



Unambiguously Detecting Hard Scatterings of Jet Partons off QGP Quasiparticles Using Jet Substructure Observables

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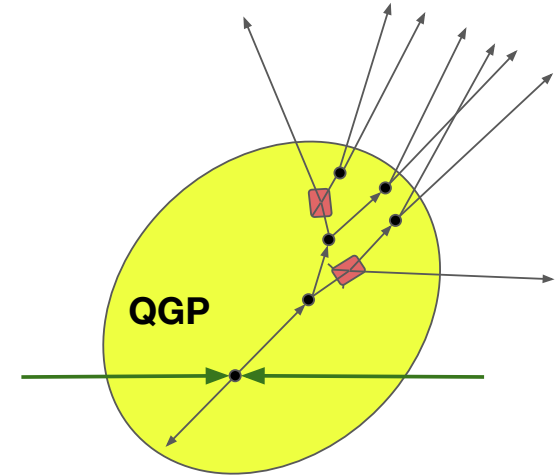
In collaboration with Zach Hulcher (SLAC), Arthur Lin (MIT),
Daniel Pablos (Oviedo U.), and Krishna Rajagopal (MIT)

Based on [2603.08776](#) and [2603.23596](#)

Revealing the Short-Distance Structure of QGP using Jets

[1808.03250](#) [D'Eramo et al.]
[2603.08776](#) [Hulcher et al.]
[2603.23596](#) [Kudinoor et al.]

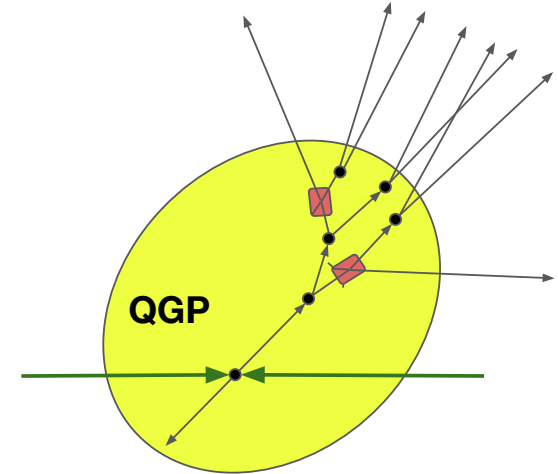
- At length scales $O(1/T)$ and longer, QGP is a liquid. Since QCD is asymptotically free, QGP must be particulate at short-distance scales. Currently, no unambiguous experimental evidence for this.



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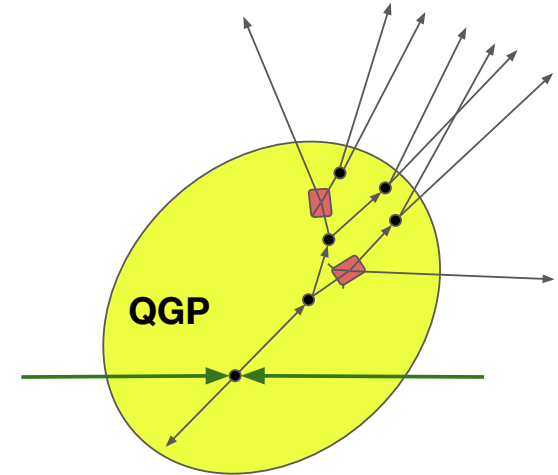
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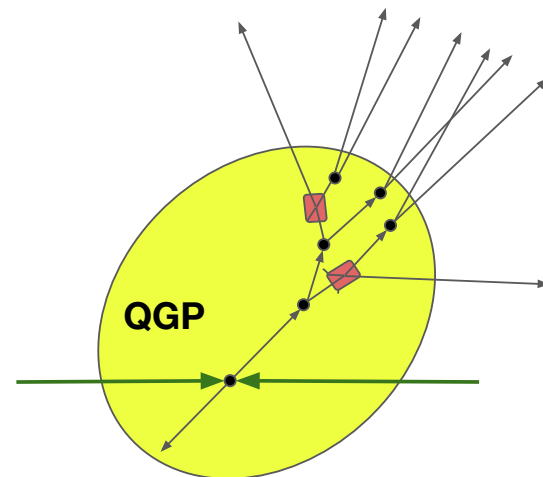
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Revealing the Short-Distance Structure of QGP using Jets

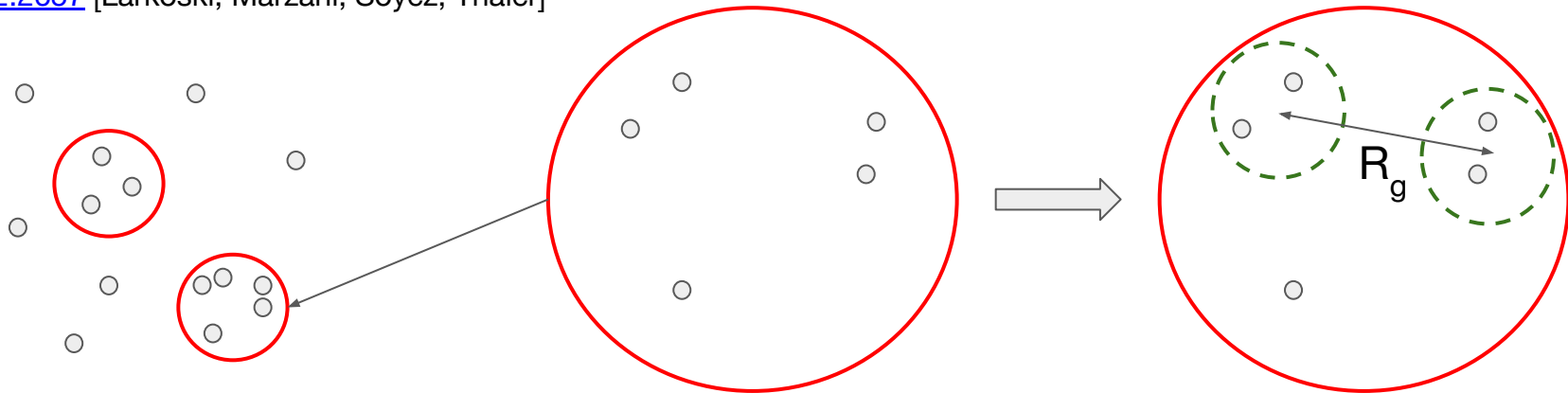
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- This presents an opportunity to **reveal the microscopic structure of QGP and to develop and test theoretical descriptions of it** (analogous to PDFs in DIS).
- Such hard scatterings can be detected using select observables that characterize the internal structure (substructure) of jets
 - Jet girth g
 - **Soft Drop angle R_g**
 - **Energy-energy correlators (EECs)**



Soft Drop

[1402.2657](#) [Larkoski, Marzani, Soyez, Thaler]



Anti- k_t jets

Look inside each jet

Re-cluster the jet while dropping/grooming away the soft prongs

R_g is the separation between the first two prongs which satisfy

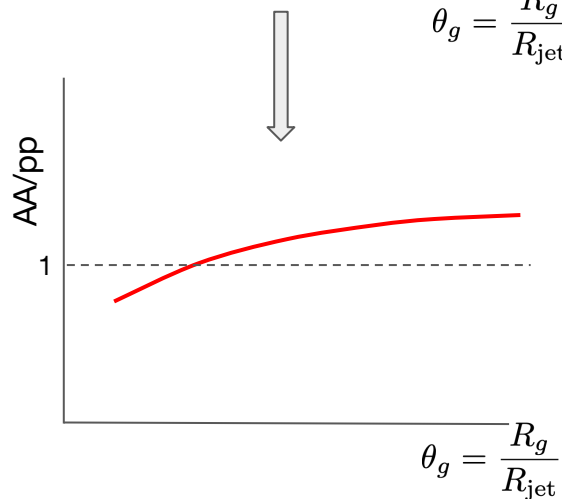
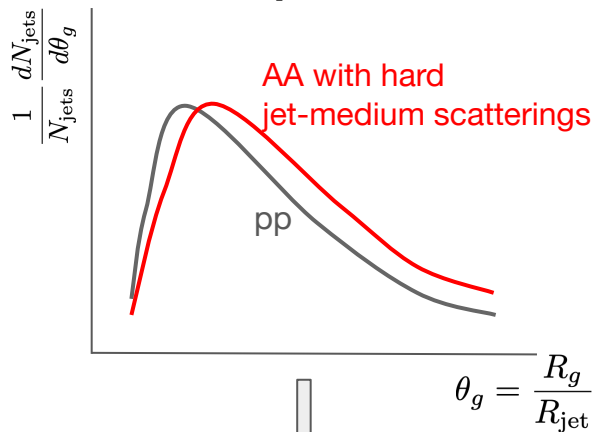
$$z_{\text{subleading}} > z_{\text{cut}} \left(\frac{R_g}{R} \right)^\beta$$

R_g measures the angle of the first hard splitting in the jet

Scale by jet radius $\theta_g = \frac{R_g}{R_{\text{jet}}}$

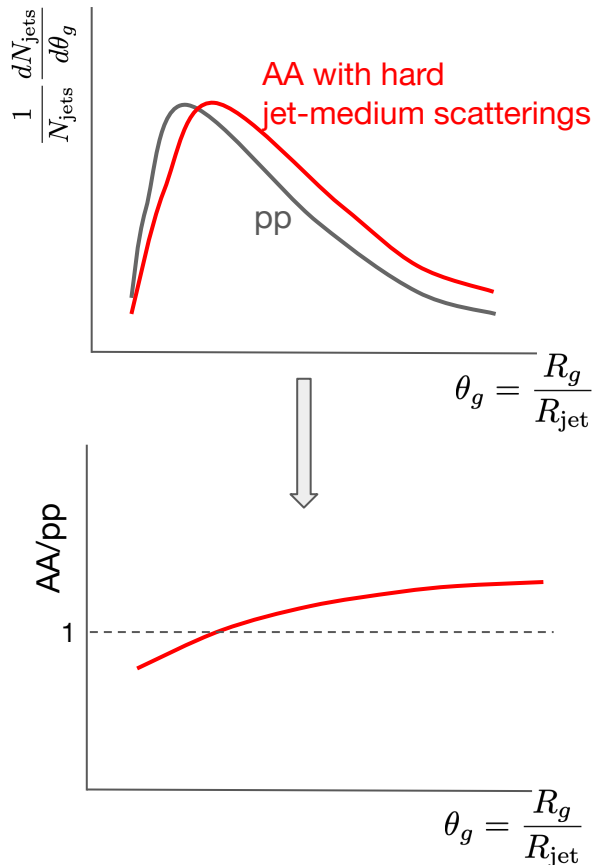
Soft Drop Angle in AA Collisions

Naive Expectation

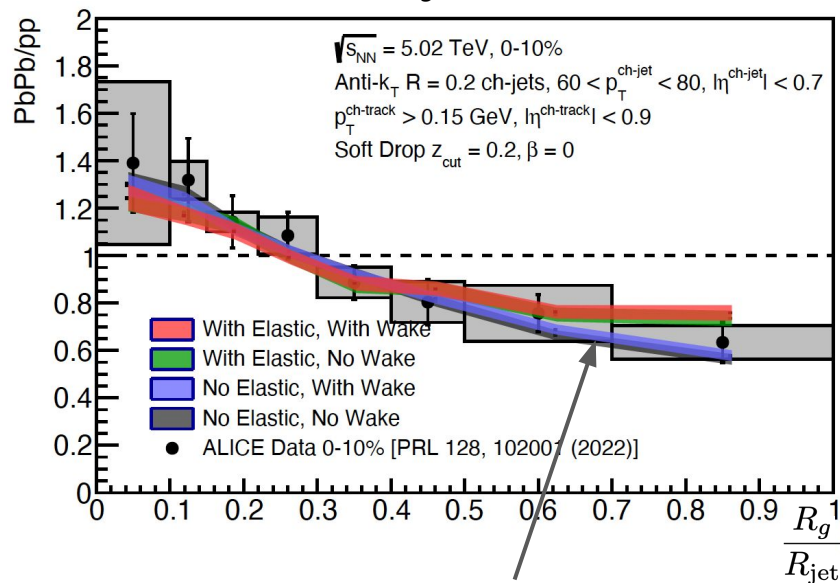


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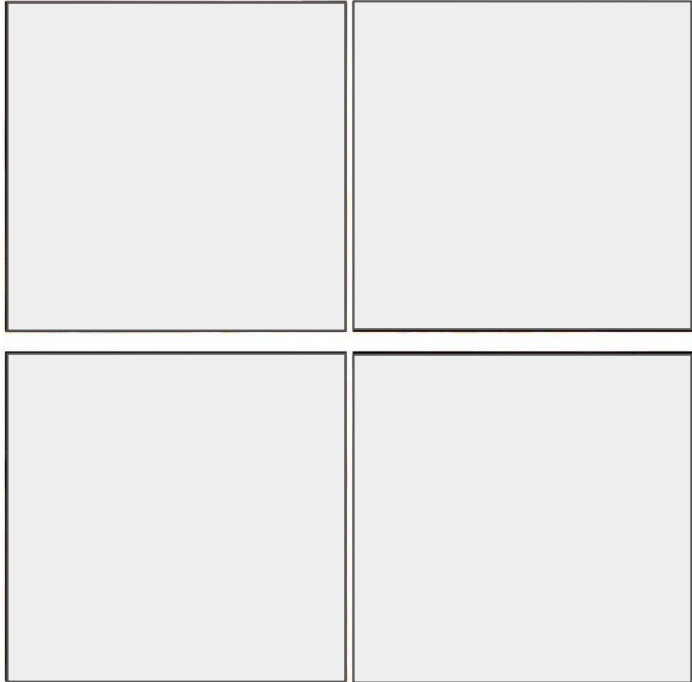
Reality in PbPb



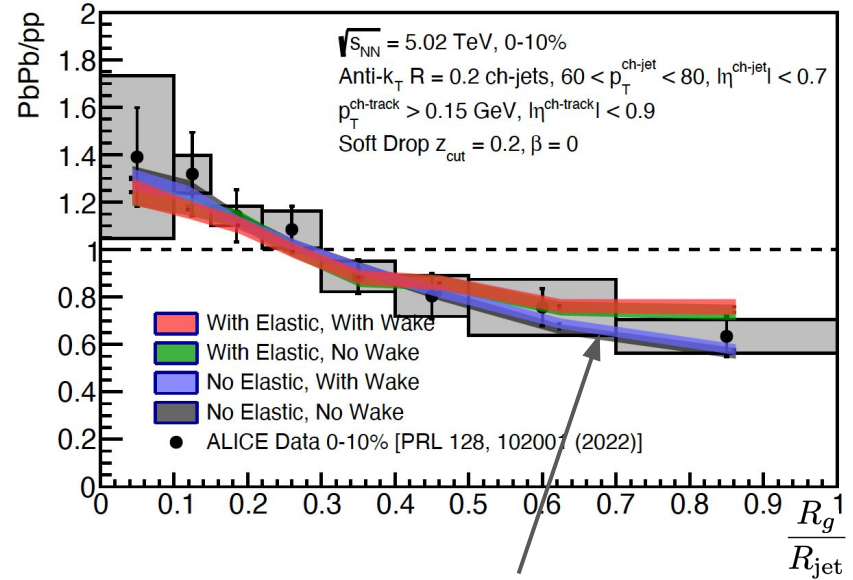
PbPb jet sample is biased towards those that have lost the least energy, which tend to be narrower



isions



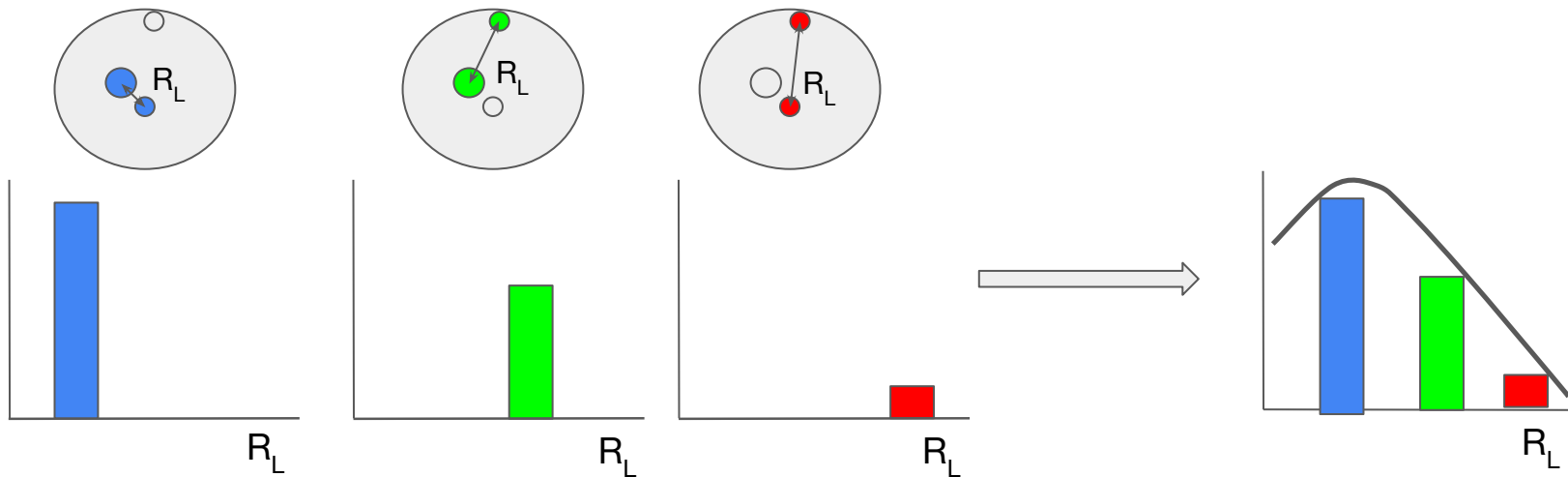
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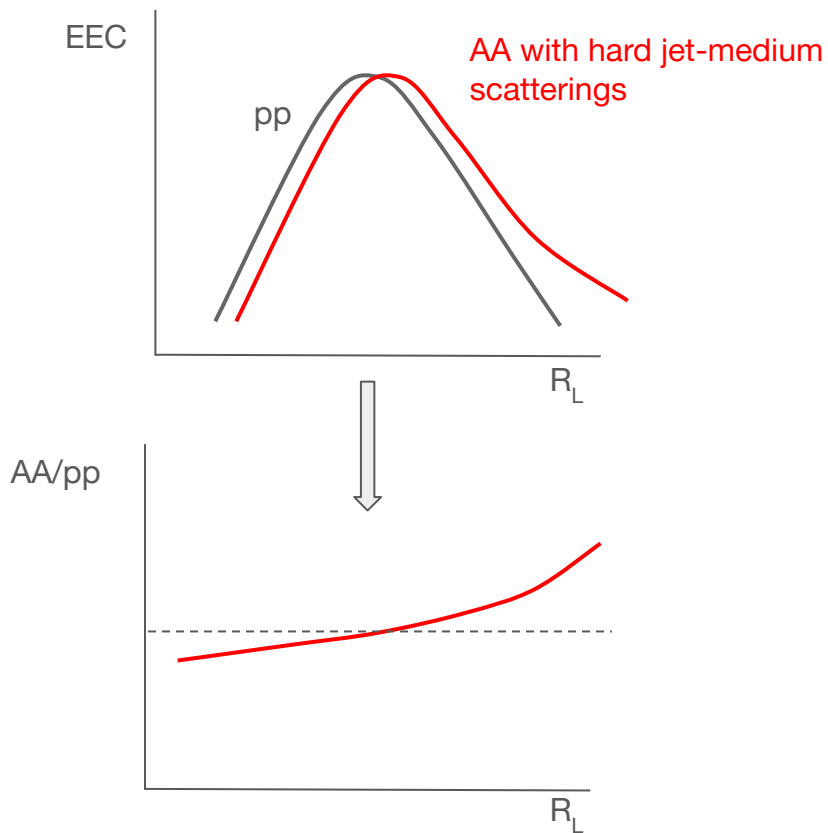
Energy-Energy Correlators (EECs)

$$\text{EEC}(R_L) = \frac{1}{\mathcal{N}} \frac{1}{\delta r} \sum_{\text{jets}} \sum_{\text{pairs} \in [R_L - \frac{\delta r}{2}, R_L + \frac{\delta r}{2}]} p_{T_i} p_{T_j}$$



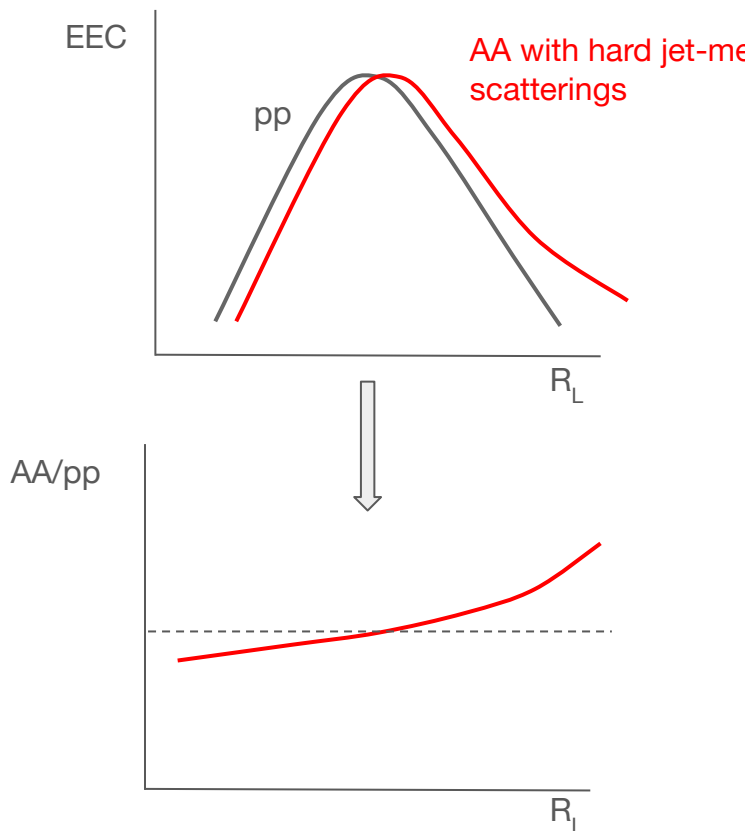
EECs in Heavy-Ion Collisions

Naive Expectation



EECs in Heavy-Ion Collisions

Naive Expectation



Reality in PbPb

[2503.19993](#)

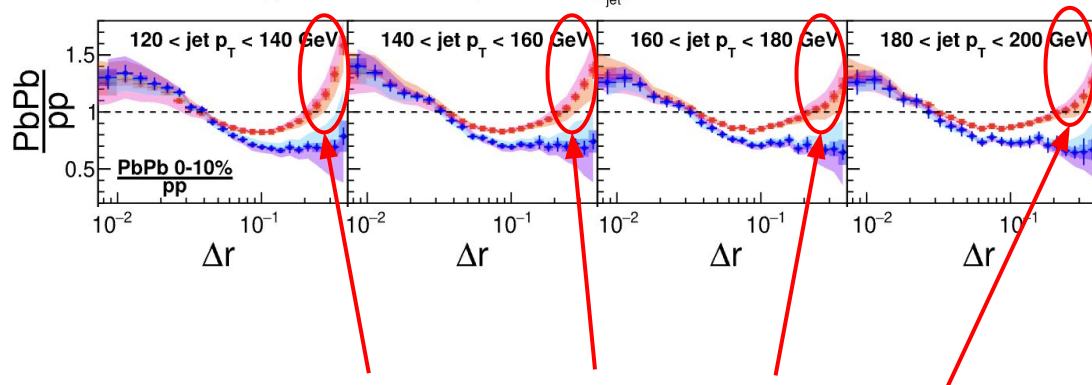
CMS

PbPb $\sqrt{s_{NN}} = 5.02$ TeV, 1.70 nb^{-1} anti- k_T $R = 0.4$

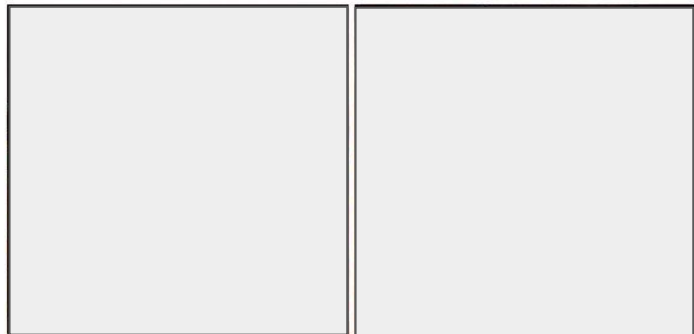
pp $\sqrt{s} = 5.02$ TeV, 302 pb^{-1}

$|\eta_{jet}| < 1.6$

$p_T^{ch} > 1 \text{ GeV}$



LET'S DECLARE VICTORY...? Not so fast!
 Soft hadrons from wakes, medium-induced radiation,
 soft jet-medium scatterings also populate large- R_L



ns

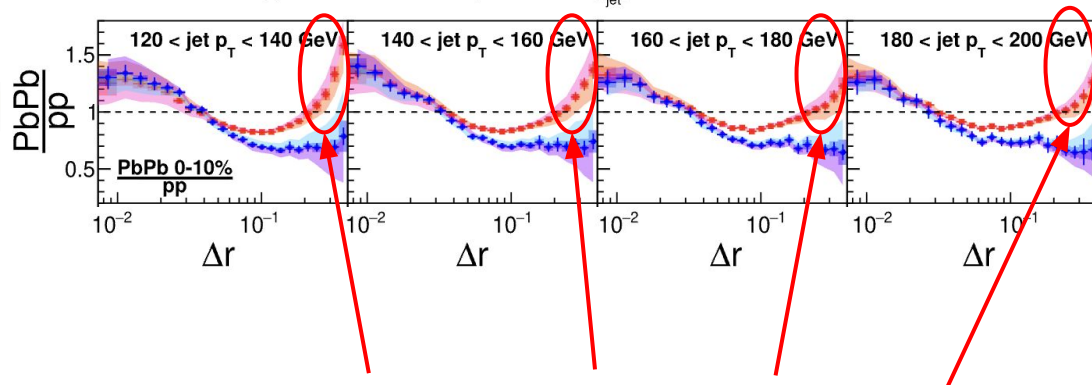
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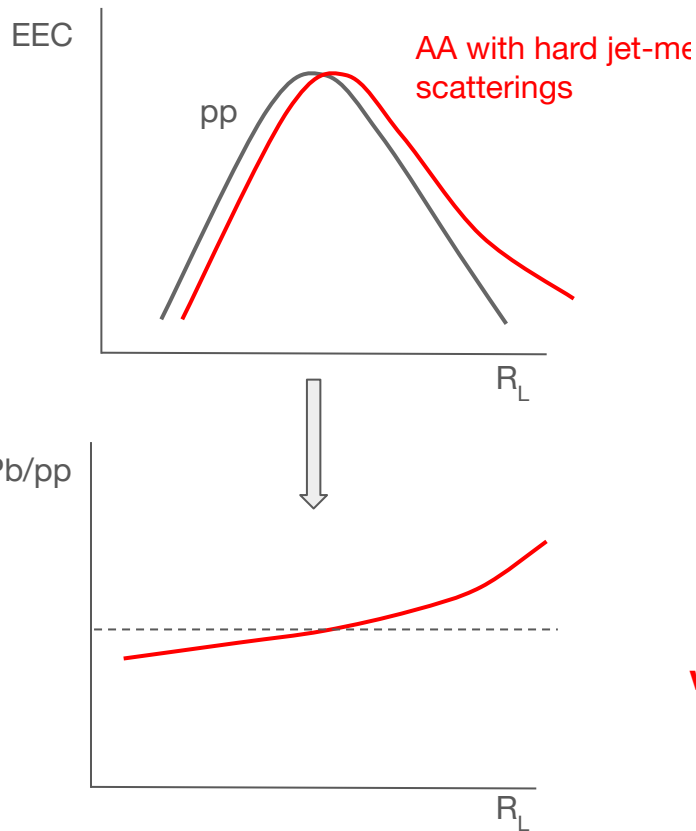


LET'S DECLARE VICTORY...? Not so fast!

Soft hadrons from wakes, medium-induced radiation, soft jet-medium scatterings also populate large- R_L

EECs with $p_T^{\text{ch-track}} > 2 \text{ GeV}$

Naive Expectation



Reality in PbPb

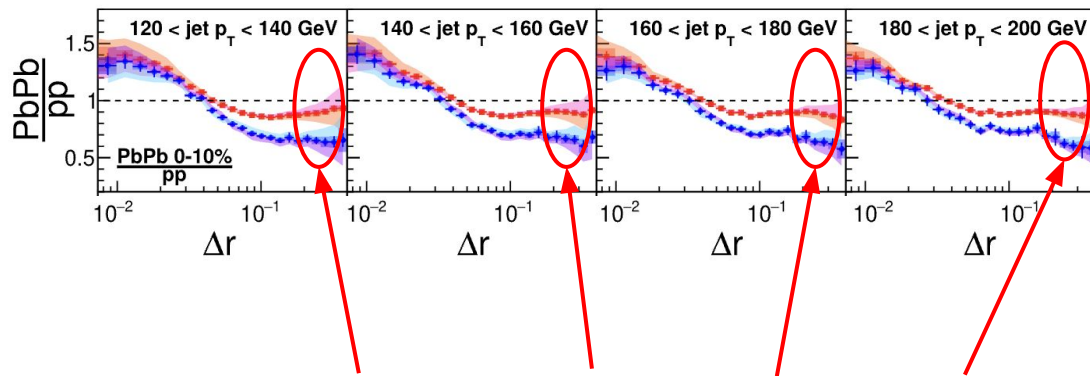
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$p_T^{\text{ch}} > 2 \text{ GeV}$



The confounding effects of energy loss and selection bias are so strong that they suppress the PbPb/pp ratio below unity...

Seeing an enhancement above unity at large R_g and/or R_L would be model-independent evidence of hard scattering of jet partons off QGP quasiparticles! How can we do this?



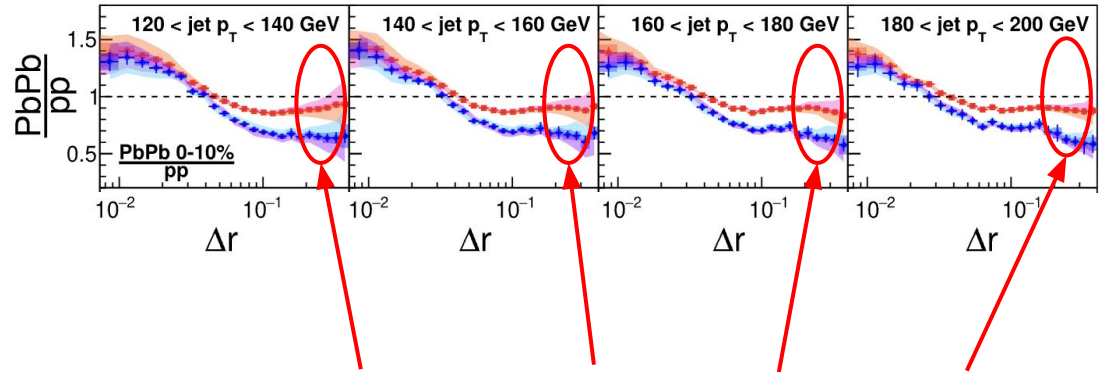
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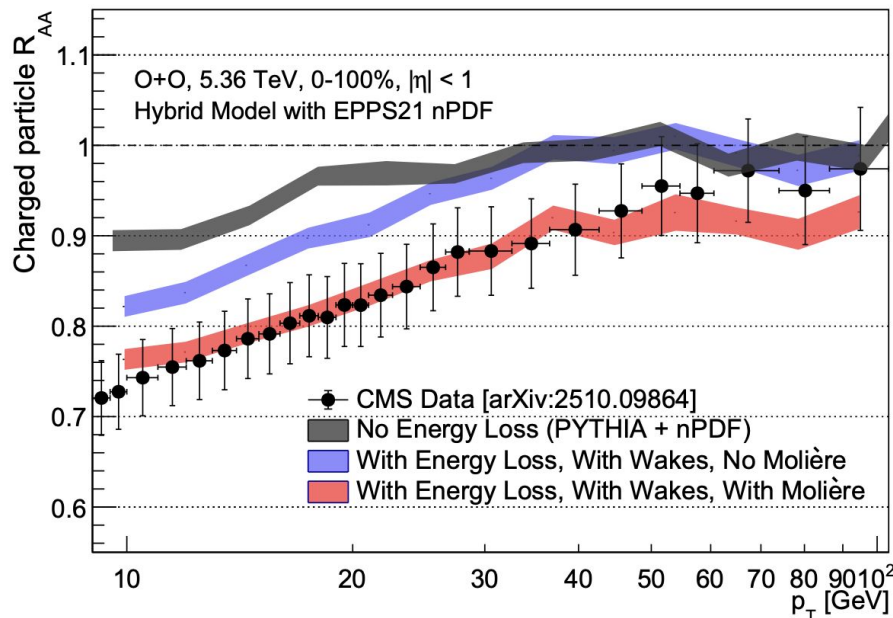
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Jet Partons Lose Less Energy in OO Collisions

[2603.23596](#) [Kudinoor, Lin, Pablos, Rajagopal]

Droplets of QGP are smaller in OO than in PbPb.

- Jet partons lose less energy in OO collisions than they do in PbPb collisions. **This means less selection bias.**
- **Hard scatterings between jet partons and QGP quasiparticles are a relatively more important effect in OO.**
 - Energy loss due to hard jet-medium scatterings scales as L
 - Weakly coupled radiative energy loss scales as L^2
 - Strongly coupled energy loss scales as L^3



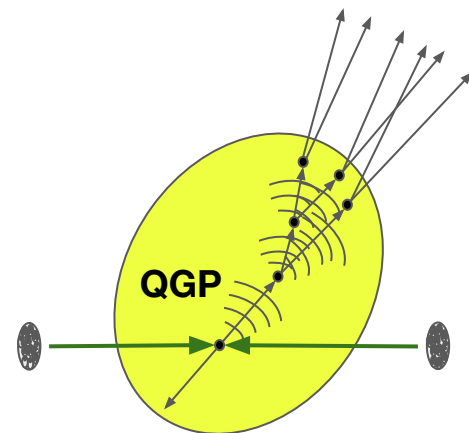
Hard jet-medium scatterings are needed for the Hybrid Model to explain CMS R_{oo} data!
(See Dani Pablos' Talk)

The Hybrid Strong/Weak Coupling Model

arXiv:[1405.3864v3](#), [1609.05842](#)

[Casalderrey-Solana, et al.]

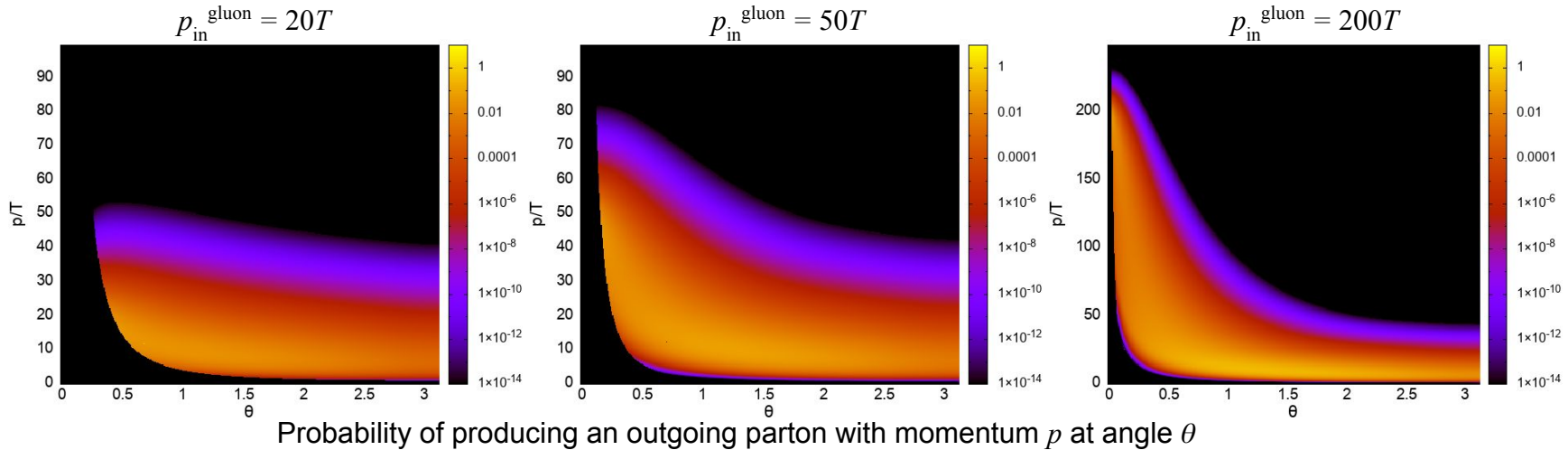
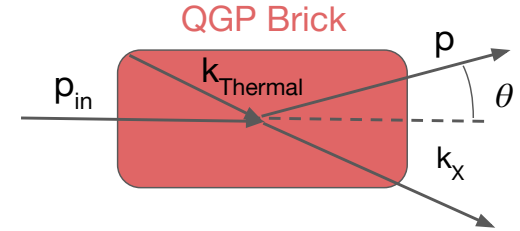
- Parton showers are implemented using PYTHIA 8
- Jet partons lose energy to the plasma as determined by a holographic energy loss formula that depends on a global-fit parameter κ_{SC} . It quantifies the strength of quenching and was fit to PbPb data for ch-hadron and jet R_{AA} .
- The lost energy thermalizes quickly and becomes a hydrodynamic wake in the plasma



A Type of Hard Jet-Medium Scattering: Molière Scattering

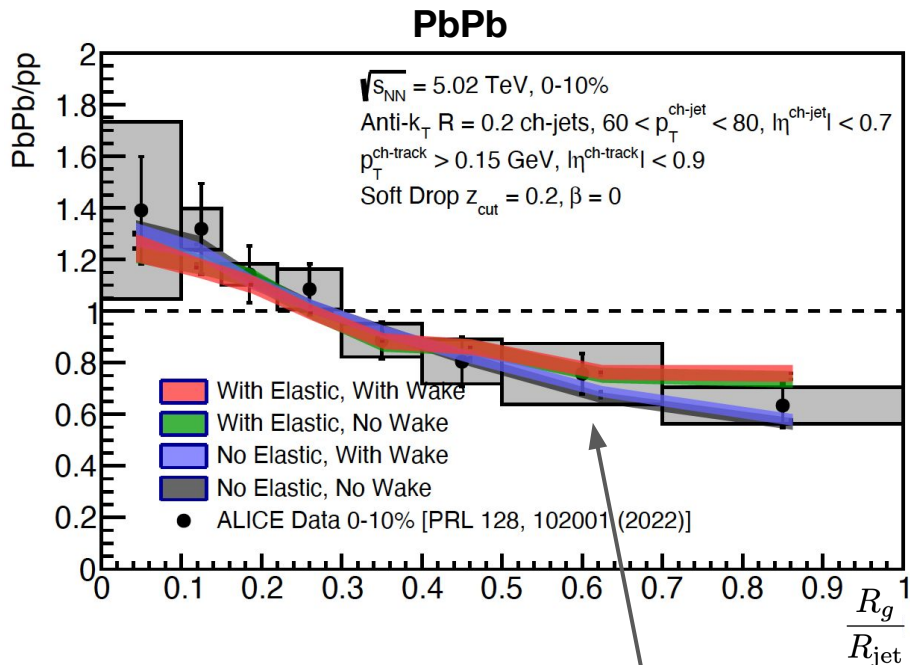
[1808.03250](#) [D'Eramo, et al.], [2603.08776](#) [Hulcher, et al.]

- Quasiparticles in QGP can be revealed by large-angle, **$2 \rightarrow 2$ scatterings** between jet partons and QGP quasiparticles at sufficiently **high momentum exchange**: $|t|, |u| > am_D^2$, $a = 10$

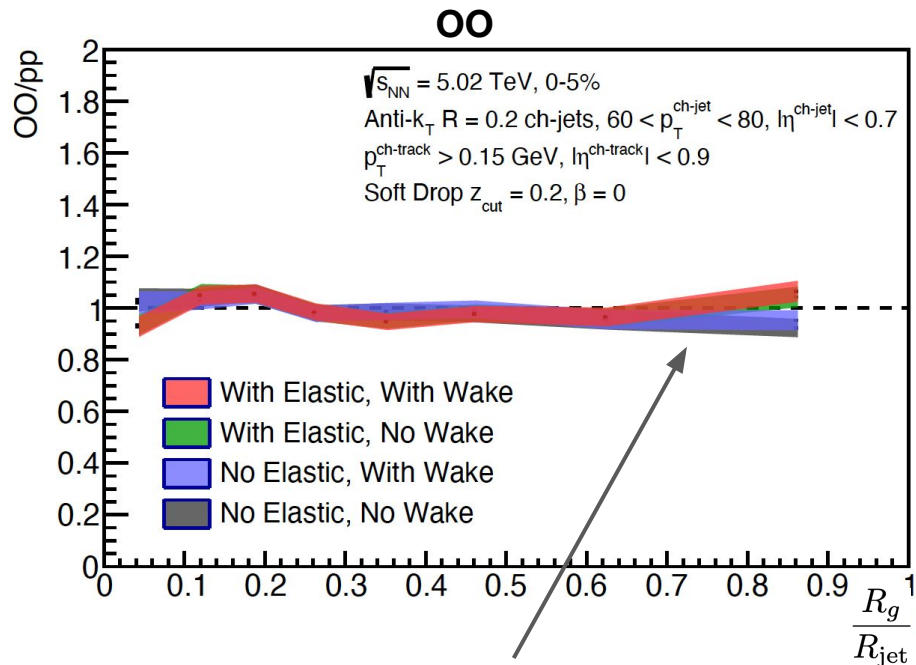


- After a “Molière scattering”, both outgoing partons can rescatter and excite wakes

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

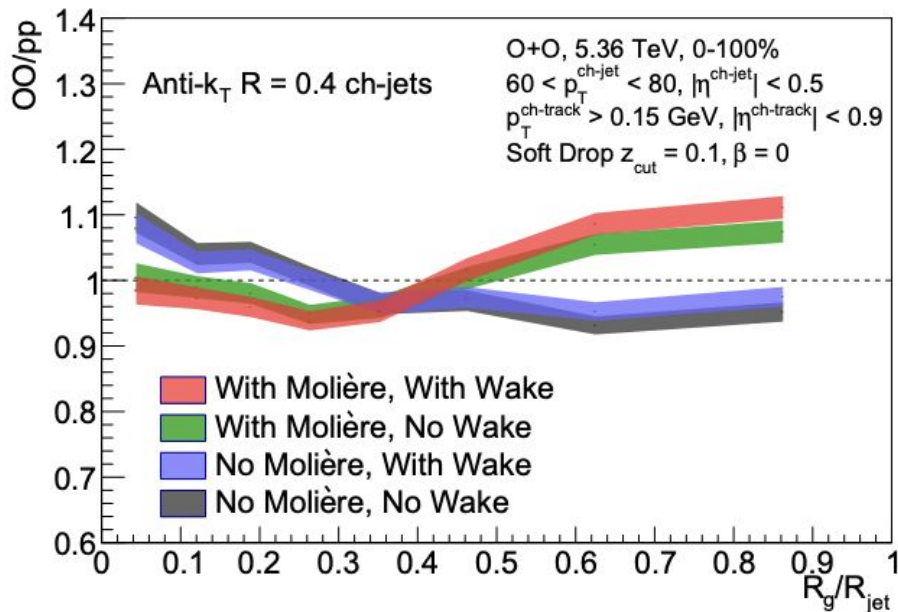


**Effects of selection bias and jet energy loss are minimal
 $\Rightarrow$ Flatter OO/pp ratio**

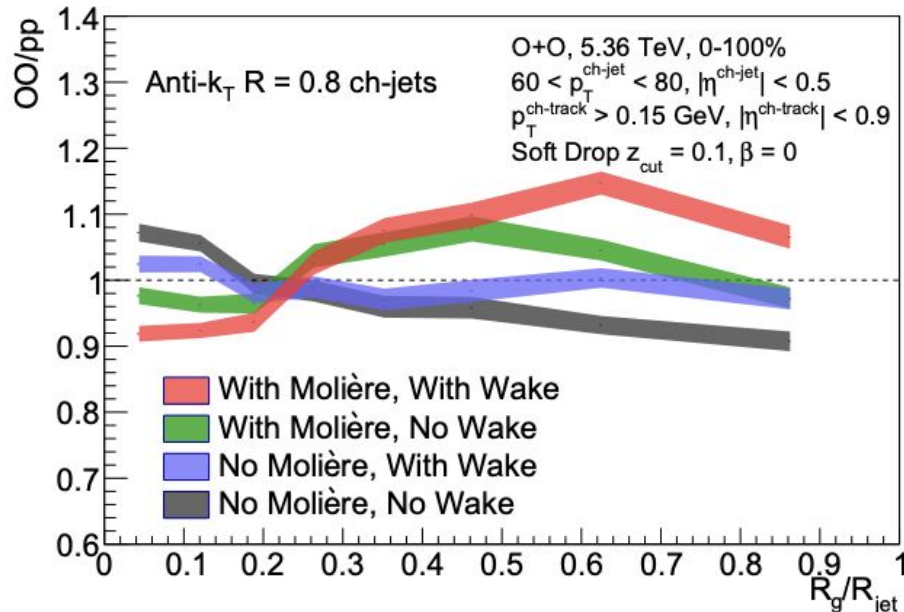
Soft Drop Angle for $R = 0.4$ and $R = 0.8$ Jets

[2603.23596](#) [Kudinoor, Lin, Pablos, Rajagopal]

OO Jets with $R = 0.4$

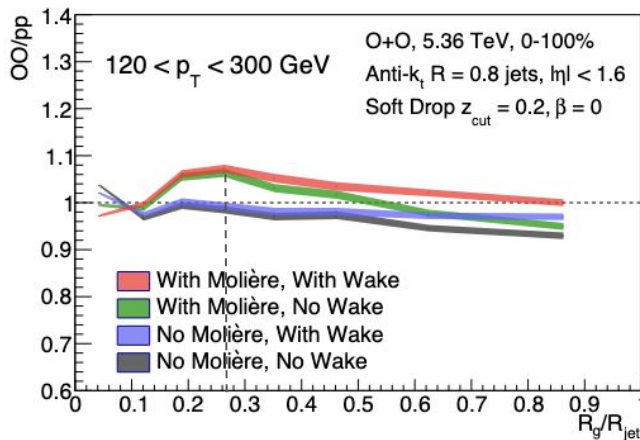
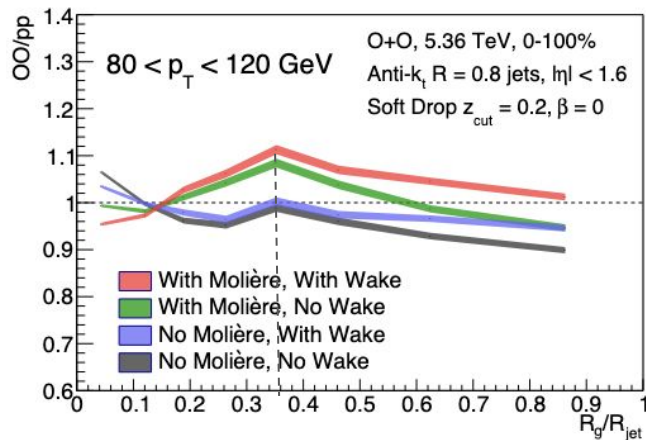
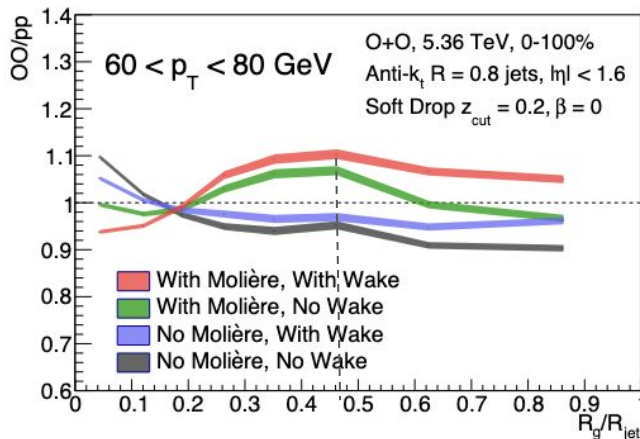
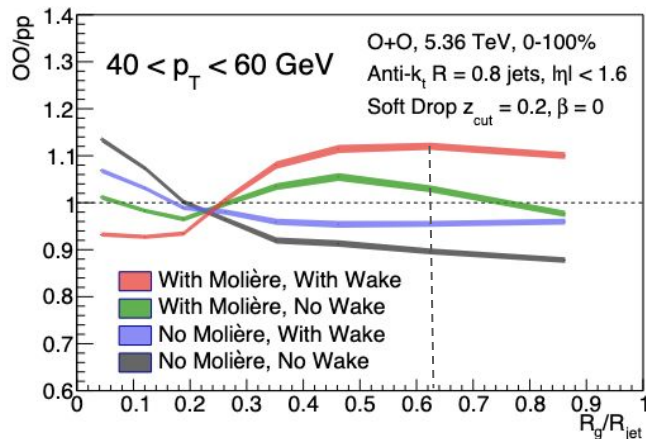


OO Jets with $R = 0.8$



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

Typical Angle of Molière Scattering



The typical angle of Molière scattering decreases as a function of jet p_T .

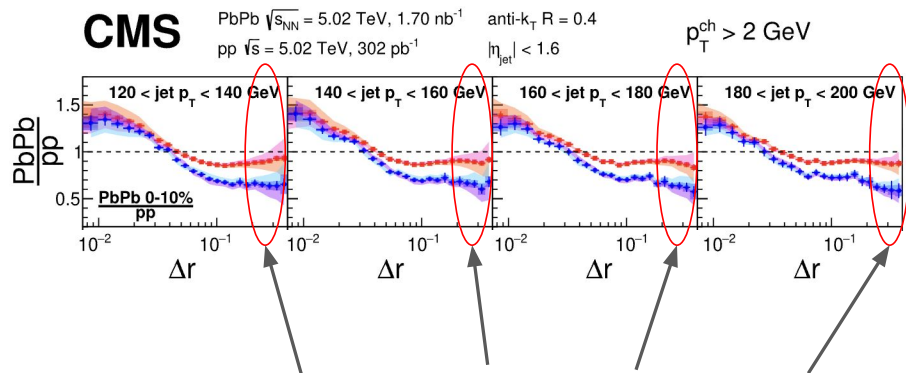
We will see this more clearly using EECs.

EECs in OO Collisions with $p_T^{\text{ch-track}} > 2 \text{ GeV}$

[2603.23596](#) [Kudinoor, Lin, Pablos, Rajagopal]

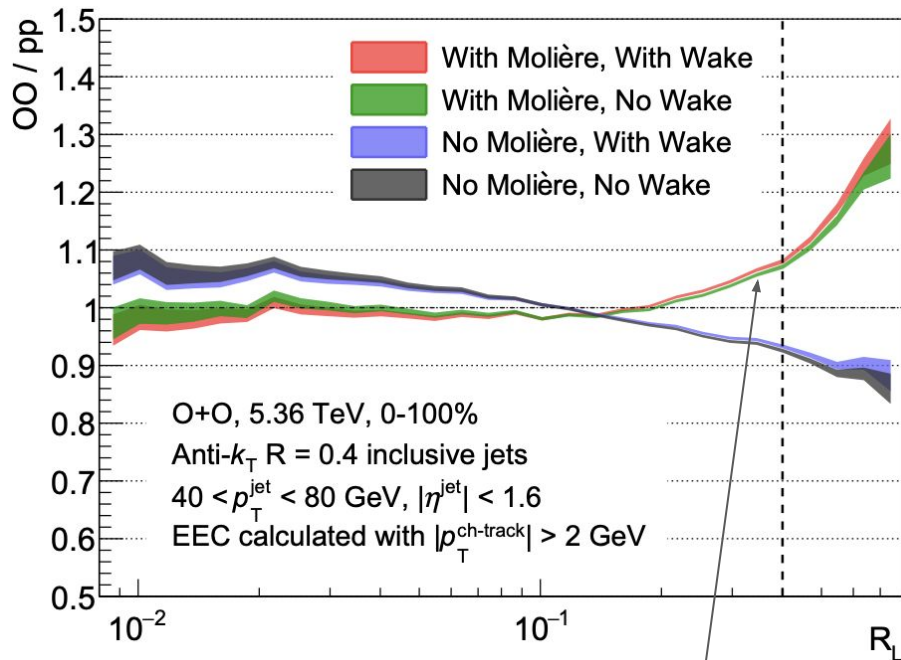
Recall in PbPb:

[2503.19993](#)



The effects of energy loss and selection bias are so strong that they suppress the PbPb/pp ratio below unity...

In OO Collisions:



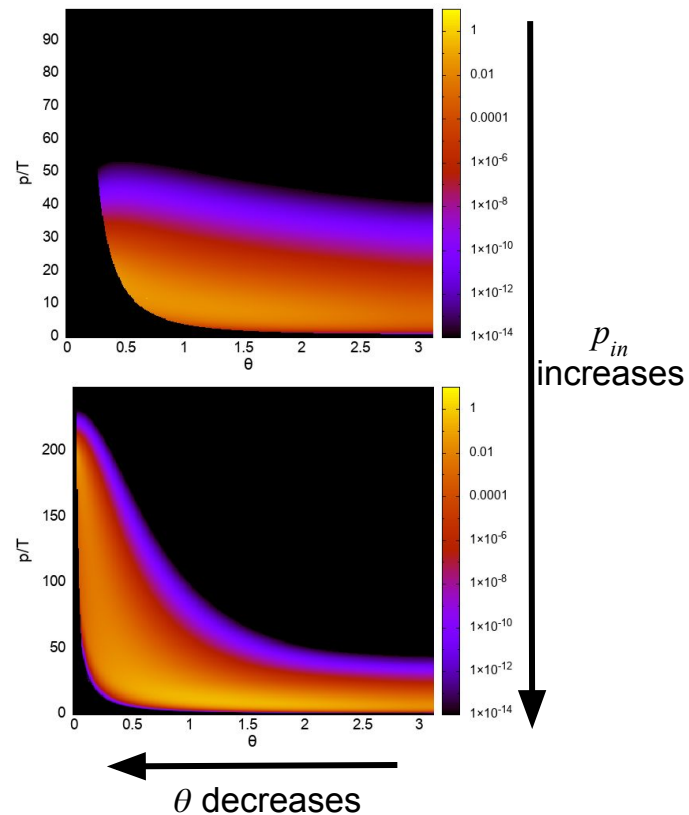
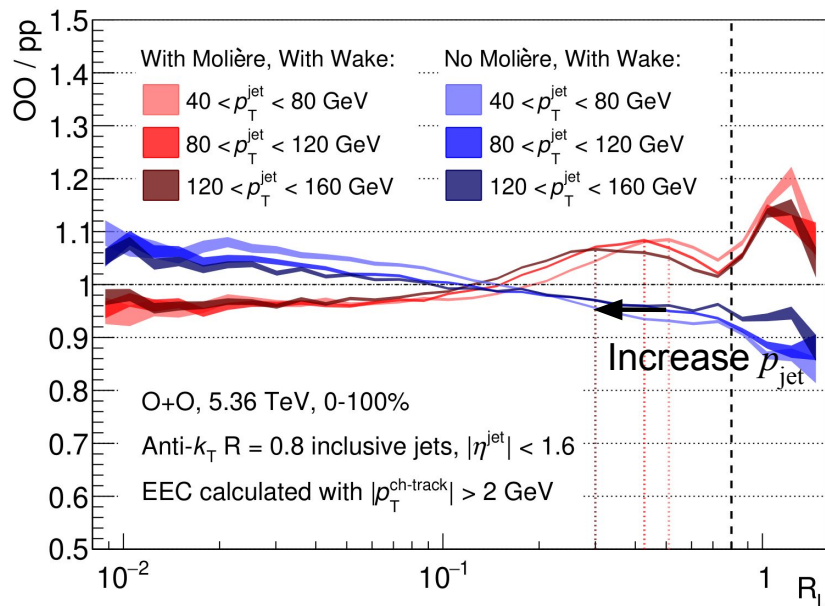
Minimal selection bias $\Rightarrow$ **Visible enhancement of the EEC at large R_L due to Molière scattering**

Revealing the Typical Angle of Molière Scattering in R = 0.8 Jets

[2603.23596](#) [Kudinoor, Lin, Pablos, Rajagopal]

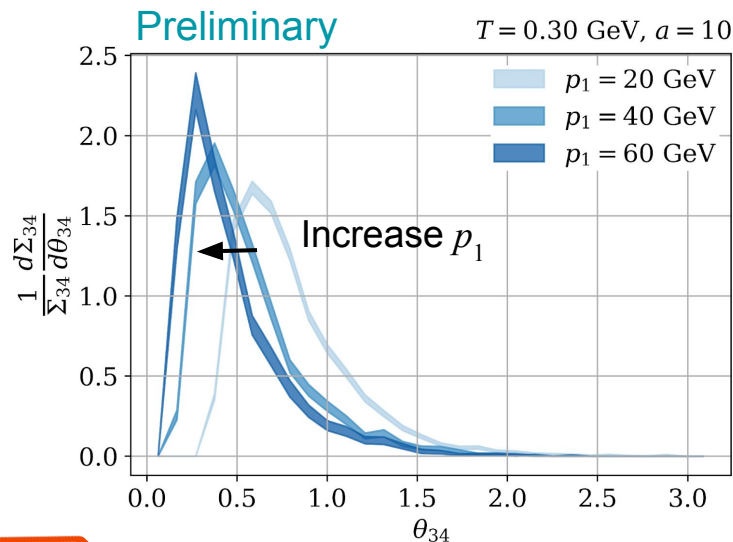
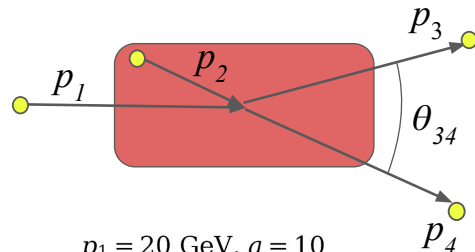
The typical angle of a Molière scattering is revealed as a bump in the OO/pp EEC ratio.

Experimental measurements of this bump would teach us about the typical scattering angles for hard jet-medium scatterings in the hot-QCD matter formed at the LHC and RHIC!



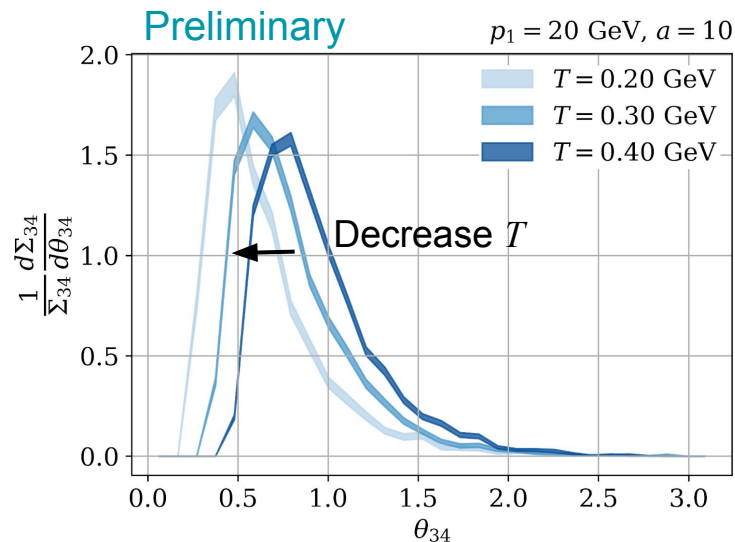
Ongoing: Semi-Analytic Calculations of the Molière Bump

- Suppose a jet parton with fixed p_1 scatters off a QGP parton with p_2 , sampled from a Boltzmann distribution of fixed temperature T .
- We calculate the EEC of the outgoing partons 3 and 4, as a function of the angle θ_{34} between them.



**NOT HYBRID
MODEL**

Higher incident parton p_T
 $\Rightarrow$ Lower typical θ_{34}



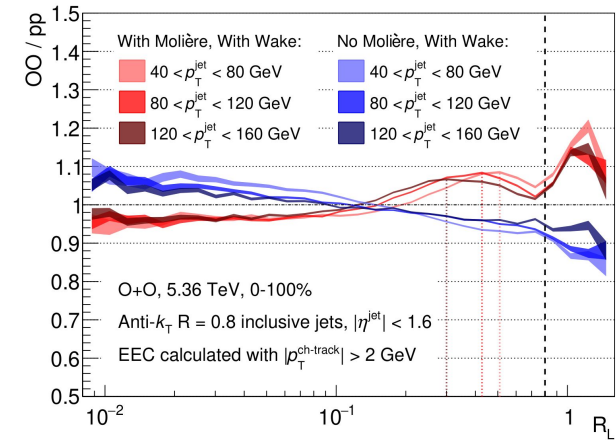
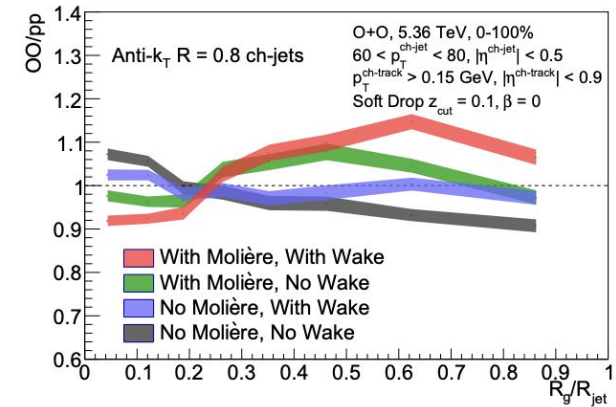
Lower momentum-exchange cutoff
 $\Rightarrow$ Lower typical θ_{34}

Key Takeaways

- Detecting hard jet-medium scatterings presents **an opportunity to reveal the microscopic structure of QGP and to develop and test theoretical descriptions of it** (analogous to PDFs in DIS).
- The confounding effects of selection bias due to jet energy loss can be minimized in **inclusive jet measurements in minimum bias OO collisions**.
- **We look forward to seeing jet substructure measurements in OO collisions from the LHC and sPHENIX.** Perhaps they will yield a discovery of hard scattering of jet partons off QGP quasiparticles. Or, comparisons between those measurements and our calculations will help make a quantitative case for the statistics needed in future OO runs.

Molière in PbPb: [2603.08776](#)

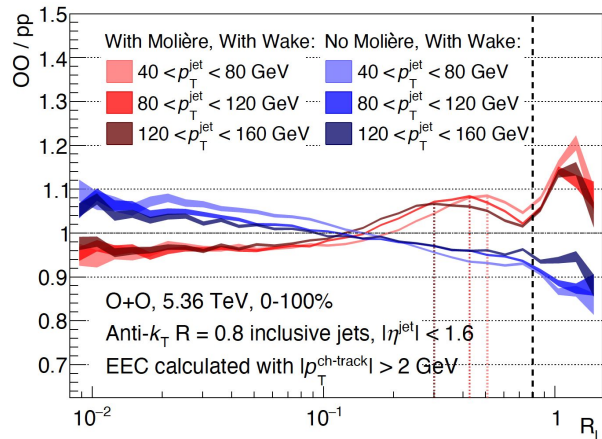
Molière in OO: [2603.23596](#)



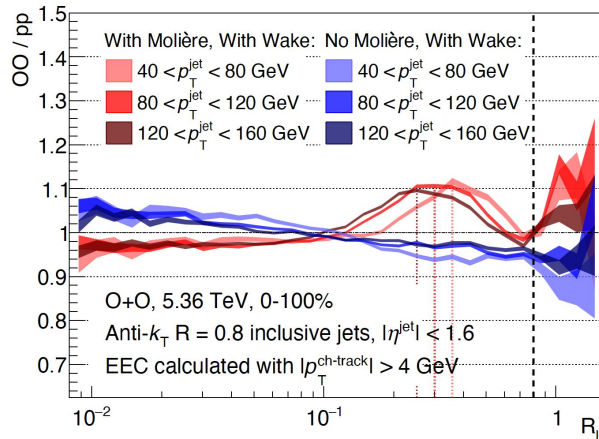
BACKUP

EECs with different track cuts (R = 0.8 Jets)

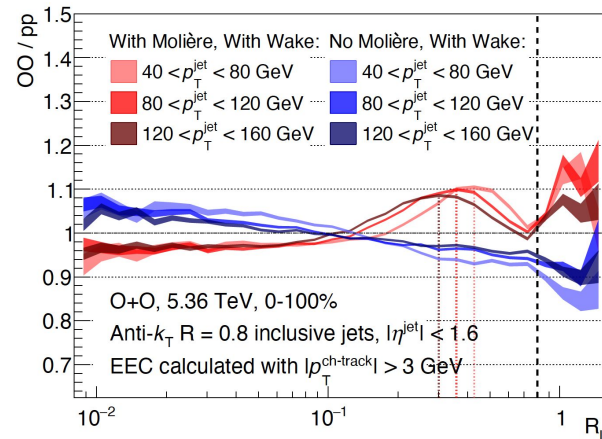
$p_T^{\text{ch-track}} > 2 \text{ GeV}$



$p_T^{\text{ch-track}} > 3 \text{ GeV}$

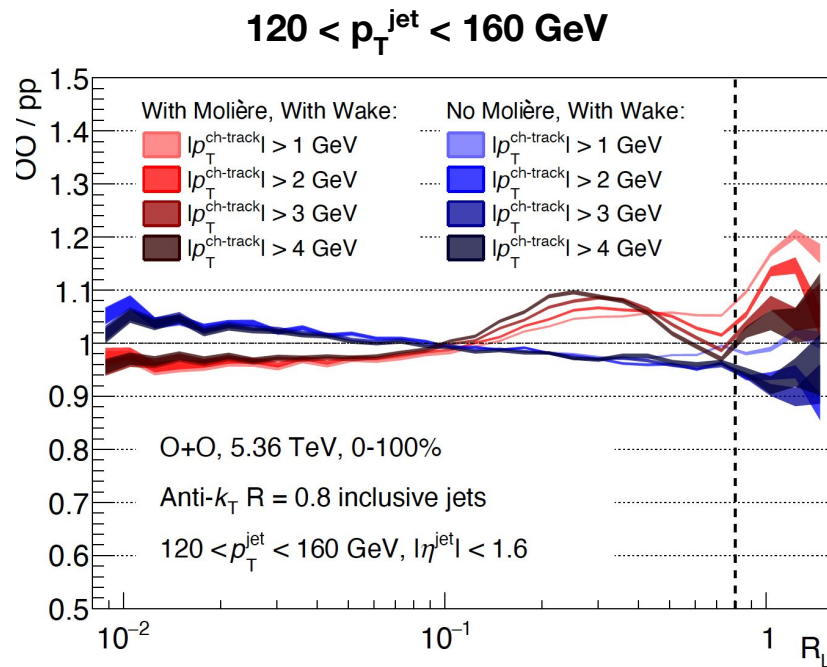
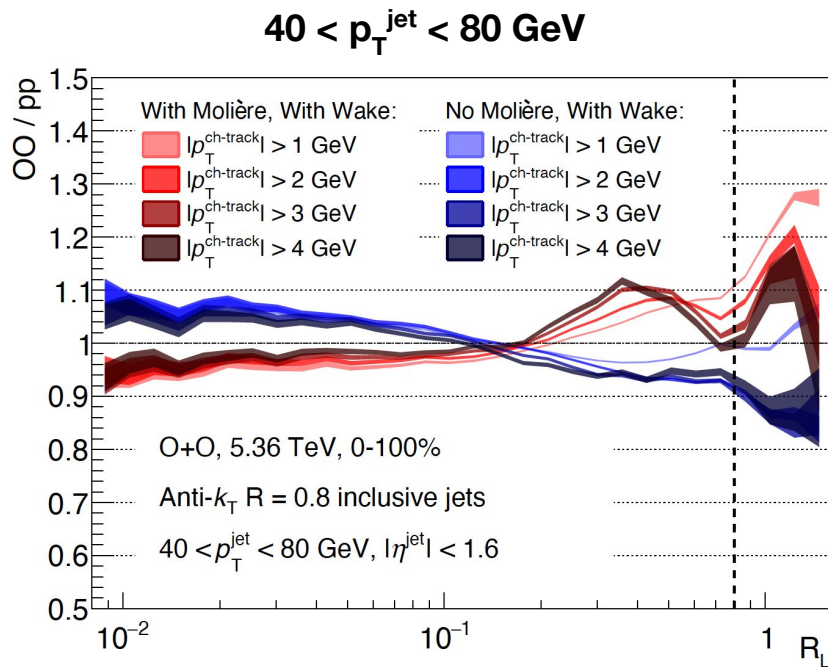


$p_T^{\text{ch-track}} > 4 \text{ GeV}$



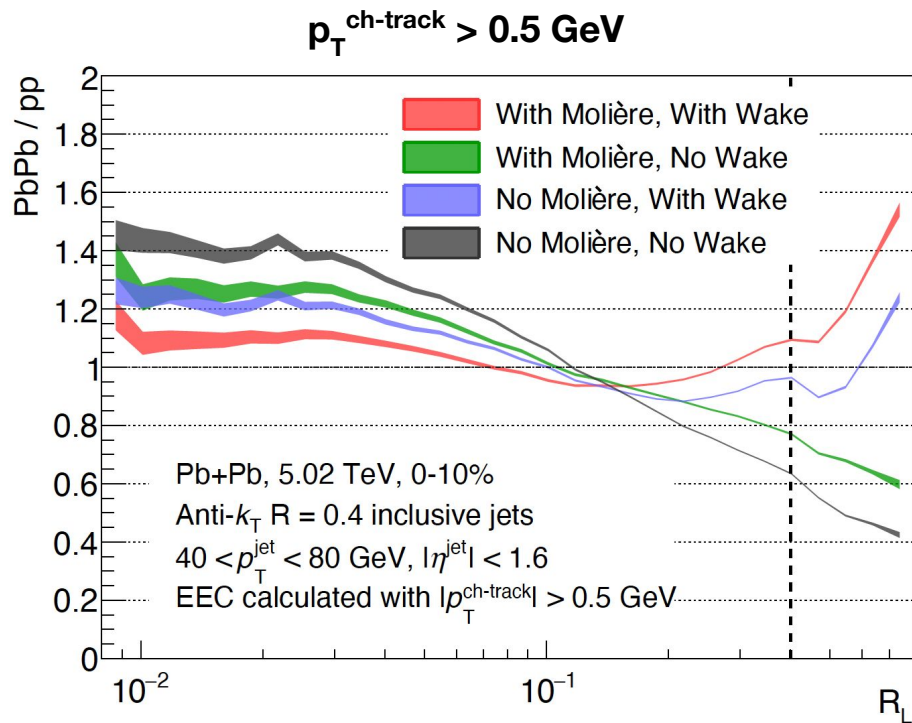
The Molière-induced enhancements and the Molière bumps are present for all of the above track p_T cuts!

How Does the Bump Depend on the Track Cut?



The Molière bump moves to smaller angles as one increases the minimum track p_T of particles used in the calculation of $\text{EEC}(R_L)$

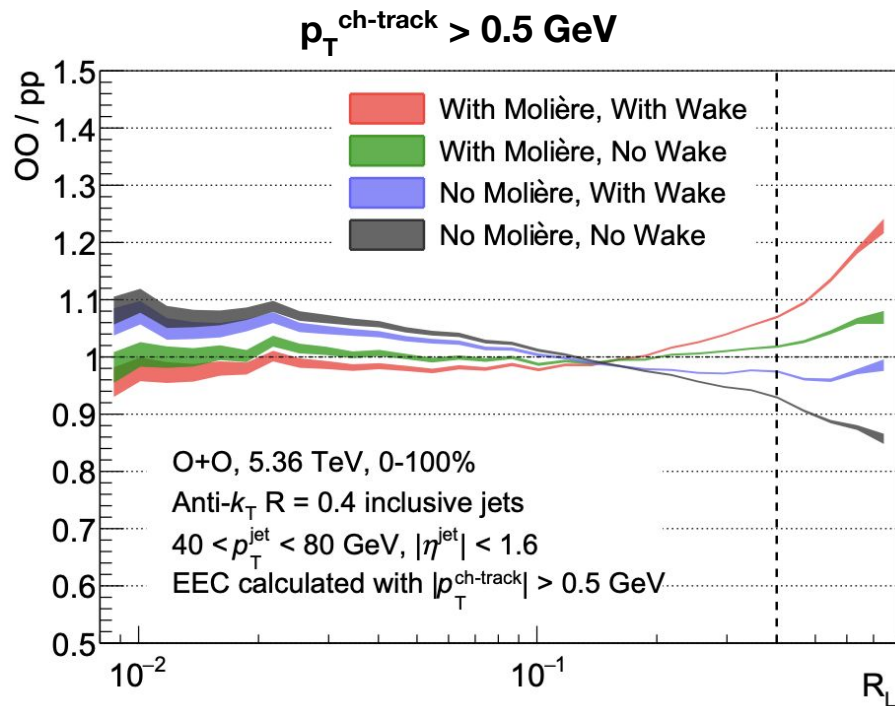
EECs in PbPb Collisions (R = 0.4 Jets)



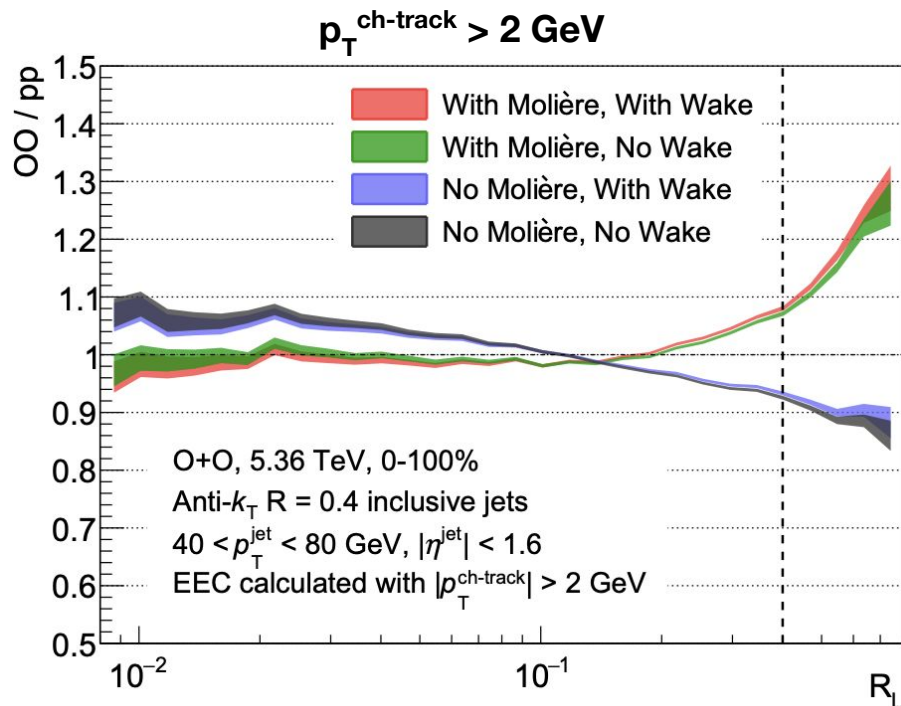
Large-angle correlations are primarily driven by broad jet-wakes

EECs in OO Collisions ($R = 0.4$ Jets)

[2603.23596](#) [Kudinoor, Lin, Pablos, Rajagopal]



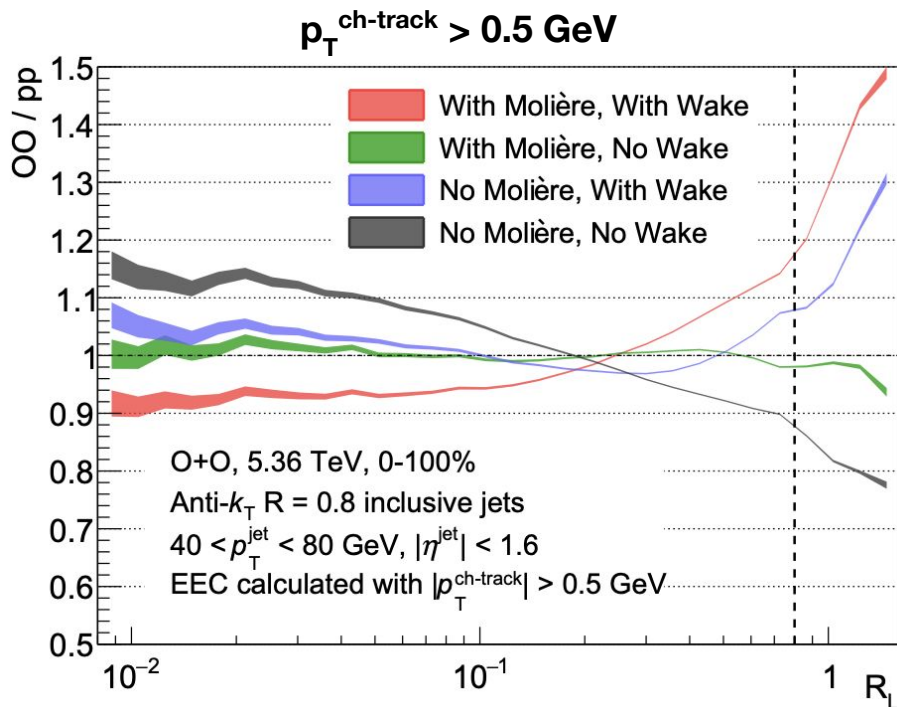
Clear large- R_L enhancements from jet-wakes and Molière scattering without the confounding effects of selection bias



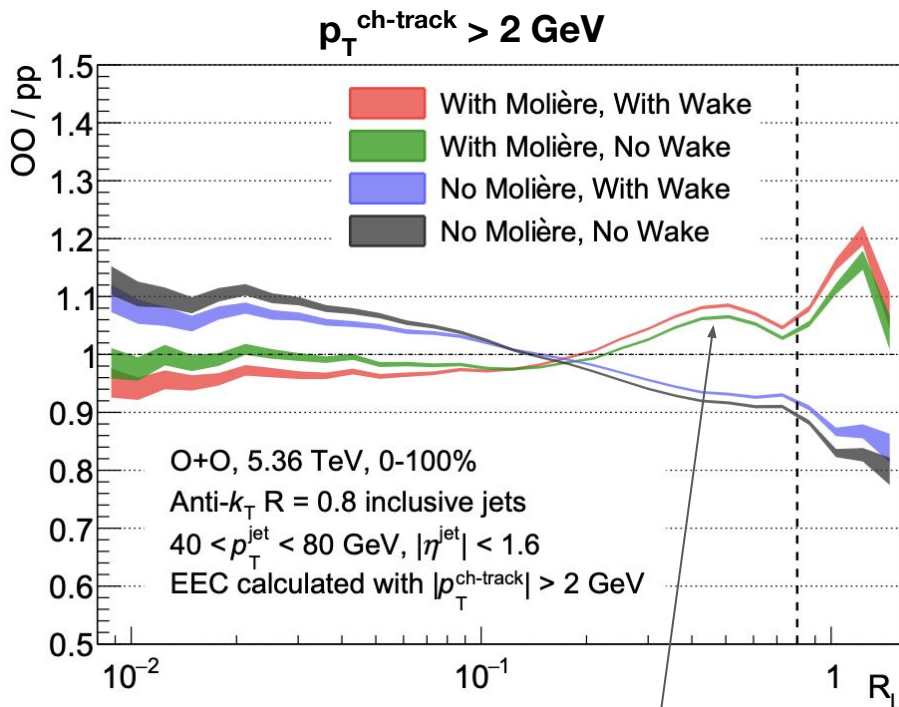
$p_T > 2 \text{ GeV}$ eliminates most of the soft wake, and **isolates the large-angle kicks from Molière scattering**

EECs in OO Collisions ($R = 0.8$ Jets)

[2603.23596](#) [Kudinoor, Lin, Pablos, Rajagopal]



Clear large- R_L enhancements especially from broad jet-wakes



Typical angle of deflection due to Molière scattering

The Hybrid Strong/Weak Coupling Model

arXiv: [1405.3864v3](#), [1609.05842](#)

[Casalderrey-Solana, et al.]

- Parton splittings that result in the jet shower are implemented using PYTHIA 8, as determined by the high-virtuality, perturbative, DGLAP evolution equations
- Jet partons lose energy to the plasma as determined by a holographic energy loss formula

$$\left. \frac{dE}{dx} \right|_{\text{strongly coupled}} = -\frac{4}{\pi} \frac{E_{\text{in}}}{x_{\text{stop}}} \frac{x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{1 - (x/x_{\text{stop}})^2}}$$

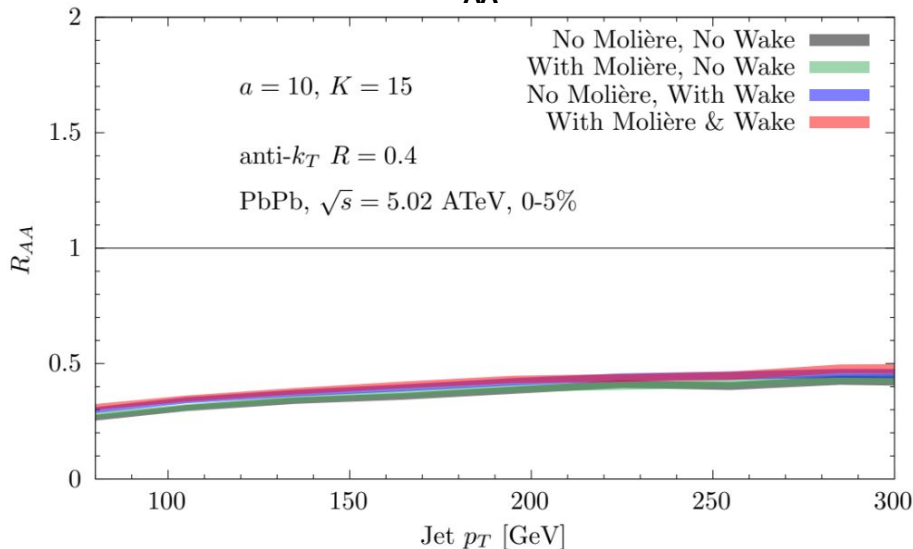
$x_{\text{stop}} \equiv E_{\text{in}}^{1/3} / (2T^{4/3} \kappa_{\text{sc}})$ is the distance a parton can travel before thermalizing with the medium. It depends on an $O(1)$ global-fit parameter κ_{sc} , that quantifies the strength of quenching. It was fit to PbPb data for ch-hadron and jet R_{AA} .

- The lost energy thermalizes quickly and becomes a hydrodynamic wake in the plasma

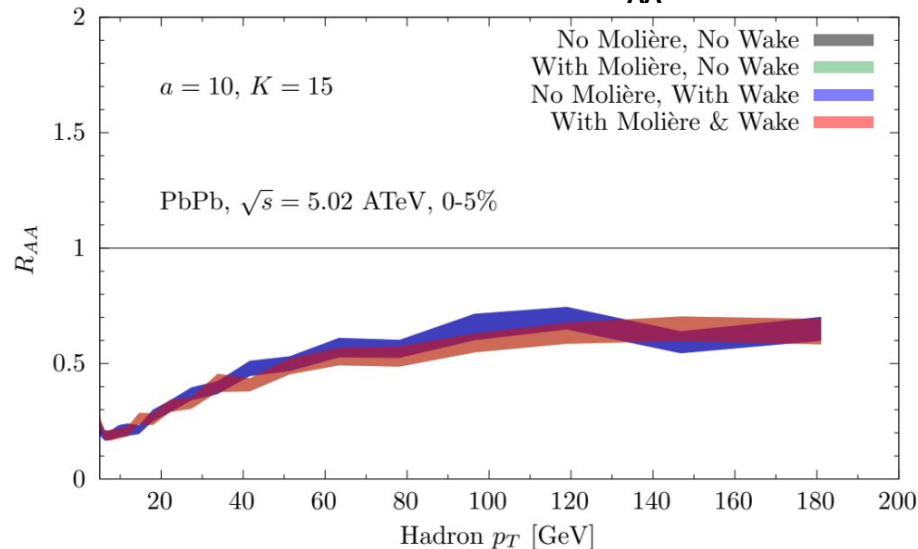
Tuning Our Quenching Parameter κ_{sc}

[2603.08776](#) [Hulcher, Kudinoor, Pablos, Rajagopal]

Jet R_{AA}



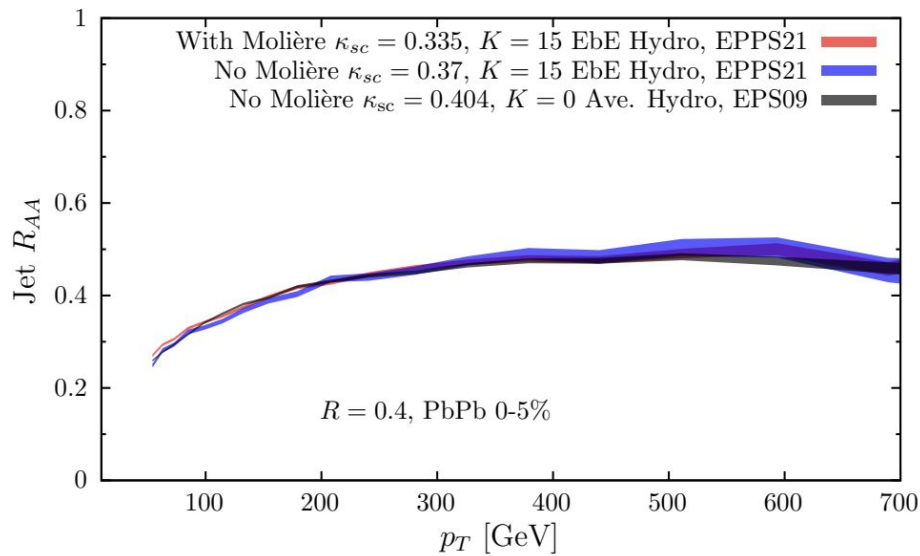
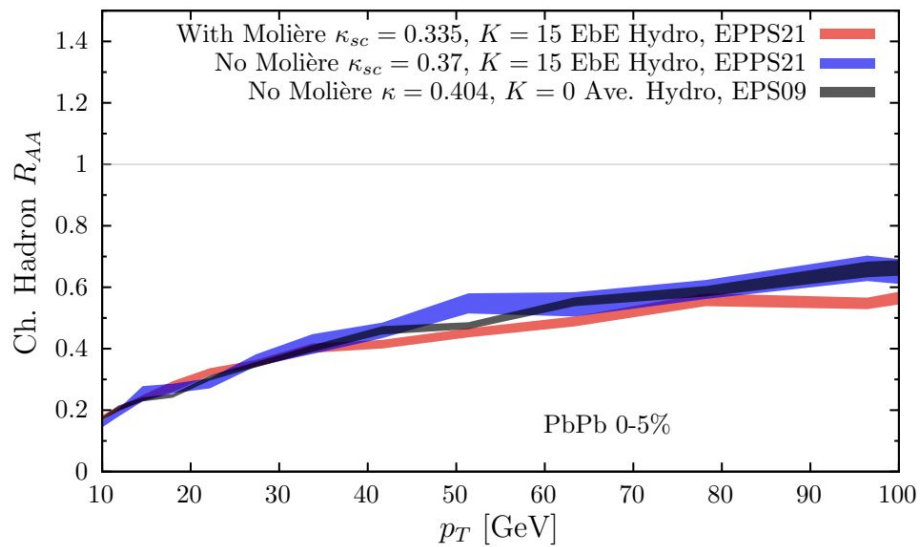
Charged-Hadron R_{AA}



We retuned κ_{sc} so that jet and charged-hadron R_{AA} were left unchanged after including Molière scattering in the model.

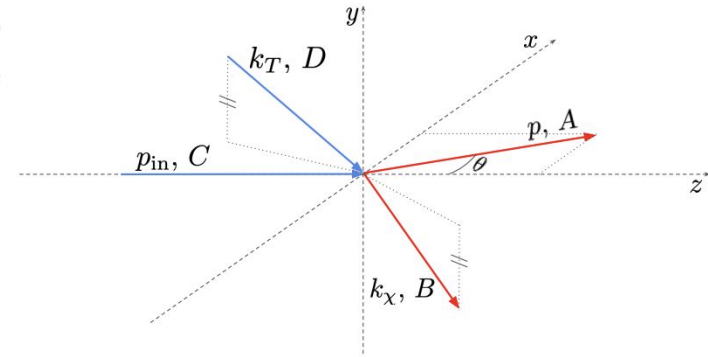
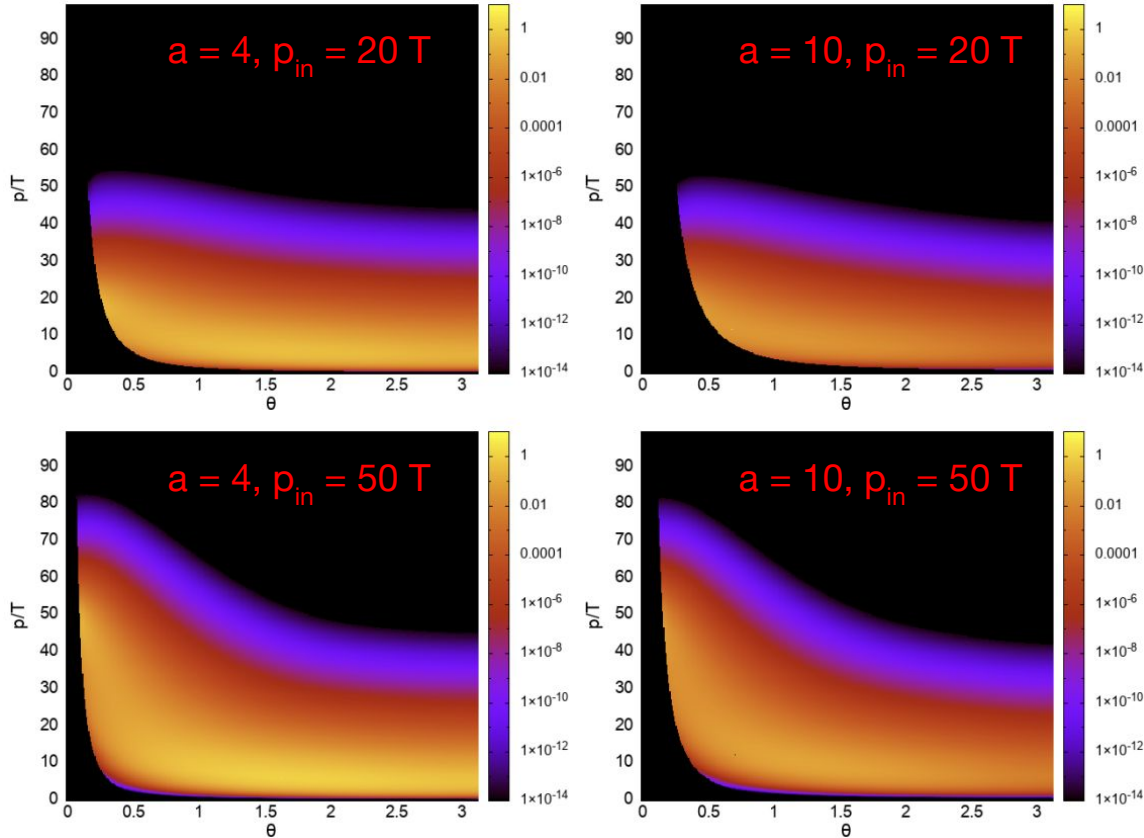
$\Rightarrow$ Molière-induced modifications to jet observables will arise from modifications to jet substructure, not overall suppression

Tuning κ_{sc} with Event-by-Event Hydrodynamic Profiles (It is tuned in PbPb collisions)



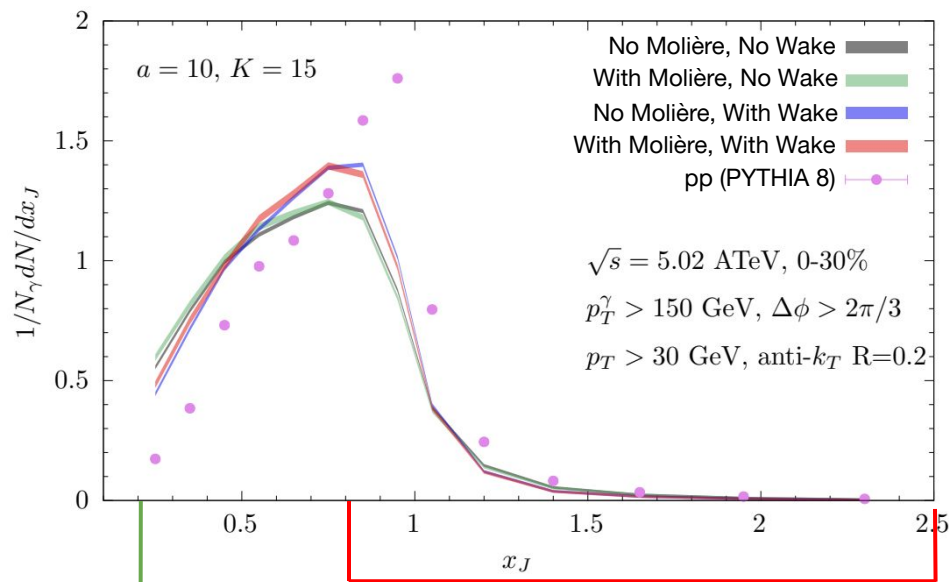
Molière Scattering

$$|t|, |u| > am_D^2$$



Use Photon-Tagged Jets

[2603.08776](#) [Hulcher, Kudinoor, Pablos, Rajagopal]



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

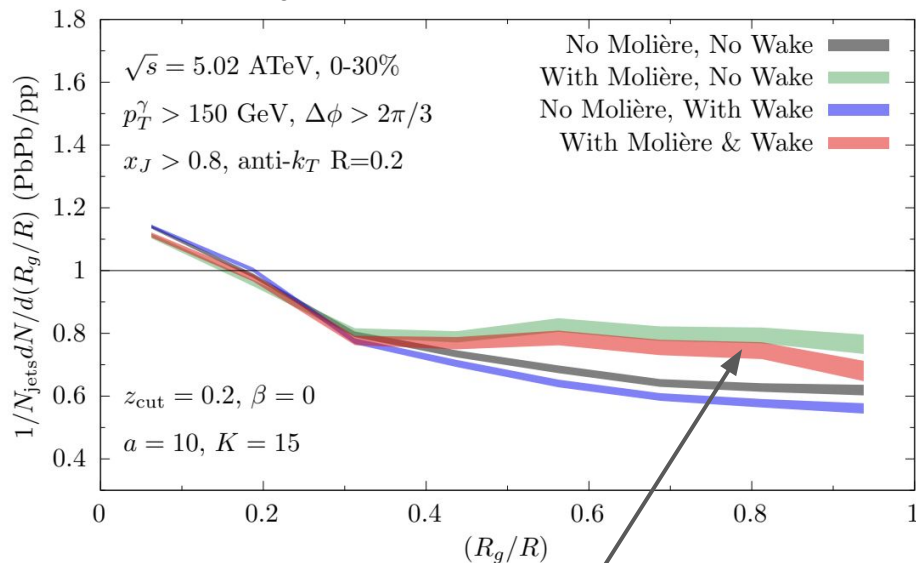
A sample of jets with $x_J > 0.2$ is less biased

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

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

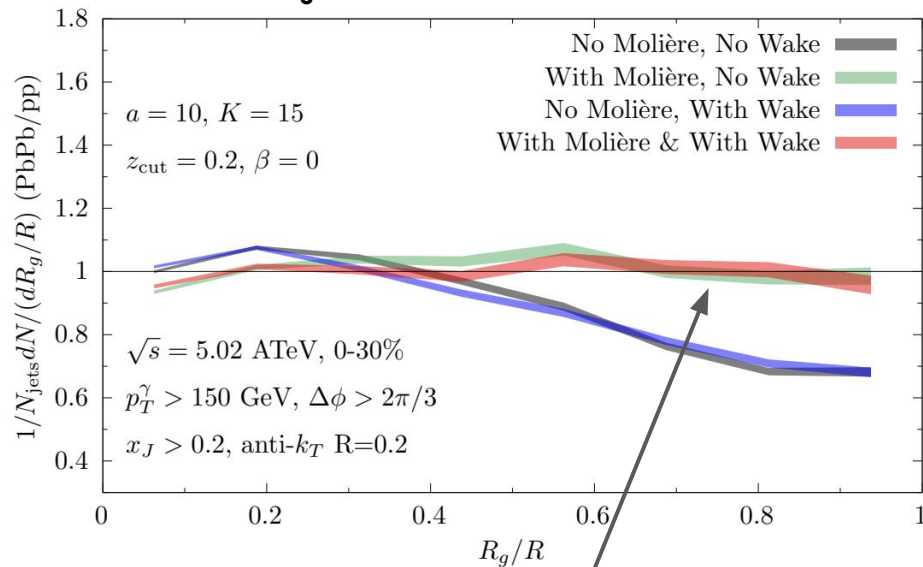
[2603.08776](#) [Hulcher, Kudinoor, Pablos, Rajagopal]

$x_J > 0.8$ (More Biased)



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

$x_J > 0.2$ (Less Biased)

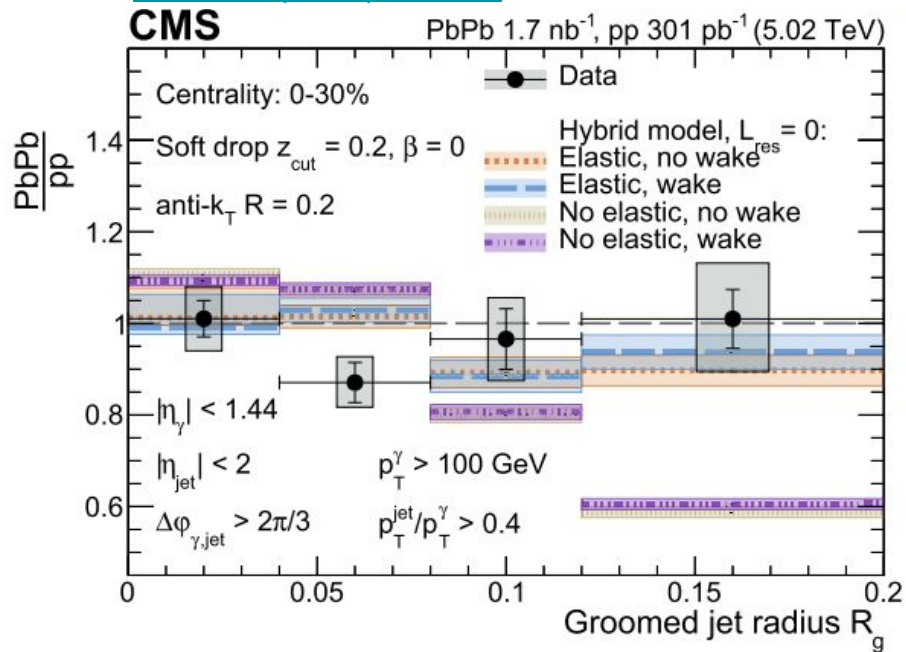


Reduce selection bias $\Rightarrow$ More detectable Molière scattering signal

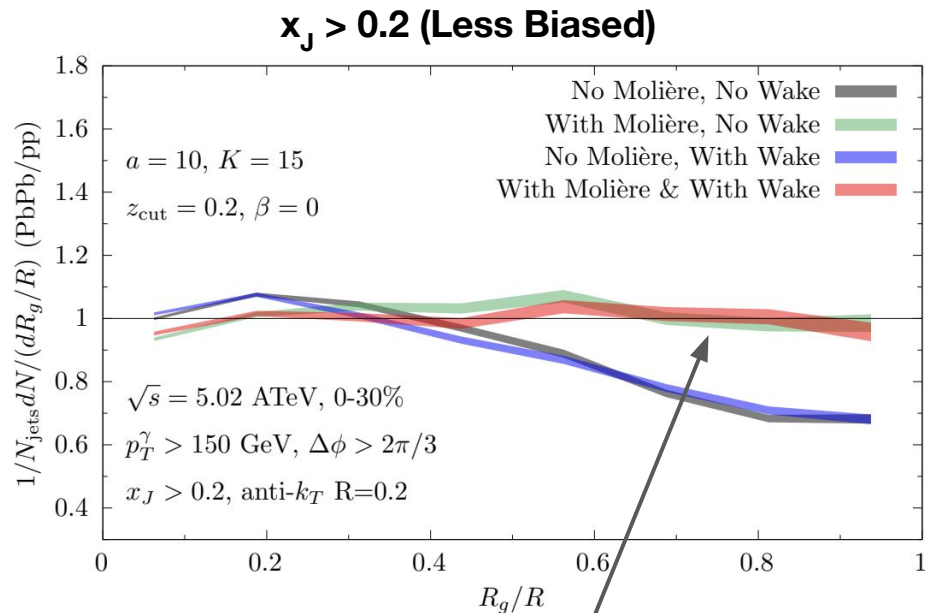
Soft Drop Angle in Photon-Tagged Jets with $R = 0.2$

[2603.08776](#) [Hulcher, Kudinoor, Pablos, Rajagopal]

[PLB 861 \(2025\) 139088](#)



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



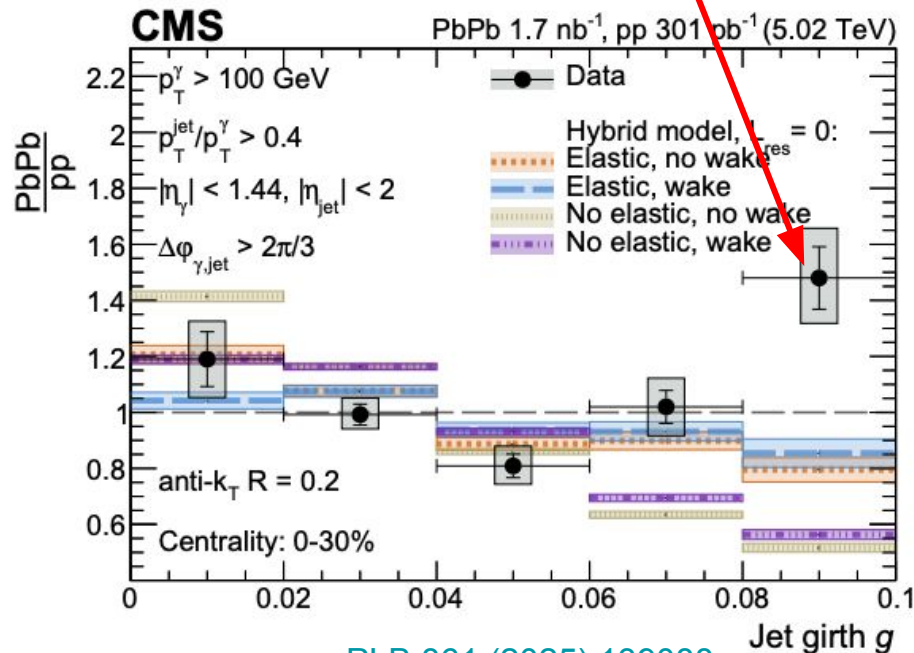
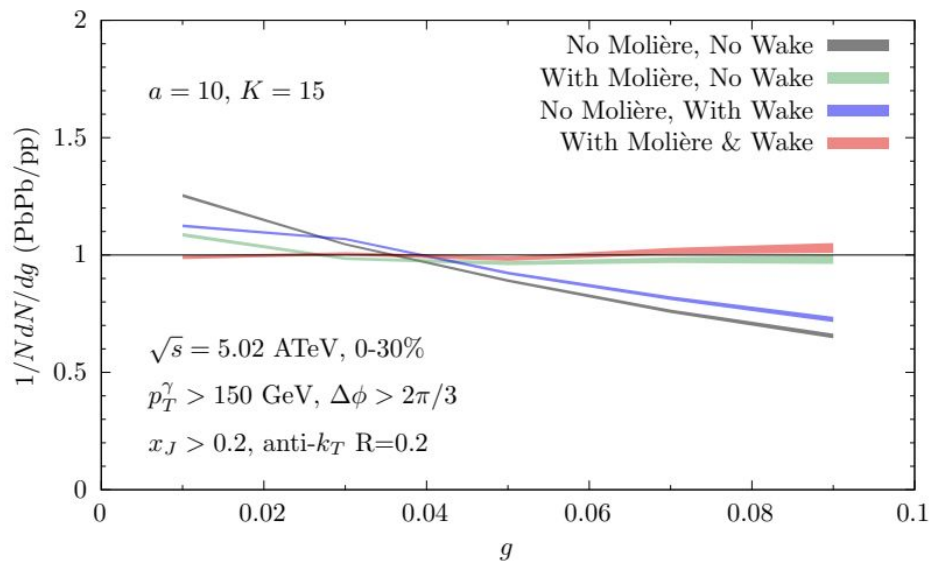
Reduce selection bias $\Rightarrow$ More detectable Molière scattering signal

Detecting Molière Scattering using Jet Girth

[2603.08776](#) [Hulcher, Kudinoor, Pablos, Rajagopal]

This is a tantalizing data point! It motivates measuring at higher p_T^γ , which allows going to lower x_J

$$g = \sum_i (p_{T,i}/p_T^{\text{jet}}) r_i$$



[PLB 861 \(2025\) 139088](#)

Jet-Induced Wakes

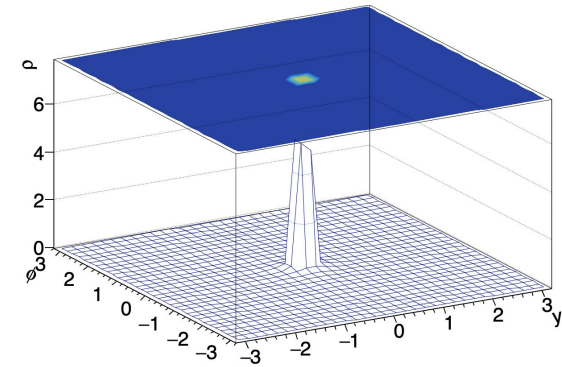
The jets pull some amount of QGP in the direction of the jet

If you compare the freezeout of a QGP droplet containing a jet-wake to a droplet without a jet-wake, it will have:

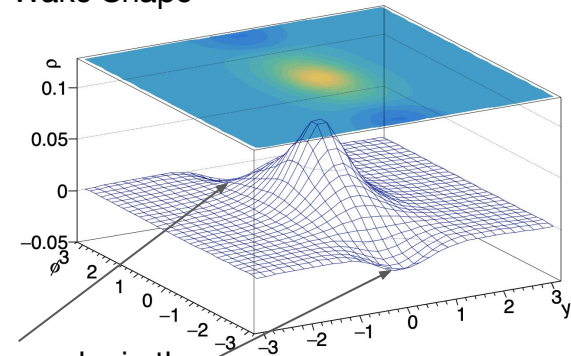
- **Positive Wake:** Additional soft particles in jet's direction
- **Negative Wake:** Depletion of soft particles in the direction opposite the jet [[CMS PAS HIN-23-006](#), [arXiv:2408.08599](#)]

Long-term Goal: To see how QGP hydrodynamizes after it has been driven out of equilibrium by a passing jet

Jet Shape



Wake Shape

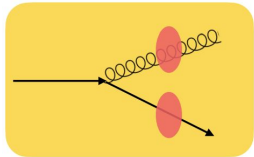


Negative wake in the direction opposite the jet

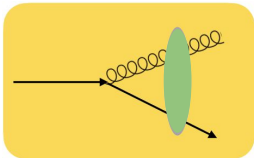
The QGP Resolution Length

At what length scale can quark-gluon plasma resolve two partons produced in a splitting?

Two partons produced in a splitting will interact with QGP independently if and only if they are separated by a distance above L_{res}



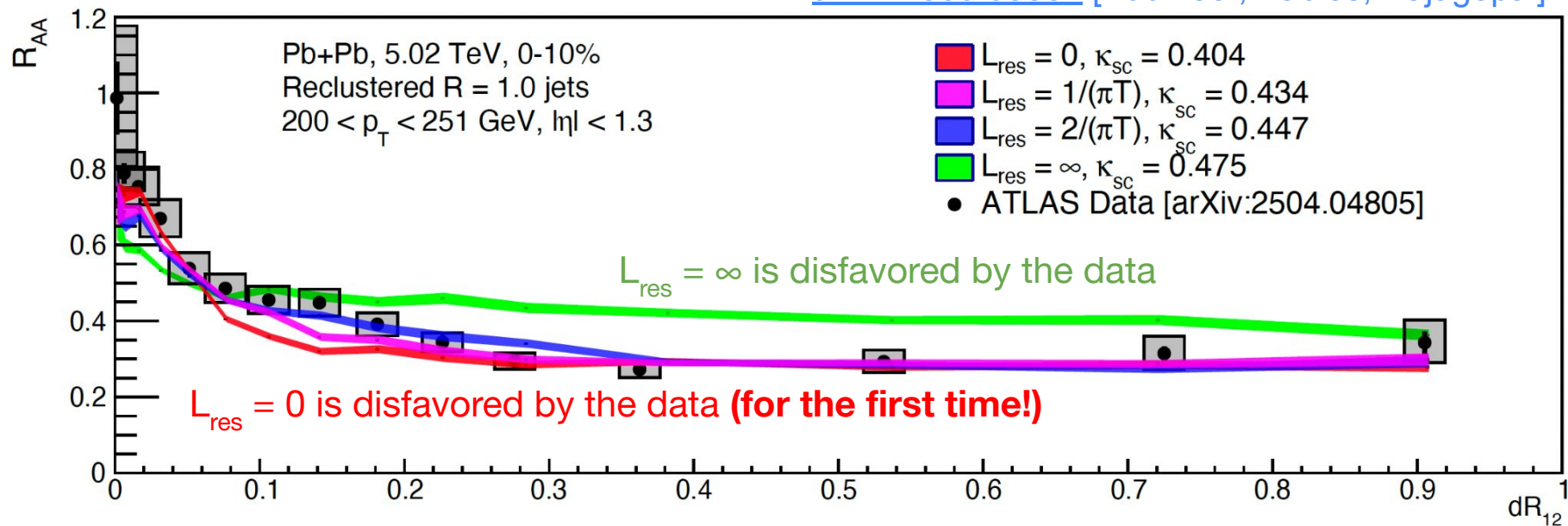
$L_{\text{res}} = 0$: Medium resolves splitting immediately after a parton splits
 $\Rightarrow$ fully **incoherent** interactions with the plasma



$L_{\text{res}} = \infty$: Medium never resolves splittings
 $\Rightarrow$ fully **coherent** interactions with the plasma

Constraining L_{res} using dR_{12} Data

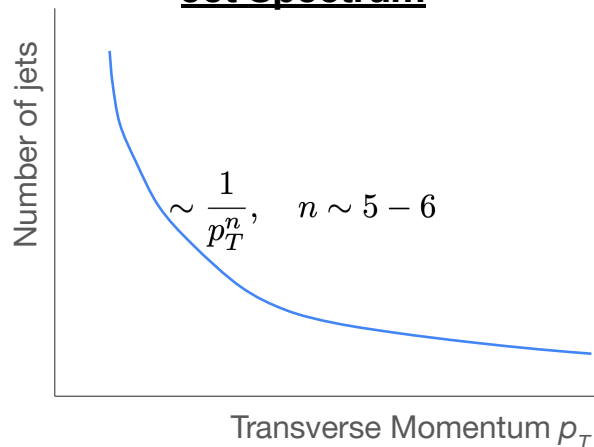
[arXiv:2509.08881](https://arxiv.org/abs/2509.08881) [Kudinoor, Pablos, Rajagopal]



At $T = 300$ MeV, $L_{\text{res}} \sim 0.2\text{-}0.4$ fm

Jet Selection Bias

Jet Spectrum



Jets in PbPb collisions lose energy to the medium

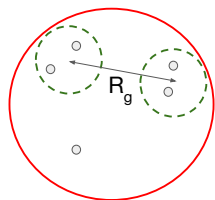
$$p_T^{\text{initial}} \geq p_T^{\text{measured}}$$

The jet spectrum is steeply falling in p_T

⇒ There are far fewer jets with higher p_T than with lower

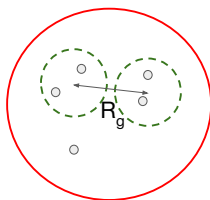
p_T

⇒ **A sample of PbPb jets is biased towards those jets that have lost the least amount of energy**



Wider

More E-loss 😭



Narrower

Less E-loss 😊

Jets with narrow substructure lose less energy to the plasma than jets with wide substructure

⇒ **A sample of PbPb jets is biased towards jets with narrower substructure**

⇒ **PbPb jets tend to have a narrower Soft Drop angle than pp jets**

QCD vs. $\mathcal{N} = 4$ SYM Theory

Use an $\mathcal{N} = 4$ SYM theory instead! The hot strongly coupled liquid phases of $\mathcal{N} = 4$ SYM theory and QCD are more similar to each other than their vacua and low energy physics (the problematic energy sector that contributes to QCD's nonconformality).

Differences between QCD and $\mathcal{N} = 4$ SYM include

- $N_c = 3$ for QCD, whereas we take the $N_c \rightarrow \infty$ limit for $\mathcal{N} = 4$ SYM calculations
- QCD is not conformal, whereas $\mathcal{N} = 4$ SYM is conformal
- QCD demonstrates asymptotic freedom (coupling becomes weaker as energies increase to infinity), whereas $\mathcal{N} = 4$ SYM is strongly coupled at all length scales
- In QCD, both the fundamental and adjoint degrees of freedom are important to thermodynamic properties of QGP, whereas in $\mathcal{N} = 4$ SYM, there are no fundamental degrees of freedom