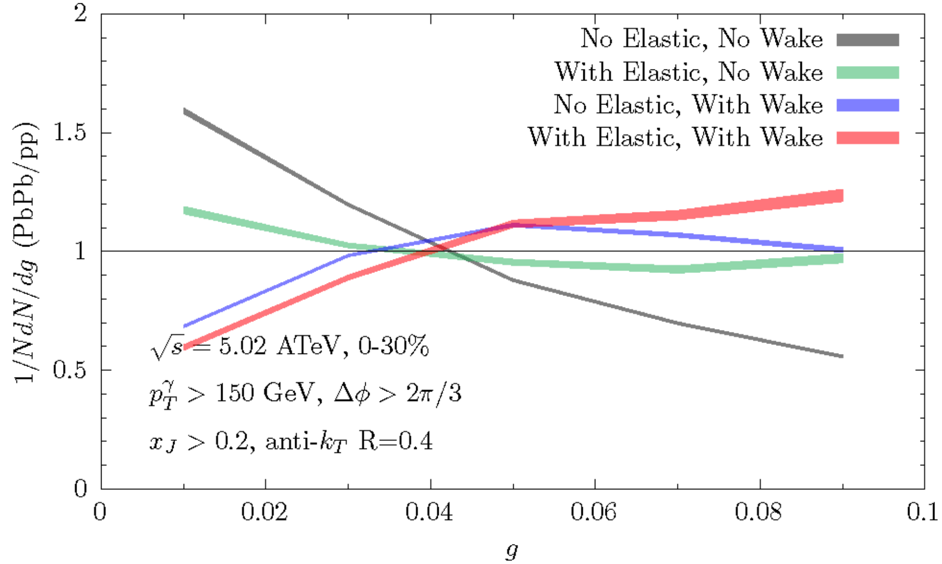
Means x_J>0.2 corresponds to p_T^{jet}>30 GeV. And, no need to go down to x_J>0.1.

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



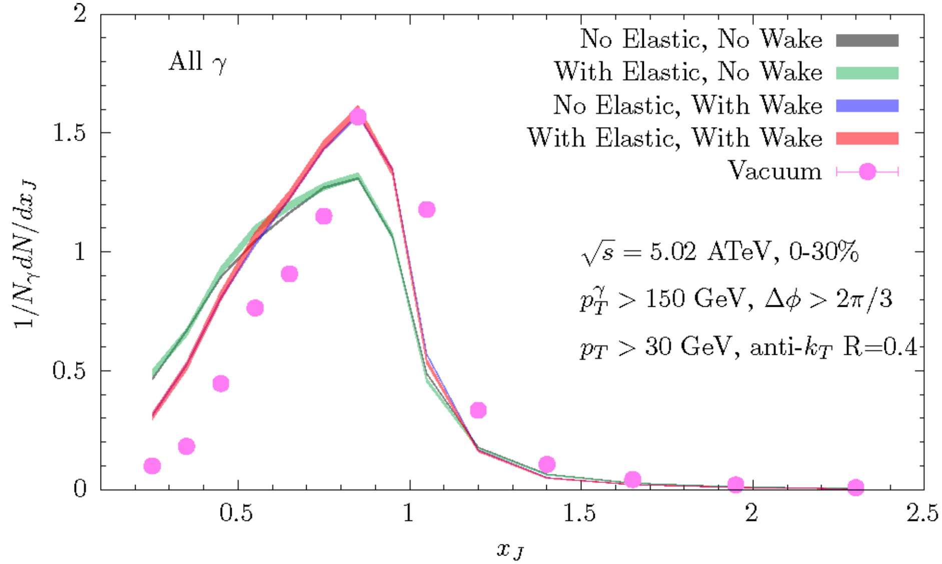
Gamma-Jet Observables with p_T^γ >150 GeV and R=0.4: R_g and Girth, with x_J>0.2



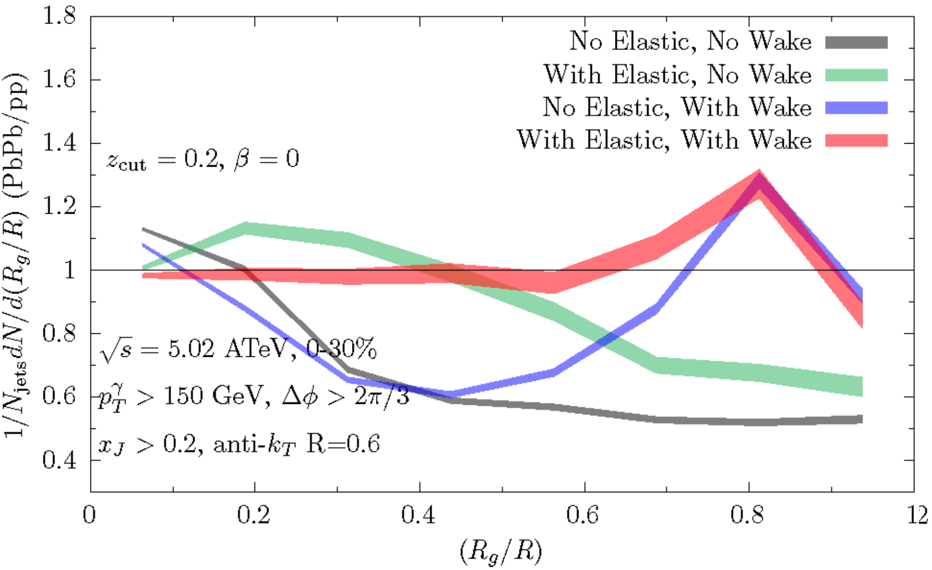


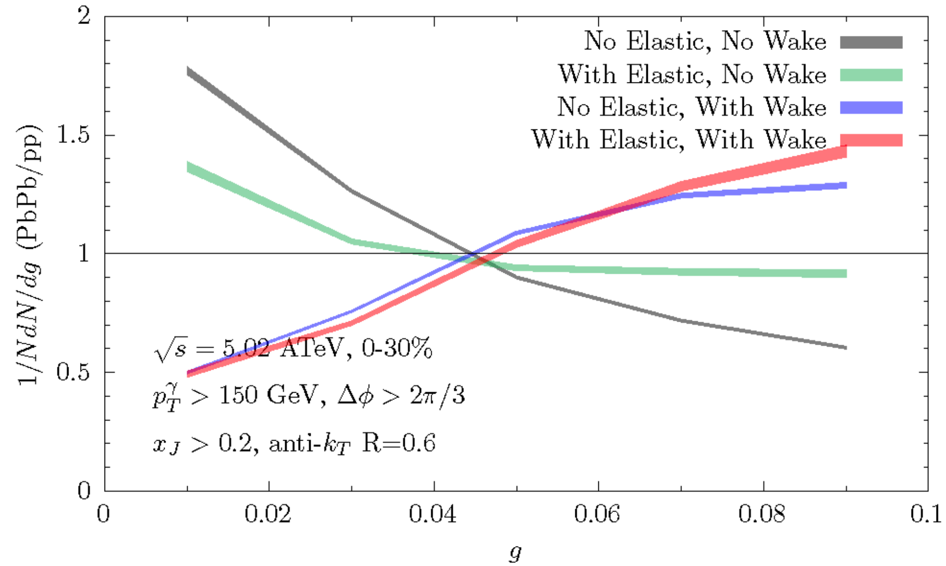
On previous slides, p_T^γ >150 GeV with R=0.2. Here, R=0.4, so that we can "catch" more wake, with little selection bias.

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



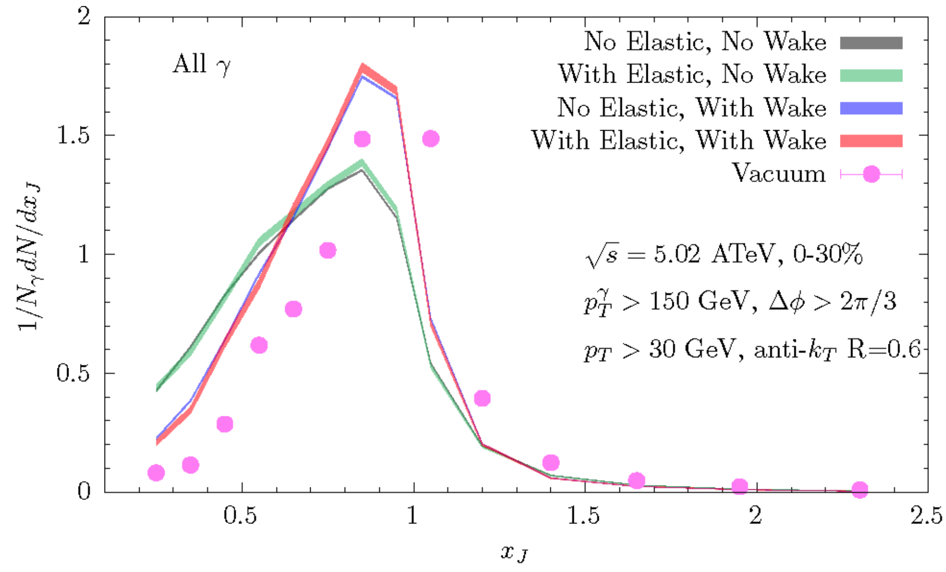
Gamma-Jet Observables with p_T^γ >150 GeV and R=0.6: R_g and Girth, with x_J>0.2



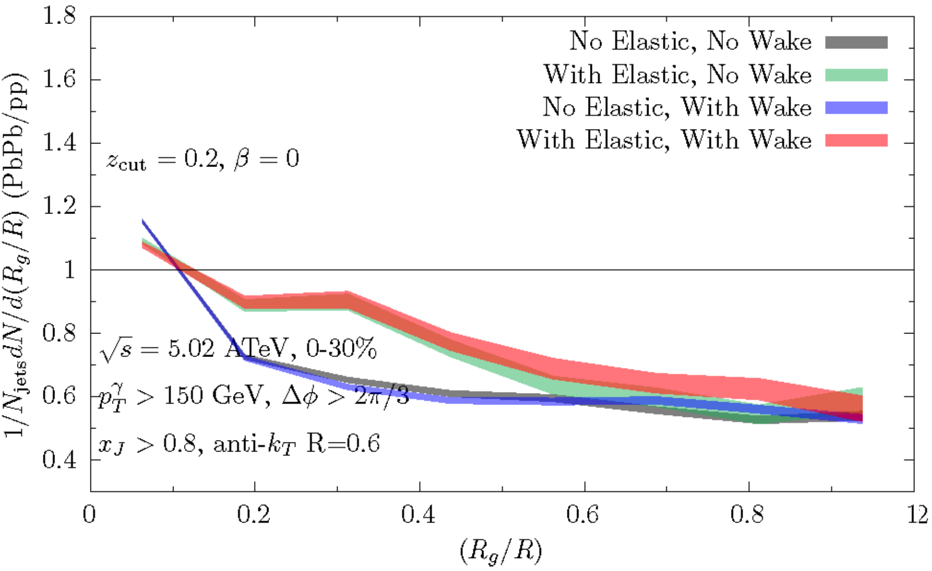


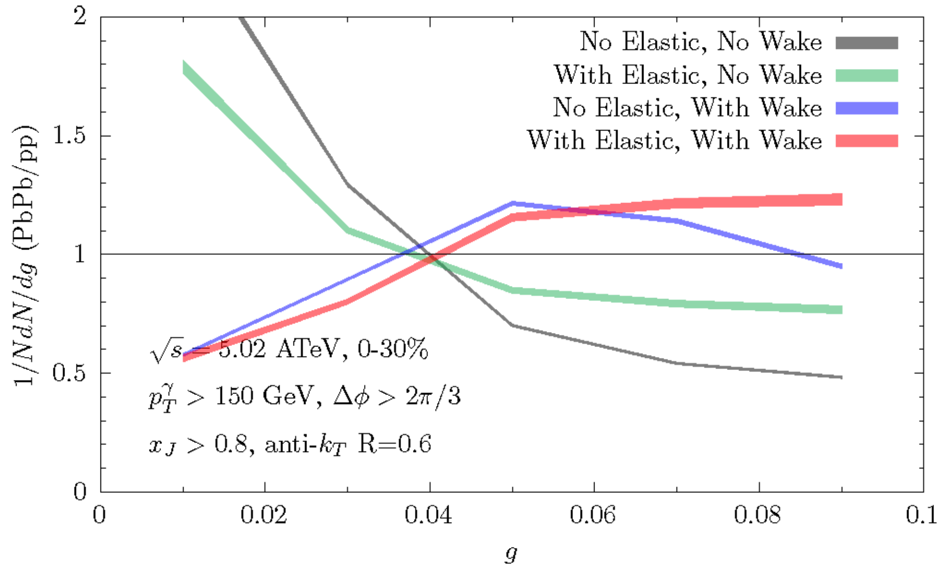
On previous slides, p_T^γ >150 GeV with R=0.2. Here, R=0.6, so that we can "catch" *even more* wake, with little selection bias.

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



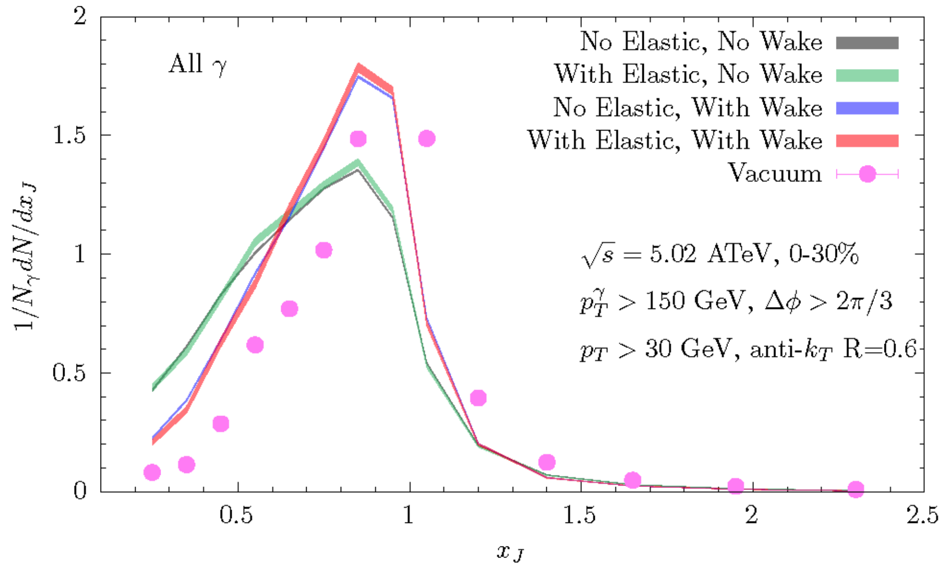
Gamma-Jet Observables with p_T^γ >150 GeV and R=0.6: R_g and Girth, with x_J>0.8





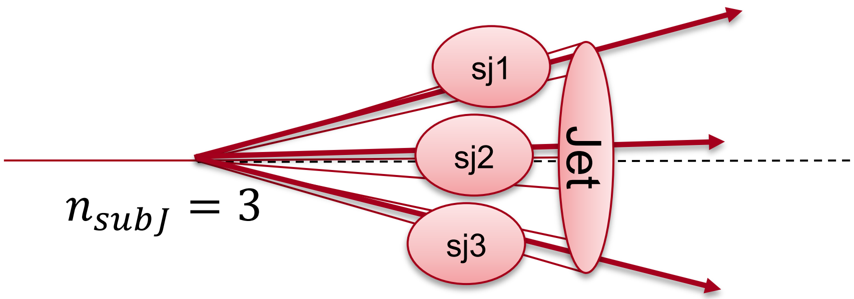
On previous slides, p_T^γ >150 GeV with R=0.2. Here, R=0.6. But, we've turned the selection bias back ON.

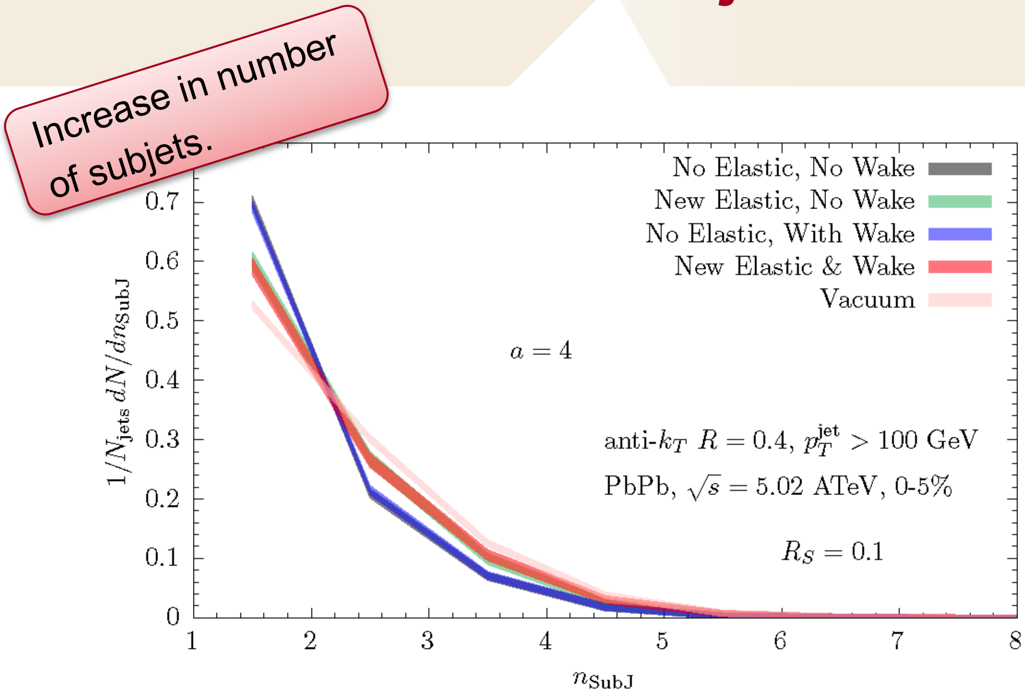
Moliere effects still substantial; selection bias dominant; wake effects *greatly reduced*, as in Brewer+Brodsky+KR.



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





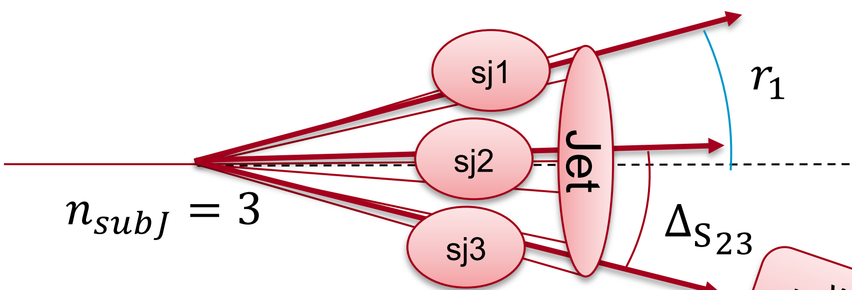
Moliere scattering visible as increase in number of subjets; no such effect coming from wake at all.

Moliere scattering also yields more separated subjets…

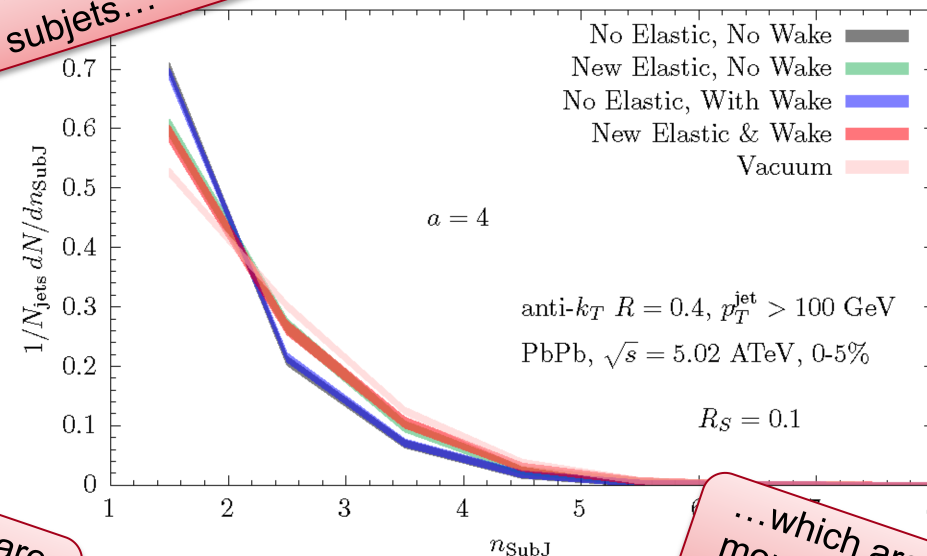
These observables are directly sensitive to "sprouting a new subjet" the intrinsic feature of Moliere scattering which makes it NOT just a bit more wake.

Inclusive Subjets

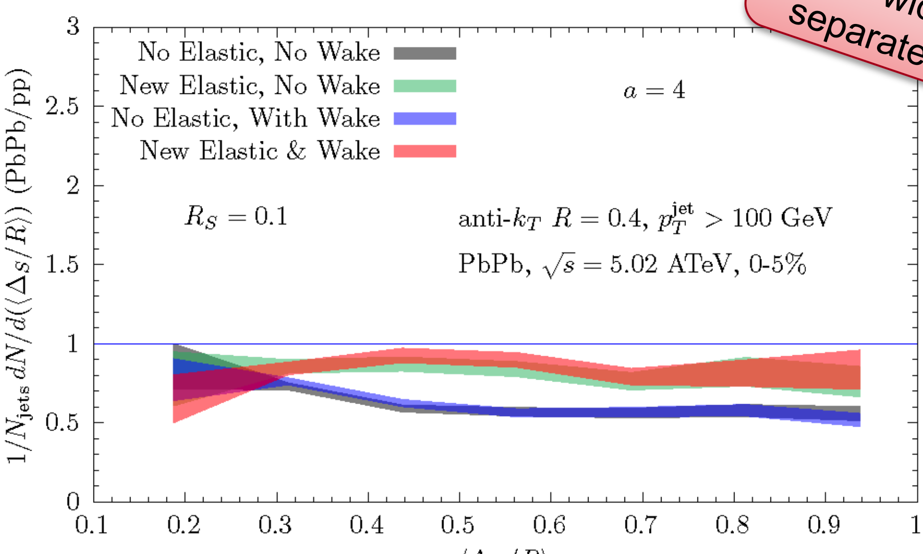
1. Reconstruct jet with R=0.4
2. Recluster each jet's particle content into subjets with R=0.1



Increase in number of subjets…



…which are more widely separated.



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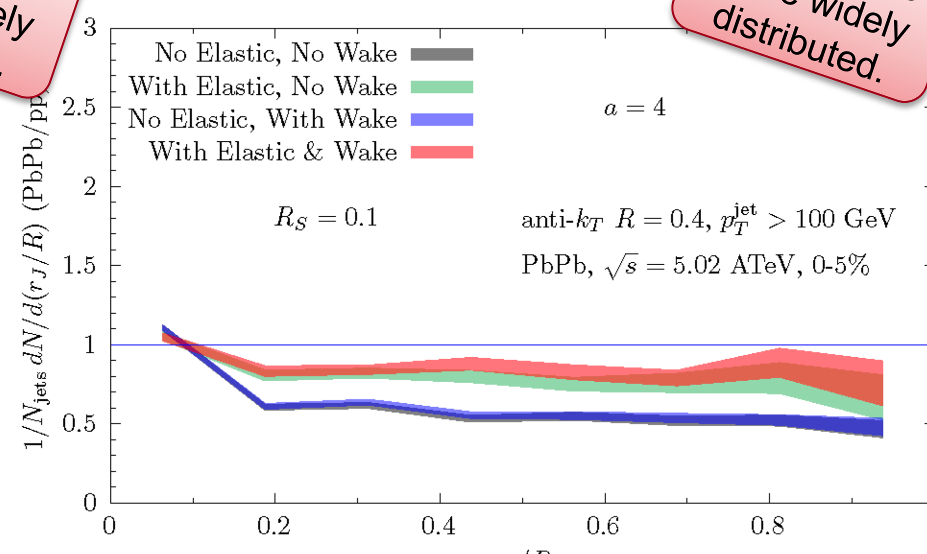


Conclusions

- 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 γ+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 γ+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 γ+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.

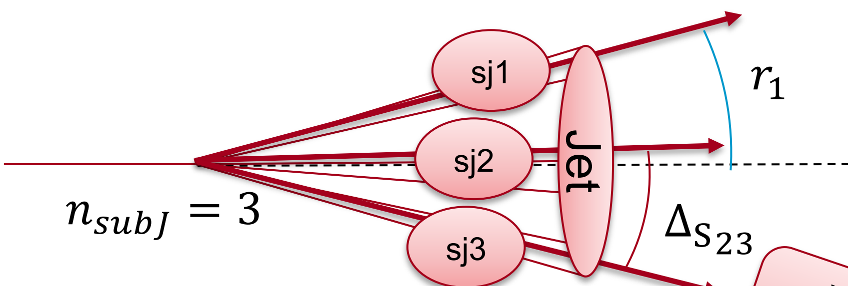
What Next?

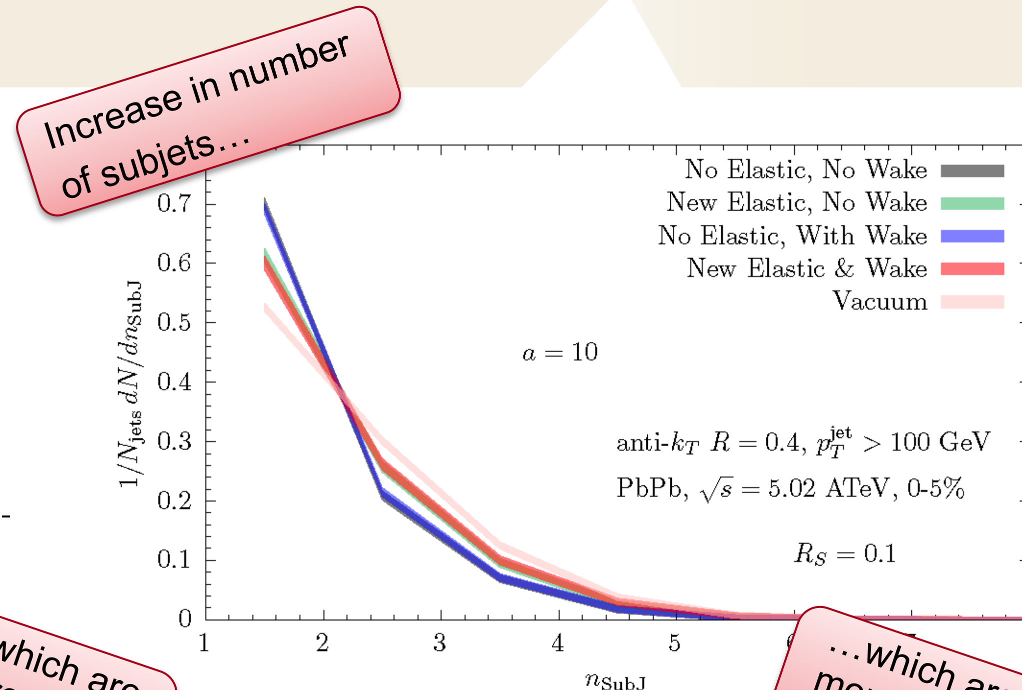
Two kinds of What Next? questions . . .

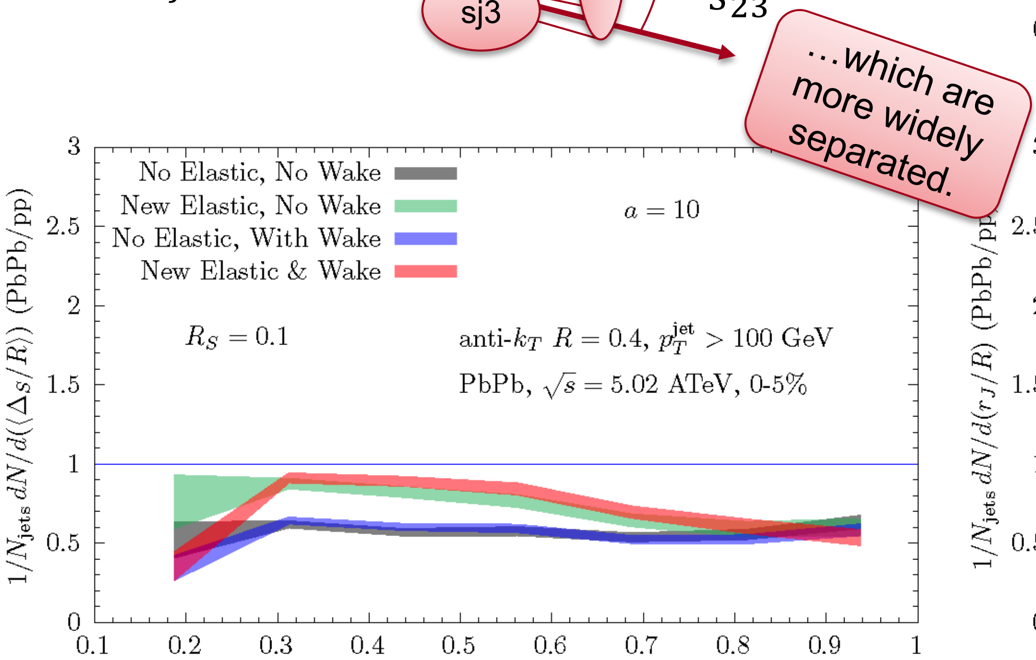
- A question that one asks after the discovery of any new form of complex matter: What is its phase diagram? For high temperature superconductors, for example, phase diagram as a function of temperature and doping. Same here! For us, doping means excess of quarks over antiquarks, rather than an excess of holes over electrons.
- A question that we are privileged to have a chance to address, after the discovery of "our" new form of complex matter: How does the strongly coupled liquid emerge from an asymptotically free gauge theory? Maybe answering this question could help to understand how strongly coupled matter emerges in other contexts.

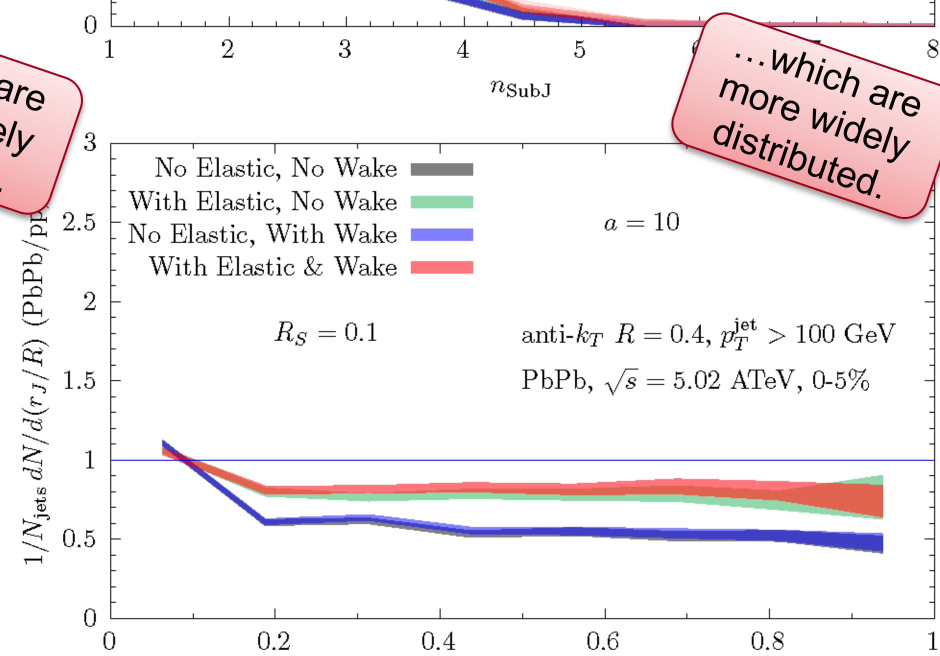
Inclusive Subjets

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







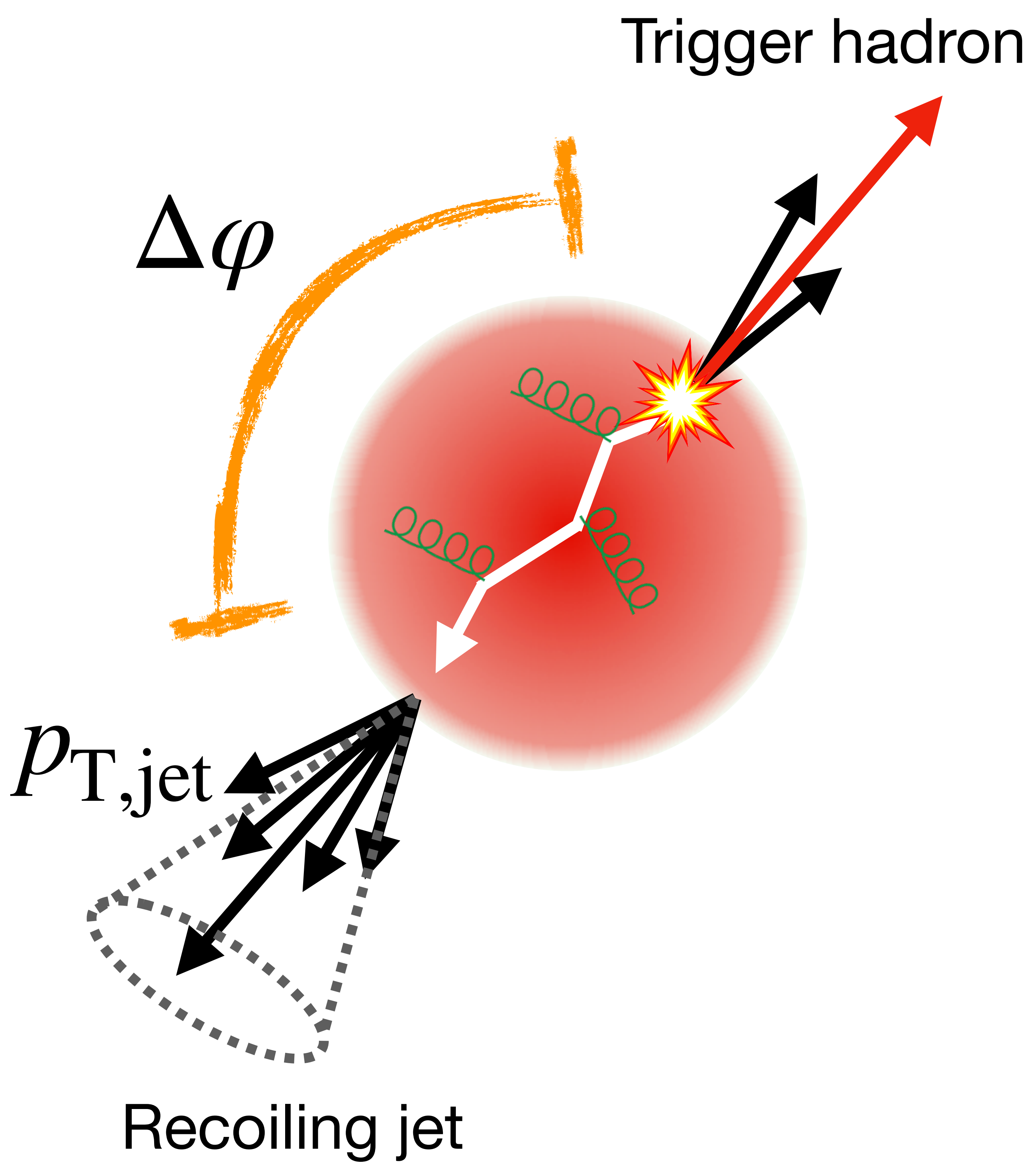


Analysis procedure

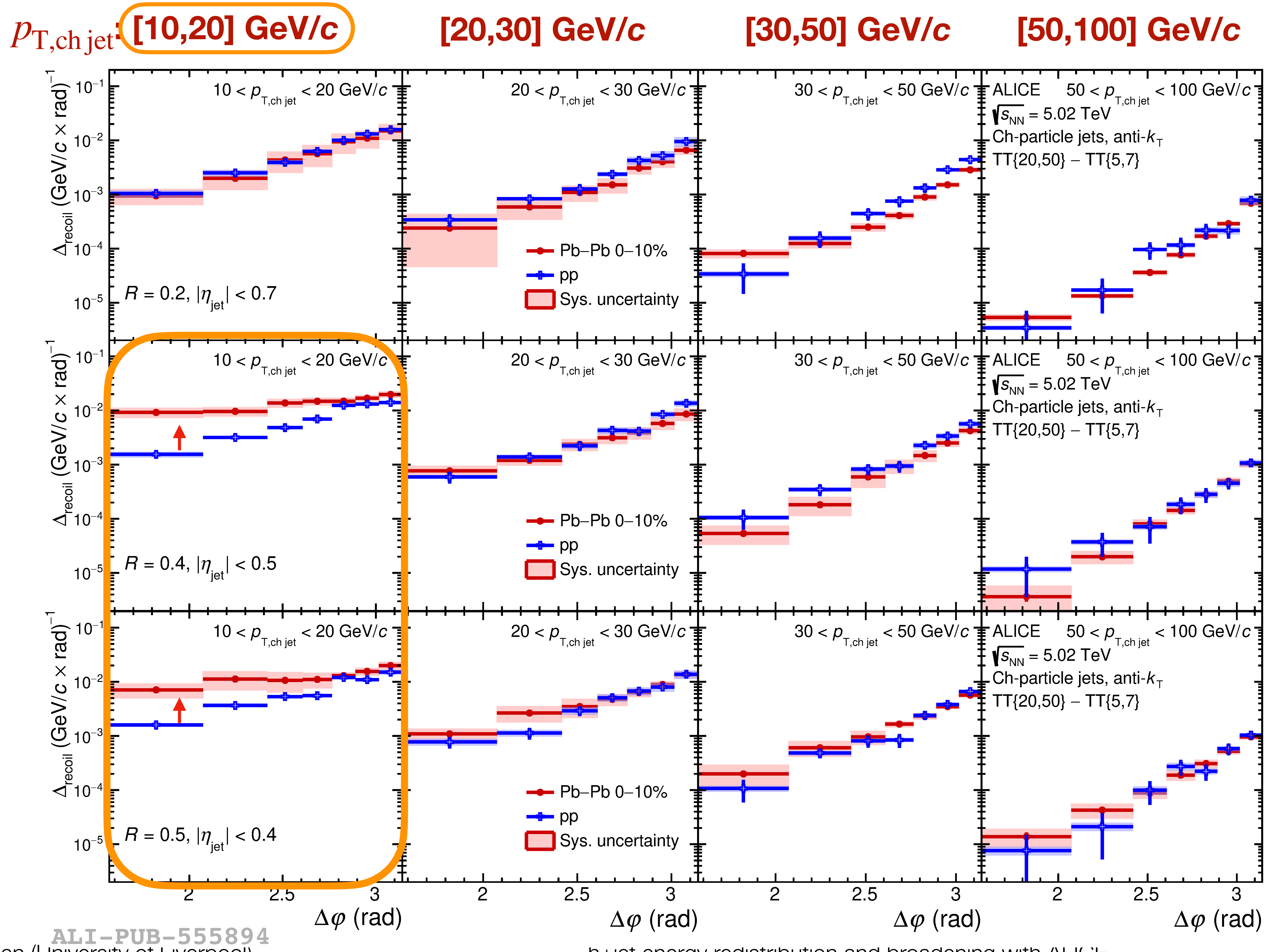
1. **Select events** based on the **presence of a high-p_{T} 'trigger' hadron**
2. **Do jet reconstruction** on these events
3. **Count jets recoiling from the trigger hadron** as function of:
   - opening angle ($\Delta\varphi$) of jet relative to trigger axis
   - transverse momentum ($p_{\mathrm{T,jet}}$)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

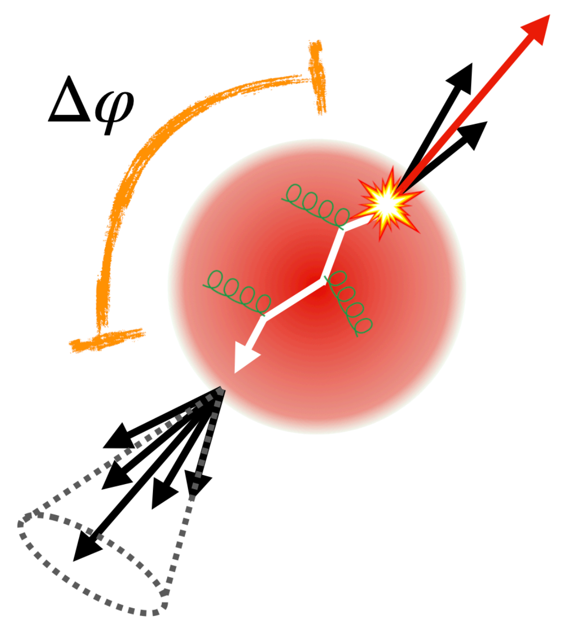
$$\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}}\frac{\mathrm{d}^3N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\mathrm{d}\Delta\varphi\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,h}}\in\mathrm{TT}} = \left(\frac{1}{\sigma^{\mathrm{AA}\to\mathrm{h+X}}}\cdot\frac{\mathrm{d}^3\sigma^{\mathrm{AA}\to\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathr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

- **Perturbatively calculable**
  Ratio between high-p_{T} hadron and jet production cross sections
- **Semi-inclusive**
  events selected based on presence of trigger → count all recoil jets in defined acceptance



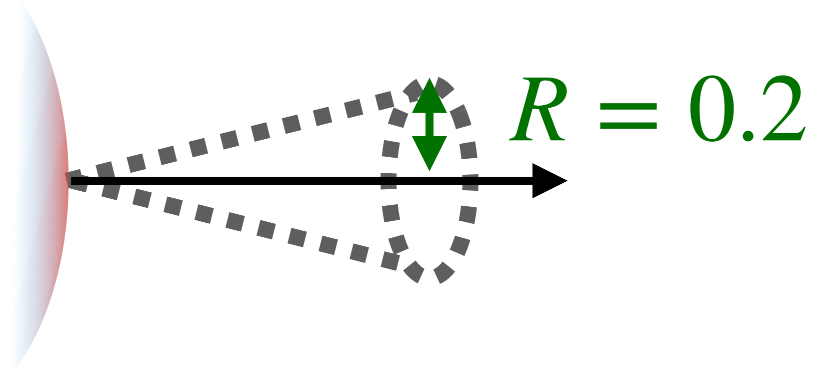
$\Delta_{\rm recoil}(\Delta\varphi)$ distributions in pp and Pb-Pb collisions



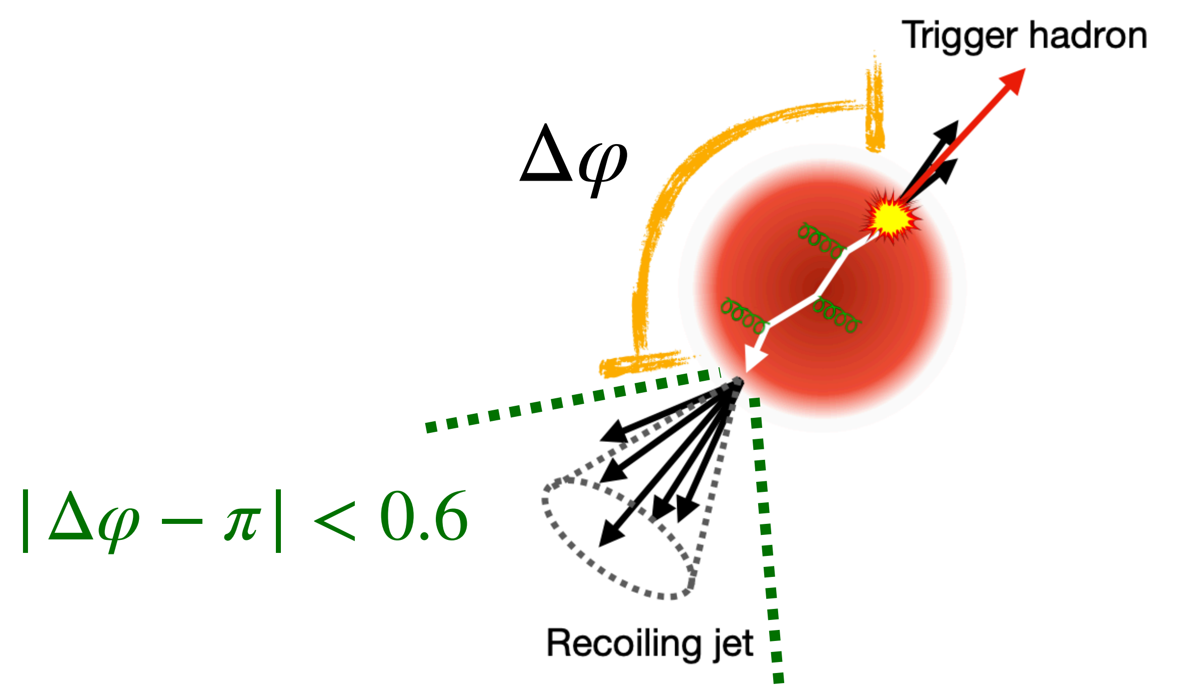


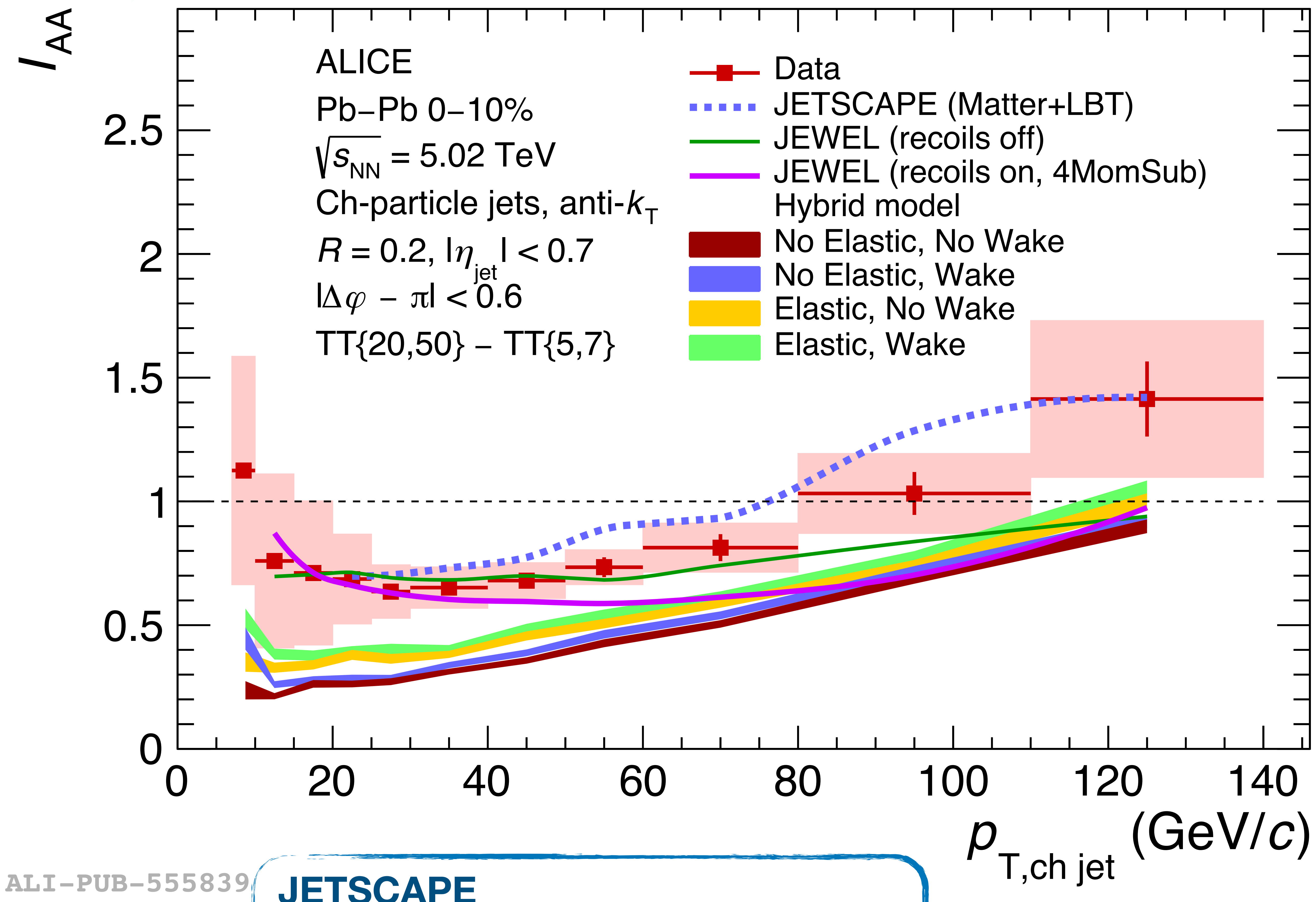
- **Significant azimuthal broadening** for R=0.4 and R=0.5 at low $p_{\rm T,ch\,jet}$

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



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





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

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'

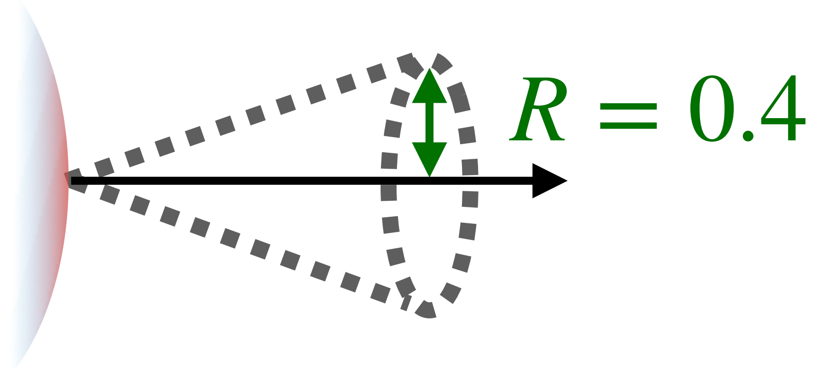
K. Zapp, EPJ C, Volume 74, Issue 2, 2014
R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141

Hybrid model

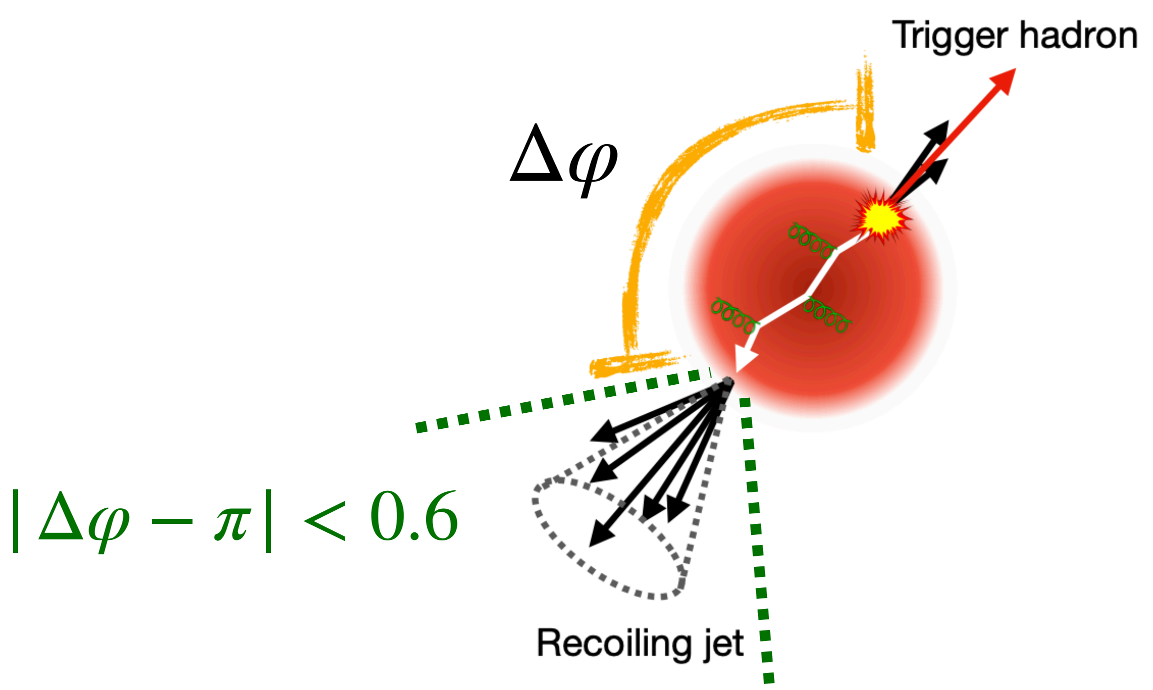
Elastic (Moliére) scatterings and wake (medium response) included

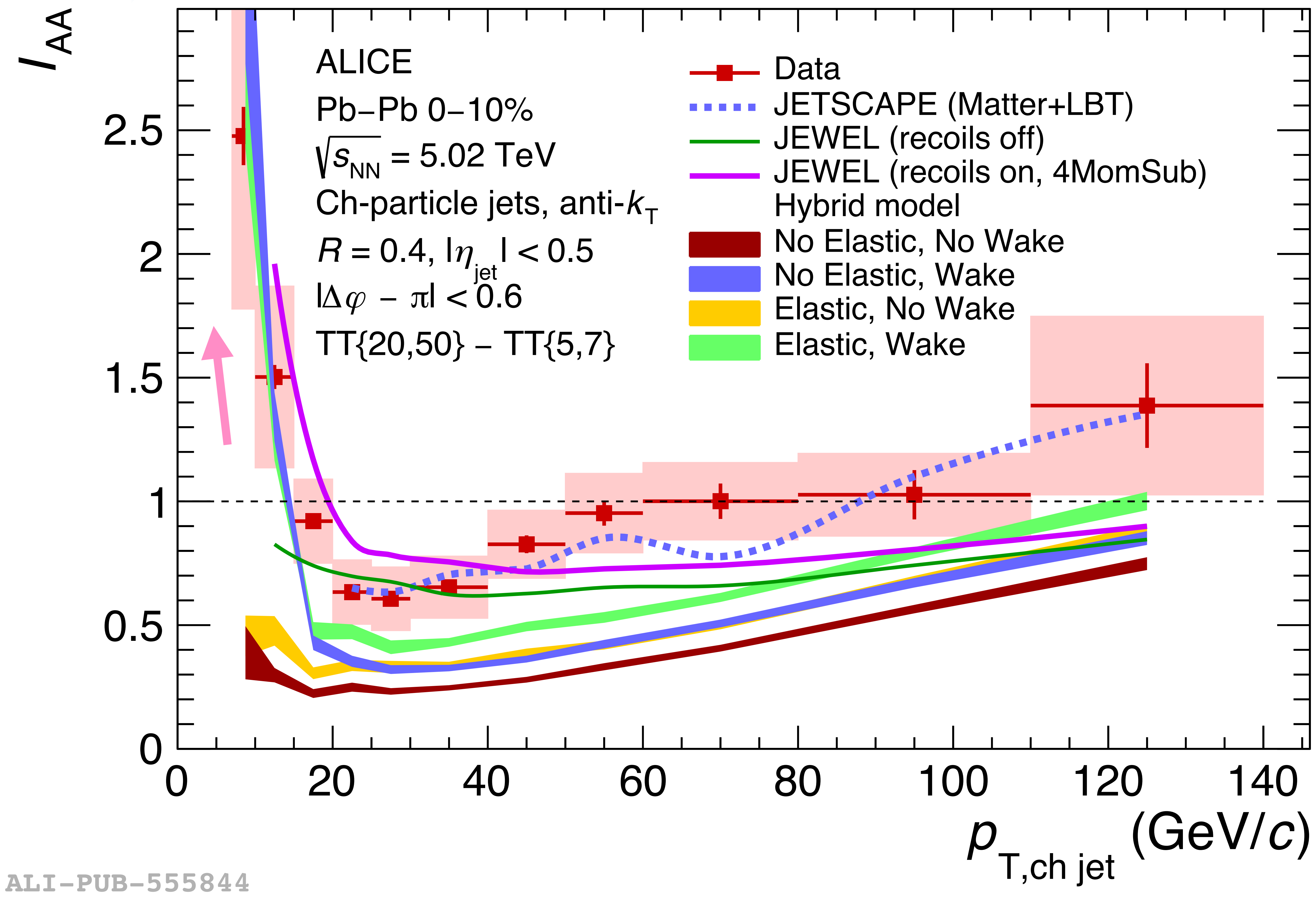
F. d'Eramo, K. Rajagopal, Y. Yin, *JHEP* 01 (2019) 172
Z. Hulcher, D. Pablos, K. Rajagopal, 2208.13593 (QM22)

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



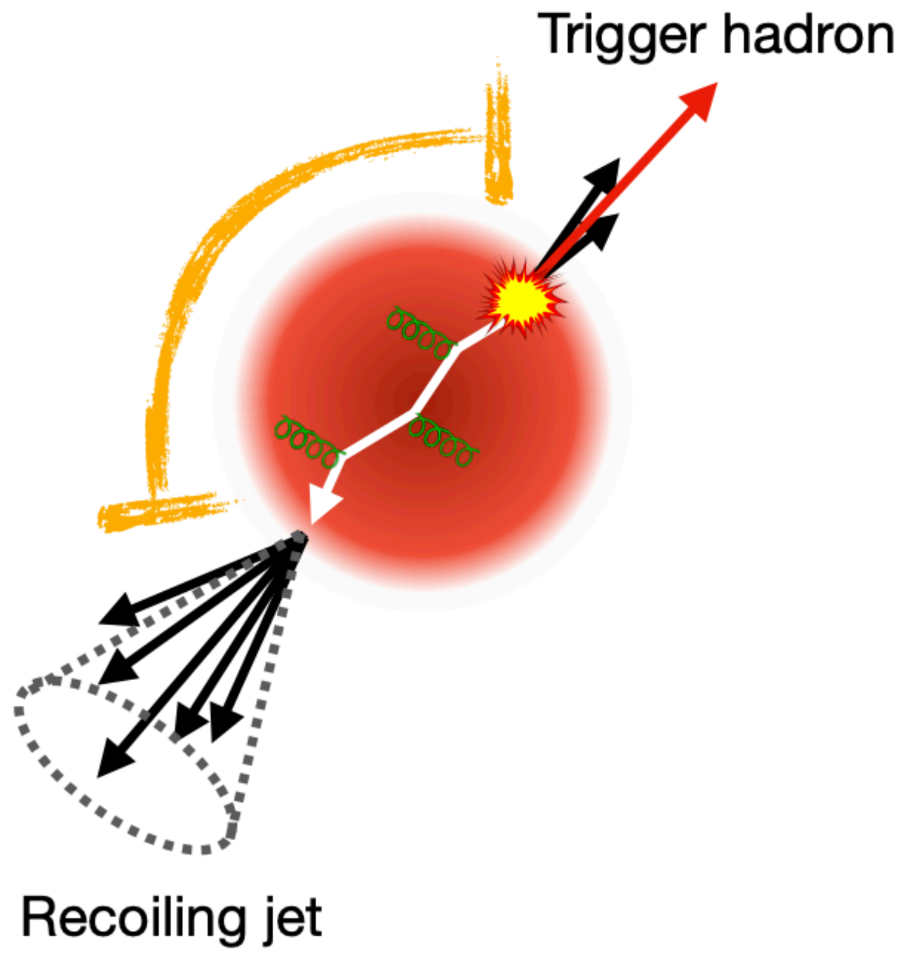
$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$

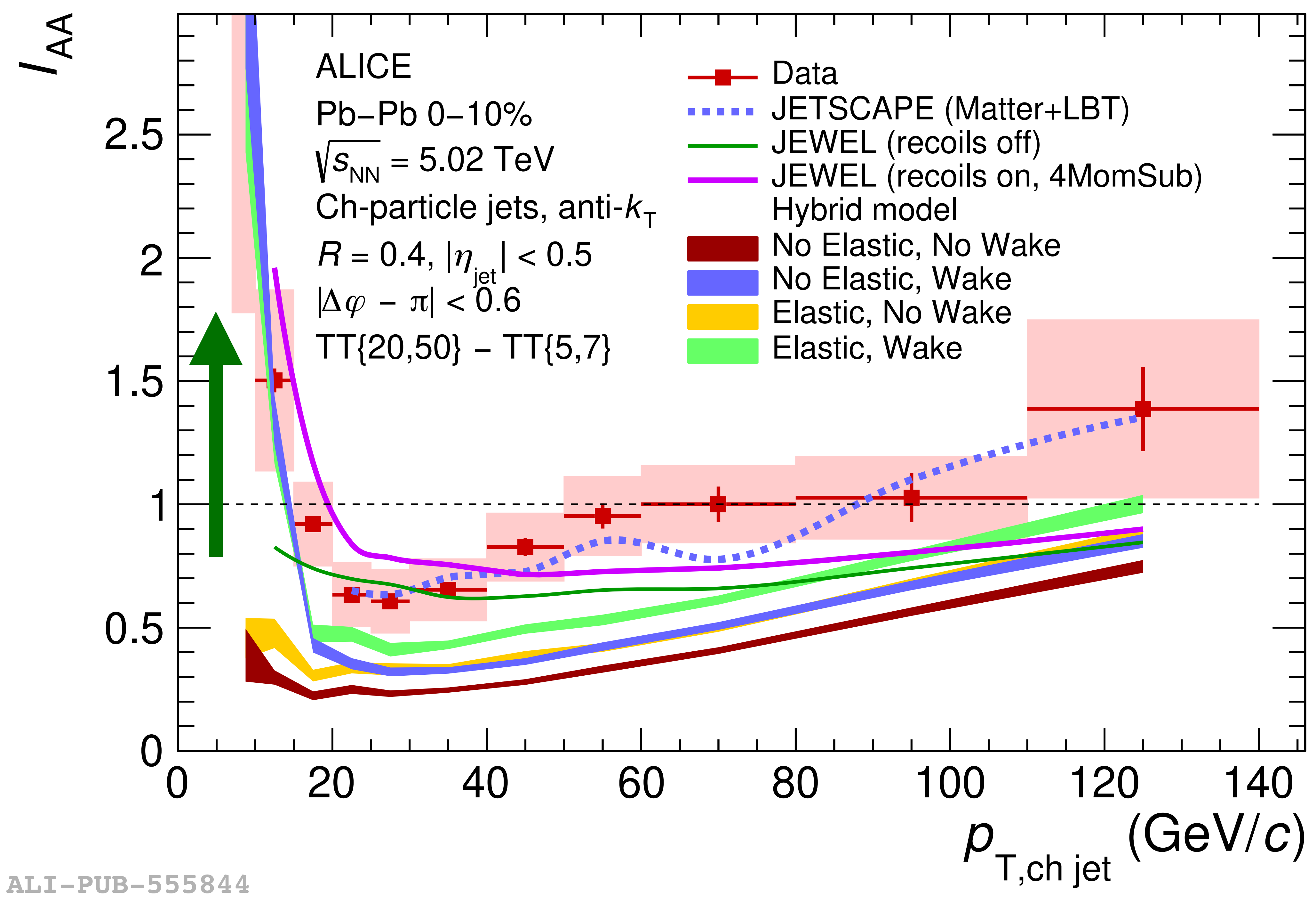


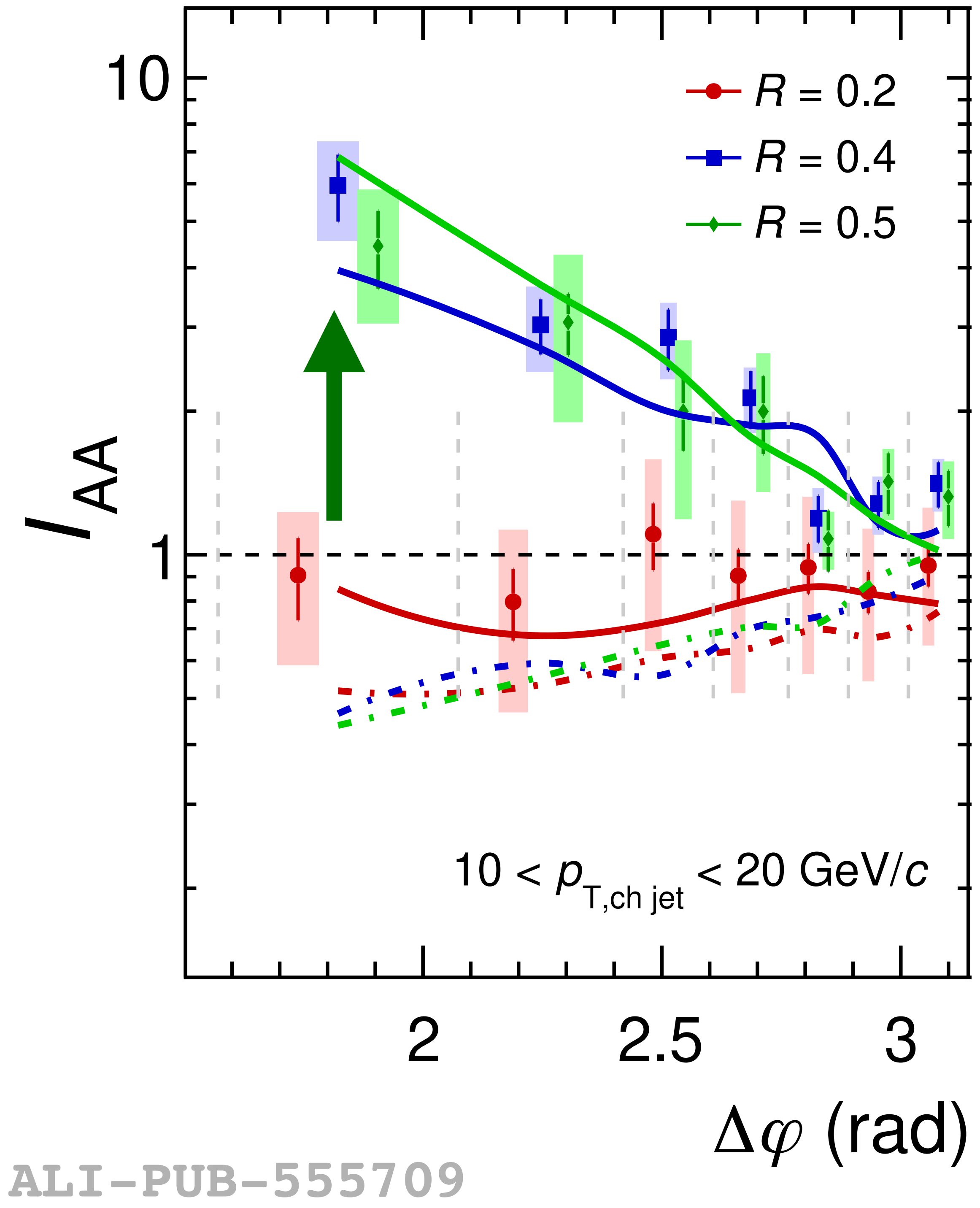


- **Suppression** at $20 < p_{T,ch\,jet} < 80$ GeV/c
  → jet energy loss
- **Rising trend with $p_{T,ch\,jet}$**
  → interplay between hadron and jet energy loss? Less trigger surface bias when $p_{T,jet} >> p_{T,trig}$?
- **Rise at low $p_{T,ch\,jet}$**
  → Energy recovery? Reproduced by models including medium response

Summary and outlook





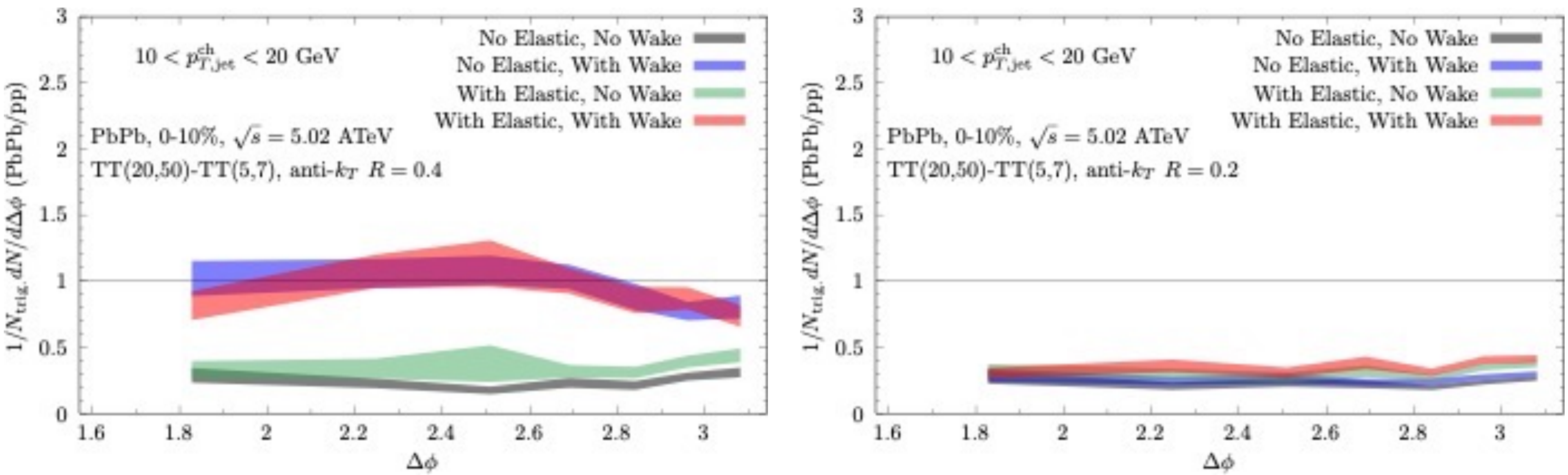


- **First observation of significant low-$p_{\mathrm{T,jet}}$ jet yield and large-angle enhancement in Pb-Pb collisions with ALICE!**
- Medium response or medium-induced soft radiation favoured as cause for both measured effects
- Looking forward to further studies with Run 3 data with ALICE after significant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

arXiv:2308.16128
arXiv:2308.16131

Hadron--Charge-Jet Acoplanarity, LHC energy

Preliminary



- Study acoplanarity in hadron - charged jet system.
- Parameters similar to ALICE
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.4 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- And indeed effect of wake seen only in the lower charged jet p_T bin
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron—Charge-Jet Acoplanarity, LHC energy

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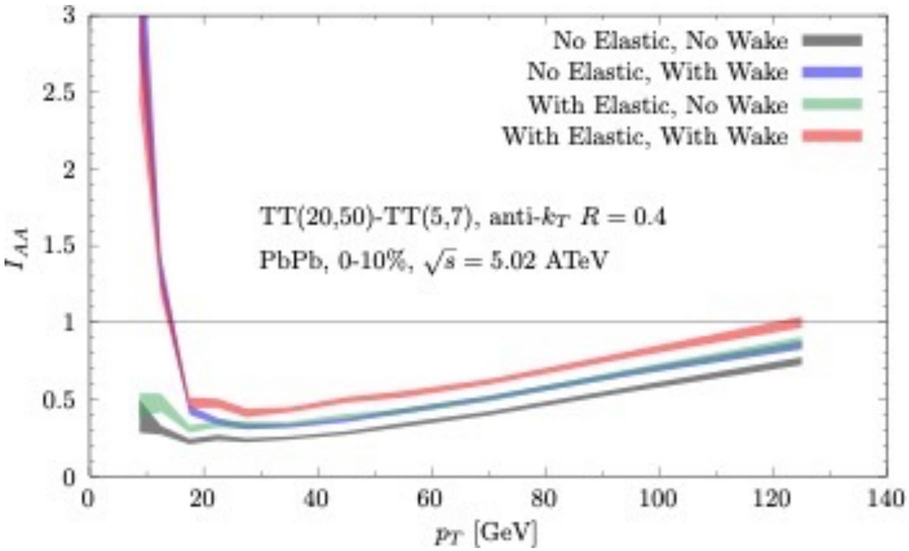

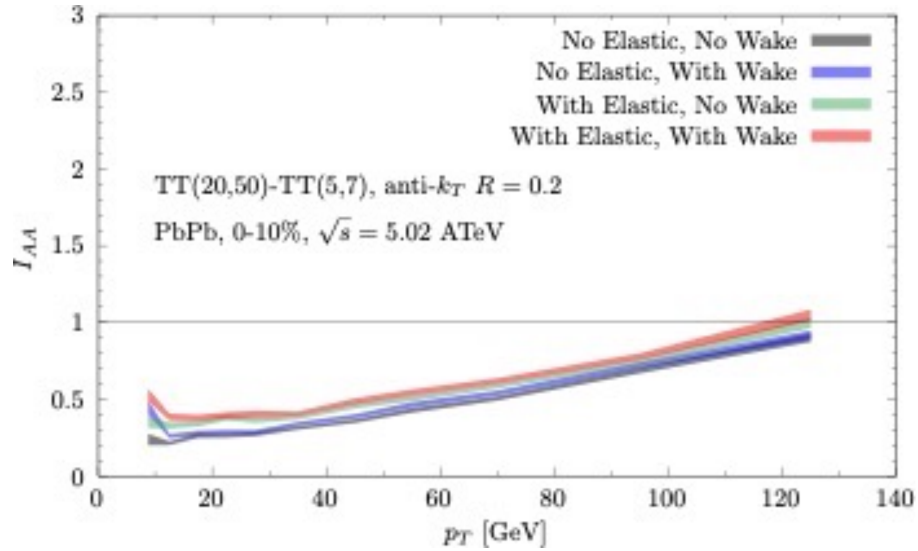

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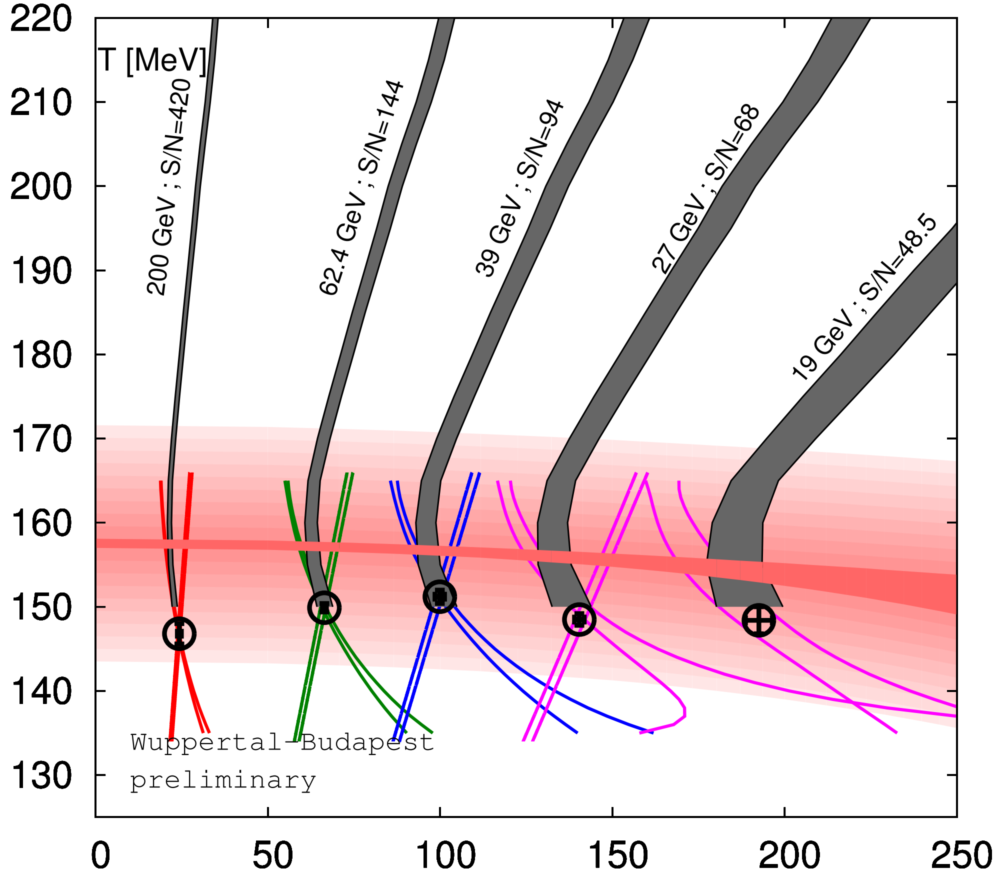
Mapping the QCD Phase Diagram

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

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

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

Mapping the Crossover Region



Wuppertal-Budapest-Houston, 1601.00466

Lattice determination of crossover region compared with freeze-out points obtained from the intersection of: (i) lattice calculations and 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 μ_B? Signs of an upturn at larger μ_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, $\ldots$, 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 → 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 → growth of critical fluctuations "lags" what it would be in equilibrium, fluctuations also persist longer than they would; expansion, radial flow → critical fluctuations advected outward; backreaction 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) Karthein, Pradeep, KR, Stephanov, Yin
- Phase diagram mapping theory+modeling tools vastly better than in 2015; being completed; data coming soon!

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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.

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- How does the liquid emerge as a function of increasing system size? What is the smallest possible droplet of the liquid?

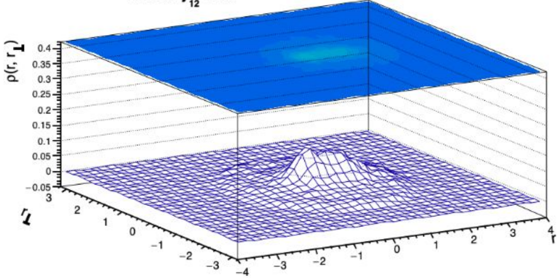
Each, in a different way, requires stressing or probing the QGP. Each can tell us about its inner workings.

Smallest possible droplet of liquid?

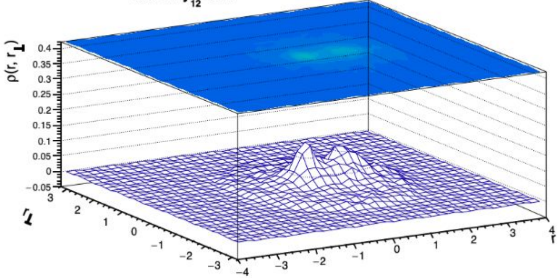
- What is the smallest possible droplet of QGP that behaves hydrodynamically? **Anyone doing holographic calculations at strong coupling, or anyone seeing effects of small lumps in the initial state visible in the final state, could have asked this question, but didn't. Question was asked by data: pPb collisions @LHC; pAu, dAu and ^{3}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. . .**

SHAPE OF PARTICLES WITH P_T < 1.0 GeV IN GAMMA-JETS IN pp COLLISIONS WITH 2 SUBJETS

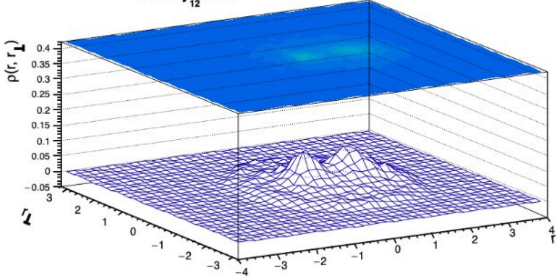
$0.6 < \Delta y_{12} < 0.8$



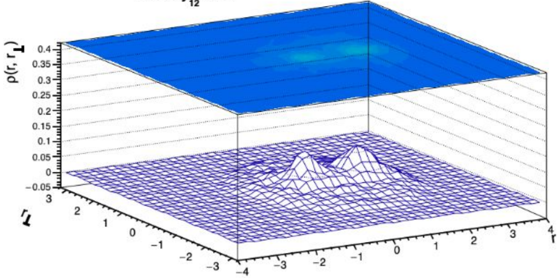
$0.8 < \Delta y_{12} < 1.0$



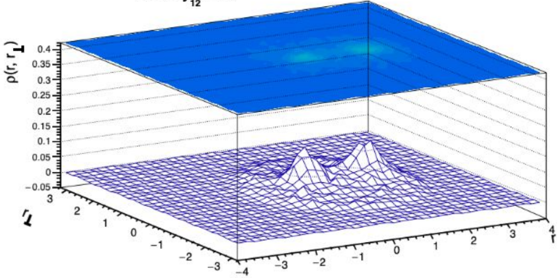
$1.0 < \Delta y_{12} < 1.2$



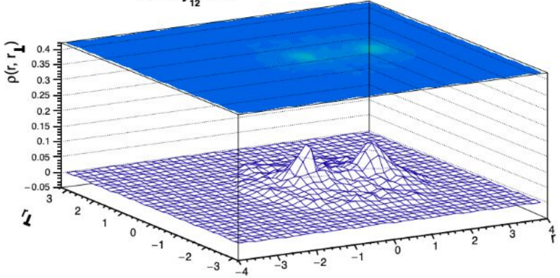
$1.2 < \Delta y_{12} < 1.4$



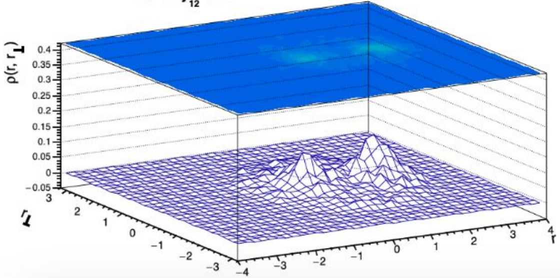
$1.4 < \Delta y_{12} < 1.6$



$1.6 < \Delta y_{12} < 1.8$



$1.8 < \Delta y_{12} < 2.0$



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 subjets are closely-separated!

Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

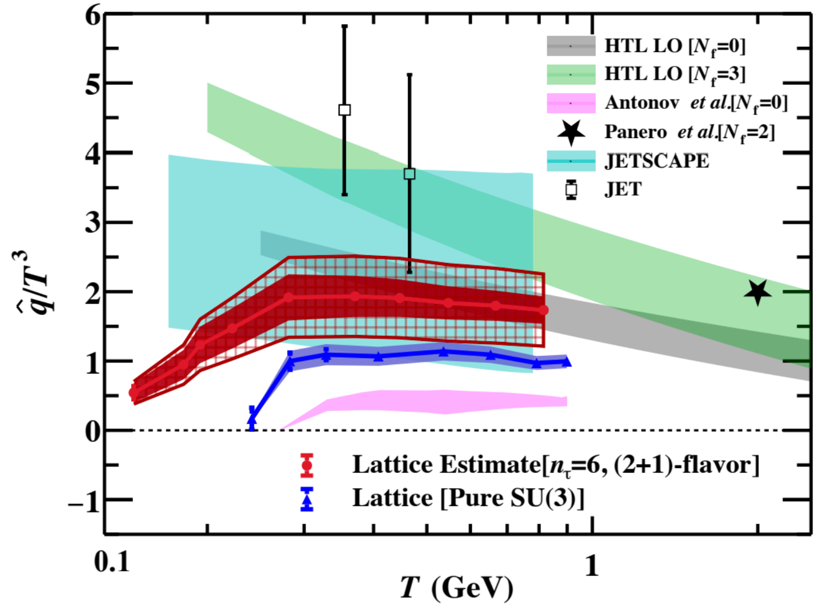
At strong coupling, holography predicts Gaussian broadening without quasi-particles (eg: N=4 SYM)

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

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

Elastic scatterings of exchanged momentum $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

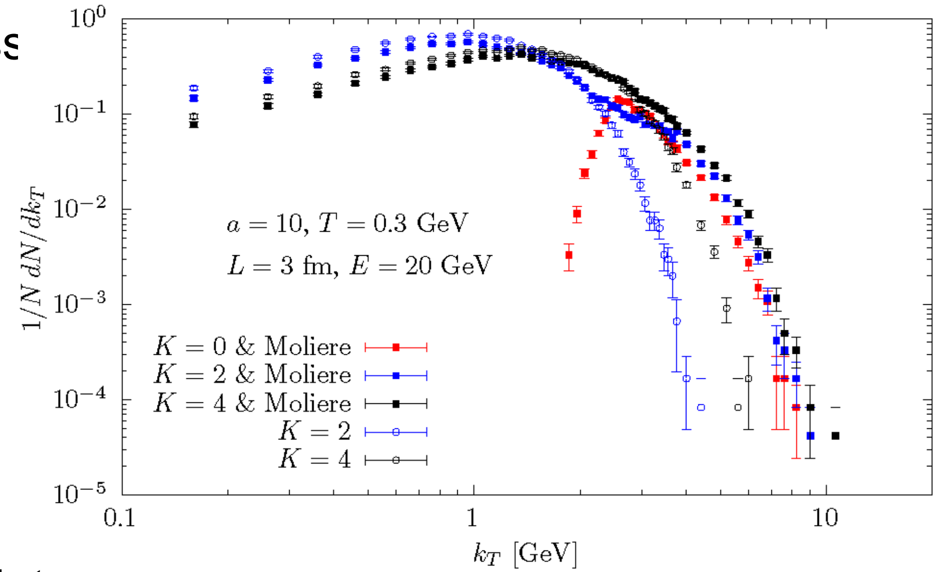
At strong coupling, holography predicts Gauss broadening without quasi-particles (eg: N=4 SYM)

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

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, $a = 10$



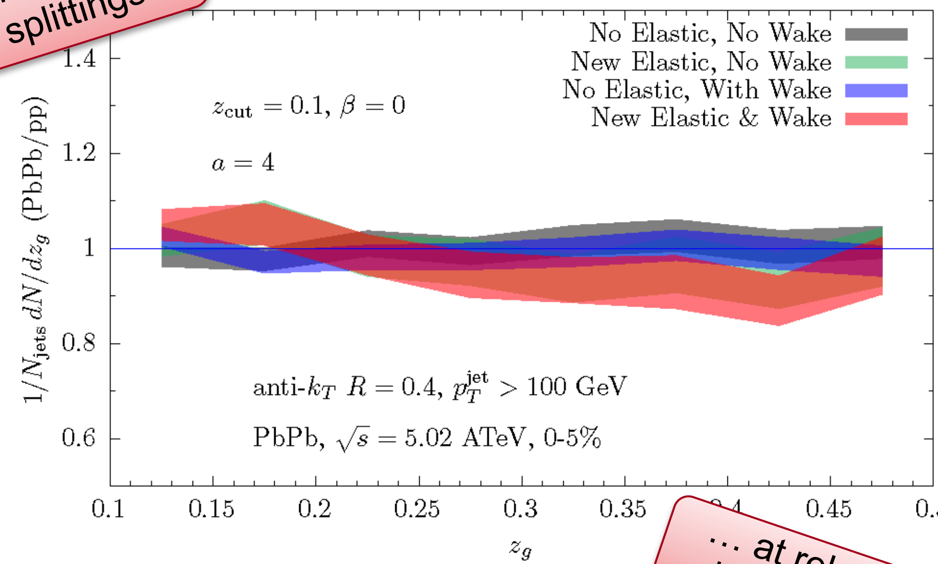
Groomed z_g and R_g

Soft Drop ($\beta = 0$)

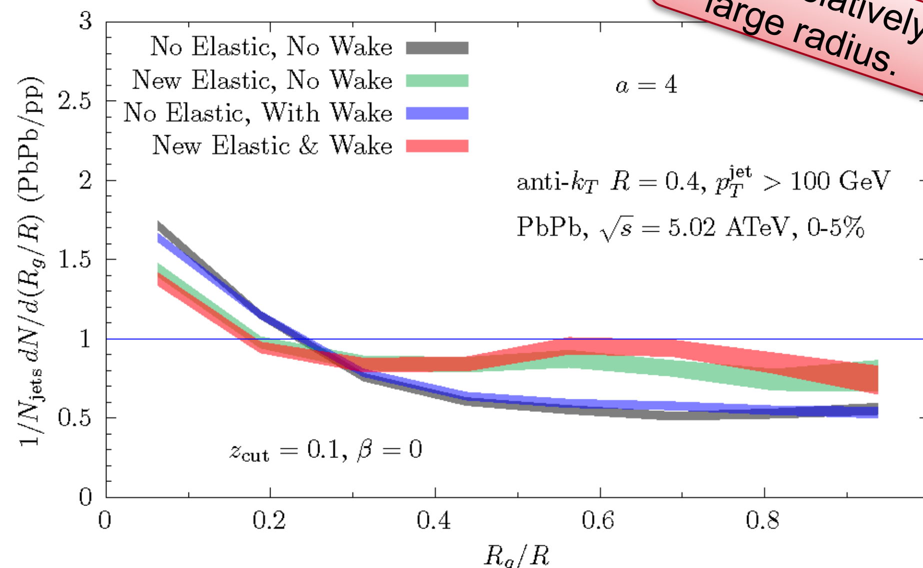
1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2, separated by angle R_g
4. If $\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} \equiv z_g > z_{cut}$, then original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and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



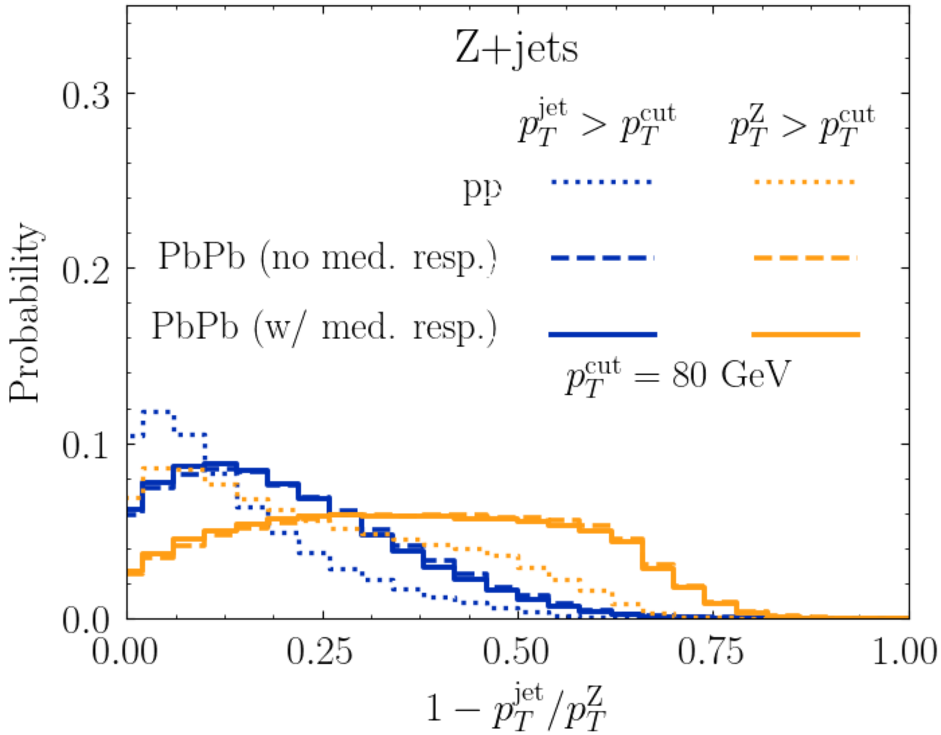
… at relatively large radius.



R=1.0 Jets made of R=0.2 Jets

- Another interesting observable, introduced by ATLAS at QM19 in Wuhan. See ATLAS publication 2301.05606.
- First reconstruct anti-k_t-$R = 0.2$ jets, call them subjets, with $p_T^{\rm subjet} > 35$ GeV; then reconstruct anti-k_t-$R = 1.0$ jets (p_T's from ~ 90 to ~ 900 GeV) from these objects.
- Find $R_{\rm AA}$ for $R = 1.0$ jets with 1 (≥ 2) subjets is less (more) suppressed. For those with 2 subjets, look at distributions of angular separation and splitting parameter.
- A way to find pairs of $R = 0.2$ jets with a chosen ΔR_{12}.
- Arjun Kudinoor, Dani Pablos and KR are investigating this observable using the hybrid model, turning Moliere off and on, turning wake off and on.
- Moliere effects seem to be small in magnitude; motivates repeating this study with somewhat lower-p_T subjets.
- Can pick two $R = 0.2$ jets with a specified separation up to $\Delta R_{12} = 1.0$ and look at the wake between and around them. An interesting arena in which to test how well models describe the dynamics of jet wakes.

Disentangling Jet Modification from Selection



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

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

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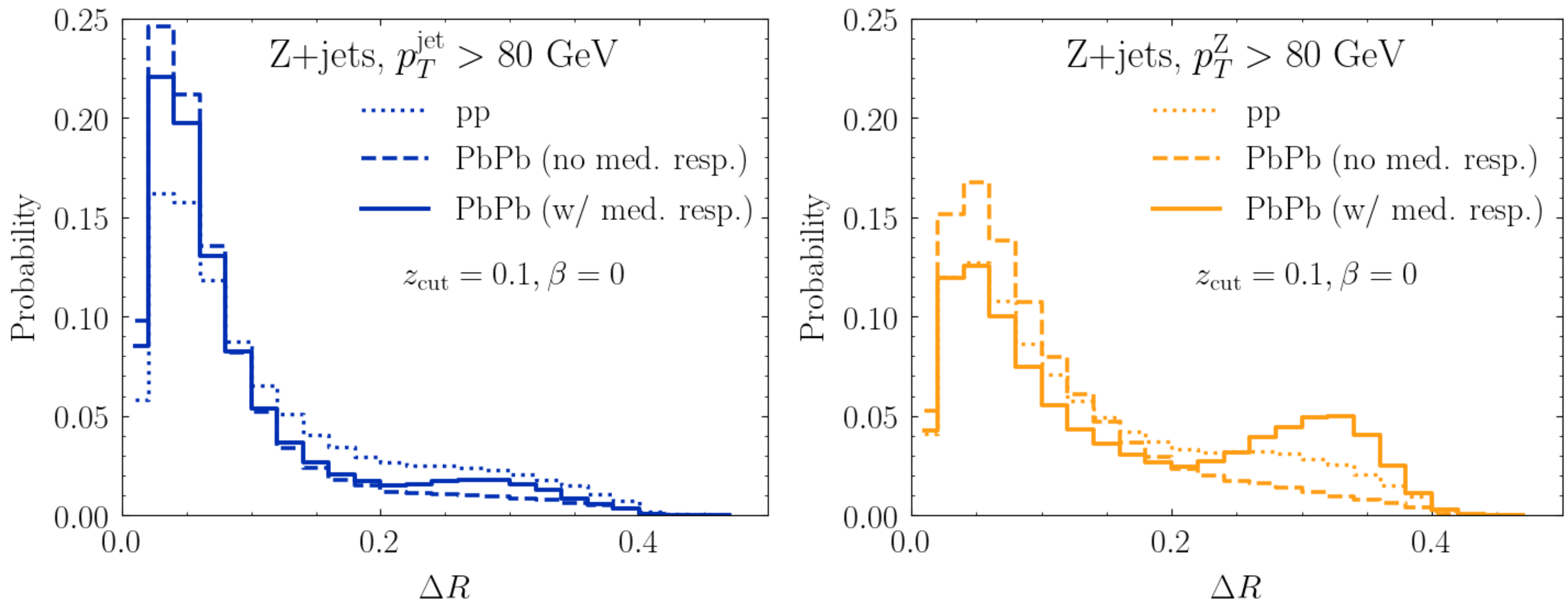


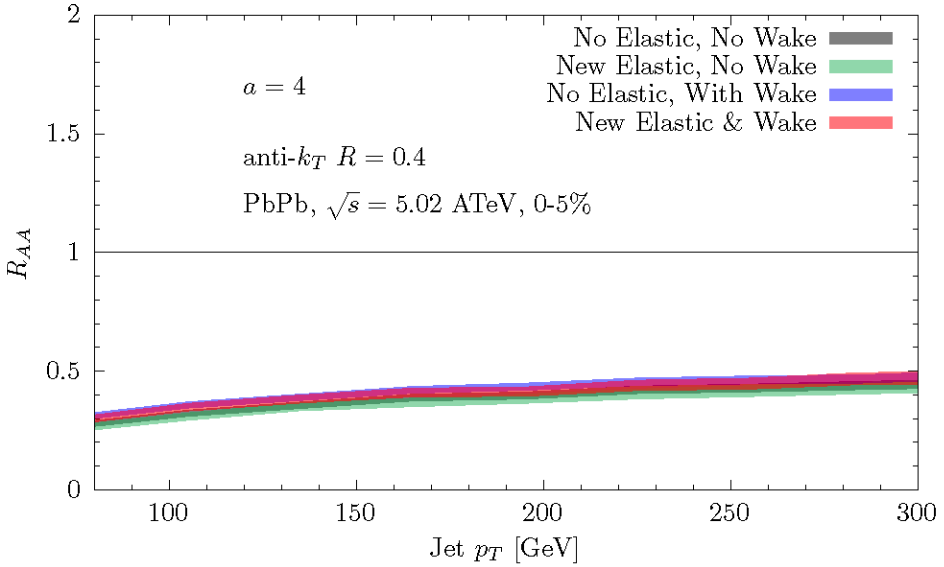
Orange: $p_T^Z > 80$ GeV; $p_T^{\text{jet}} > 30$ GeV. See jet modification.

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.

Jet R_{AA}

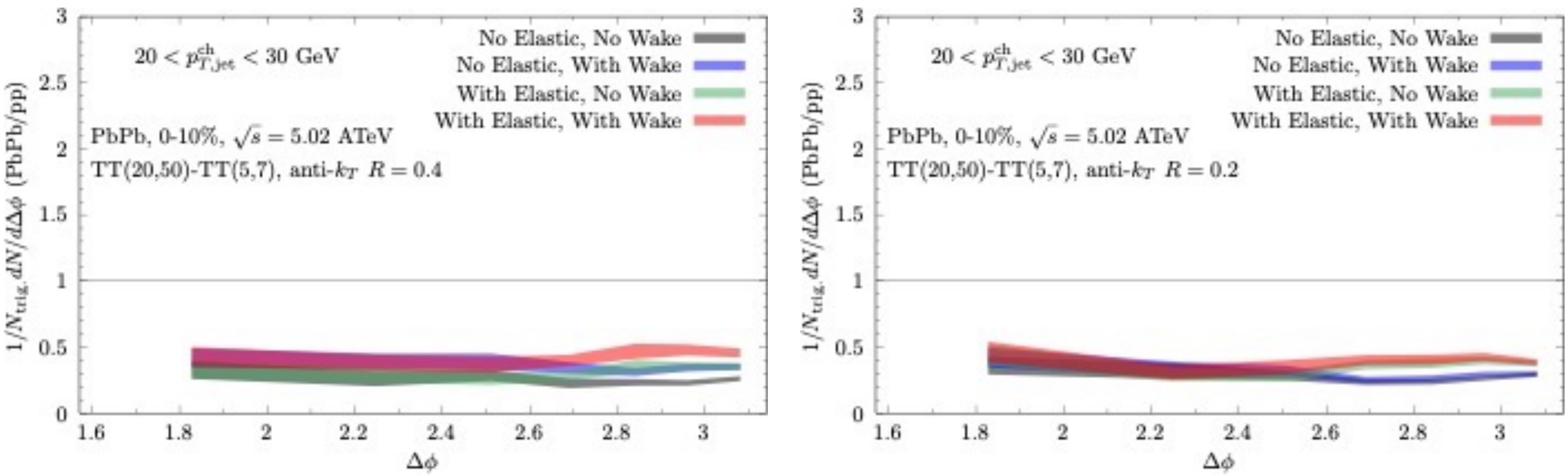
Casalderrey-Solana et al. 2019

- κ_{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 κ_{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 κ_{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.
- Parameters similar to ALICE
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.4 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- And indeed effect of wake seen only in the lower charged jet p_T bin
- Moliere scattering: jet sprouts added prongs, not much overall deflection

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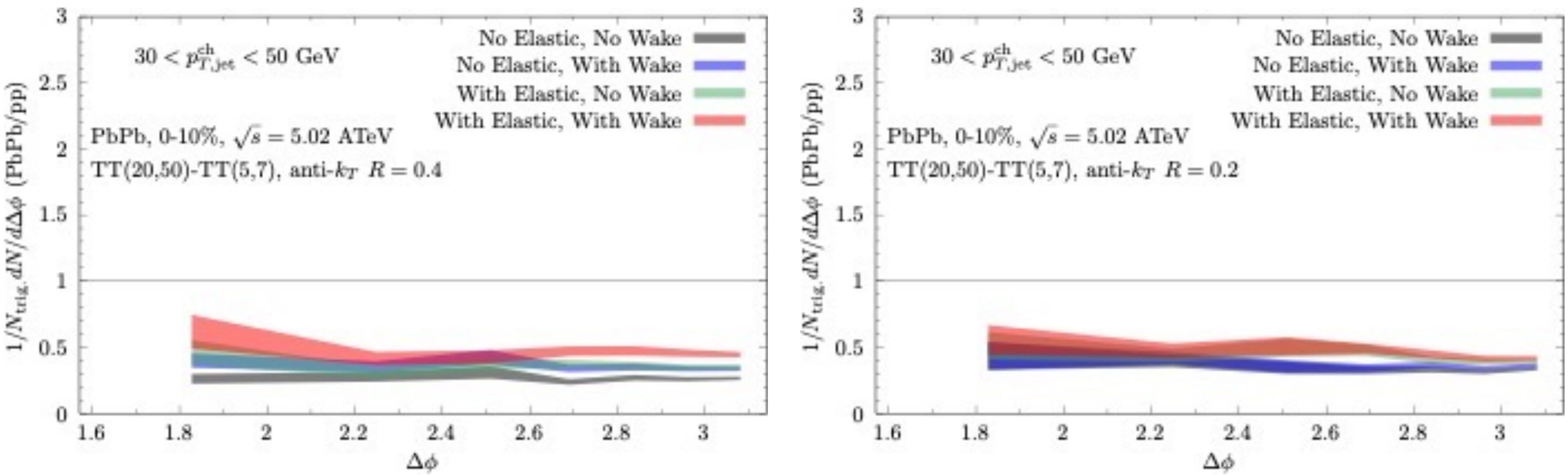

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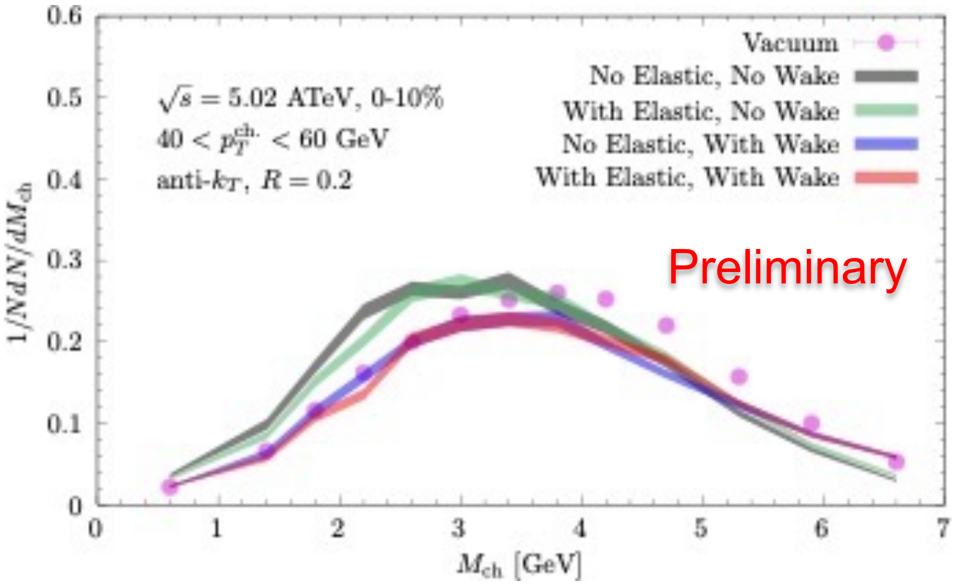
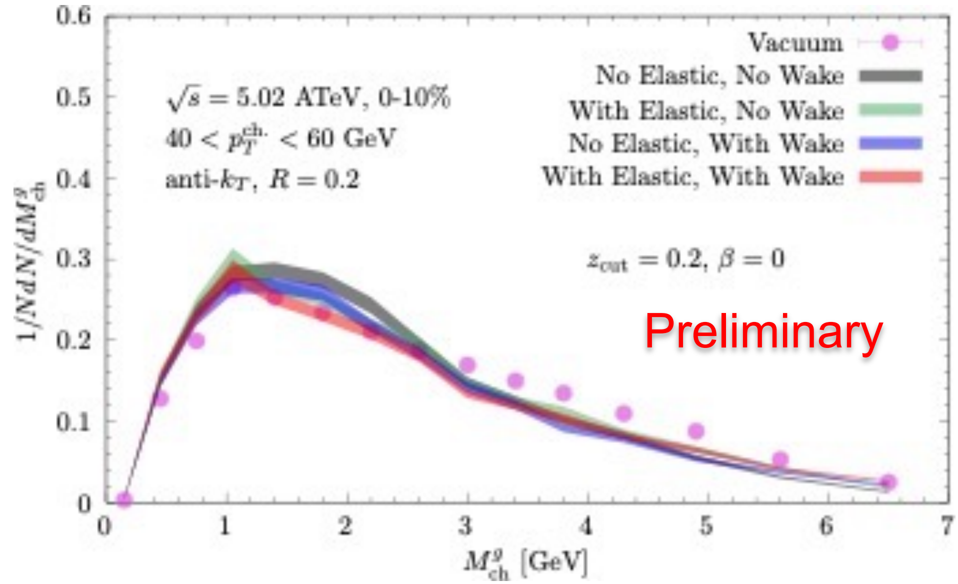
Jet Mass, and Groomed Jet Mass





→ 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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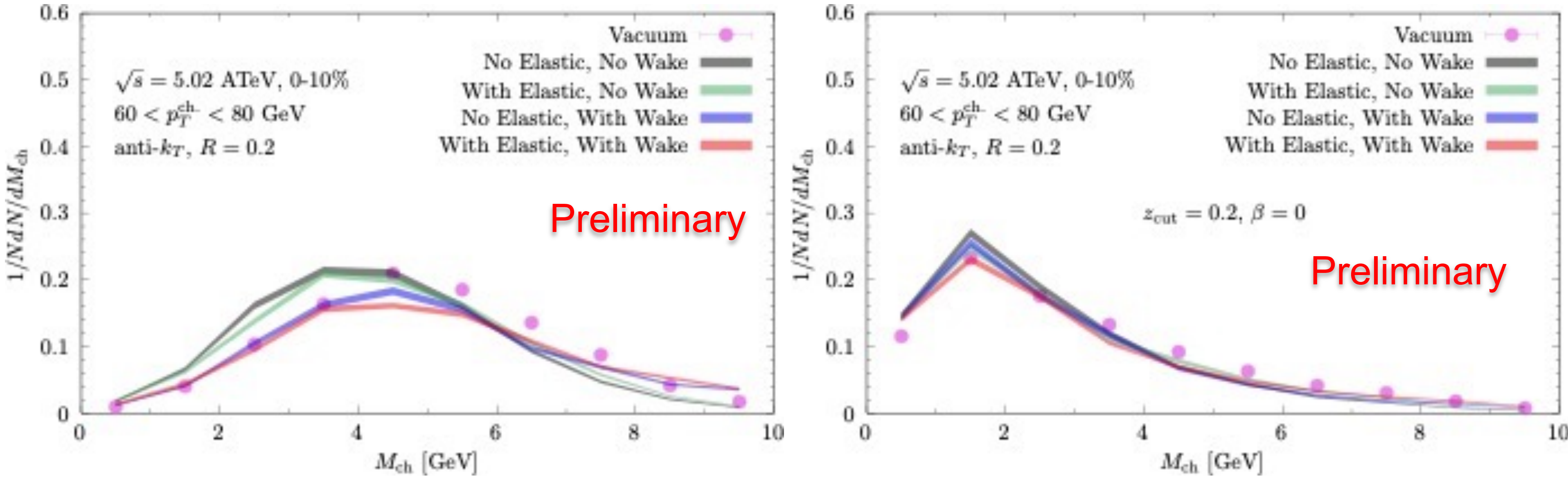

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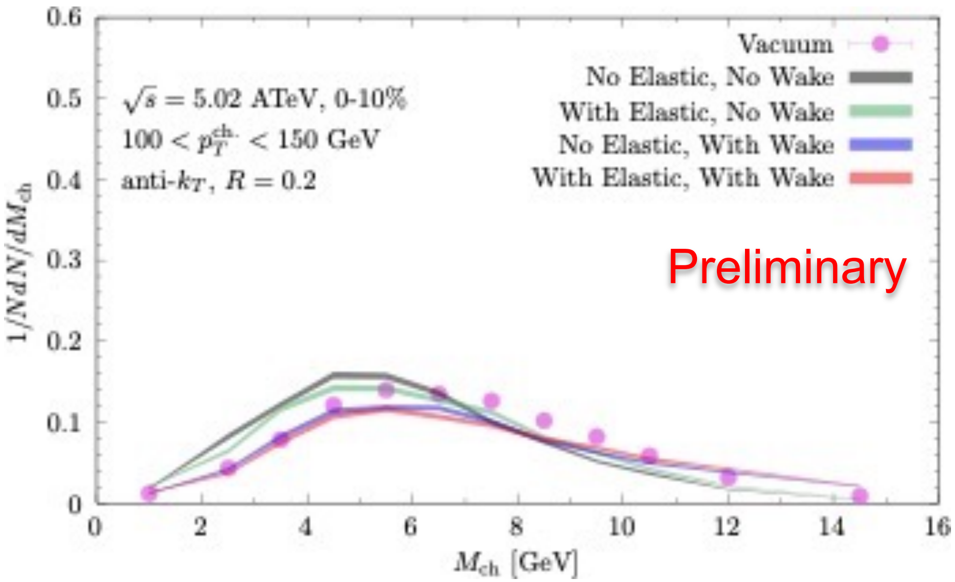

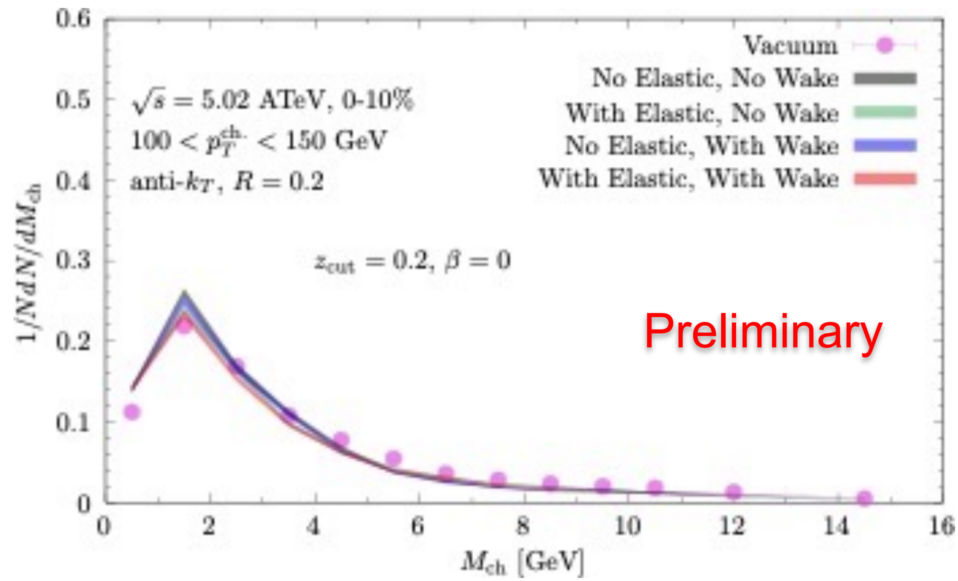

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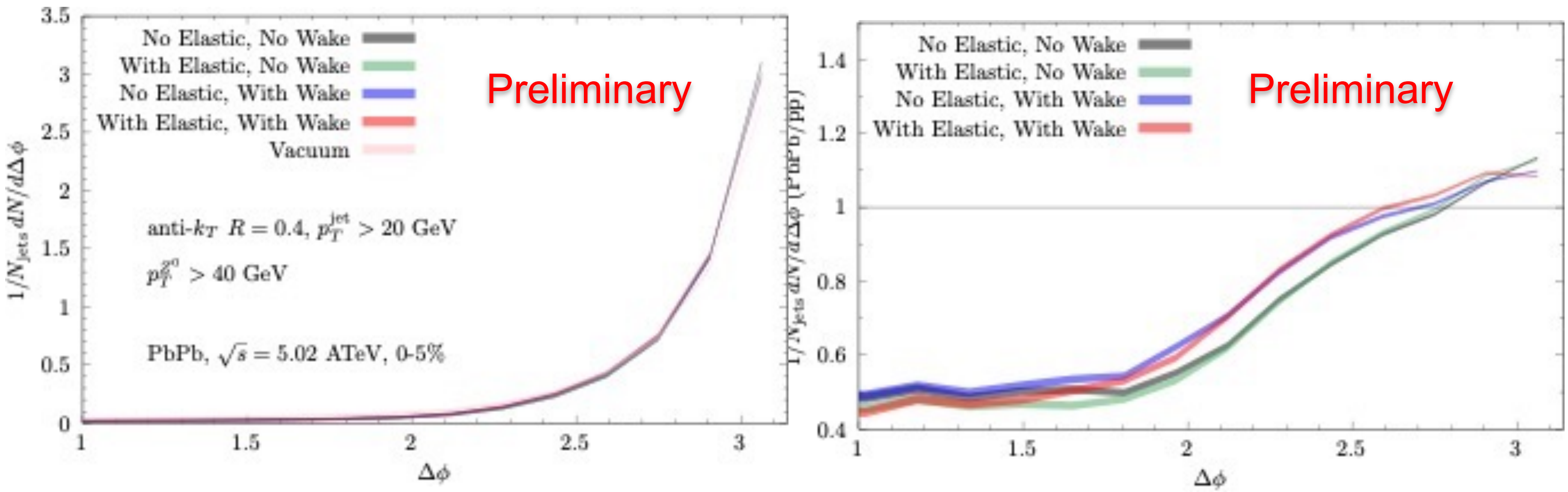
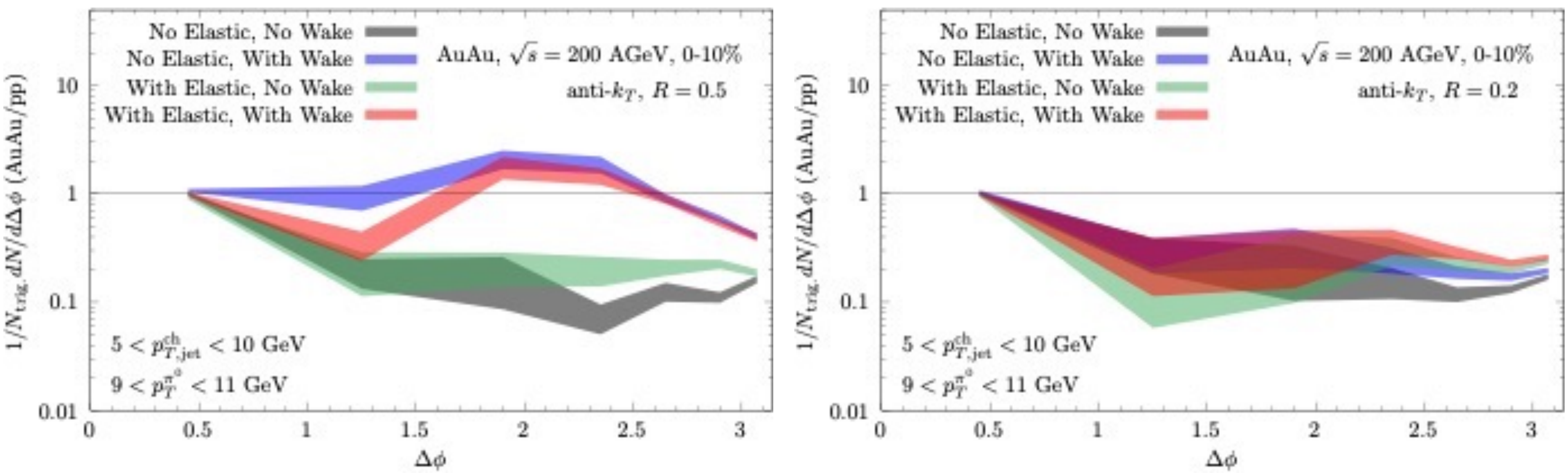
Z-Jet Acoplanarity



- 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 kT, 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
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.5 jets, not for R=0.2
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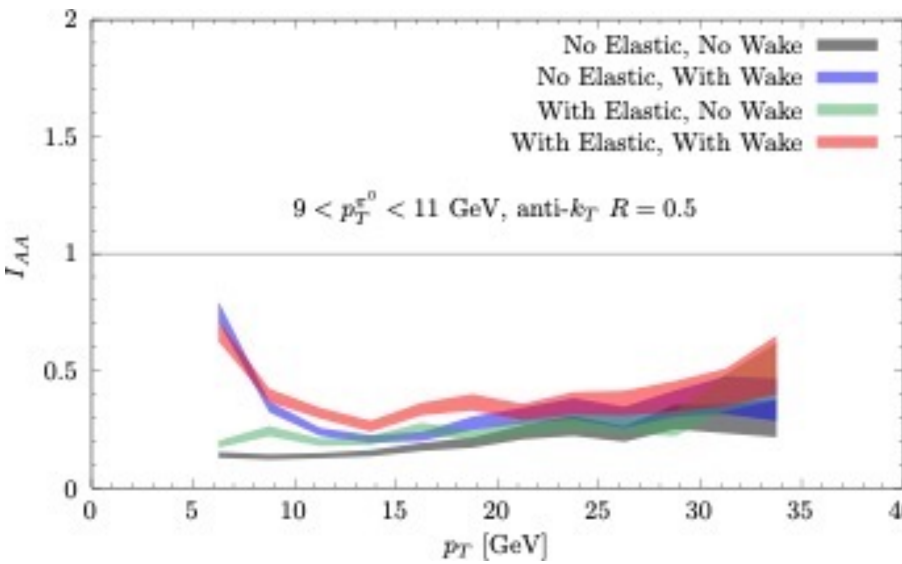
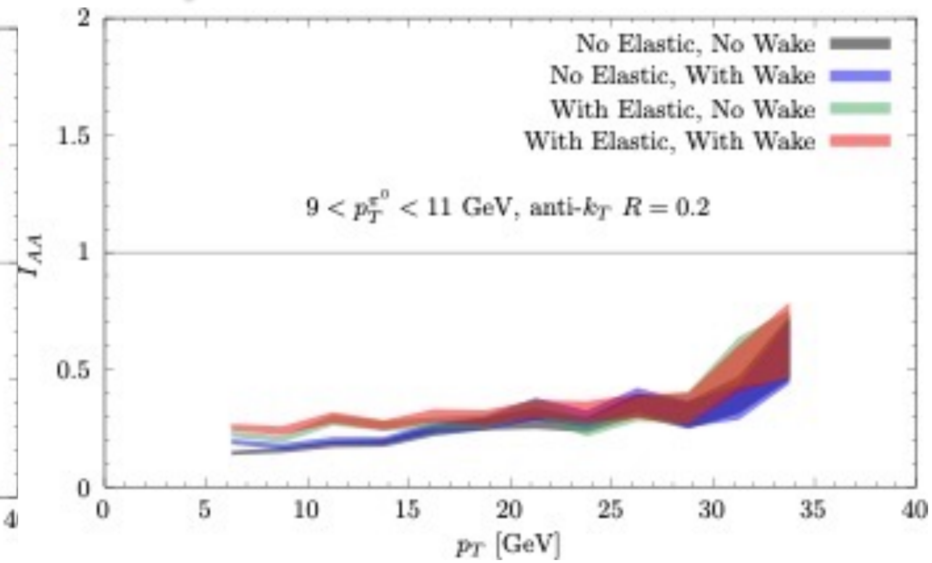
Hadron--Charge-Jet Acoplanarity, RHIC energy

Preliminary





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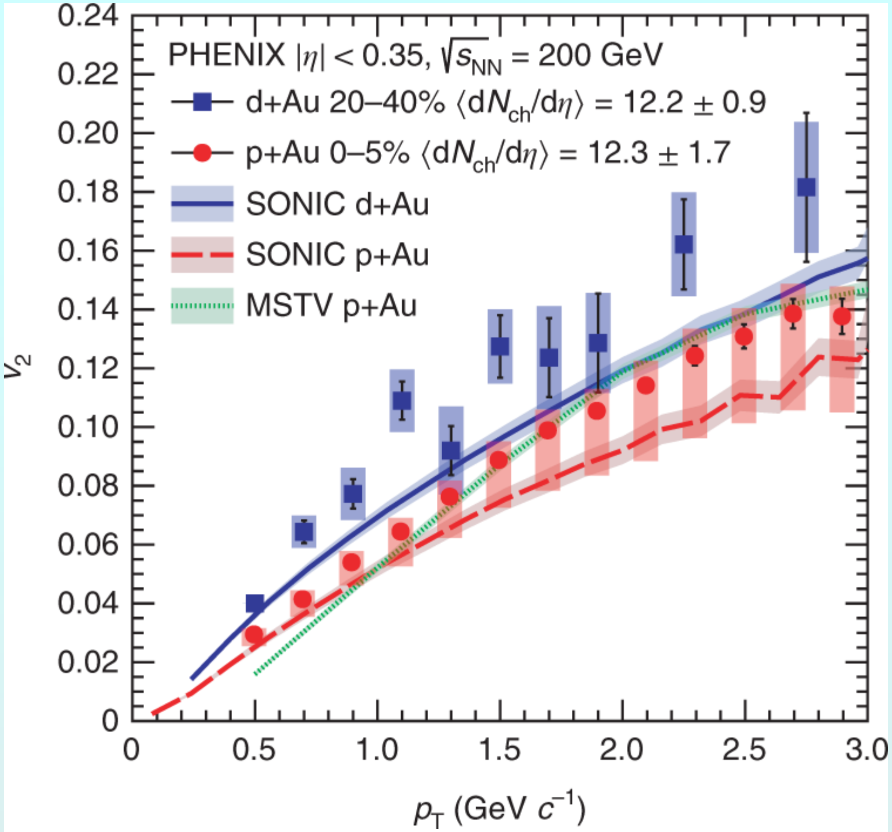
Eeek! Hydrodynamics in small systems!

PHENIX Collaboration

Nature Physics (2018)

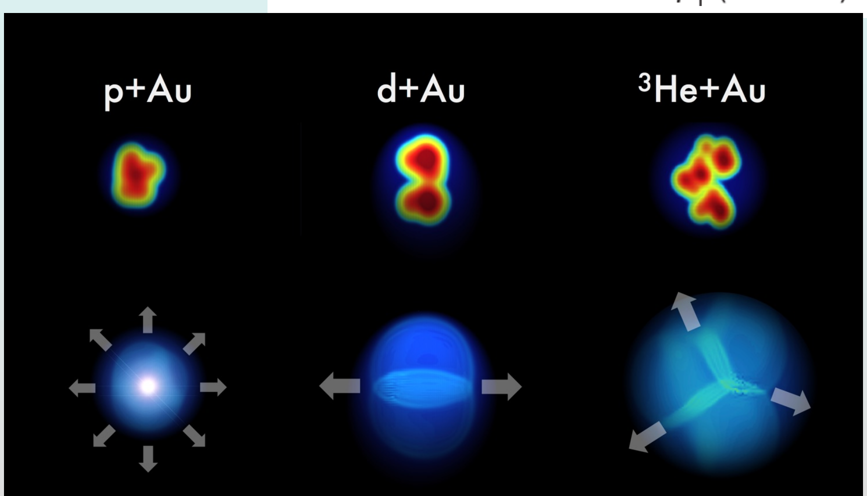


Not big & dense

But, we see collective flow!

Seeded by the initial geometry

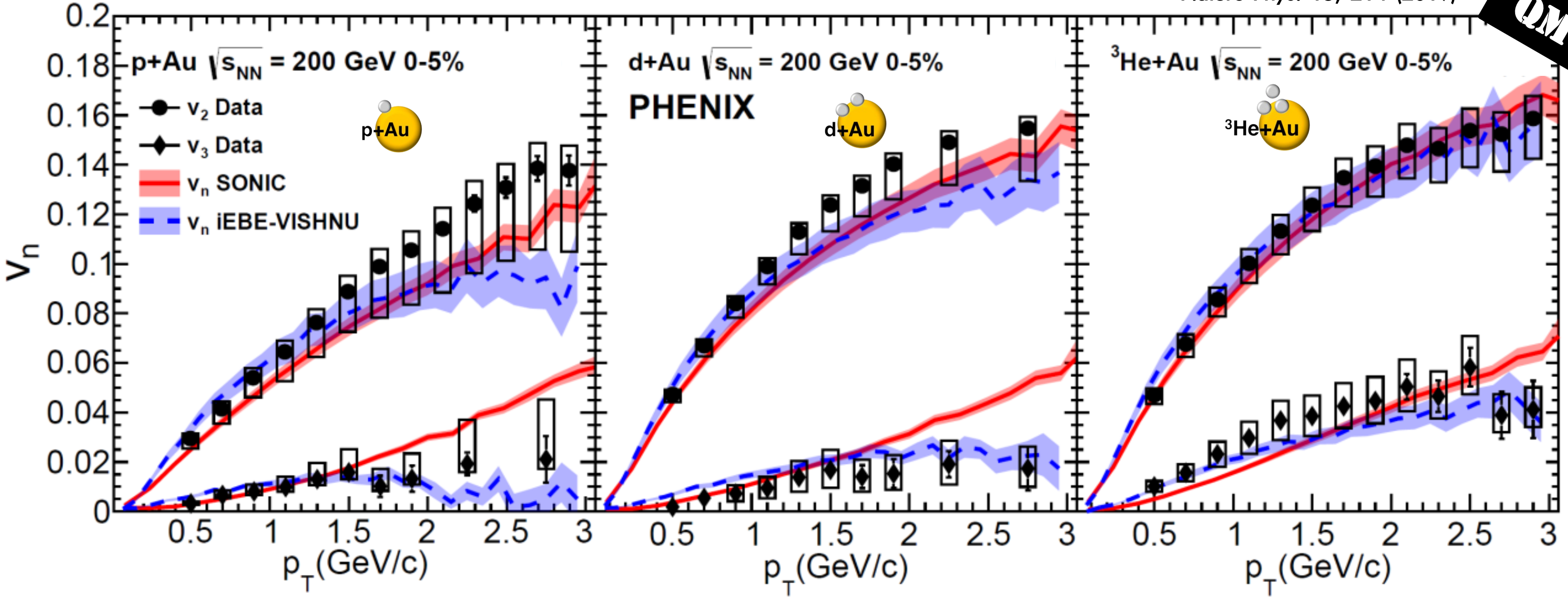
A small droplet of QGP?!



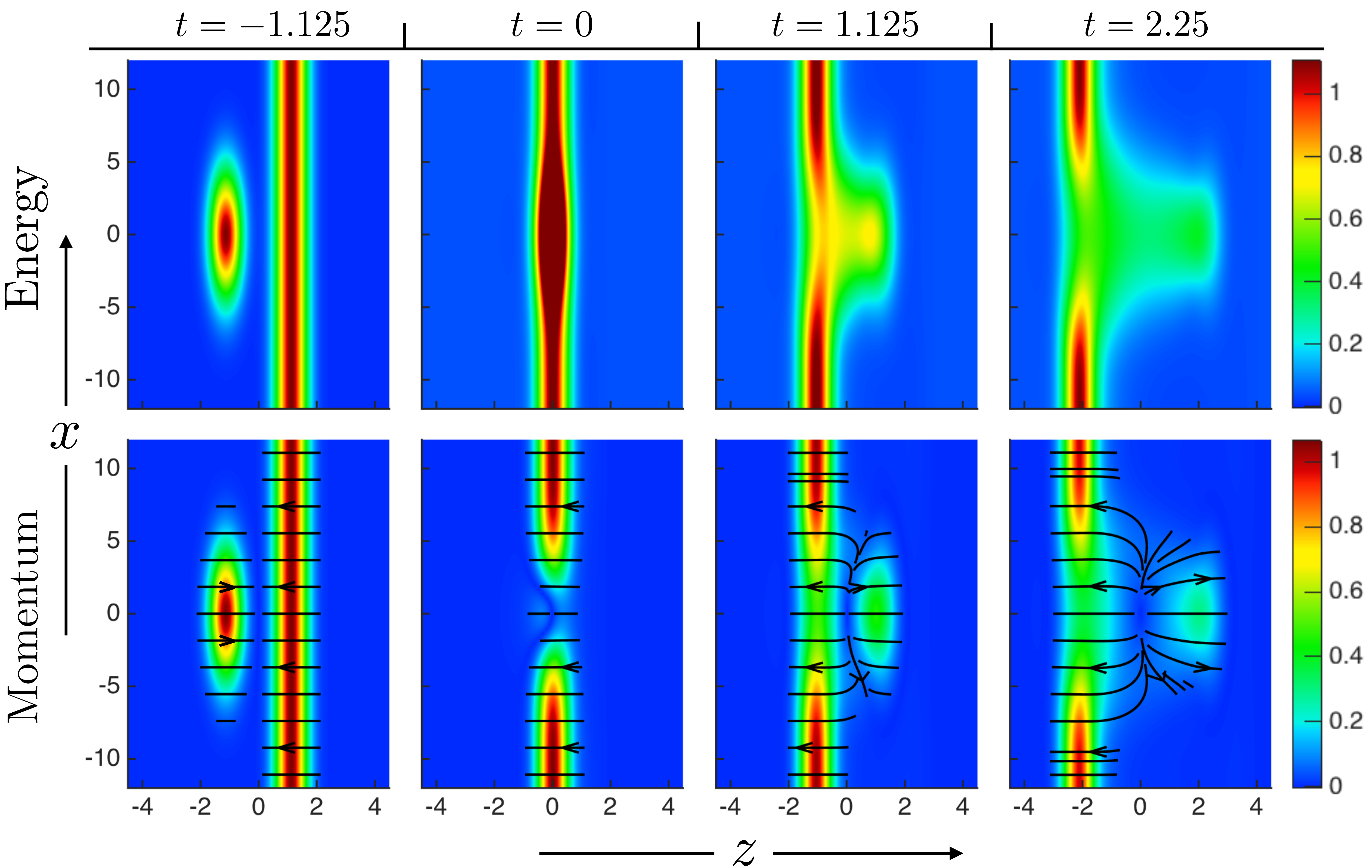
Collectivity in small systems

Nature Phys. 15, 214 (2019)

QM19



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



$t = -1.125$
$t = 0$
$t = 1.125$
$t = 2.25$
Energy
Momentum
x
z
10
5
0
-5
-10
-4
-2
0
2
4
1
0.8
0.6
0.4
0.2
0

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}HeAu data @RHIC.
- Subsequently, holographic calculations of a "proton" of radius R colliding with a sheet show hydrodynamic flow in the final state as long as the collision has enough energy such that $RT_{\rm hydrodynamization} \gtrsim 0.5$ to 1.
- 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 η, 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...

$\mathcal{N}=4$ Supersymmetric Yang Mills

- A gauge theory specified by two parameters: N_c and $g^2 N_c \equiv \lambda$.
- Conformal. (λ does not run.)
- If we choose λ 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: $\underbrace{AdS_5}_{4+1 \text{ "big" dimensions}} \times \underbrace{S_5}_{}$ → 5 "curled up" dim.
- In the $N_c \to \infty$, $\lambda \to \infty$ limit, the string theory reduces to classical gravity. ∴ calculations easy at strong coupling.

Thermodynamics at Strong Coupling

- In the $N_c \to \infty$ and $\lambda \to \infty$ 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.

η/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’?

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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

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

Gubser Klebanov Tseytlin Peet....

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

Son Policastro 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 η/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 η/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:**

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + \frac{15\,\zeta(3)}{(g^2N_c)^{3/2}} + \frac{5}{16}\frac{(g^2N_c)^{1/2}}{N_c^2} + \ldots\right)$$

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. $g^2N_c = 12.6$, 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 η/s as small as it is, there can be no 'transport peak', meaning no self-consistent description in terms of quark- and gluon-quasiparticles. [Q.p. description self consistent if $\tau_{\rm qp} \sim (5\eta/s)(1/T) \gg 1/T$.]

- Other "fluids" with no quasiparticle description include: the "strange metals" (including high-T_c superconductors above T_c); quantum spin liquids; matter at quantum critical points;...

- 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 η/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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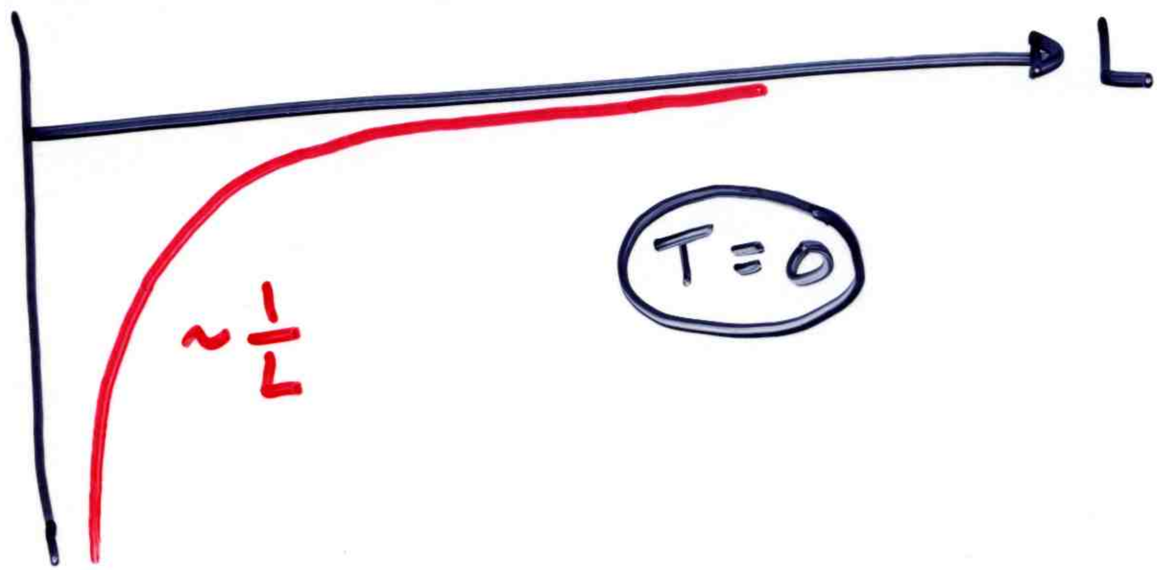
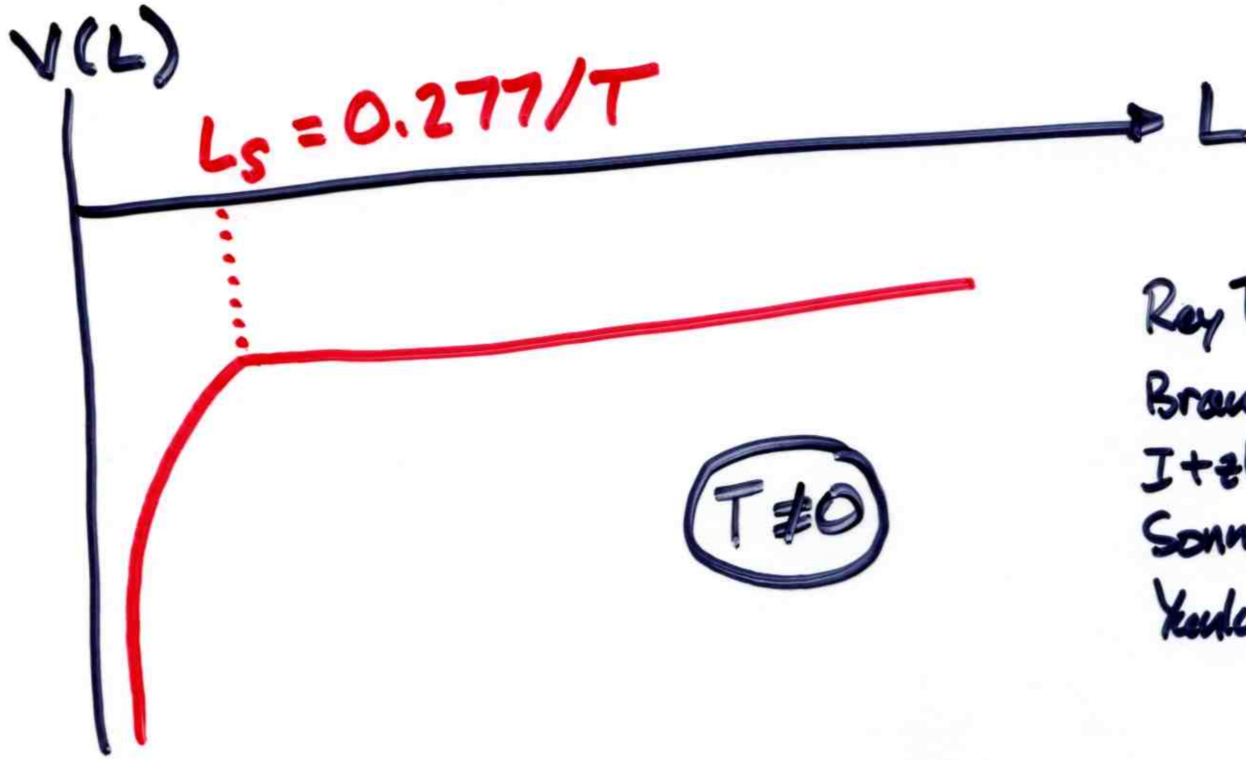
SCREENING IN N=4

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

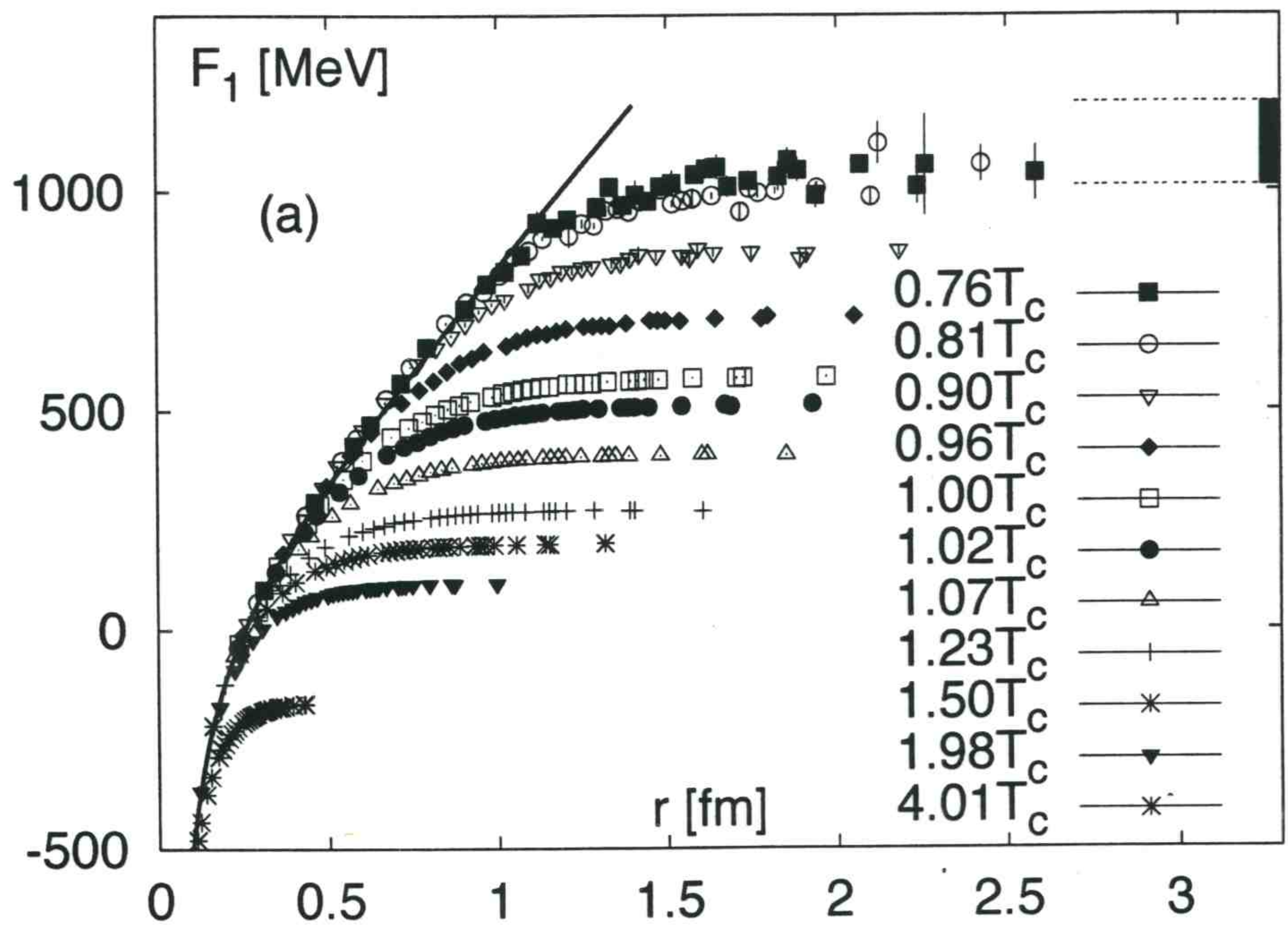




Rey Theisen Yee;
Brandhuber
Itzhaki
Sonnenschein
Yankielowicz

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

Maldacena; Witten; Gubser Klebanov Polyakov; ....

N=4 SYM is equivalent to Type IIB String theory on $\underbrace{AdS_5}_{\text{4+1 "big" dimensions}} \times \underbrace{S_5}_{\text{5 curled up dimension}}$

Translation Dictionary:

N=4 SYM gauge theory in 3+1 dim — String theory in 4+1(+5) dim

$$\frac{g^2 N_c}{4\pi N_c} = g_{string}$$

[$N_c \to \infty$ at fixed $g^2 N_c$ means $g_{string} \to 0$]

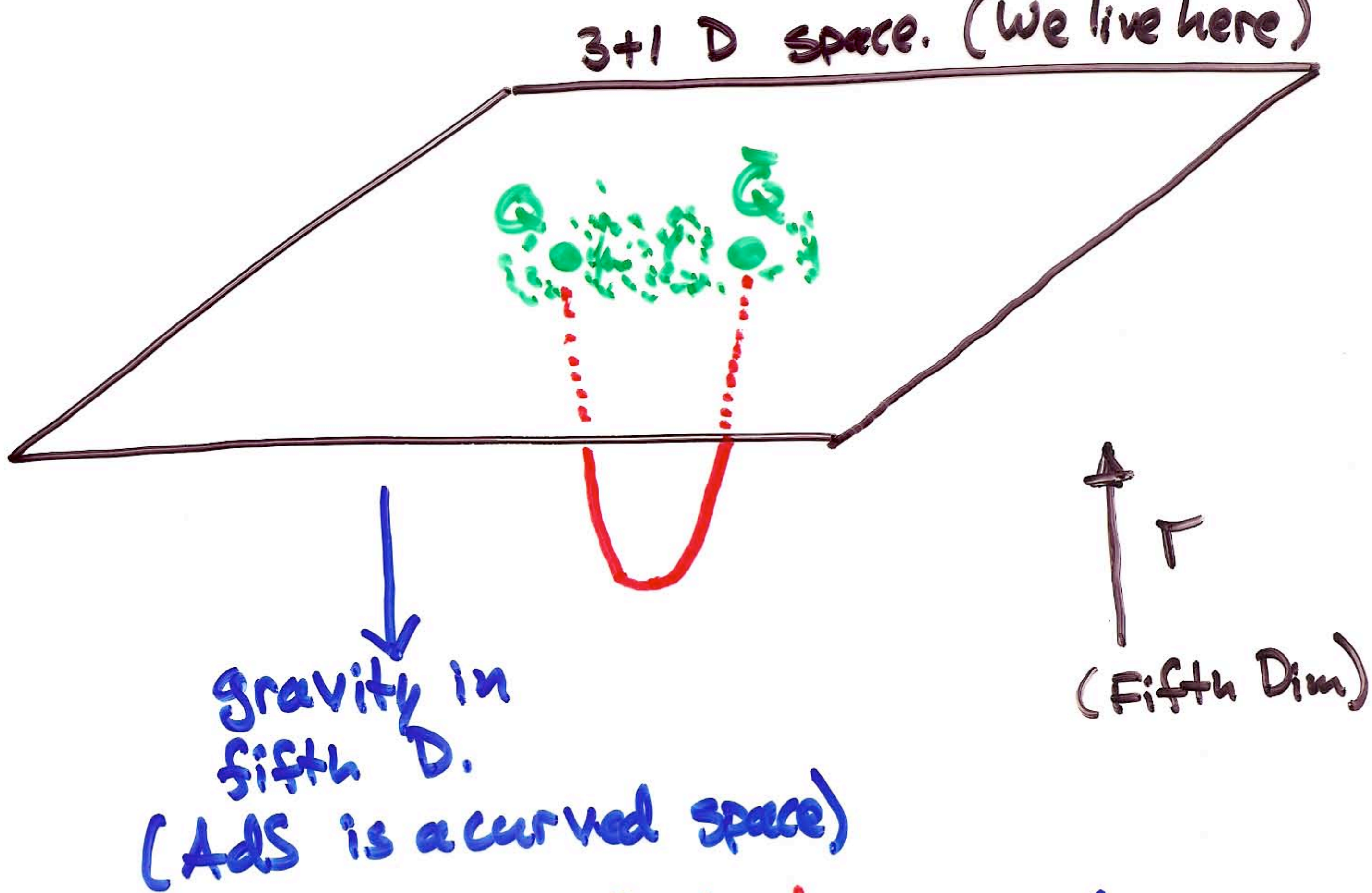
$$\sqrt{g^2 N_c} = R^2/\alpha'$$

[R: AdS curvature
$\frac{1}{2\pi\alpha'}$: string tension]

Heat the gauge theory to a temperature T. $= T_H = r_0/\pi R^2$ — Add a Black hole in the 5^{th} dimension, with

[r_0: location of BH horizon in fifth dim.]

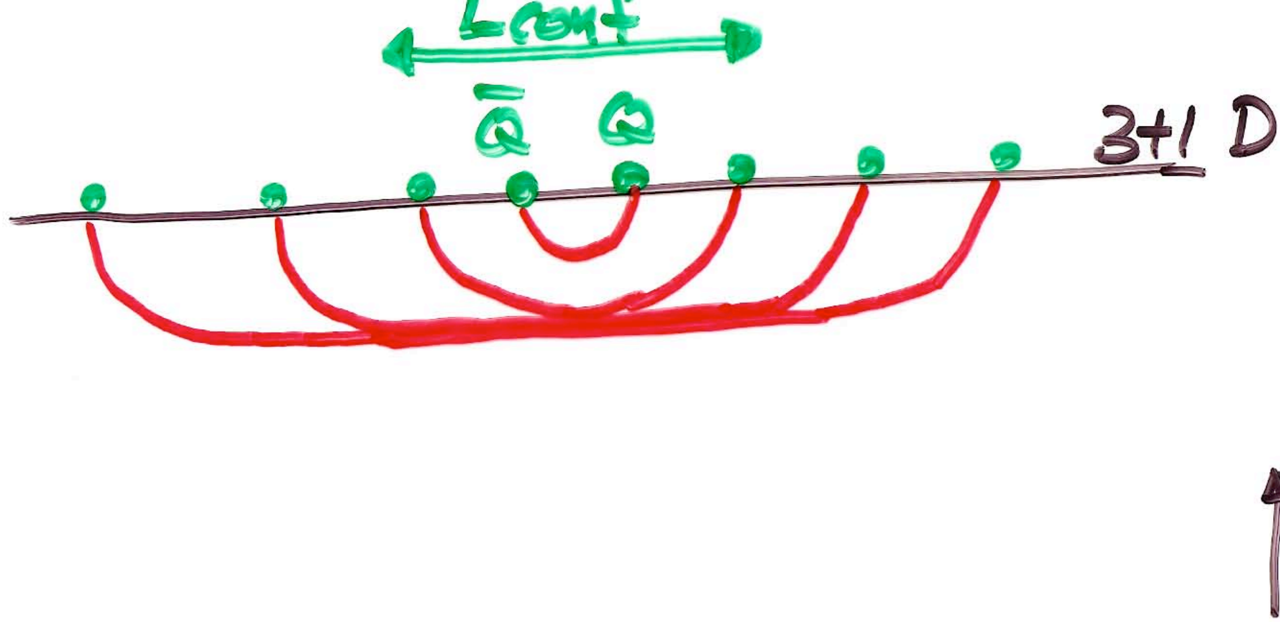
How can strings in 5D describe, say, force between Q and $\bar{Q}$ in a 4D gauge theory?



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

CONFINEMENT?

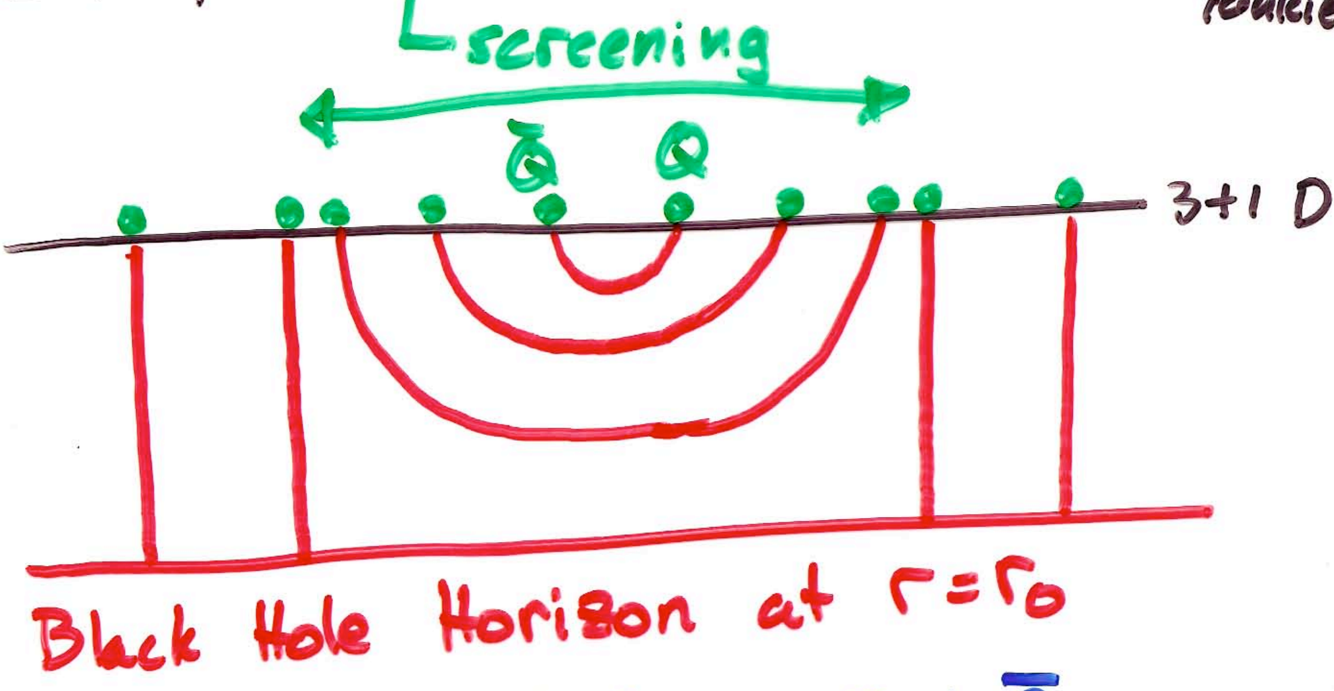
Here's how confinement can arise....



- 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 Itzhaki Sonnenschein Yankielowicz



- 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, $M \to \infty$, 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.

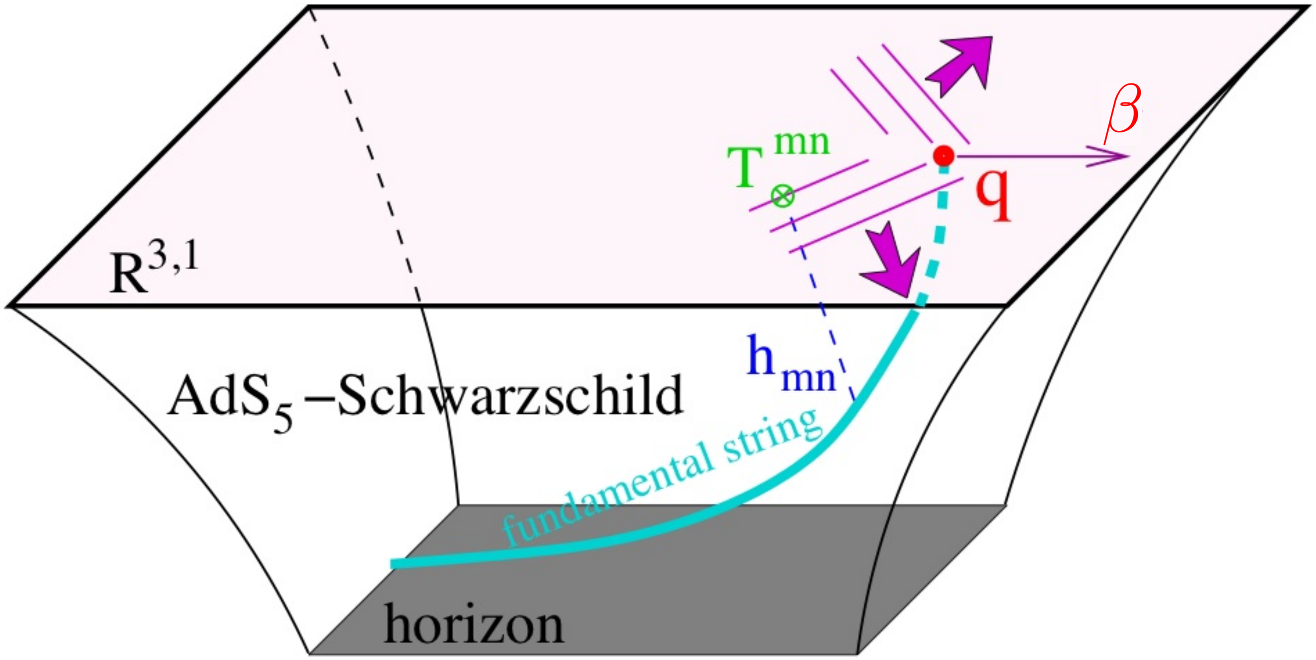
- *Caveat emptor:* **At finite M, this picture only applies for**

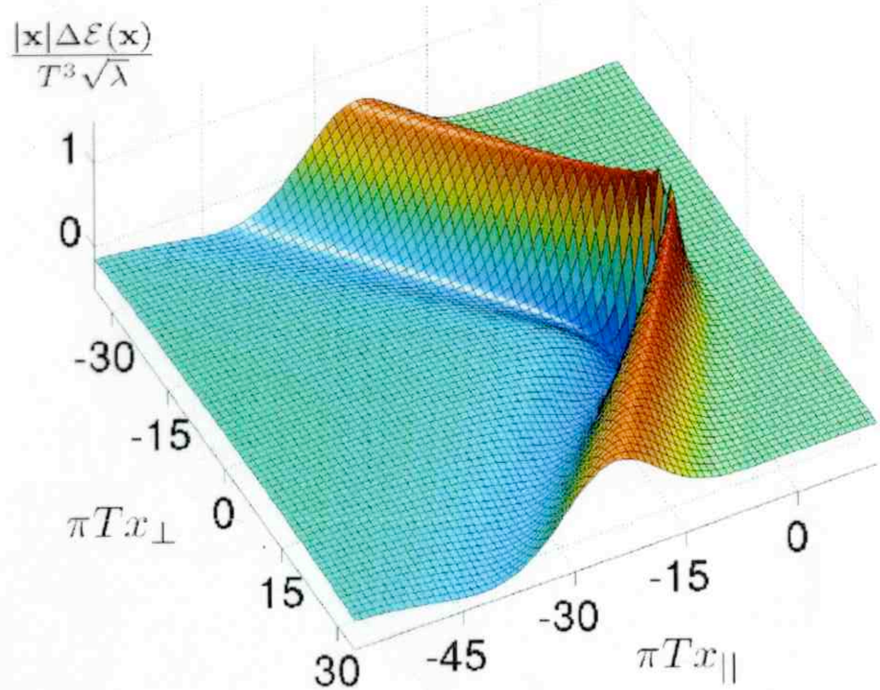
$$\sqrt{\gamma} \ll \frac{M}{T\sqrt{\lambda}} .$$

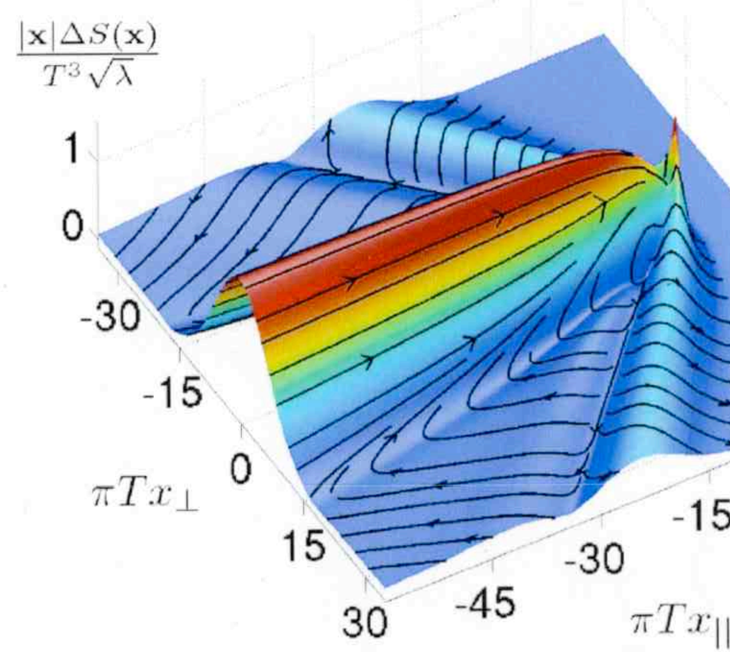
Eg for b quarks at the LHC validity is $p_T \lesssim 20 - 40$ GeV. Higher p_T heavy quarks behave like light quarks.

Dragging a Heavy Quark through Strongly Coupled Plasma

HKKKY, G, 2006







Energy density.

Nb: Specific heat $\propto N_c^2$ amplifies effect of heat over motion in $\mathcal{E}$. So, this plot tells you where there is heating. Ie compression.

Ie SOUND.

Momentum flow.

Mach cone and wake.

Chesler + Yaffe

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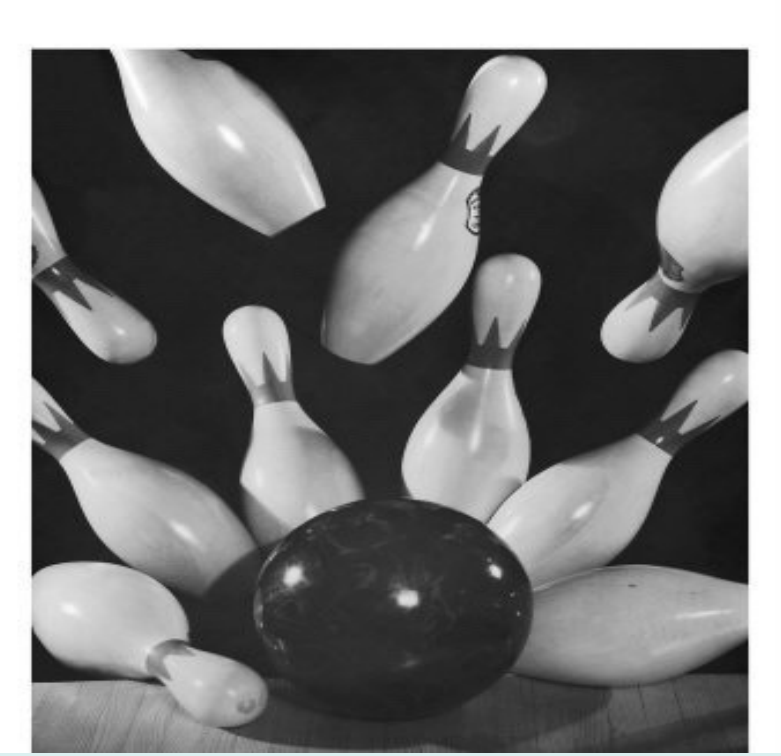
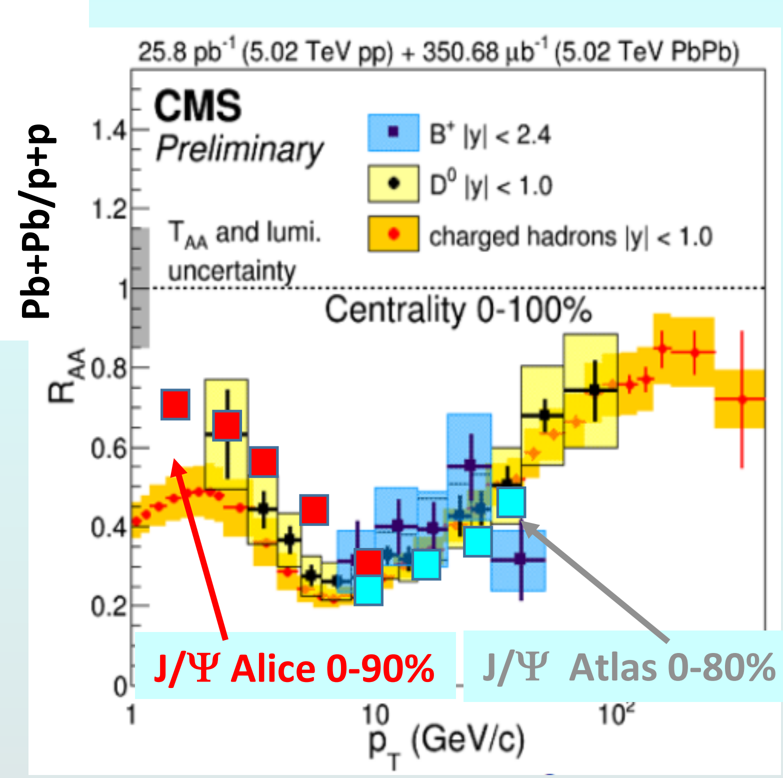
An astounding result!



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:

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

where

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

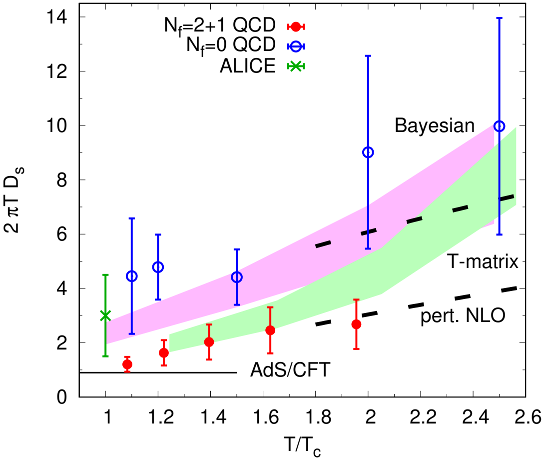
- So, the calculation of the drag force is at the same time a calculation of the heavy quark diffusion constant D. And, for $\lambda \simeq 12.6$ (the value we used several slides ago) the diffusion constant in strongly coupled plasma is $D \simeq 1.1/(2\pi T)$.

- 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.

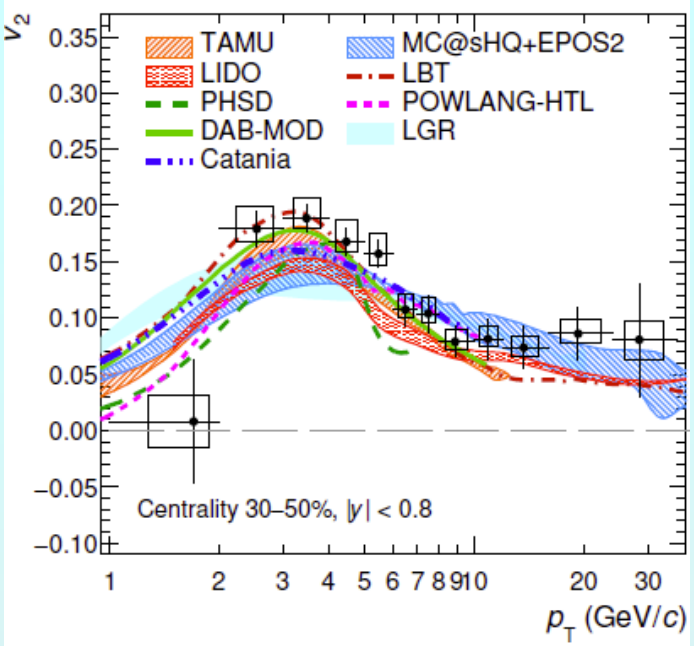
Diffusion coefficient

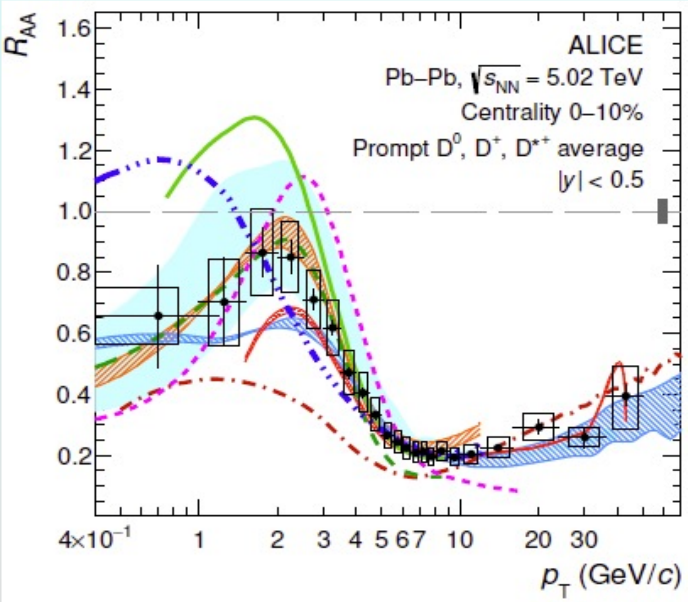
- Results for $D_s = 2T^2/\kappa$ shows lower than quenched behavior

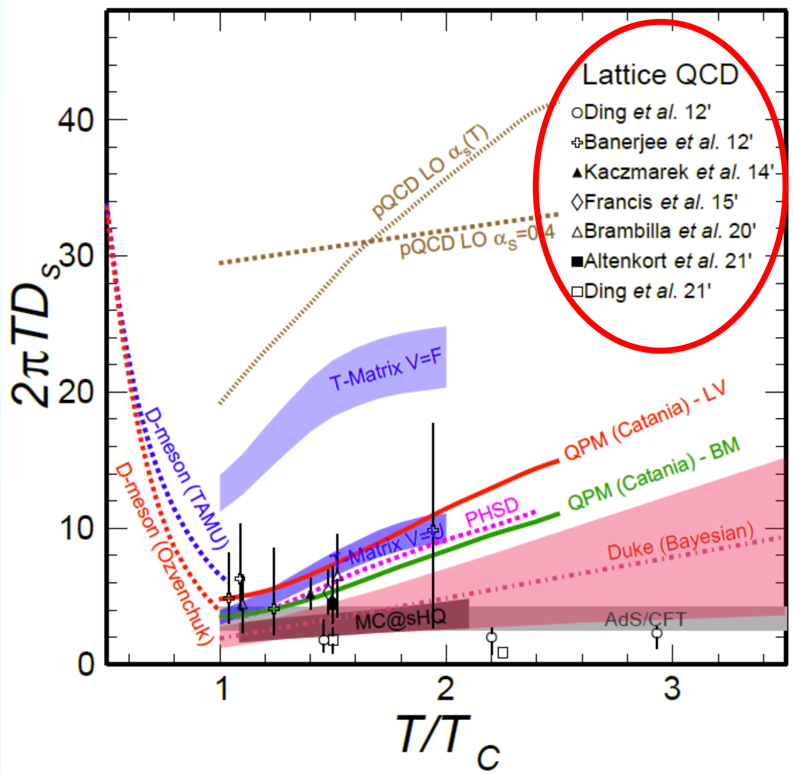
- $6D_s$ is the mean distance squared traveled by unit time
- T-Matrix results updated compared to figure in paper, R. Rapp et al. [arxiv:1612.09318][arxiv:1711.03282]



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







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

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

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

for R_{AA} (v_2)

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HKKKY, G, C-Y&T 2006

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

where

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

- **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 $N_c^2 \to \infty$, $\lambda \to \infty$ 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 $N_c^2 \to \infty$, $\lambda \to \infty$ limit, for plasma of any gauge theory with a gravity dual. η/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. $\hat{q} \sim 3$-$5\ \mathrm{GeV}^2/\mathrm{fm}$ at $T = 300\ \mathrm{MeV}$. $\frac{\hat{q}_{LHC}}{\hat{q}_{RHIC}} \sim \frac{(dN/d\eta)_{LHC}}{(dN/d\eta)_{RHIC}}$
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. $T_{diss}(v) \simeq T_{diss}(0)\,(1-v^2)^{1/4}$ 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 $T \sim$ 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????