Arjun Kudinoor
ask81@cam.ac.uk

Massachusetts Institute of Technology

Using AdS/CFT to visualize jet and wake-substructure in heavy ion collisions

Abstract and more info

Arjun Kudinoor
Collaborators: Krishna Rajagopal (MIT), Daniel Pablos (INFN)

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Arjun Kudinoor
ask81@cam.ac.uk

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- Visualizing jet and wake substructure
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TOPIC 1
Quark gluon plasma and jets

Arjun Kudinoor
ask81@cam.ac.uk

DROPLETS OF THE EARLY UNIVERSE

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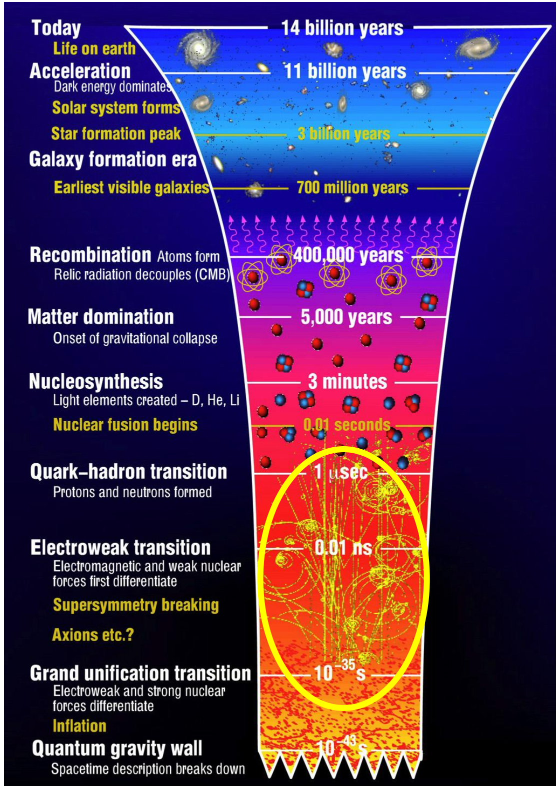
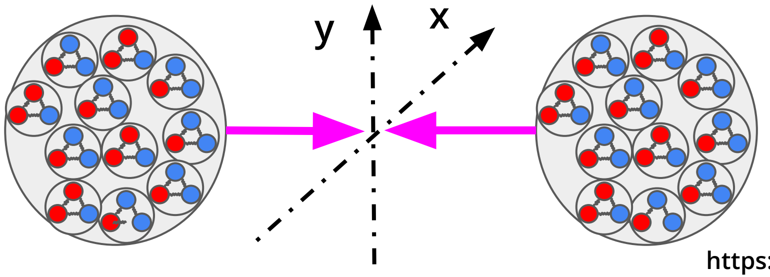
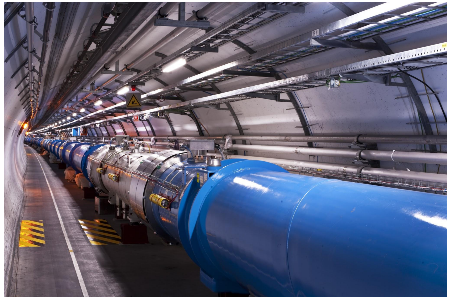
1. THE EARLY UNIVERSE



From: Centre for Theoretical Cosmology, Cambridge University

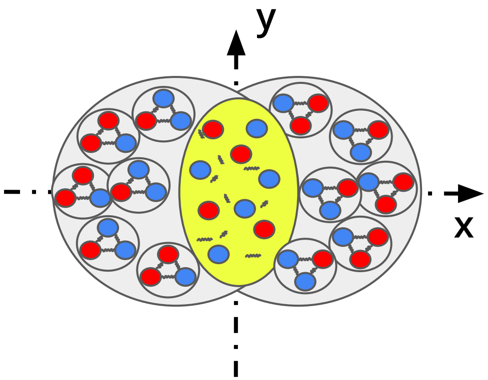
2. HEAVY ION COLLISIONS





https://en.wikipedia.org/wiki/Large_Hadron_Collider

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

Arjun Kudinoor
ask81@cam.ac.uk

PROBING THE PHYSICS OF QUARK GLUON PLASMA

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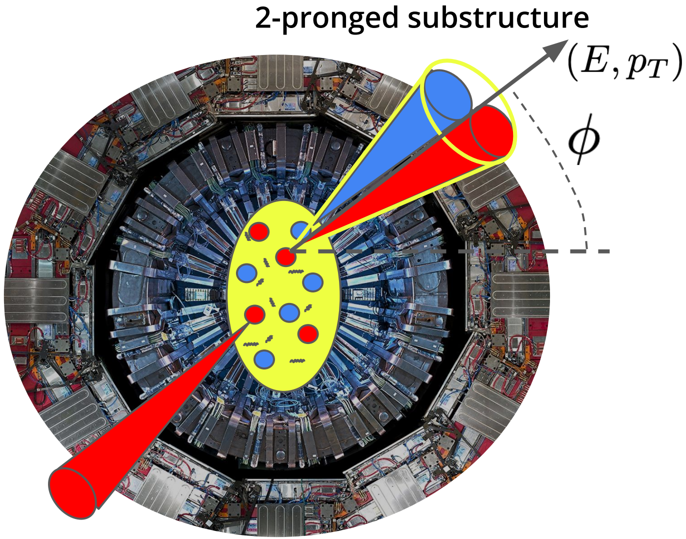
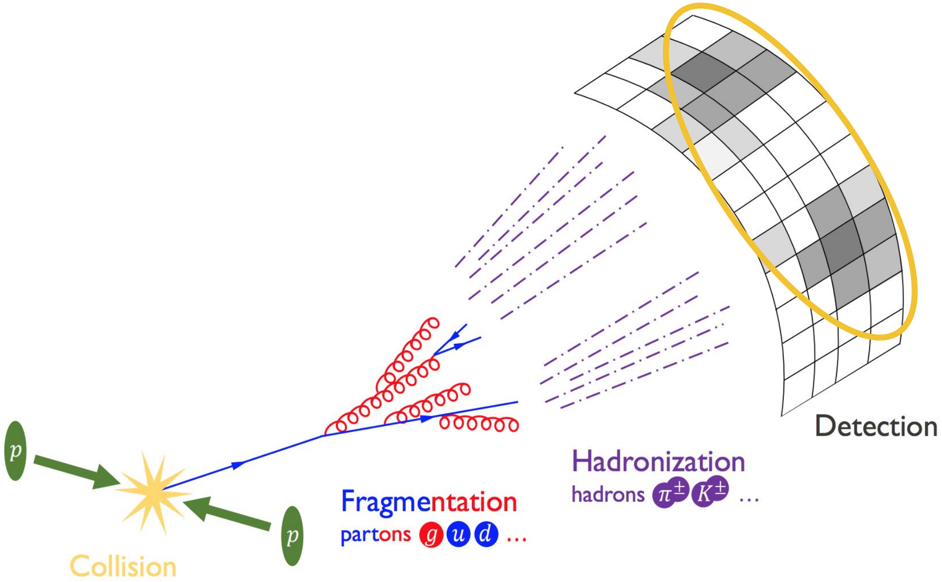
Often, energetic sprays of hadrons shoot out of the QGP. We call these sprays jets.
Jets are probes to understand the physics of QGP because they carry information about **energy, momentum, angular distribution, and internal structure** that can reveal the nature of QCD physics in quark gluon plasma.

Example: Jet energy loss can tell us about the viscosity and density of QGP



Detector image from: CMS



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

Seems simple enough... What’s the catch?

Arjun Kudinoor
ask81@cam.ac.uk

THE STRONG/WEAK COUPLING PROBLEM

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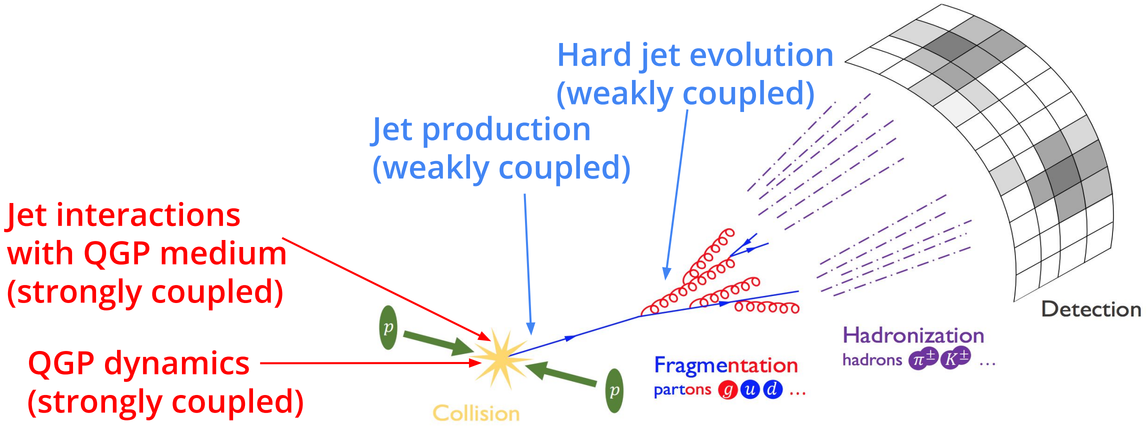
The physics of jets and QGP hydrodynamics have both weakly and strongly coupled aspects. Calculations are intractable at strong coupling using standard perturbative methods.

"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)



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Arjun Kudinoor
ask81@cam.ac.uk

How do we perform jet energy loss calculations at strong coupling?

TOPIC 2
Using AdS/CFT
A useful nonperturbative technique

Arjun Kudinoor
ask81@cam.ac.uk

THE HYBRID/STRONG WEAK COUPLING MODEL

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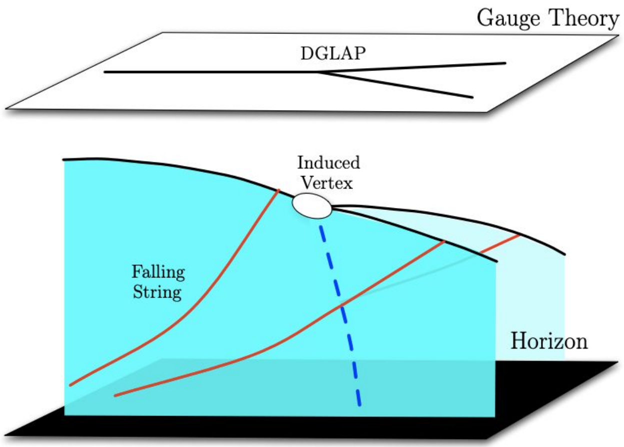
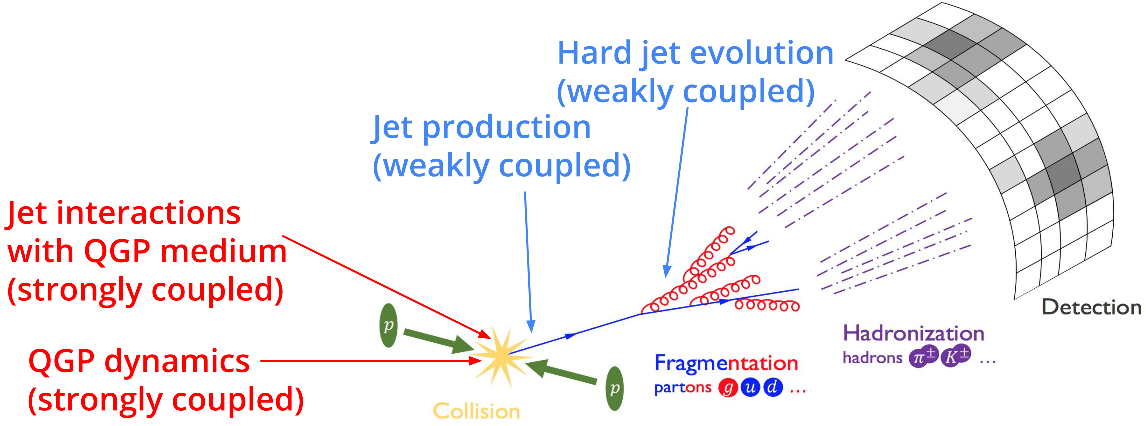
- Treat weakly coupled physics perturbatively
- Treat strongly coupled processes using AdS/CFT
    - Find the stringy gravity dual of QCD ← **umm...**
    - Describe your particles in using strings that hang from the boundary theory into the bulk spacetime
    - Calculate the observables you desire (energy loss, momenta, etc.)

Difficult calculations in strongly coupled gauge theories may be solved in its more tractable weakly coupled (small curvature) gravitational dual.



arXiv:1405.3864v3



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Arjun Kudinoor
ask81@cam.ac.uk

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

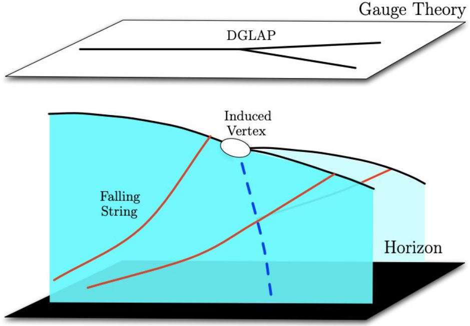
- $N_c=3$ for QCD, whereas we take the $N_c \to \infty$ limit for $\mathcal{N}=4$ SYM calculations
- QCD is not conformal, whereas $\mathcal{N}=4$ SYM is conformal
- QCD demonstrates asymptotic freedom (coupling becomes weaker as energies increase to infinity), whereas $\mathcal{N}=4$ SYM is strongly 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, and must be, treated qualitatively and not quantitatively.

Arjun Kudinoor
ask81@cam.ac.uk
Massachusetts Institute of Technology

THE HYBRID MODEL IN PRACTICE

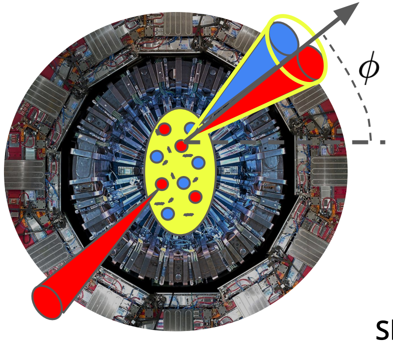
- $\mathcal{N} = 4\ SU(N_c)$ SYM theory $\longleftrightarrow$ IIB string theory in $AdS_5 \times S_5$
  - Cast particles as strings hanging from the 4-dimensional boundary into the 5-dimensional AdS bulk spacetime
  - Calculate observables of interest (ex: energy loss)
- Monte Carlo simulations of heavy ion collisions
  - Feed in some holographic calculations from above
  - Run the simulation and manipulate the output data to calculate more **observables that experimentalists can verify** using actual collider data



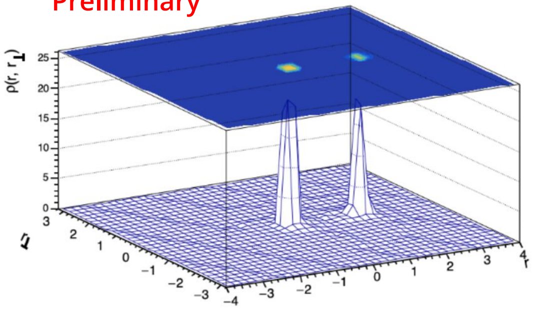
arXiv:1405.3864v3

JET SUBSTRUCTURE

2-pronged substructure

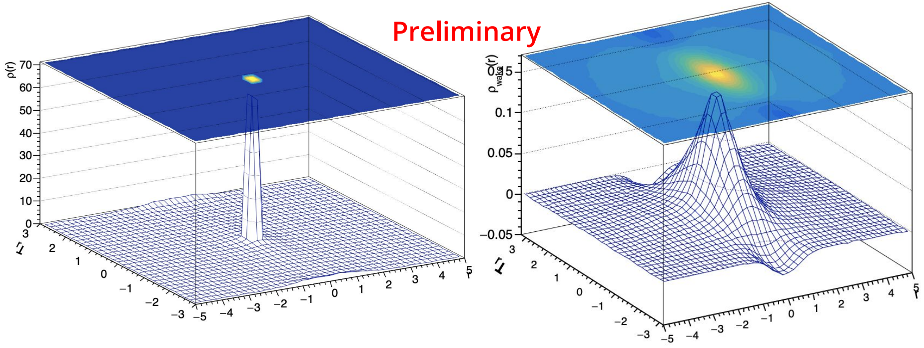


Detector image from: CMS



Shape of R = 2.0 anti-kt jet with 2 subjets separated by 1.8 < Δy < 2.0 (Pb+Pb collisions)

JET-WAKES



Shape of R = 0.2 anti-kt jet (left) and its wake (right) in 0-5% centrality Pb+Pb collisions

TOPIC 3
Visualizing jet and wake substructure

Guiding question: When are the wakes left by different hard structures (jets) distinguishable?

Constructing Wide Jets from Skinny Subjets — ATLAS

[arXiv: 2301.05606] In Oct 2023, ATLAS published a paper that studied the substructure-dependence of large-radius jet suppression in Pb+Pb collisions at 5.02 TeV. They used the following procedure to reconstruct the large-radius jets:

1) Skinny jets with radius R = 0.2 were reconstructed using the anti-k_T algorithm

2) Large-radius R = 1.0 jets, restricted to |y| < 2.0, were reconstructed by clustering the R = 0.2 skinny (sub)-jets with p_T > 35 GeV and |η| < 3.0 using the anti-k_T algorithm with R = 1.0

3) The k_T algorithm was used to recluster the R = 0.2 subjets of each large-radius R = 1.0 jet, to define two substructure observables

$$\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta\phi_{12}^2} \qquad \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$$

Respectively, these are the angular separation and k_T splitting scale between the two hardest constituents in the penultimate step of the k_T-reclustering

Example: If the large-radius jet had two R = 0.2 subjets, then these two subjets would be the two hardest constituents in question. If the large-radius jet had only 1 subjet, then $\Delta R_{12} = 0$ and $\sqrt{d_{12}} = 0$.

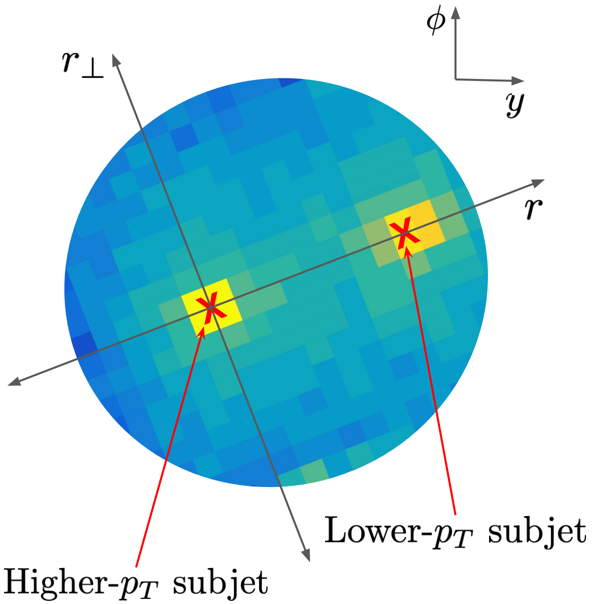
OUR COORDINATE SYSTEM

- We first constructed large-radius R = 2.0 jets from small-radius R = 0.2 subjets using the same procedure as ATLAS. We are using a larger radius of R = 2.0 to observe how the substructure of jet-wakes differs between closely-separated and far-separated subjets.

- Restrict to only R = 2.0 jets with 1 or 2 subjets

- Given a large-radius R = 2.0 jet with two subjets, we define a coordinate system (r, $r_\perp$) as such:

  1) Let the higher-p_T and lower-p_T subjets be located at $(y_{\rm high}, \phi_{\rm high})$ and $(y_{\rm low}, \phi_{\rm low})$, respectively.
  2) Define the origin of our new coordinates to be at $(y_{\rm high}, \phi_{\rm high})$ and define the r-axis to point positively in the direction of $(y_{\rm low}, \phi_{\rm low})$.
  3) Define the $r_\perp$-axis to be perpendicular to the r-axis, such that $\hat{r} \times \hat{r}_\perp = \hat{y} \times \hat{\phi}$.



- For an R = 2.0 jet with 1 subjet, the r-axis is centered on the y-coordinate of the subjet, and points in the y-direction. Similarly, the $r_\perp$-axis is centered on the ϕ-coordinate of the subjet, and points in the ϕ-direction

JET SHAPE OBSERVABLES

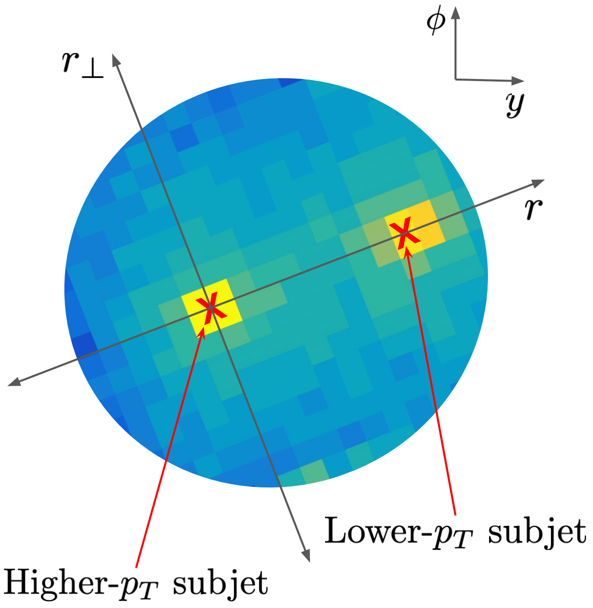
Now, we define the jet shape to measure the average fraction of a jet's transverse momentum within specified ranges of r and $r_\perp$. We can select large-radius jets in different ranges of ΔR_{12} (or Δy_{12}) to study the dependence of jet shape on subjet-separation.

For a specified range of ΔR_{12} (or Δy_{12}), we have the following jet shape observables:

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

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

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



Important 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.

TOPIC 4
Results from gamma-jet calculations

GAMMA-JETS IN Pb+Pb COLLISIONS

- We show results of the jet shapes calculated for gamma-jet events in Pb+Pb collisions. Gamma-jets are jet events where the recoiling jet is a photon.

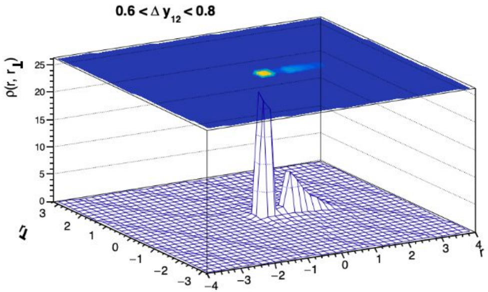
- The photon produces no wake of its own, and so the jet shape will look cleaner than in the case of dijet events (events with almost back-to-back jets).

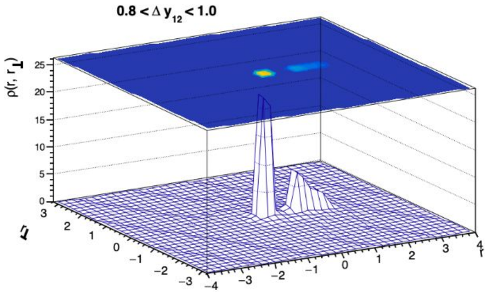
- Photons were selected using the following selection and isolation criteria:
  - $p_T^{\gamma} > 100$ GeV
  - $|\eta^{\gamma}| < 1.44$
  - The total transverse energy around a 0.4 radius of the photon must be less than 5 GeV
  - $\Delta\phi_{\gamma,\,jet} > 2\pi/3$

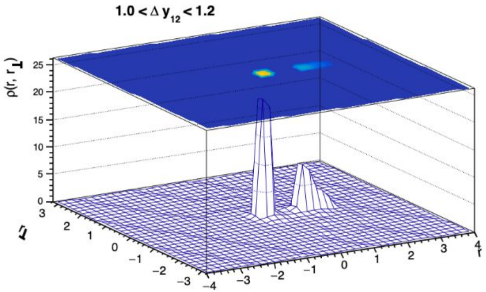
<u>**Important note:**</u> The photon is not considered a jet on its own in our analysis. So, **none of the photons contribute to the jet shape observables** we calculated.

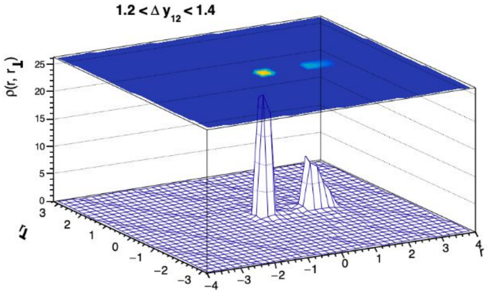
- Large radius R = 2.0 jets were constructed from R = 0.2 subjets whose $|p_T| > 35$ GeV and $|\eta| < 3.0$. In our analysis of gamma-jets, we restricted to examining only the large-radius jets with $|y| < 2.0$ and $50 < p_T < 1000$ GeV.

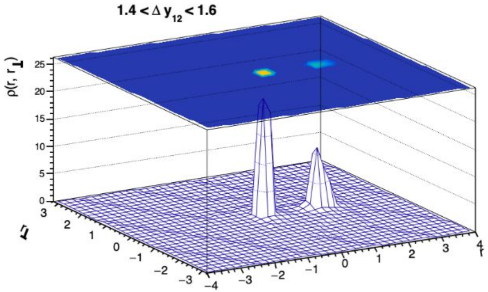
JET SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

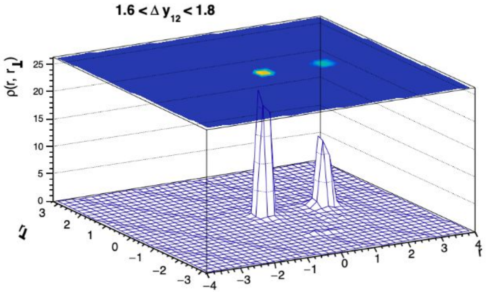


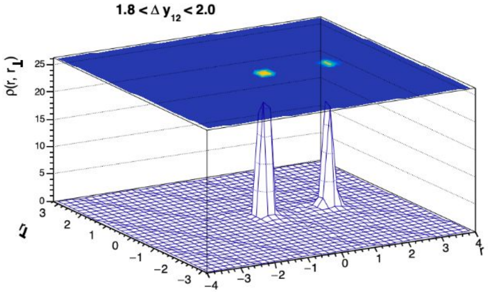






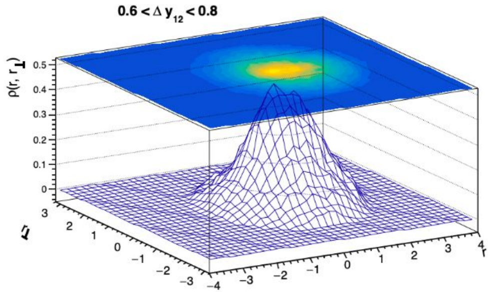


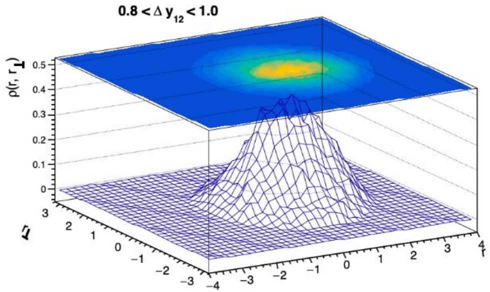


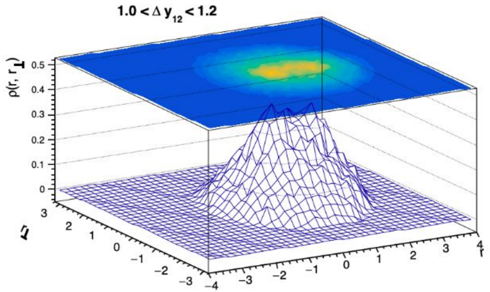


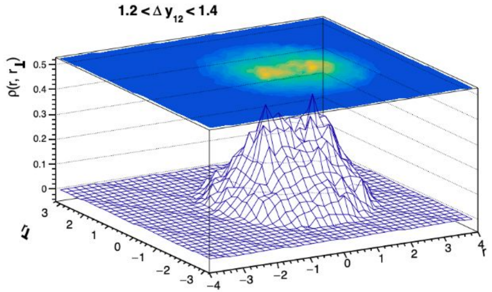
They look as we expected…

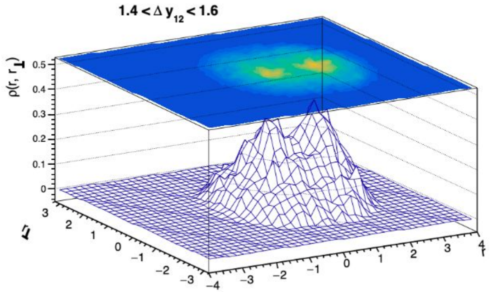
WAKE SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

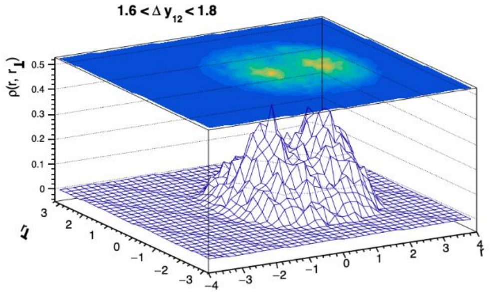


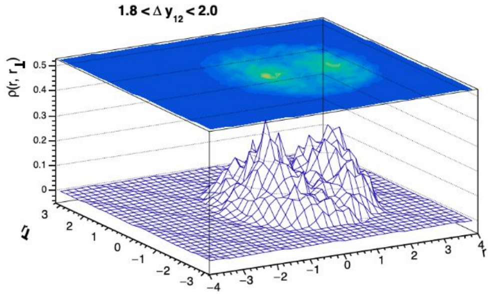








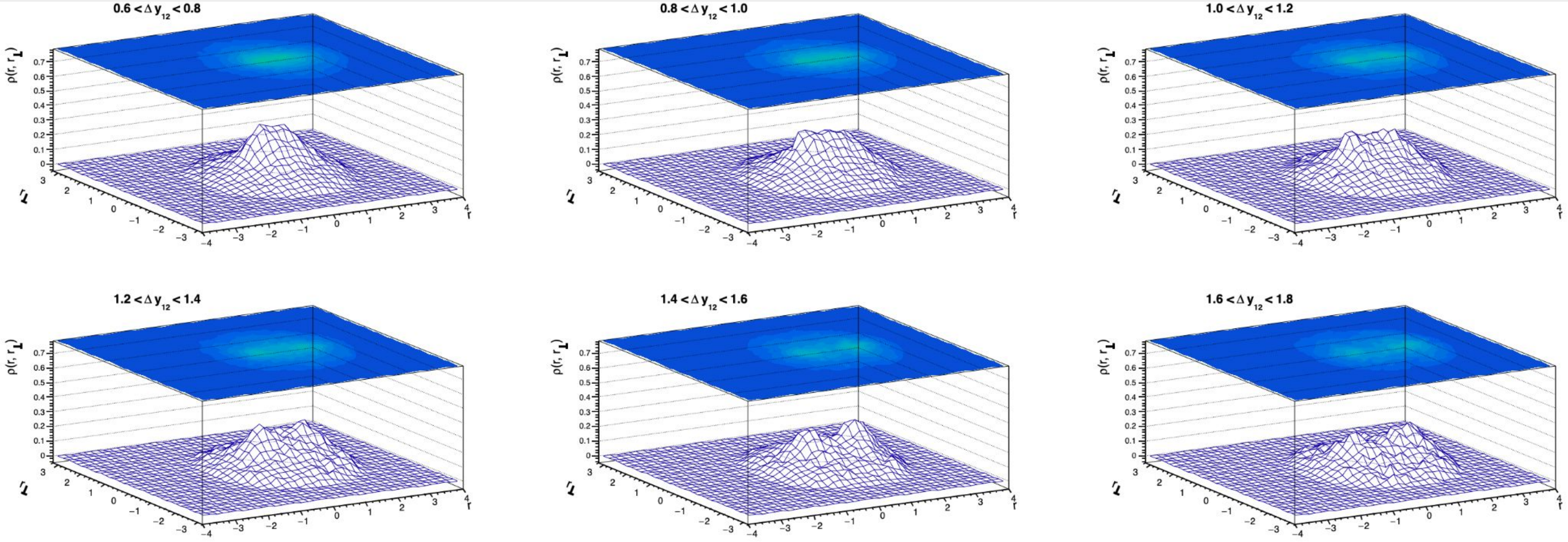


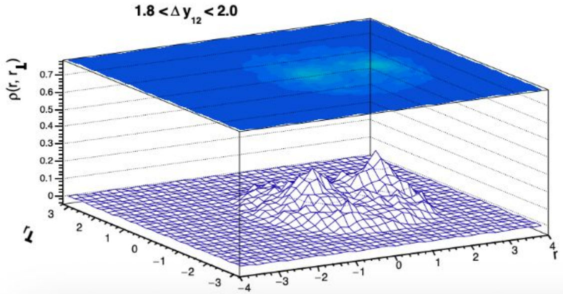


For closely-separated subjets ($\Delta y_{12} < 1.0$), there is a single wake produced by 2 hard structures (the subjets). **Two distinct wakes are visibly produced only when the subjets are far-separated** (around $\Delta y_{12} > 1.2$)!

Can we see this in experiments?

SHAPE OF PARTICLES WITH P_T < 1.0 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

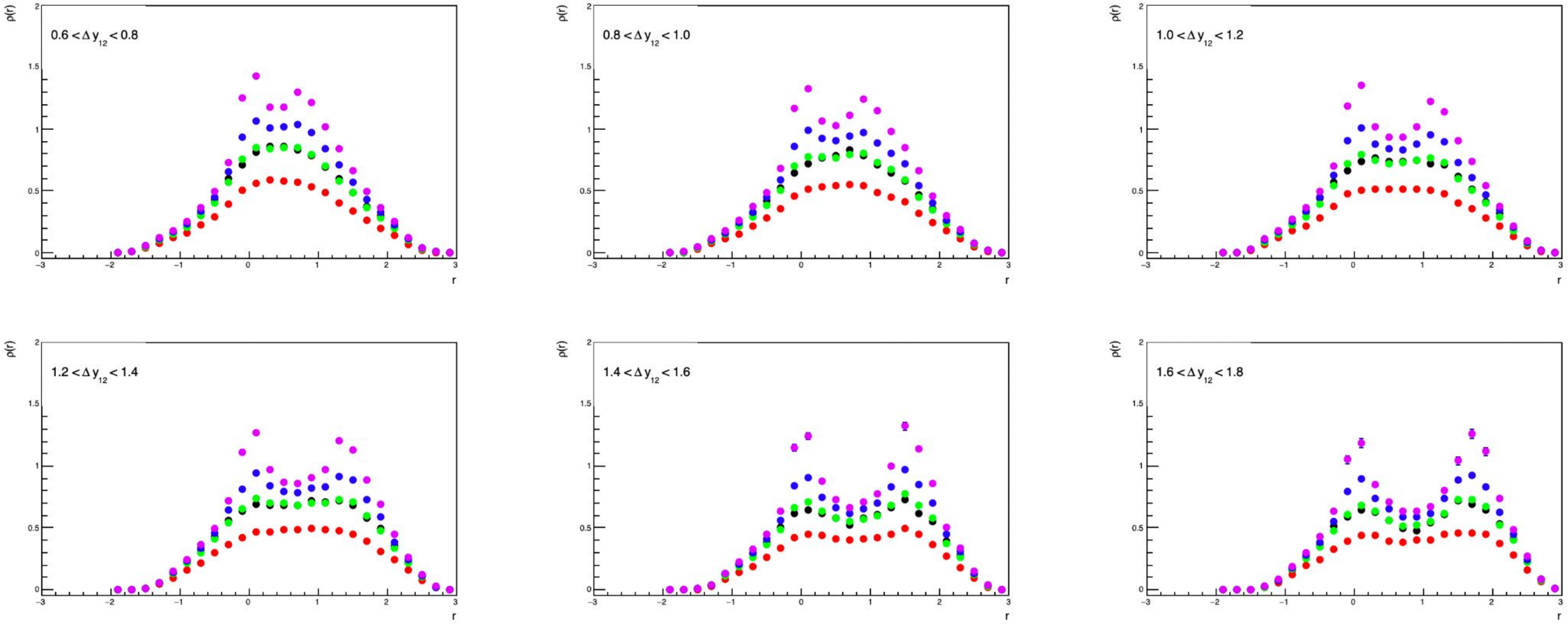


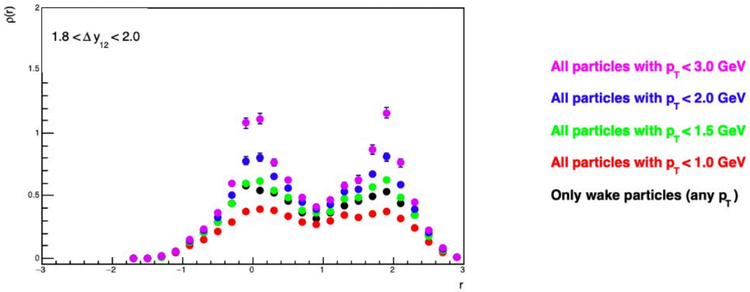


Looking at the shape of all particles (wake + nonwake) with p_T < 1 GeV acts as a good proxy of the 3-dimensional shape of the wake. The wake-substructures match!

But, **experimentalists subtract the background** when they calculate observables. This amounts to discounting particles with p_T below some cutoff (e.g. 0.7 GeV, https://link.springer.com/article/10.1007/JHEP05(2018)006).

SHAPE OF WAKE AND SOFT PARTICLES GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS





The projection of the jet shape onto the r-axis for soft particles with $p_T < 1.5$ GeV most resembles the shape of the wake!

Perhaps restricting to particles with $0.7 < p_T < 1.5$ GeV will give us a good visual proxy for the wake in experiments!

SUMMARY

- Jets are useful phenomena to study the physics of QCD at high temperatures

- AdS/CFT is a useful tool to probe the strongly coupled, nonperturbative regimes of jet physics

- The substructure of the wake sourced by a jet's energy loss is nontrivially dependent on subjet-separation
    - When 2 subjets are closely-separated by $\Delta y_{12} < 1.0$ a single wake is produced, whereas when 2 subjets are far-separated (around $\Delta y_{12} > 1.4$), two distinct subwakes are produced.

- This nontrivial dependence of wake-substructure on jet-substructure illuminates a way to visualize jet-wakes in experiments

<u>**Remarks**</u>

- In this presentation, I have only included the results for our analysis of gamma-jets. The results for an analysis of inclusive jets yielded qualitatively similar conclusions.

- The results presented here are for the hybrid strong/weak coupling model, not for nature. **The main point is that our analysis presents methods and observables that experimentalists can use to see the wake and study wake-substructure!**

Arjun Kudinoor
ask81@cam.ac.uk

WAYS TO LEARN MORE

Website: https://www.arjunkudinoor.com/talks/hep

- These slides
- References to read (textbooks, papers)
- You can contact me

THANKS FOR LISTENING!

BACKUP SLIDES

Arjun Kudinoor
ask81@cam.ac.uk

THE GAUGE-GRAVITY DUALITY

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dim-4 CFTs of gauge (particle) fields $\longleftrightarrow$ dim-5 gravitational theories in AdS spacetime

Also called the AdS/CFT correspondence, first proposed by Juan Maldacena in 1997. A particular formulation conjectures an equivalence between the two descriptions of N_c D3-branes:

1) A hyperplane of flat spacetime with open strings attached. The low energy limit is described by an $\mathcal{N}=4$ SYM theory with gauge group $SU(N_c)$.
2) A curved spacetime geometry where only closed strings propagate. The low energy limit is described by a closed Type IIB string theory in $AdS_5 \times S_5$.

Equating the low-energy limits gives a duality

$$\mathcal{N}=4\ SU(N_c)\ \text{SYM theory} \quad \longleftrightarrow \quad \text{IIB string theory in } AdS_5 \times S_5$$

Punchline: Difficult calculations in strongly coupled gauge theories may be solved in its more tractable weakly coupled (small curvature) gravitational dual; vice versa. The planar (large N_c) strongly coupled (large $\lambda = g_{\text{YM}}^2 N_c$) limit of the SYM theory can be described using just a classical supergravity dual.

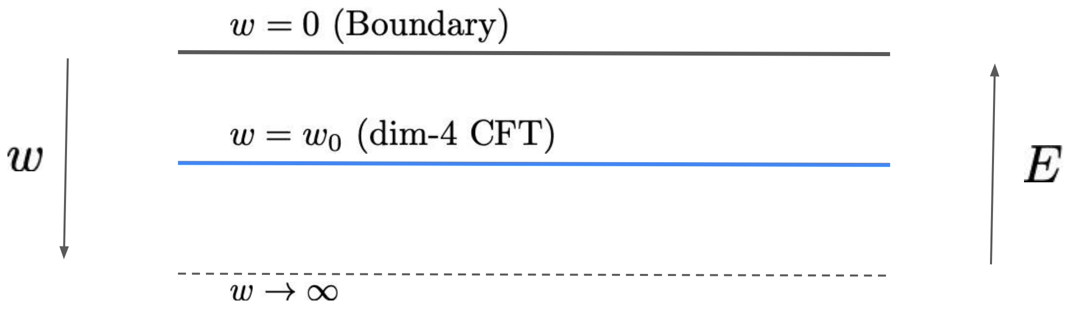
Reference: arXiv:1101.0618

Arjun Kudinoor
ask81@cam.ac.uk

HOLOGRAPHY

Massachusetts Institute of Technology

Suppose we have a 4-dimensional non-gravitational Minkowski CFT at energy scale $E_0 \sim \frac{1}{w_0}$, where ω is a 5th space-like dimension. So, we can describe this 4-dimensional gauge theory at all energy scales as a 5-dimensional holographic theory with coordinates (t, x, y, z, w).



The most general (4+1)-dimensional metric that is consistent with Poincaré in 4 dimensions is

$$ds^2 = \Omega^2(w)(-dt^2 + dx^2 + dy^2 + dz^2 + dw^2).$$

A CFT is invariant under rescalings $(t, x, y, z) \mapsto C(t, x, y, z)$. So, $\Omega(w) \mapsto \frac{1}{C}\Omega(w)$ under $w \mapsto Cw$.

Thus, $\Omega(w) = \frac{R}{w}$ and $ds^2 = \frac{R^2}{w^2}(-dt^2 + dx^2 + dy^2 + dz^2 + dw^2)$.

This is the metric of (4+1)-dimensional AdS spacetime with constant negative curvature proportional to $\frac{1}{R^2}$, i.e. this 5-dimensional spacetime has gravity!

SHAPES OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 1 SUBJET