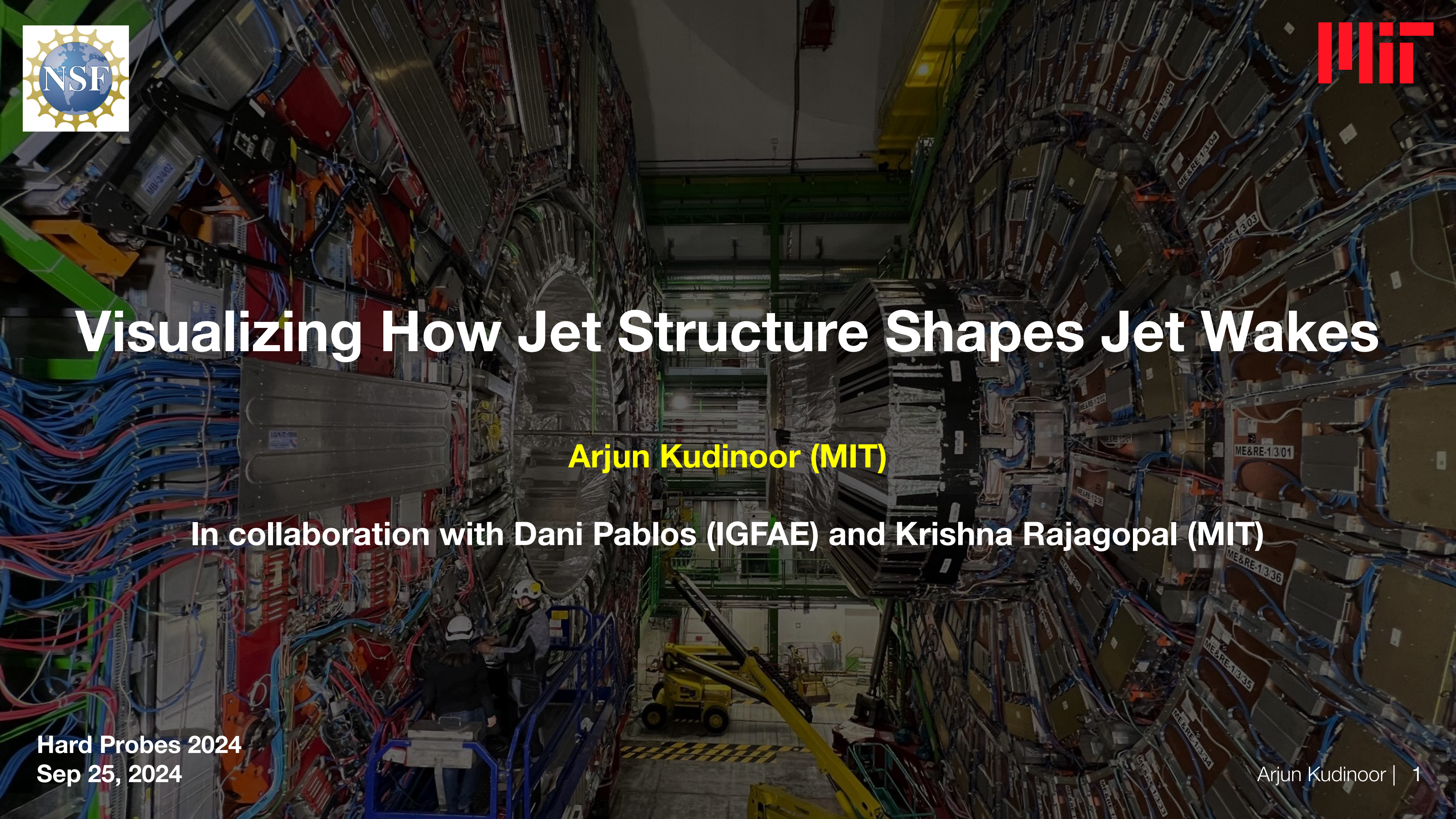


Visualizing How Jet Structure Shapes Jet Wakes

Arjun Kudinoor (MIT)

In collaboration with Dani Pablos (IGFAE) and Krishna Rajagopal (MIT)

Hard Probes 2024
Sep 25, 2024

AGENDA

TOPIC 1: The Hybrid Strong/Weak Coupling Model of Heavy Ion Collisions
TOPIC 2: Probing the resolution length of QGP using large-radius jet suppression
TOPIC 3: Visualizing jet-wakes and their structure using jet shape observables

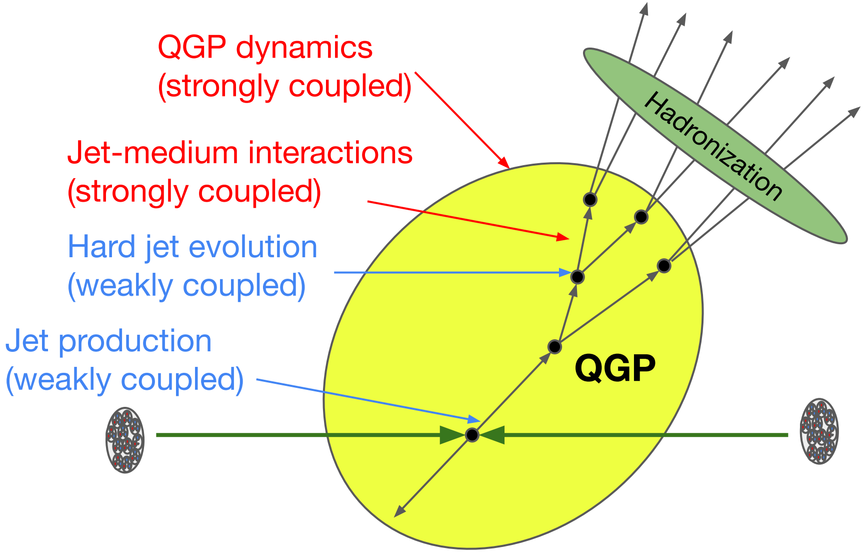
TOPIC 1

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.])



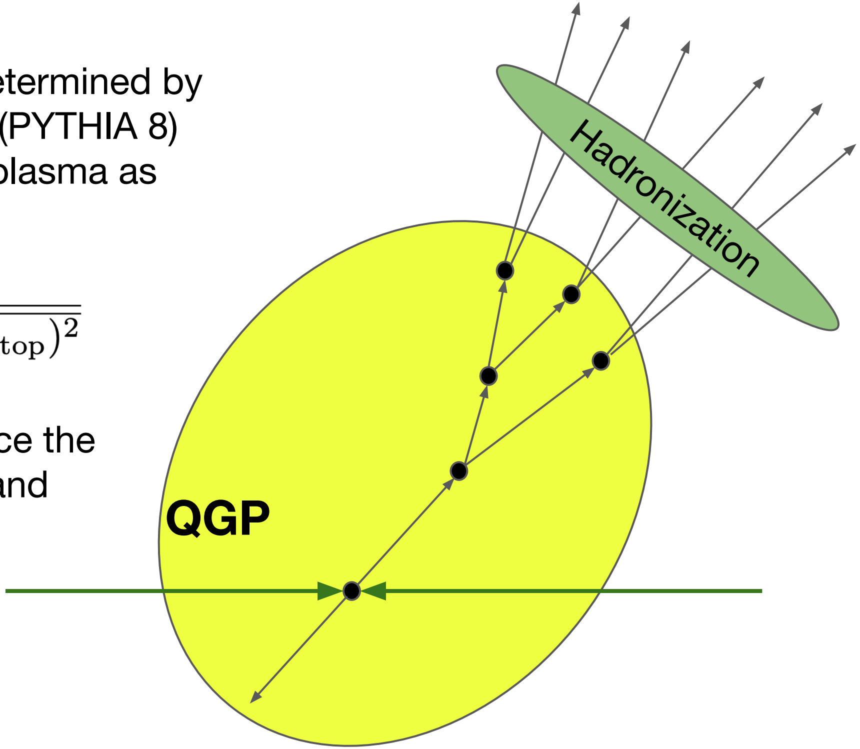
HOLOGRAPHIC PARTON ENERGY LOSS

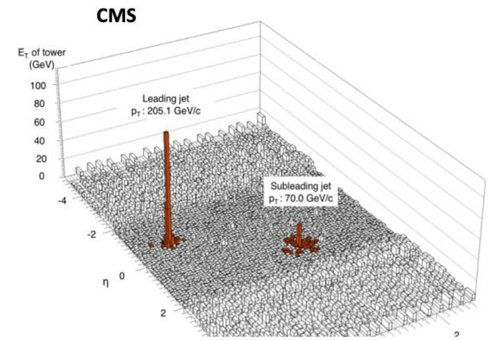
arXiv:1405.3864v3 [Casalderrey-Solana, et al.]

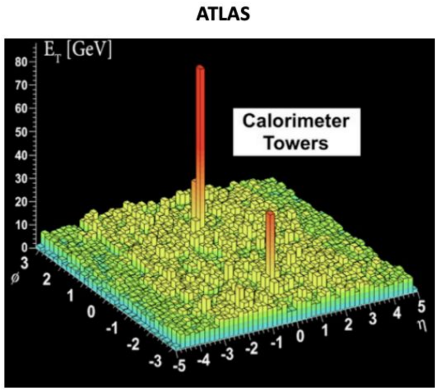
- Parton splittings that result in the jet shower are determined by the high-virtuality, perturbative, DGLAP equations (PYTHIA 8)
- Each parton loses energy to the strongly coupled plasma as determined by a holographic energy loss formula

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

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.



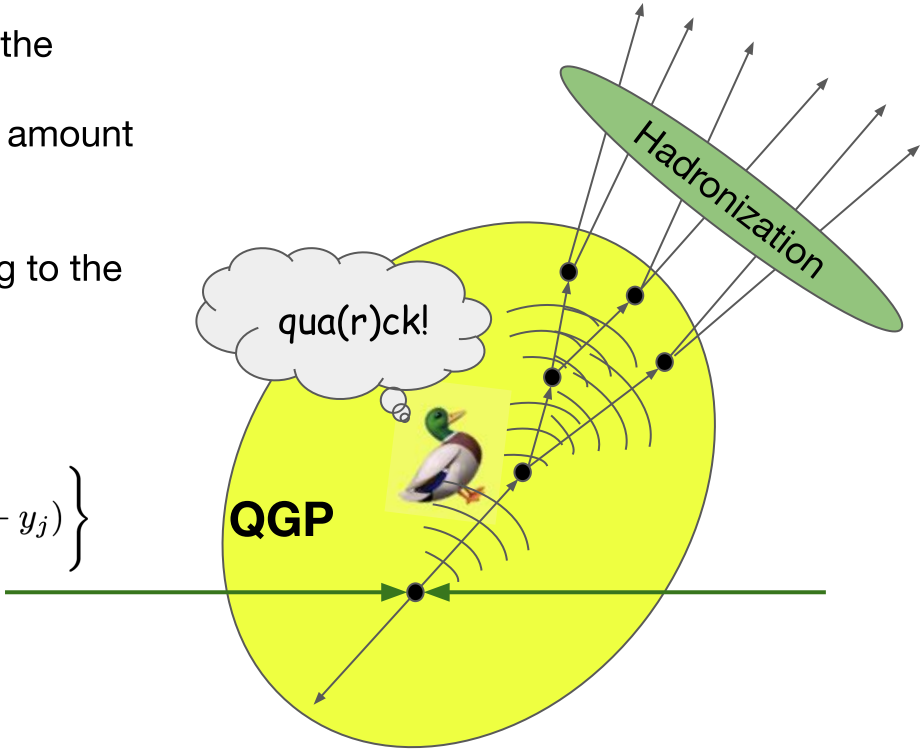




arXiv:1405.3864v3 [Casalderrey-Solana, et al.]

- 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.

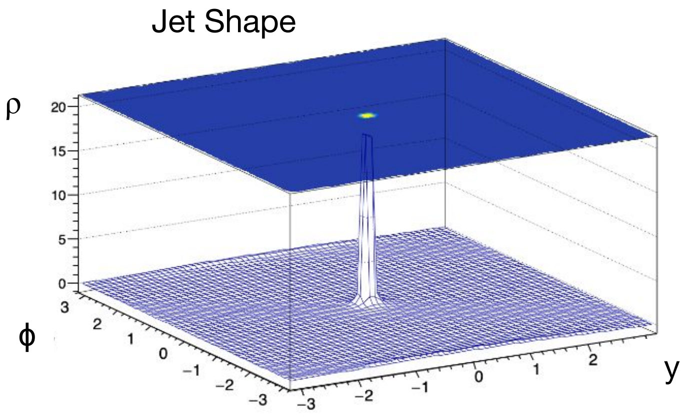
$$E\frac{d\Delta N}{d^3p} = \frac{1}{32\pi}\frac{m_T}{T^5}\cosh(y-y_j)e^{-\frac{m_T}{T}\cosh(y-y_j)} \times \left\{p_T\Delta p_T\cos(\phi-\phi_j) + \frac{1}{3}m_T\frac{\Delta E}{\cosh(y_j)}\cosh(y-y_j)\right\}$$

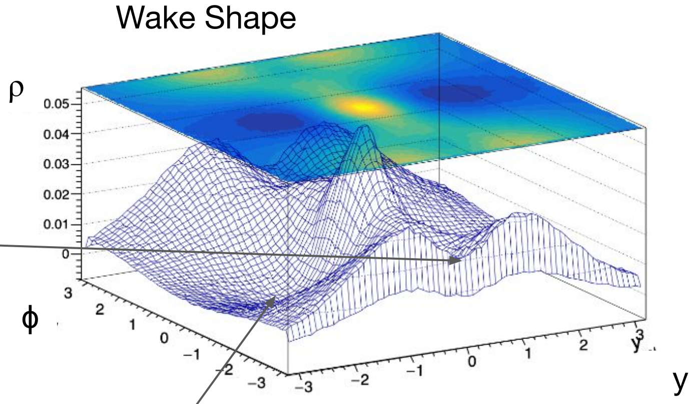


POSITIVE AND NEGATIVE WAKES

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



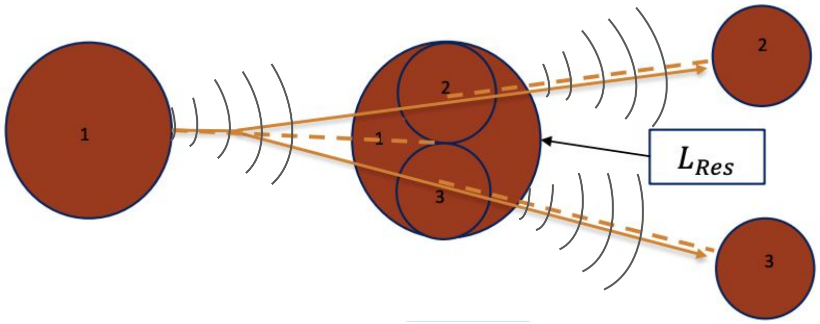


TOPIC 2
Probing the Resolution Length of QGP Using Large-Radius Jet Suppression

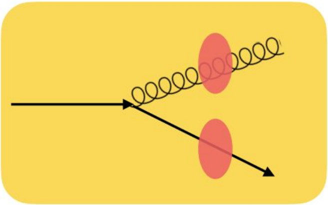
QGP RESOLUTION LENGTH

- 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.

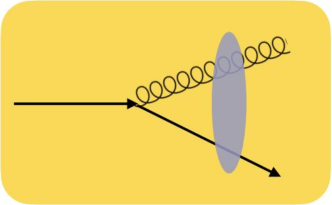
- In our implementation, L_{res} only applies to partons within the same parton shower. Two partons belonging to showers that were **initiated by two different partons** are treated as resolved structures regardless of their separation.



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}

- We study the energy loss experienced by jets with multiple hard structures, as a function of the angle between such structures. This allows us to probe the QGP resolution length.

- We study an observable introduced by ATLAS at QM 2019, arXiv: 2301.05606, and shown in **Martin Rybar's talk**

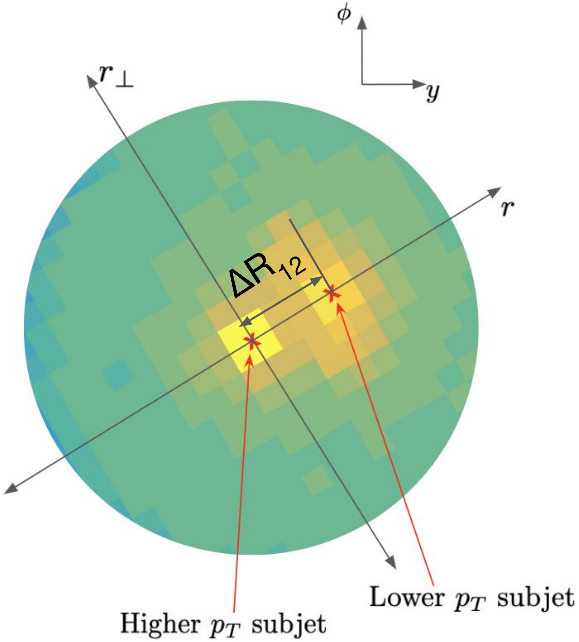
Anti-k_t R = 0.2 jets
p_T > 35 GeV, $|\eta| < 3.0$

↓

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

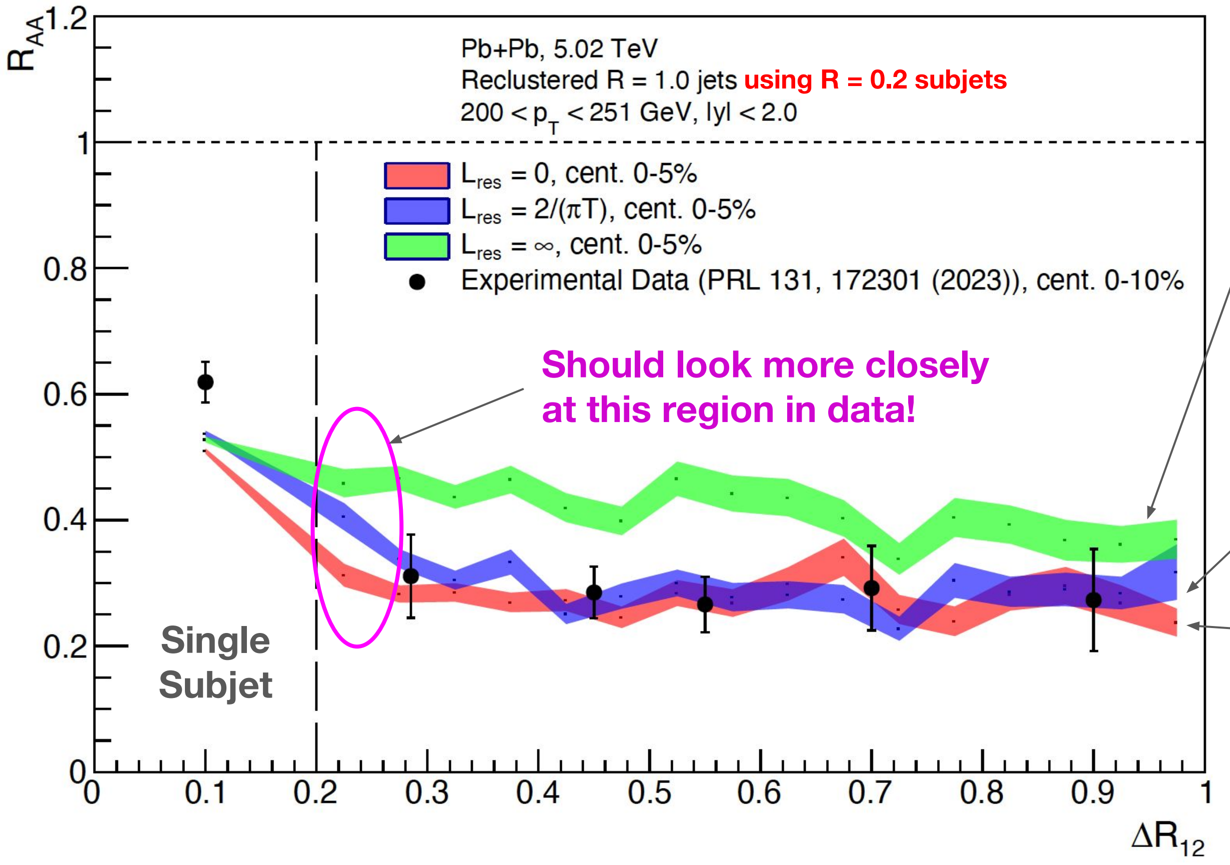
↓

Recluster with k_t-algorithm
to obtain ΔR_{12}



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

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

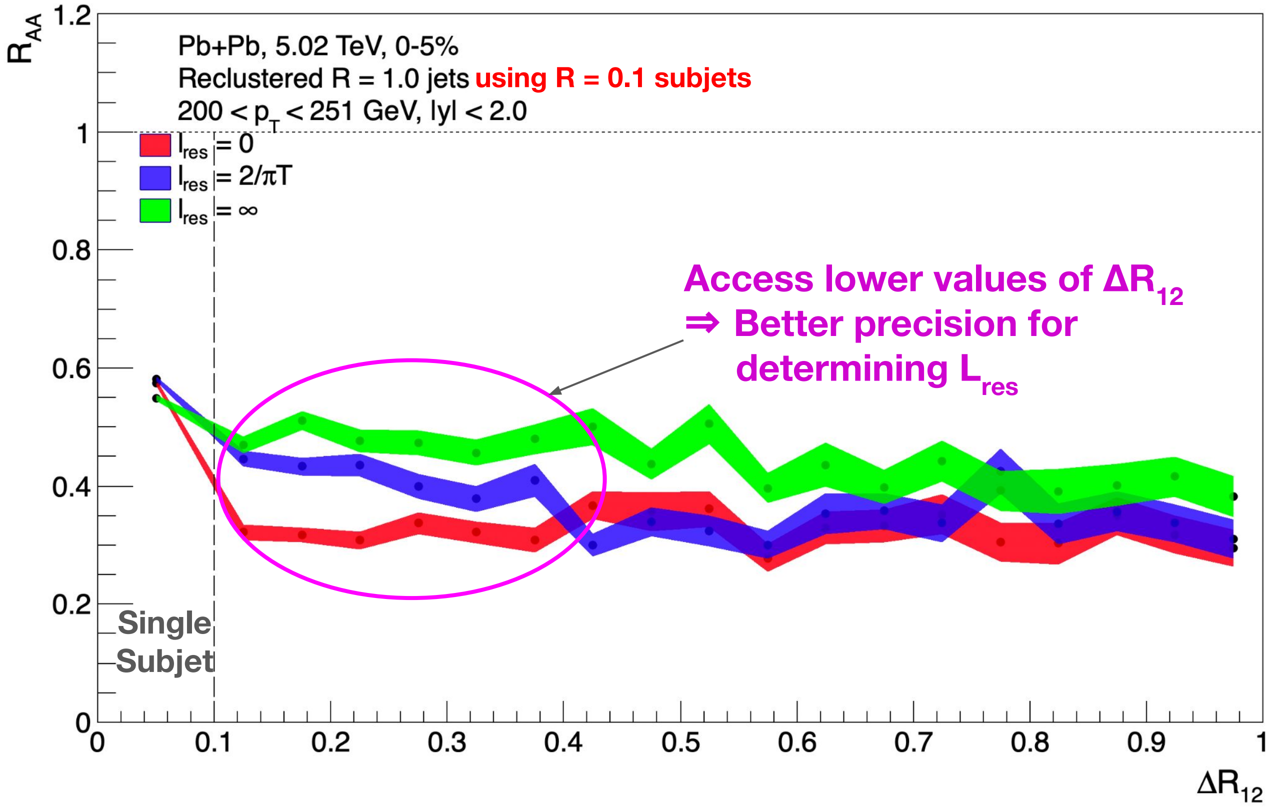


$L_{res} = \infty$: **Disfavored** by data. Partons within each shower are unresolved, and so R_{AA} is roughly independent of ΔR_{12}. Not entirely independent because jets with larger ΔR_{12} can contain subjets from different hard scatterings, which lose energy independently.

$L_{res} = 0$ 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.

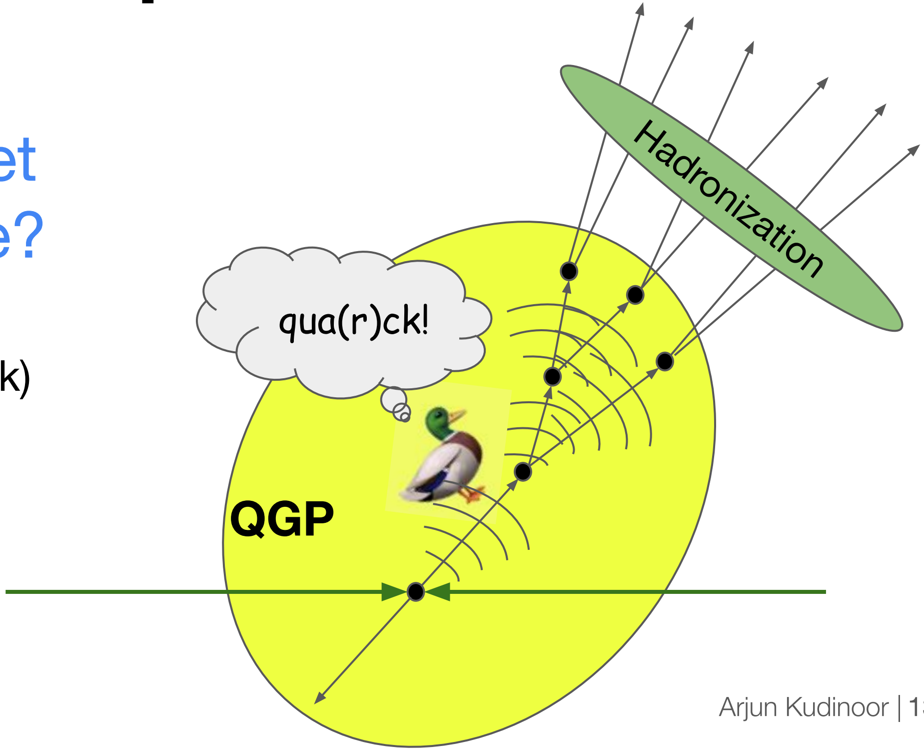
What if we reduce the size of the subjets? R = 0.2 → R = 0.1



TOPIC 3
Imaging the Structure of Jet Energy Loss Using Novel Jet-Shape Observables

How does the structure of a jet affect the structure of its wake?

(Assume $L_{res} = 0$ for the remainder of this talk)

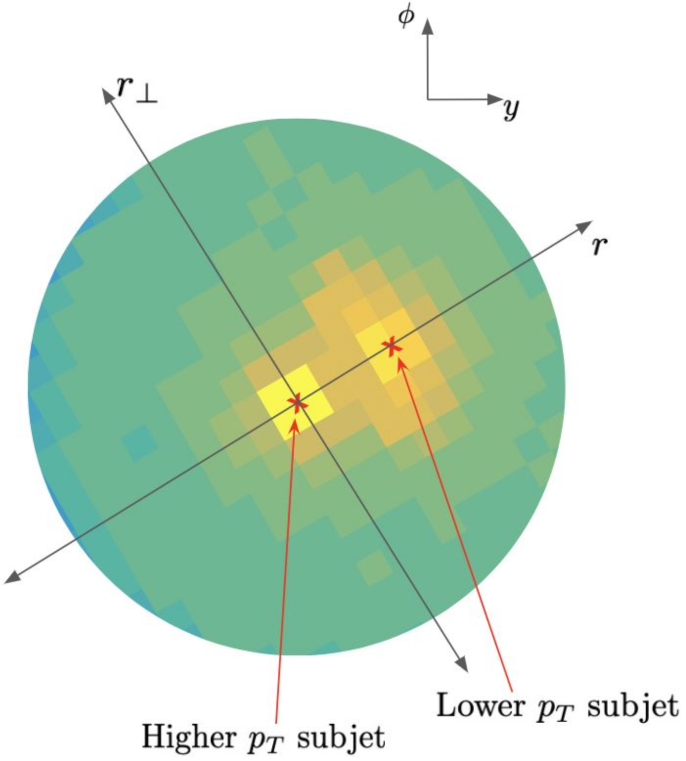


A NEW JET SHAPE OBSERVABLE

- Simplest multi-subjet case – **two subjets**
- **R = 2.0** jets reconstructed from R = 0.2 subjets
- Restrict to **gamma-jet** analysis
  → Photons dont produce wakes
  → No contamination in jets from negative wakes

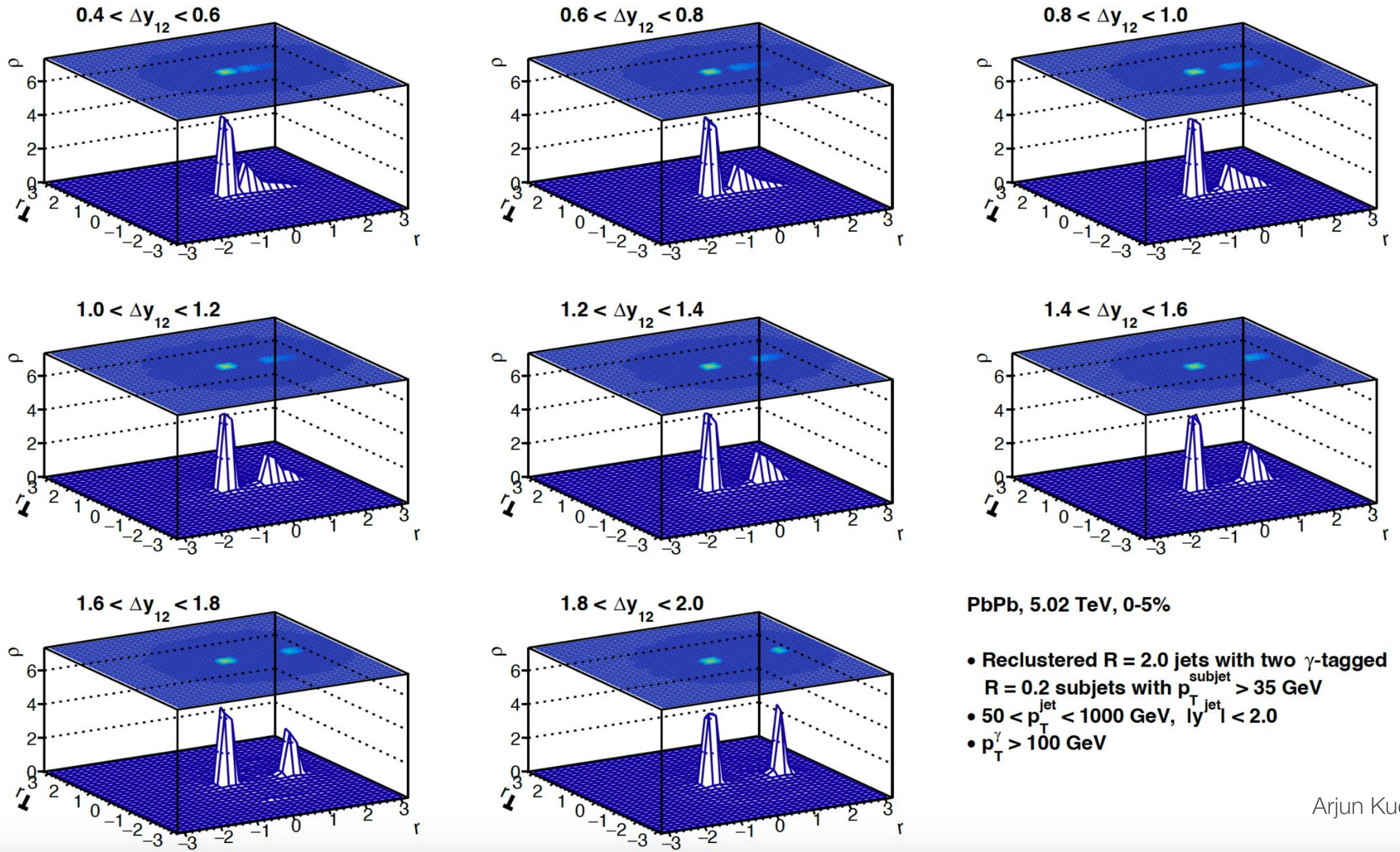
$$\rho^{2\mathrm{d}}(r, r_\perp) = \frac{1}{\Delta y_{12}} \frac{1}{\Delta r} \frac{1}{\Delta r_\perp} \frac{1}{N_{\mathrm{jet}}} \sum_{\mathrm{jets}} \left(\frac{1}{p_T^{\mathrm{jet}}} \left[p_T \right]_{(r-\frac{\Delta r}{2}, r_\perp - \frac{\Delta r_\perp}{2})}^{(r+\frac{\Delta r}{2}, r_\perp + \frac{\Delta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

In our calculations of jet shapes, we include all particles within an R = 2.0 radius of the axis of each large-radius jet, not just the particles inside the R = 0.2 skinny subjets.

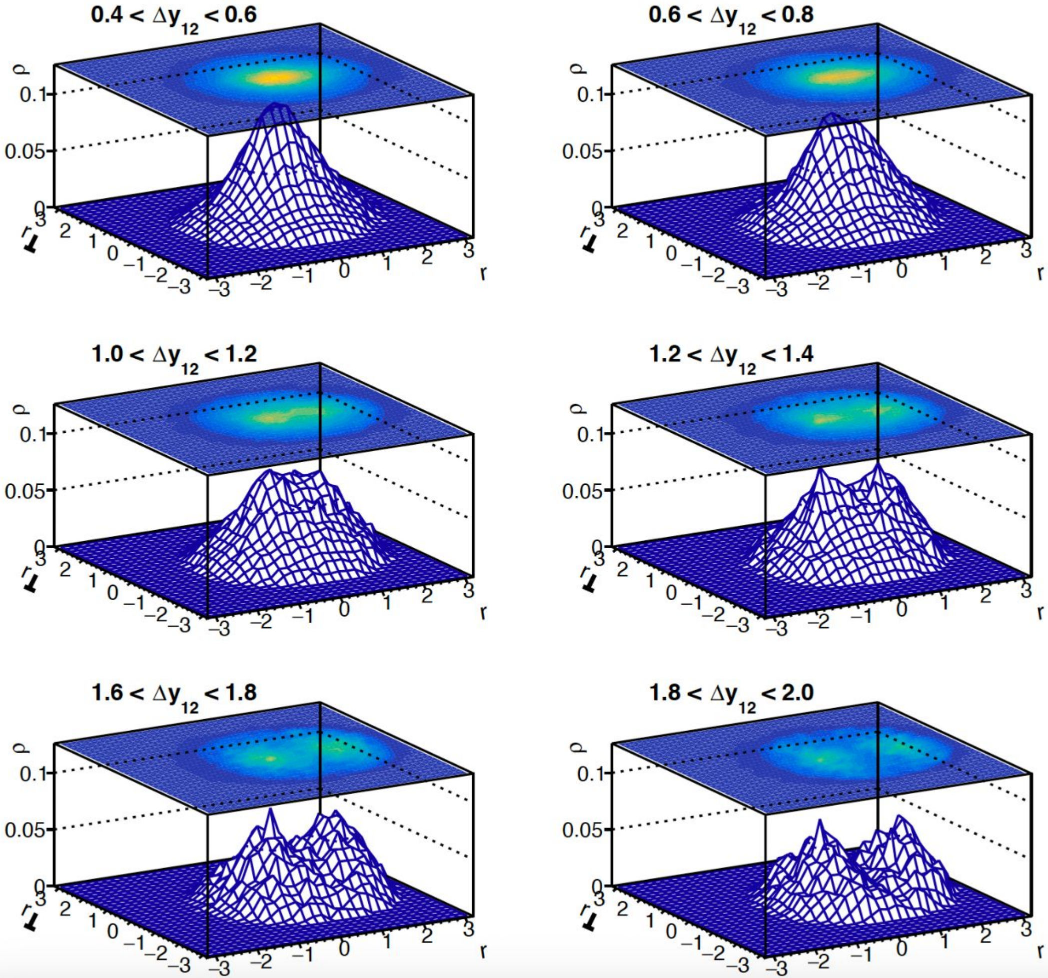


- **Photon selection and isolation criteria:**
  - $p_T^\gamma > 100$ GeV and $|\eta^\gamma| < 1.44$
  - $\Sigma E_T < 5$ GeV around r = 0.4 of the photon
- **R = 0.2 subjets:** $p_T > 35$ GeV, $|\eta| < 3.0$, $\Delta\phi_{\gamma,\,\mathrm{subjet}} > 2\pi/3$
- **R = 2.0 jets:** $|y| < 2.0$, $50 < p_T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

Pb+Pb: FULL JET SHAPE



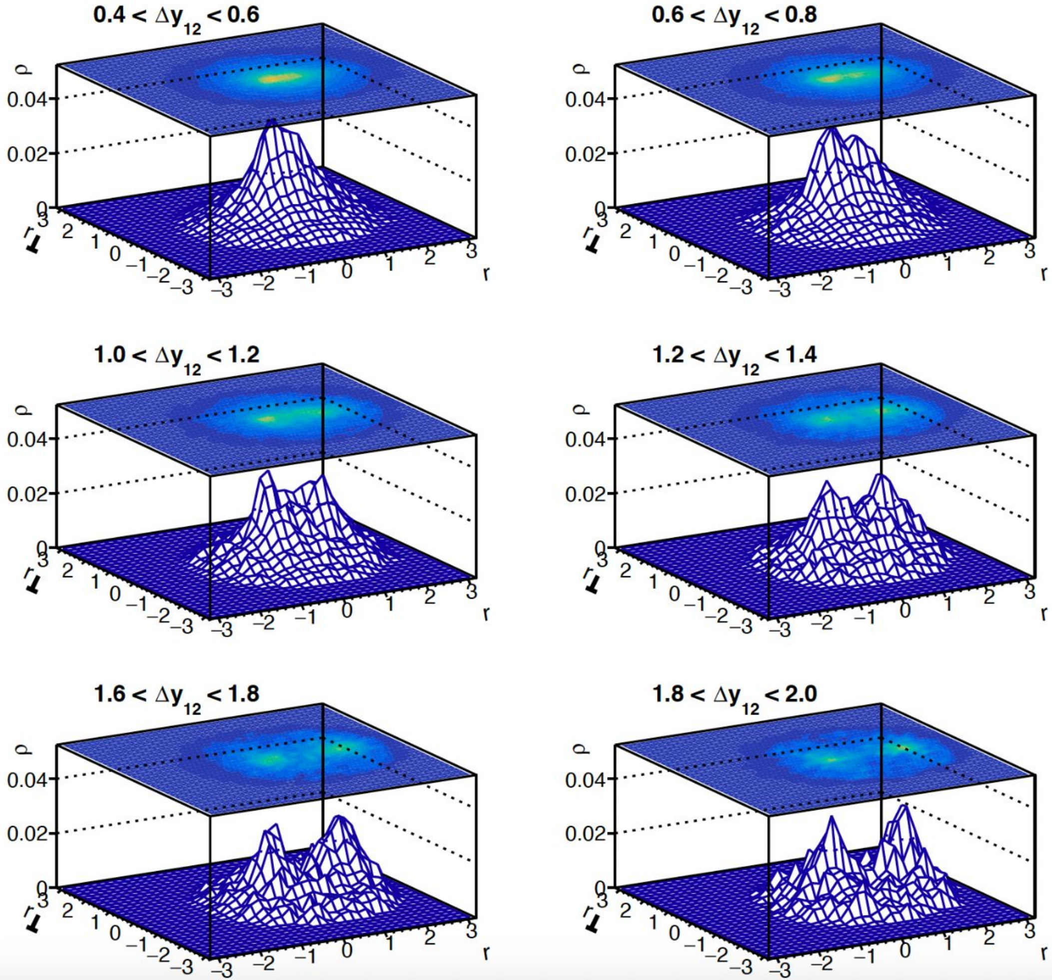
Pb+Pb: WAKE SHAPE



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 $\Delta y_{12} > 1.2$)!

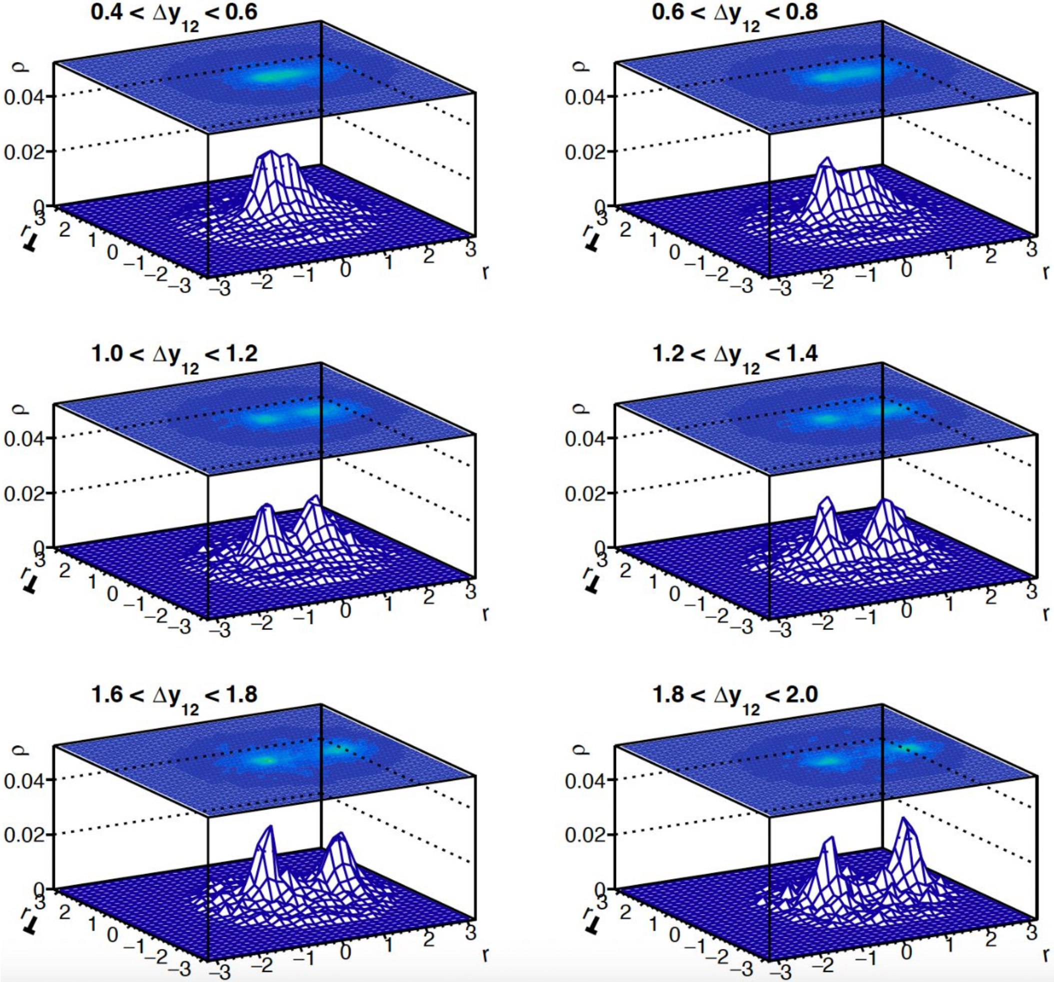
How can we see this in experiments?

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



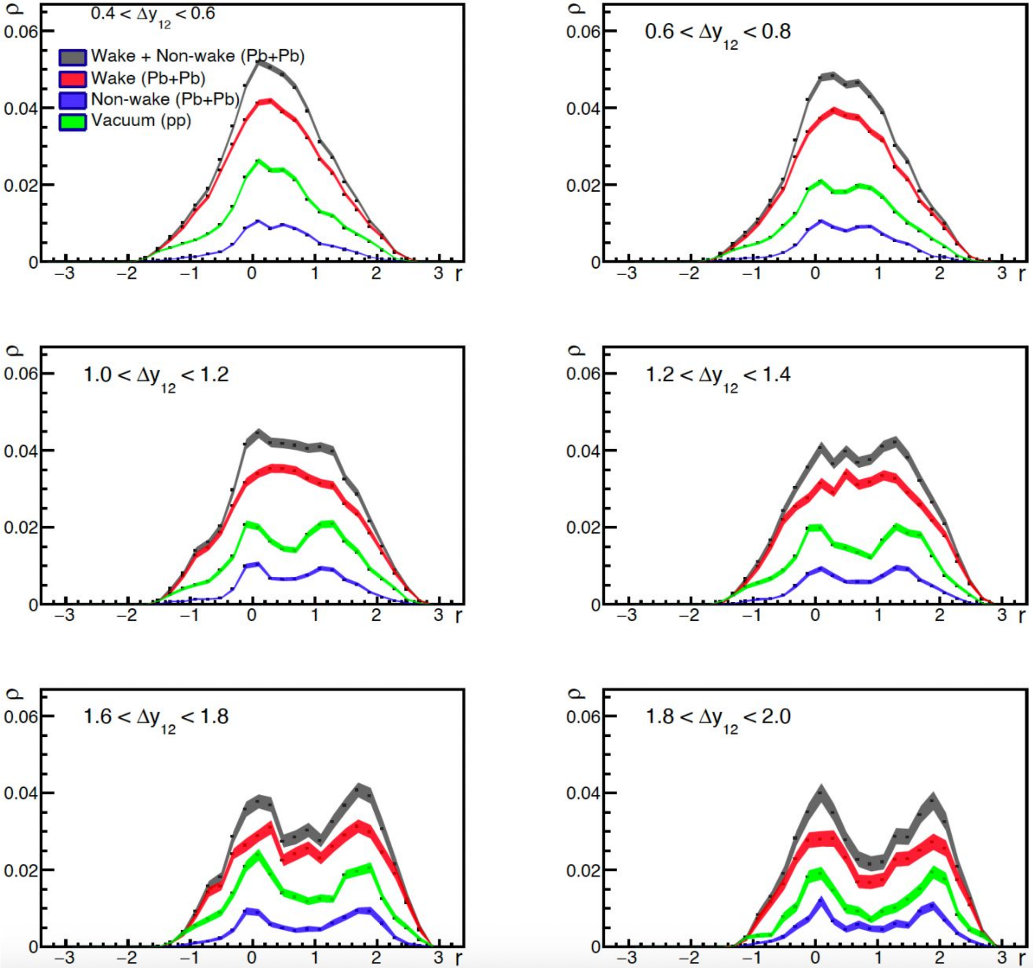
Only a single-pronged structure is visible at low angular separation even when low-p_T non-wake hadrons are included. However, two-pronged structures appear at lower angles than when we restrict to using only hadrons belonging to the wake.

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



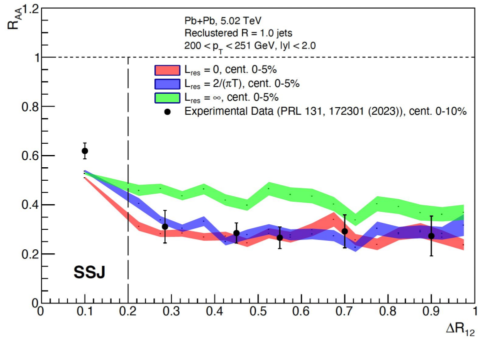
Wake + Nonwake (Pb+Pb)
Wake (Pb+Pb)
Non-Wake (Pb+Pb)
Vacuum (pp)

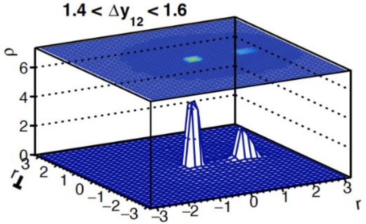
The wake dominates this kinematic region

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

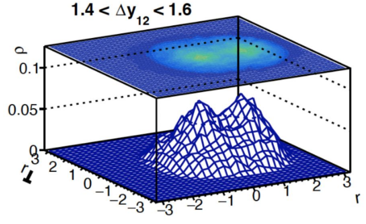
KEY TAKEAWAYS

- We confirm that **QGP resolves partons within parton showers** via our jet suppression analyses of large-radius jets reconstructed using skinny subjets.
- Large-radius jets with multiple subjets produce multiple sub-wakes if the subjets are far-separated. We **can image these wakes and their internal structure** using the novel jet shape observables we introduced here.
- If we restrict to measuring jet shapes using only those hadrons with low momenta ~0.7-1.0 GeV, then we can visualize the wake in an experimentally feasible way. **Let's image the wake in experiments!**

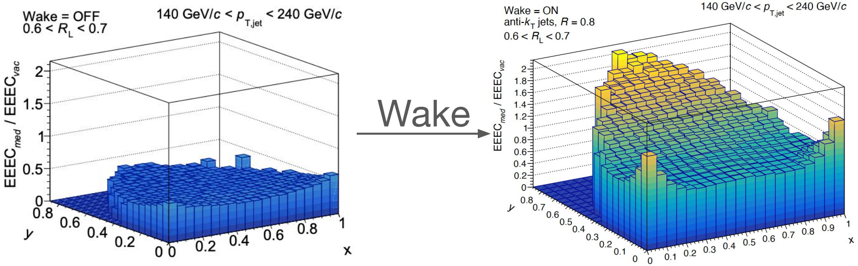




Jet Shape



Wake Shape



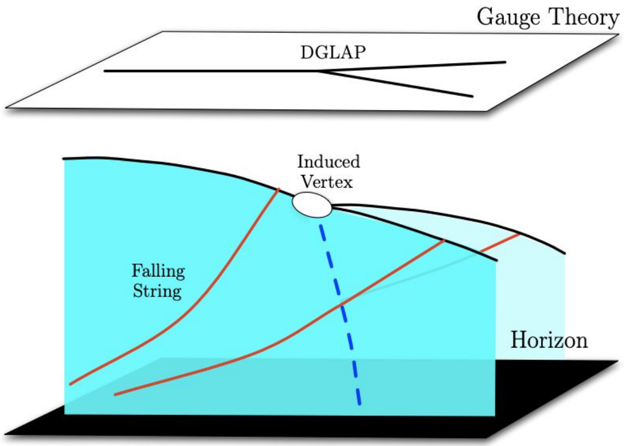
Other observables, like energy correlators, can also be used to image the wake!
Ananya Rai's Poster + arXiv: 2407.13818

BACKUP

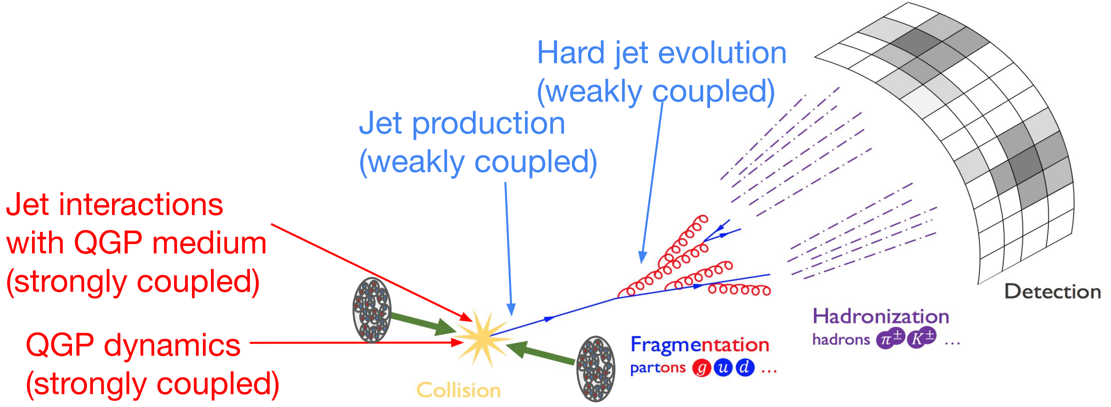
THE HYBRID STRONG/WEAK COUPLING MODEL

- 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)

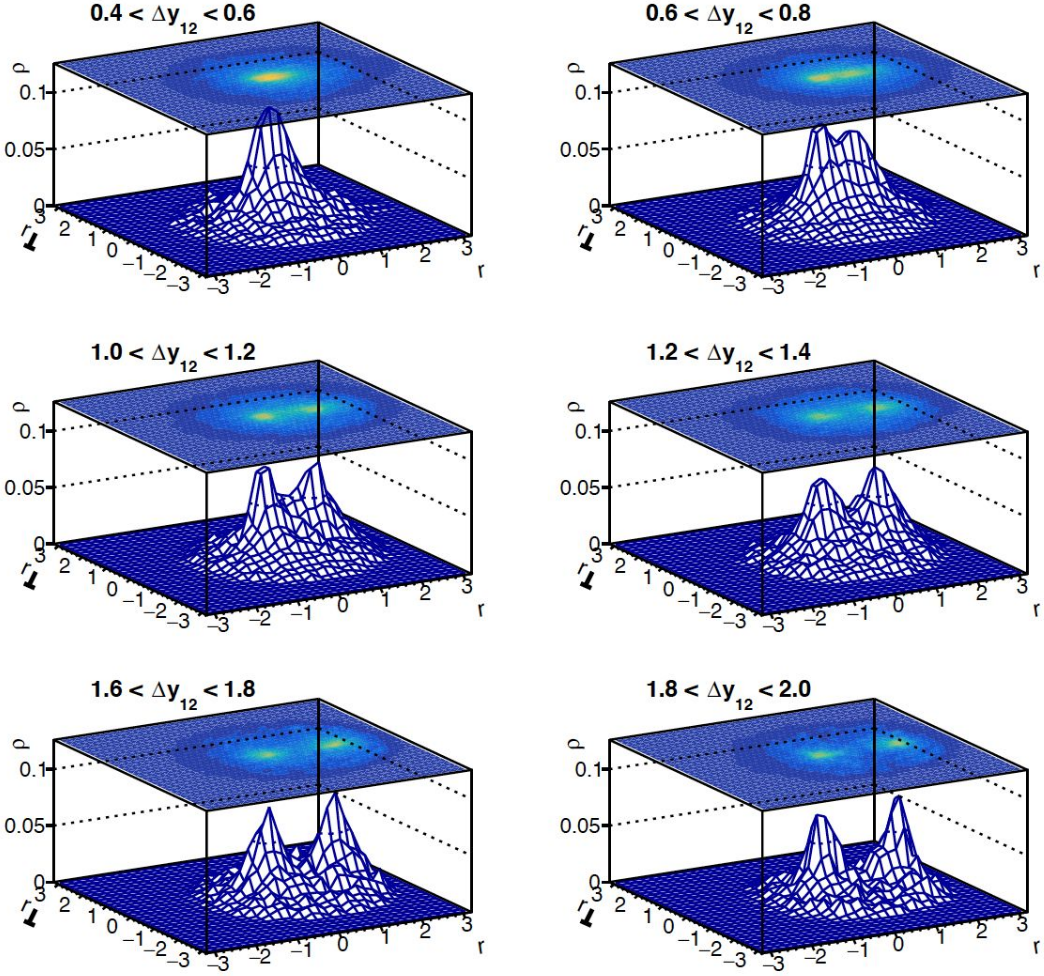
Missing p_T observables – 2016

- Adding the soft particles from the wake is necessary if we aim to describe data. It also seems that our treatment of the wake does not fully capture what the data calls for.
- If goal is seeing larger angle scattering of partons in the jet, ignore the wake, look at observables sensitive to 5-20 GeV partons; groomed jet substructure observables.
- Lets focus on wake: what was key oversimplification?
- We *assumed* that the wake rapidly equilibrates, and becomes a small perturbation on the hydro flow and hence a small perturbation to the final state particles. The only thing the thermalized particles in the final state remembers is the energy and net momentum deposited by the jet. This is natural at strong coupling.
- We assumed the perturbations to the final state spectra due to the wake are small at all p_T. Need not be so at intermediate p_T.
- To diagnose how well these approximations are justified in reality we need more sophisticated observables...

Missing p_T observables – 2016

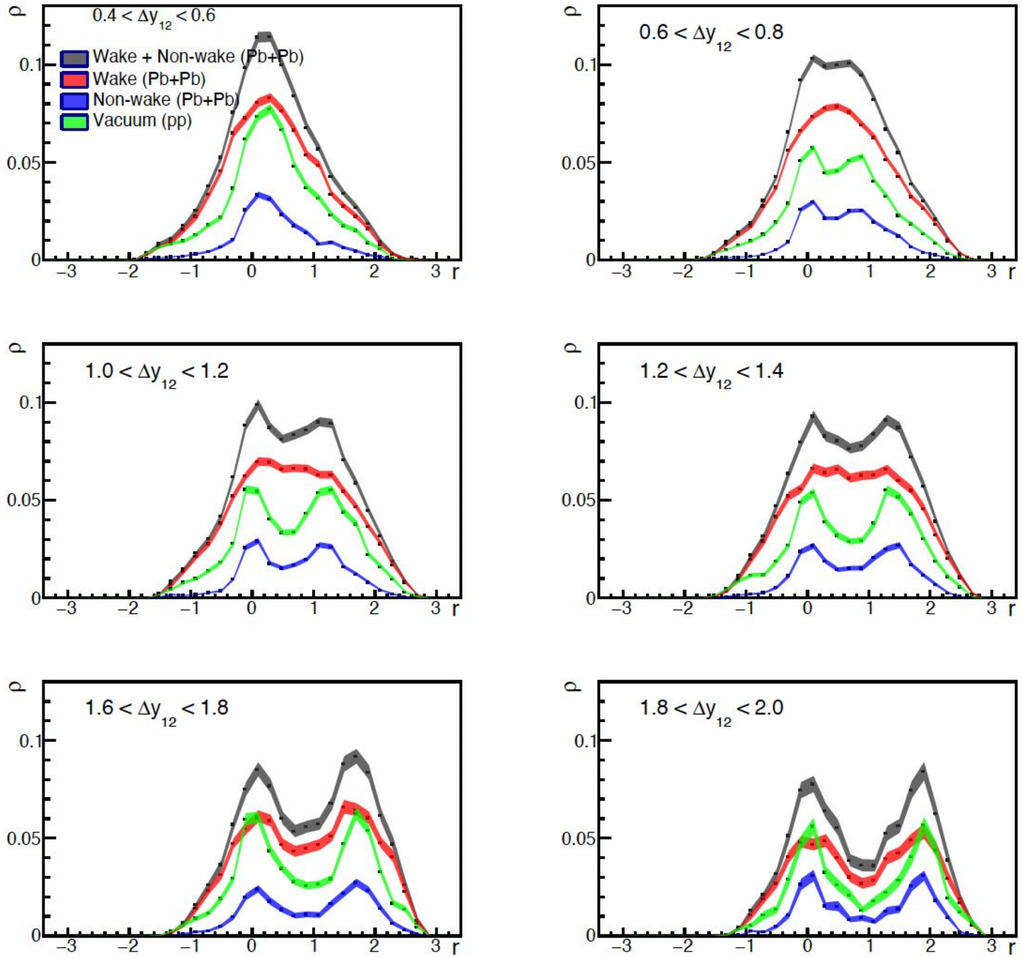
- Our characterization of the wake is on the right track. BUT:
- We have too many particles with 0.5 GeV$< p_T <$2 GeV.
- We have too few particles with 2 GeV$< p_T <$4 GeV.
- The energy and momentum given to the plasma by the jet may not fully thermalize. Further improving our model to describe the low-p_T component of jets, as reconstructed, requires full-fledged calculation of the wake.
- Others, using other calculational frameworks, should add background, include the wake, subtract background, and compare to data on Missing-p_T observables. Can we determine whether the energy lost by the jet — namely the wake in the plasma — does not fully thermalize, remembering more than just its energy and momentum?

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.

MOST FAR-SEPARATED SUBJETS DUE TO INITIAL STATE RADIATION