A New Angle on Visualizing Jet (and) Wake Substructure

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MIT

work in progress with

Arjun Kudinoor (Cambridge University)

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plus brief look at new tools being developed by Jean Du Plessis, DP and KR; and by Yen-Jie Lee, DP and KR

ECT* Workshop on New Jet Quenching Tools...

ECT*, Trento, Italy; February 12, 2024

Why Jets?

- **The remarkable utility of hydrodynamics, eg. in describing the dynamics of small lumps in the initial state in AA collisions, tells us that to see how liquid QGP is put together from quarks and gluons, we need probes with fine resolution; probes that resolve scales $\ll$ size of lumps coming from the initial state that behave hydrodynamically, and scales $\ll 1/T_{\text{hydrodynamization}}$.**
- **Jets, as multiscale probes, provide best chance for scattering off a droplet of QGP to see its inner workings.**
- **Jets in heavy ion collisions** *also* **offer the best chance of watching how QGP hydrodynamizes. Jets leave wakes in the liquid. Can we see how they hydrodynamize and flow? Best shot at experimental access to this physics.**
- **$\rightarrow$ not easy to decode the wealth of info that jets contain! Need high statistics LHC and sPHENIX data; and need** *New Jet Quenching Tools*, **including new observables and improved models.**

How you can learn from a model

- **There are things you can do with a model (here, the Hybrid Model) that you cannot do with experimental data. Eg, turn physical effects off and on . . .**
- **. . . but that nevertheless teach us important lessons for how to look at, and learn from, experimental data.**
- EXAMPLE FROM MY TALK AT QM23: **Identifying which jet observables are more sensitive to the presence of quasi-particles — scatterers — in the QGP-soup. And, which are more sensitive to the wakes that jets make in the soup. My (slightly updated) QM slides are in the backup.**
- EXAMPLES FOR TODAY: New ways to "see" observable **effects of jet wakes. And the substructure of jet wakes.**
- **That is, examples of how to use a model as a** *TOOL* **with which to identify the experimental observables that best serve as** *TOOLS* **for defined/designed purposes.**
- **But first, a** *very* **brief intro to the Hybrid Model. . . (And an equally brief advertisement for an improvement to this tool coming soon.)**

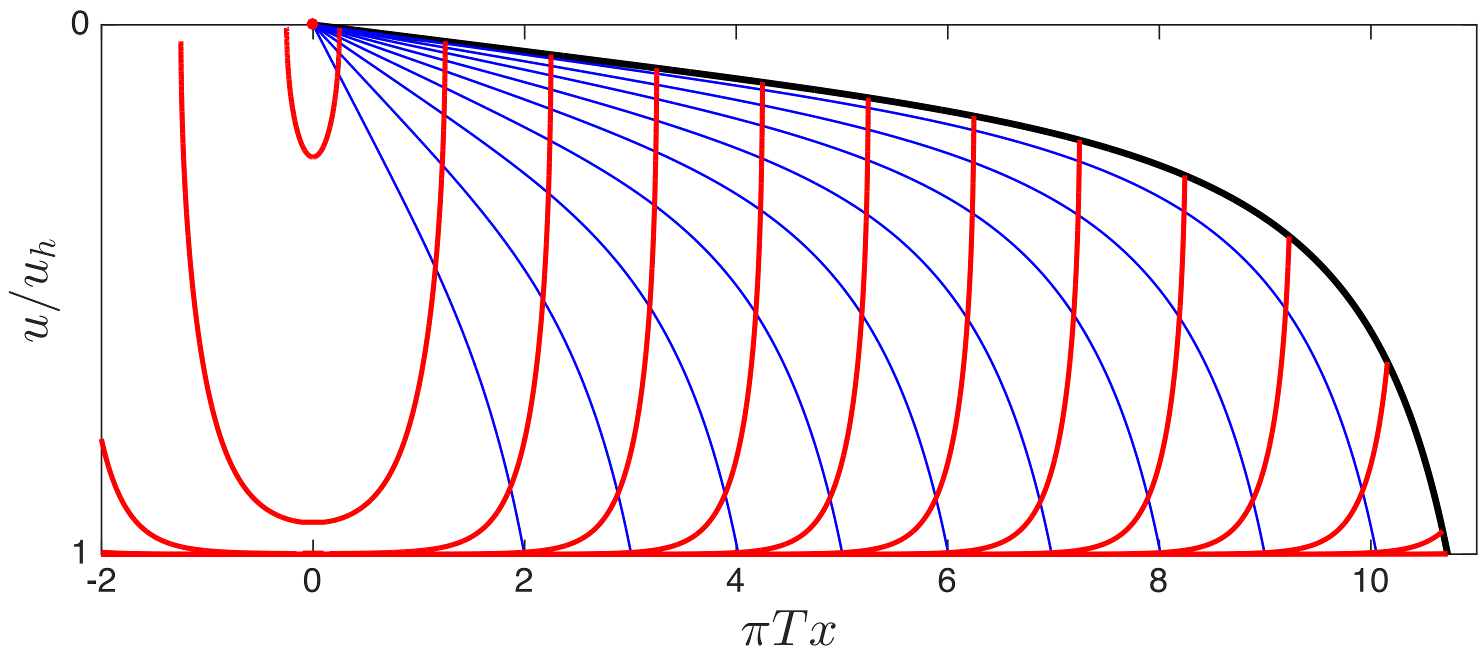
A Hybrid Approach

Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 2014,15,16; Hulcher, DP,KR, '17; JCS,ZH,GM,DP,KR, '18; JCS,GM,DP,KR, '19; JCS,GM,DP,KR, Yao, '20

- **Hard scattering and the fragmentation of a hard parton produced in a hard scattering are weakly coupled phenom-ena, well described by pQCD.**
- **The medium itself is a strongly coupled liquid, with no apparent weakly coupled description. And, the energy the jet loses seems to quickly become one with the medium.**
- **Try a hybrid approach. Think of each parton in a parton shower à la PYTHIA losing energy à la dE/dx for light quarks in strongly coupled liquid.**
- **Look at R_{AA} for jets and for hadrons, dijet asymmetry, jet fragmentation function, photon-jet and Z-jet observ-ables. Upon fitting one parameter, *lots* of data described well. Value of the fitted parameter is reasonable: x_{therm} (energetic parton thermalization distance) 3-4 times longer in QGP than in $\mathcal{N}=4$ SYM plasma at same T.**
- **Then: add the wake in the plasma; add resolution effects; look at jet shapes, jet masses jet substructure observables; add Molière scattering...**

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756, 1511.07567



- Take a highly boosted light quark and shoot it through strongly coupled plasma...
- A fully geometric characterization of energy loss. Which is to say a new form of intuition. Energy propagates along the blue curves, which are null geodesics in the bulk. When one of them falls into the horizon, that's energy loss! Precisely equivalent to the light quark losing energy to a hydrodynamic wake in the plasma.

Implementation of Hybrid Model

Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1405.3864,1508.00815

- **Jet production and showering from PYTHIA.**
- **Embed the PYTHIA parton showers in hydro background. (2+1D hydro from Heinz and Shen.)**
- **Between one splitting and the next, each parton in the branching shower loses energy according to**

$$\frac{1}{E_{\rm in}}\frac{dE}{dx} = -\frac{4x^2}{\pi x_{\rm therm}^2}\frac{1}{\sqrt{x_{\rm therm}^2 - x^2}}$$

  where $x_{\rm therm} \equiv E_{\rm in}^{1/3}/(2\kappa_{\rm SC}T^{4/3})$ **with** $\kappa_{\rm SC}$ **one free parameter that to be fixed by fitting to one experimental data point. (**$\kappa_{\rm SC} \sim 1 - 1.5$ **in** $\mathcal{N} = 4$ **SYM; smaller** $\kappa_{\rm SC}$ **means** $x_{\rm therm}$ **is longer in QGP than in** $\mathcal{N} = 4$ **SYM plasma with same** T**.)**
- **Turn energy loss off when hydrodynamic plasma cools below a temperature that we vary between 145 and 170 MeV. (This, plus the experimental error bar on the one data point, becomes the uncertainty in our predictions.)**
- **Reconstruct jets using anti-**k_T**.**

Perturbative Shower … Living in Strongly Coupled QGP

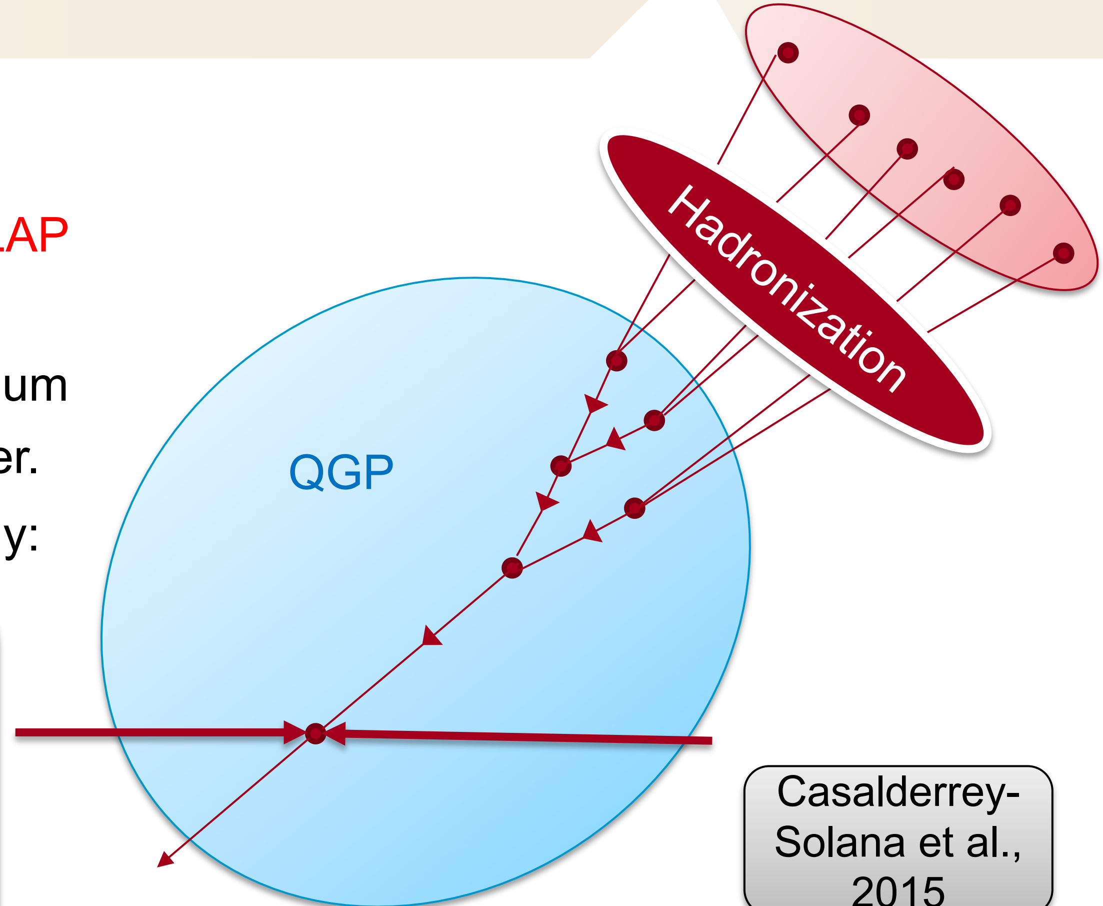
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}}$$

$$\tau = \frac{2E}{Q^2}$$

O(1) fit const.



Casalderrey-Solana et al., 2015

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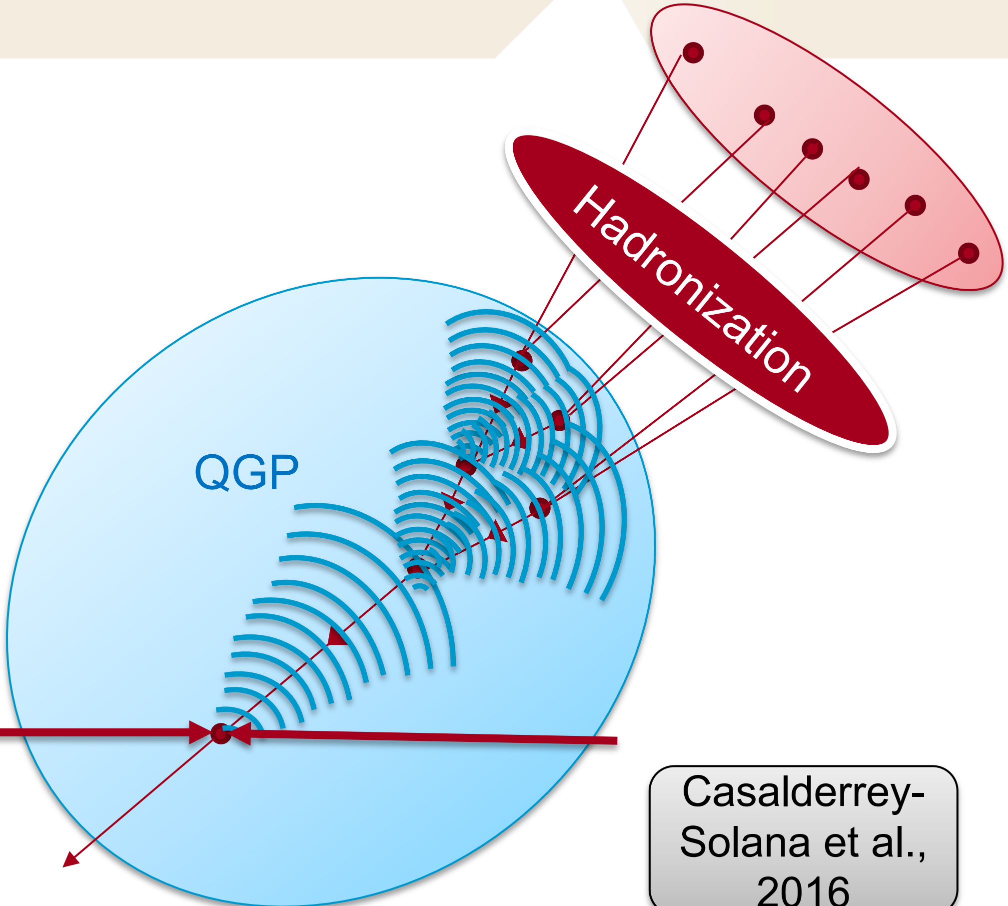

Casalderrey-Solana et al., 2016

Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

Heavy Quark dE/dx At Strong Coupling

Jean Du Plessis, Pablos, KR

- **What if a quark in the jet is a heavy quark? Can we include heavy quarks in the hybrid model? Means we need dE/dx for heavy quarks in strongly coupled plasma.**
- **While a heavy quark is ultrarelativistic, it's dE/dx is that of a light quark. As it loses energy and becomes less relativistic, it must begin to behave like a heavy quark, drag to a stop, and diffuse. An AdS/CFT calculation worth doing! Pending that...**
- **A very heavy quark pulled at a constant velocity v experiences a drag force: $dp/dt = -\eta_{\text{drag}} p$** HKKKY, G, 2006
- **Apply this formula for a decelerating heavy quark, and turn it into dE/dx ...**
- **Match the two expressions for dE/dx at a point, doing so such that E and dE/dx are continuous.**
- **In progress: use this to describe heavy quarks in hybrid model. Calculate R_{AA} for b-jets, B and D mesons; and then other heavy quark observables...**

Heavy Quark dE/dx At Strong Coupling

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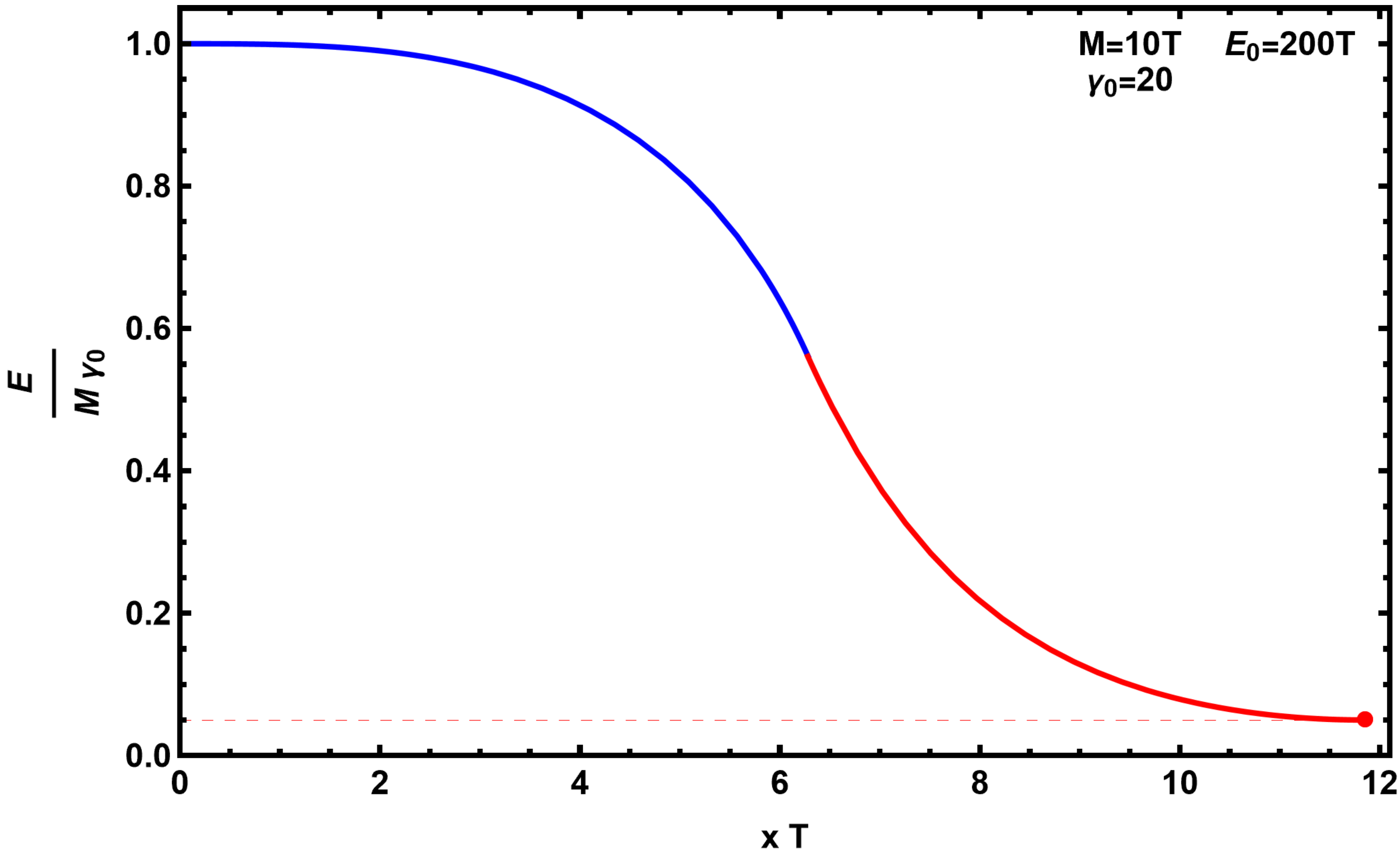

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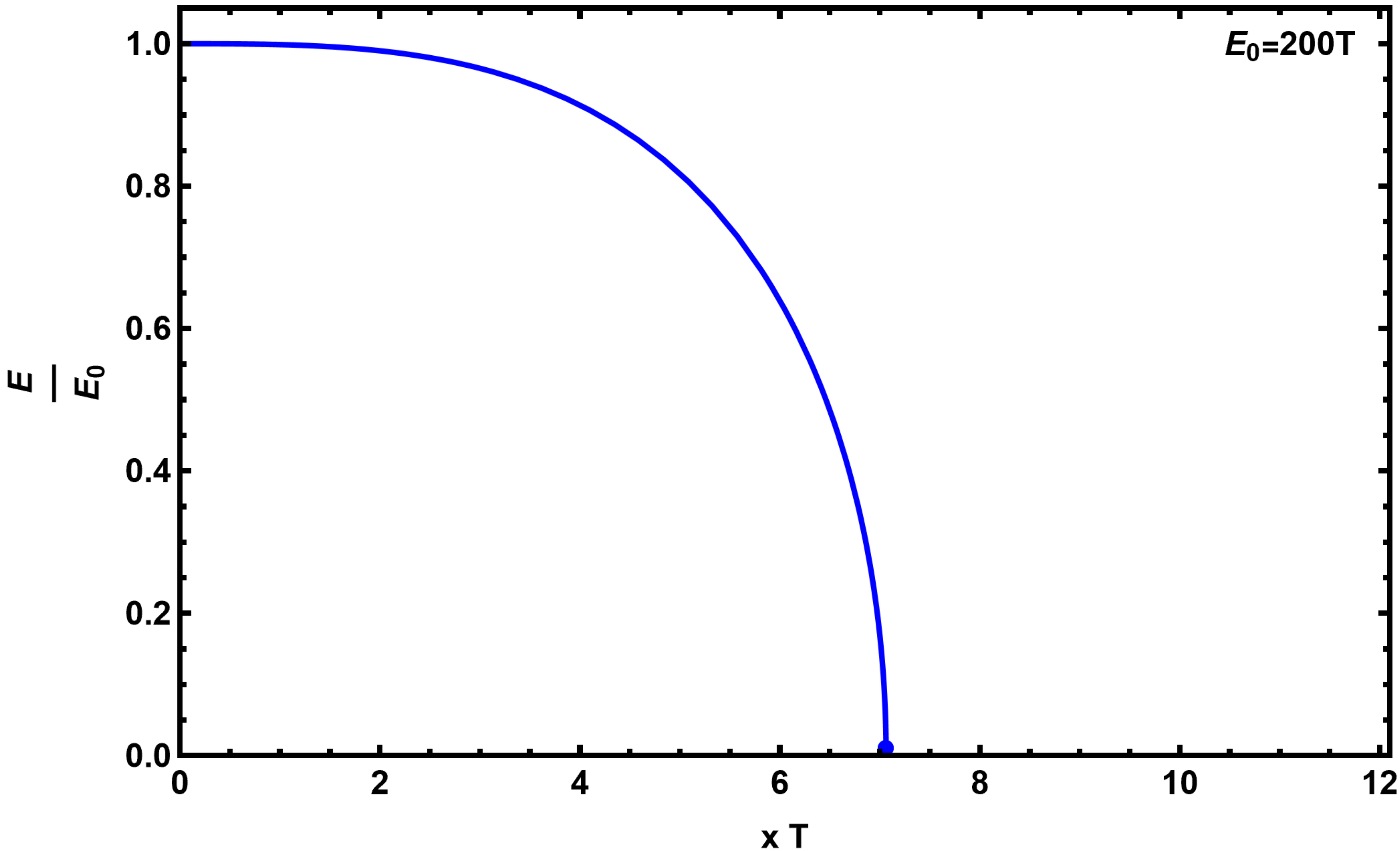

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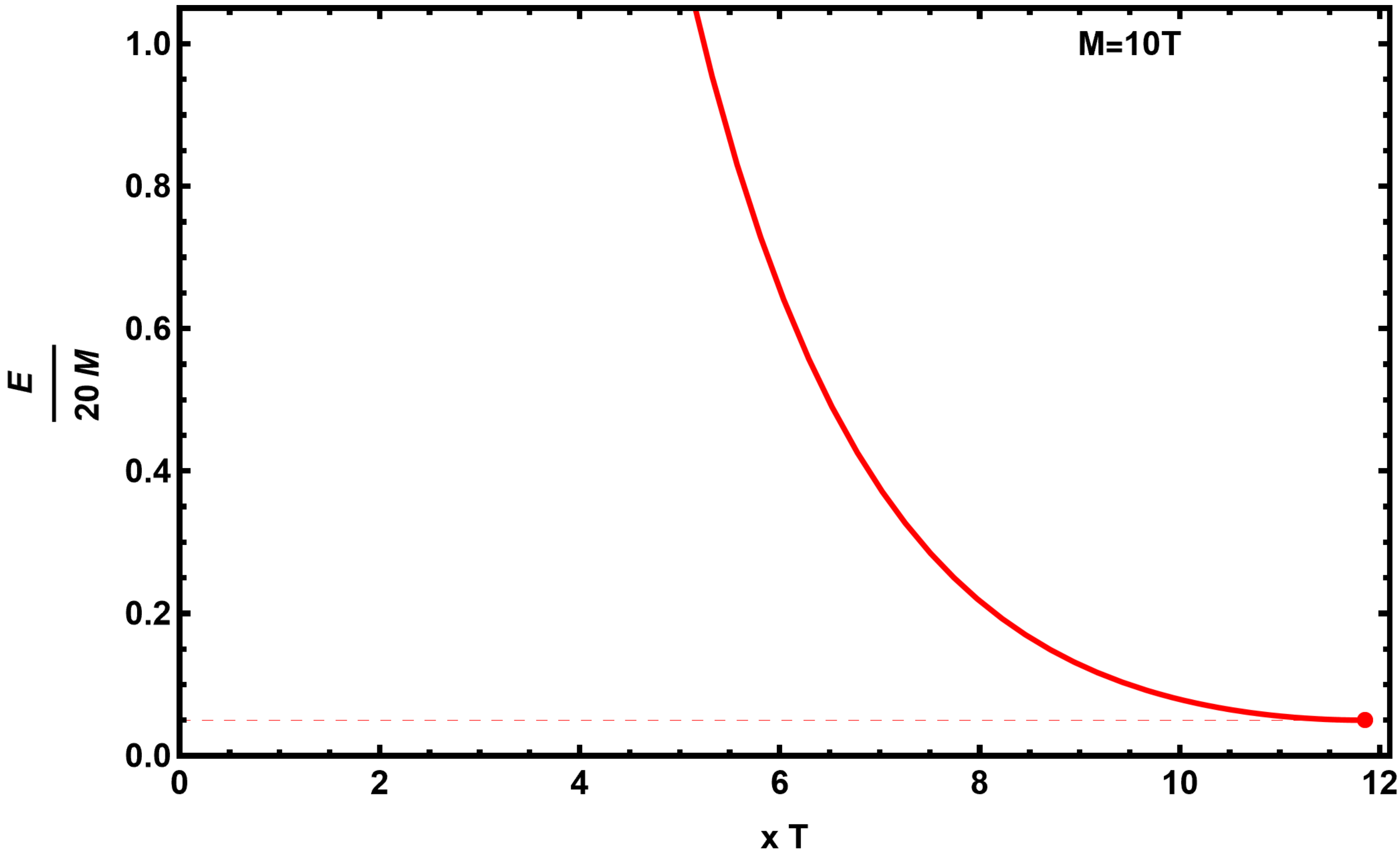

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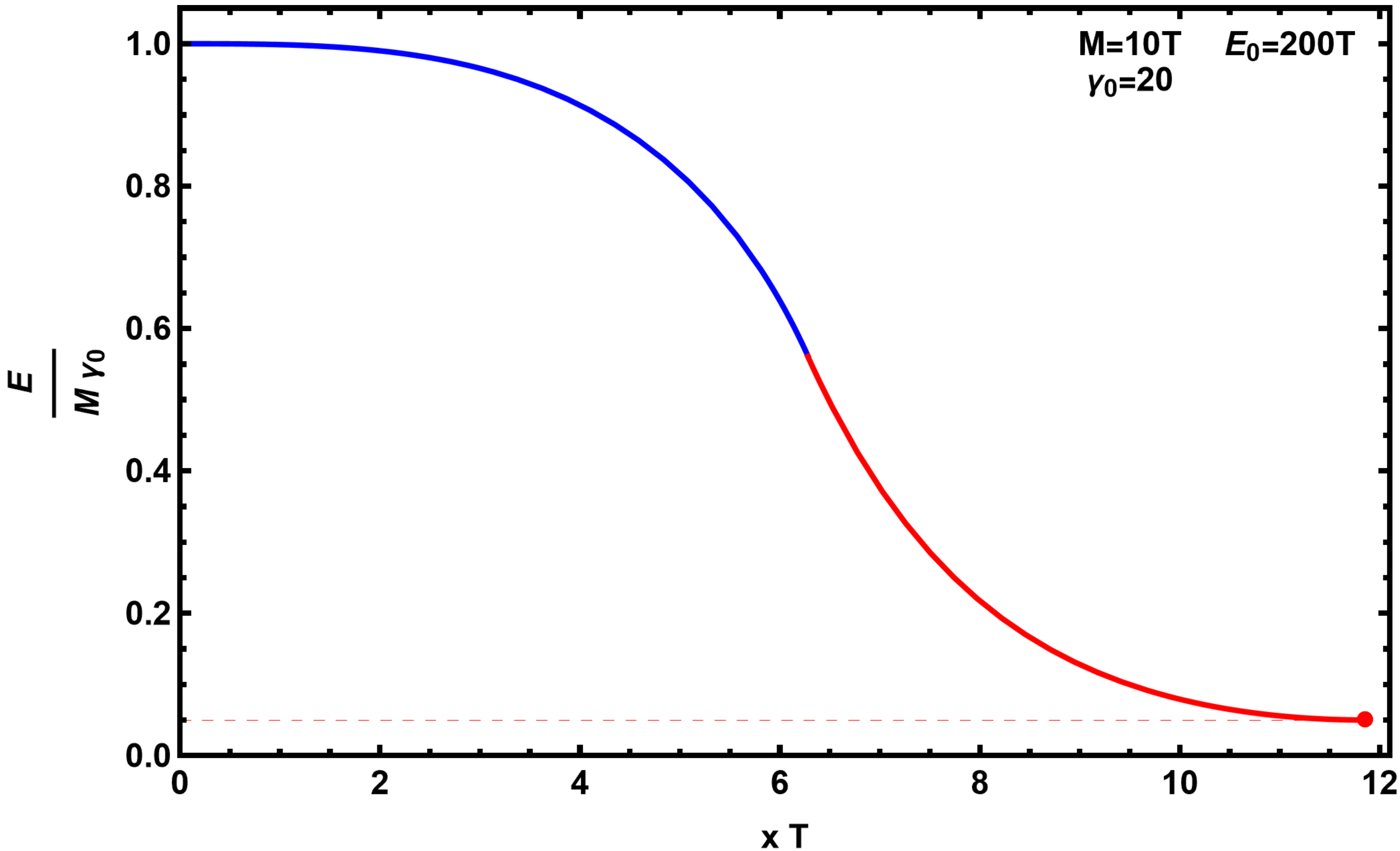

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Do Subjets Have Separate Wakes?

- **A question prompted by an interesting observable, introduced by ATLAS at QM19. See 2301.05606.**
- **First reconstruct anti-k_t-$R = 0.2$ jets, call them subjets, with $p_T^{\text{subjet}} > 35$ GeV; then reconstruct anti-k_t-$R = 1.0$ jets from these objects.**
- **ATLAS finds R_{AA} for $R = 1.0$ jets with 1 (≥ 2) subjets is less (more) suppressed. For jets with 2 subjets, look at angular separation and splitting parameter.**
- **Another perspective: a way to find events with two skinny $R = 0.2$ (sub)jets with a specified separation ΔR_{12}. Then, look at all the particles in such events and ask about the shape of the wake of this two-pronged object.**
- **In a model, we can turn the wake off and on. Use this ability to learn how to use this observable, this tool, to learn something interesting from data.**
- **For today an aside: Moliere scattering effects are small in magnitude; motivates repeating this study with lower-p_T subjets.**

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 $|\eta| < 3.0$ 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 $\sqrt{d_{12}} = 0$.

Constructing Wide Jets from Skinny Subjets — ATLAS

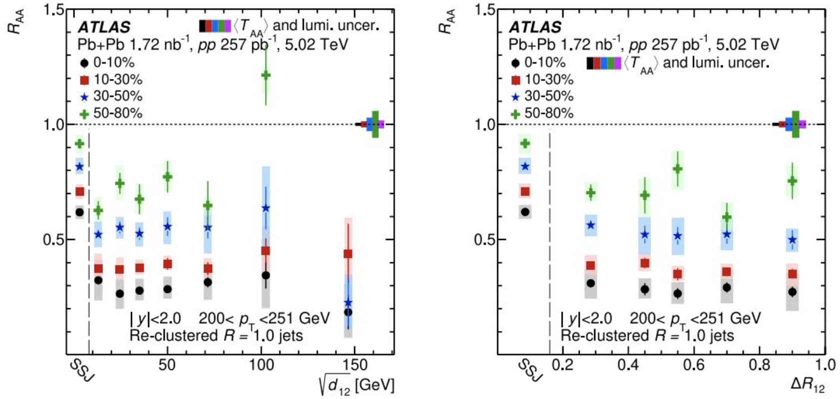
[arXiv: 2301.05606] To quantify the suppression of large-radius jet production in Pb+Pb collisions at 5.02 TeV, ATLAS measured the nuclear modification factor

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{d^2 N^{AA}/dy\, dp_T}{d^2 \sigma^{pp}/dy\, dp_T}$$

as a function of $\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta \phi_{12}^2}$ and $\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$. R_{AA} measures the ratio of jet production in heavy ion (here, Pb+Pb) collisions to jet production in proton-proton collisions, at specified values of jet rapidity and transverse momentum.

Among other things, ATLAS found that large-radius R = 1.0 jets were more suppressed when they had multiple subjets, than when they had only 1 subjet.

Furthermore, the suppression of large-radius R = 1.0 jets with multiple subjets did not depend on the angular separation ΔR_{12} or splitting scale $\sqrt{d_{12}}$ between the hardest constituents in the penultimate k_T-reclustering step.

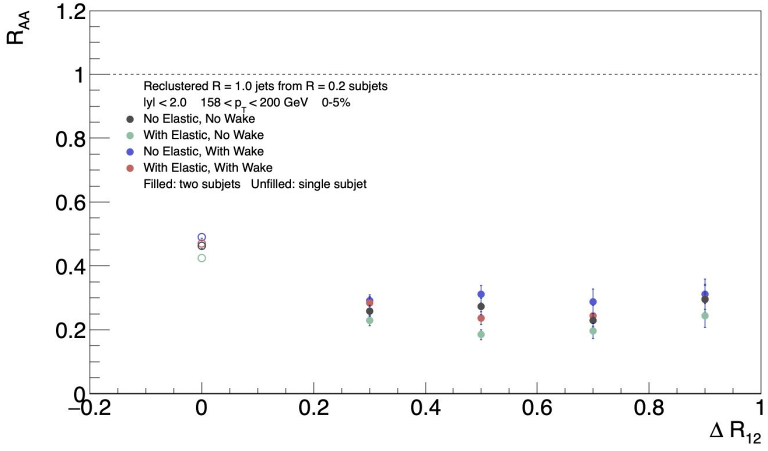


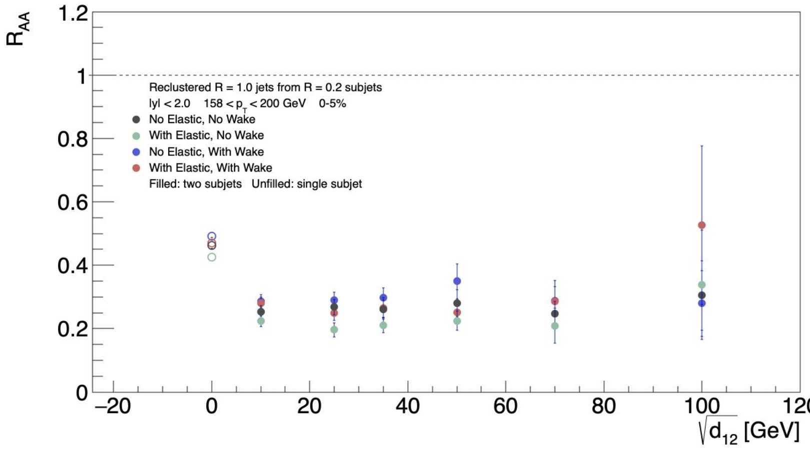
Constructing Wide Jets from Skinny Subjets — Hybrid Model

We were able to reproduce these qualitative results using the hybrid model. The plots below show R_{AA} as a function of ΔR_{12} and $\sqrt{d_{12}}$, for R = 1.0 jets with |y| < 2.0 and 158 < p_T < 200 GeV. Only large-radius jets with 1 and 2 subjets were included in these plots.

Regardless of whether or not the hadrons from the wake were included in the initial anti-k_T reconstruction of R = 0.2 jets, and regardless of whether or not elastic scattering was included,

- R = 1.0 jets were more suppressed when they had 2 subjets, than when they had 1 subjet
- R = 1.0 jets with 2 subjets showed no dependence on ΔR_{12} and $\sqrt{d_{12}}$



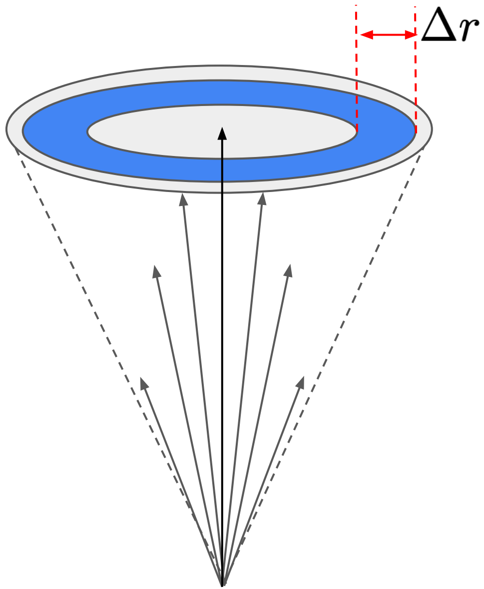


Energy loss (jet suppression) is independent of subjet-separation. What about the shape of the resulting wake?

JET SHAPE

One can visualize jet substructure using an observable called jet shape. Jet shape measures the average fraction of a jet's transverse momentum inside an annulus of some specified width around the axis of the jet.

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{p_T(r-\frac{\Delta r}{2}, r+\frac{\Delta r}{2})}{p_T^{\text{jet}}}$$



<u>Problem:</u> Suppose we had a large-radius jet with two subjets. These two subjets could be present anywhere within the jet. So, the jet shape will simply produce a smear of transverse momentum fractions across the whole area of the large-radius jet.

We need to **redefine our coordinates and the jet shape** so we may clearly observe what happens in the region between subjets.

A NEW COORDINATE SYSTEM

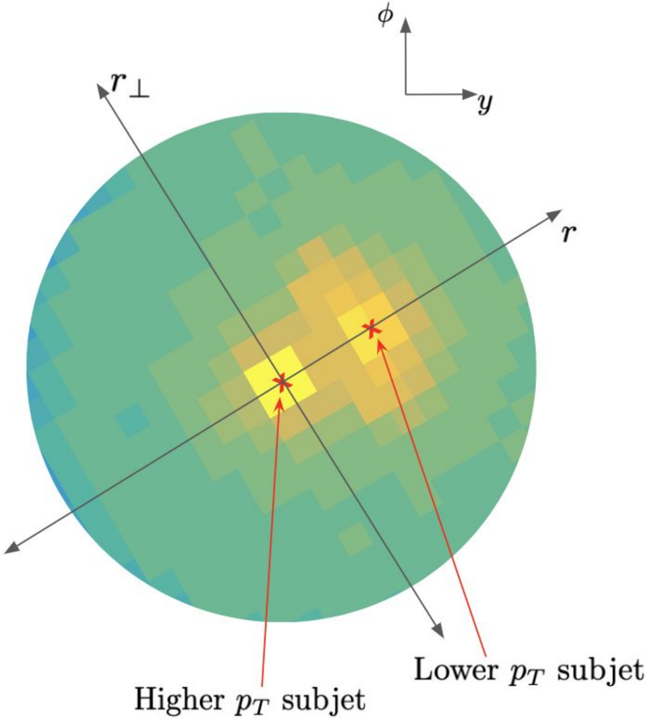
- We first constructed large-radius R = 2.0 jets from small-radius R = 0.2 subjets using the same procedure as ATLAS. We are using a larger radius of R = 2.0 to observe how the substructure of jet-wakes differs between closely-separated and far-separated subjets.

- 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 $(y_{\text{high}}, \phi_{\text{high}})$ and $(y_{\text{low}}, \phi_{\text{low}})$, respectively.
   2) Define the origin of our new coordinates to be at $(y_{\text{high}}, \phi_{\text{high}})$ and define the r-axis to point positively in the direction of $(y_{\text{low}}, \phi_{\text{low}})$.
   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



NEW JET SHAPE OBSERVABLES

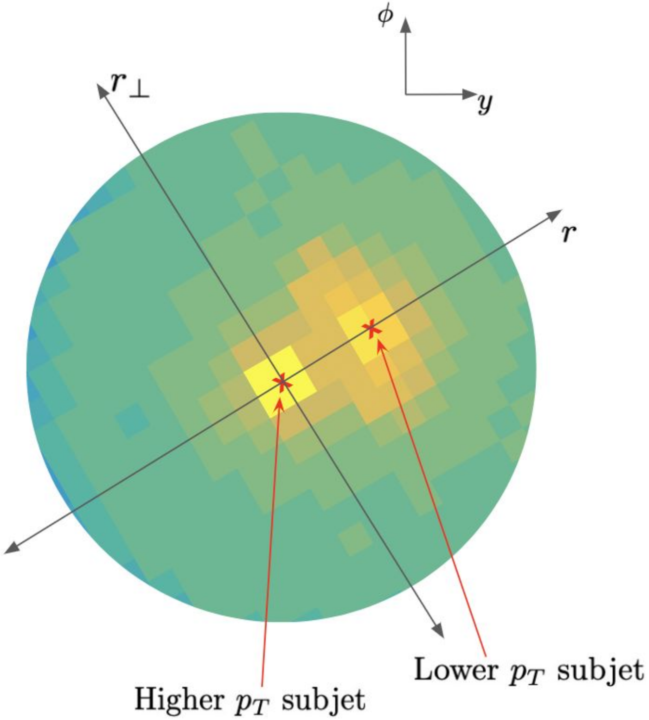
Now, we redefine the jet shape to measure the average fraction of a jet's transverse momentum within specified ranges of r and $r_\perp$. We can select large-radius jets in different ranges of ΔR_{12} (or Δy_{12}) to study the dependence of jet shape on subjet-separation.

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

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

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

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



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.

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.

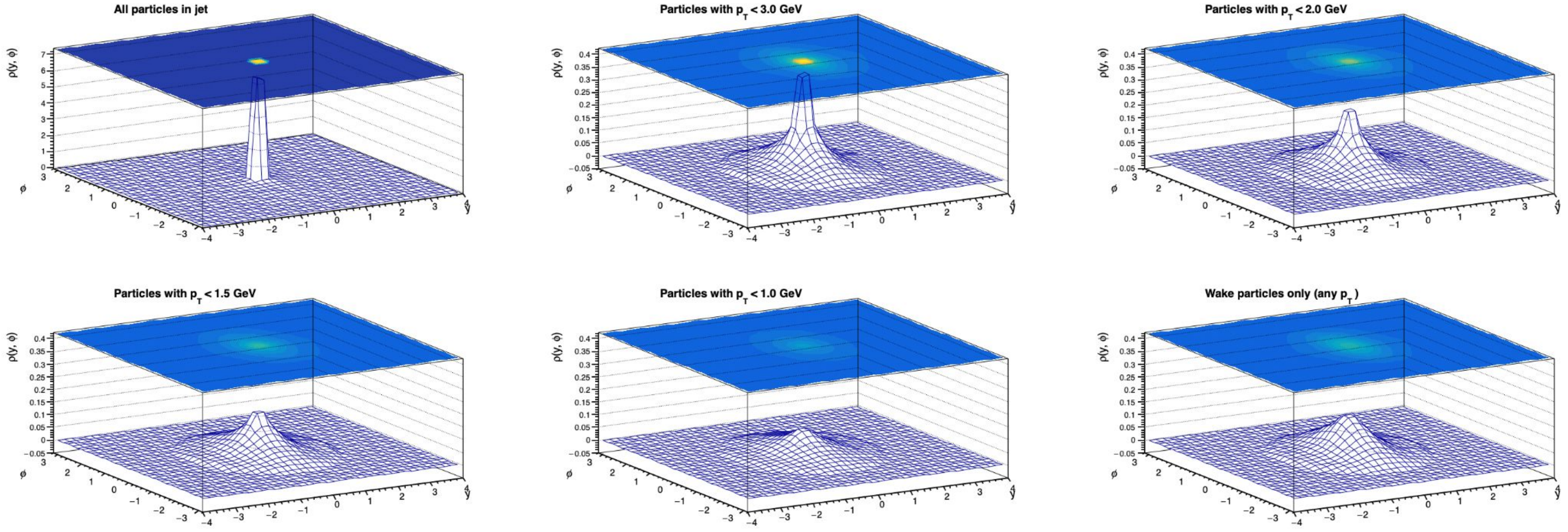
- The photon produces no wake of its own, and so the jet shape will look cleaner than in the case of dijet events (events with almost back-to-back jets).

- 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
    - $\Delta\phi_{\gamma,\text{ jet}} > 2\pi/3$

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 the large-radius jets with $|y| < 2.0$ and $50 < p_T < 1000$ GeV.

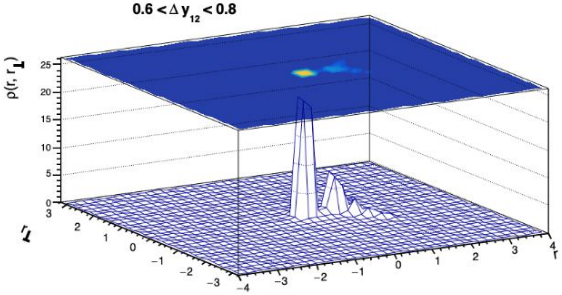
SHAPES OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 1 SUBJET

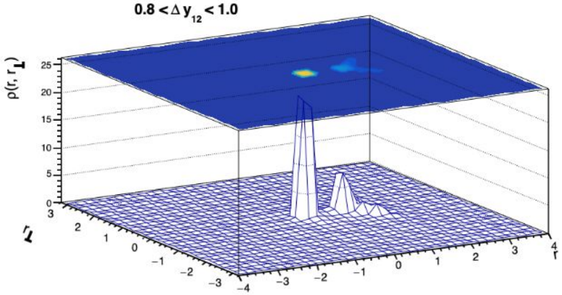


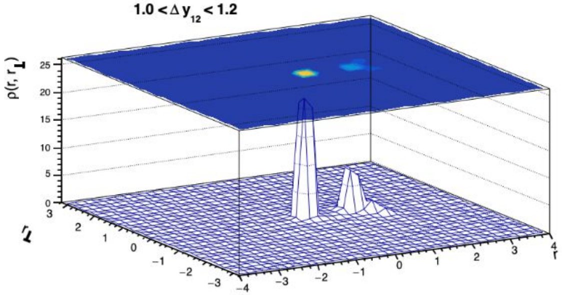
Note that the shape of the wake most closely resembles the shape of the particles with p_T < 1.5 GeV. If experimentalists can remove the background from heavy ion collision measurements without removing all particles within this range of p_T, then we can SEE the wake!

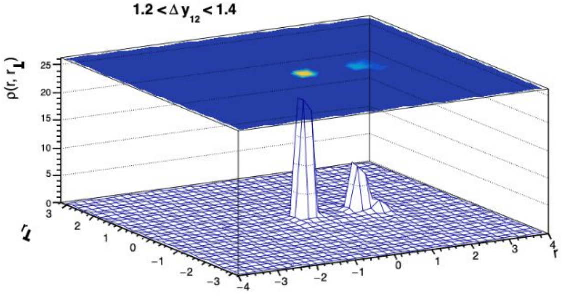
But, this is not clear enough – is there another, clearer way to differentiate the wake particles from all soft particles? **Hint: Let's look at the jet and wake substructure.**

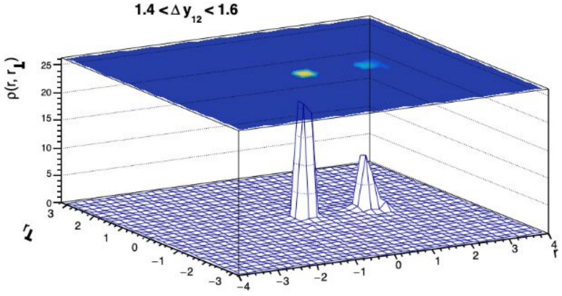
JET SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

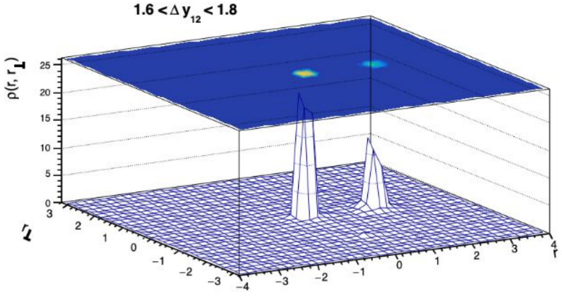


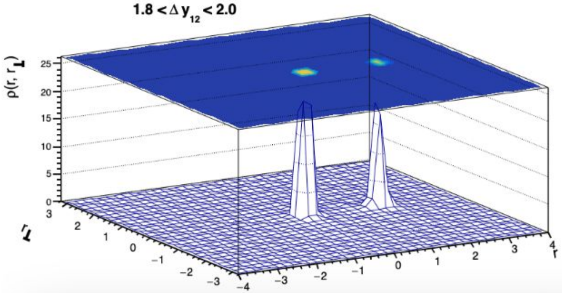






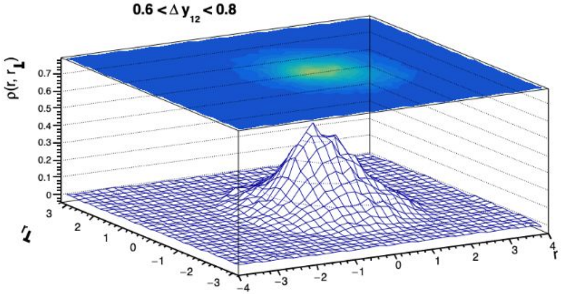


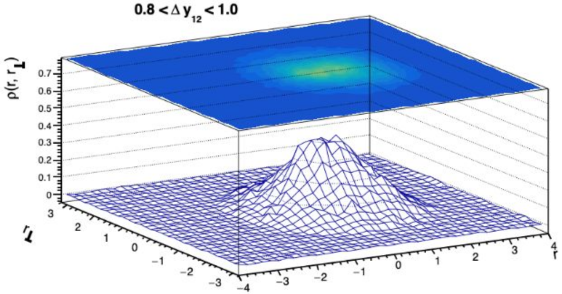


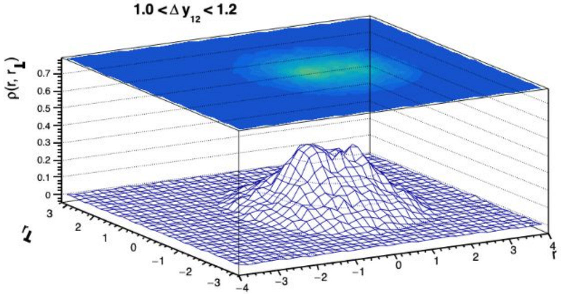


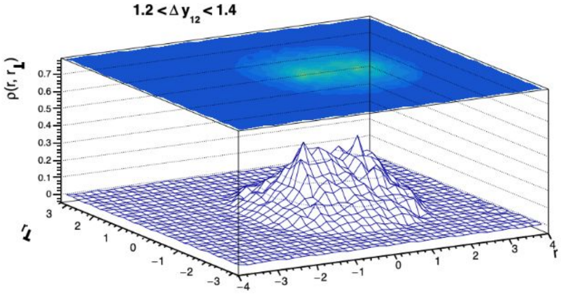
They look as we expected…

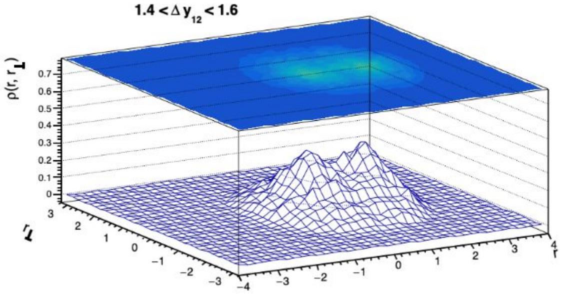
WAKE SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

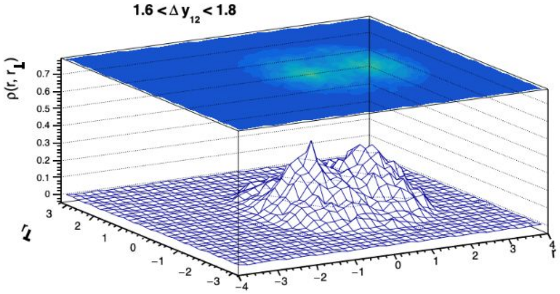


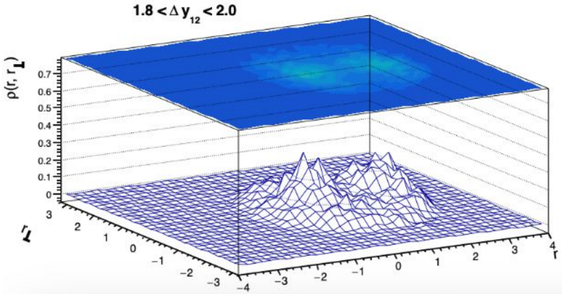










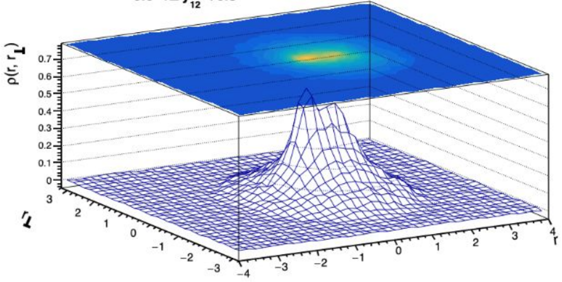


For closely-separated subjets ($\Delta y_{12} < 1.0$), there is a single wake produced by 2 hard structures (the subjets). **Two distinct wakes are visibly produced only when the subjets are far-separated** (around $\Delta y_{12} > 1.4$)!

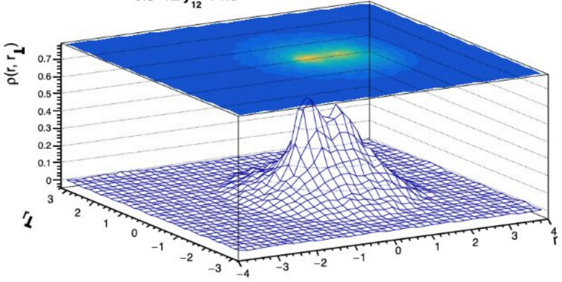
Can we see this in experiments?

SHAPE OF PARTICLES WITH P_T < 1.5 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

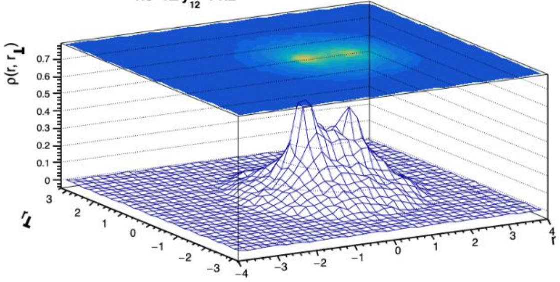
$0.6 < \Delta y_{12} < 0.8$



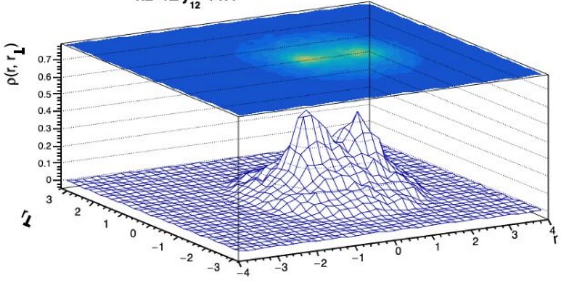
$0.8 < \Delta y_{12} < 1.0$



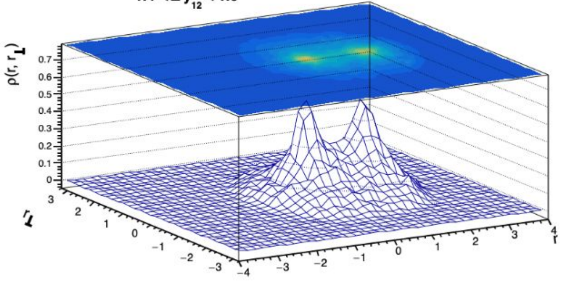
$1.0 < \Delta y_{12} < 1.2$



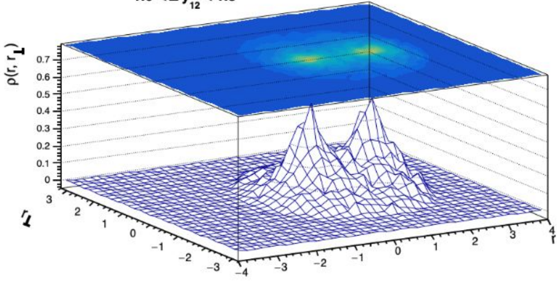
$1.2 < \Delta y_{12} < 1.4$



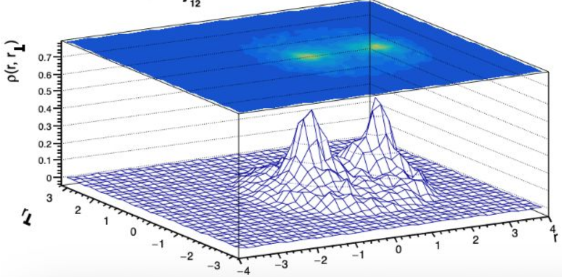
$1.4 < \Delta y_{12} < 1.6$



$1.6 < \Delta y_{12} < 1.8$



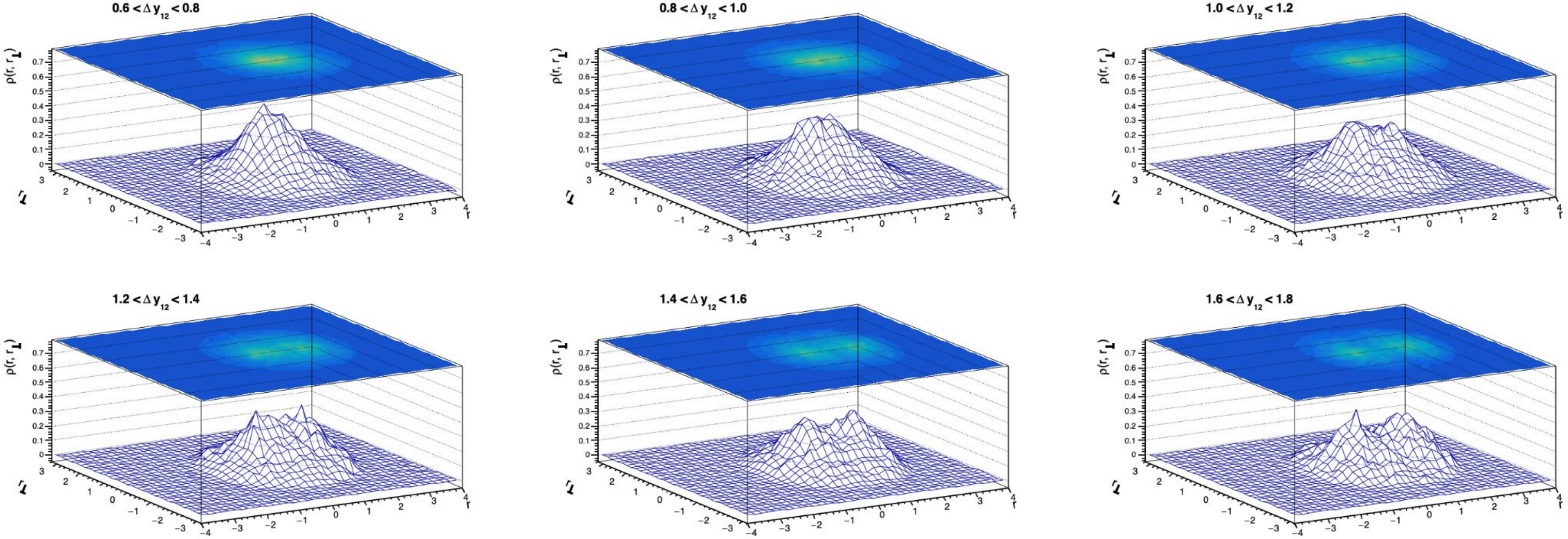
$1.8 < \Delta y_{12} < 2.0$

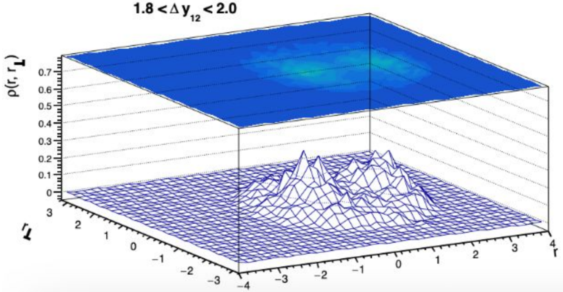


Experimentalists look for the wake by restricting to observing particles with low-p_T.

If we restrict to calculating the jet shape for particles with p_T < 1.5 GeV, then it resembles the shape of the wake – in particular, it is difficult to distinguish between two soft structures for Δy_{12} < 1.0, and easier for larger Δy_{12}.

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

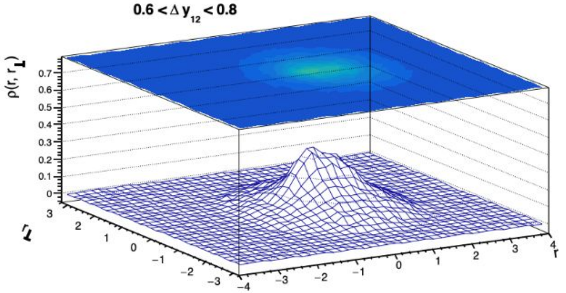


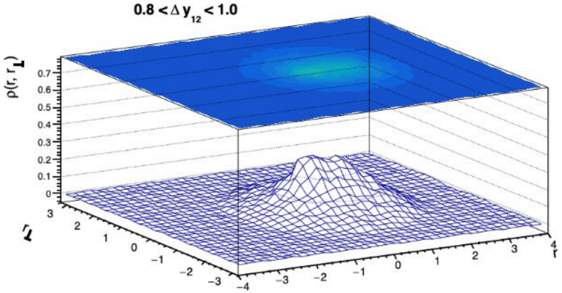


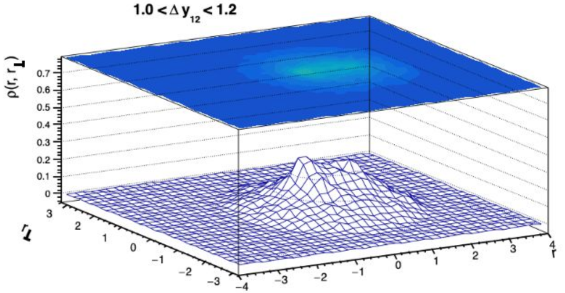
For closely-separated subjets (Δy_{12} < 1.0), there is a single wake produced by 2 hard structures (the subjets). **Two distinct wakes are visibly produced only when the subjets are far-separated** (around Δy_{12} > 1.4)!

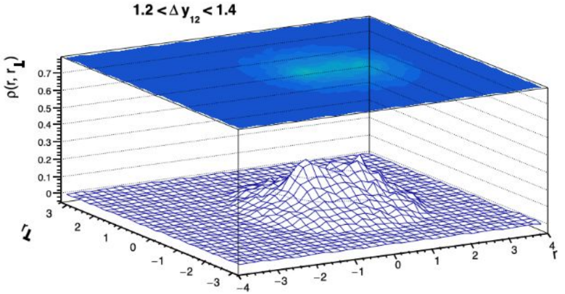
Can we see this in experiments?

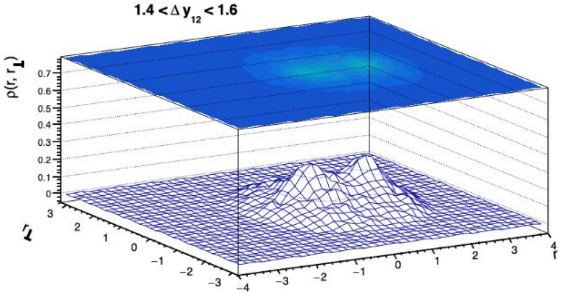
SHAPE OF PARTICLES WITH P_T < 1.0 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

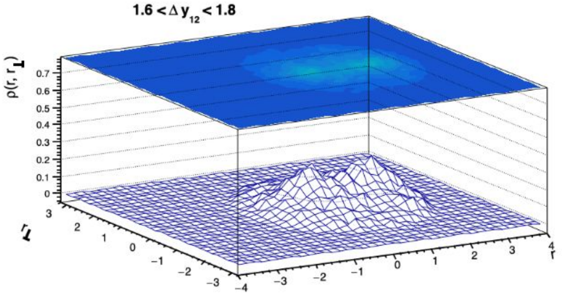


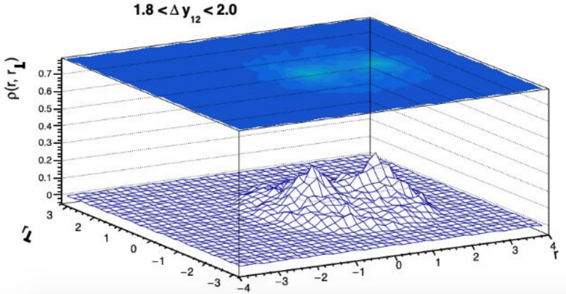




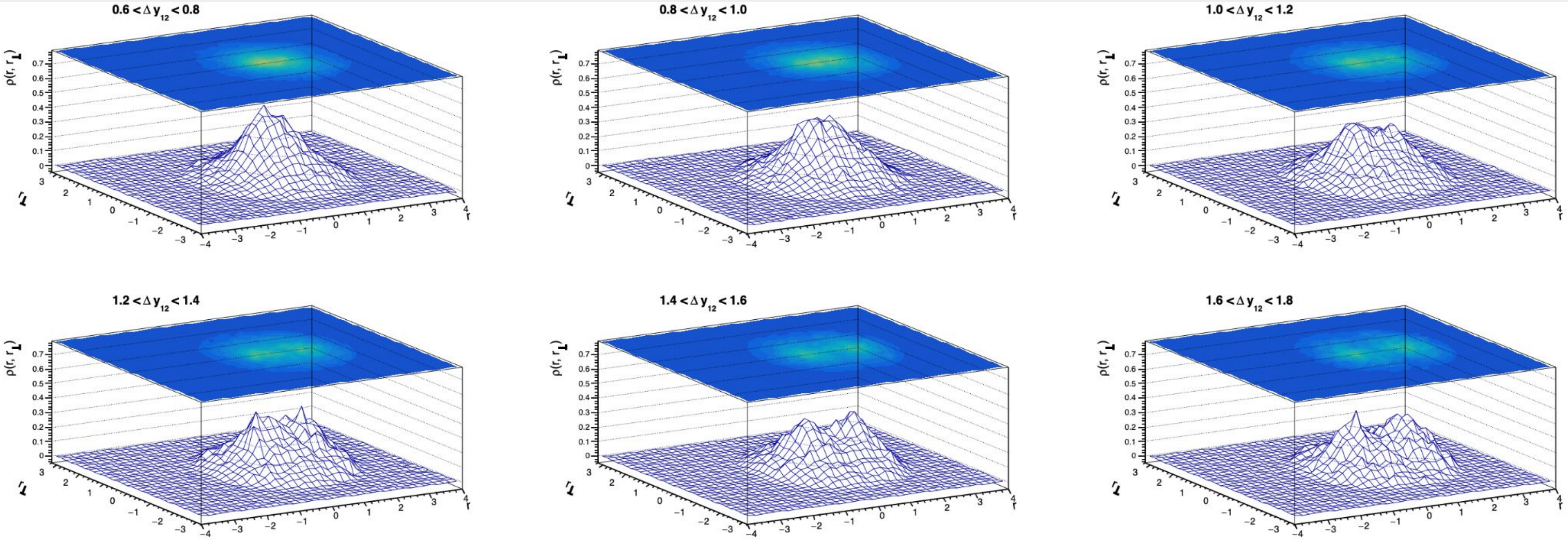


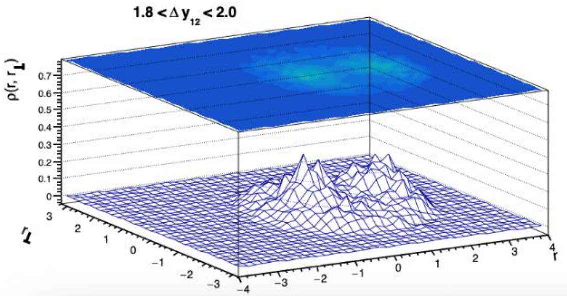






WAKE SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

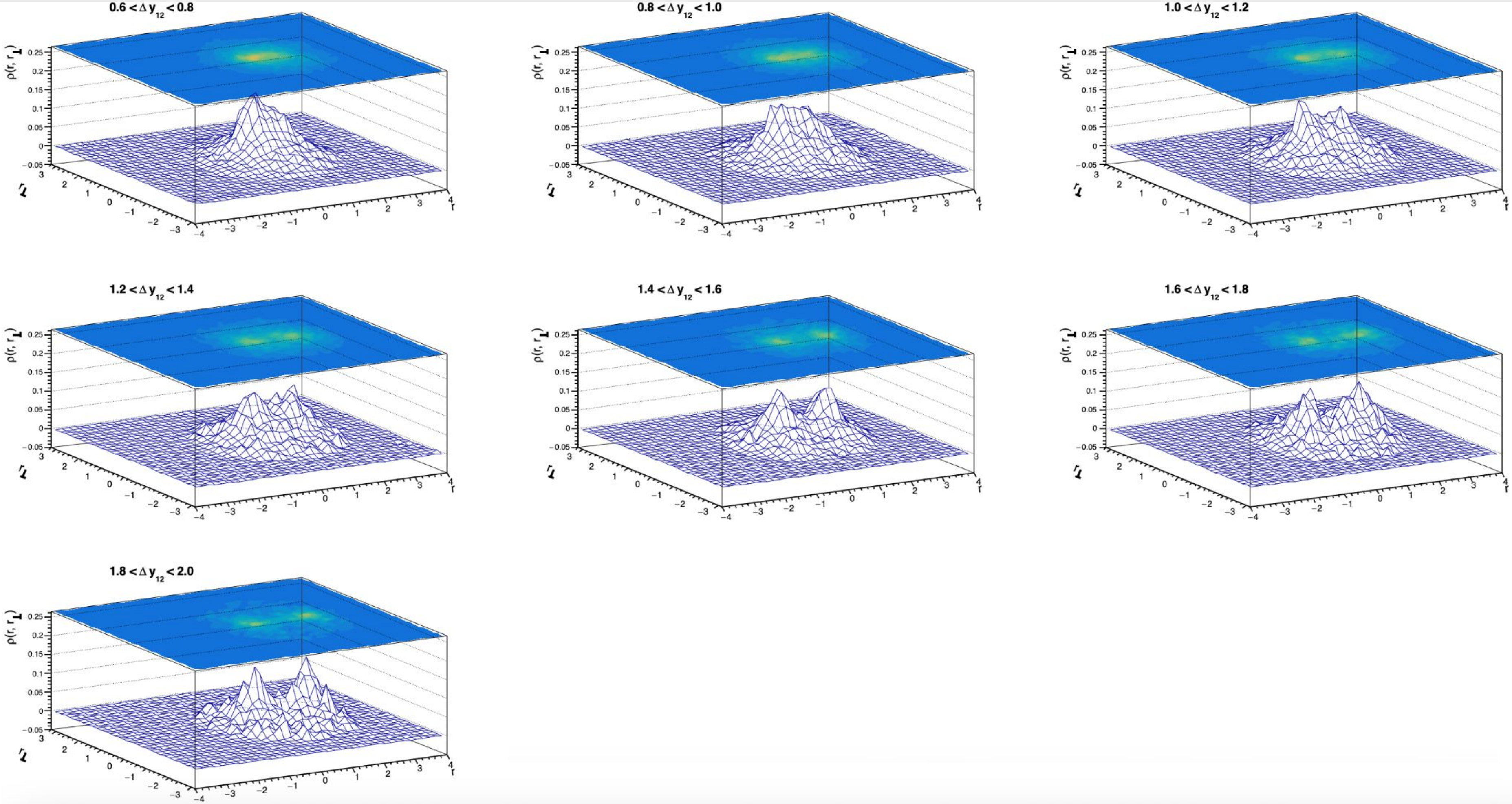




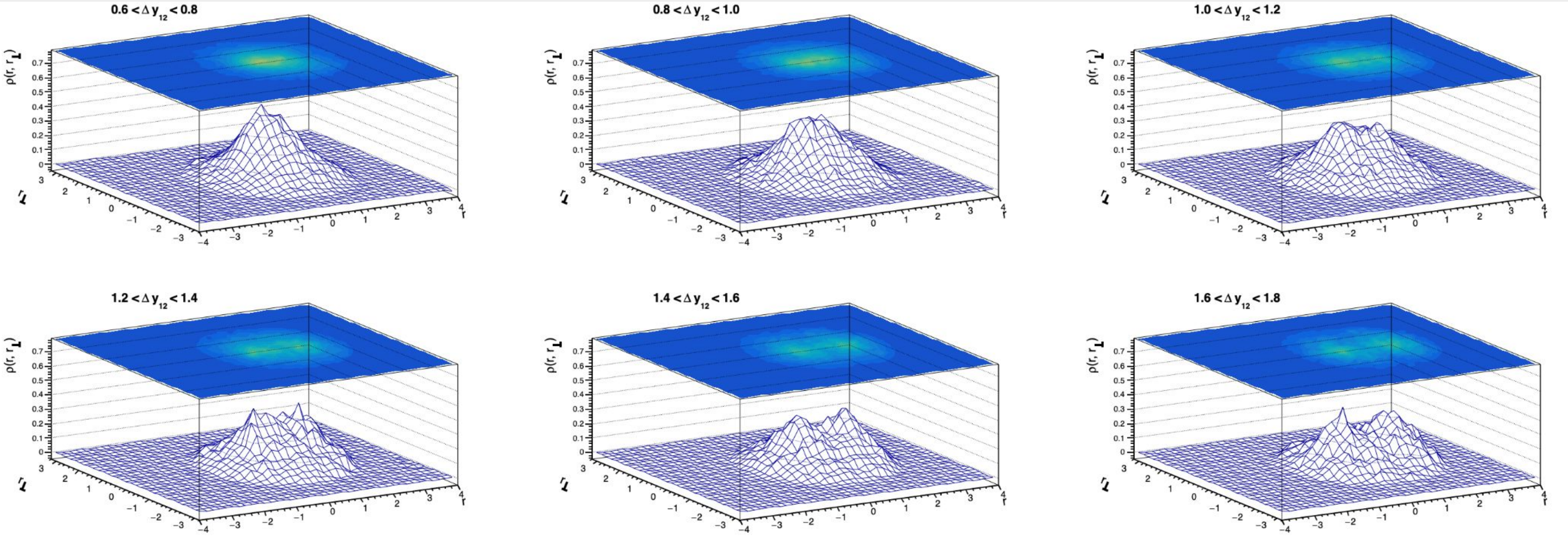
For closely-separated subjets (Δy_{12} < 1.0), there is a single wake produced by 2 hard structures (the subjets). **Two distinct wakes are visibly produced only when the subjets are far-separated** (around Δy_{12} > 1.4)!

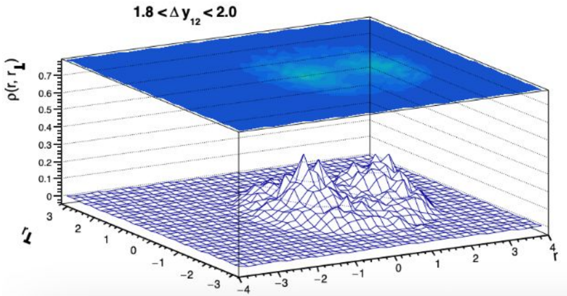
Can we see this in experiments?

ALL PARTICLES WITH 0.7 < P_T < 1 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS



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

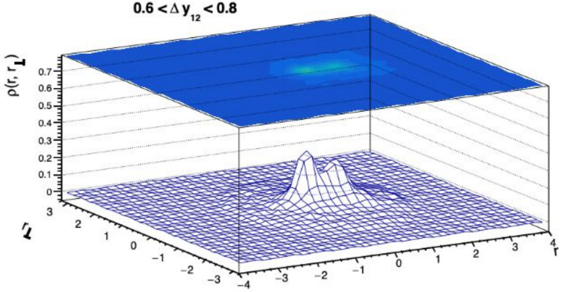


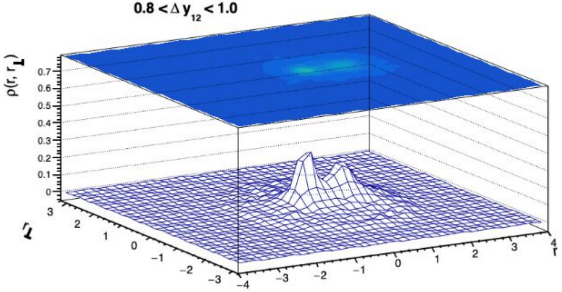


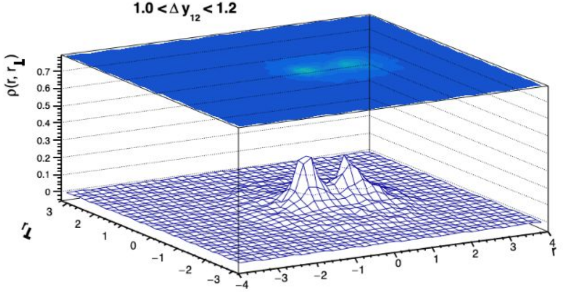
For closely-separated subjets ($\Delta y_{12} < 1.0$), there is a single wake produced by 2 hard structures (the subjets). **Two distinct wakes are visibly produced only when the subjets are far-separated** (around $\Delta y_{12} > 1.4$)!

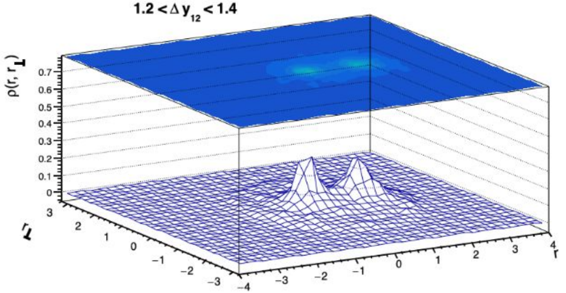
Can we see this in experiments?

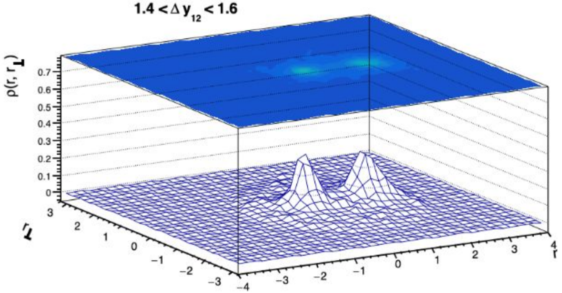
SHAPE OF PARTICLES WITH P_T < 1.5 GeV IN GAMMA-JETS IN pp COLLISIONS WITH 2 SUBJETS

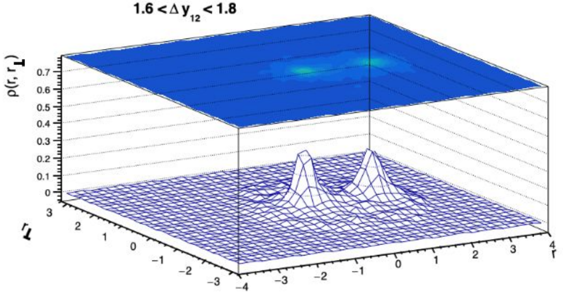


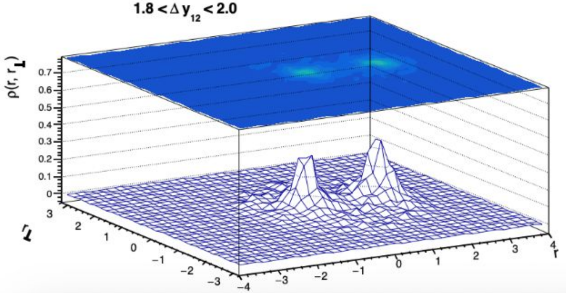






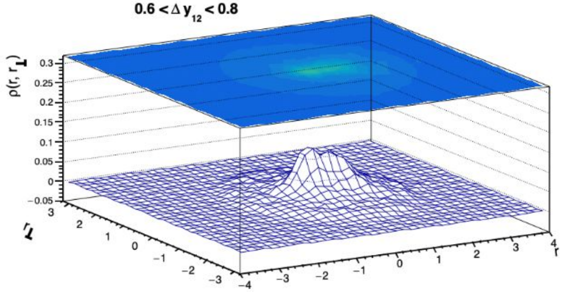


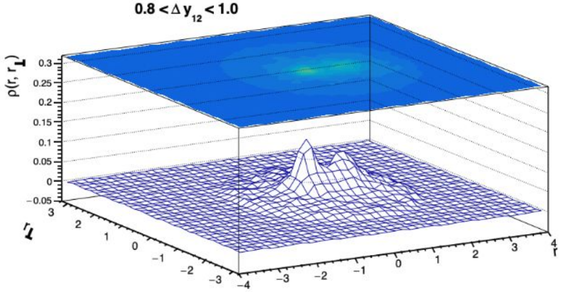


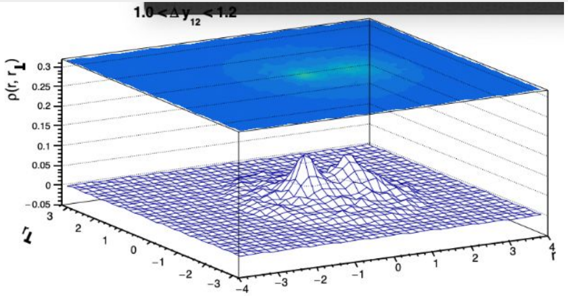


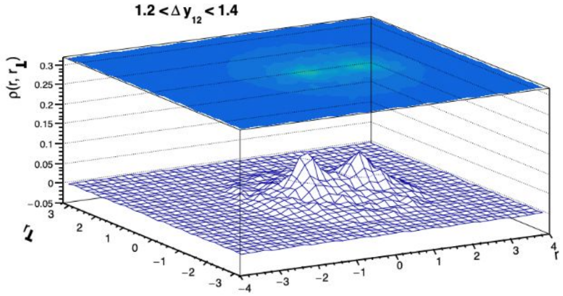
There are two distinct peaks, regardless of subjet-separation in the vacuum (pp) case

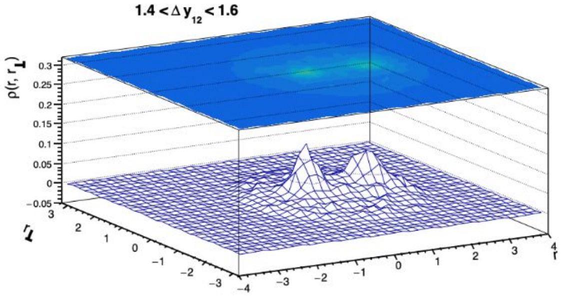
SHAPE OF PARTICLES WITH P_T < 1.0 GeV IN GAMMA-JETS IN pp COLLISIONS WITH 2 SUBJETS

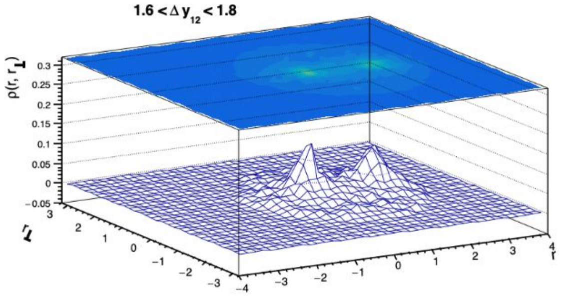


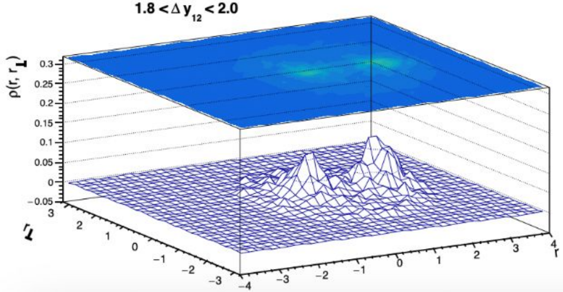






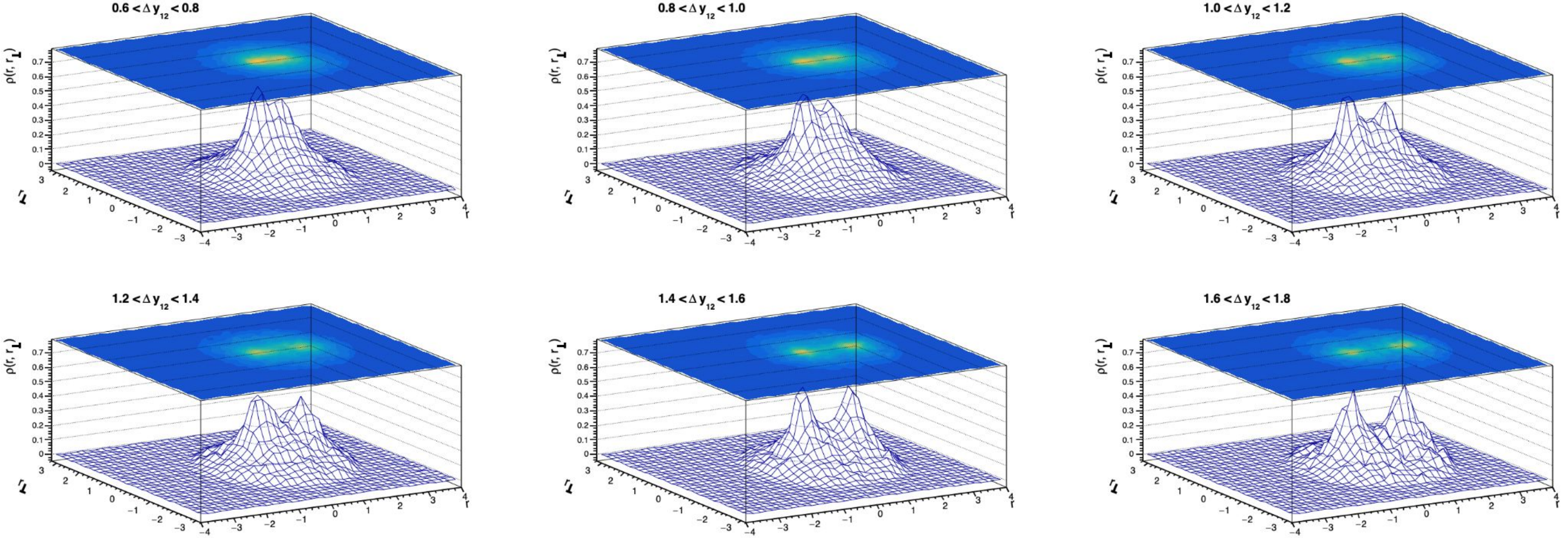


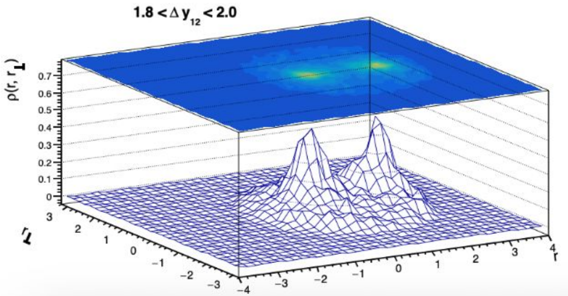




At very low p_T of less than 1.0 GeV, there are still two distinct peaks in the vacuum (pp) case… even when the subjets are closely-separated!

SHAPE OF PARTICLES WITH P_T < 1.5 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

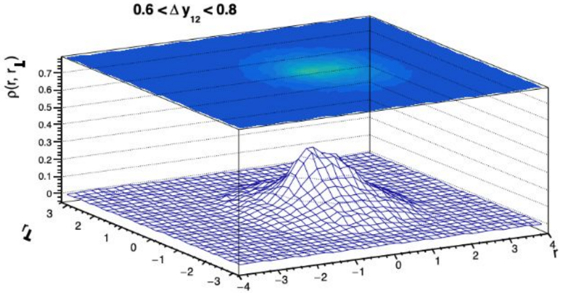


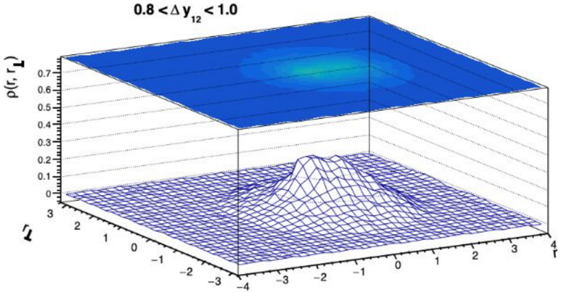


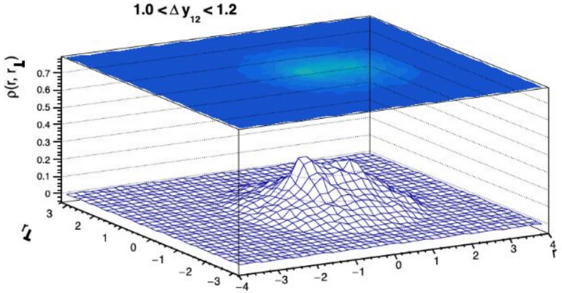
Experimentalists look for the wake by restricting to observing particles with low-p_T.

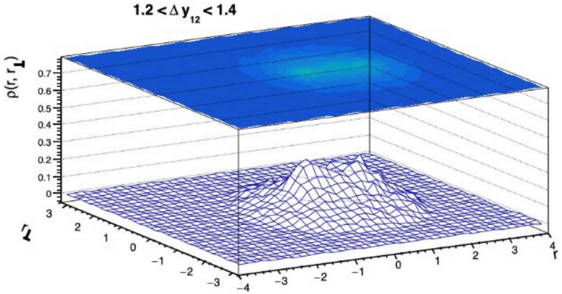
If we restrict to calculating the jet shape for particles with p_T < 1.5 GeV, then it resembles the shape of the wake – in particular, it is difficult to distinguish between two soft structures for $\Delta y_{12} < 1.0$, and easier for larger Δy_{12}.

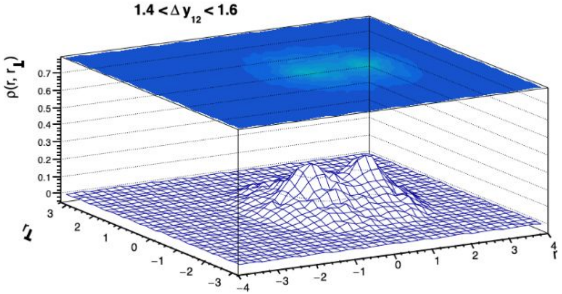
SHAPE OF PARTICLES WITH P_T < 1.0 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

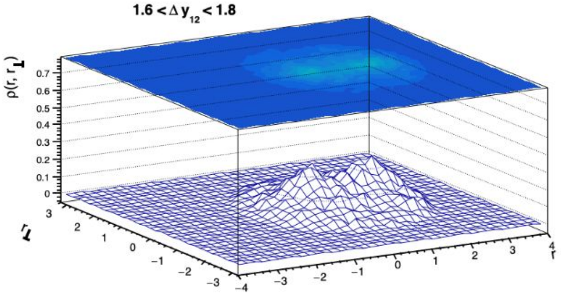


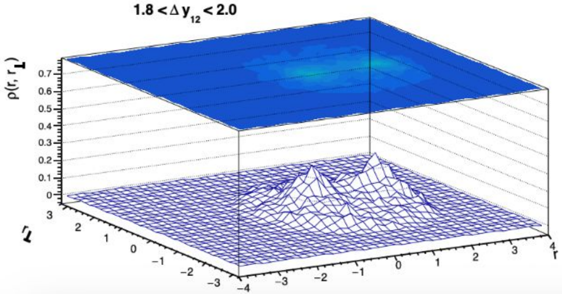




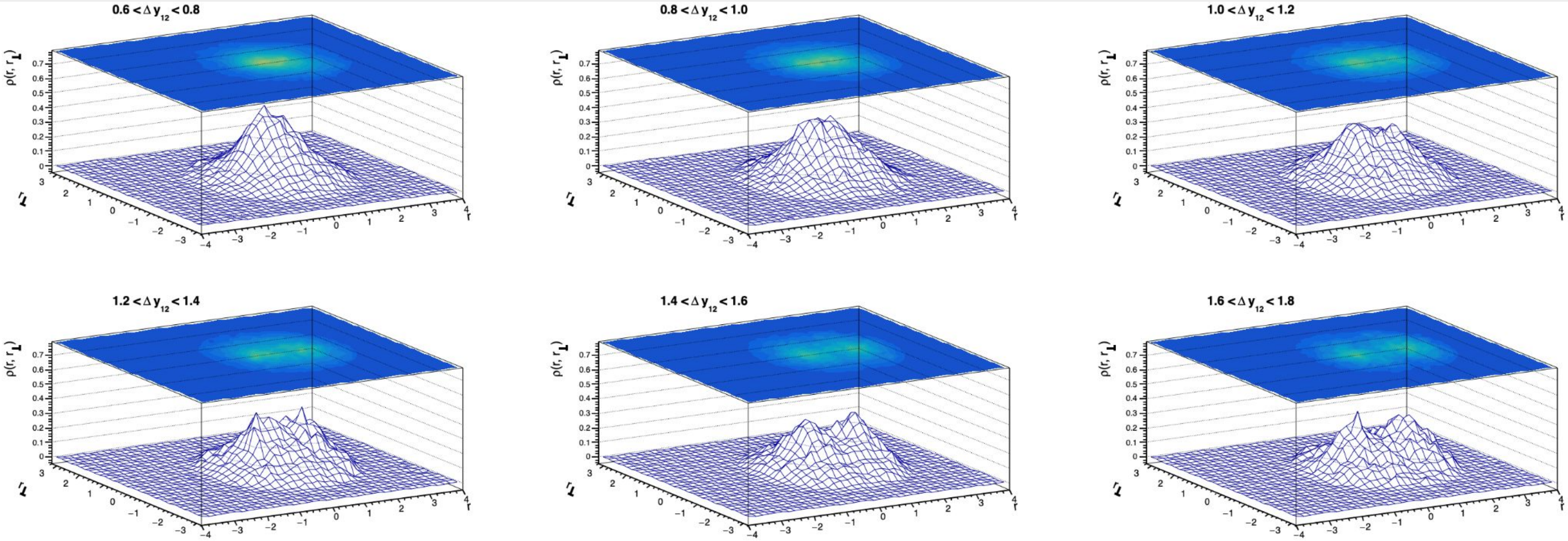


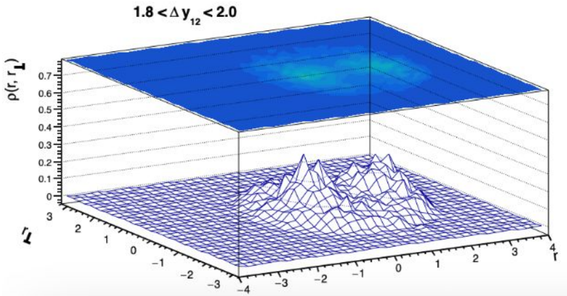






WAKE SHAPE OF GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS





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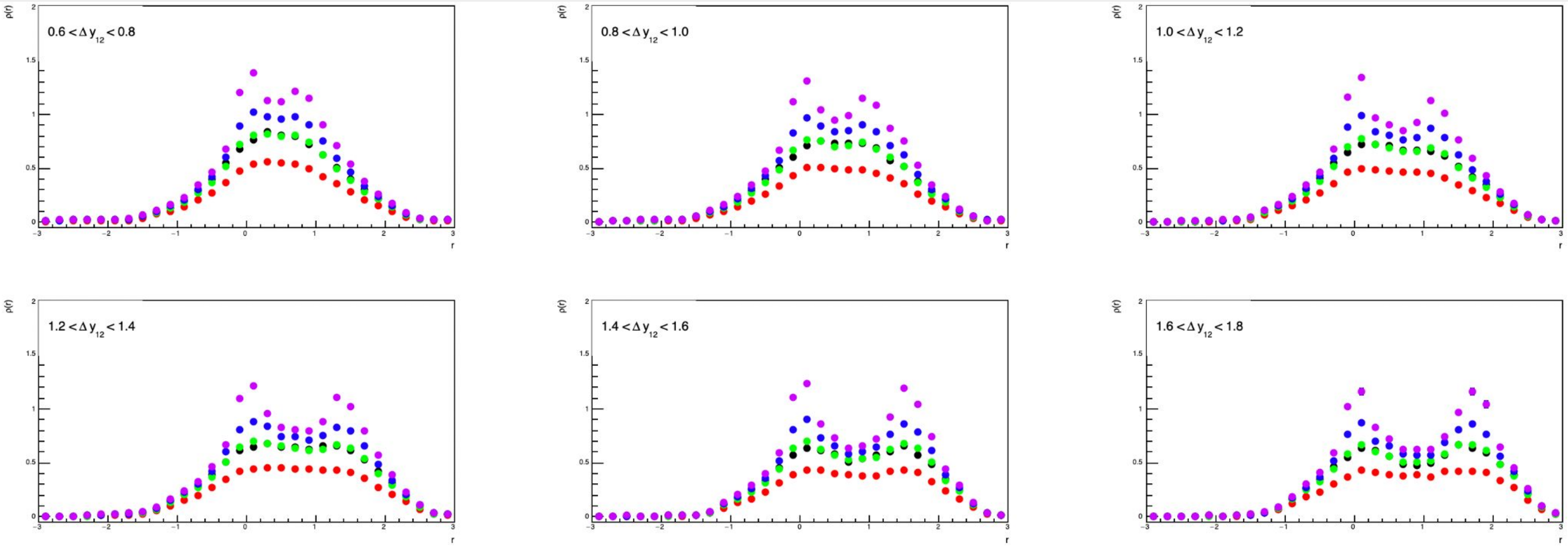
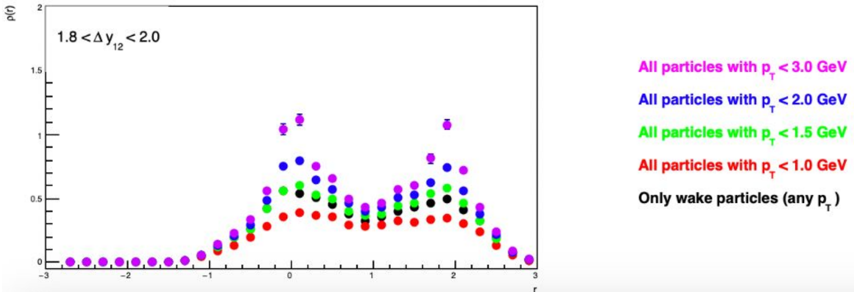
Can we see this in experiments?

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

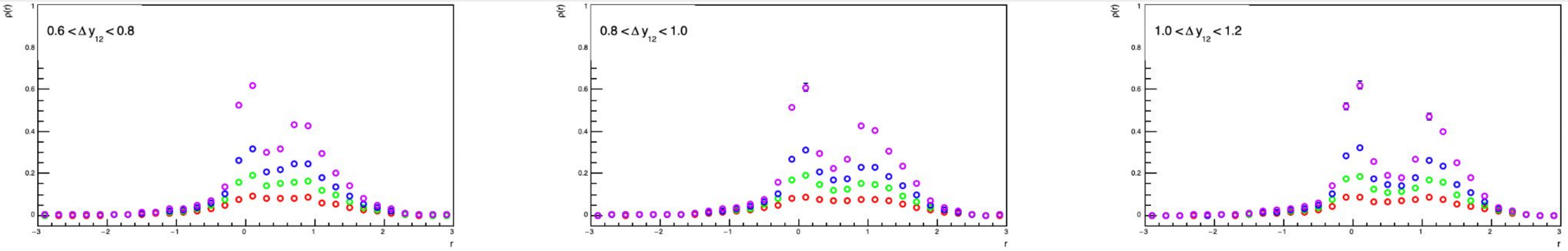


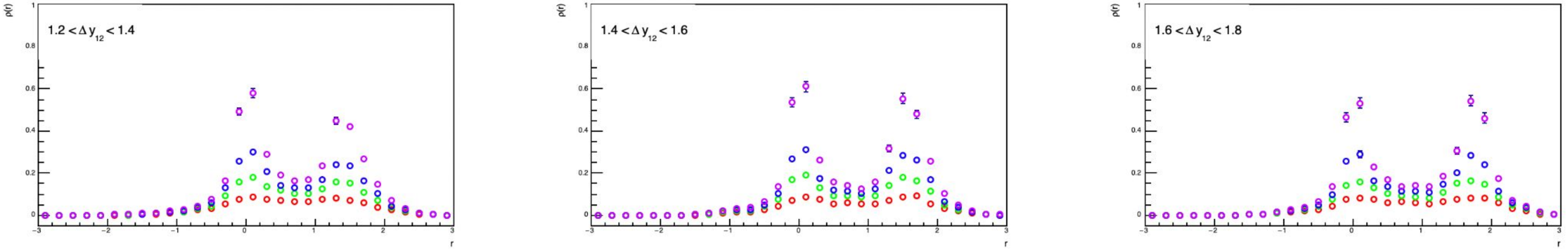


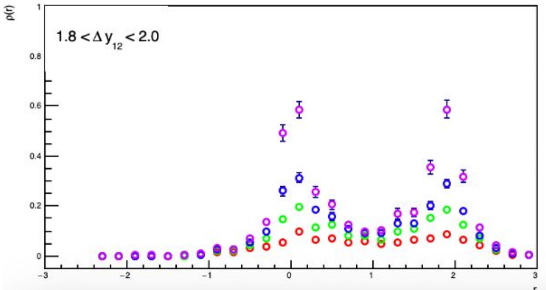
Experimental testability: Look at the jet shape of soft particles with p_T < 1.5 GeV since it most resembles the shape of the wake.

Is the shape of the subset of wake particles within these soft particles different from the shape of non-wake particles with p_T < 1.5 GeV?

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







Non-wake particles with $p_T < 3.0$ GeV
Non-wake particles with $p_T < 2.0$ GeV
Non-wake particles with $p_T < 1.5$ GeV
Non-wake particles with $p_T < 1.0$ GeV

Yes! There are 2 distinct structures in the subjet-separation range of $1.0 < \Delta y_{12} < 1.4$ when we exclude the wake from particles with $p_T < 1.5$ GeV.

In other words, the wake fills in the space between these two distinct soft structures. **We should look for this filling-in property of the wake in experiments.**

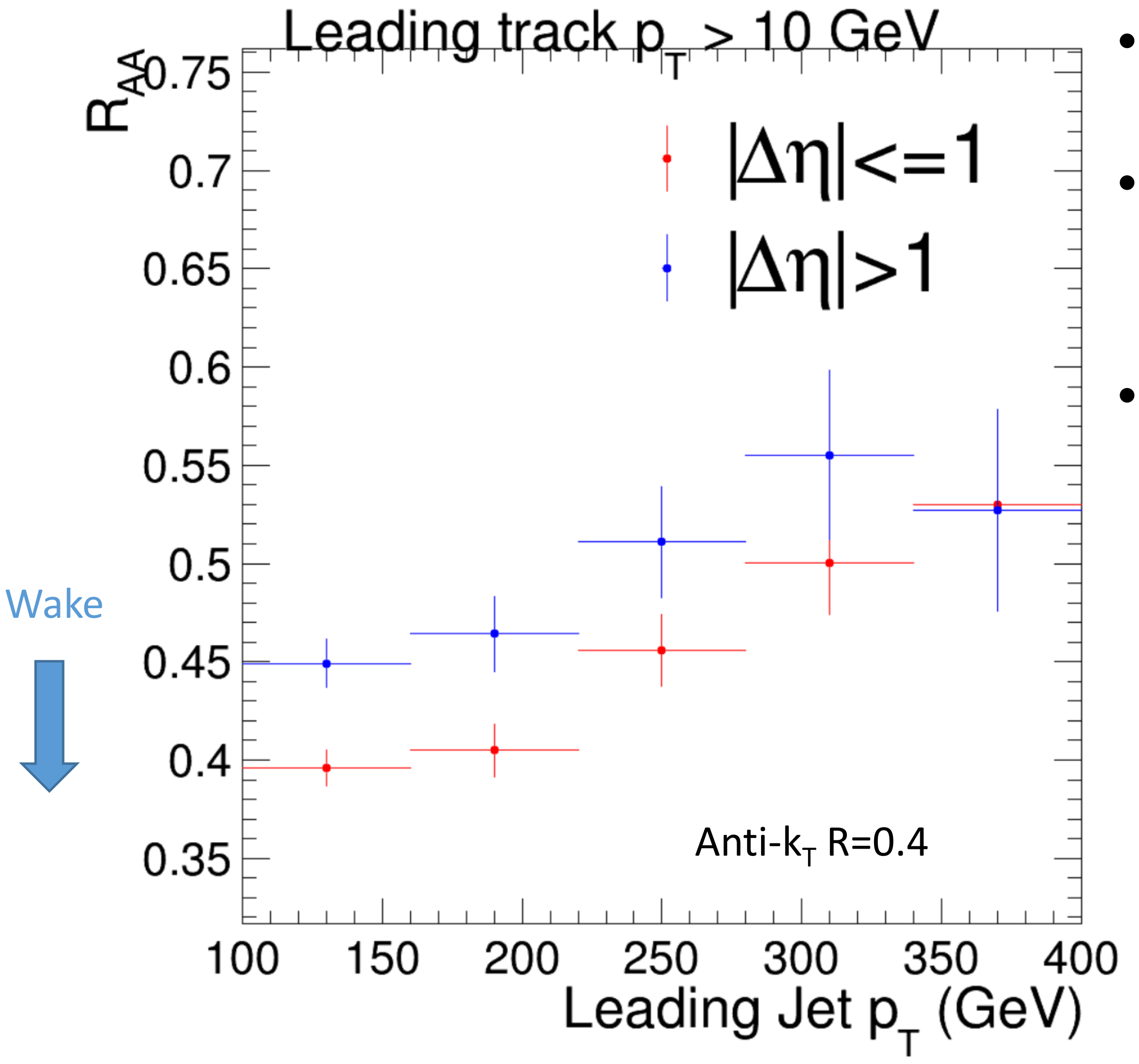
Do Subjets Have Separate Wakes?

- Only when they are far apart!
- With the crude hybrid model wake: for $\Delta y > 1.4$, two separated wakes; for $\Delta y < 1.0$, the two skinny subjets (each has $R = 0.2$; well-separated?) have a common wake.
- Particles with $p_T < 1$ GeV, or with $0.7 < p_T < 1$ GeV, are good proxies for the wake; $p_T < 1.5$ GeV is reasonable.
- Note: in pp, the skinny subjets are separate even in these low p_T bins. Seeing two subjets $\Delta y \sim 0.8$ apart merge at low p_T in heavy ion collisions $\to$ wake!
- Seeing the wake separate into two subwakes when Δy is large enough visualizes the size of the wake.
- We can further optimize this study, in conversation with experimentalists, to find the best practical ways to use two-skinny-subjet events as a new angle with which to visualize the shape of the (sub)wake(s)!
- The current hybrid model implementation of the wake is crude, and is too wide and too soft. We will improve it. The real point, today, is that we have identified a tool with which experimentalists can visualize (sub)wake(s)!

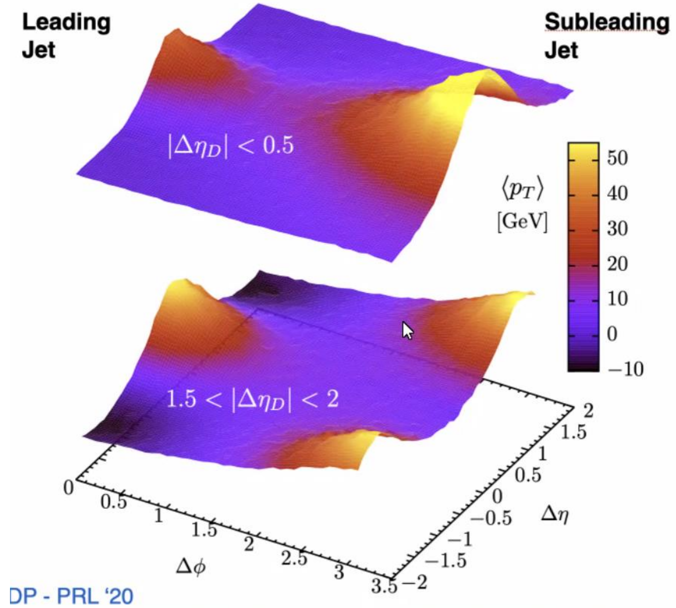
More Tools for Seeing Jet Wakes!

- See Hannah Bossi's talk tomorrow for a hybrid model study that introduces another new tool with which to see the "shape" of jet wakes.... Albeit with a different meaning of the word shape. An energy-energy-energy correlator...
- And, to conclude my talk here, three further observables from work in progress by Yen-Jie Lee, Dani Pablos and KR. Here again, the hybrid model teaches us how to craft and interpret these observables as tools with which to visualize jet wakes.

R_{AA} of Leading Jet in Different Configuration



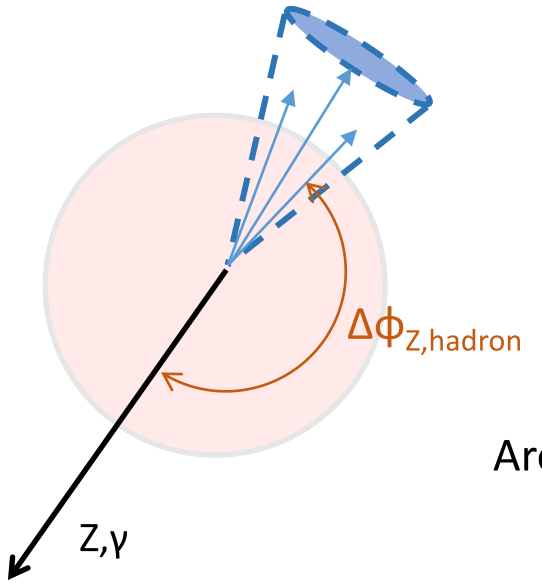
- The leading jet opposite the subleading jet overlaps with the latter's negative wake.
- To avoid reconstruction of the subleading jet, the |Δη| is measured between the leading track in the opposite hemisphere and the leading jet.
- One expect Larger cone sizes increase the negative wake captured in the jet cone



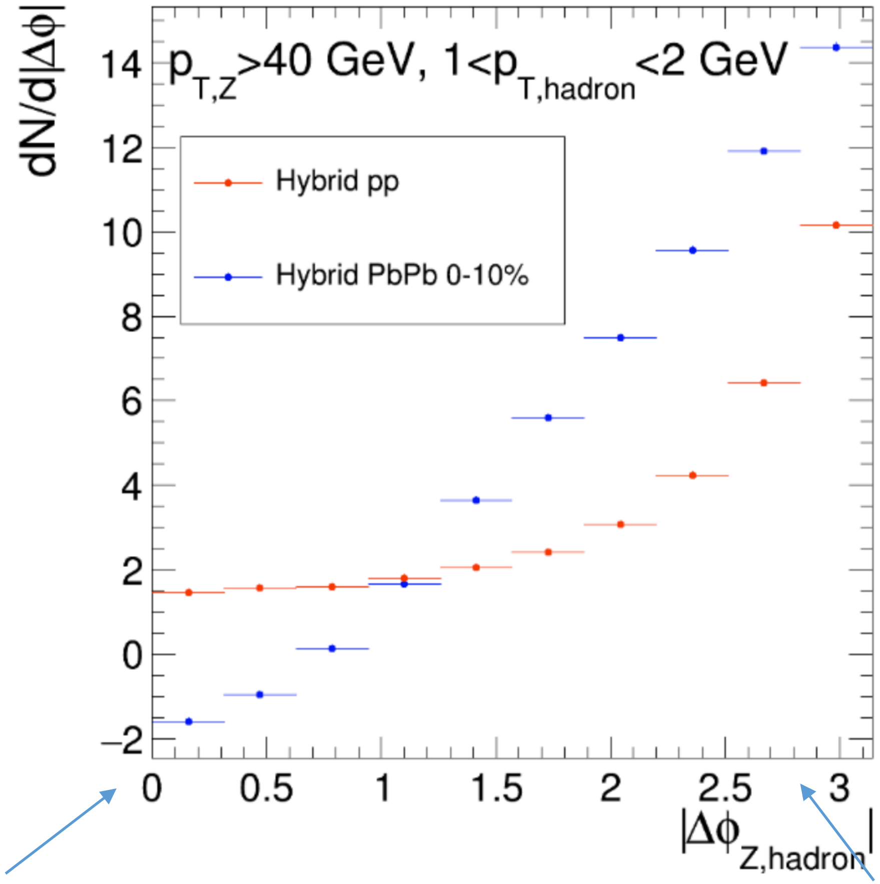
Z-Hadron Angular Correlation vs. Hadron p_T

- At low hadron p_T (1-2 GeV): Depletion around Z boson and broadening of the away-side peak

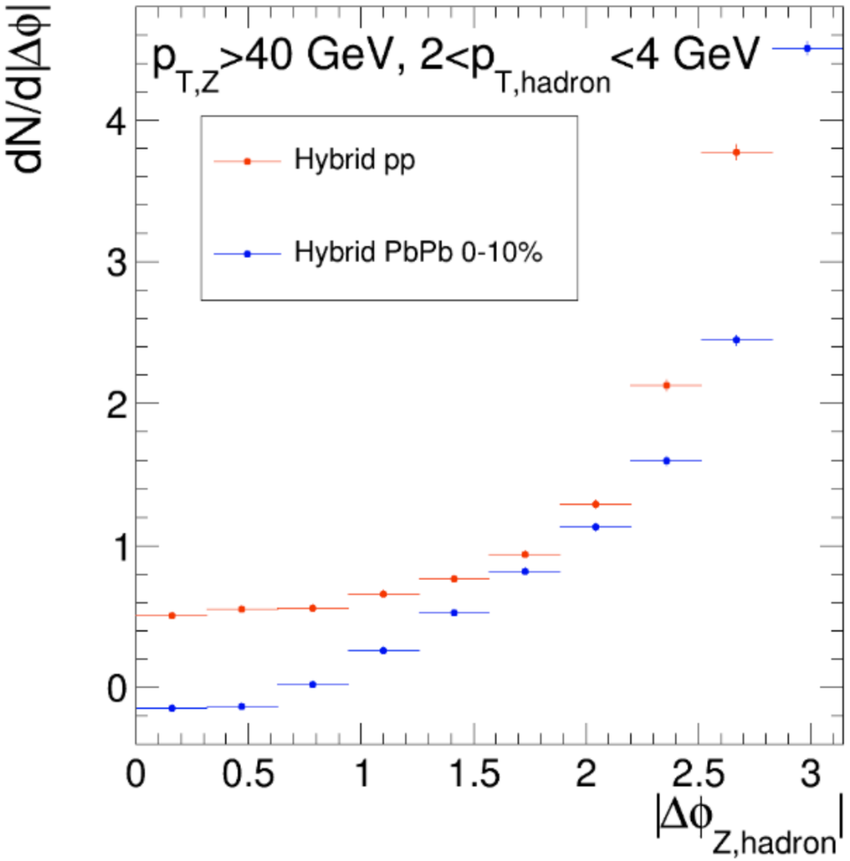
- Higher hadron p_T (2-4 GeV): Lower associated yield across all the $\Delta\phi$ interval



$1 < p_T < 2$ GeV



$2 < p_T < 4$ GeV



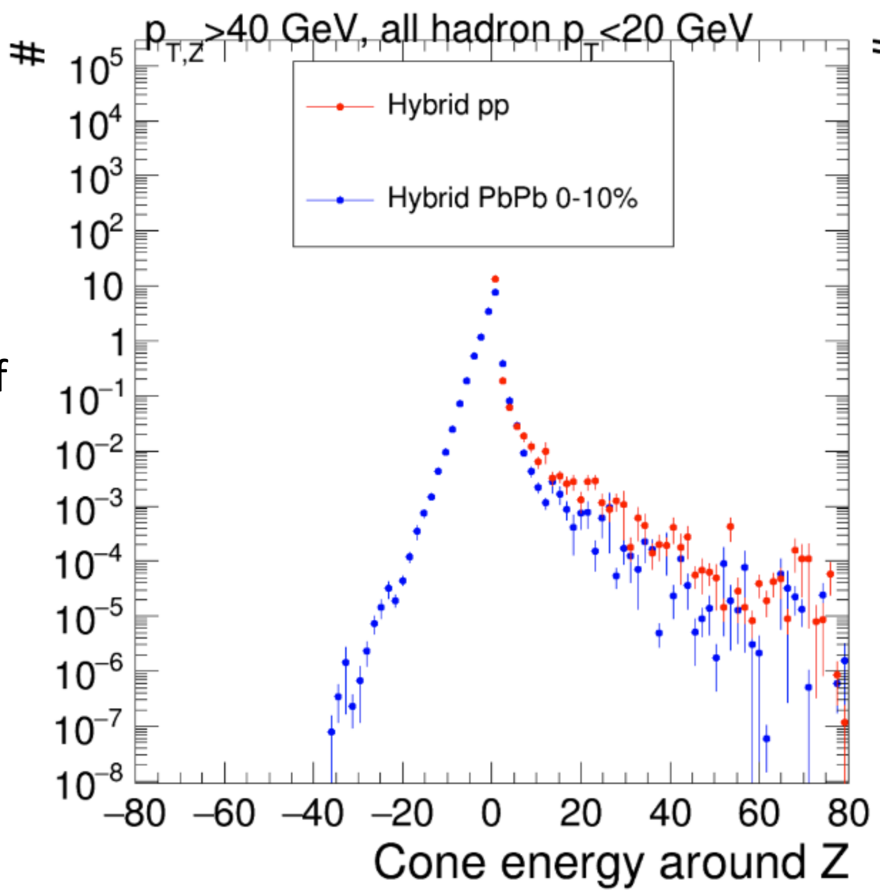
Around the Z

Around the jet

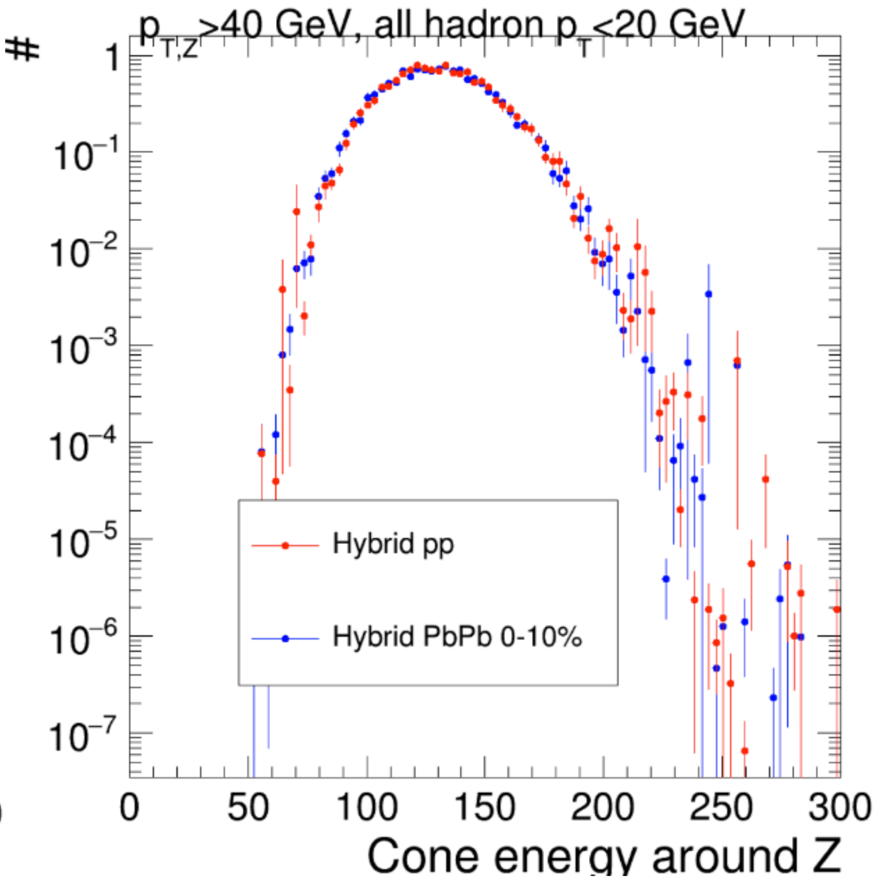
Cluster the Negative Wake around Z Boson

- With a cone of R=0.4 around Z, one could capture negative wake
- A HYDJET sample, which is tuned to match CMS PbPb data at 5.02 TeV, was used to study the effect from UE in cone
- Hybrid + HYDJET shows a small shift of the cone energy toward smaller value
- Baseline UE distribution could be studied with very high accuracy using large Minimum-Bias sample
- The observable could be further improved using cones around the axis that is opposite to the direction of the jet (or leading track)

Hybrid Z-hadron only



Hybrid Z-hadron + HYDJET



Do Subjets Have Separate Wakes?

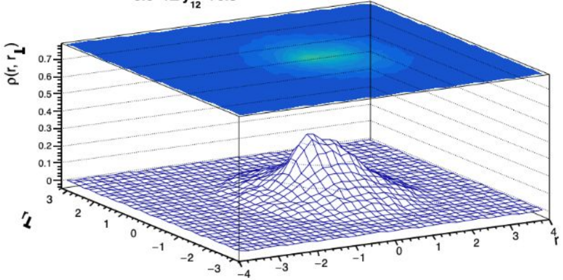
- Only when they are far apart!
- With the crude hybrid model wake: for $\Delta y > 1.4$, two separated wakes; for $\Delta y < 1.0$, the two skinny subjets (each has $R = 0.2$; well-separated?) have a common wake.
- Particles with $p_T < 1$ GeV, or with $0.7 < p_T < 1$ GeV, are good proxies for the wake; $p_T < 1.5$ GeV is reasonable.
- Note: in pp, the skinny subjets are separate even in these low p_T bins. Seeing two subjets $\Delta y \sim 0.8$ apart merge at low p_T in heavy ion collisions $\rightarrow$ wake!
- Seeing the wake separate into two subwakes when Δy is large enough visualizes the size of the wake.
- We can further optimize this study, in conversation with experimentalists, to find the best practical ways to use two-skinny-subjet events as a new angle with which to visualize the shape of the (sub)wake(s)!
- The current hybrid model implementation of the wake is crude, and is too wide and too soft. We will improve it. The real point, today, is that we have identified a tool with which experimentalists can visualize (sub)wake(s)!

BACKUP SLIDES

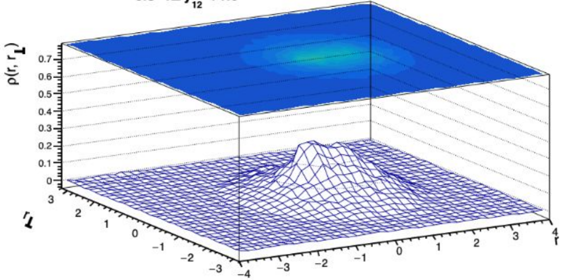
Only particles with $0 < p_T < 1$ GeV

ALL PARTICLES WITH $0 < P_T < 1$ GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

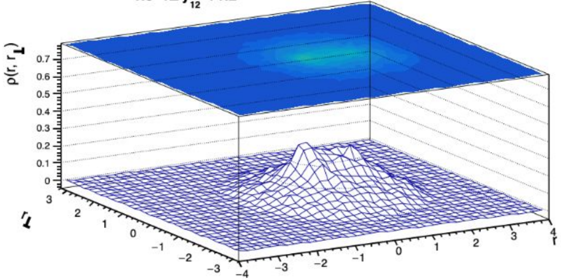
$0.6 < \Delta y_{12} < 0.8$



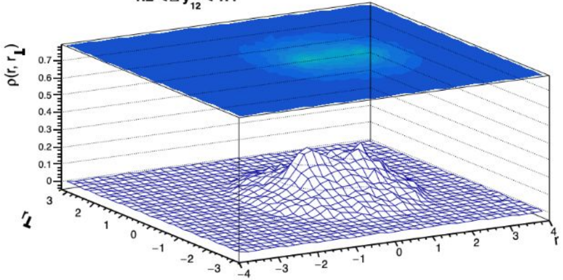
$0.8 < \Delta y_{12} < 1.0$



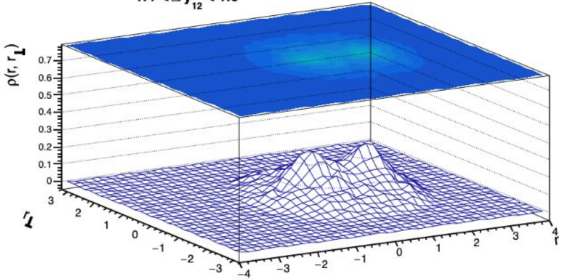
$1.0 < \Delta y_{12} < 1.2$



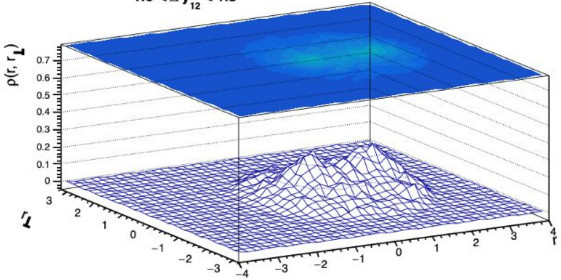
$1.2 < \Delta y_{12} < 1.4$



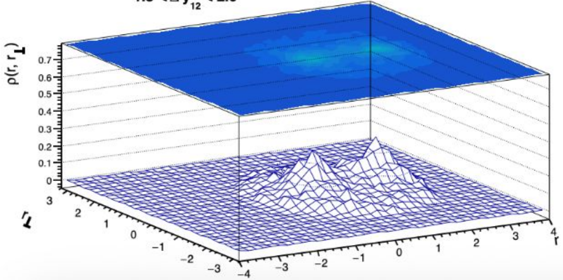
$1.4 < \Delta y_{12} < 1.6$



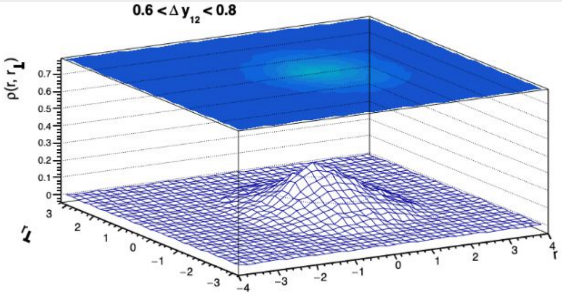
$1.6 < \Delta y_{12} < 1.8$

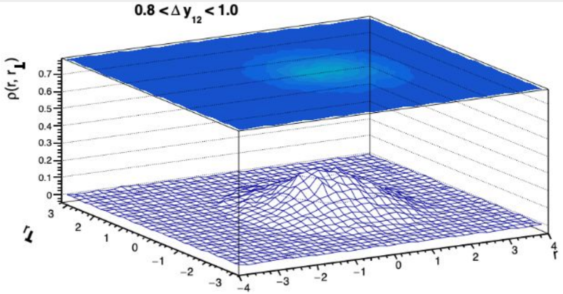


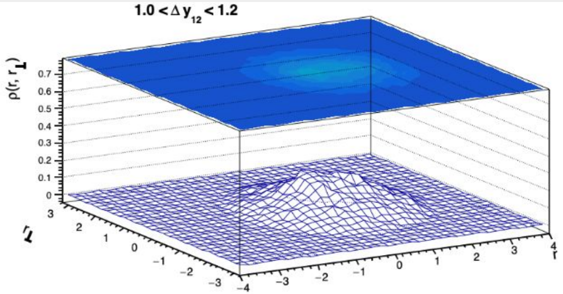
$1.8 < \Delta y_{12} < 2.0$

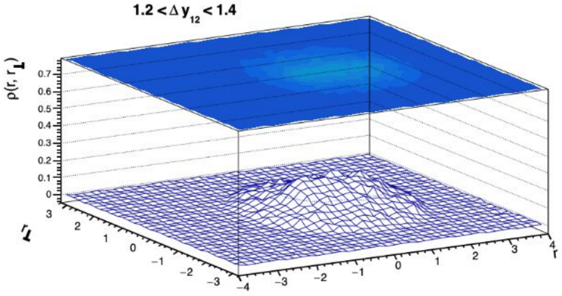


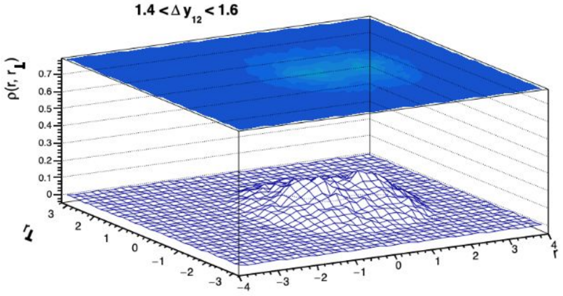
WAKE PARTICLES WITH 0 < P_T < 1 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

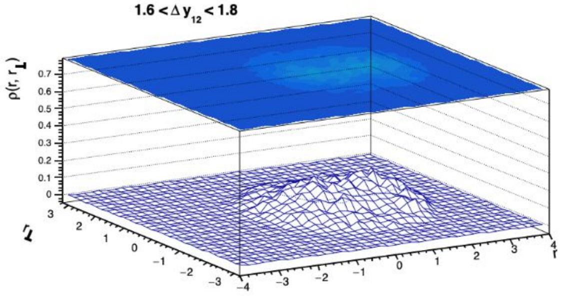


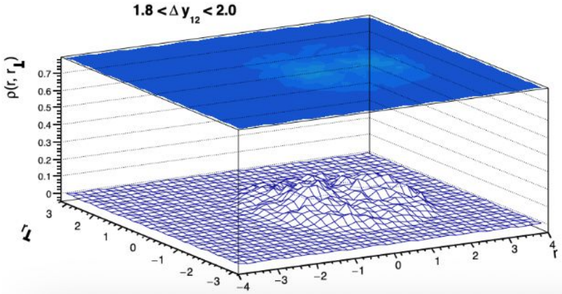




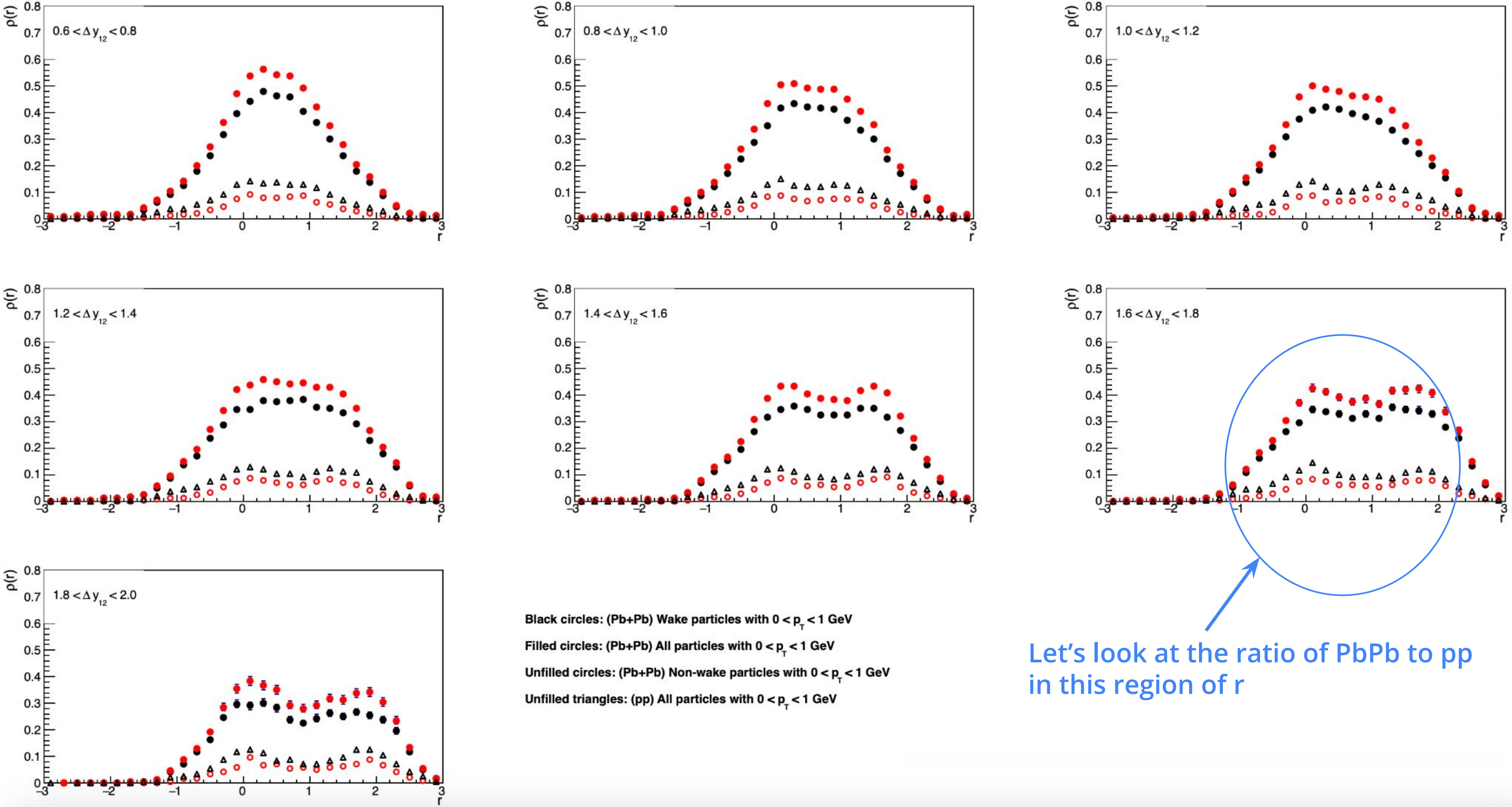








SHAPE OF PARTICLES WITH 0 < P_T < 1 GeV IN GAMMA-JETS WITH 2 SUBJETS



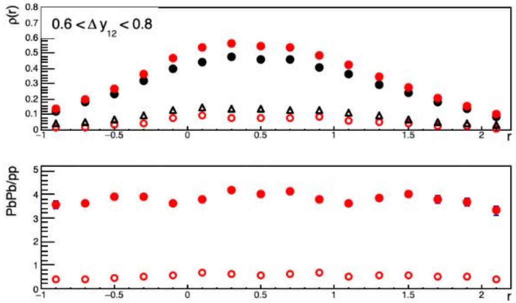
Black circles: (Pb+Pb) Wake particles with 0 < p_T < 1 GeV

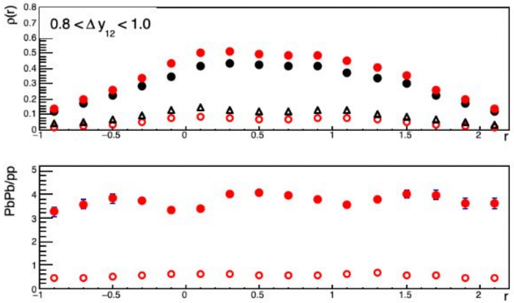
Filled circles: (Pb+Pb) All particles with 0 < p_T < 1 GeV

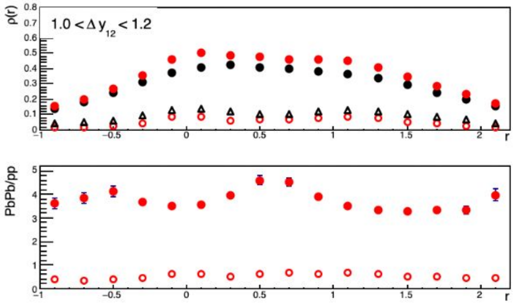
Unfilled circles: (Pb+Pb) Non-wake particles with 0 < p_T < 1 GeV

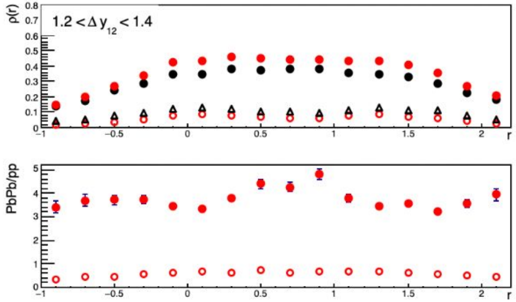
Unfilled triangles: (pp) All particles with 0 < p_T < 1 GeV

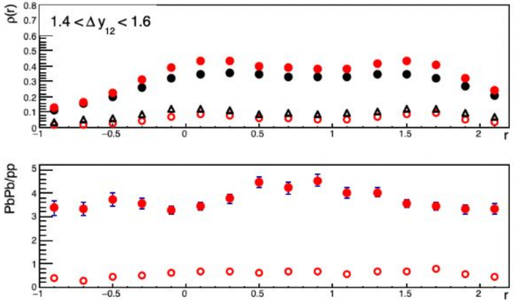
PbPb/pp JET SHAPE RATIOS OF PARTICLES WITH 0 < P_T < 1 GeV IN GAMMA-JETS WITH 2 SUBJETS

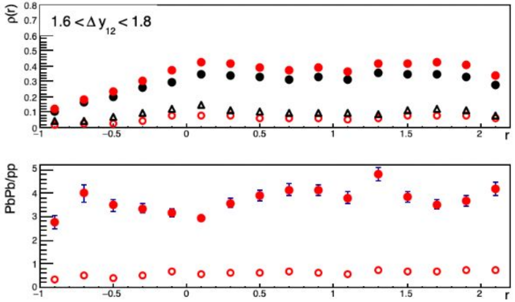


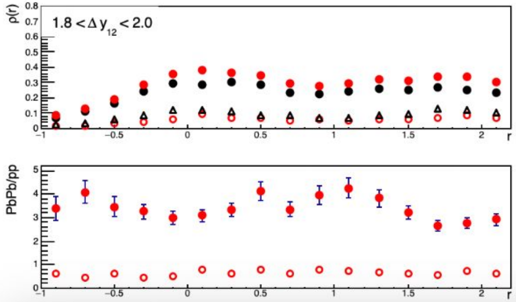












Black circles: (Pb+Pb) Wake particles with 0 < p_T < 1 GeV

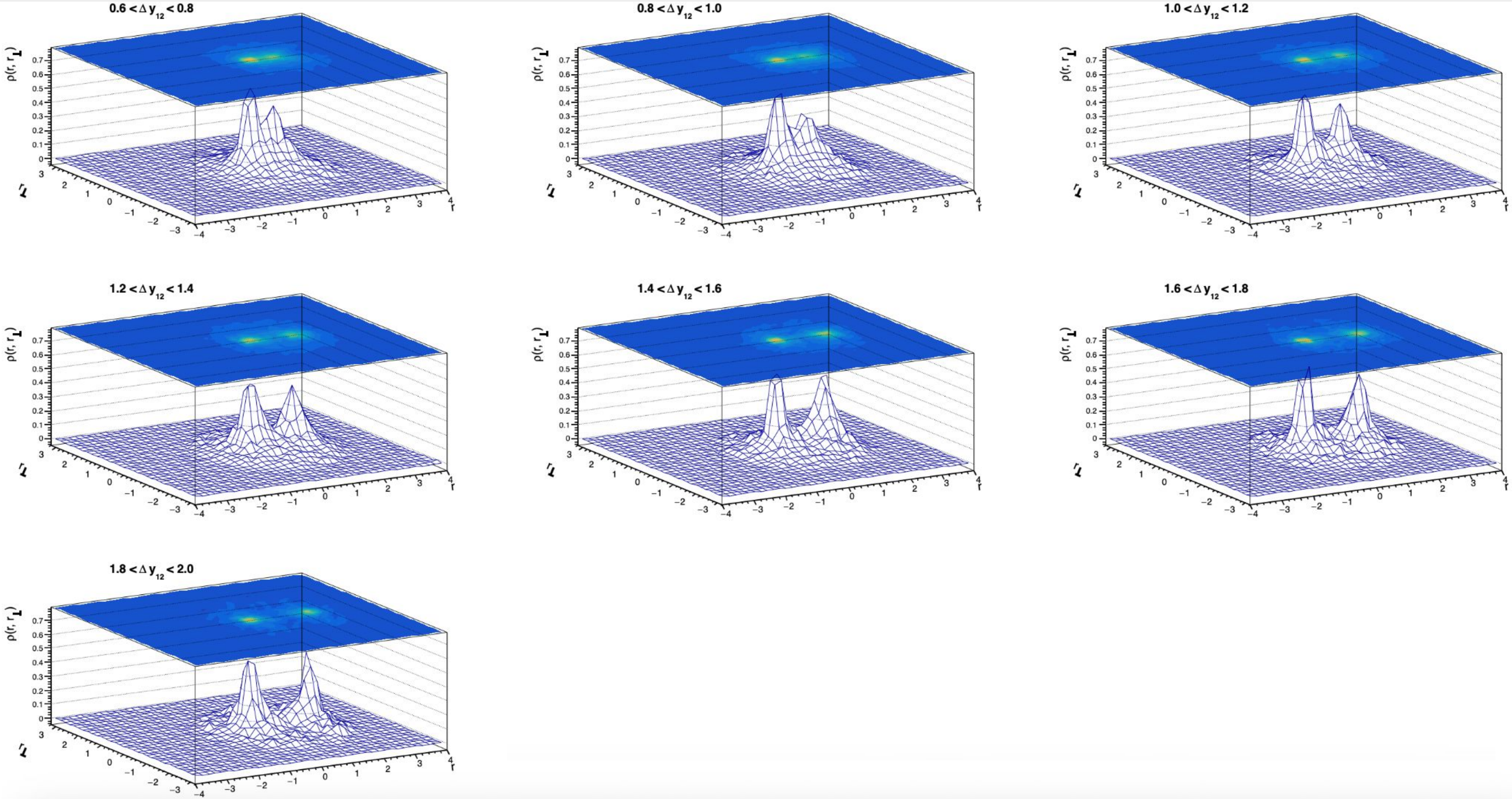
Filled circles: (Pb+Pb) All particles with 0 < p_T < 1 GeV

Unfilled circles: (Pb+Pb) Non-wake particles with 0 < p_T < 1 GeV

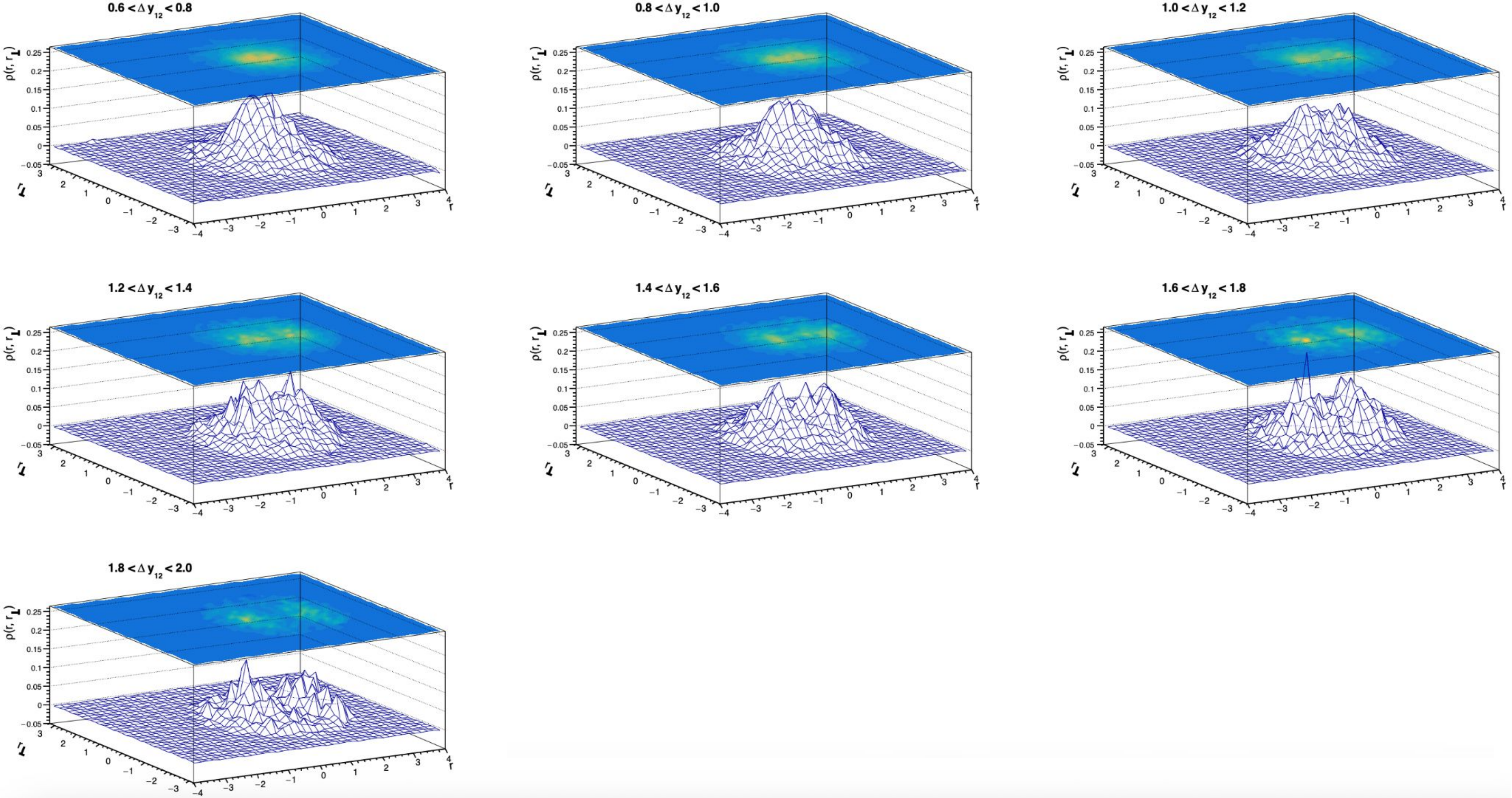
Unfilled triangles: (pp) All particles with 0 < p_T < 1 GeV

Only particles with $1 < p_T < 2$ GeV

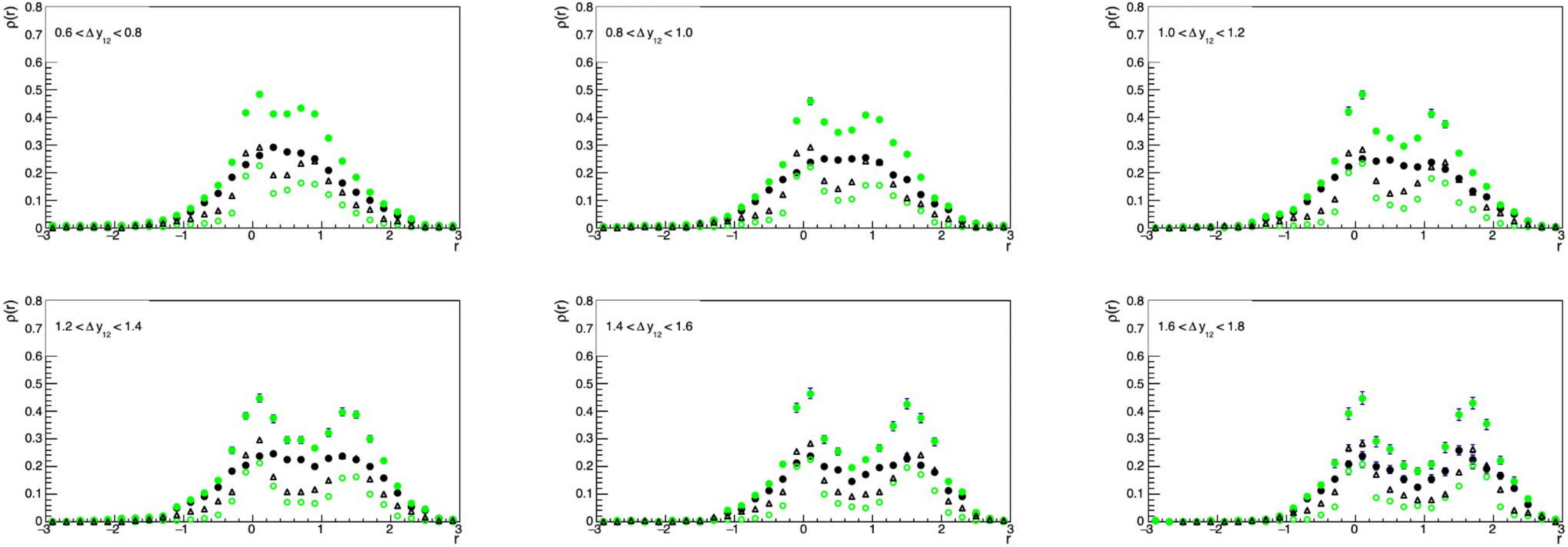
ALL PARTICLES WITH 1 < P_T < 2 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

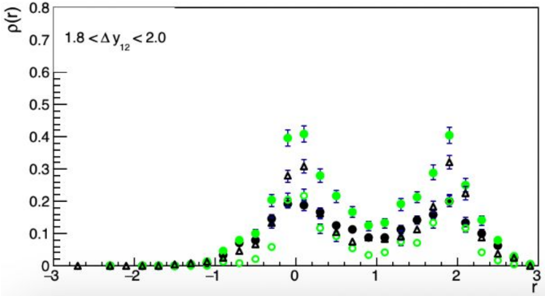


WAKE PARTICLES WITH 1 < P_T < 2 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS



SHAPE OF PARTICLES WITH 1 < P_T < 2 GeV IN GAMMA-JETS WITH 2 SUBJETS





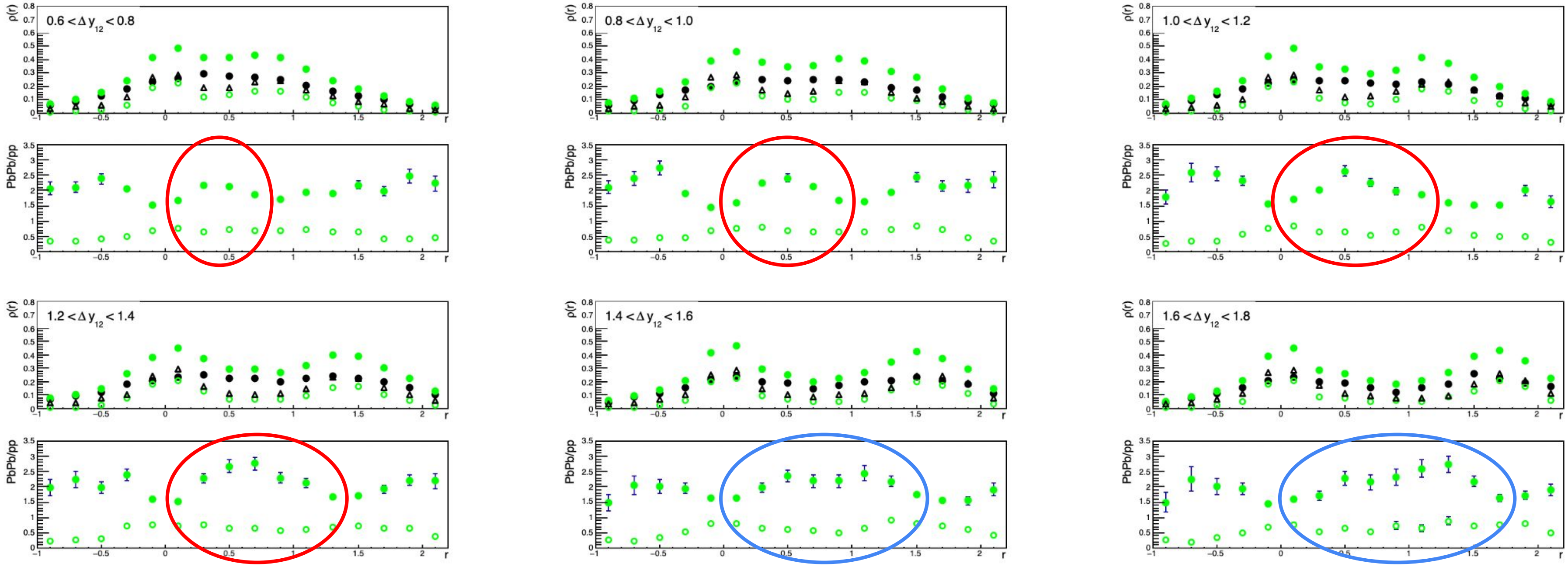
Black circles: (Pb+Pb) Wake particles with 1 < p_T < 2 GeV

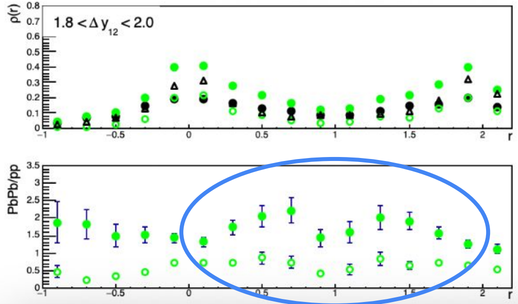
Filled circles: (Pb+Pb) All particles with 1 < p_T < 2 GeV

Unfilled circles: (Pb+Pb) Non-wake particles with 1 < p_T < 2 GeV

Unfilled triangles: (pp) All particles with 1 < p_T < 2 GeV

PbPb/pp JET SHAPE RATIOS OF PARTICLES WITH $1 < P_T < 2$ GeV IN GAMMA-JETS WITH 2 SUBJETS





Black circles: (Pb+Pb) Wake particles with $1 < p_T < 2$ GeV

Filled circles: (Pb+Pb) All particles with $1 < p_T < 2$ GeV

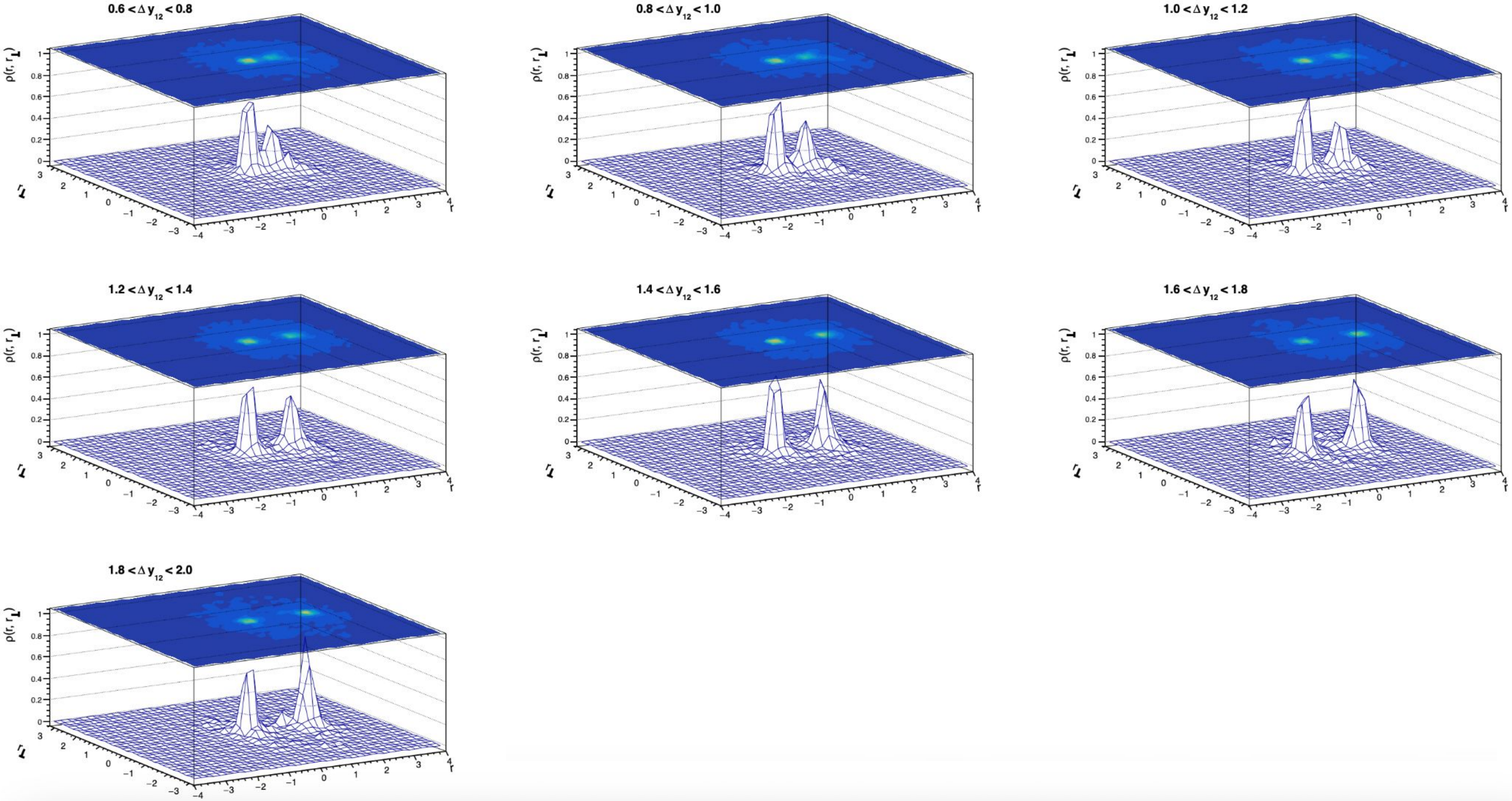
Unfilled circles: (Pb+Pb) Non-wake particles with $1 < p_T < 2$ GeV

Unfilled triangles: (pp) All particles with $1 < p_T < 2$ GeV

- **Singular peaks between closely-separated subjets appear in the PbPb/pp ratio when wake particles are included!**
- **(Stat. insignificant) Two peaks + a valley between far-separated subjets appear when wake particles are included!**
- **When wake particles are excluded, PbPb/pp remains flat between the two subjets!**

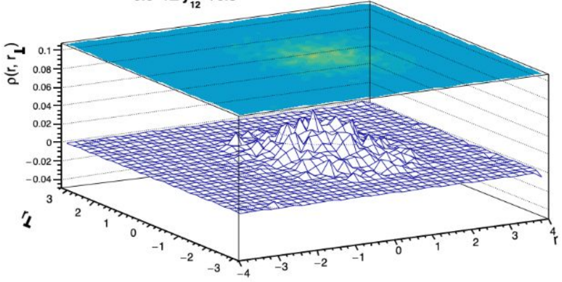
Only particles with $2 < p_T < 3$ GeV

ALL PARTICLES WITH $2 < P_T < 3$ GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

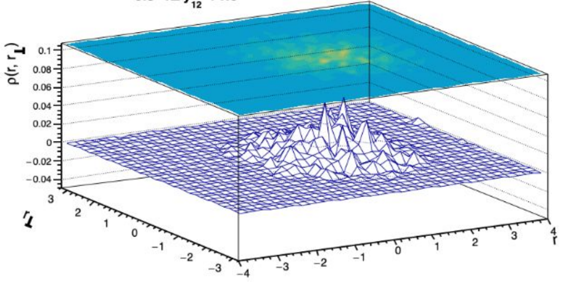


WAKE PARTICLES WITH 2 < P_T < 3 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

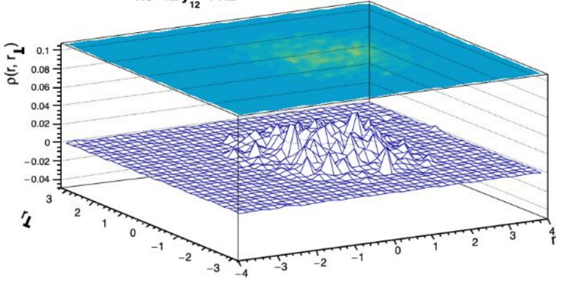
$0.6 < \Delta y_{12} < 0.8$



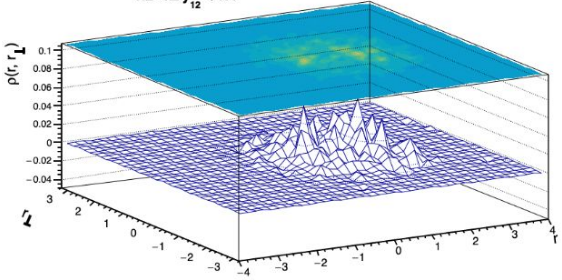
$0.8 < \Delta y_{12} < 1.0$



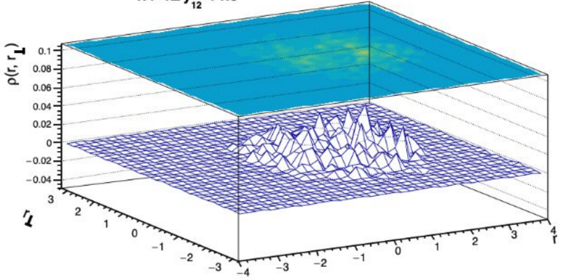
$1.0 < \Delta y_{12} < 1.2$



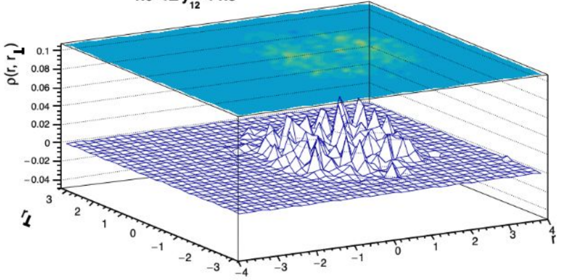
$1.2 < \Delta y_{12} < 1.4$



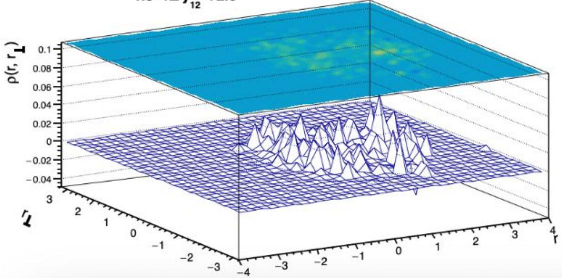
$1.4 < \Delta y_{12} < 1.6$



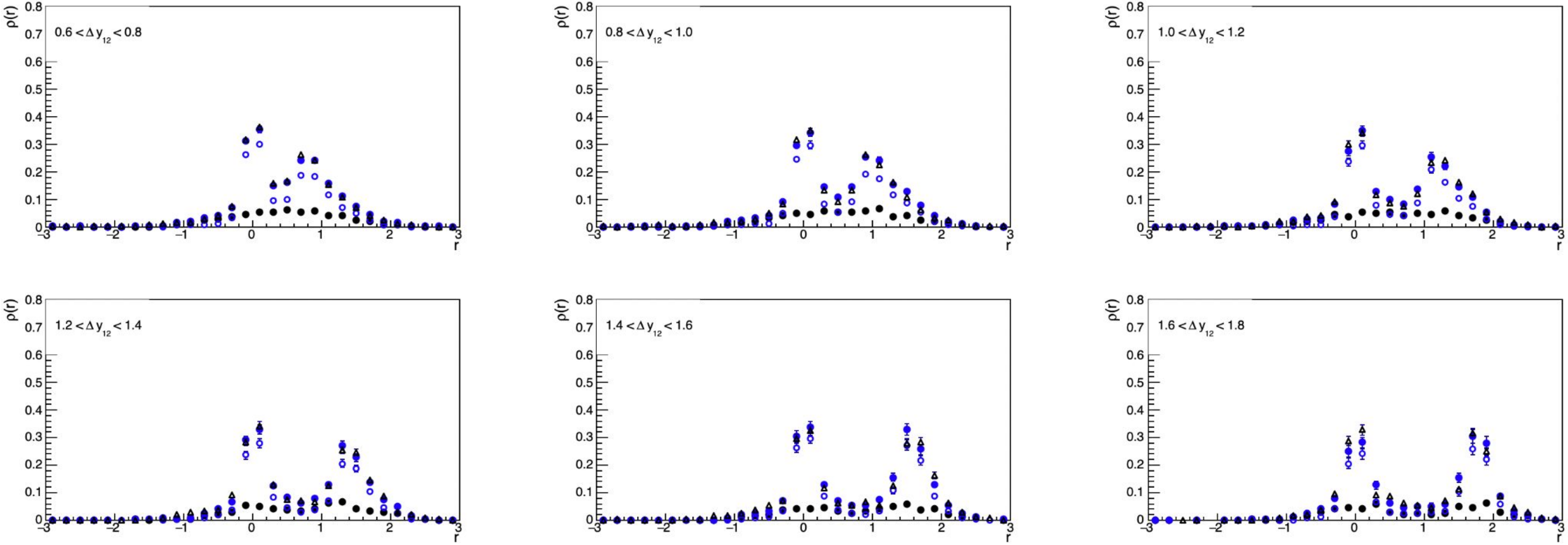
$1.6 < \Delta y_{12} < 1.8$

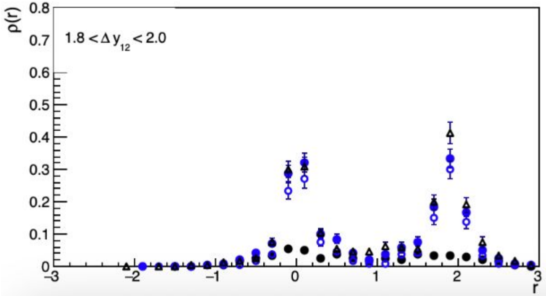


$1.8 < \Delta y_{12} < 2.0$



SHAPE OF PARTICLES WITH 2 < P_T < 3 GeV IN GAMMA-JETS WITH 2 SUBJETS





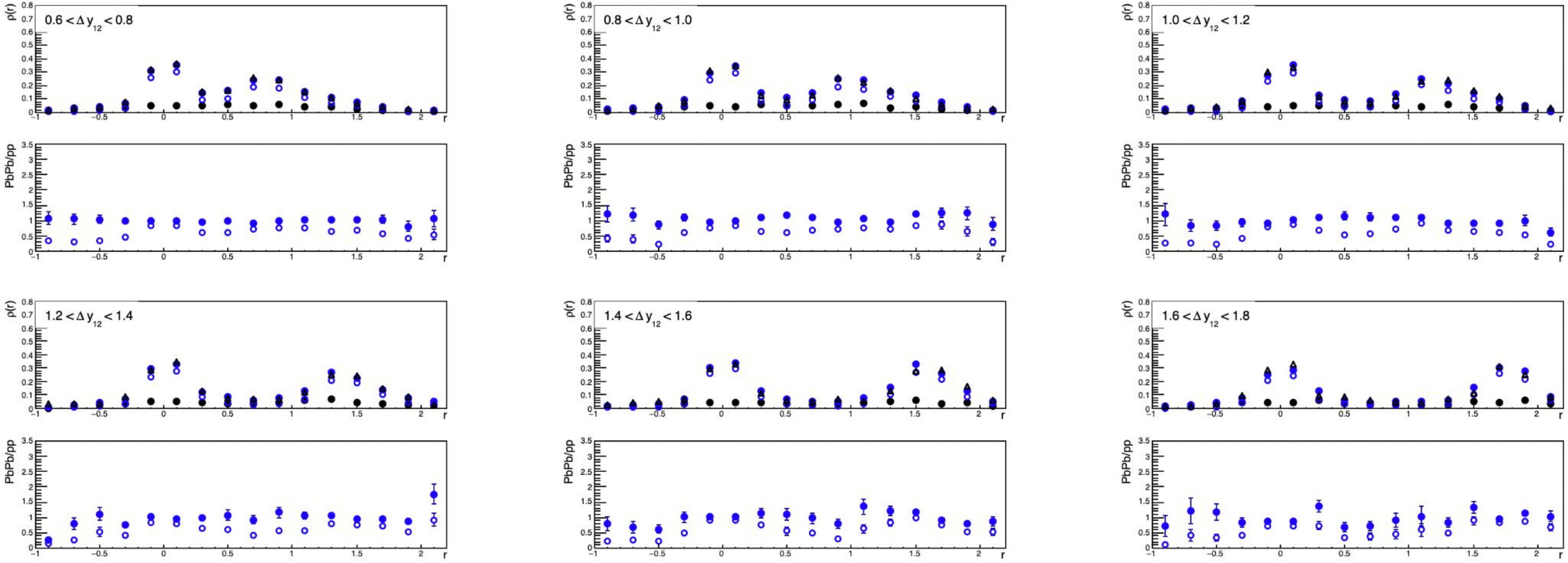
Black circles: (Pb+Pb) Wake particles with 2 < p_T < 3 GeV

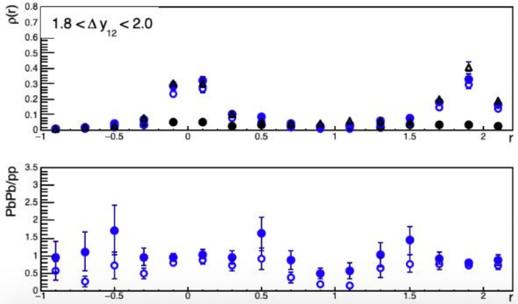
Filled circles: (Pb+Pb) All particles with 2 < p_T < 3 GeV

Unfilled circles: (Pb+Pb) Non-wake particles with 2 < p_T < 3 GeV

Unfilled triangles: (pp) All particles with 2 < p_T < 3 GeV

PbPb/pp JET SHAPE RATIOS OF PARTICLES WITH 2 < P_T < 3 GeV IN GAMMA-JETS WITH 2 SUBJETS





Black circles: (Pb+Pb) Wake particles with 2 < p_T < 3 GeV

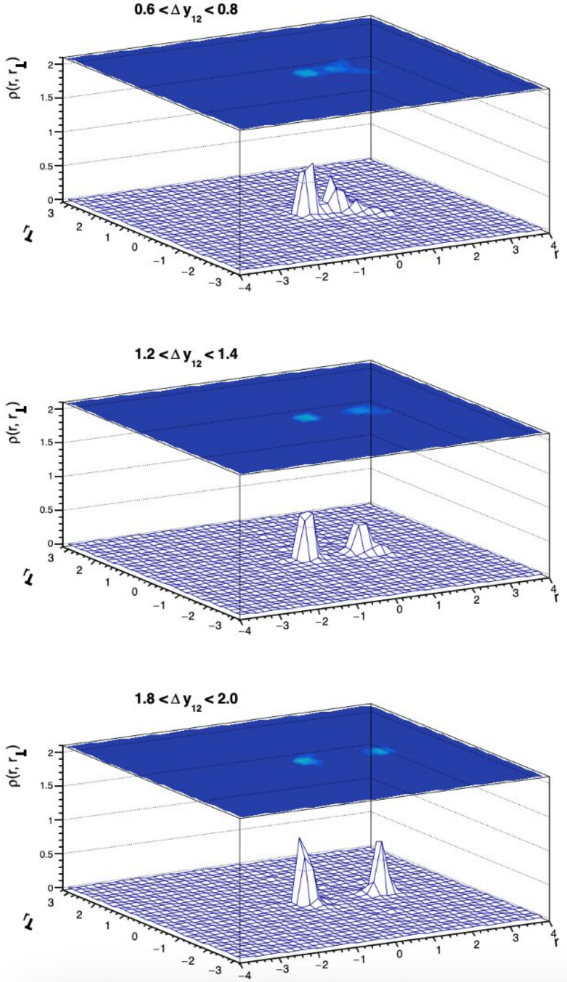
Filled circles: (Pb+Pb) All particles with 2 < p_T < 3 GeV

Unfilled circles: (Pb+Pb) Non-wake particles with 2 < p_T < 3 GeV

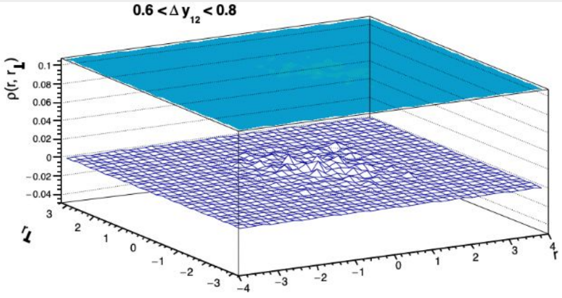
Unfilled triangles: (pp) All particles with 2 < p_T < 3 GeV

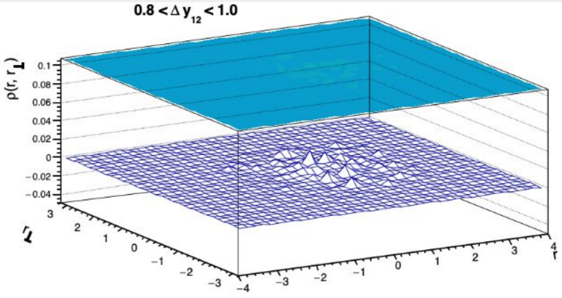
Only particles with $3 < p_T < 4$ GeV

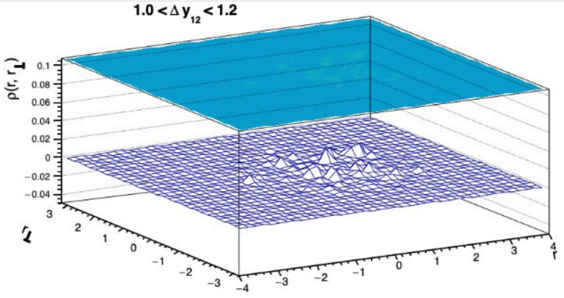
ALL PARTICLES WITH $3 < P_T < 4$ GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

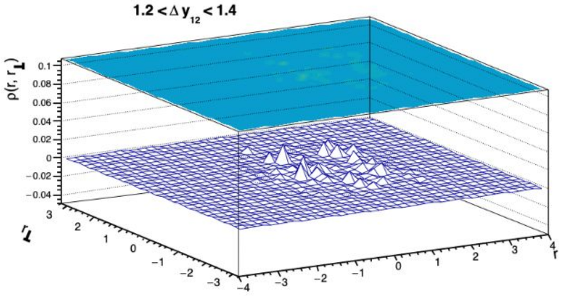


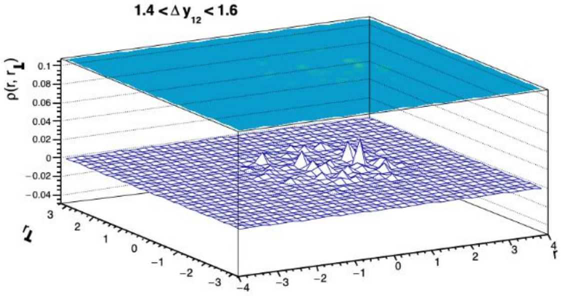
WAKE PARTICLES WITH 3 < P_T < 4 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

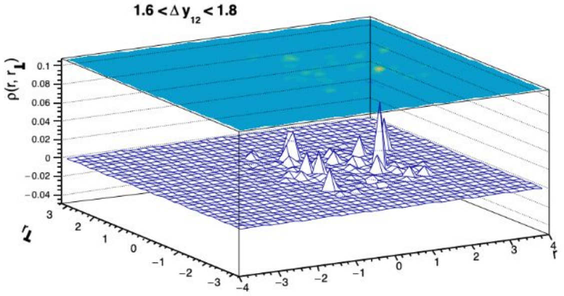


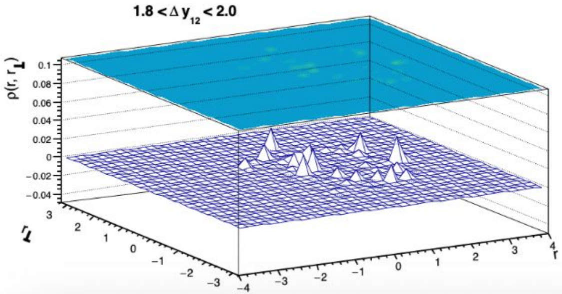




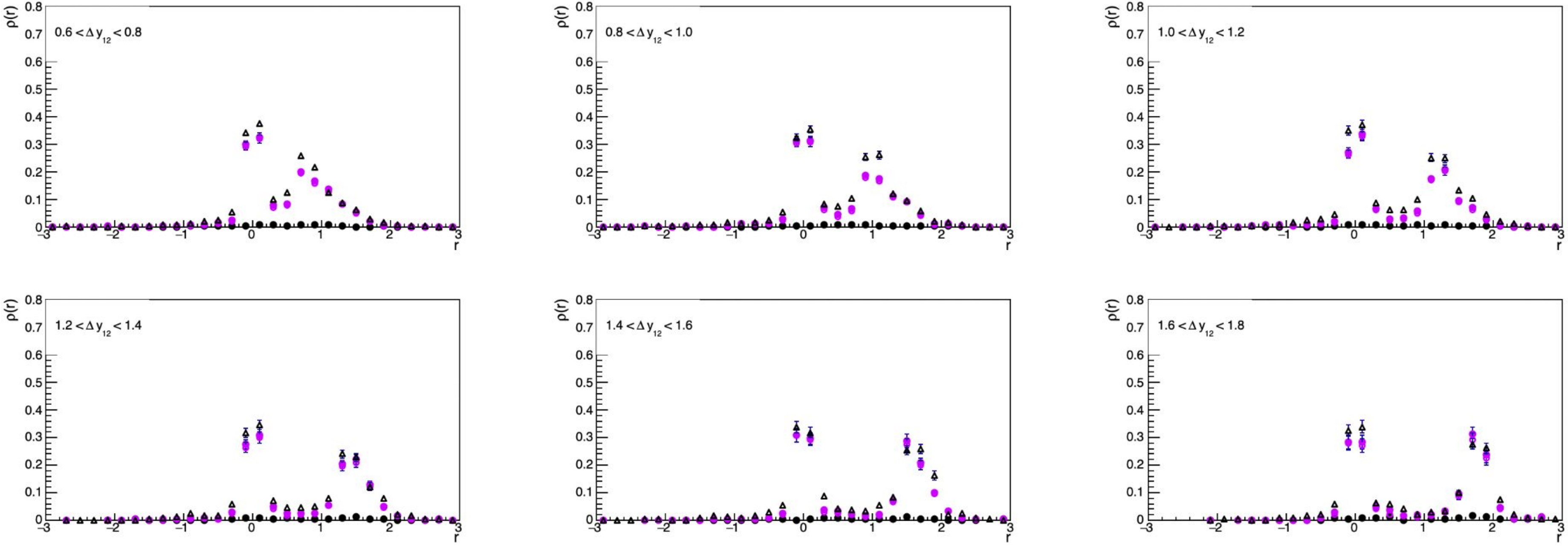


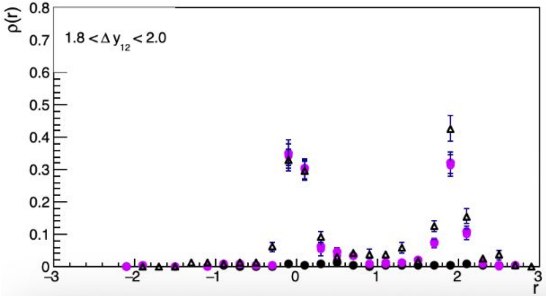






SHAPE OF PARTICLES WITH 3 < P_T < 4 GeV IN GAMMA-JETS WITH 2 SUBJETS





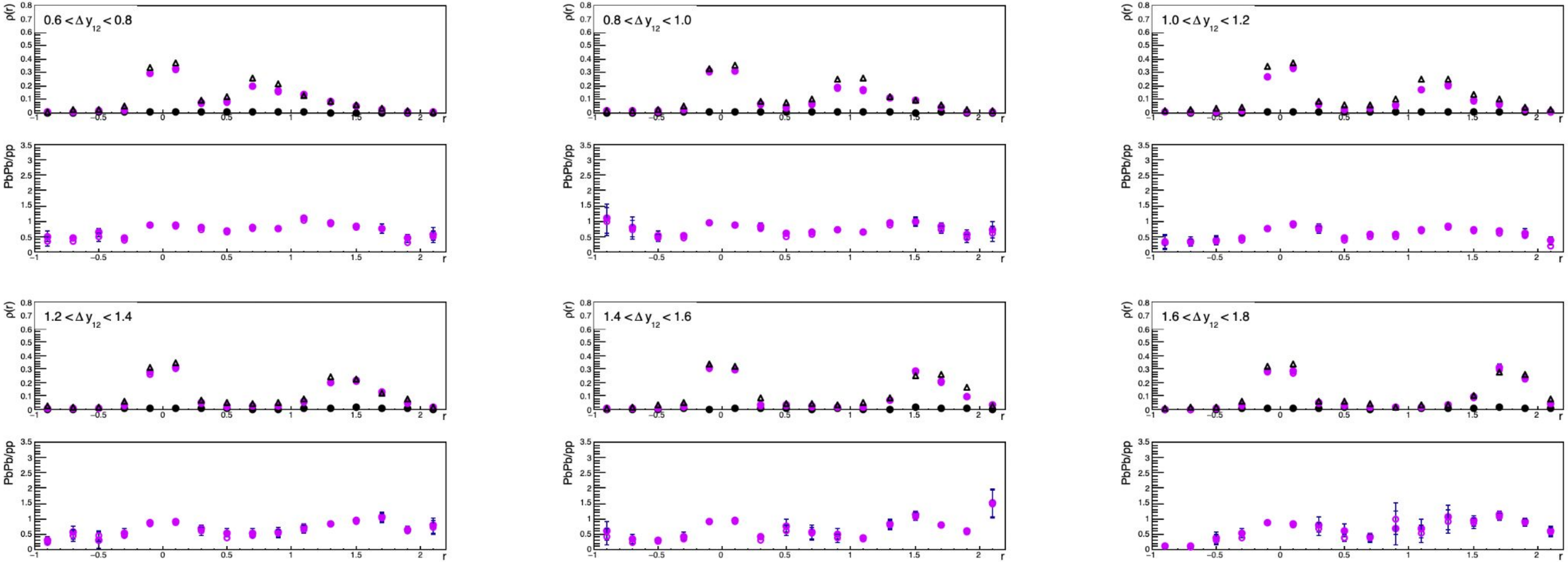
Black circles: (Pb+Pb) Wake particles with 3 < p_T < 4 GeV

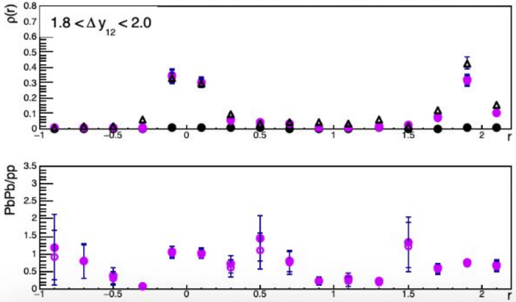
Filled circles: (Pb+Pb) All particles with 3 < p_T < 4 GeV

Unfilled circles: (Pb+Pb) Non-wake particles with 3 < p_T < 4 GeV

Unfilled triangles: (pp) All particles with 3 < p_T < 4 GeV

PbPb/pp JET SHAPE RATIOS OF PARTICLES WITH 3 < P_T < 4 GeV IN GAMMA-JETS WITH 2 SUBJETS





Black circles: (Pb+Pb) Wake particles with 3 < p_T < 4 GeV

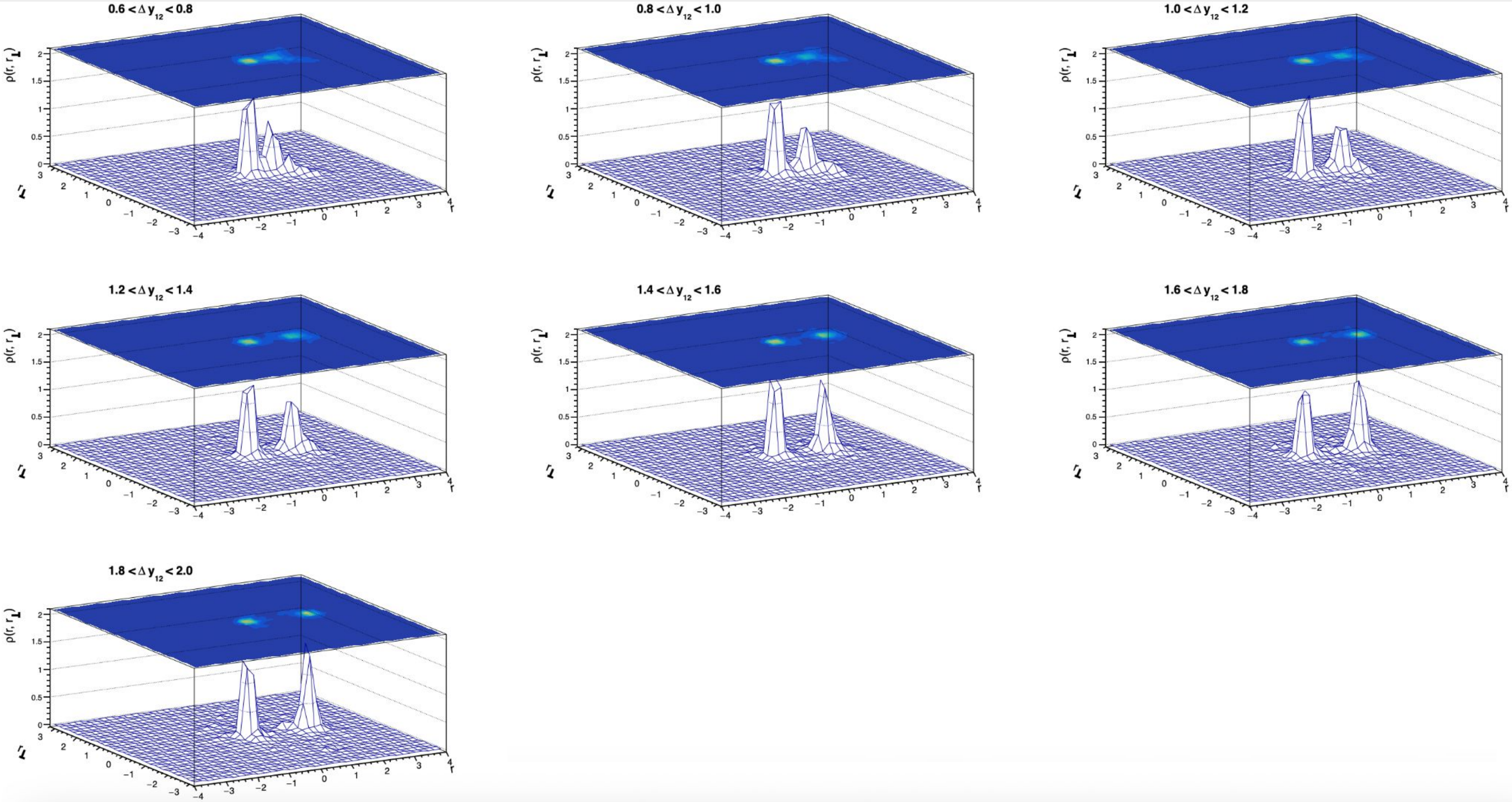
Filled circles: (Pb+Pb) All particles with 3 < p_T < 4 GeV

Unfilled circles: (Pb+Pb) Non-wake particles with 3 < p_T < 4 GeV

Unfilled triangles: (pp) All particles with 3 < p_T < 4 GeV

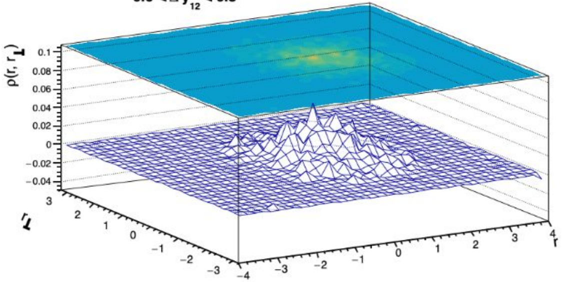
Only particles with $2 < p_T < 4$ GeV

ALL PARTICLES WITH 2 < P_T < 4 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

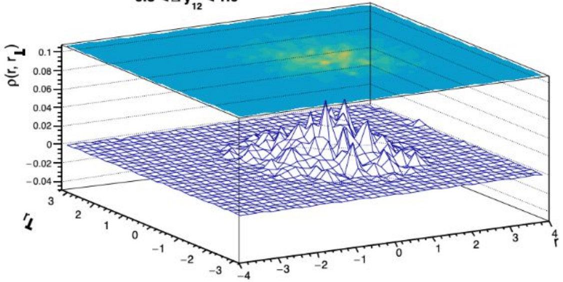


WAKE PARTICLES WITH 2 < P_T < 4 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

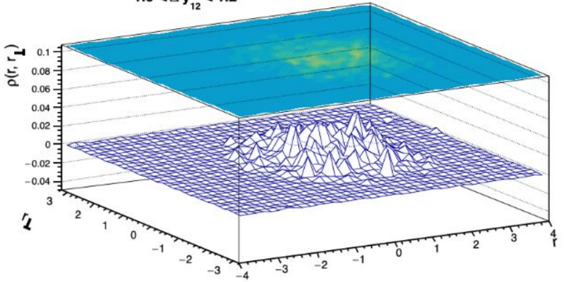
$0.6 < \Delta y_{12} < 0.8$



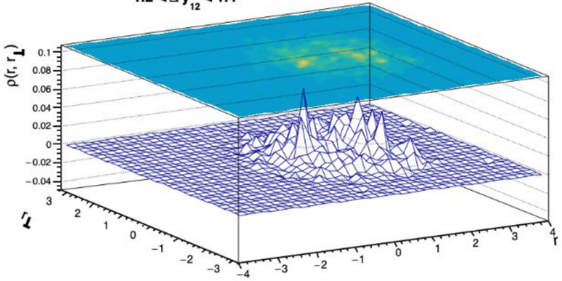
$0.8 < \Delta y_{12} < 1.0$



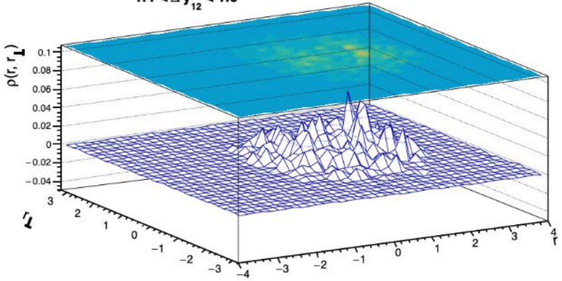
$1.0 < \Delta y_{12} < 1.2$



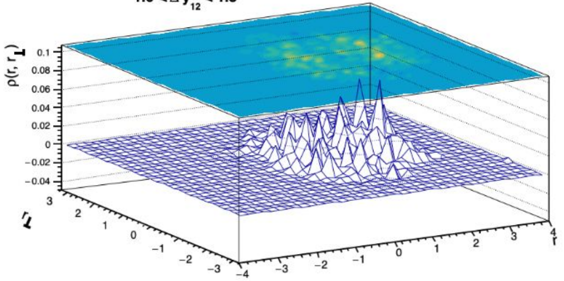
$1.2 < \Delta y_{12} < 1.4$



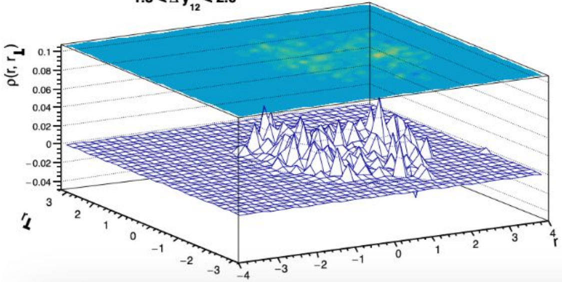
$1.4 < \Delta y_{12} < 1.6$



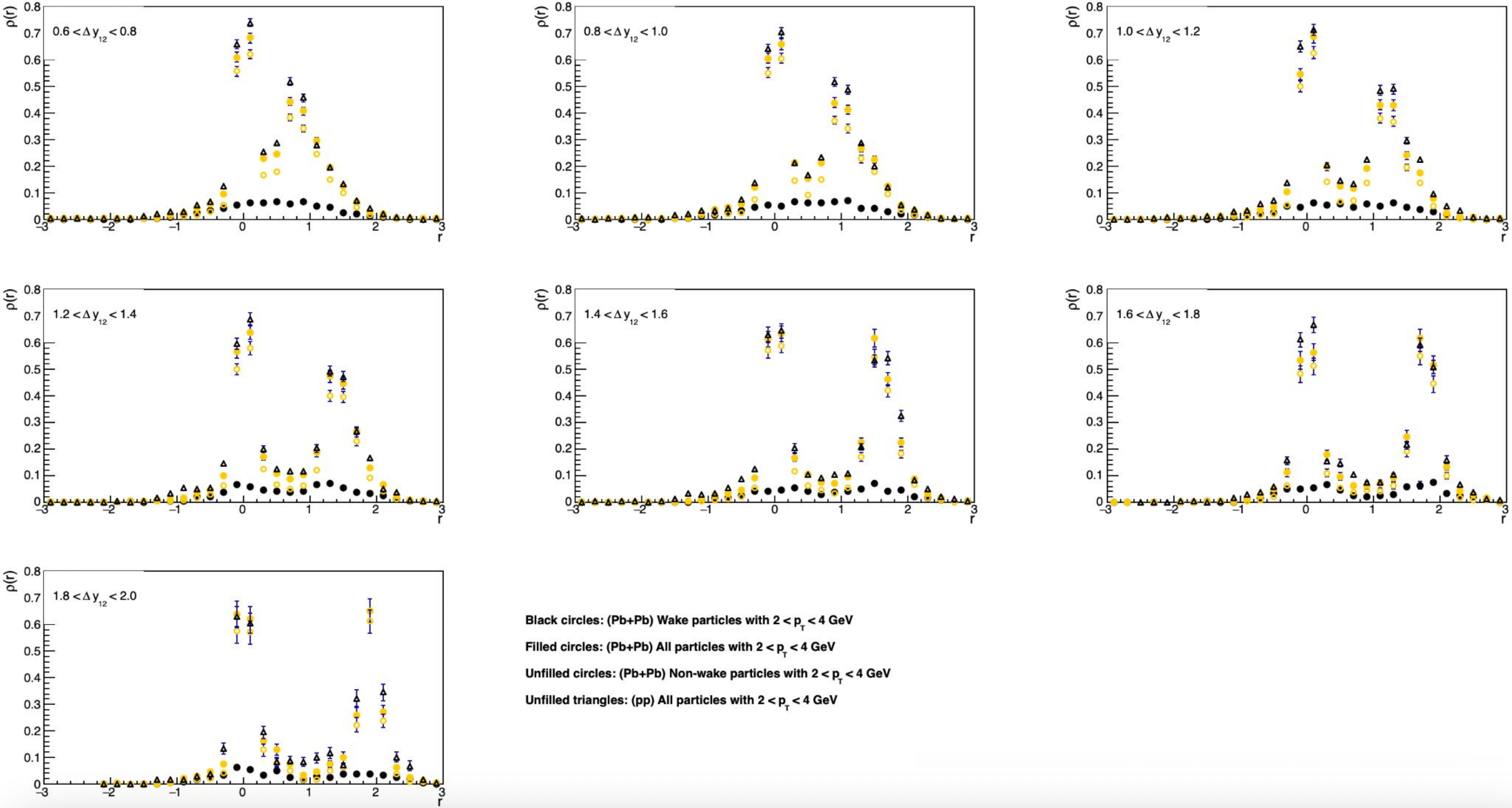
$1.6 < \Delta y_{12} < 1.8$



$1.8 < \Delta y_{12} < 2.0$



SHAPE OF PARTICLES WITH 2 < P_T < 4 GeV IN GAMMA-JETS WITH 2 SUBJETS



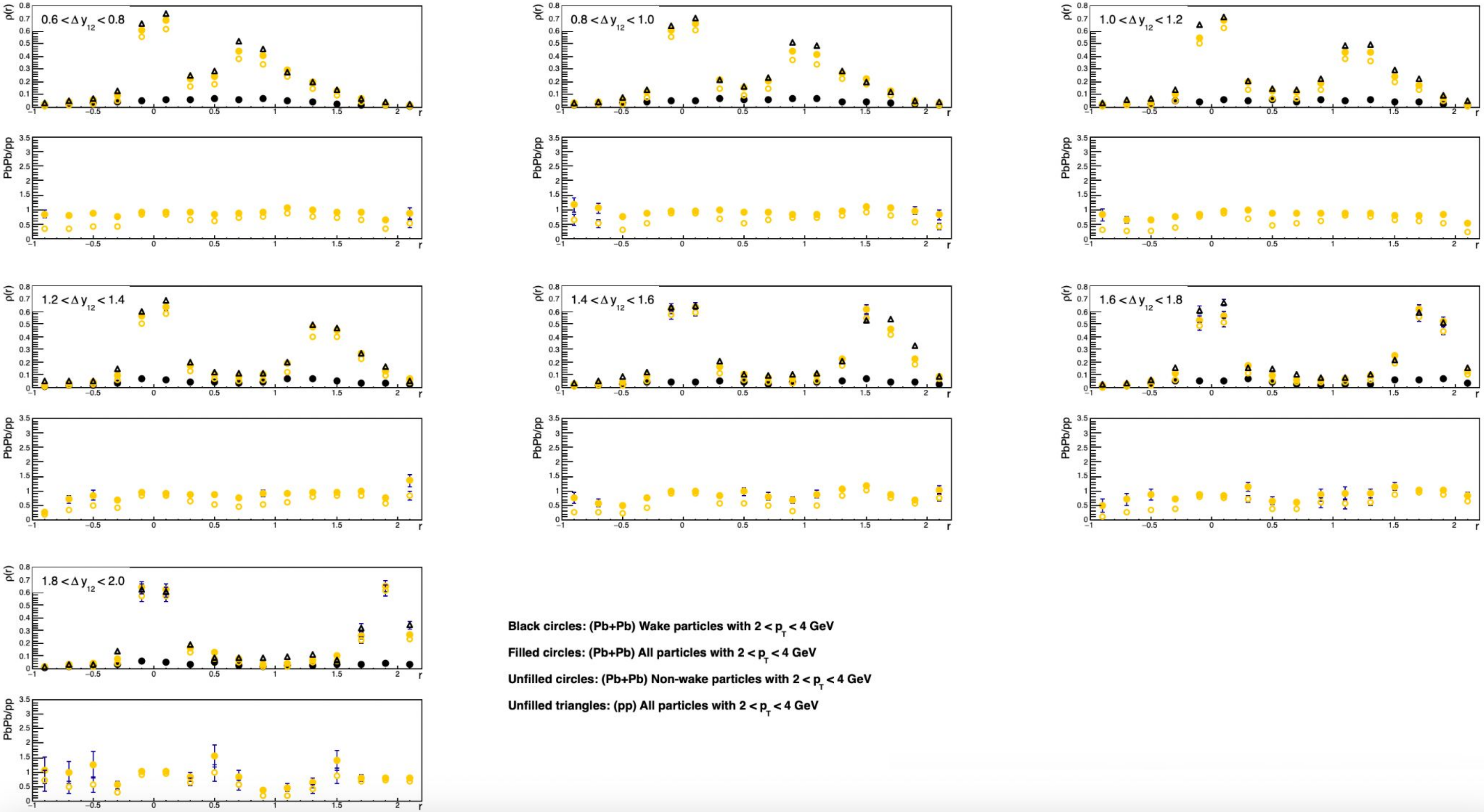
Black circles: (Pb+Pb) Wake particles with 2 < p_T < 4 GeV

Filled circles: (Pb+Pb) All particles with 2 < p_T < 4 GeV

Unfilled circles: (Pb+Pb) Non-wake particles with 2 < p_T < 4 GeV

Unfilled triangles: (pp) All particles with 2 < p_T < 4 GeV

PbPb/pp JET SHAPE RATIOS OF PARTICLES WITH 2 < P_T < 4 GeV IN GAMMA-JETS WITH 2 SUBJETS



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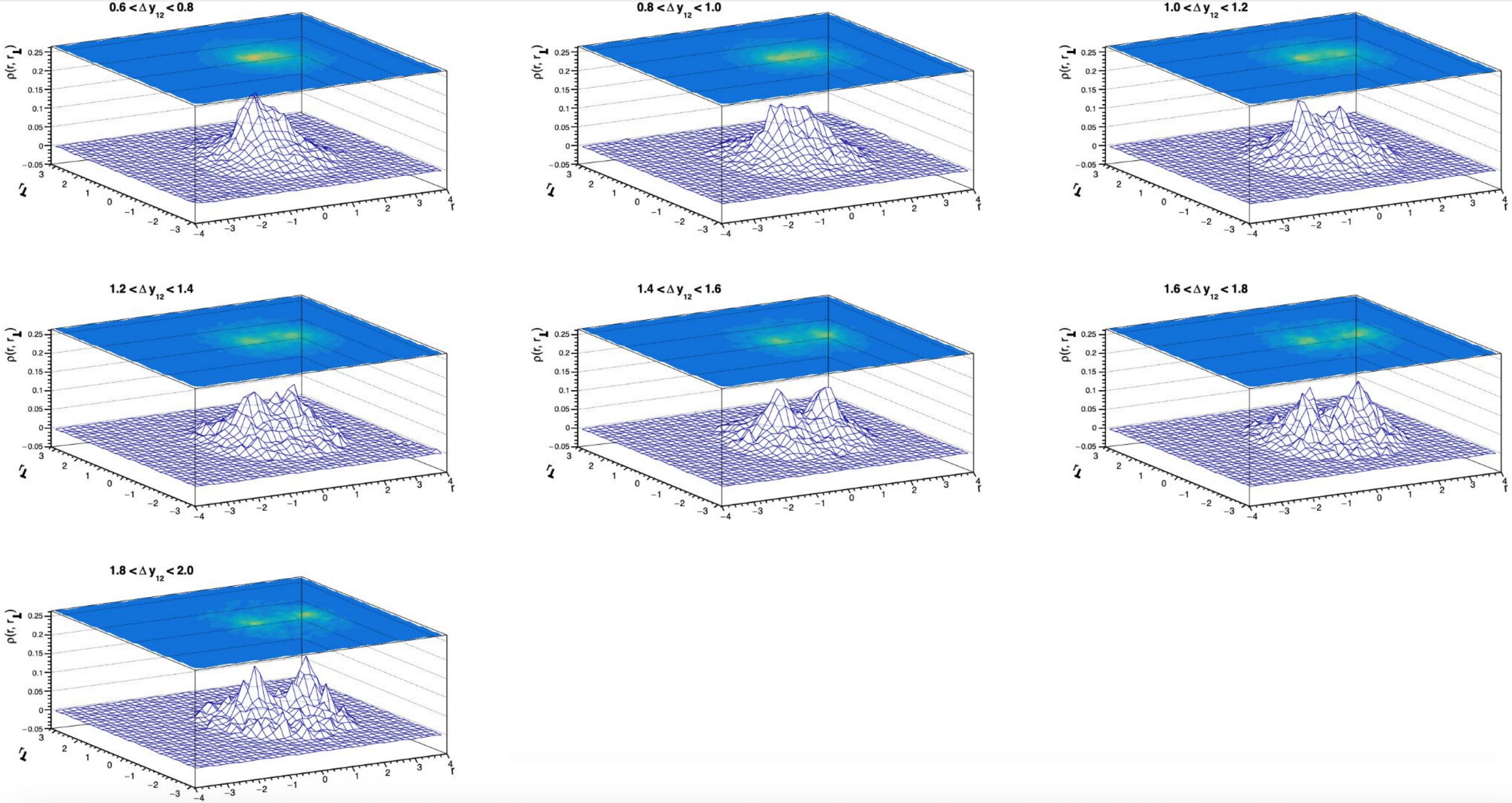
Unfilled circles: (Pb+Pb) Non-wake particles with 2 < p_T < 4 GeV

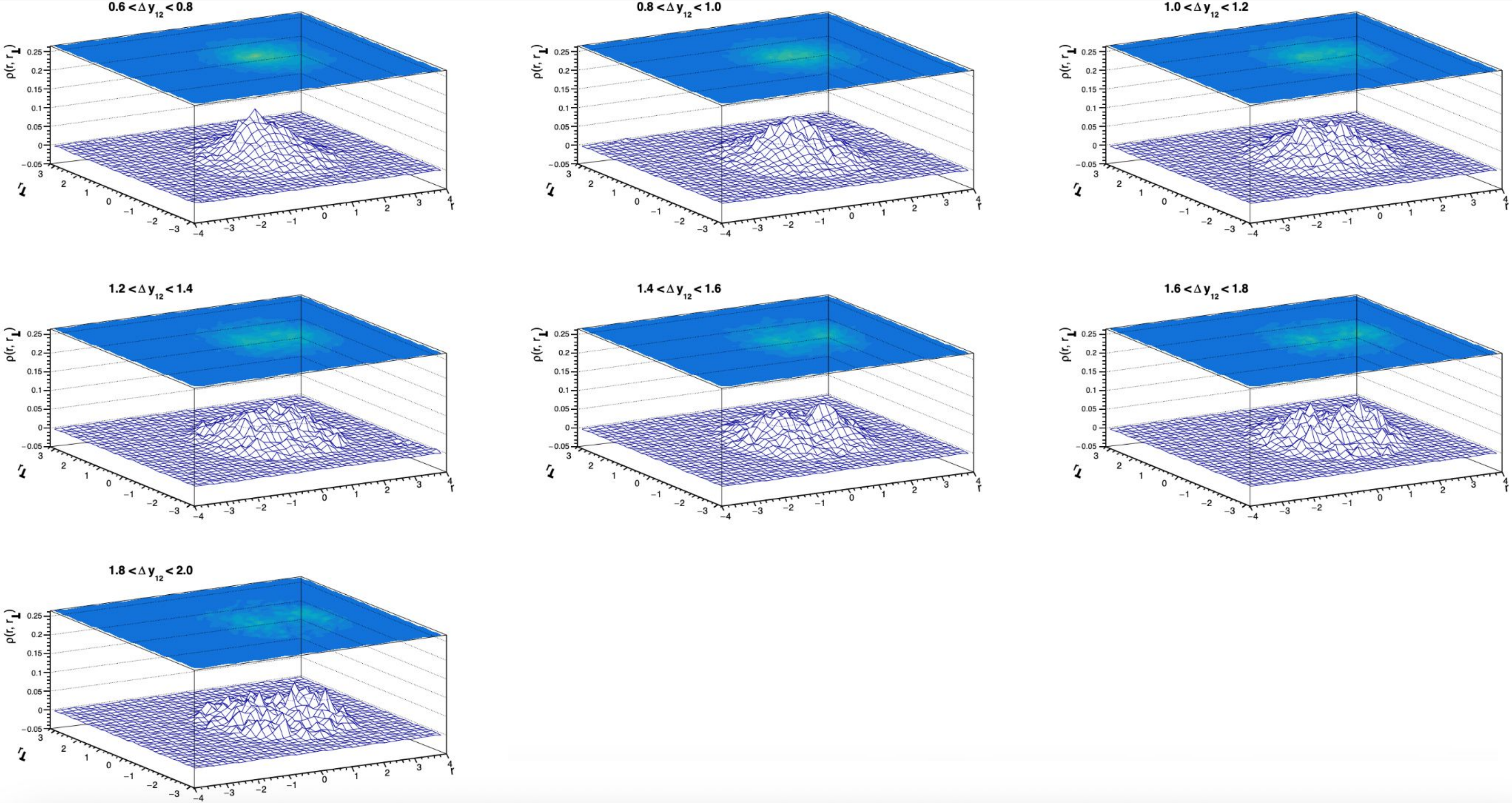
Unfilled triangles: (pp) All particles with 2 < p_T < 4 GeV

Only particles with $0.7 < p_T < 1$ GeV

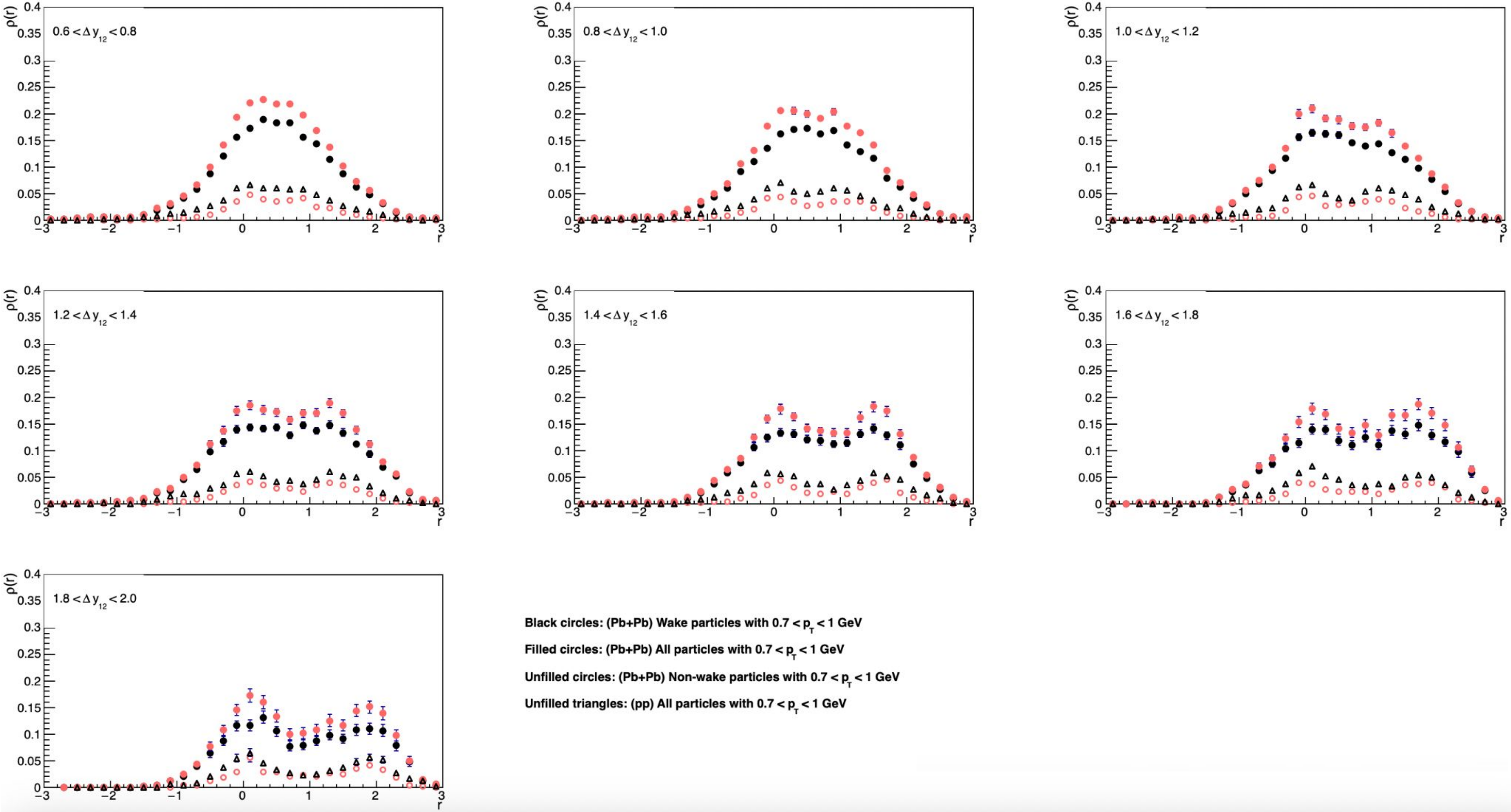
ALL PARTICLES WITH 0.7 < P_T < 1 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS



WAKE PARTICLES WITH 0.7 < P_T < 1 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS



SHAPE OF PARTICLES WITH 0.7 < P_T < 1 GeV IN GAMMA-JETS WITH 2 SUBJETS



Black circles: (Pb+Pb) Wake particles with 0.7 < p_T < 1 GeV

Filled circles: (Pb+Pb) All particles with 0.7 < p_T < 1 GeV

Unfilled circles: (Pb+Pb) Non-wake particles with 0.7 < p_T < 1 GeV

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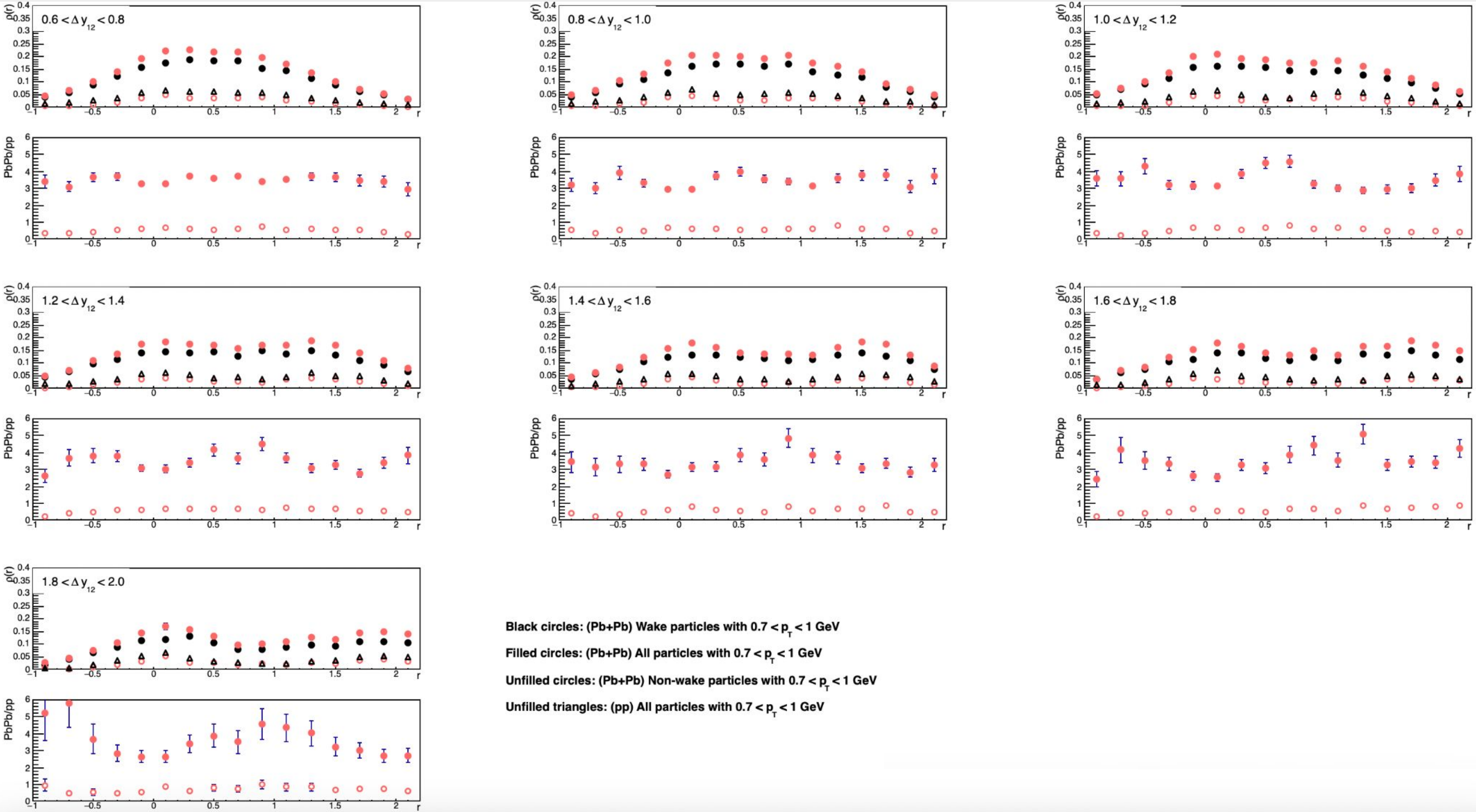
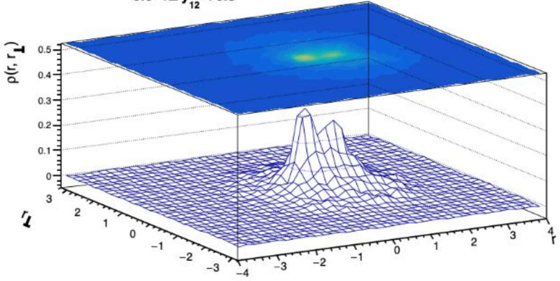
PbPb/pp JET SHAPE RATIOS OF PARTICLES WITH 0.7 < P_T < 1 GeV IN GAMMA-JETS WITH 2 SUBJETS



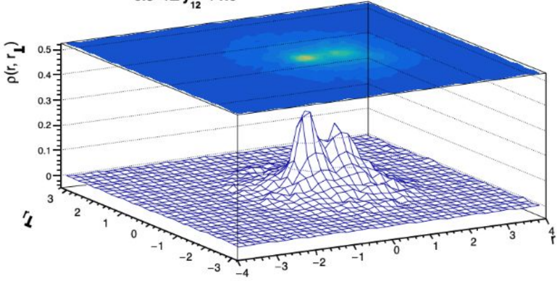
Only particles with $1 < p_T < 1.6$ GeV

ALL PARTICLES WITH 1 < P_T < 1.6 GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

$0.6 < \Delta y_{12} < 0.8$



$0.8 < \Delta y_{12} < 1.0$



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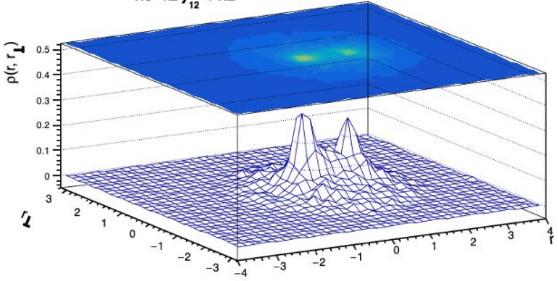
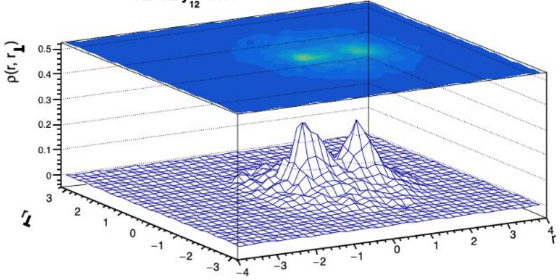


$1.2 < \Delta y_{12} < 1.4$



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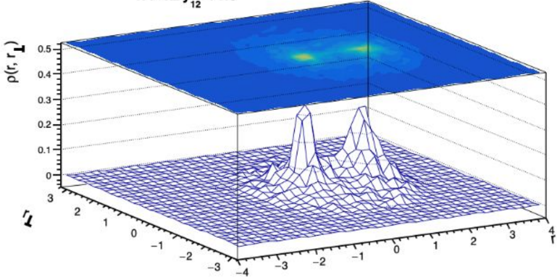

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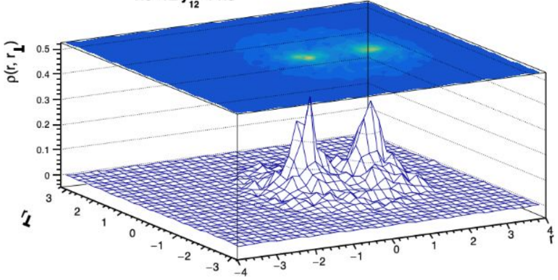
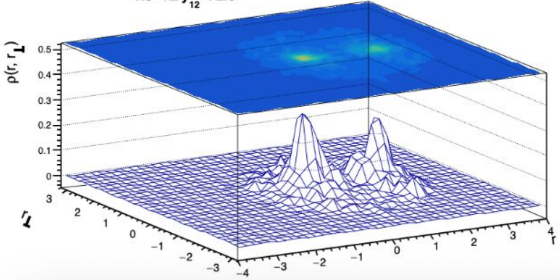
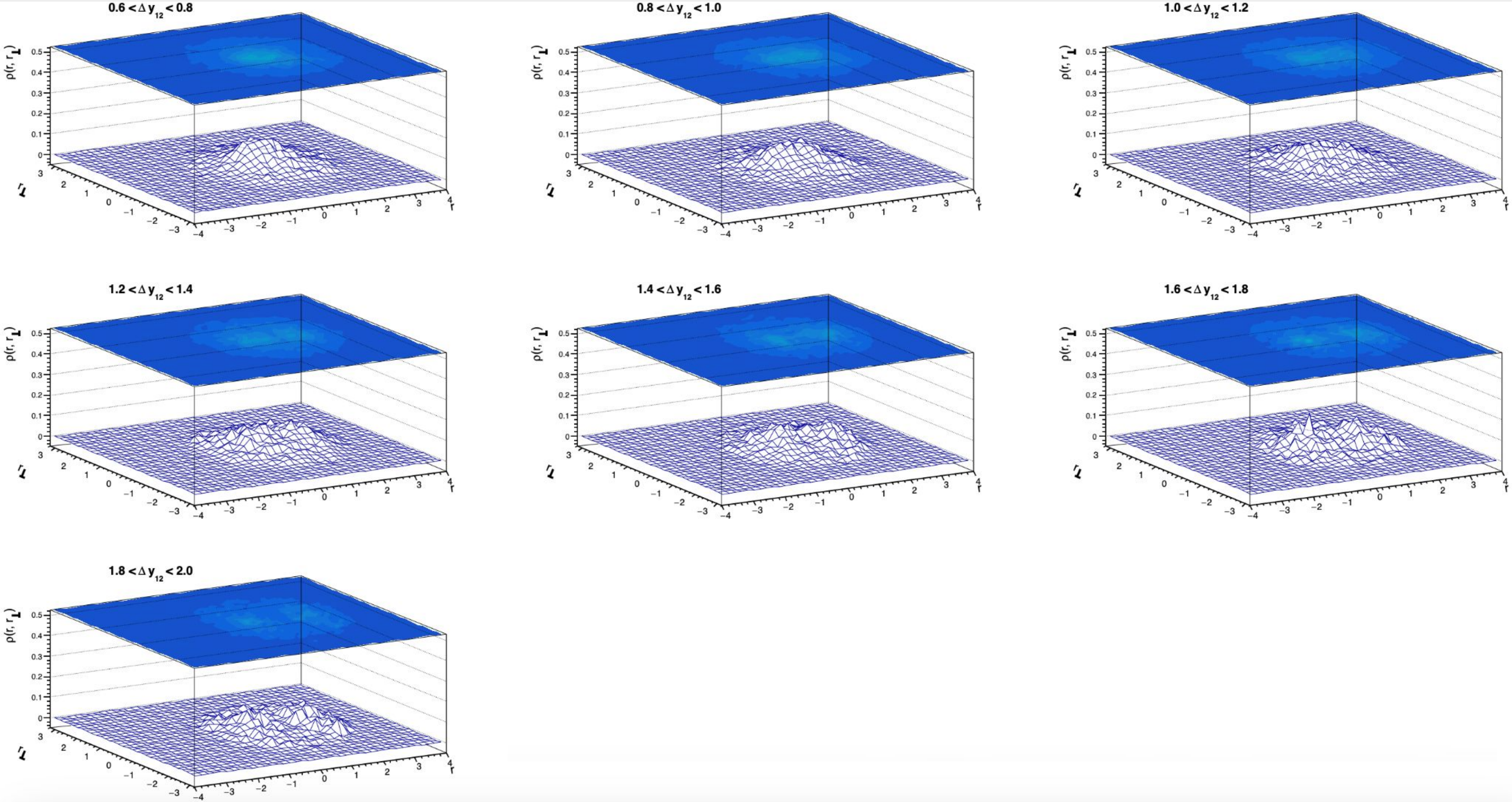


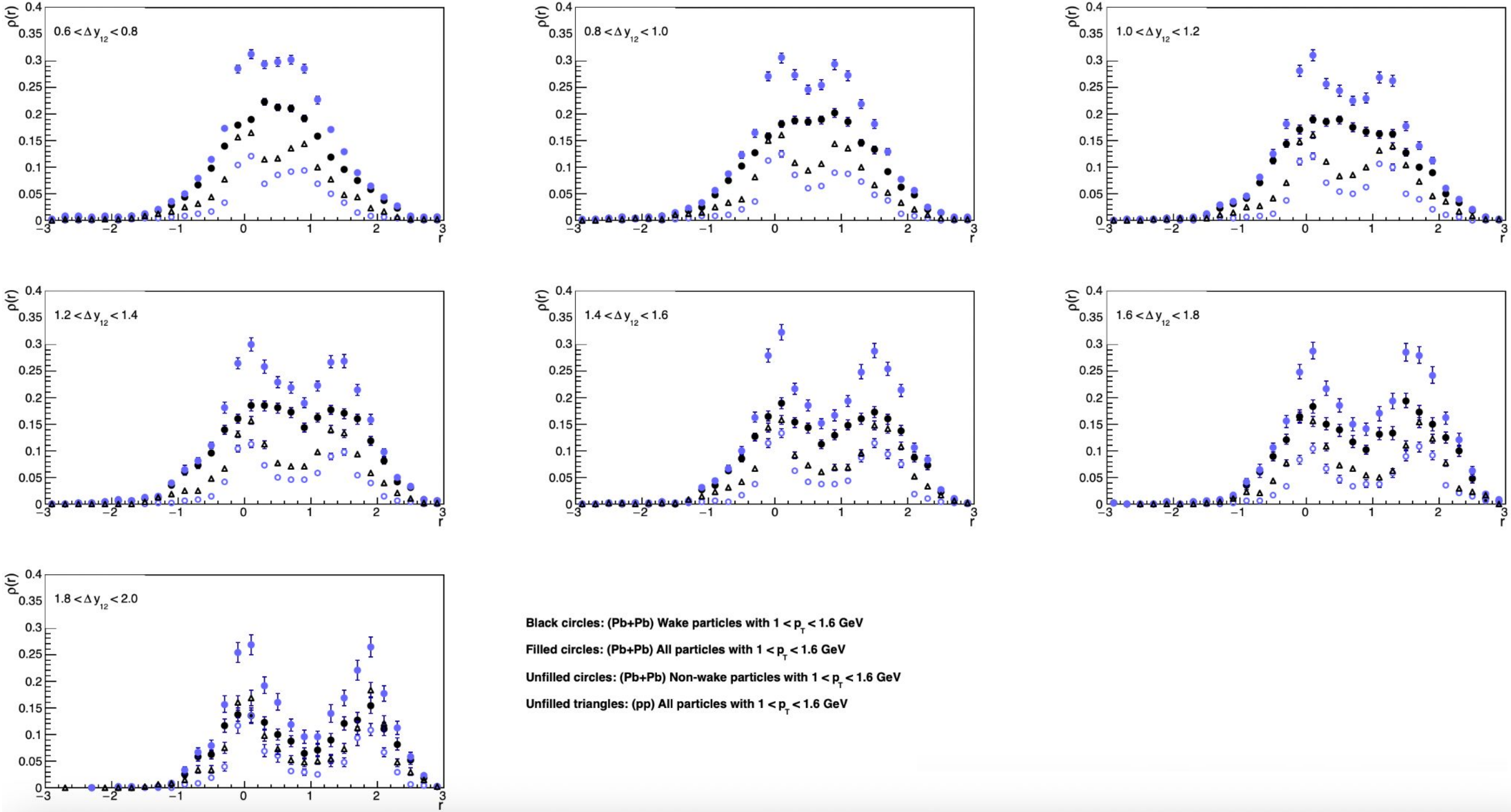
$1.8 < \Delta y_{12} < 2.0$



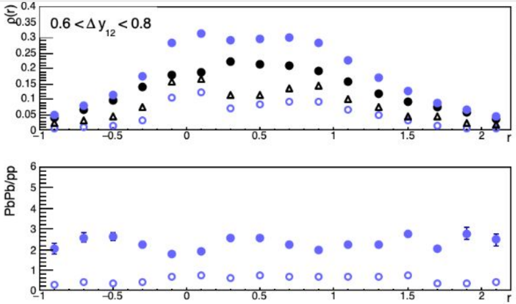
WAKE PARTICLES WITH $1 < P_T < 1.6$ GeV IN GAMMA-JETS IN Pb+Pb COLLISIONS WITH 2 SUBJETS

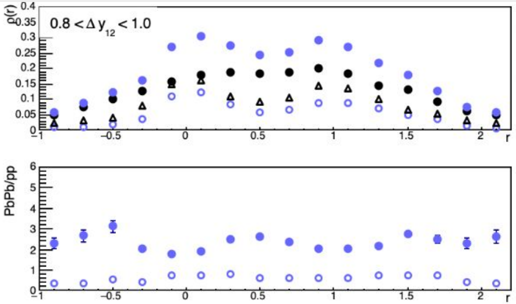


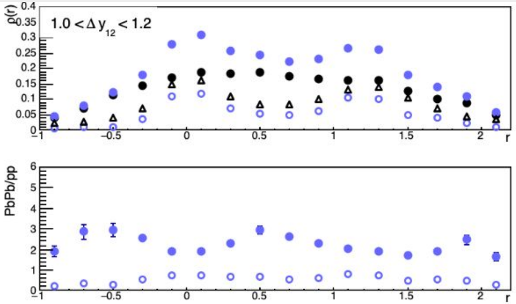
SHAPE OF PARTICLES WITH 1 < P_T < 1.6 GeV IN GAMMA-JETS WITH 2 SUBJETS

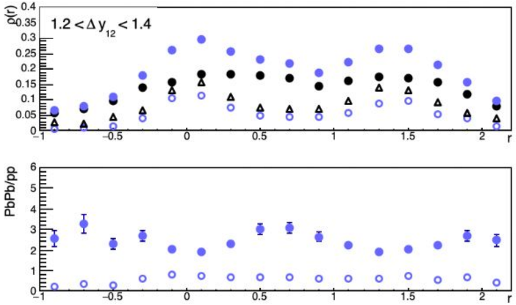


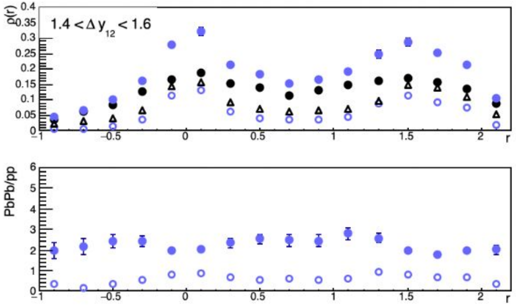
PbPb/pp JET SHAPE RATIOS OF PARTICLES WITH 1 < P_T < 1.6 GeV IN GAMMA-JETS WITH 2 SUBJETS

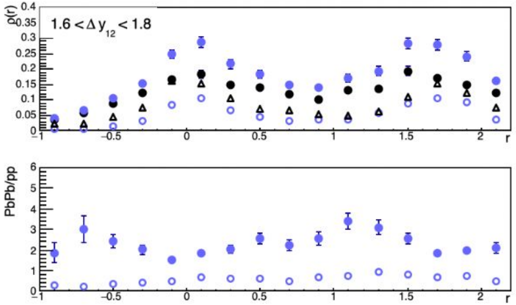


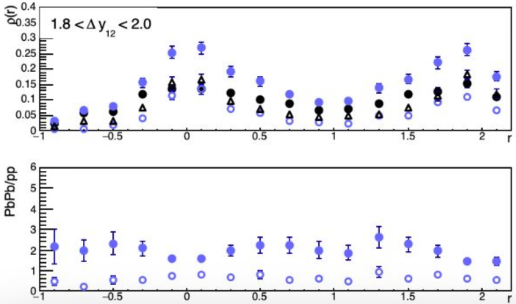












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Unfilled triangles: (pp) All particles with 1 < p_T < 1.6 GeV

Identifying Jet Observables with which to "See" the Short-Scale Structure of QGP

Krishna Rajagopal
MIT

with
Zach Hulcher (Stanford)
Dani Pablos (INFN Torino)

Quark Matter 2023
Houston, Texas; September 5, 2023

Why Jets?

- The remarkable utility of hydrodynamics, eg. in describing the dynamics of small lumps in the initial state in AA collisions, tells us that to see the inner workings of QGP, namely to see how the liquid is put together from quarks and gluons, we will need probes with fine resolution.
- Need probes that resolve scales $\ll$ size of lumps coming from the initial state that behave hydrodynamically, and scales $\ll 1/T_{\text{hydrodynamization}}$.
- Jets, as multiscale probes, provide best chance for scattering off a droplet of QGP to see its inner workings.
- Jets in heavy ion collisions *also* offer the best chance of watching how QGP hydrodynamizes. Jets leave a wake in the medium. Can we see how it hydrodynamizes, and then flows? Best shot at experimental access to this physics.
- $\to$ not easy to decode the wealth of info that jets contain! (Need high statistics LHC and sPHENIX data; and need to use today's data to build baseline of understanding.)

How you can learn from a model

- There are things you can do with a model (here, the Hybrid Model) that you cannot do with experimental data. (Eg, turn physical effects off and on) ...
- ... but that nevertheless teach us important lessons for how to look at, and learn from, experimental data.
- TODAY's EXAMPLE: identifying which jet observables are more sensitive to the presence of quasiparticles — scatterers — in the QGP-soup. And, which are more sensitive to the wakes that jets make in the soup.
- Disentangling effects of jet modification from effects of jet selection. In simulations; in Z+jet or γ+jet data. 2110.13159 Brewer, Brodsky, KR
- Using jet substructure modification to probe QGP resolution length. Can QGP "see" partons within a jet shower (rather than losing energy coherently)? 1707.05245 ZH, DP, KR; 1907.11248 Casalderrey-Solana, Milhano, DP, KR. (Apparent answer: yes. Eg., 2303.13347 ALICE)
- But first, a *very* brief intro to the Hybrid Model...

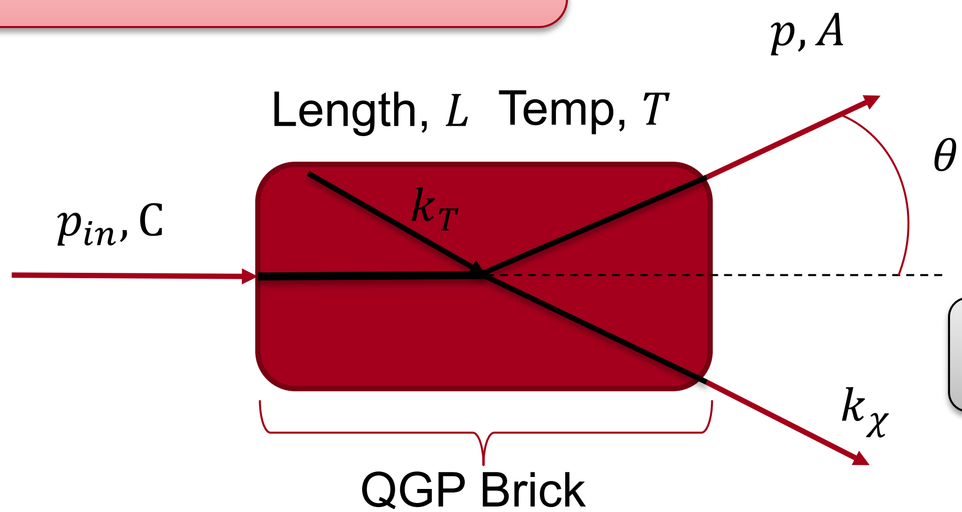
Why Molière scattering?
Why add to Hybrid Model?

- QGP, at length scales $\mathcal{O}(1/T)$, is a strongly coupled liquid. Flow, and jet observables sensitive to parton energy loss, are well-described (eg in hybrid model) in such a fluid, without quasiparticles.
- At shorter length scales, probed via large momentum-exchange, asymptotic freedom $\rightarrow$ quasiparticles matter.
- High energy partons in jet showers *can* probe particulate nature of QGP. Eg via power-law-rare, high-momentum-transfer, large-angle, Molière scattering
- "Seeing" such scattering is first step to probing micro-scopic structure of QGP.
- What jet observables are sensitive to effects of high-momentum-transfer scattering? To answer, need to turn it off/on.
- Start from Hybrid Model – in which any particulate effects are definitively off! Add Molière, and look at effects...

Moliere Scattering in a brick of QGP (D'Eramo, KR, Yin, 2019)

Power-law-rare medium kicks which can probe particle constituents of QGP

In JEWEL, LBT, MARTINI, harder to turn off



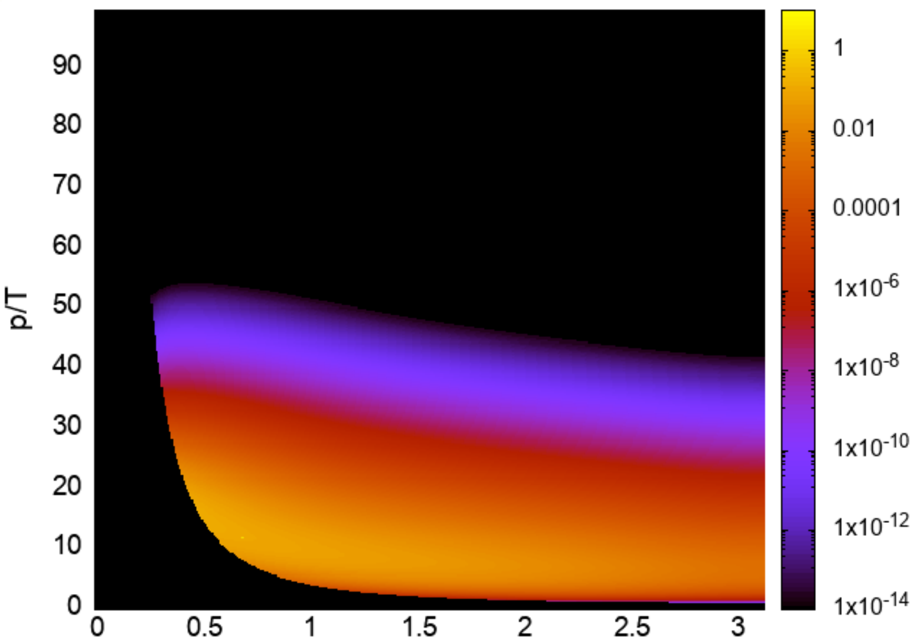
D'Eramo et al., 2019

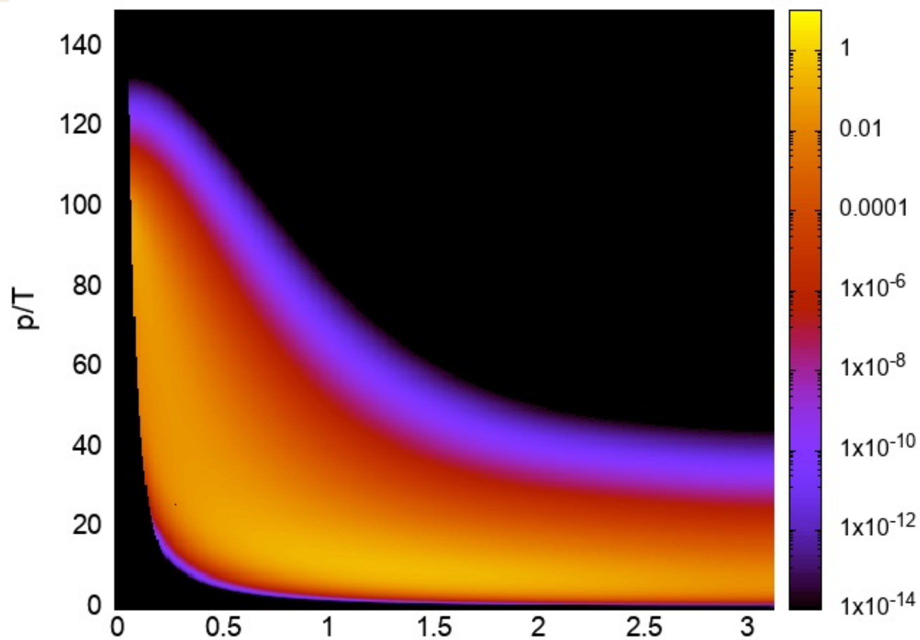
- Sufficiently hard scattering should be perturbative.
- High p_T particle can be deflected, changing its energy and direction.
- Recoiling particle, k_χ, a new particle to be quenched
- Thermal particle, k_T, from BE/FD distribution, removed from medium.

Tree-Level 2-2 massless scattering amplitudes

$$F^{C\to A}(p,\theta;p_{in}) = \sum_{nDB} \frac{c_{DBn}^{C\to A}}{2(4\pi)^3}\left(\frac{p\sin(\theta)}{p_{in}|\boldsymbol{p}-\boldsymbol{p_{in}}|T}\right)\int_{k_{min}}^{\infty} dk_T\, n_D(k_T)\left[1\pm n_B(k_\chi)\right]\int_0^{2\pi}\frac{d\phi}{2\pi}\frac{\left|M^{(n)}\right|^2}{g_s^4}$$

Results (for a QGP brick)





Incoming gluon, $p_{in} = 20T, \mathrm{L} = 15/T$

Incoming gluon, $p_{in} = 100T,\ \ \mathrm{L} = 15/T$

- Excluding $\tilde{u} > 10\, m_D^2$ not a simple curve on this plot, but effects visible
- Restricting to $\tilde{u}, \tilde{t} > 10\, m_D^2$ excludes soft scatterings; justifies assumptions made in amplitudes; avoids double counting. Can vary where to set this cut…
- Analytical results → fast to sample
- Apply at every time step, to every rung, in every shower, in Hybrid Model Monte Carlo…. And, if a scattering happens, two subsequent partons then lose energy a la Hybrid

Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

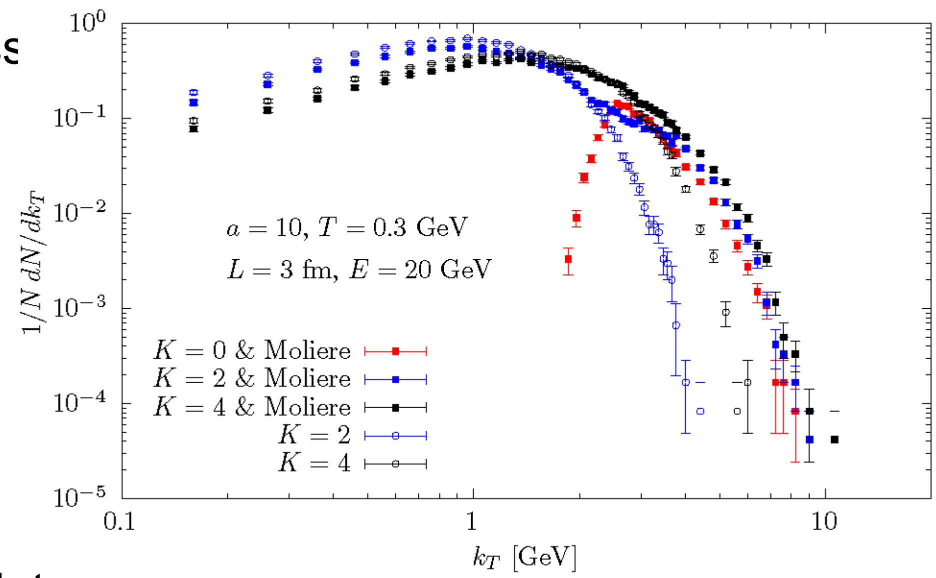
At strong coupling, holography predicts Gauss broadening without quasi-particles (eg: N=4 SYM)

$$P(k_\perp) \sim \exp\left(-\frac{\sqrt{2}k_\perp^2}{\hat{q}L^-}\right) \qquad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$

Adding this in hybrid model (C-S et al 2016) yielded little effect on jet observables.

Today, Bayesian inference from hadron R_{AA} data indicates $P(k_\perp) \sim K\, T^3$ with $K \sim 2-4$. This need not have anything to do with quasiparticles.

- Add Moliere scattering with momentum exchanges $> m_D$; here, $a = 10$



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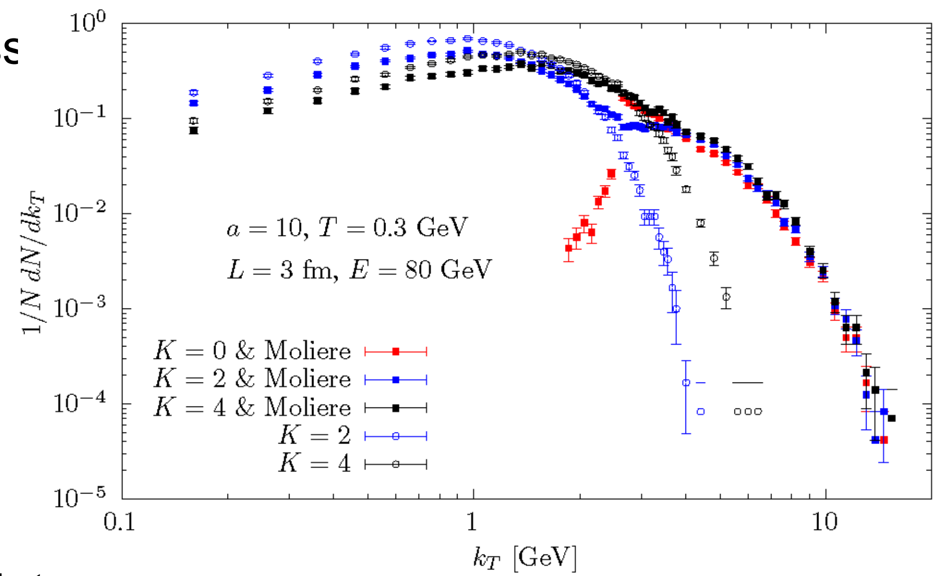
- Add Moliere scattering with momentum exchanges $> m_D$; here, $a = 10$ and 80 GeV incident jet parton



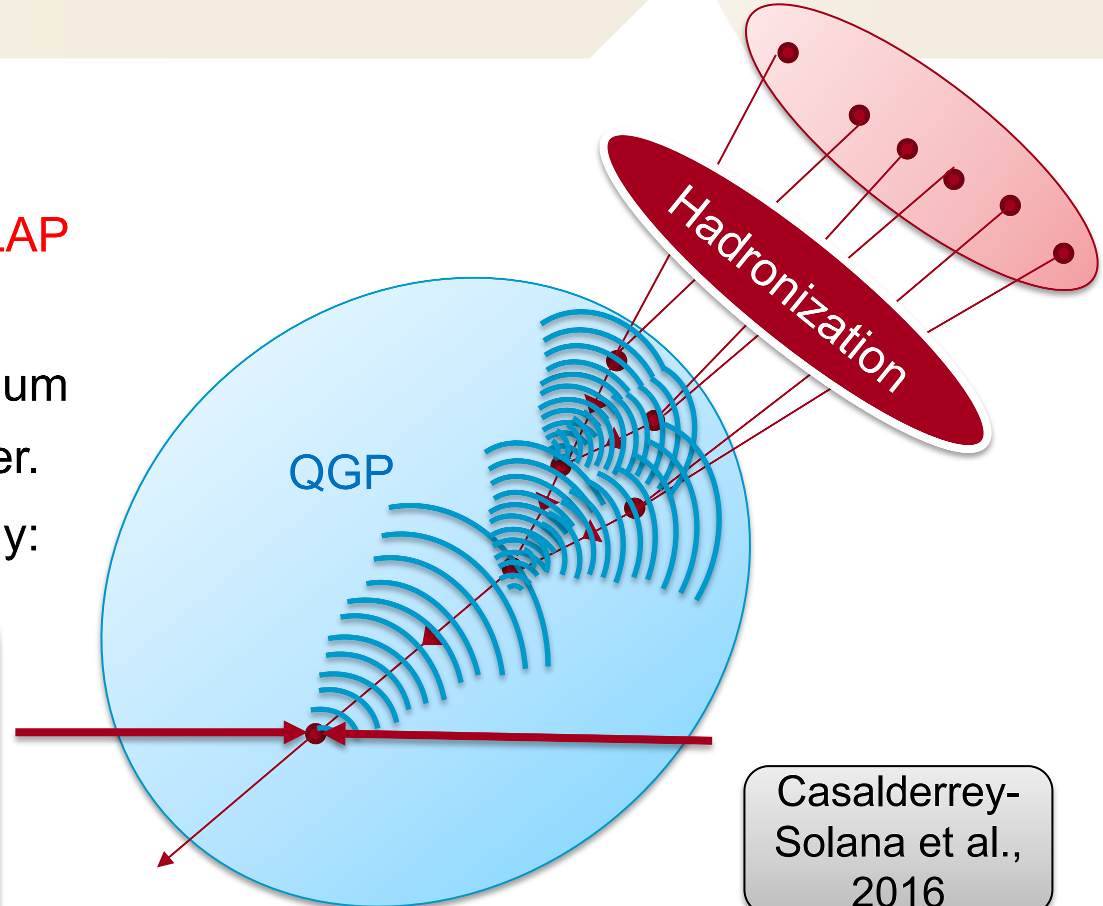
Perturbative Shower … Living in Strongly Coupled QGP

- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}} \qquad \tau = \frac{2E}{Q^2}$$

O(1) fit const.



Casalderrey-Solana et al., 2016

Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y - \eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right)\right]$$

Adding Moliere Scattering to Hybrid Model

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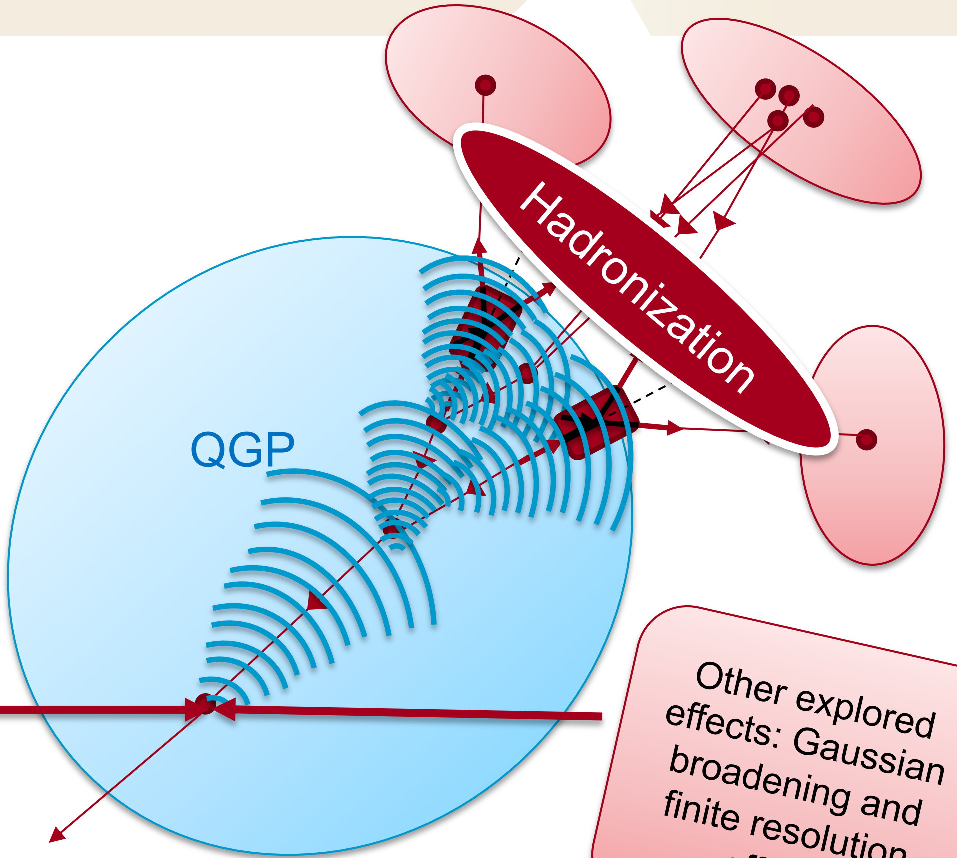


Other explored effects: Gaussian broadening and finite resolution effects

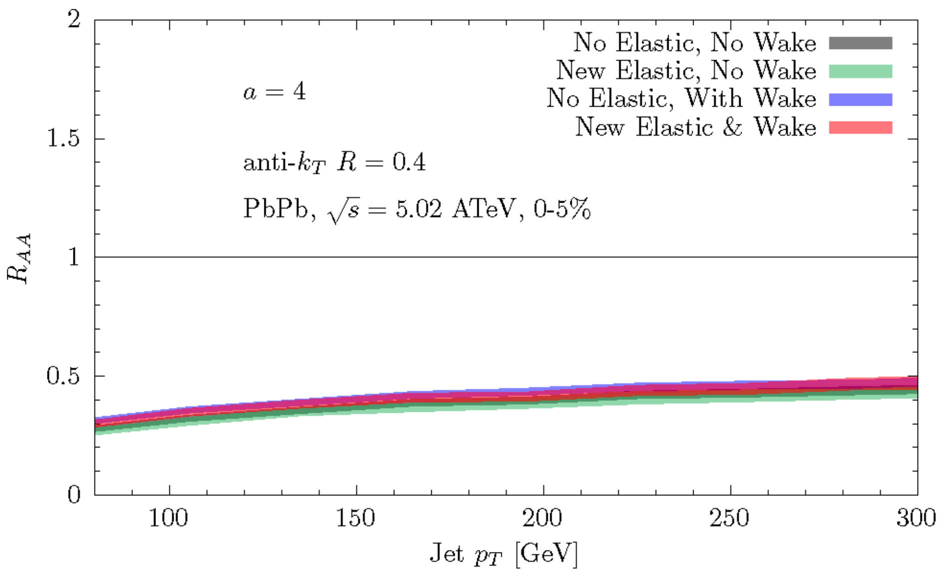
Energy and momentum conservation → activate hydrodynamic modes of plasma

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

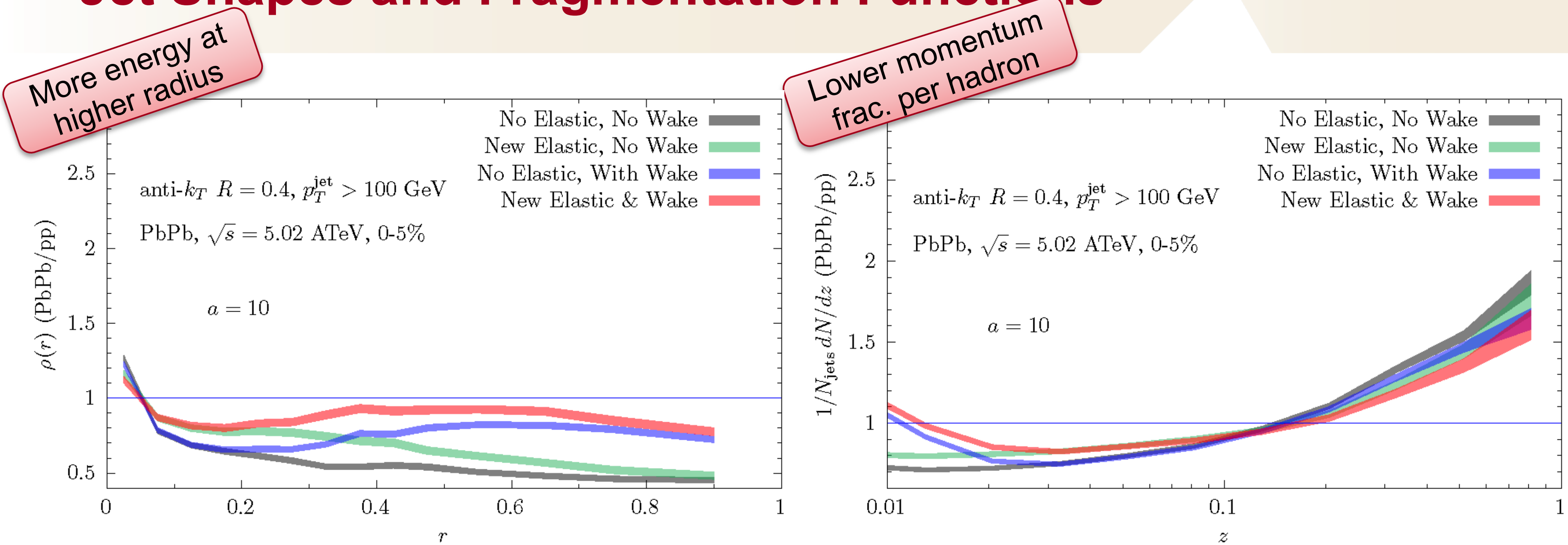
Jet R_{AA}

Casalderrey-Solana et al. 2019

- κ_{sc} previously fit with jet and hadron suppression data from ATLAS+CMS at 2.76+5.02 TeV
- Elastic scatterings lead to slight additional suppression; refit κ_{sc} . That means red is on top of blue in this plot by construction. (Addition of the elastic scatterings yields only small change to value of κ_{sc}.)
- Adding the hadrons from the wake allows the recovery of part of the energy within the jet cone; blue and green slightly below red and blue.



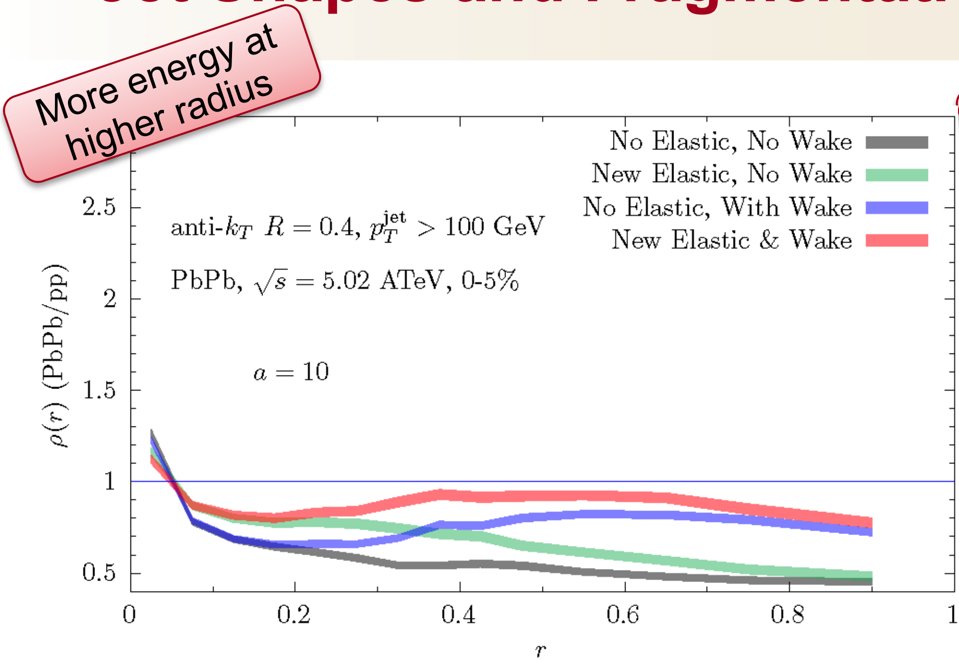
Jet Shapes and Fragmentation Functions

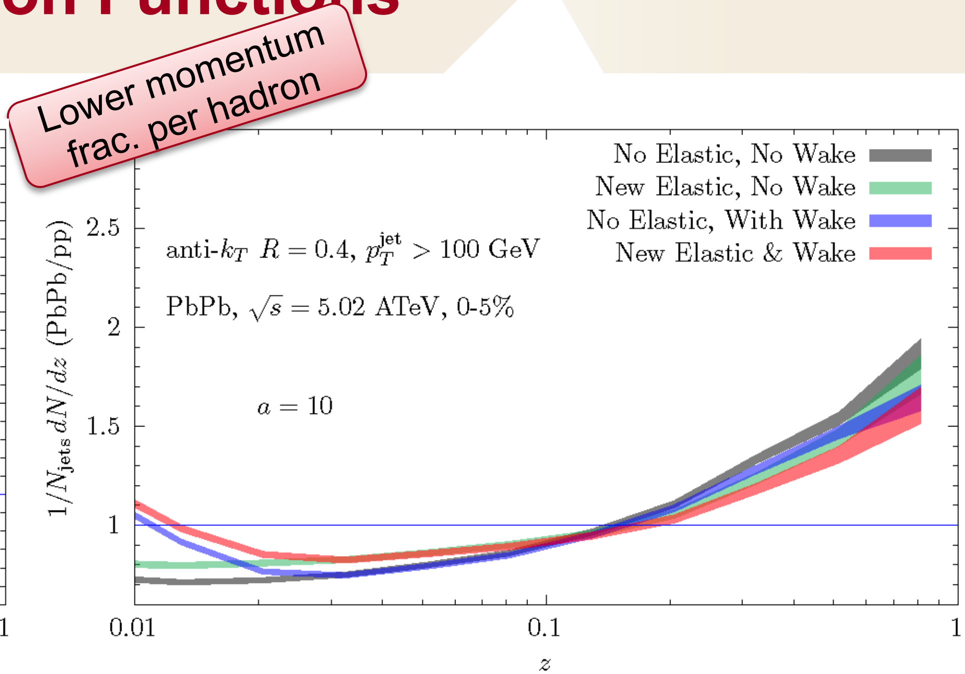


Elastic scattering effects look very similar to wake effects, but smaller.

- Moliere scattering transfers jet energy to high angle and lower momentum fraction particles. So does energy loss to wake in fluid.
- In **these observables**, effect of Moliere looks like just a bit more wake.
- In principle sensitive to Moliere, but in practice not: more sensitive to wake.
- Moliere effects are even slightly smaller if $\tilde{u}, \tilde{t} > \mathrm{a}\, m_D^2$ with a=10.
- What if we look at groomed observables? Less sensitive to wake…

Jet Shapes and Fragmentation Functions





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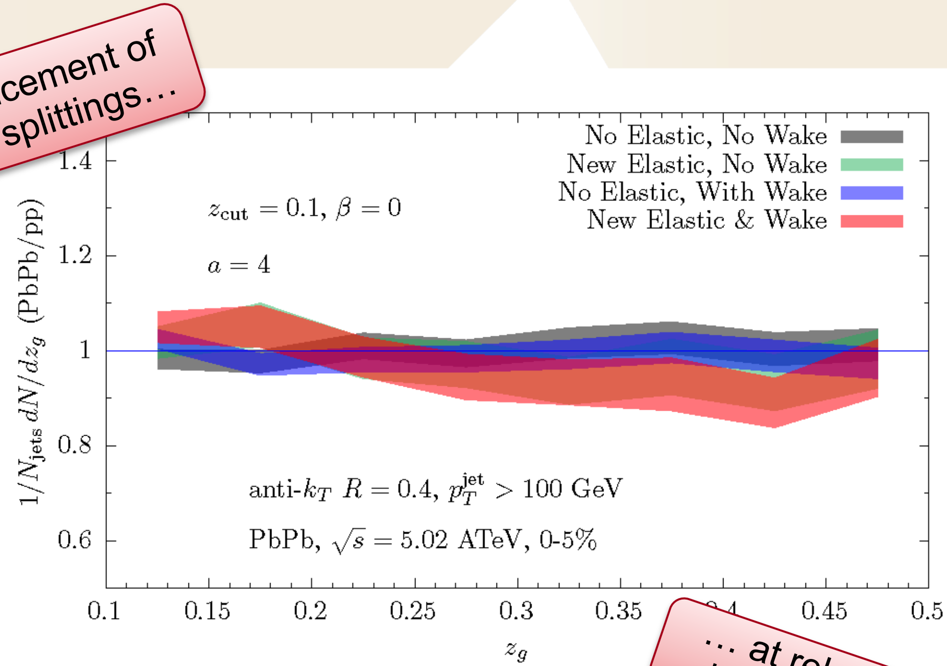
- What if we look at groomed observables? Less sensitive to wake…

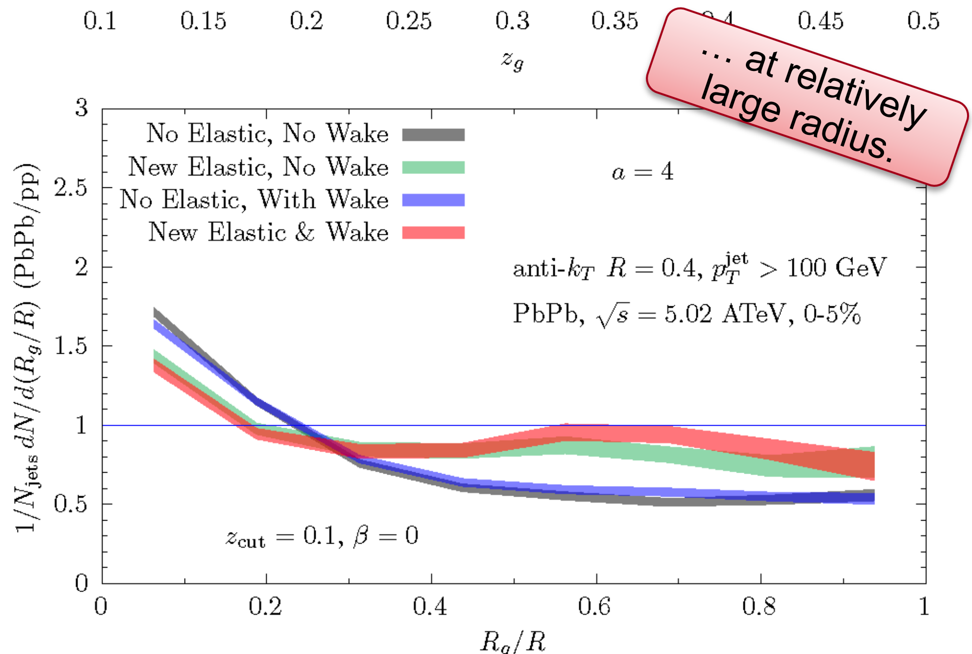
Groomed z_g and R_g

Soft Drop ($\beta = 0$)

1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2, separated by angle R_g
4. If $\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} \equiv z_g > z_{cut}$, then original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and repeat

Much less sensitivity to wake; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere on R_g are dominant, with a=4 or 10.





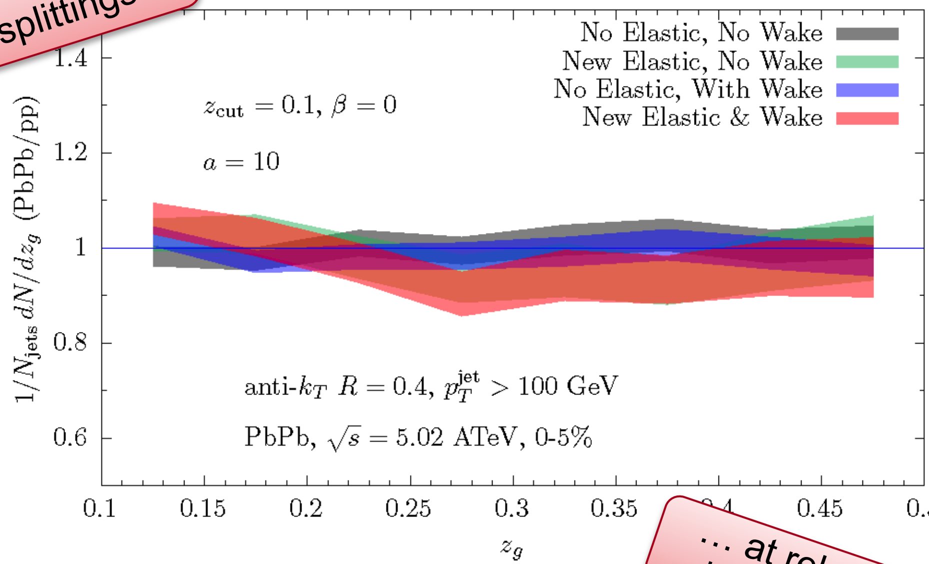
Groomed z_g and R_g

Soft Drop ($\beta = 0$)

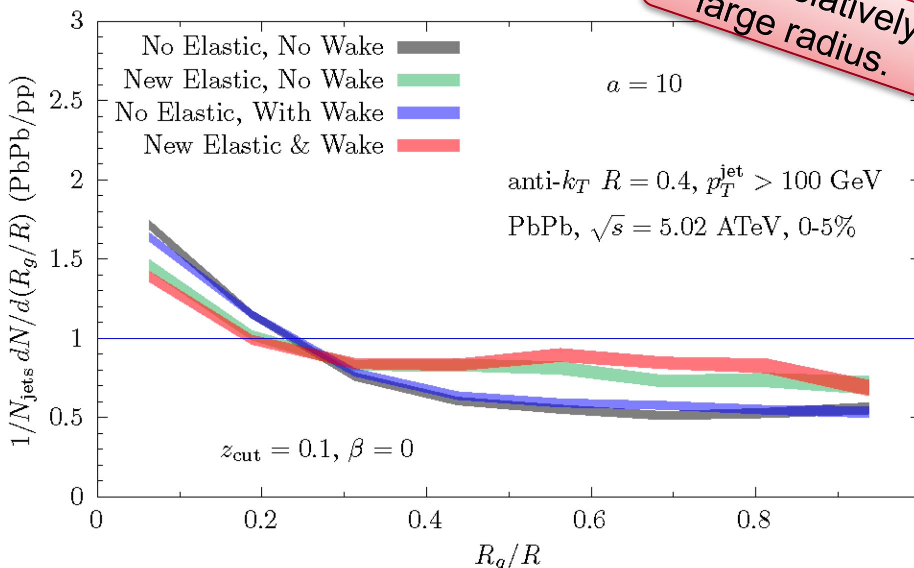
1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2, separated by angle R_g
4. If $\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} \equiv z_g > z_{cut}$, then original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and repeat

Much less sensitivity to wake; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere on R_g are dominant, with a=4 or 10.

Enhancement of softer splittings…



… at relatively large radius.



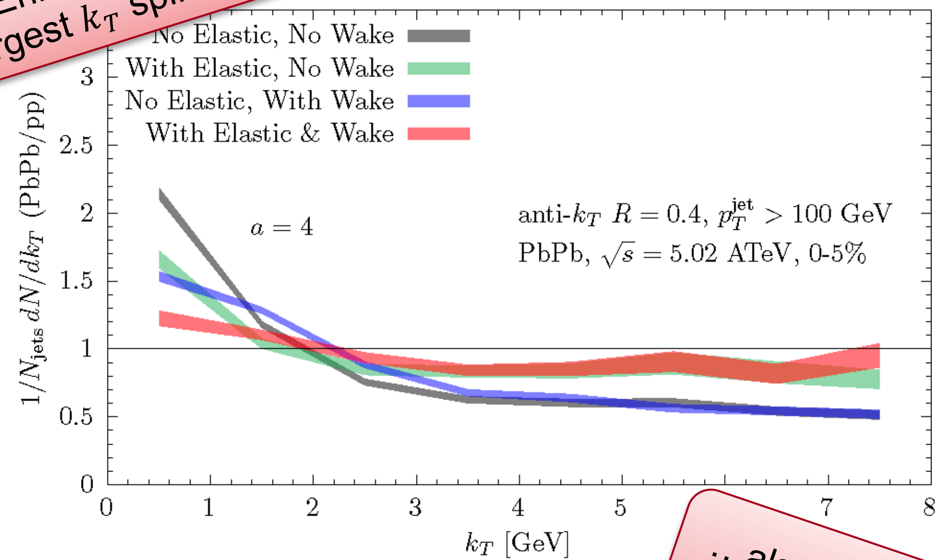
Leading k_T

1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2
4. Note k_T of splitting
5. Follow primary branch until the end.
6. Record largest k_T

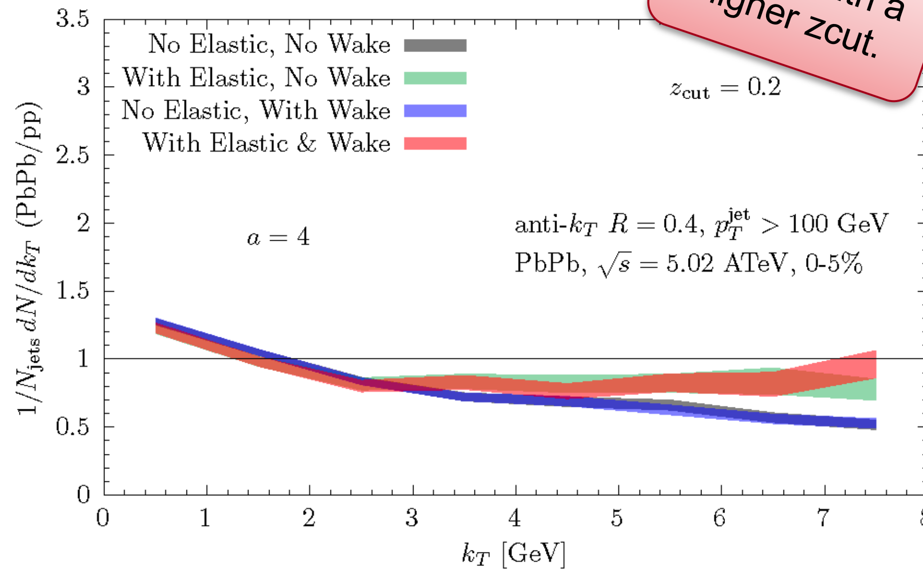
$$k_T = \min(p_{T1}, p_{T2}) \sin(R_g)$$

Similar message also for this groomed observable: Moliere scattering effects show up; much larger than wake effects.

Enhancement of largest k_T splittings…



…also with a higher zcut.



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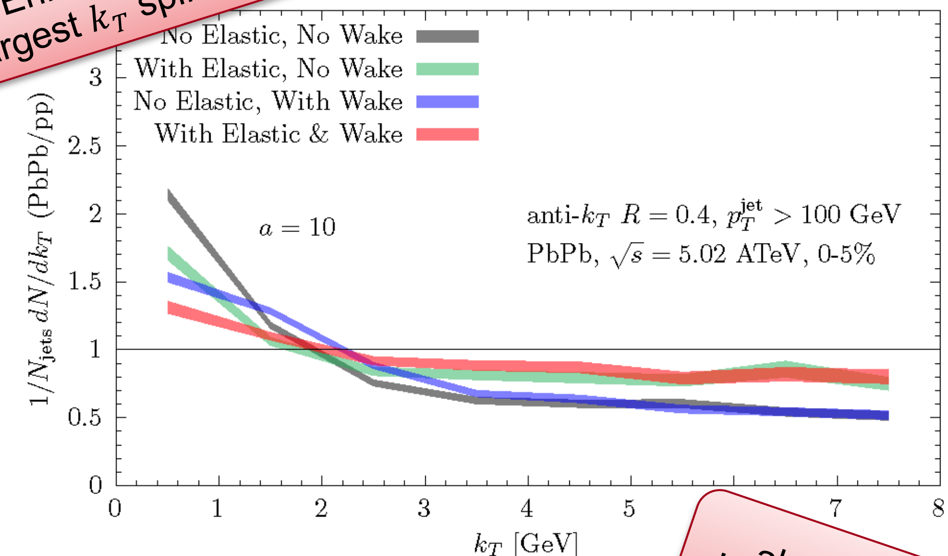
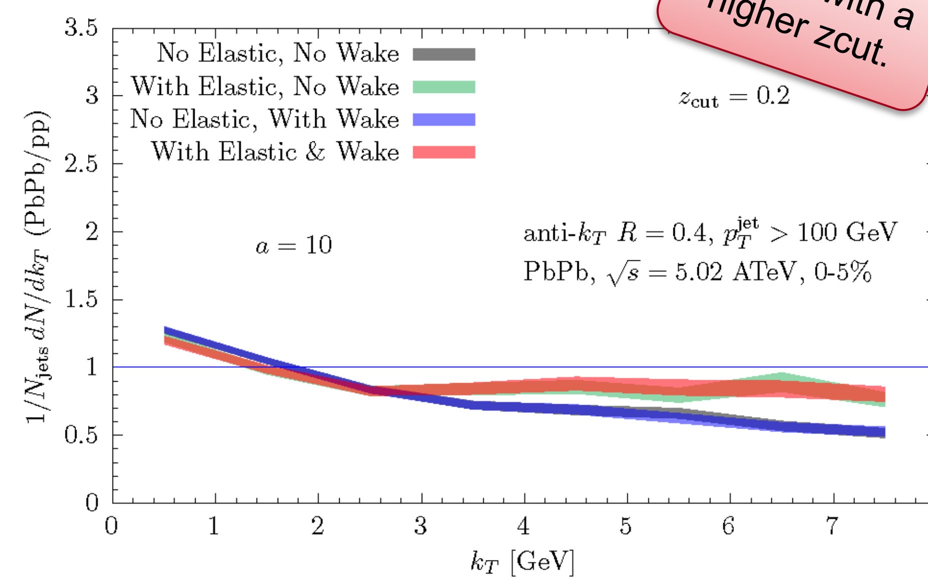
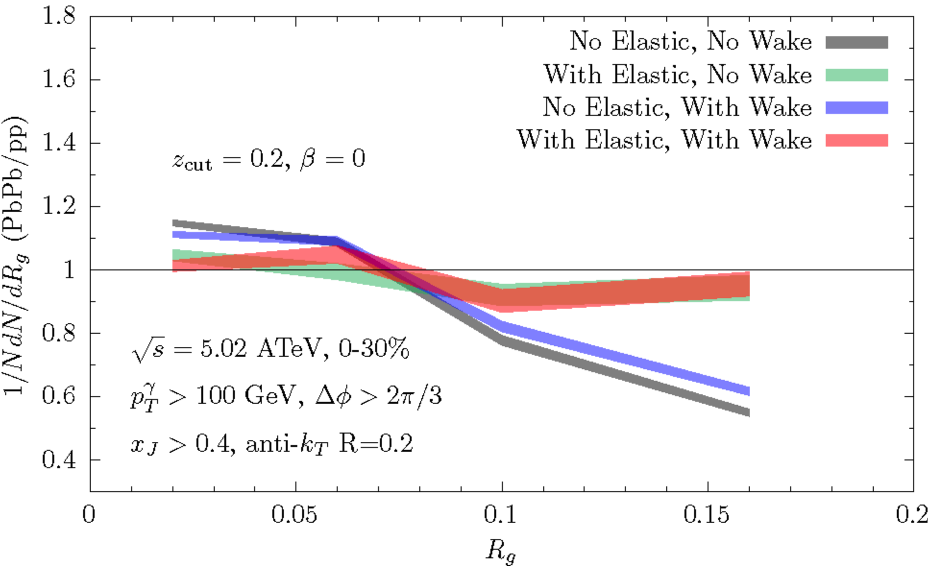
Enhancement of largest k_T splittings…

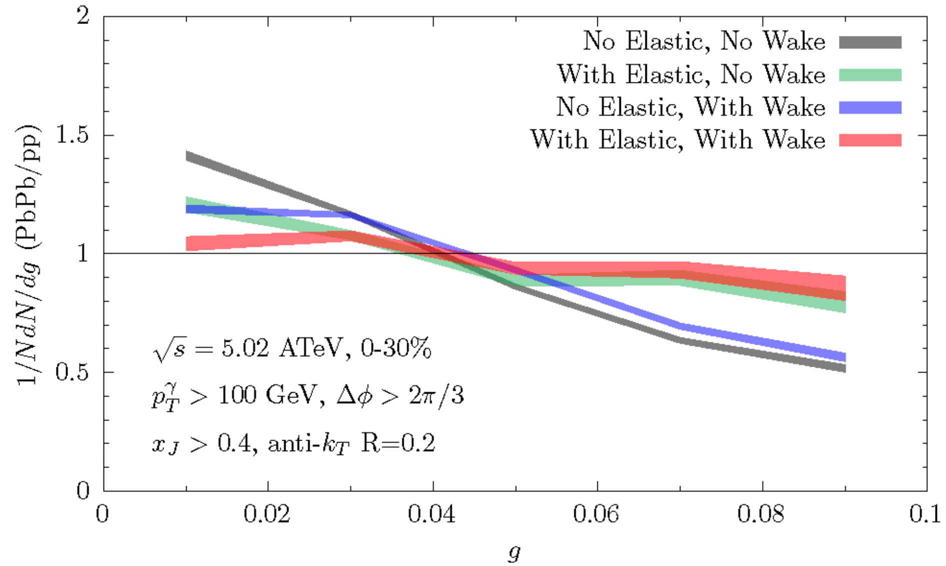


…also with a higher zcut.

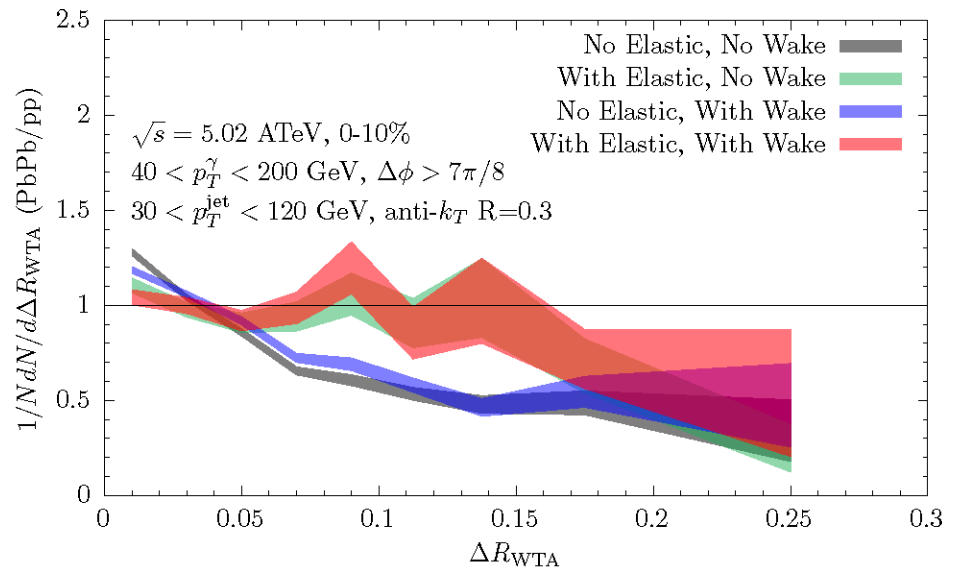


Three "groomed" gamma-Jet Observables: R_g, Girth, and angle between standard and WTA axes

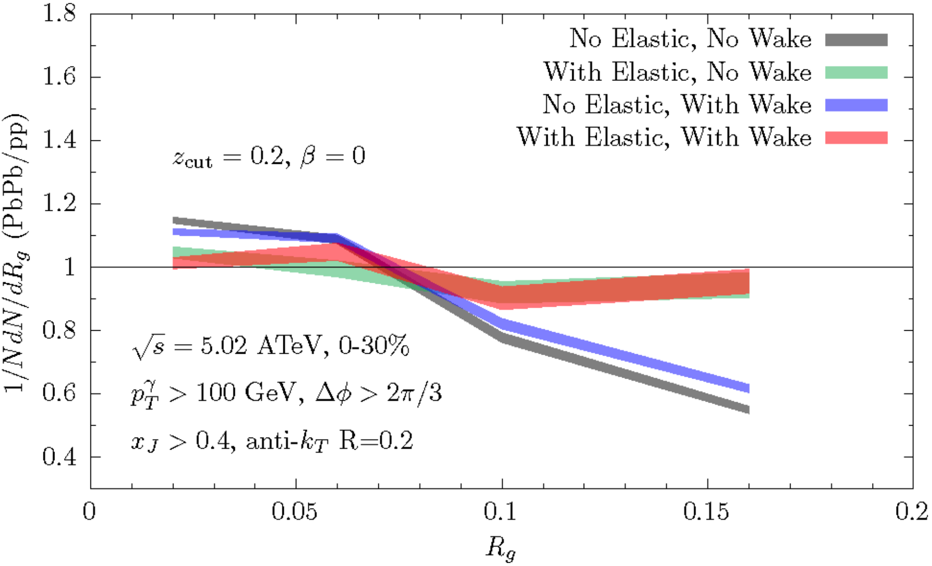


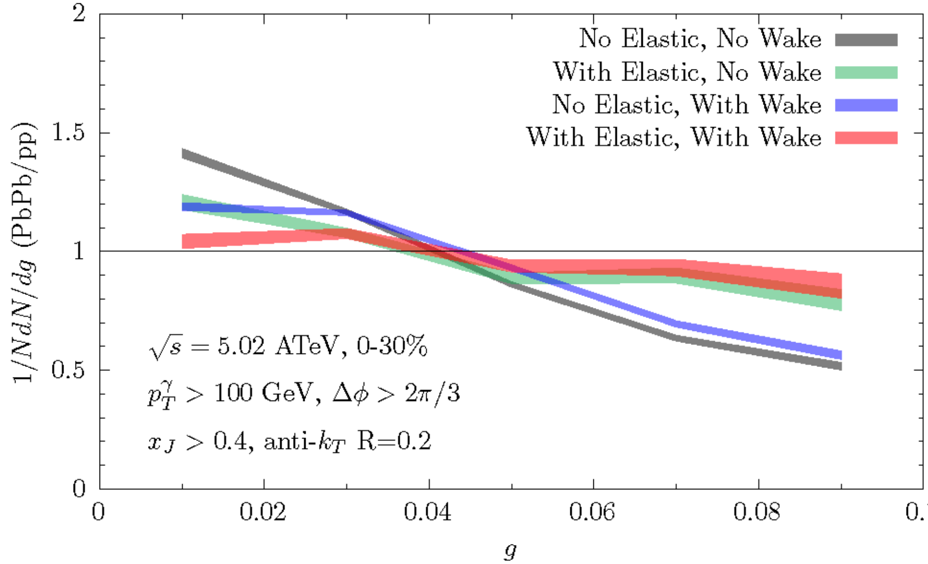


All show much less sensitivity to wake: R=0.2; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere are very much dominant.



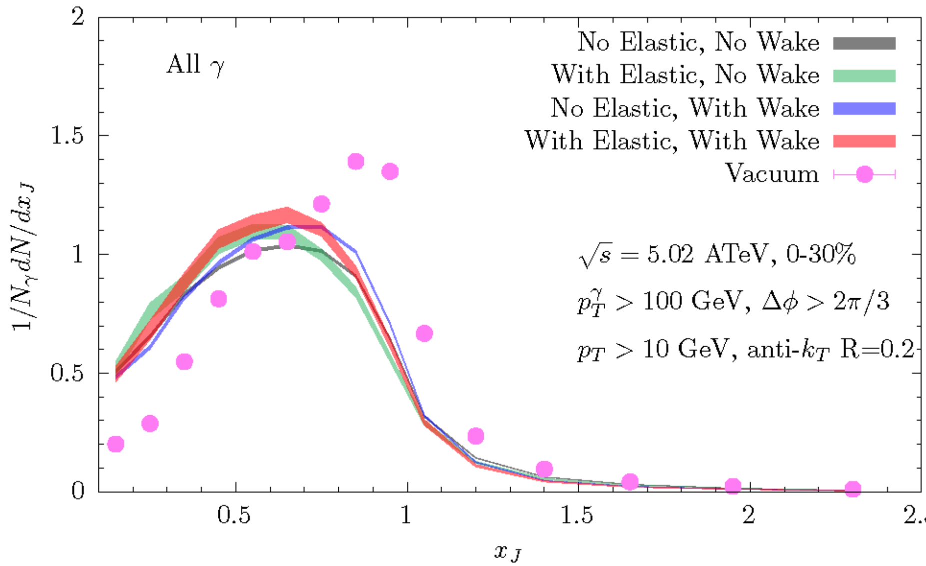
Gamma-Jet Observables: R_g and Girth



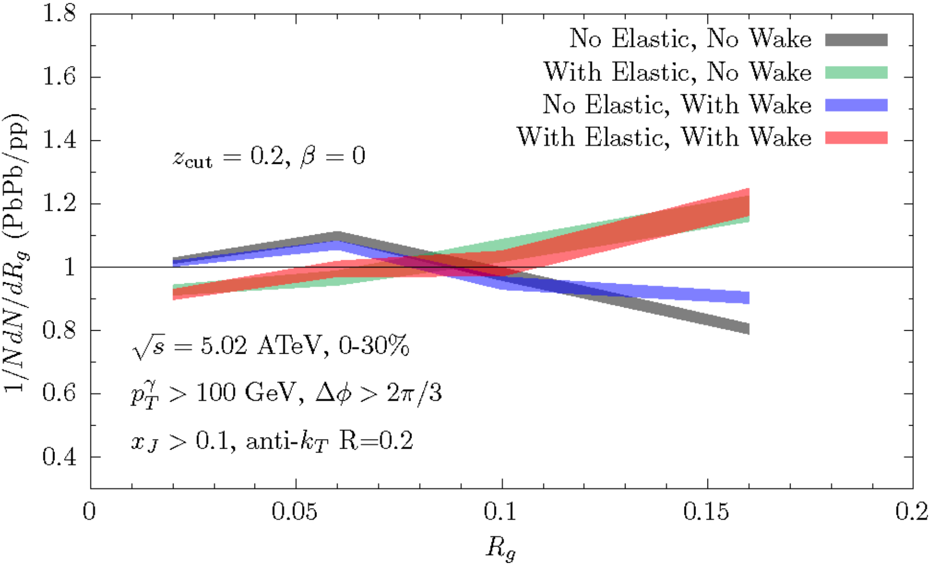


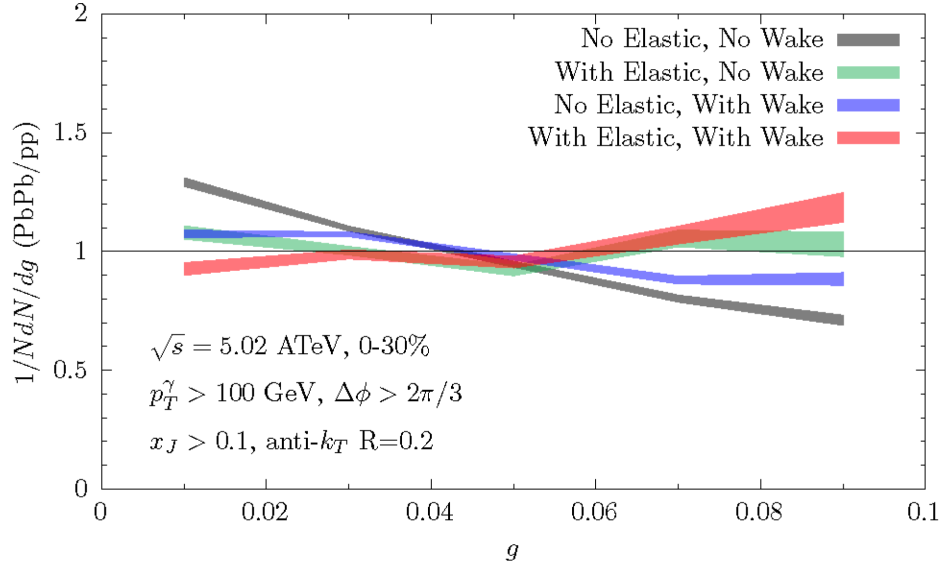
All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

But why is R_{AA} below 1? Selection bias! With x_J>0.4 selection, missing too many of the most modified jets.



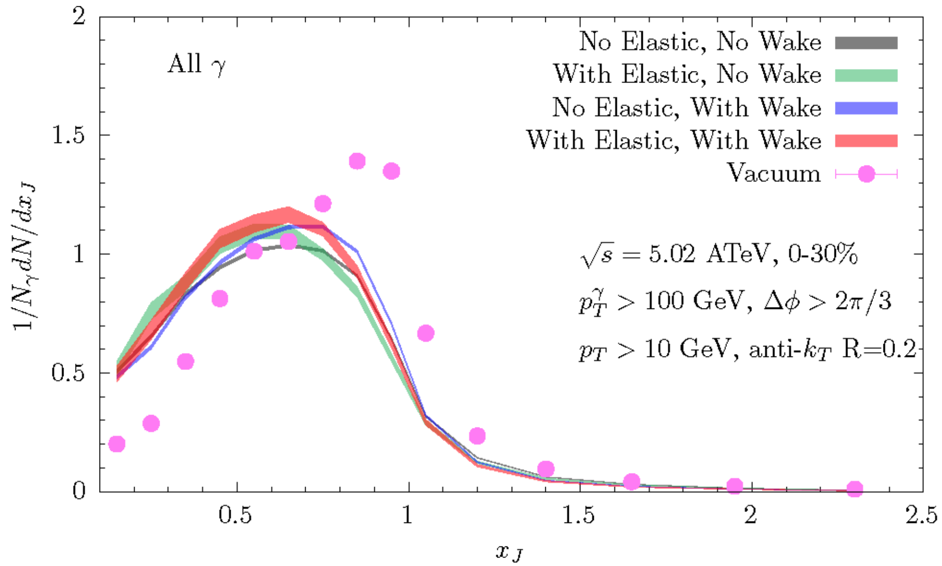
Gamma-Jet Observables: R_g and Girth, with x_J>0.1



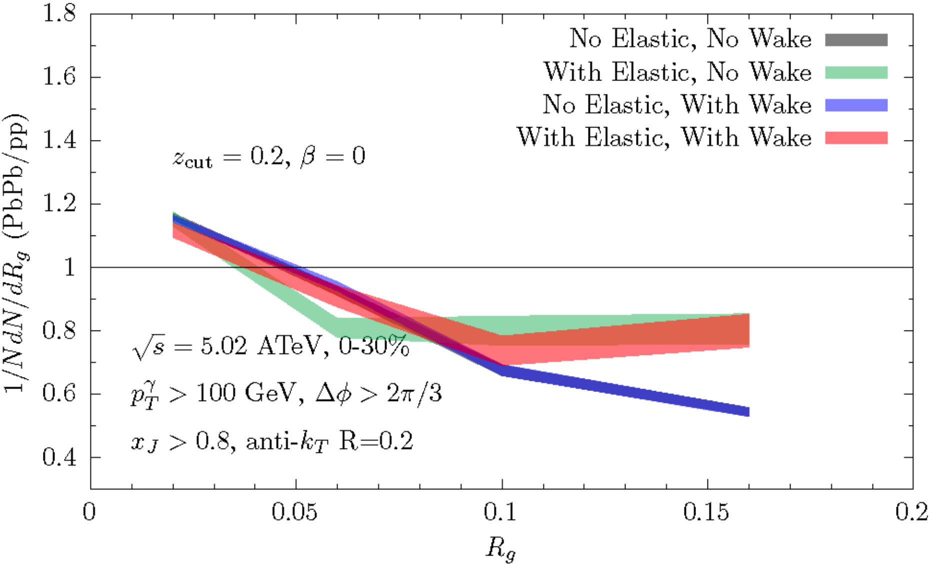


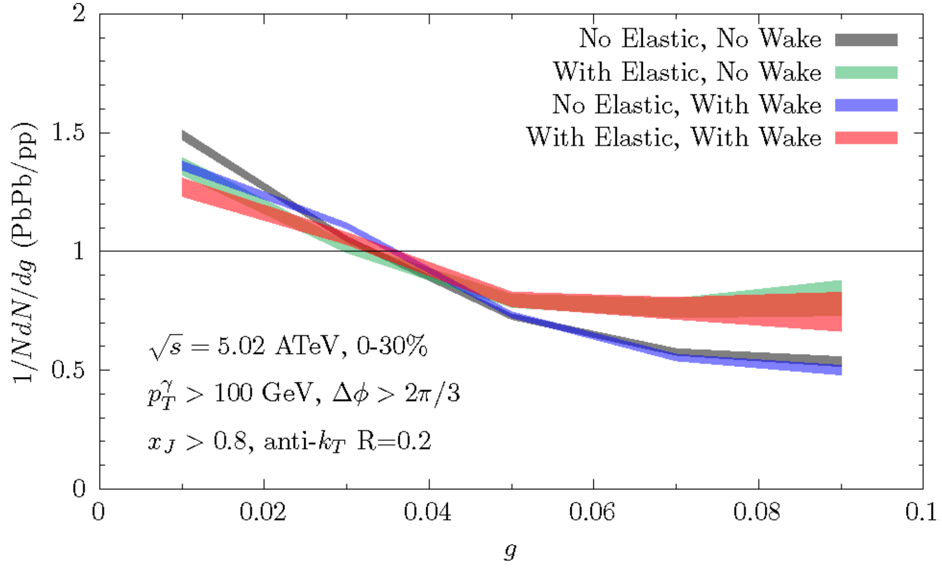
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.1. Moliere scattering important, and causes R_{AA} >1.

Selection bias reduced (cf Brewer+Brodsky+KR); some effects of wake visible.



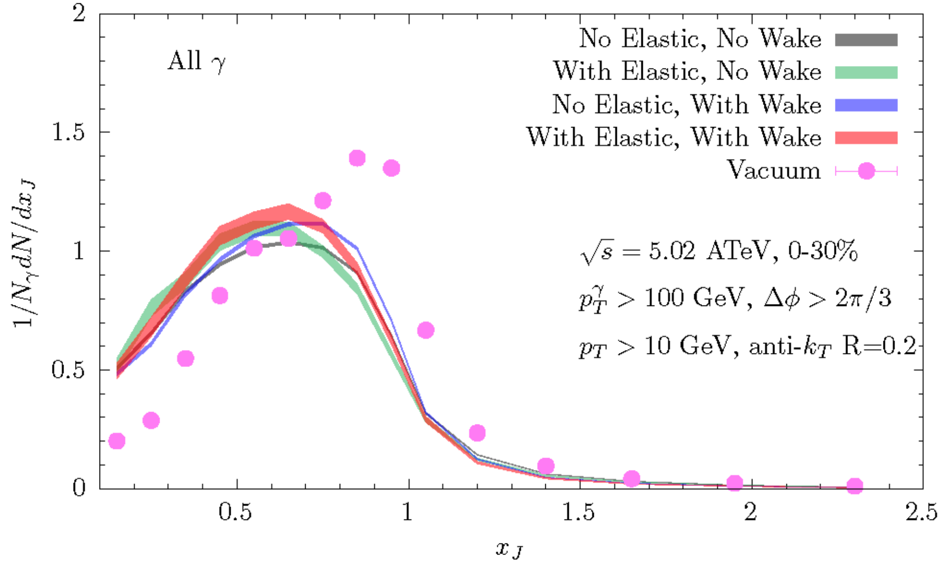
Gamma-Jet Observables: R_g and Girth, with x_J>0.8



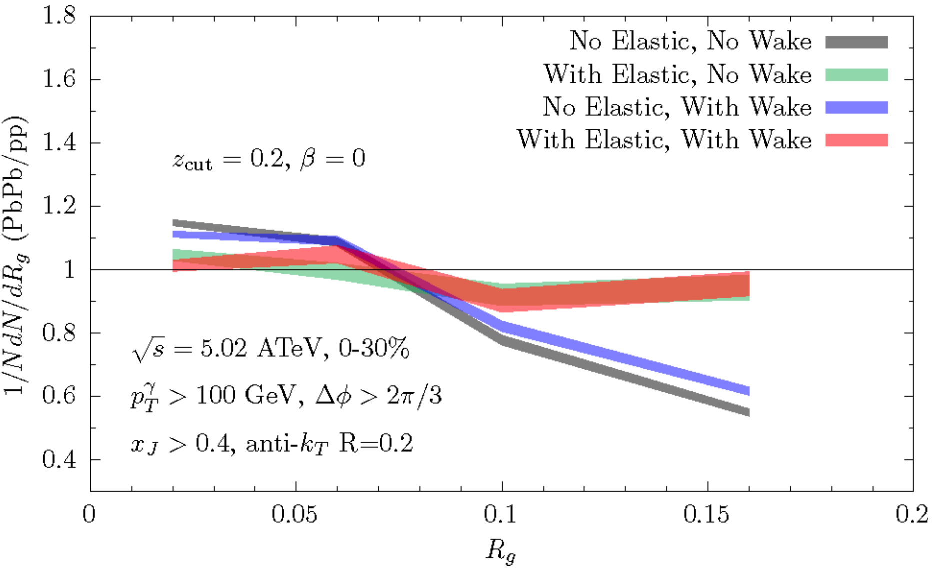


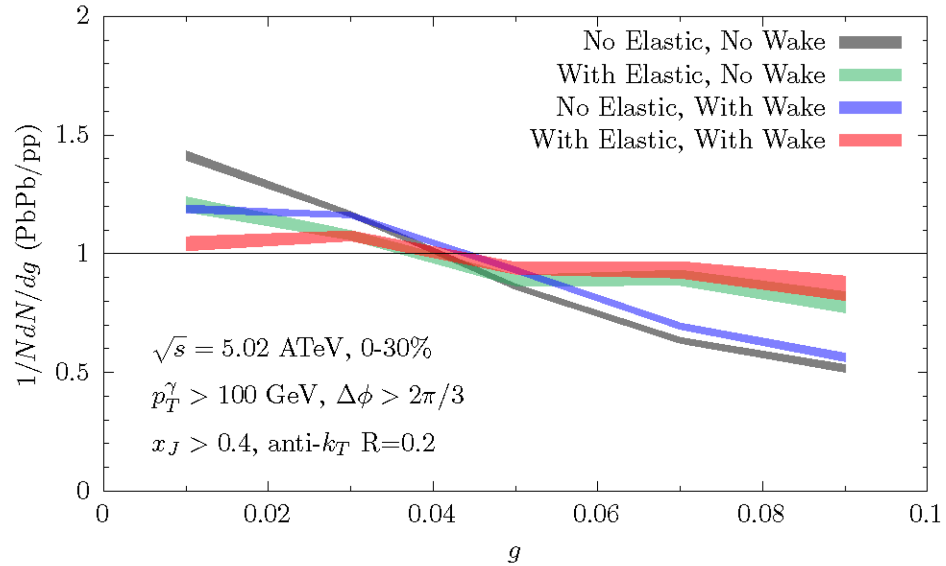
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.8. Selection bias increased.

Moliere scattering still important, and but selection bias so strong that it does not yield R_{AA} >1.



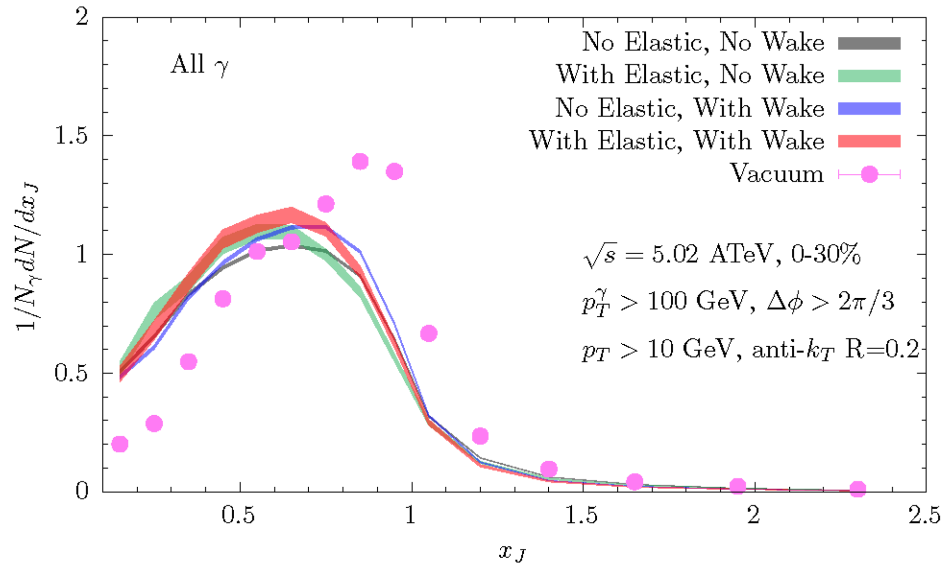
Gamma-Jet Observables: R_g and Girth, with $x_J>0.4$



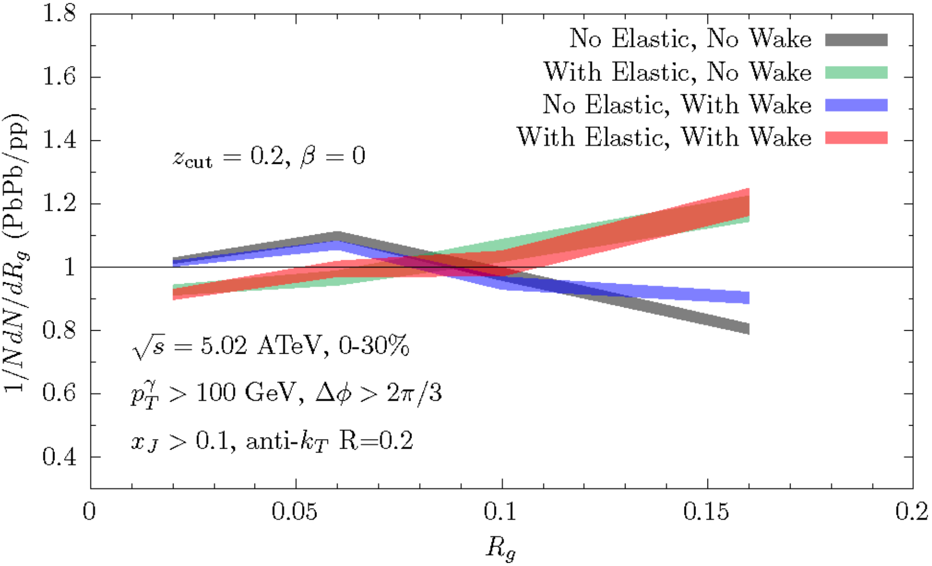


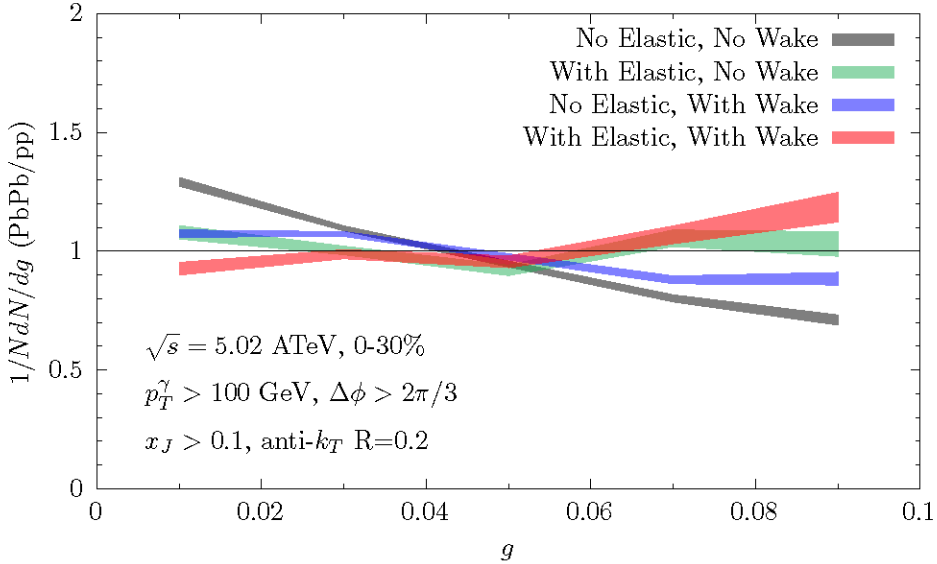
All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

But why is R_{AA} below 1? Selection bias! With $x_J>0.4$ selection, missing too many of the most modified jets.



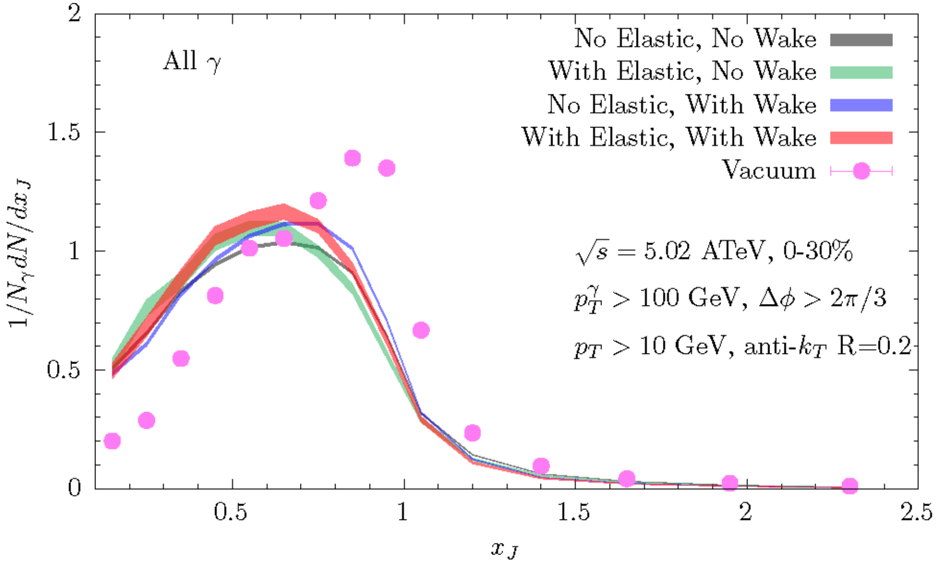
Gamma-Jet Observables: R_g and Girth, with x_J>0.1



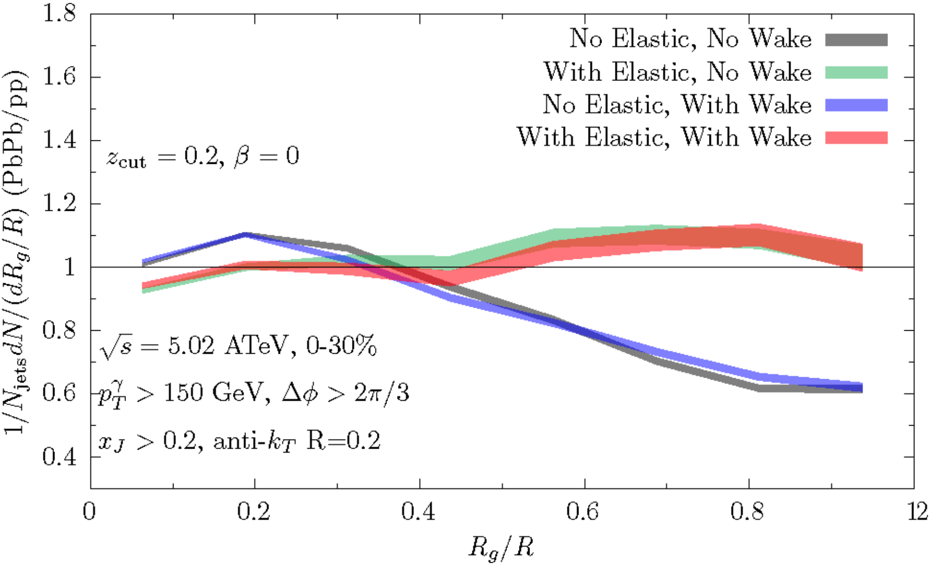


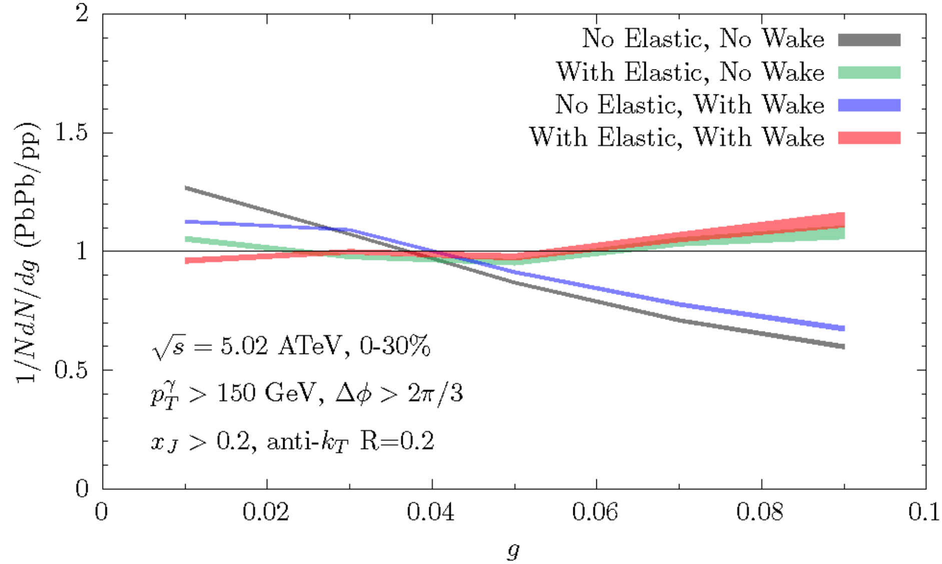
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.1. Moliere scattering important, and causes R_{AA} >1.

Selection bias reduced (cf Brewer+Brodsky+KR); some effects of wake visible.



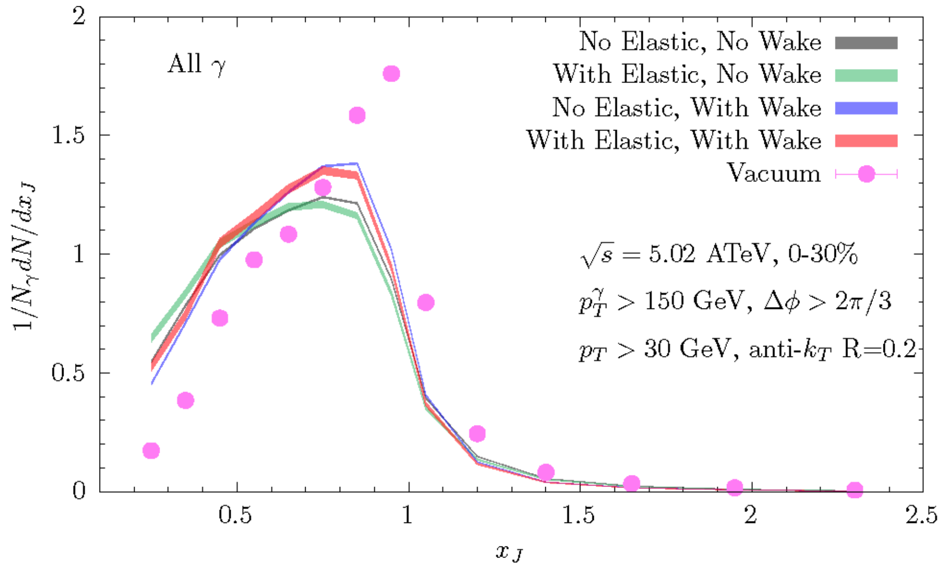
Gamma-Jet Observables with p_T^γ >150 GeV: R_g and Girth, with x_J>0.2



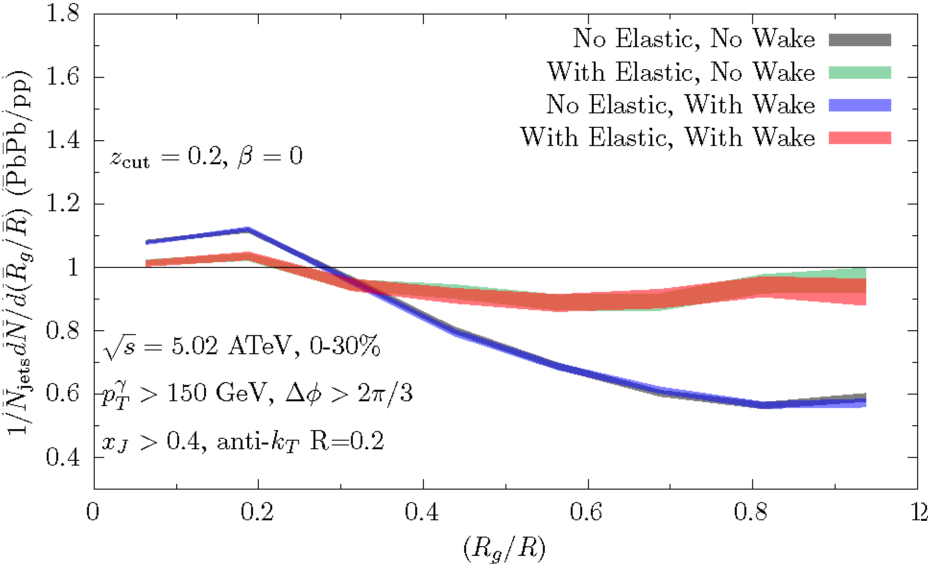


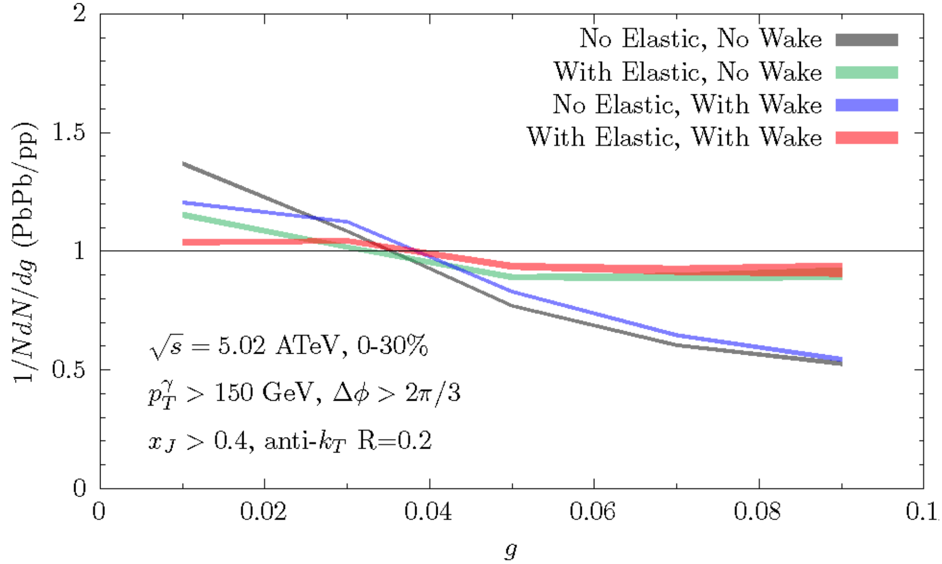
On previous slides, p_T^γ >100 GeV; here, p_T^γ >150 GeV.
Means x_J>0.2 corresponds to p_T^{jet}>30 GeV. And, no need to go down to x_J>0.1.

Moliere effects substantial; selection bias reduced; wake effects negligible.



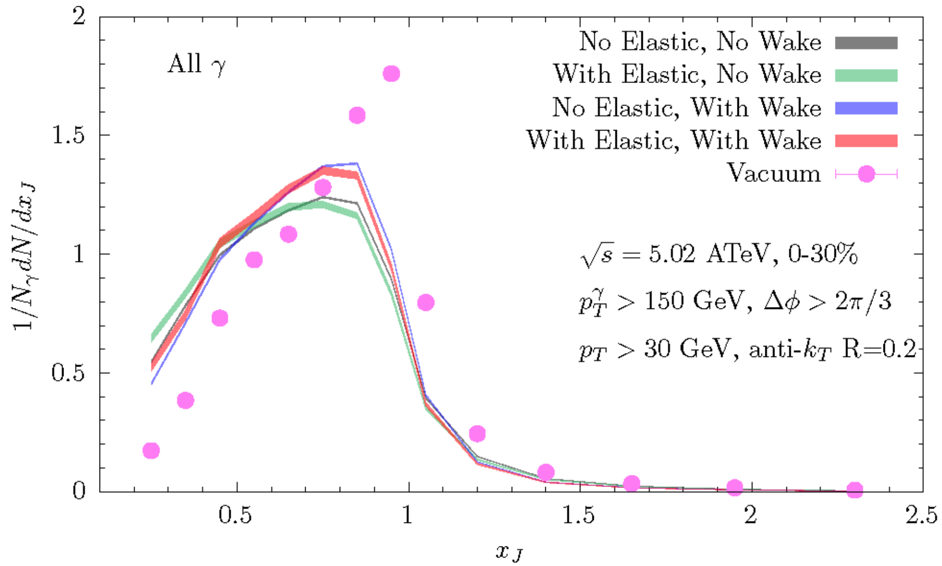
Gamma-Jet Observables with p_T^γ >150 GeV: R_g and Girth, with x_J>0.4



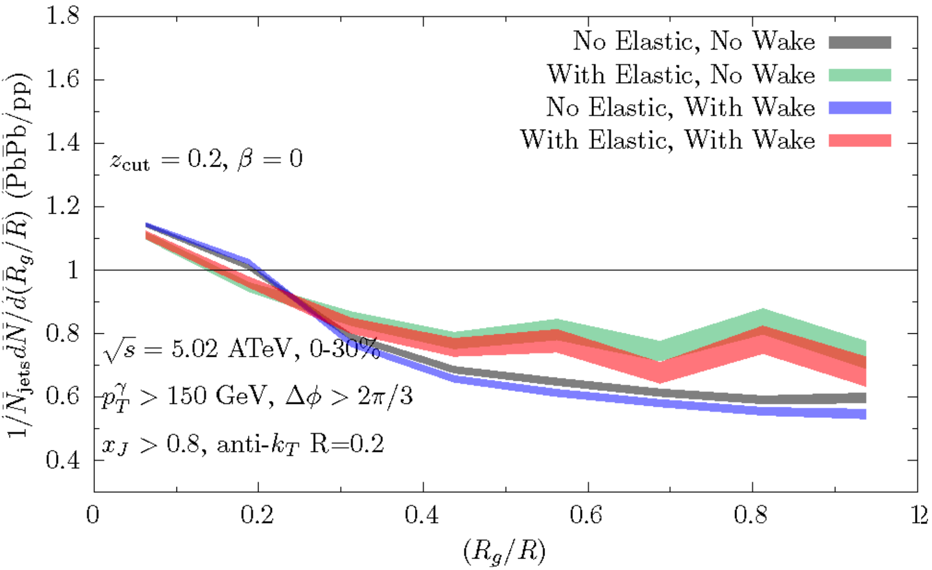


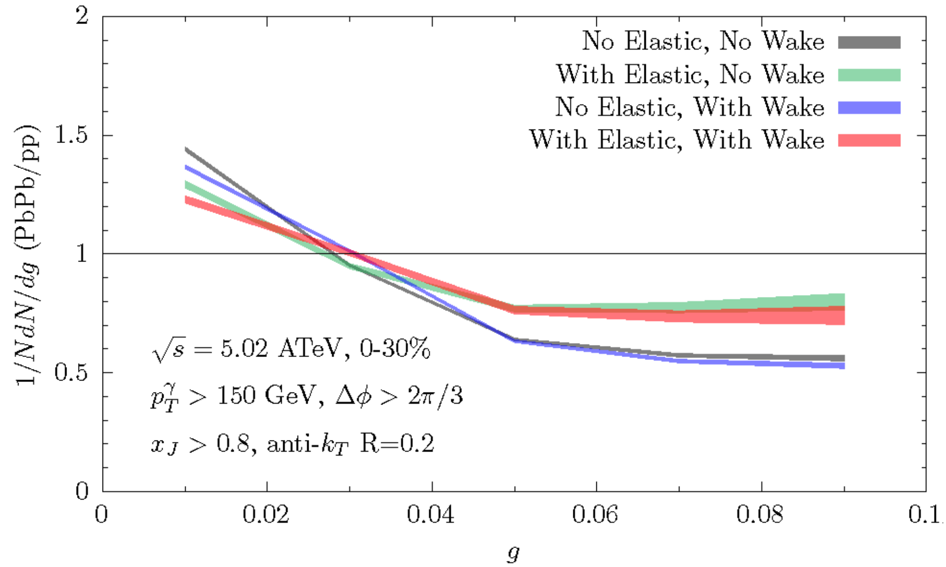
On previous slides, p_T^γ >100 GeV; here, p_T^γ >150 GeV. Means x_J>0.4 corresponds to p_T^{jet}>60 GeV.

Moliere effects substantial; selection bias significant; wake effects negligible.



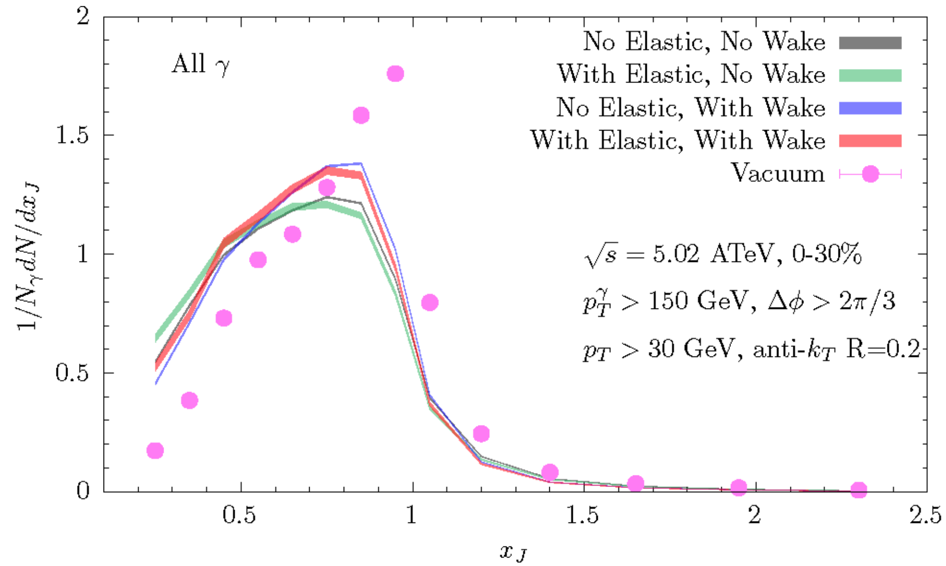
Gamma-Jet Observables with p_T^{γ} >150 GeV: R_g and Girth, with x_J>0.8



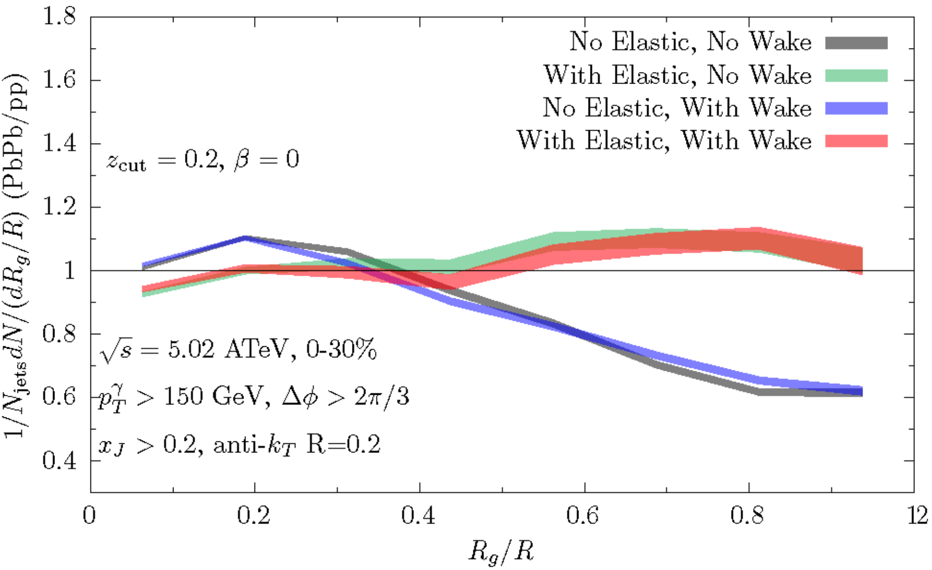


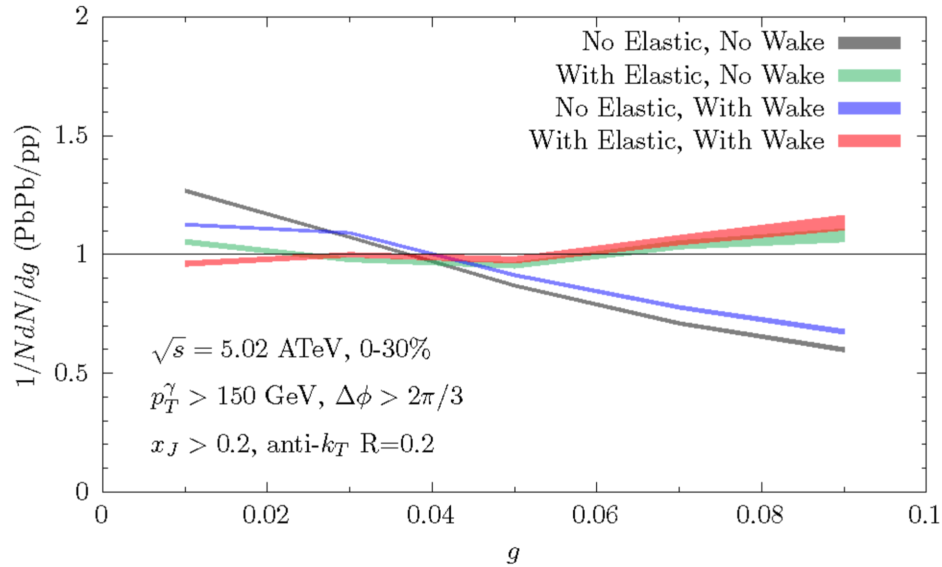
On previous slides, p_T^{γ} >100 GeV; here, p_T^{γ} >150 GeV.
Means x_J>0.8 corresponds to p_T^{jet}>120 GeV.

Moliere effects substantial; selection bias dominant; wake effects negligible.



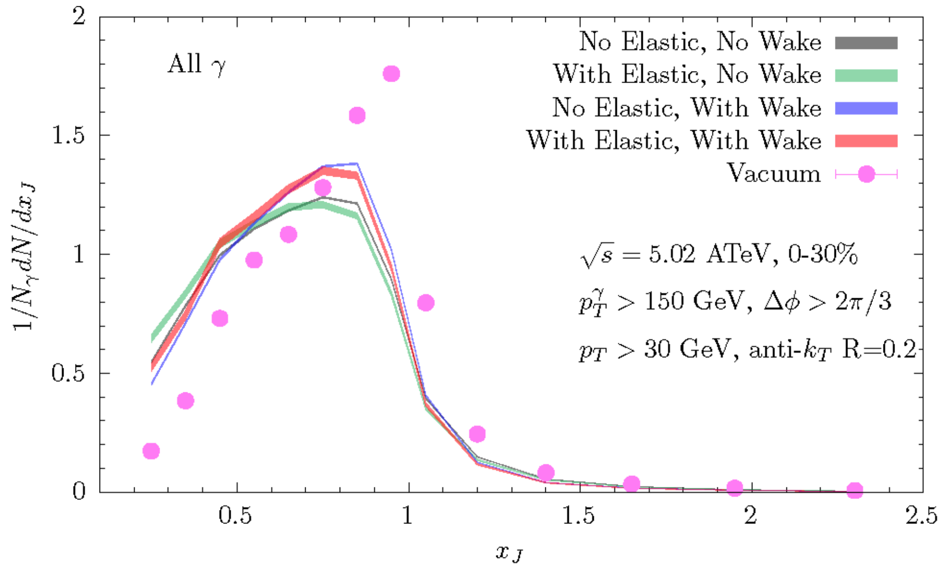
Gamma-Jet Observables with p_T^{γ} >150 GeV: R_g and Girth, with x_J>0.2



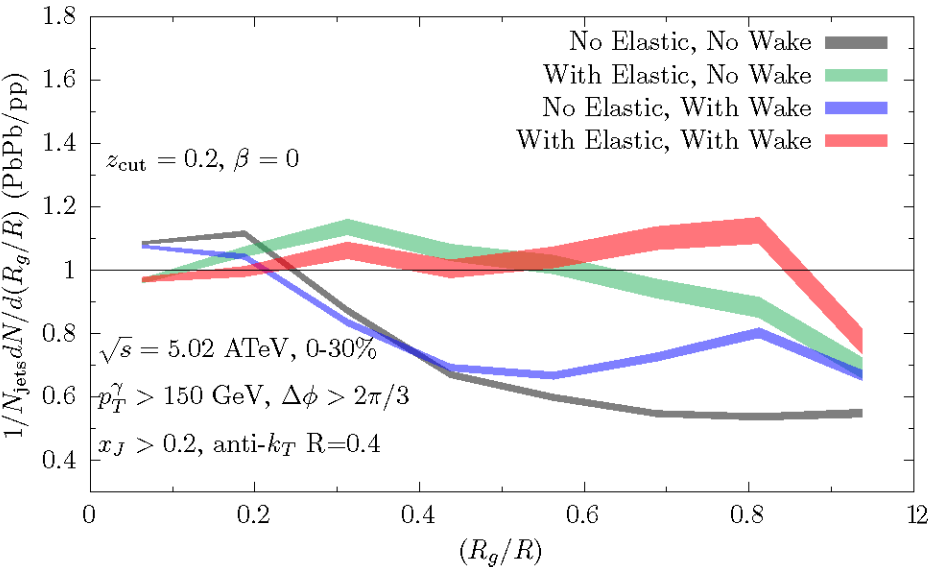


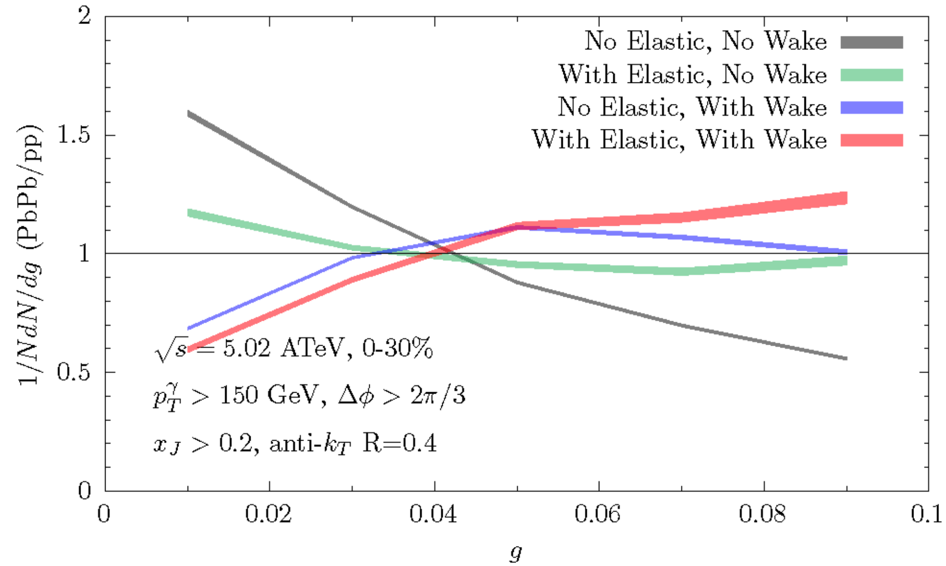
On previous slides, p_T^{γ} >100 GeV; here, p_T^{γ} >150 GeV.
Means x_J>0.2 corresponds to p_T^{jet}>30 GeV. And, no need to go down to x_J>0.1.

Moliere effects substantial; selection bias reduced; wake effects negligible.



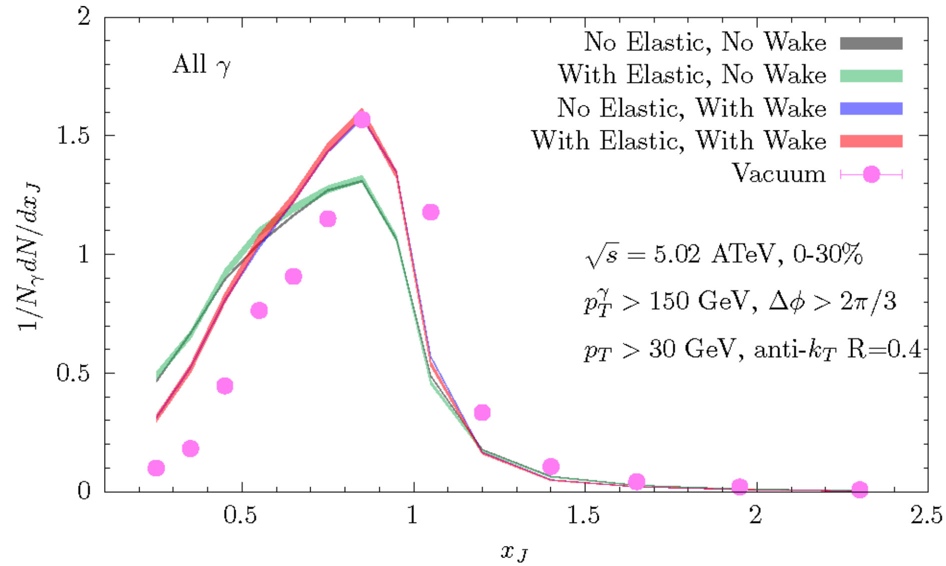
Gamma-Jet Observables with p_T^{γ} >150 GeV and R=0.4: R_g and Girth, with x_J>0.2



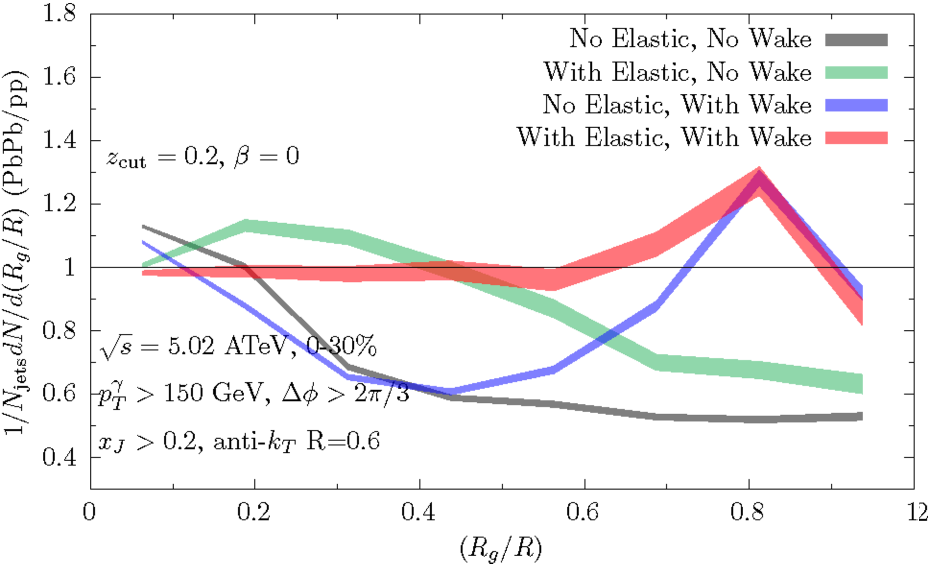


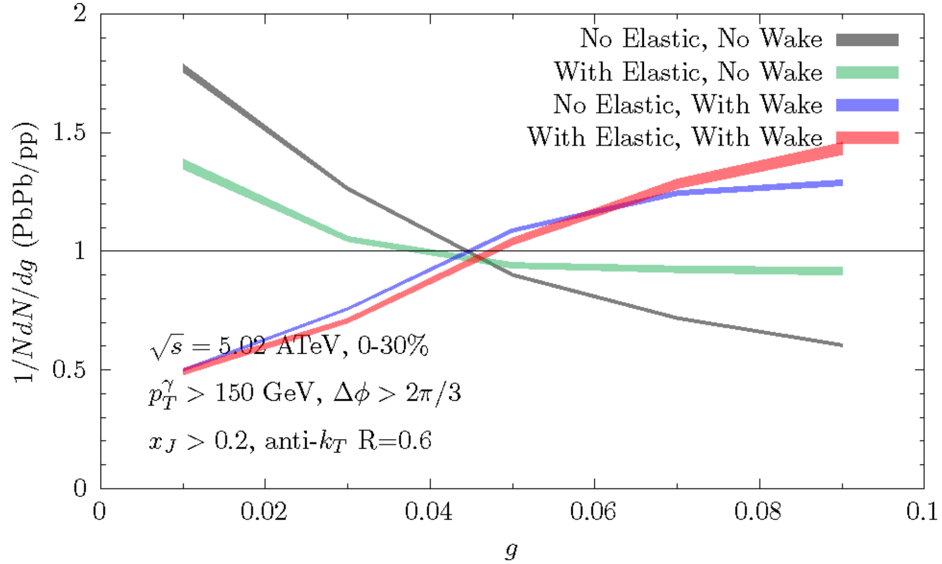
On previous slides, p_T^{γ} >150 GeV with R=0.2. Here, R=0.4, so that we can "catch" more wake, with little selection bias.

Moliere effects substantial; selection bias reduced; wake effects significant.



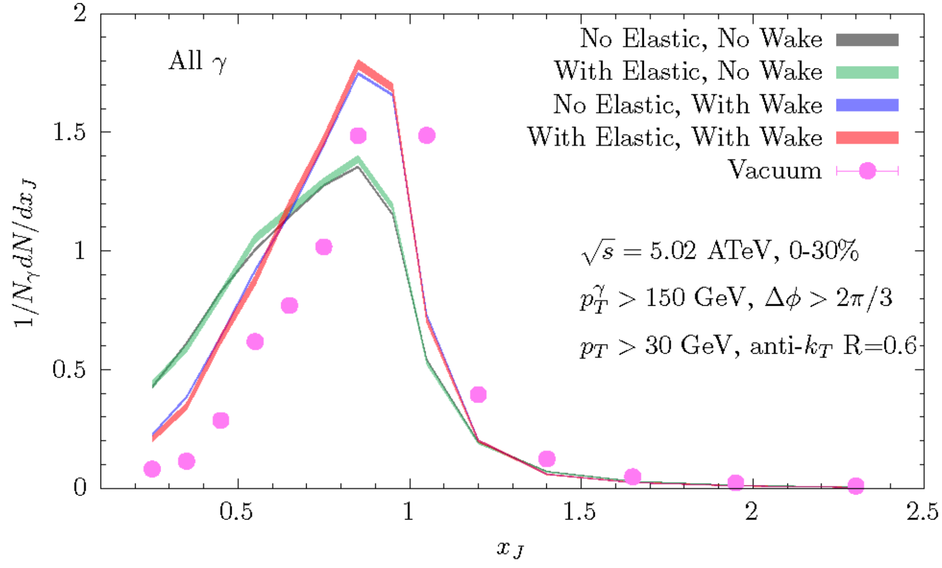
Gamma-Jet Observables with $p_T^\gamma > 150$ GeV and R=0.6: R_g and Girth, with $x_J > 0.2$



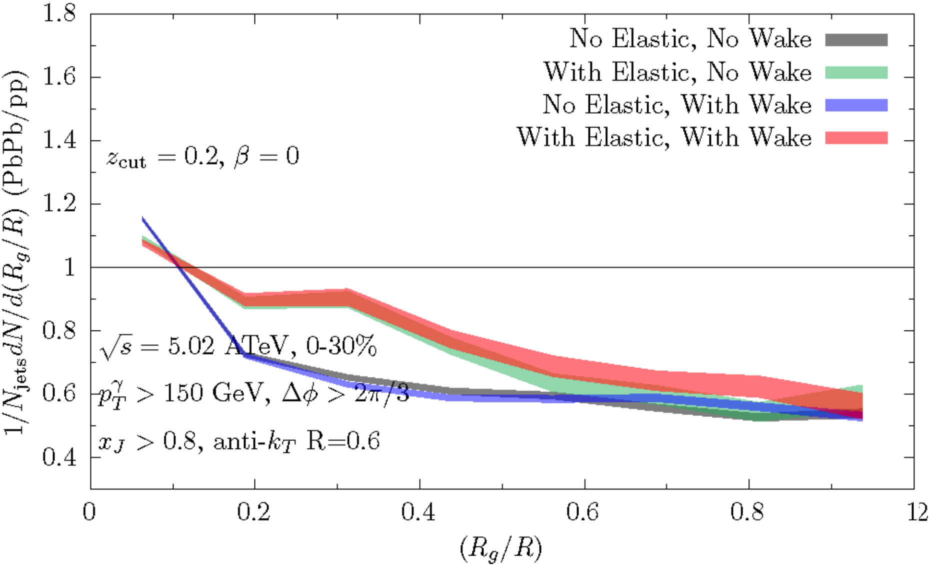


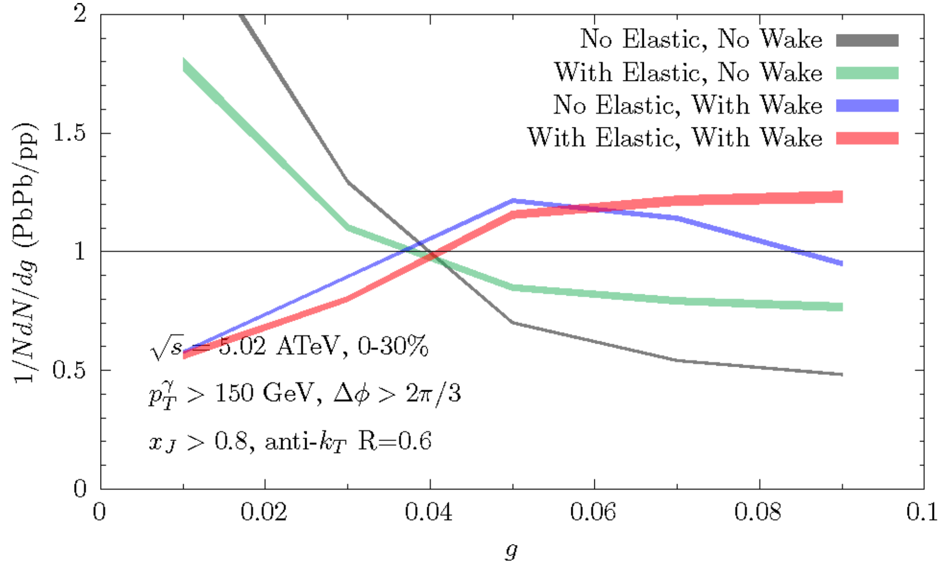
On previous slides, $p_T^\gamma > 150$ GeV with R=0.2. Here, R=0.6, so that we can “catch” *even more* wake, with little selection bias.

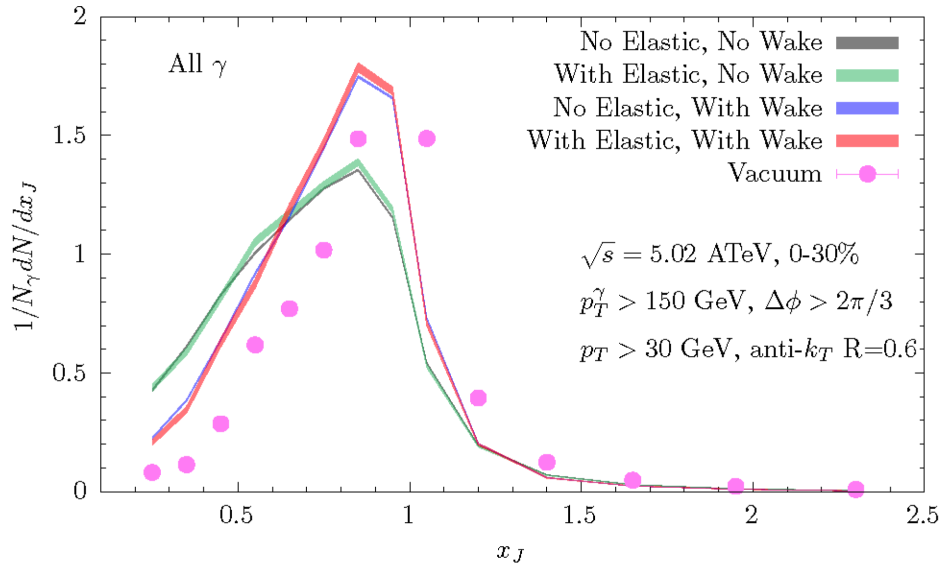
Moliere effects substantial; selection bias reduced; wake effects enormous, and as in Brewer+Brodsky+KR.



Gamma-Jet Observables with p_T^{γ} >150 GeV and R=0.6: R_g and Girth, with x_J>0.8





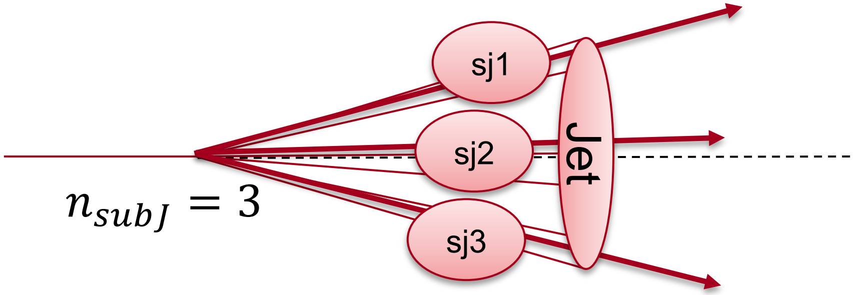


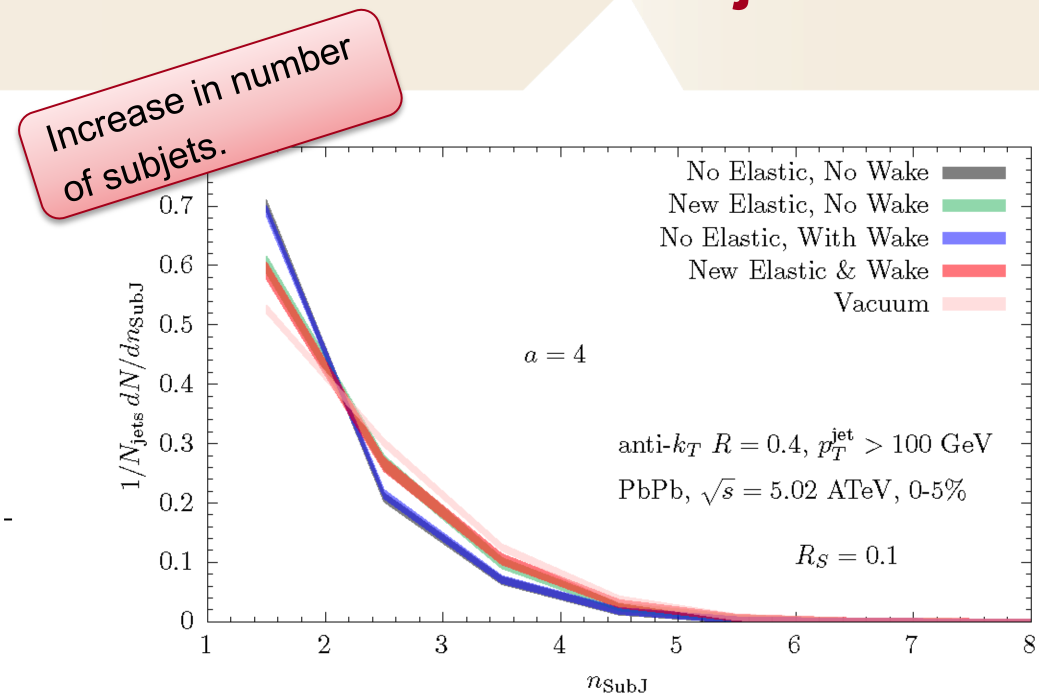
On previous slides, p_T^{γ} >150 GeV with R=0.2. Here, R=0.6. But, we've turned the selection bias back ON.

Moliere effects still substantial; selection bias dominant; wake effects *greatly reduced*, as in Brewer+Brodsky+KR.

Inclusive Jets within Inclusive Jets: Inclusive Subjets

1. Reconstruct jet with R=0.6
2. Recluster each jet's particle content into subjets with R=0.15





Moliere scattering visible as increase in number of subjets; no such effect coming from wake at all.

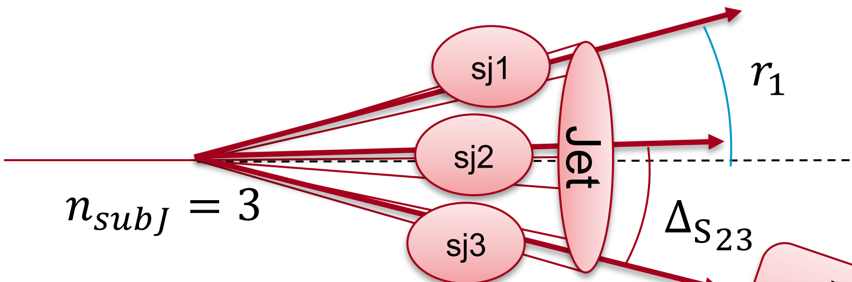
Moliere scattering also yields more separated subjets…

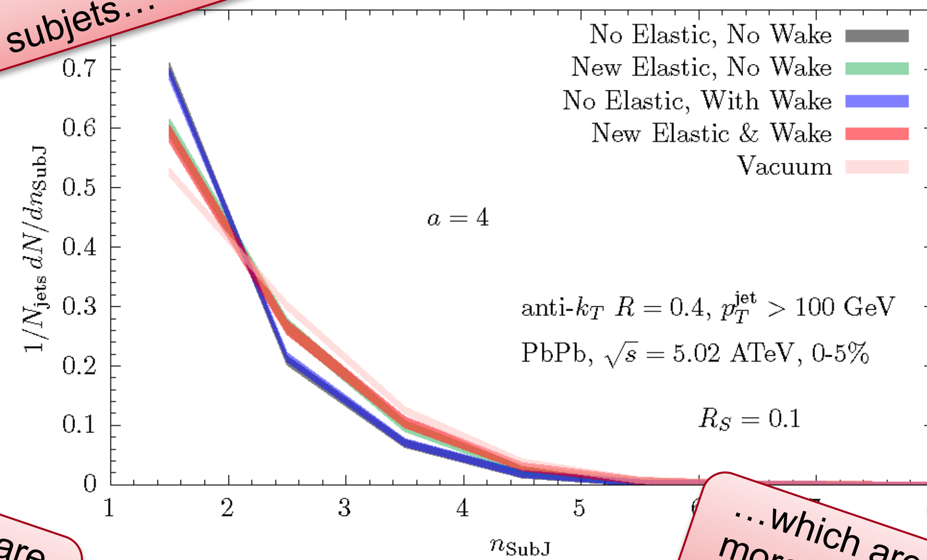
These observables are directly sensitive to "sprouting a new subjet" the intrinsic feature of Moliere scattering which makes it NOT just a bit more wake.

Inclusive Subjets

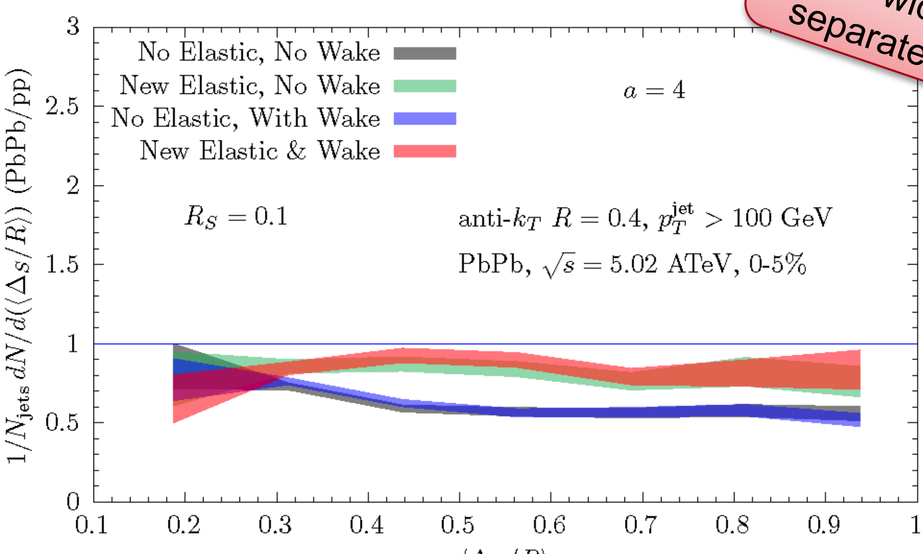
1. Reconstruct jet with R=0.4
2. Recluster each jet's particle content into subjets with R=0.1

Increase in number of subjets…

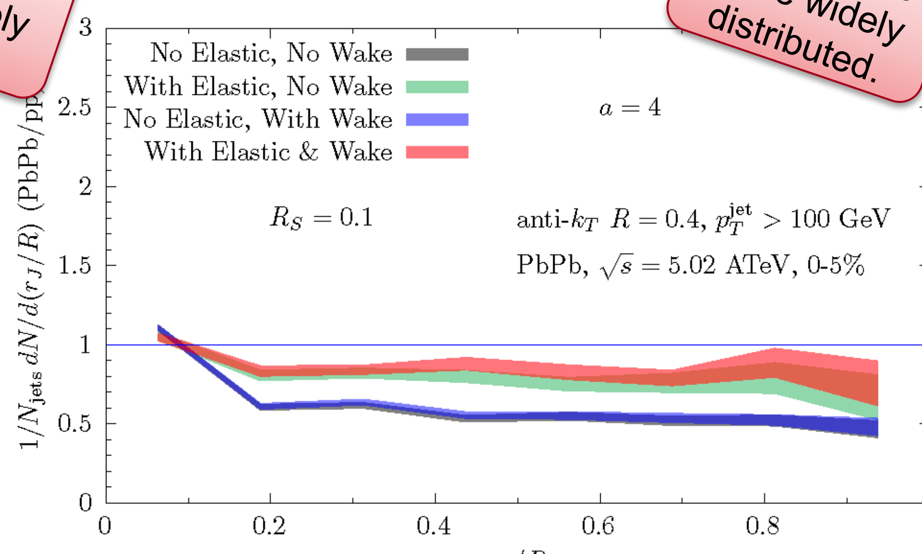




…which are more widely separated.

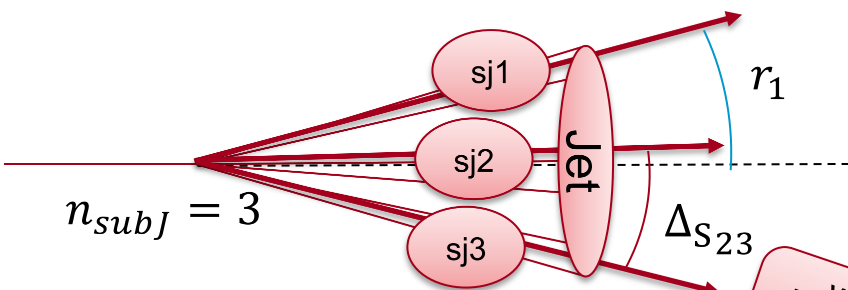


…which are more widely distributed.

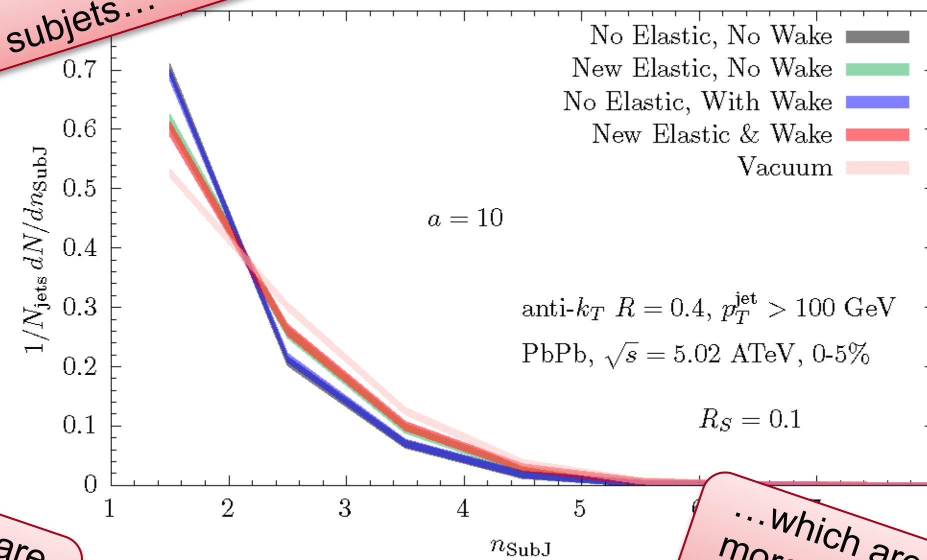


Inclusive Subjets

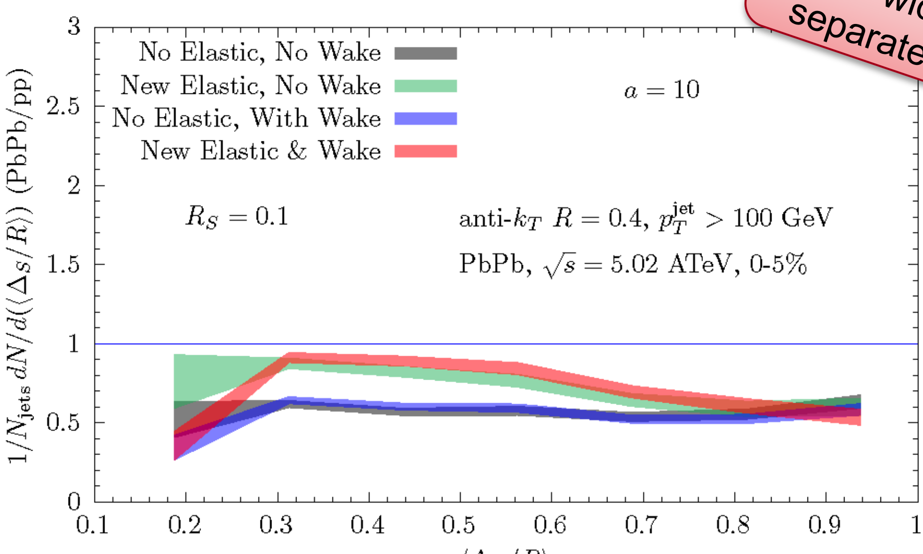
1. Reconstruct jet with R=0.4
2. Recluster each jet's particle content into subjets with R=0.1



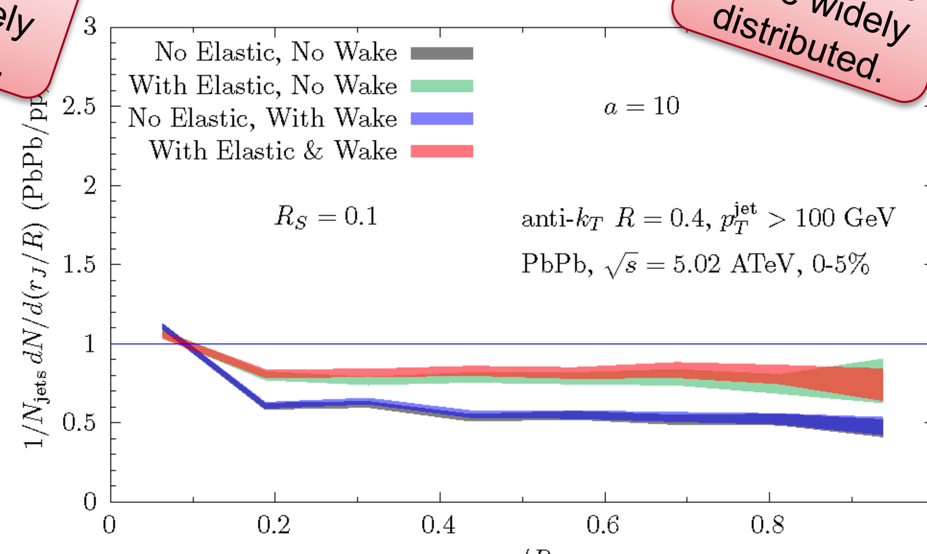
Increase in number of subjets…



…which are more widely separated.



…which are more widely distributed.



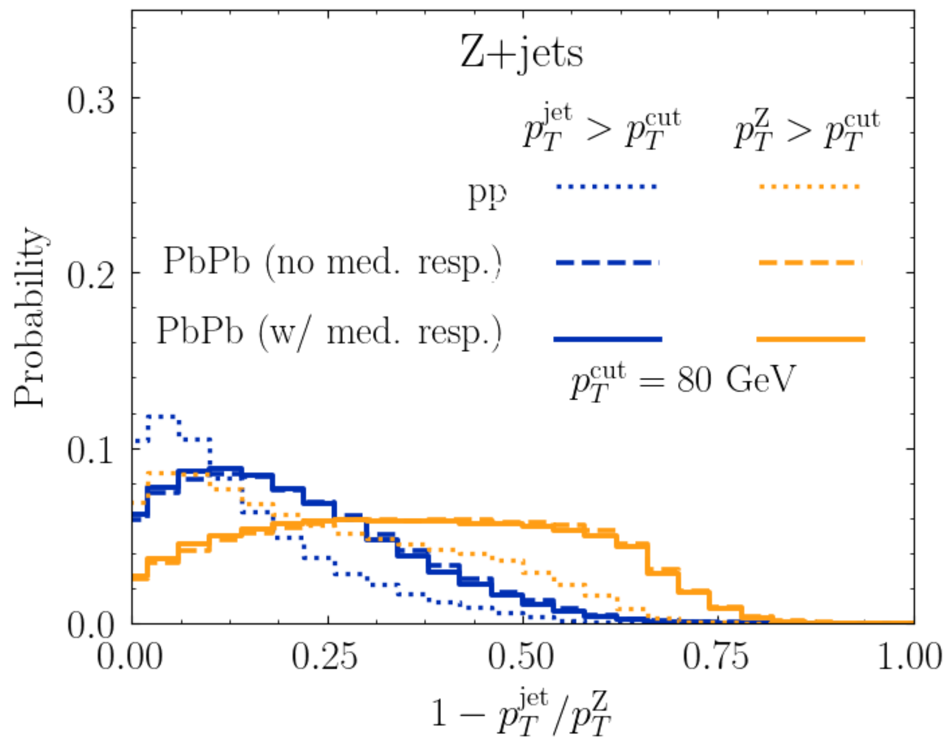
Conclusions

- Studied the effect of elastic Moliere scattering of jet partons off medium partons on jet observables in the perturbative regime.
- For "overall shape observables" (jet shapes; FF) effects of Moliere scattering are similar to, and smaller than, effects of wake.
- Grooming helps, by grooming away the soft particles from the wake. Effects of Moliere scattering dominate the modification of several groomed observables (R_g, Leading k_T, Girth, WTA axis angle.)
- R_g and girth observables in γ+jet events can be "engineered" to reduce (or enhance) selection bias by selecting with x_J > a low (or high) threshold. When selection bias is reduced, Moliere scattering yields R_{AA}>1.
- R_g and girth observables in γ+jet events can be "engineered" to remove (or highlight) effects of the wake by choosing small R (or large R with x_J > a low threshold).
- Modification of inclusive subjet observables (number, and angular spread, of subjets) are especially sensitive to the presence of Moliere scatterings. These observables are unaffected by the wake. They reflect what it is that makes the effects of scattering different from those of the wake.
- Subjet and γ+jet observables may also be influenced by other ways in which jet shower partons "see" particulate aspects of the QGP. That's great!
- Acoplanarity observables that we have investigated to date show little sensitivity to Moliere scattering; significant sensitivity to the wake in many cases.

Jets as Probes of QGP

- Theorists taking key steps...
- Disentangling jet modification from jet selection.
- Showing that QGP *can* resolve structure within jet shower.
- Jet wakes in droplets of QGP.
- Selecting those jet substructure observables that *are* sensitive to scattering of jet partons off QGP partons, and are *not* sensitive to particles coming from the wake: 2208.13593 and in progress, Hulcher, Pablos, KR.
  - Builds upon theoretical framework for computing Molière scattering in QGP, and finding point-like scatterers in a liquid developed in: 1808.03250 D'Eramo, KR, Yin
- Next several years will be the golden age of HIC jet physics: sPHENIX, LHC runs 3 and 4, new substructure observables. *Many* theory advances, here and elsewhere, whet our appetite for the feast to come. We shall learn about the microscopic structure of QGP, and the dynamics of rippling QGP.

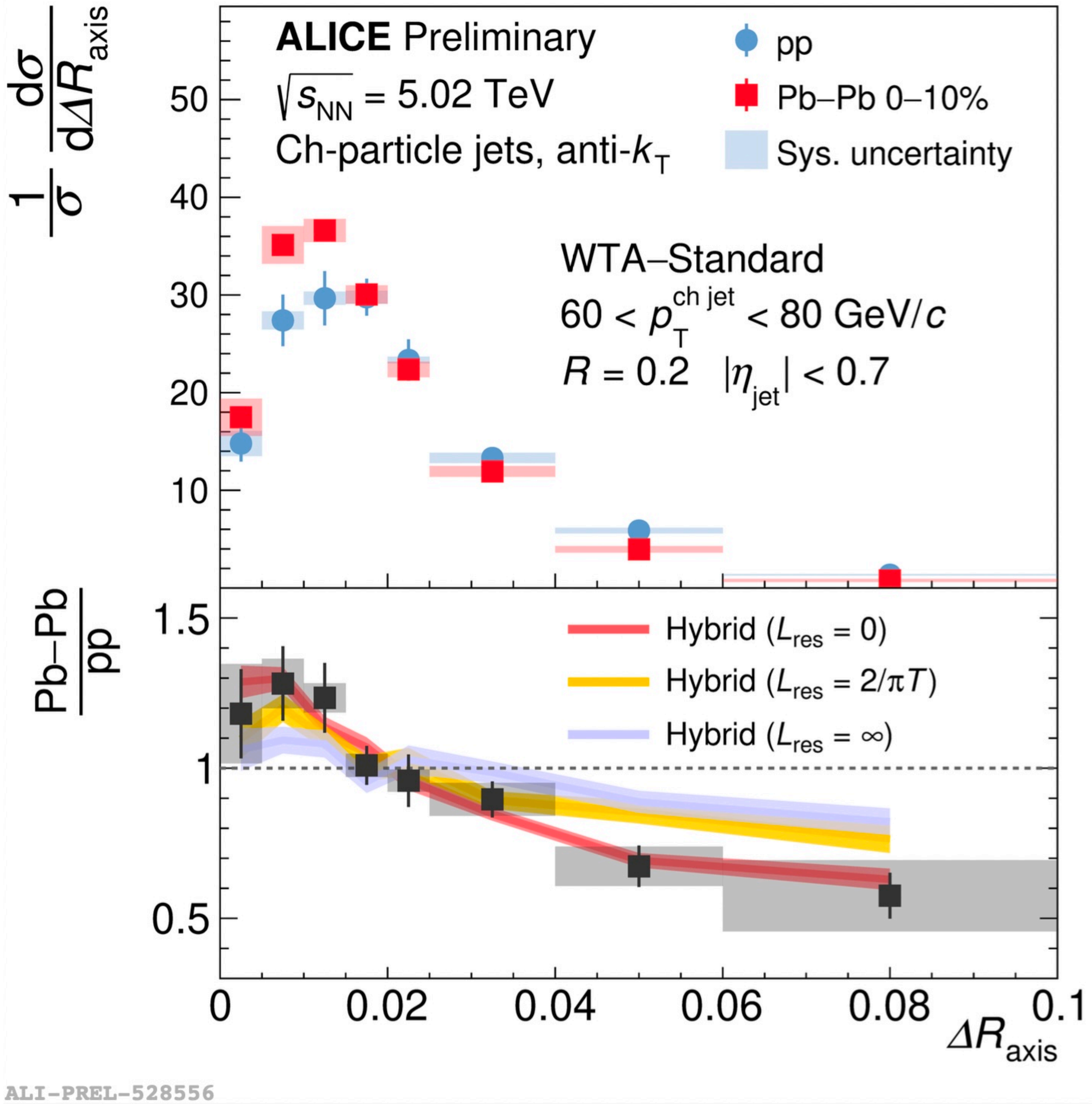
Disentangling Jet Modification from Selection

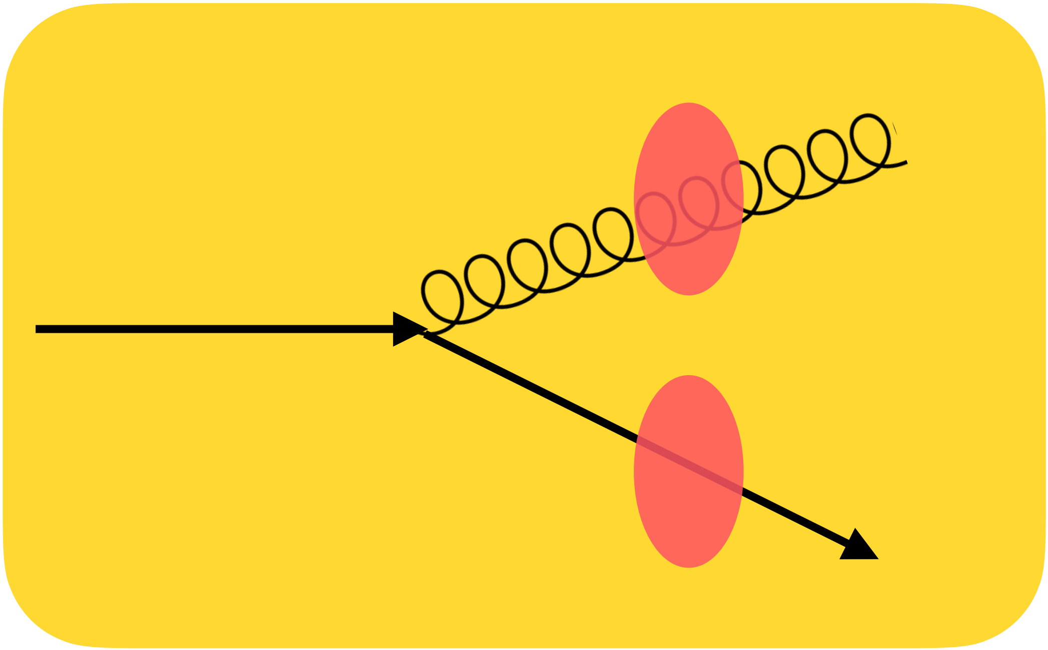


Orange: $p_T^Z > 80$ **GeV;** $p_T^{\rm jet} > 30$ **GeV**

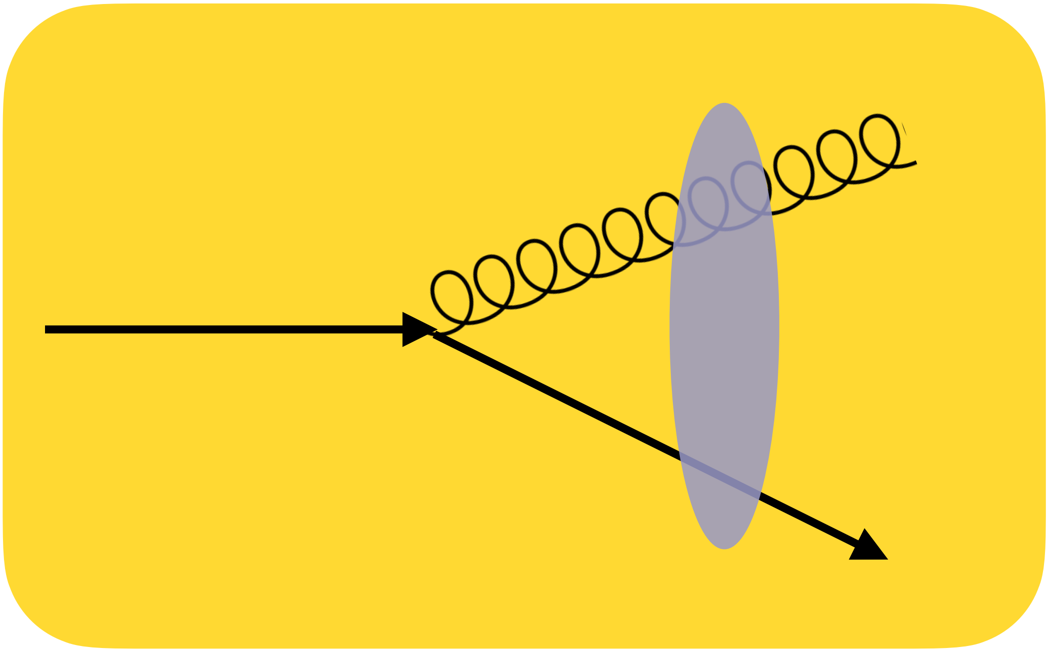
Blue: $p_T^{\rm jet} > 80$ **GeV;** $p_T^Z > 30$ **GeV — jet selection biases toward those jets that lose less energy**

Medium resolution length, L_{res}





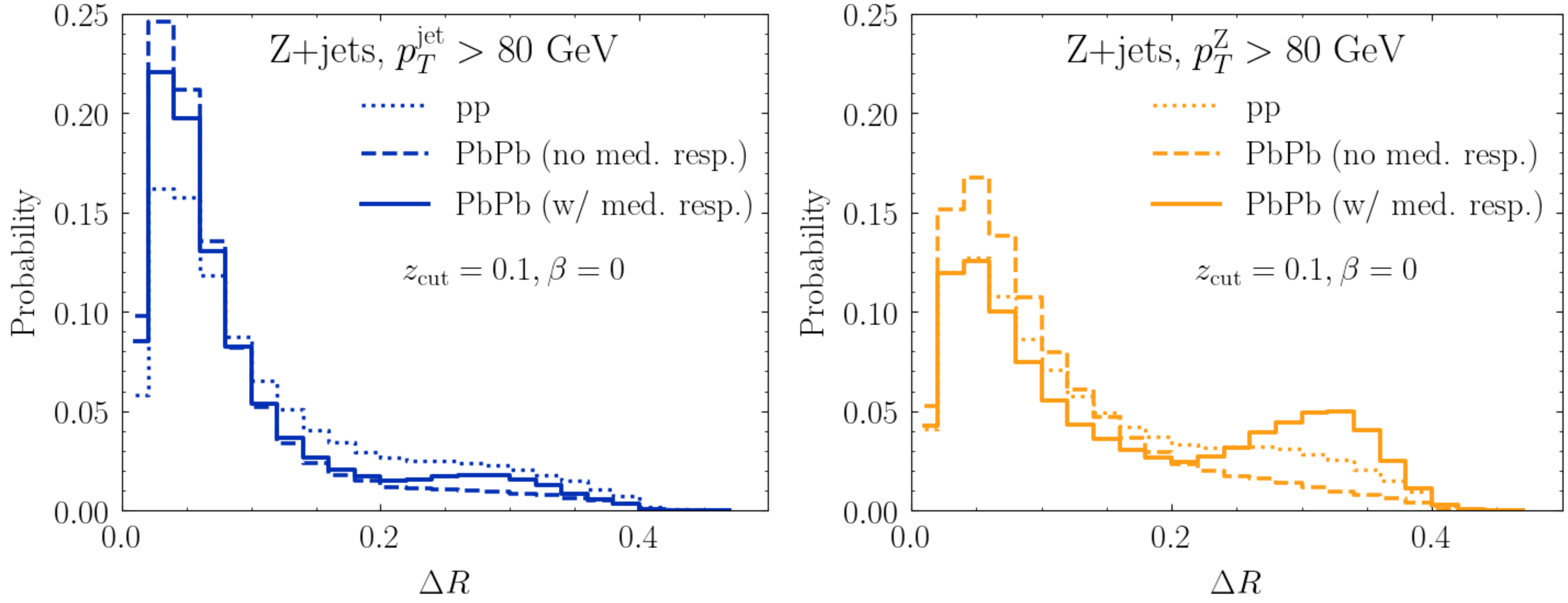
L_{res} = 0: medium resolves splitting immediately after parton fragments.
Fully-incoherent energy loss



L_{res} = ∞: medium does not resolve splitting.
Fully-coherent energy loss

Data favors mechanisms of incoherent energy loss in the QGP

Disentangling Jet Modification from Selection



Orange: $p_T^{Z} > 80$ GeV; $p_T^{\rm jet} > 30$ GeV. See jet modification.

Blue: $p_T^{\rm jet} > 80$ GeV; $p_T^{Z} > 30$ GeV — jet selection biases toward those jets that lose less energy. These jets are skinnier. And the bias is toward less jet modification.