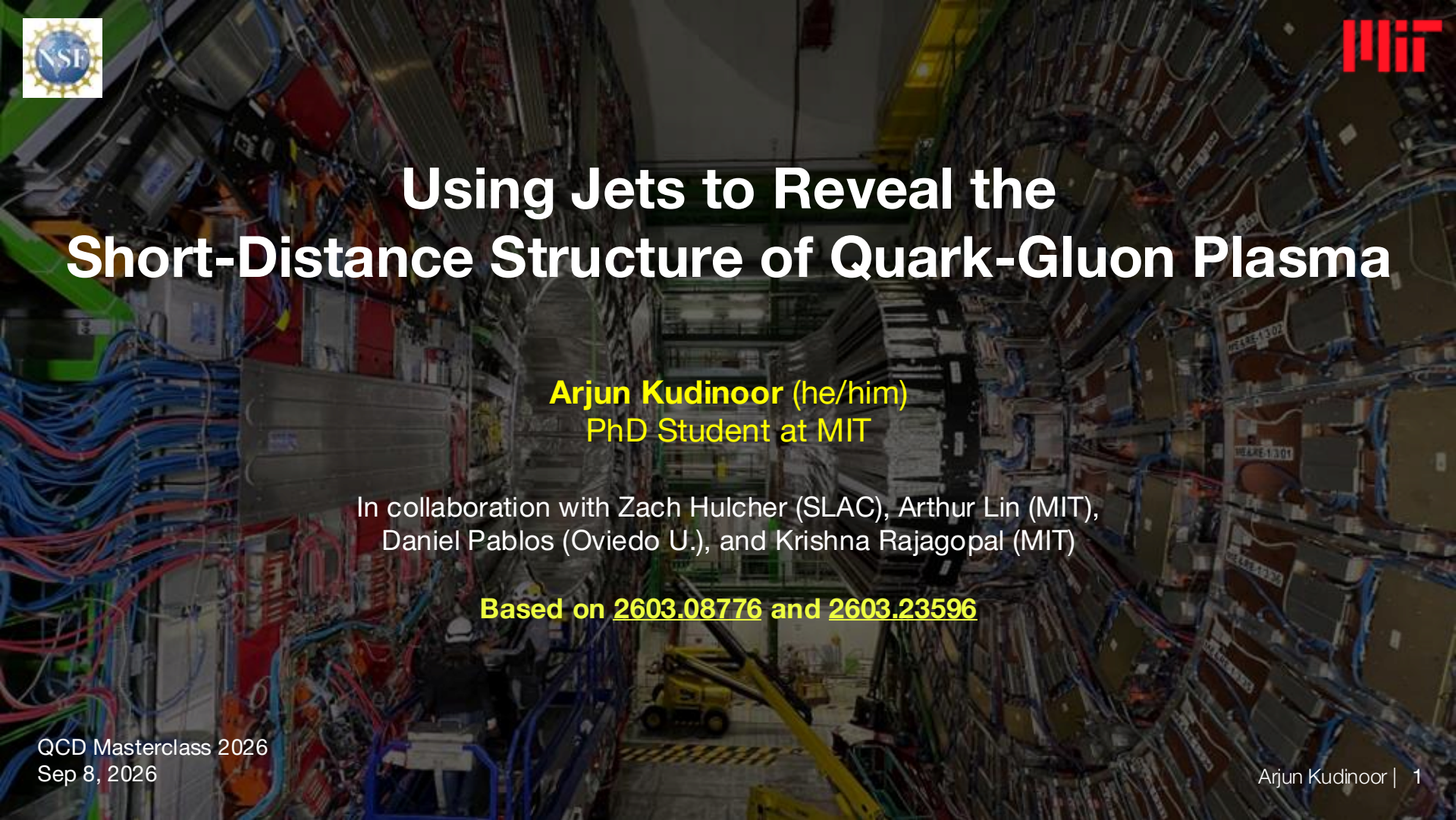


Using Jets to Reveal the Short-Distance Structure of Quark-Gluon Plasma

Arjun Kudinoor (he/him)
PhD Student at MIT

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

Based on 2603.08776 and 2603.23596

QCD Masterclass 2026
Sep 8, 2026

The Primordial Plasma

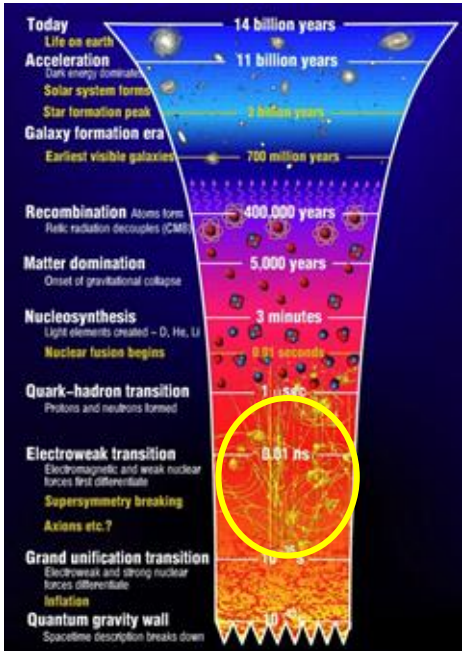
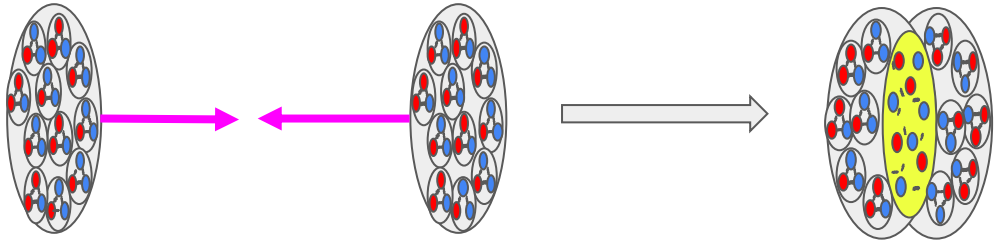


Image credit: Centre for Theoretical Cosmology, Cambridge University



In heavy-ion collisions a strongly coupled liquid, called **quark-gluon plasma (QGP)**, is formed

- The **first liquid** to exist
- At a few trillion degrees, the **hottest liquid** that has ever existed
- The **most liquid liquid** to exist

Recreating the Primordial Plasma in the Lab

Droplets of QGP are recreated at facilities like the LHC and RHIC

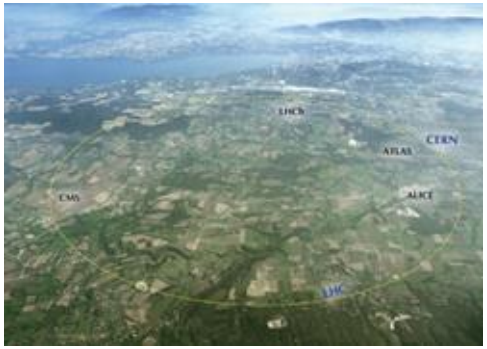


Image credit: CERN

PbPb
XeXe
OO (most recent)
NeNe (most recent)

Image credit: BNL

AuAu
CuCu
UU
RuRu
ZrZr
OO (most recent)

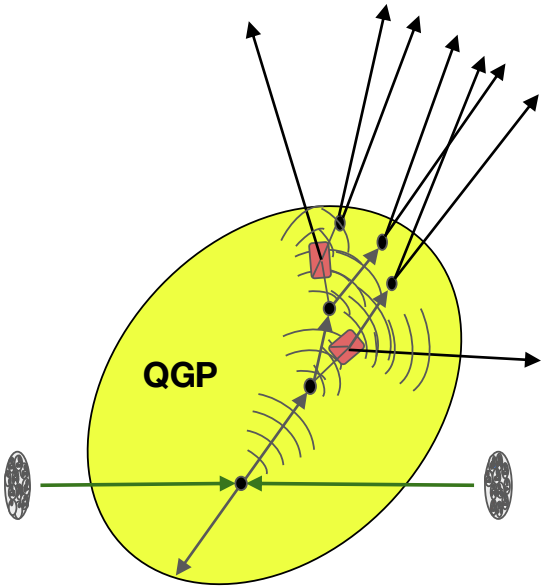
A Smashing Success: Relativistic Heavy Ion Collider Wraps up Final Collisions

Milestone caps a quarter century of groundbreaking discoveries — with more to come from final run's largest-ever dataset — plus technological advances in accelerators, detectors, and computing

February 6, 2026

Image credit: Brookhaven National Laboratory

Jets as Probes of QGP



Hard partons in jets traverse and interact with the QGP droplet.
These interactions are imprinted onto the measured final state.

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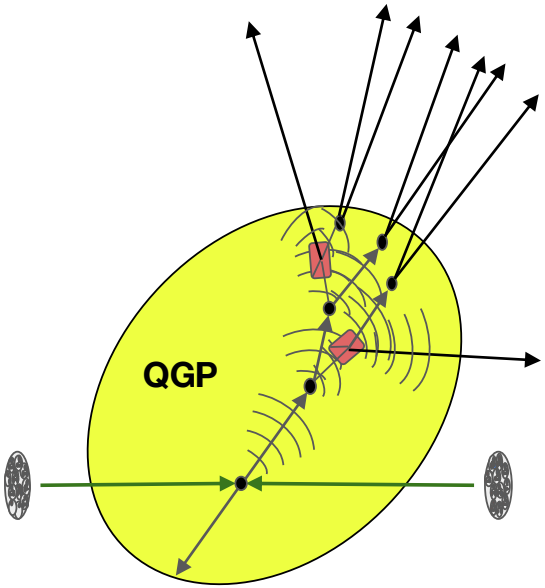

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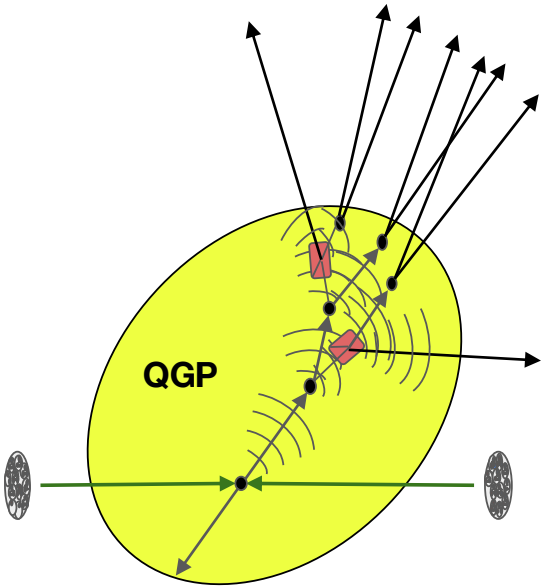

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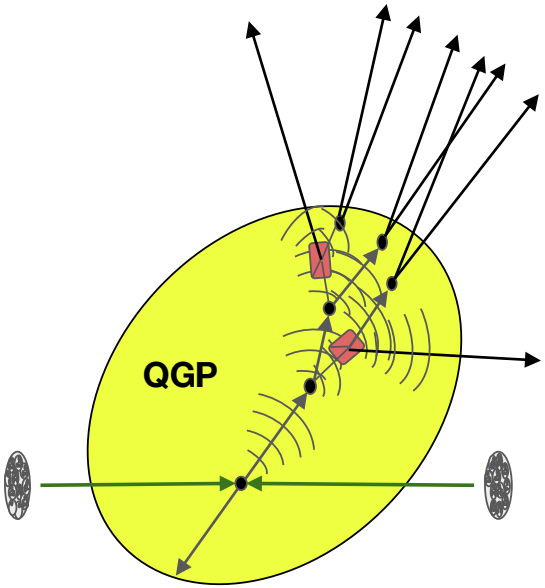

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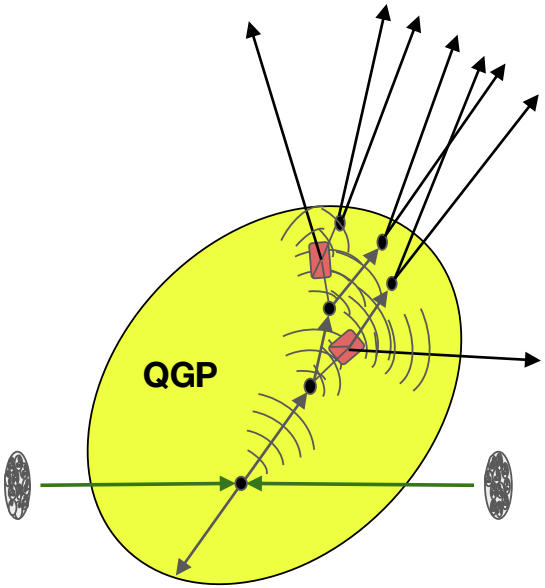

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Hard scatterings of jet partons off QGP constituents
What is the microscopic structure of hot-QCD matter?

Revealing the Short-Distance Structure of QGP using Jets

1808.03250 [D'Eramo et al.]
2603.08776 [Hulcher et al.]
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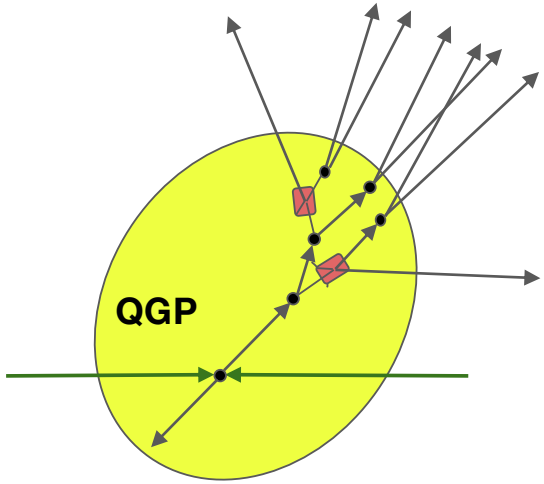

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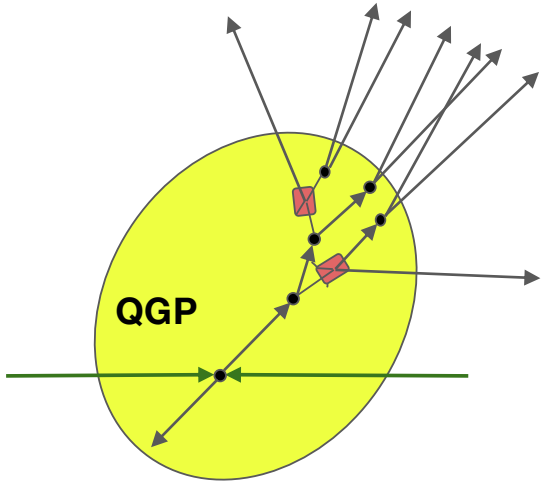

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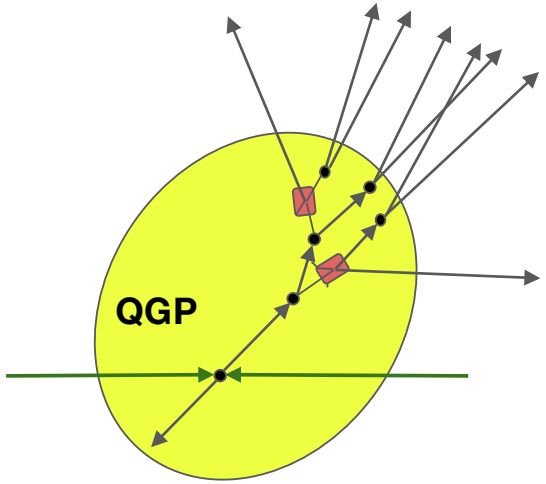

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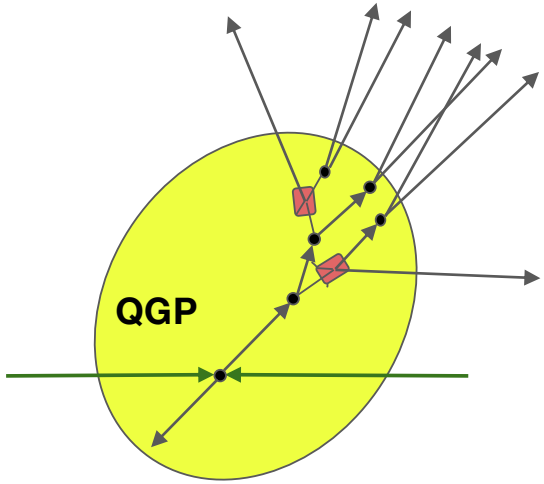
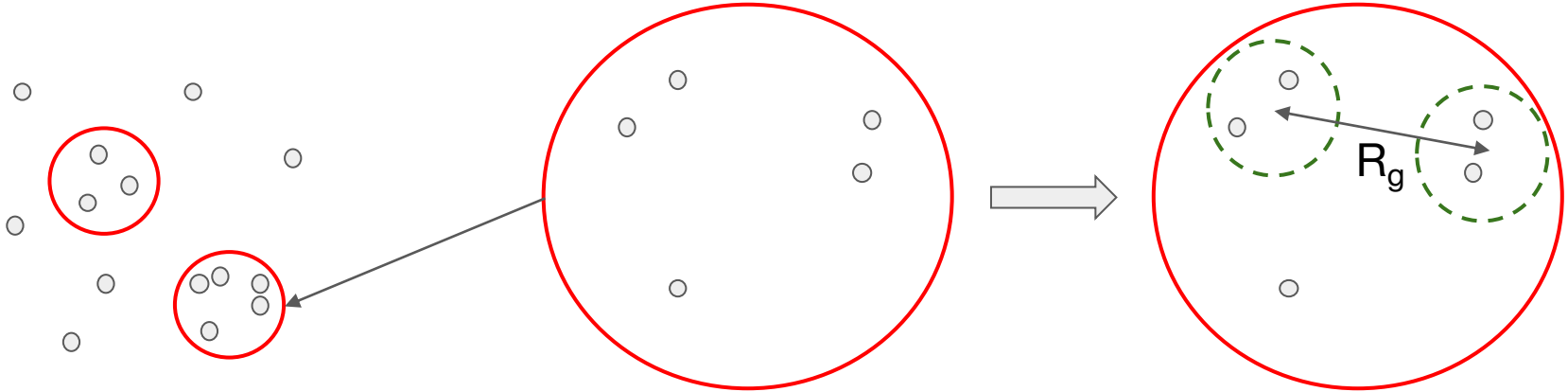
- This presents an opportunity to **reveal the microscopic structure of QGP and to develop and test theoretical descriptions of it** (analogous to PDFs in DIS).
- Such hard scatterings can be detected using select observables that characterize the internal structure (substructure) of jets
  - Jet girth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



Probing Hard Scatterings using Soft Drop

arXiv: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

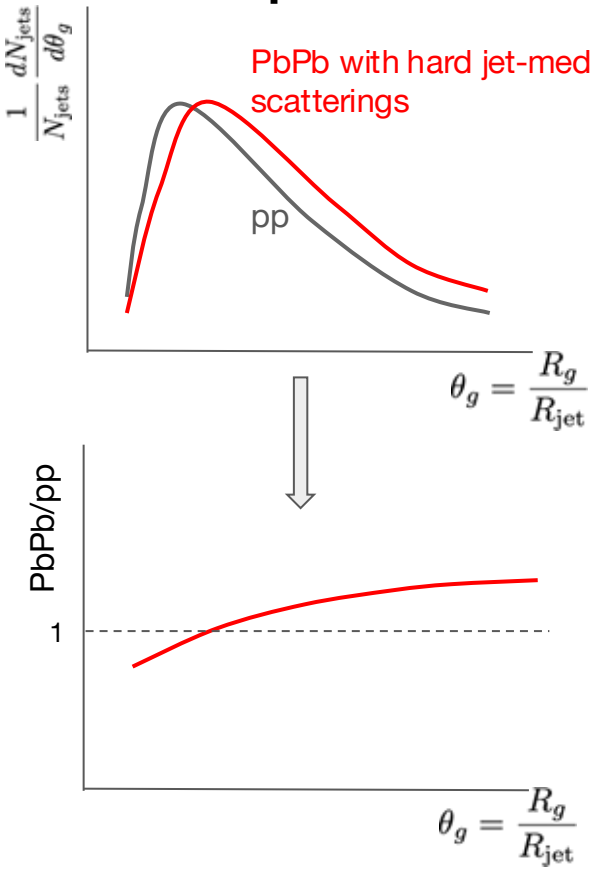
$$z_{\text{subleading}} > z_{\text{cut}} \left(\frac{R_g}{R}\right)^{\beta}$$

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

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

Soft Drop Angle in PbPb Collisions

Naive Expectation



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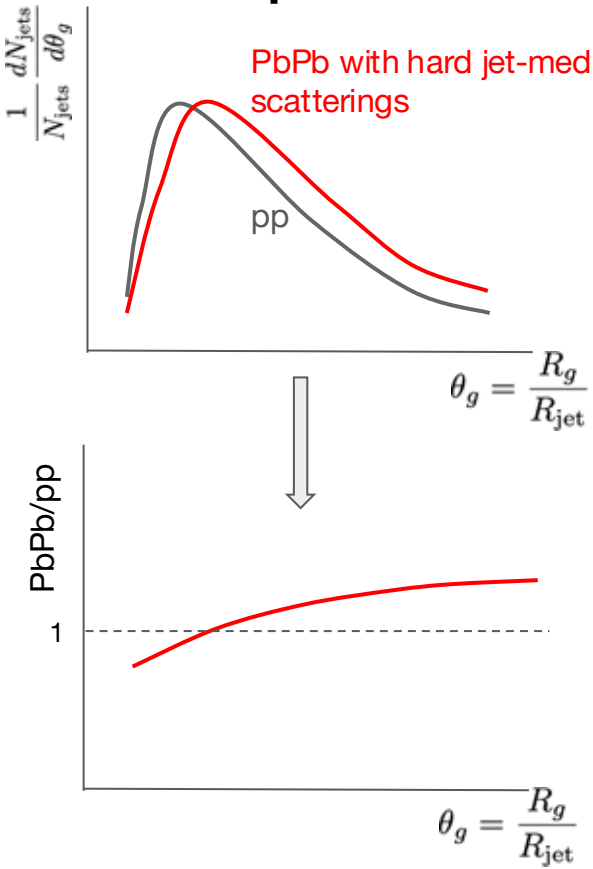
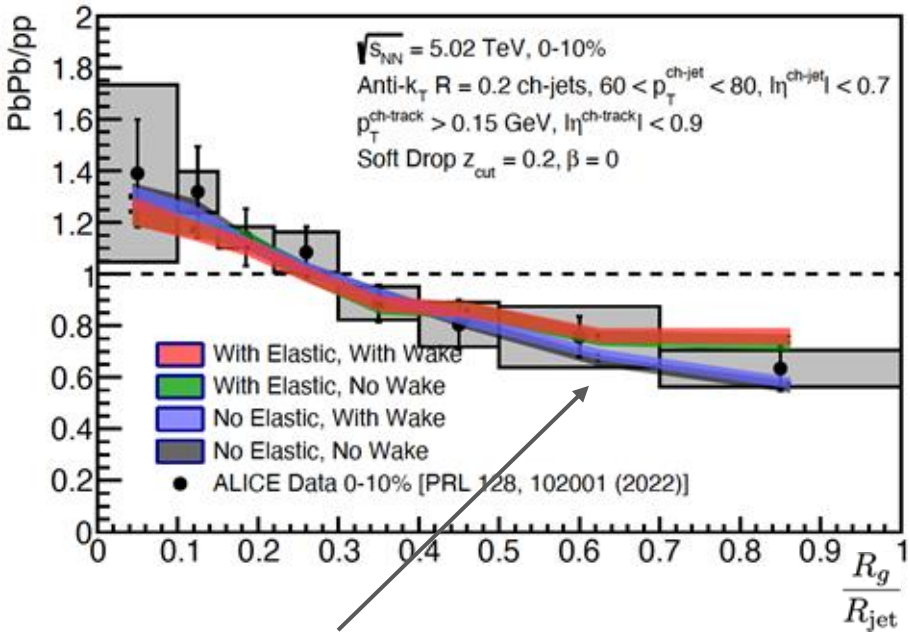


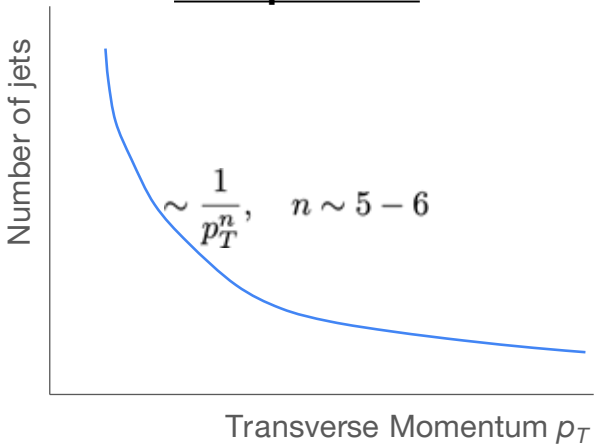
Reality



We observe a narrowing, not a broadening! What's going on?? 👀

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**

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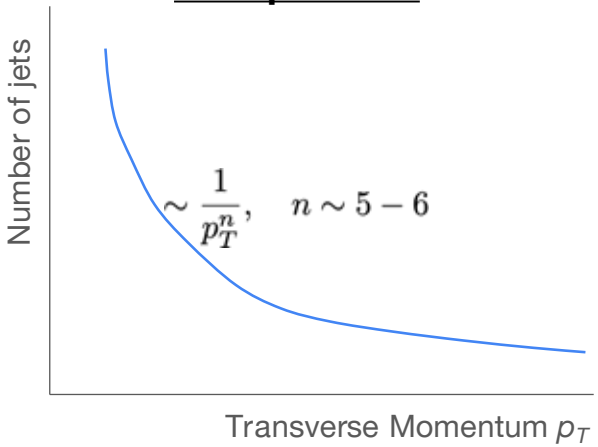
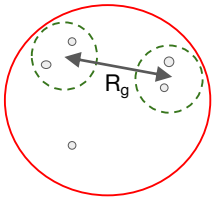
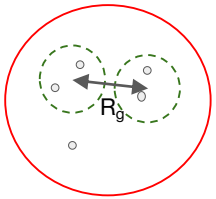




Wider
More E-loss 😭



Narrower
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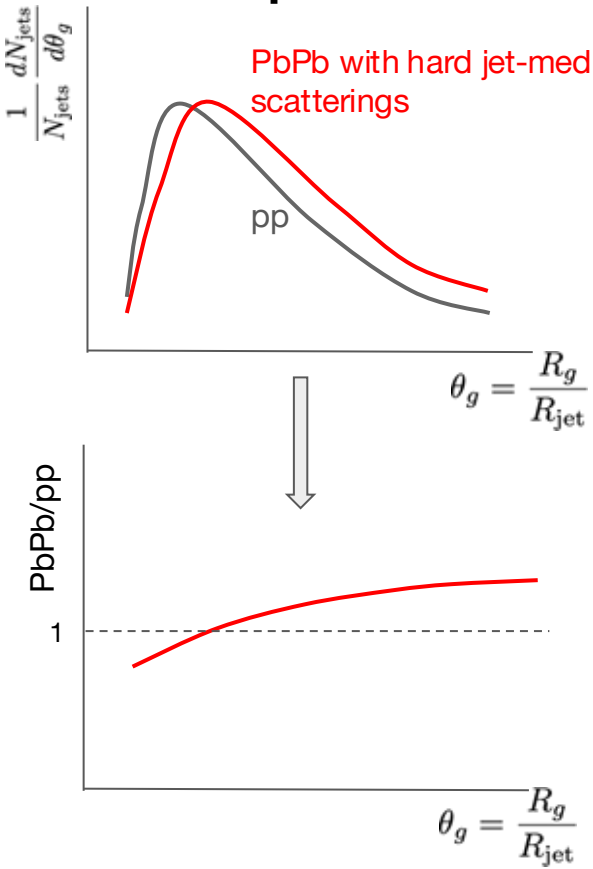
Jets with narrow substructure lose less energy to the plasma than jets with wide substructure
⇒ **A sample of PbPb jets is biased towards jets with narrower substructure**
⇒ **PbPb jets tend to have a narrower Soft Drop angle than pp jets**

Soft Drop Angle in PbPb Collisions

Naive Expectation



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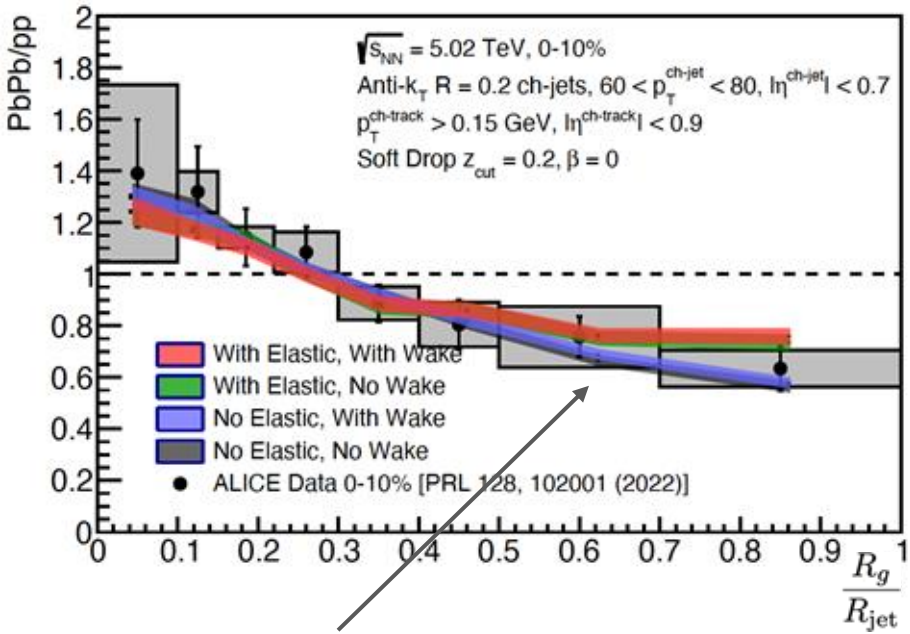

PbPb jet sample is biased towards those jets that have lost the least energy, which tend to be narrower

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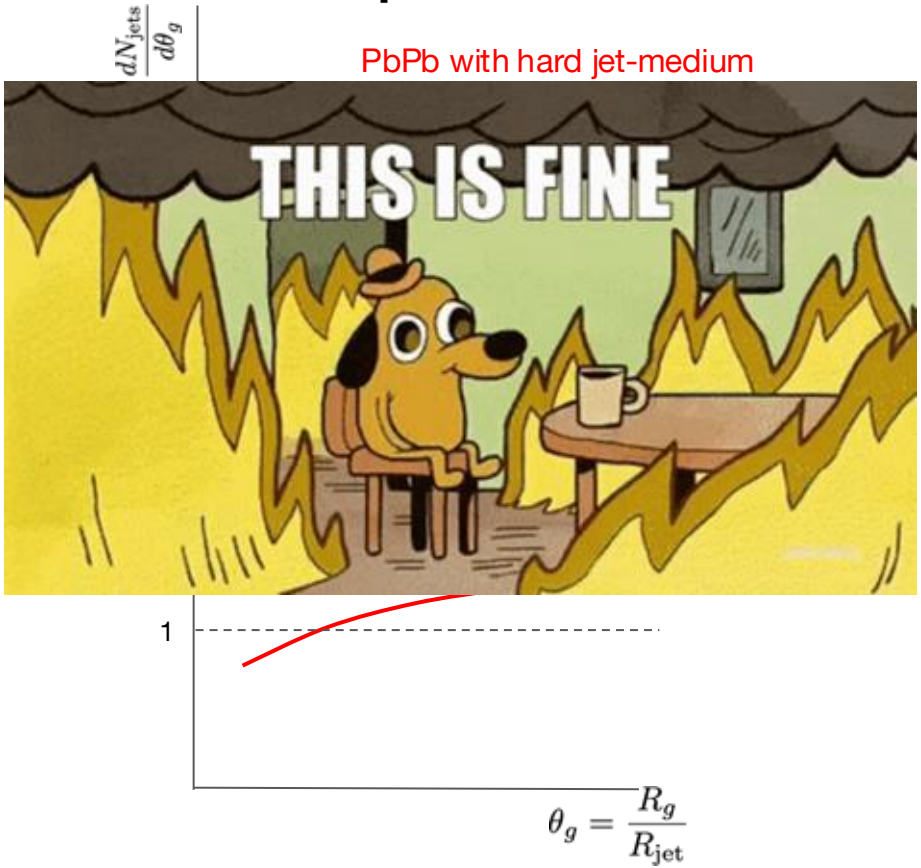

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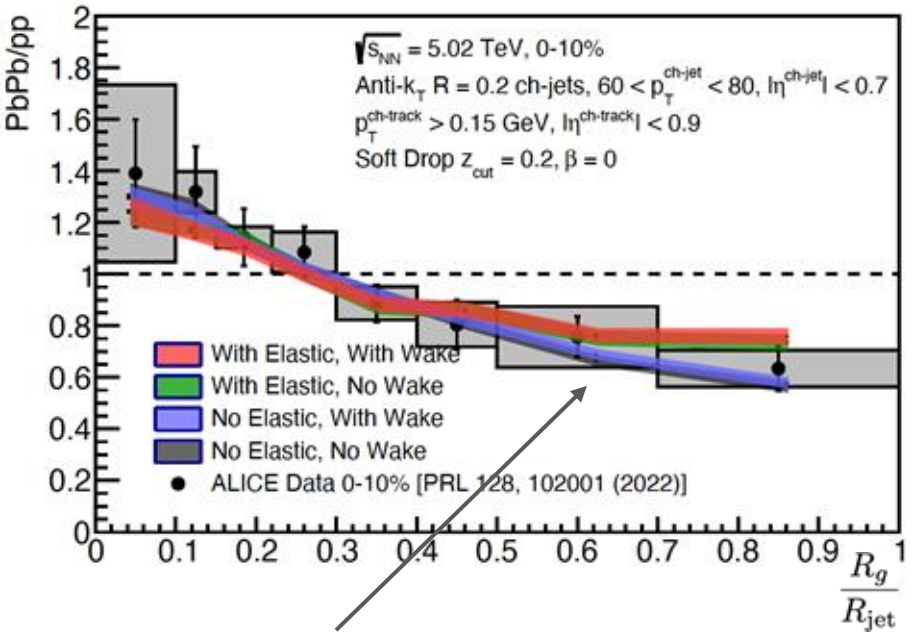

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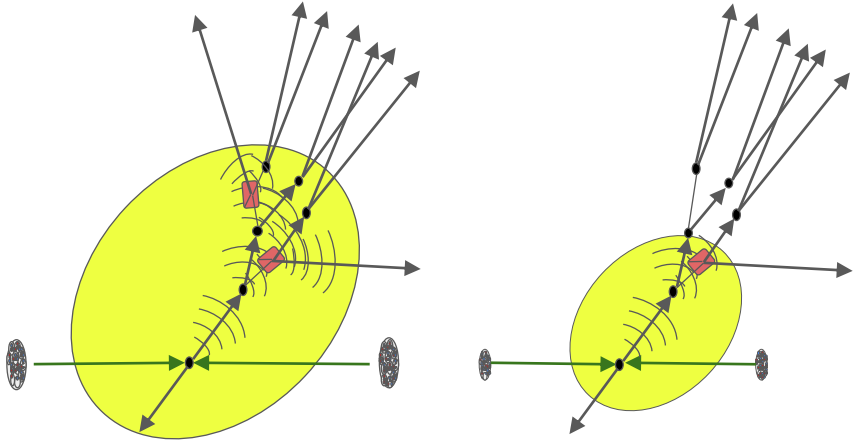
Jet Partons Lose Less Energy in Oxygen–Oxygen Collisions

QGP droplets 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.**

- Energy loss due to collisions scales linearly with the path length traversed, while weakly coupled radiative energy loss and strong-coupling-based energy loss exhibit superlinear path-length dependence. **Collisional interactions are relatively more important in OO.**



The Hybrid Strong/Weak Coupling Model

arXiv:1405.3864v3, 1609.05842
[Casalderrey-Solana, et al.]

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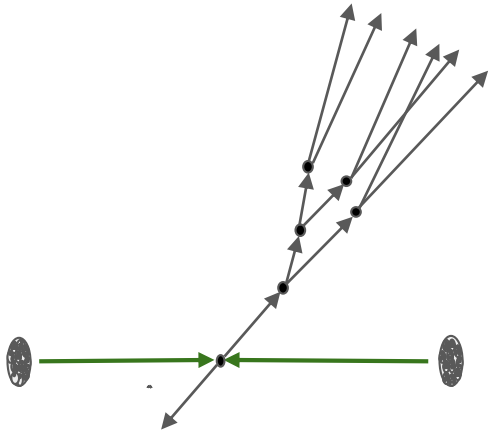

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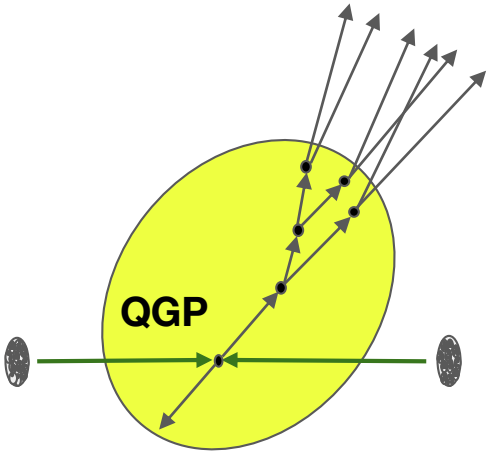
$x_{\text{stop}} \equiv E_{\text{in}}^{1/3}/(2T^{4/3}\kappa_{\text{sc}})$ is the distance a parton can travel before thermalizing with the medium. It depends on an O(1) global-fit parameter κ_{sc}, that quantifies the strength of quenching. It was fit to PbPb data for ch-hadron and jet R_{AA}.



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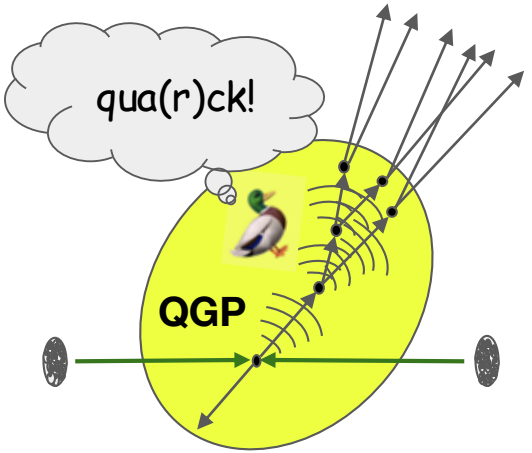
- The lost energy thermalizes quickly and becomes a hydrodynamic wake in the plasma



Molière Scattering in the Hybrid Model

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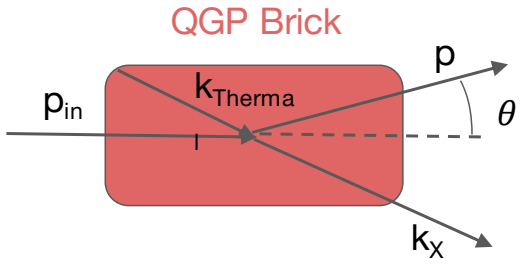

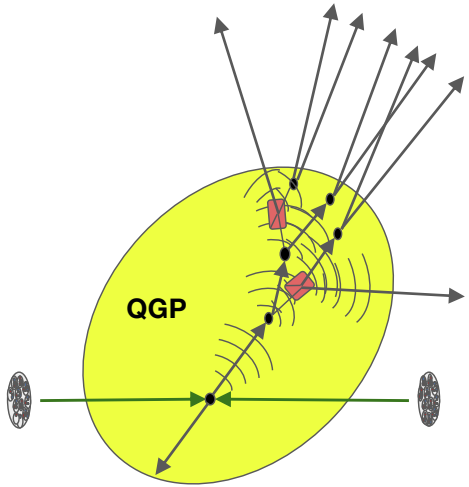

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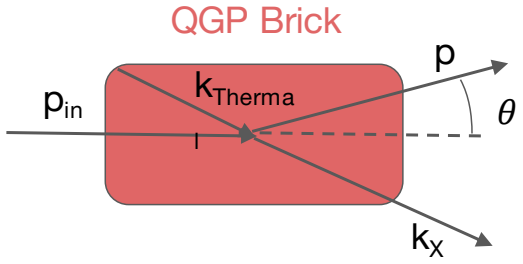

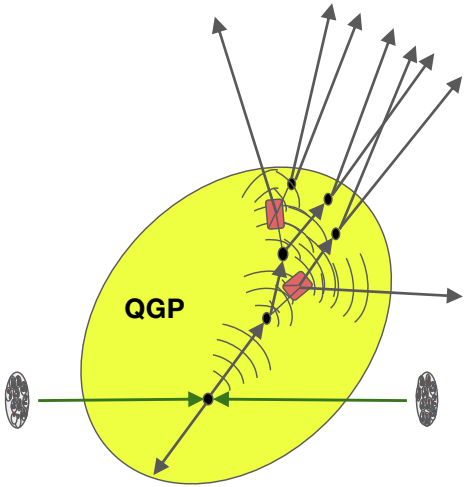

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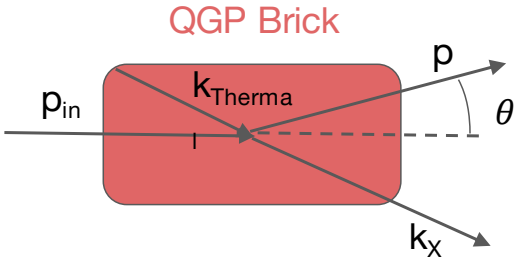
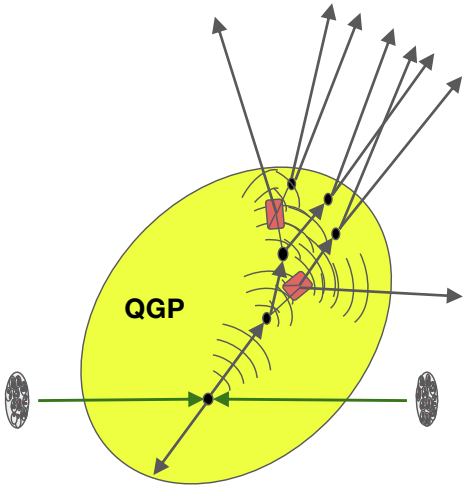
- For each jet parton, the tree-level 2→ 2 scattering probability is evaluated; if a scattering occurs, the final-state kinematics are sampled from the corresponding matrix element.





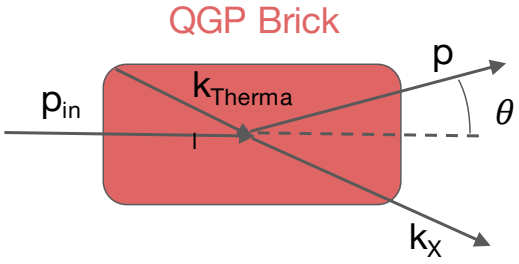
Molière Scattering in the Hybrid Model

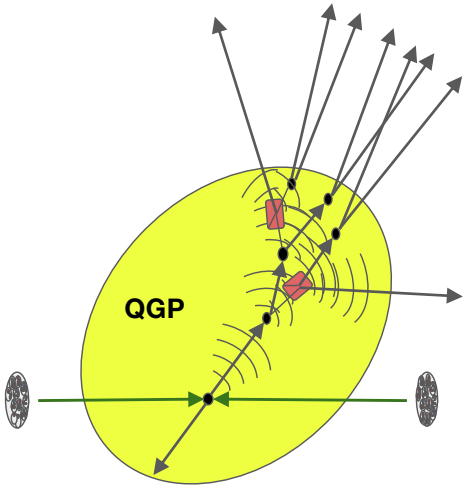
1808.03250 [D'Eramo et al.], 2603.08776 [Hulcher et al.]

- We implement rare, large-angle, **2→2 scatterings** between jet partons and quasiparticles in the medium only at sufficiently **high momentum exchange**

$$|t|, |u| > a m_D^2, \quad a = 10$$

- Massless quasiparticles, assumed to be in thermal equilibrium with the medium, are sampled from Bose-Einstein and Fermi–Dirac distributions. This is an assumption, which should be confronted with future data!
- For each jet parton, the tree-level 2→ 2 scattering probability is evaluated; if a scattering occurs, the final-state kinematics are sampled from the corresponding matrix element.
- After such a "Molière scattering", both outgoing partons can rescatter and excite wakes in the medium.



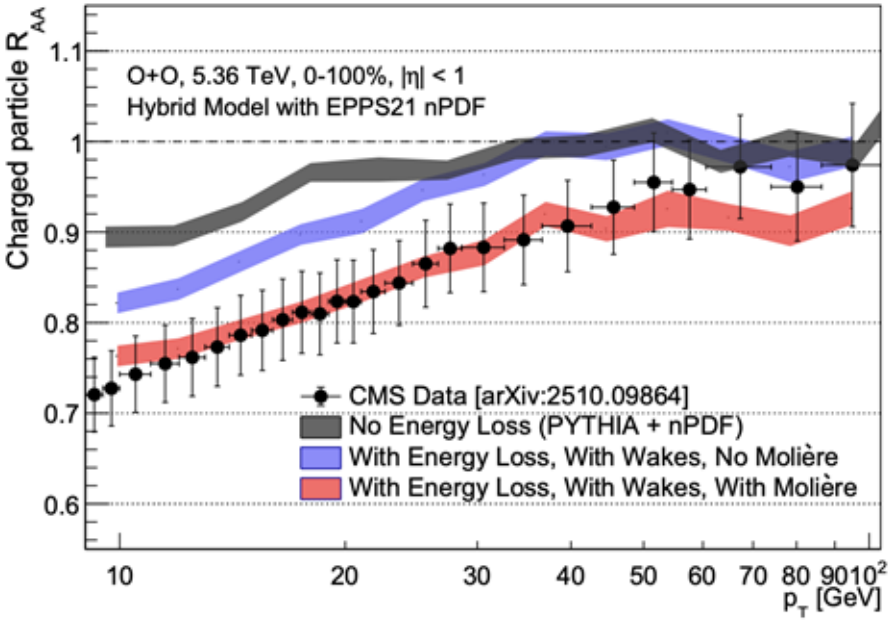


Confronting Recent OO Data

2603.23596 [Kudinoor, Lin, Pablos, Rajagopal]

Molière scatterings are necessary for agreement between our model and CMS data on high-p_T charged-particle suppression.

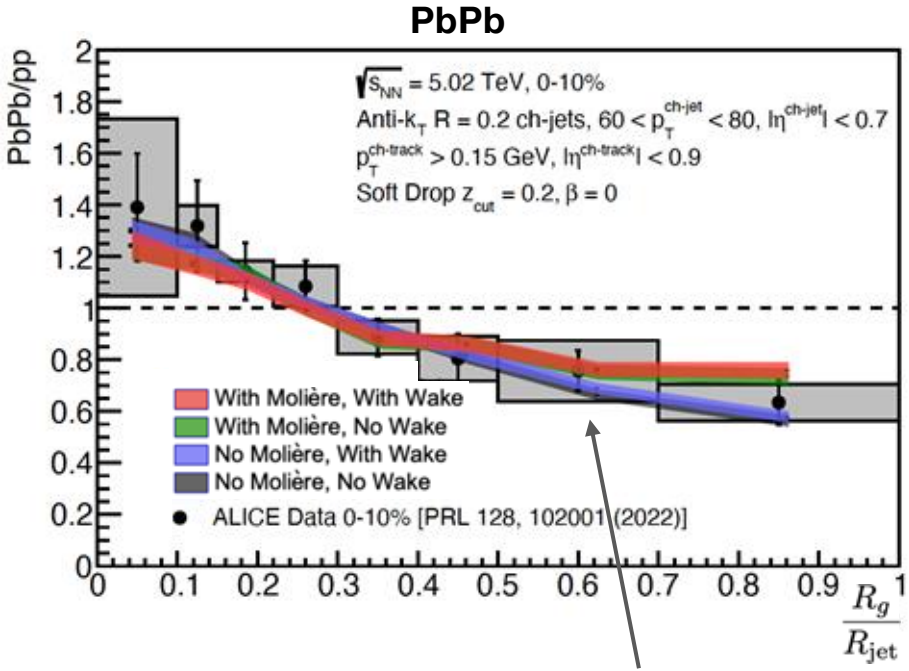
No OO data was used in the choice of our model parameters! Parameters were chosen by comparing our model calculations to data from PbPb collisions.

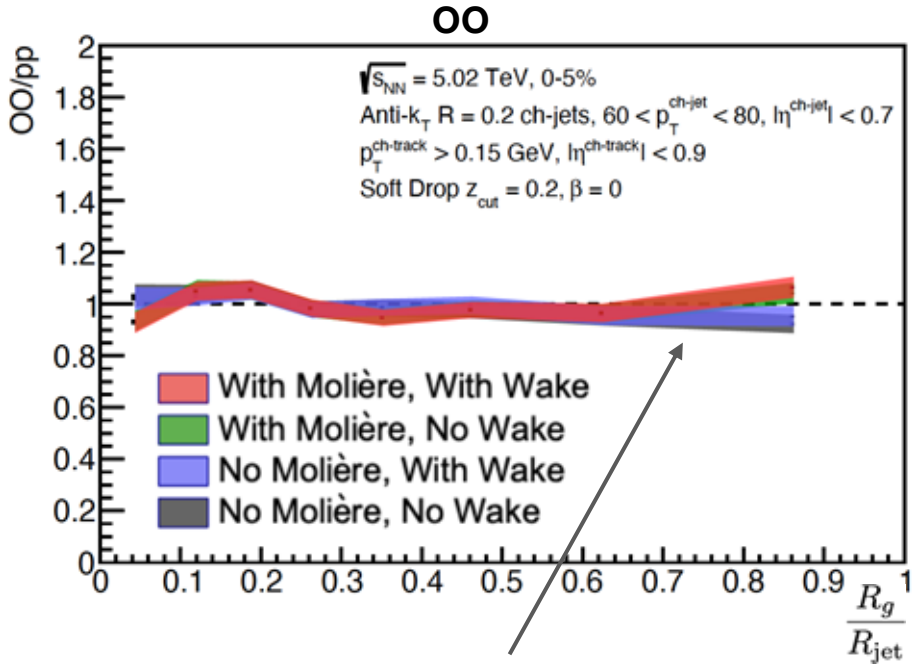


Recall: R_{AA} is the number of charged-hadrons in a pT-bin in OO collisions relative to that in the corresponding number of pp collisions

Soft Drop Angle for R = 0.2 Jets

2603.23596 [Kudinoor, Lin, Pablos, Rajagopal]





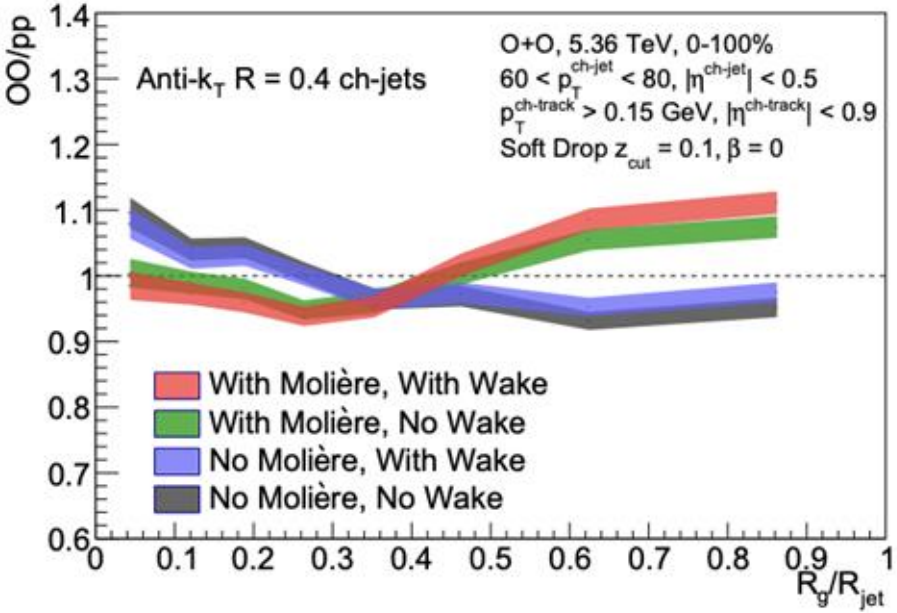
PbPb jet sample is biased towards those that have lost the least energy, which tend to be narrower

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

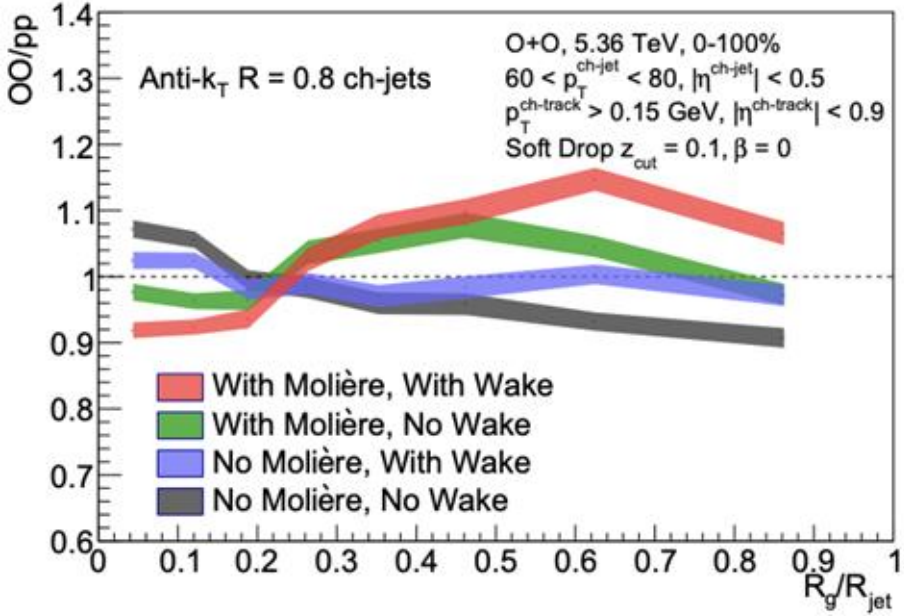
Soft Drop Angle for R = 0.4 and R = 0.8 Jets

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

Summary

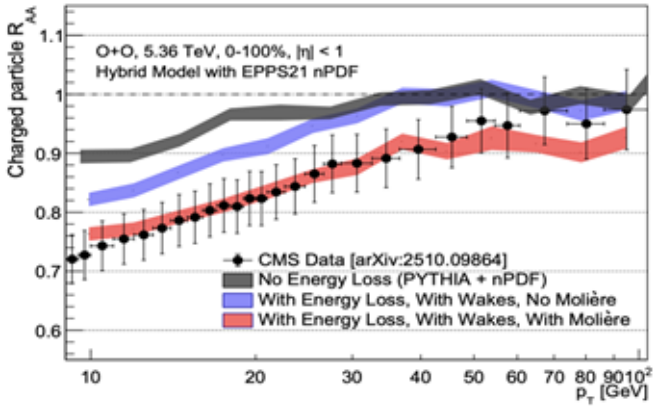
Quasiparticles in QGP can be revealed by rare, hard, large-angle Molière scatterings between jet partons and QGP constituents.

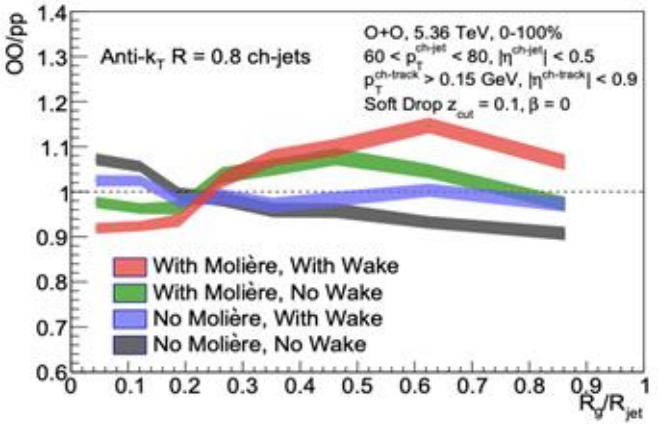
The confounding effects of selection bias due to jet energy loss can be minimized in **inclusive jet substructure measurements in OO collisions**.

Detecting Molière scattering experimentally would **open the door to studying the microscopic structure of QGP** and to develop and test theoretical descriptions of it (analogous to PDFs in DIS).

For more, check out:

- 2603.23596 (R_g and energy correlators in OO)!
- 2603.08776 (R_g and jet girth in gamma-tagged PbPb)



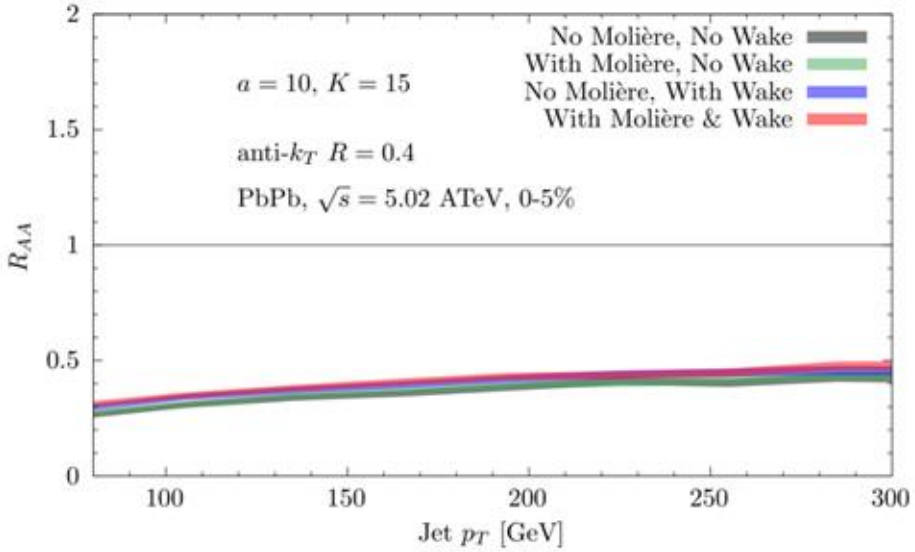


BACKUP

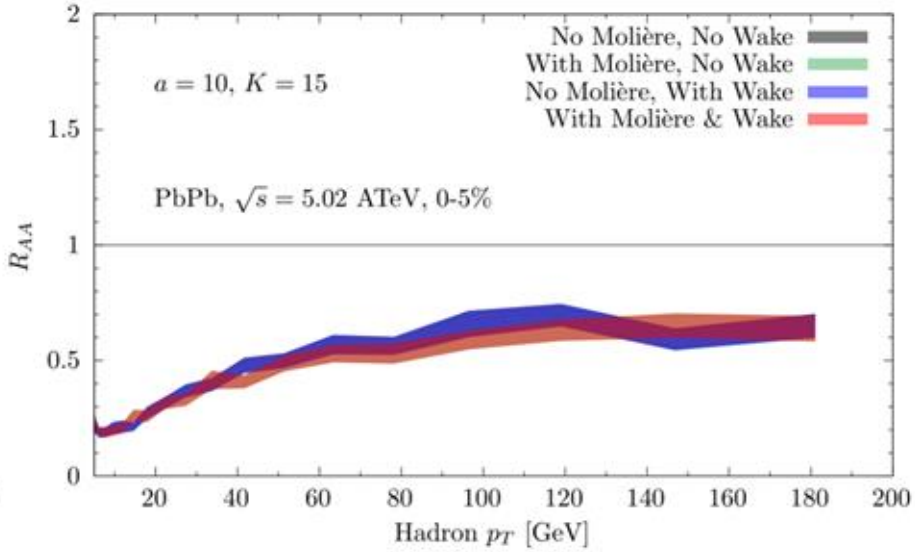
Tuning Our Quenching Parameter κ_{sc}

2603.08776 [Hulcher, Kudinoor, Pablos, Rajagopal]

Jet R_{AA}



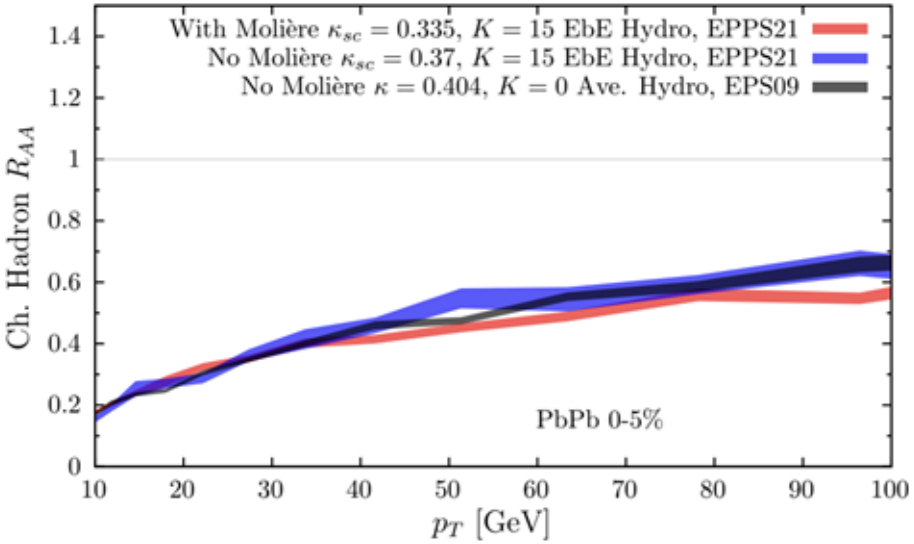
Charged-Hadron R_{AA}

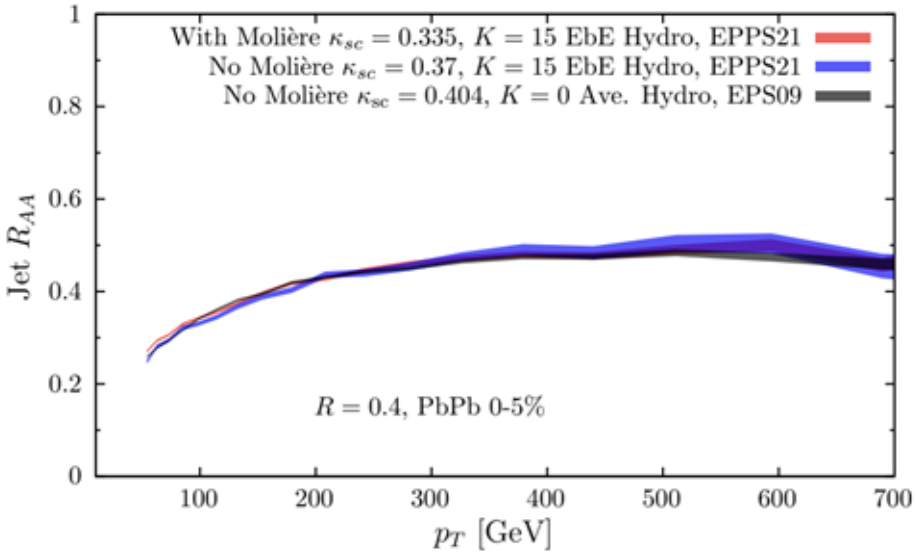


We retuned κ_{sc} so that jet and charged-hadron R_{AA} were left unchanged after including Molière scattering in the model.

⇒ Molière-induced modifications to jet observables will arise from modifications to jet substructure, not overall suppression

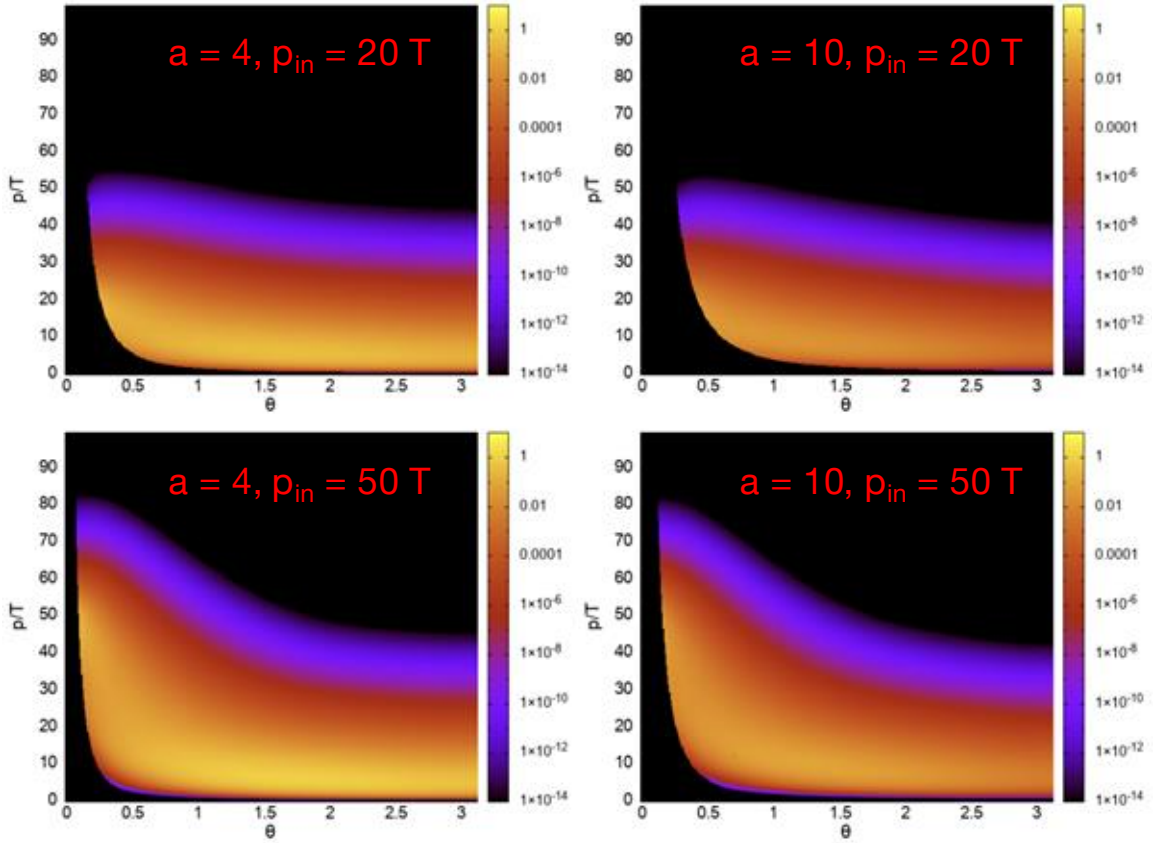
Tuning κ_{sc} with Event-by-Event Hydrodynamic Profiles (It is tuned in PbPb collisions)

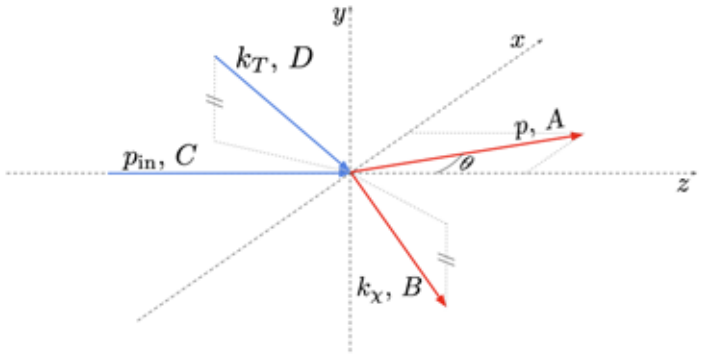




Molière Scattering

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



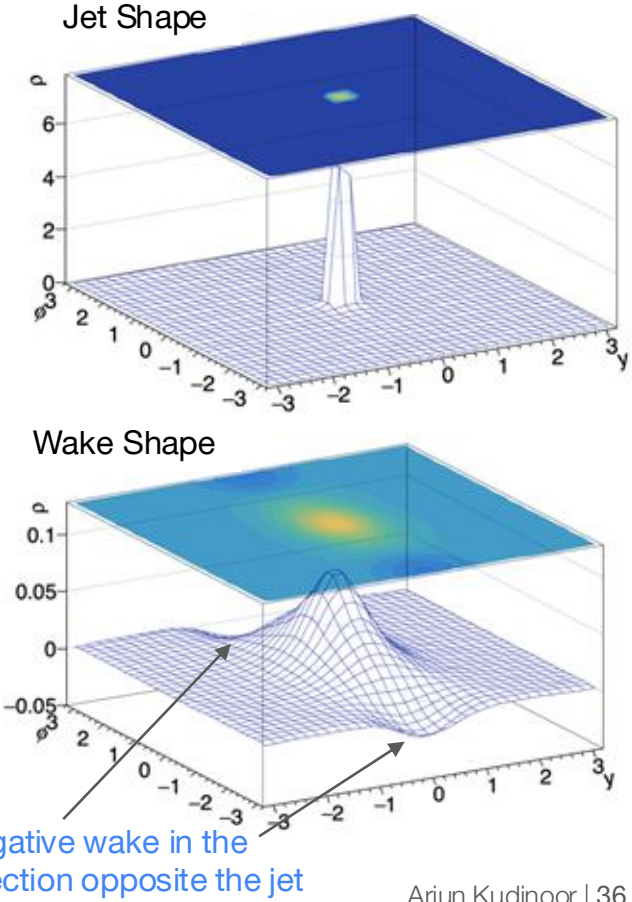


“Medium Response” and Jet-Induced Wakes

- Due to soft exchanges with the medium, hard partons in jets lose energy as they move through droplets of QGP formed in heavy ion collisions

- The energy lost by each parton is deposited into the plasma in the form of a wake

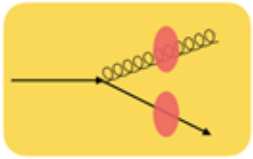
- The jets pulls some amount of QGP in the direction of the jet. So, when you compare the freezeout of a QGP droplet containing a jet wake to one without, it will have:
  - **Positive Wake:** Additional soft particles in jet’s direction
  - **Negative Wake:** Depletion of soft particles in the direction opposite the jet [CMS PAS HIN-23-006, arXiv:2408.08599]



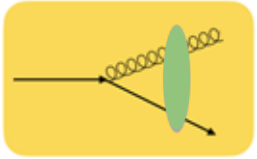
The QGP Resolution Length

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}



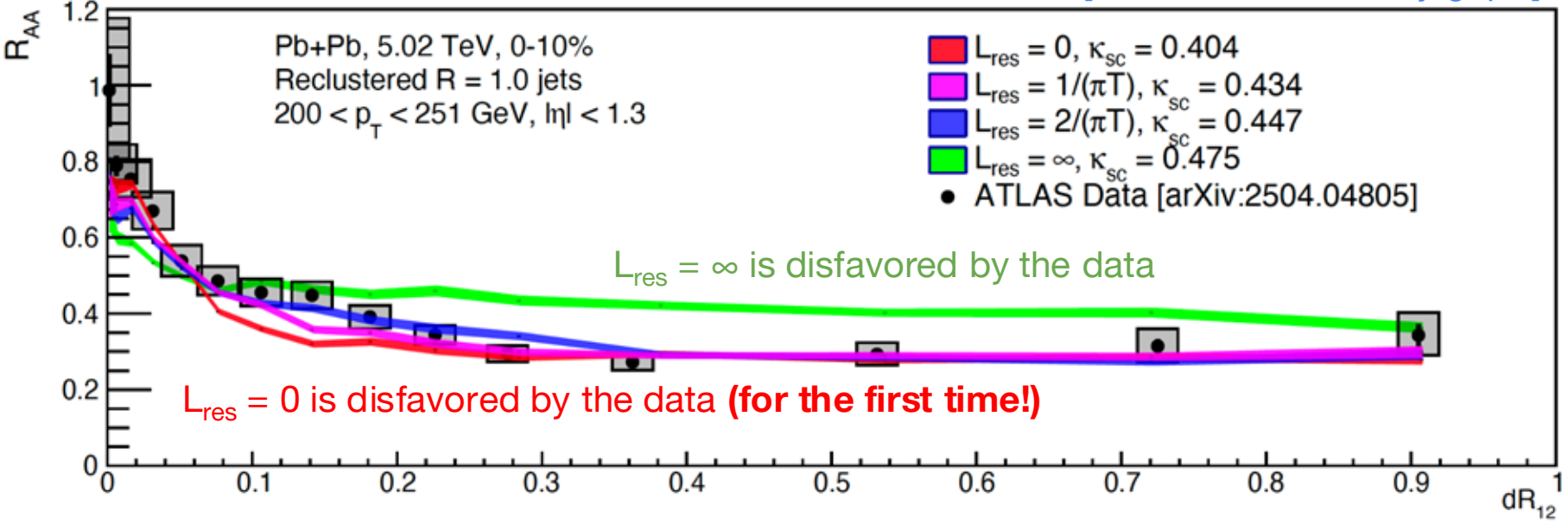
$L_{res} = 0$: Medium resolves splitting immediately after a parton splits
⇒ fully **incoherent** interactions with the plasma



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

Constraining L_{res} using dR_{12} Data

arXiv:2509.08881 [Kudinoor, Pablos, Rajagopal]



At T = 300 MeV, L_{res}~ 0.2-0.4 fm

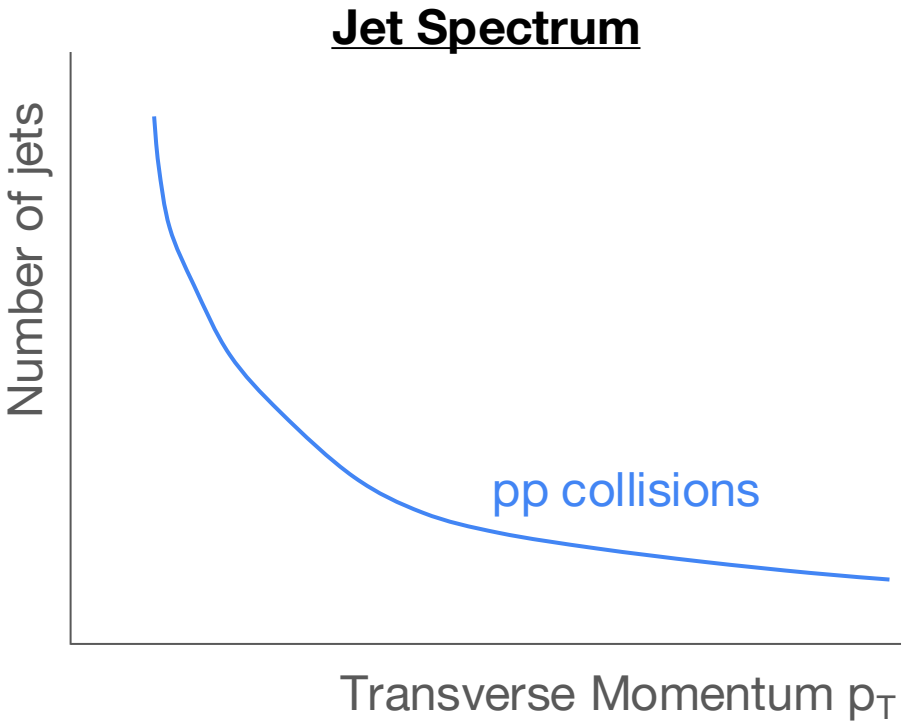
QCD vs. $\mathcal{N} = 4$ SYM Theory

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).

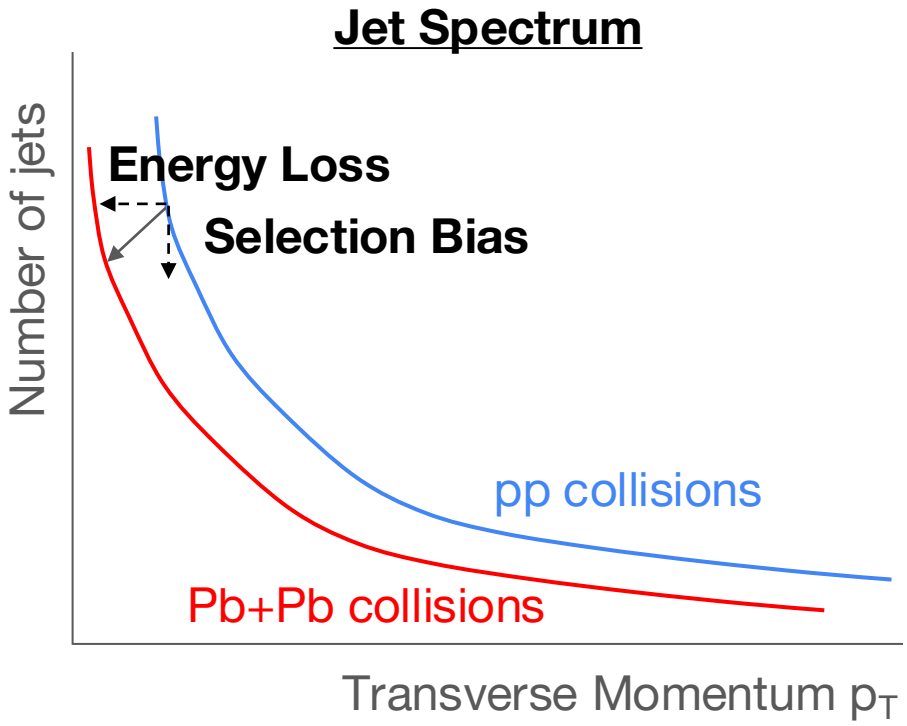
Differences between QCD and $\mathcal{N} = 4$ SYM include

- $N_c = 3$ for QCD, whereas we take the $N_c \to \infty$ 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

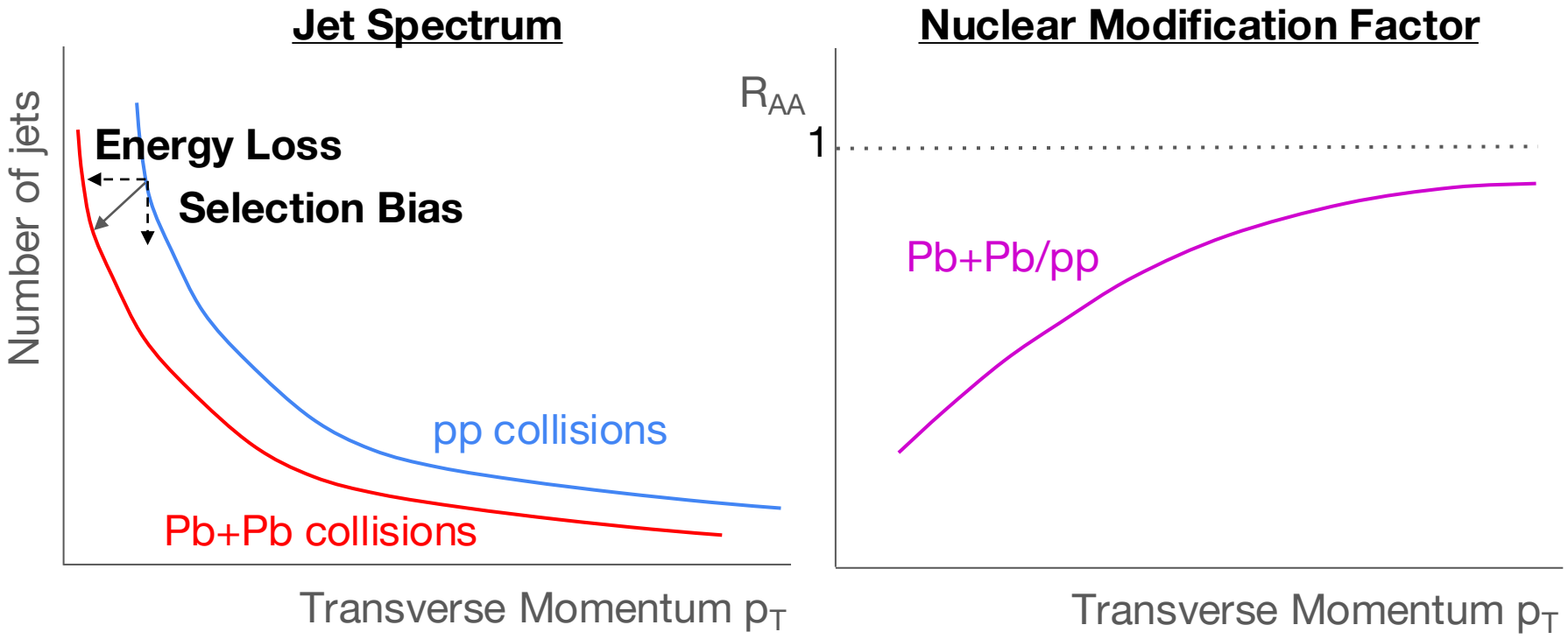
The Canonical Jet Quenching Observable



The Canonical Jet Quenching Observable

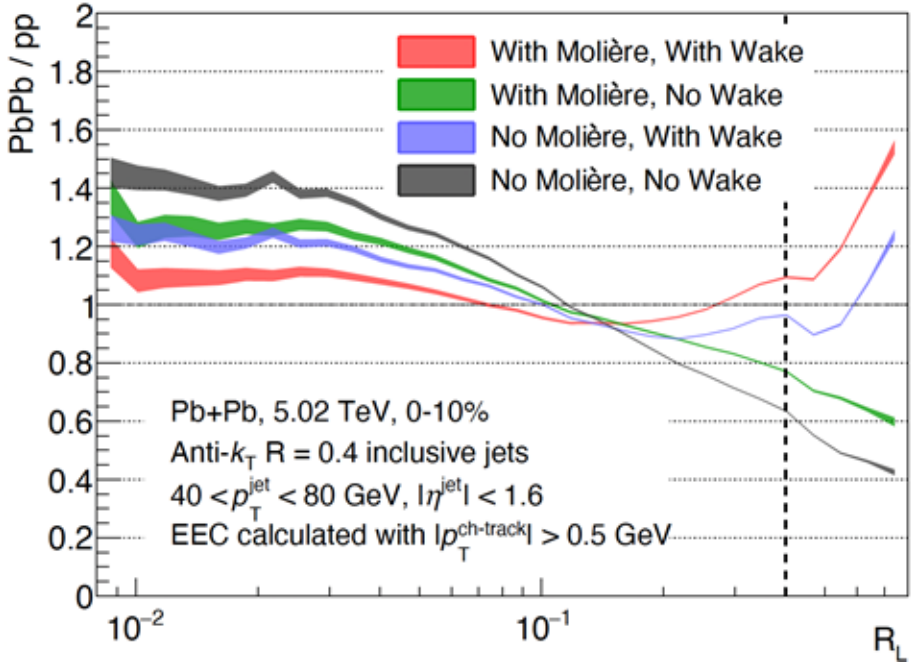


The Canonical Jet Quenching Observable



EECs in PbPb Collisions (R = 0.4 Jets)

$p_T^{\text{ch-track}} > 0.5$ GeV

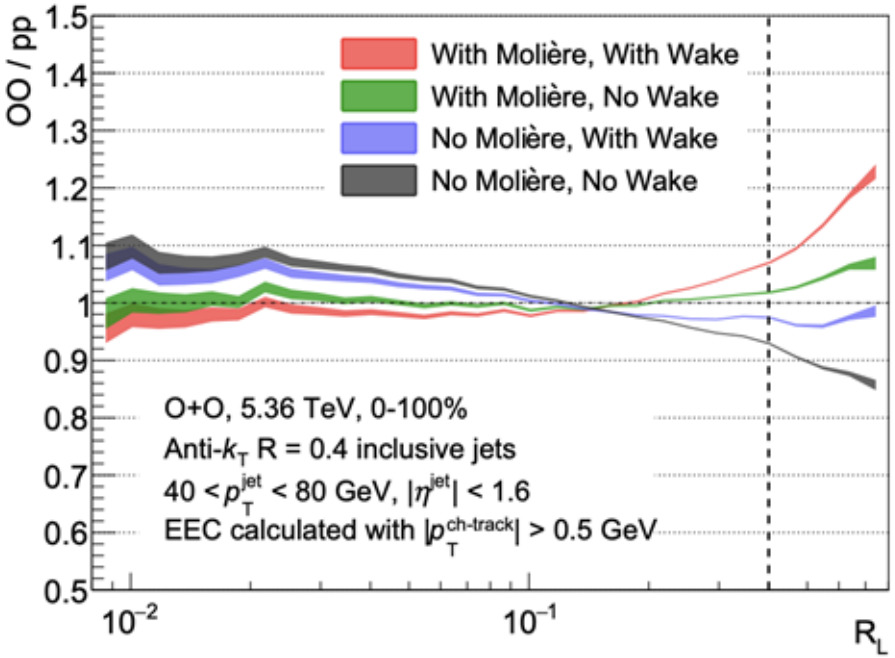


Large-angle correlations are primarily driven by broad jet-wakes

EECs in OO Collisions (R = 0.4 Jets)

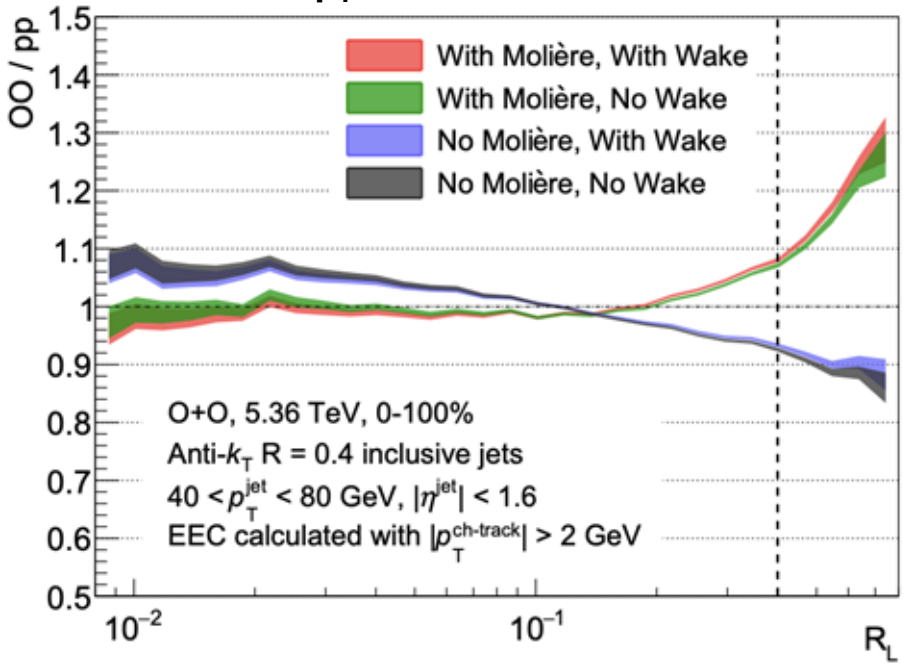
2603.23596 [Kudinoor, Lin, Pablos, Rajagopal]

$p_T^{\text{ch-track}} > 0.5$ GeV



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

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

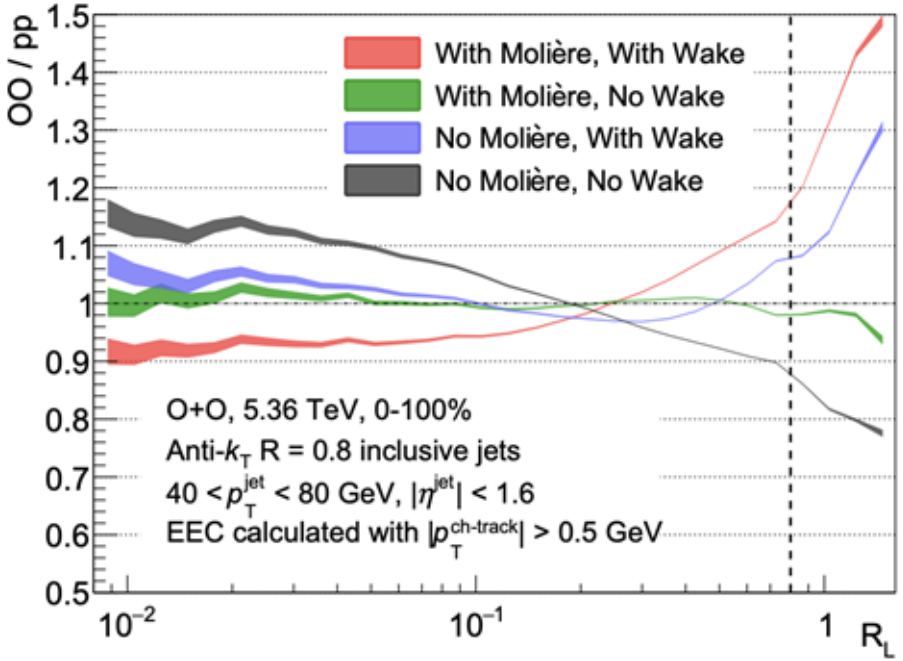


$p_T > 2$ GeV eliminates most of the soft wake, and isolates the large-angle kicks from Molière scattering

EECs in OO Collisions (R = 0.8 Jets)

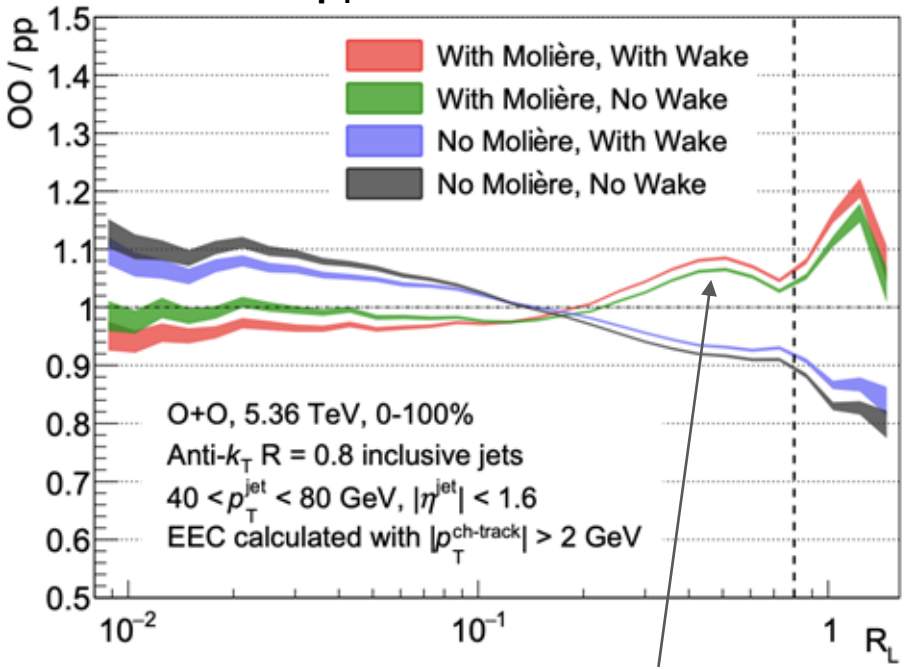
2603.23596 [Kudinoor, Lin, Pablos, Rajagopal]

$p_T^{\text{ch-track}} > 0.5$ GeV



Clear large-R_L enhancements especially from broad jet-wakes

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



Typical angle of deflection due to Molière scattering