Imaging Jet Energy Loss Using Substructure Observables

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OUTLINE

✅ **TOPIC 0.1:** The Hybrid Strong/Weak Coupling Model of Heavy Ion Collisions
✅ **TOPIC 0.2:** Effects of the Wake on 3-point Energy Correlators

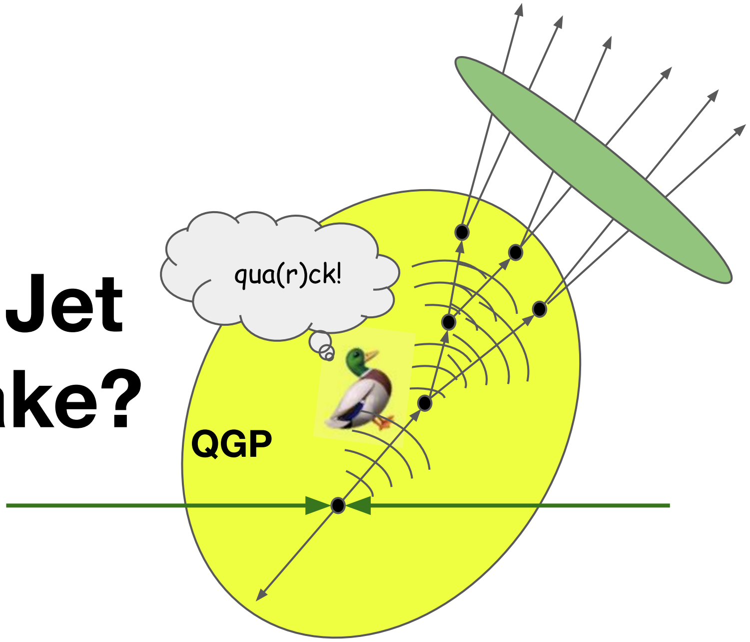
Imaging the Wake

TOPIC 1: Visualizing jet-wakes and their structure using jet shape observables
TOPIC 2: Understanding the effects of the Wake and Moliere scattering on EECs

Probing the QGP Resolution Length

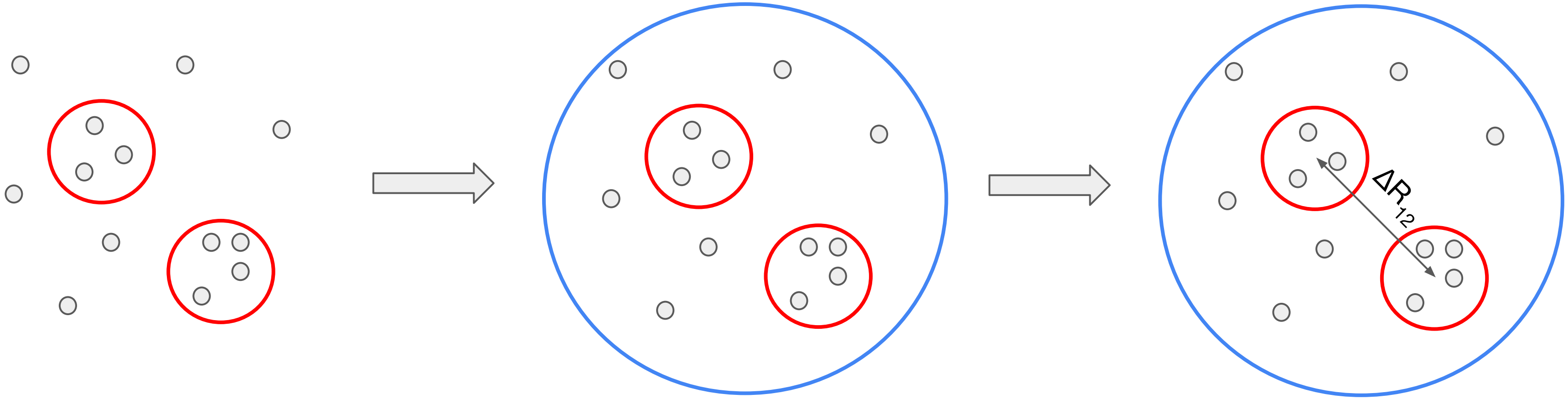
TOPIC 3: Probing the resolution length of QGP using large-radius jet suppression

TOPIC 1
How does the Structure of a Jet Shape the Structure of its Wake?



USING JET SUBSTRUCTURE AS A PROBE OF L_{RES}

Look at RE-clustered jets introduced by ATLAS at QM 2019, arXiv: 2301.05606, shown in **Martin Rybar's talk @ Hard Probes 2024**



Anti-k_t R = 0.2 jets
$p_T > 35$ GeV, $|\eta| < 3.0$

Recluster R = 0.2 jets into
anti-k_t R = 2.0 jets
$p_T > 50$ GeV, $|y| < 2.0$

Recluster with k_t-algorithm
to obtain ΔR_{12}

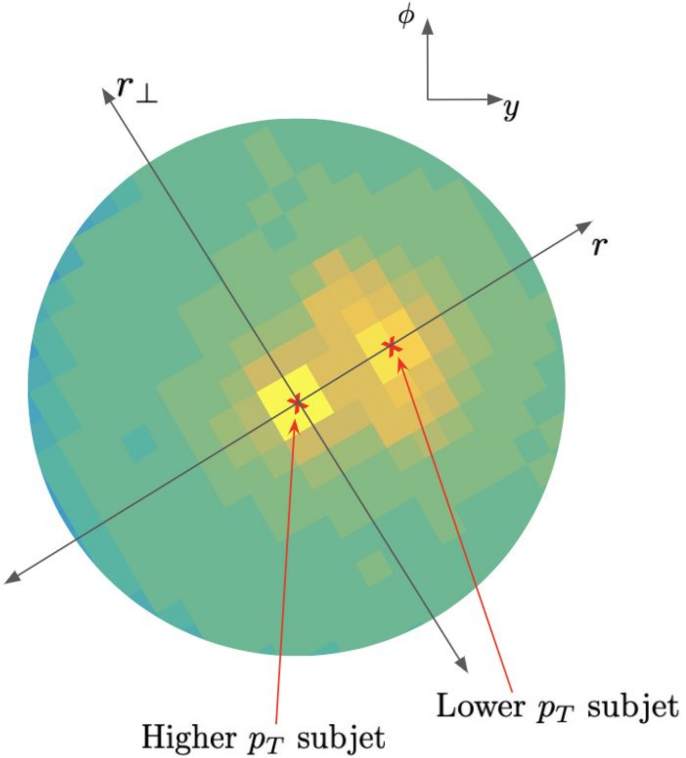
- $\Delta R_{12} = [\, (\Delta y_{12})^2 + (\Delta \phi_{12})^2 \,]^{½}$ = separation between the two constituents in the penultimate k_t-clustering step
- Reclustered R = 1.0 jet with two R = 0.2 subjets ⇒ ΔR_{12} = angular separation between the two subjets

A NEW JET SHAPE OBSERVABLE

- Simplest multi-subjet case – **two subjets**
- Restrict to **gamma-jet** analysis
  → Photons dont produce wakes
  → No contamination in jets from negative wakes

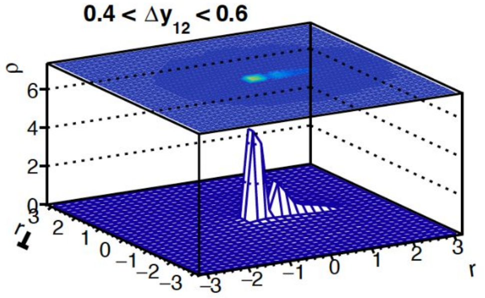
$$\rho^{2d}(r, r_\perp) = \frac{1}{\Delta y_{12}} \frac{1}{\Delta r} \frac{1}{\Delta r_\perp} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \left(\frac{1}{p_T^{\text{jet}}} \left[p_T \right]_{(r-\frac{\Delta r}{2}, r_\perp - \frac{\Delta r_\perp}{2})}^{(r+\frac{\Delta r}{2}, r_\perp + \frac{\Delta r_\perp}{2})} \right)$$

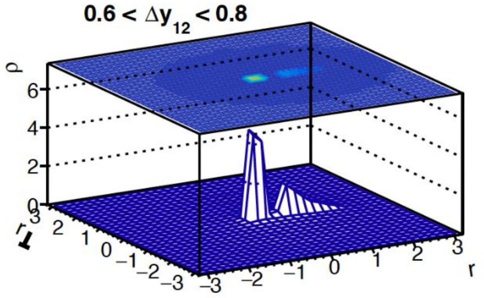
Our jet shape sums over **all hadrons within an R = 2.0 radius** of the reclustered R = 2.0 jet-axis, not just the hadrons inside the R = 0.2 skinny subjets.

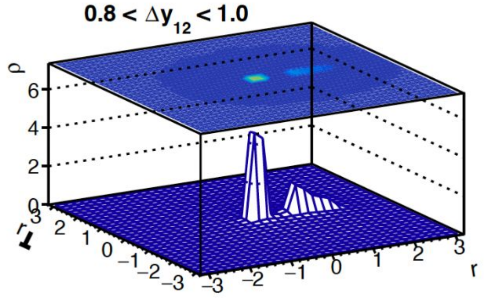


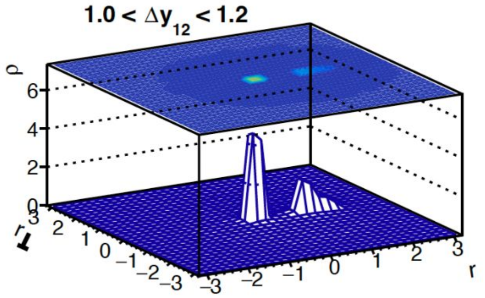
- **Photon selection and isolation criteria:**
  - $p_T^\gamma > 100$ GeV and $|\eta^\gamma| < 1.44$
  - $\Sigma E_T < 5$ GeV around r = 0.4 of the photon
- **R = 0.2 subjets:** $p_T > 35$ GeV, $|\eta| < 3.0$, $\Delta\phi_{\gamma,\text{ subjet}} > 2\pi/3$
- **R = 2.0 jets:** $|y| < 2.0$, $50 < p_T < 1000$ GeV, 2 subjets

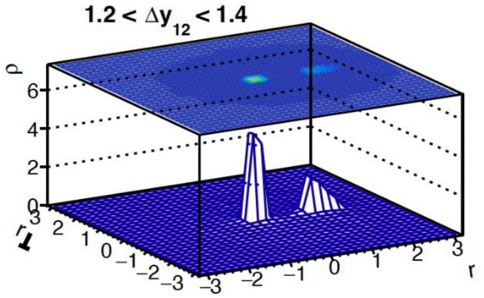
Pb+Pb: FULL JET SHAPE

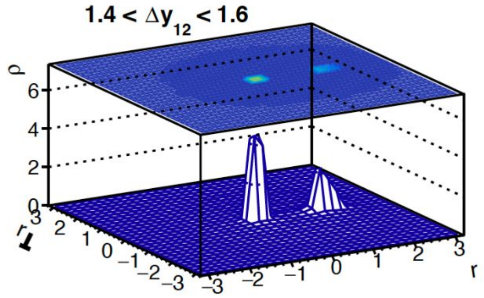


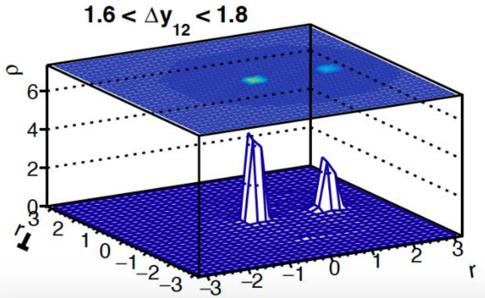


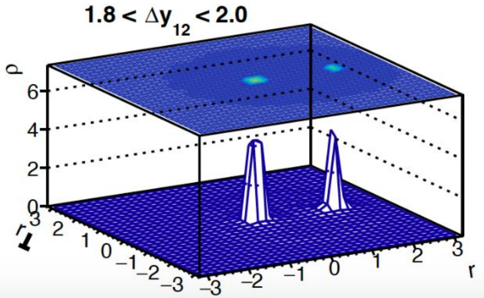








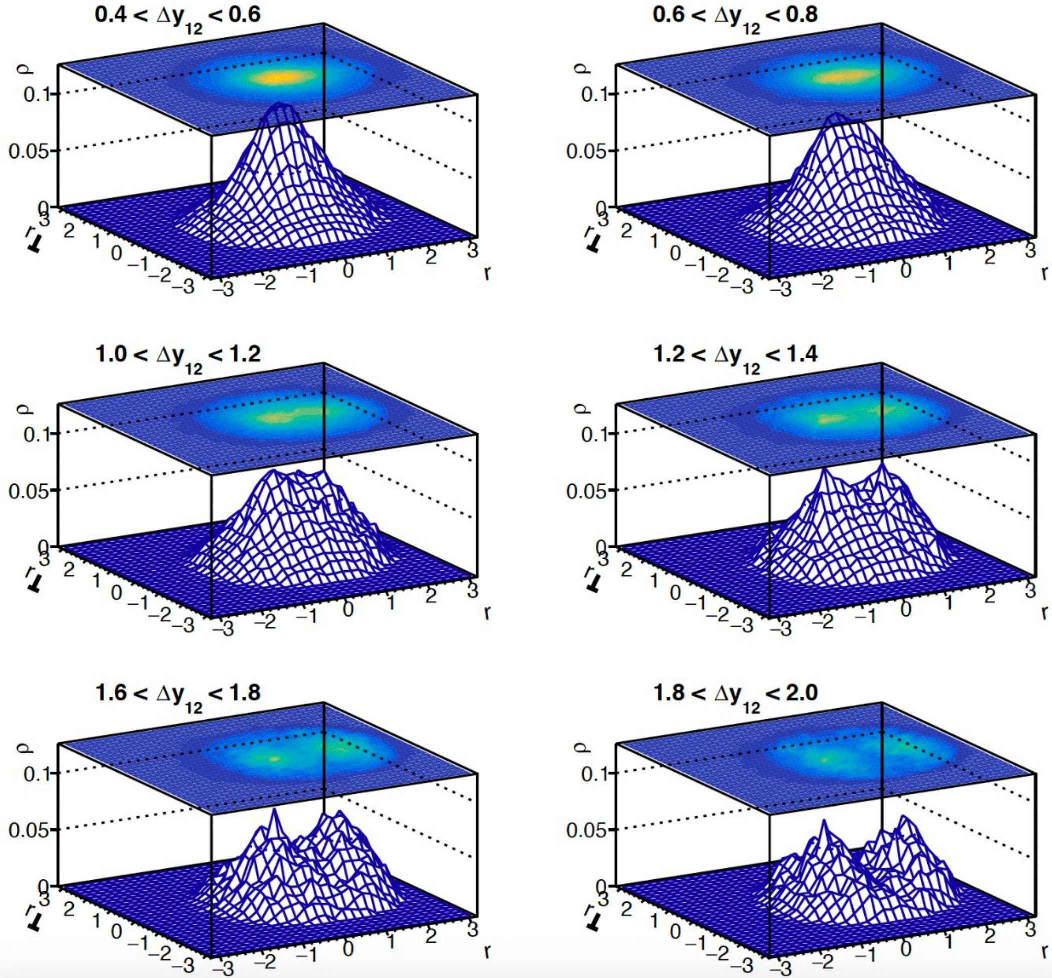




PbPb, 5.02 TeV, 0-5%

- **Reclustered R = 2.0 jets with two γ-tagged R = 0.2 subjets with $p_T^{subjet} > 35$ GeV**
- **$50 < p_T^{jet} < 1000$ GeV, $|y^{jet}| < 2.0$**
- **$p_T^{\gamma} > 100$ GeV**

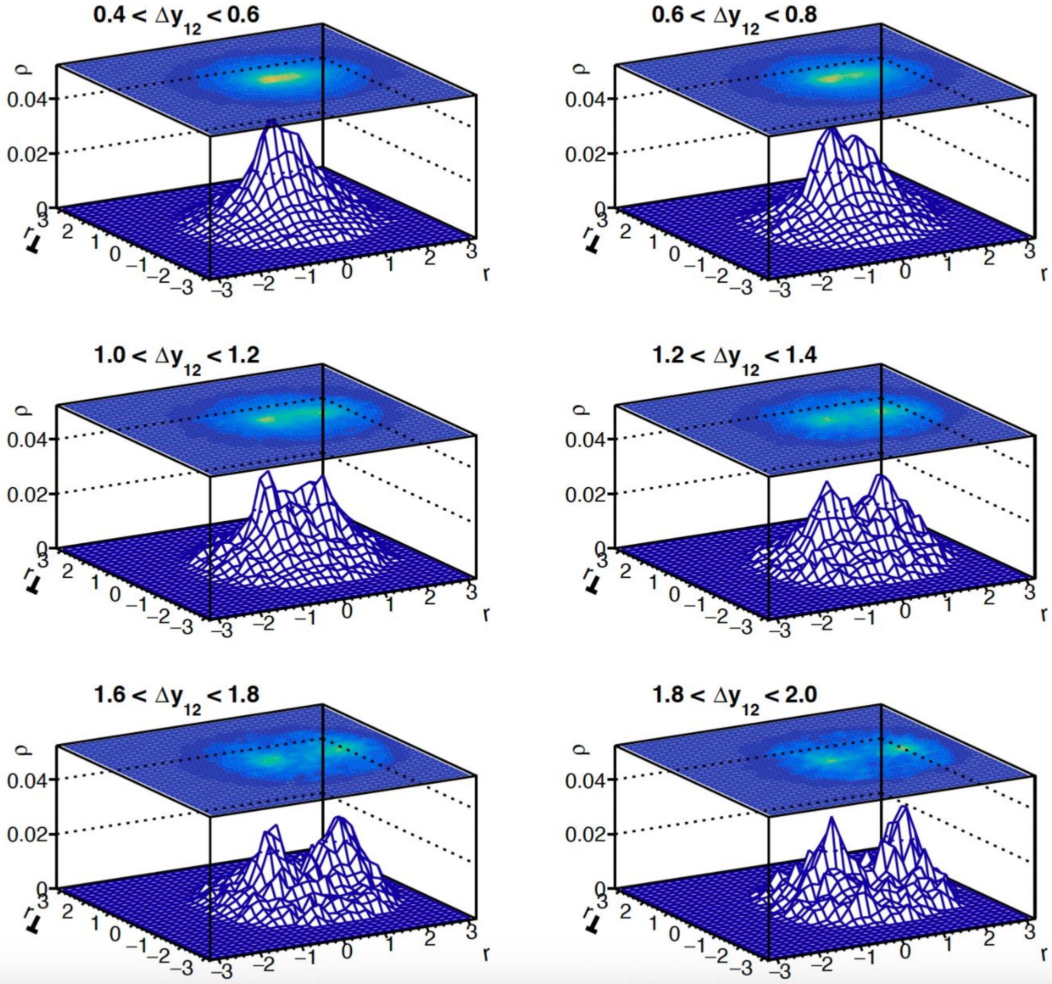
Pb+Pb: WAKE SHAPE



For closely-separated subjets ($\Delta y_{12} < 1.0$), there is a single wake produced by 2 hard structures (the subjets). **Two distinct wakes are visibly produced only when the subjets are far-separated** (around $\Delta y_{12} > 1.2$)!

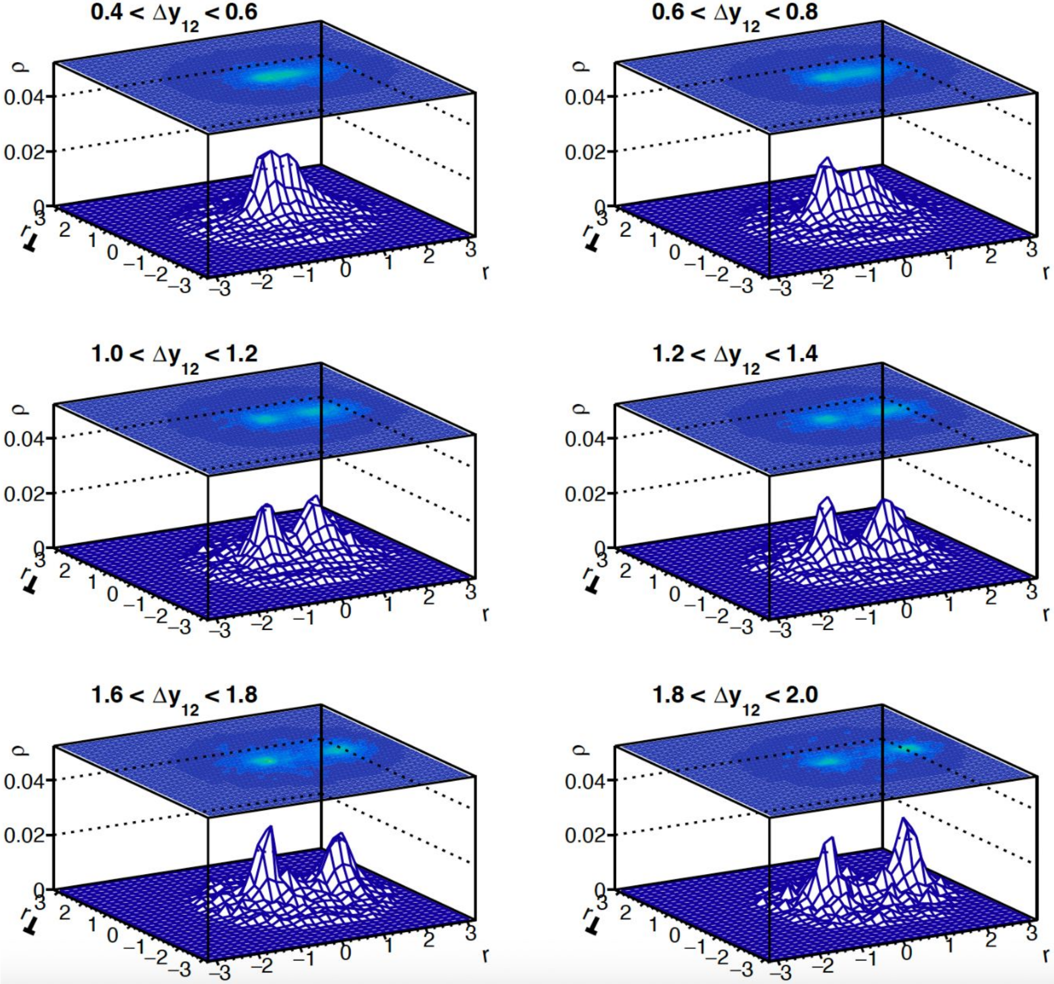
How can we see this in experiments?

Pb+Pb: SHAPE OF WAKE + NONWAKE HADRONS WITH $0.7 < p_T < 1.0$ GeV



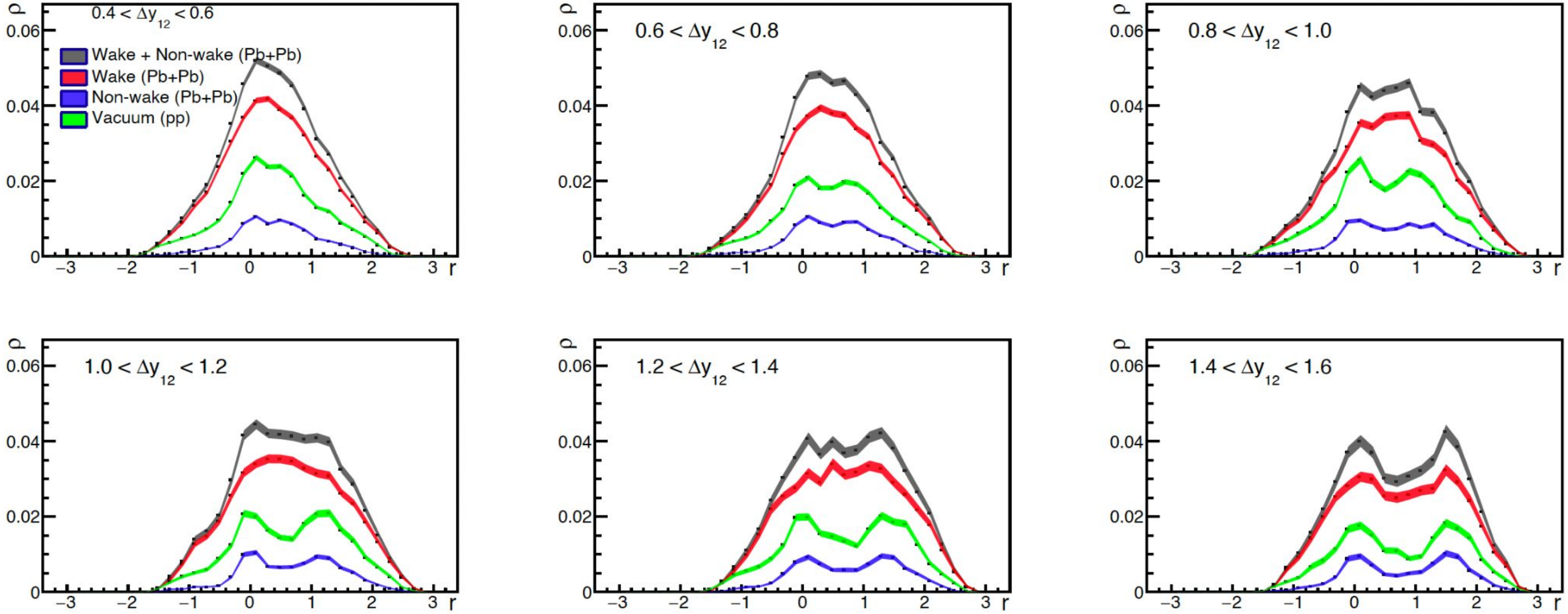
Only a single-pronged structure is visible at low angular separation even when low-p_T non-wake hadrons are included. However, two-pronged structures appear at lower angles than when we restrict to using only hadrons belonging to the wake.

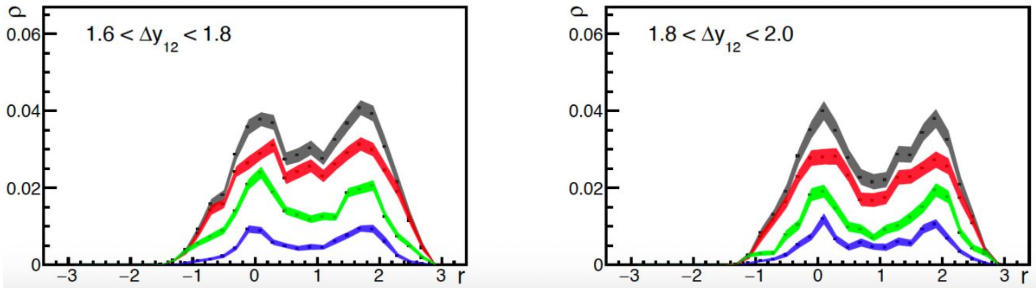
VACUUM (pp): SHAPE OF HADRONS WITH $0.7 < p_T < 1.0$ GeV

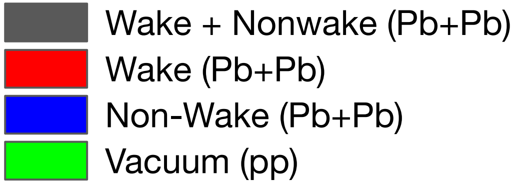


In the absence of the medium, sharp two-pronged structures appear at much lower angles than when the medium, and thereby the wakes in it, are present.

PROJECTING THE SHAPES ONTO THE r-AXIS: HADRONS WITH $0.7 < p_T < 1.0$ GeV







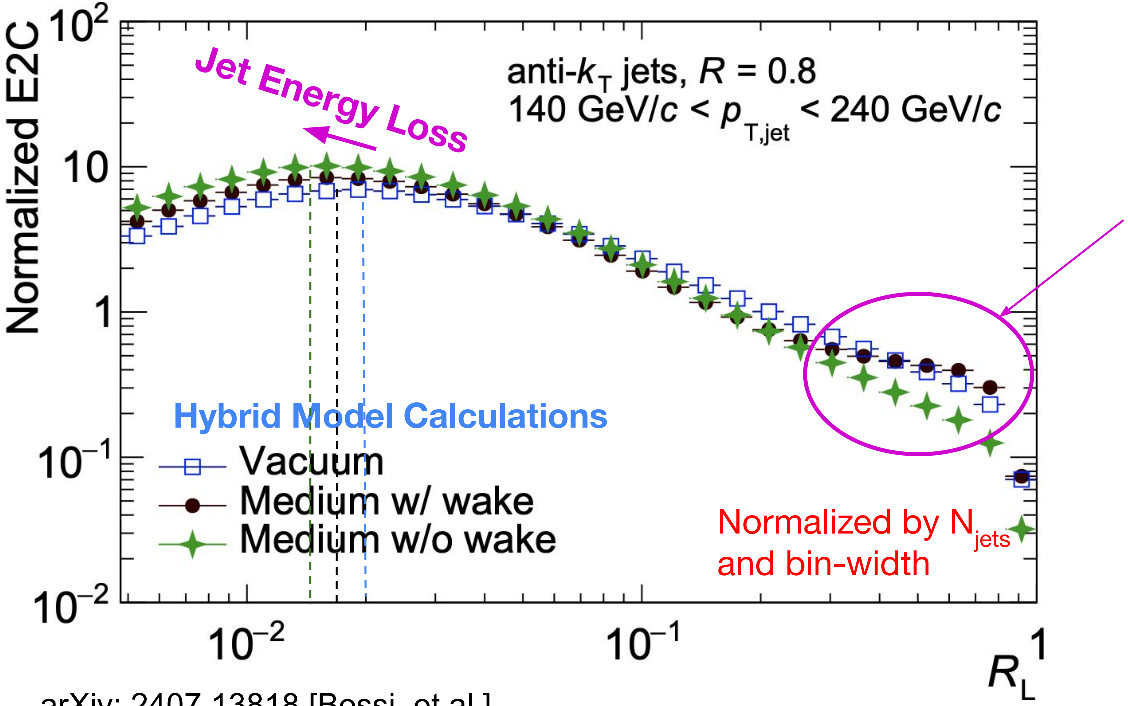
The wake dominates this kinematic region

⇒ We can literally SEE the substructure of large-radius jet-wakes!

TOPIC 2
Imaging the Wake AND Elastic Scattering Using EECs

TWO-POINT ENERGY CORRELATORS

$$\frac{d\Sigma}{d\theta} = \int d\vec{n}_{1,2} \frac{\langle \epsilon(\vec{n}_1)\epsilon(\vec{n}_2)\rangle}{Q^2} \delta(\vec{n}_1 \cdot \vec{n}_2 - \cos(\theta)) \Rightarrow \mathrm{EEC}(R_L) = \frac{1}{\aleph} \frac{d\left(\Sigma_{\mathrm{jets}} \Sigma_{i \neq j} \frac{p_{T,i} p_{T,j}}{(p_T^{\mathrm{jet}})^2}\right)}{dR_L}$$



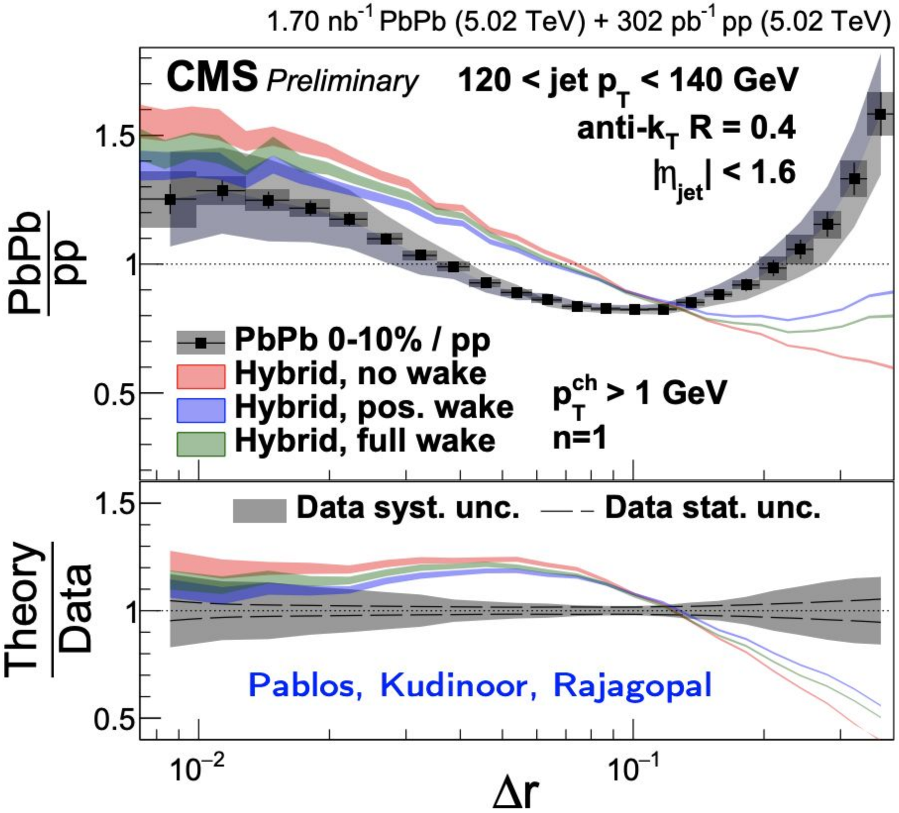
The wake enhances the EEC at large angles

arXiv: 2407.13818 [Bossi, et al.]

+ Ananya Rai's Poster @ Hard Probes 2024

OUR PREDICTIONS VS. CMS DATA

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



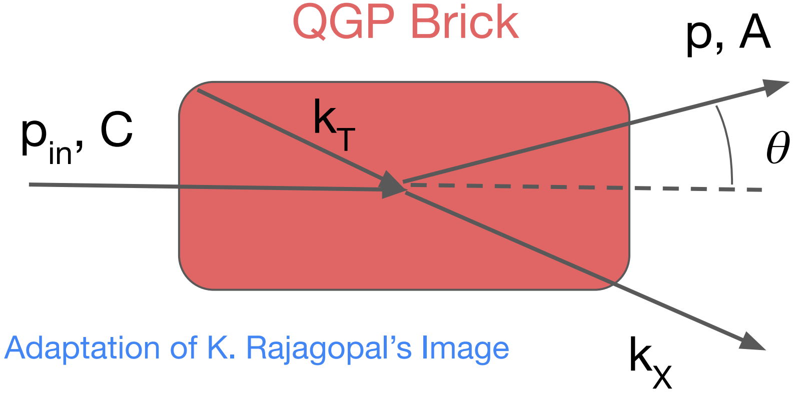
$$\mathrm{EEC}(R_L) = \frac{1}{(\Sigma_{\mathrm{jets}}\Sigma_{i\neq j}(p_{T,i})^n(p_{T,j})^n)} \frac{d\,(\Sigma_{\mathrm{jets}}\Sigma_{i\neq j}(p_{T,i})^n(p_{T,j})^n)}{dR_L}$$

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!**

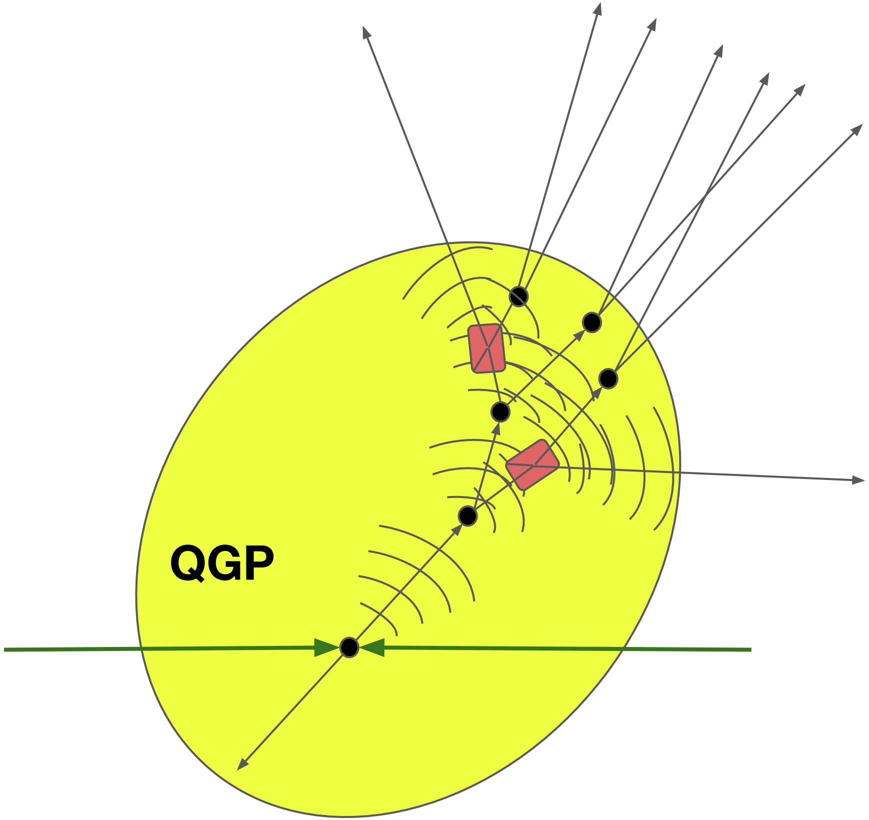
* Self-normalized, charged track EECs

ELASTIC SCATTERING



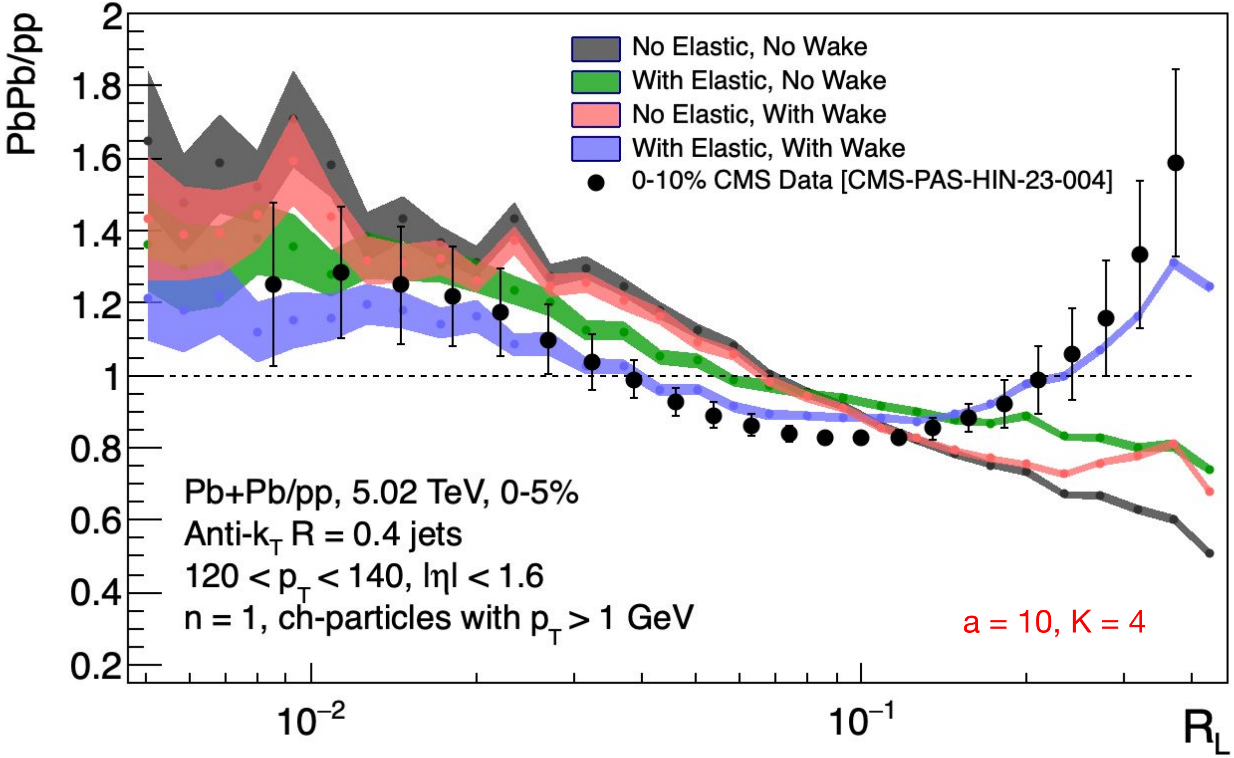
Adaptation of K. Rajagopal's Image

- 2→2 medium kicks, which can probe the particle constituents of QGP
- Sufficiently high momentum exchanges should be perturbative
- Recoiling particles k_X also lose energy and produce wakes
- Thermal particles k_T are removed from the medium (aka "holes")



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

EFFECT ON EEC RATIOS: n = 1, p_T^{ch} > 1 GeV

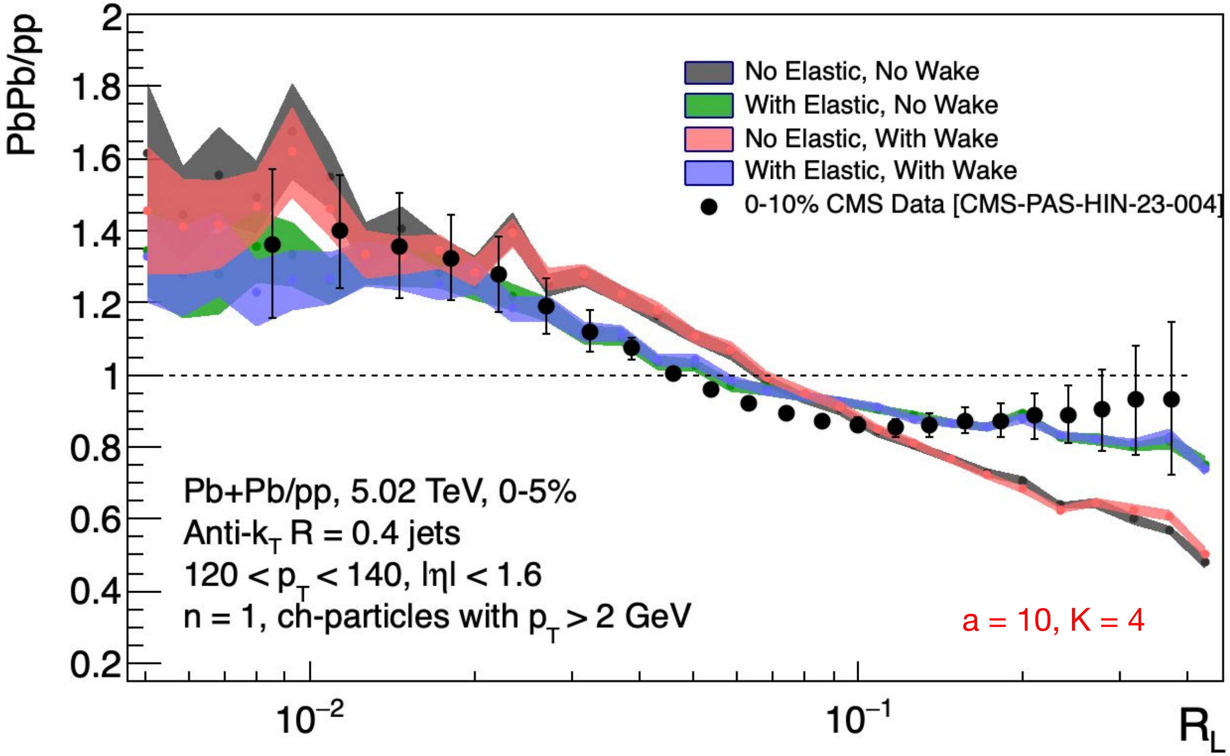


We need both elastic scattering and the wake for the model to agree with the data.

Crucial feature: Both partons involved in an elastic scattering produce their own wakes!

* Self-normalized, charged track EECs

EFFECT ON EEC RATIOS: n = 1, p_T^{ch} > 2 GeV



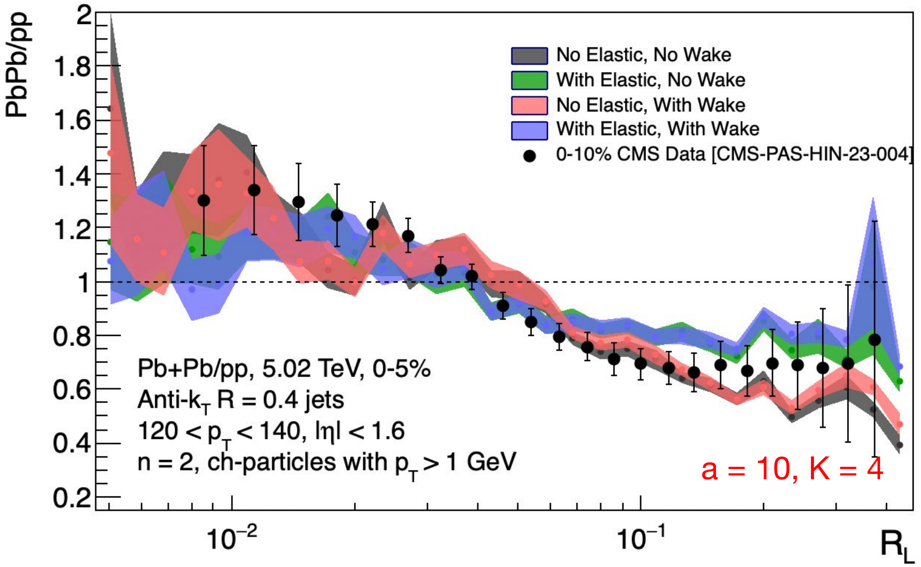
Wake is effectively removed by this track cut.

Structure resulting from elastic scatterings survives.

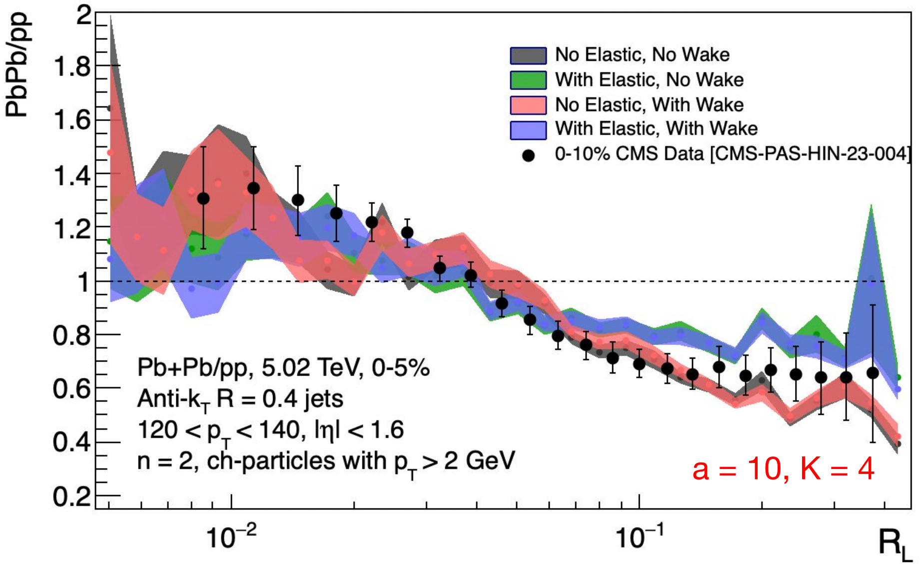
* Self-normalized, charged track EECs

EFFECT ON EEC RATIOS: 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

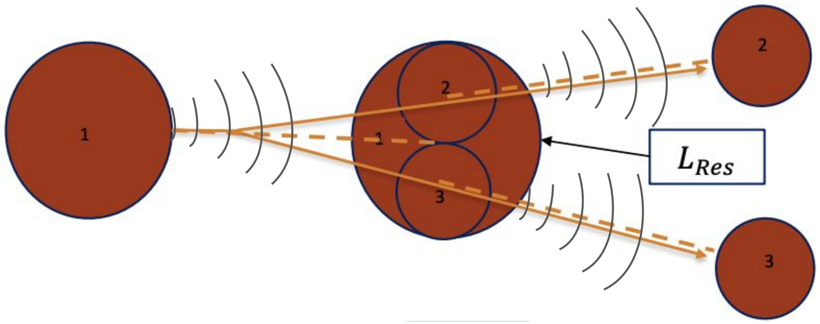
* Self-normalized, charged track EECs

TOPIC 3
Probing the Resolution Length of QGP Using Large-Radius Jet Suppression

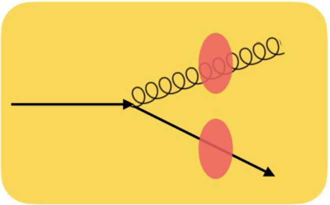
QGP RESOLUTION LENGTH

- If two partons that result from the **same splitting** are separated by a length smaller than L_{res}, then they will lose energy to the plasma – and produce a wake – as if they were a single parton.

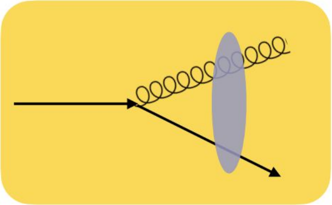
- In our implementation, L_{res} only applies to partons within the same parton shower. Two partons belonging to showers that were **initiated by two different partons** are treated as resolved structures regardless of their separation.



arXiv: 1707.05245 [Hulcher, Pablos, Rajagopal]



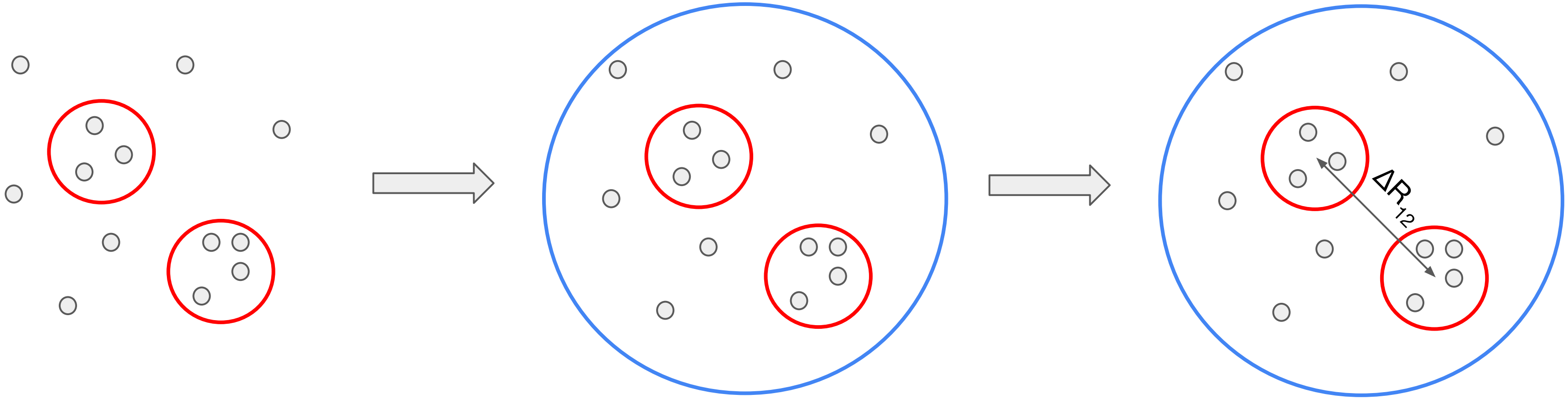
L_{res} = 0: The medium resolves splitting immediately after a parton fragments
⇒ fully incoherent energy loss



L_{res} = ∞: The medium never resolves splittings
⇒ fully coherent energy loss

USING JET SUBSTRUCTURE AS A PROBE OF L_{RES}

Now look at re-clustered R = 1.0 inclusive jets with multiple subjets.
(As opposed to re-clustered R = 2.0 jets with only two gamma-subjets)



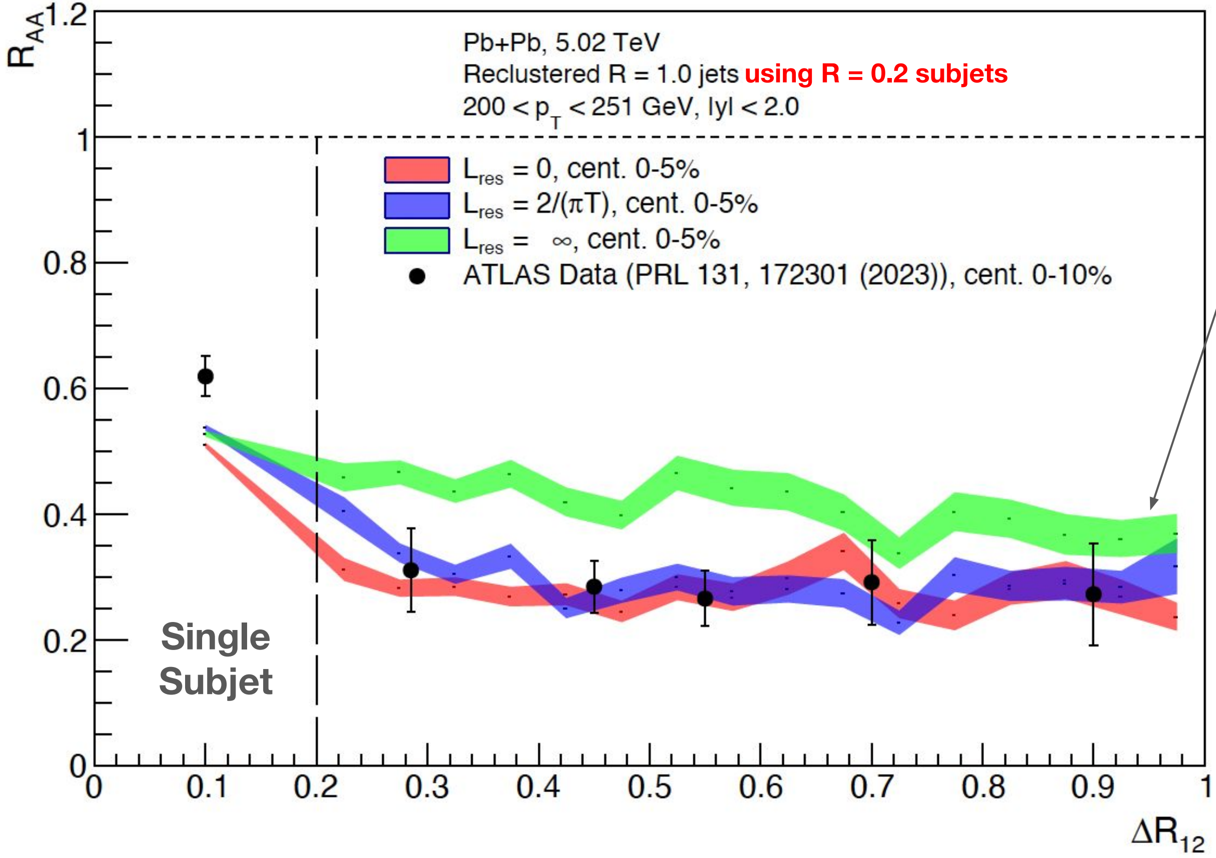
Anti-k_t R = 0.2 jets
$p_T > 35$ GeV, $|\eta| < 3.0$

Recluster R = 0.2 jets into
anti-k_t R = 1.0 jets
$p_T > 158$ GeV, $|y| < 2.0$

Recluster with k_t-algorithm
to obtain ΔR_{12}

- $\Delta R_{12} = [\,(\Delta y_{12})^2 + (\Delta \phi_{12})^2\,]^{1/2}$ = separation between the two constituents in the penultimate k_t-clustering step
- Reclustered R = 1.0 jet with two R = 0.2 subjets ⇒ ΔR_{12} = angular separation between the two subjets

LARGE-RADIUS JET SUPPRESSION AS A PROBE OF L_{RES}

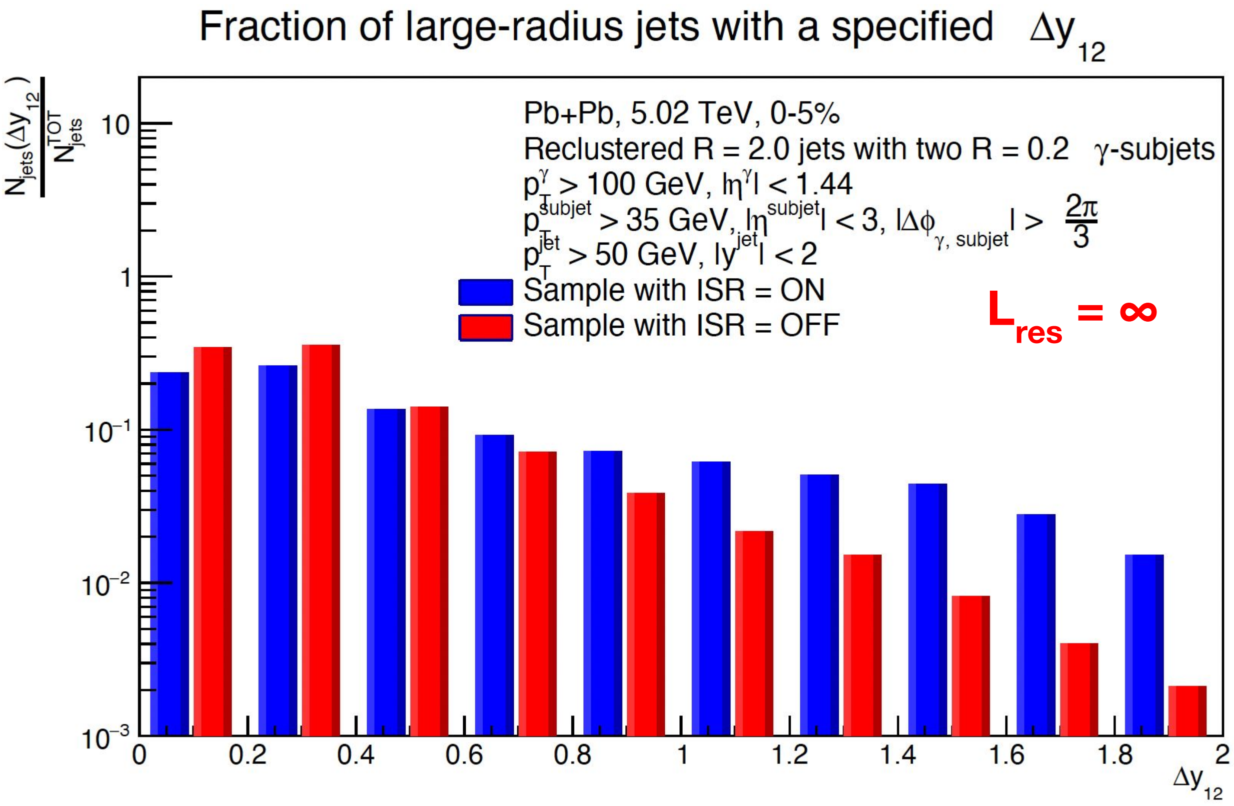


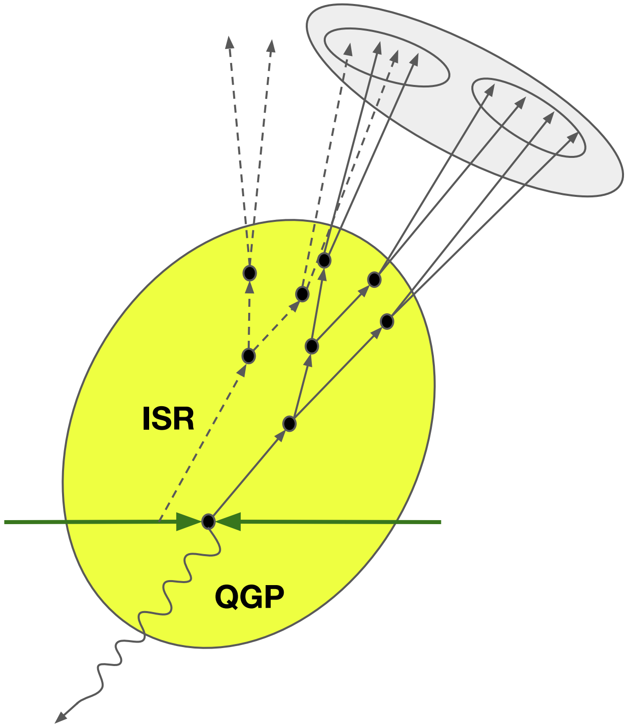
$L_{res} = \infty$: **Disfavored** by data. Partons within each shower are unresolved, and so R_{AA} is roughly independent of ΔR_{12}.

Why is it not entirely independent of ΔR_{12}?

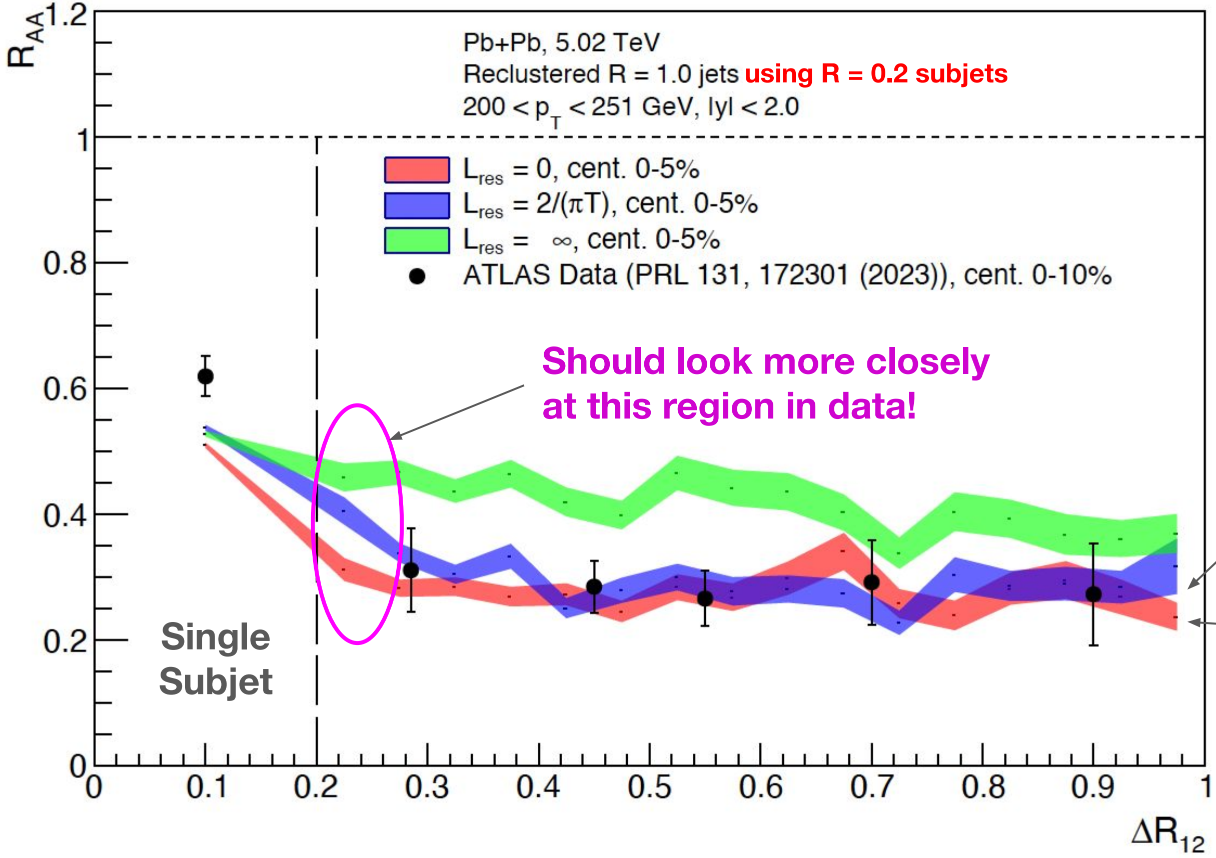
Jets with larger ΔR_{12} can contain subjets from different hard scatterings, which lose energy independently.

FARTHEST-SEPARATED SUBJETS ARE DUE TO INITIAL STATE RADIATION





LARGE-RADIUS JET SUPPRESSION AS A PROBE OF L_{RES}



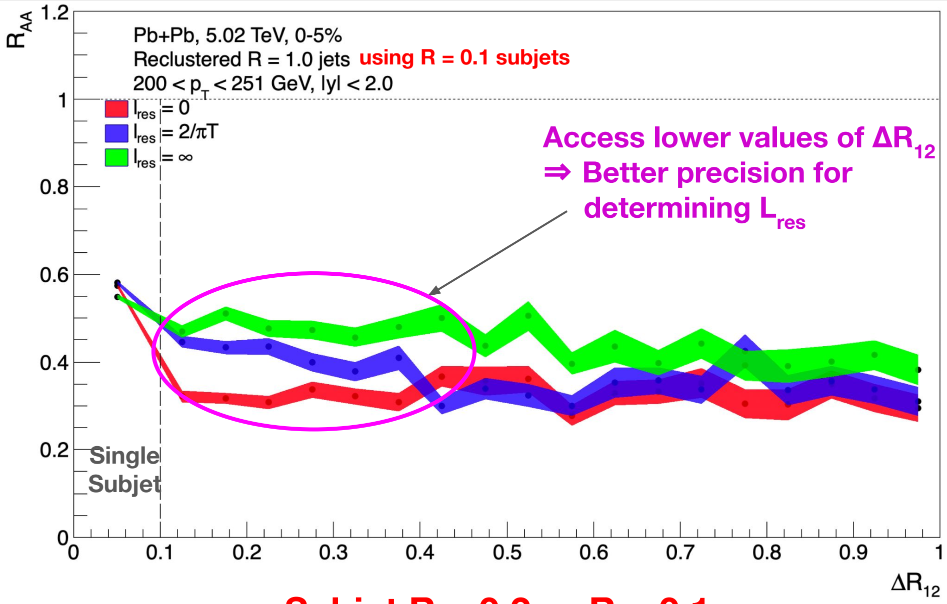
$L_{res} = 0$ and $L_{res} = 2/(\pi T)$ are **consistent** with the data.

$L_{res} = 0$ also shows constant suppression as a function of $\Delta R_{12} > 0$. Single subjets are suppressed far less than large-radius jets with multiple subjets.

MORE IDEAS

- Soft-drop suppression analysis
  → arXiv: 2405.02737 [CMS]
  → Phys. Rev. C 107 (2023) 054909 [ATLAS]
  → arXiv: 2208.13593 [Hulcher, Pablos, Rajagopal]

- Substructure dependence on dijet asymmetry
  → Au+Au data for de-clustered 0.4 jets with 0.1 subjets is already available at RHIC energies
  arXiv: 1903.12115 [Elayavalli, STAR]



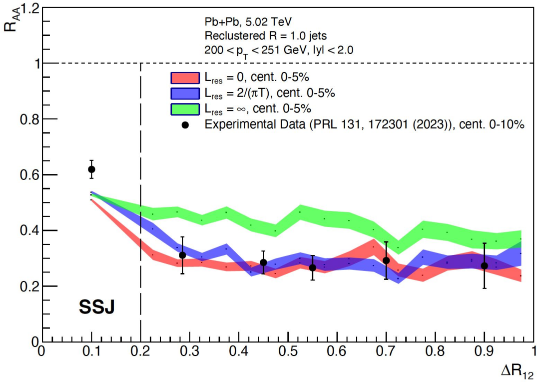
Subjet R = 0.2 → R = 0.1

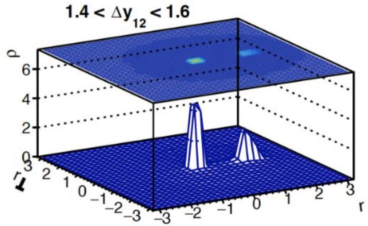
KEY TAKEAWAYS

- We **can image wake substructure** in large-radius jets in an **experimentally feasible way** using the novel jet shape observables we introduced here.

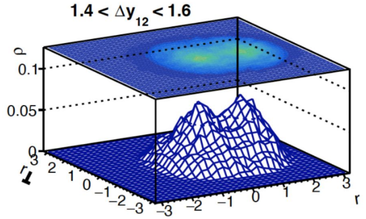
- The fact that **elastically scattered particles produce their own wakes** is crucial for explaining the Hybrid Model's agreement with the CMS measurements of EECs in heavy ion collisions.

- We confirm that **QGP resolves partons within parton showers**. We must keep the presence of ISR in mind when interpreting large-radius jet analyses with far-separated subjets.

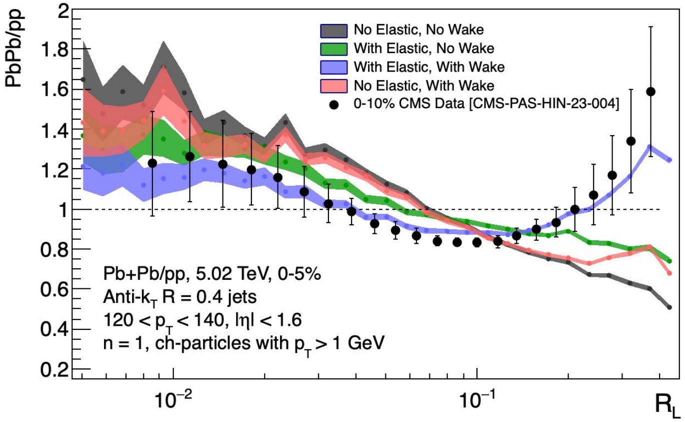




Jet Shape



Wake Shape



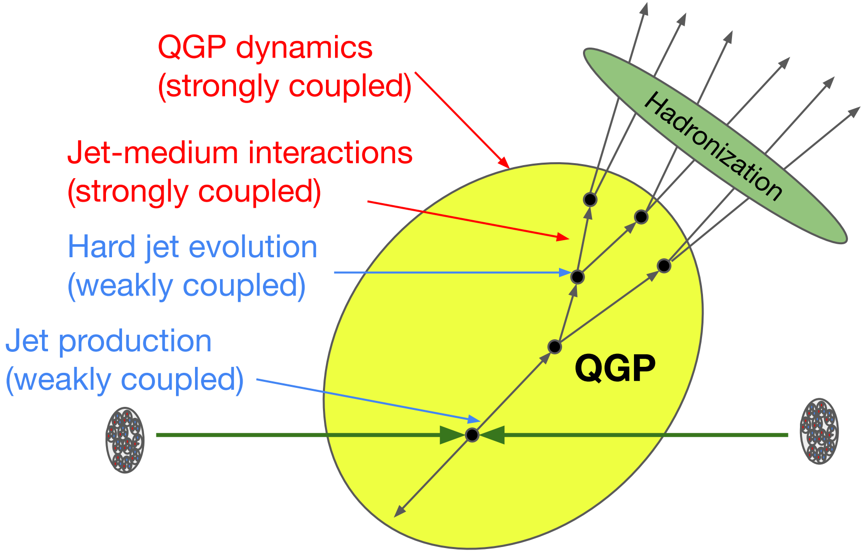
BACKUP

TOPIC 0
The Hybrid Strong/Weak Coupling Model Of Heavy Ion Collisions

STRONG/WEAK COUPLING REGIMES

The physics of jets and QGP hydrodynamics have both weakly and strongly coupled aspects.
Calculations are intractable at strong coupling using standard perturbative methods.

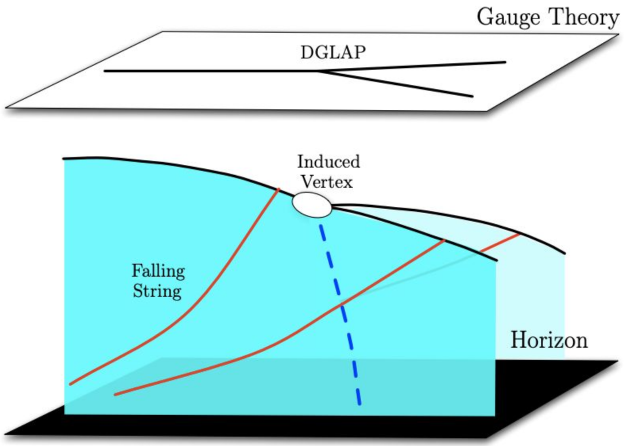
"A successful phenomenological model that describes the modifications of jets in the medium, today, must be **a hybrid model in which one can simultaneously treat the weakly coupled physics of jet production and hard jet evolution and the strongly coupled dynamics of the [QGP] medium and the soft exchanges between the jet and the medium**" (arXiv:1405.3864v3 [Casalderrey-Solana, et al.])



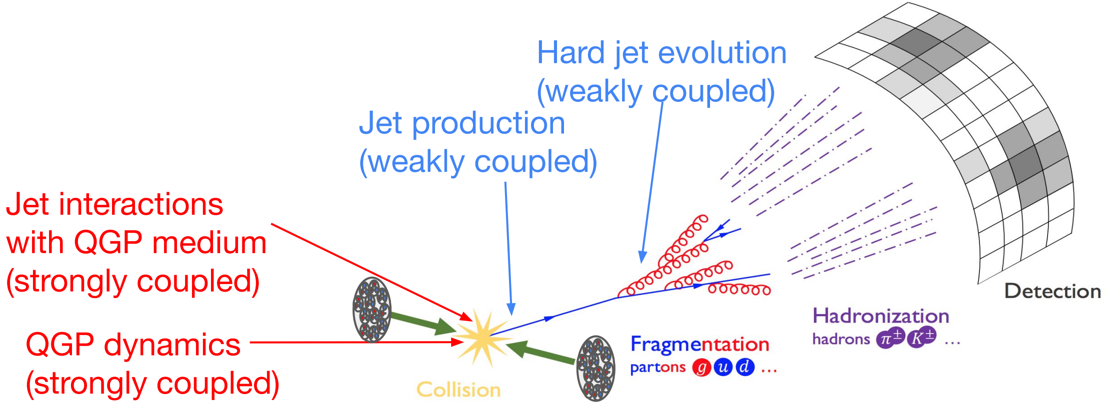
THE HYBRID STRONG/WEAK COUPLING MODEL

- 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.]



https://www.ericmetodiev.com/post/jetformation/

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)

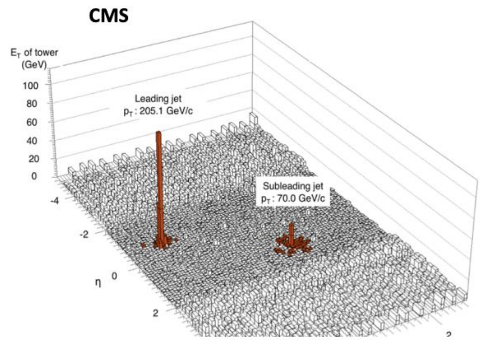
HOLOGRAPHIC PARTON ENERGY LOSS

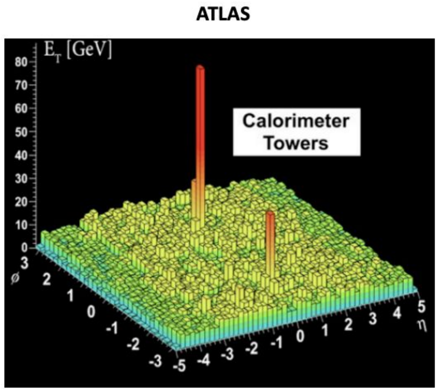
arXiv:1405.3864v3 [Casalderrey-Solana, et al.]

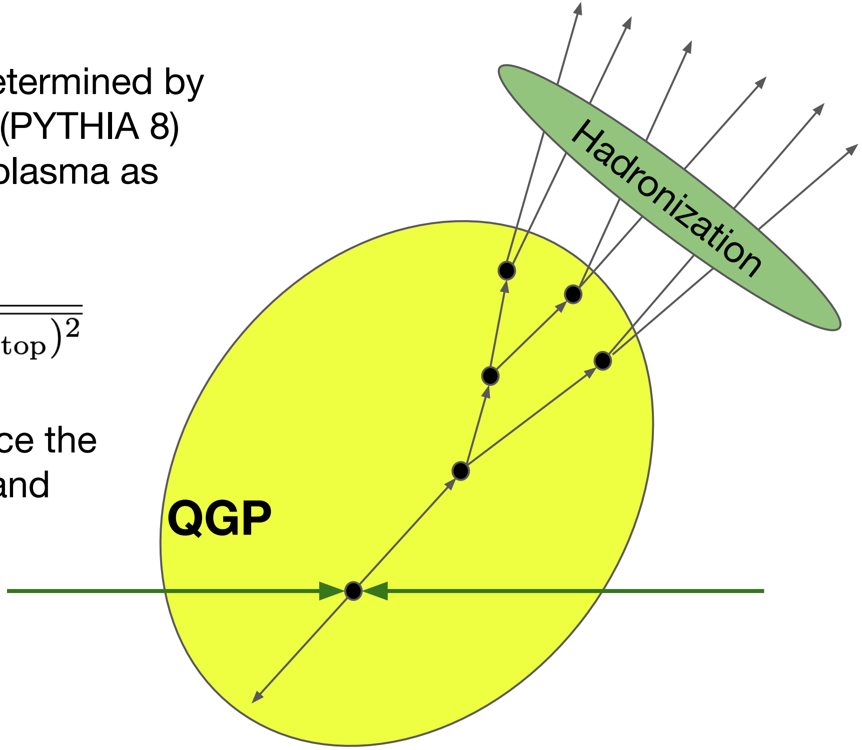
- Parton splittings that result in the jet shower are determined by the high-virtuality, perturbative, DGLAP equations (PYTHIA 8)
- Each parton loses energy to the strongly coupled plasma as determined by a holographic energy loss formula

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

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.





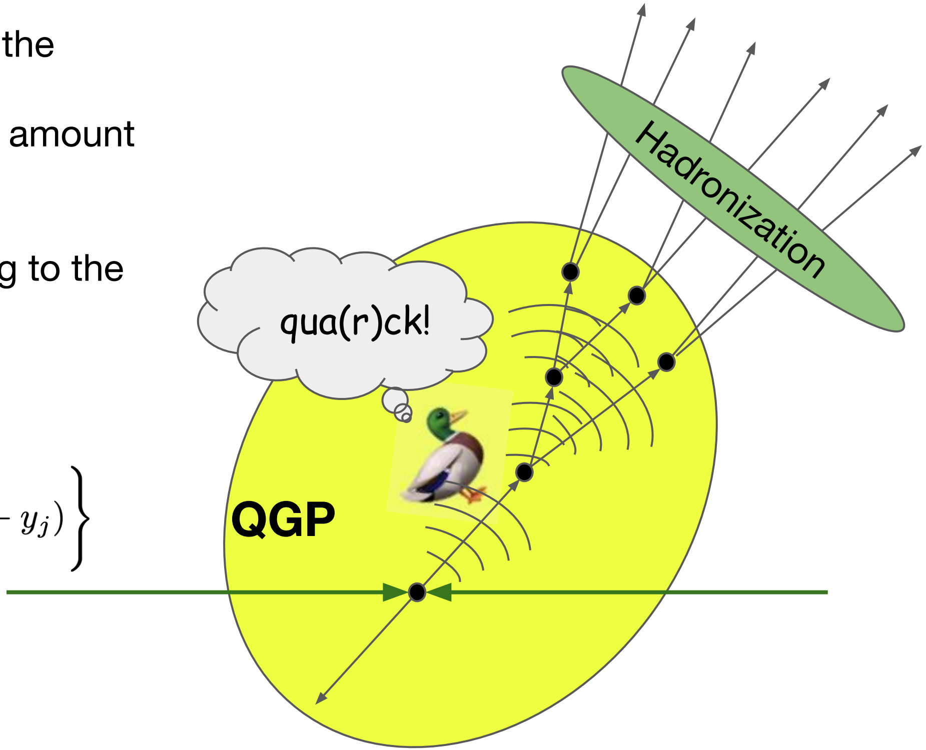


JET-INDUCED WAKES

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

- The energy lost by each parton is deposited into the plasma in the form of a wake.
- One way to think of this is that the jet pulls some amount of QGP in the direction of the jet.
- In the Hybrid Model, a wake is generated by the production of low-momentum hadrons, according to the momentum spectrum.

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

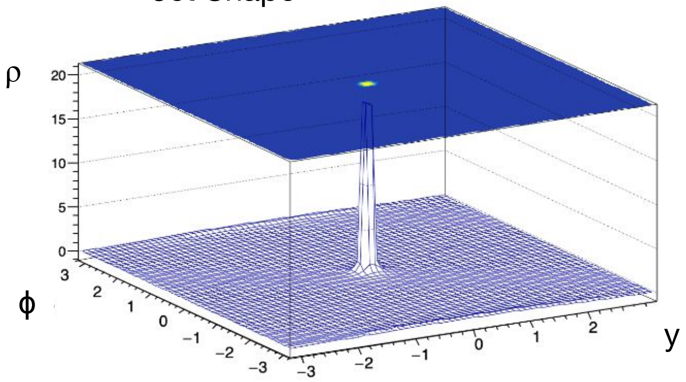


POSITIVE AND NEGATIVE WAKES

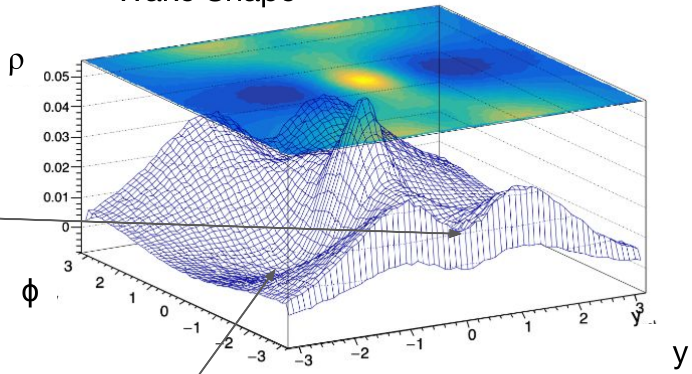
The jet pulls some amount of QGP in the direction of the jet. So, when you compare the freezeout of a QGP droplet containing a jet wake to one without, it will have:

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

Jet Shape



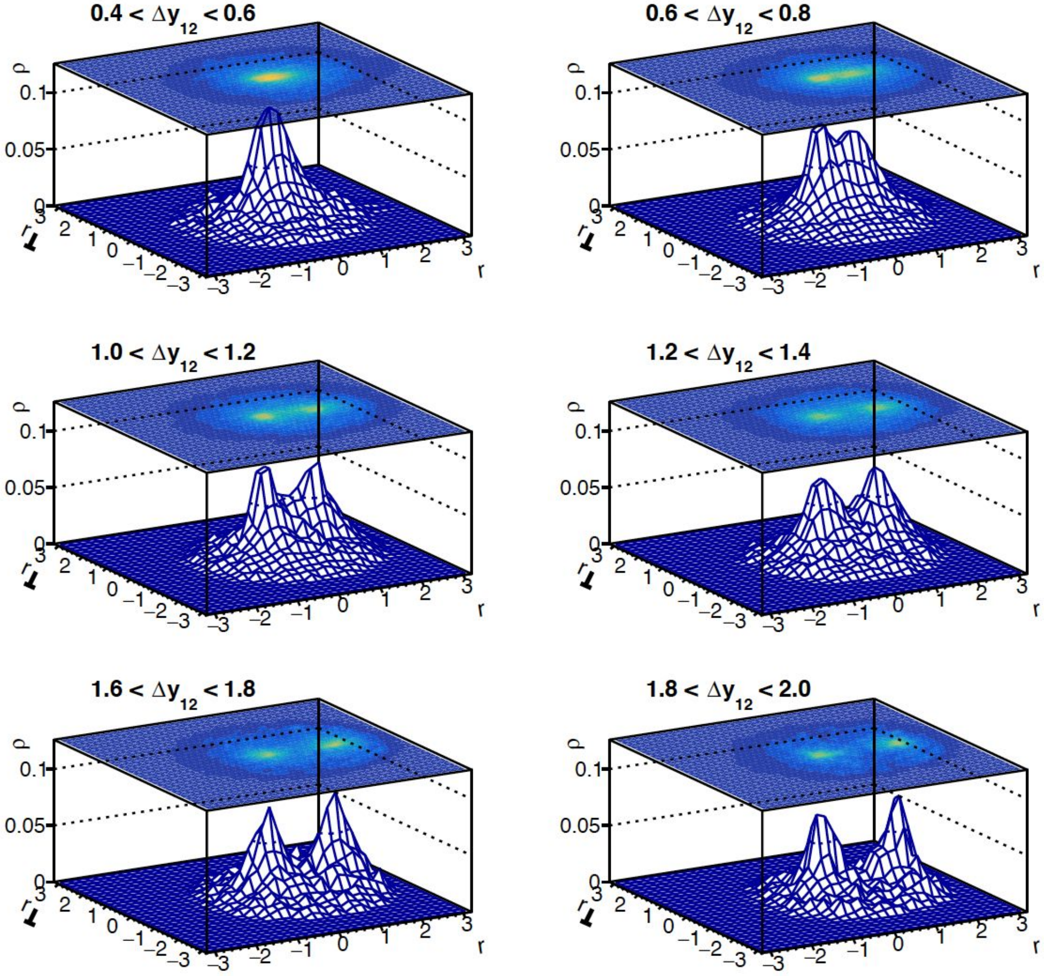
Wake Shape



Negative wake in the ϕ-direction opposite the jet

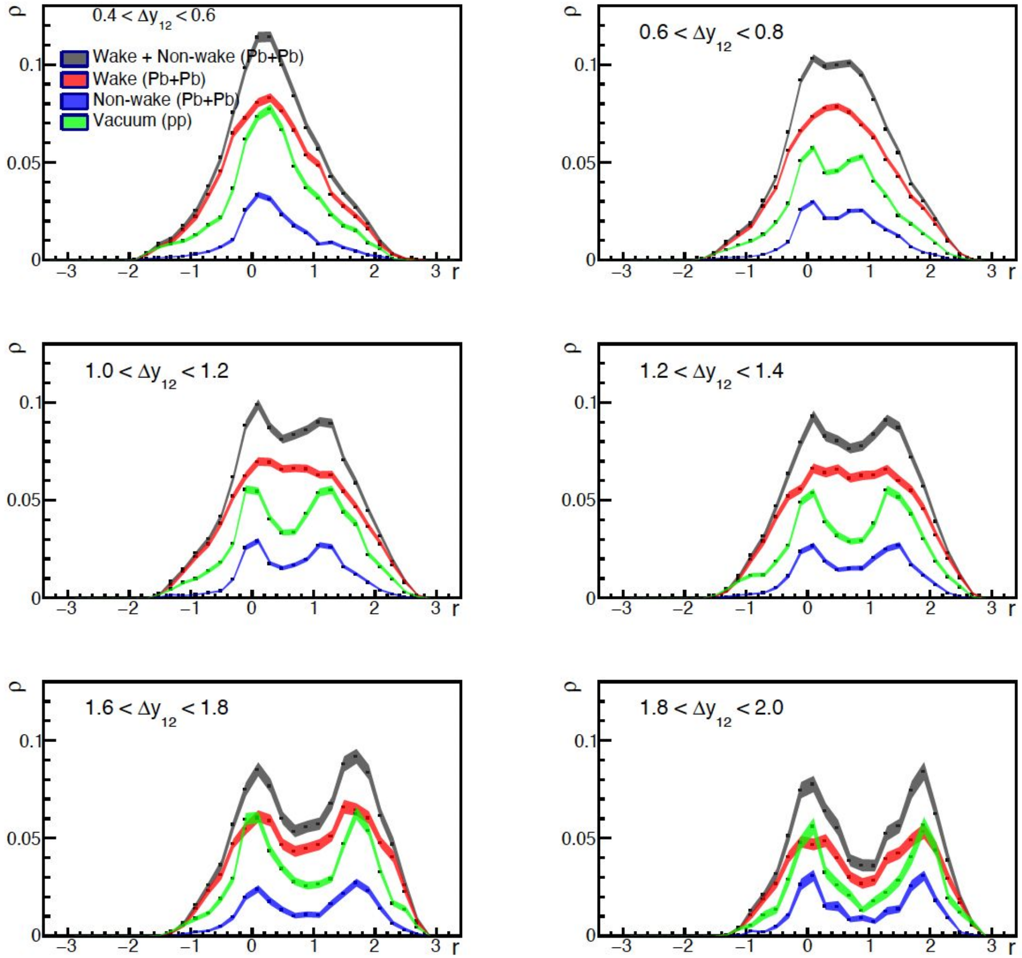
Negative wake from the away-side jet

Pb+Pb: SHAPE OF WAKE + NONWAKE HADRONS WITH 0.7 < p_T < 1.5 GeV



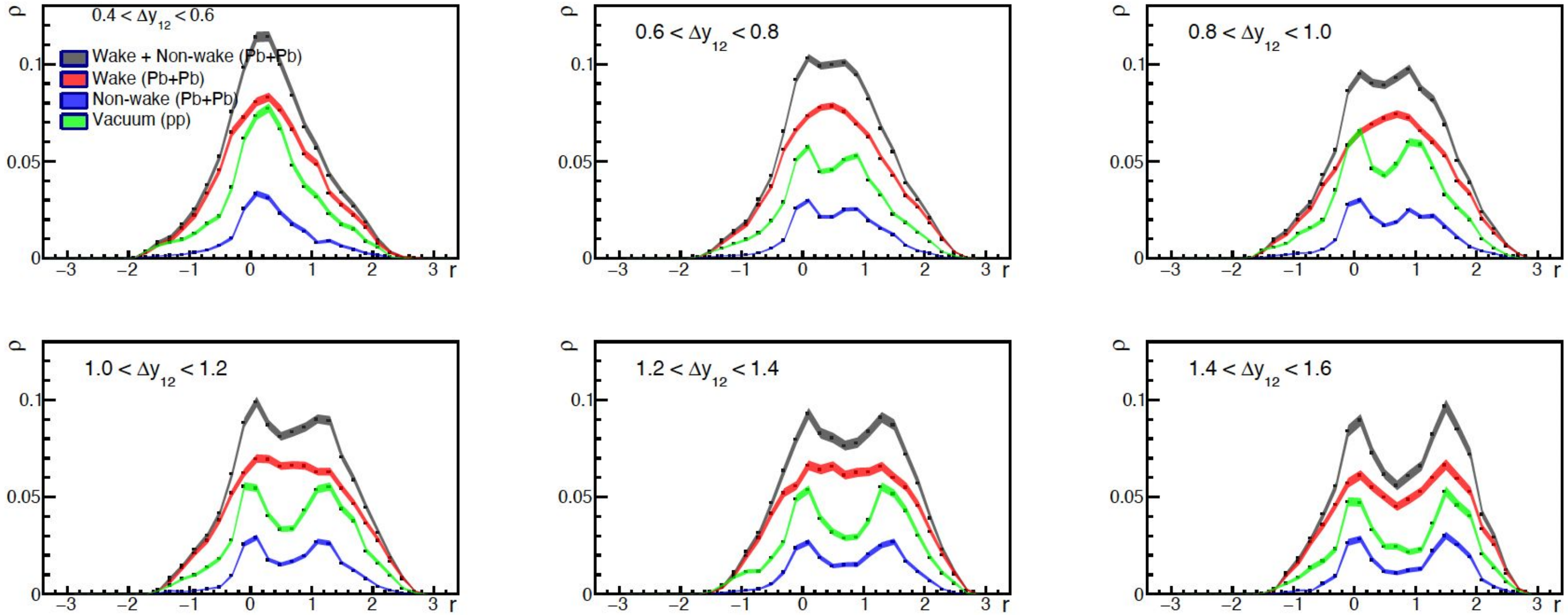
Two-pronged structures emerge at lower subjet-separations due to the higher presence of non-wake hadrons (as compared to the 0.7 < p_T < 1.0 GeV case)

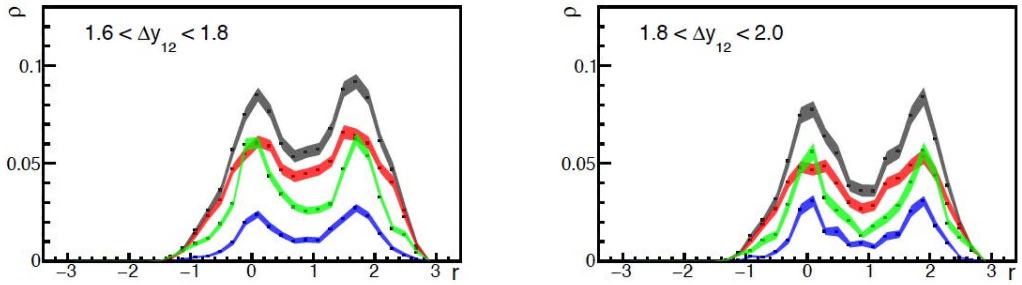
PROJECTING THE SHAPES ONTO THE r-AXIS: HADRONS WITH $0.7 < p_T < 1.5$ GeV



In this kinematic regime, the wake and non-wake contributions are comparable. So the experimentally measurable jet shape (in gray) will be "contaminated" by the presence of non-wake hadrons.

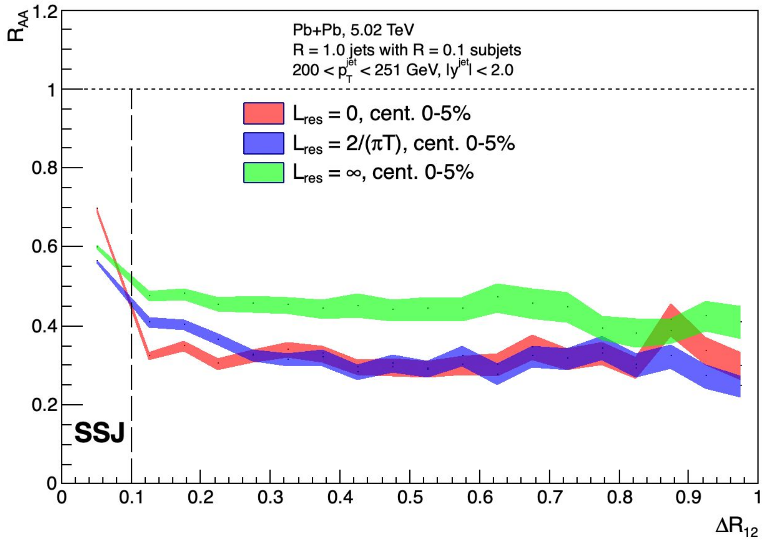
PROJECTING THE SHAPES ONTO THE r-AXIS: HADRONS WITH $0.7 < p_T < 1.5$ GeV

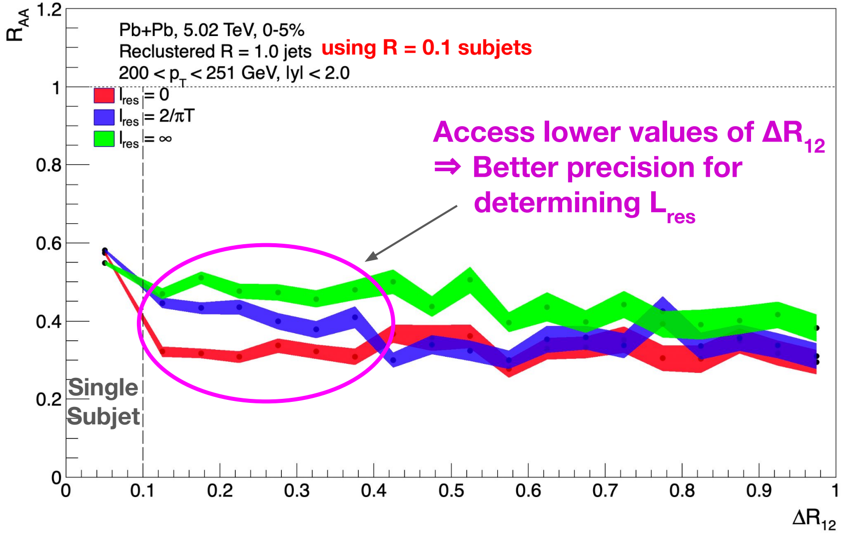


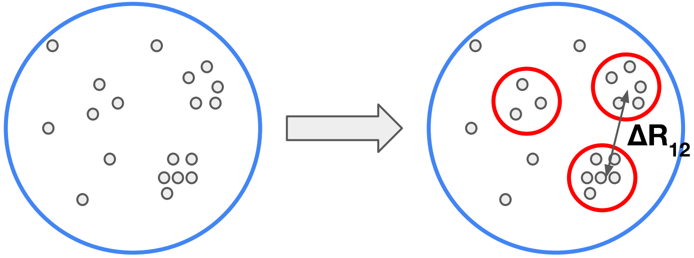


In this kinematic regime, the wake and non-wake contributions are comparable. So the experimentally measurable jet shape (in gray) will be “contaminated” by the presence of non-wake hadrons.

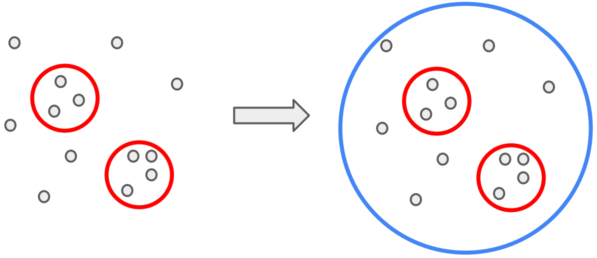
DE-CLUSTERING VS. RE-CLUSTERING







ΔR_{12} between leading and subleading subjets



De-clustering vs. Re-clustering