Novel Probes of the Primordial Hot Quark Soup

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Heavy Ion Collisions: What Next?

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

- The first liquid that ever existed; the "original liquid"...
- The liquid from which the protons and neutrons in today's universe formed, as the liquid fell apart into mist.
- At a few trillion degrees, the hottest liquid that has ever existed.
- The earliest complex form of matter.
- The most liquid liquid that has ever existed, with a specific viscosity $\eta/s \sim 0.1$.
- 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 What Next?, namely the challenges for the decade to come. But first, a *very* brief Intro, taking advantage of Marco van Leeuwen's talk yesterday...

Quark-Gluon Plasma

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

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

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

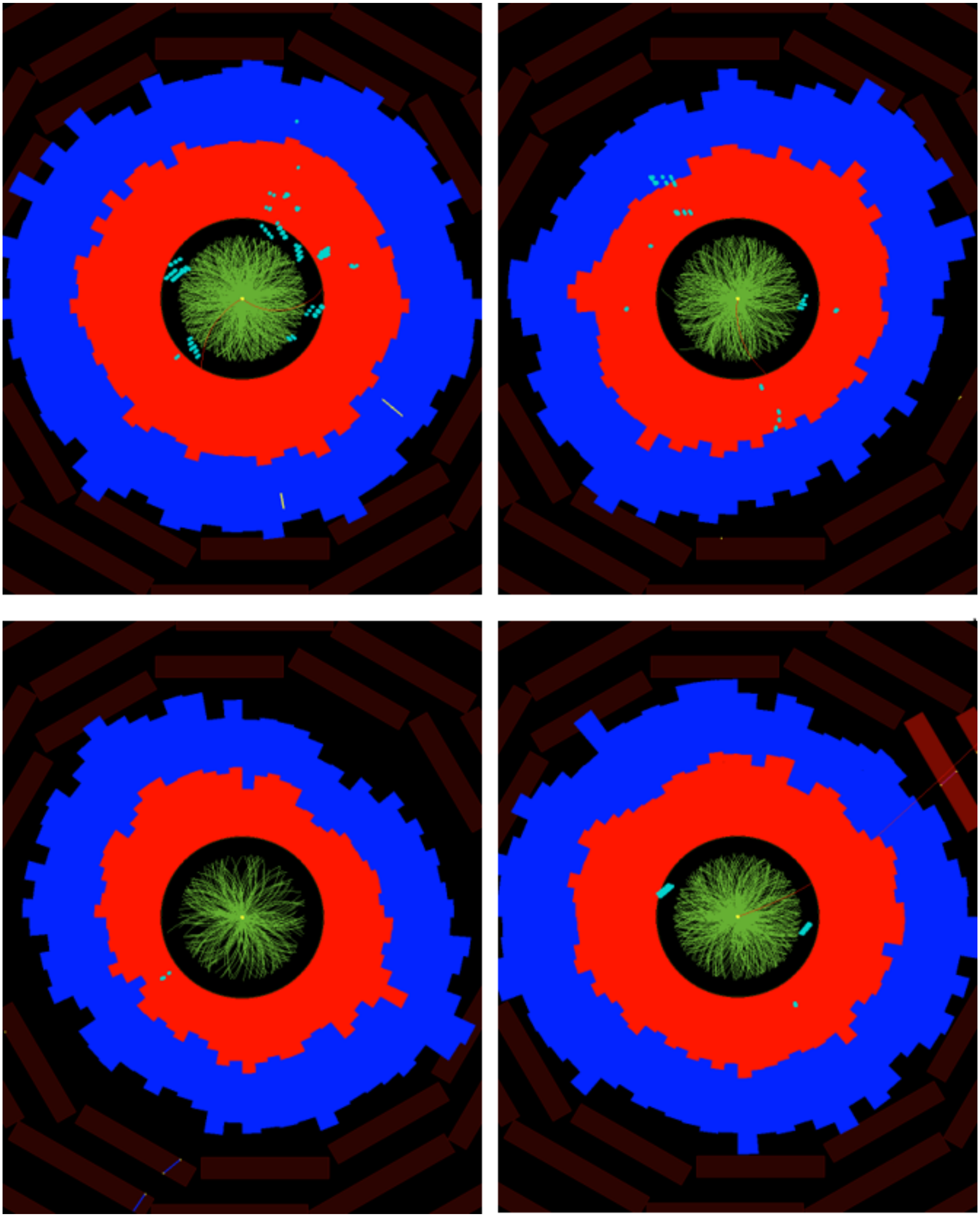
Liquid Quark-Gluon Plasma

- 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.

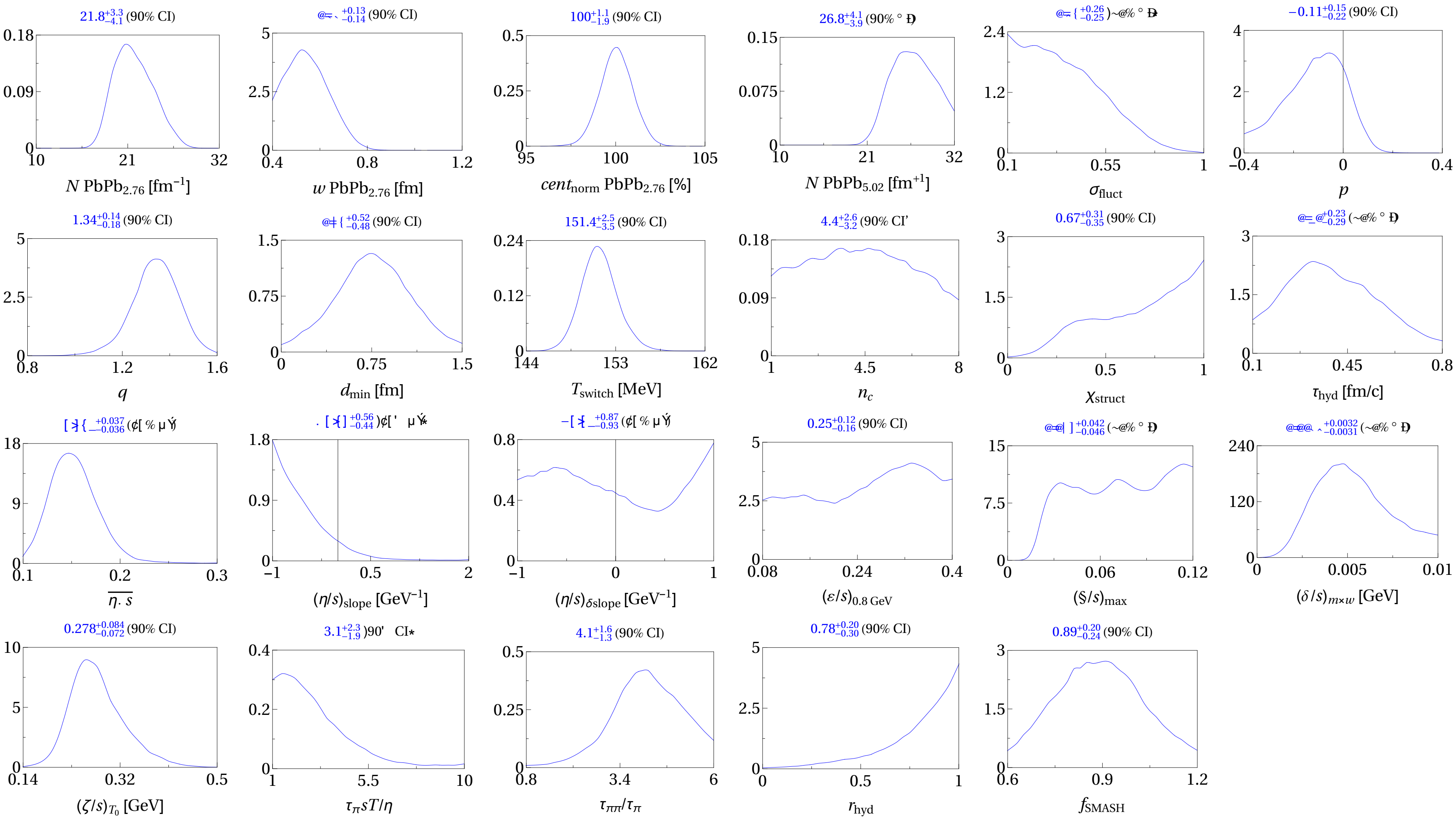
- The discovery that it is a strongly coupled liquid is what has made QGP interesting to a broad scientific community.



η/s from RHIC and LHC data

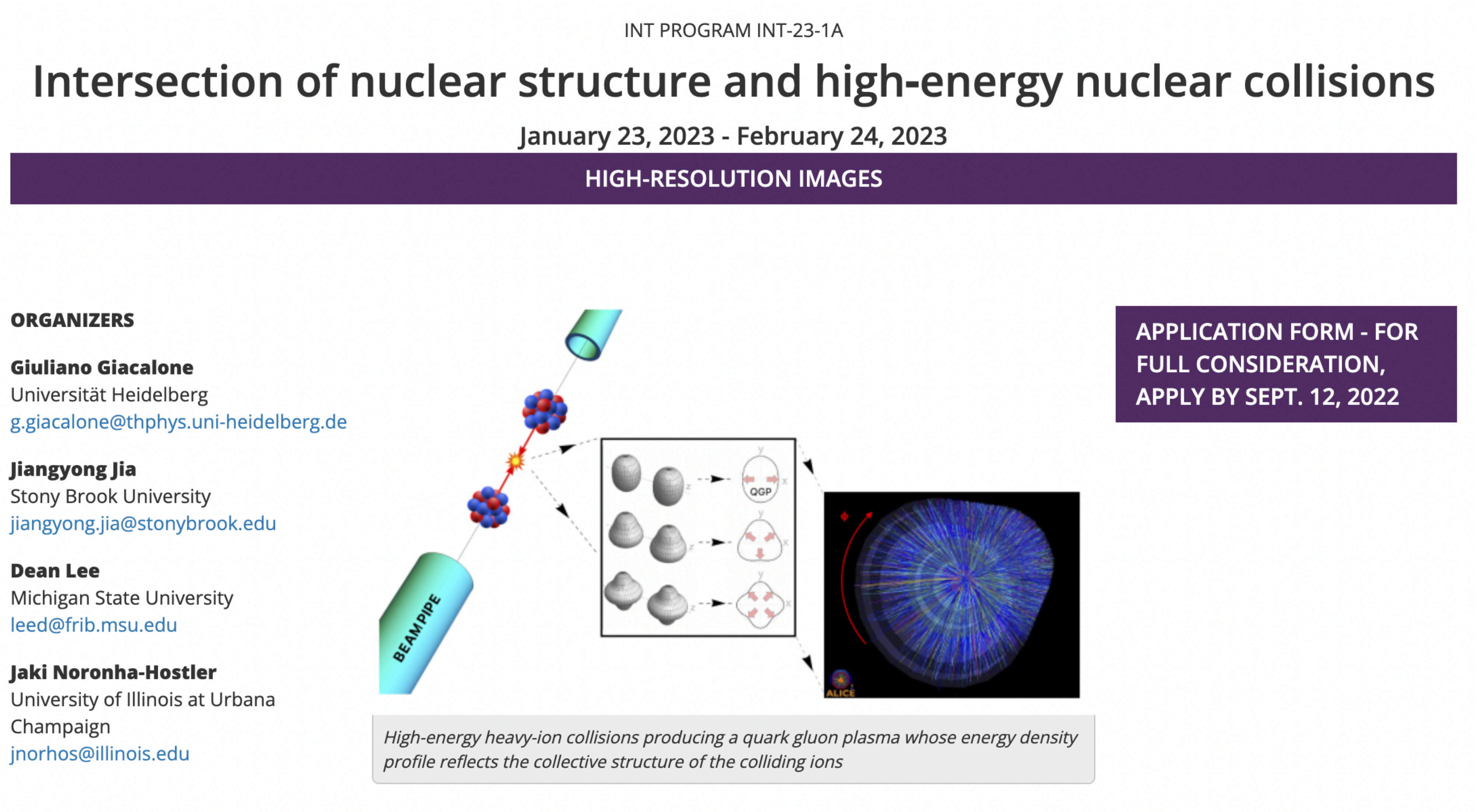
- I have given you the beginnings of a story that has played out over the past decade. I will now cut to the chase, leaving out many interesting chapters and oversimplifying.
- Using relativistic viscous hydrodynamics to describe expanding QGP, *produced in an initially lumpy heavy ion collision*, using 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.

Eg. of Today's State of the Art



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

What the State of the Art Makes Possible...



INT PROGRAM INT-23-1A

Intersection of nuclear structure and high-energy nuclear collisions

January 23, 2023 - February 24, 2023

HIGH-RESOLUTION IMAGES

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High-energy heavy-ion collisions producing a quark gluon plasma whose energy density profile reflects the collective structure of the colliding ions

APPLICATION FORM - FOR FULL CONSIDERATION, APPLY BY SEPT. 12, 2022

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

Govert Nijs

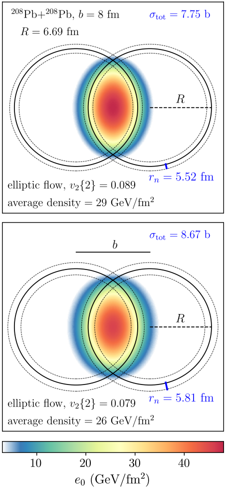
September 6, 2023

Based on:

- Giacalone, GN, van der Schee, 2305.00015

Do we have observables sensitive to a_n?

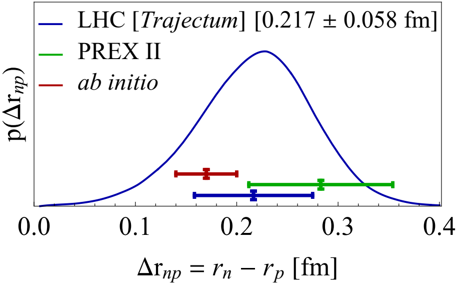
- Initial geometry is sensitive to a_n. Larger nuclei lead to:
    - Larger hadronic PbPb cross-section,
    - Larger initial QGP size,
    - Smaller initial QGP eccentricity.
- Final state observables are in turn sensitive to initial geometry. Larger Δr_{np} leads to:
    - Larger hadronic PbPb cross-section,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



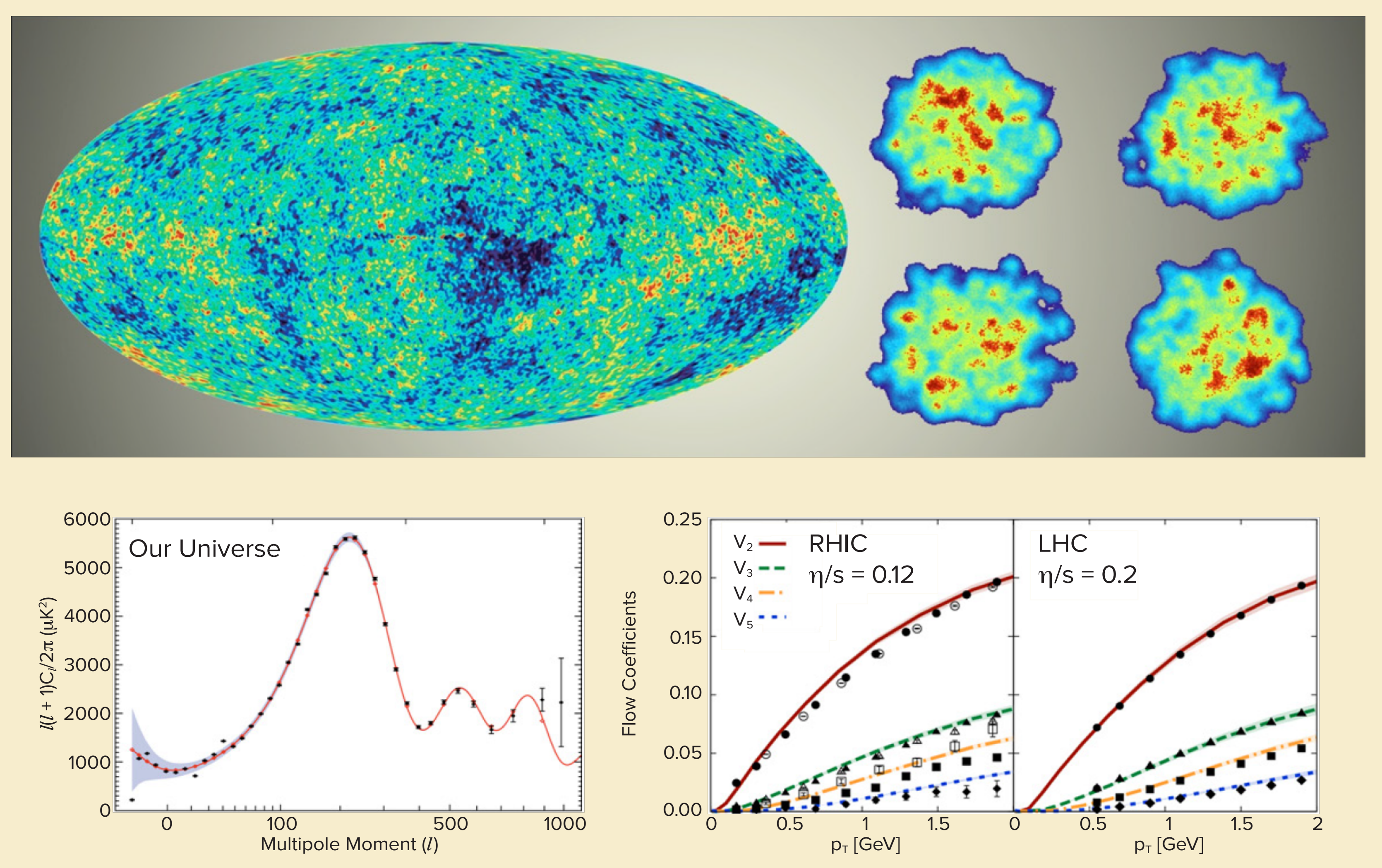
[Giacalone, GN, van der Schee, 2305.00015]

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.



[Giacalone, GN, van der Schee, 2305.00015; PREX, 2102.10767; Hu et al., *Nat. Phys.* **18**, 1196–1200 (2022)]



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

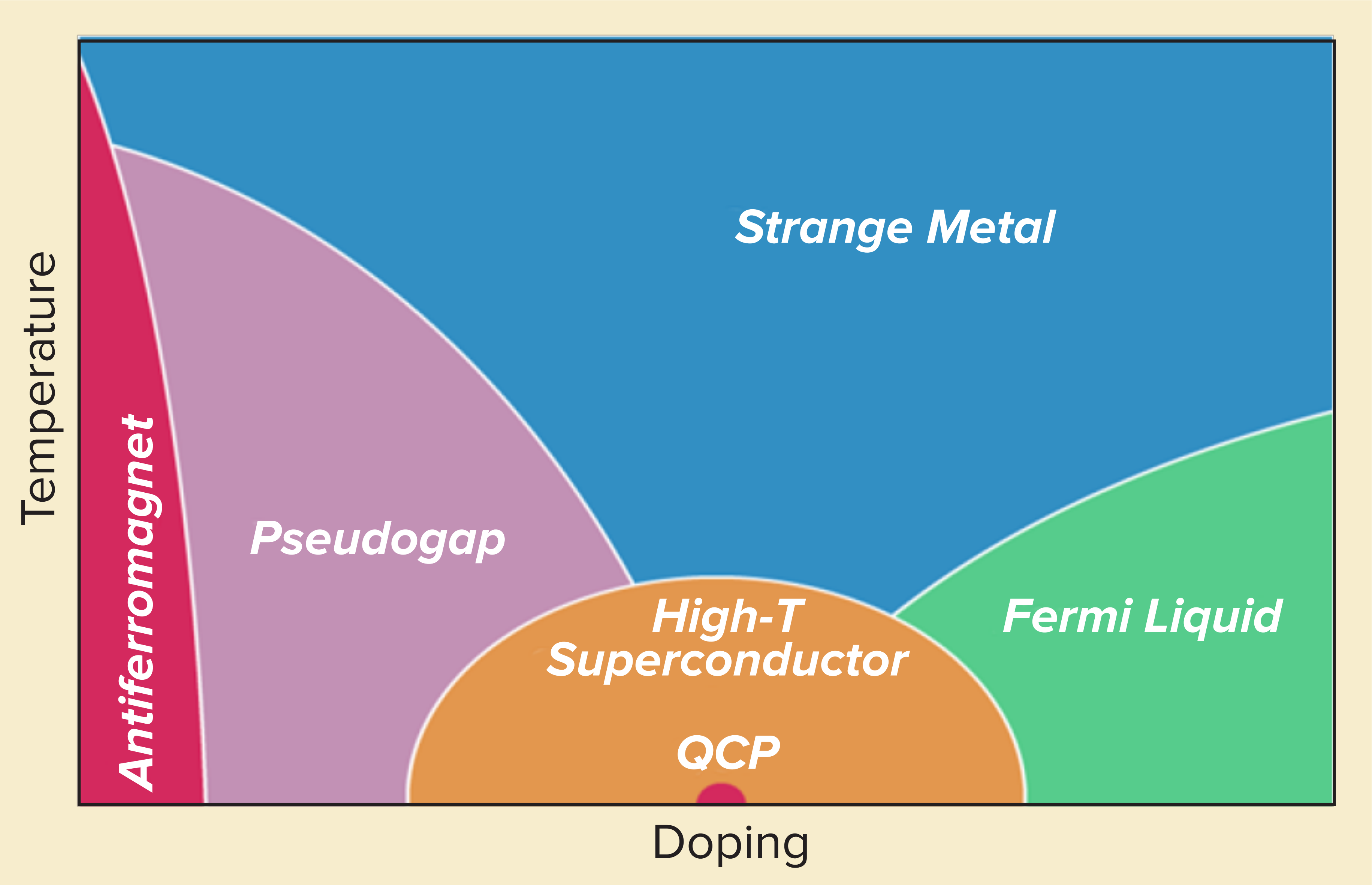
- Heavy ion collisions only up to v_6 at present. But they have billions of events. And, they can do controlled variations of the initial conditions, to understand systematics...

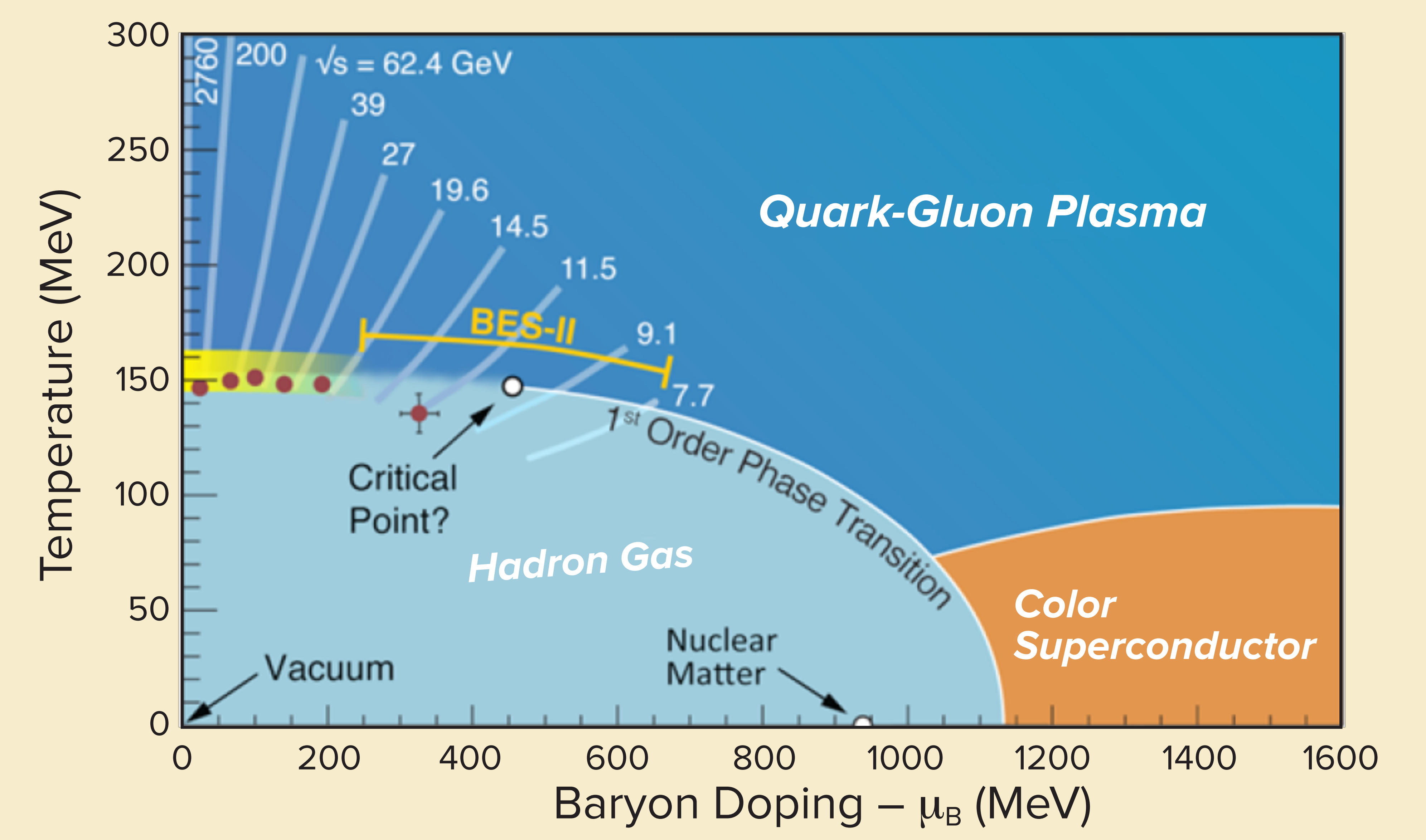
What Next?

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

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

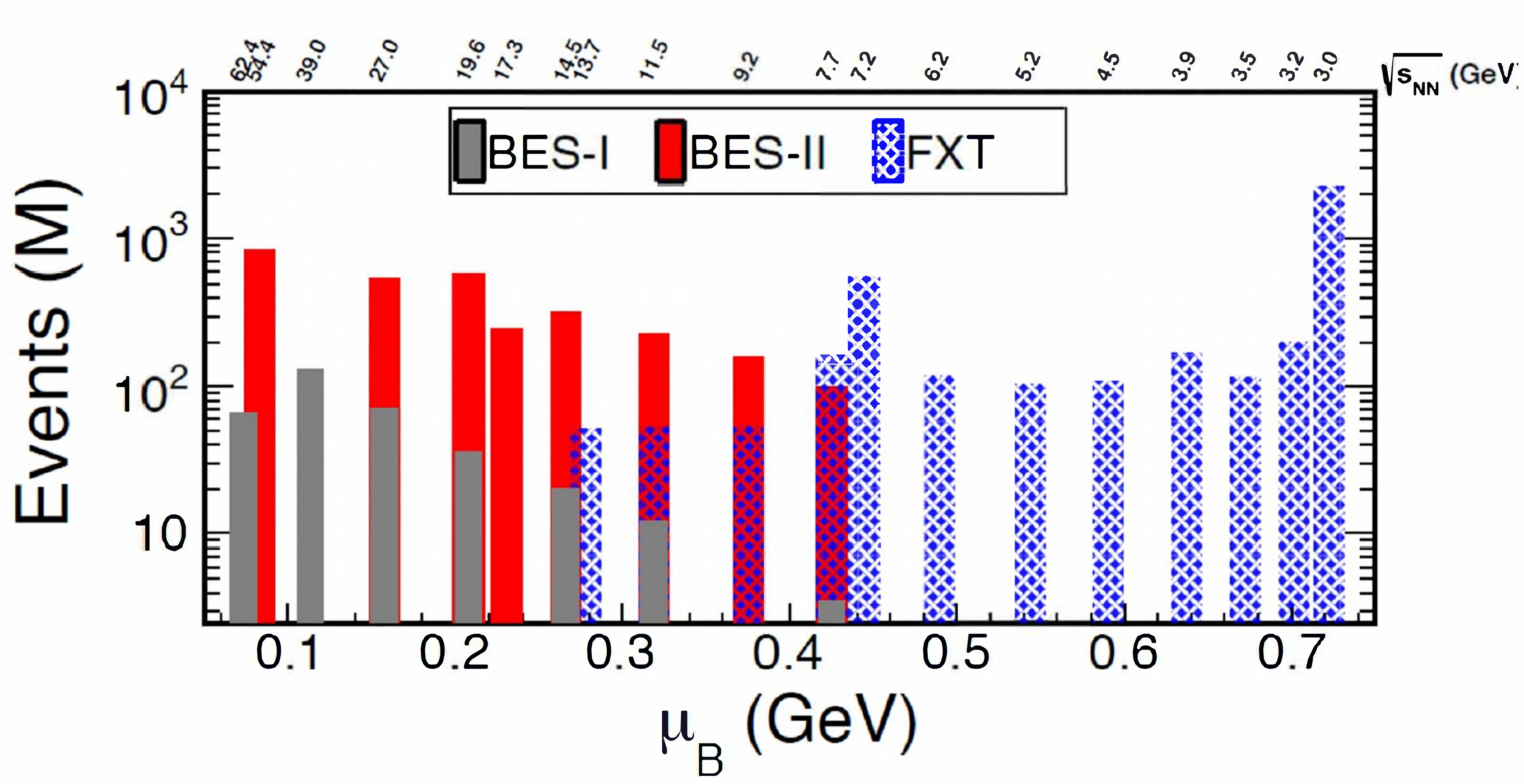
  Three different variants of this question...


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



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

RHIC BES II Data Taken...

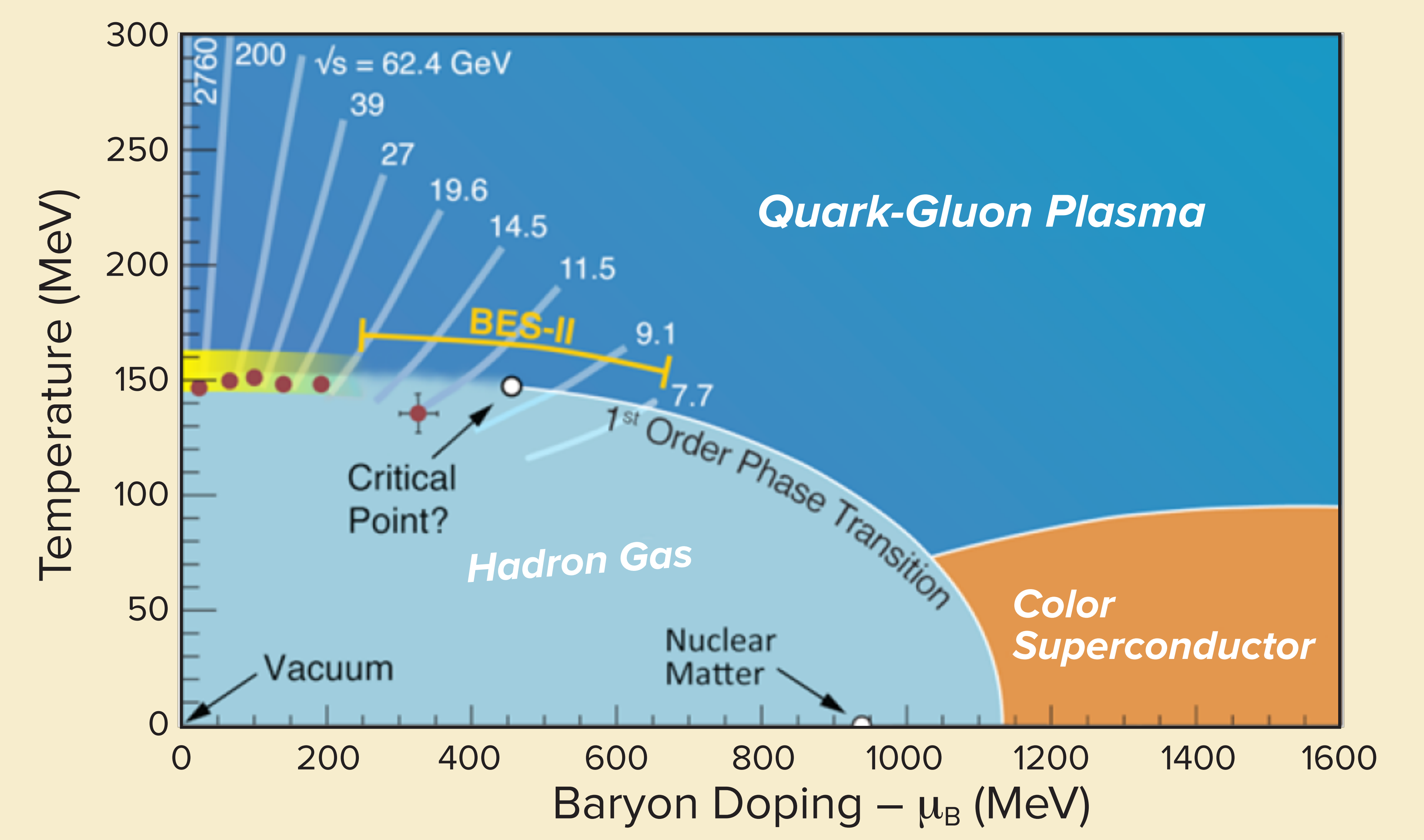


Mapping the QCD Phase Diagram

- 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.



300
250
200
150
100
50
0
Temperature (MeV)
0
200
400
600
800
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1200
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1600
Baryon Doping – μ_B (MeV)
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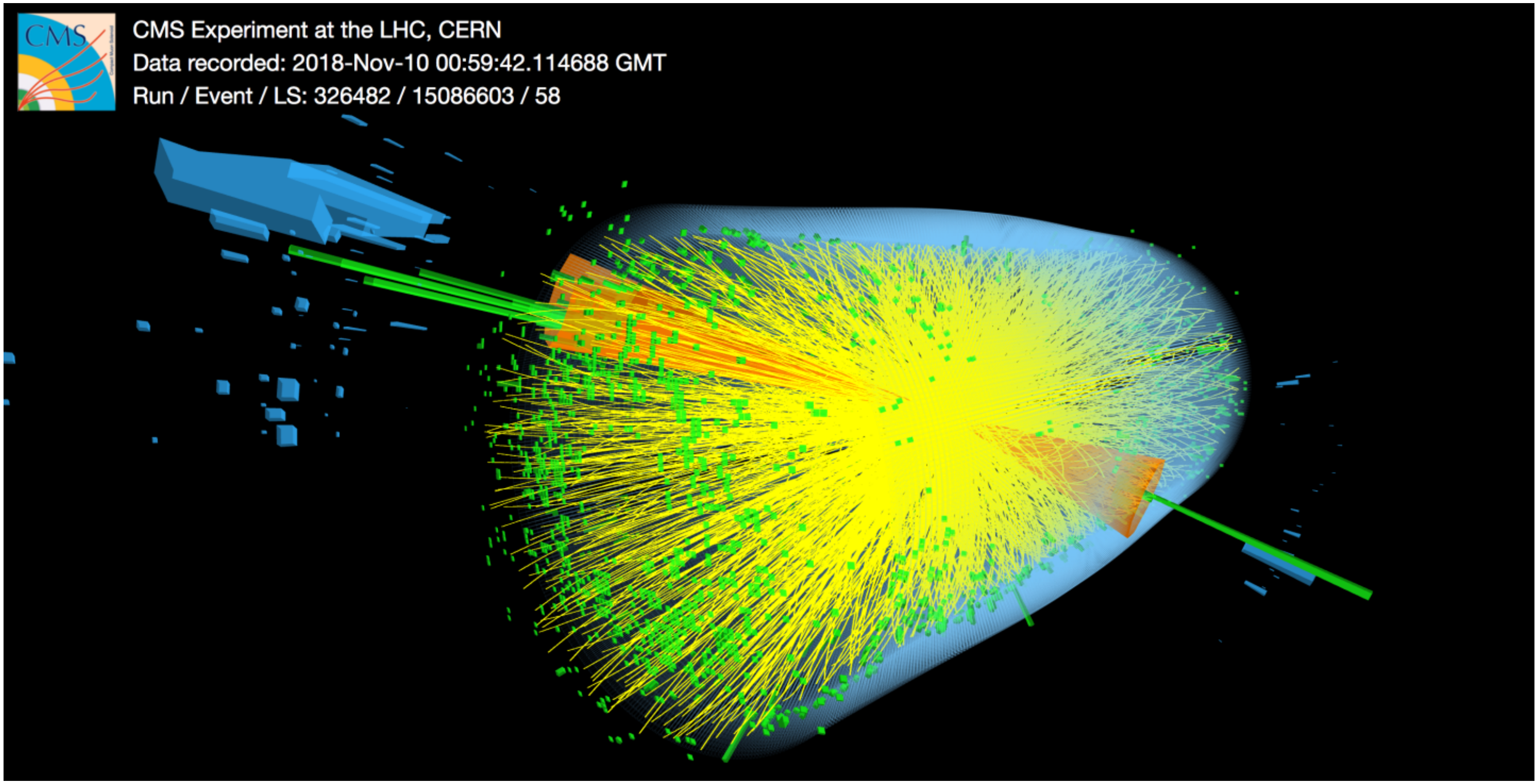
  Three different variants of this question...

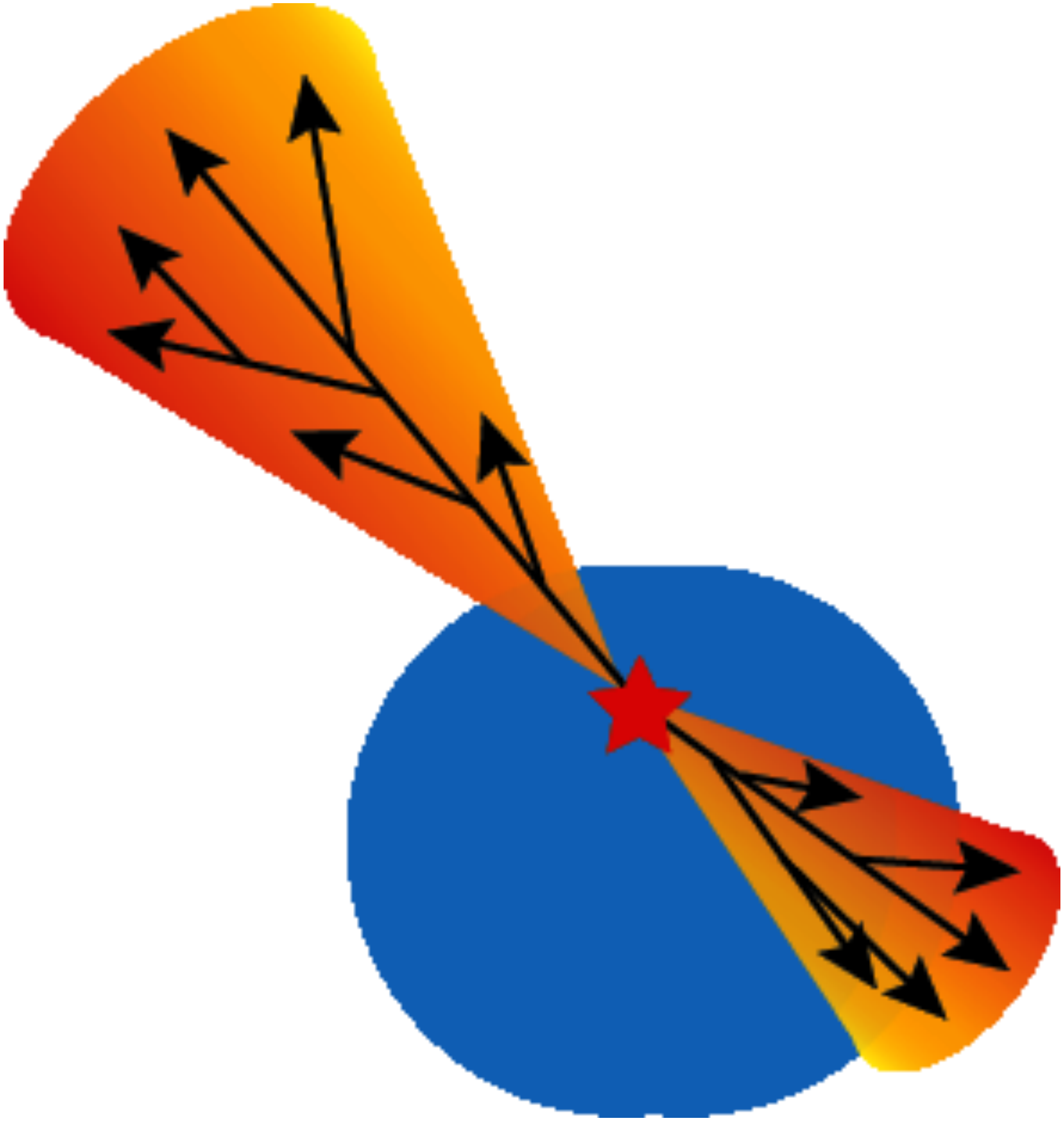
Probing the Original Liquid

- 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.
- → 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



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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. . .

Perturbative Shower … Living in Strongly Coupled QGP

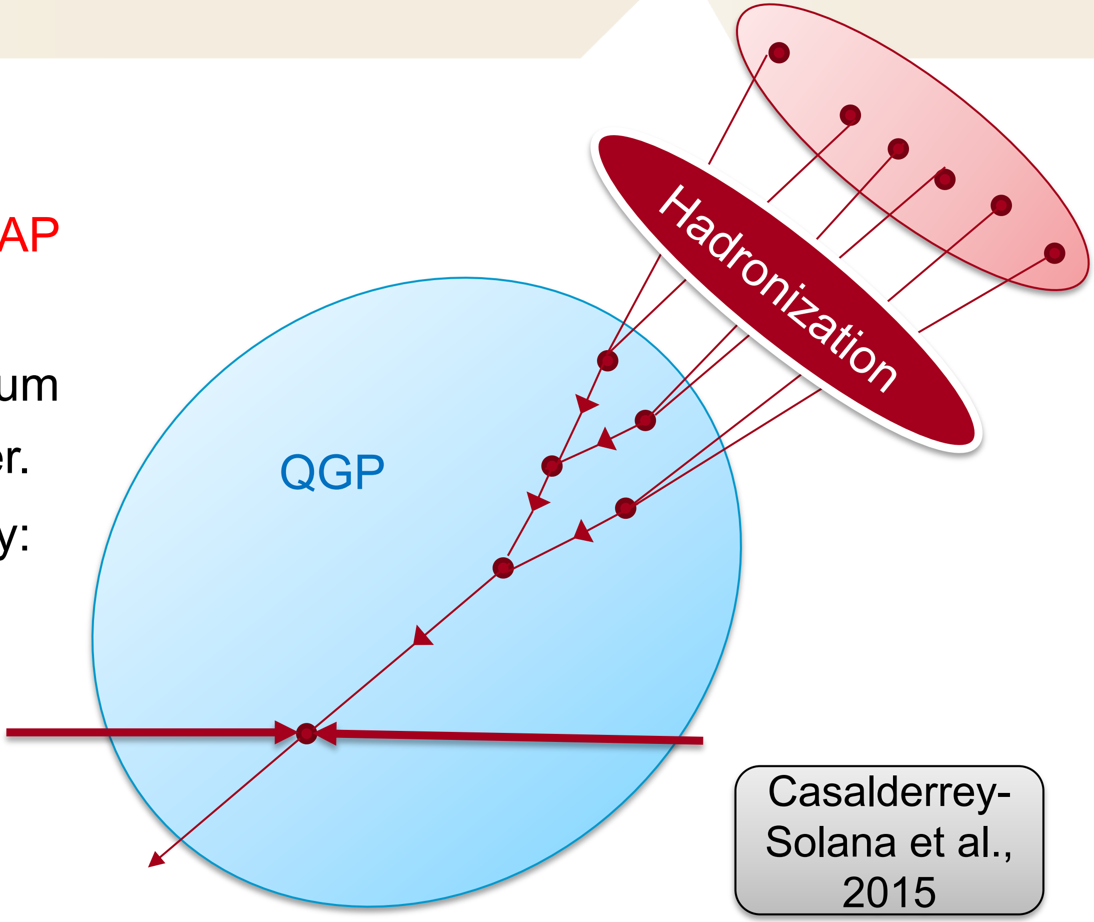
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

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

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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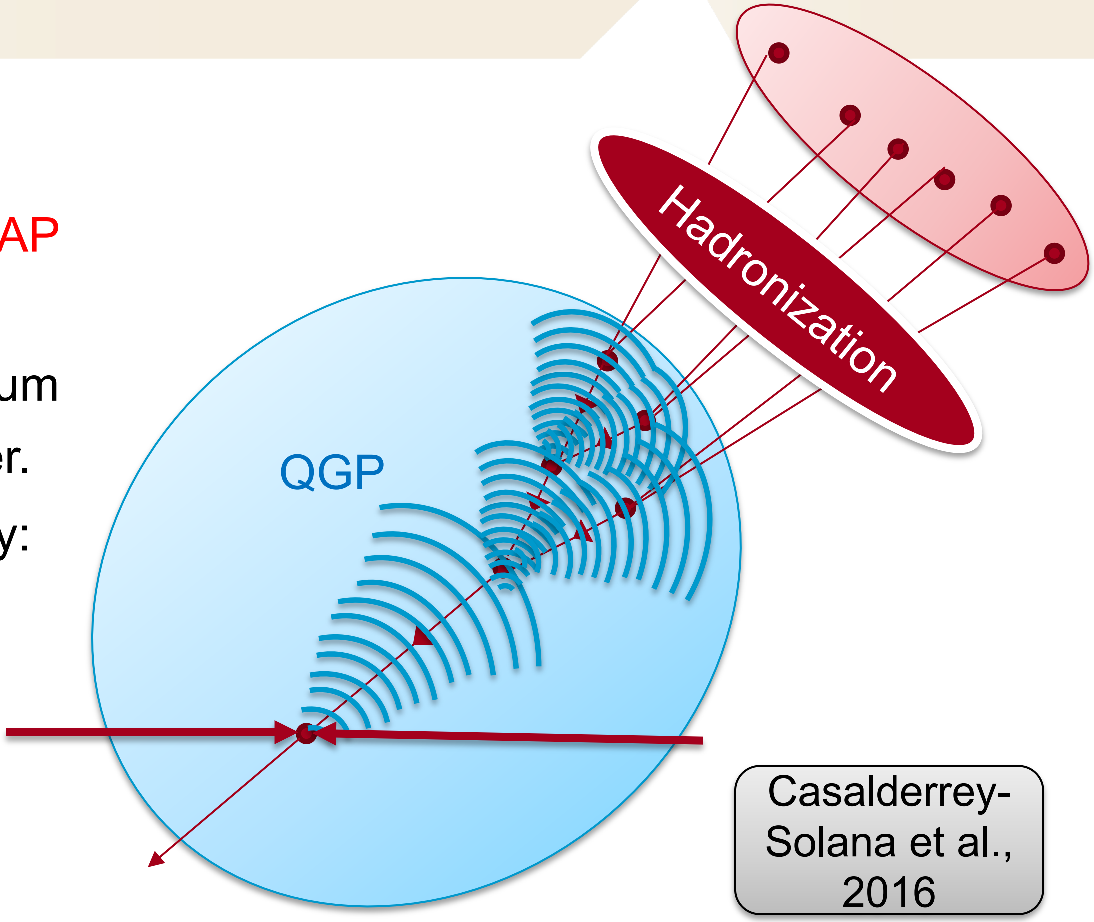


Casalderrey-Solana et al., 2016

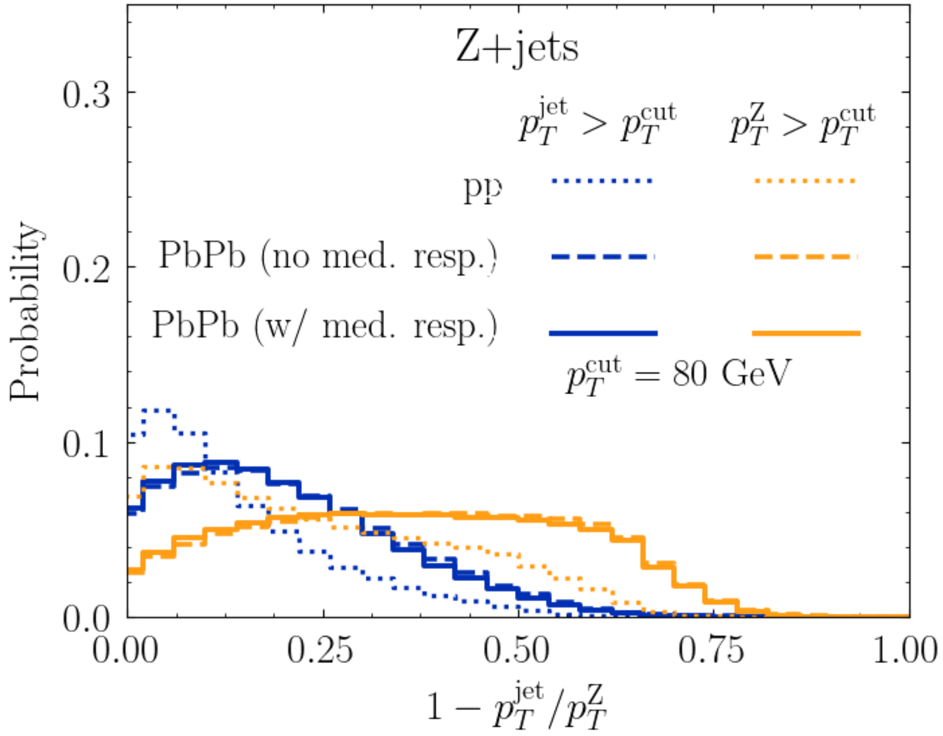
Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

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

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.

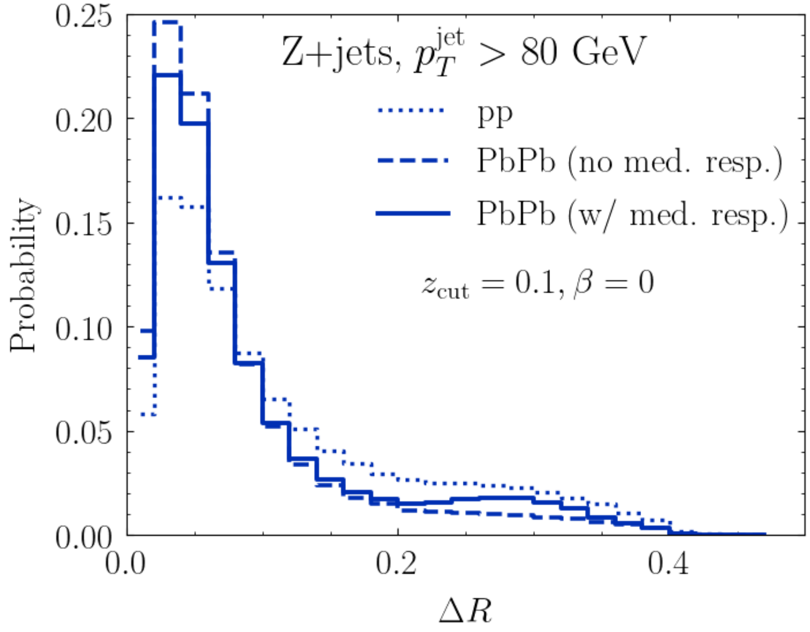
Disentangling Jet Modification from Selection

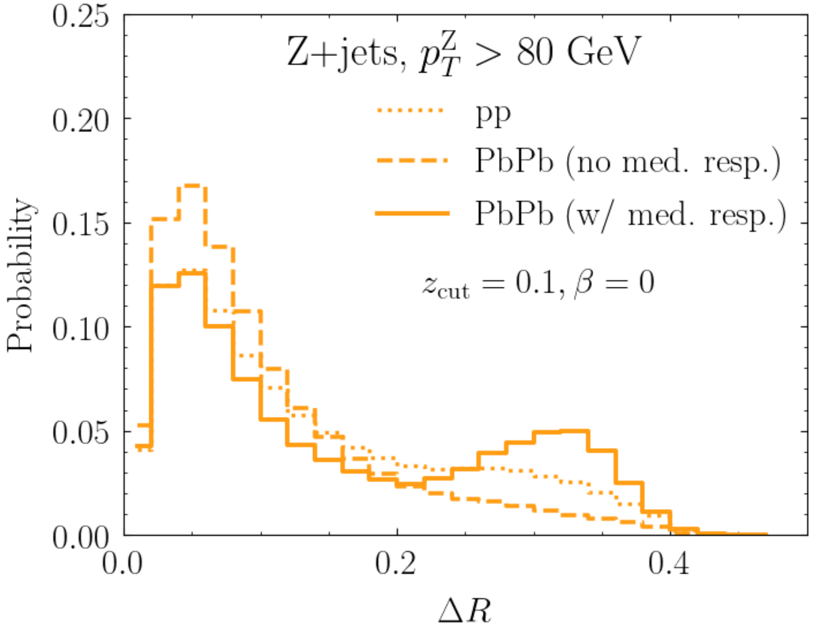


Orange: $p_T^Z > 80$ GeV; $p_T^{\rm jet} > 30$ GeV

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

Disentangling Jet Modification from Selection

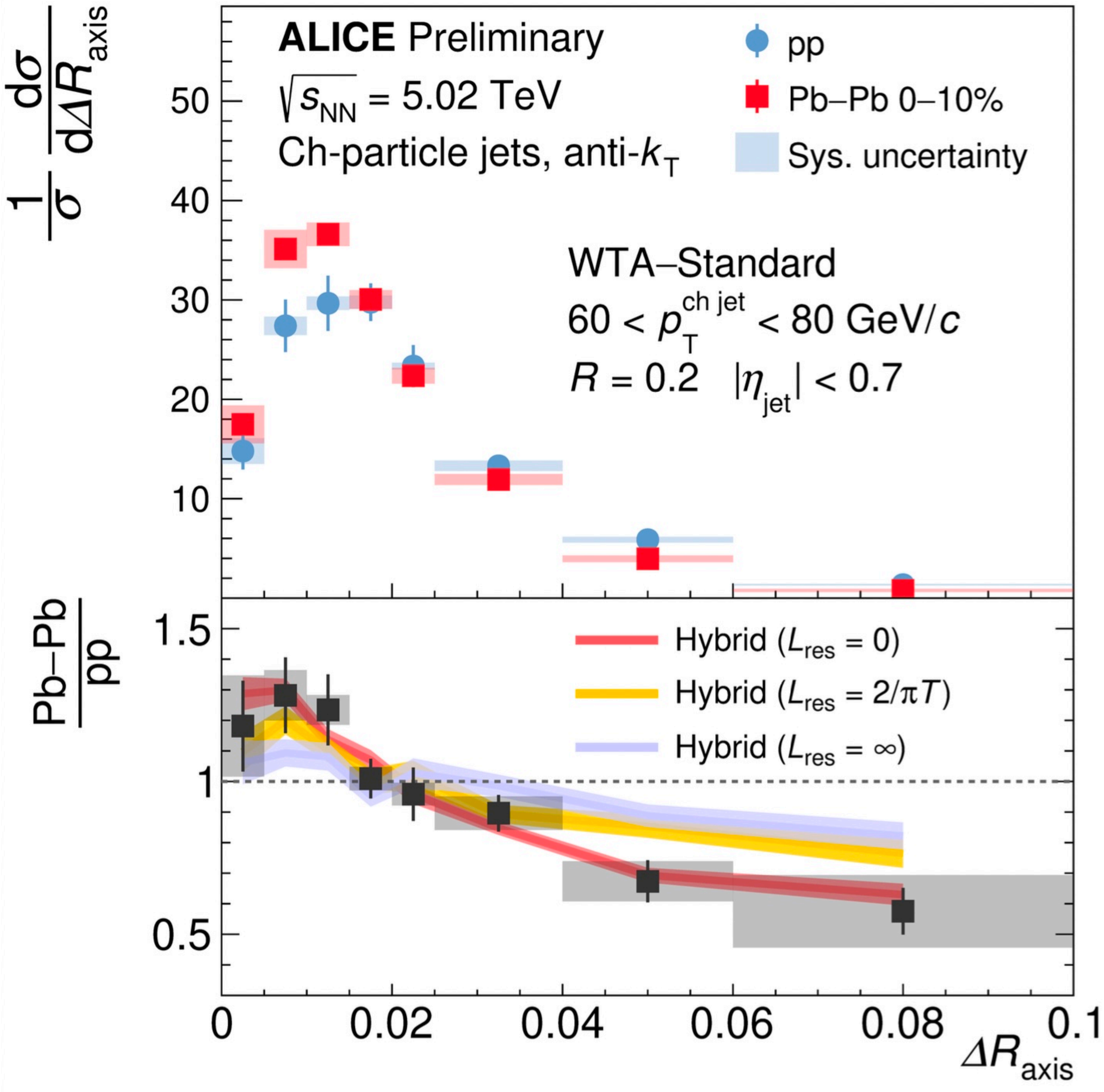




Orange: $p_T^Z > 80$ GeV; $p_T^{\text{jet}} > 30$ GeV. See jet modification.

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

Medium resolution length, L_{res}



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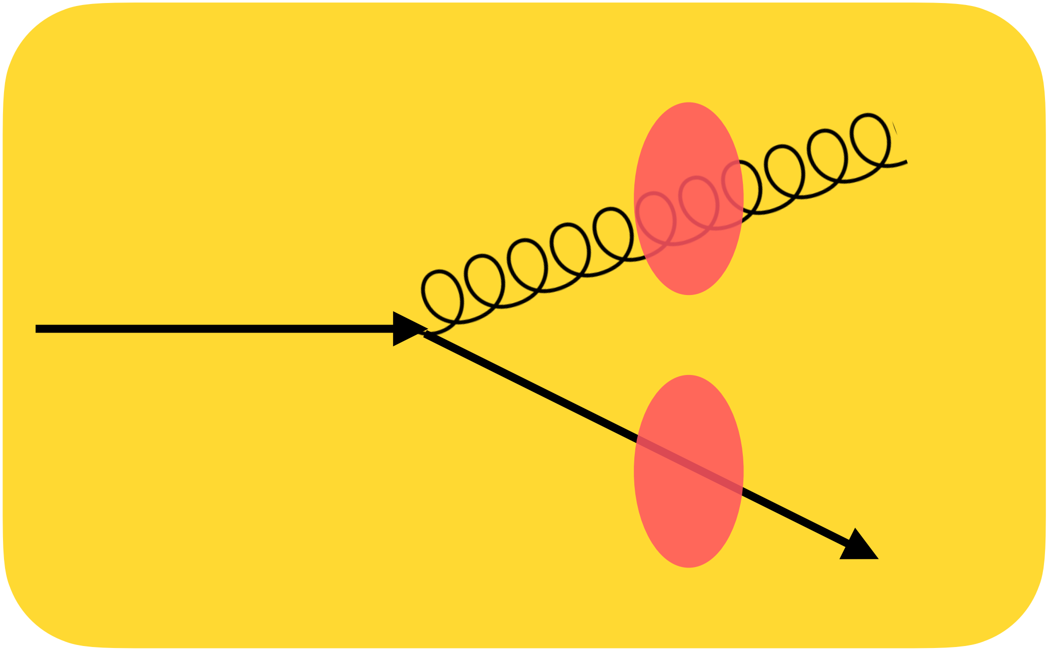
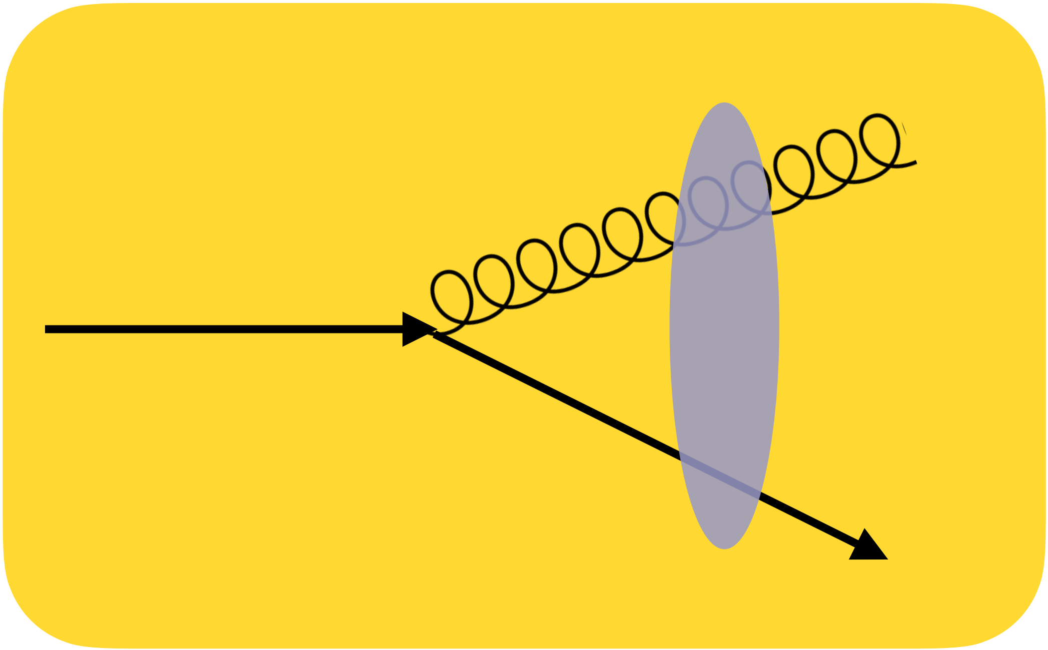


L_{res} = 0: medium resolves splitting immediately after parton fragments.
Fully-incoherent energy loss



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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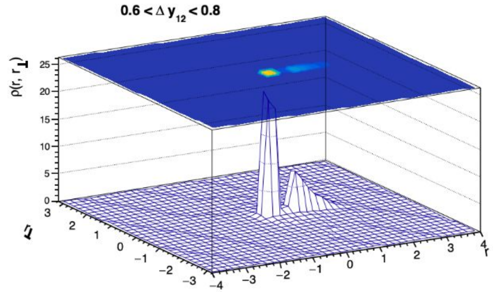
Jets as Probes of QGP

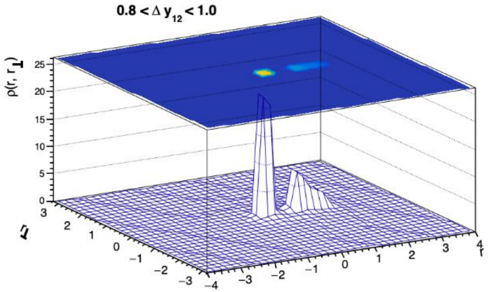
- Jet wakes in droplets of QGP.
  - Momentum/energy “lost” by parton shower → wake in the fluid → spray of soft hadrons, many in the jet. Jets in HIC are not just the parton shower hadronized.
  - To use jets as probes, must calculate, or understand+avoid, wake. Wake also interesting: study equilibration.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

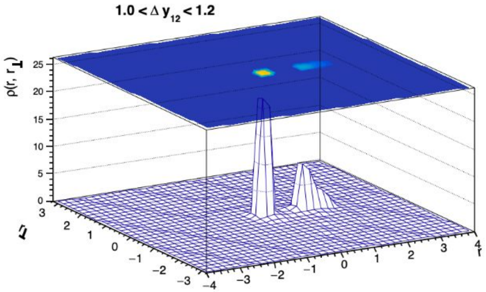
Do Subjets Have Separate Wakes?

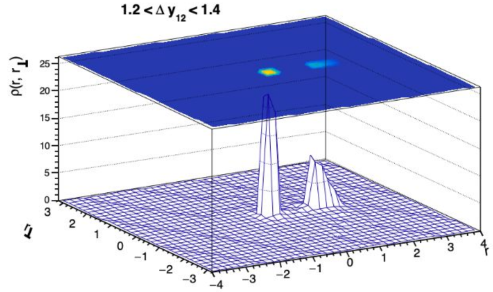
- A question prompted by an interesting observable, introduced by ATLAS at QM19. See 2301.05606.
- First reconstruct anti-k_t-$R = 0.2$ jets, call them subjets, with $p_T^{\text{subjet}} > 35$ GeV; then reconstruct anti-k_t-$R = 1.0$ jets from these objects.
- ATLAS finds R_{AA} for $R = 1.0$ jets with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

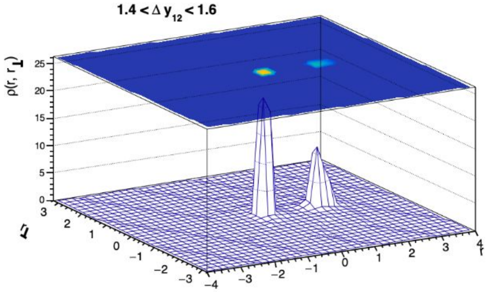
JET SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

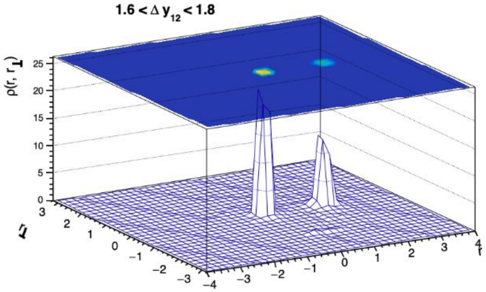

$0.6 < \Delta y_{12} < 0.8$

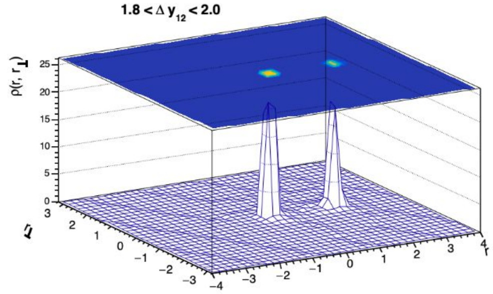

$0.8 < \Delta y_{12} < 1.0$


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


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

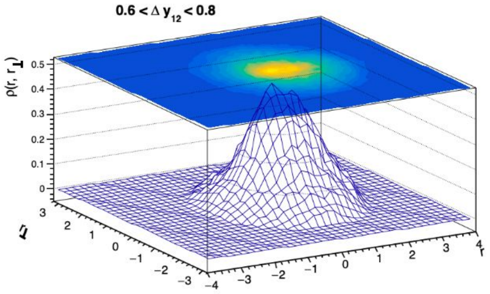

$1.4 < \Delta y_{12} < 1.6$

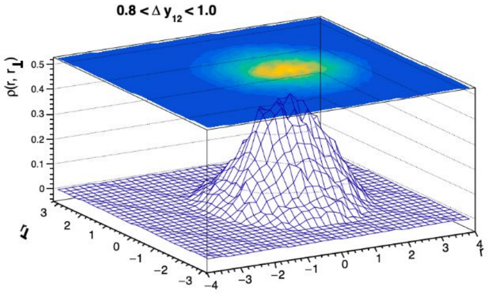

$1.6 < \Delta y_{12} < 1.8$

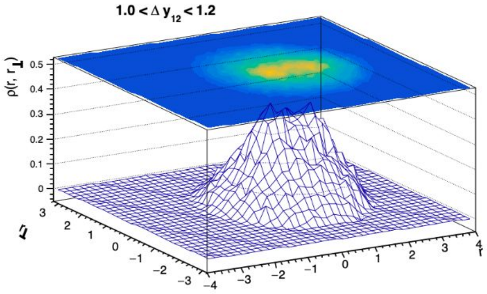

$1.8 < \Delta y_{12} < 2.0$

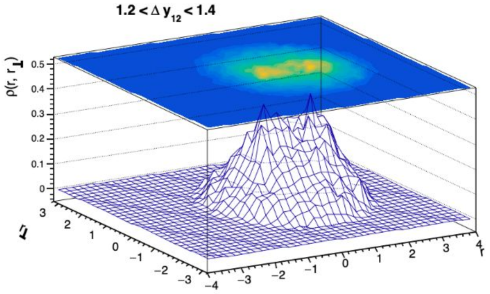
They look as we expected…

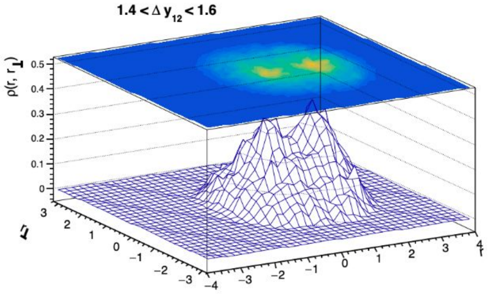
WAKE SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

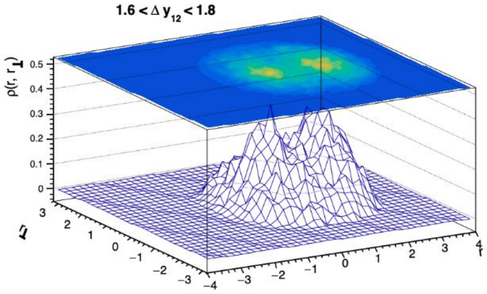


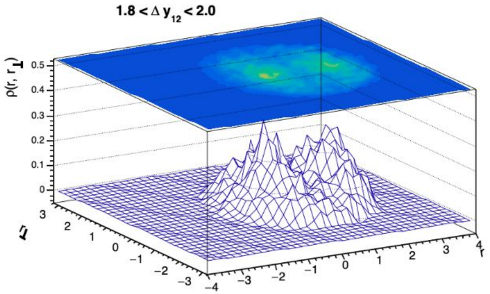








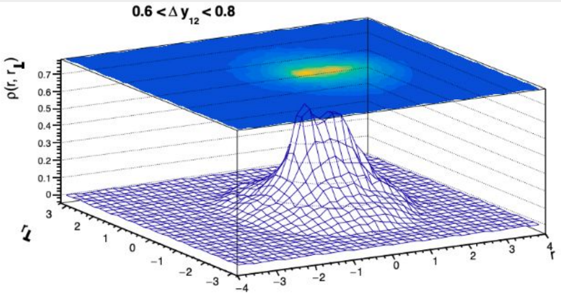


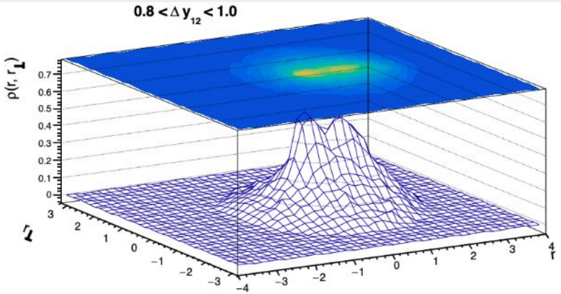


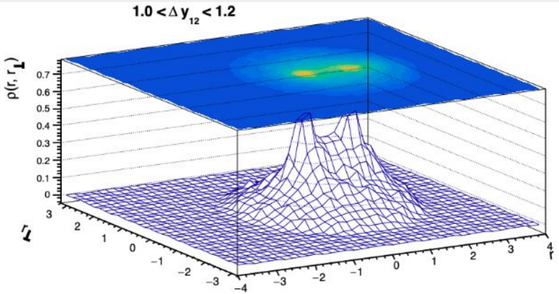
For closely-separated subjets ($\Delta y_{12} < 1.0$), there is a single wake produced by 2 hard structures (the subjets). **Two distinct wakes are visibly produced only when the subjets are far-separated** (around $\Delta y_{12} > 1.4$)!

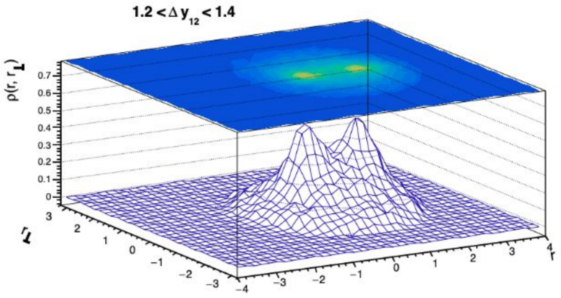
Can we see this in experiments?

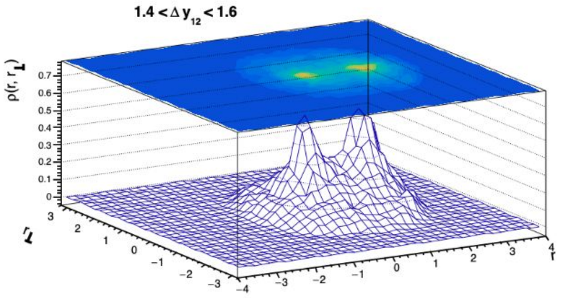
SHAPE OF PARTICLES WITH P_T < 1.5 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

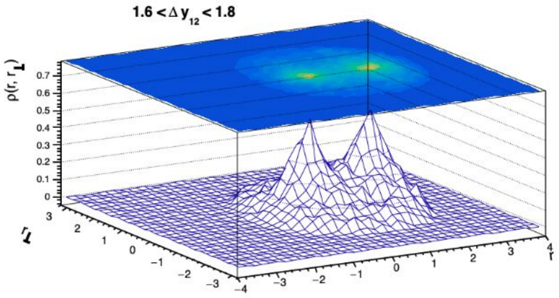

$0.6 < \Delta y_{12} < 0.8$


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


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


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


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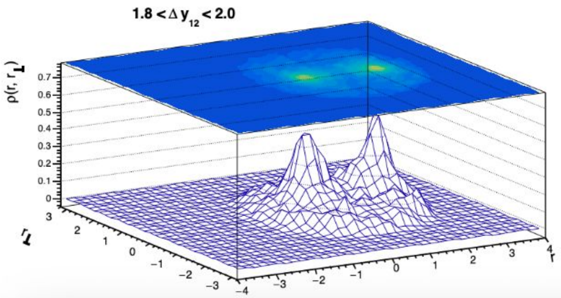
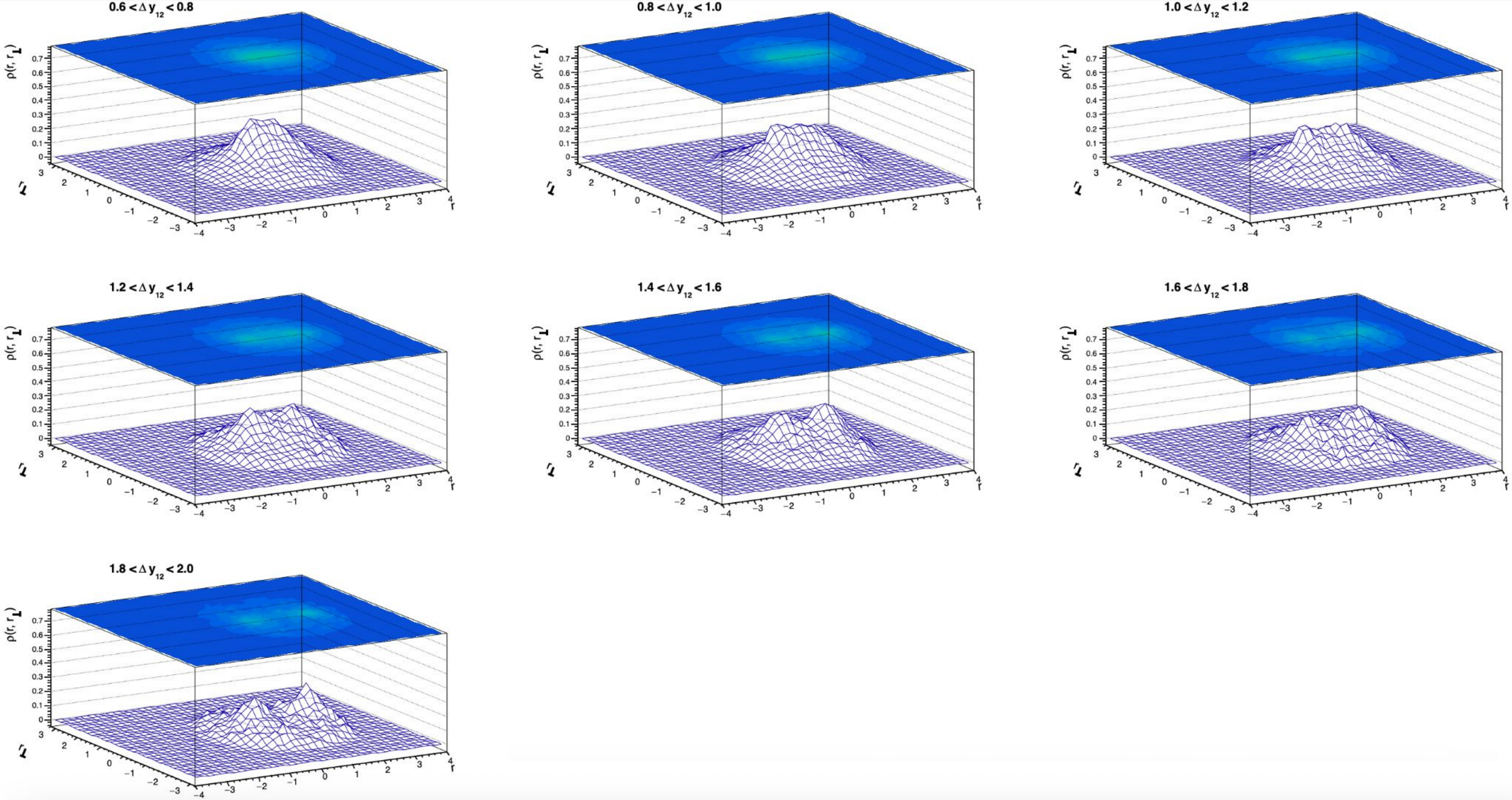

$1.8 < \Delta y_{12} < 2.0$

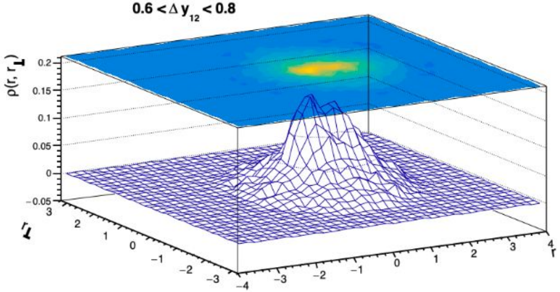
Experimentalists look for the wake by restricting to observing particles with low-p_T.

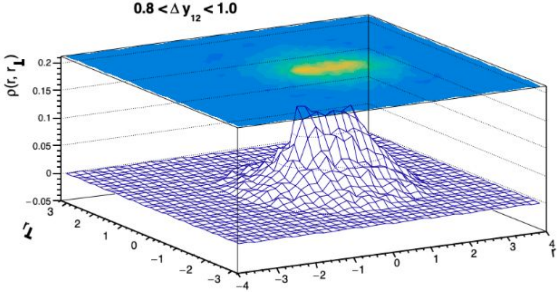
If we restrict to calculating the jet shape for particles with p_T < 1.5 GeV, then it resembles the shape of the wake – in particular, it is difficult to distinguish between two soft structures for $\Delta y_{12} < 1.0$, and easier for larger Δy_{12}.

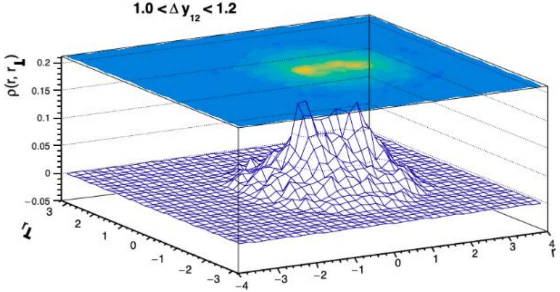
SHAPE OF PARTICLES WITH $P_T < 1.0$ GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

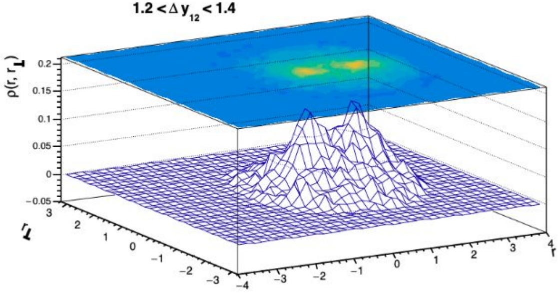


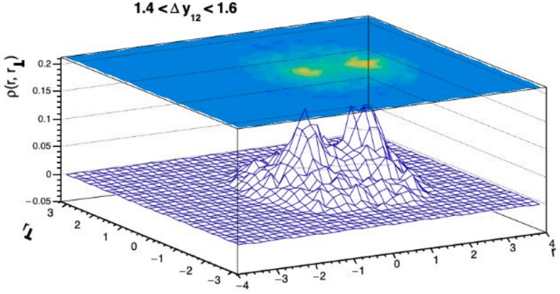
ALL PARTICLES WITH $0.7 < P_T < 1$ GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS


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


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


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


$1.2 < \Delta y_{12} < 1.4$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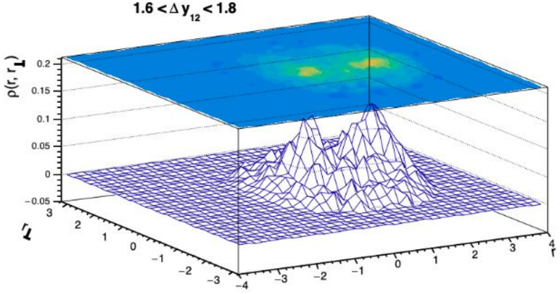
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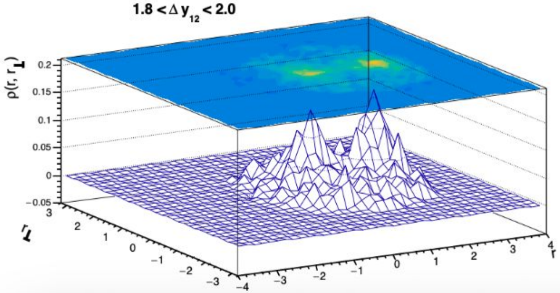
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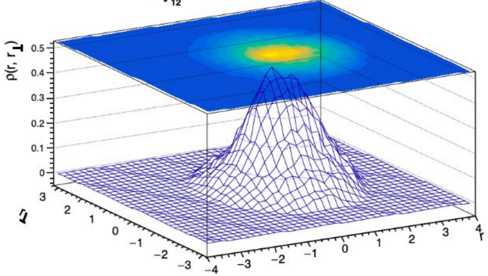
WAKE SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

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



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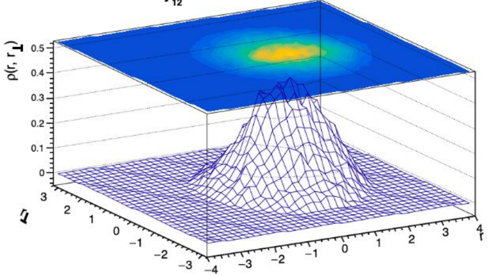

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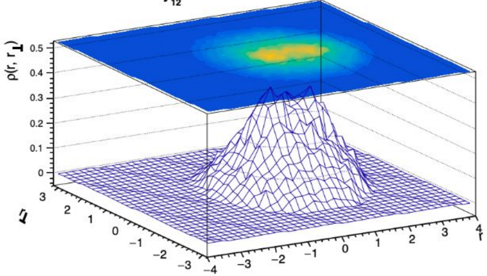

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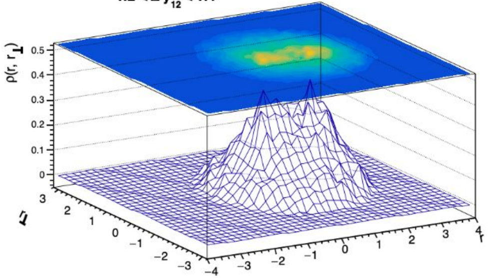

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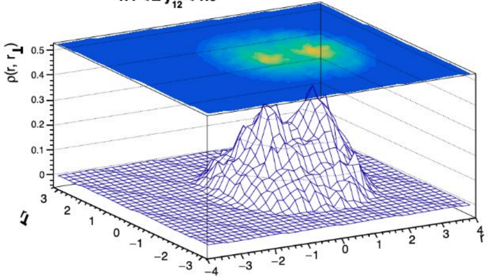

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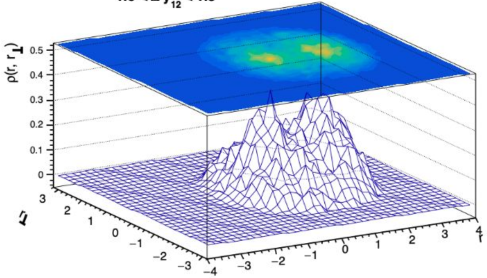

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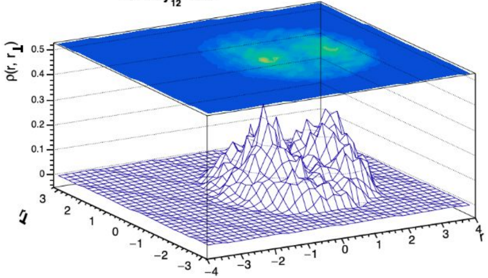


For closely-separated subjets ($\Delta y_{12} < 1.0$), there is a single wake produced by 2 hard structures (the subjets). **Two distinct wakes are visibly produced only when the subjets are far-separated** (around $\Delta y_{12} > 1.4$)!

Can we see this in experiments?

Do Subjets Have Separate Wakes?

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

Massachusetts
Institute of
Technology

Imaging the wake of the jet with Energy Correlators

Hannah Bossi (MIT)

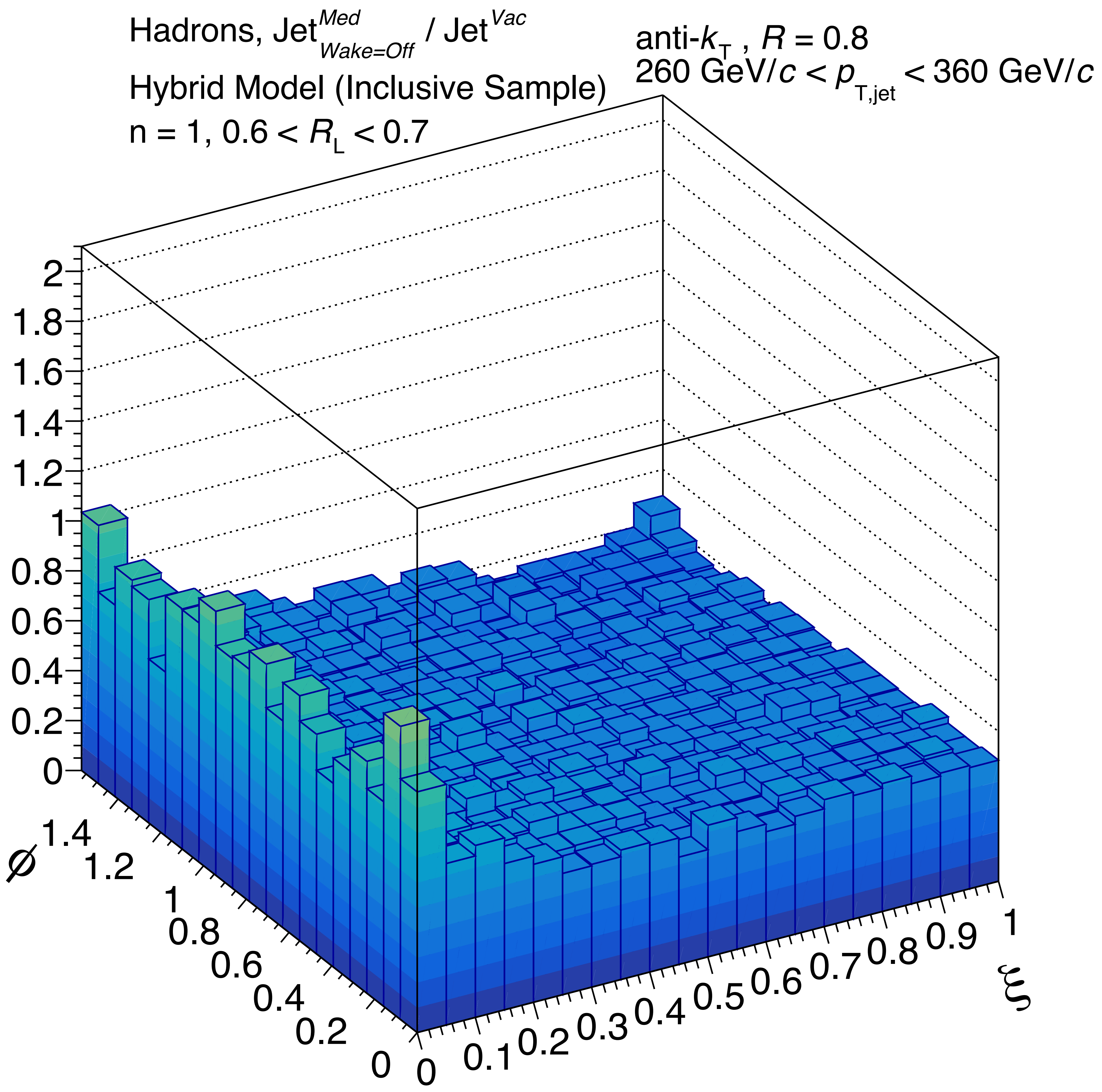
ECT* Jet Tools Workshop, Trento, Italy

February, 13th, 2024

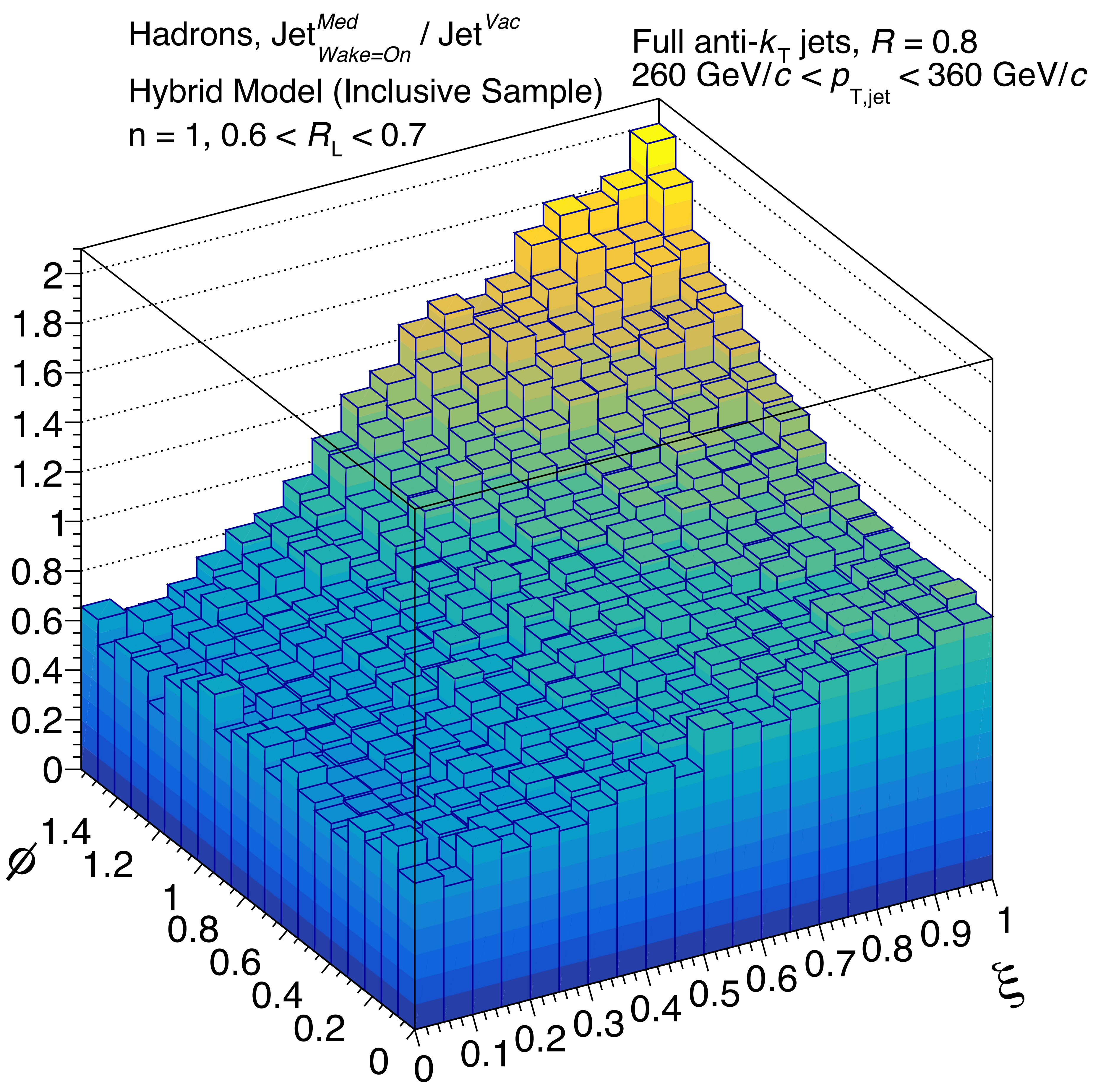
Based on work in progress with Ian Moult (Yale), Dani Pablos (Santiago), Ananya Rai (Yale), Krishna Rajagopal (MIT), and Arjun Srinivasan Kudinoor (Cambridge)

MIT HIG’s work was supported by US DOE-NP

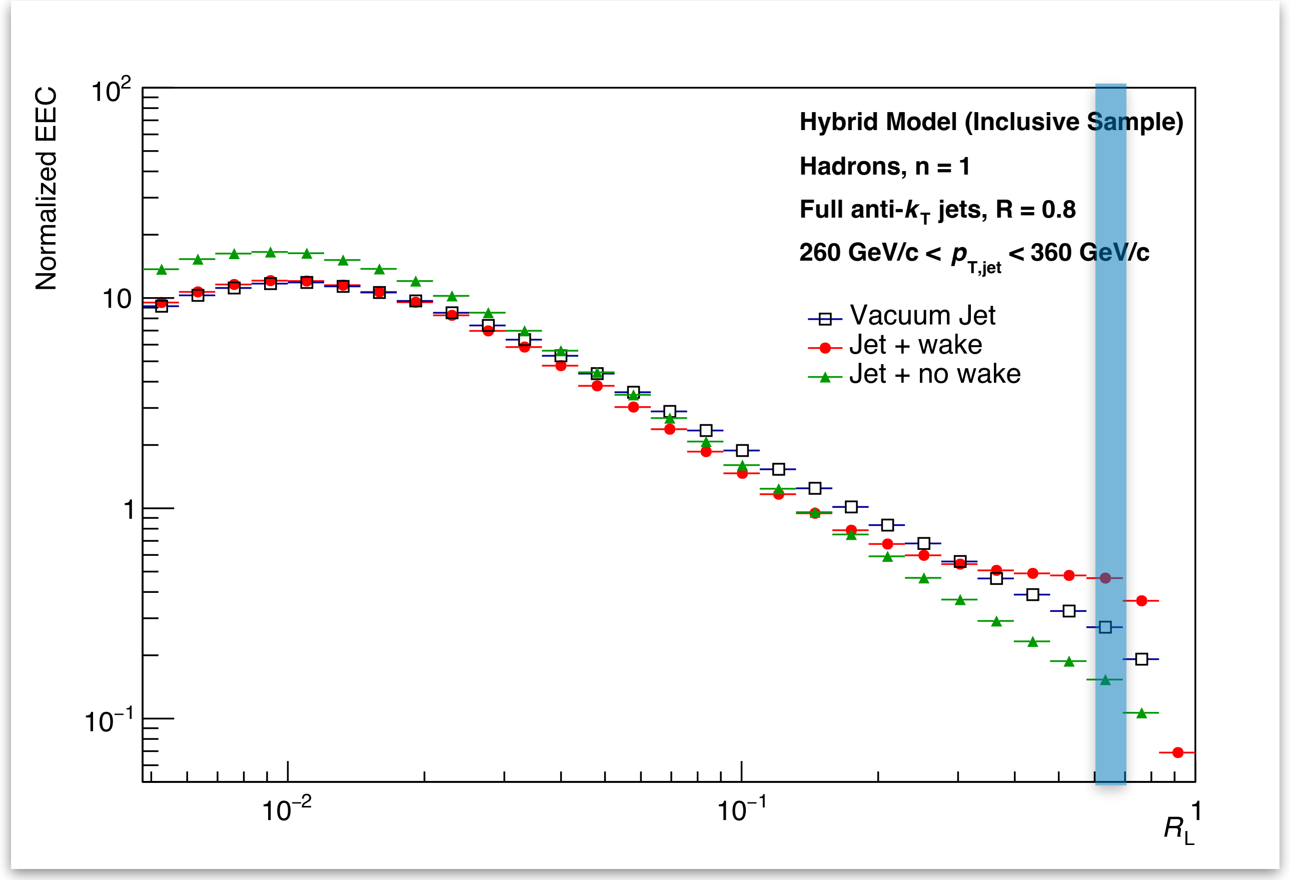
Ratios to vacuum



No wake / vacuum



Wake / vacuum



- ***Wake leaves clear signatures in comparison to 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.**

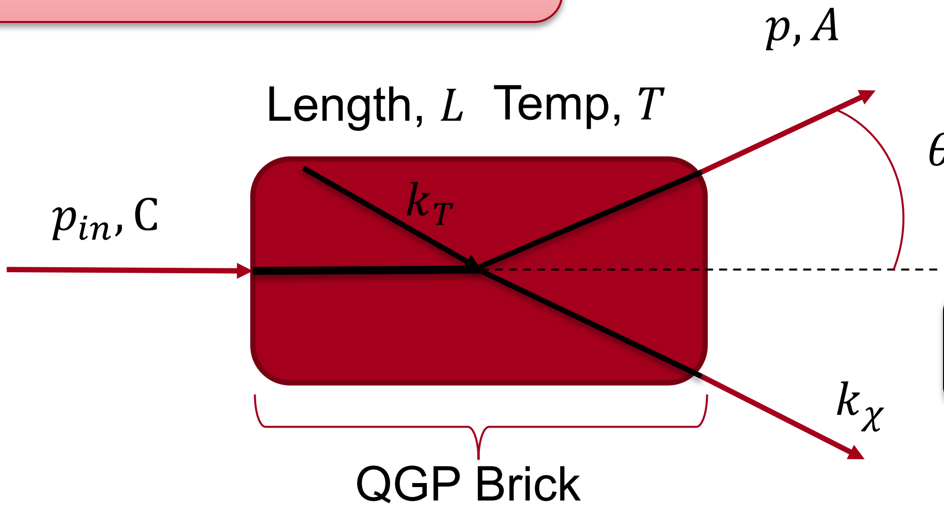
Why Molière scattering?
Why add to Hybrid Model?

- 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 → 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



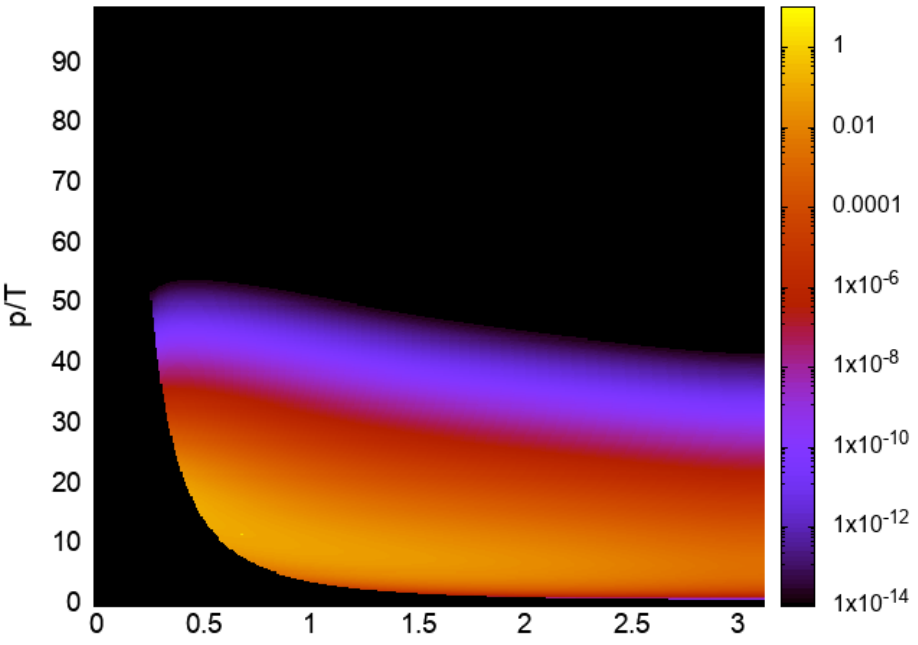
D'Eramo et al., 2019

- 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.

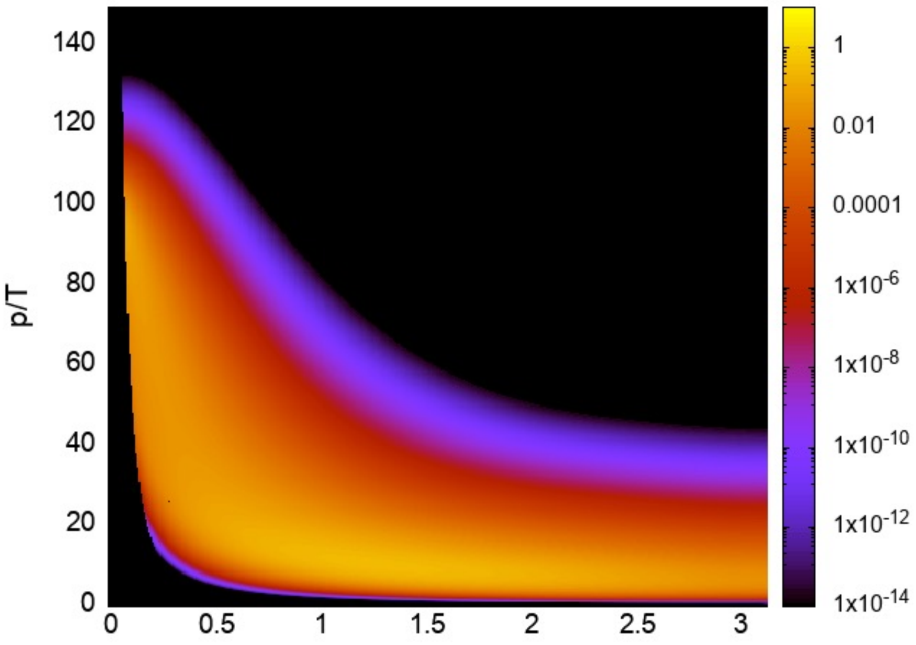
Tree-Level 2-2 massless scattering amplitudes

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

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

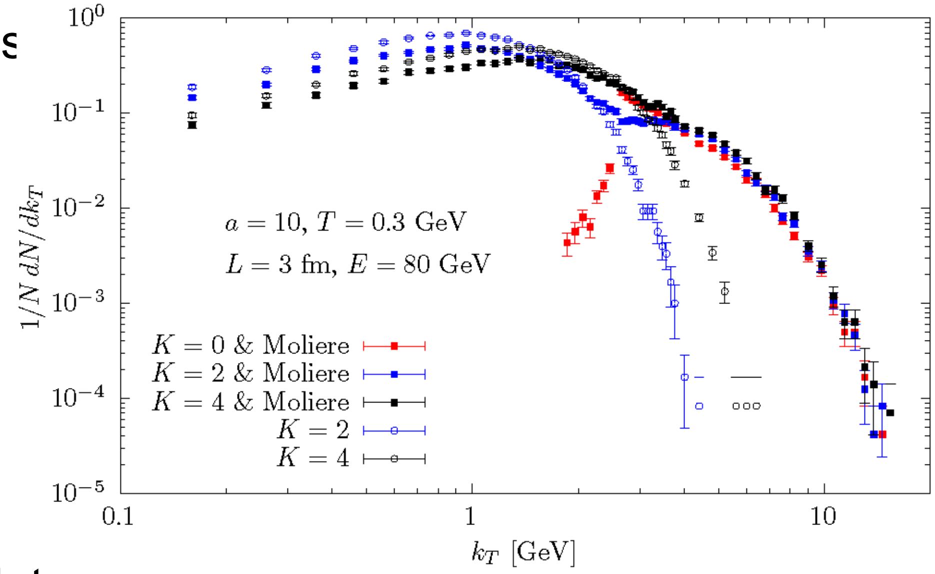
At strong coupling, holography predicts Gauss broadening without quasi-particles (eg: N=4 SYM)

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

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

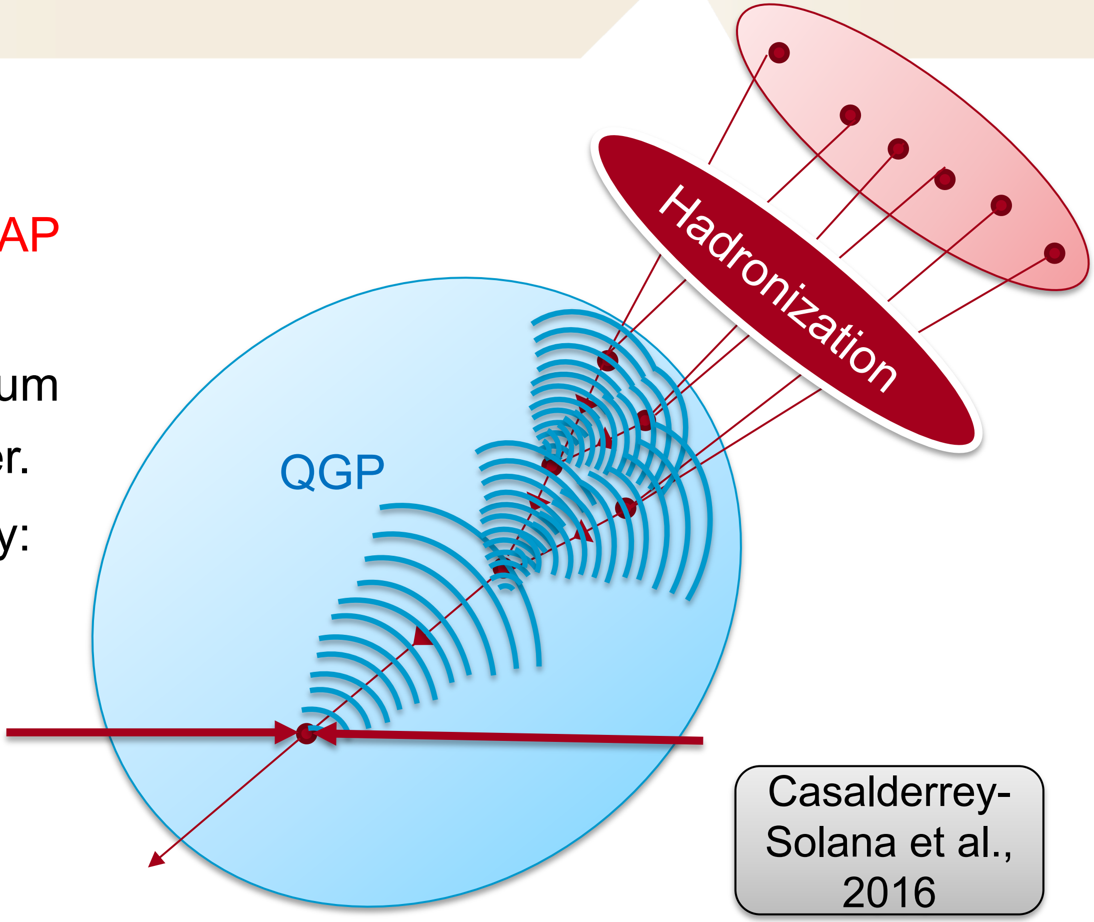
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

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

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., 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:

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

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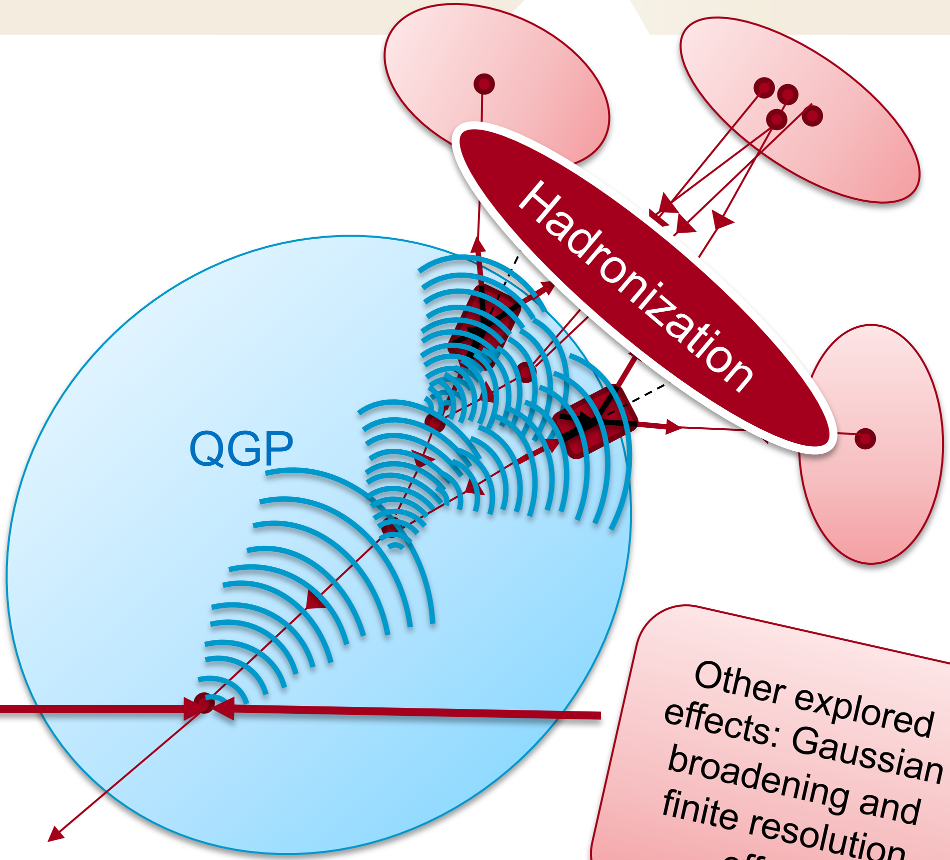


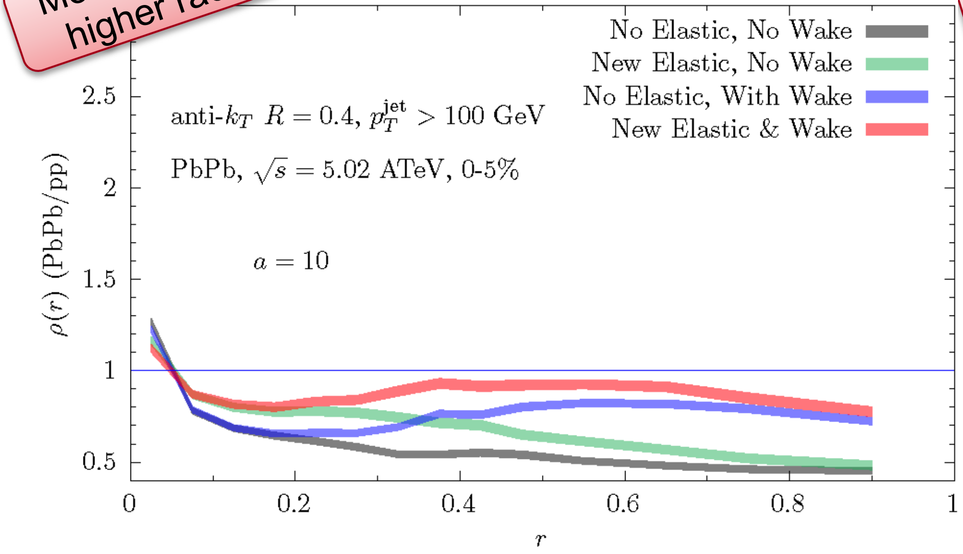
Other explored effects: Gaussian broadening and finite resolution effects

Energy and momentum conservation → activate hydrodynamic modes of plasma

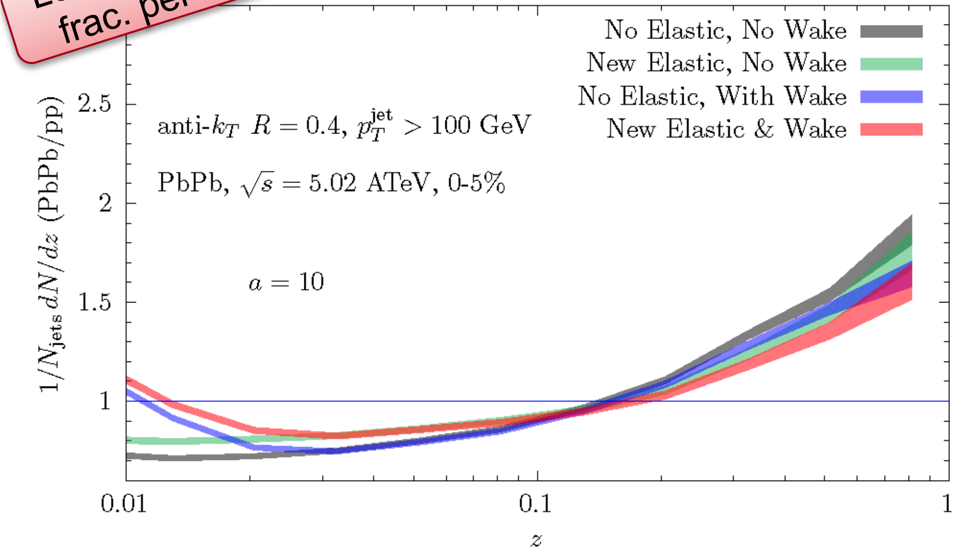
$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y - \eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right)\right]$$

Jet Shapes and Fragmentation Functions

More energy at higher radius



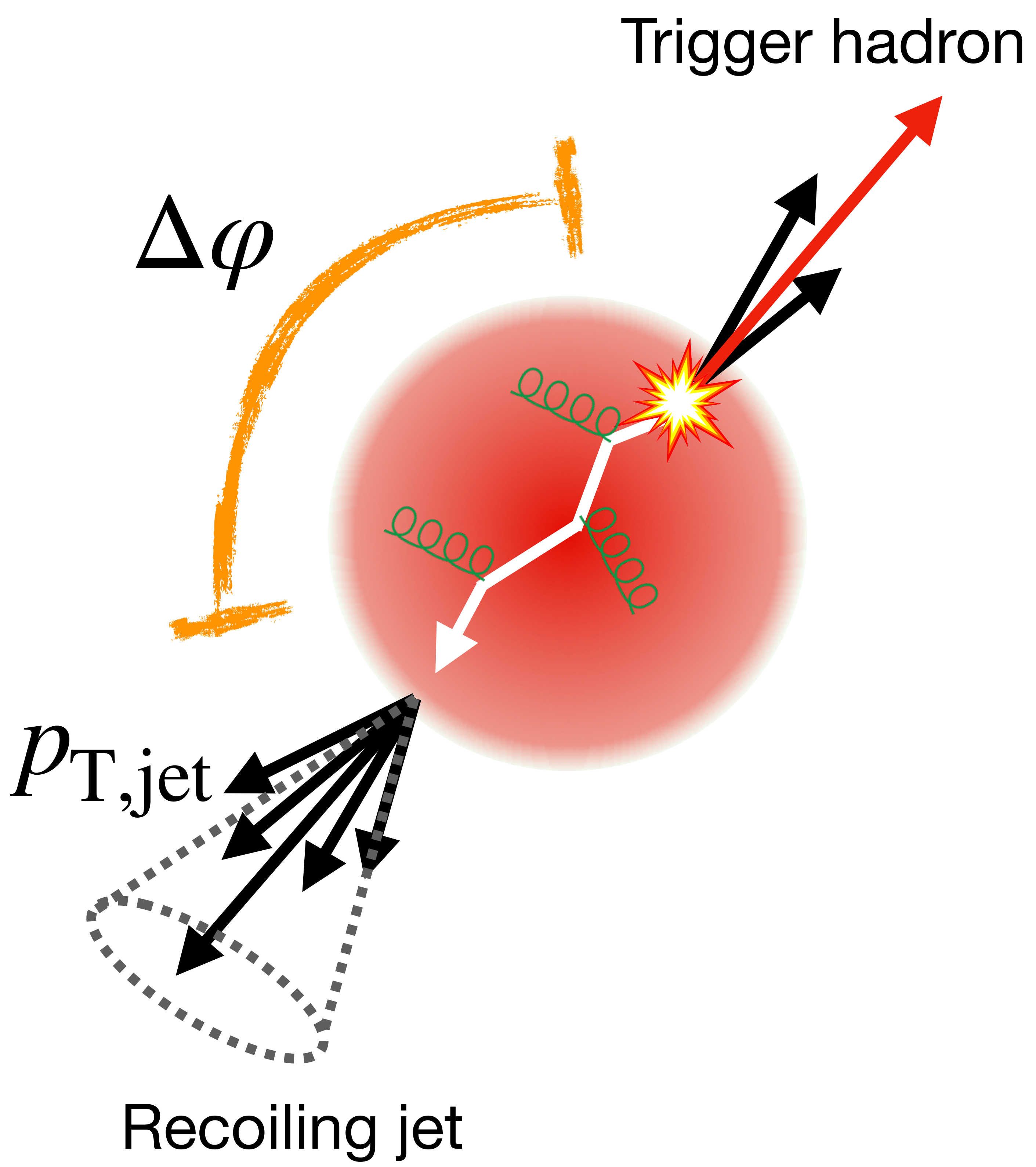
Lower momentum frac. per hadron



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

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

Analysis procedure

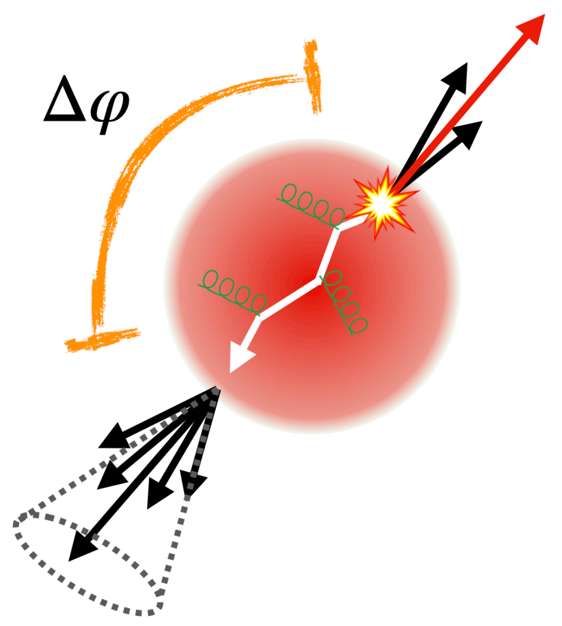


1. **Select events** based on the **presence of a high-p_{T} 'trigger' hadron**
2. **Do jet reconstruction** on these events
3. **Count jets recoiling from the trigger hadron** as function of:
   - opening angle ($\Delta\varphi$) of jet relative to trigger axis
   - transverse momentum ($p_{\mathrm{T,jet}}$)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

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

- **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

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

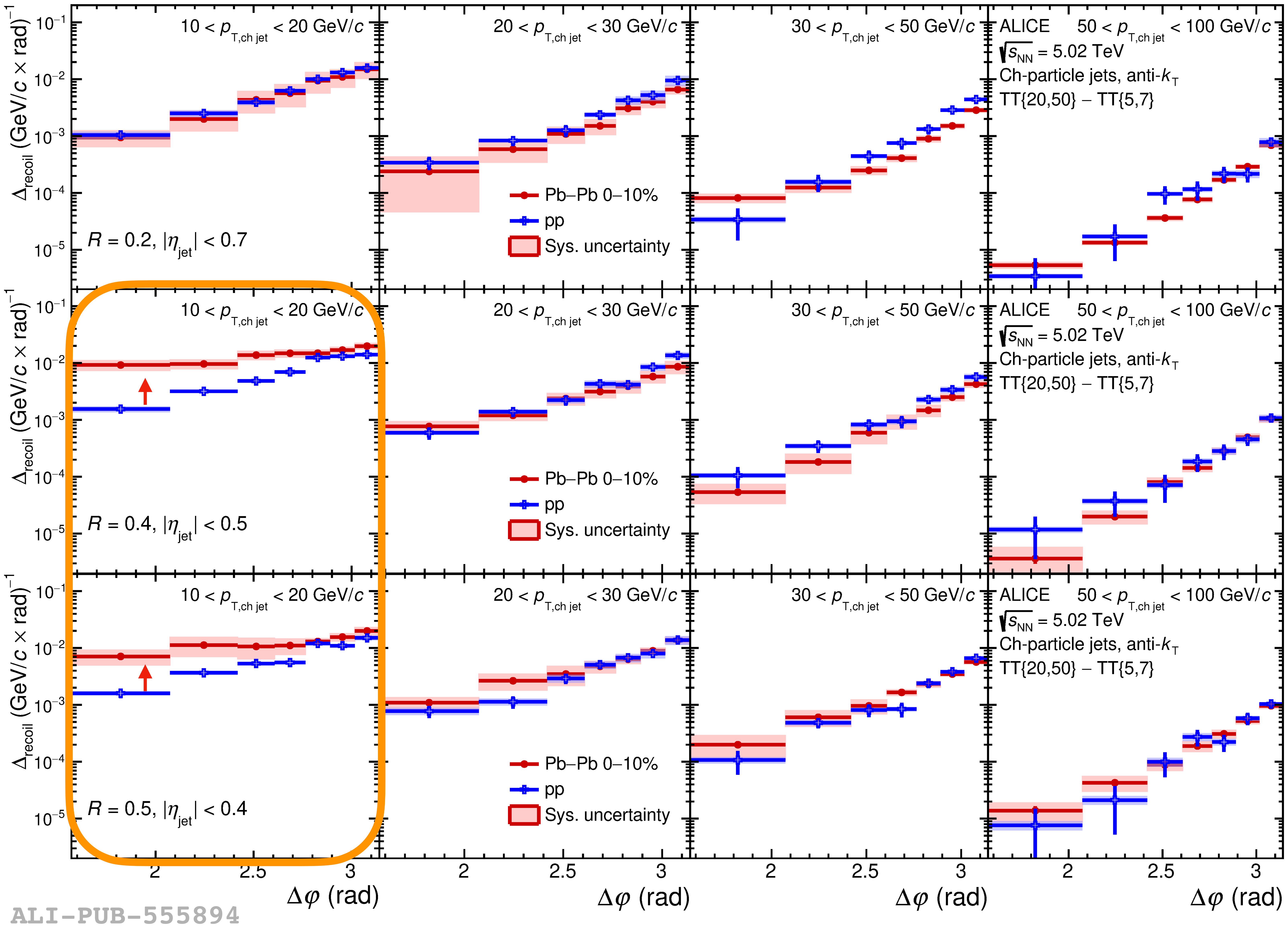


$p_{\mathrm{T,ch\,jet}}$: **[10,20] GeV/*c*** **[20,30] GeV/*c*** **[30,50] GeV/*c*** **[50,100] GeV/*c***

***R*=0.2**

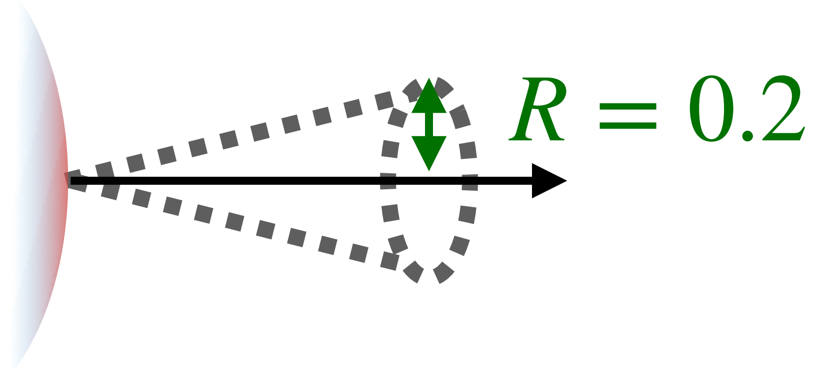
***R*=0.4**

***R*=0.5**

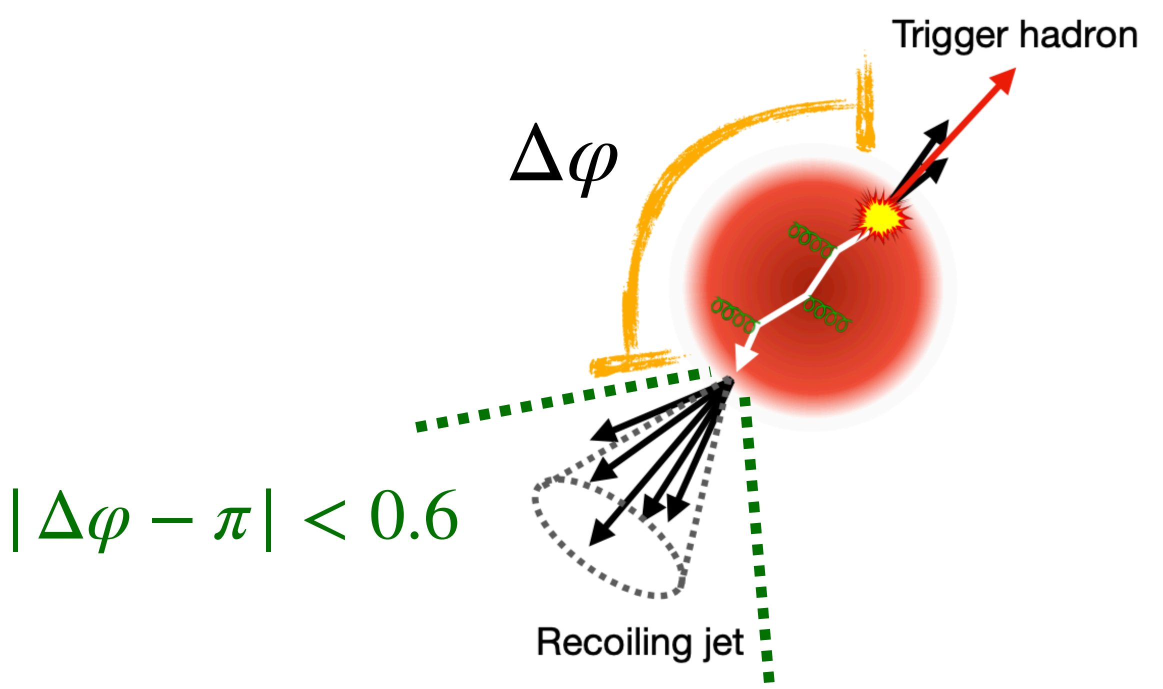


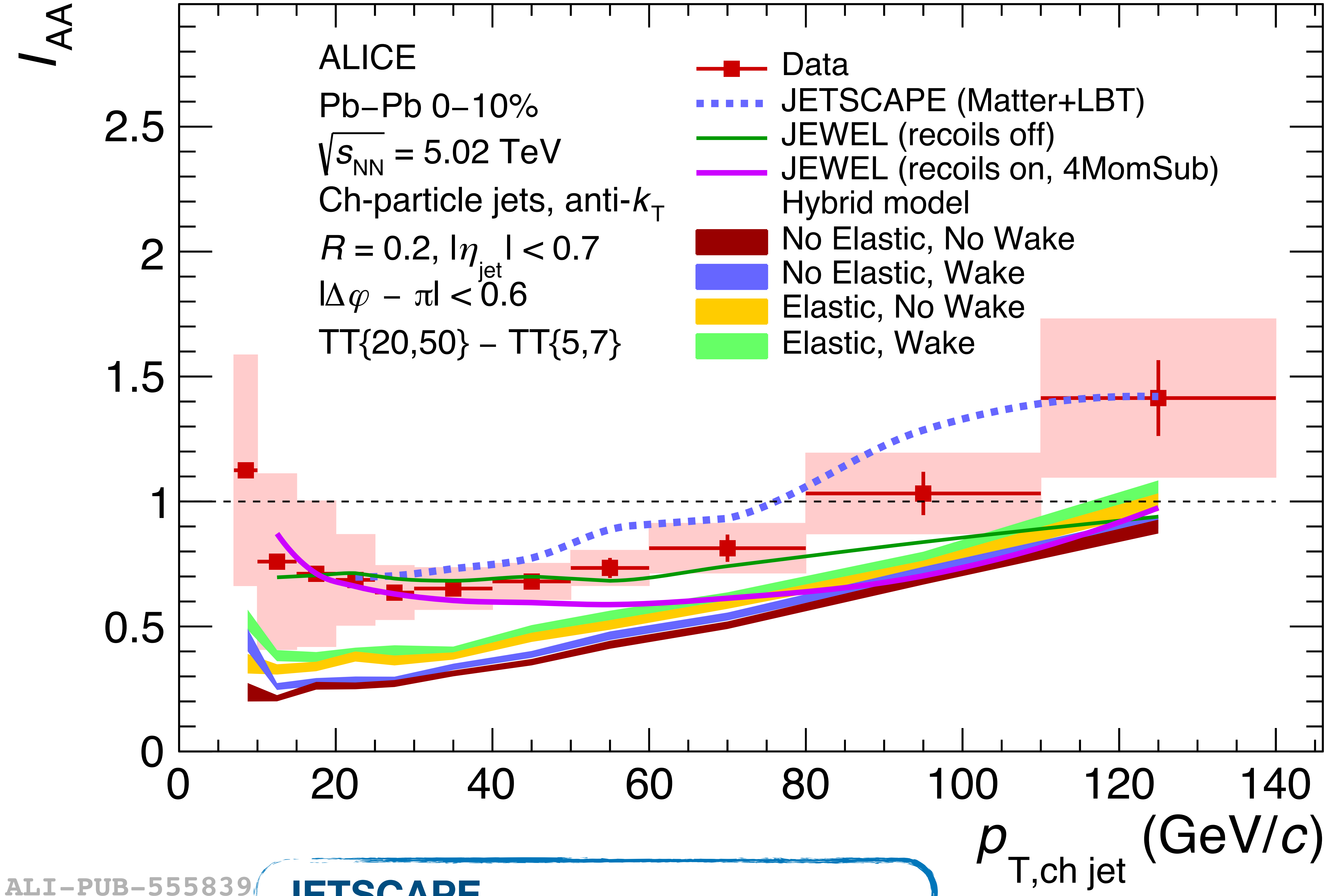
- **Significant azimuthal broadening** for R=0.4 and R=0.5 at low $p_{\mathrm{T,ch\,jet}}$

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



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





ALI-PUB-555839

- **Suppression** at 20 < $p_{T,\mathrm{ch\,jet}}$ < 80 GeV/c → jet energy loss
- **Rising trend with $p_{T,\mathrm{ch\,jet}}$** → interplay between hadron and jet energy loss? Less trigger surface bias when $p_{T,\mathrm{jet}} >> p_{T,\mathrm{trig}}$?
- Models (Hybrid, JETSCAPE) capture rising trend
- JEWEL describes low-$p_{T,\mathrm{jet}}$ 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’

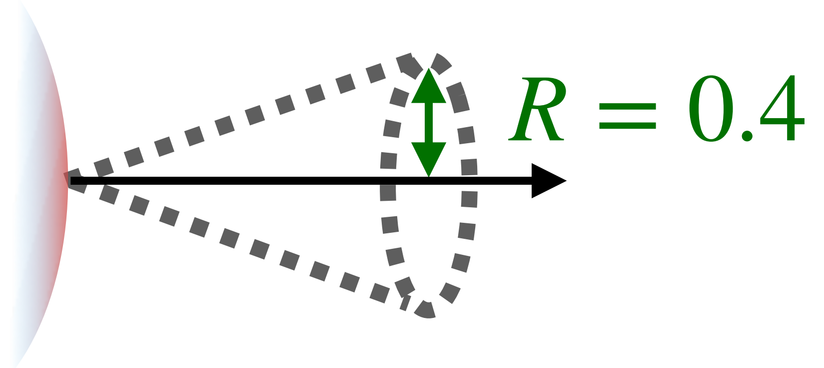
K. Zapp, EPJ C, Volume 74, Issue 2, 2014
R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141

Hybrid model

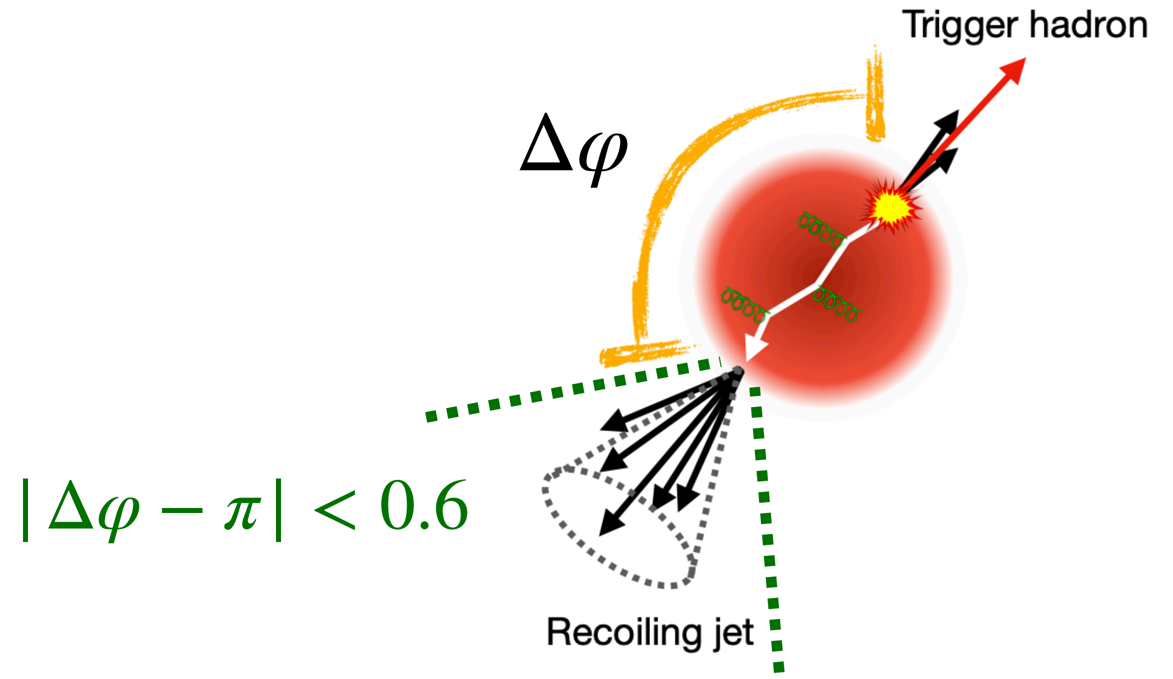
Elastic (Moliére) scatterings and wake (medium response) included

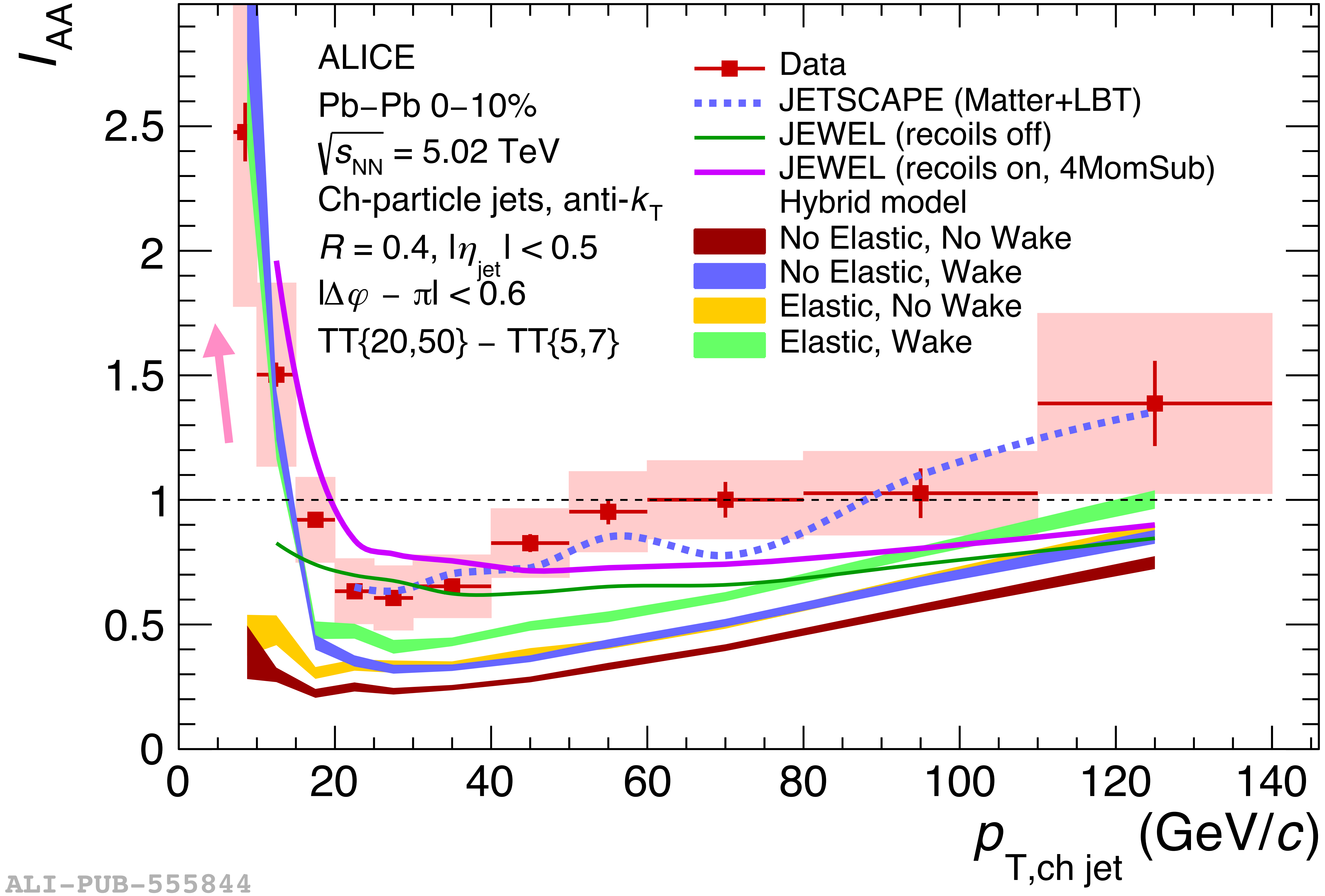
F. d’Eramo, K. Rajagopal, Y. Yin, *JHEP* 01 (2019) 172
Z. Hulcher, D. Pablos, K. Rajagopal, 2208.13593 (QM22)

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



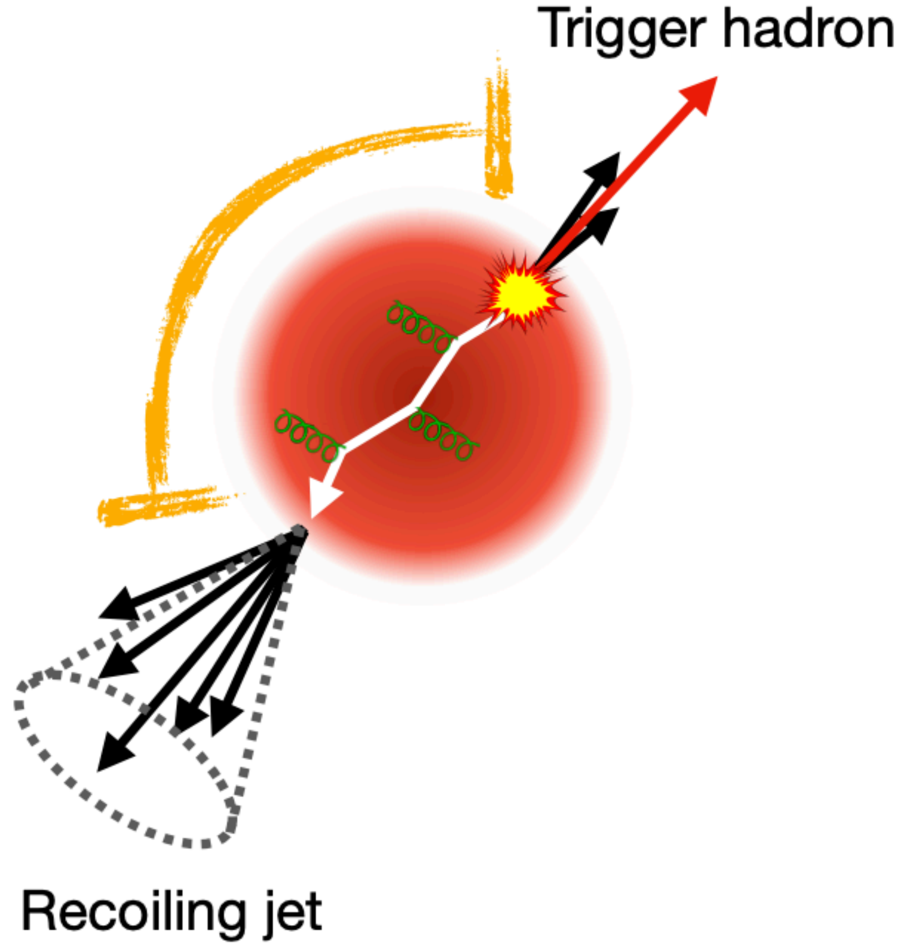
$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$

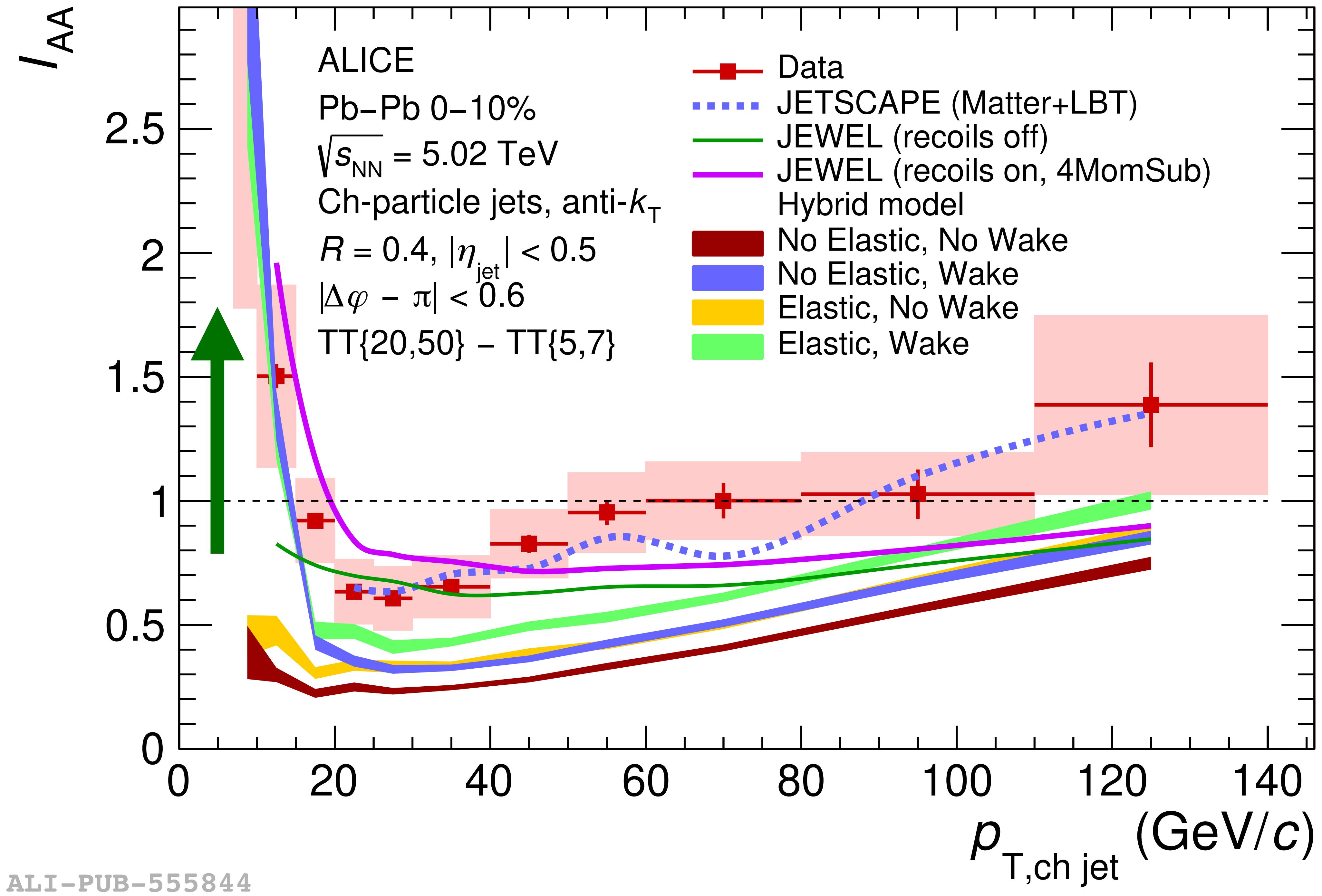




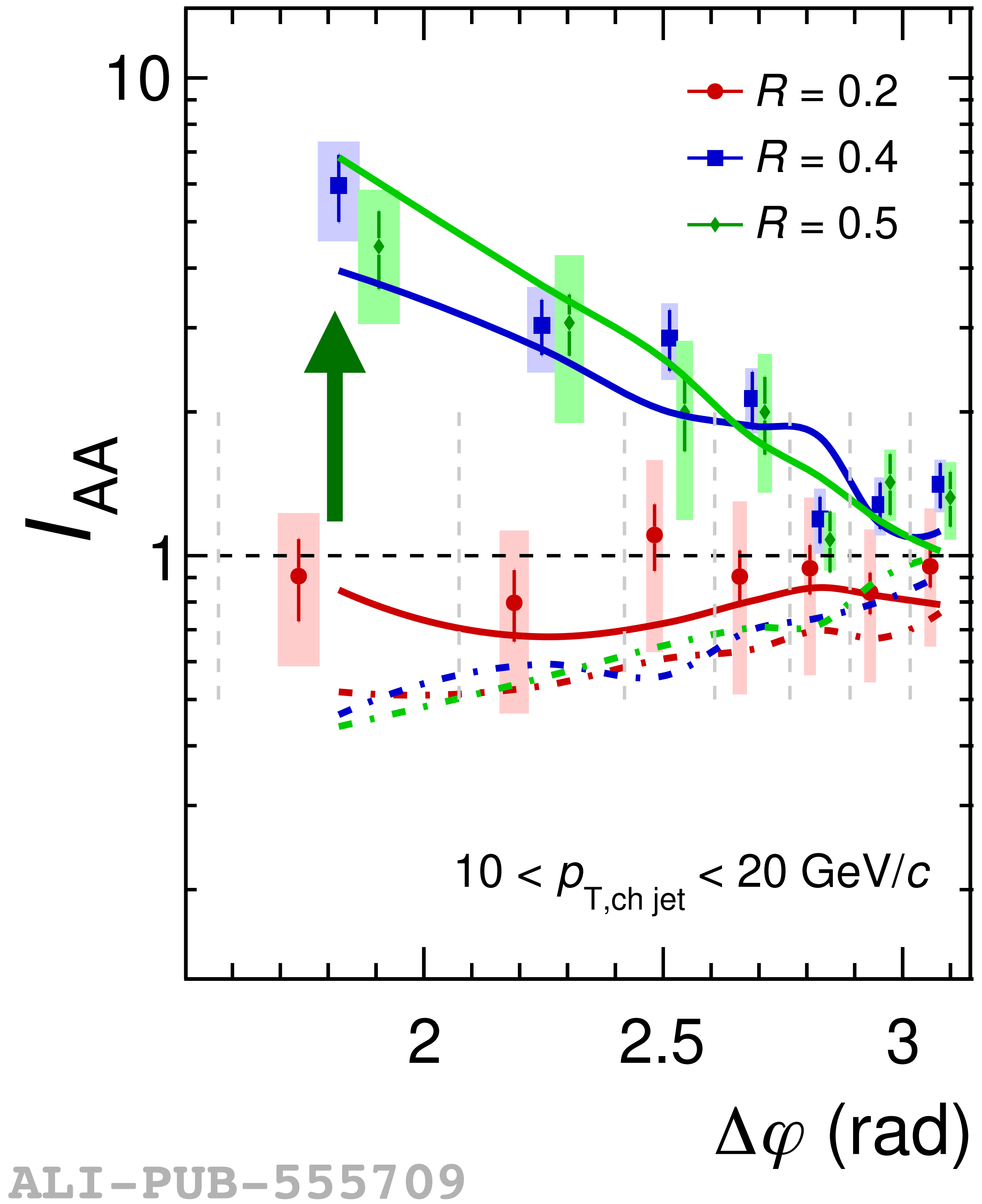
- **Suppression** at 20 < $p_{T,ch\,jet}$ < 80 GeV/c
  → jet energy loss
- **Rising trend with $p_{T,ch\,jet}$**
  → interplay between hadron and jet energy loss?
  Less trigger surface bias when $p_{T,jet} >> p_{T,trig}$?
- **Rise at low $p_{T,ch\,jet}$**
  → Energy recovery? Reproduced by models including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

Summary and outlook





ALI-PUB-555844



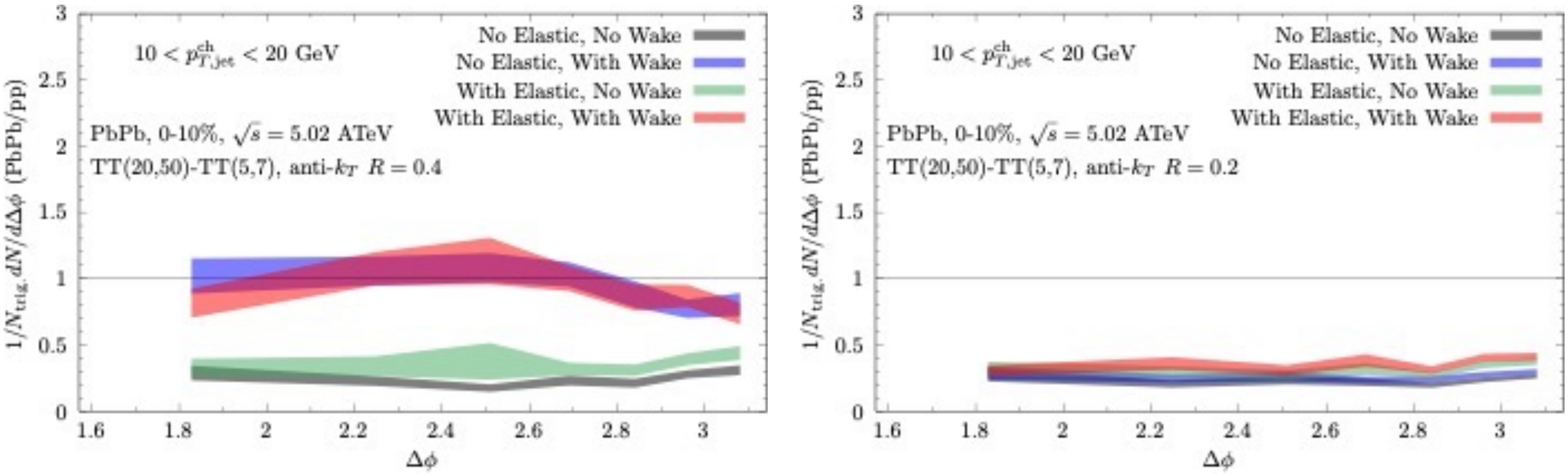
ALI-PUB-555709

- **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

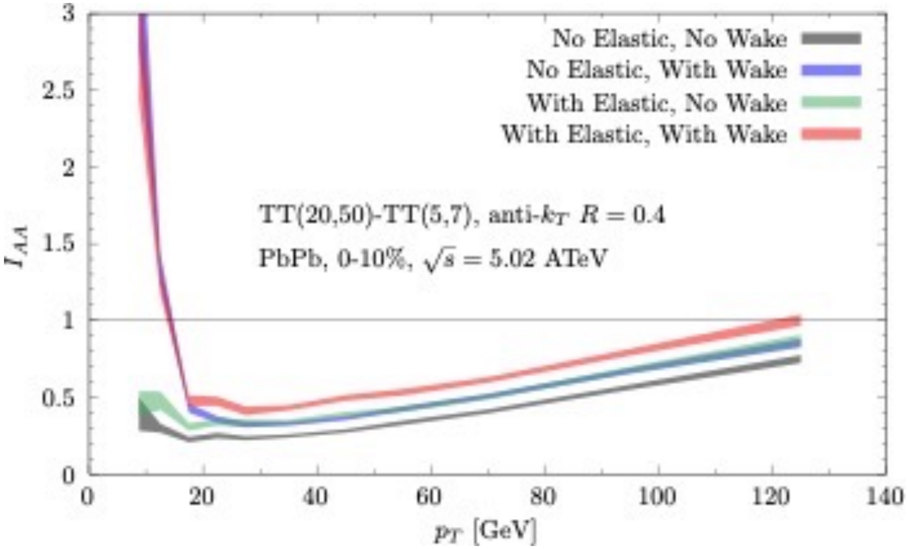
Preliminary

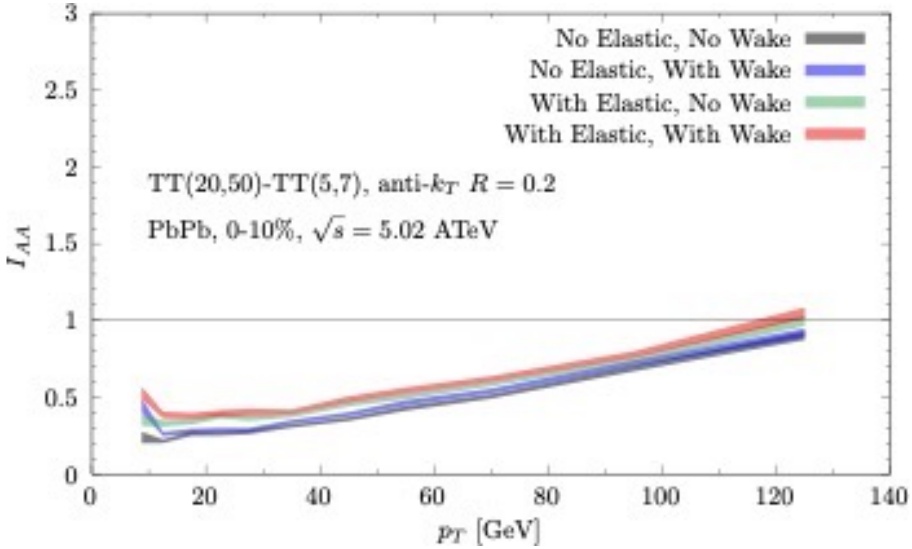


- Study acoplanarity in hadron - charged jet system.
- Parameters similar to ALICE
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.4 jets, not for R=0.2
- I_{AA} indicates effect 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

Preliminary





- Study acoplanarity in hadron - charged jet system.
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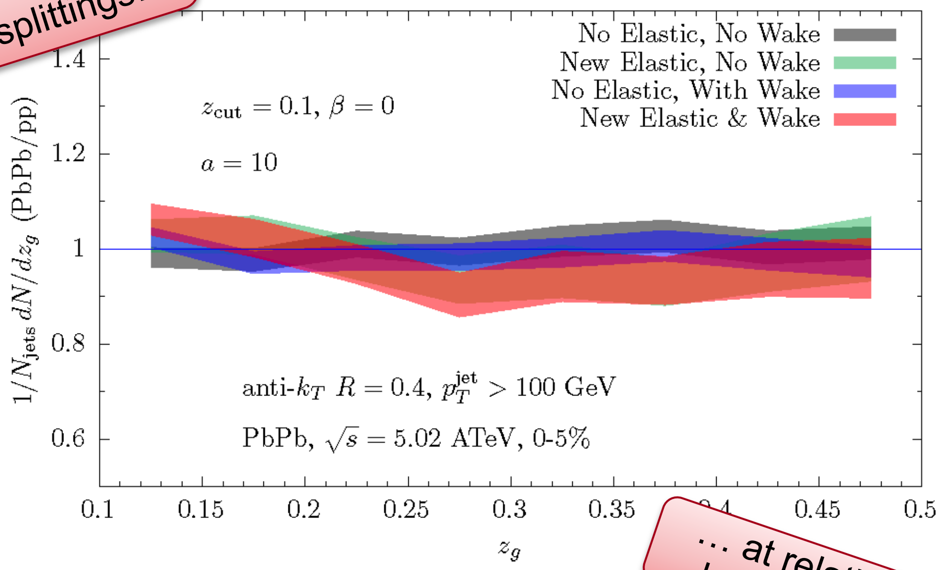
Groomed z_g and R$_g$

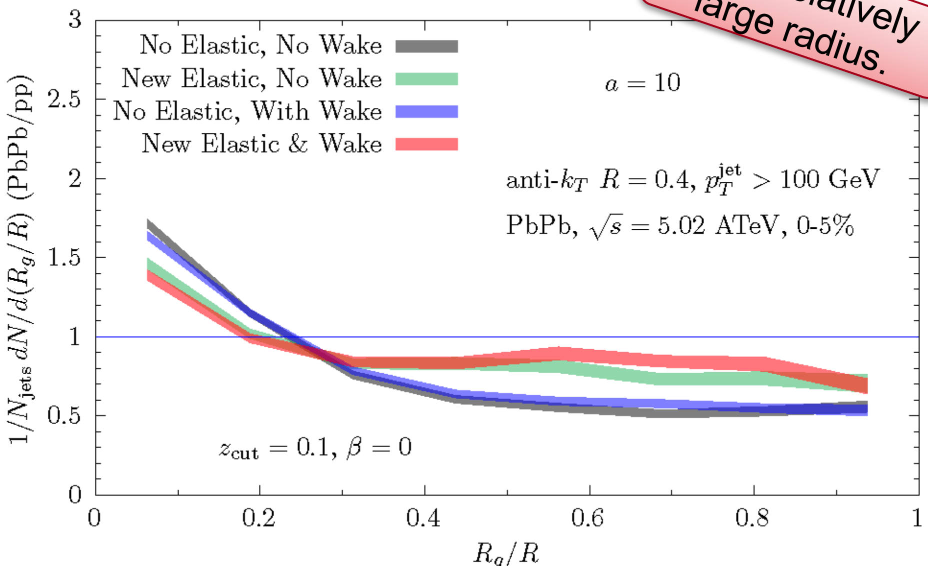
Soft Drop ($\beta = 0$)

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

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



Enhancement of softer splittings…



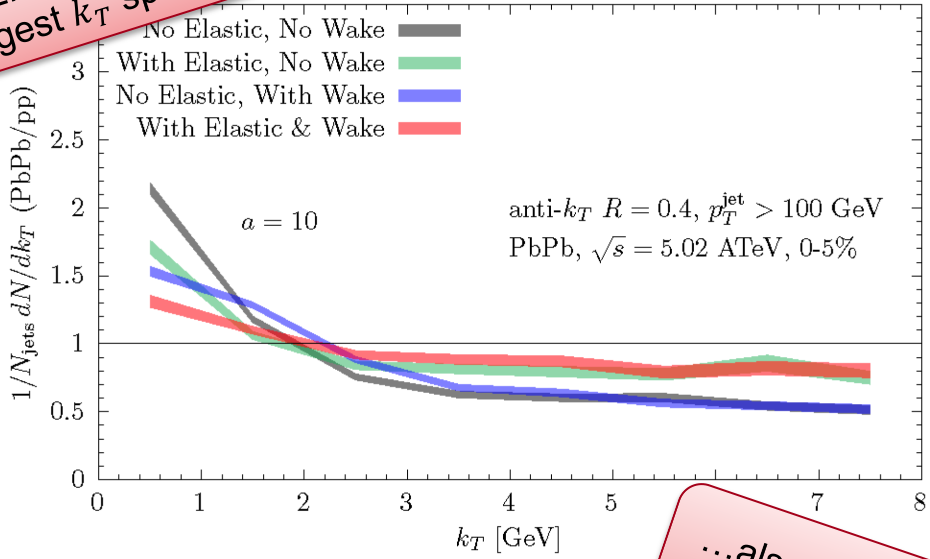
… at relatively large radius.

Leading k_T

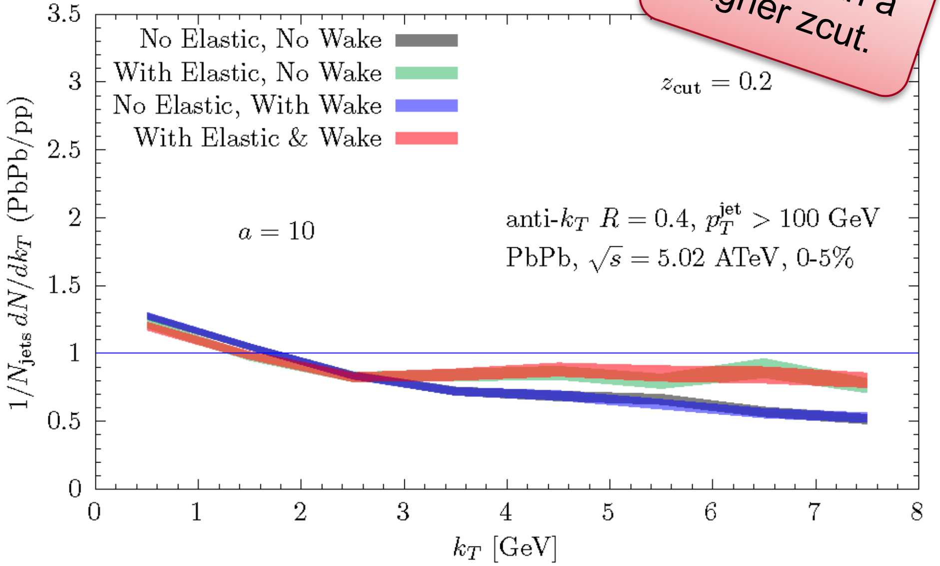
1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2
4. Note k_T of splitting
5. Follow primary branch until the end.
6. Record largest k_T

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

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

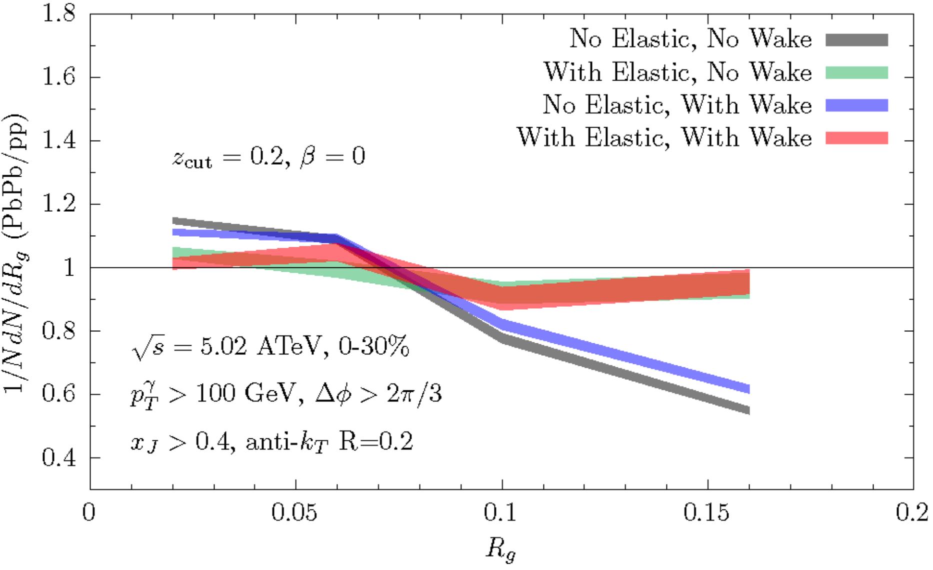


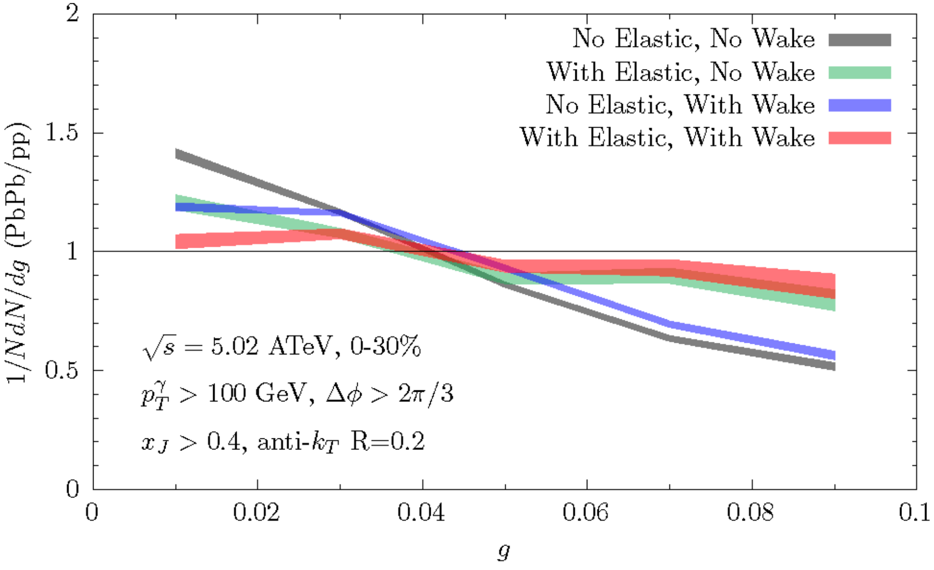
Enhancement of largest k_T splittings…



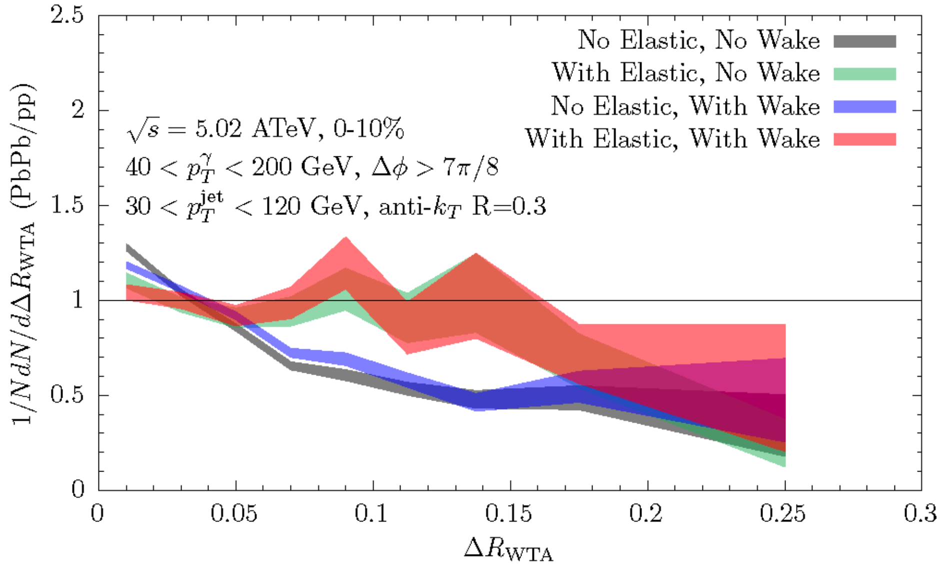
…also with a higher zcut.

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

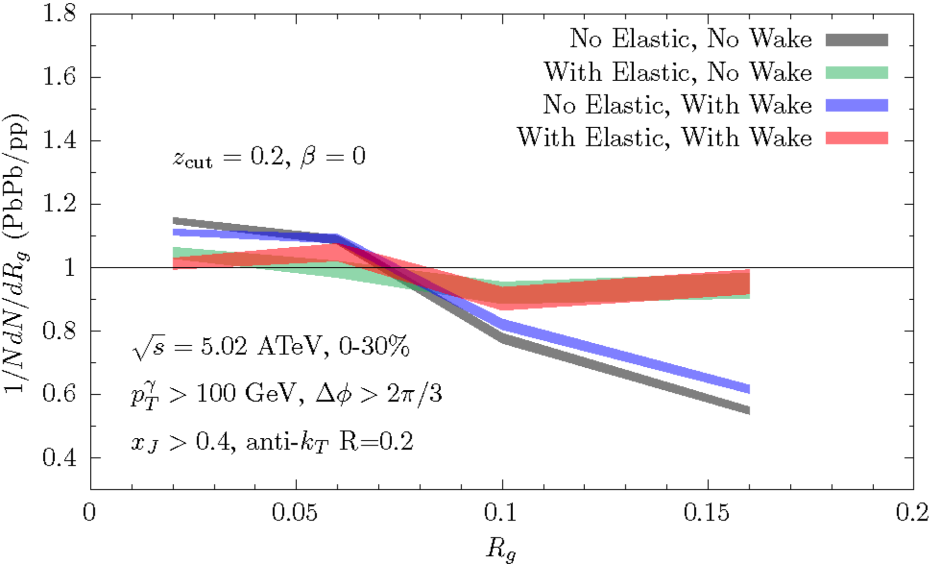


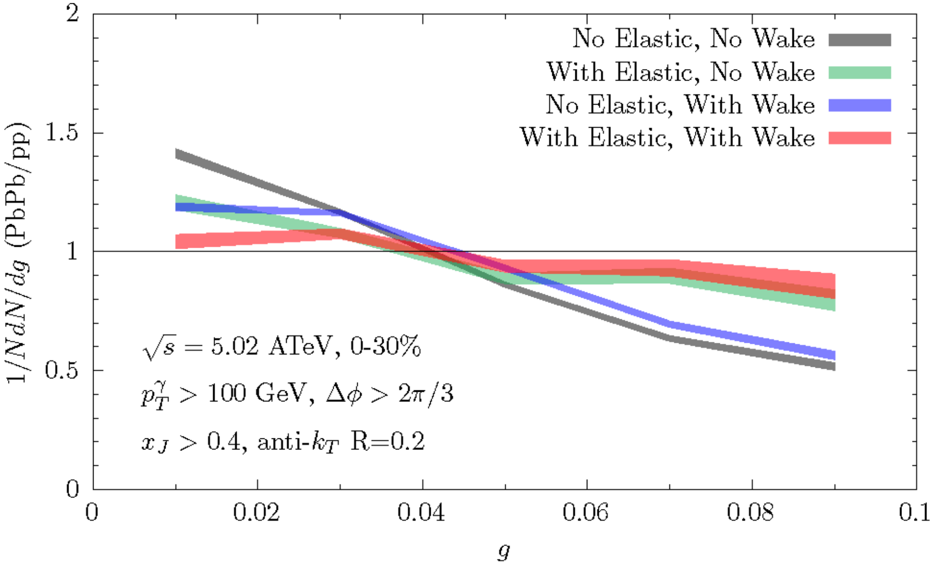


All show much less sensitivity to wake: R=0.2; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere are very much dominant.



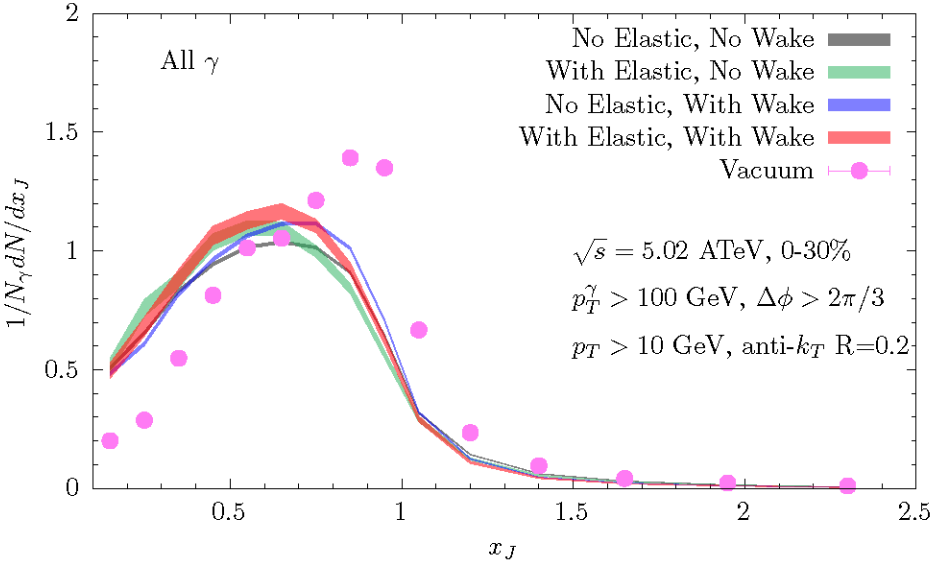
Gamma-Jet Observables: R_g and Girth



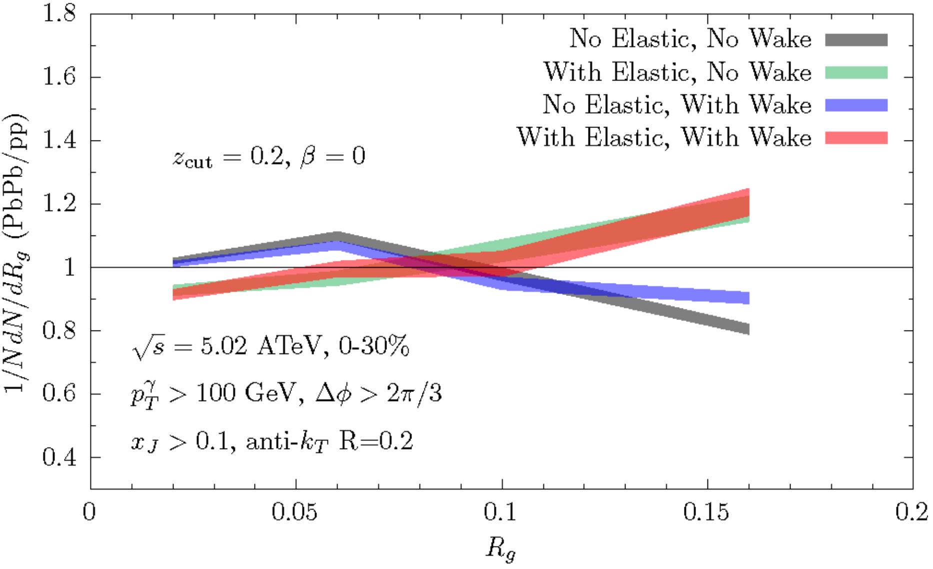


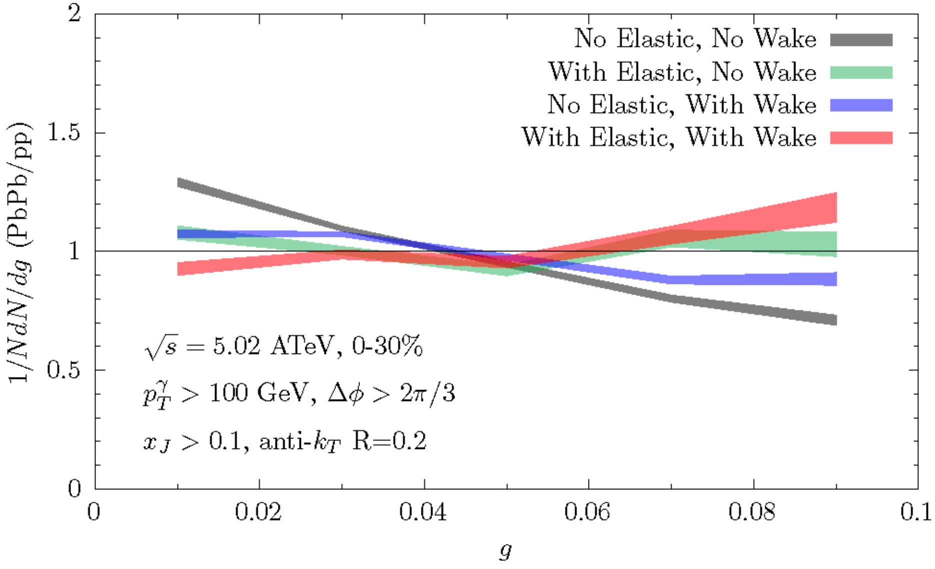
All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

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



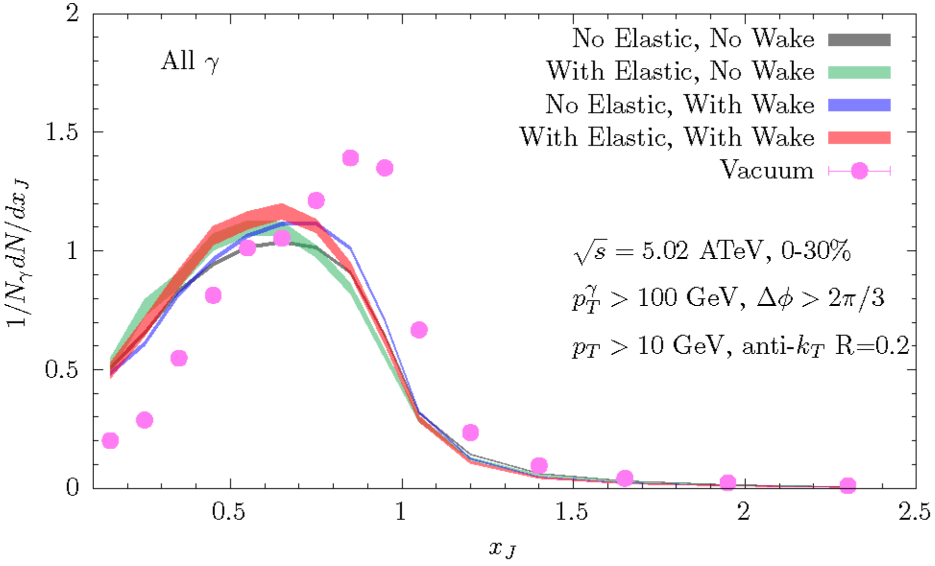
Gamma-Jet Observables: R_g and Girth, with $x_J>0.1$



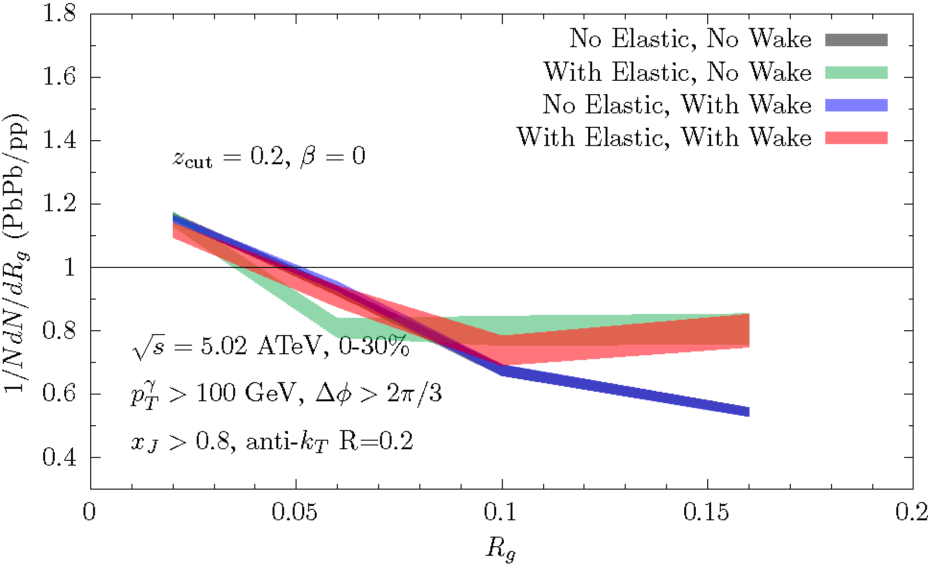


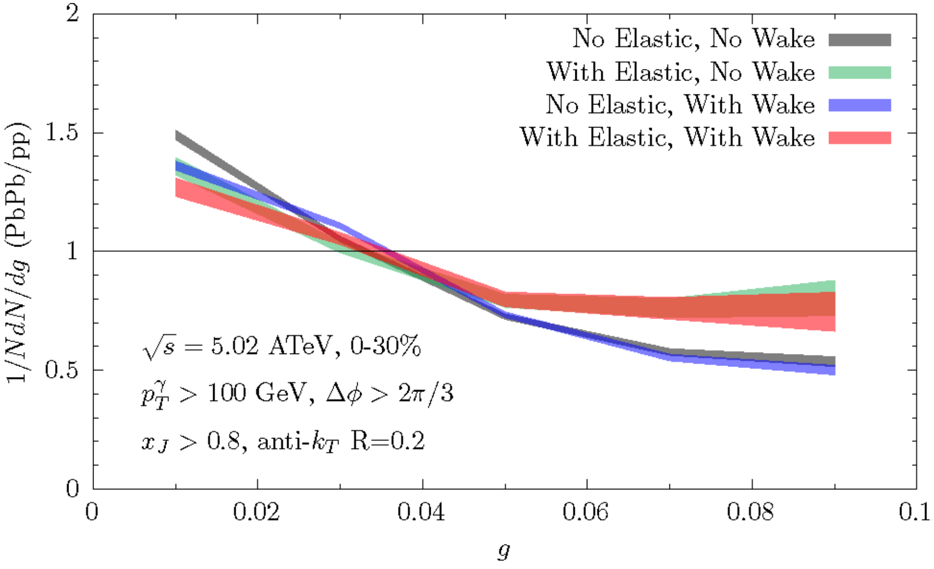
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.1. Moliere scattering important, and causes R_{AA} >1.

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



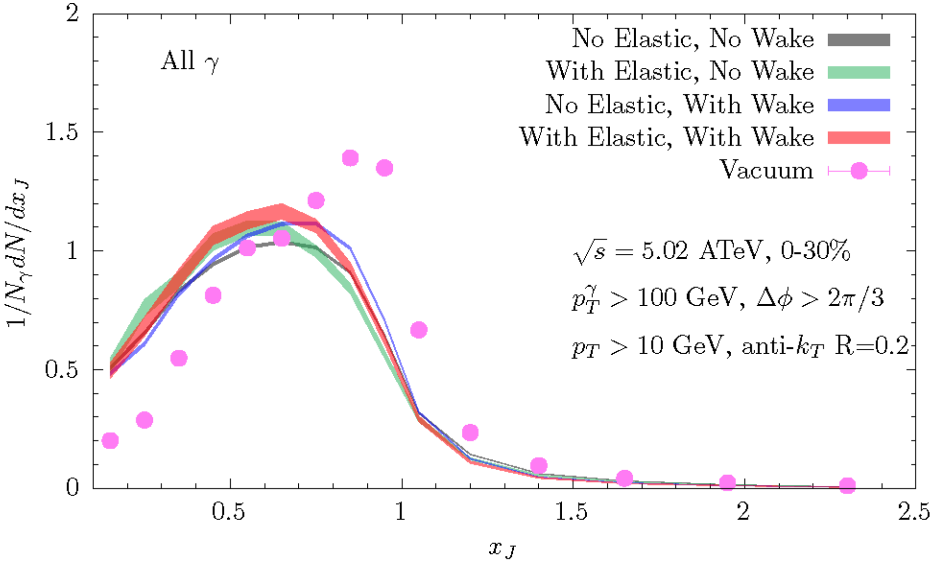
Gamma-Jet Observables: R_g and Girth, with x_J>0.8



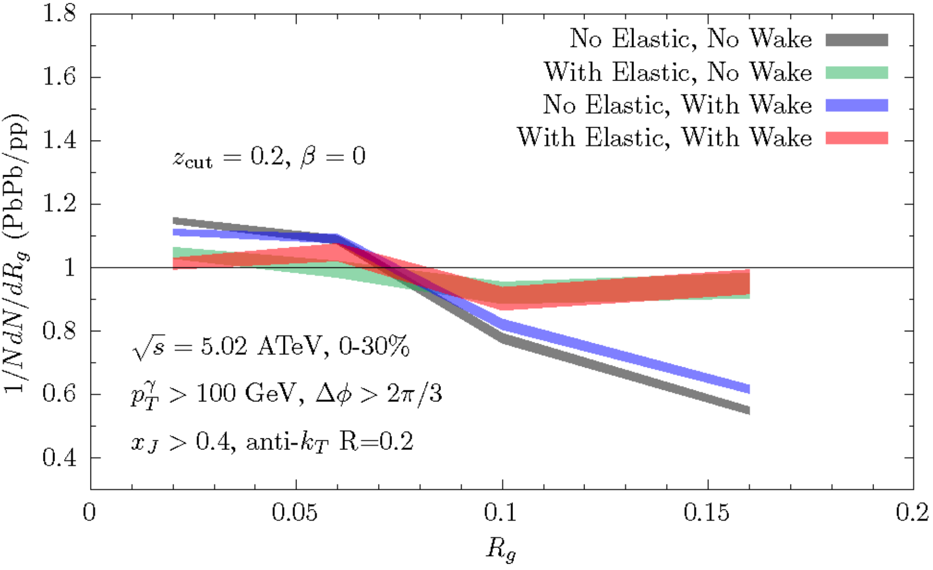


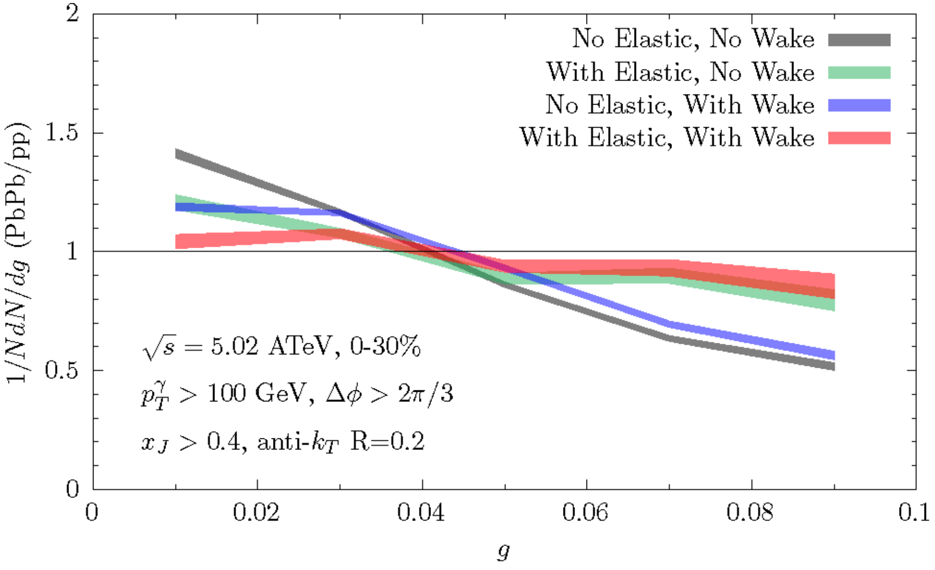
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.8. Selection bias increased.

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





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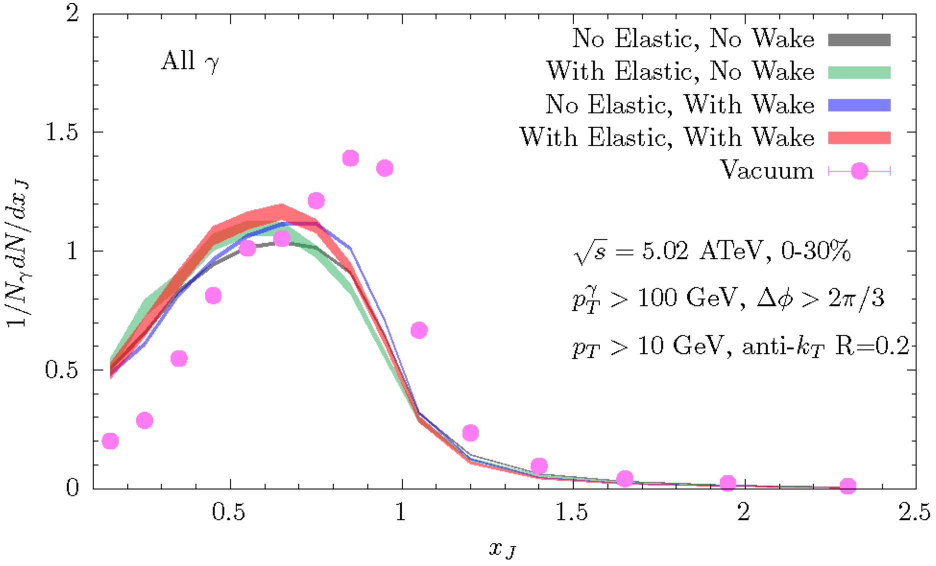
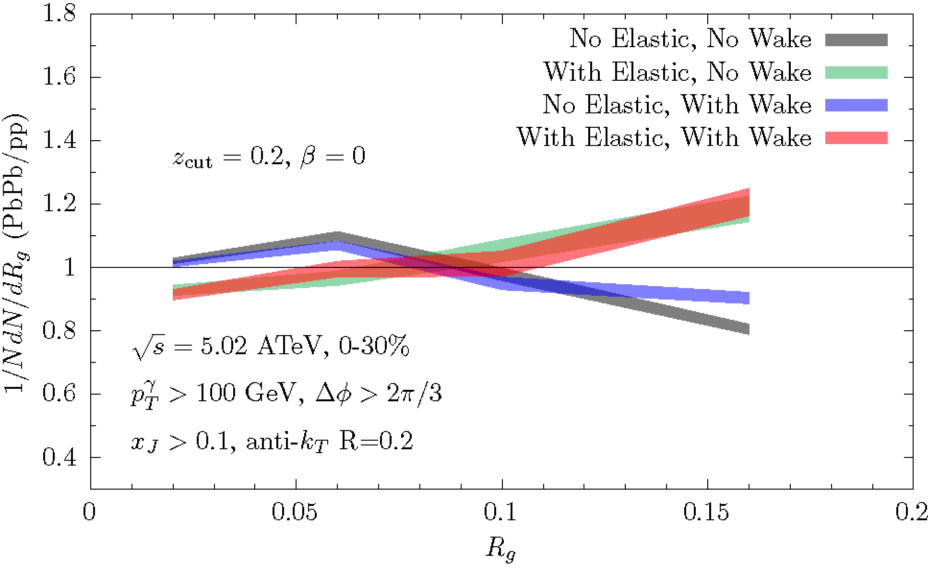
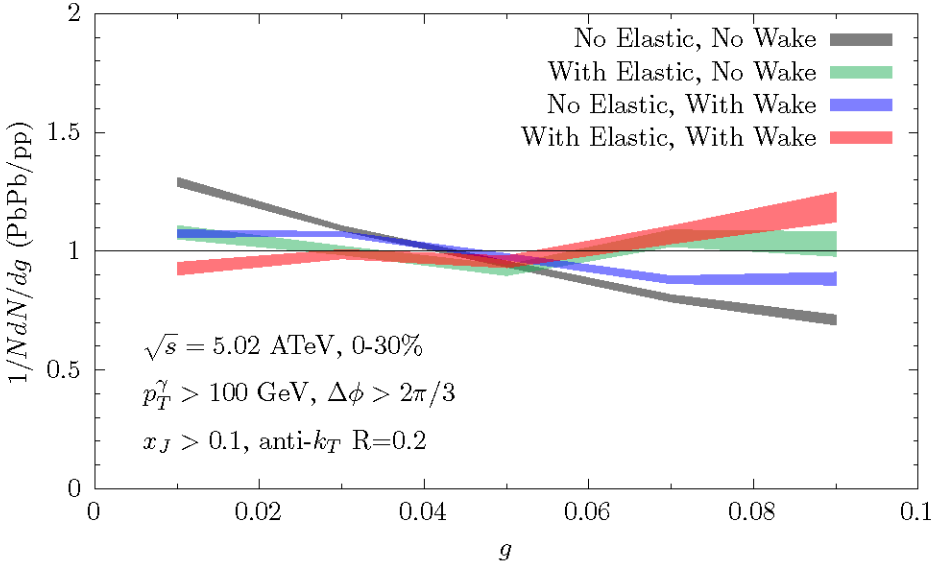


Gamma-Jet Observables: R_g and Girth, with $x_J>0.1$





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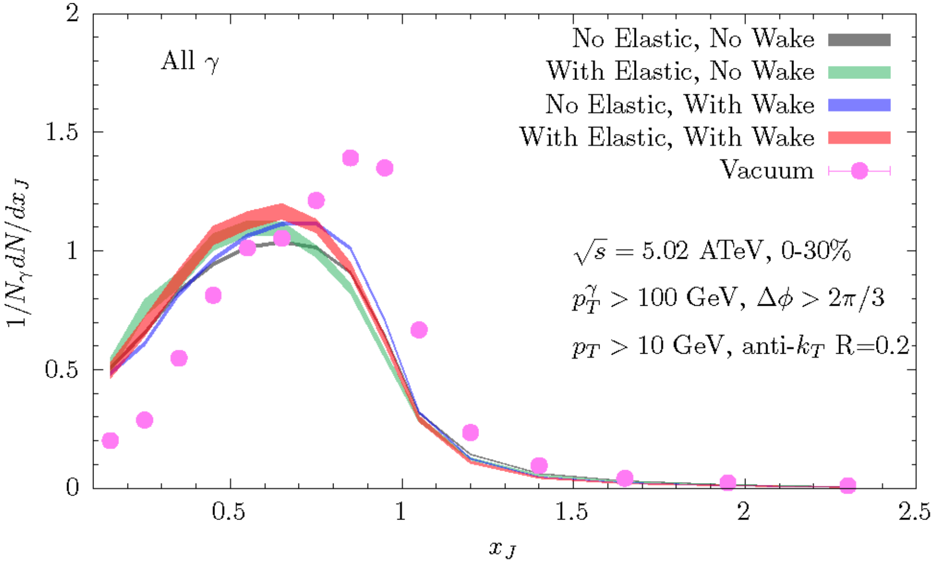


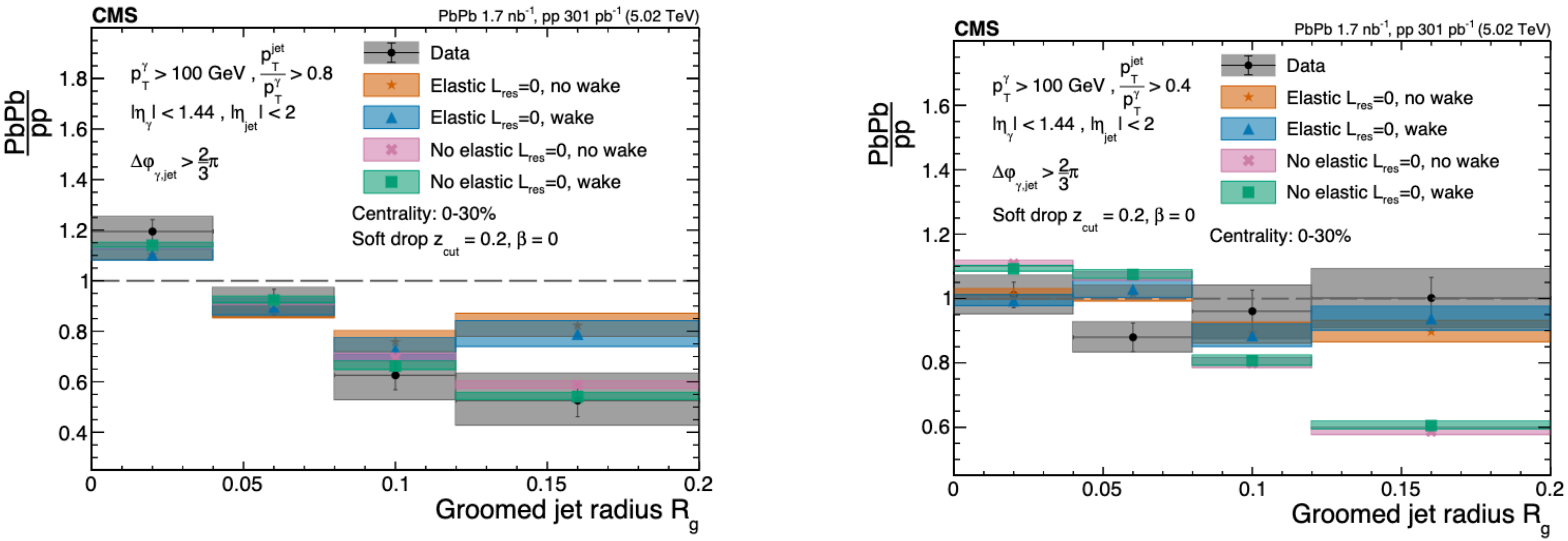
lesson 4: it seems all we see is survivor bias

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

lesson 4: it seems all we see is survivor bias

γ-jet substructure: suppression of the survivor bias

PbPb

less quenched xJ>0.8

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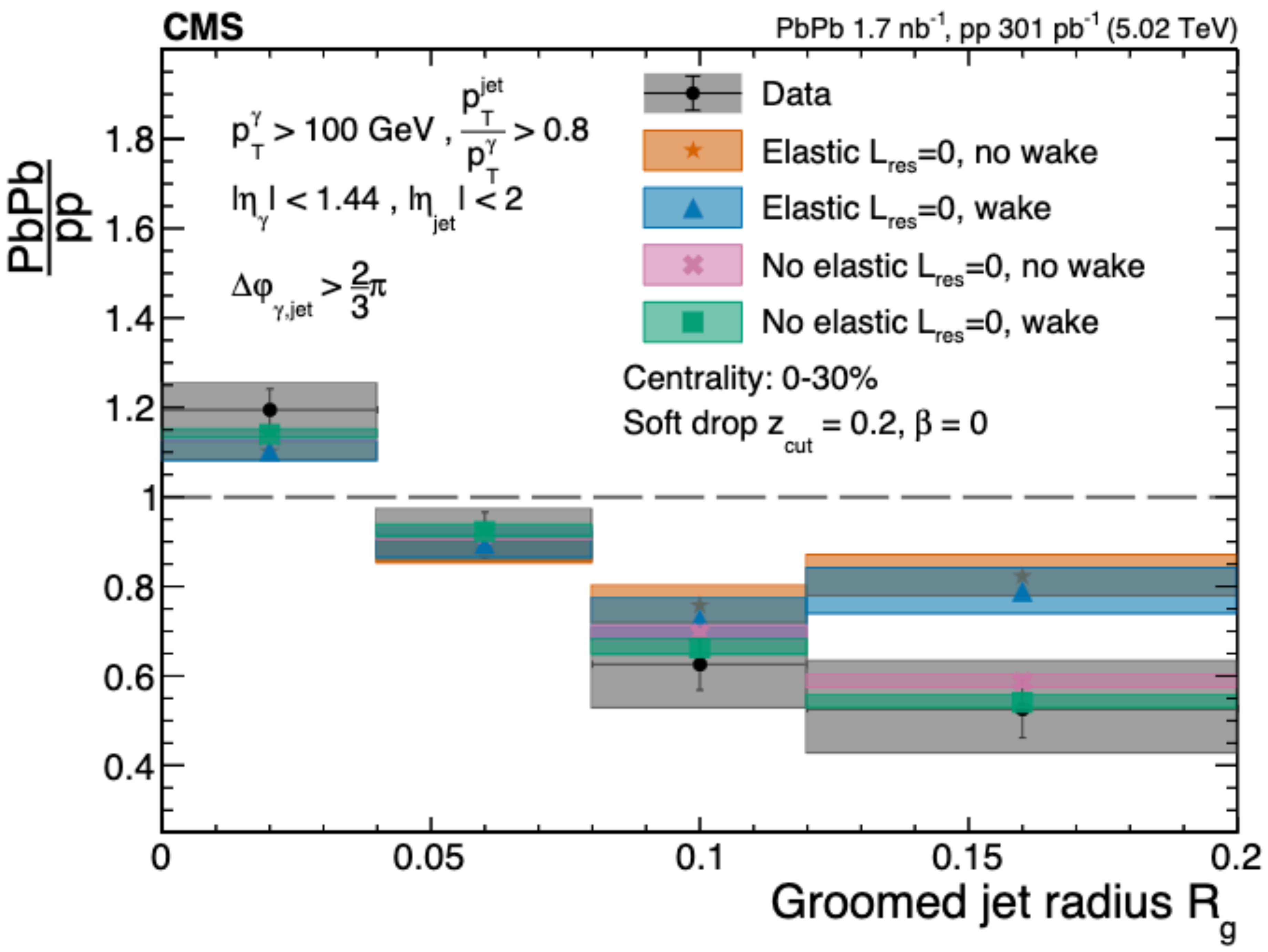
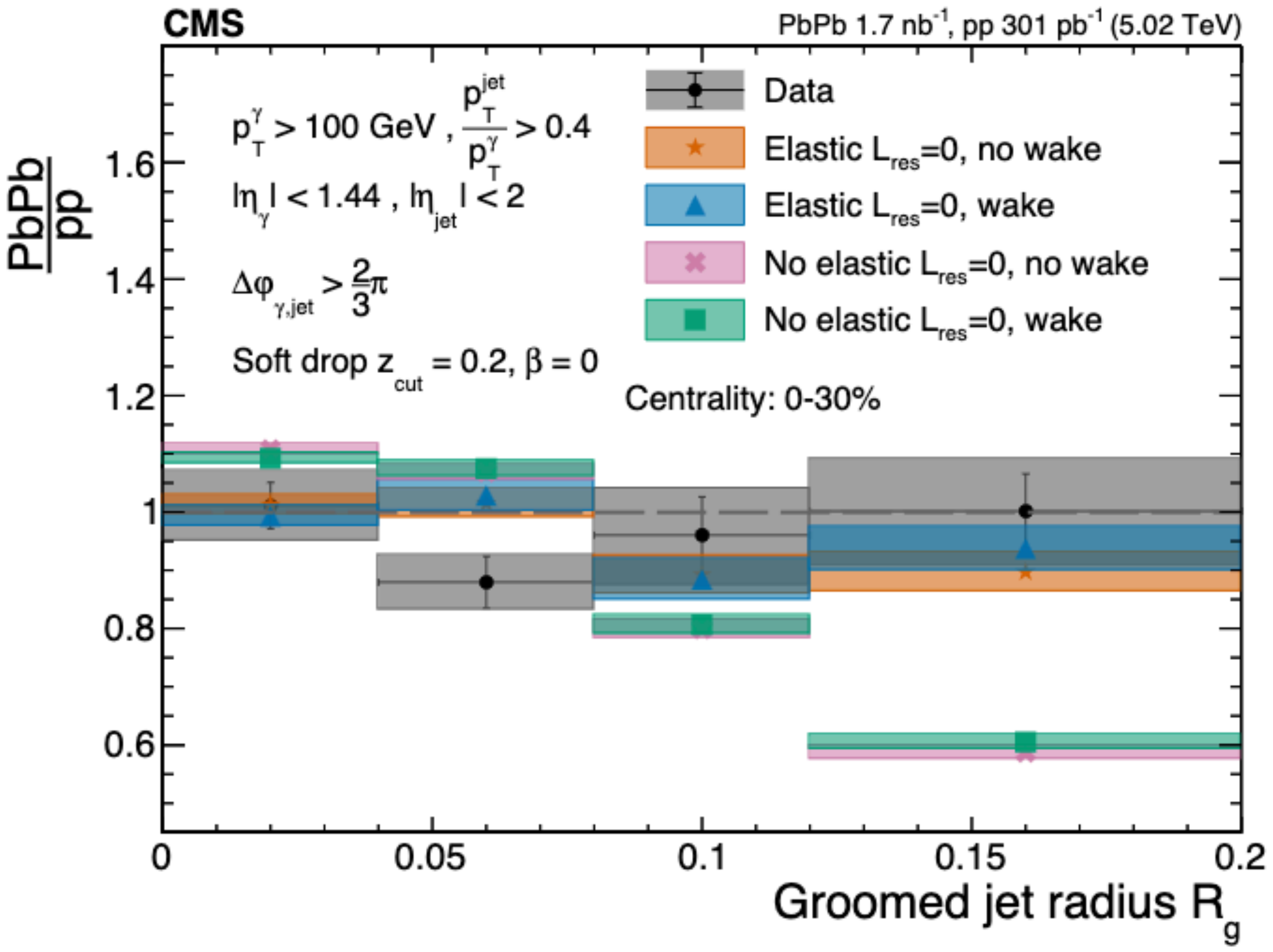




Comparison to the Hybrid model (*Rajagopal et al, JHEP 10 (2014) 019*)

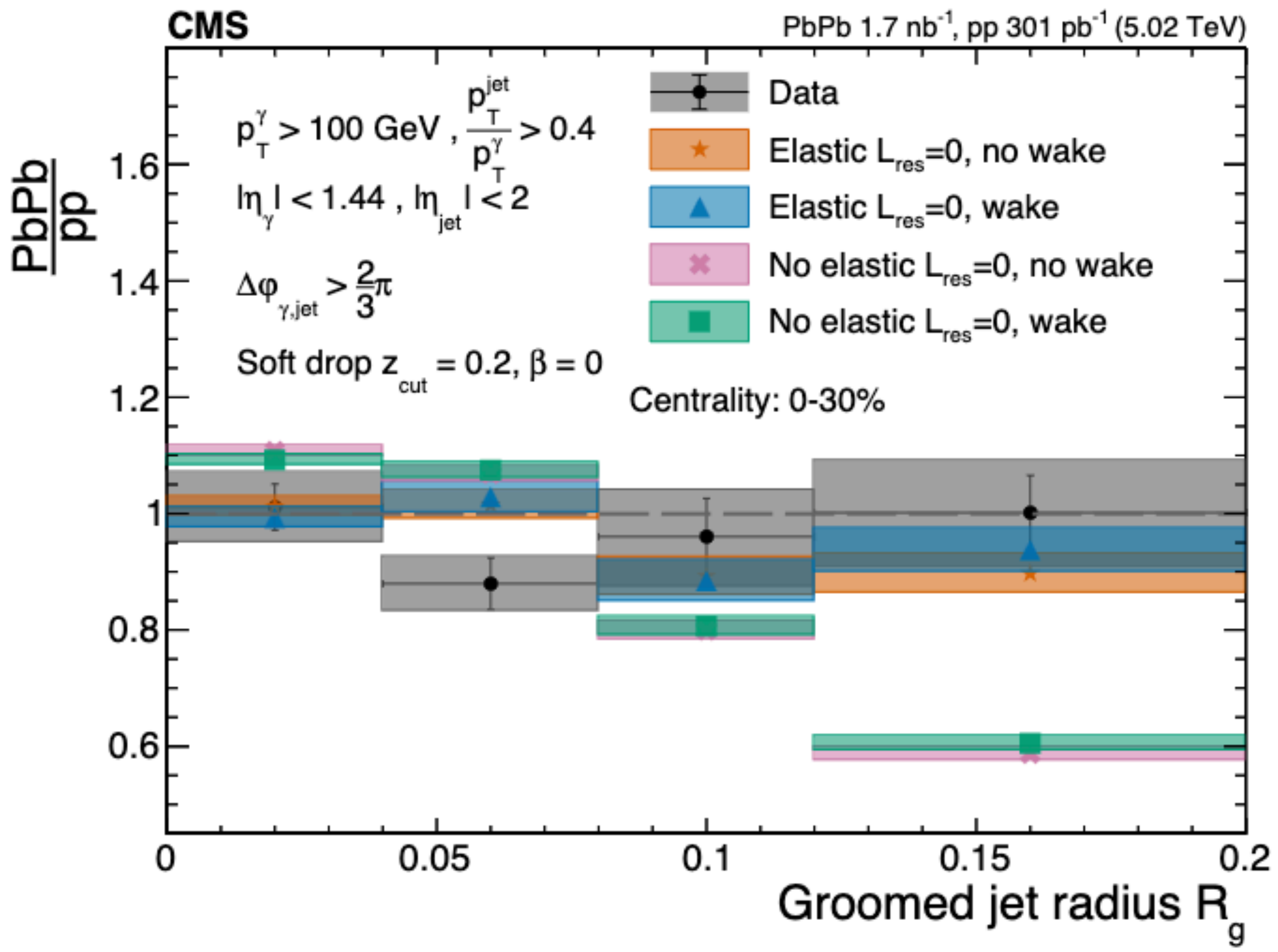
Not a single set of parameters describes the differential data consistently
Great constraining power of the data

small-R suppresses nonperturbative effects like the wake!

CMS-PAS-HIN-23-001

γ-jet substructure, prospects

xJ>0.4



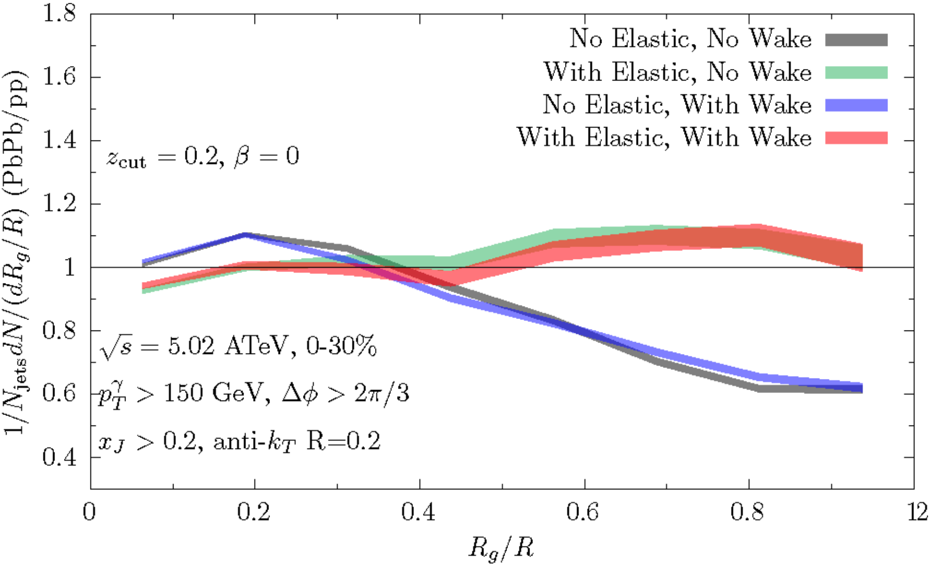
The survivor bias can be fully suppressed when $x_J \rightarrow 0$
(the model has a strong survivor bias down to xJ=0.1)

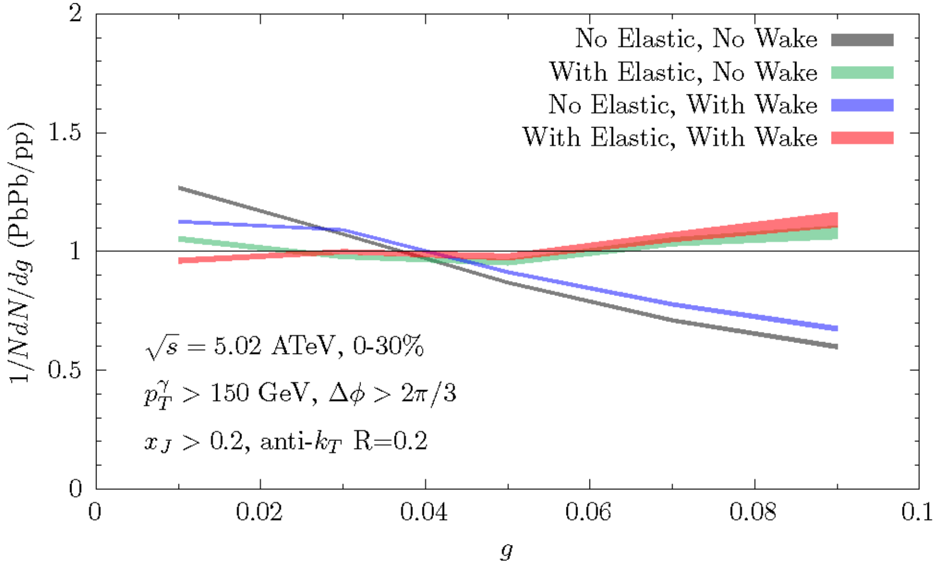
Since low jet p_T is limited by detector effects, such zero bias limit can be achieved by increasing the energy of the photons

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

CMS-PAS-HIN-23-001

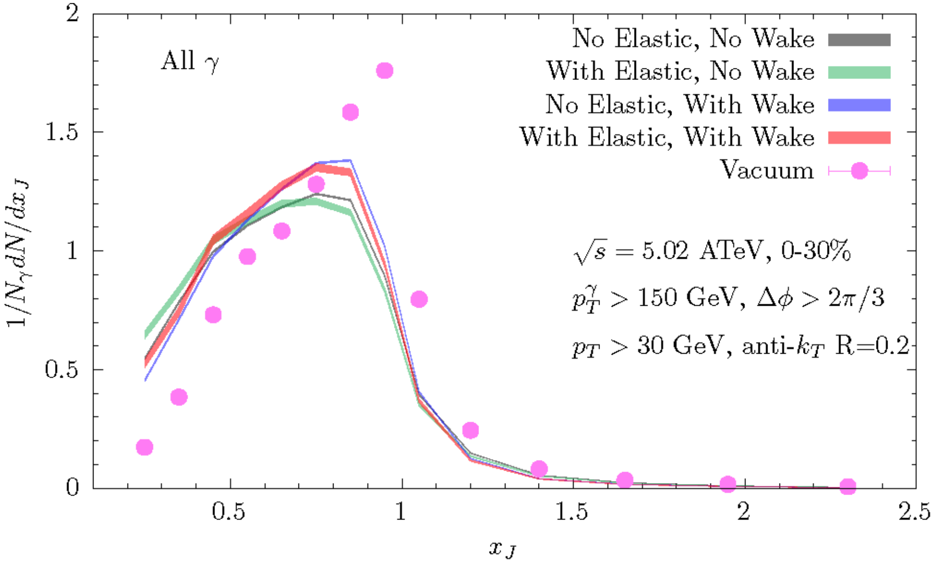
Gamma-Jet Observables with p_T^{γ} >150 GeV: R_g and Girth, with x_J>0.2



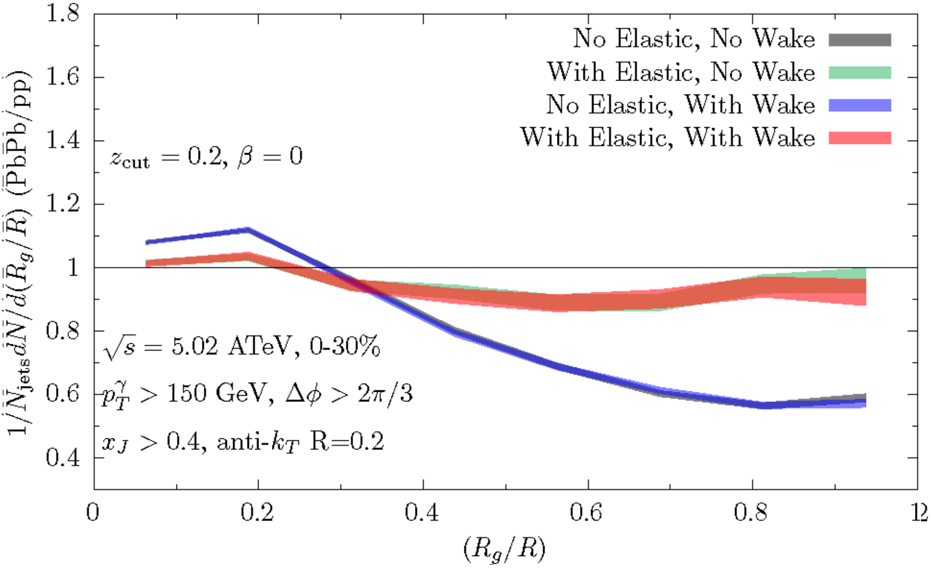


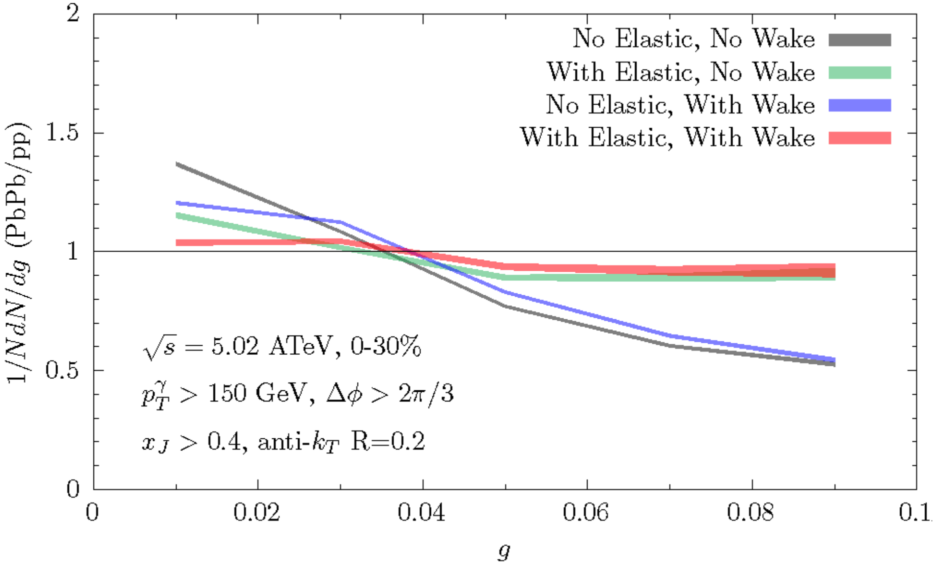
On previous slides, p_T^{γ} >100 GeV; here, p_T^{γ} >150 GeV. Means x_J>0.2 corresponds to p_T^{jet}>30 GeV. And, no need to go down to x_J>0.1.

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



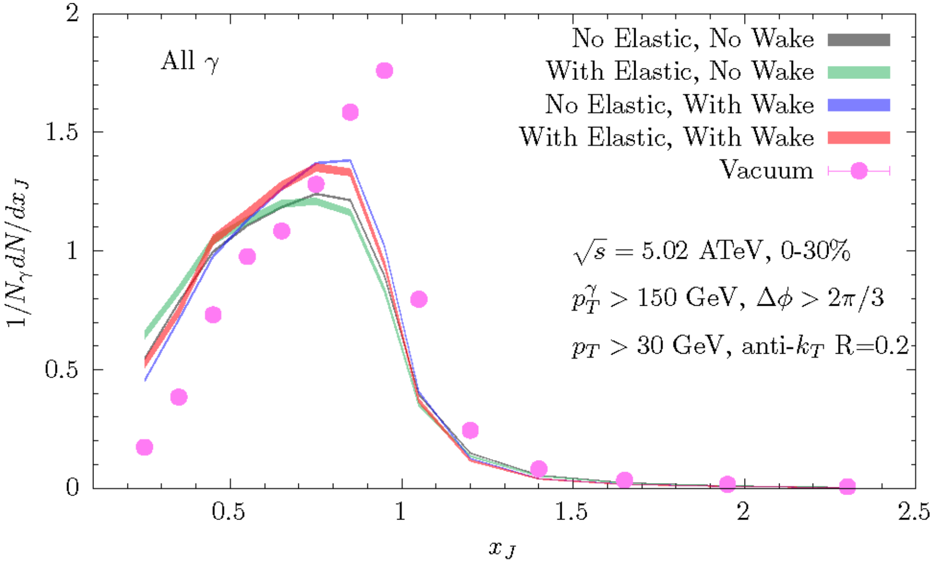
Gamma-Jet Observables with p_T^{γ} >150 GeV: R_g and Girth, with x_J>0.4



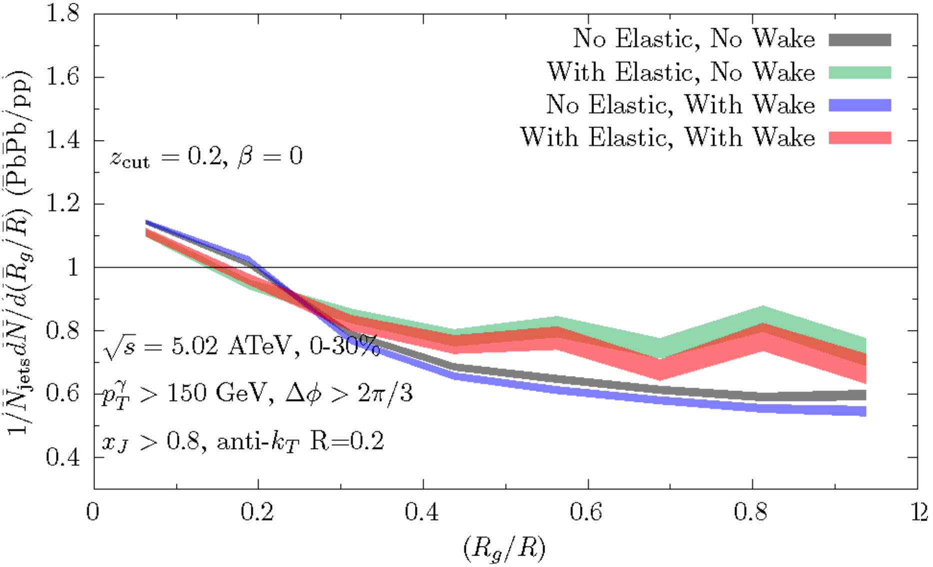


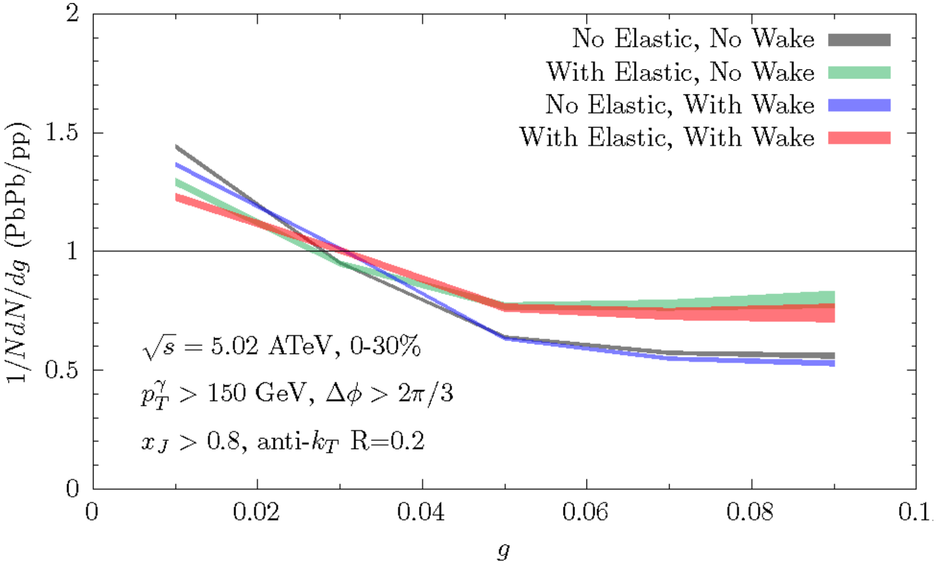
On previous slides, p_T^{γ} >100 GeV; here, p_T^{γ} >150 GeV. Means x_J>0.4 corresponds to p_T^{jet}>60 GeV.

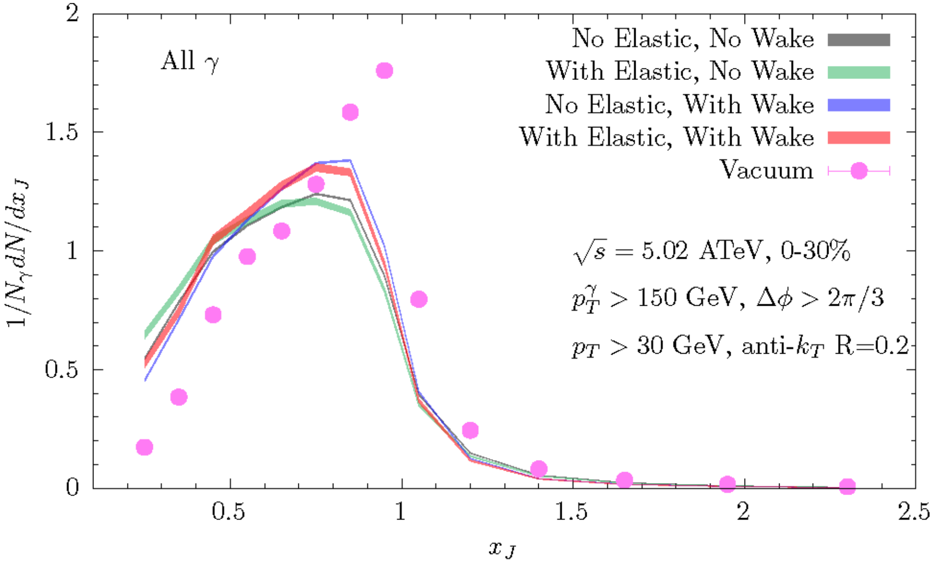
Moliere effects substantial; selection bias significant; wake effects negligible.



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



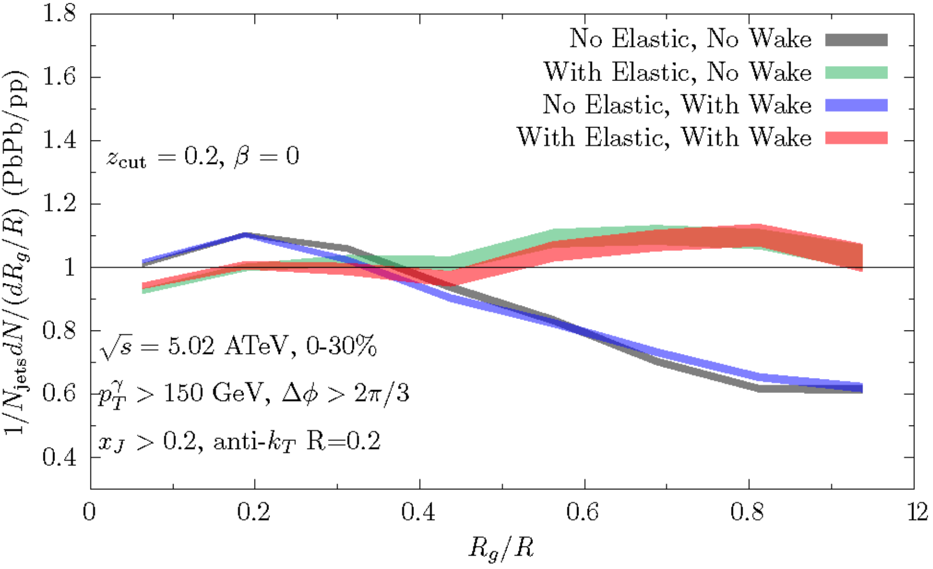


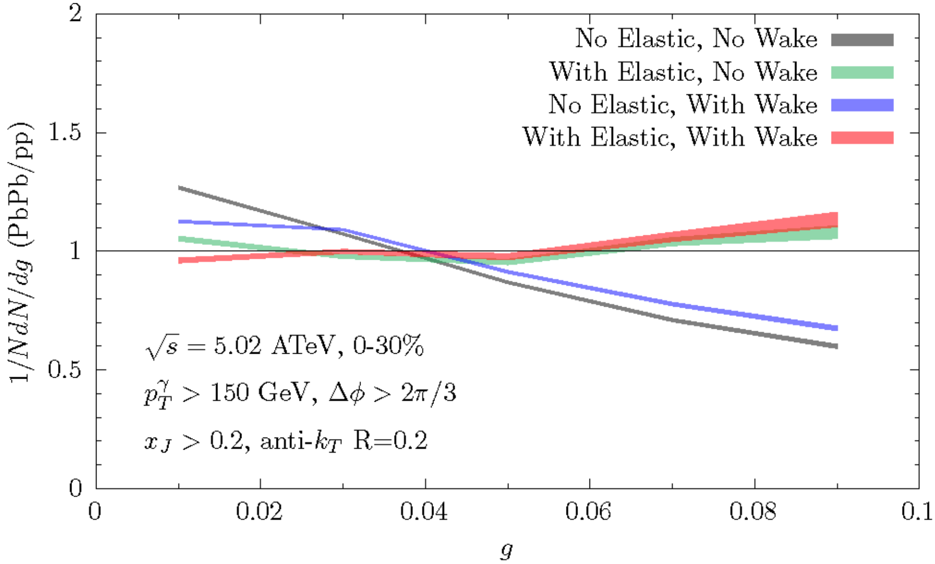


On previous slides, p_T^γ >100 GeV; here, p_T^γ >150 GeV.
Means x_J>0.8 corresponds to p_T^{jet}>120 GeV.

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

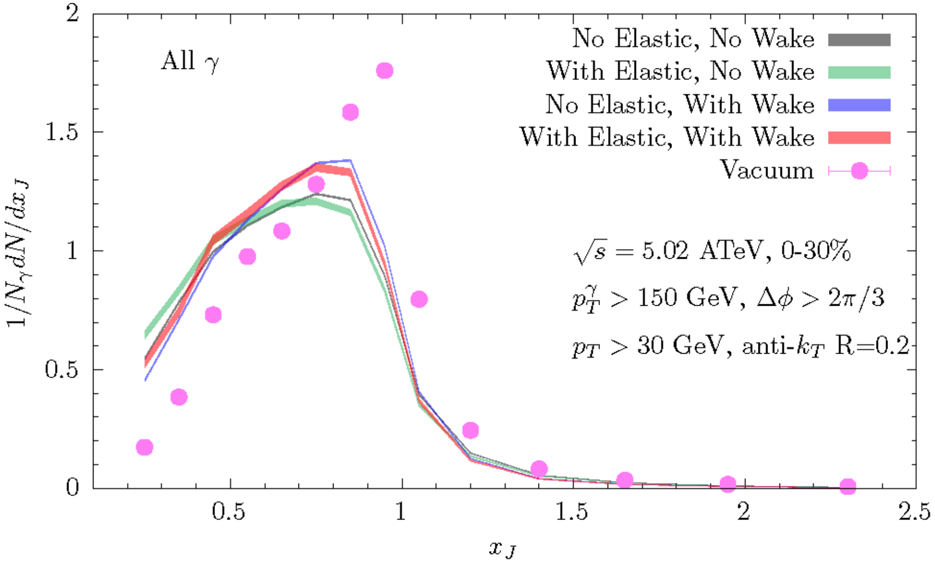
Gamma-Jet Observables with p_T^γ >150 GeV: R_g and Girth, with x_J>0.2



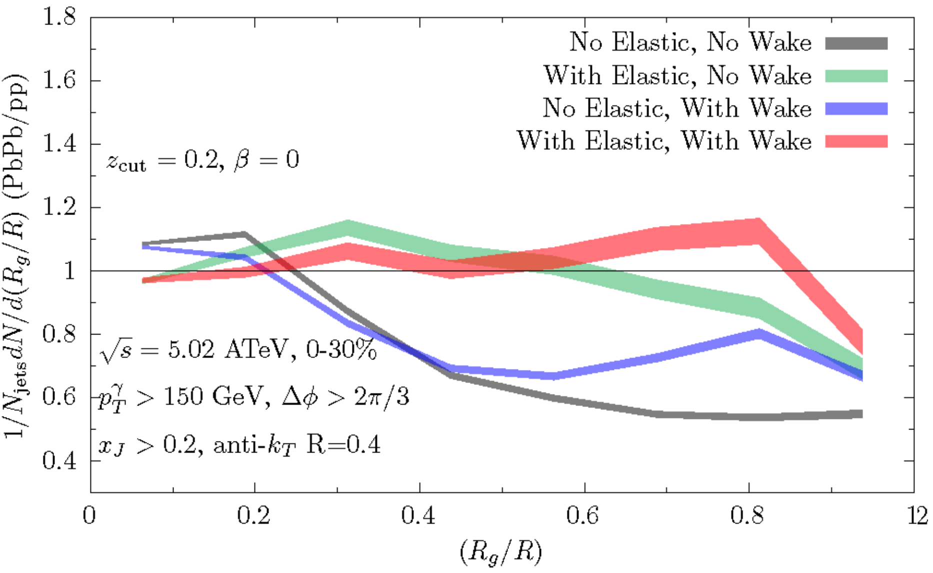


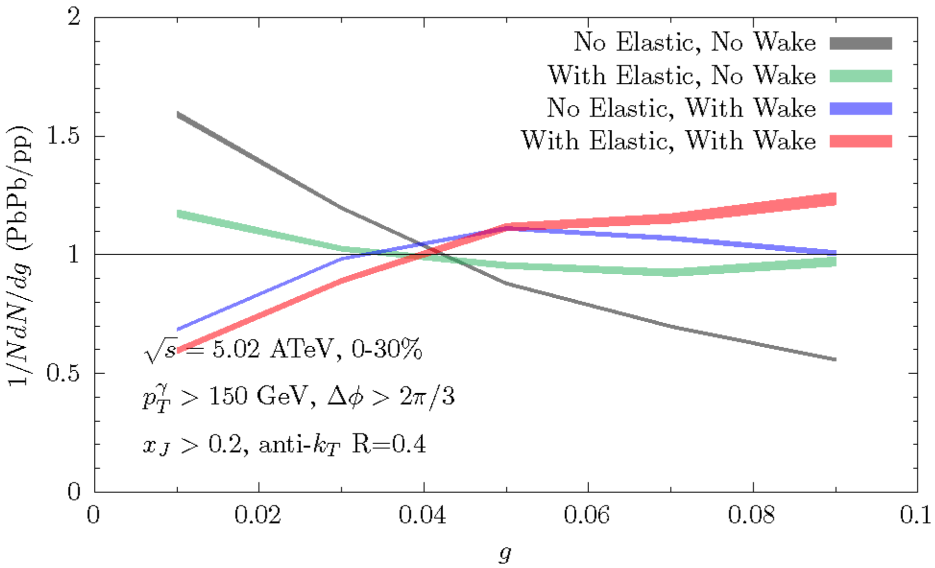
On previous slides, p_T^γ >100 GeV; here, p_T^γ >150 GeV.
Means x_J>0.2 corresponds to p_T^{jet}>30 GeV. And, no need to go down to x_J>0.1.

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



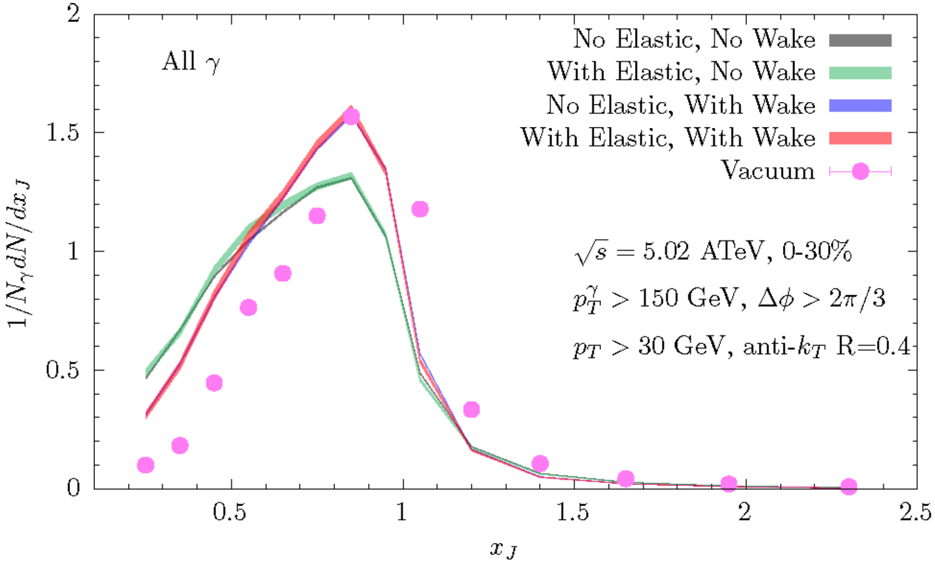
Gamma-Jet Observables with $p_T^{\gamma} > 150$ GeV and R=0.4: R_g and Girth, with $x_J > 0.2$



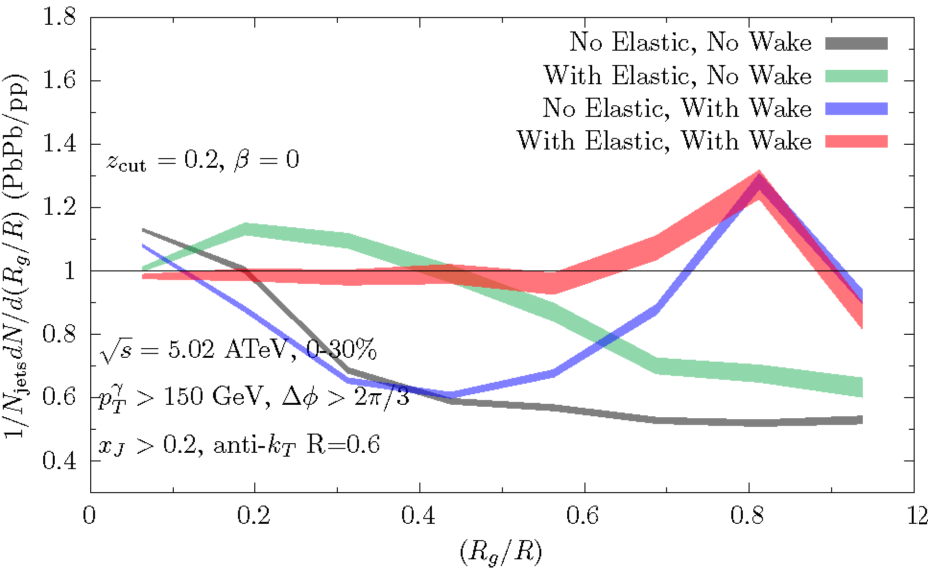


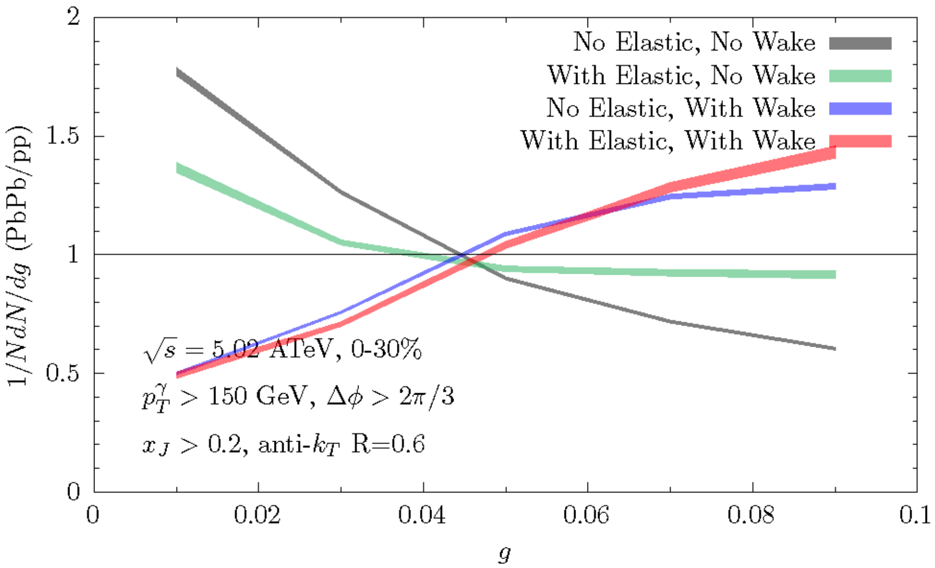
On previous slides, $p_T^{\gamma} > 150$ GeV with R=0.2. Here, R=0.4, so that we can “catch” more wake, with little selection bias.

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



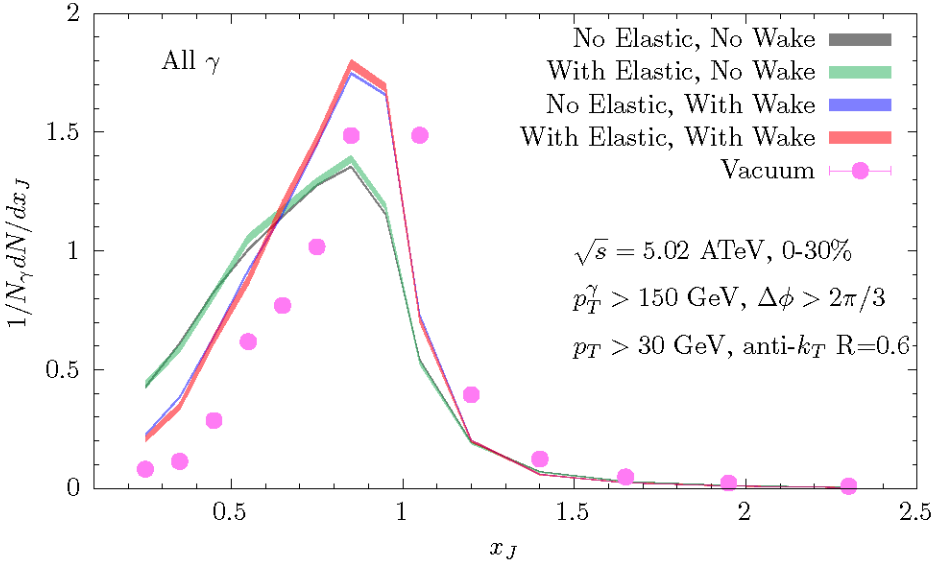
Gamma-Jet Observables with p_T^γ >150 GeV and R=0.6: R_g and Girth, with x_J>0.2



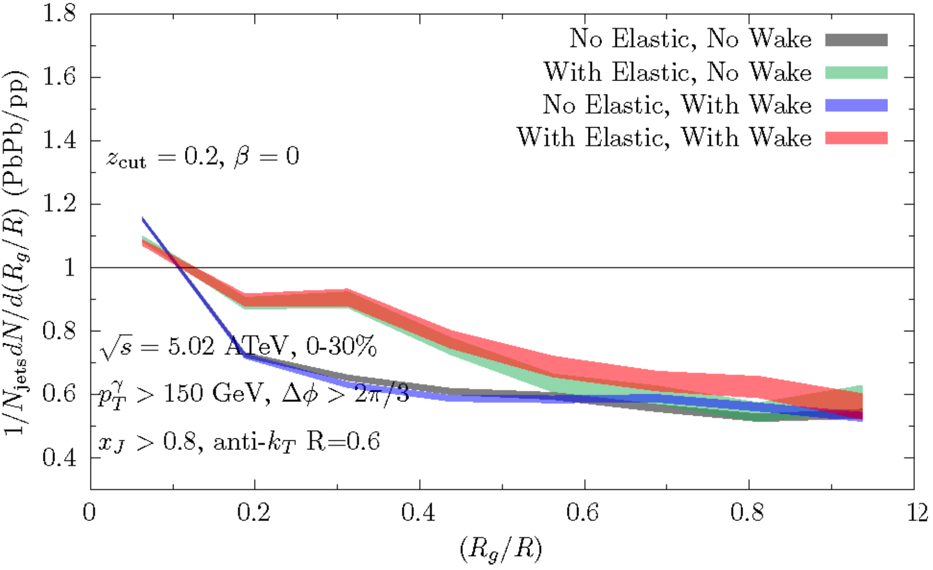


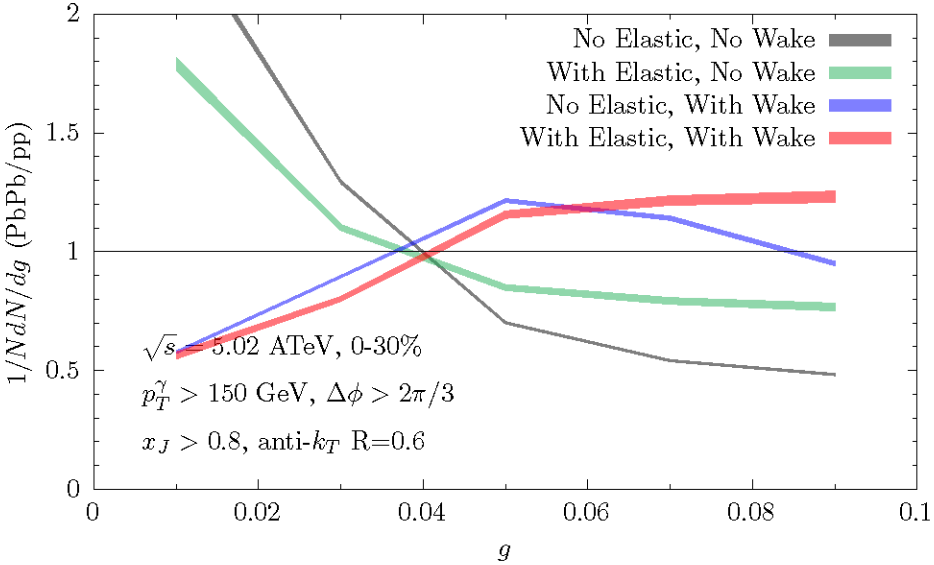
On previous slides, p_T^γ >150 GeV with R=0.2. Here, R=0.6, so that we can “catch” *even more* wake, with little selection bias.

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



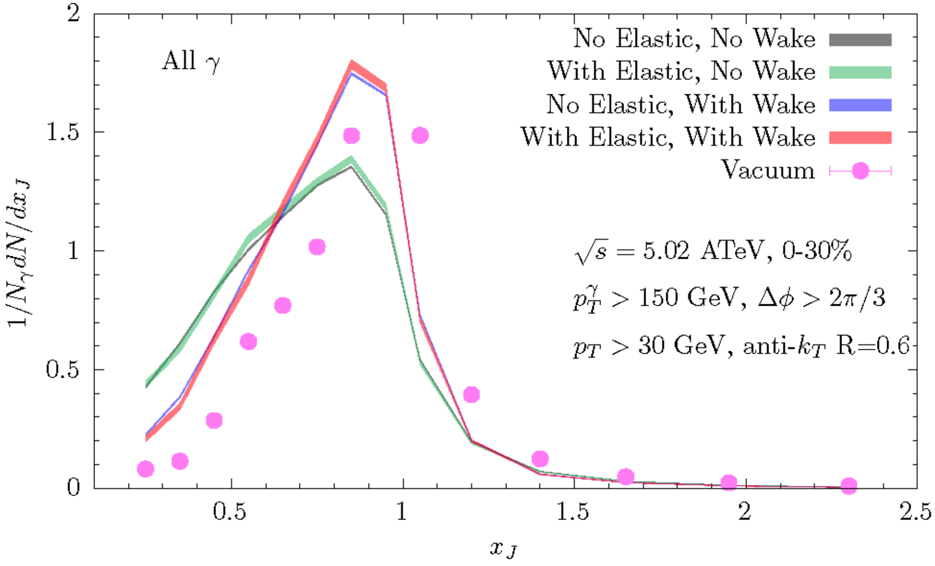
Gamma-Jet Observables with p_T^γ >150 GeV and R=0.6: R_g and Girth, with x_J>0.8





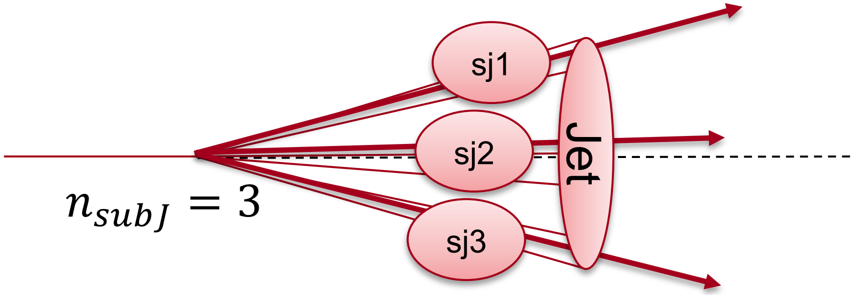
On previous slides, p_T^γ >150 GeV with R=0.2. Here, R=0.6. But, we've turned the selection bias back ON.

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

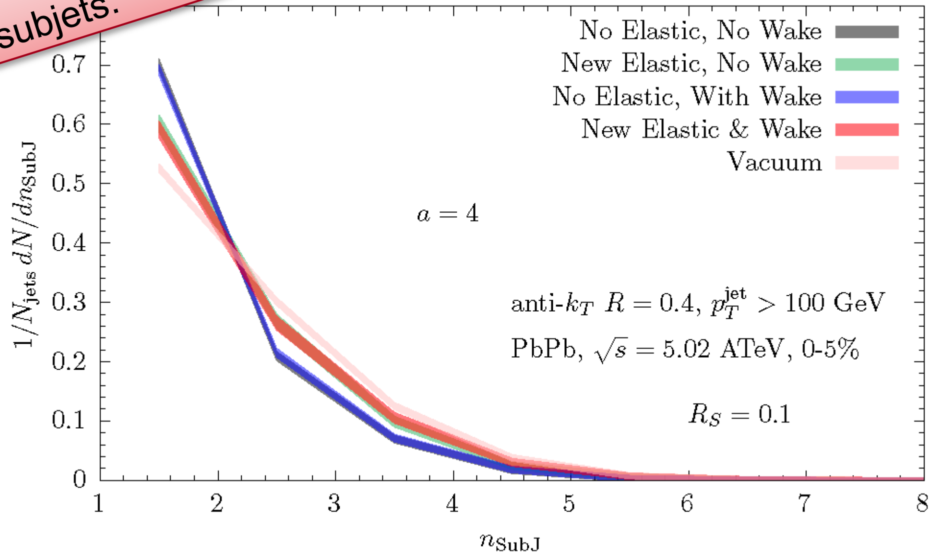


Inclusive Jets within Inclusive Jets: Inclusive Subjets

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



Increase in number of subjets.



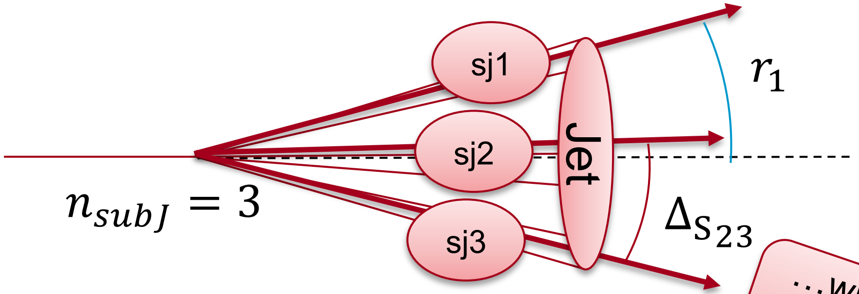
Moliere scattering visible as increase in number of subjets; no such effect coming from wake at all.

Moliere scattering also yields more separated subjets…

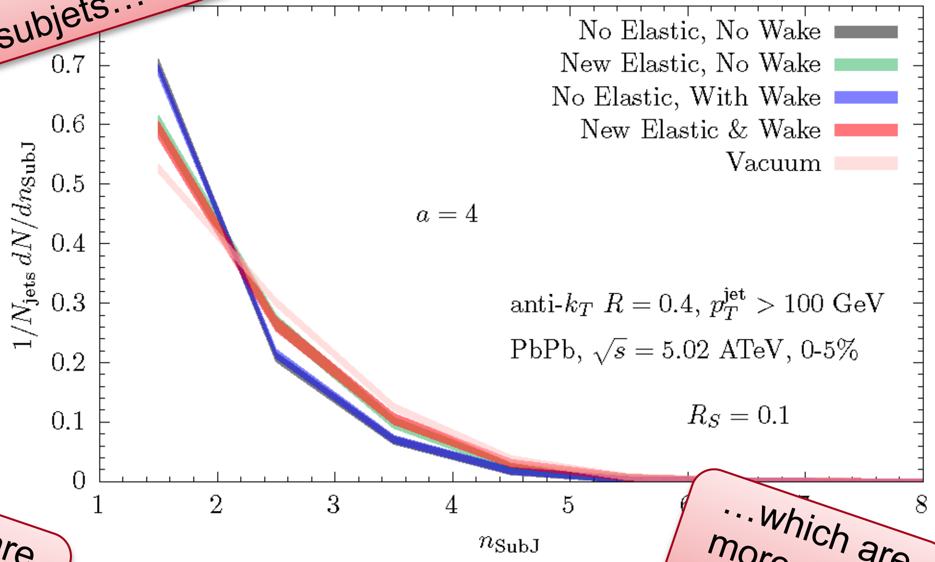
These observables are directly sensitive to "sprouting a new subjet" the intrinsic feature of Moliere scattering which makes it NOT just a bit more wake.

Inclusive Subjets

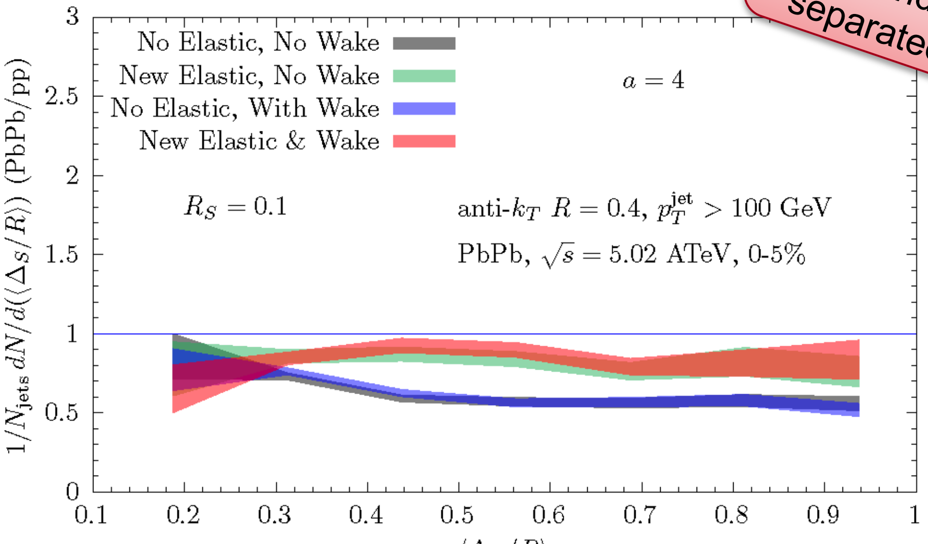
1. Reconstruct jet with R=0.4
2. Recluster each jet's particle content into subjets with R=0.1



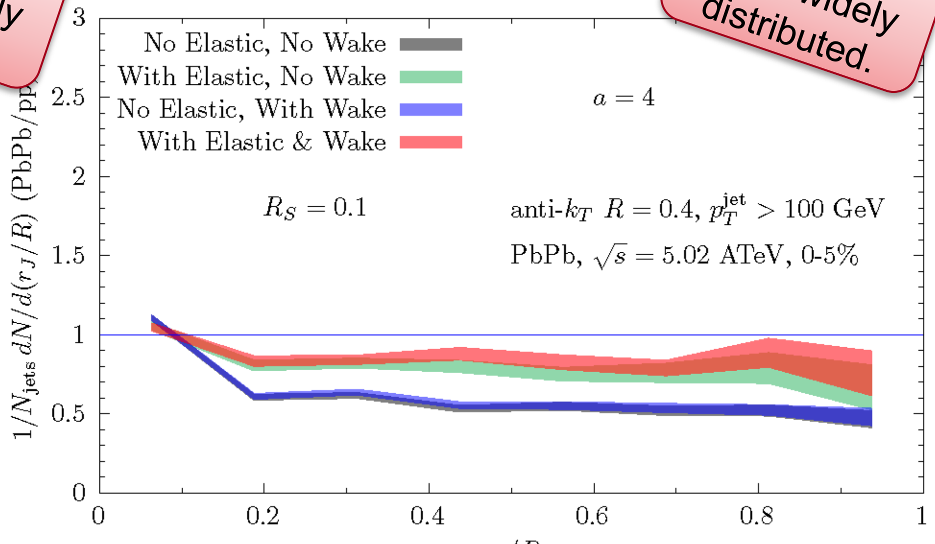
Increase in number of subjets…



…which are more widely separated.

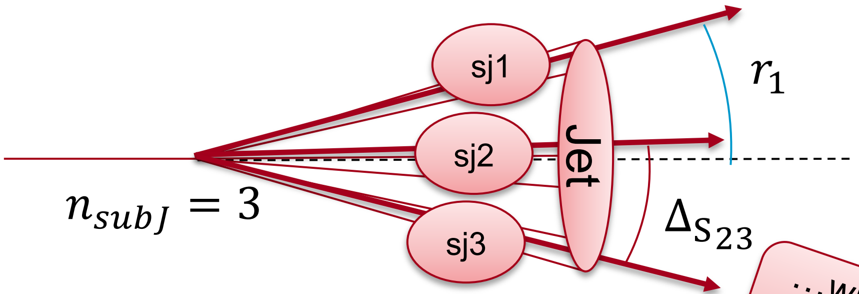


…which are more widely distributed.

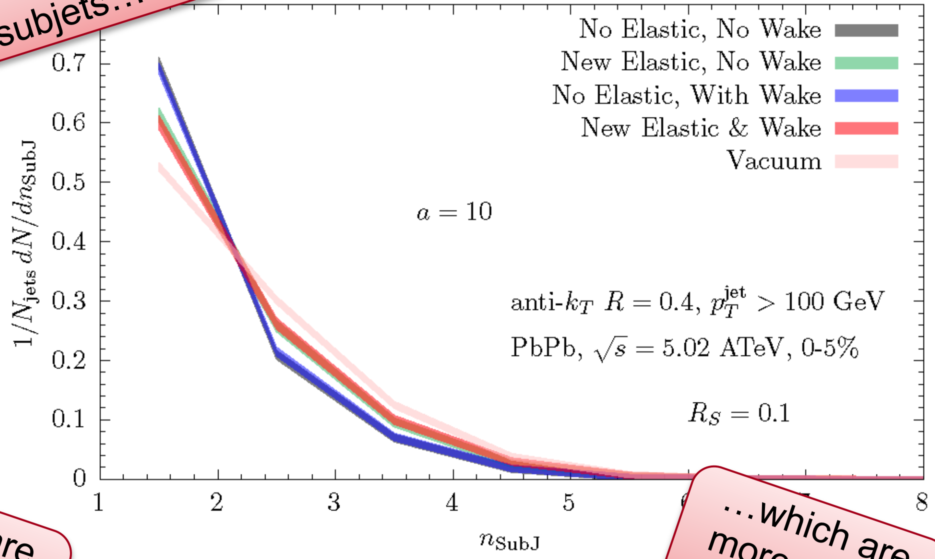


Inclusive Subjets

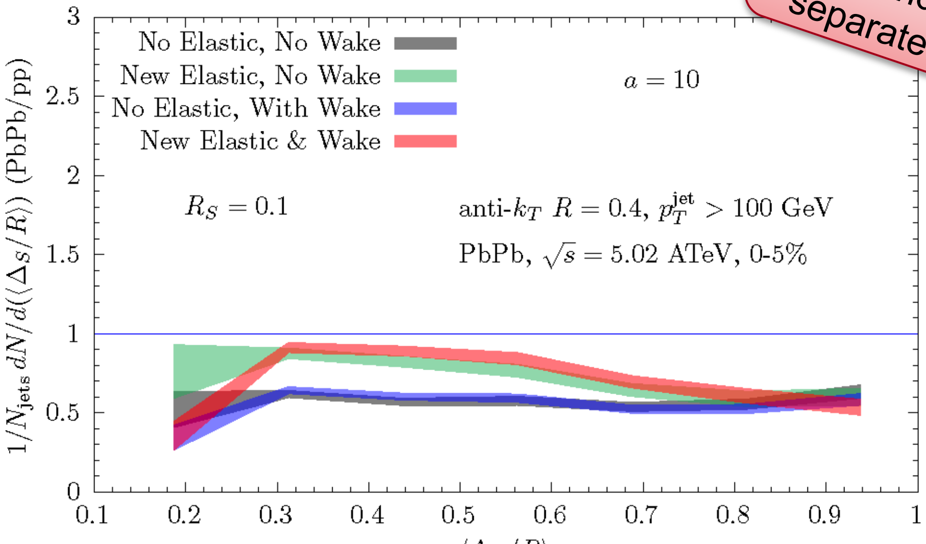
1. Reconstruct jet with R=0.4
2. Recluster each jet's particle content into subjets with R=0.1



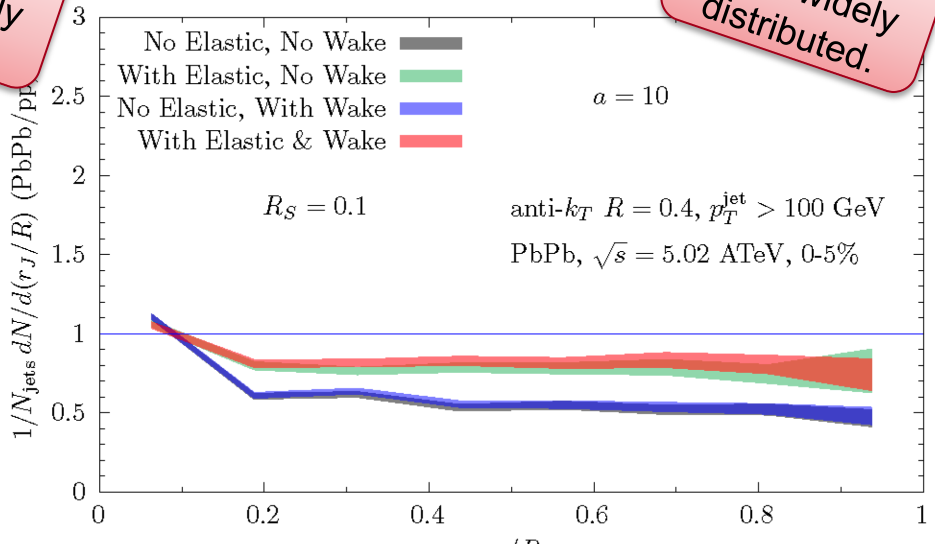
Increase in number of subjets…



…which are more widely separated.



…which are more widely distributed.



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.

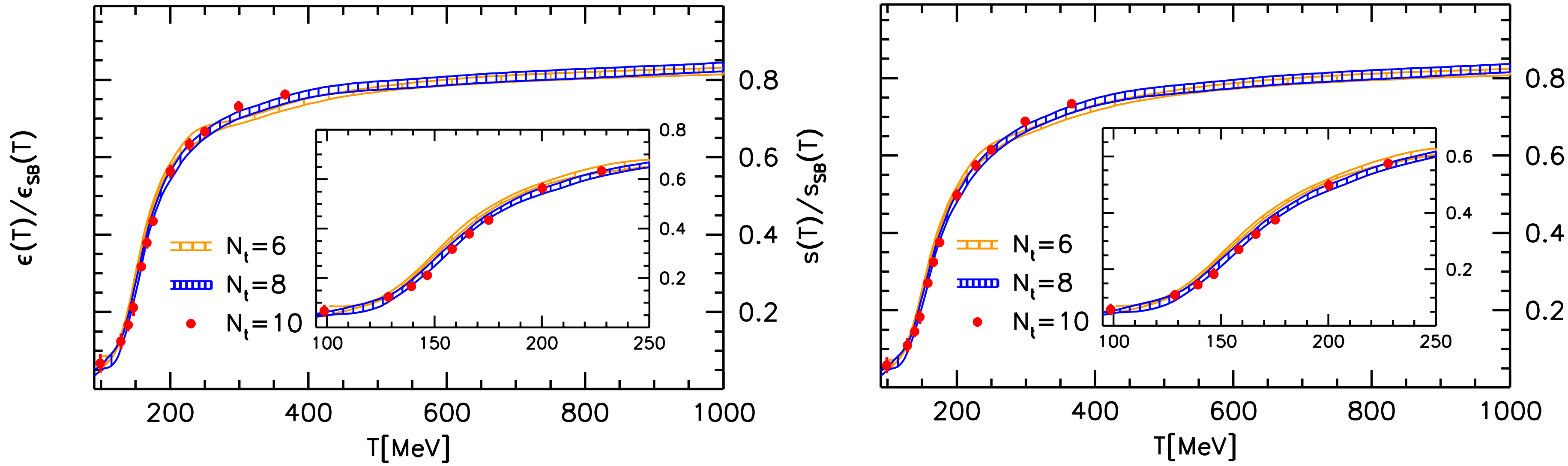
What Next?

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

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

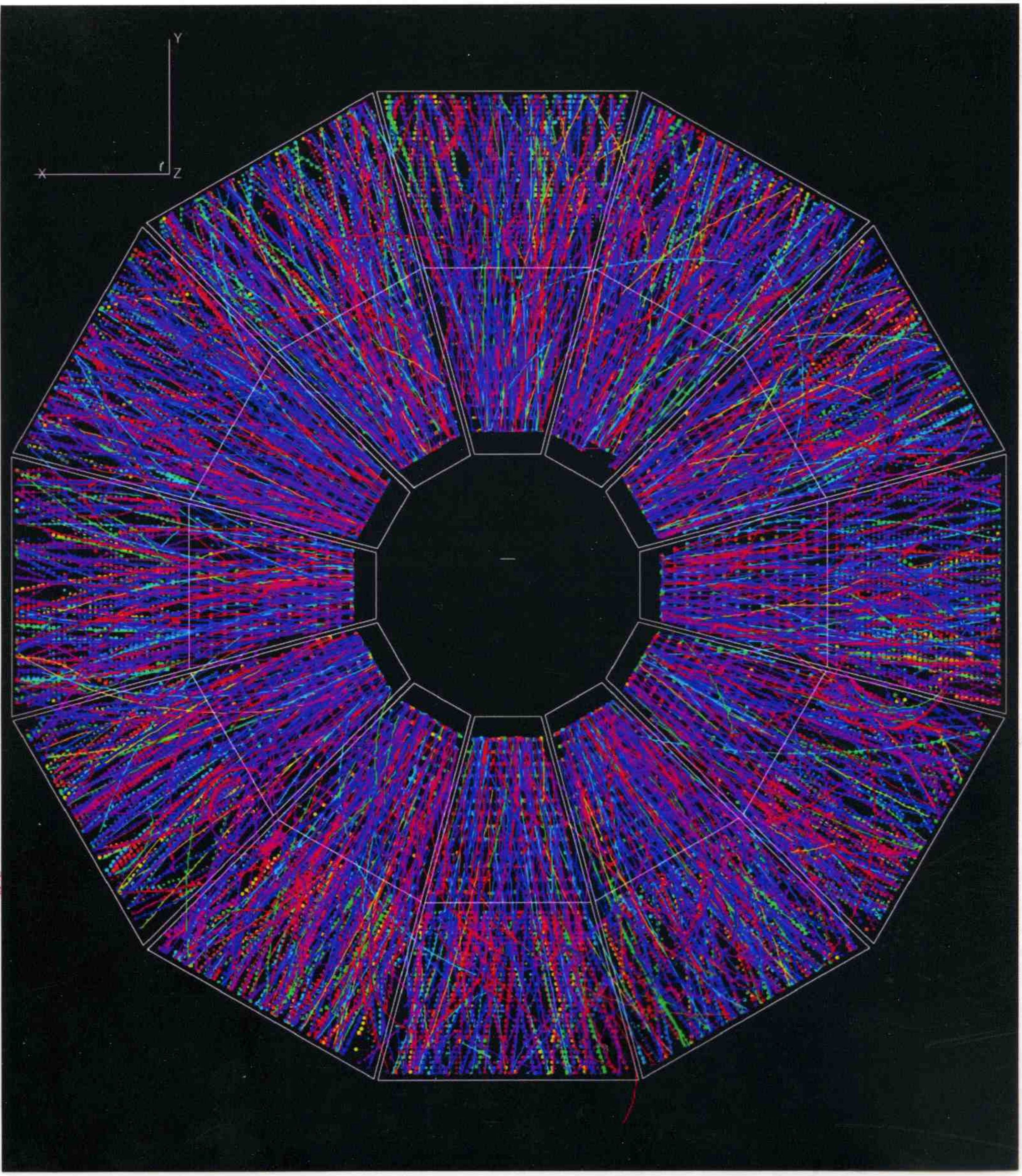
QGP Thermodynamics on the Lattice

Endrodi et al, 2010



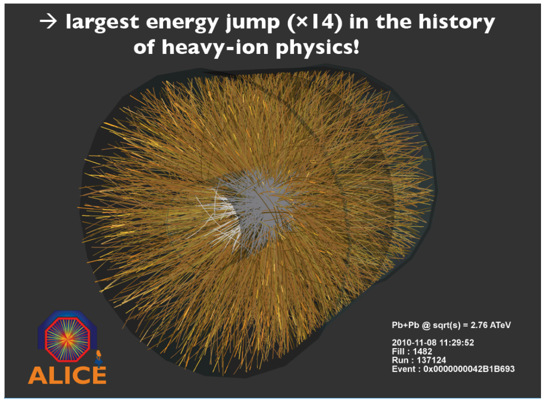
Above $T_{\text{crossover}} \sim$ 150-200 MeV, QCD = QGP. QGP static properties can be studied on the lattice.

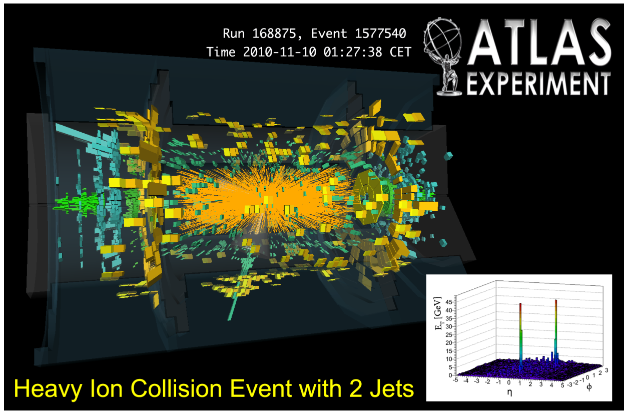
BUT: don't try to infer dynamic properties from static ones! Although its thermodynamics is almost that of ideal, noninteracting gas, QGP, this stuff is very different in its dynamical properties. [Lesson from experiment+hydrodynamics. But, also from the large class of gauge theories with holographic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



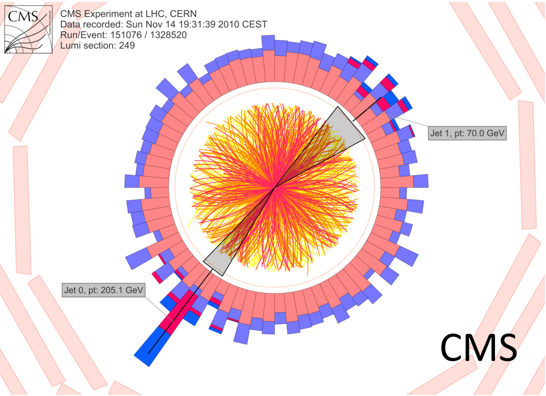
STAR

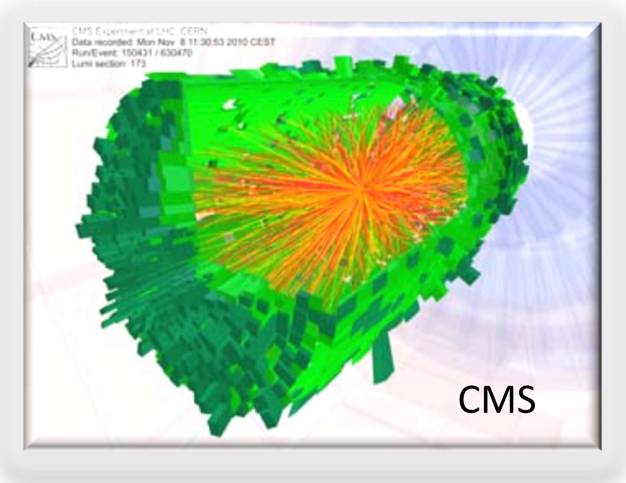
Nov 2010 first LHC Pb+Pb collisions





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





Integrated
Luminosity = $10\ \mu b^{-1}$

Rapid Equilibration?

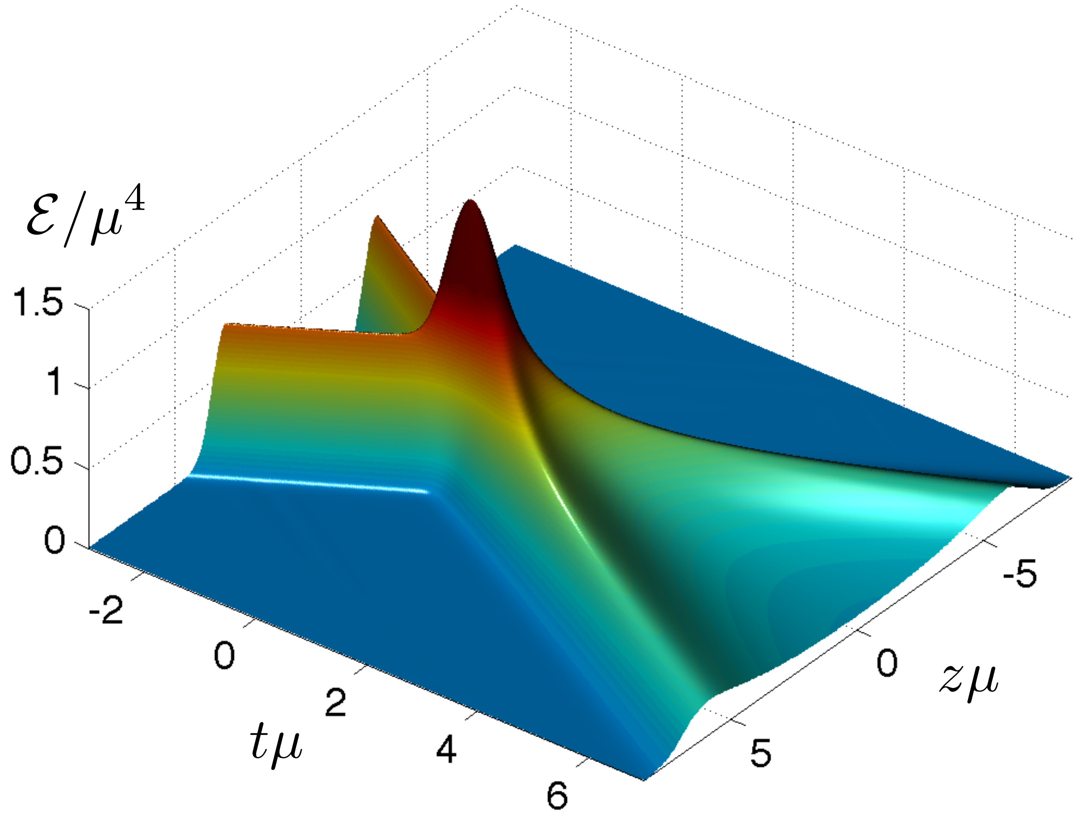
- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.

- 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?

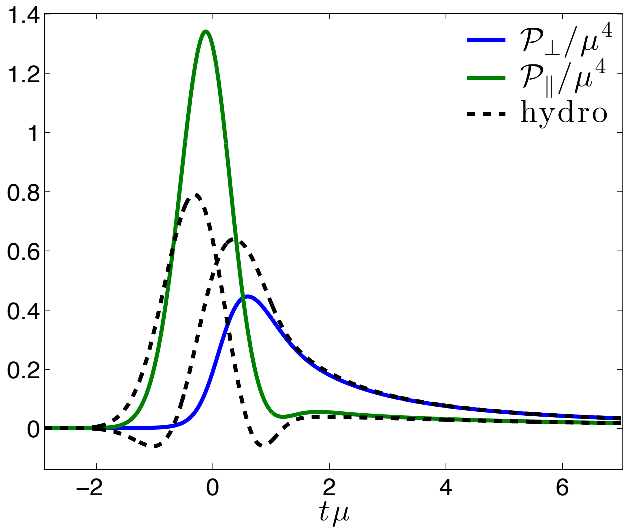
Colliding Strongly Coupled Sheets of Energy



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.

Ultracold Fermionic Atom Fluid

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

- NanoKelvin temperatures, instead of TeraKelvin.

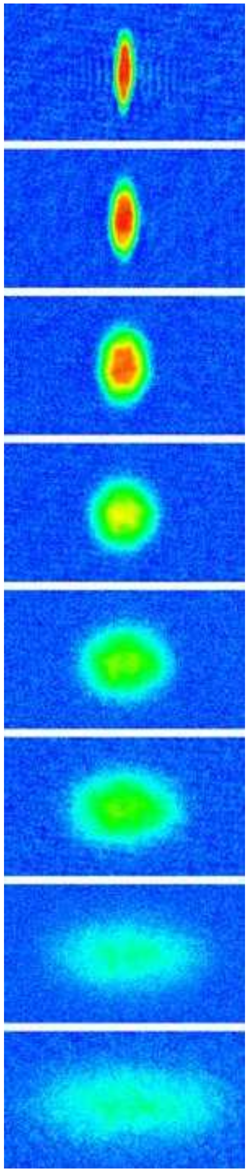
- Ultracold cloud of trapped fermionic atoms, with their two-body scattering cross-section tuned to be infinite. A strongly coupled liquid indeed. (Even though it's conventionally called the "unitary Fermi gas".)

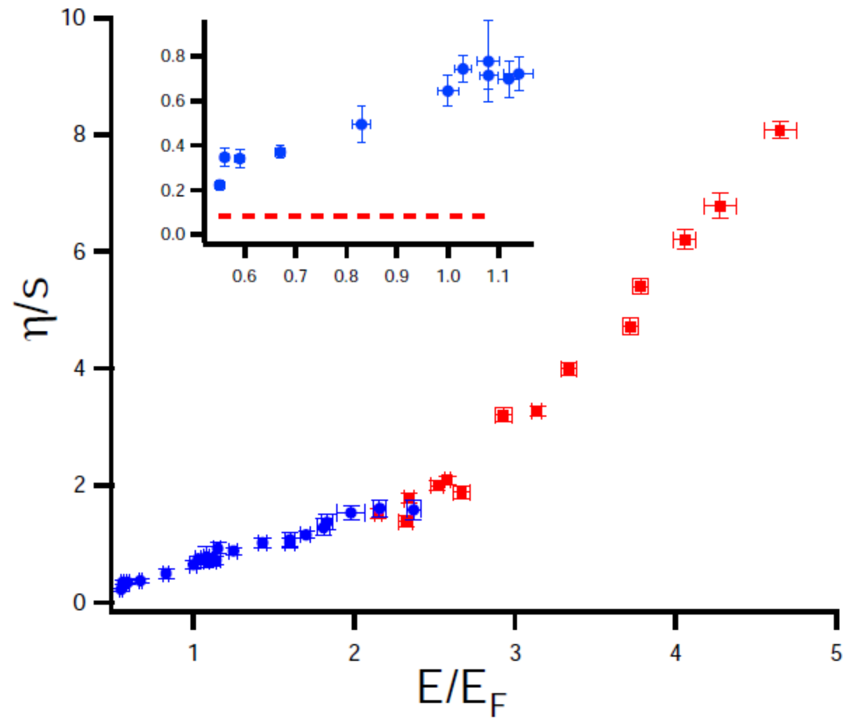
- Data on elliptic flow (and other hydrodynamic flow patterns that can be excited) used to extract η/s as a function of temperature. . .

Viscosity to entropy density ratio

consider both collective modes (low T)

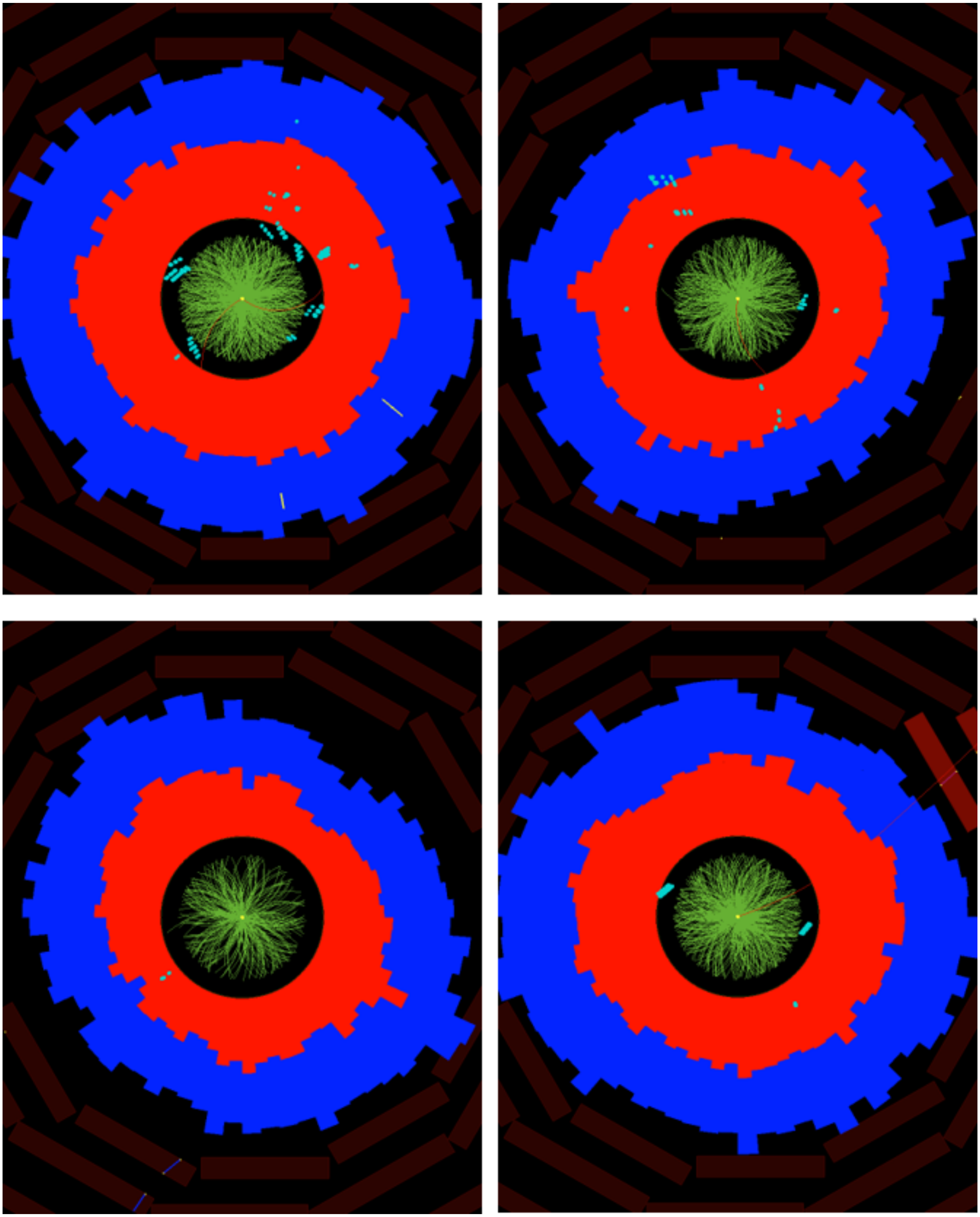
and elliptic flow (high T)





Cao et al., Science (2010)

$$\eta/s \leq 0.4$$



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 $\tau_{\text{qp}} \sim (5\eta/s)(1/T) \gg 1/T$.]

- 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 2022? Many improvements, but big picture was solid in 2015! I will highlight two ways in which it has been consolidated.

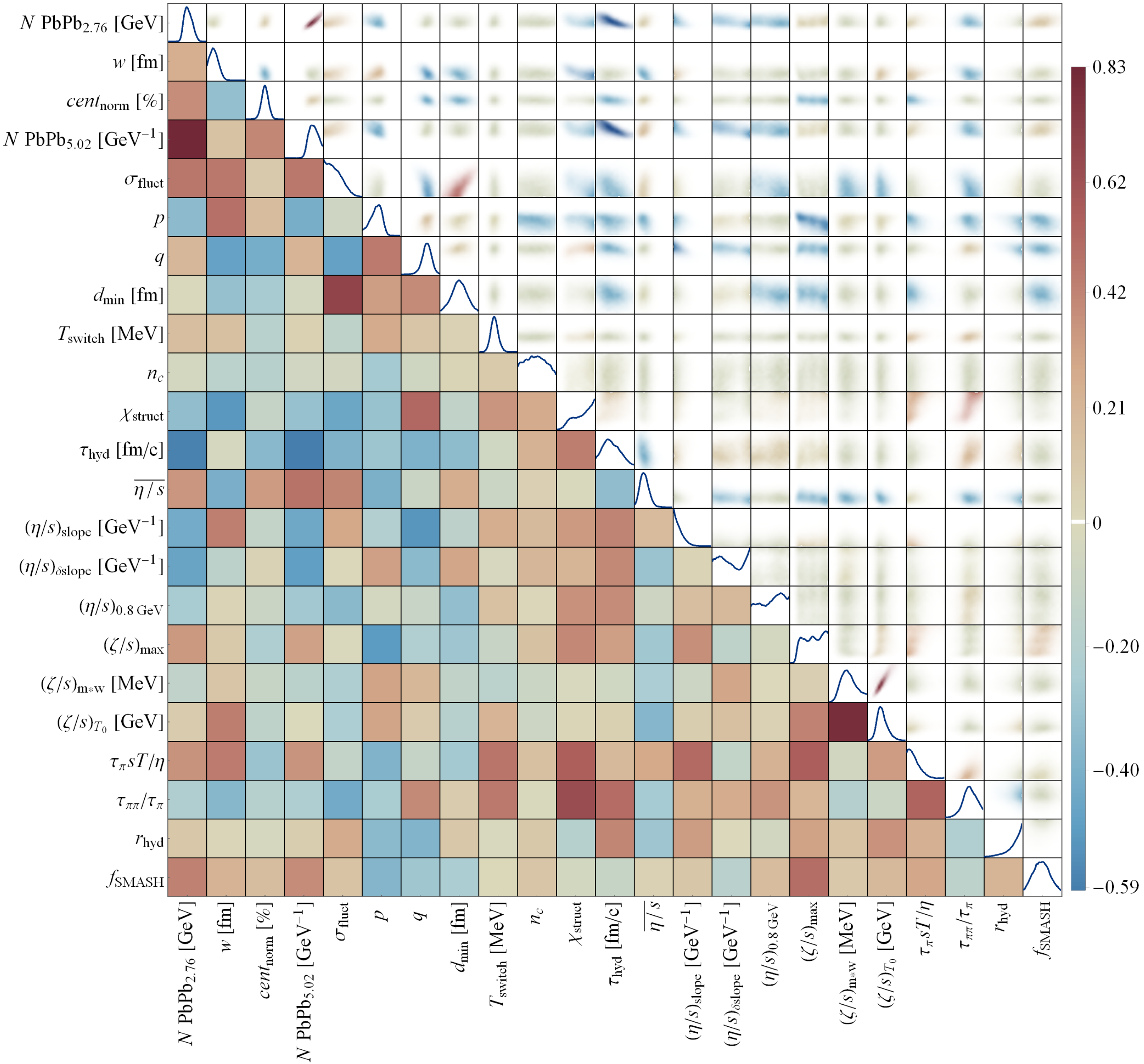
2024 Updates to 2015 Intro

- **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, Scheihing-Hitschfeld, Steinhorst, Yan, Yin, KR...

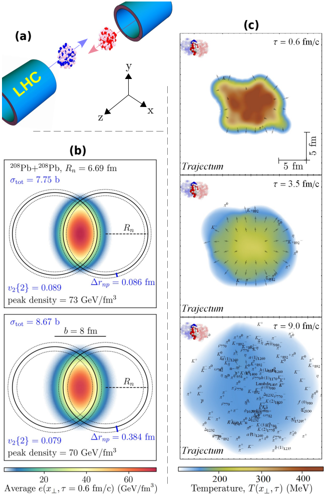
- **Quantification! including uncertainty quantification. Via work of *many* experimentalists and theorists, we now have more, and more precise, experimental data that, together with improved theoretical modeling, are driving Bayesian determinations, by multiple groups, of the "shape" of the fluid at the time of hydrodynamization, and key properties of QGP and their temperature dependence.**

Eg. of Today's State of the Art



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

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.

[Giacalone, GN, van der Schee, 2305.00015; STAR, 2204.01625; PREX, 2102.10767]

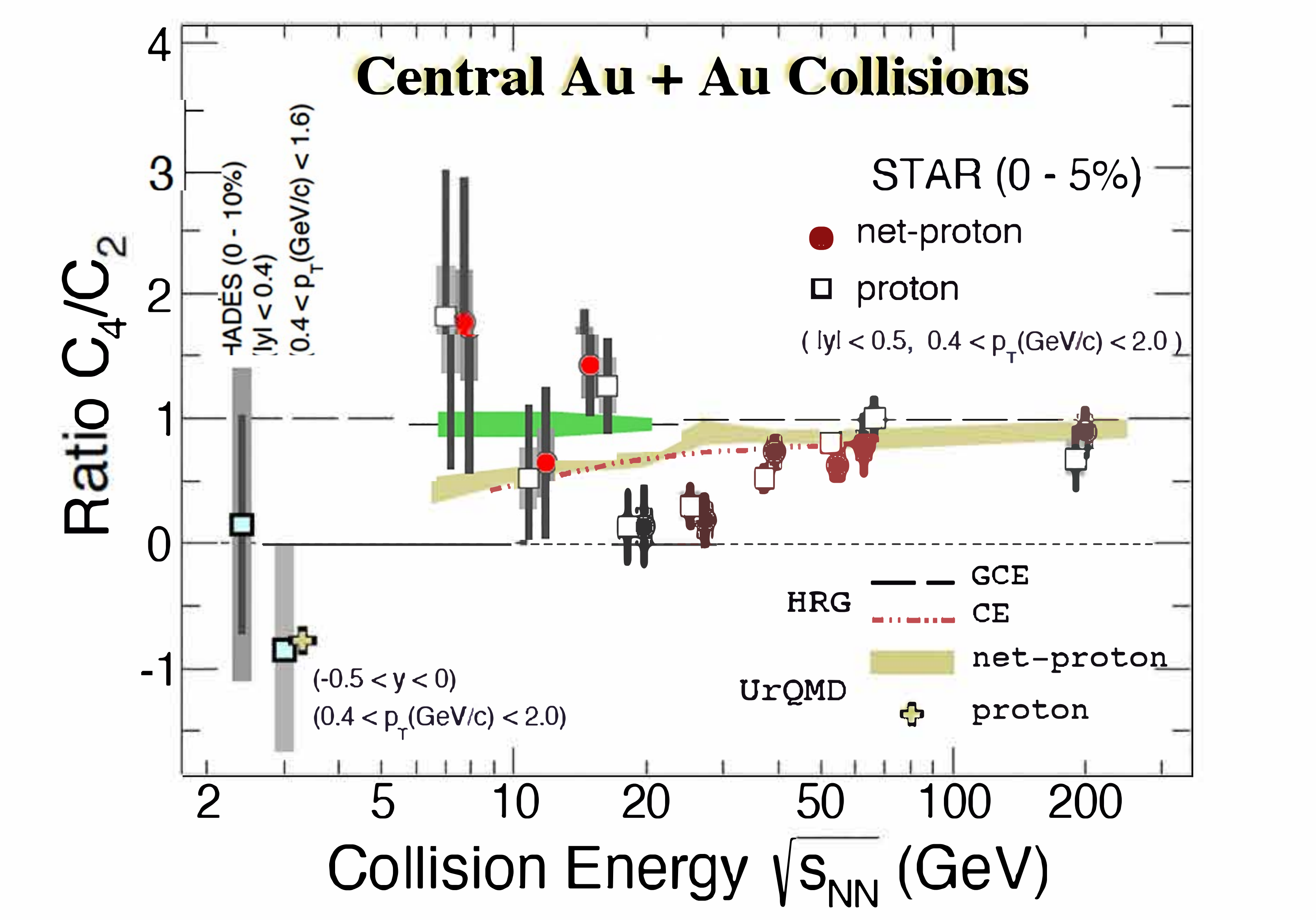
η/s from RHIC and LHC data

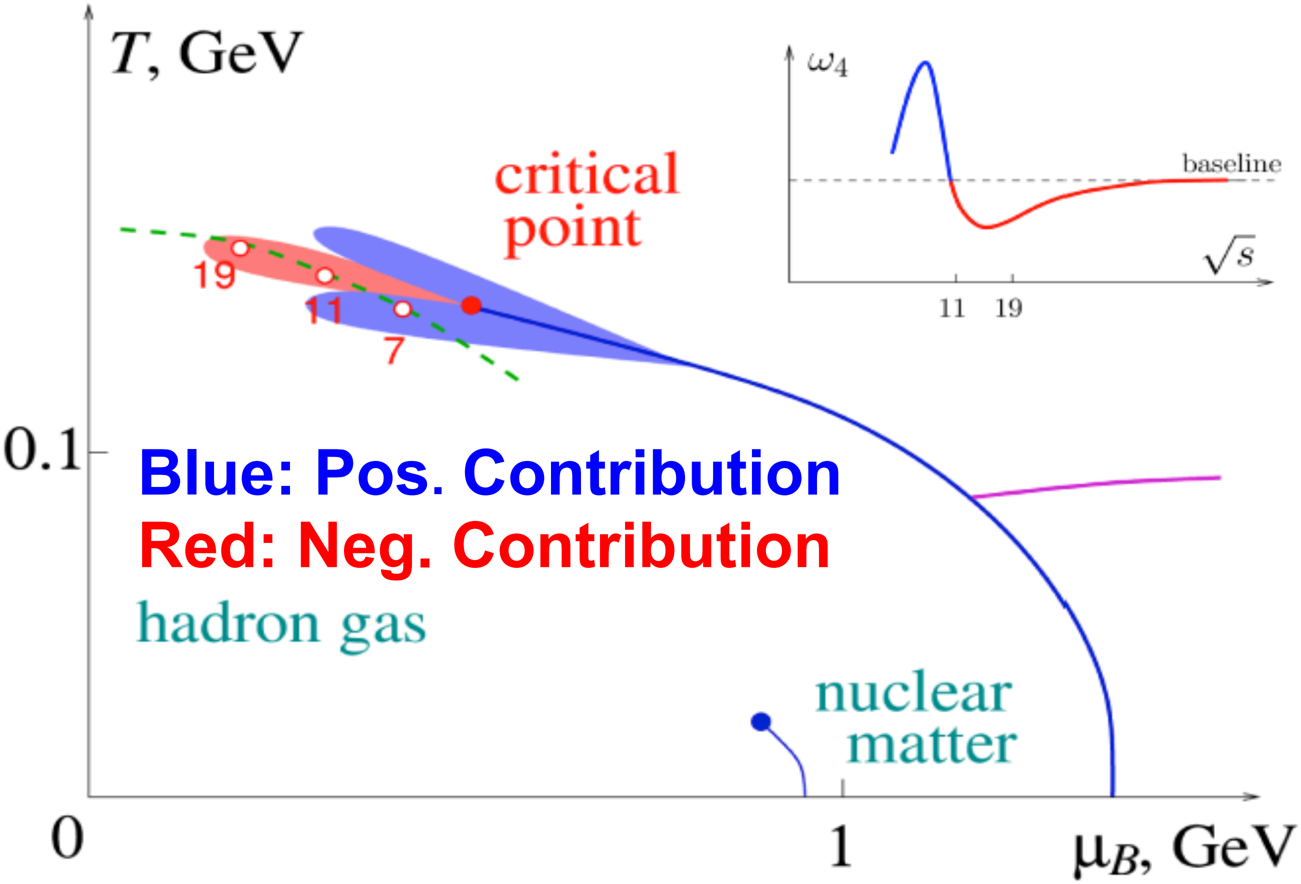
- **I have given you the beginnings of a story that has played out over the past decade. I will now cut to the chase, leaving out many interesting chapters and oversimplifying.**
- **Using relativistic viscous hydrodynamics to describe expanding QGP,** *produced in an initially lumpy heavy ion collision*, **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.**

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... Slides from 2015 almost completely superseded.
- Enormous progress on theory and modeling, by many people. Including by the BEST collaboration – see 2108.13867 for a summary.
- Phase II of the RHIC Beam Energy Scan data taking was completed in 2021. We await results with great interest and anticipation.

Proton Kurtosis, before BES II

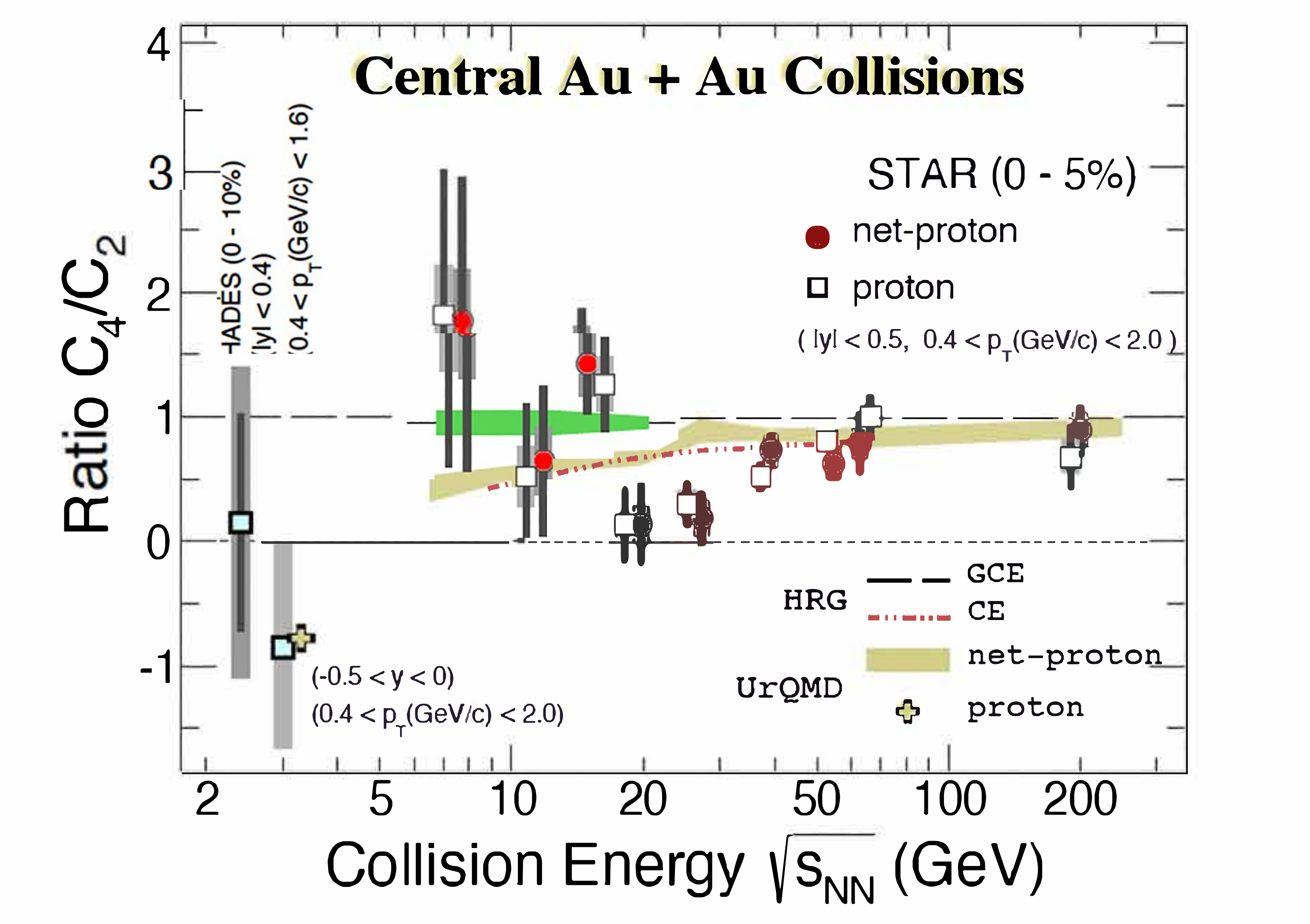


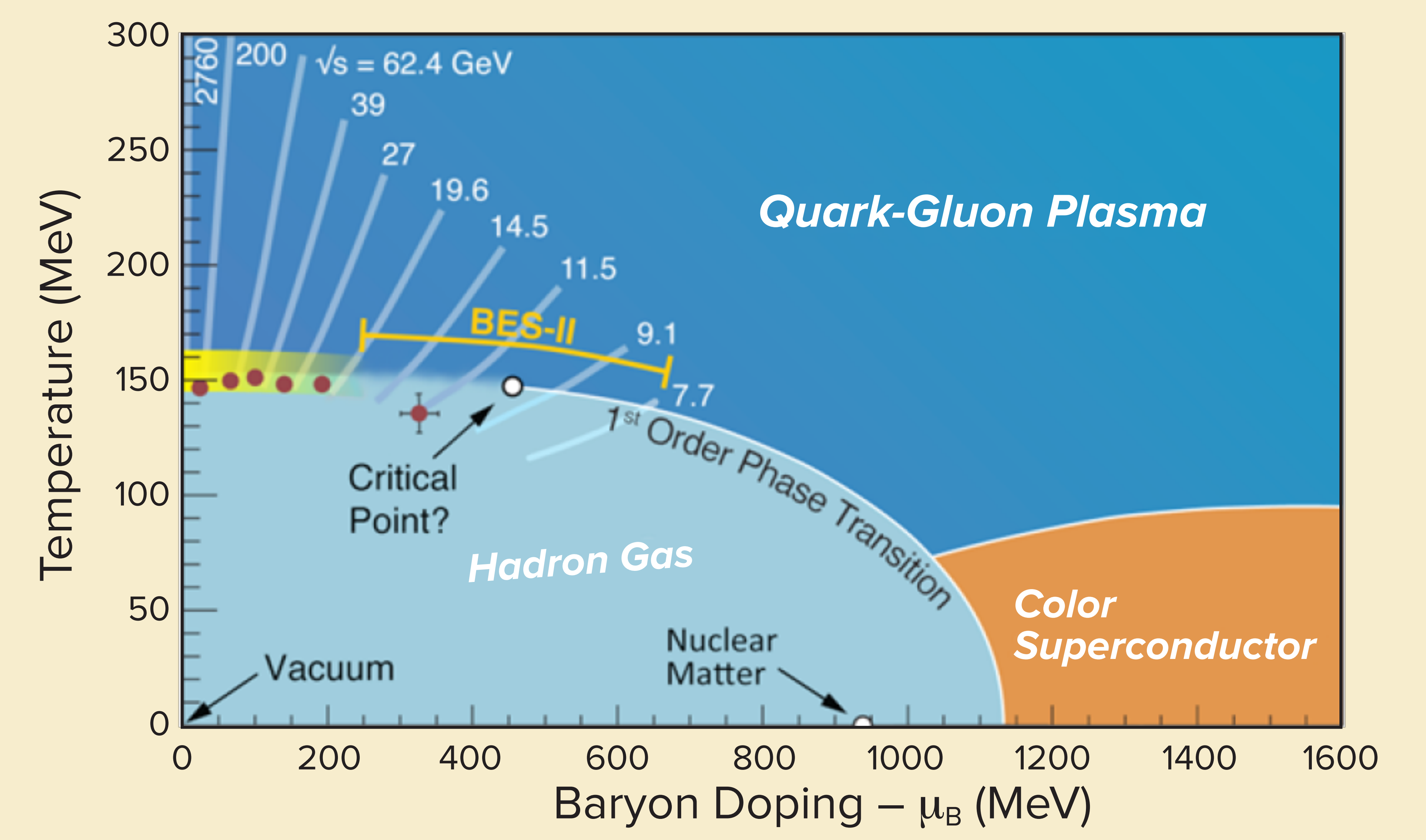


Blue: Pos. Contribution

Red: Neg. Contribution

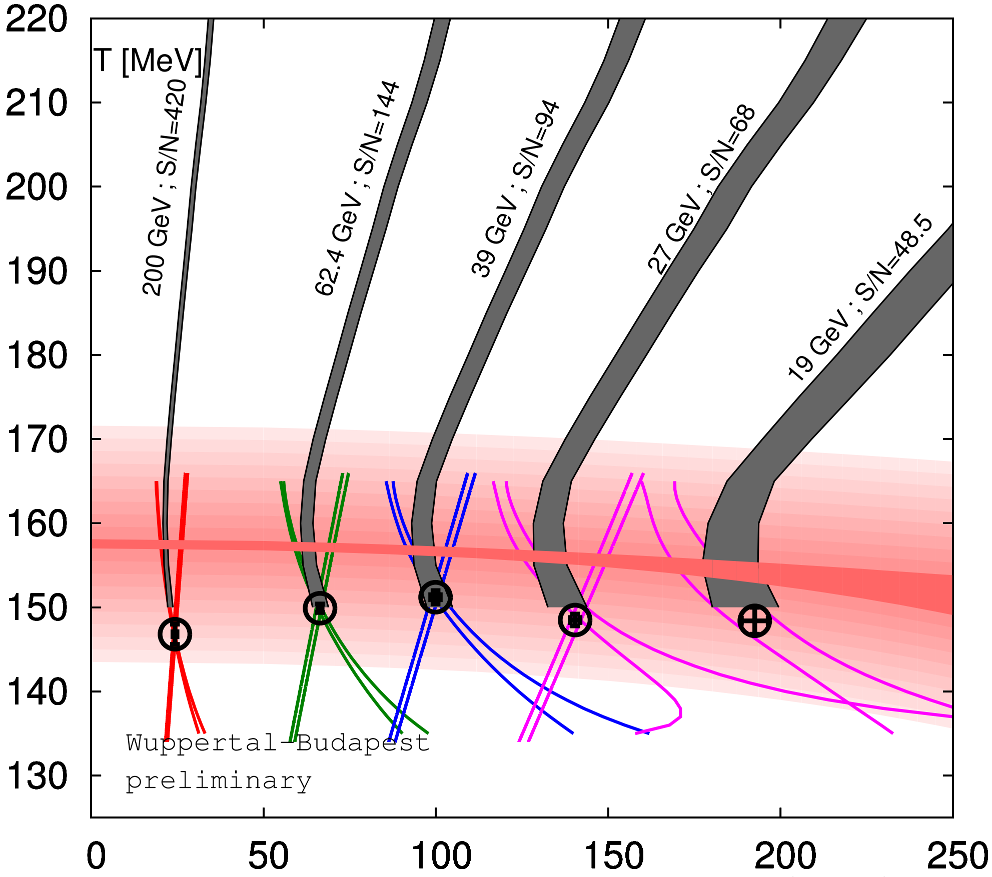
Proton Kurtosis, before BES II





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

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, . . ., 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; back-reaction on hydrodynamics turns out to be small.
- Freezeout of critical fluctuations.

Mapping the QCD Phase Diagram

- **Finding, or excluding, a critical point requires theory and modeling, with ingredients including:**
- **Energy and baryon number in initial stages.**
- **Equation of State (EoS)**
- **Hydrodynamics. Critical fluctuations.**
- Freezeout of critical fluctuations
  - **Freezing out Hydro+ so as to faithfully turn the critical fluctuations described via Hydro+ into fluctuations of observed proton multiplicities: 2204.00639 Pradeep, KR, Stephanov, Yin**
  - . . . **faithfully turn the** *higher moments of* **the critical fluctuations into the** *skewness and kurtosis of* **observed proton multiplicities (in progress) 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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Probing the Original Liquid

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

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

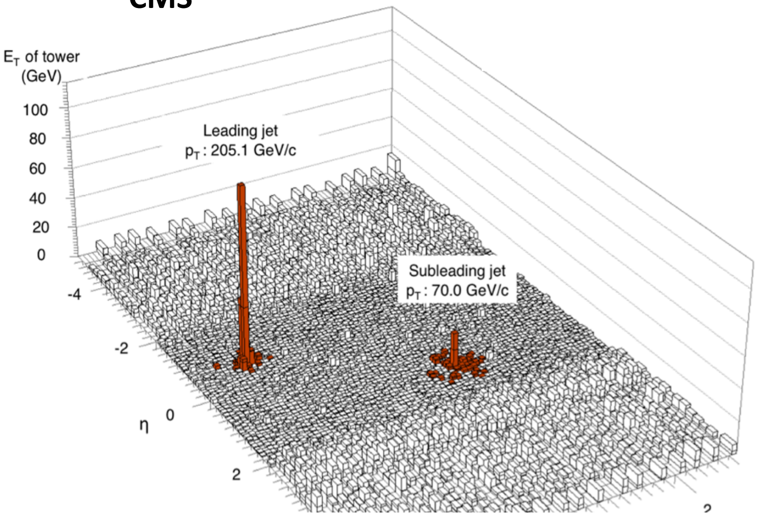
Each, in a different way, requires stressing or probing the QGP. Each can tell us about its inner workings.

Smallest possible droplet of liquid?

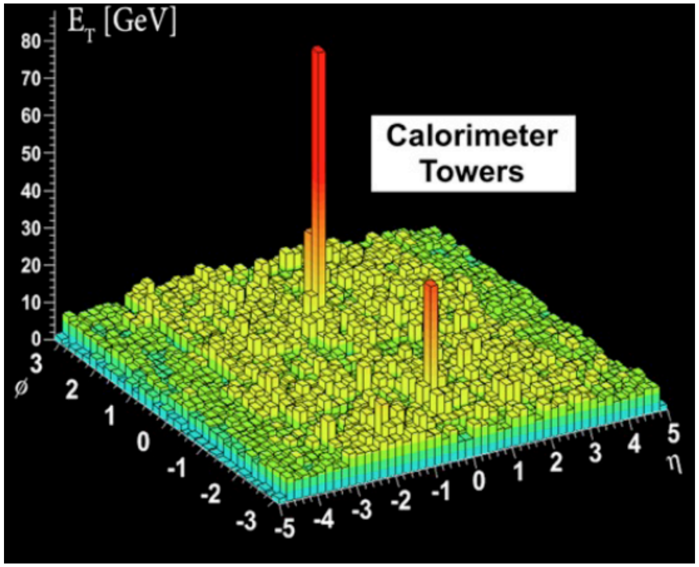
- What is the smallest possible droplet of QGP that behaves hydrodynamically? Anyone doing holographic calculations at strong coupling, or anyone seeing effects of small lumps in the initial state visible in the final state, could have asked this question, but didn't. Question was asked by data: pPb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

Jet Quenching, in brief

CMS

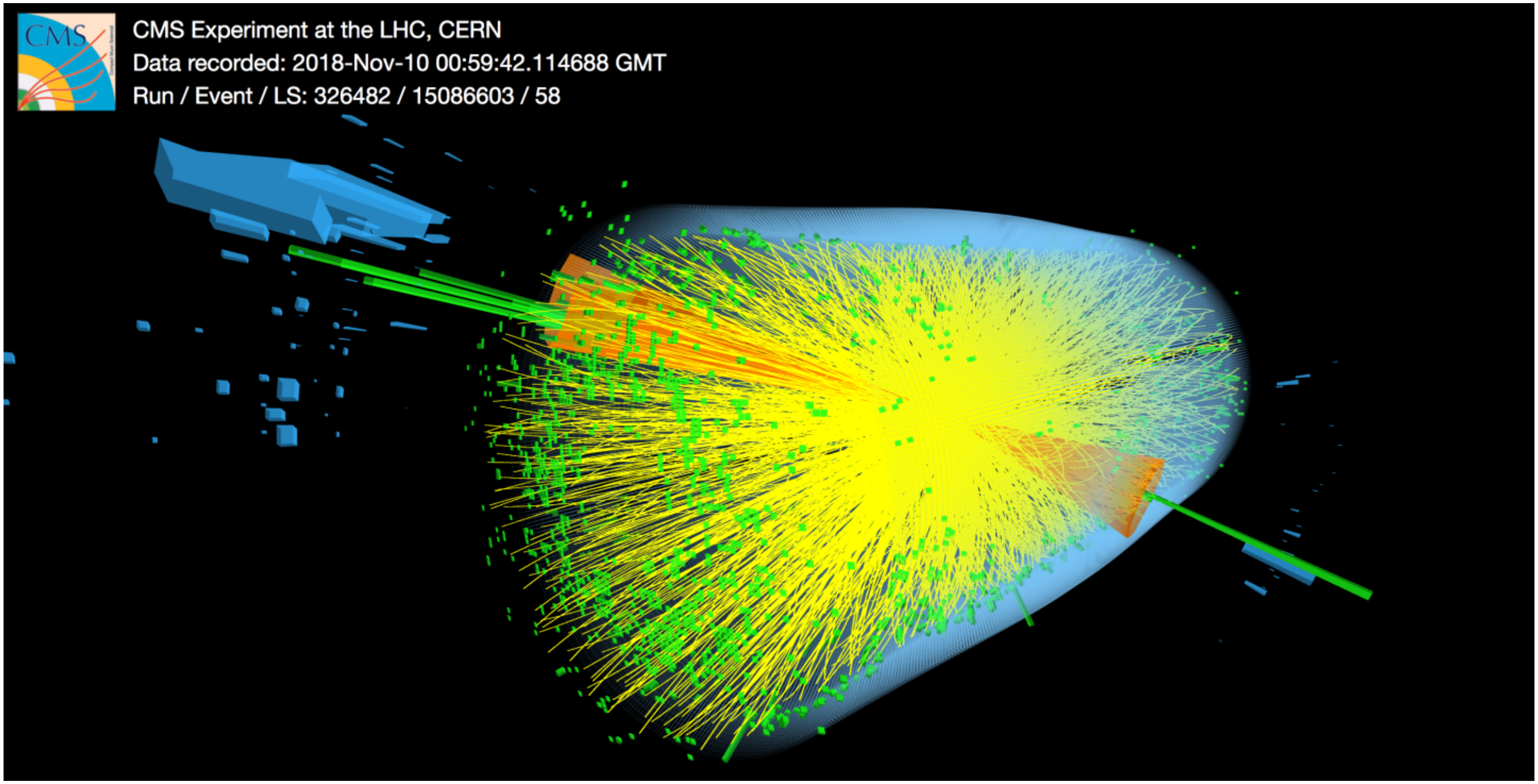


ATLAS



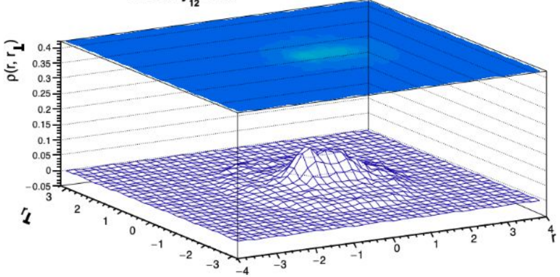
Jet quenching discovered @ RHIC; @ LHC, seen instantly!

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

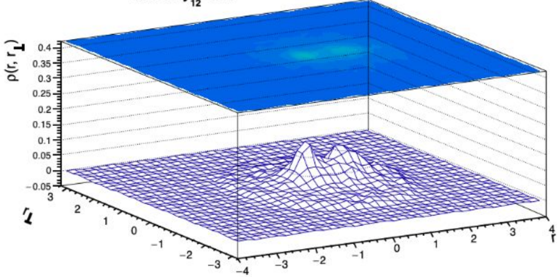

CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-10 00:59:42.114688 GMT
Run / Event / LS: 326482 / 15086603 / 58

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

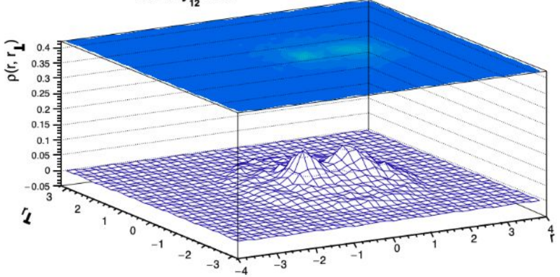
$0.6 < \Delta y_{12} < 0.8$



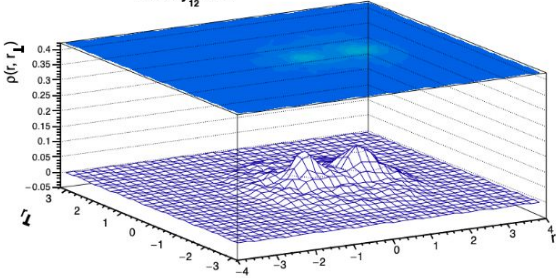
$0.8 < \Delta y_{12} < 1.0$



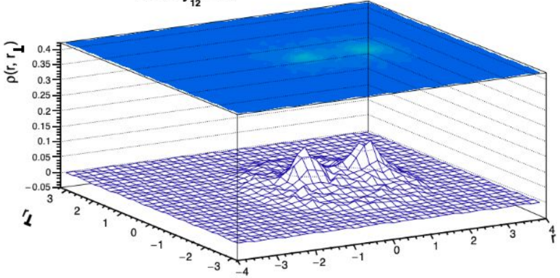
$1.0 < \Delta y_{12} < 1.2$



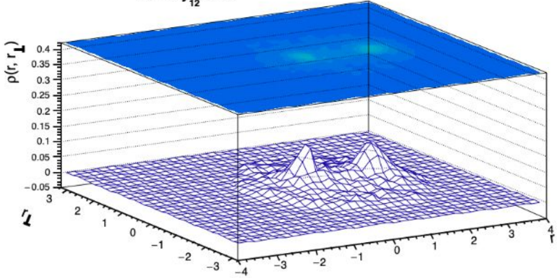
$1.2 < \Delta y_{12} < 1.4$



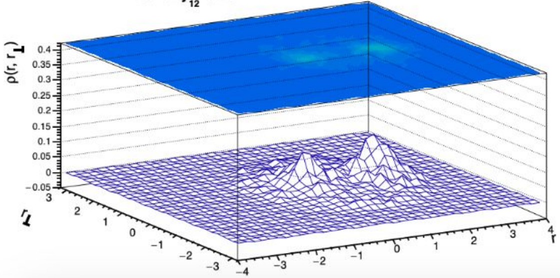
$1.4 < \Delta y_{12} < 1.6$



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



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



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!

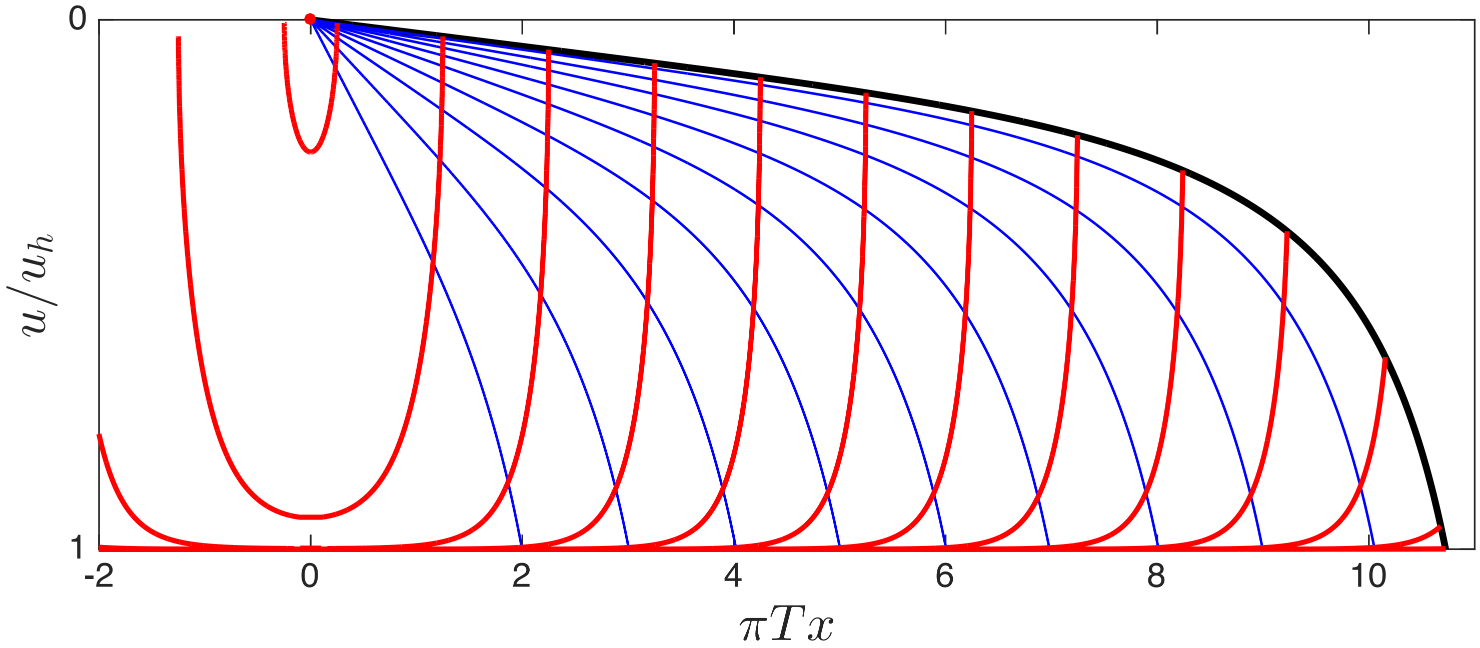
A Hybrid Approach

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**

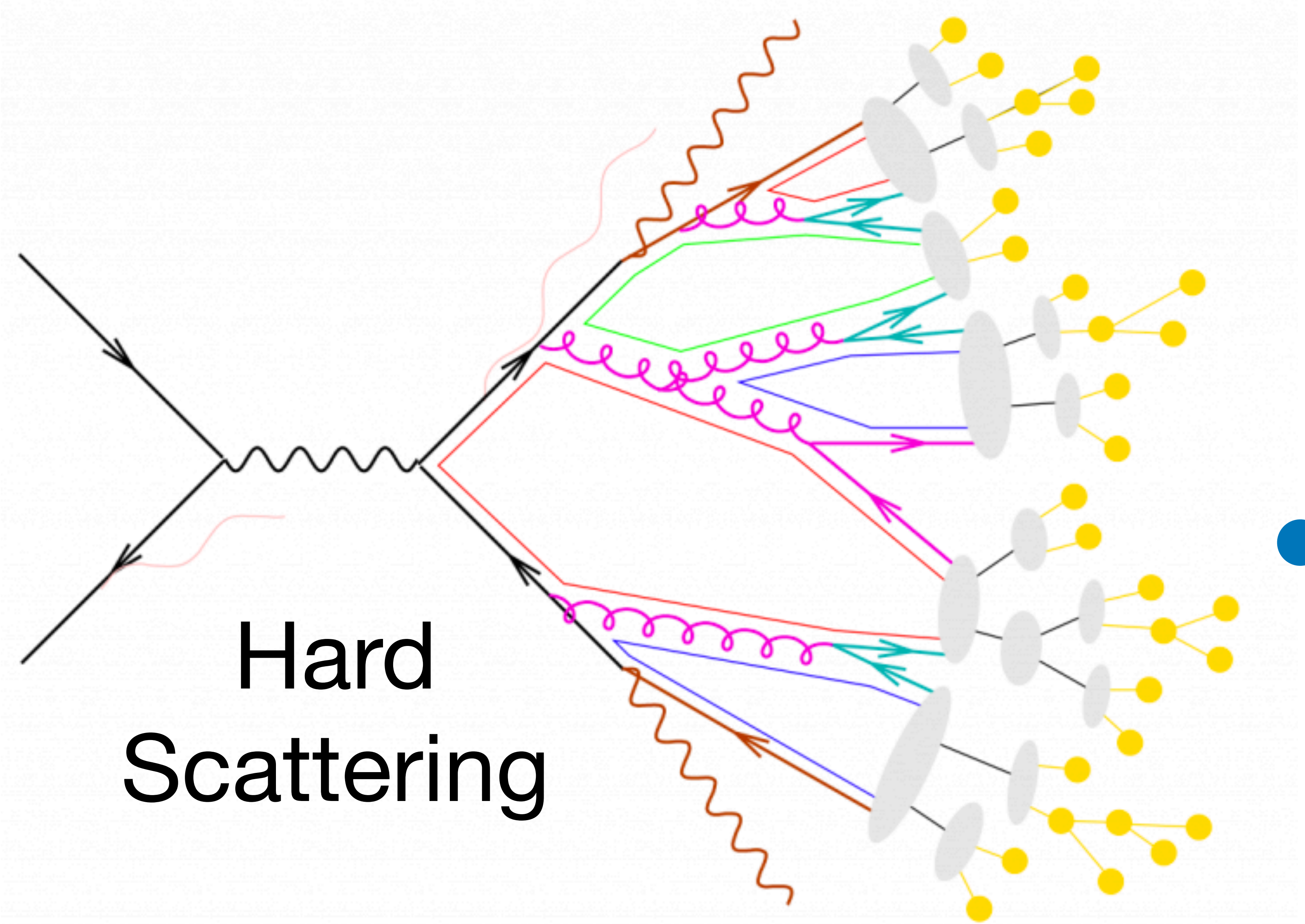
$$\frac{1}{E_{\text{in}}}\frac{dE}{dx} = -\frac{4x^2}{\pi x^2_{\text{therm}}}\frac{1}{\sqrt{x^2_{\text{therm}} - x^2}}$$

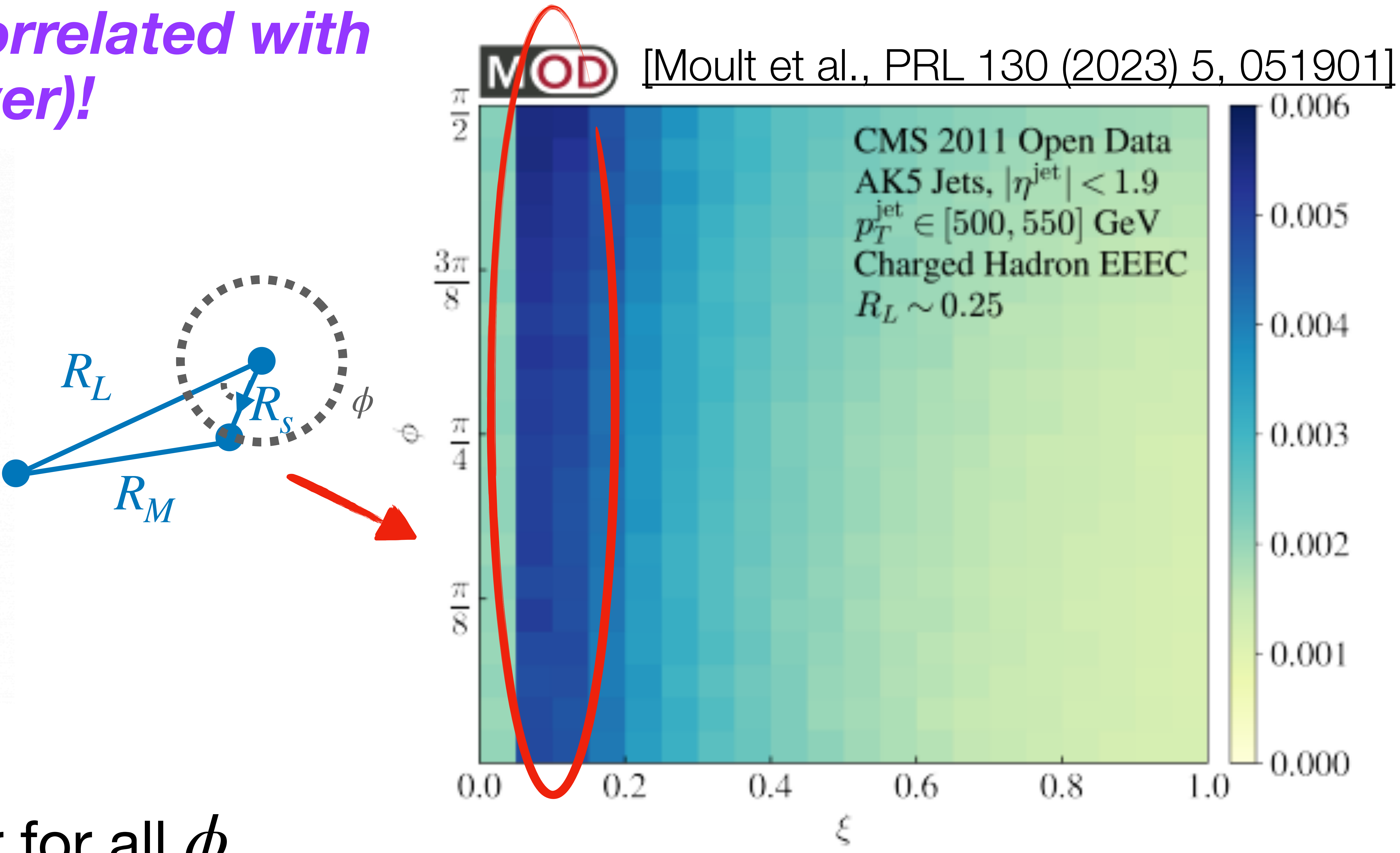
  where $x_{\text{therm}} \equiv E_{\text{in}}^{1/3}/(2\kappa_{\text{sc}}T^{4/3})$ with κ_{sc} one free parameter that to be fixed by fitting to one experimental data point. ($\kappa_{\text{sc}} \sim 1 - 1.5$ in $\mathcal{N} = 4$ SYM; smaller κ_{sc} means x_{therm} is longer in QGP than in $\mathcal{N}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

3-point correlator in vacuum

- Let's explore the 3-point correlator in vacuum at a fixed R_L slice!

In vacuum all emissions are correlated with the same source (parton shower)!





[Moult et al., PRL 130 (2023) 5, 051901]

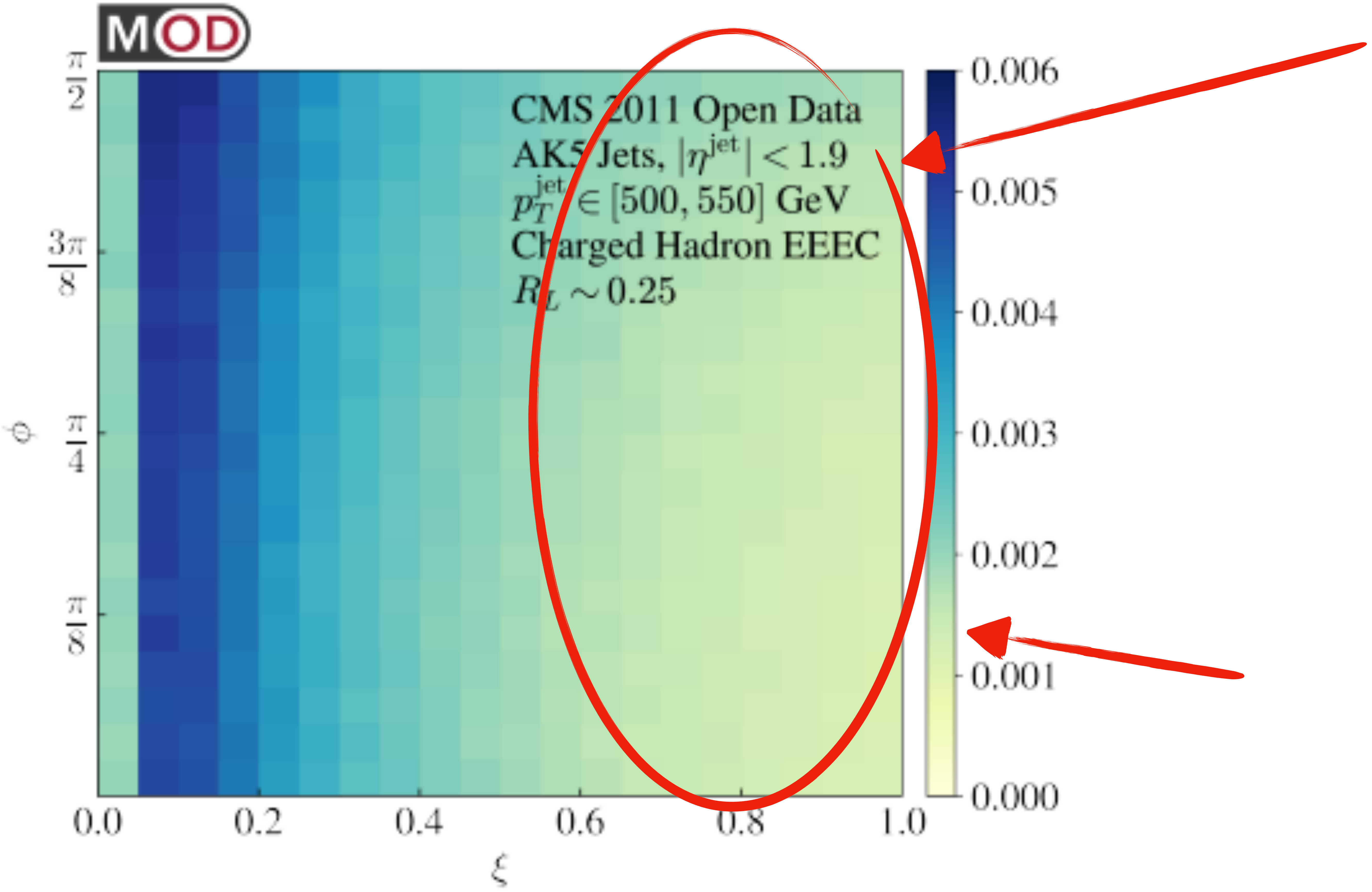
When ξ is small, behavior similar for all ϕ

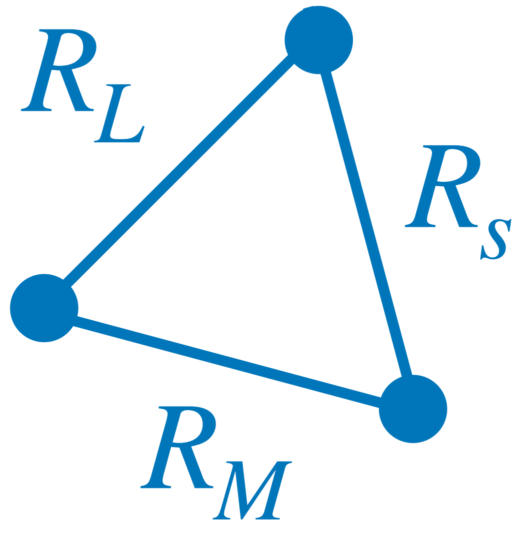
In small angle limit, reflect 2-point correlator

3-point correlator in vacuum

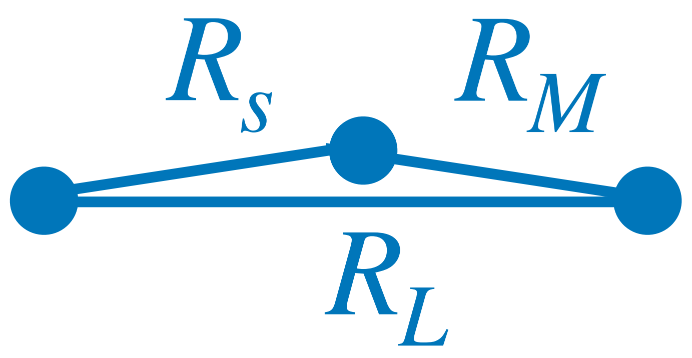
- Let's explore the 3-point correlator in vacuum at a fixed R_L slice!

[Moult et al., PRL 130 (2023) 5, 051901]





Upper right corner is populated with equilateral triangles

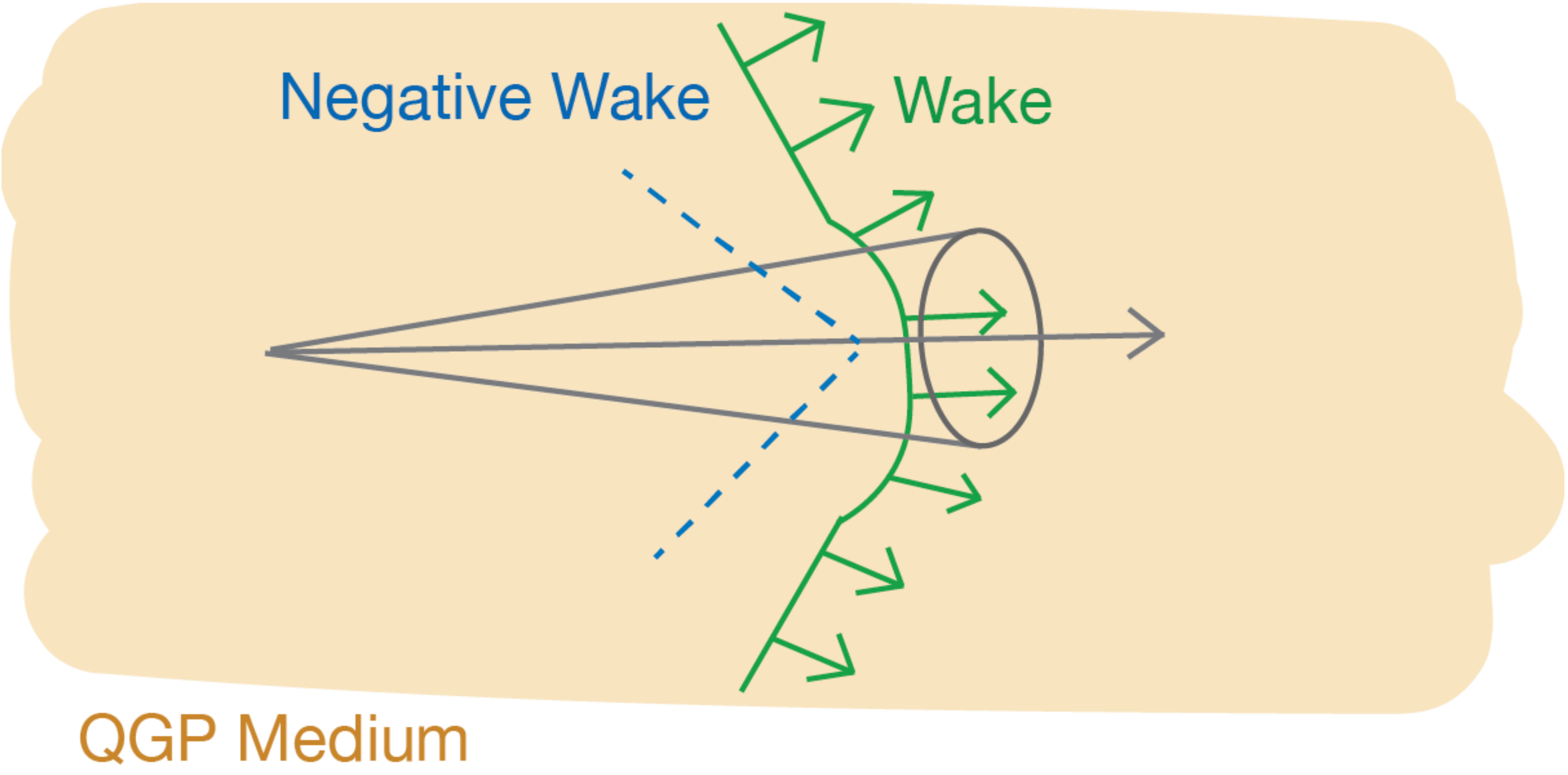


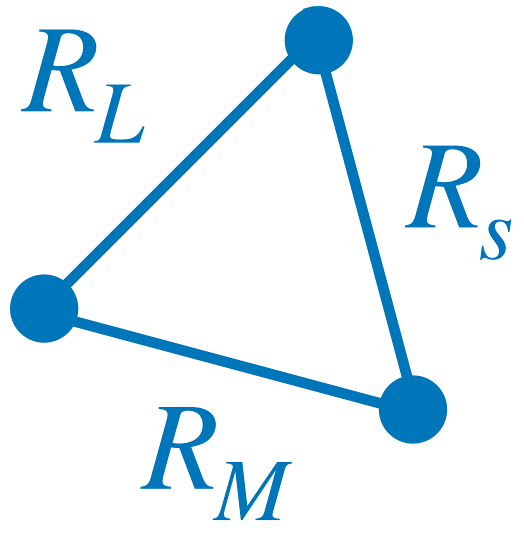
Bottom right corner is populated with "squished" triangles

These features are not prominent in vacuum!

Exposing the wake with 3-point correlators

Idea: Study one type of medium response (wake) via its distinct shape dependence in the 3-point correlator



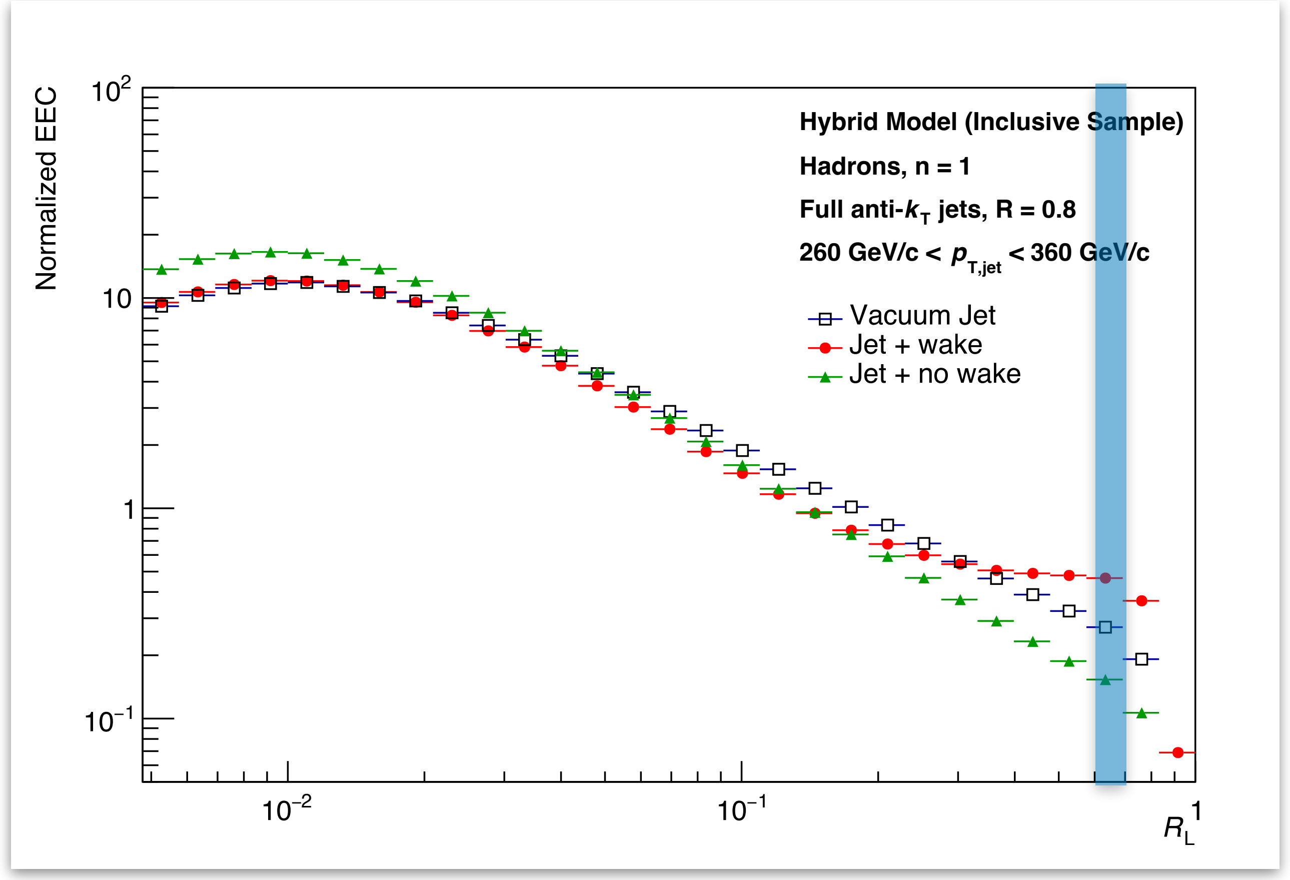


Wake should "fill in" region unpopulated in vacuum!

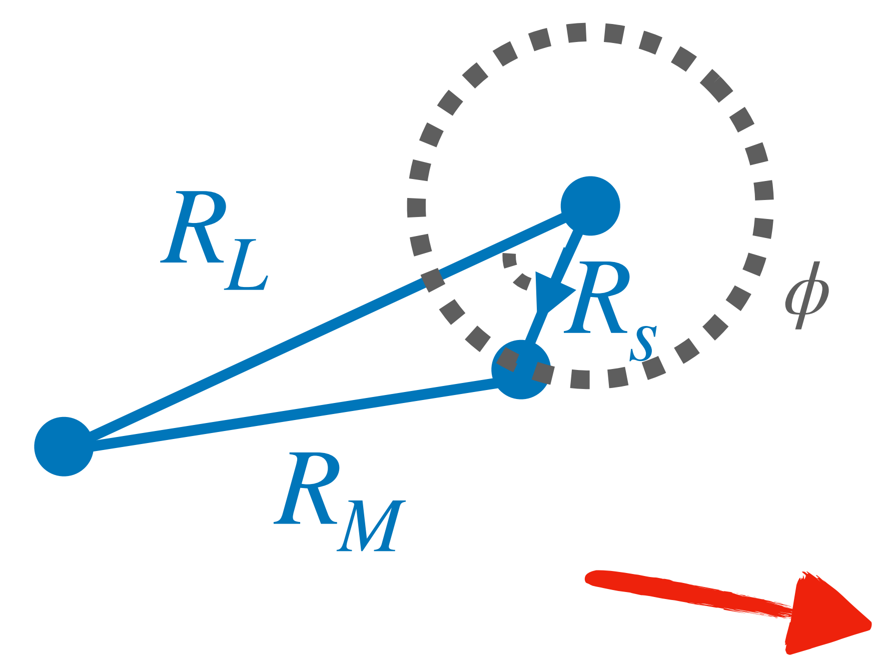
Still will have parton shower contributions, but now in addition have a broader and softer contribution from the wake.

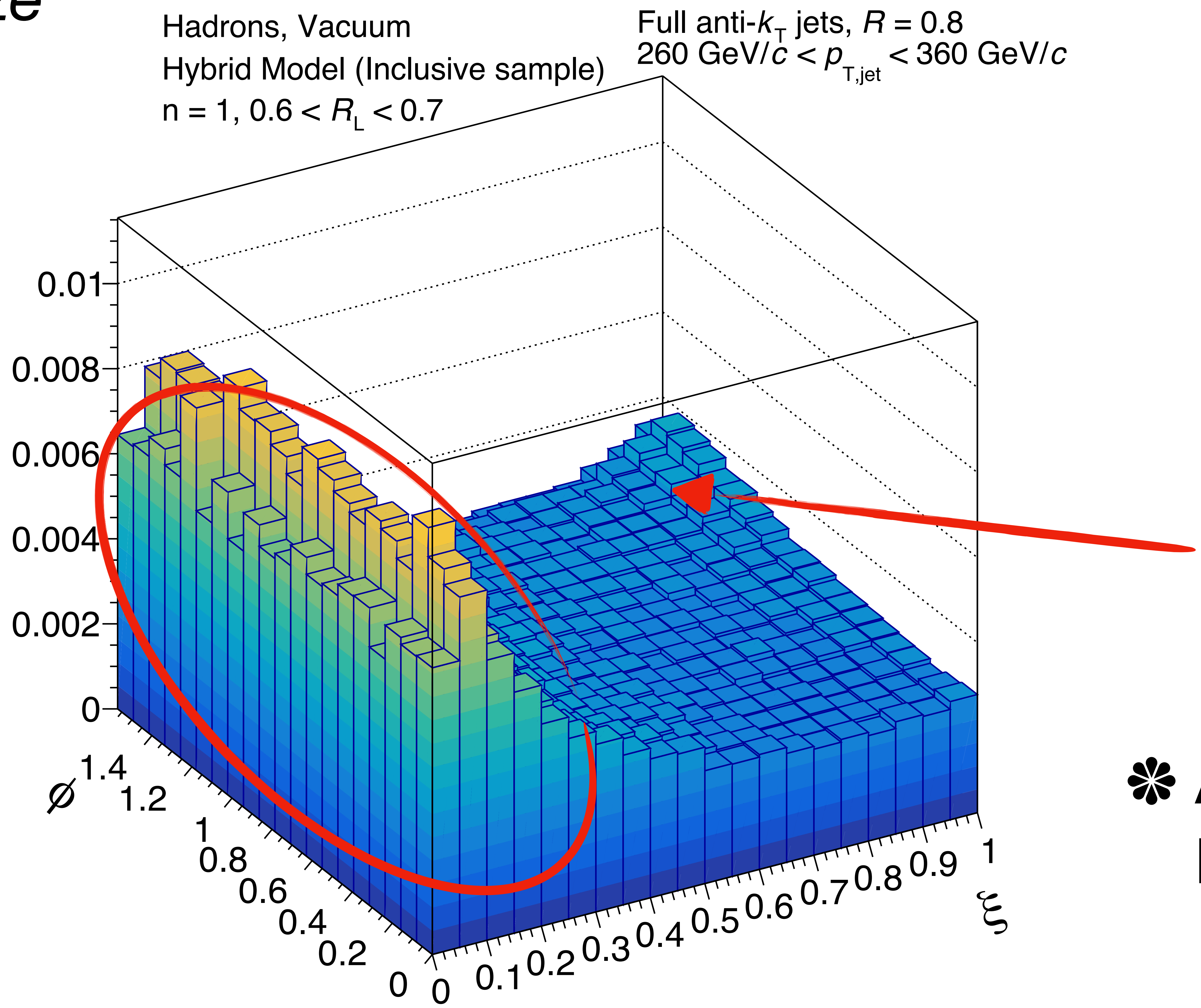
Outline: first discuss an idealized case, then go over some practical considerations for experimental applications!

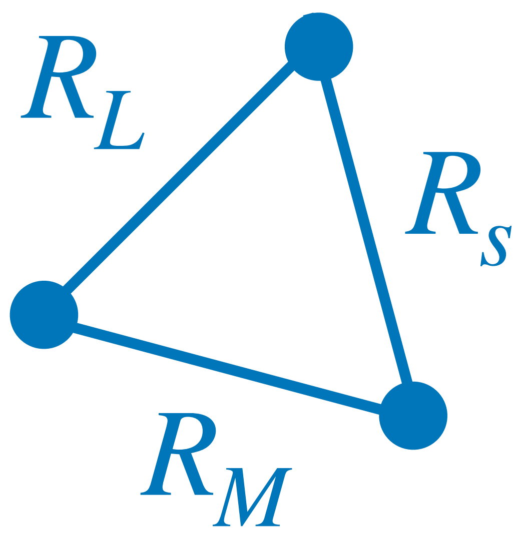
Shape dependence in vacuum



Can also visualize this in 3D!



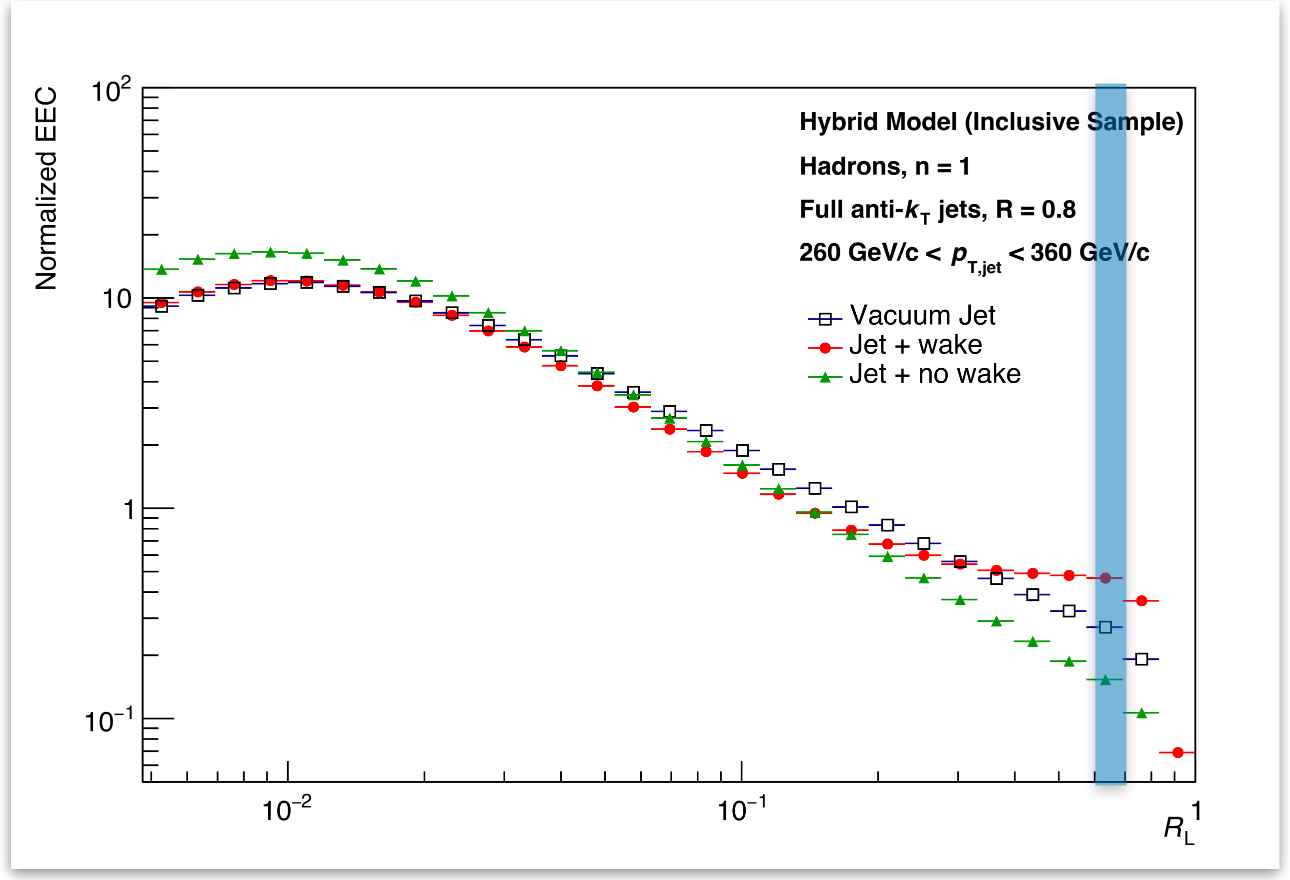


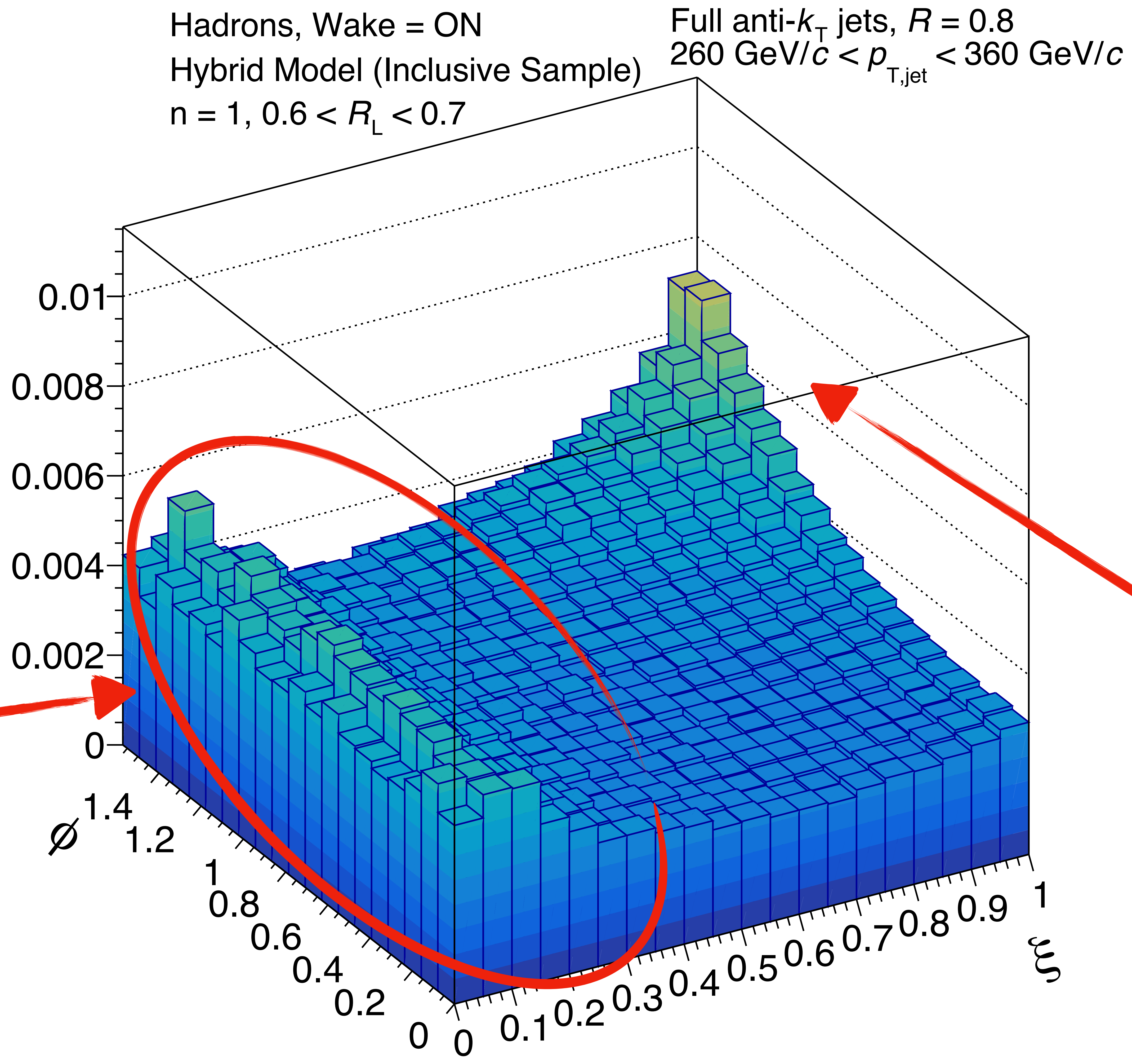


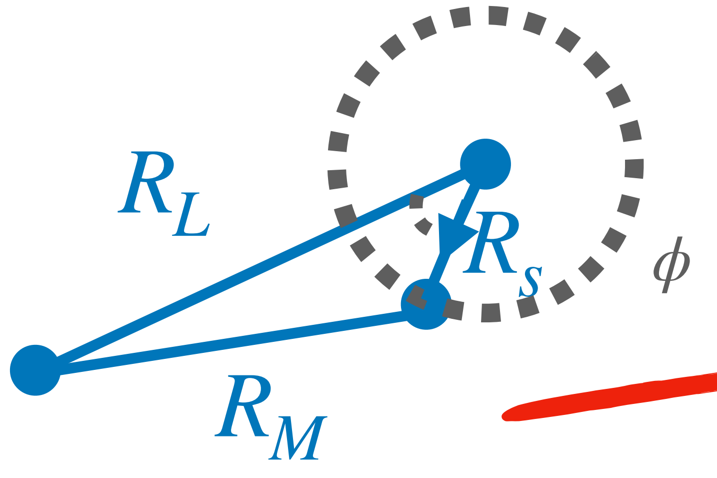
- ❃ All other shapes not prominent in vacuum!

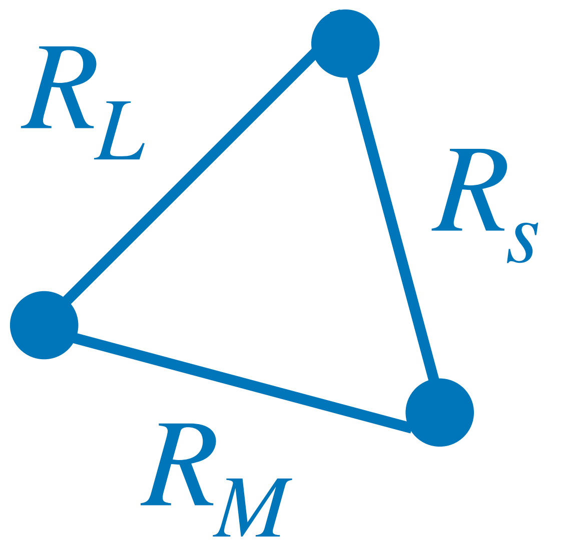
- ❃ All emissions correlated with the same source (parton shower)

Shape dependence in medium (with wake)









- Large rise in equilateral structures due to the presence of the uncorrelated wake!

- ***Dramatically different shape dependence when the wake is included!***

Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

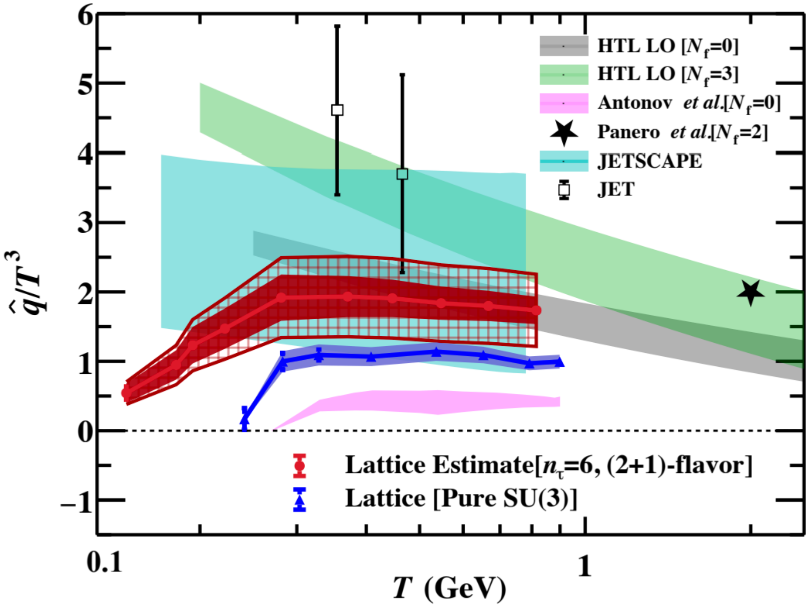
At strong coupling, holography predicts Gaussian broadening without quasi-particles (eg: N=4 SYM)

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

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

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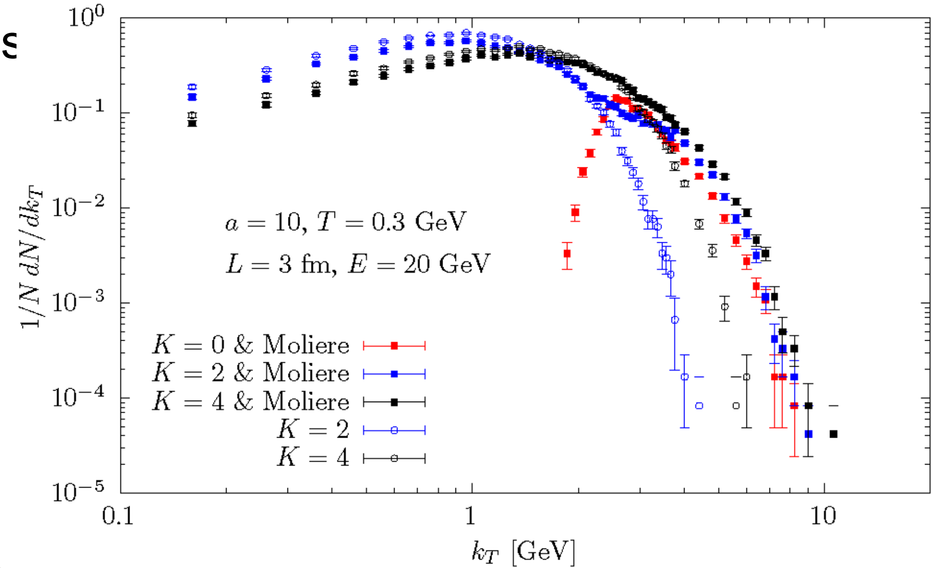

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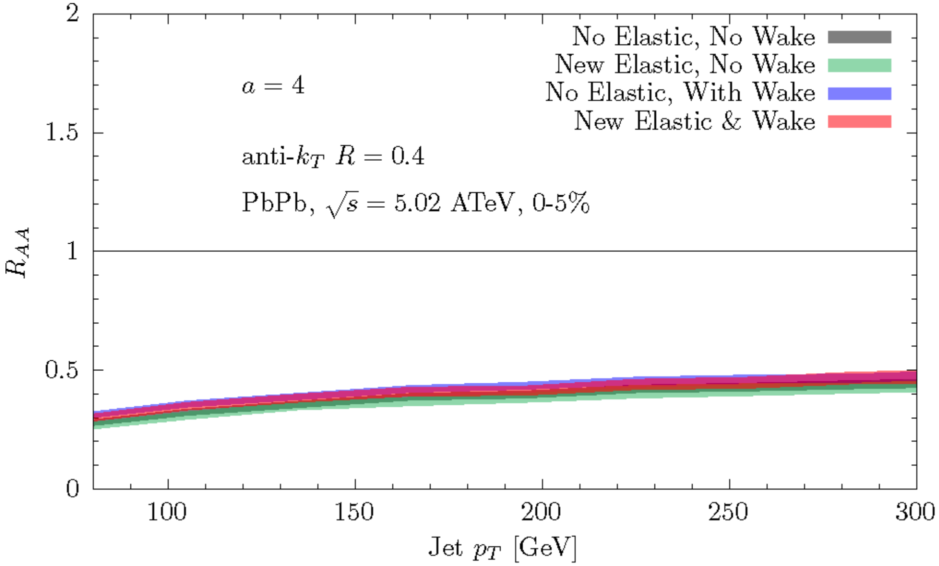
- Add Moliere scattering with momentum exchanges $> m_D$; here, $a = 10$

Jet R_{AA}

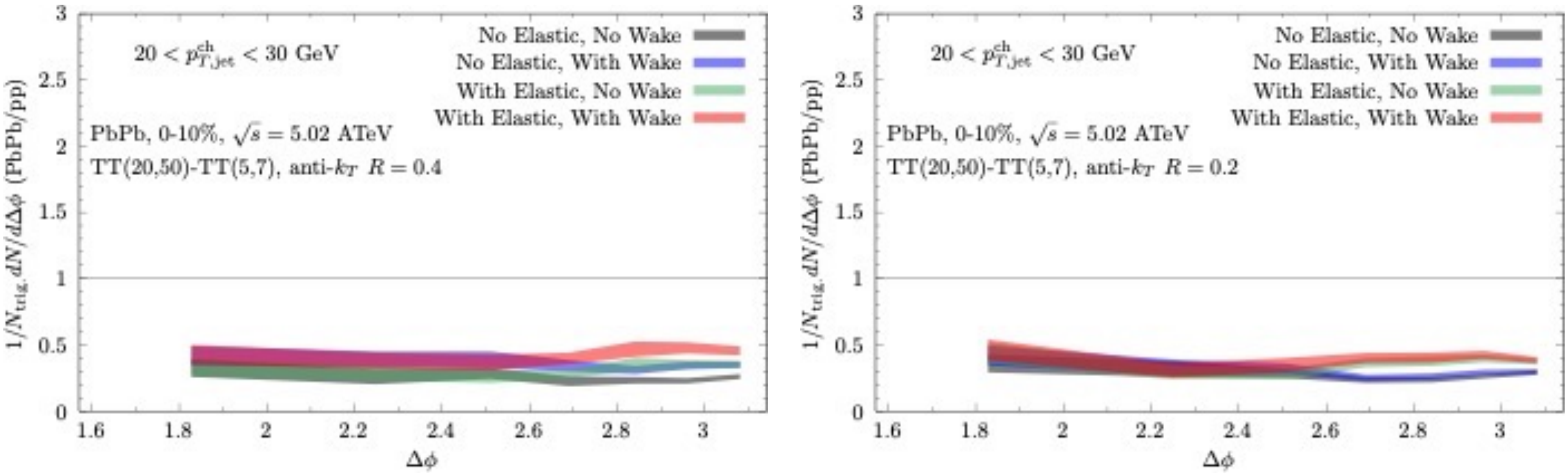
Casalderrey-Solana et al. 2019

- 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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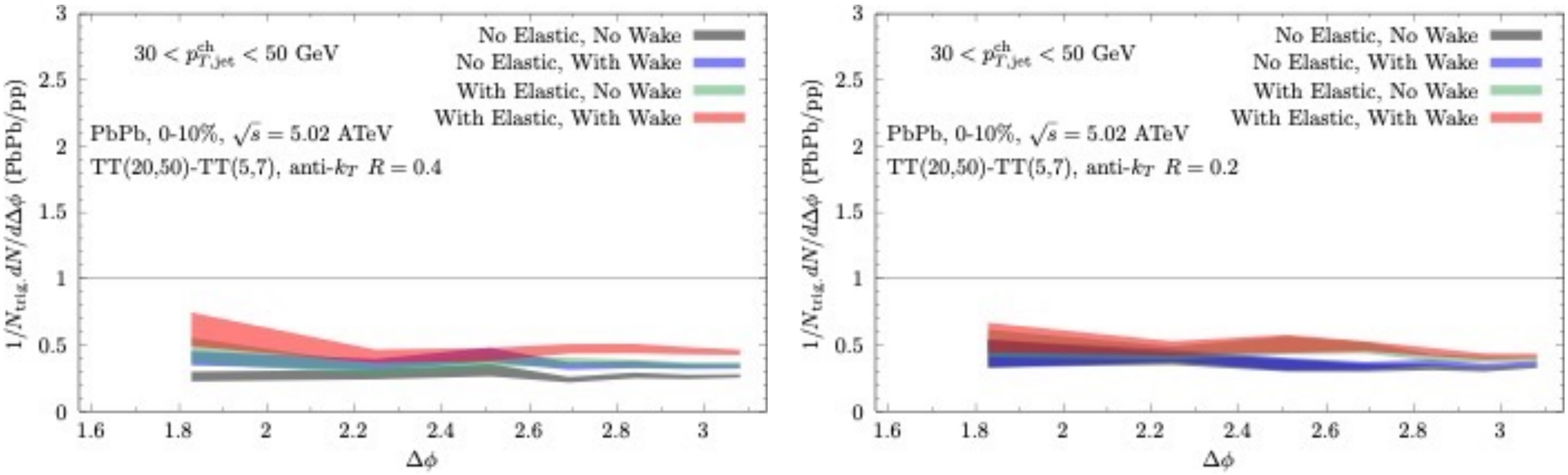

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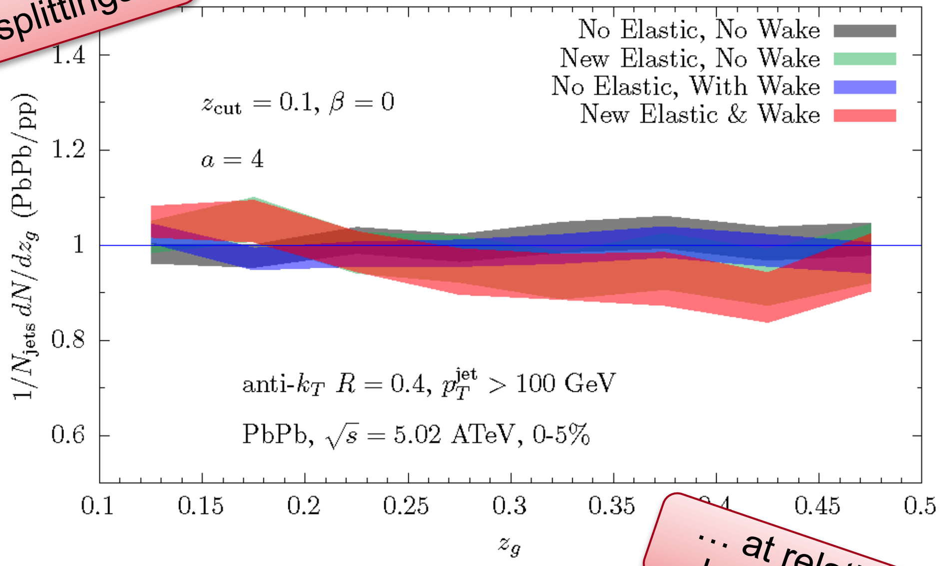
Groomed z_g and R$_g$

Soft Drop ($\beta = 0$)

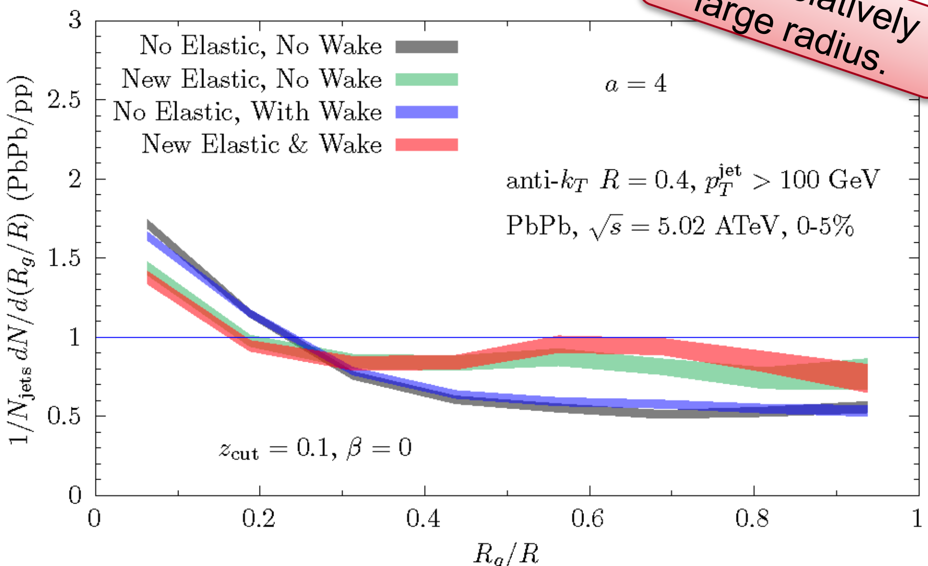
1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2, separated by angle R$_g$
4. If $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} \equiv z_g > z_{cut}$, then original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and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

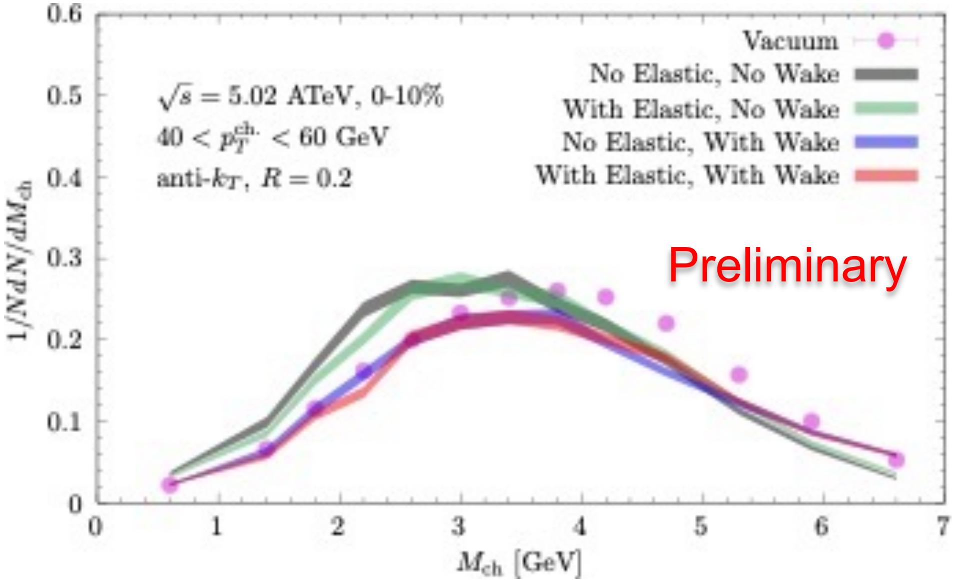
Enhancement of softer splittings…

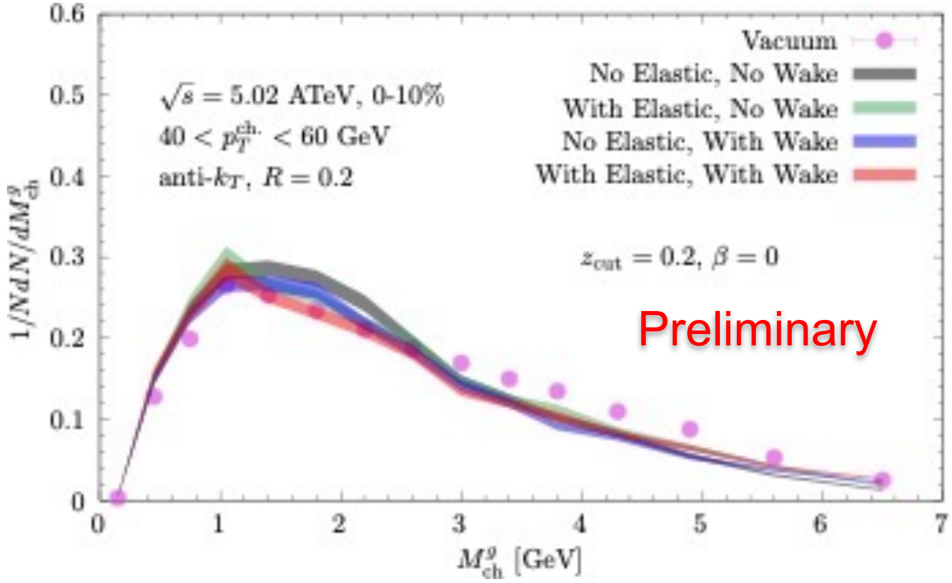


… at relatively large radius.



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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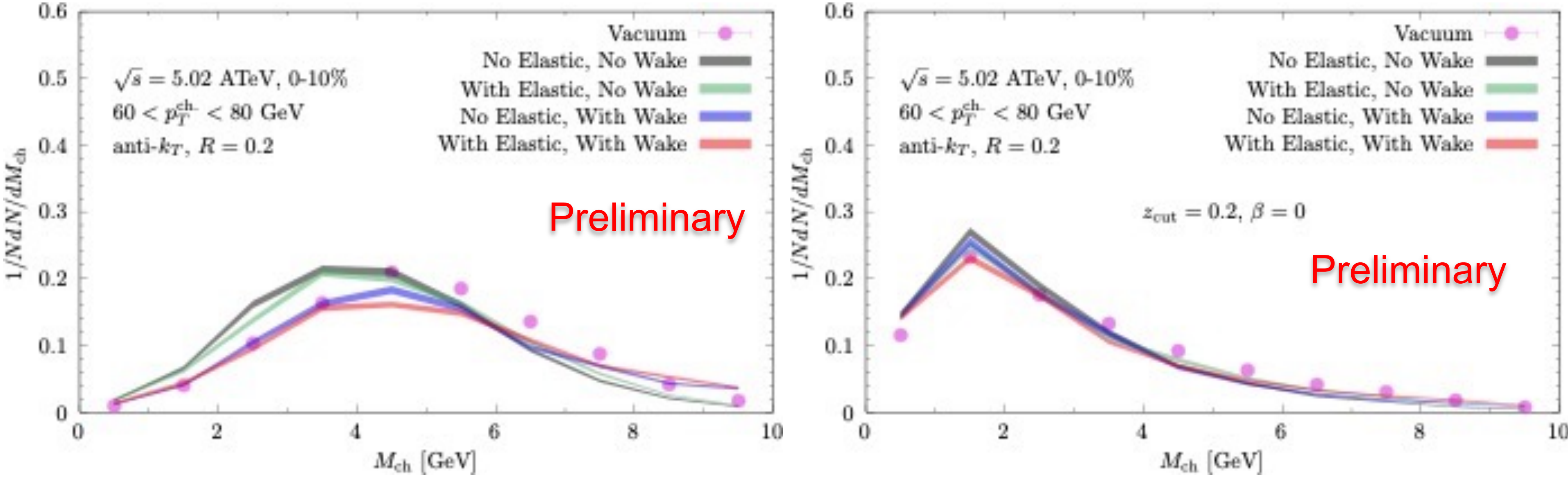

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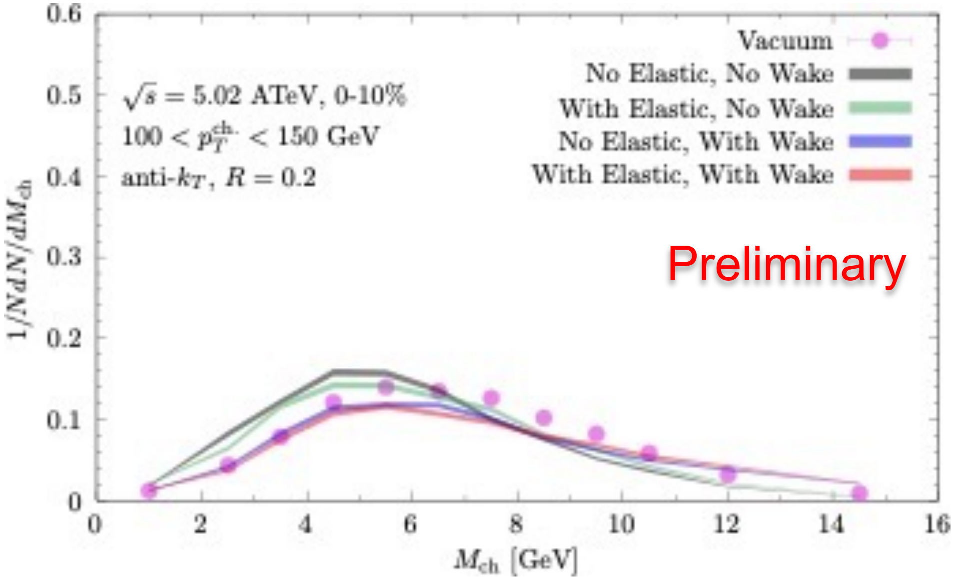

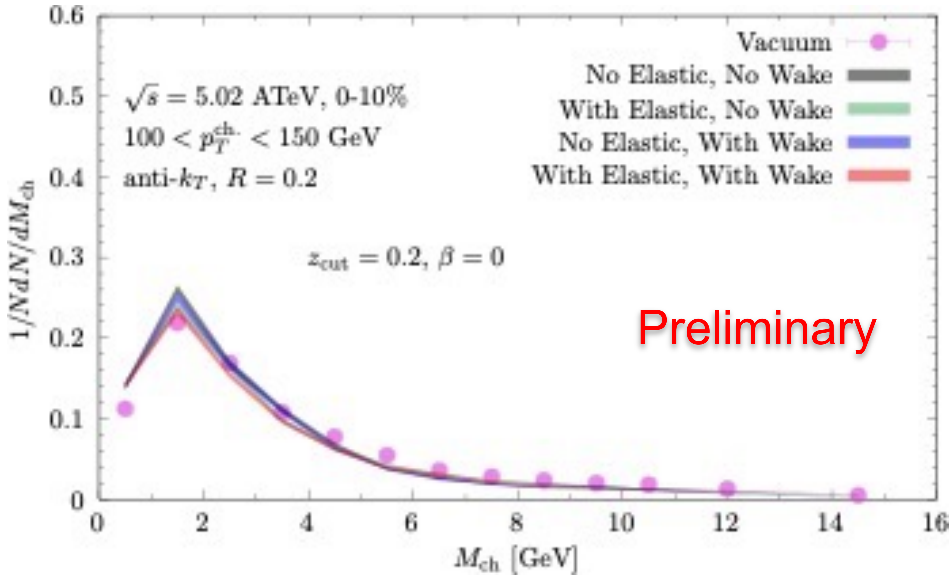

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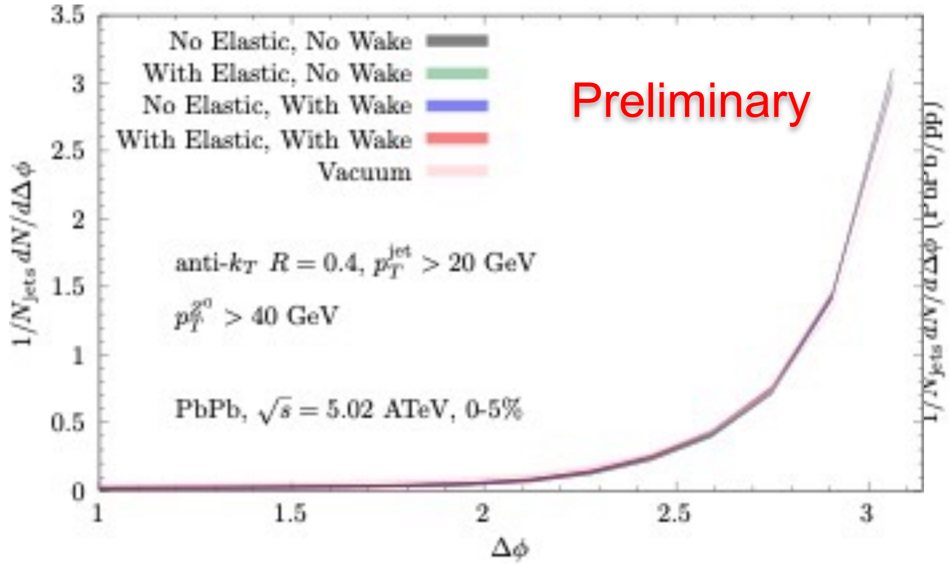
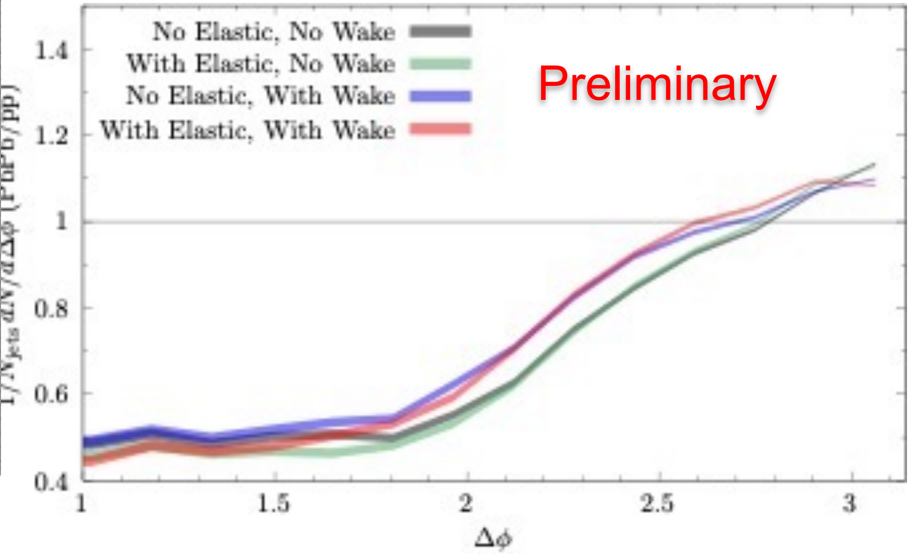
Z-Jet Acoplanarity

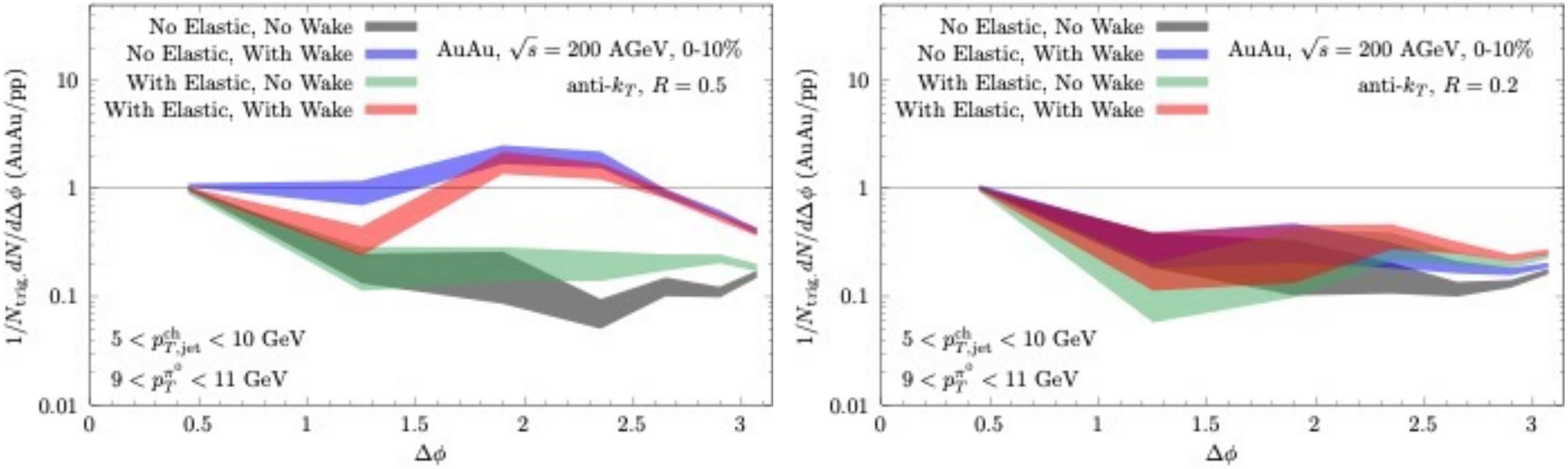




- Study acoplanarity in boson-jet system: Z-jet.
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Similar conclusions for acoplanarities at even lower p_T , via hadron—charged-jet correlations. Should look also Gamma-D, $D\overline{D}$ 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

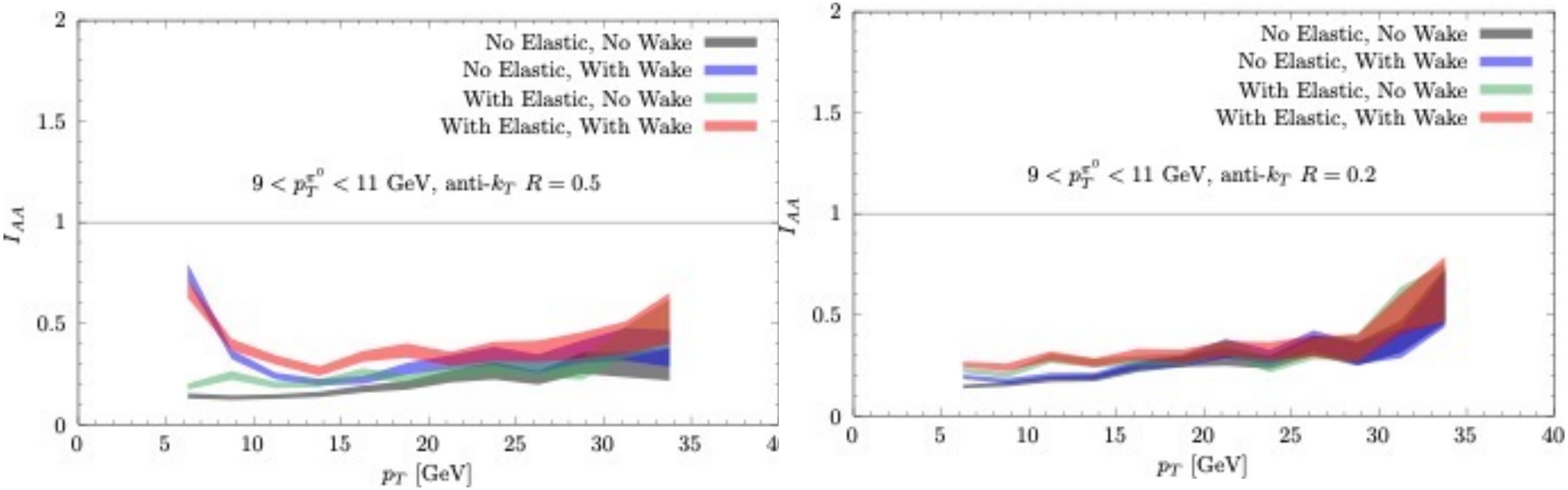
Preliminary



- 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
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron--Charge-Jet Acoplanarity, RHIC energy

Preliminary



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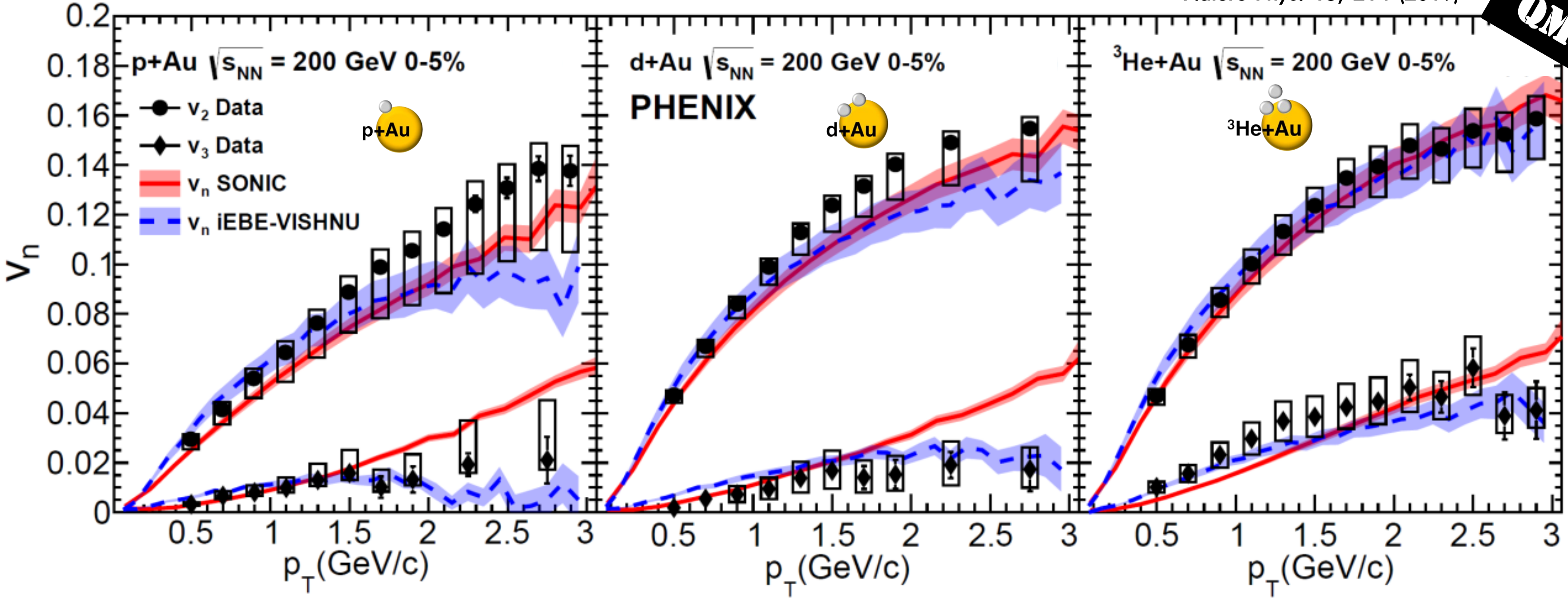
Collectivity in small systems

Nature Phys. 15, 214 (2019)

QM19

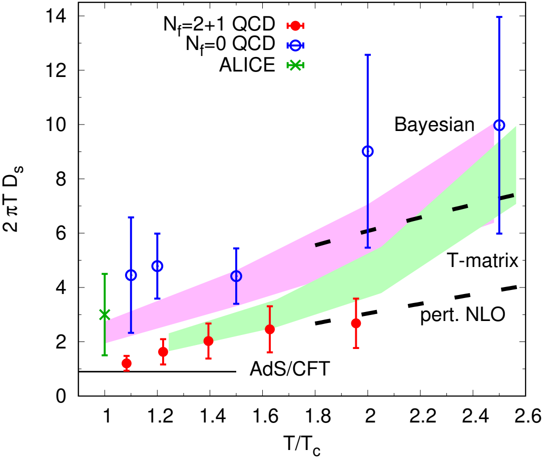


- Evidence of QGP droplets in small collision systems
- Smaller v_2 in p+Au and larger v_3 in ^{3}He+Au

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 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:

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

where

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

- 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. . .