The Great Awakening of Quark Gluon Plasma

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MIT CTP Graduate Seminar
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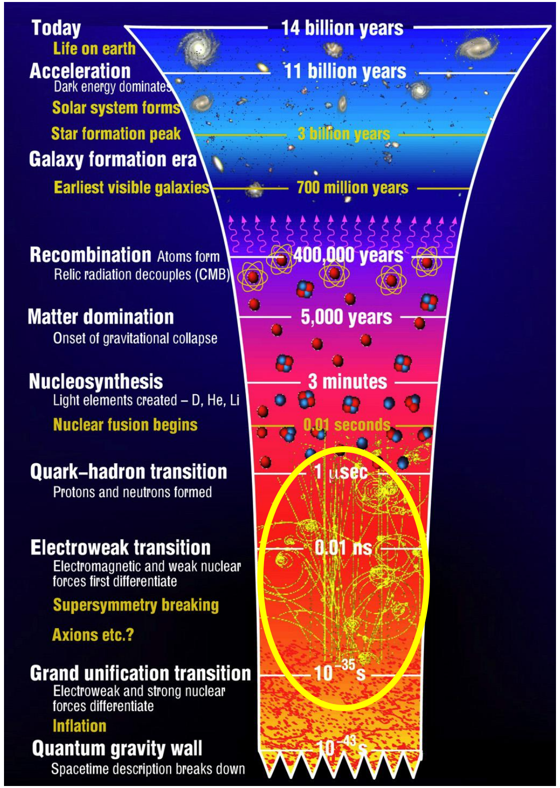
AGENDA

TOPIC 1: Quark Gluon Plasma and Jets in Heavy Ion Collisions
TOPIC 2: Imaging Jet-Induced Wakes using Energy Correlators
TOPIC 3: Imaging Wake Substructure using Novel Jet-Shape Observables

TOPIC 1
Quark Gluon Plasma and Jets In Heavy Ion Collisions

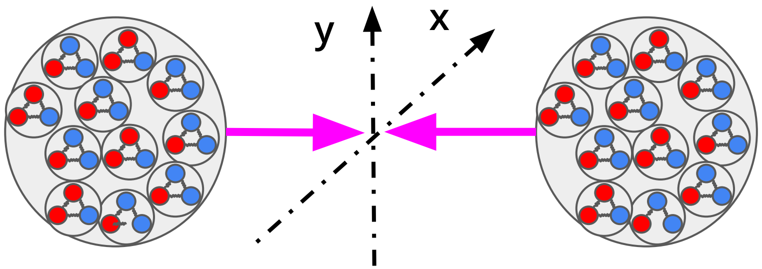
DROPLETS OF THE EARLY UNIVERSE

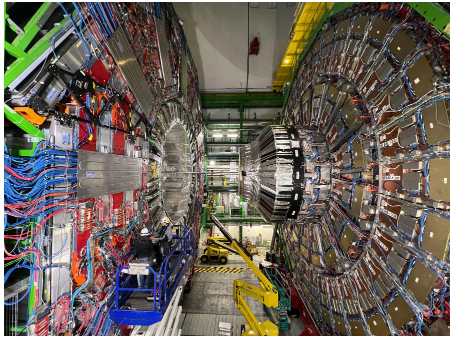
1. THE EARLY UNIVERSE



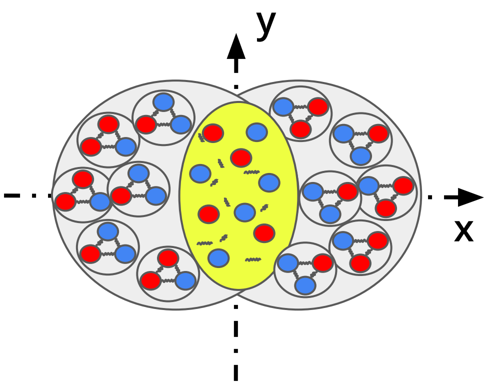
From: Centre for Theoretical Cosmology, Cambridge University

2. HEAVY ION COLLISIONS





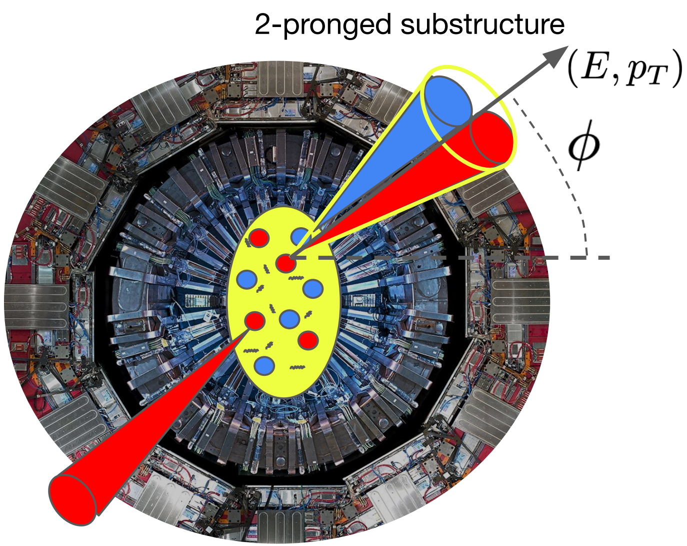
3. QUARK GLUON PLASMA



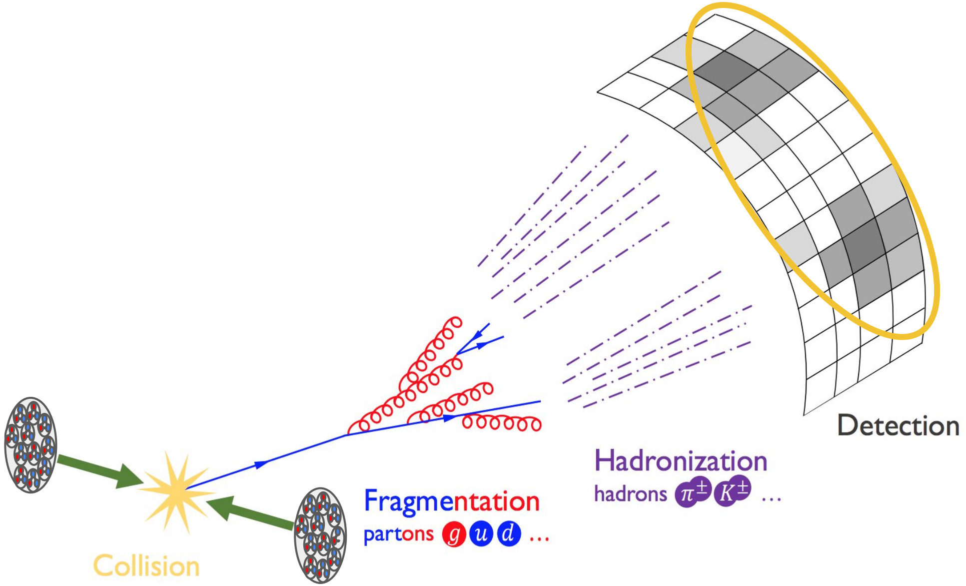
- The **first liquid** to exist
- Origin of protons and neutrons
- At a few trillion degrees, the **hottest liquid** that has ever existed
- The **most liquid liquid** to exist
- Quarks are **deconfined**, yet **strongly interacting**

https://indico.fysik.su.se/event/8016/contributions/12121/attachments/5069/6726/QC23_Rajagopal_Lectures_v2.pdf

Often, energetic sprays of hadrons shoot out of the QGP. We call these sprays **jets**.
Jets are probes to understand the physics of QGP because they carry information about **energy, momentum, angular distribution, and internal structure** that can reveal the nature of QCD physics in quark gluon plasma.



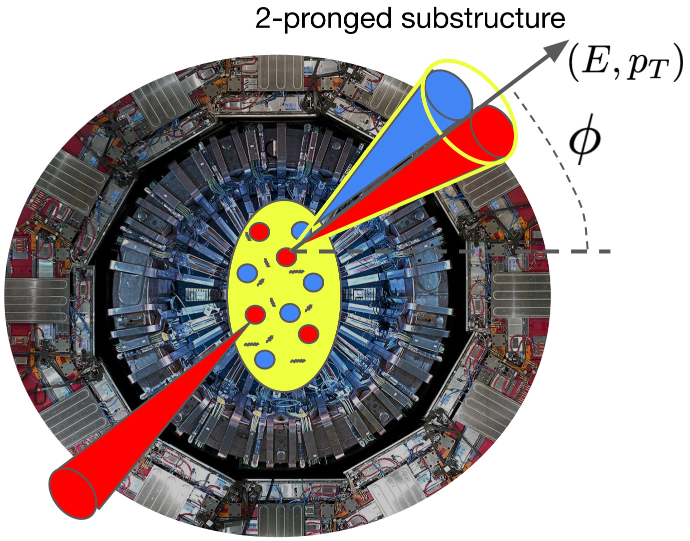
Detector image from: CMS



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

Some Goals

- To show that QGP can resolve structures within a jet shower (QGP has a finite resolution length)
- To show that we can observe wakes left by energetic partons within QGP
- To test Rutherford-like scattering of jet quarks/gluons off of QGP quarks/gluons
- To characterize the microscopic structure of the original liquid and its ripples



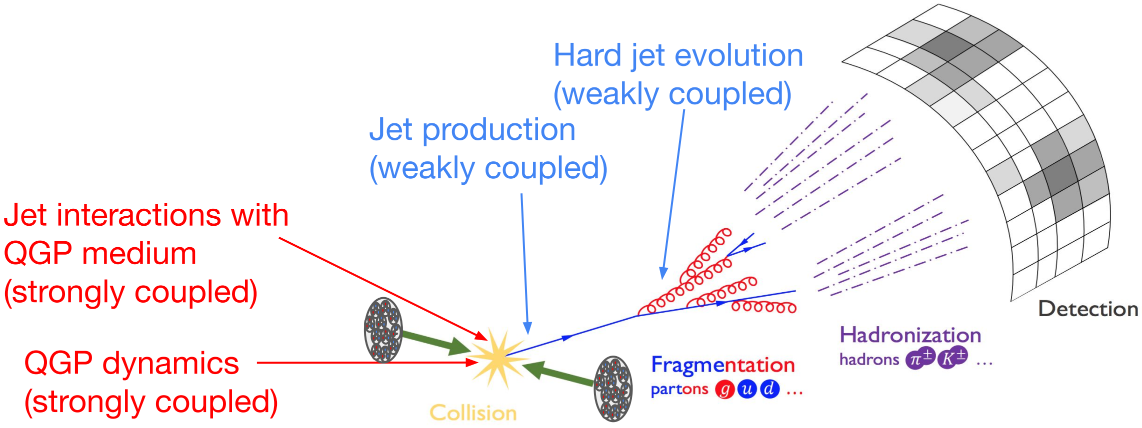
Detector image from: CMS

How do we model jets in 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)



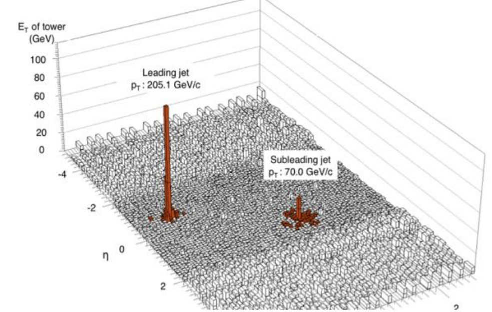
Modified from: https://www.ericmetodiev.com/post/jetformation/

- 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 plasma as determined by a holographic energy loss formula

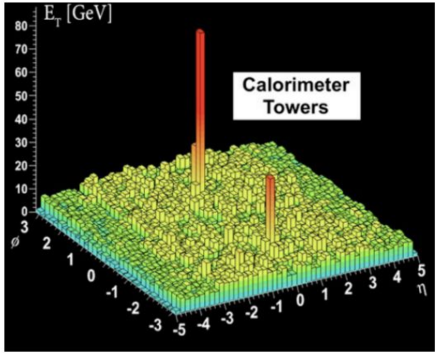
$$\left.\frac{dE}{dx}\right|_{\text{strongly coupled}} = -\frac{4}{\pi}\frac{E_{\text{in}}}{x_{\text{stop}}}\frac{x^2}{x_{\text{stop}}^2}\frac{1}{\sqrt{1-(x/x_{\text{stop}})^2}}$$

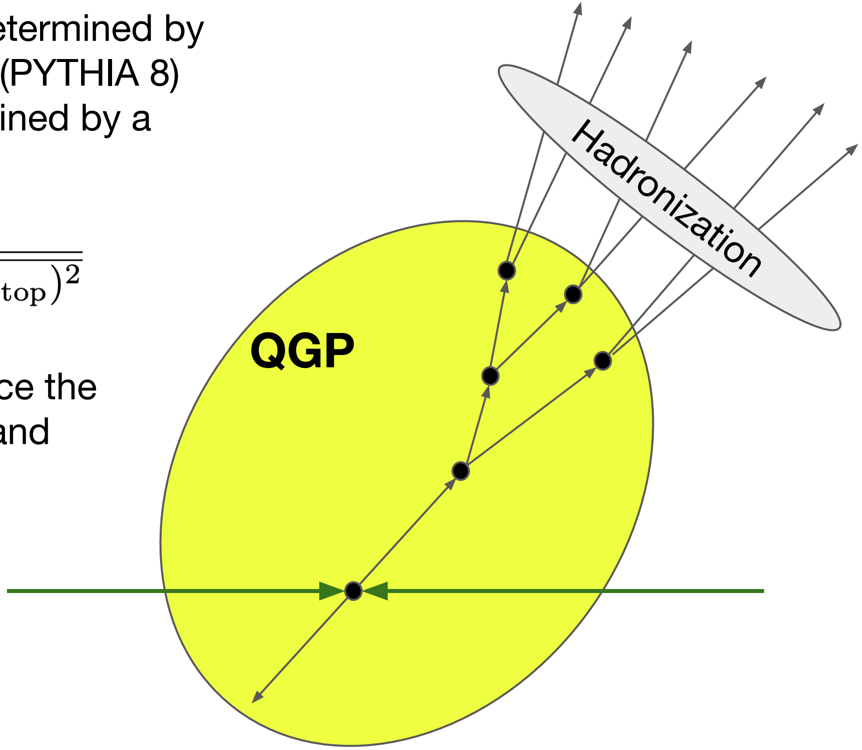
Here, $x_{\text{stop}} \equiv E_{\text{in}}^{1/3}/(2T^{4/3}\kappa_{\text{sc}})$ is the maximum distance the parton can travel within the plasma before thermalizing and equilibrating with the plasma.

CMS



ATLAS

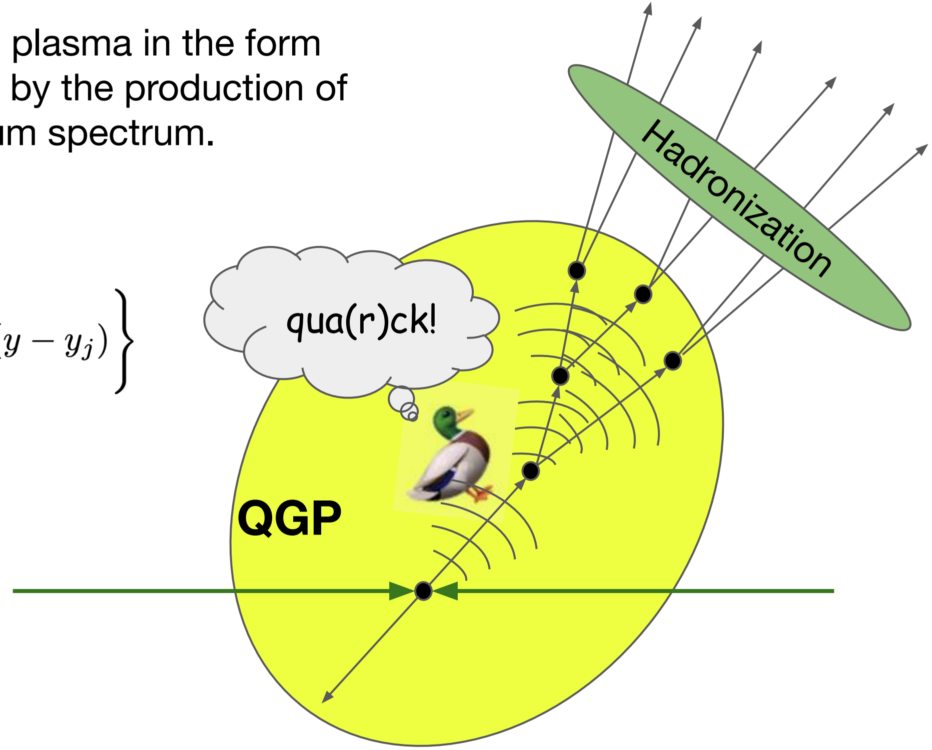




arXiv:1405.3864v3 [Casalderrey-Solana, et al.]

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.

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



A way to think of this is that 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:

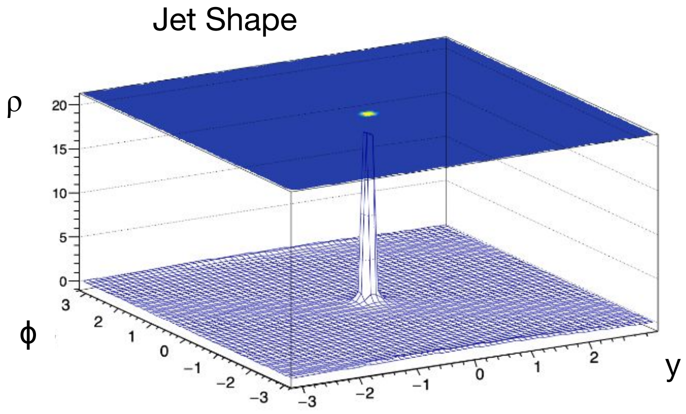
1) Additional soft particles in the jet direction
2) A depletion of soft particles in the direction opposite the jet

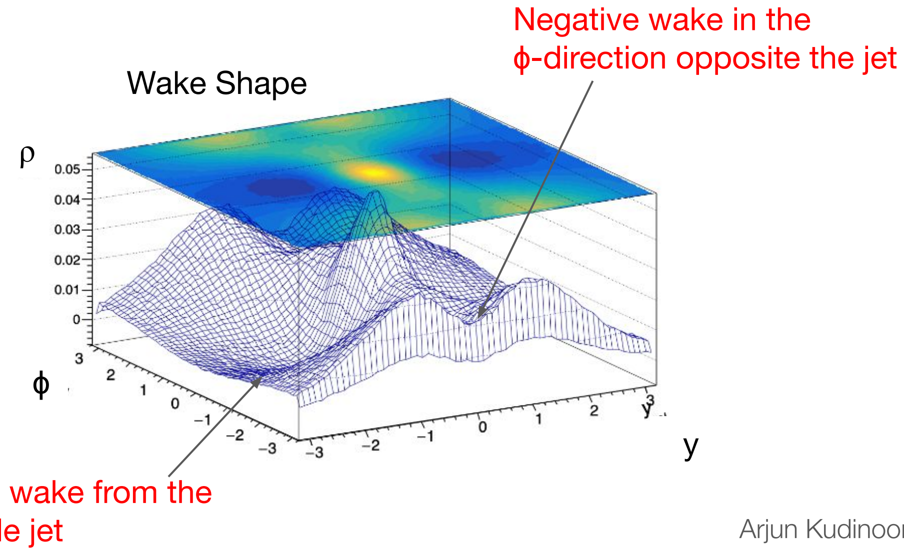
arXiv:1405.3864v3 [Casalderrey-Solana, et al.]

THE WAKE IN THE HYBRID STRONG/WEAK COUPLING MODEL OF JET QUENCHING

After running the Hybrid Model Monte Carlo for Pb+Pb collisions, a list containing three types of outgoing hadrons is produced:

- **Non-wake** particles: Hadrons that result from jet fragmentation
- **Positive wake** particles: Wake hadrons due to a jet pulling the plasma in its direction
- **Negative wake** particles: Wake “hadrons” that represent a depletion of the momentum distribution of the hadrons from the plasma in the direction opposite a jet



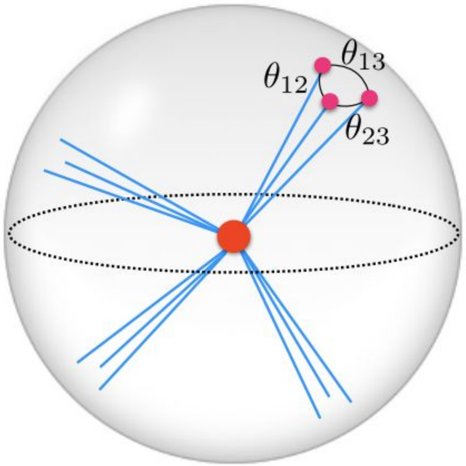


arXiv: 2407.13818

TOPIC 2

Imaging Jet-Induced Wakes Using Energy Correlators

ENERGY CORRELATORS



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

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

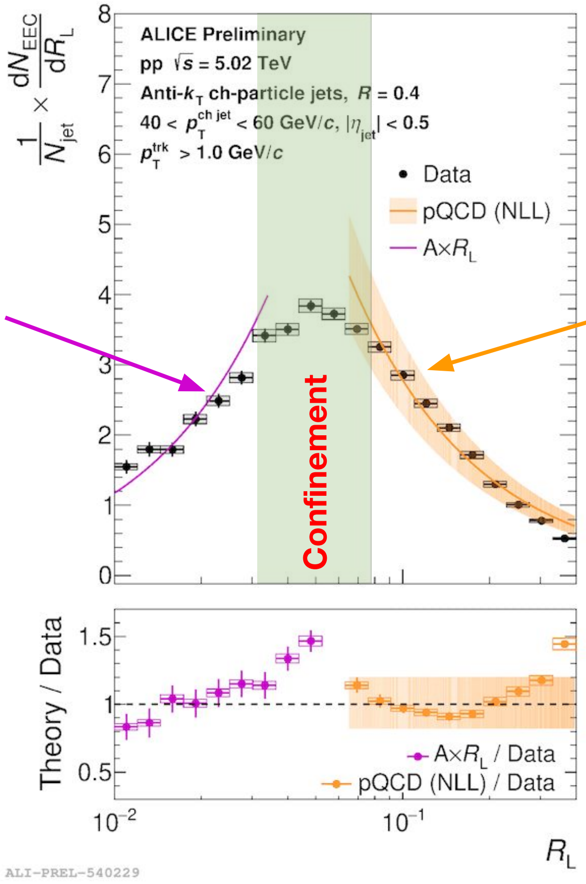
where $d\Omega_{\vec{n}}$ is the area element on the detector, $\Delta\hat{R}_L$ is an operator selecting the largest angular distance between the N particles, and the average is over an ensemble of jets with energy E_{jet}.

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.

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)

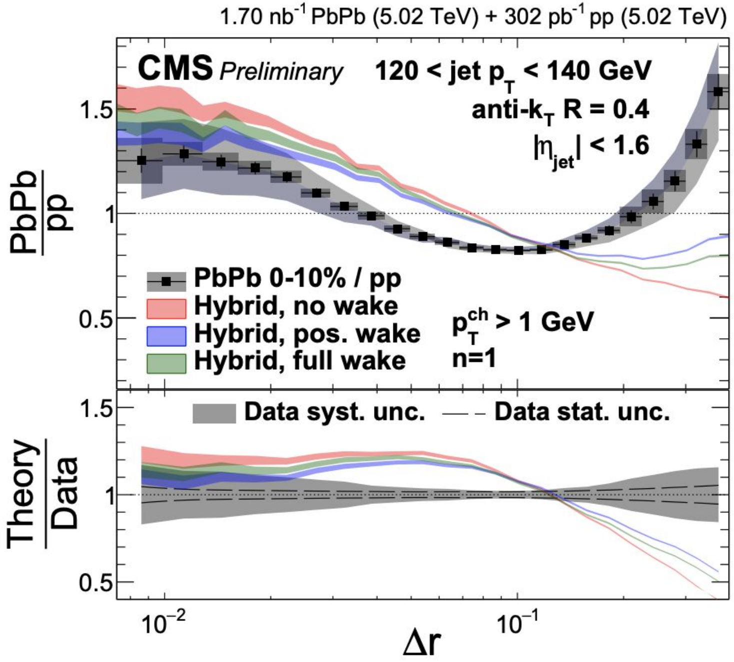
CHARGED-JET EECs IN-MEDIUM vs. IN-VACUUM

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

- The wake populates the large-angle region of phase space that is relatively unpopulated in vacuum (no QGP). This pushes the EEC up at large R_L (here Δr).

- Our Hybrid Model predictions **underestimate** the large-angle enhancement in the EEC ratio.
  - The wake is too wide and too low energy.
  - Other features like elastic scattering, transverse momentum broadening, etc. are not included in the model prediction and may affect EECs at high angles.

CMS-PAS-HIN-23-004

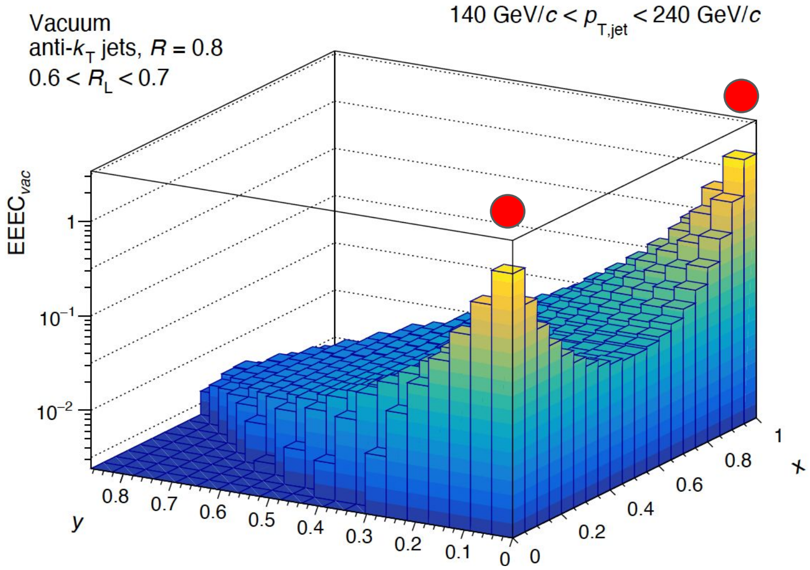


Pablos, Kudinoor, Rajagopal

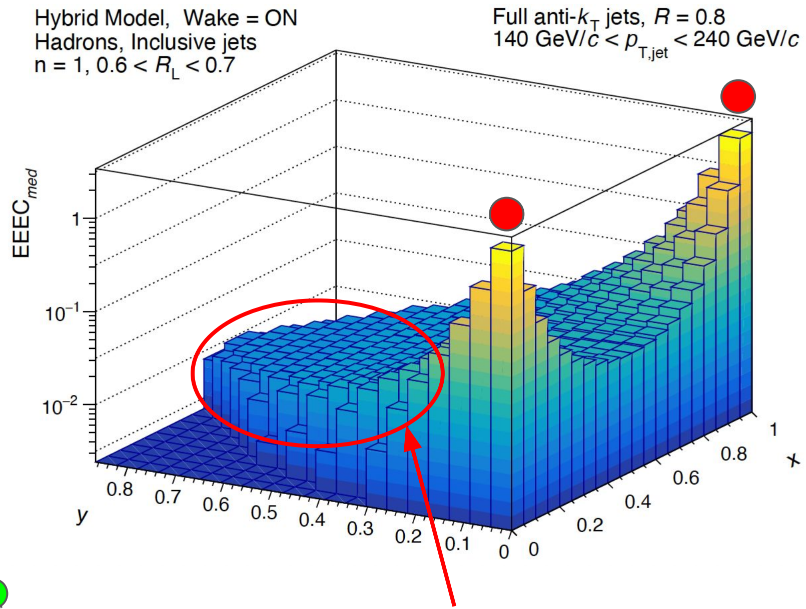
Image Credit: Jussi Viinikainen

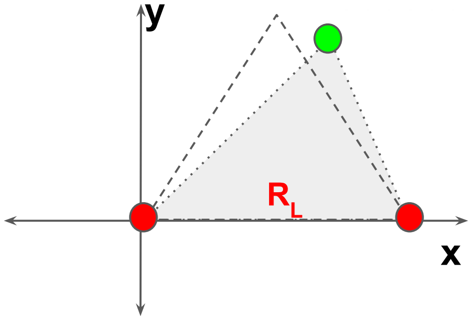
3-POINT EEECs IN-VACUUM vs. IN-MEDIUM

Vacuum EEEC



Pb+Pb With Wake EEEC

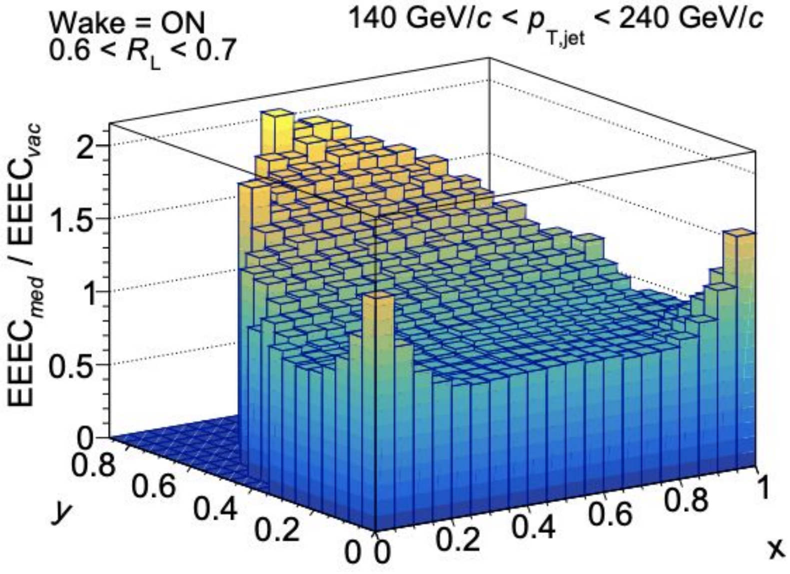




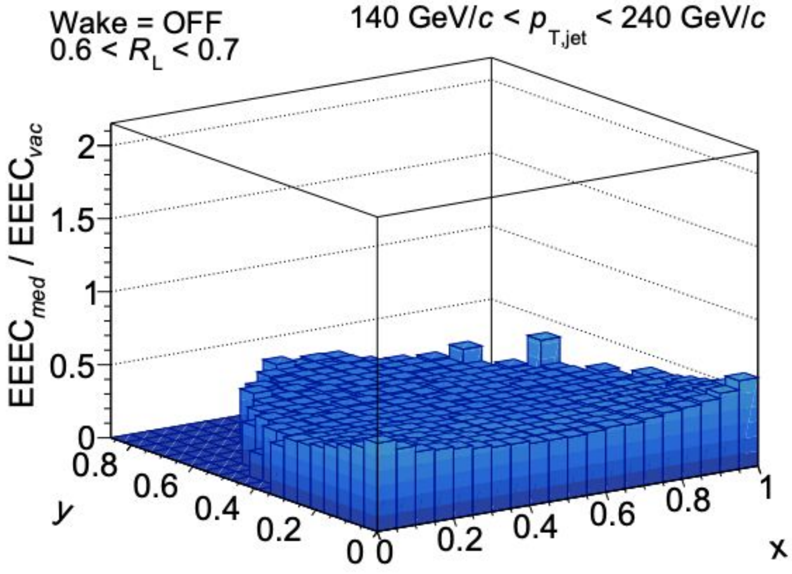
The wake fills in the phase space relatively unpopulated in vacuum.

arXiv: 2407.13818 [Bossi, et al.]

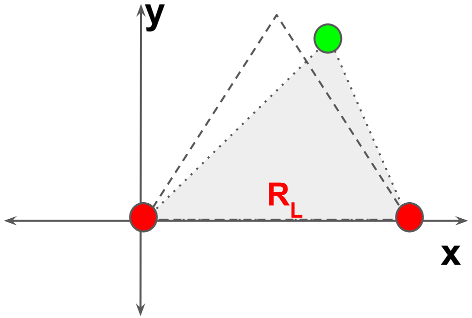
3-POINT EEEC RATIOS WITH AND WITHOUT WAKES



WITH WAKE

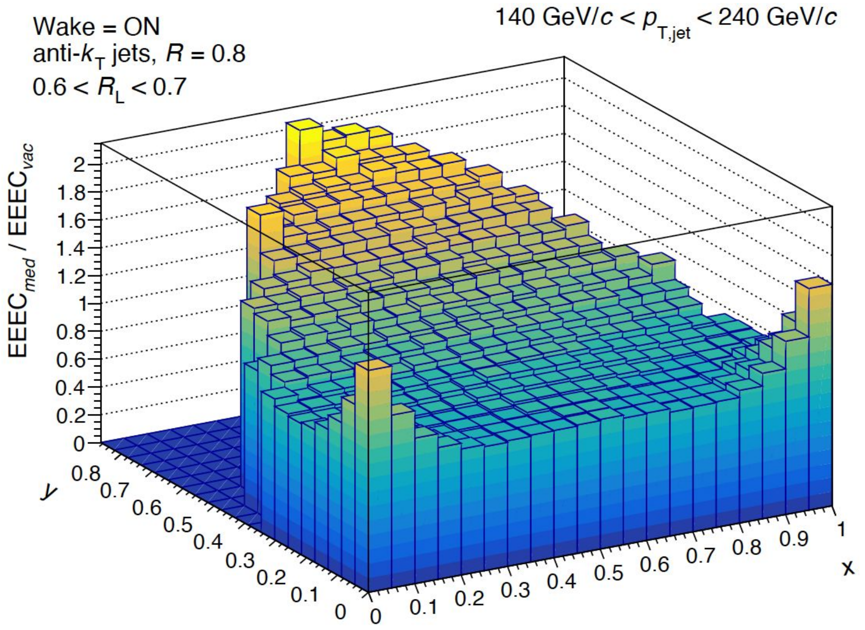


WITHOUT WAKE



arXiv: 2407.13818 [Bossi, et al.]

- **At large angles, over a broad kinematic range, medium/vacuum ratio is completely dominated by the wake.**
- **The shape of the medium response is encoded into an enhancement of equilateral structures in the EEEC, seen most prominently using the medium/vacuum ratio.**
- **Let's look for this large signal in other models and experiments!**



arXiv: 2407.13818 [Bossi, et al.]

TOPIC 3
Imaging Wake Substructure Using Novel Jet-Shape Observables

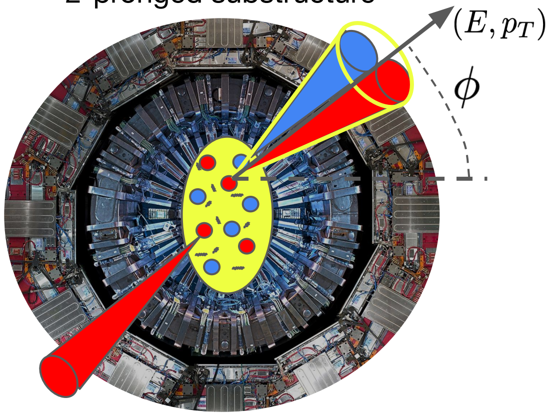
GUIDING QUESTION

Does the wake have an internal structure?

More specifically, does the internal structure of a jet affect the internal structure of its wake?

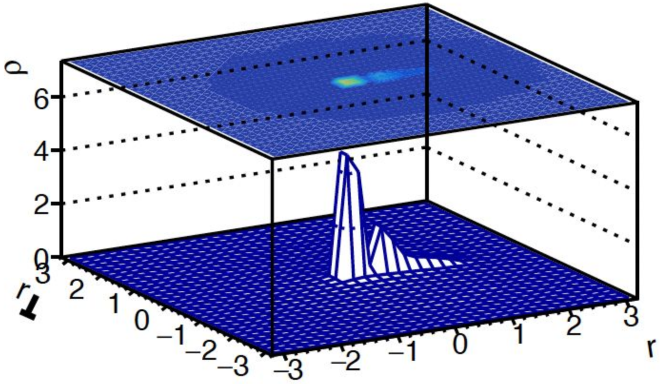
- Jet shapes measure the angular distribution of hadronic energy within a jet
- This allows us to literally visualize the internal structure of jets

2-pronged substructure



Detector image from: CMS

Jet Shape



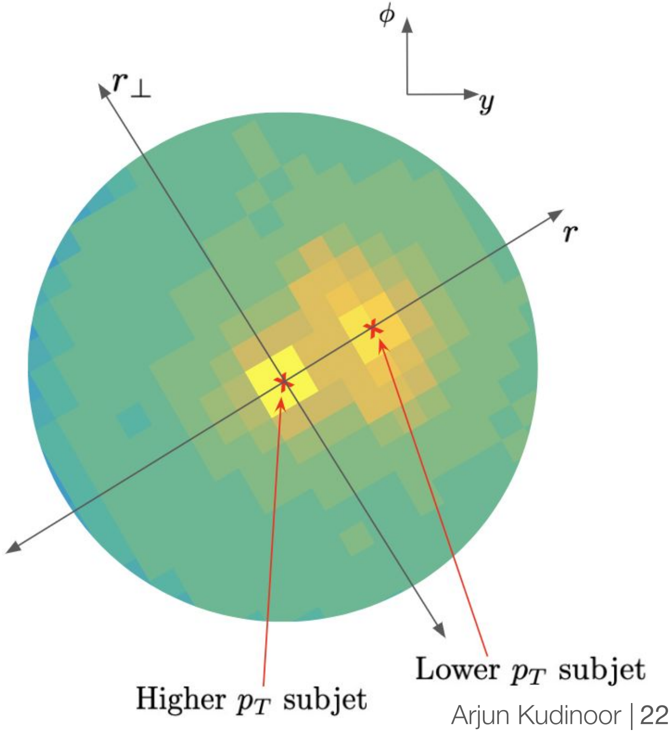
Jet Selection Criteria

1) Construct R = 0.2 anti-kt jets with p_T > 35 GeV and $|\eta|$ < 3.0.
2) Construct R = 2.0 k_t-jets with the R = 0.2 jets as the constituents of the large-radius jet.
3) Select those large-radius R = 2.0 jets with $|y|$ < 2.0, 50 < p_T < 1000 GeV, and two R = 0.2 (sub)jets.

Jet Shapes

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

$$\rho^{1d}(r) = \text{Proj}_r(\rho^{2d}(r, r_\perp))$$



Remarks

- 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.
- When experimentalists measure jet shape, they have to subtract the background – we don't have to do this.
- Only including hadrons from the wake in our calculation of jet shape allows us to plot the shape of the large-radius jet-wake.

GAMMA-JETS IN Pb+Pb COLLISIONS

- We first show results of the jet shapes calculated for gamma-jet events in Pb+Pb collisions, without elastic scattering. Gamma-jets are jet events where the recoiling jet is a photon.

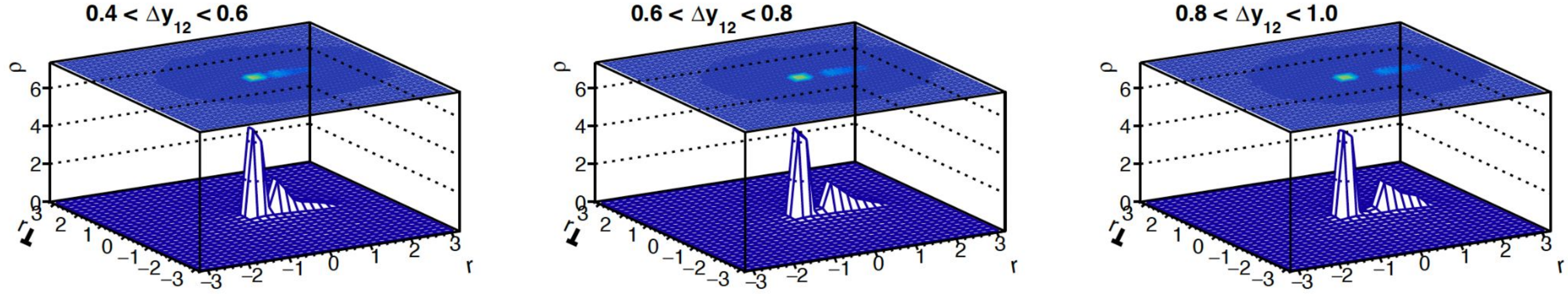
- The photon produces no wake of its own, and so the jet shape will look cleaner than in the case of dijet events (events with almost back-to-back jets).

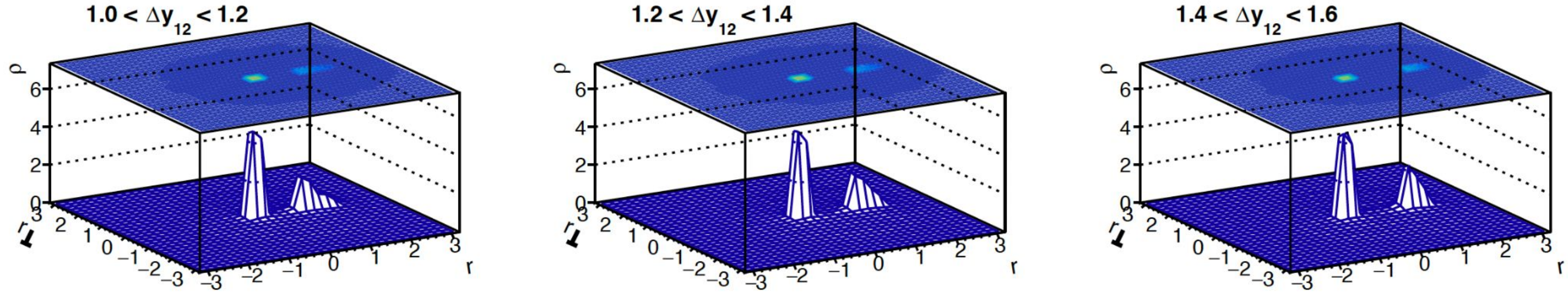
- Photons were selected using the following selection and isolation criteria:
    - $p_T^{\gamma} > 100$ GeV
    - $|\eta^{\gamma}| < 1.44$
    - The total transverse energy around a 0.4 radius of the photon must be less than 5 GeV
    - $\Delta\phi_{\gamma,\, jet} > 2\pi/3$

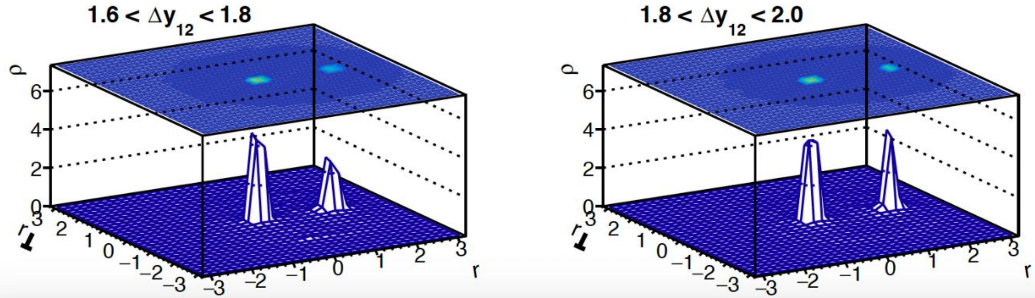
Important note: The photon is not considered a jet on its own in our analysis. So, **none of the photons contribute to the jet shape observables** we calculated.

- Large radius R = 2.0 jets were constructed from R = 0.2 subjets whose $|p_T| > 35$ GeV and $|\eta| < 3.0$. In our analysis of gamma-jets, we restricted to examining only those large-radius jets with $|y| < 2.0$, $50 < p_T < 1000$ GeV, and 2 subjets.

Pb+Pb: FULL JET SHAPE



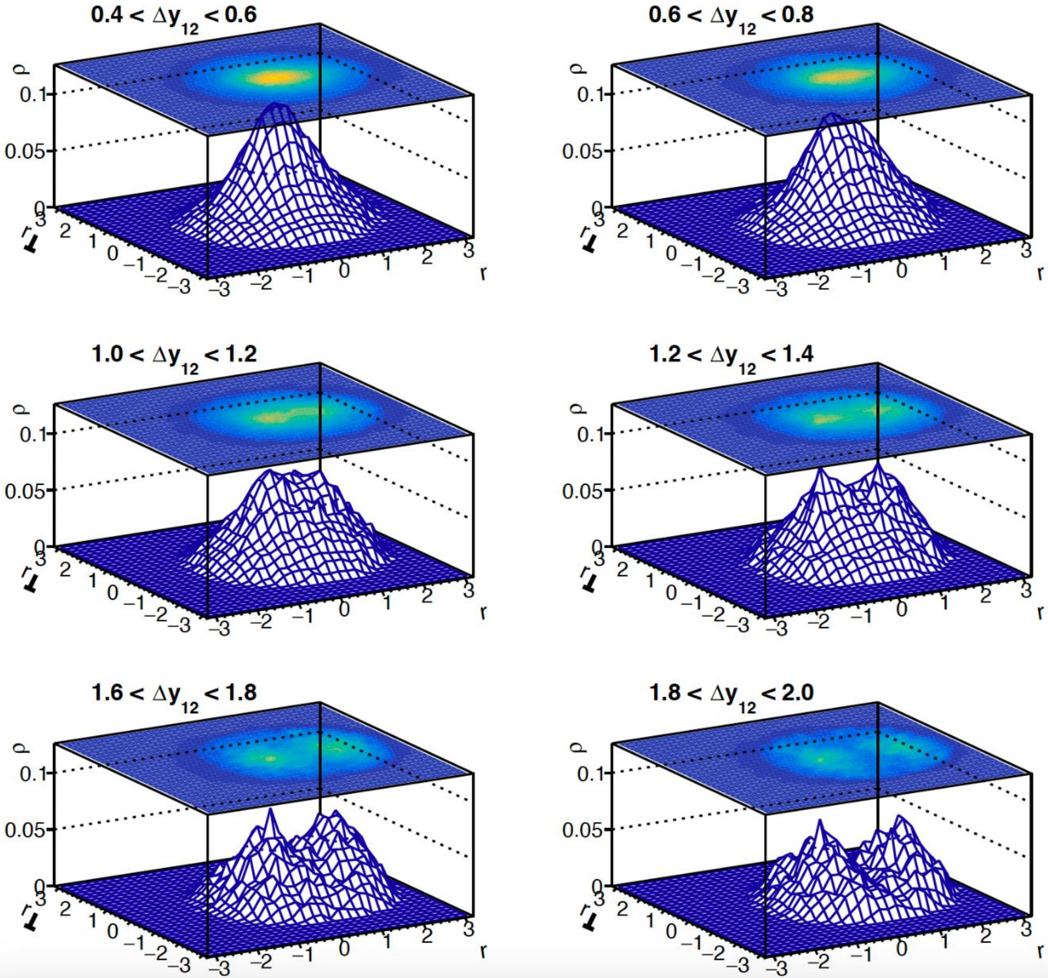




PbPb, 5.02 TeV, 0-5%

- **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**

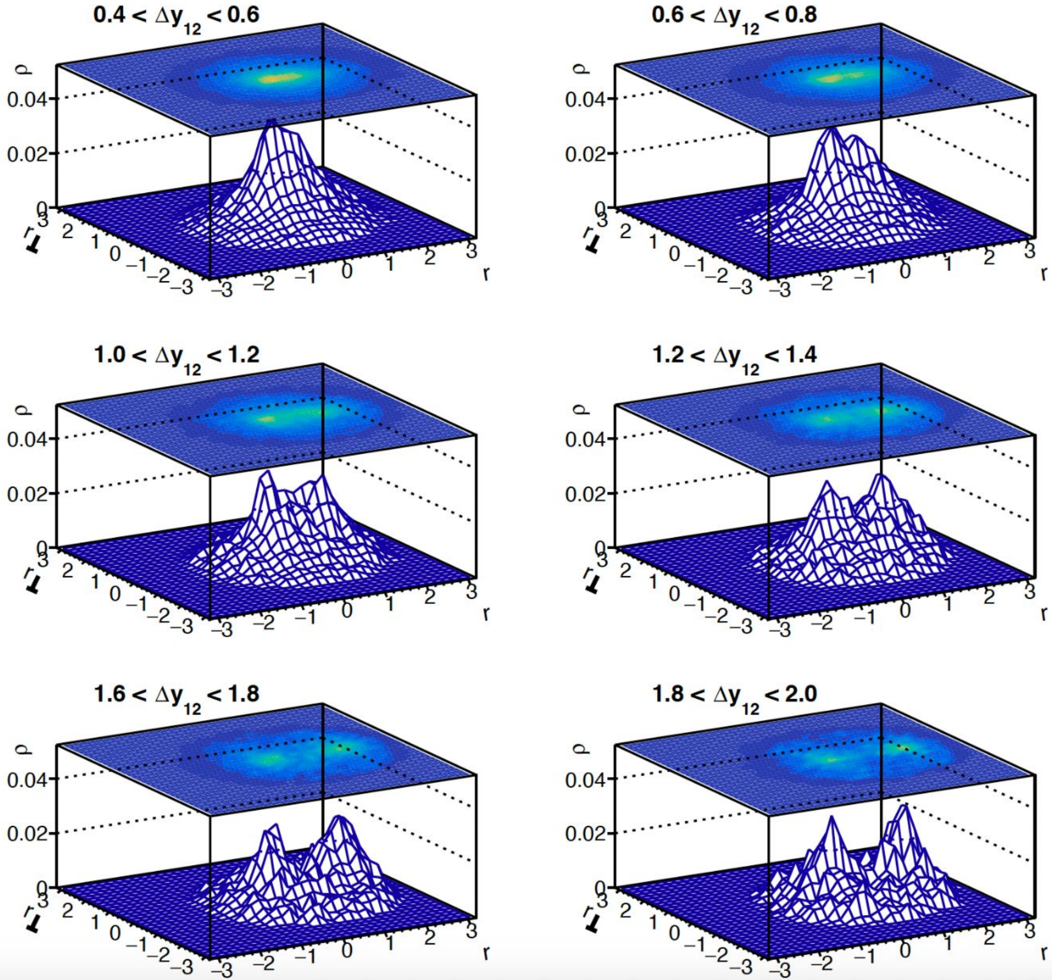
Pb+Pb: WAKE SHAPE



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

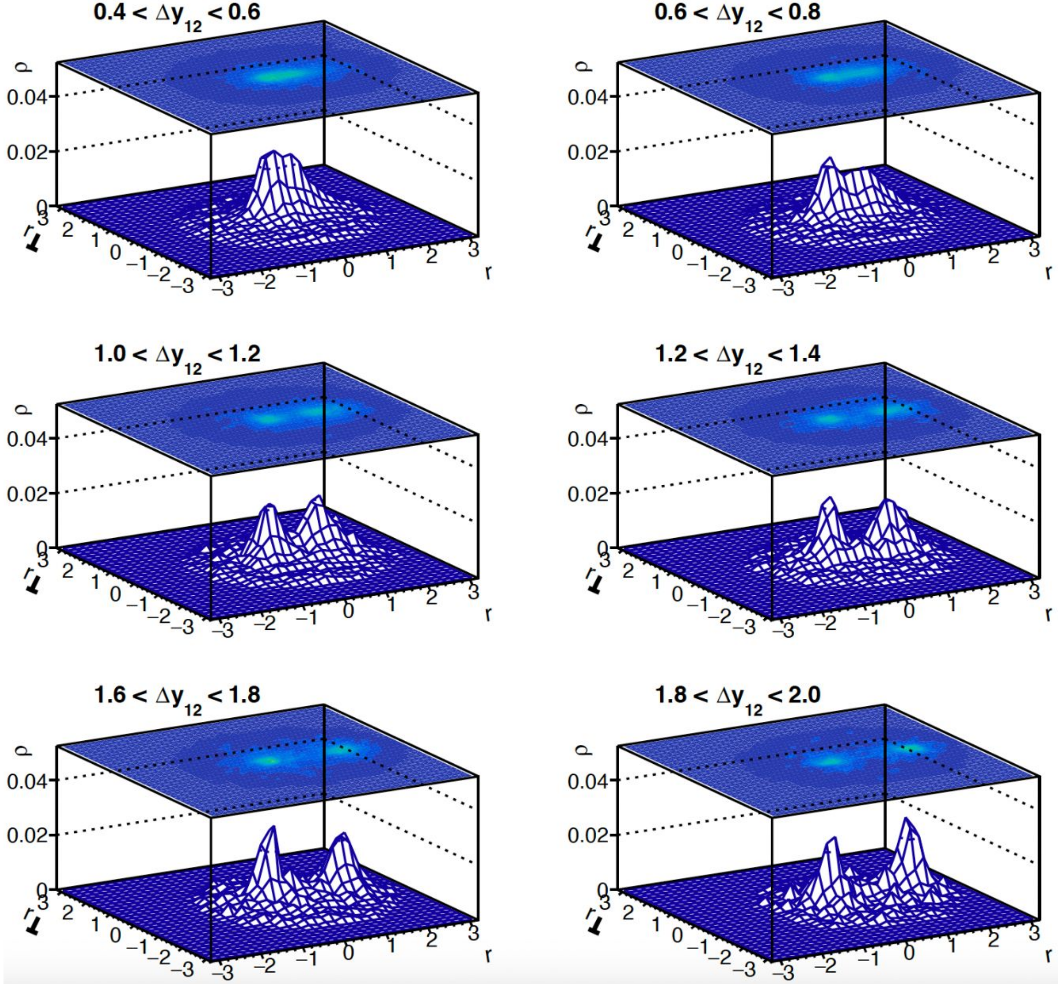
Can we see this in experiments?

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



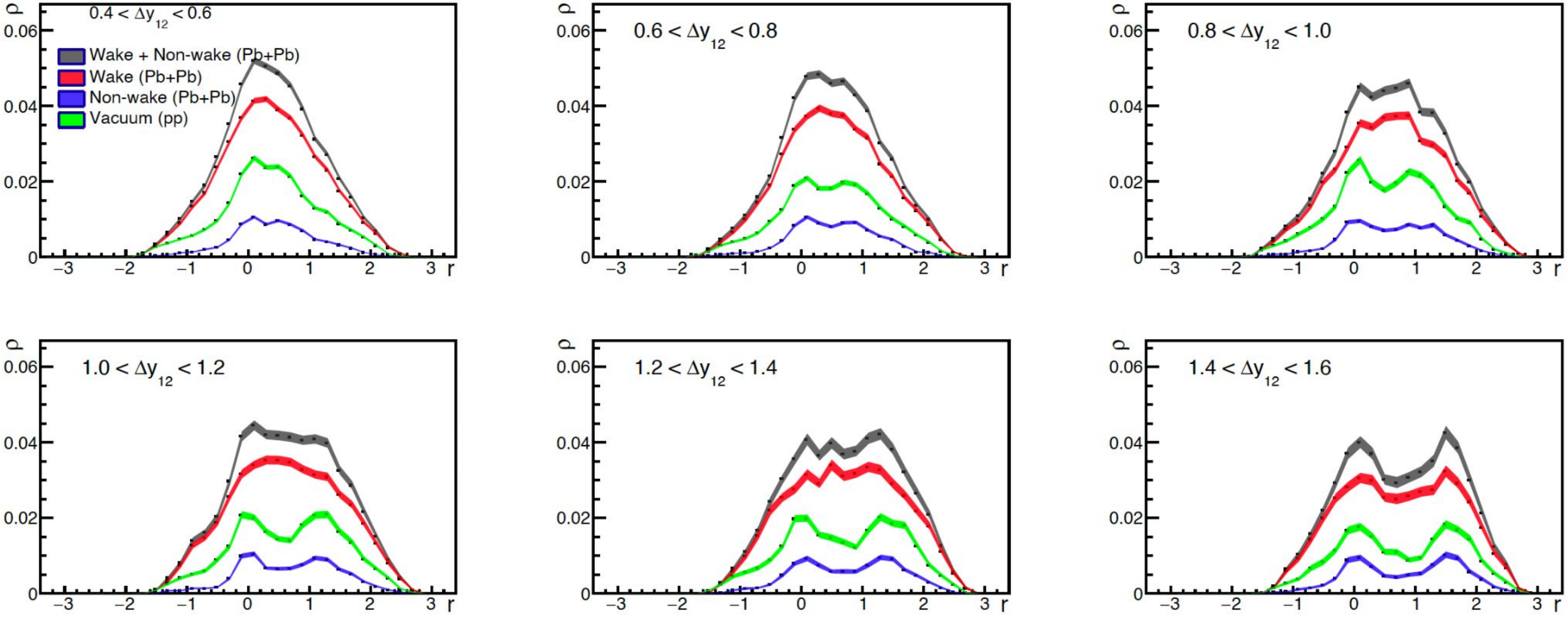
Only a single-pronged structure is visible at low angular separation even when low-p_T non-wake particles are included. However, two-pronged structures appear at lower angles than when we restrict to using only hadrons belonging to the wake.

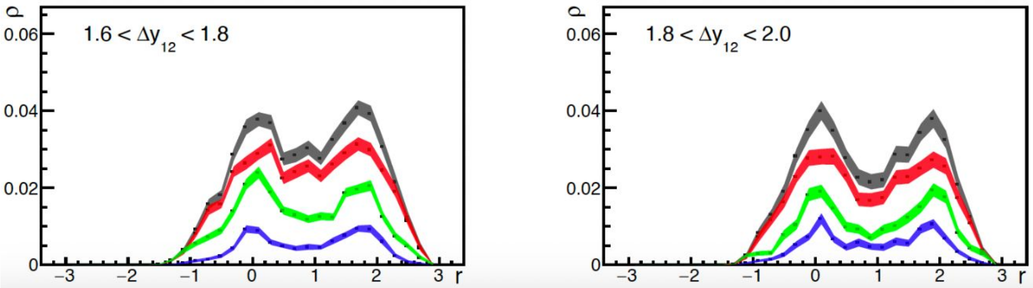
VACUUM (pp): SHAPE OF HADRONS WITH 0.7 < p_T < 1.0 GeV



In the absence of the QGP, very sharp two-pronged structures appear at much lower angles than when QGP (and thereby wakes) is present.

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





The wake (red) dominates this kinematic region, and so experiments that can access this region of hadrons can plot the grey band.

This would allow us to literally SEE the substructure of large-radius jet-wakes!

SUMMARY

- **Jets are useful probes of QCD physics at high, but still finite, temperatures.**

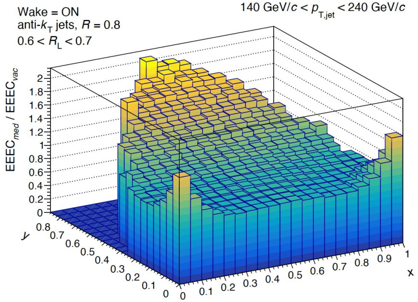
- **Jet-wakes tell us how high-energy partons interact with the strongly coupled QGP.**

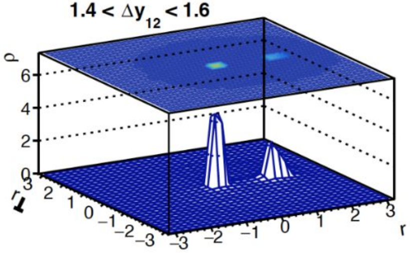
- **We can image the wake using energy correlator and jet shape observables.**

- **The structure of jets shapes the structure of their wakes in a way that can be imaged.**

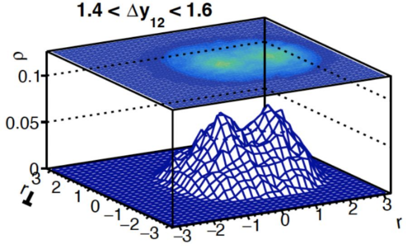
- **Let's look for similar signals of jet-wakes and their substructure in other models and experiments!**

THANKS FOR LISTENING!





Jet Shape



Wake Shape

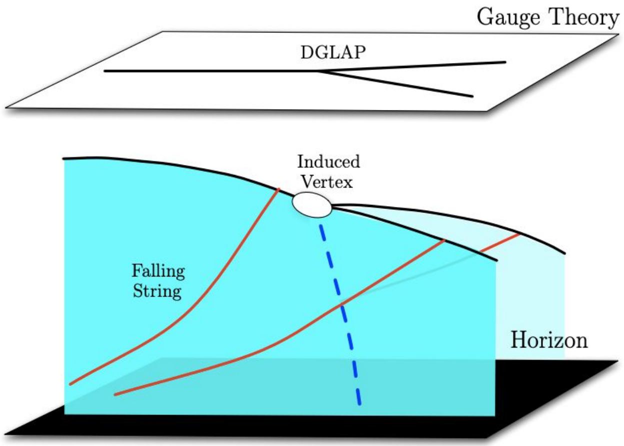
Feedback

BACKUP

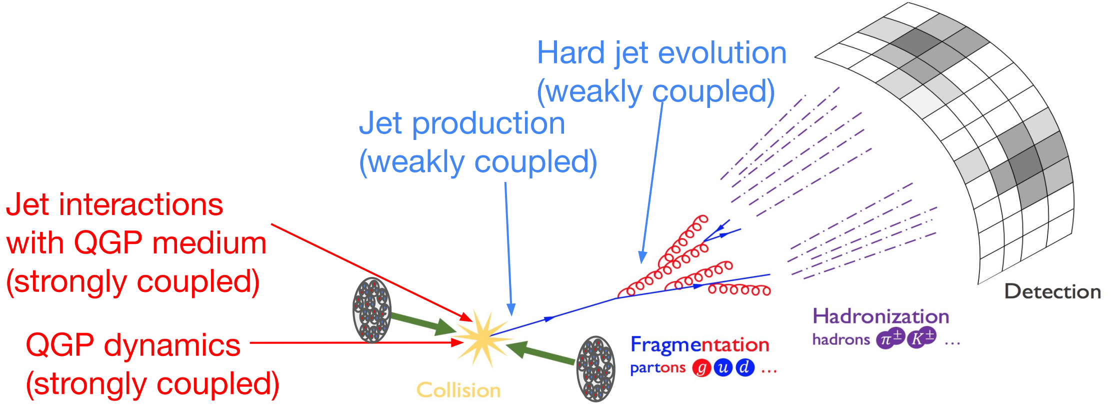
THE HYBRID STRONG/WEAK COUPLING MODEL

- 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/

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)

Slide Credit: Krishna Rajagopal

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...

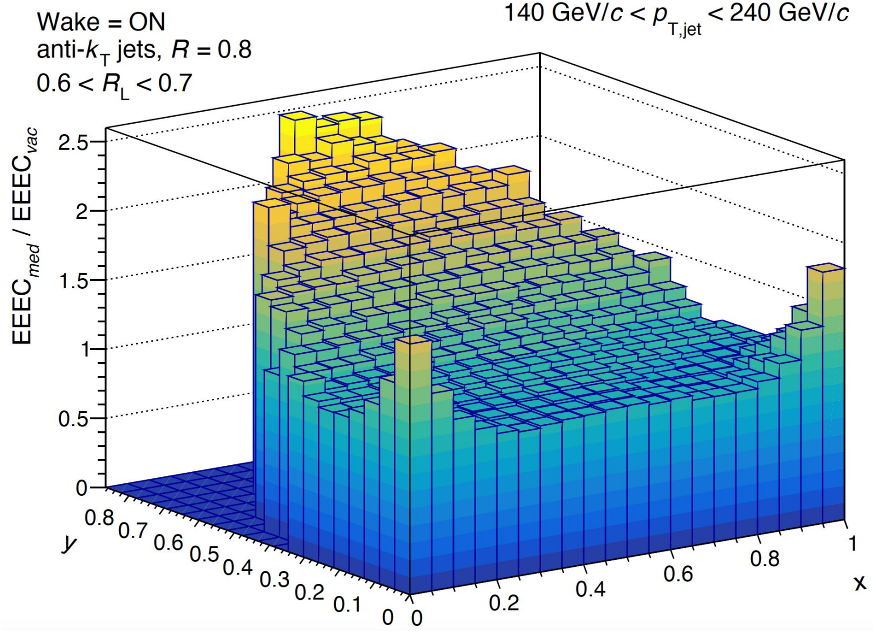
Slide Credit: Krishna Rajagopal

Missing p_T observables – 2016

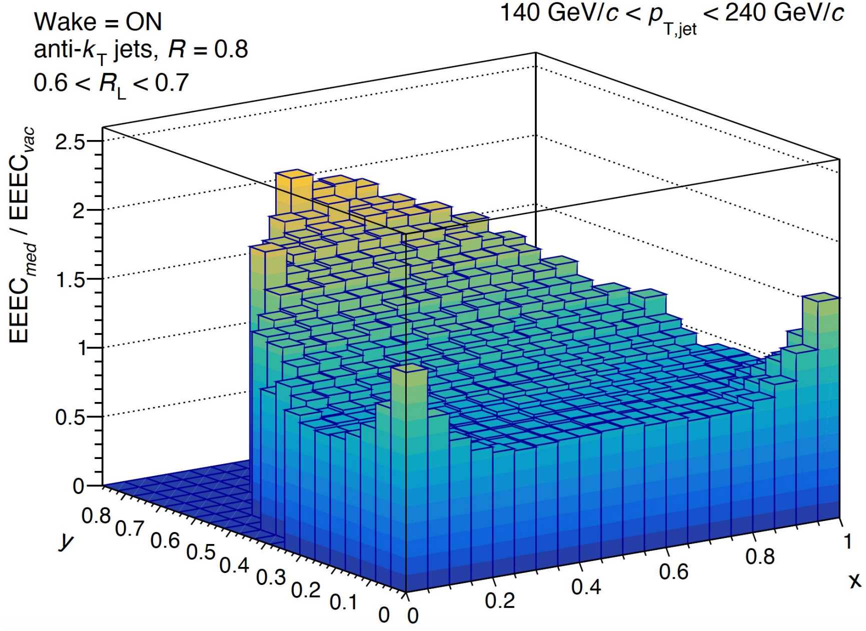
- Our characterization of the wake is on the right track. BUT:
- We have too many particles with 0.5 GeV$< p_T <$2 GeV.
- We have too few particles with 2 GeV$< p_T <$4 GeV.
- The energy and momentum given to the plasma by the jet may not fully thermalize. Further improving our model to describe the 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?

After subtracting the negative wake particles from inclusive-jet events, the equilateral enhancement is reduced, but still significant.

Ignoring negative wake particles altogether

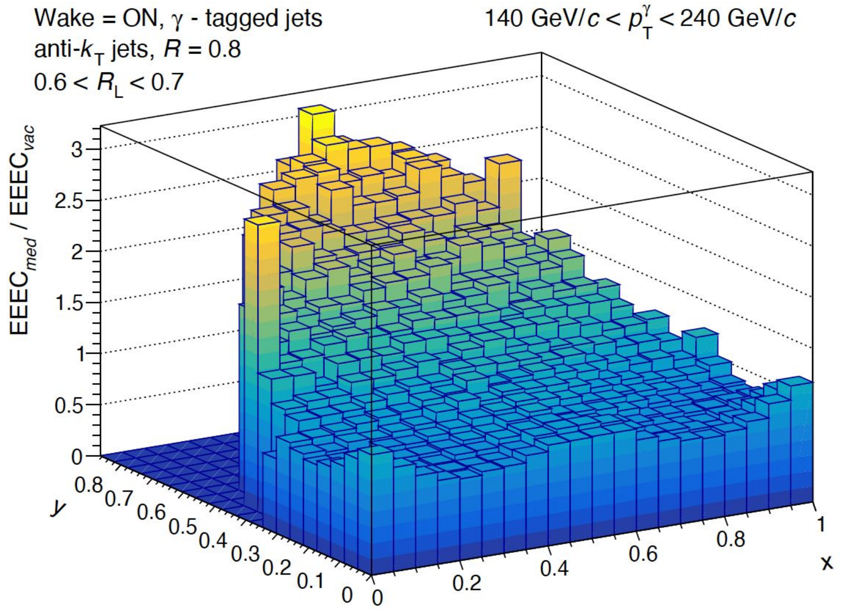


Negative wake subtracted



Negative wake has almost no effect on the equilateral enhancement of gamma-jet EEECs!

Ignoring negative wake particles altogether



Negative wake particles subtracted with R_{sub} = 0.5