An EEC Way to See the Interplay Between Elastic Scatterings and Jet Wakes

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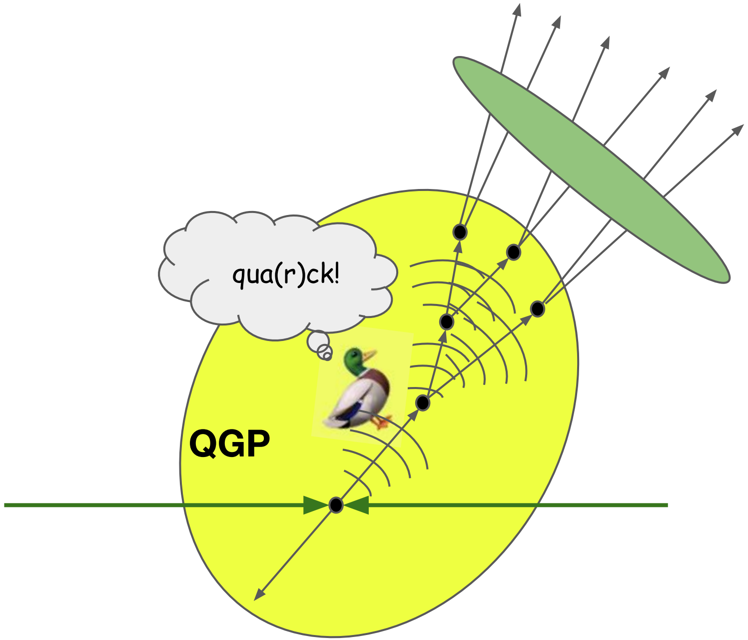
Hot Jets 2025
Jan 8, 2025

Outline

- The **Hybrid Strong/Weak Coupling Model** of Jet Quenching
    - Jet-Wakes
    - Elastic Scattering
- Understanding the interplay between wakes and elastic scattering using **2-point EECs**
- Exploring the effects of wakes and elastic scattering on **3-point EECs**
    - Can we see how elastic scatterings with the medium modify a jet's wake?
    - Can we isolate the effects of wakes and elastic scatterings using 3-point (or higher-point) EECs?

TOPIC 1
The Hybrid Model

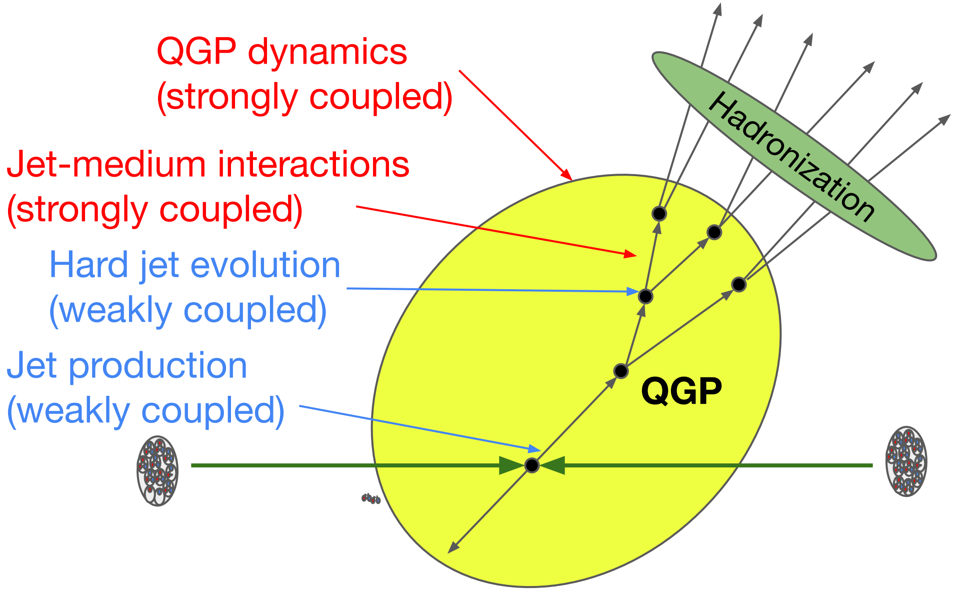


Hybrid Strong/Weak Coupling Model

A successful phenomenological model must be a **hybrid model** that simultaneously treats the

- **Weakly coupled** physics of hard scatterings and fragmentation of hard partons
- **Strongly coupled** dynamics of the QGP medium and the soft exchanges between partons in jets and the medium

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



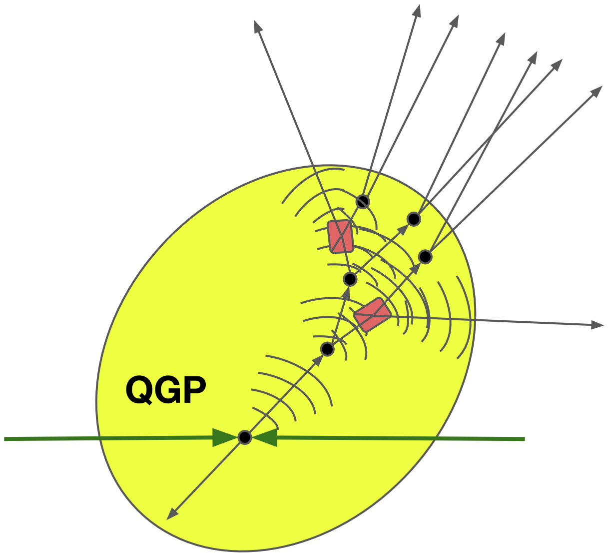
Energy Loss In The Hybrid Model

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

- Parton splittings that result in the jet shower are determined by the high-virtuality, perturbative, DGLAP equations (PYTHIA 8)
- Each parton loses energy to the strongly coupled plasma as determined by a holographic energy loss formula

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

Here, $x_{\text{stop}} \equiv E_{\text{in}}^{1/3}/(2T^{4/3}\kappa_{\text{sc}})$ is the maximum distance the parton can travel within the plasma before thermalizing and equilibrating with the plasma.



- There are many physical effects we can turn on/off in the Hybrid Model.
  - **Jet-Wakes:** Energy lost by each parton is deposited into the plasma in the form of a wake
  - **Elastic Scatterings:** $2 \to 2$ scatterings between hard partons in the jet and quasi-particles in the medium
  - QGP Resolution Length (not in this talk): The medium's ability to resolve partons only if they are separated by a length greater than L_{res}

Jet-Induced Wakes

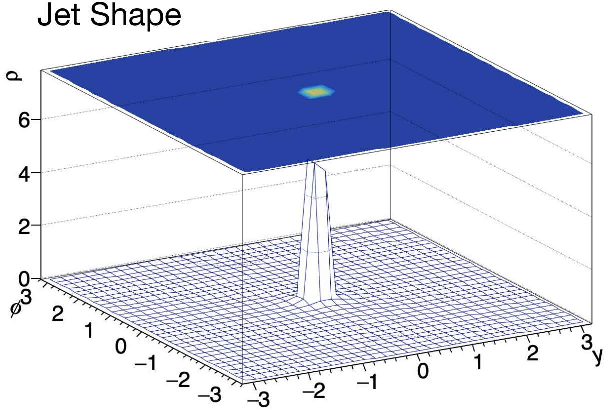
- The energy lost by each parton is deposited into the plasma in the form of a wake.
- In the Hybrid Model, a wake is generated by the production of low-momentum hadrons, according to the momentum spectrum

$$E\frac{d\Delta N}{d^3p} = \frac{1}{32\pi}\,\frac{m_T}{T^5}\cosh(y-y_j)e^{-\frac{m_T}{T}\cosh(y-y_j)} \times \left\{p_T\Delta p_T\cos(\phi-\phi_j)+\frac{1}{3}m_T\,\frac{\Delta E}{\cosh(y_j)}\cosh(y-y_j)\right\}$$

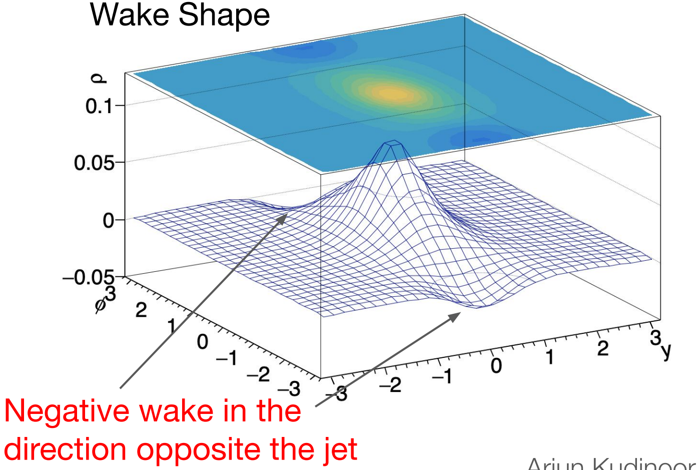
The jet pulls some amount of QGP in the direction of the jet. So, when you compare the freezeout of a QGP droplet containing a jet wake to one without, it will have:

1) **Positive Wake:** Additional soft particles in the jet's direction
2) **Negative Wake:** Depletion of soft particles in the direction opposite the jet

Jet Shape



Wake Shape



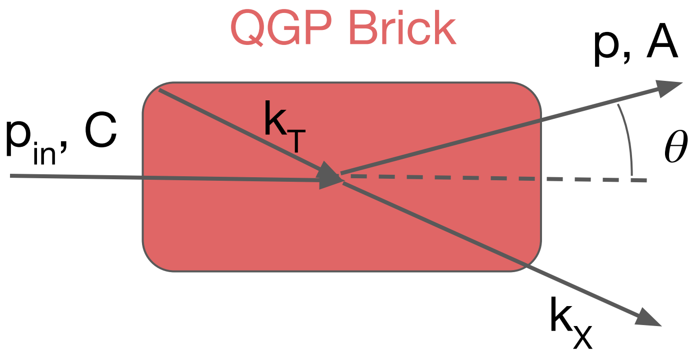
arXiv: 1808.03250 [D'Eramo, et al.]

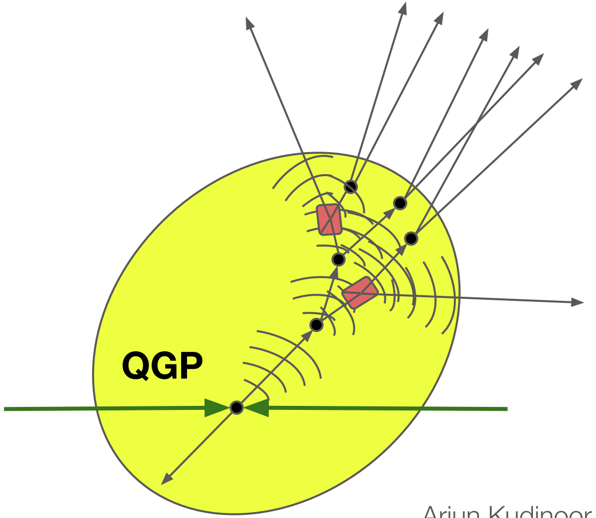
Motivation

- QGP, at length scales O(1/T), is a strongly coupled liquid. Flow and jet observables sensitive to parton energy loss, are well-described in such a fluid, without quasi-particles.
- At shorter length scales, probed via large momentum exchange, asymptotic freedom mandates the presence of quasi-particles
- First step to **probing the particulate nature and microscopic structure** of the QGP

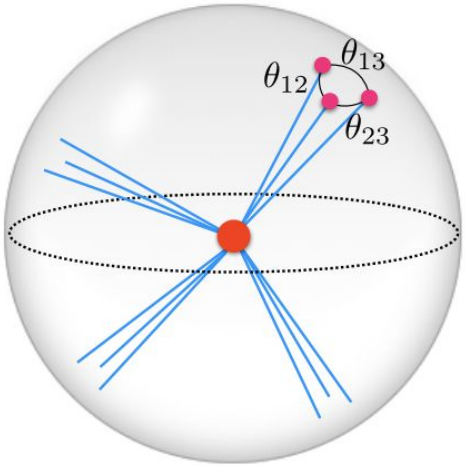
Implementation in the Hybrid Model

- **2→2 kicks** between particles in the jet shower and quasi-particles in the medium
- Sufficiently high momentum exchanges should be perturbative
- **Recoiling particles k_X lose energy and produce wakes**
- Thermal particles k_T are removed from the medium (aka "holes")





TOPIC 2
Imaging the Wake AND Elastic Scattering Using EECs



arXiv: 1912.11050 [Chen, et al.]

Let $\langle \mathcal{E}(\vec{n}_1)...\mathcal{E}(\vec{n}_k)\rangle$ be the correlation function of asymptotic energy fluxes in the n-direction

$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} \int_0^\infty dt r^2 n^i T_{0i}(t, r\vec{n})$$

To isolate the scaling behavior of energy correlators as a function of angular size, we integrate over the shape of the energy correlators, keeping only their longest side fixed (arXiv: 2004.11381). This gives the projected N-point correlator

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

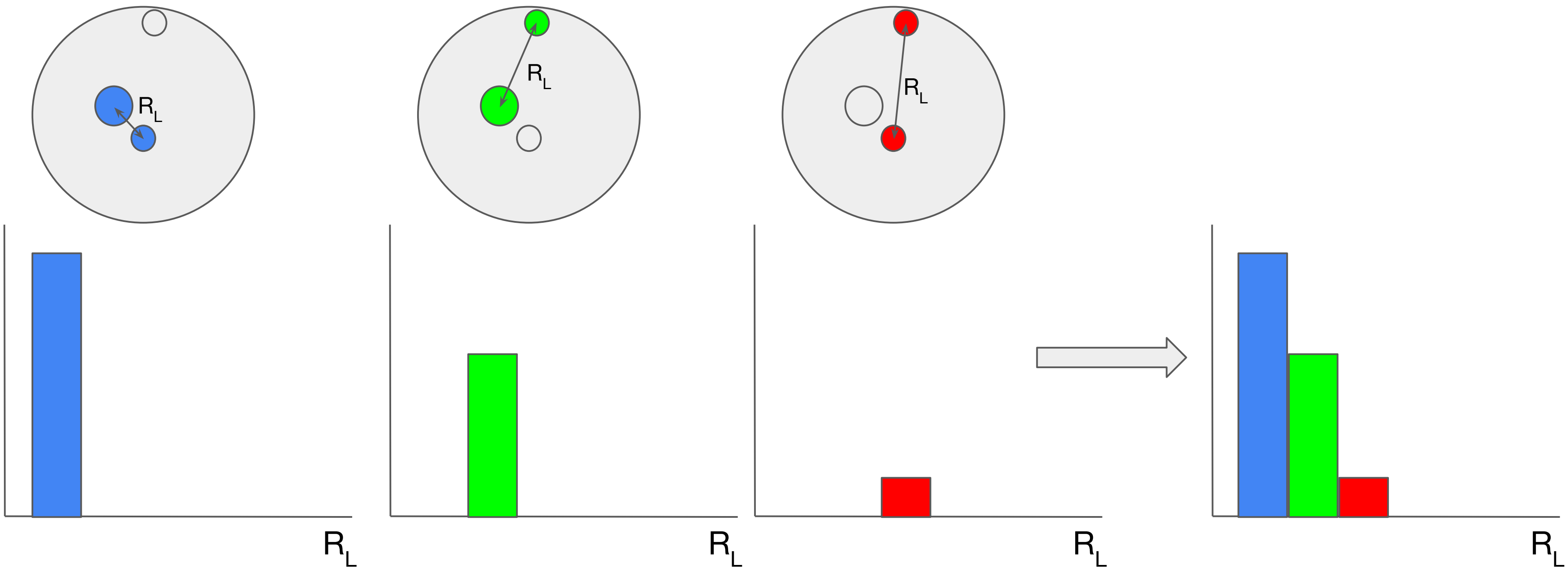
where $d\Omega_{\vec{n}}$ is the area element on the detector, $\Delta\hat{R}_L$ is an operator selecting the largest angular distance between the N particles, and the average is over an ensemble of jets with energy E_{jet}.

In hadron collider environments, we use p_T instead as the energy coordinate and $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$ as the angular coordinate.

In this talk, we will examine **the E2C and the full shape-dependent EEEC** (which is a function of 3 angles between triplets of particles)

2-Point EECs

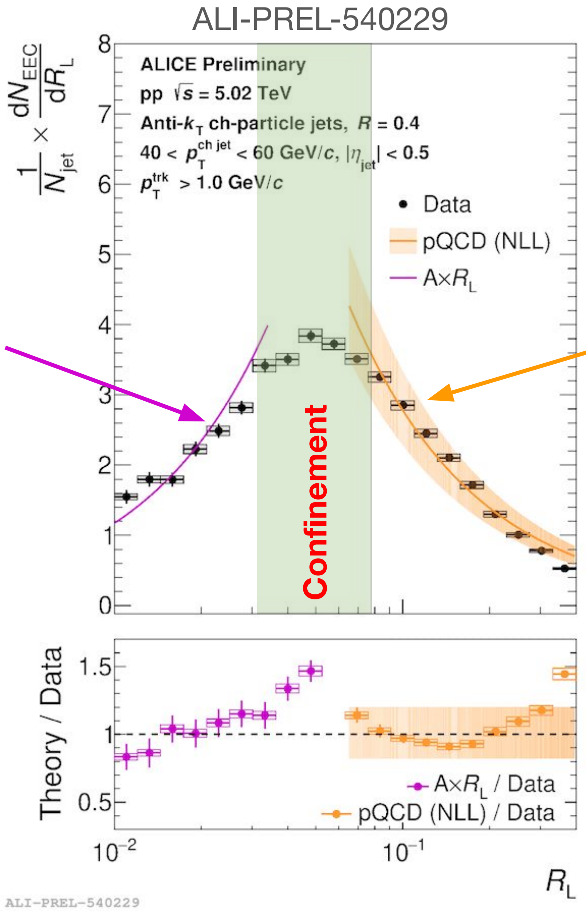
$$\frac{d\Sigma}{d\theta} = \int d\vec{n}_{1,2} \frac{\langle \epsilon(\vec{n}_1)\epsilon(\vec{n}_2)\rangle}{Q^2} \delta(\vec{n}_1 \cdot \vec{n}_2 - \cos(\theta)) \Rightarrow \mathrm{EEC}(R_L) = \sum_{i_1, i_2 \in \mathrm{jet}} \int dR_L \frac{p_T^{i_1} p_T^{i_2}}{p_{T,\mathrm{jet}}^2} \delta(R_L - \Delta\hat{R}_L)$$



2-Point EEC In Vacuum (No QGP)

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

Images the evolution of non-interacting hadrons (at late times)



Images the perturbative QCD evolution of partons (at early times)

Can extract value of α_s by looking at the pQCD-side scaling of the E3C/E2C ratio

2-Point EEC In Vacuum (No QGP)

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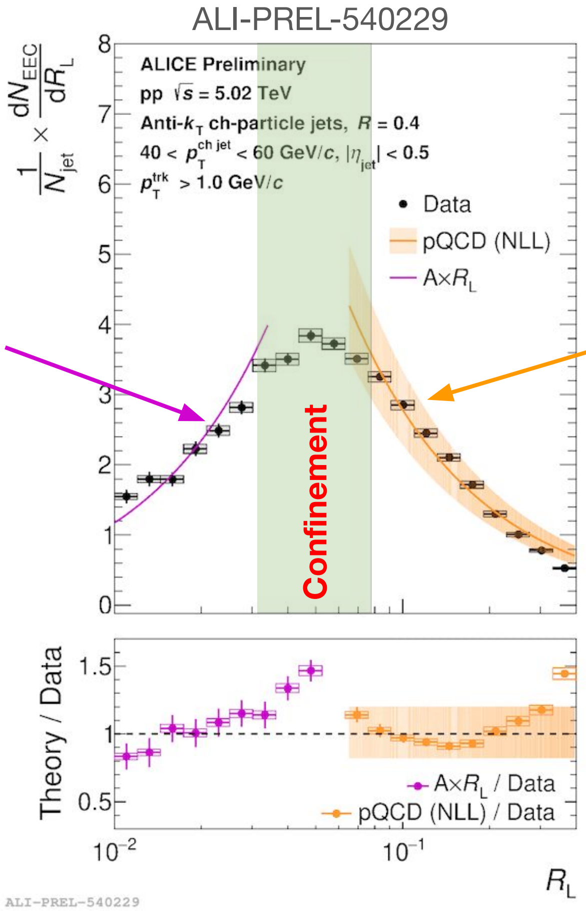


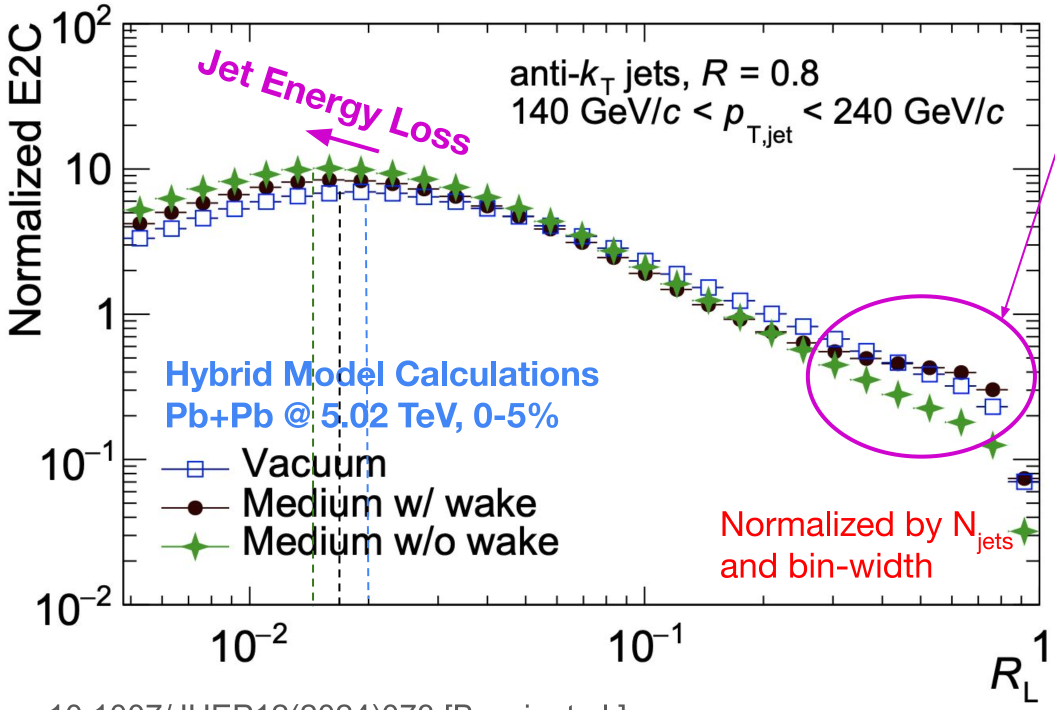
Images the evolution of non-interacting hadrons (at late times)

Images the perturbative QCD evolution of partons (at early times)

Can extract value of α_s by looking at the pQCD-side scaling of the E3C/E2C ratio

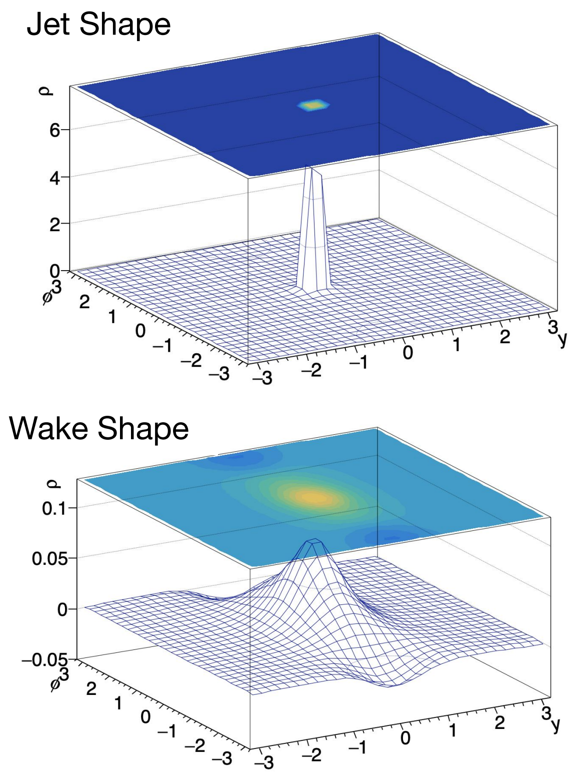
EECs can help reveal the presence and interplay between different physical processes that occur during heavy-ion collisions (e.g. wakes and elastic scattering)

2-Point EECs In Heavy Ions (Hybrid Model)



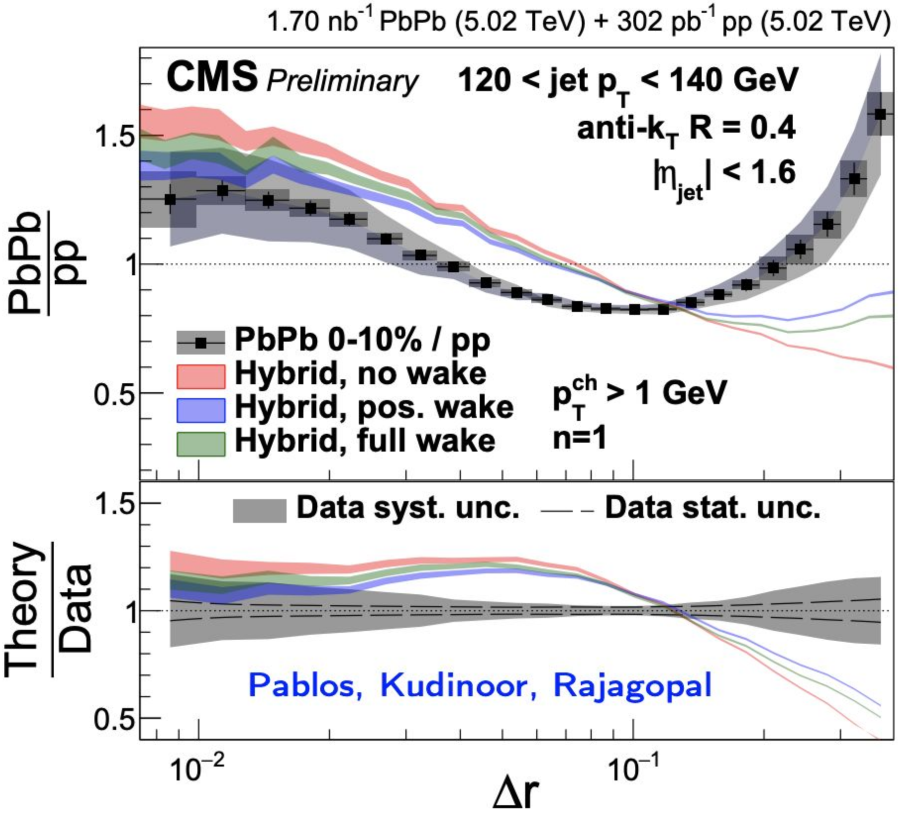
10.1007/JHEP12(2024)073 [Bossi, et al.]

The BROAD wake enhances the EEC at large angles



Our Predictions vs. CMS Data

CMS-PAS-HIN-23-004 **+ Jussi's Talk @ Hard Probes**



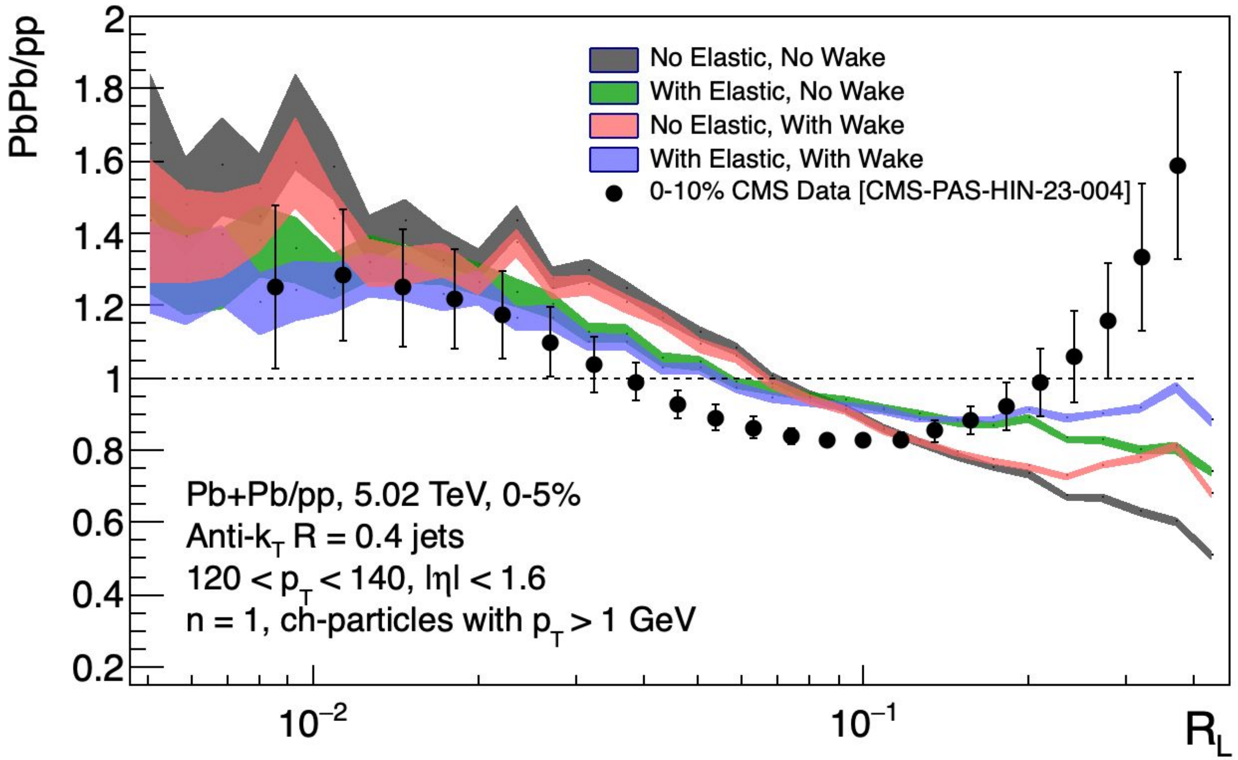
$$\mathrm{EEC}(R_L) = \frac{1}{(\Sigma_{\text{jets}}\Sigma_{i\neq j}(p_{T,i})^n(p_{T,j})^n)}\frac{d\left(\Sigma_{\text{jets}}\Sigma_{i\neq j}(p_{T,i})^n(p_{T,j})^n\right)}{dR_L}$$

Our model **underestimated** the large-angle enhancement observed in the CMS data.

- Hybrid **wake is too soft** ⇒ Wake is largely removed by the 1 GeV track cut
- Hybrid **wake is too wide** ⇒ Much of the wake lies outside R = 0.4 jet radius
- Other physical processes are excluded… **ELASTIC SCATTERING!**

* Self-normalized, charged track EECs

Including Elastic Scattering: n = 1, $p_T^{ch} > 1$ GeV



Elastic scattering modifies the structure of the wake, as well as modifying the structure of the parton shower

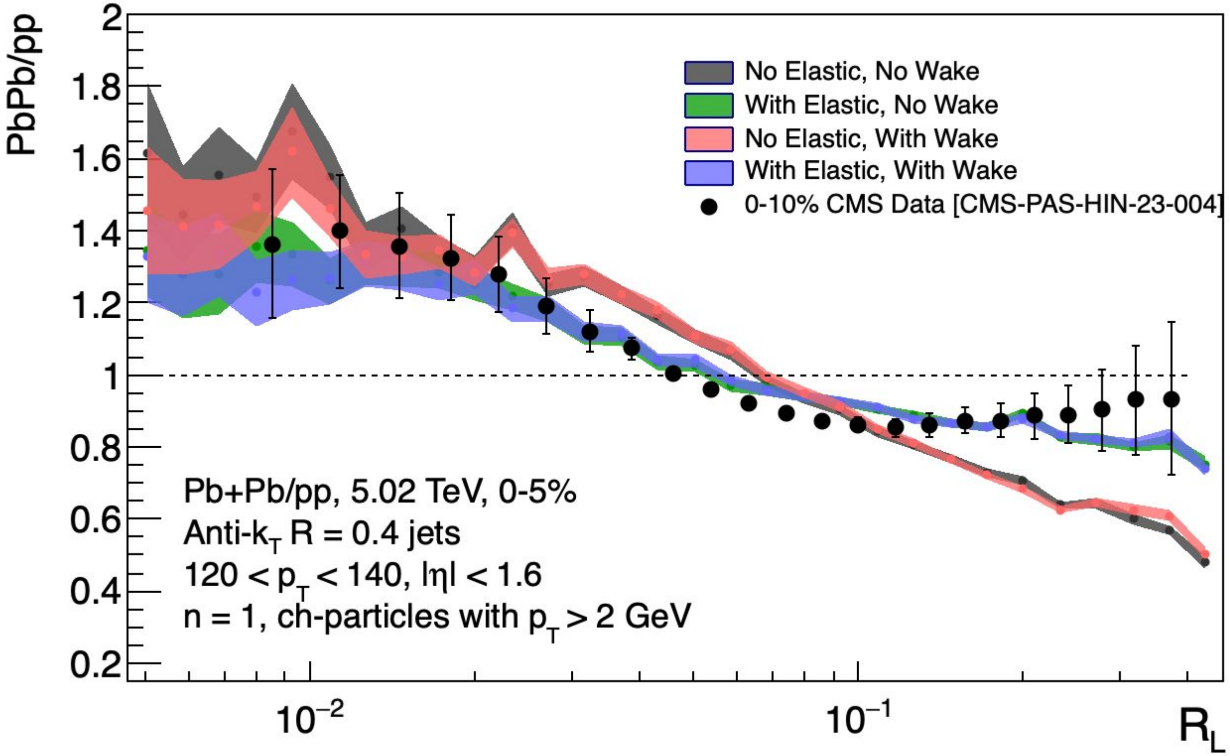
Why? Crucially, both partons involved in an elastic scattering produce their own wakes!

Having both elastic scattering and the wake gets us closer to the data. However, even with elastic scattering, our model underestimates the data because the wake is still too soft and too wide.

* Self-normalized, charged track EECs

Note: Differences with respect to preliminary results shown at HP2024 were due to track p_T cuts inconsistent with those used in CMS data.

n = 1, p_T^{ch} > 2 GeV



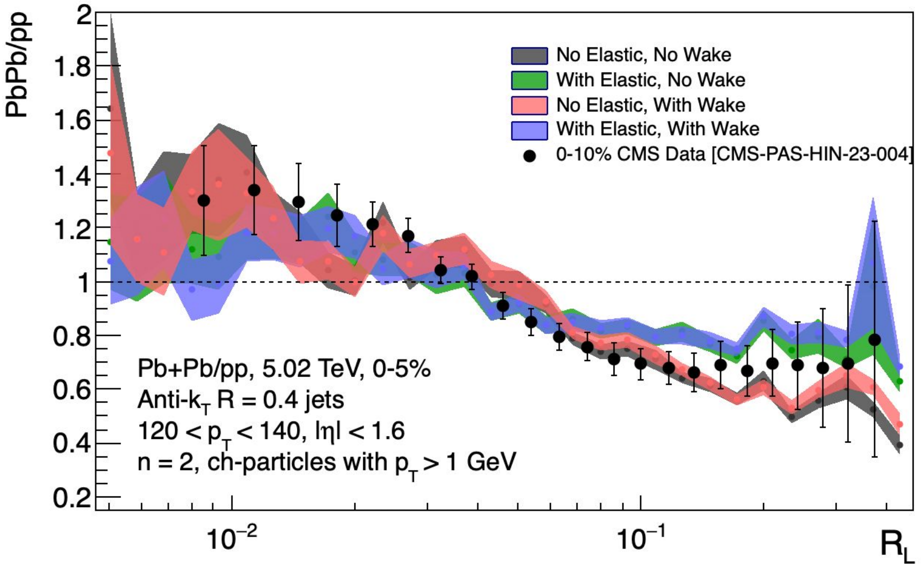
Wake is effectively removed by this track cut.

Modification to shape of parton shower resulting from elastic scatterings survives

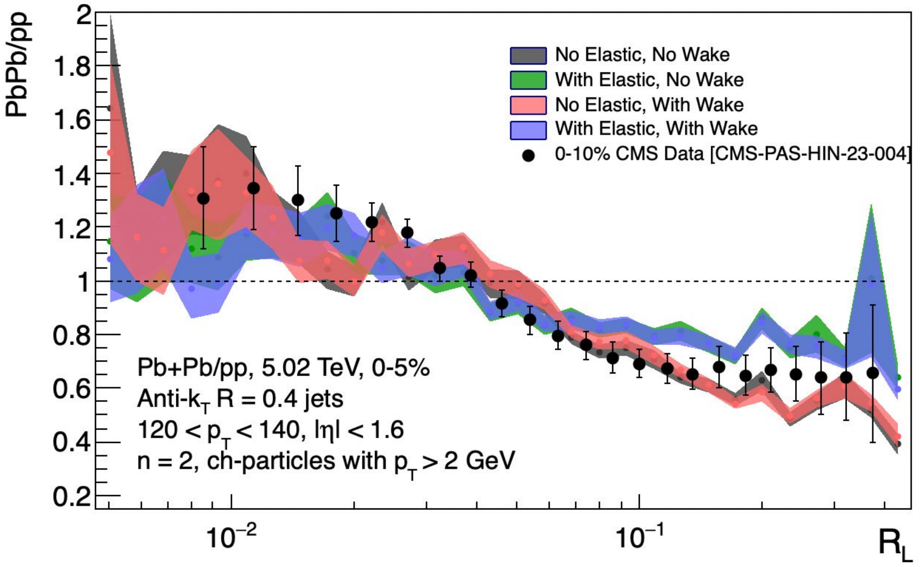
* Self-normalized, charged track EECs

n = 2

$p_T^{ch} > 1$ GeV



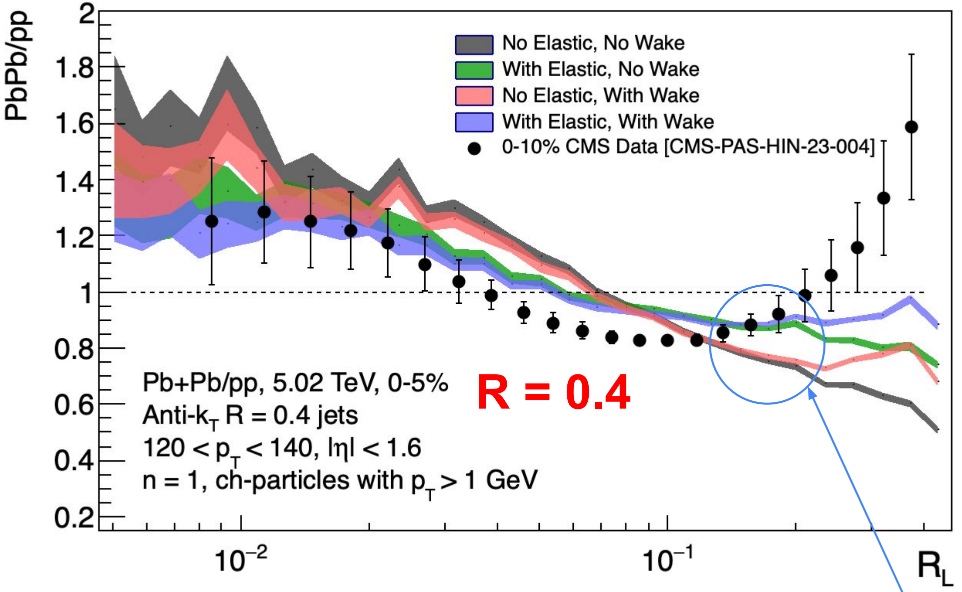
$p_T^{ch} > 2$ GeV

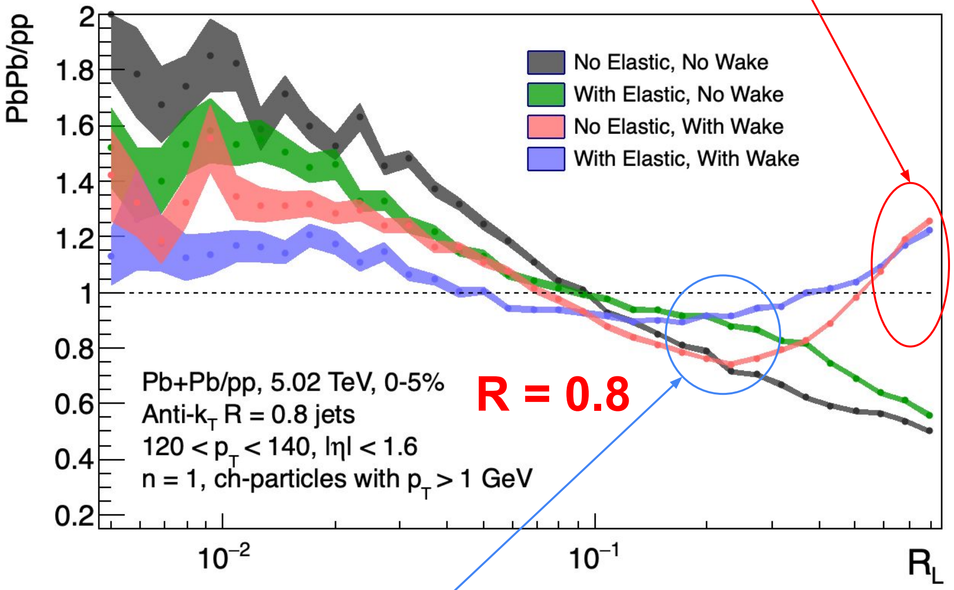


All curves are within the error bars because the
soft physics is suppressed
by the n = 2 exponential weighting

* Self-normalized, charged track EECs

EECs For Larger Jet Radius





Wake dominates at large angles

Maybe we can see elastic scattering effects at smaller angles?
→ EEEC at 0.2 < R_L < 0.3

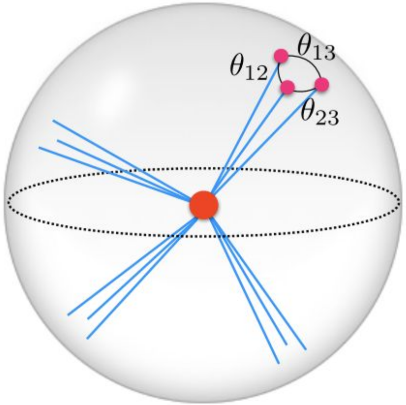


Image from arXiv: 1912.11050
[Chen, et al.]

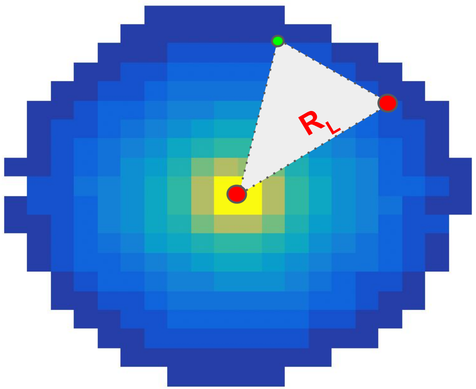
TOPIC 3
Exploring the Wake and Elastic Scattering using 3-Point EEECs

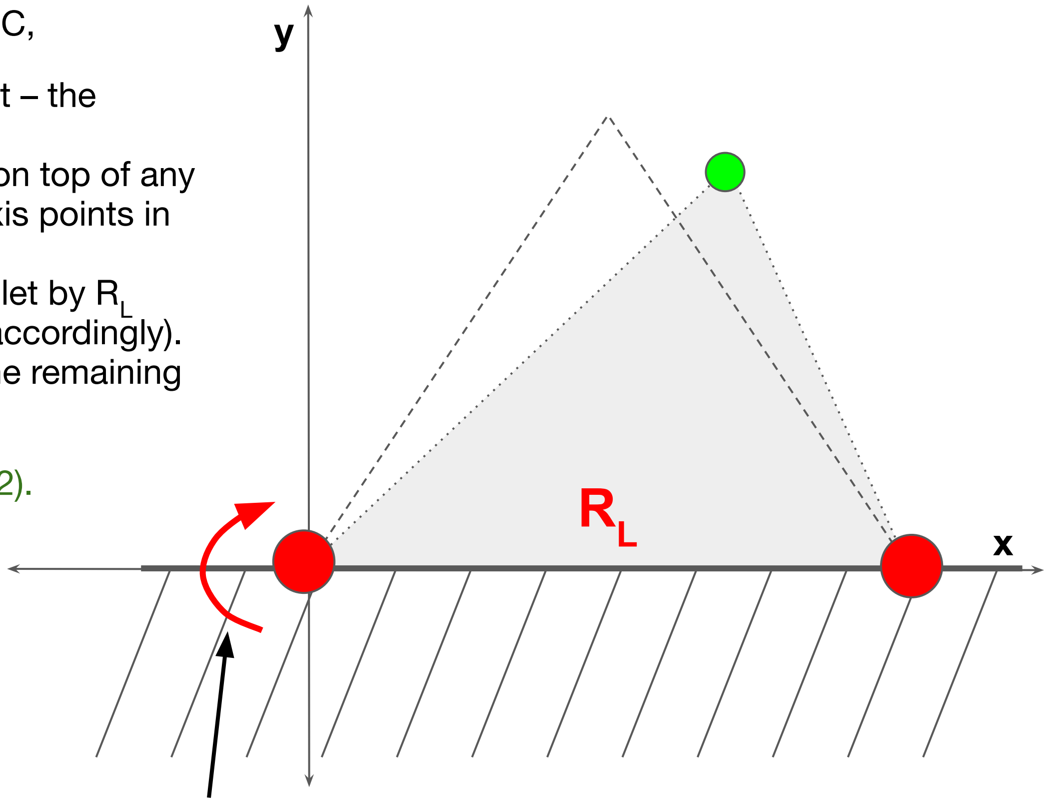
Our Coordinates

For each triplet of particles that contribute to the EEEC,

1) Find the two particles that are separated the most – the distance between them defines R_L.
2) Define (x, y) coordinates such that the origin lies on top of any one of the two particles from step 1, and the x-axis points in the direction of the other particle from step 1.
3) Scale all lengths of the triangle formed by the triplet by R_L (equivalently, set $R_L = 1$ and rescale the triangle accordingly).
4) Fill the EEEC in bins of the (x, y) coordinates of the remaining third particle in the triplet

Ex: Equilateral triangles correspond to $(x, y) = (½, \sqrt{3}/2)$.





Green points below this line are equivalent to green points symmetrically above this line

EEEC With Wake (But Not Elastic Scattering)

10.1007/JHEP12(2024)073 [Bossi, et al.]

Pb+Pb, 5.02 TeV, 0-5%

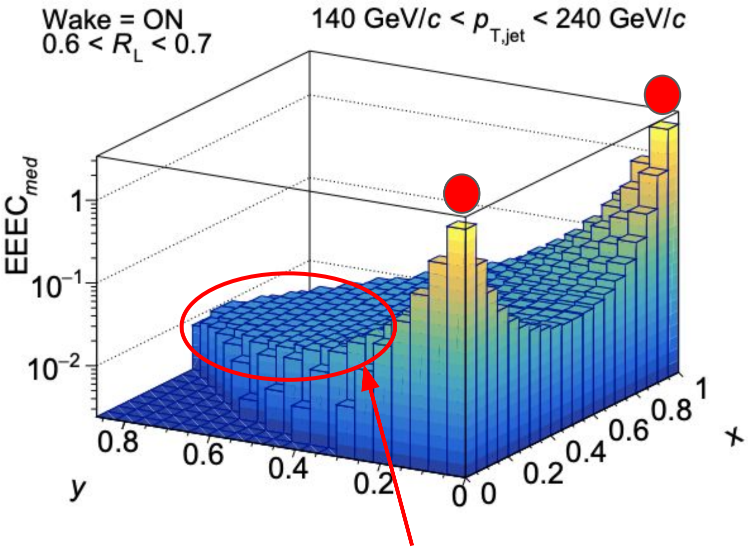
Anti k_t R = 0.8 jets

$140 < p_T < 240$ GeV

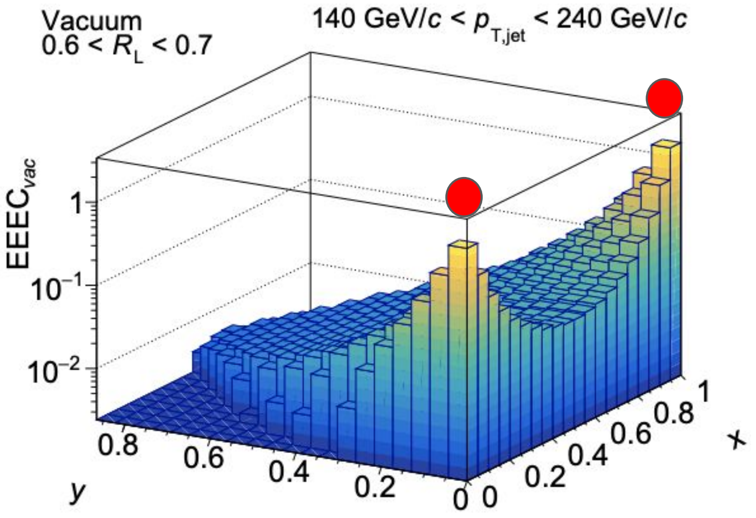
$|\eta| < 2.0$

$0.6 < R_L < 0.7$

Pb+Pb (With Wake)

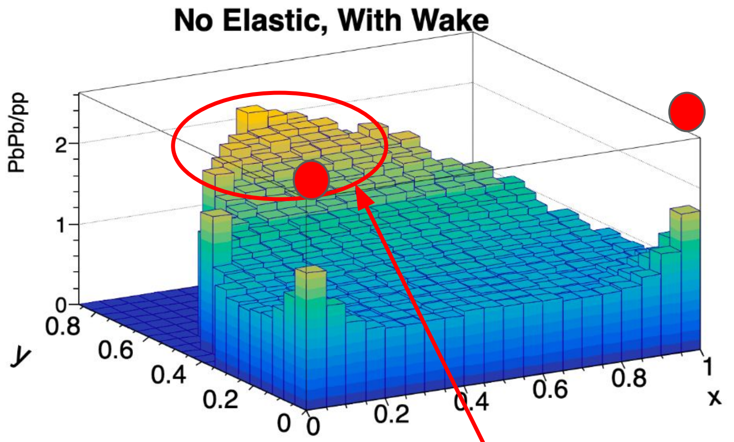


Vacuum (pp)



The wake fills in the phase space relatively unpopulated in vacuum.

PbPb/pp EEEC Ratios



Pb+Pb, 5.02 TeV, 0-5%
Anti k_t R = 0.8 jets
$140 < p_T < 240$ GeV
$|\eta| < 2.0$

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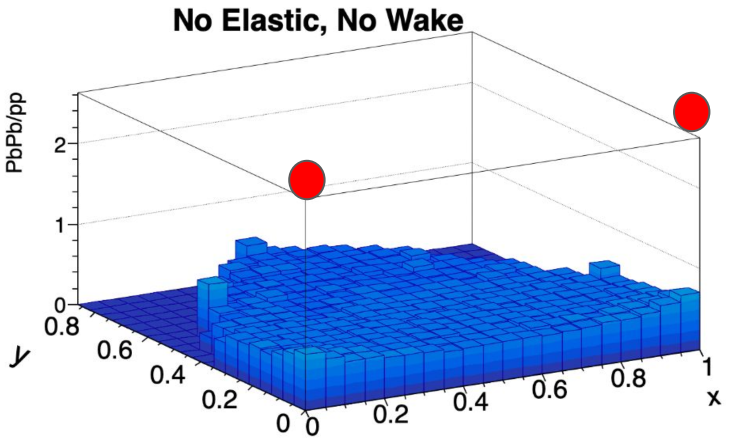
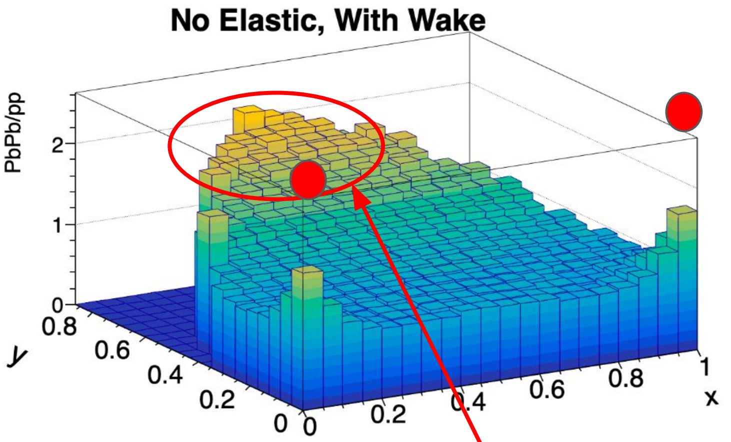
The wake results in an enhancement of equilateral structures when compared to collisions in vacuum

PbPb/pp EEEC Ratios





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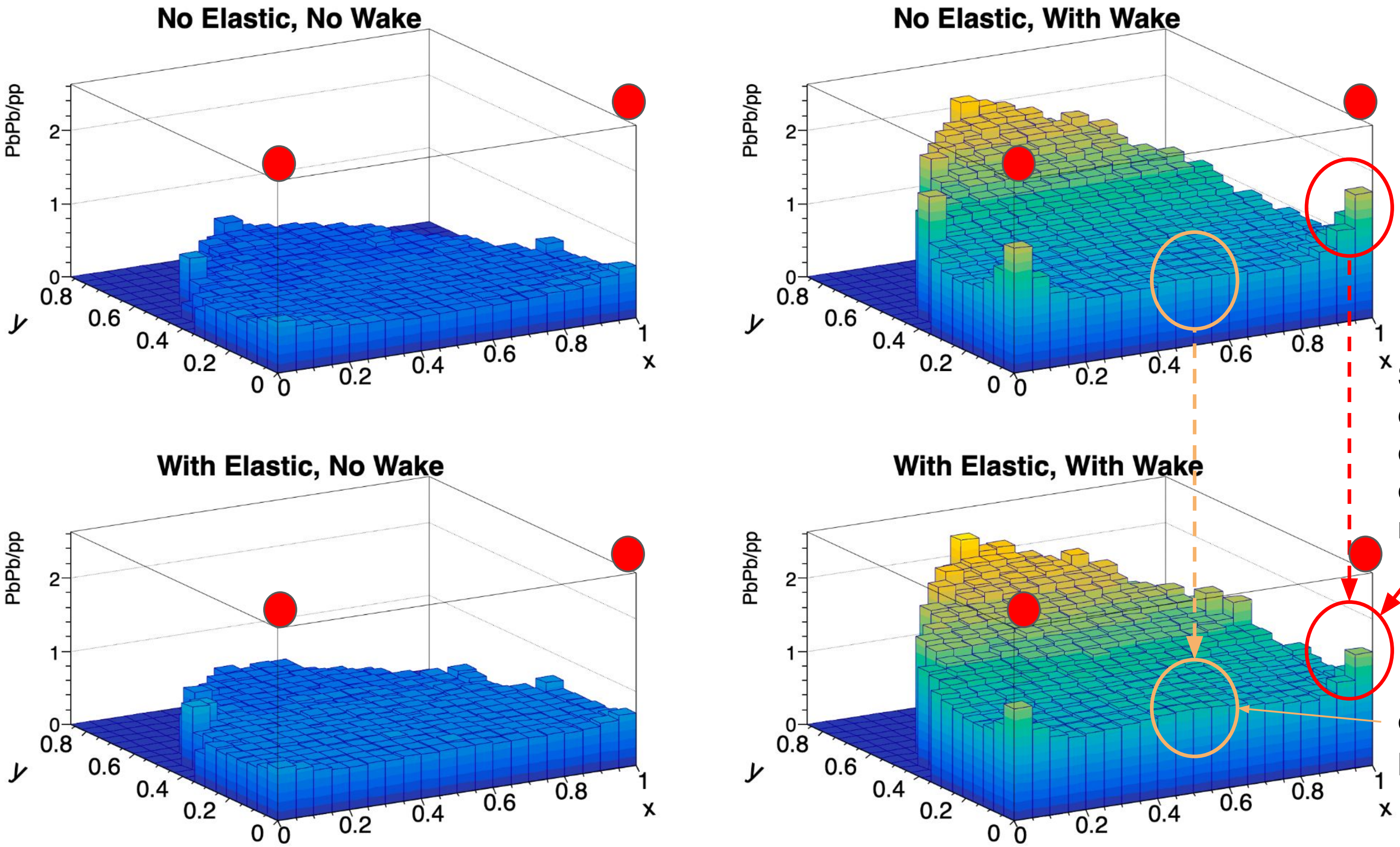
What if we include elastic scattering?

How Do Elastic Scatterings Modify The Wake?



Pb+Pb, 5.02 TeV, 0-5%

Anti k_t R = 0.8 jets

140 < p_T < 240 GeV

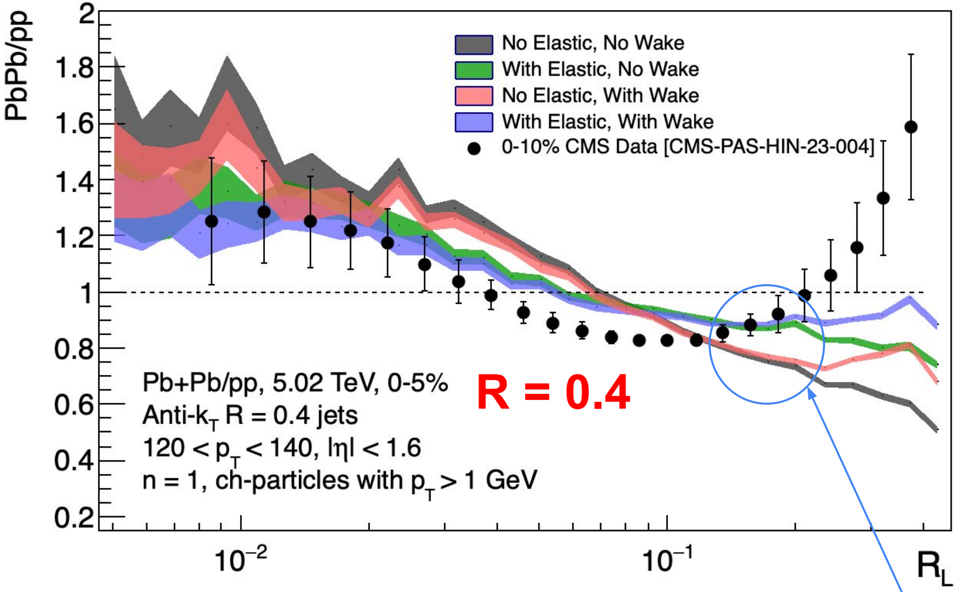
|η| < 2.0

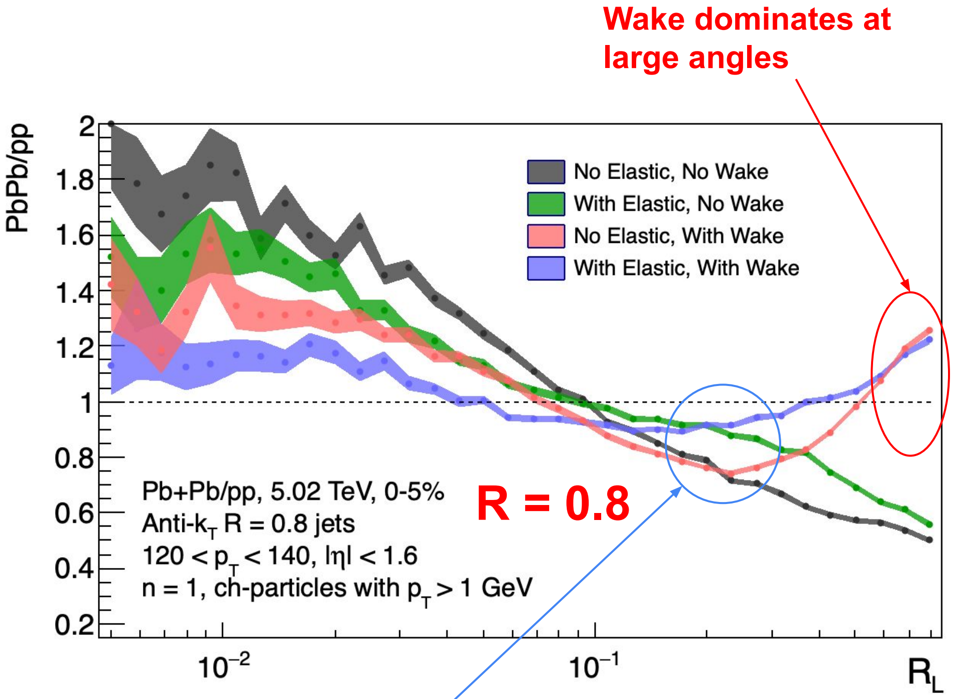
0.6 < R_L < 0.7

Slight modification to collinear enhancement due to small-angle deflections from medium kicks.

Kicked particles then occupy other areas of phase space

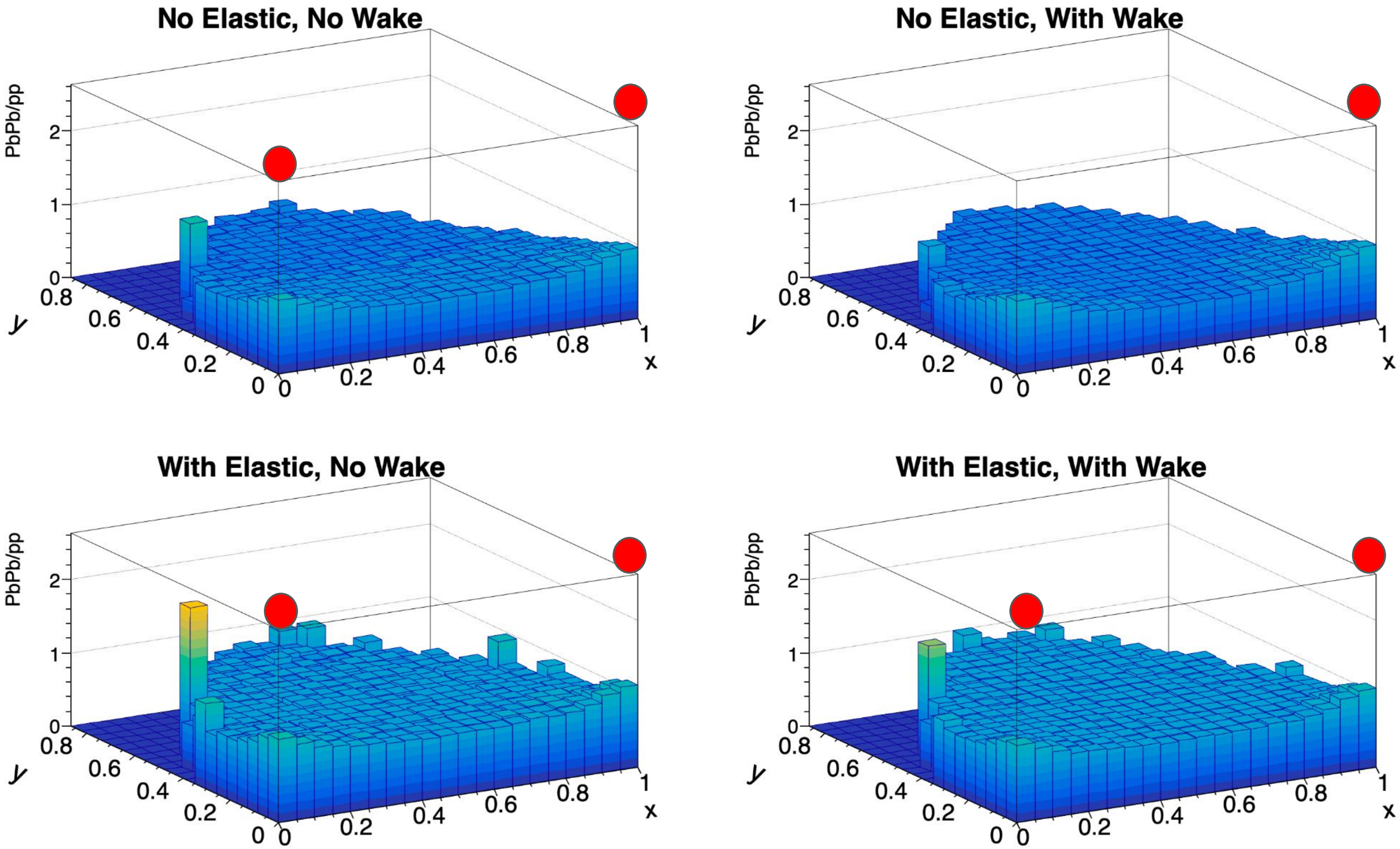
EEC For Larger Jet Radius





Maybe we can see elastic scattering effects at smaller angles?
→ EEEC at 0.2 < R_L < 0.3

0.2 < R_L < 0.3 – PbPb/pp EEEC RATIOS



Pb+Pb, 5.02 TeV, 0-5%

Anti k_t R = 0.8 jets

140 < p_T < 240 GeV

|η| < 2.0

0.2 < R_L < 0.3

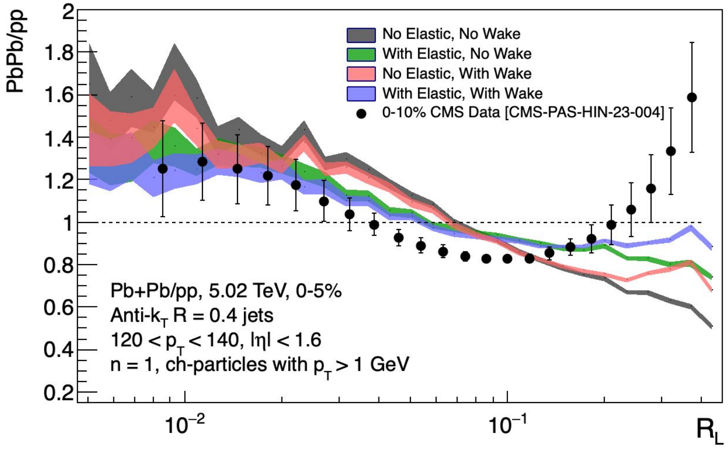
The plateau filled in by elastically scattered particles yields a larger ratio overall. This is especially true for equilateral structures

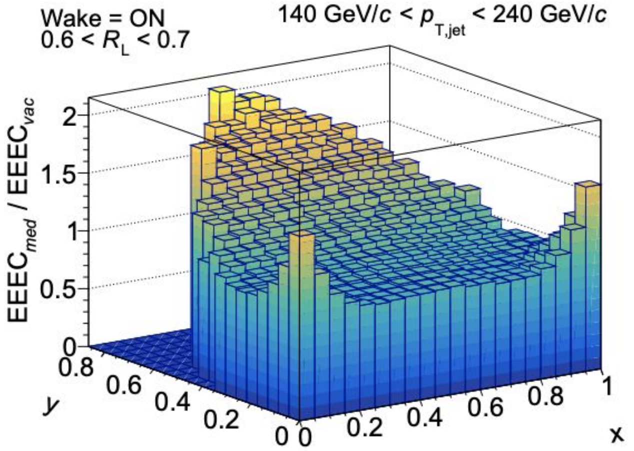
Key Takeaways

- EECs are a useful tool to **image the interplay between different physical processes** in heavy ion collisions (e.g. wakes and elastic scattering)

- The fact that **elastically scattered particles produce their own wakes** is crucial for the Hybrid Model to get closer to the CMS measurements of EECs in heavy ion collisions.

- Higher-point (> 3) EECs may offer a way to **isolate regions of phase space that are affected by each physical process** in heavy ion collisions.





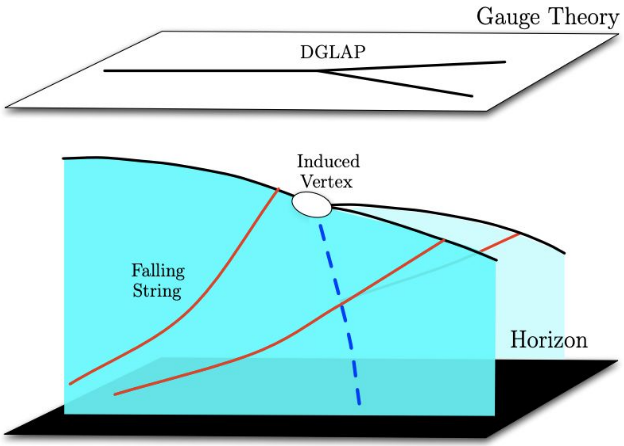
10.1007/JHEP12(2024)073 [Bossi, et al.]

BACKUP

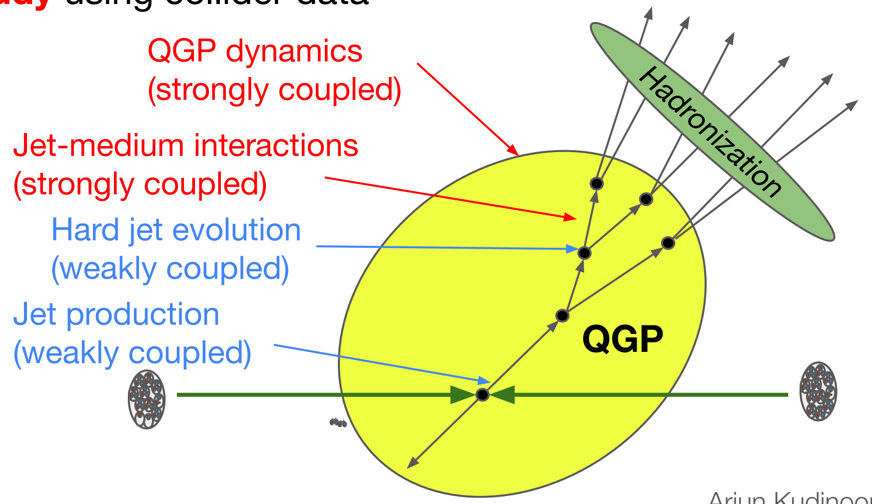
Hybrid Model Workflow

- Treat weakly coupled physics perturbatively
- Treat strongly coupled processes using AdS/CFT
  - Find the stringy gravity dual of ~~QCD~~ **N=4 SYM**
  - Describe your particles in using strings that hang from the boundary theory into the bulk spacetime
  - Calculate the observables you desire (energy loss, momenta, etc.)
- Monte Carlo simulations of heavy ion collisions
  - Feed in energy loss calculations for light quarks and gluons from above
  - Run the simulation and manipulate the output data to calculate **observables that experimentalists can study** using collider data

Difficult calculations in strongly coupled gauge theories may be solved in their more tractable weakly coupled gravitational dual.



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



QCD vs. $\mathcal{N}=4\ SU(N_c)$ SYM Theory

Use an $\mathcal{N}=4\ SU(N_c)$ SYM theory instead! The hot strongly coupled liquid phases of $\mathcal{N}=4\ SU(N_c)$ 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).

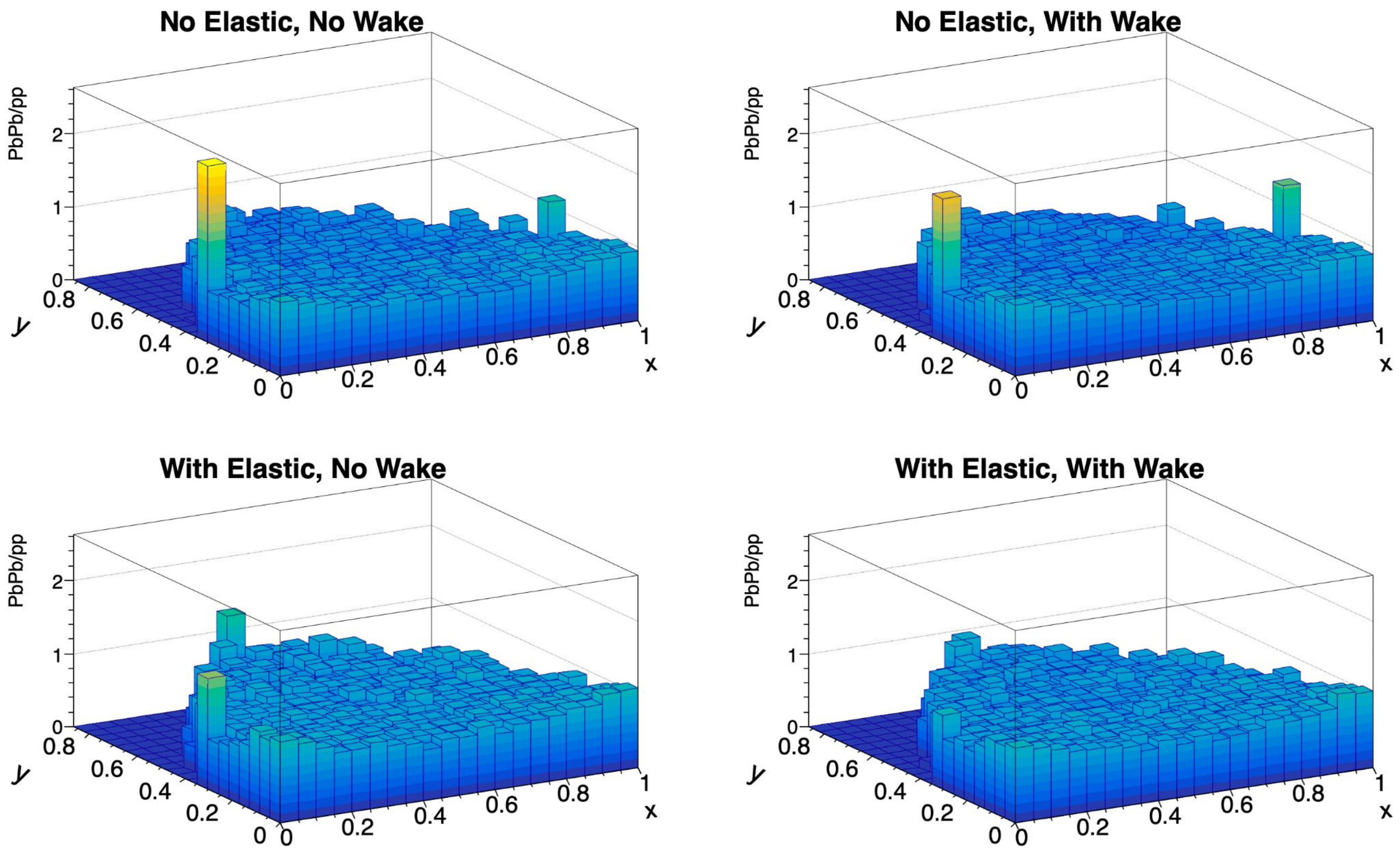
Differences between QCD and $\mathcal{N}=4$ SYM include

- $N_c=3$ 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

So, insights from hybrid model calculations in $\mathcal{N}=4$ SYM are treated qualitatively.

- $\mathcal{N}=4\ SU(N_c)$ SYM theory $\longleftrightarrow$ IIB string theory in $AdS_5 \times S_5$
  - Cast particles as strings hanging from the 4-dimensional boundary into the 5-dimensional AdS bulk spacetime
  - Calculate observables of interest (ex: energy loss)

CMS Jets | $0.15 < R_L < 0.2$ | PbPb/pp EEEC Ratios



Pb+Pb, 5.02 TeV, 0-5%

Anti k_t R = 0.4 jets

$120 < p_T < 200$ GeV

$|\eta| < 1.6$

Using only charged particle tracks with $p_T > 1$ GeV

$0.15 < R_L < 0.2$