Looking at Protons Through a QGP Lens

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2026 Strong and Electroweak Matter 2026

Helsinki, Finland; August 17, 2026

Quark-Gluon Matter
Under Pressure

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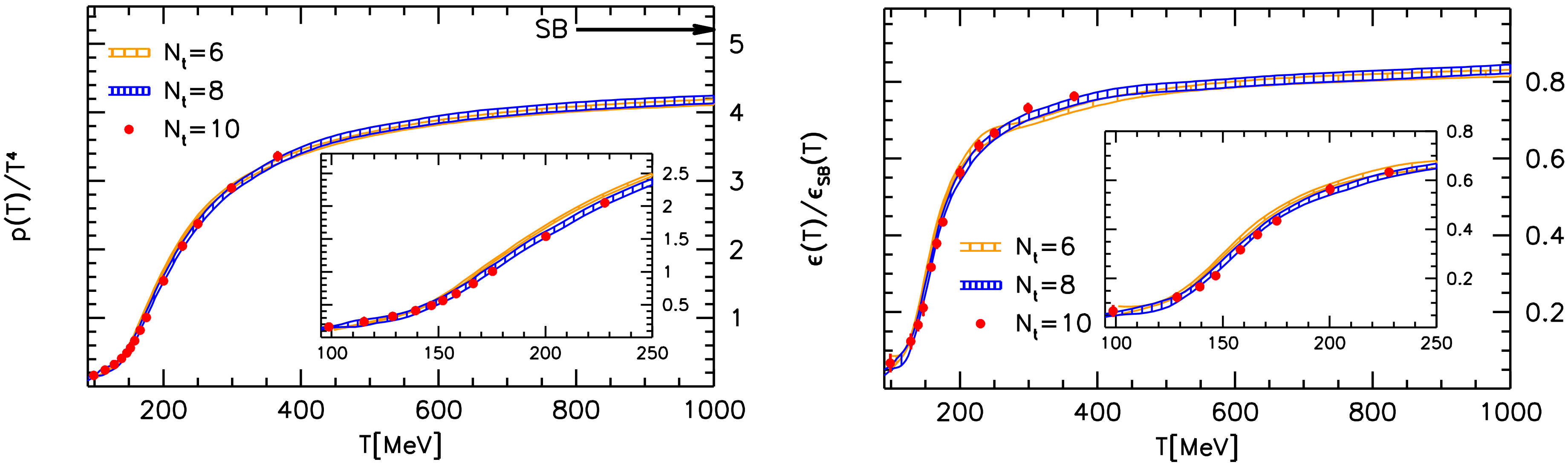
QGP Thermodynamics

Endrodi et al, 2010



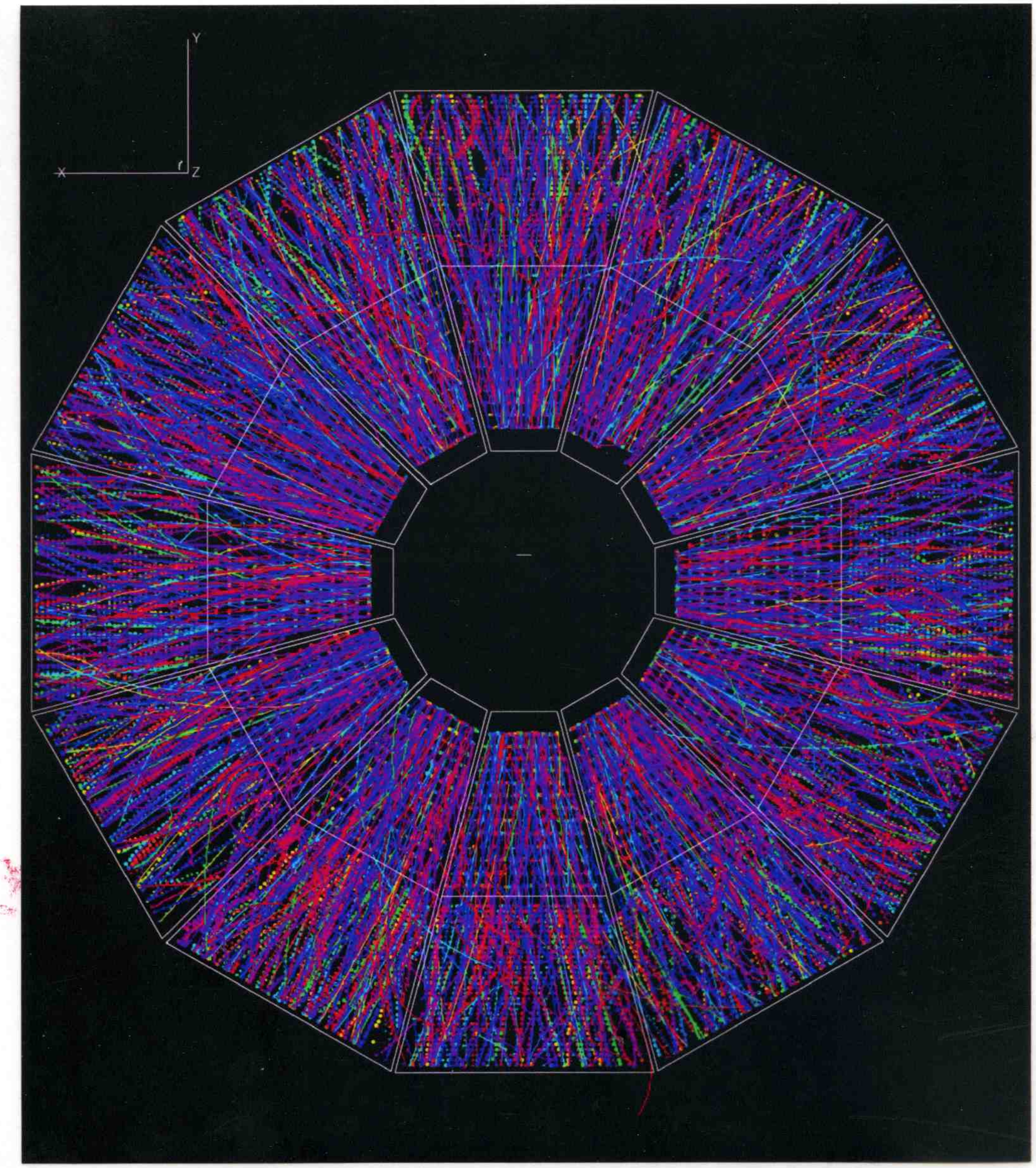
Above $T_{\text{crossover}} \sim$ 150 MeV (1.7 trillion degrees), QCD = QGP. QGP pressure and energy and entropy can be calculated reliably.

P(5 trillion degree quark matter)=P(430 MeV quark matter) $=2.5\times10^{31}$ atmospheres!! Hot quark matter, under pressure! $=7\times10^{24}\times$ pressure at the center of the earth...

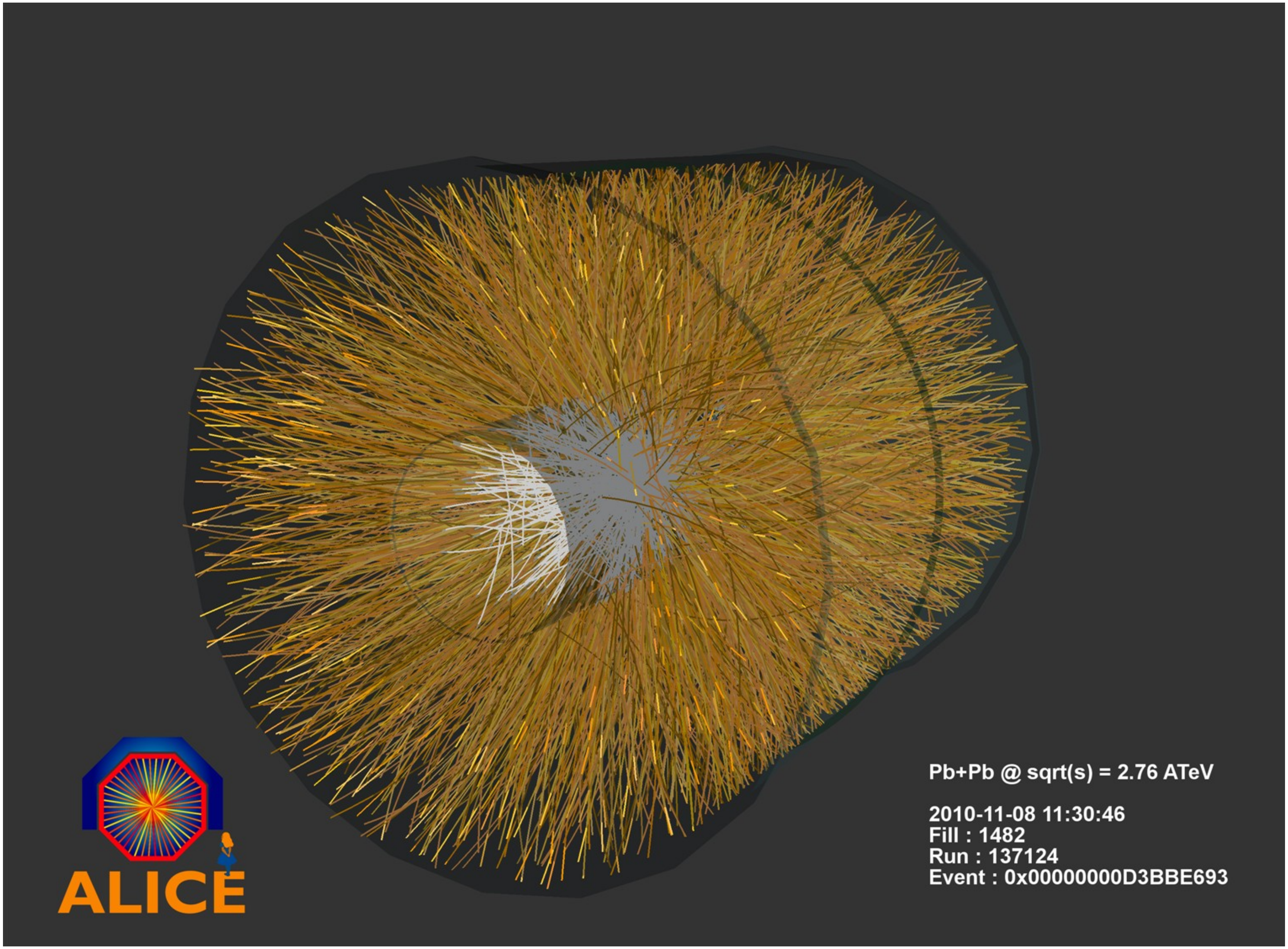
BUT: Although its pressure is almost that of ideal, noninteracting gas, QGP, this stuff is *very* different in its dynamical properties...

Hot Quark Matter Dynamics

- Understanding what hot quark matter is *actually* like, how it behaves, had to wait until scientists reproduced droplets of it!! By accelerating, and colliding, heavy nuclei to make droplets of hot quark matter.
- In 1983, Busza and Goldhaber calculated that collisions with energies > 100 GeV were needed. Almost a factor of 100 greater than accelerators could produce in 1983.
- Since 2000, the Relativistic Heavy Ion Collider, RHIC at Brookhaven National Lab near New York, achieves 200 GeV collisions of Au nuclei. Since 2010, the Large Hadron Collider, LHC at CERN near Geneva, achieves 2700-5000 GeV collisions of Pb nuclei.
- Recreating “Little Bangs”. Only 10^{-14} m in size. Hot quark matter explodes, expands, cools, forms ordinary protons and it’s cousins within 10^{-22} seconds.



STAR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Hot Quark Matter Dynamics

- **Understanding what hot quark matter is *actually* like, how it behaves, had to wait until scientists reproduced droplets of it!! By accelerating, and colliding, heavy nuclei to make droplets of hot quark matter.**

- **These collisions really are making little droplets of hot big bang matter!**

- **But what we see is the debris, after the hot matter has exploded.**

- **How can we learn about the behavior of the hot matter produced in the collision? What have we learned?**

Hot Quark Soup!

- Surprise! By 2005, analyses of RHIC data on how *asymmetric* blobs of hot Big Bang matter expand (explode) revealed that trillions-of-degrees-hot quark matter is a LIQUID!!
- Rutherford looked for "pudding", and unexpectedly found point-like nuclei in atoms. Friedman, Kendall and Taylor unexpectedly found point-like quarks in protons.
  This surprise has the opposite character! Looking for a hot gas, found a hot liquid.
- Hot quark soup turns out to be *very* liquid-like. Less internal dissipation as it flows (quantified via a parameter called η/s) than in all other known liquids except one.
- The discovery that it is a strongly coupled liquid makes hot quark soup interesting to a broader scientific community. (Much more interesting than a gas.)
- How was this discovery made? Not à la Rutherford...

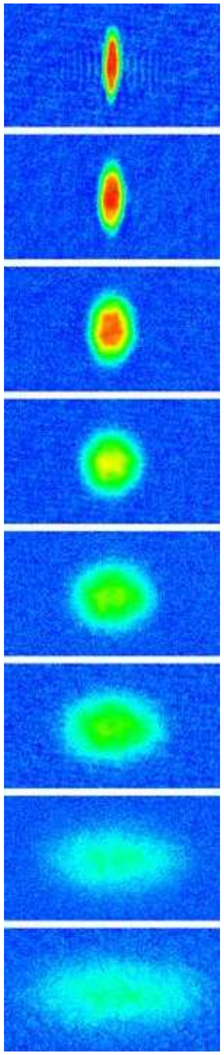
Ultracold Fermionic Atom Fluid

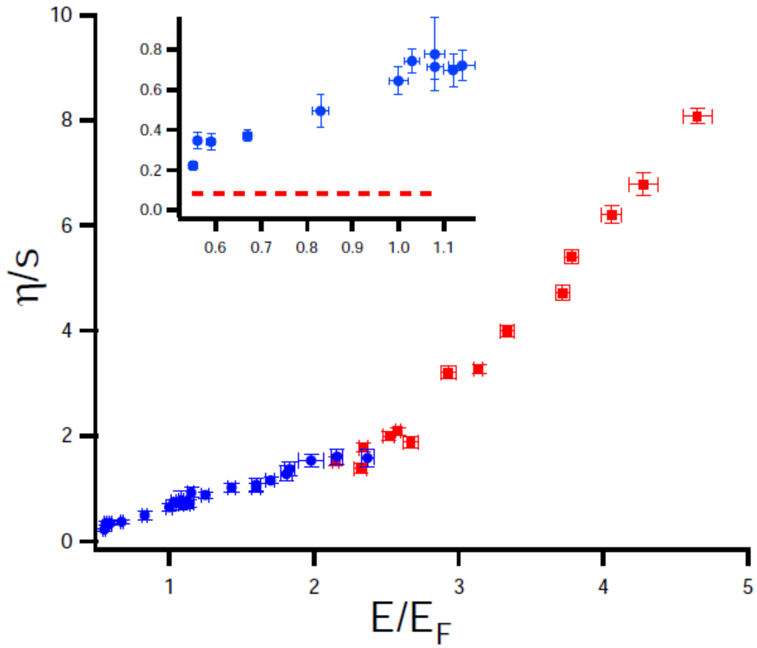
- The one terrestrial fluid with η/s comparably small to that of QGP.
- NanoKelvin temperatures, instead of TeraKelvin.
- Ultracold cloud of trapped atoms, with their interactions tuned to be infinite. A strongly coupled liquid indeed.
- Data on hydrodynamic flow patterns can be used to extract η/s as a function of temperature...

Viscosity to entropy density ratio

consider both collective modes (low T)

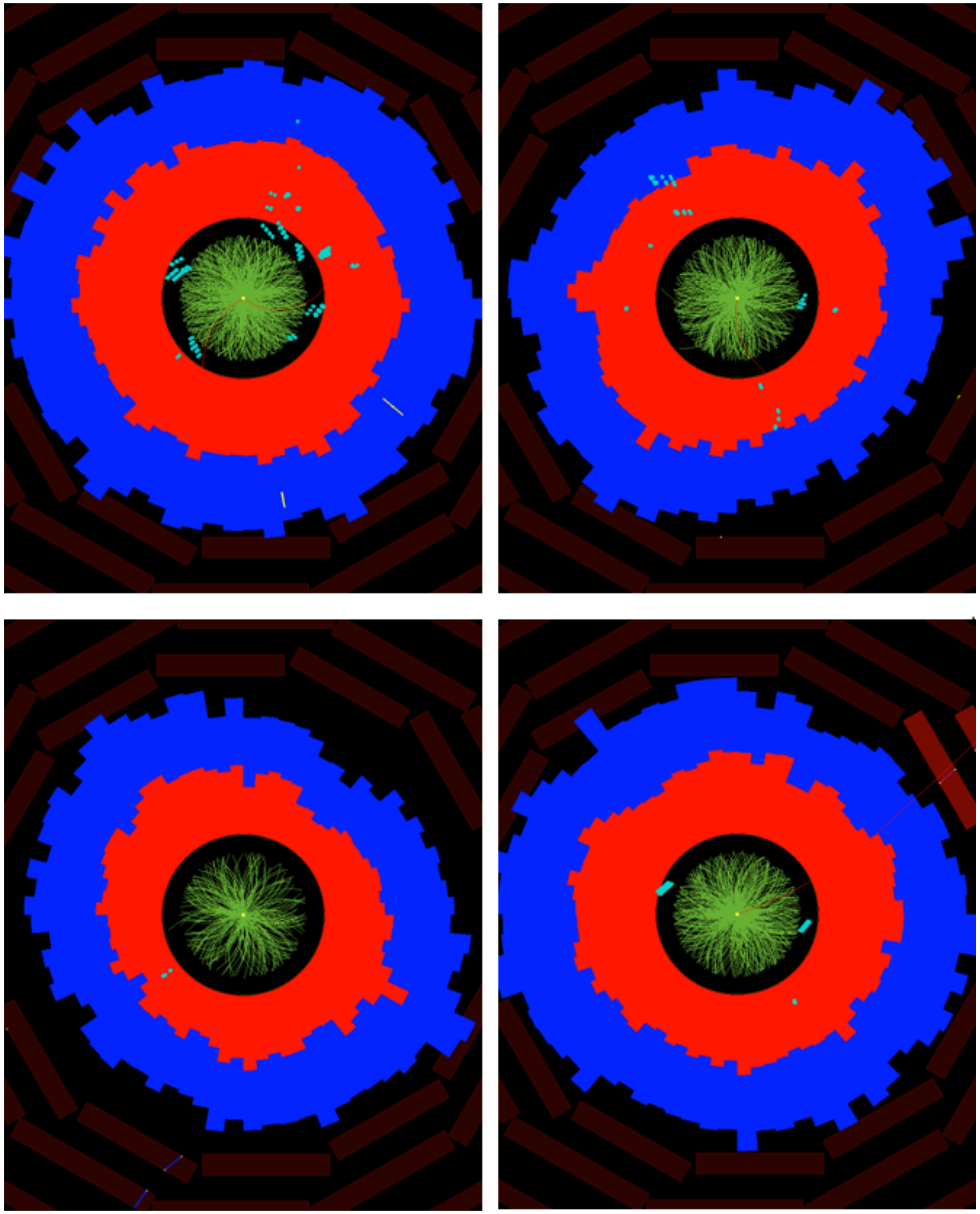
and elliptic flow (high T)





Cao et al., Science (2010)

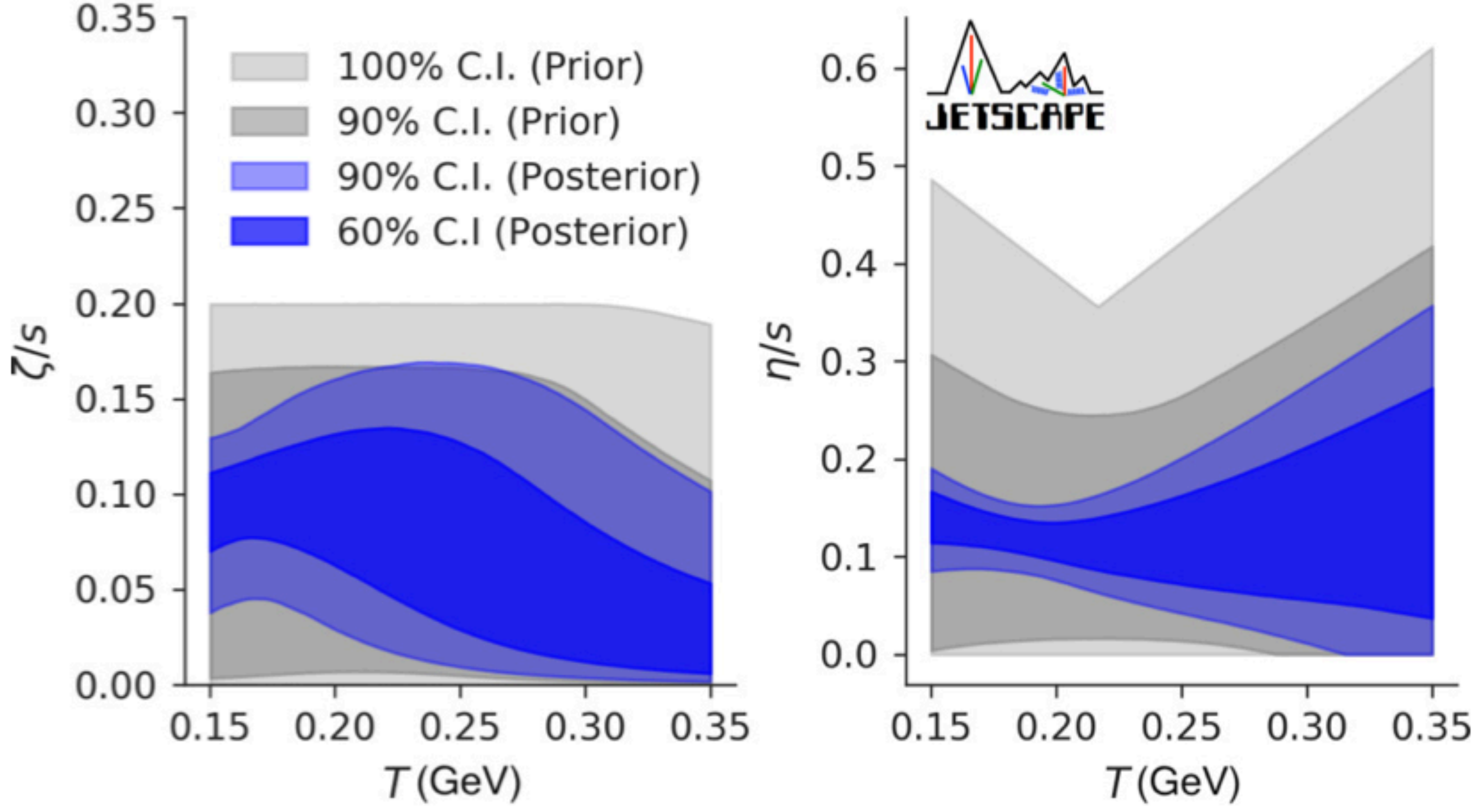
$$\eta/s \leq 0.4$$



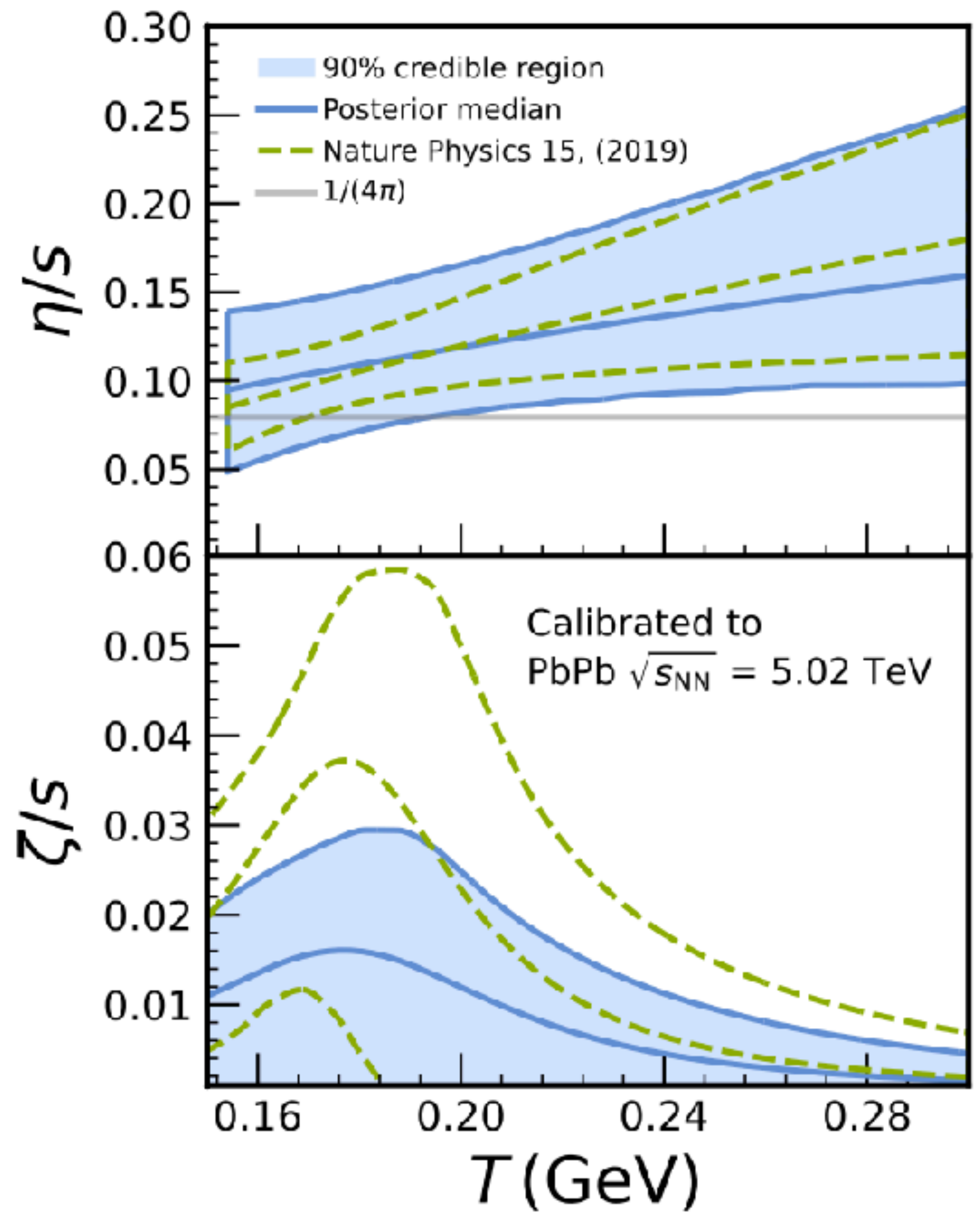
Bulk EoS: Non-equilibrium

Combined Bayesian analysis of Au+Au (RHIC) and Pb+Pb (LHC)

JETSCAPE, Phys. Rev. C **103** (2021) 054904



Parkkila, Onnerstad & Kim, Phys. Rev. C **104** (2021) 054904



Hot Quark Soup!

- **Hydrodynamic analyses of how asymmetric blobs of hot Big Bang matter (produced in off-center collisions) explode reveal a very liquid-like liquid, with $0.1 < \eta/s < 0.2$.**
- **η/s is between 1 and 10 for ordinary liquids, and is > 100 for gases. Hot quark soup is "more hydrodynamic than the original hydro".**
- **Quarks and gluons in hot quark soup diffuse, without being confined in protons. Hot quark soup flows. Quarks and gluons are always bumping into each other. Very much *not* a gas; mean free paths so short as to be hard to define.**
- **Quarks and gluons are *not* confined — but also *not* free.**
- **Aside: $\eta/s = 1/(4\pi) \approx 0.08$ for the "hot soup phases" in all known QCD-like theories with strongly coupled phases that are "holograms" of a 4+1-dimensional gravity theory "heated by" a 3+1-dimensional black hole.**

Jets as Probes

- Goal long established: see microscopic particulate structure of liquid QGP at short length scales; see jet partons scatter off QGP quasiparticles; “Rutherford”; “DIS”.
- Are we there? Getting close. QGP sees jet substructure!
- PbPb and AuAu collisions: parton energy loss and jet wakes. Interesting in their own right. Substantial theory advances, recent and coming. Substantial experimental advances, recent and coming. Eg unambiguous evidence for jet wakes. Jet wakes can teach us about how QGP equilibrates.
- New jet substructure observables: Soft Drop splitting angle R_g. Lund plane. Energy correlators. From HEP, but we are putting them to better uses!
- Oxygen-oxygen collisions may be perfect arena in which to see hard scattering of jet partons off QGP quasiparticles.
- Major advances in experiment to come... sPHENIX, LHC Runs 4&5

Add Molière Scattering . . .

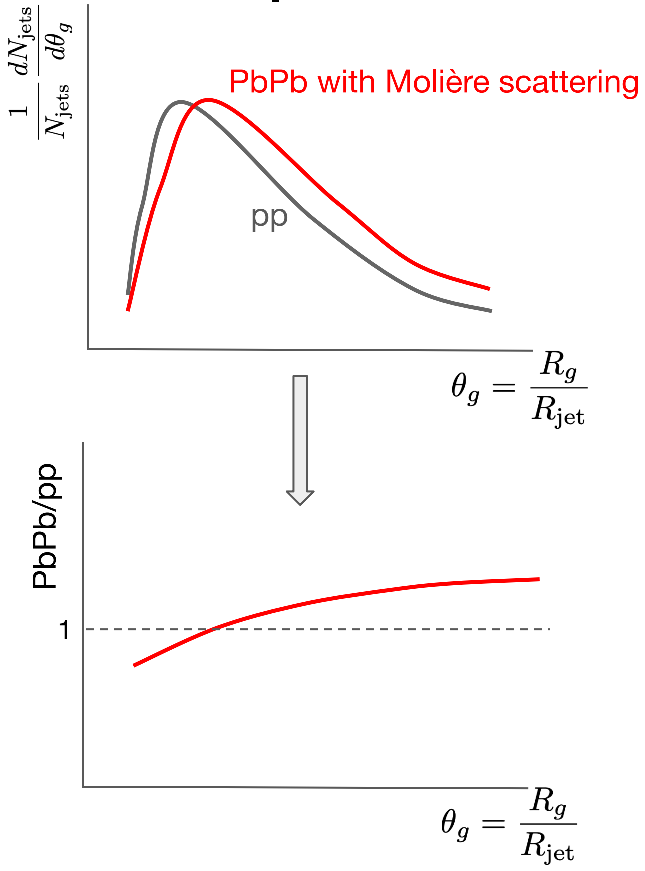
- QGP, at length scales $\mathcal{O}(1/T)$, is a strongly coupled liquid. Flow, and jet observables sensitive to parton energy loss, are well-described (eg in hybrid model) in such a fluid, without quasiparticles.
- At shorter length scales, probed via large momentum-exchange, asymptotic freedom $\rightarrow$ quasiparticles matter.
- High energy partons in jet showers *can* probe particulate nature of QGP. Eg via power-law-rare, high-momentum-transfer, large-angle, Molière scattering
- “Seeing” such scattering is first step to probing micro-scopic 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. . .

Why Look for Molière Scattering in O+O Collisions

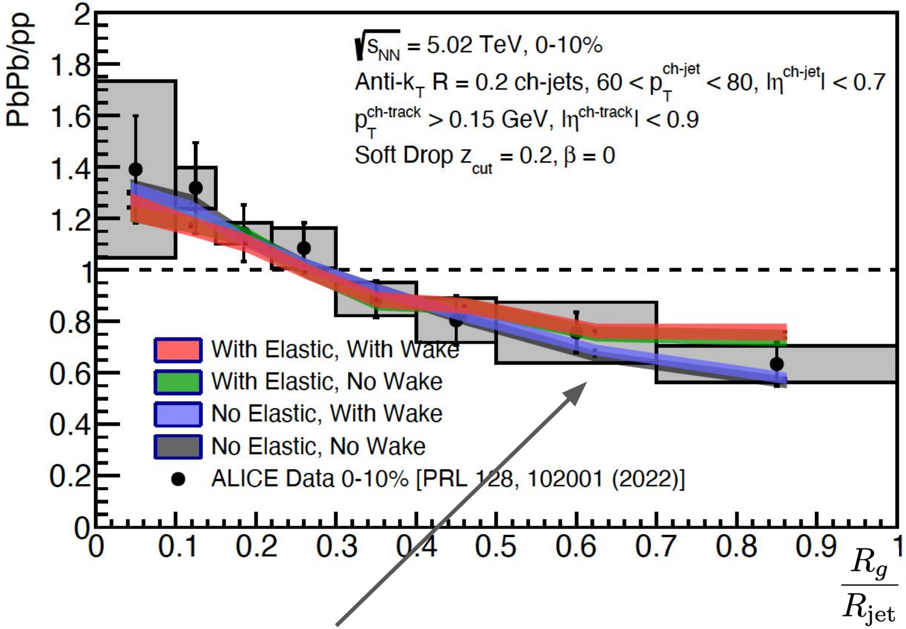
- The challenge in Pb+Pb collisions: how to discern effects of Molière scattering (makes jets sprout an extra prong, and so get wider) given the confounding effect of energy loss + selection bias (jets you select in Pb+Pb are those that lose less energy, which are the narrower jets).
- First O+O collisions @LHC in July 2025. And, the last RHIC run, in February 2026, was an O+O run with sPHENIX collecting 181% of the data they hoped for.
- First show that jets do lose energy in O+O collisions. Then, because they lose *less* energy than in Pb+Pb, see that Molière scattering has distinctive observable consequences!
- "Seeing" such scattering is first step to probing microscopic structure of QGP.

Soft Drop Angle in PbPb Collisions

Naive Expectation



Reality



PbPb jet sample is biased towards those that have lost the least energy, which tend to be narrower

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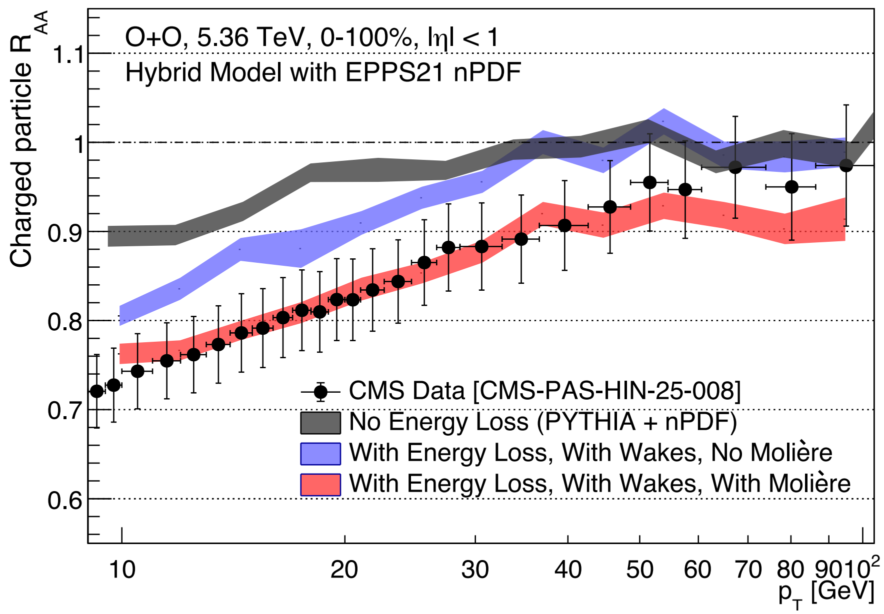
Jets as Probes

Kudinoor. Lin. Pablos. KR, 2603.23596



Earliest hard probes measurements in OO collisions from ALICE, ATLAS, CMS shown in December. sPHENIX and STAR data coming soon — tremendous OO run at RHIC.

Effects of large momentum transfer, $2 \to 2$ elastic scattering — Molière scattering — linear with in-medium path length L, so relatively more important in OO than PbPb.

First hadron R_{AA} and dijet asymmetry data consistent with importance of Molière scattering…

… but this is a model DEpendent comparison.

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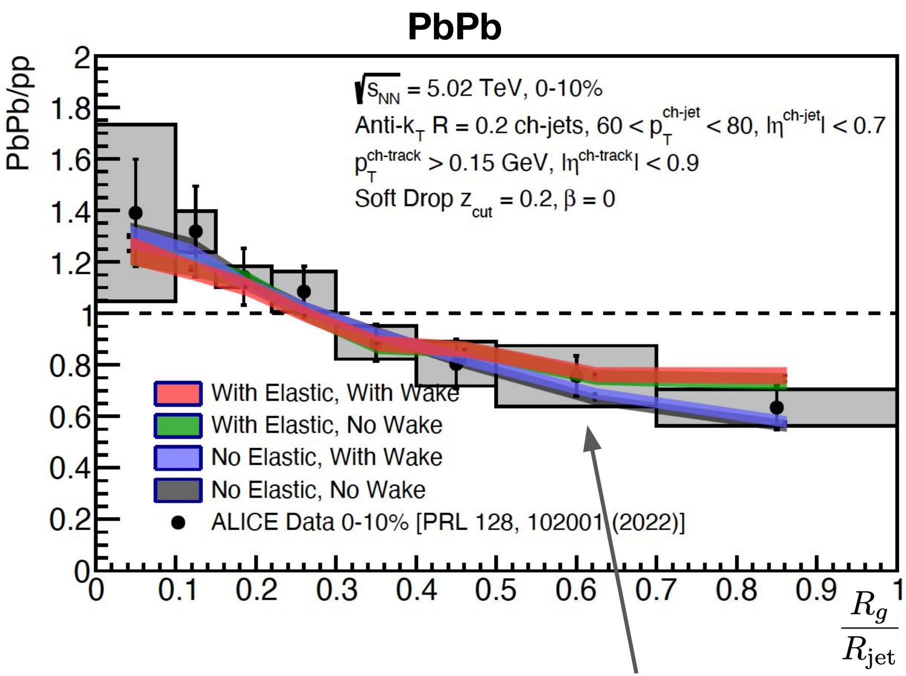
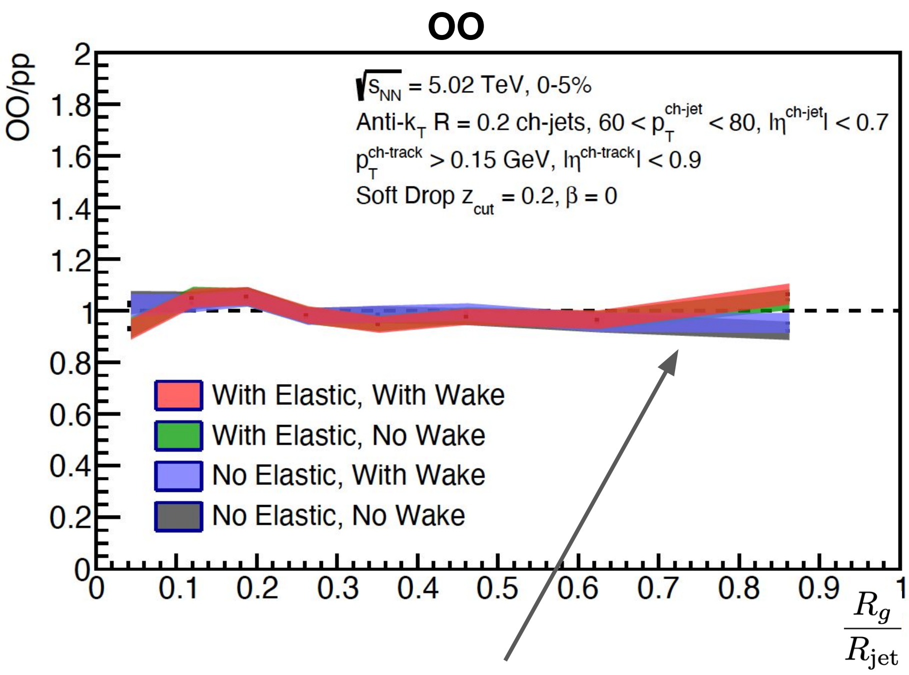
Soft Drop Angle for R = 0.2 Jets



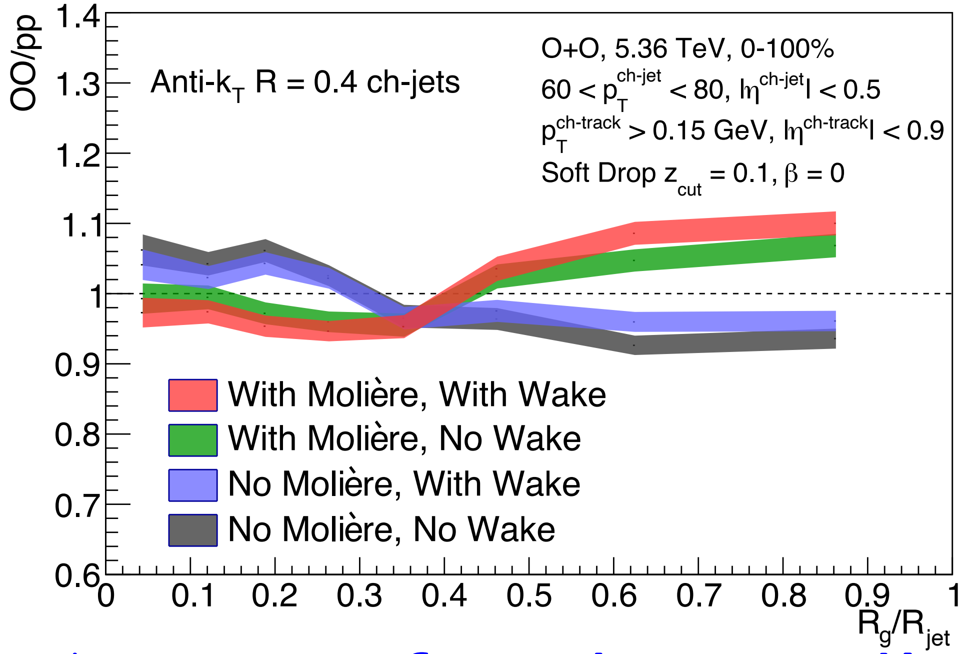


PbPb jet sample is biased towards those that have lost the least energy, which tend to be narrower

Effects of selection bias and jet energy loss are minimal ⇒ Flatter OO/pp ratio

Jets as Probes

Kudinoor, Lin, Pablos, KR, 2603.23596



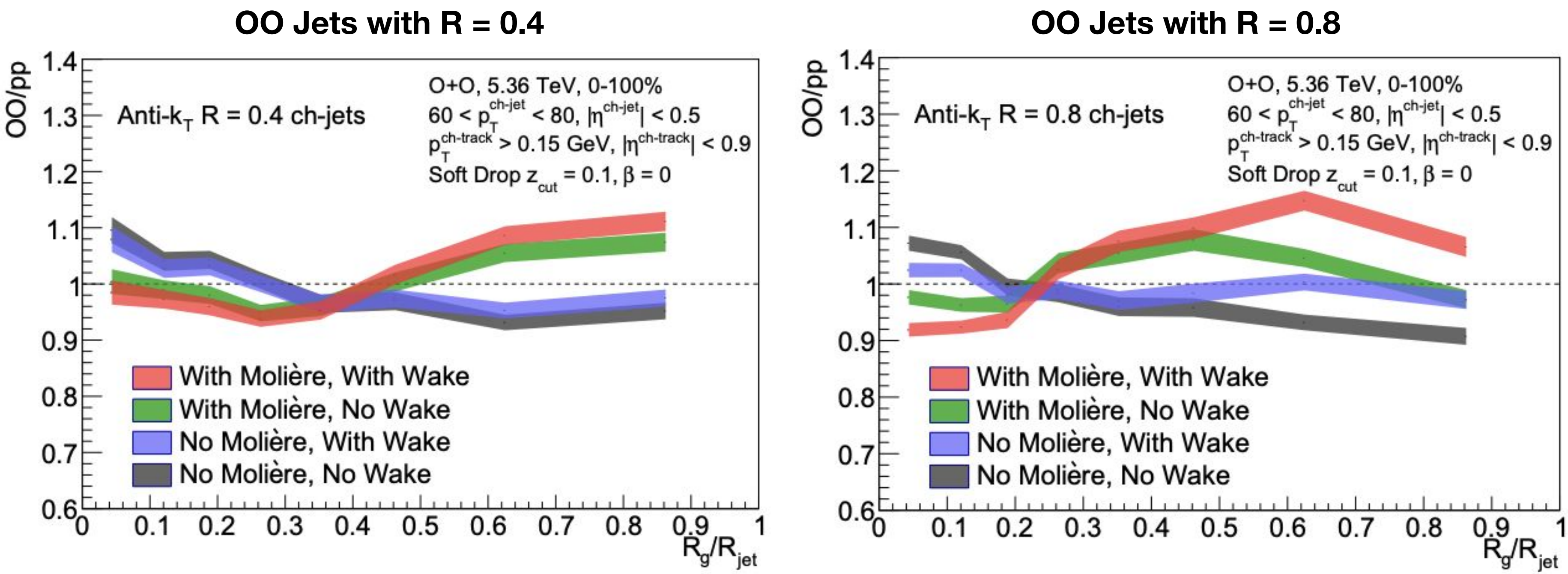
R_g is a *groomed* measure of angular separation between semi-hard structures within jets. Just what we need.

Grooming greatly reduces effects of jet wakes. But, in PbPb, very large confounding effects from selection bias due to energy loss. Not here!

Seeing OO/pp ratio of R_g above unity, in experimental data, would be a distinctive, model-independent, signature of hard scattering of jet partons off QGP.

Soft Drop Angle for R = 0.4 and R = 0.8 Jets

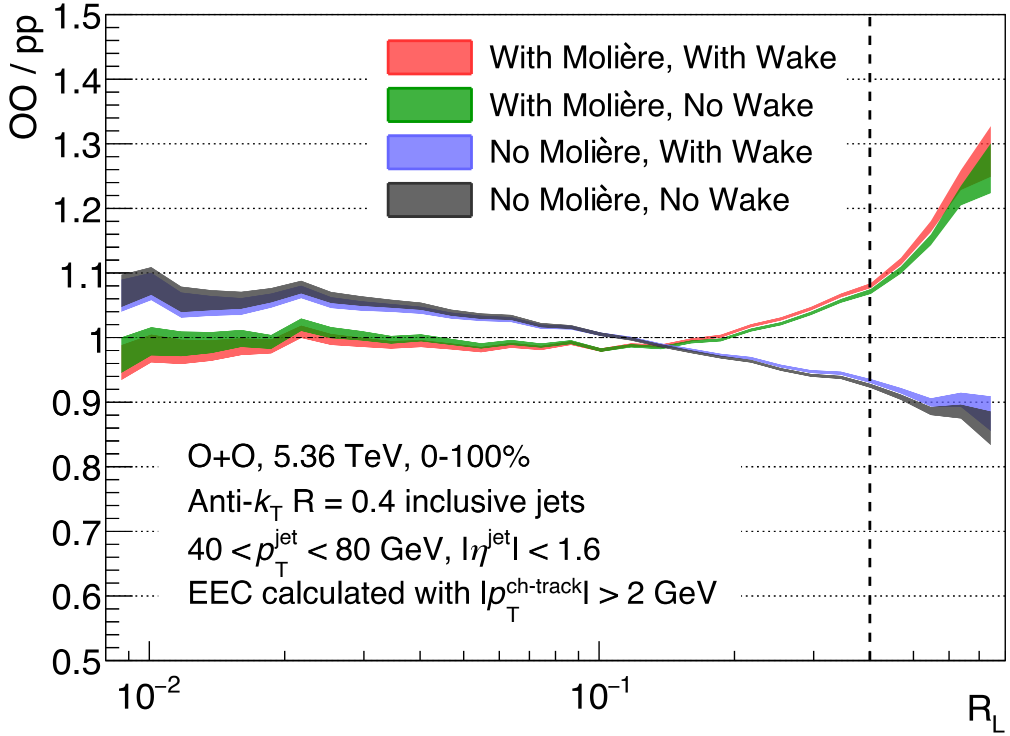
2603.23596 [Kudinoor, Lin, Pablos, Rajagopal]



Distinctive consequence of Molière scatterings:
More jets with R_g > 0.2 in OO collisions than in pp collisions

Jets as Probes

Kudinoor, Lin, Pablos, KR, 2603.23596



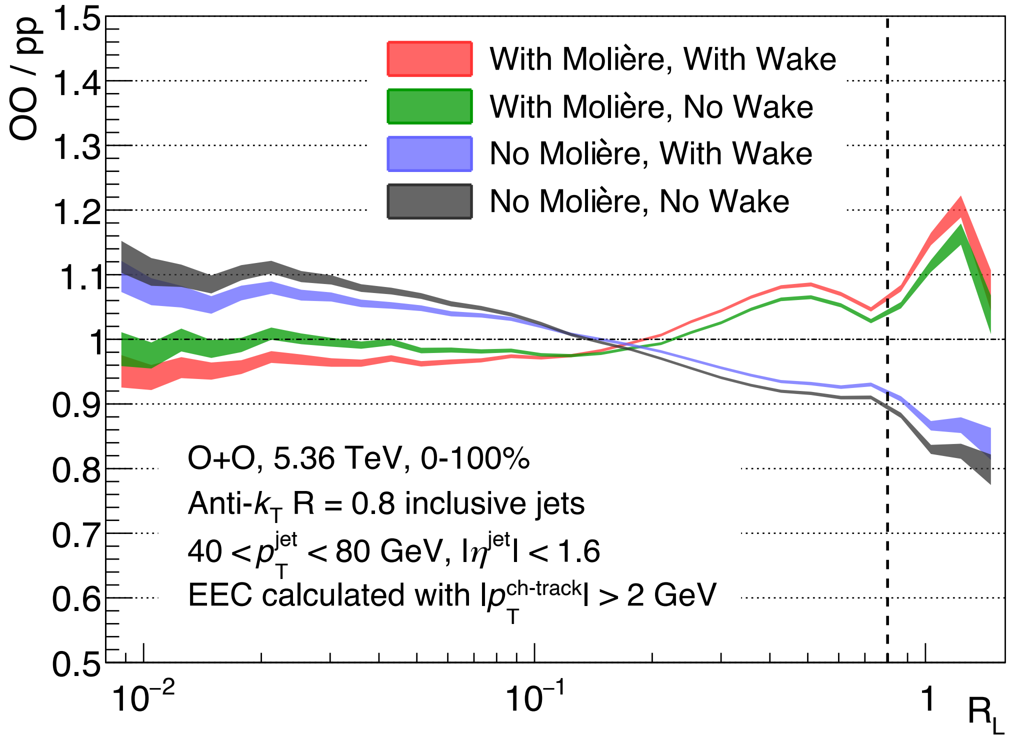
Energy-energy correlator (EEC) is also well-suited for the task — *if* "groomed" by imposing a track cut, $p_T^{\text{track}} > 2$ GeV.

Little effect of jet wakes. Confounding effects of energy loss (smaller in OO) overwhelmed by effects of hard scattering.

Seeing OO/pp ratio of EEC above unity, in experimental data, would be a distinctive, model-independent, signature of hard scattering of jet partons off QGP.

Jets as Probes

Kudinoor, Lin, Pablos, KR, 2603.23596



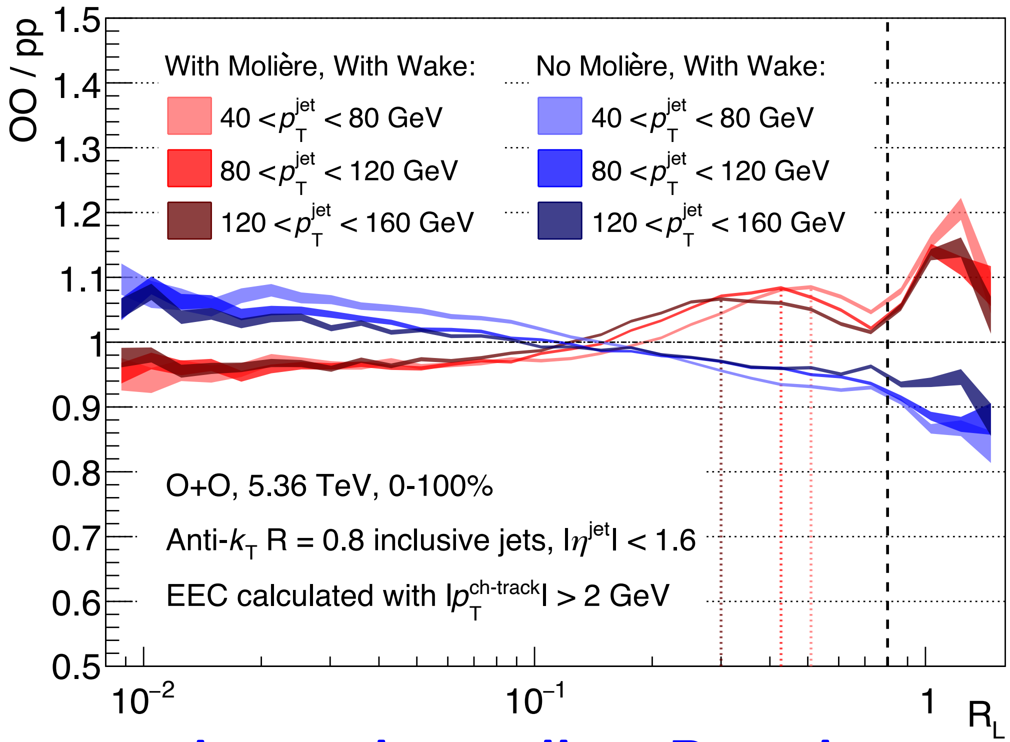
Energy-energy correlator (EEC) is also well-suited for the task — *if* "groomed" by imposing a track cut, $p_T^{\text{track}} > 2$ GeV.

In OO collisions, can make these measurements in wider jets with $R_{\text{jet}} = 0.8$. Reveals a "bump" at $R_L \sim 0.5$!

Is this the angular scale of deflections due to Molière scattering? If so, seeing this bump in the OO/pp EEC ratio in experimental data, would be of exceptional interest!

Jets as Probes

Kudinoor, Lin, Pablos, KR, 2603.23596



The bump moves toward smaller R_L when you increase jet p_T — what you expect if this is the angular scale of hard scattering of jet partons off QGP quasiparticles!

Seeing this bump in the OO/pp EEC ratio in experimental data, at an $0.2 < R_L < R_{\rm jet} \sim 0.8$, and seeing its jet-$p_T$-dependence, would be a *third* distinctive, model-independent, signature of hard scattering of jet partons off QGP.

Jets as Probes

- **Goal in sight! See microscopic particulate structure of liquid QGP at short length scales; see jet partons scatter off QGP quasiparticles. To get there we need** ...

- **Measurement of jet substructure observables in OO and PbPb from both RHIC and LHC. If QGP@RHIC more strongly coupled, hard scattering of jet partons off QGP quasiparticles should be less apparent.**

- **OO collisions may be perfect arena for seeing hard scattering of jet partons off QGP. PbPb collisions** *are* **perfect arena for studying jet wakes, the response of the QGP.**

- **Luminosity in LHC Runs 4&5. Both PbPb and OO. 10x the current OO statistics will make a substantial impact.**

- **Advances in both theory and modeling.**

- **Need Bayesian analyses of jet and heavy flavor data together, to constrain parameters governing jet quenching, resolution,** *scattering off QGP quasiparticles, microscopic properties of QGP*, **drag, diffusion, hadronization.**

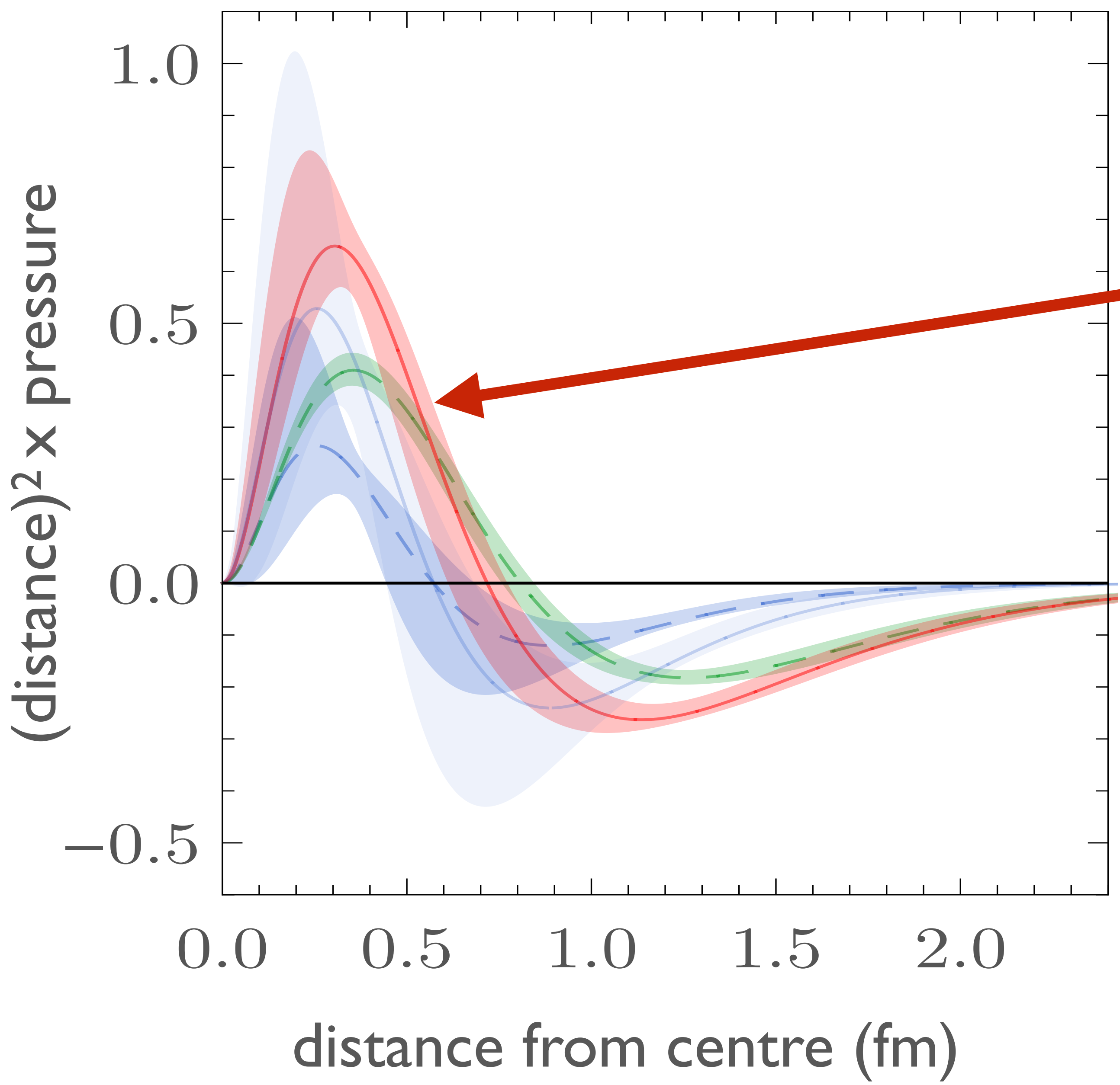
Recall Jets as Probes of QGP...

- **What I described previously was outstanding progress toward seeing** *individual* **quasiparticles, at short length scales, in QGP. And the path to doing so.**
- **The path to addressing the question: How can we use jets to see the inner workings of QGP?**
- **But, we** *know* **that QGP is a strongly coupled liquid. That means that short-range quasiparticle-quasiparticle correlations are strong and important.**
- **Could we** *ever* **see how the quasiparticle right next to the quasiparticle that a jet parton just struck and scattered off responds? Could we ever see strong** *Short-Range Correlations* **in QGP?**
- **This would take our investigation of the microscopic structure of QGP to a new level ...**
- **Surely impossible. Or is it?**

Quark-Gluon Matter Under Pressure

- **Where else do we find quark-gluon matter under pressure?**
- **In a proton!! Protons form from tiny drops of QGP, 10-20 microseconds after the big bang, or 10**$^{-22}-10^{-21}$ **seconds after a HIC. What is the pressure inside a proton?**
- **Answer:** $\sim$ **(0.07-0.7) GeV/fm**$^3 \sim (1.1-11)\times 10^{29}$ **atmospheres!** [Extracted from SIDIS data (Burkert, Elouadrhiri, Girod, '18) and from lattice calculations (Shanahan, Detmold '18; Pefkou, Hackett, Shanahan '21, '23)]
- **This is pressure of QGP at** $T = T_p \sim 155-200$ **MeV, at or just above** T **at which it falls apart into a mist of protons!**
- **Remarkably, protons have kept this high interior pressure since they formed.**
- **Even more remarkably, protons don't explode! That is the essence of confinement — which squeezes/compresses a tiny bit of 155 MeV QGP into each proton at its birth.**

Pressure inside the proton



Total pressure including **gluon** (lattice QCD) and **quark** (experiment) contributions

- Total pressure by combining theory + experiment
- Peak pressure near centre ~10^{35} Pascal, greater than estimated for neutron stars
- Gluons extend radial pressure distribution

[V. D. Burkert et al, Nature 557 (2018)]

[*Phys.Rev.Lett.* 122, 072003 (2019), *Phys.Rev.D* 99, 014511 (2019), *Phys.Rev.D* 108, 114504 (2023), *Phys.Rev.Lett.* 132, 251904 (2024)]

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- Answer: $\sim$ (0.07-0.7) GeV/fm^3. This is the pressure of QGP at $T = T_p \sim 155 - 200$ MeV, at or just above T at which it falls apart into a mist of protons!
- Note: spherical droplet of QGP with $V_p \equiv 938$ MeV$/\varepsilon(T_p)$, $\varepsilon(T)$ from lattice QCD, and radius 0.86 fm / 0.49 fm has $T_p =$ 155/200 MeV, ie. ε and pressure of a proton.
- Remarkably, protons have kept this high interior pressure since they formed.
- Even more remarkably, protons don't explode! That is the essence of confinement — which squeezes/compresses a tiny bit of 155 MeV QGP into each proton at its birth.

Entropy of Protons through a QGP Lens

- **If pressure in a proton is pressure of hot quark-gluon plasma with $T = T_p \sim 155 - 200$ MeV...**
- **What about entropy? The hot QGP from which one proton forms after the Big Bang has $S_{\text{thermal}} \sim (5.2 - 7.3)k_B$. Isn't the entropy of a proton zero? What about the second law of thermodynamics?**
- **Quantum state of a proton has *entanglement entropy*. Three estimates, each qualitative, with different uncertainties: $(7-8)k_B$; $(7-8)k_B$; $(5-9)k_B$** [Kharzeev, KR, arXiv:2605.19058]
- **Thermal entropy from Big Bang QGP $\to$ entanglement entropy inside protons $\to$ released as thermal entropy (and more entropy produced) when nuclei collide.**
- **Confinement (the essence of confinement?) as the rearrangement of thermal entropy into entanglement entropy!**

Entropy of Protons through a QGP Lens

Kharzeev, KR 2605.19058

- **One estimate (that I won't describe today) extrapolates from past work quantifying longitudinal entanglement entropy of struck parton in DIS with the other partons.**
- **Second estimate (that I also won't describe today) is an attempt to use basic facts that we know about protons to estimate the entanglement entropy of the three valence quarks, by tracing over all the rest.**
- **Both give similar rough estimate:** $S_{\text{entanglement}}/k_B \sim 7-8$, **with uncertainties hard to quantify, but different.**
- **Third estimate starts by taking seriously the notion that a proton has an internal effective temperature** $T_p \ldots$. **Although** $\rho = |p\rangle\langle p|$ **has** $\text{Tr}\rho \ln \rho = 0$, **if we decompose the Hilbert space into resolved (infrared) and unresolved (ultraviolet) sectors, the reduced density matrix** $\rho_{\text{IR}} = \text{Tr}_{\text{UV}}|p\rangle\langle p|$ **can take an approximately thermal form.**

Entropy of Protons through a QGP Lens

Kharzeev, KR 2605.19058; with thanks to Mark Srednicki

- **A somewhat formal argument, that does not yield a quantitative estimate...**
- **If $E_p = \mathrm{Tr}\rho_p H$, where the reduced density matrix of the proton takes the thermal form**

$$\rho_p = \frac{1}{Z(T_p)} e^{-H/T_p} \; , \qquad Z(T_p) = \mathrm{Tr} e^{-H/T_p}$$

where T_p is some effective internal temperature characterizing the entanglement spectrum of the quantum state of the proton, not the temperature of an external bath, then formally, equating $E_p = \mathrm{Tr}\rho_p H = -\partial/\partial\beta \ln Z$ serves to fix T_p in terms of E_p.

- **Then, $S/k_B = -\mathrm{Tr}\rho_p \ln \rho_p$. Voilà!**

Entropy of Protons through a QGP Lens

Kharzeev, KR 2605.19058

- **A somewhat informal argument, that yields an estimate** ...
- **A proton has a Hagedorn density of excited states with invariant mass** M**:** $\rho_p^H(M) = A_p \exp(M/T_H)/(M^2+M_r^2)^{5/4}$ **where a fit to masses of** > 3000 **hadrons gives** $M_r = 0.5$ GeV**,** $T_H = 0.1672$ **GeV, and** $A_p < A = 0.4735$ **GeV**$^{3/2}$**.**
- **Take the idea of** T_p **seriously: probability that proton is found in an excited state with mass** M **is**

$$p(M) = \frac{1}{Z}\rho_p^H(M)\exp\left(-\frac{M}{T_p}\right) \qquad Z = \int_{M_p}^{\infty} dM\,\rho_p^H(M)\exp\left(-\frac{M}{T_p}\right)$$

and

$$S/k_B = -\int_{M_p}^{\infty} dM\,\rho_p^H(M)\frac{p(M)}{\rho_p^H(M)}\ln\left(\frac{p(M)}{\rho_p^H(M)}\right) = \int_{M_p}^{\infty} dM\,p(M)\left(\frac{M}{T_p} + \ln Z\right)$$

Entropy of Protons through a QGP Lens

Kharzeev, KR 2605.19058

- $\rho_p^H(M) = A_p \exp(M/T_H)/(M^2 + M_r^2)^{5/4}$ **with** $M_r = 0.5$ GeV**,** $T_H = 0.1672$ **GeV, and** $A_p < A = 0.4735$ **GeV$^{3/2}$.**

- **Take the idea of T_p seriously: probability that proton is found in an excited state with mass M is**

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- **Note: Z is finite as long as $T_p < T_H$. Note: S depends on A_p only logarithmically; take $A_p = A/10$; lack of knowledge of $\ln A_p/A$ is a source of uncertainty.**

- **For $T_p = 155/160/165$ MeV, we find $S/k_B = 5.3/6.3/8.5$!!!**

- **Third estimate: $S \sim (5 - 9) k_B$.**

Entropy of Protons through a QGP Lens

Kharzeev, KR 2605.19058

- The agreement between the Gibbs entropy of the drop of QGP from which a proton forms at freezeout and three very different estimates of the internal (entanglement) entropy of a proton could be a quadruple coincidence.
- Or, will poking at this coincidence — and the questions it raises — advance our understanding of confinement, hadron structure, QGP, and the QCD crossover transition?
- How does idea that at the QCD transition Gibbs entropy of QGP rearranges into quantum entanglement entropy within hadrons help us to understand freezeout? Entropy production in collisions? Confinement?

Quark-Gluon Matter, Under Pressure

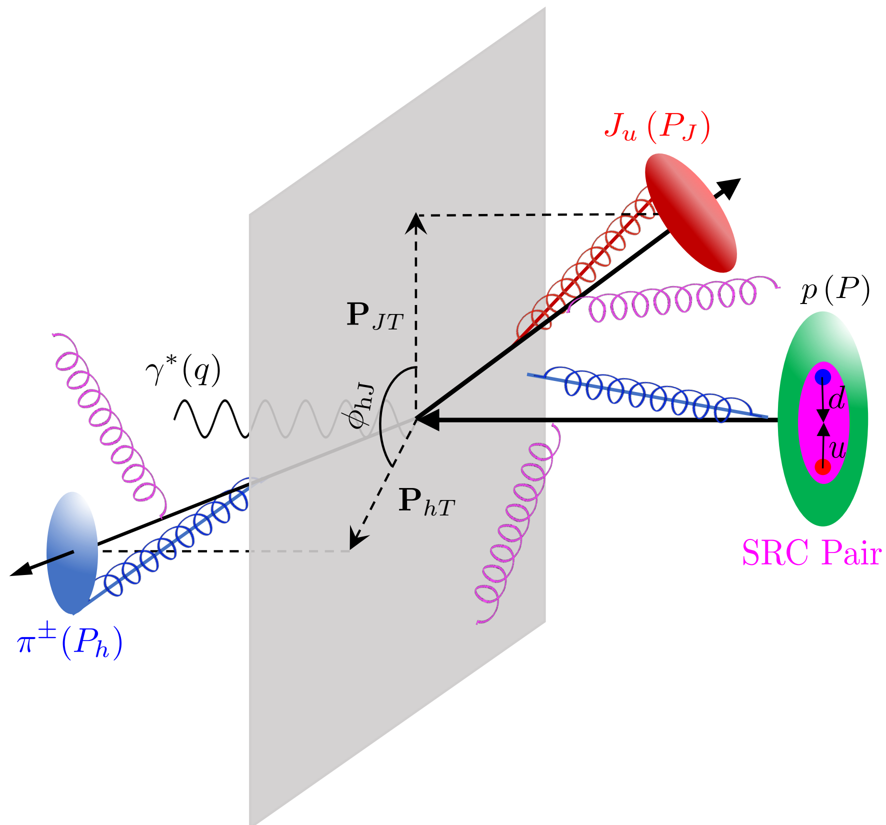
- **Protons form from tiny drops of QGP. The internal pressure, energy density,** *and entropy* **of a proton are comparable to that of the drop of QGP from which it formed.**

- **What further lessons can we learn about the interior of a proton from hot QGP? The same strong correlations that make QGP a liquid, and that give the proton its entanglement entropy, can be directly measured at the Electron-Ion Collider!!** [Peng, KR, Terry, 2606.17133]

- **QGP at temperatures** $\sim T_p$ **is a strongly coupled fluid: strong correlations between the momenta of fluid cells that are near each other in position space. Strong** *Short-Range Correlations*. **Macroscopic manifestation: strongly coupled liquid QGP. Can we see the microscopic mechanism, directly, within protons?? How can** *partonic SRCs* **be measured at the EIC?** [Peng, KR, Terry, 2606.17133]

An EIC Measurement. . .

[Peng, KR, Terry, 2606.17133]



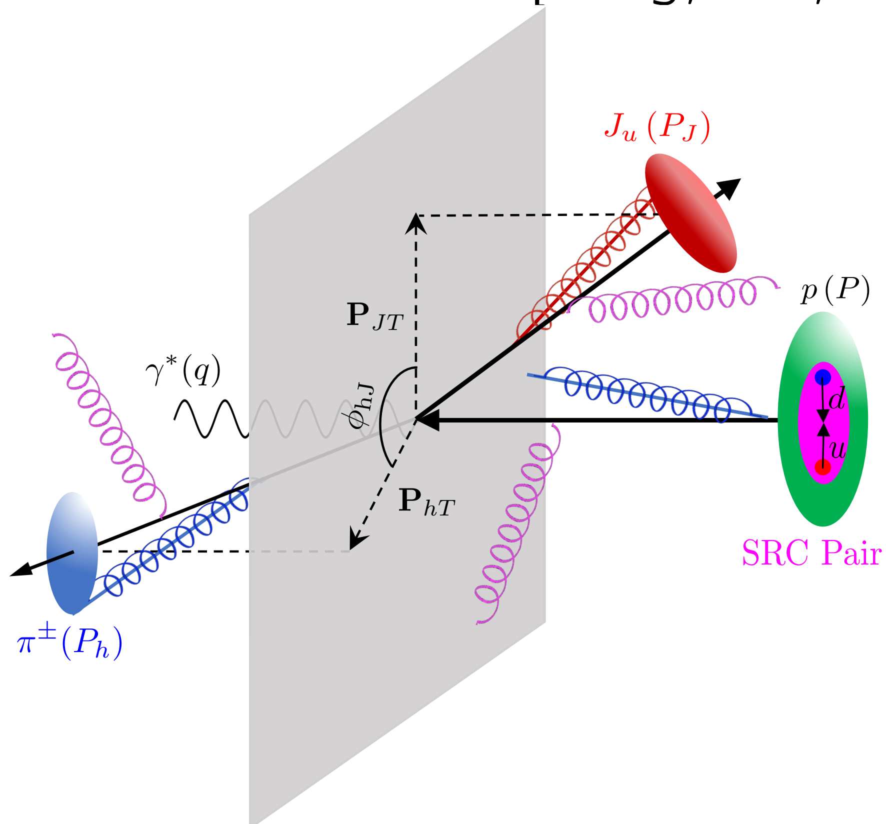
Incident electron (via virtual photon) kicks a u quark from the proton.

If all you measure is the scattered electron and the jet, all you can learn about is (generalized) parton distribution functions.

So, measure the blue hadron too!

An EIC Measurement...

[Peng, KR, Terry, 2606.17133]



Measure the correlations in ϕ (azimuthal angle around the virtual-photon direction) between...

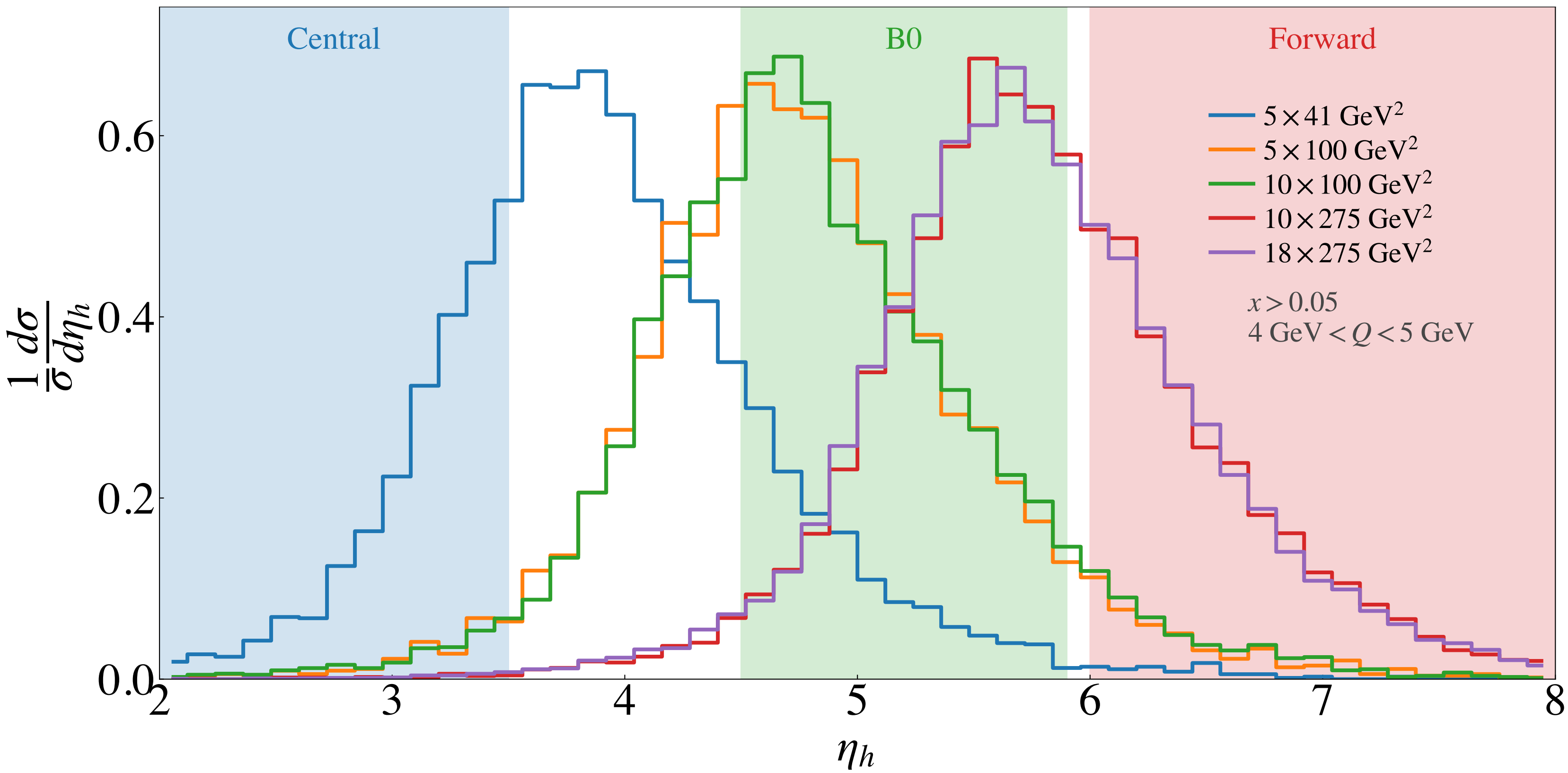
... the u-jet (jet with leading π^+) that the virtual photon kicked ...

... and a π^- (containing a d-quark that the u was strongly correlated with).

Direct access to strong Diquark Short Range Correlations inside a proton. Which is to say inside quark-gluon matter under pressure.

An EIC Measurement...

[Peng, KR, Terry, 2606.17133]

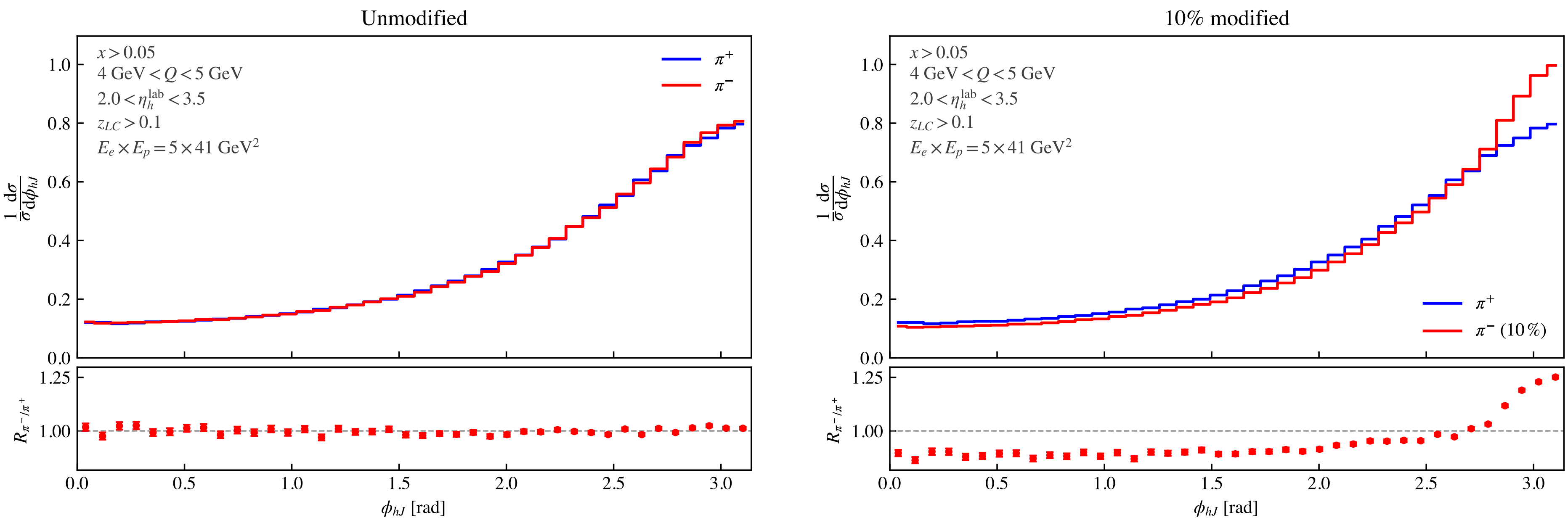


EIC is *designed* to measure the scattered electron and hence Q. EIC is *deisgned* to measure the jet that the virtual photon kicked.

PYTHIA simulation shows that $\pi^{+/-}$ from fragments of the proton can be measured in the central detector in EIC collisions with $E_e = 5$ or 10 GeV and $E_p = 41$ GeV. Also makes clear that B0 detector is important for larger E_p, if it can identify $\pi^{+/-}$. On next slides, $E_p = 41$ GeV and $\eta_h < 3.5$.

An EIC Measurement...

[Peng, KR, Terry, 2606.17133]

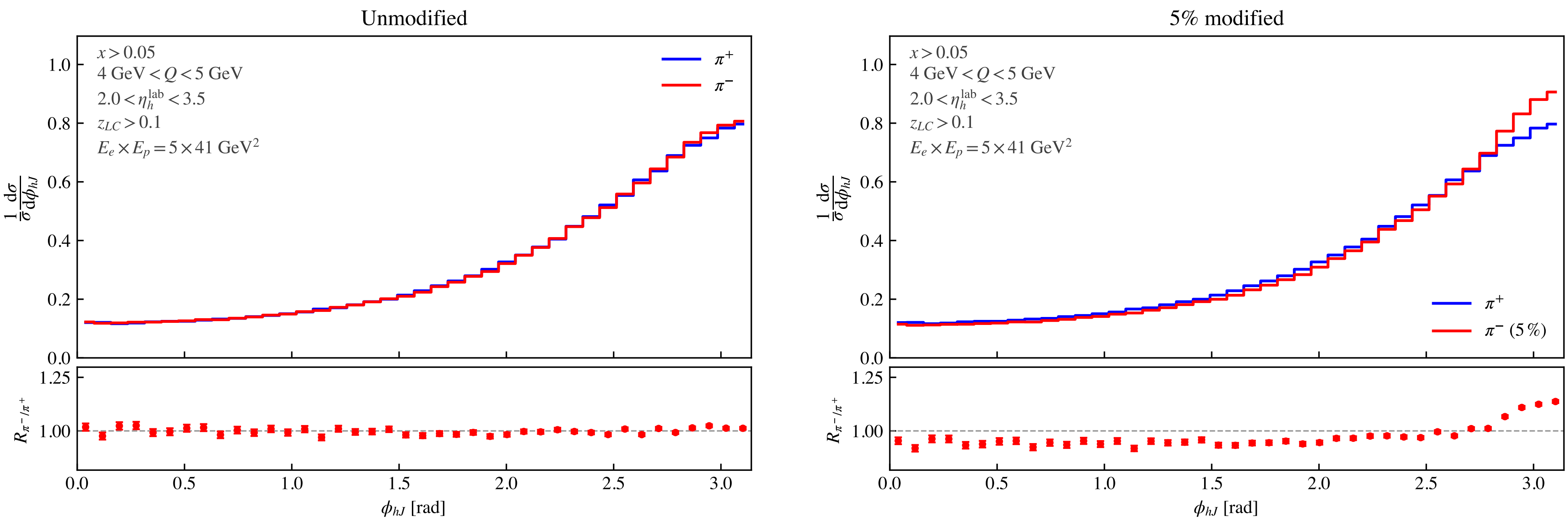


Left panel: PYTHIA, unaltered. $\phi_{hJ}\equiv\phi_h-\phi_J$. J is u-jet. ϕ_{hJ} distribution $\sim$ same for π^+ and π^-: no diquark SRC in protons in PYTHIA. Shape of ϕ_{hJ} distribution comes from momentum conservation.

Right panel: we have altered 10% of the events in the PYTHIA simulation. Crude model of effects of ud-diquark SRCs in proton. Only π^- affected in simulation; u-jet; d from proton remnant $\rightarrow\pi^-$. Signal is π^-/π^+ ratio above one around $\phi_{hJ}\sim 180^\circ$. Nb: this crude model is not a prediction; an illustration of how to look for partonic SRCs with the EIC.

An EIC Measurement...

[Peng, KR, Terry, 2606.17133]



Left panel: PYTHIA, unaltered. $\phi_{hJ} \equiv \phi_h - \phi_J$. J **is** u**-jet.** ϕ_{hJ} **distribution** $\sim$ **same for** π^+ **and** π^-**: no diquark SRC in protons in PYTHIA. Shape of** ϕ_{hJ} **distribution comes from momentum conservation.**

Right panel: we have altered 5% of the events in the PYTHIA simulation. Crude model of effects of ud**-diquark SRCs in proton. Only** π^- **affected in simulation;** u**-jet;** d **from proton remnant** $\to \pi^-$**. Signal is** π^-/π^+ **ratio above one around** $\phi_{hJ} \sim 180°$**. Nb: this crude model is not a prediction; an illustration of how to look for partonic SRCs with the EIC.**

Probing Quark-Gluon Matter Under Pressure

- **Where else do we find quark-gluon matter under pressure? In a proton!!**
- **Protons form from tiny drops of QGP. The internal pressure, energy density,** *and entropy* **of a proton are comparable to that of the drop of QGP from which it formed.**
- **What lessons can we learn about the interior of a proton from hot QGP?**
- **Macroscopic volume of QGP at $T \sim T_p$ is a strongly coupled fluid: strong correlations between momenta of fluid cells near each other in position space. Microscopic implication: strong** *Short-Range Correlations*. **How can partonic SRCs be measured, directly??**
- **Seeing strong parton-parton correlations would show that protons cannot be described one parton at a time by (generalized) PDFs. As important to our image of the proton as seeing that QGP is a strongly coupled liquid.**

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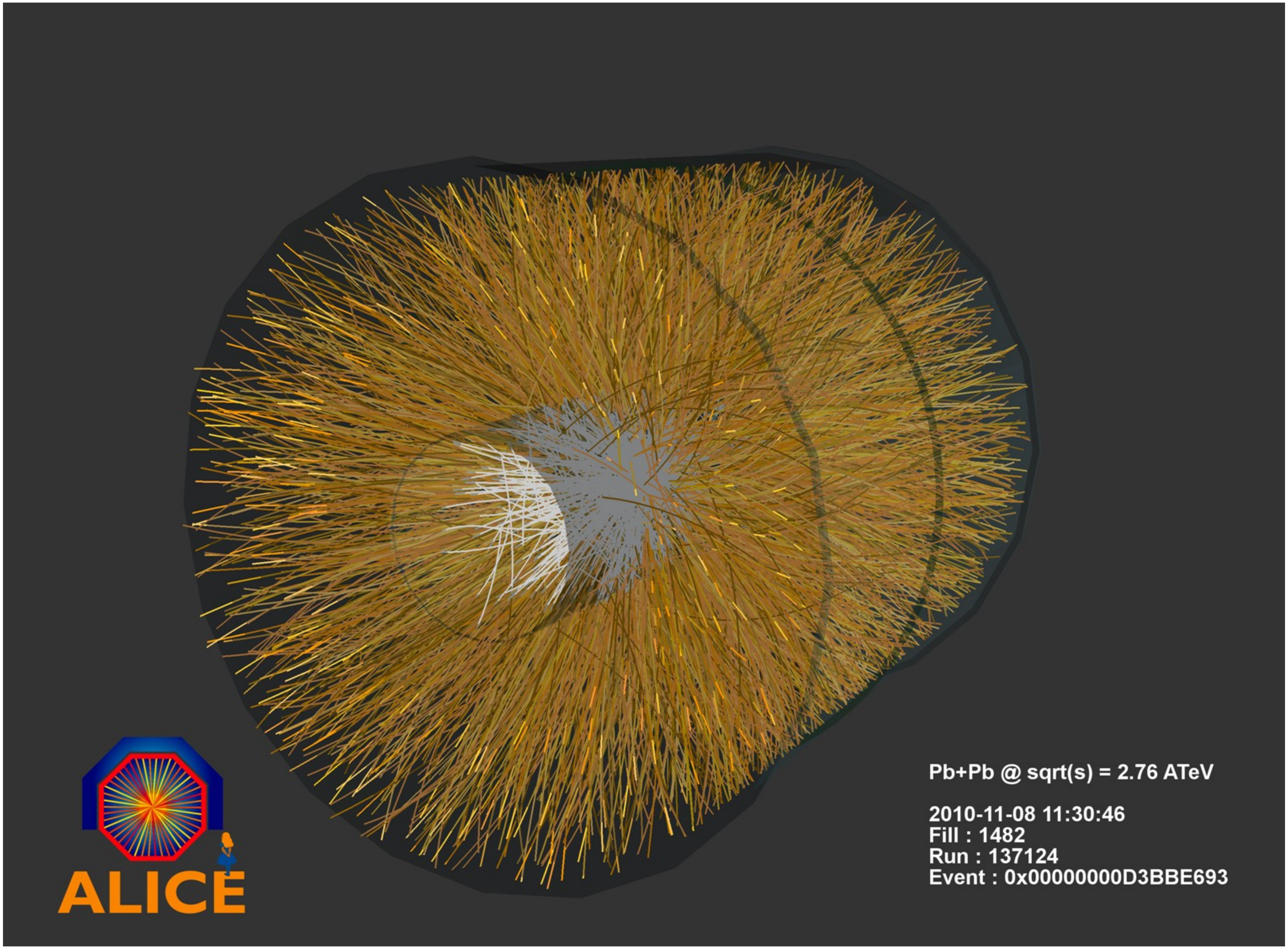
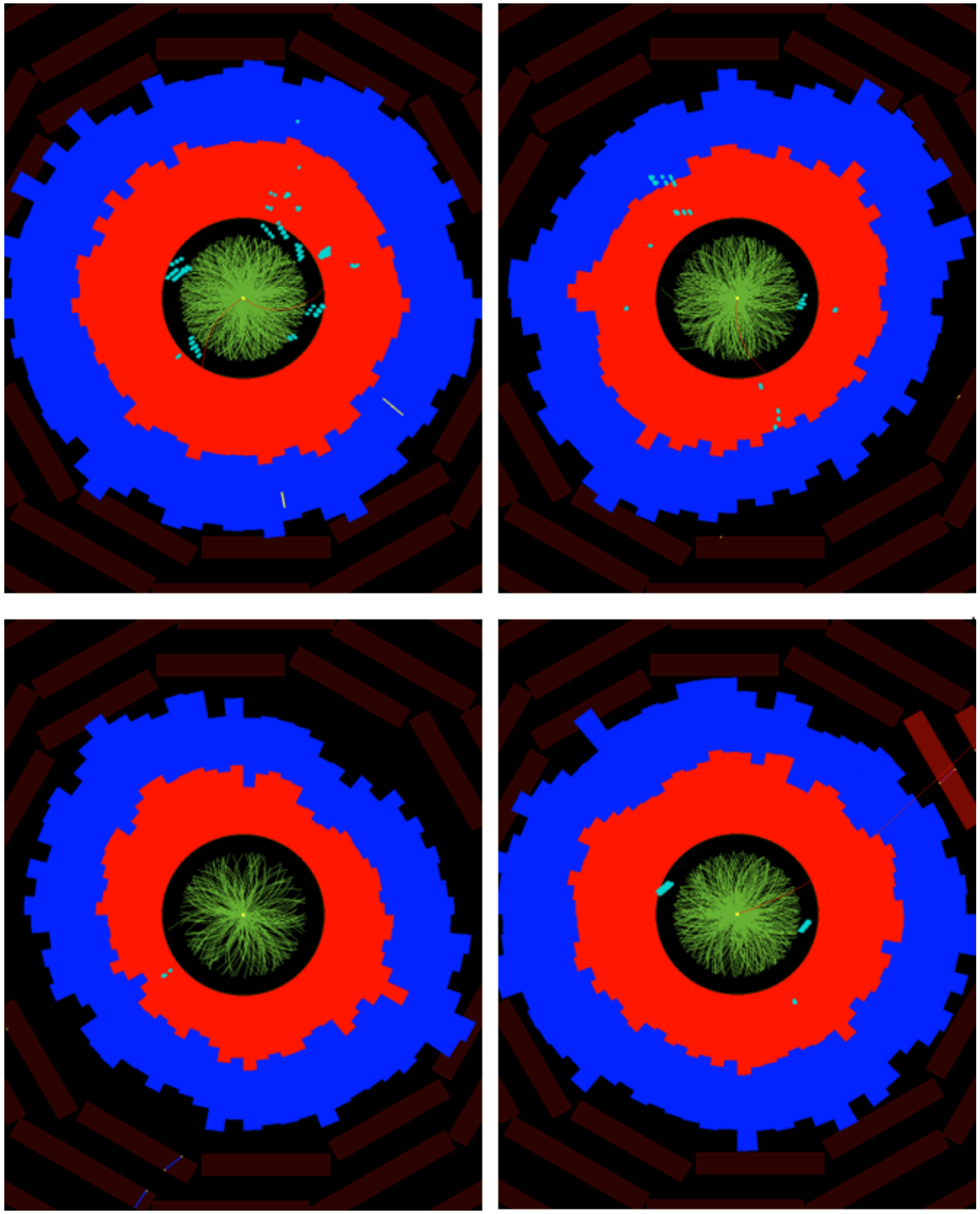
- **Seeing strong parton-parton correlations would show that protons cannot be described one parton at a time by (generalized) PDFs. As important to our image of the proton as seeing that QGP is a strongly coupled liquid.**

Quark-Gluon Matter, Under Pressure

- The universe was filled with hot quark soup for the first 10-20 microseconds after the Big Bang.
- LHC and RHIC heavy ion collisions recreate droplets of this hot quark soup, which promptly explode! From the shape of these Little Bangs, learn that hot quark soup is a very liquid-like liquid.
- New measurements of jets in heavy ion collisions reveal wakes that jets create in droplets of hot quark soup and, soon, will allow us to probe its microscopic structure.
- Cold quark soup is found at the centers of the heaviest neutron stars. Almost as high pressure, but the weight of the star prevents it from exploding.
- Quark soup inside a proton has a higher pressure than in a neutron star! "QCD confines" $\leftrightarrow$ QCD describes that protons *don't* explode. We are just beginning to learn the lessons that hot quark soup teaches us about protons.



ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

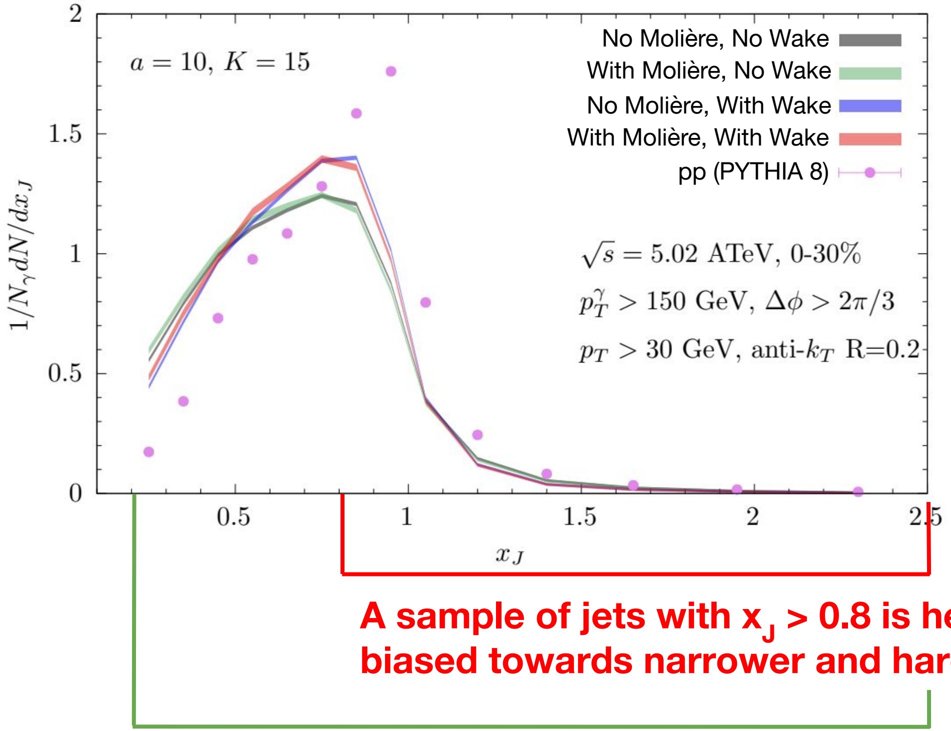


Hot Quark Soup, Under Pressure

- What does hot quark soup, with a pressure greater than 2×10^{31} atmospheres, do??
- If it fills the entire universe, it expands "slowly". It takes $\sim 10-20$ microseconds to cool, and fall apart into a mist of protons. (That continues to expand, and form structure, over the next 13 billion years.)
- If you make a little droplet of the stuff, with nothing around it, it explodes!
- And, the shape of the explosion tells you about the shape of the droplet, and about its liquidness.

Use Photon-Tagged Jets

2603.08776 [Hulcher, Kudinoor, Pablos, Rajagopal]



- Photons do not interact strongly with QGP
- Selecting on p_T^γ lets us select on the initial energy scale of the scattering
- $x_J = p_T^{jet} / p_T^\gamma$ estimates the amount of energy lost by the recoiling jet

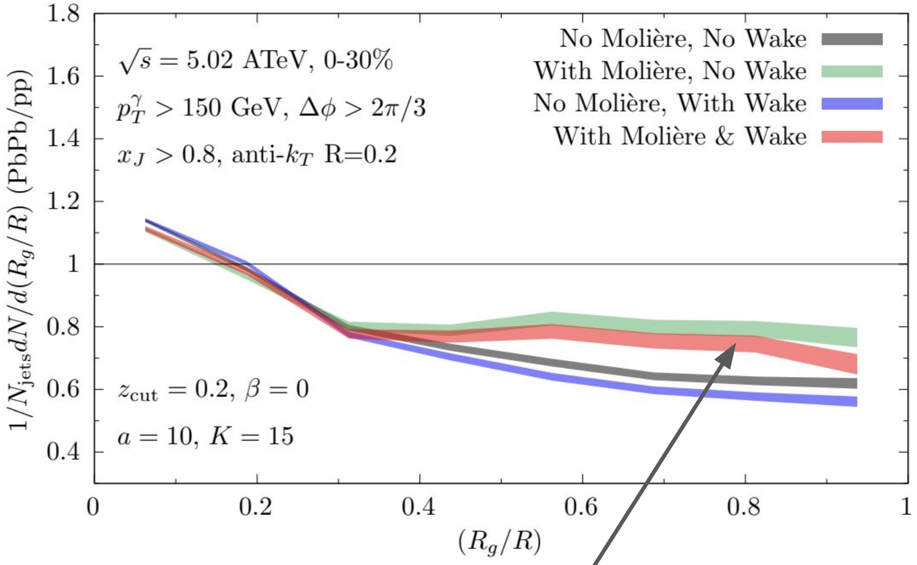
A sample of jets with $x_J > 0.8$ is heavily biased towards narrower and harder jets

A sample of jets with $x_J > 0.2$ is less biased

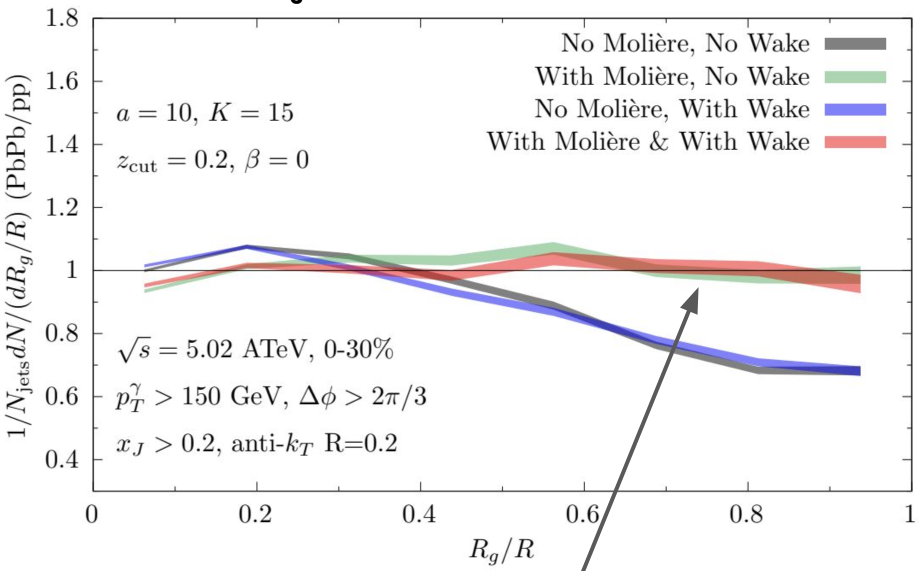
Soft Drop Angle in Photon-Tagged Jets with R = 0.2

2603.08776 [Hulcher, Kudinoor, Pablos, Rajagopal]

x_J > 0.8 (More Biased)



x_J > 0.2 (Less Biased)



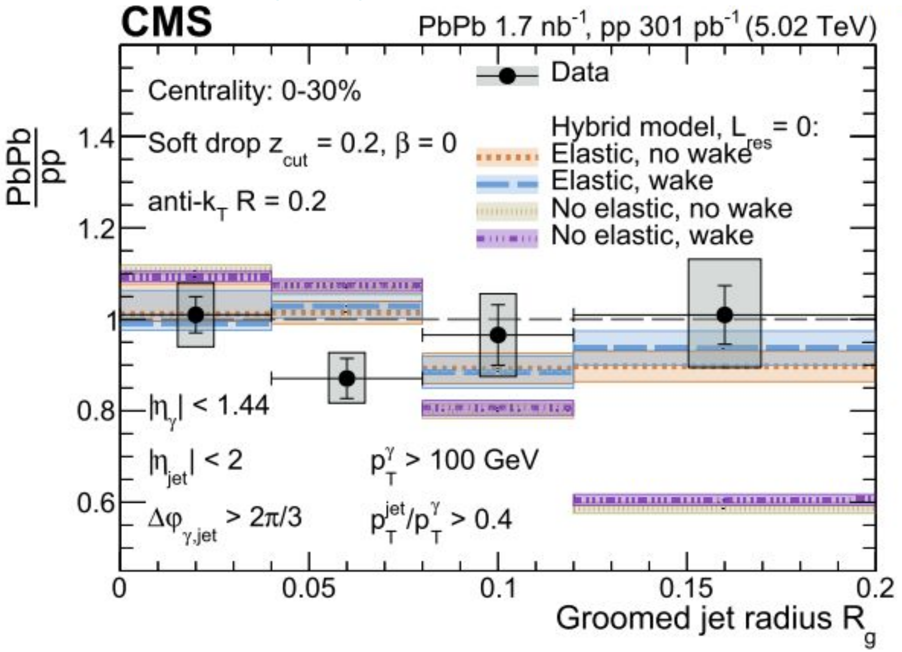
Molière scattering increases the number of jets with large R_g, but not enough to overcome selection bias effects

Reduce selection bias ⇒ More detectable Molière scattering signal

Soft Drop Angle in Photon-Tagged Jets with R = 0.2

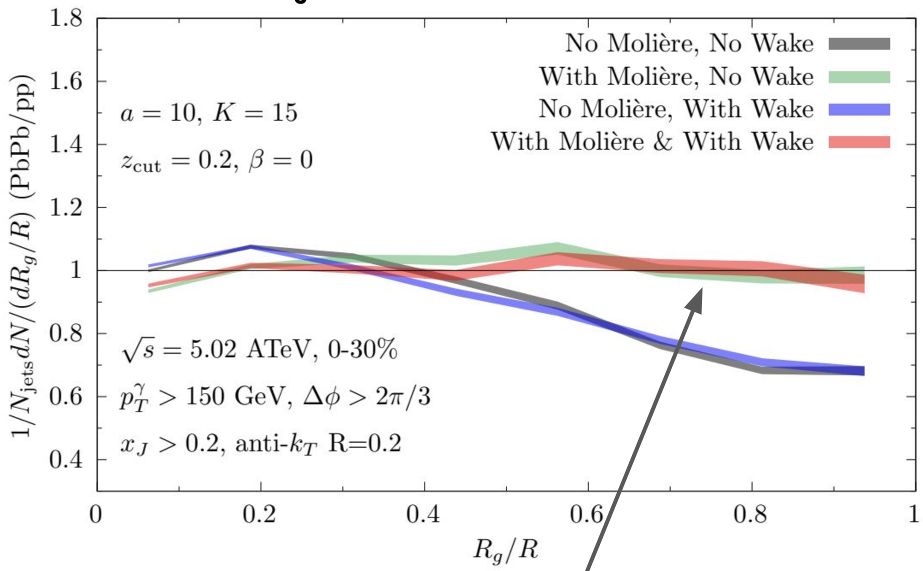
2603.08776 [Hulcher, Kudinoor, Pablos, Rajagopal]

PLB 861 (2025) 139088



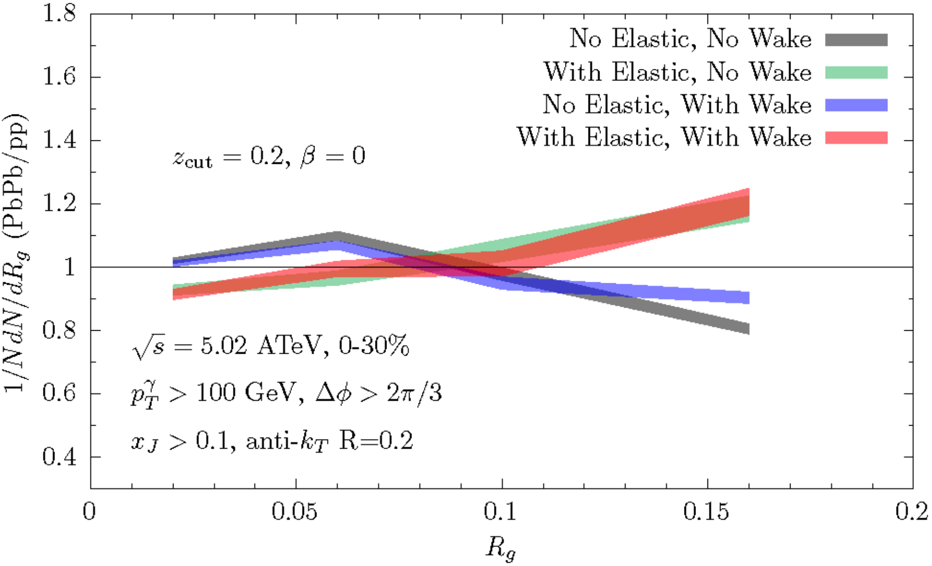
Relatively flat ratio around unity is also seen in CMS data!

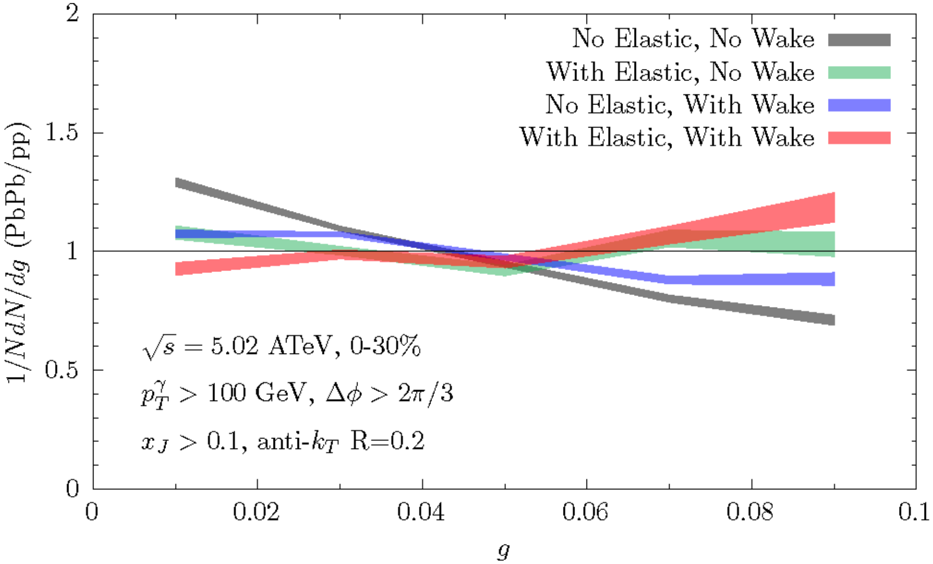
x_J > 0.2 (Less Biased)



Reduce selection bias ⇒ More detectable Molière scattering signal

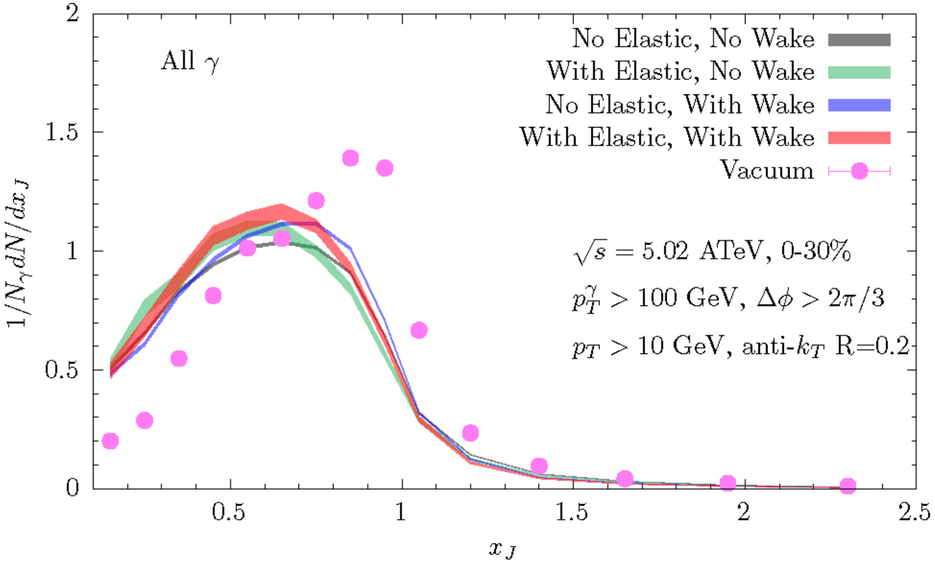
Gamma-Jet Observables: R_g and Girth, with x_J>0.1



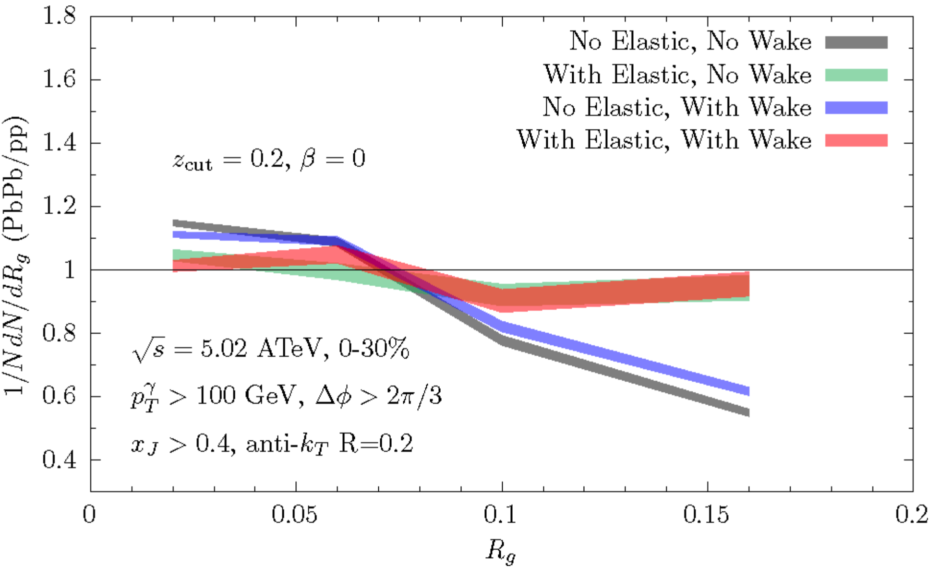


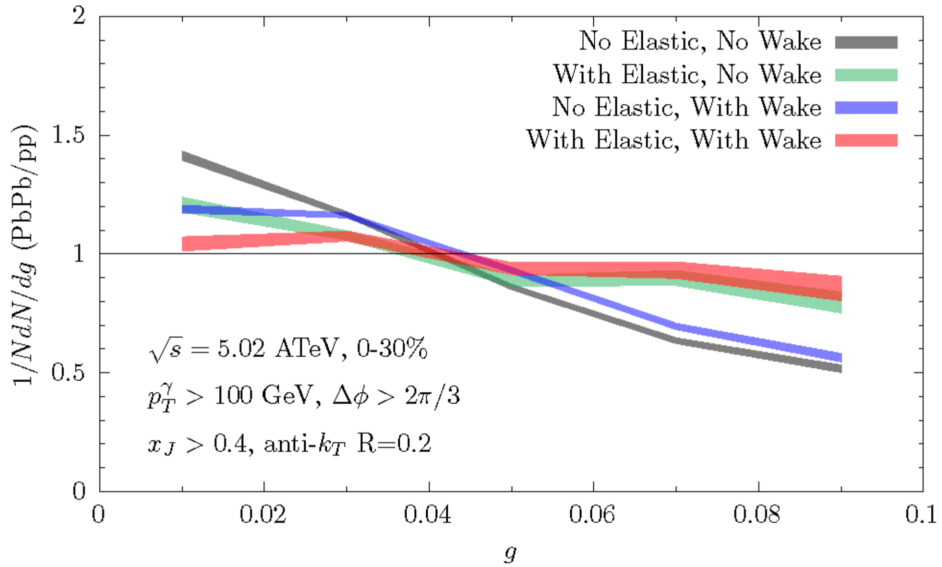
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.1. Moliere scattering important, and causes R_{AA} >1.

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



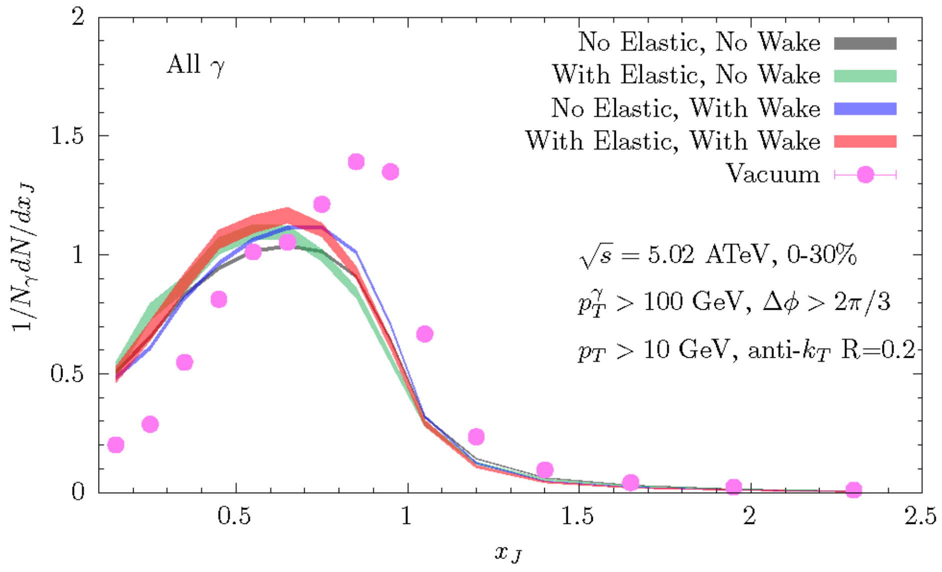
Gamma-Jet Observables: R_g and Girth, with x_J>0.4



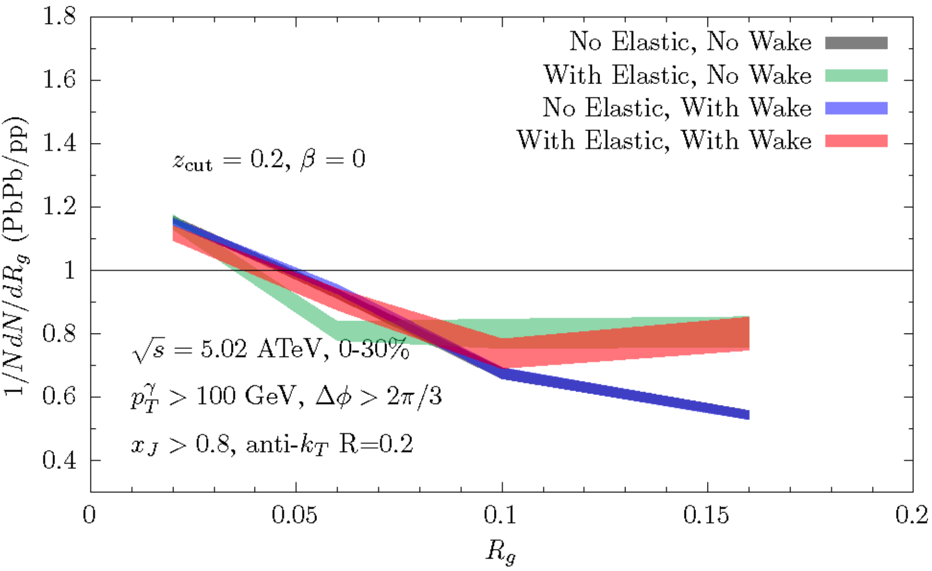


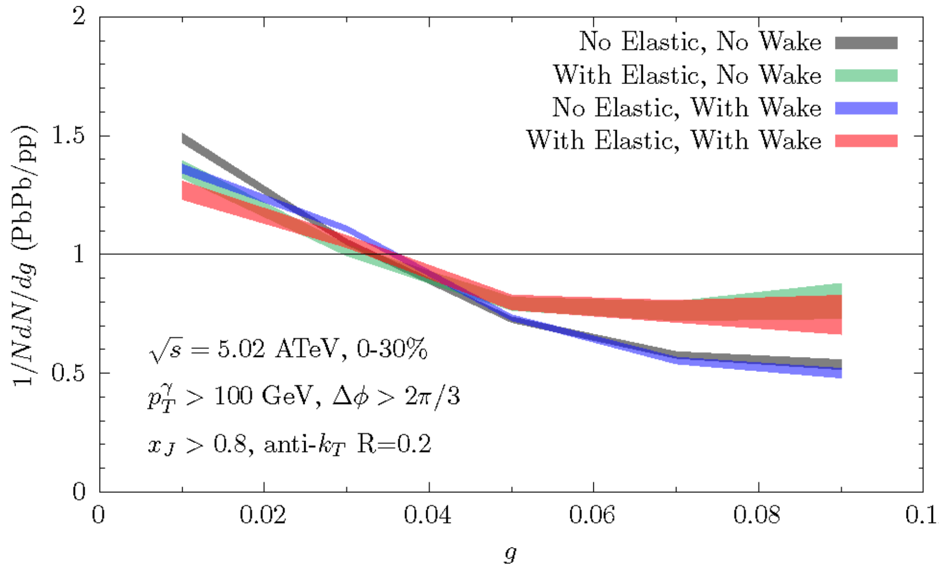
All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

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



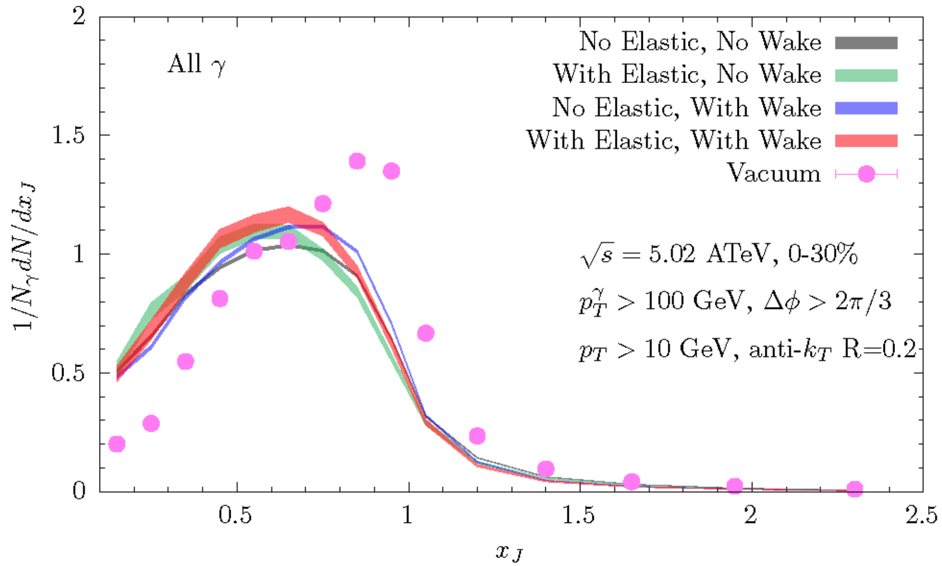
Gamma-Jet Observables: R_g and Girth, with x_J>0.8



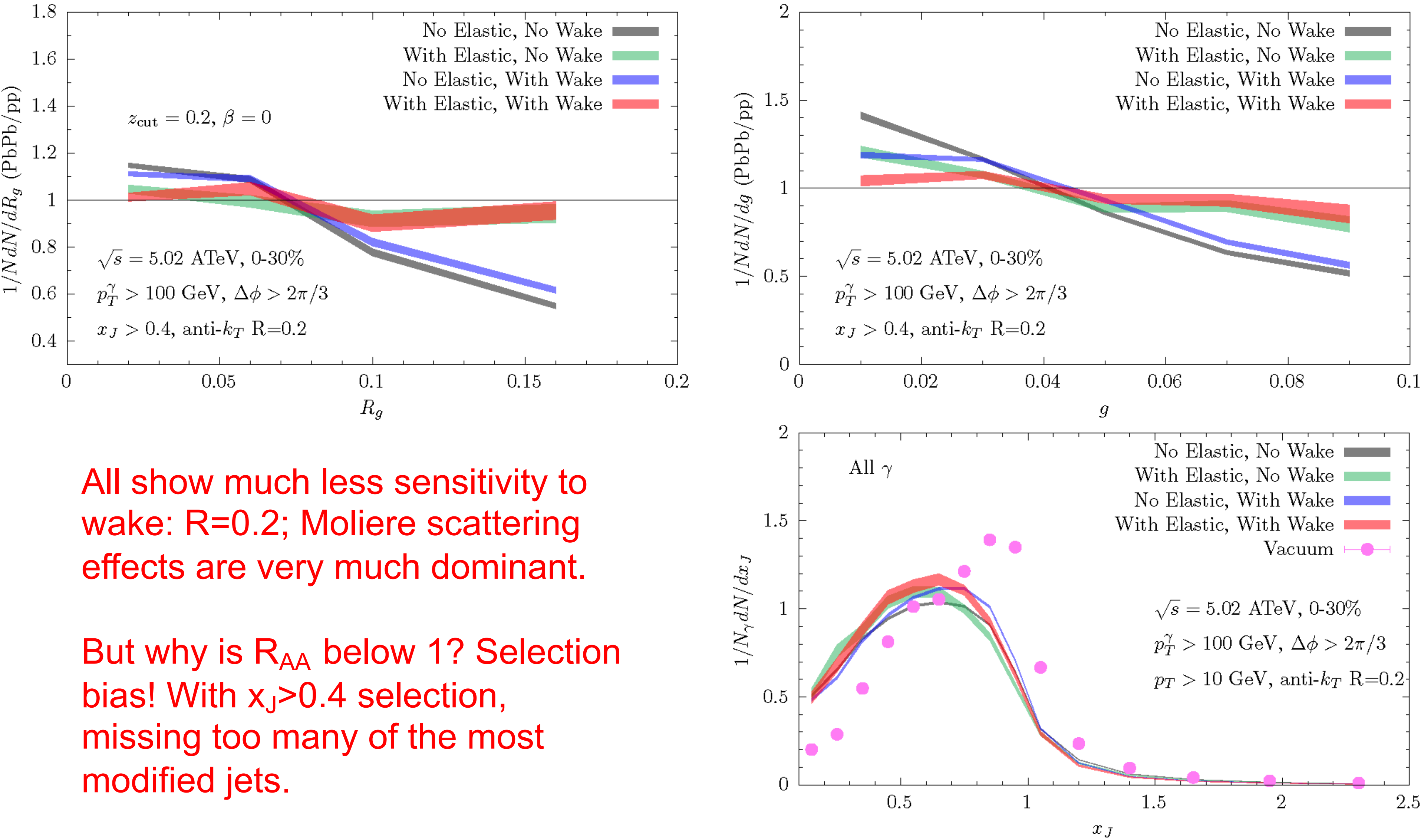


On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.8. Selection bias increased.

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



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



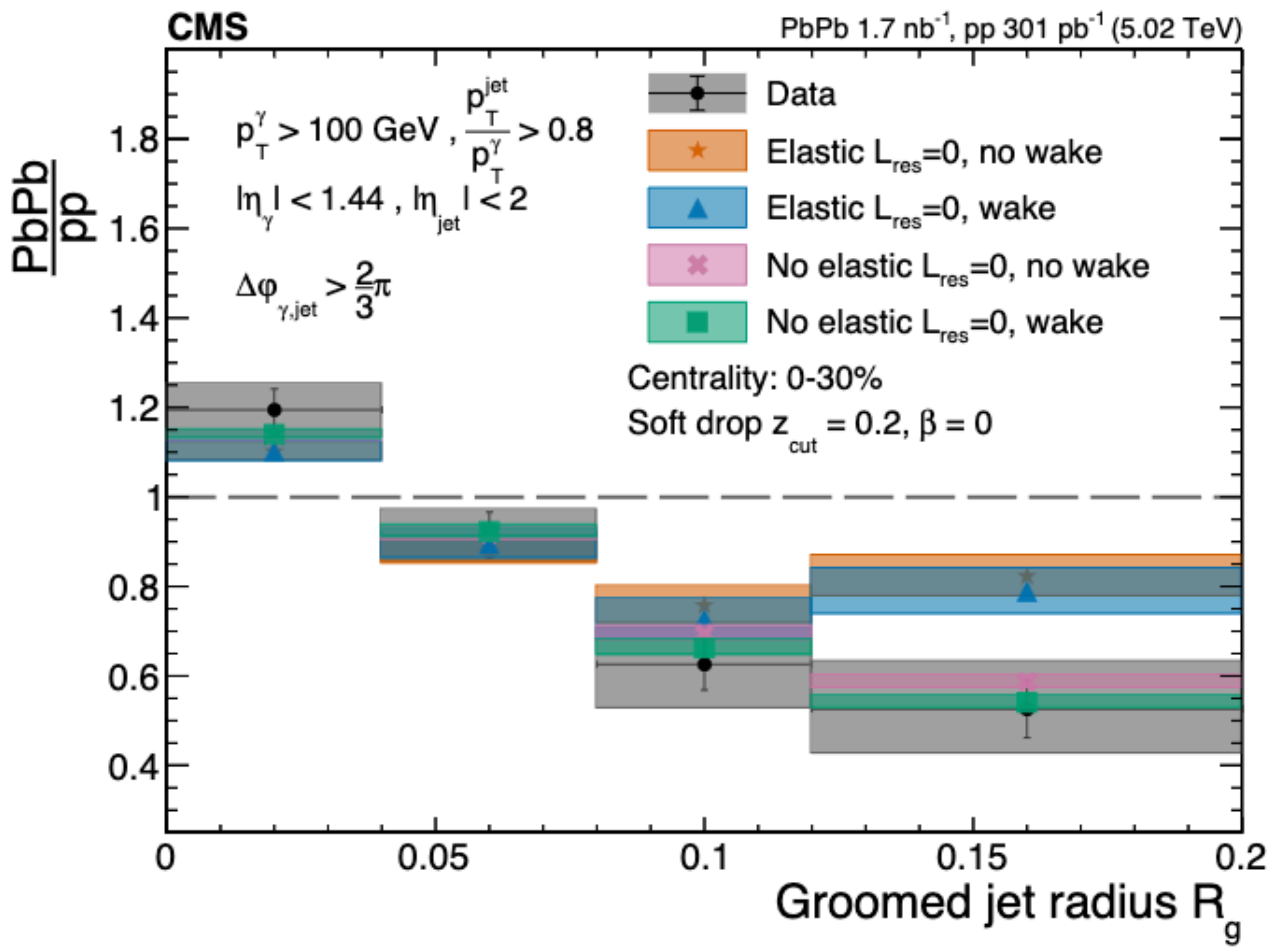
All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

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

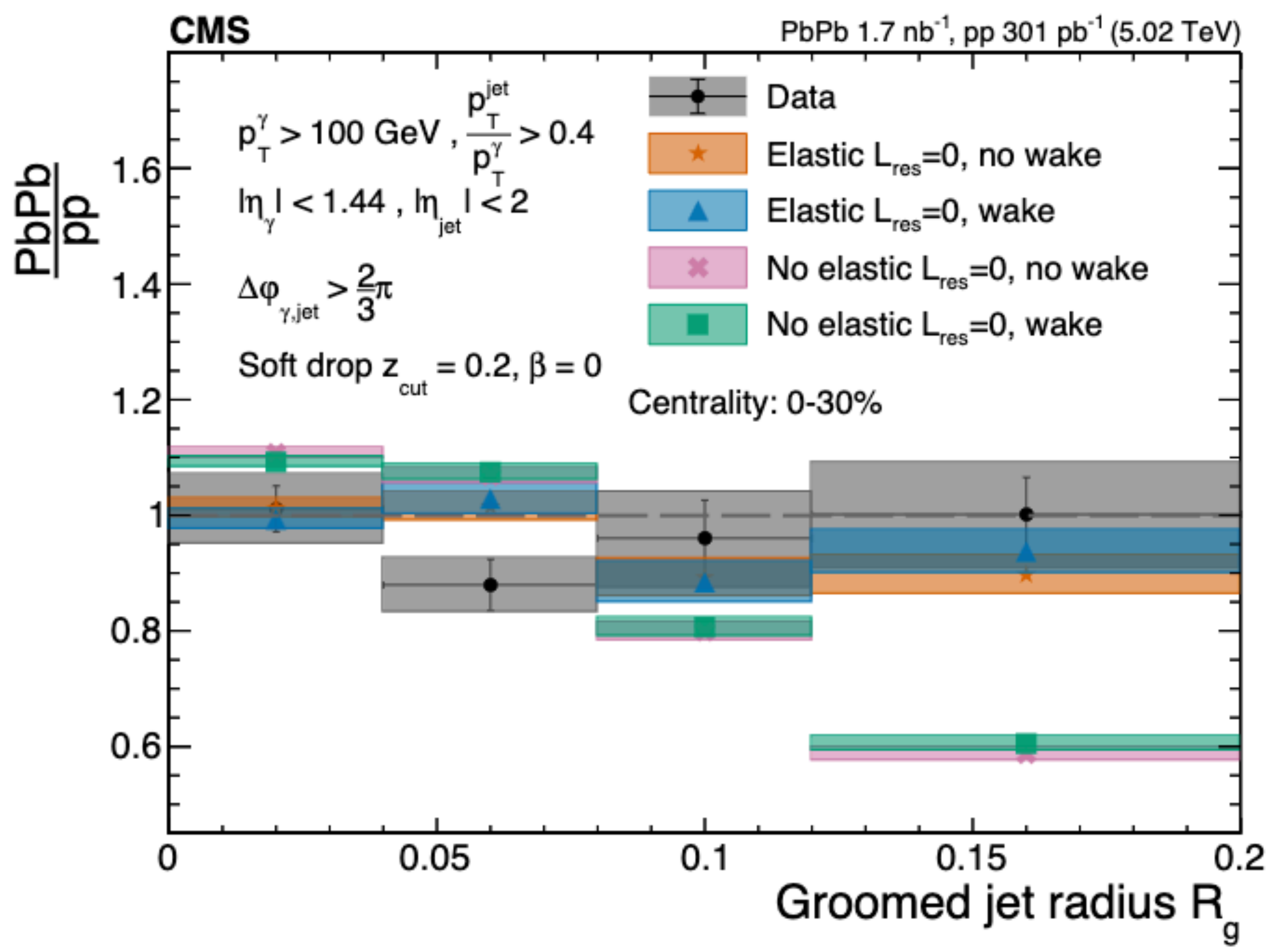
γ-jet substructure: suppression of the survivor bias

PbPb

less quenched xJ>0.8



more quenched xJ>0.4



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

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

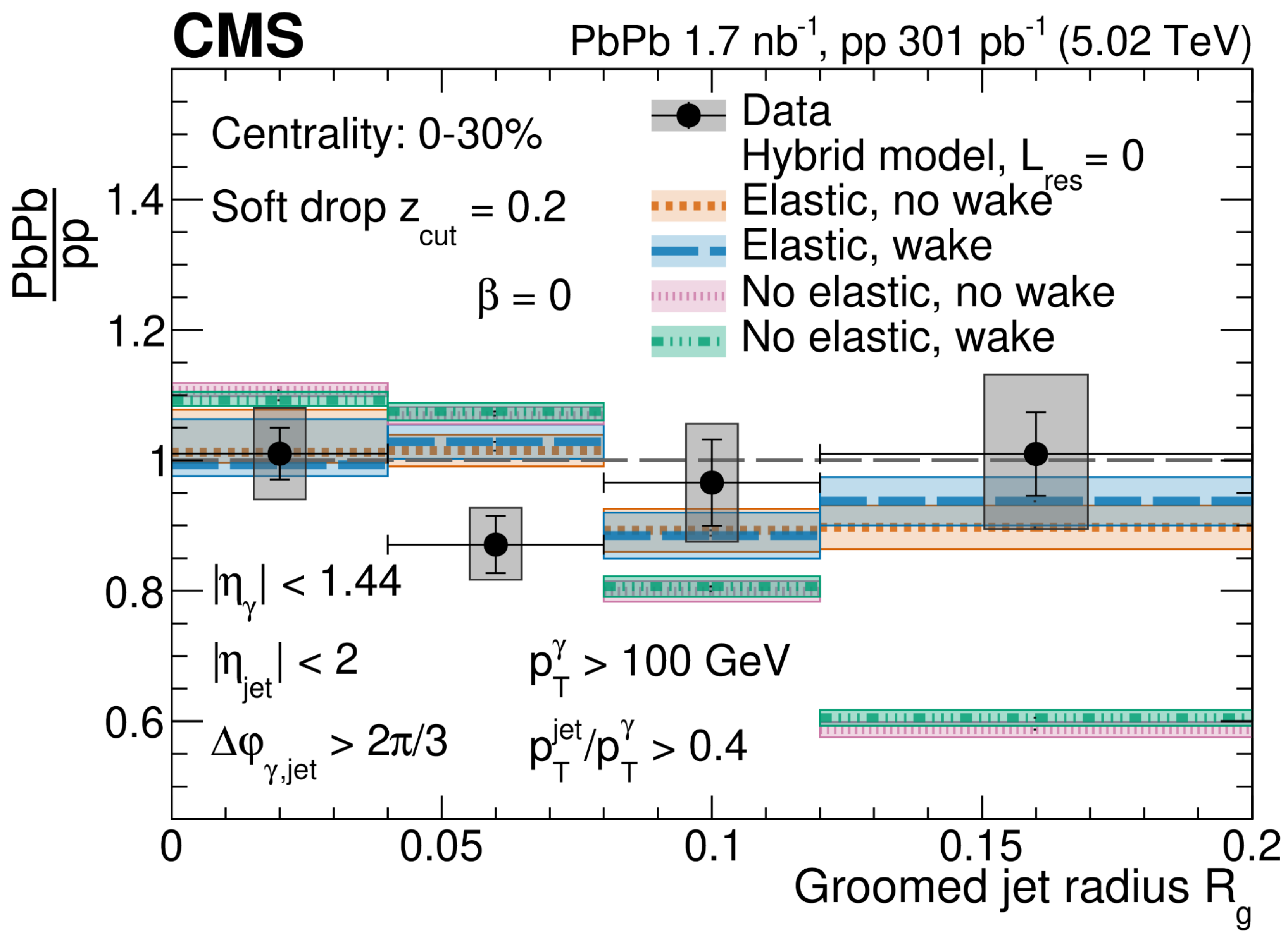
small-R suppresses nonperturbative effects like the wake!

CMS-PAS-HIN-23-001

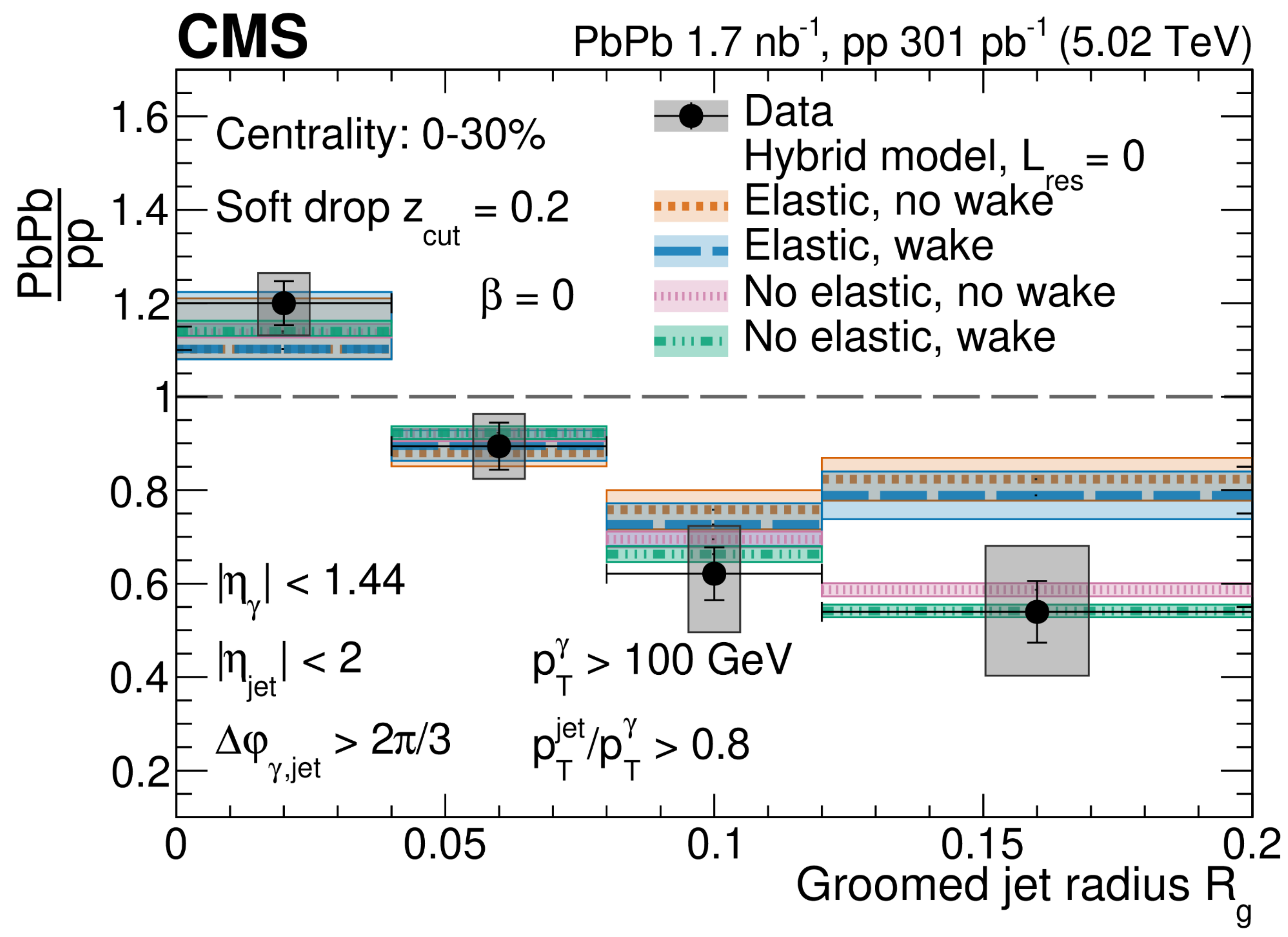
Summary

- Groomed jet radius and girth measured in γ+jet events in pp and PbPb
  - Leading recoil jet from p_T > 100 GeV photons studied for two selections:

$x_{\gamma j} > 0.4$ (w/ quenched jets):
no narrowing observed



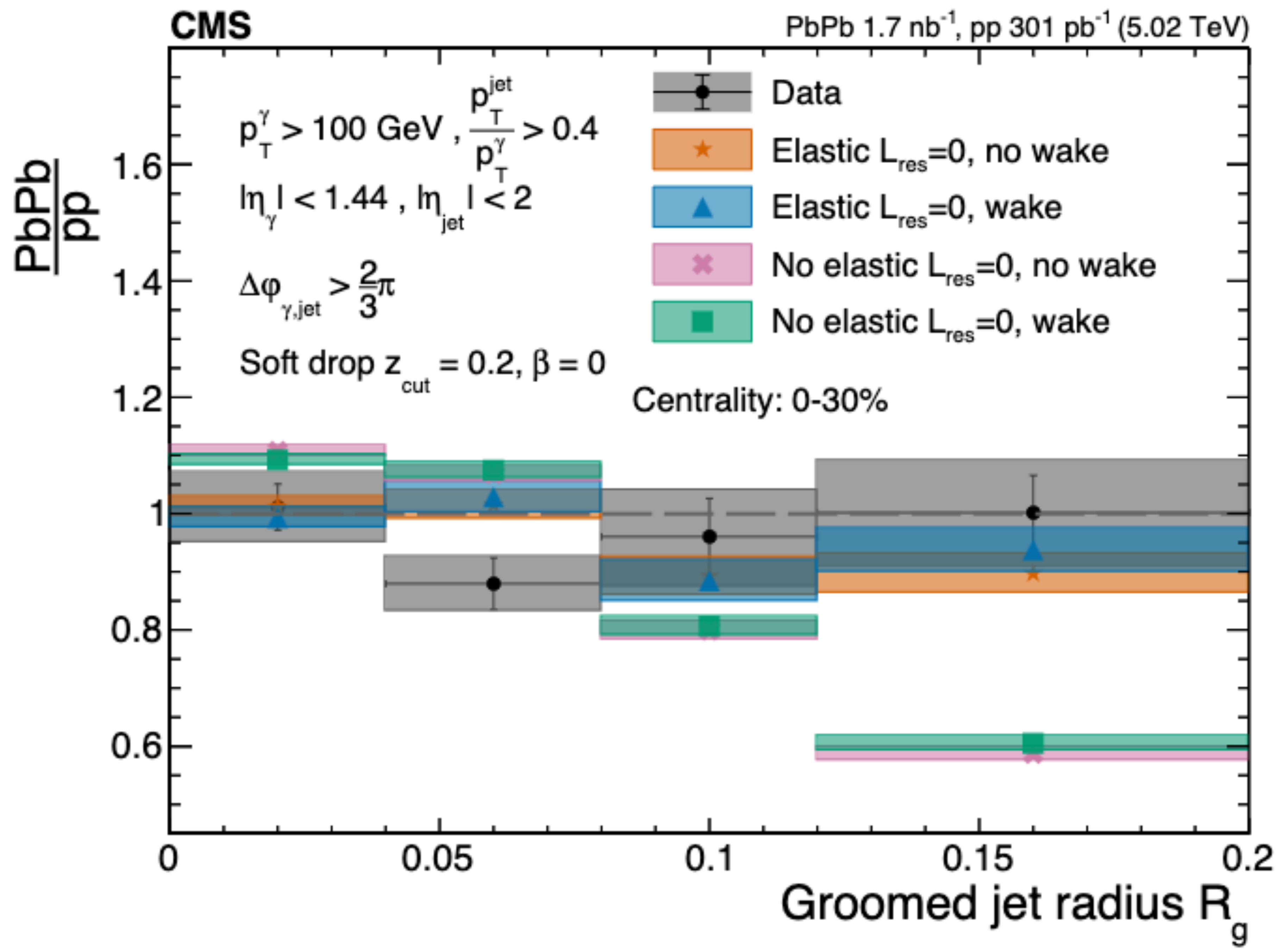
$x_{\gamma j} > 0.8$ (less quenched jets):
narrowing is restored



CMS, arXiv:2405.0273

γ-jet substructure, prospects

xJ>0.4



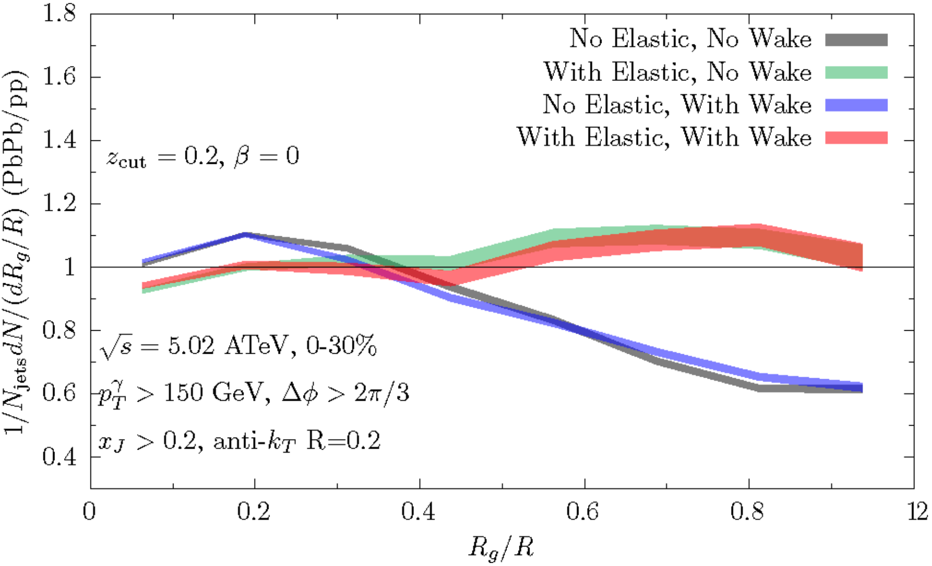
The survivor bias can be fully suppressed when $x_J \to 0$
(the model has a strong survivor bias down to xJ=0.1)

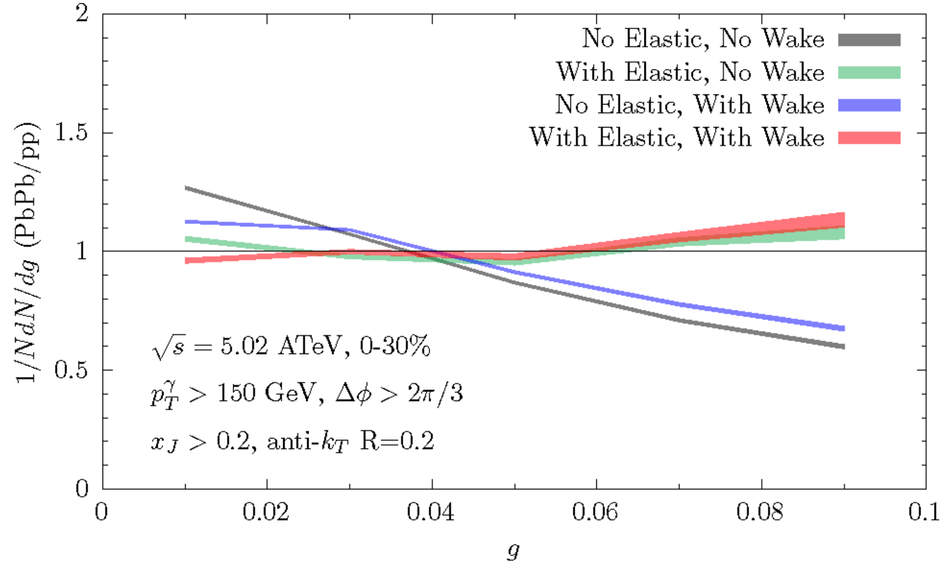
Since low jet p_T is limited by detector effects, such zero bias limit can be achieved by increasing the energy of the photons

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

CMS-PAS-HIN-23-001

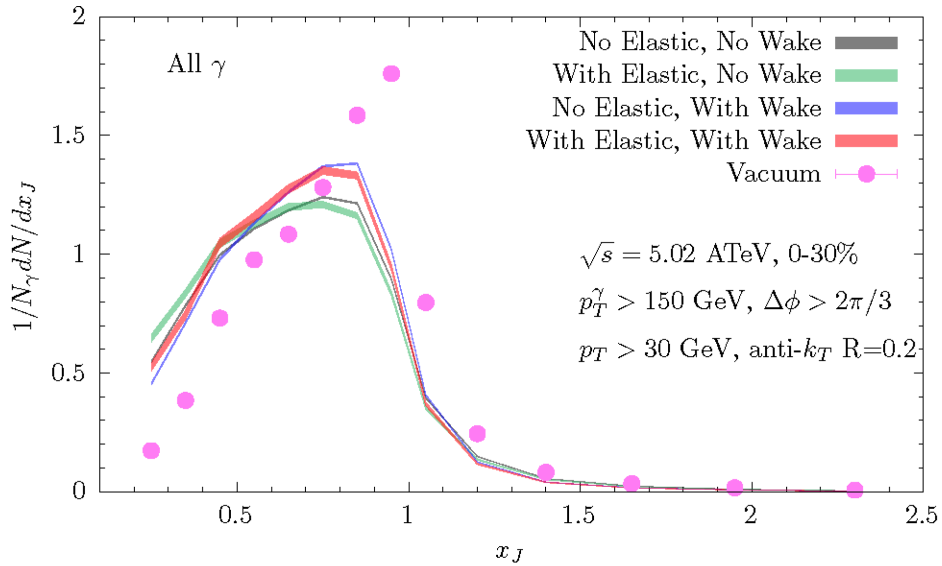
Gamma-Jet Observables with $p_T^\gamma > 150$ GeV: R_g and Girth, with $x_J > 0.2$



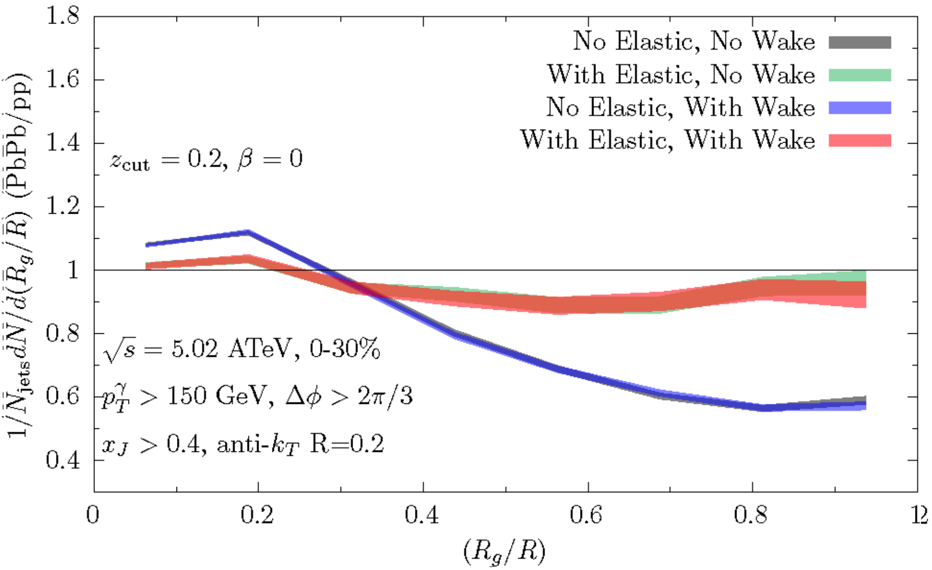


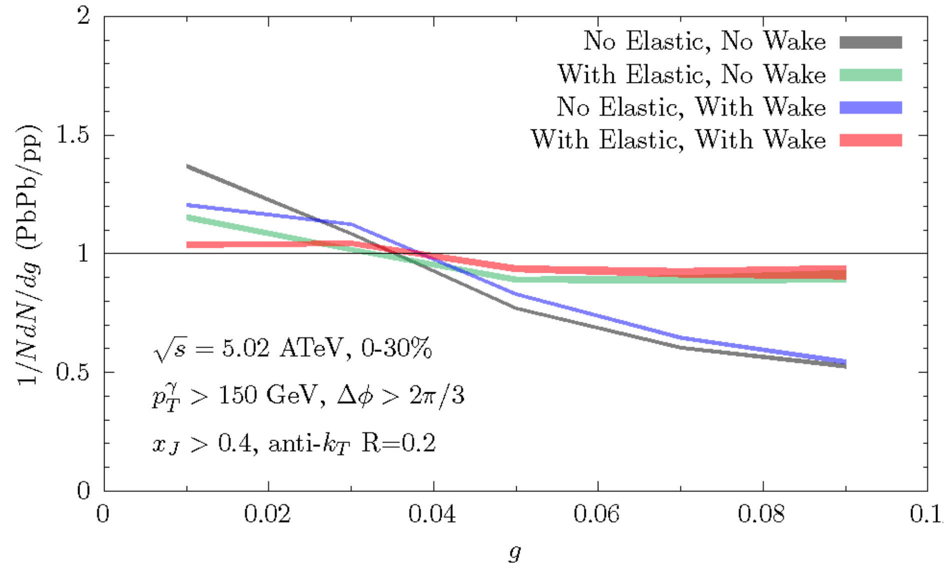
On previous slides, $p_T^\gamma > 100$ GeV; here, $p_T^\gamma > 150$ GeV. Means $x_J > 0.2$ corresponds to $p_T^{jet} > 30$ GeV. And, no need to go down to $x_J > 0.1$.

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



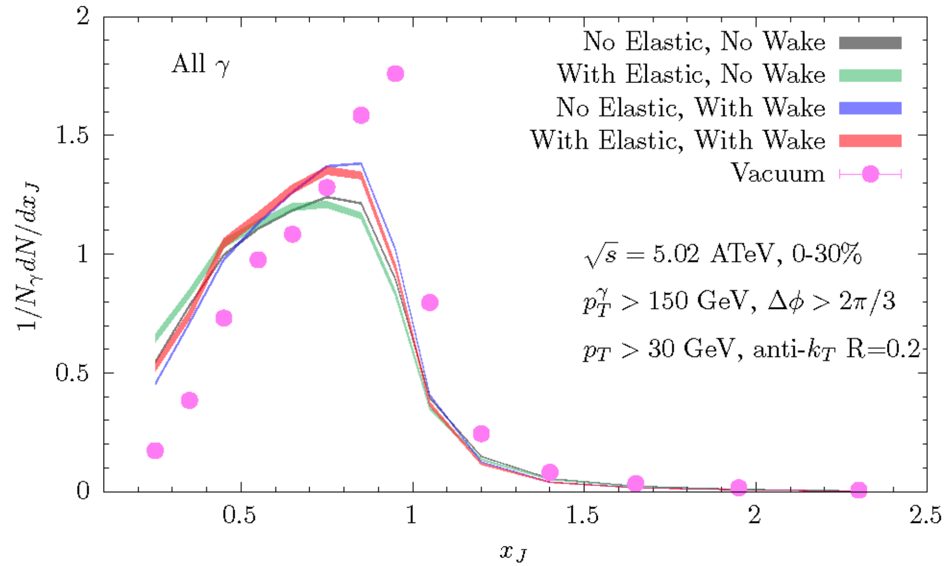
Gamma-Jet Observables with p_T^γ >150 GeV: R_g and Girth, with x_J>0.4



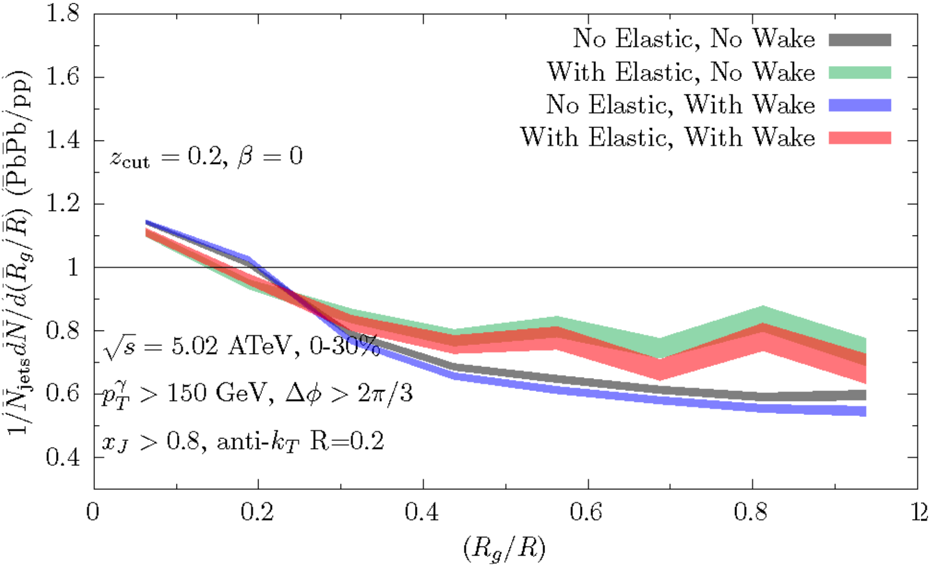


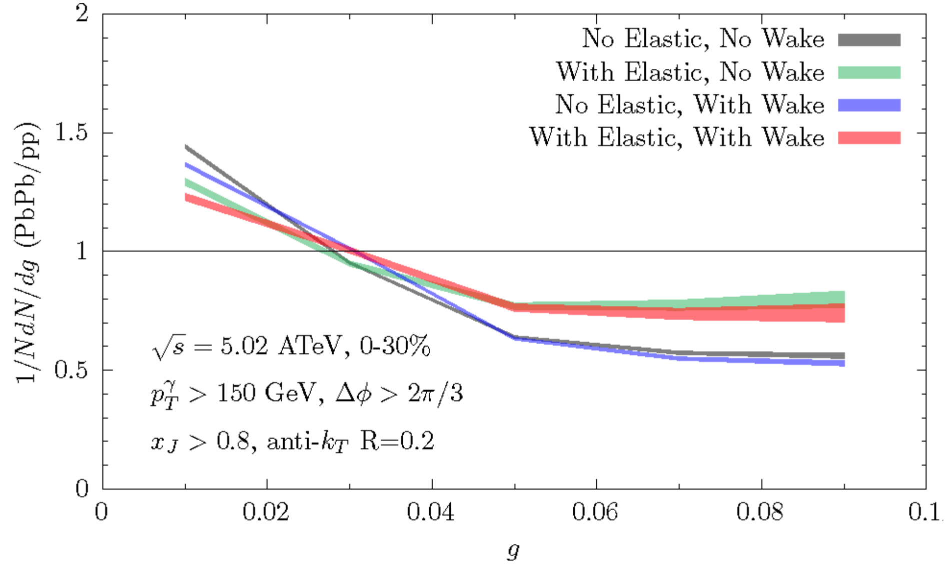
On previous slides, p_T^γ >100 GeV; here, p_T^γ >150 GeV.
Means x_J>0.4 corresponds to p_T^{jet}>60 GeV.

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



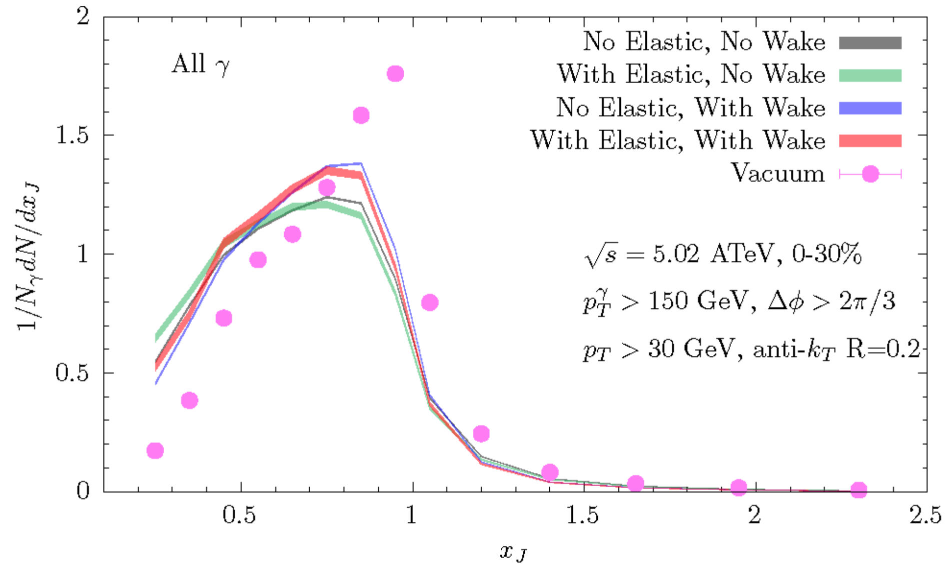
Gamma-Jet Observables with p_T^γ >150 GeV: R_g and Girth, with x_J>0.8



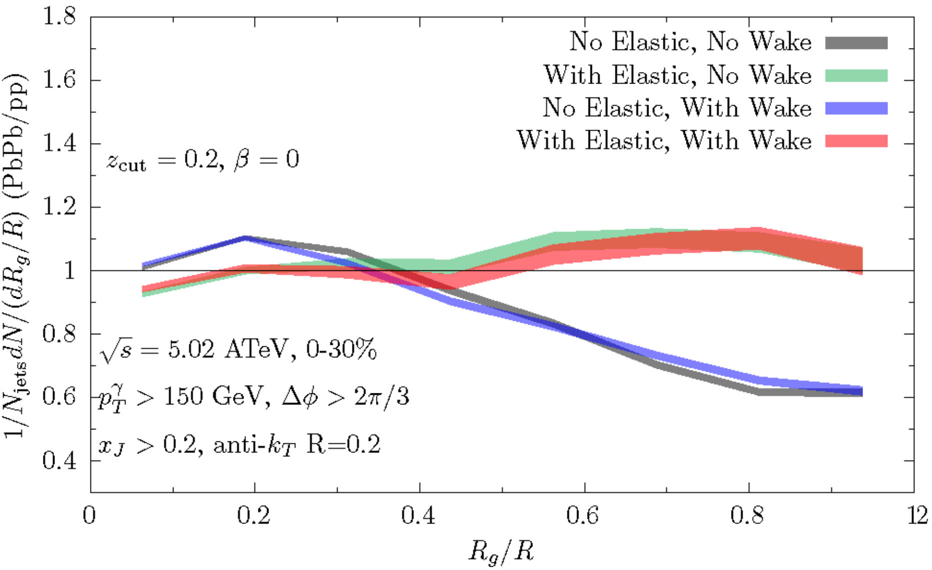


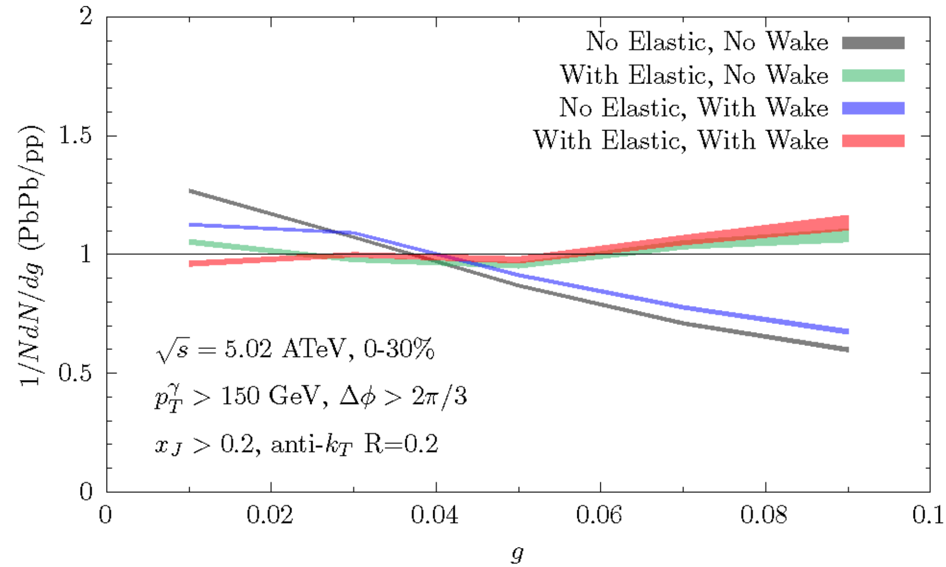
On previous slides, p_T^γ >100 GeV; here, p_T^γ >150 GeV.
Means x_J>0.8 corresponds to p_T^{jet}>120 GeV.

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



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





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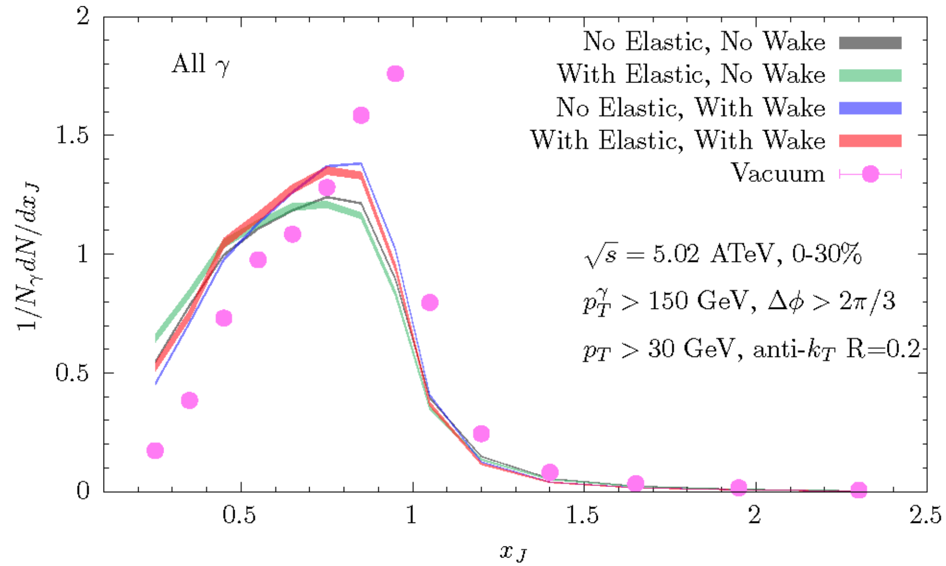
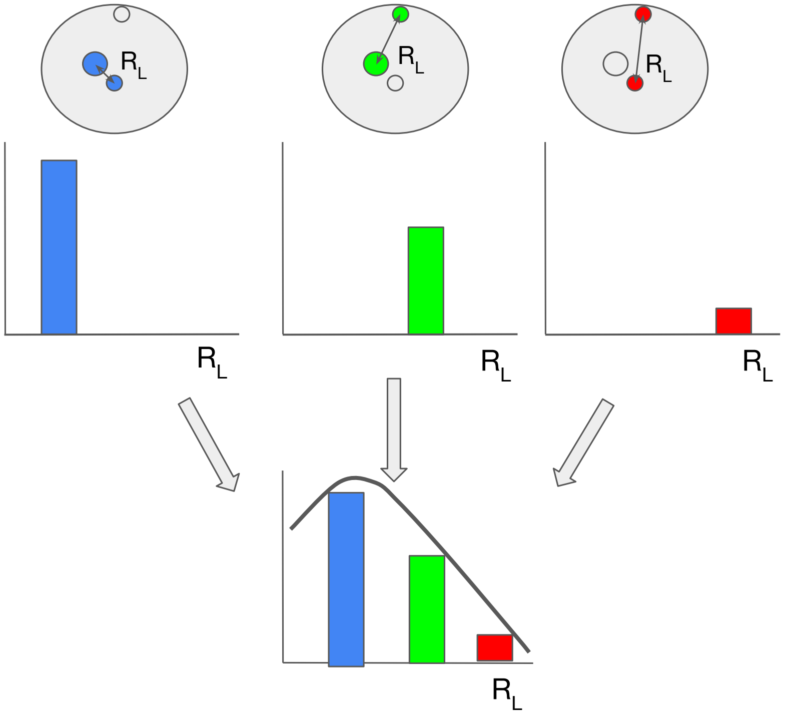
Moliere effects substantial; selection bias reduced; wake effects negligible.



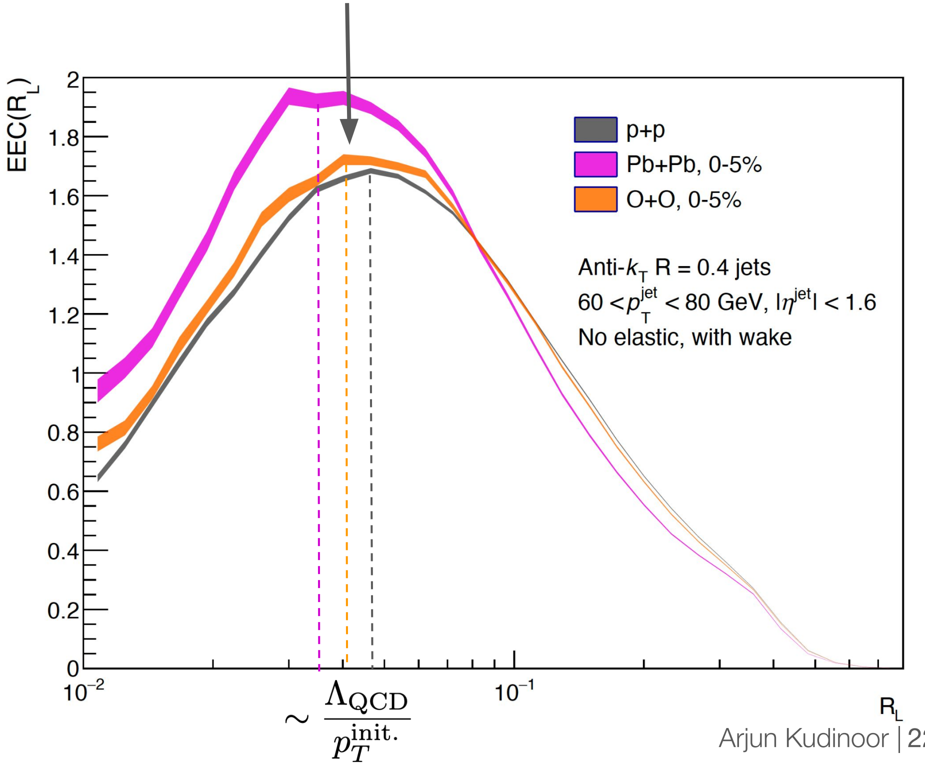
Energy-Energy Correlators

2409.12687 [ALICE]
2503.19993 [CMS]
2409.07514 [Andres et al.]

$$\mathrm{EEC}(R_L) = \sum_{i_1, i_2 \in \mathrm{jet}} \int dR_L \frac{p_T^{i_1} p_T^{i_2}}{p_{T,\mathrm{jet}}^2} \delta(R_L - \Delta \hat{R}_L)$$

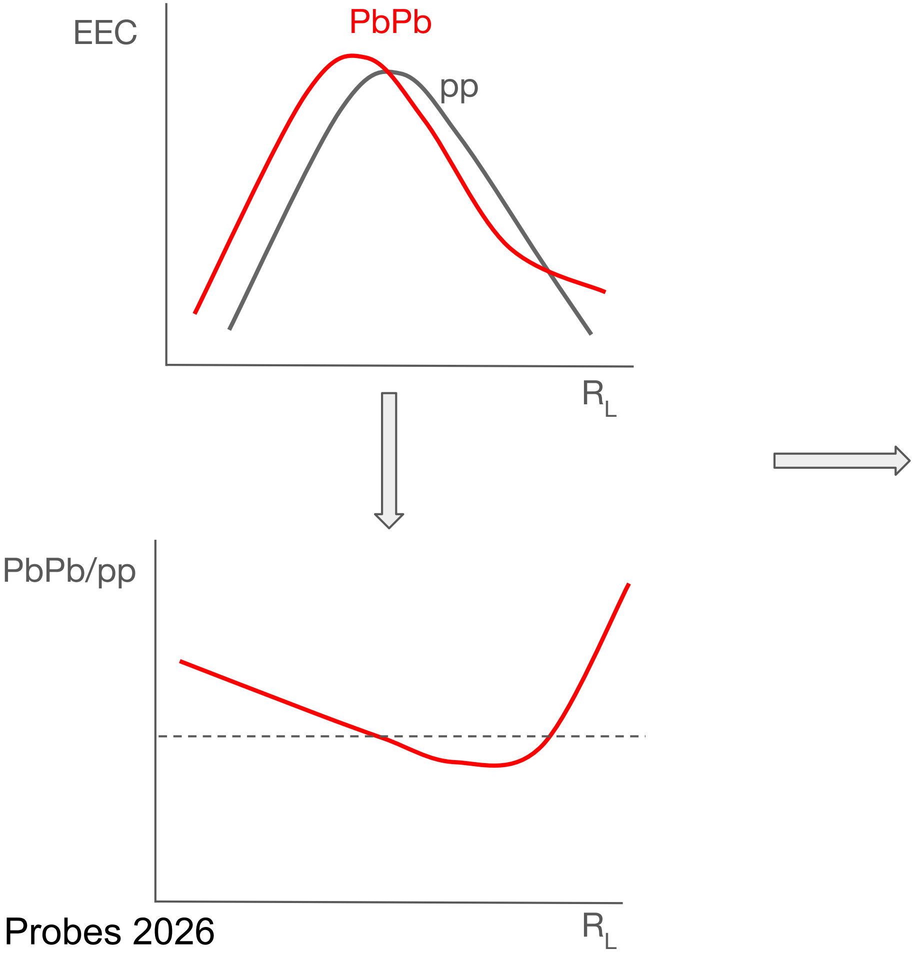


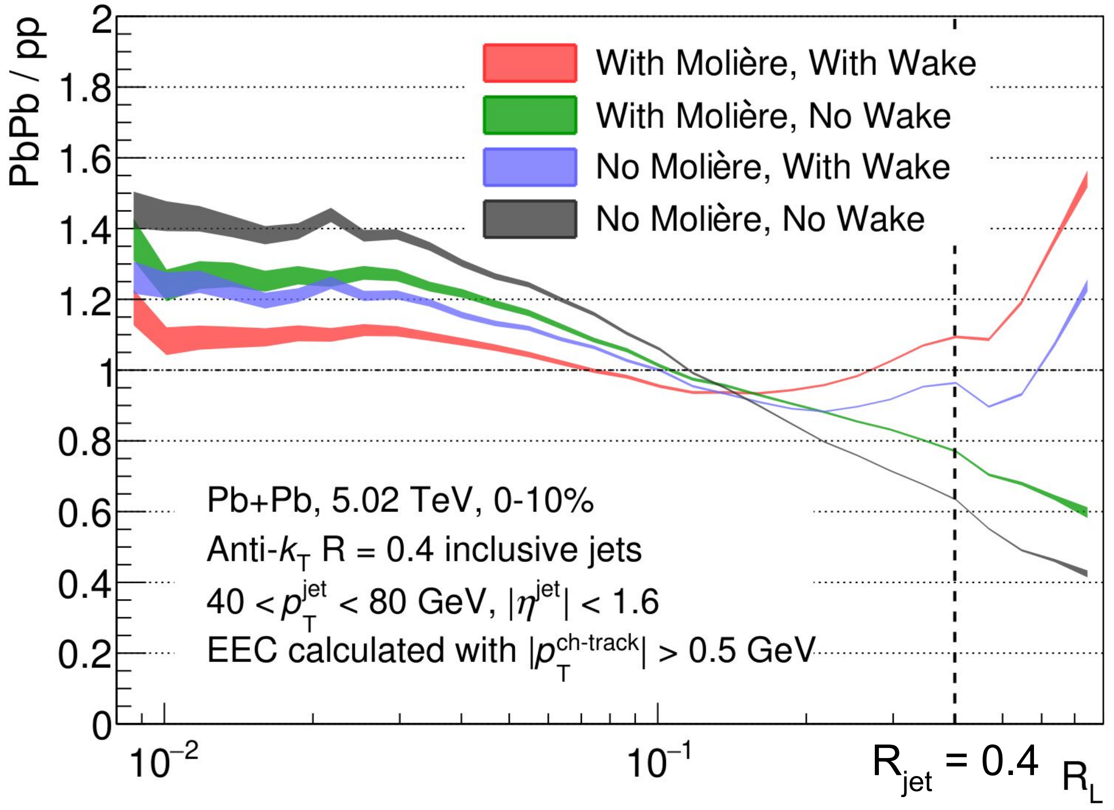
Jet energy loss
⇒ EEC shifts left



EECs in PbPb Collisions

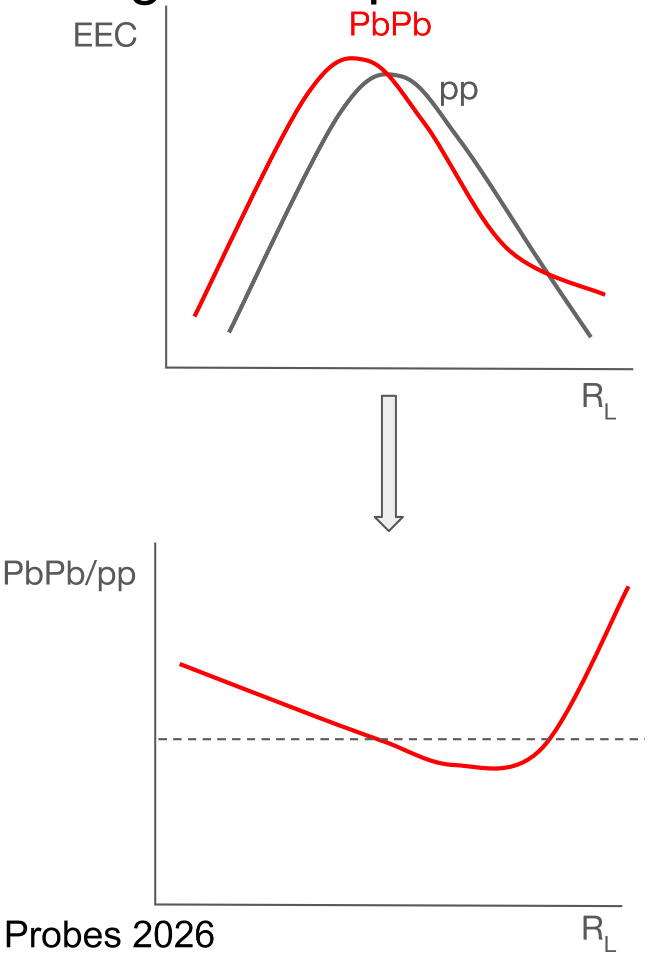
In PbPb, wake dominates large angle correlations
It is difficult to disentangle Molière scattering from the wake



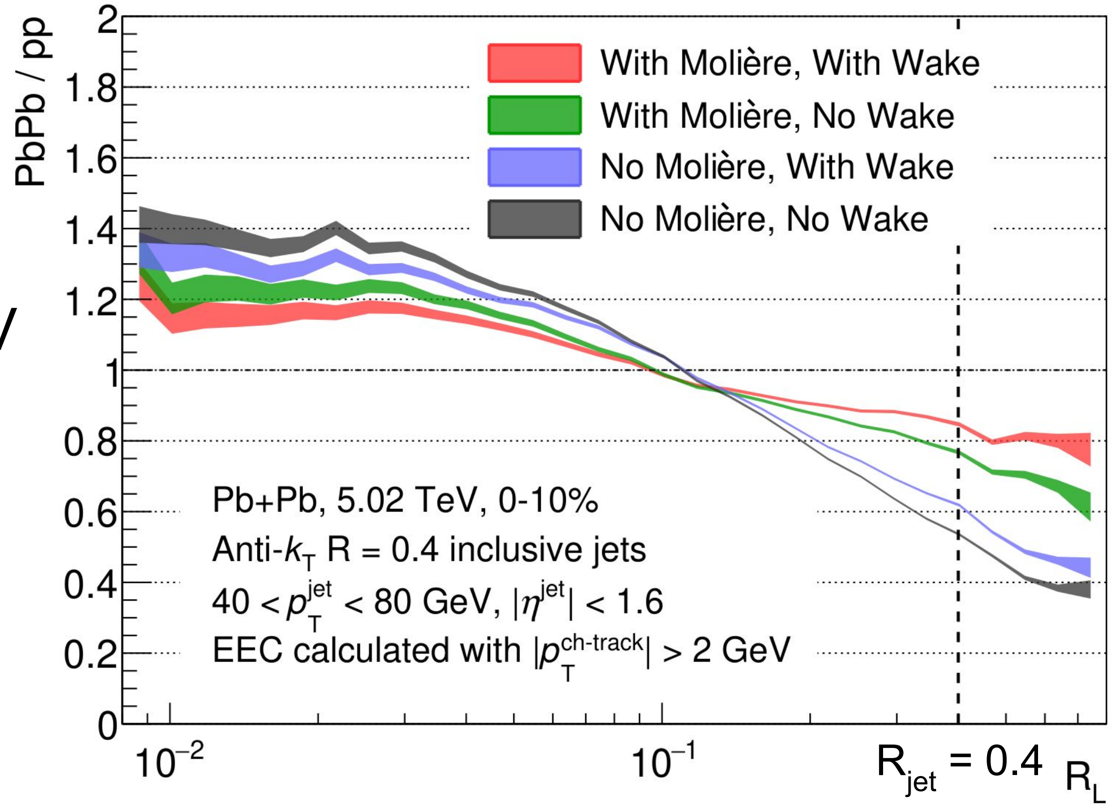


Why OO? EECs in PbPb Collisions

Apply track cut p_T > 2 GeV to remove the soft wake and isolate Molière scattering
However, selection bias in PbPb competes with Molière scattering, unambiguous experimental evidence of Molière scattering is hard to see



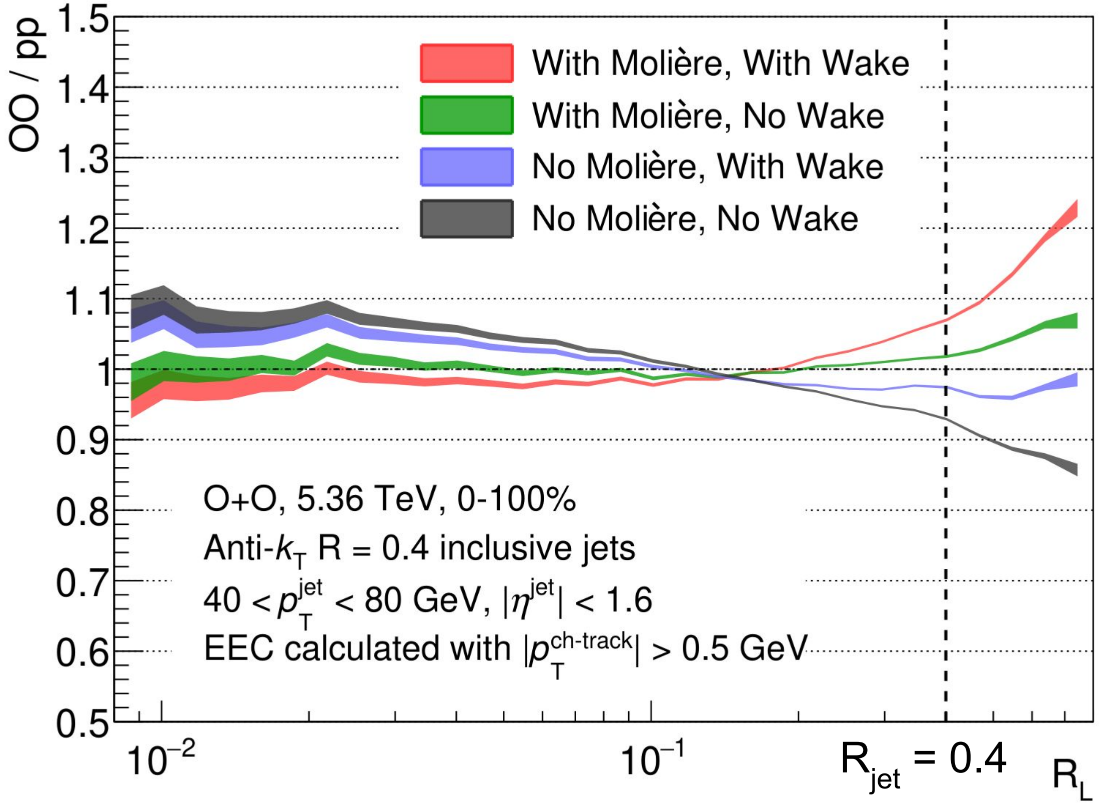
Track cut
p_T > 2 GeV



Charged Hadron EECs of R = 0.4 Jets

Jet reconstruction & EEC calculation scheme: [Phys.Lett.B 866 (2025) 139556]
OO/pp ratio shows relative increase/decrease of EEC due to medium effects

- Reduced selection bias ⇒ OO/pp ratios of EEC go above one at large R_L

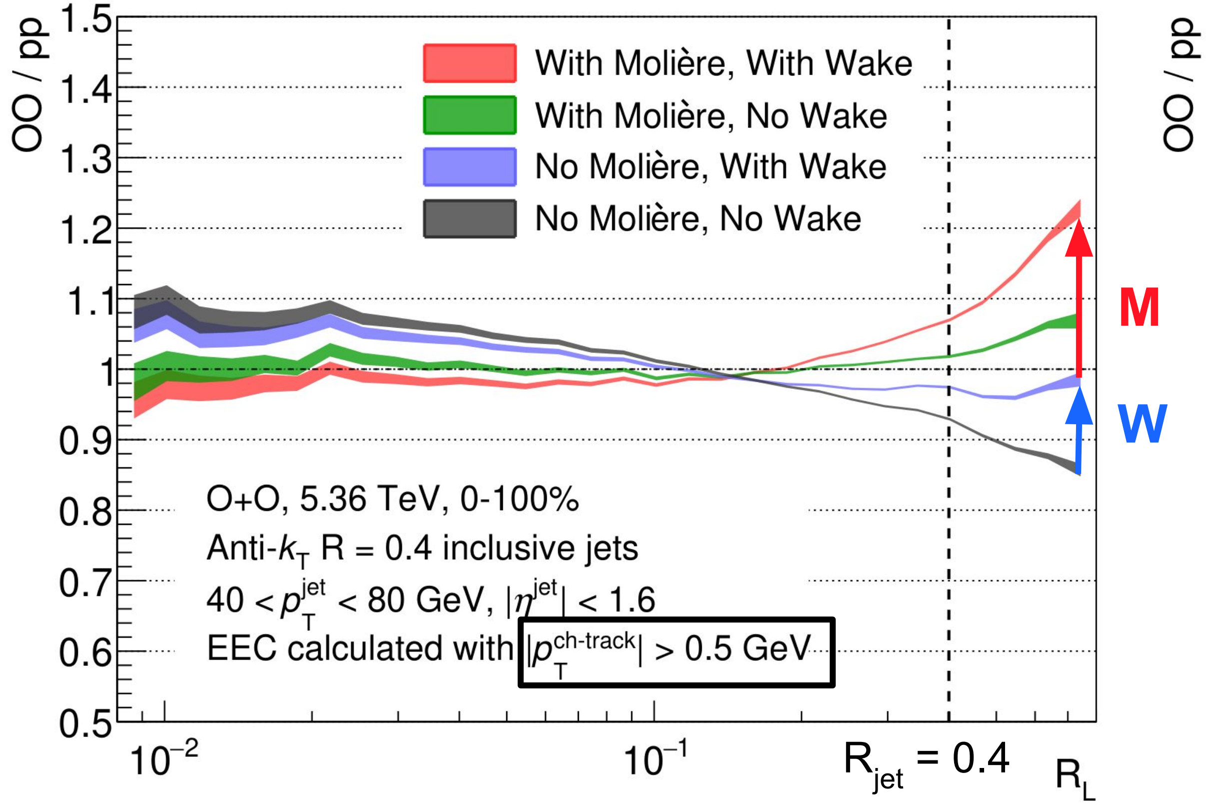


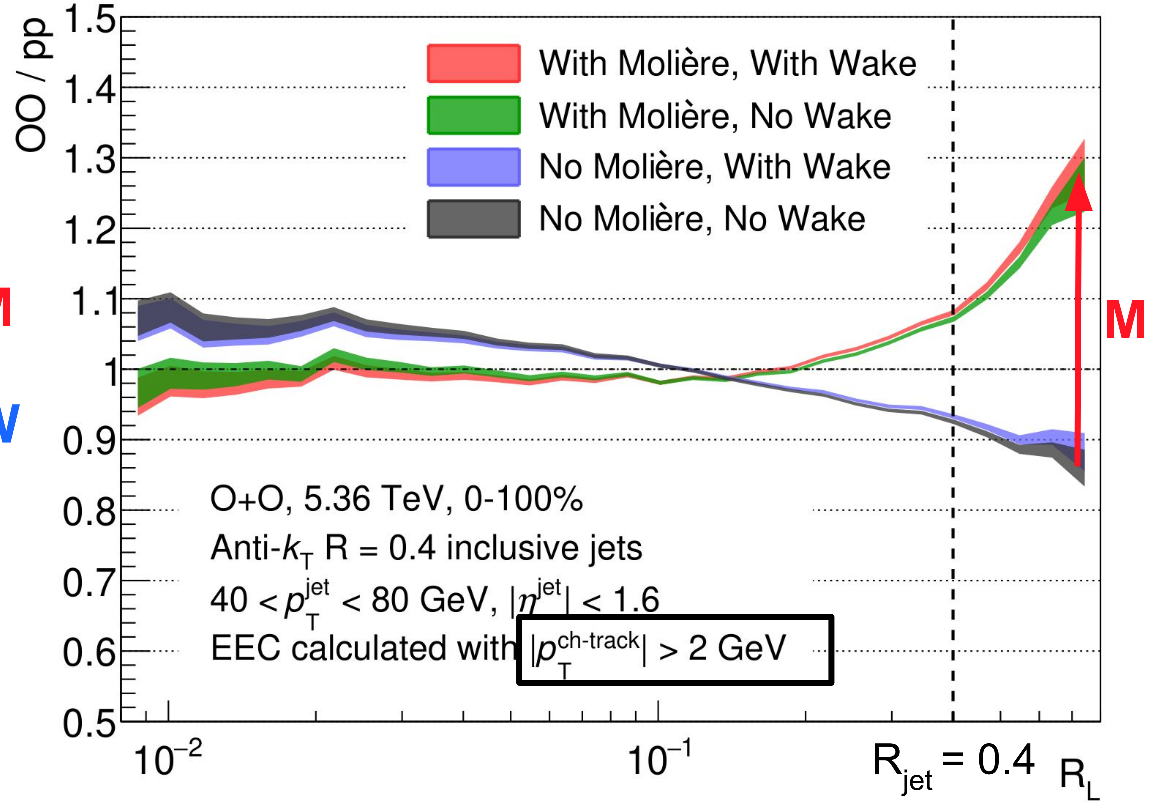
2603.23596 [Kudinoor, AL, Pablos, Rajagopal]

Charged Hadron EECs of R = 0.4 Jets

W: Wake ; M:Molière

- Reduced selection bias ⇒ OO/pp ratios of EEC go above one at large R_L
- Large angle contribution of Molière scattering and wake are of comparable magnitude
- Imposing ch-track cut p_T > 2 GeV removes wake particles



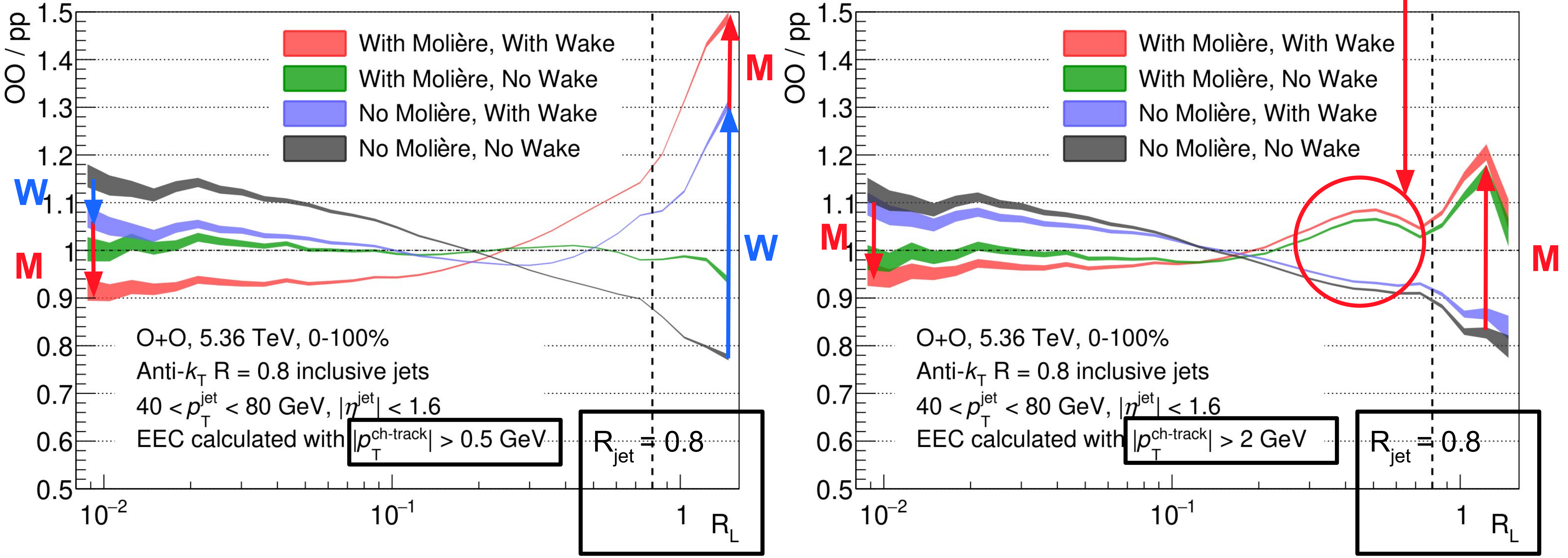


2603.23596 [Kudinoor, AL, Pablos, Rajagopal]

Charged Hadron EECs of R = 0.8 Jets

W: Wake ; M:Molière

- Small angle: Molière scattering broaden the jet core ⇒ EEC ratio is suppressed to below 1
- Large angle: hard track cut **reveals Molière scattering as a bump**
- $R_L > R_{jet}$: excludes jet core, EEC is dominated by wake–wake correlation

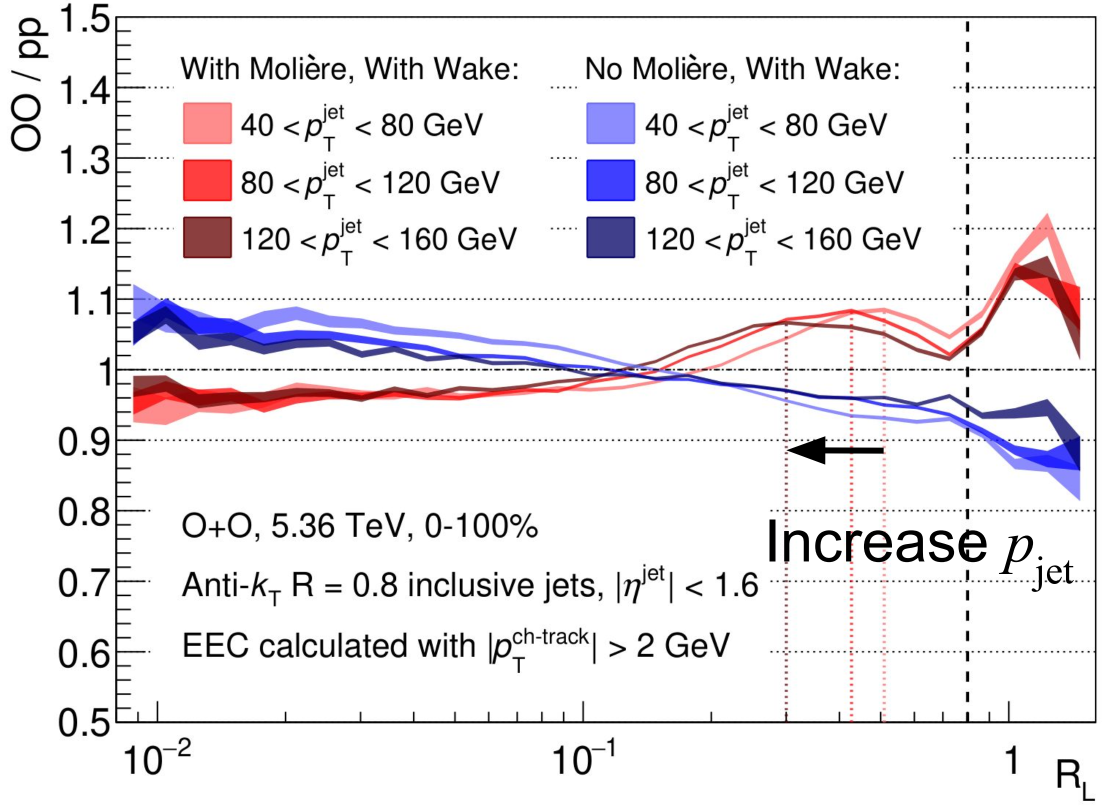


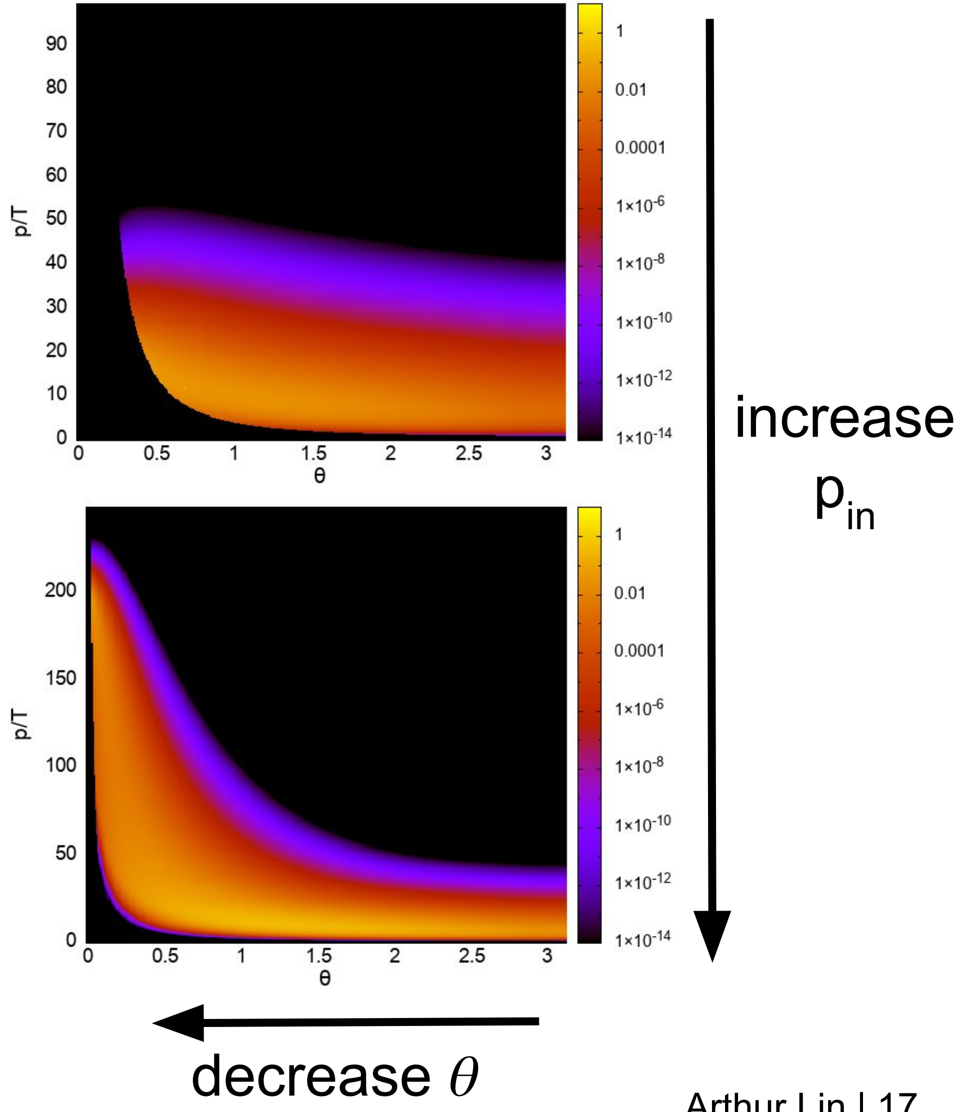
2603.23596 [Kudinoor, AL, Pablos, Rajagopal]

Bump on EEC: Typical Angle of Molière Scattering

arXiv: 2603.08776 [Hulcher et. al]

Bump moves to the left as jet momentum increases
Experimental measurement of this feature would be solid evidence of Molière scattering!





2603.23596 [Kudinoor, AL, Pablos, Rajagopal]