Jet substructure in heavy ions (experiment)

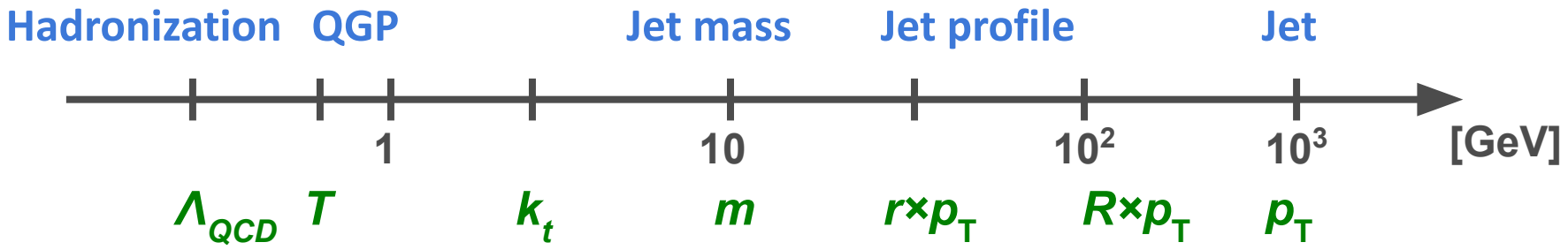
Martin Rybar

LHCP 2022

16th May 2022

Why jet substructure?

- Jets are not point-like but complex & multiscale objects.



Why jet substructure in HI?

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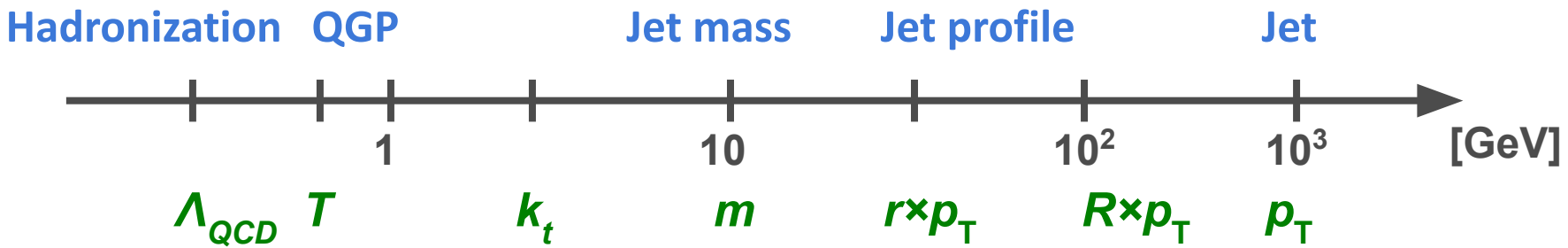
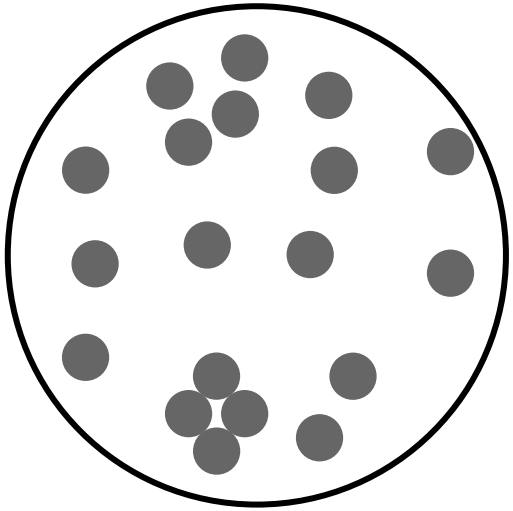


- We can use various jet substructure observables to probe different regimes.
  - What are the properties and degrees of freedom of QGP at length scales between point-like partons and hydrodynamic modes?
  - How does the color charge interact and lose energy?
  - What are the effective scales of the interactions determining the energy loss?
  - How does the hadronization process work?

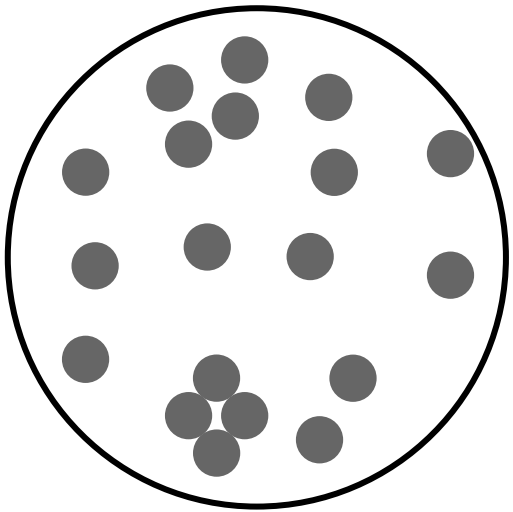
Jet definition & substructure



“Conventional” jet made of particles/tracks/towers/clusters

Fragmentation functions, track-jet correlations and jet shapes (can be extended to large angles).

Jet definition & substructure



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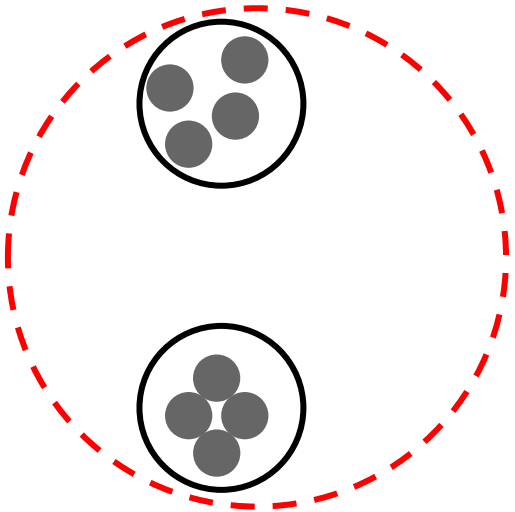
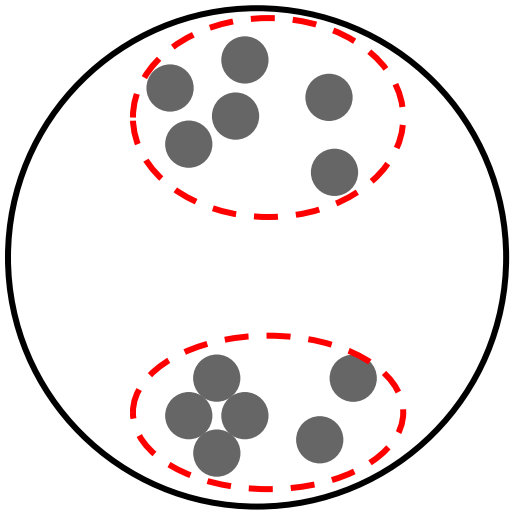


Re-clustered jet from smaller jets, prong finder or *R*-scan

Large-R jets designed for boosted W/Z/t; focus on hard structure; sub-jets.



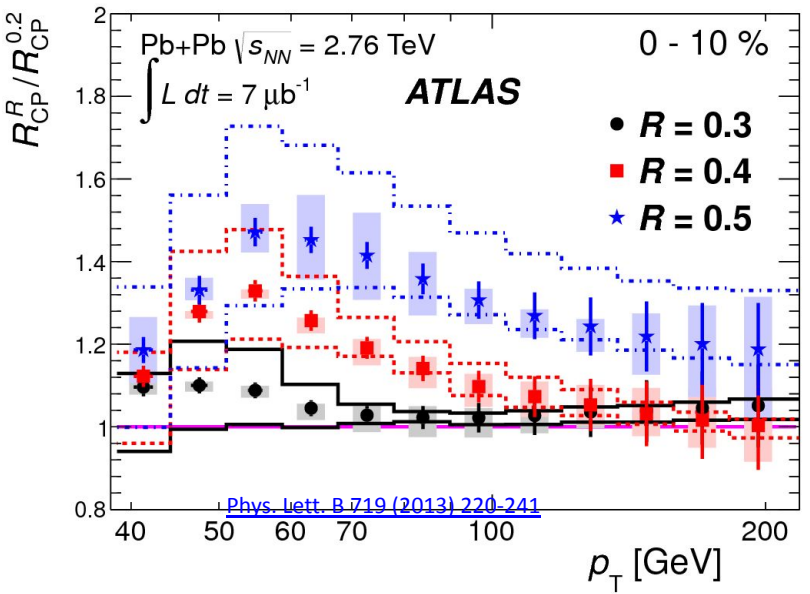
De-clustered & groomed jet: Trimming, SoftDrop, Prunning...

Large-scale structure; declustering follow the splitting evolution; grooming parameters ⇔ affects physics.

Radial scan

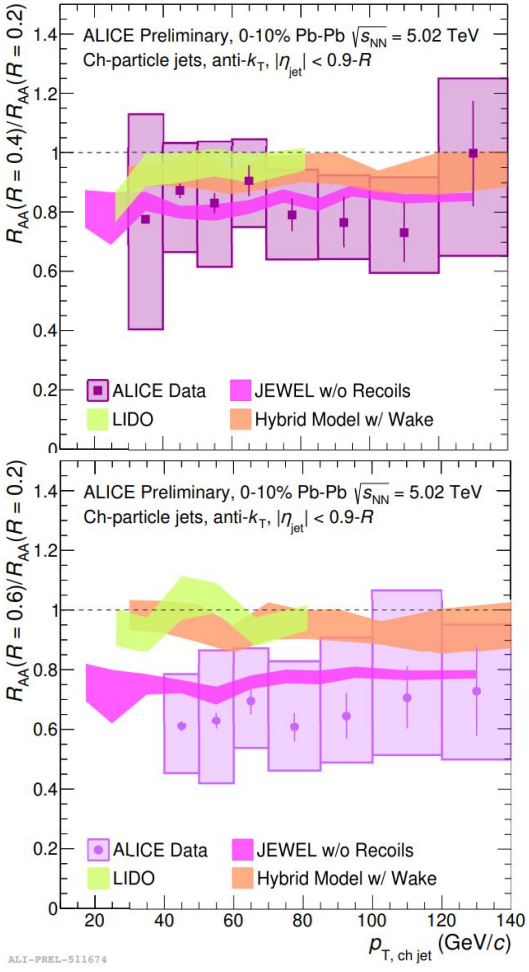
Comparison of inclusive jets for different jet radii → recovery + medium response vs flavour fraction + more resolved structure.

What we know from past measurements…

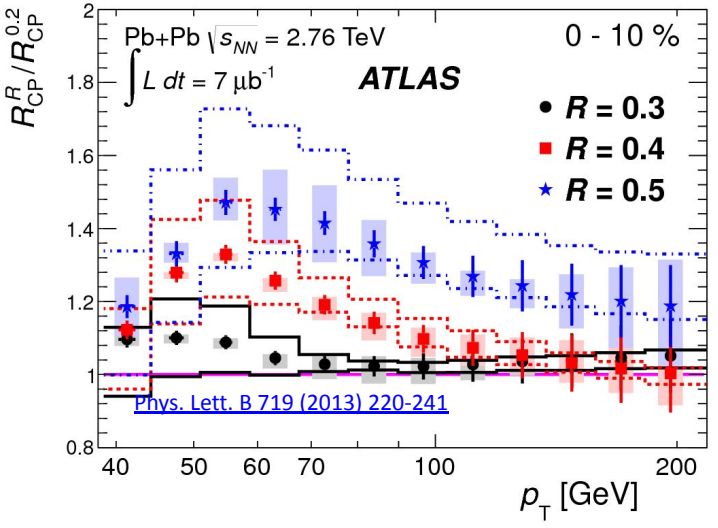


- The observation expected from theory: JHEP 0811:093,2008 and PLB 713 (2012) 224-232

Radial scan



Suggests increasing suppression for larger R.

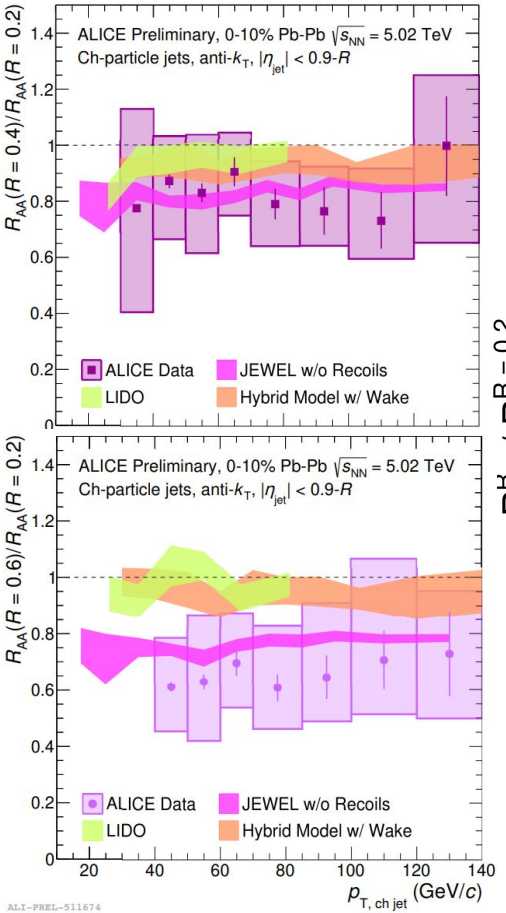


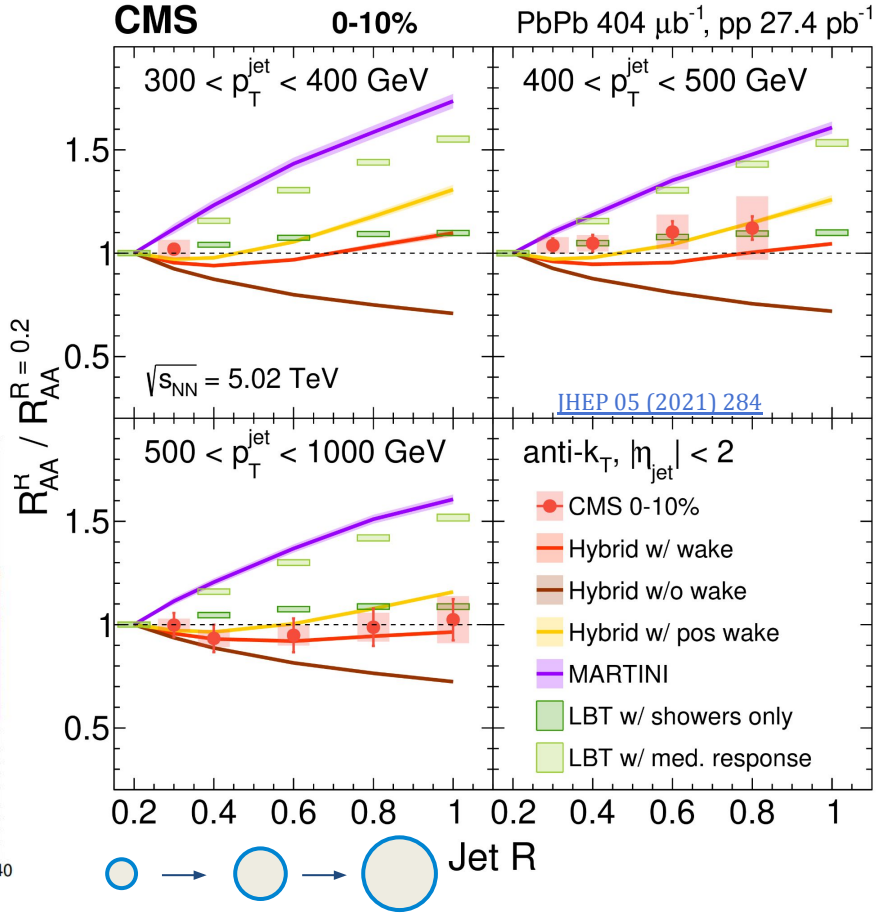
Tension with ATLAS result?

- Larger systematics
- Charged vs full jet? (3/2 in the energy scales)
- 2.76 TeV vs 5.02 TeV & slightly different phase-space can not explain the difference.
- Lower-level details & comparison is needed.

Radial scan

- Many competing effect when changing the jet size.





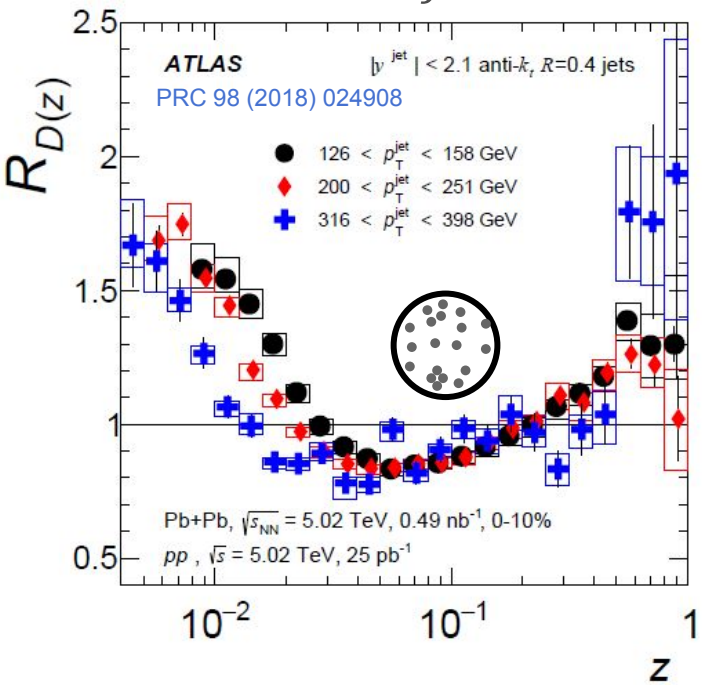
No significant R dependence at high p_T seen by CMS.

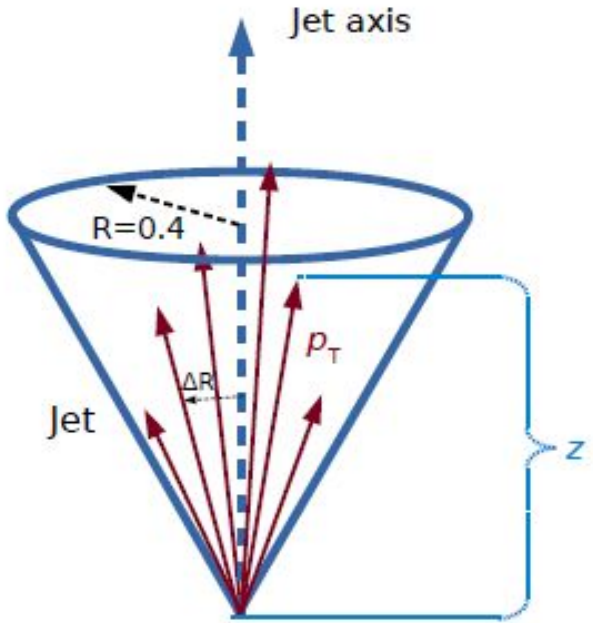
Different phase space & relatively large uncertainties.

Models going in both directions.

Jet fragmentation

Inclusive jets FF

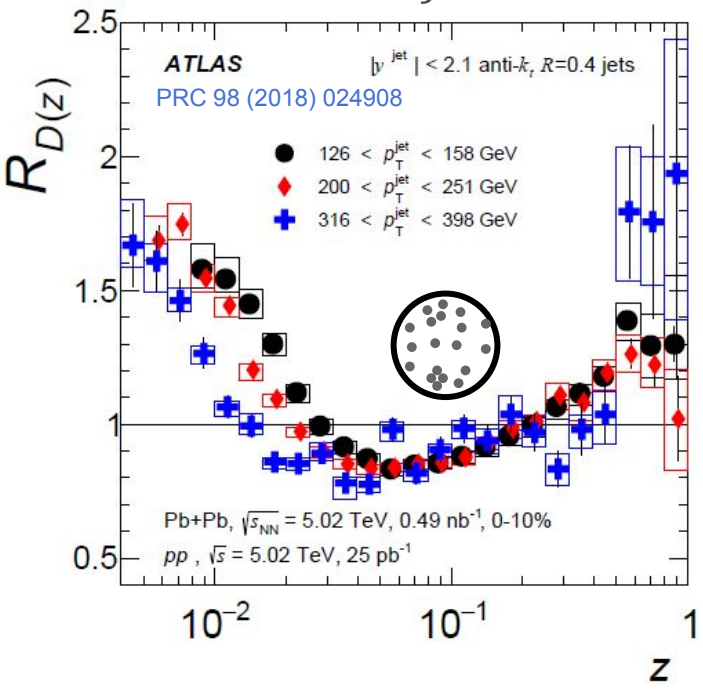




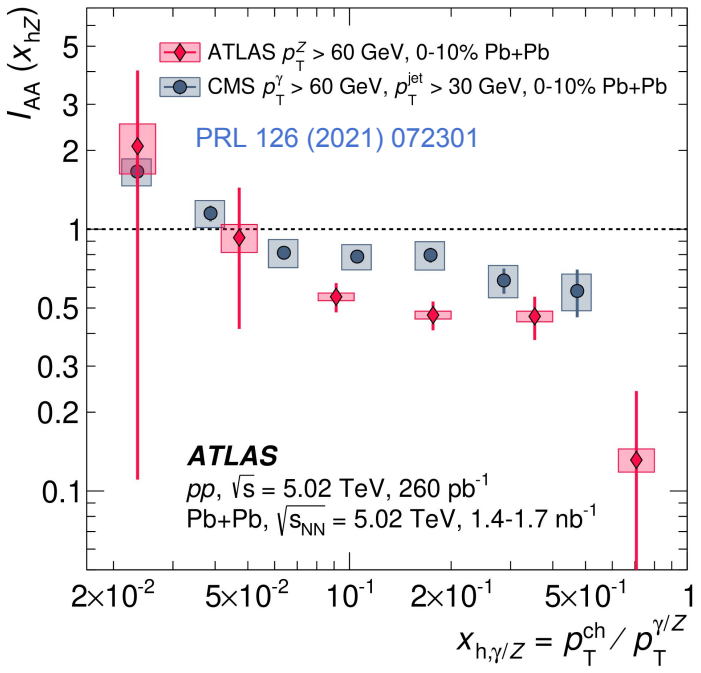
- Moving from “first generation” studies of inclusive jet fragmentation…

Jet fragmentation

Inclusive jets FF

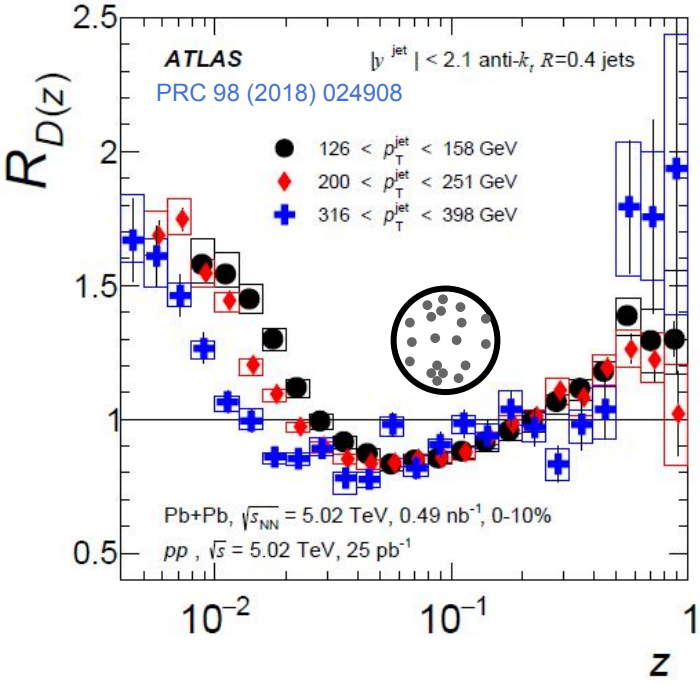


Z-tagged yields



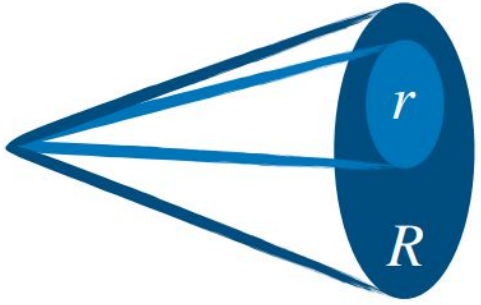
…to Z-tagged (and γ-tagged) fragmentation measurements and angular correlations (See talk by Yaxian Mao for more details)...

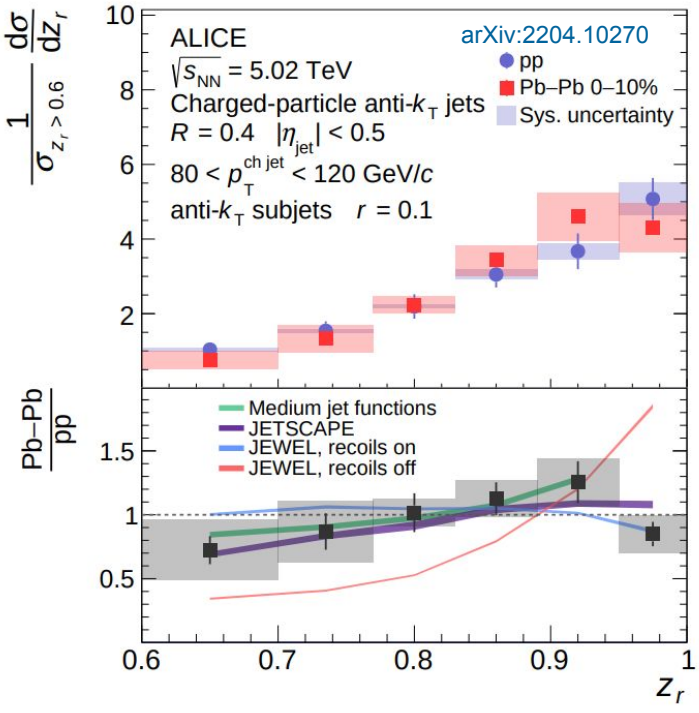
Sub-jet fragmentation



Using R=0.1 sub-jets

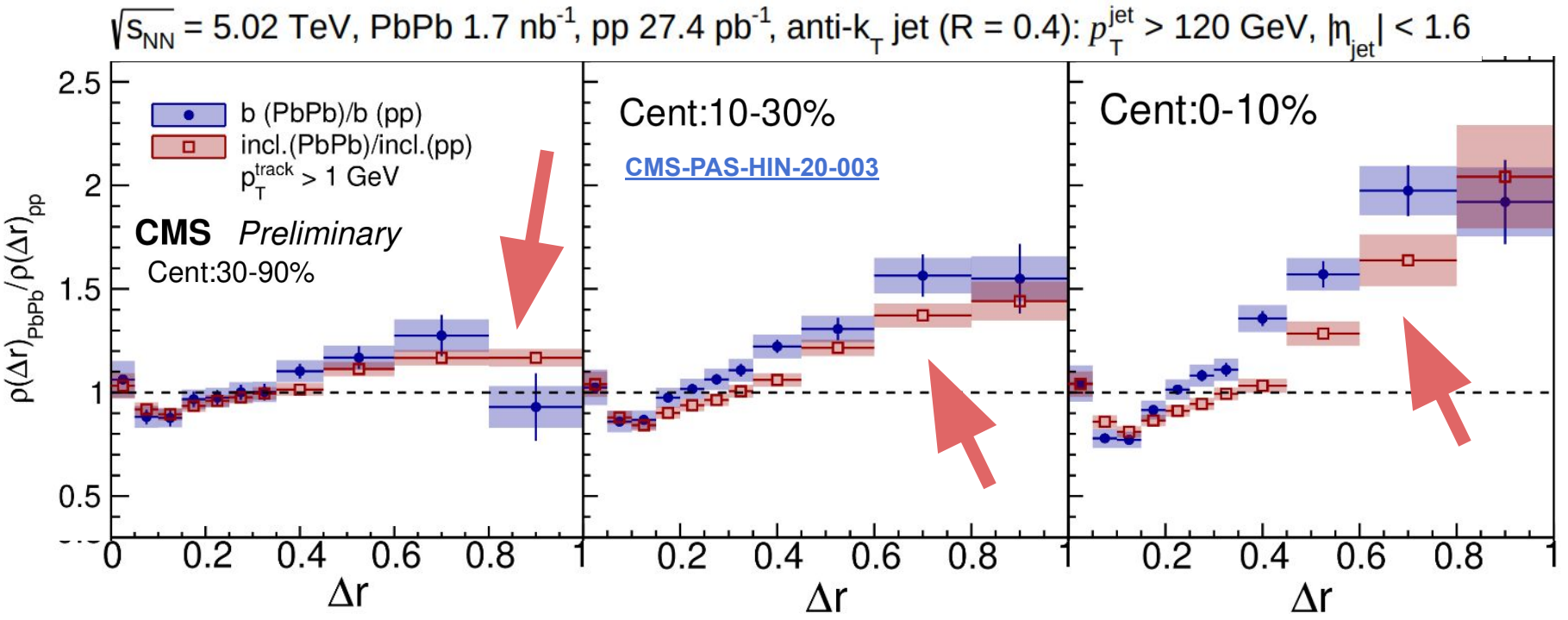
$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$





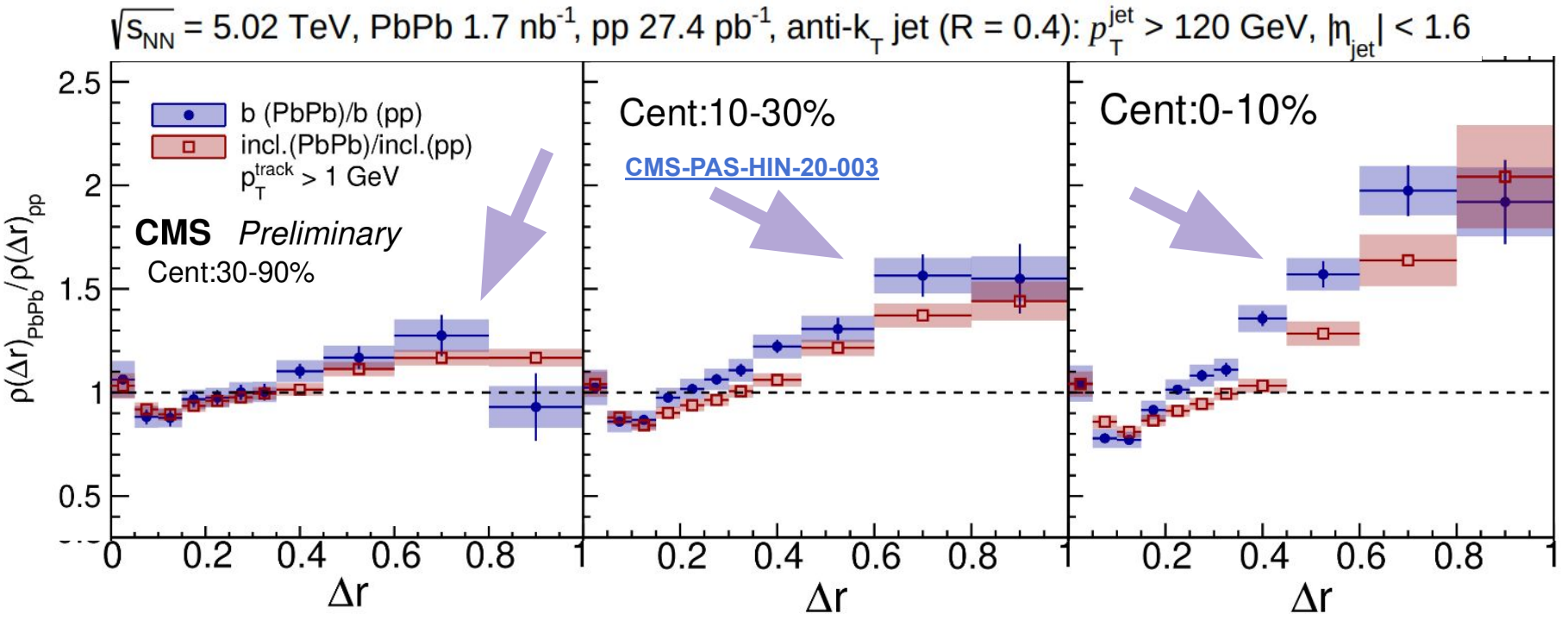
…and (almost) back since understanding the high-z might be key ingredients in our understanding of role of color charge.

Radial profile - inclusive jets



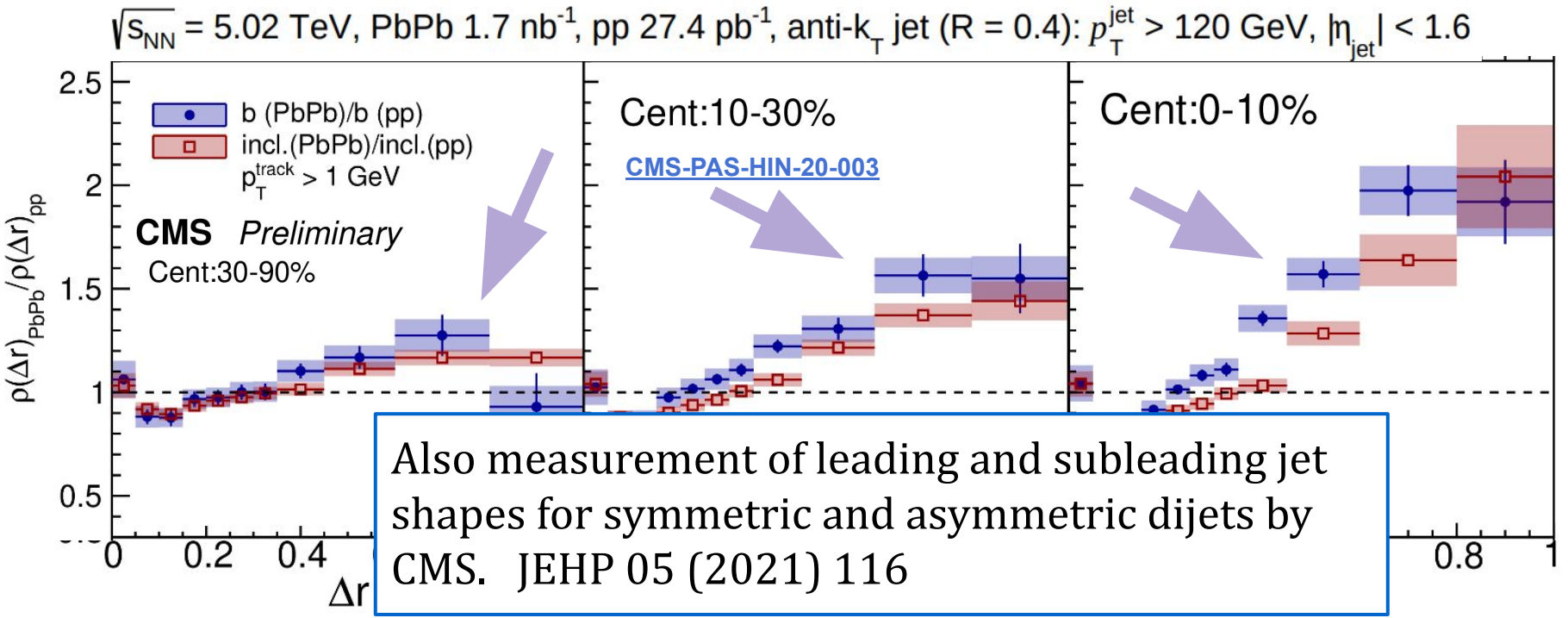
- Core largely unmodified; but jets are broader in more central Pb+Pb.
- Energy re-distributed toward and behind the jet edge in low p_T particles.
- More differential studies…

Radial profile - b-jets



- Similar pattern as for inclusive jets but quantitatively larger
- Do we see effect of flavour or mass (dead cone)?
    - Model comparison is needed.

Radial profile - b-jets



Also measurement of leading and subleading jet shapes for symmetric and asymmetric dijets by CMS. JEHP 05 (2021) 116

- Similar pattern as for inclusive jets but quantitatively larger
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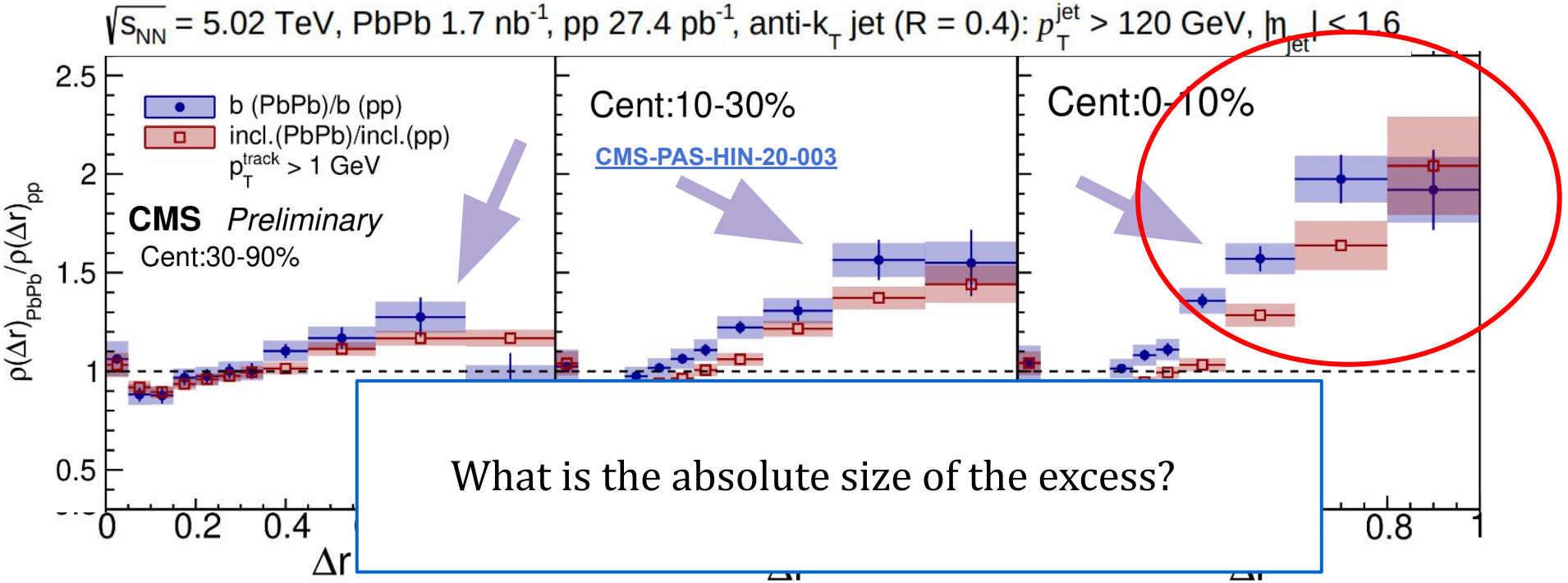
Radial profile - b-jets



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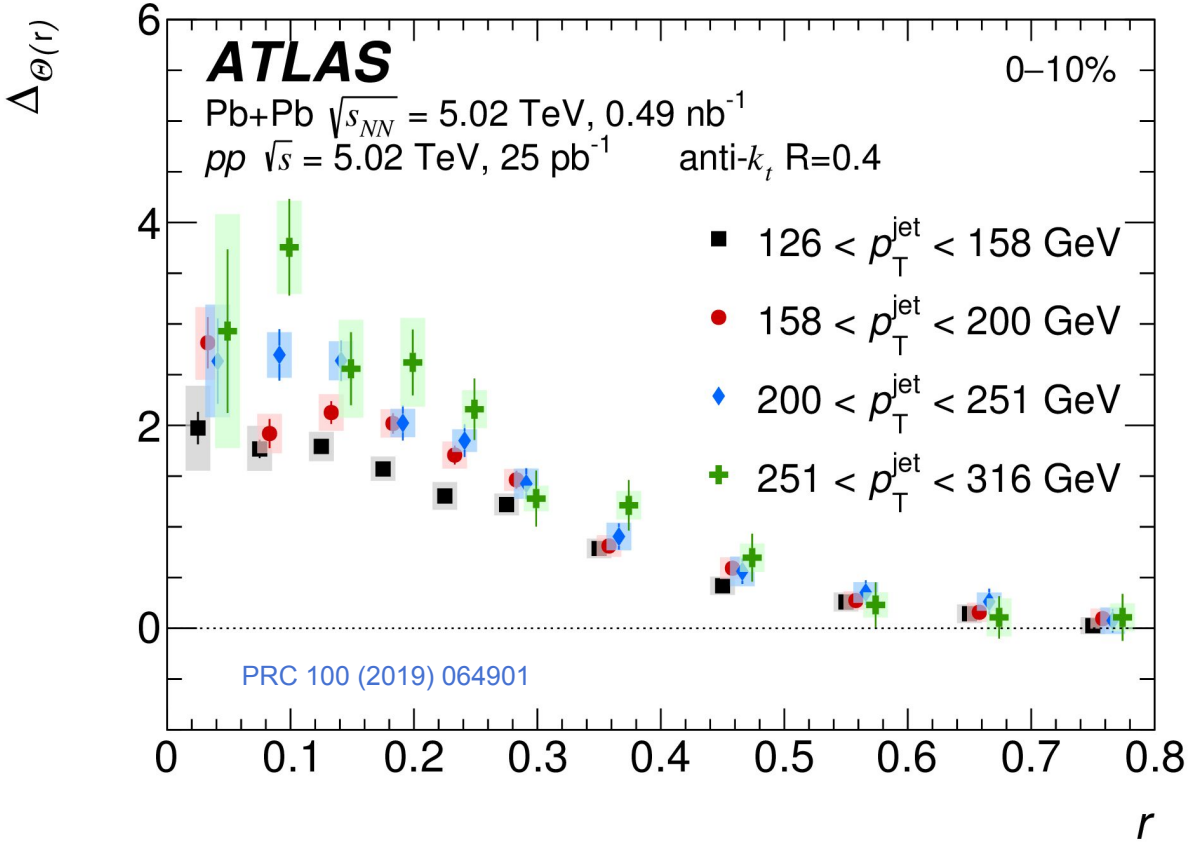
Radial profile



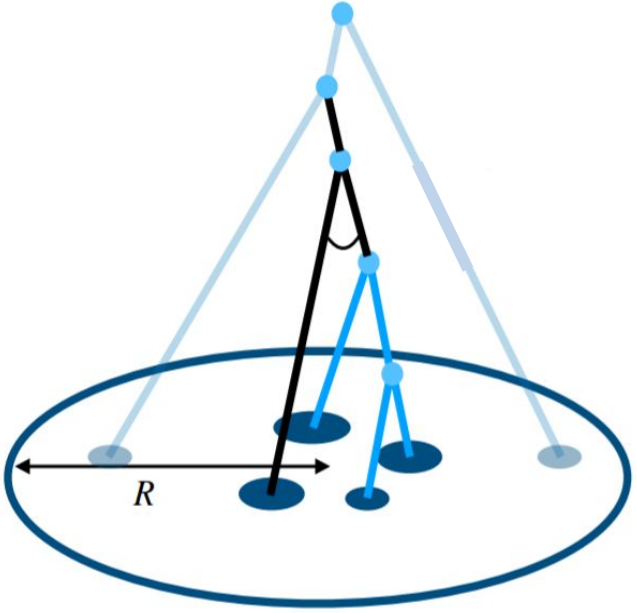
$$\Theta(r) = \int_{1\ \mathrm{GeV}}^{4\ \mathrm{GeV}} D(p_T, r)\, dp_T$$

$$\Delta_{\Theta(r)} = \Theta(r)_{\mathrm{Pb+Pb}} - \Theta(r)_{pp}$$

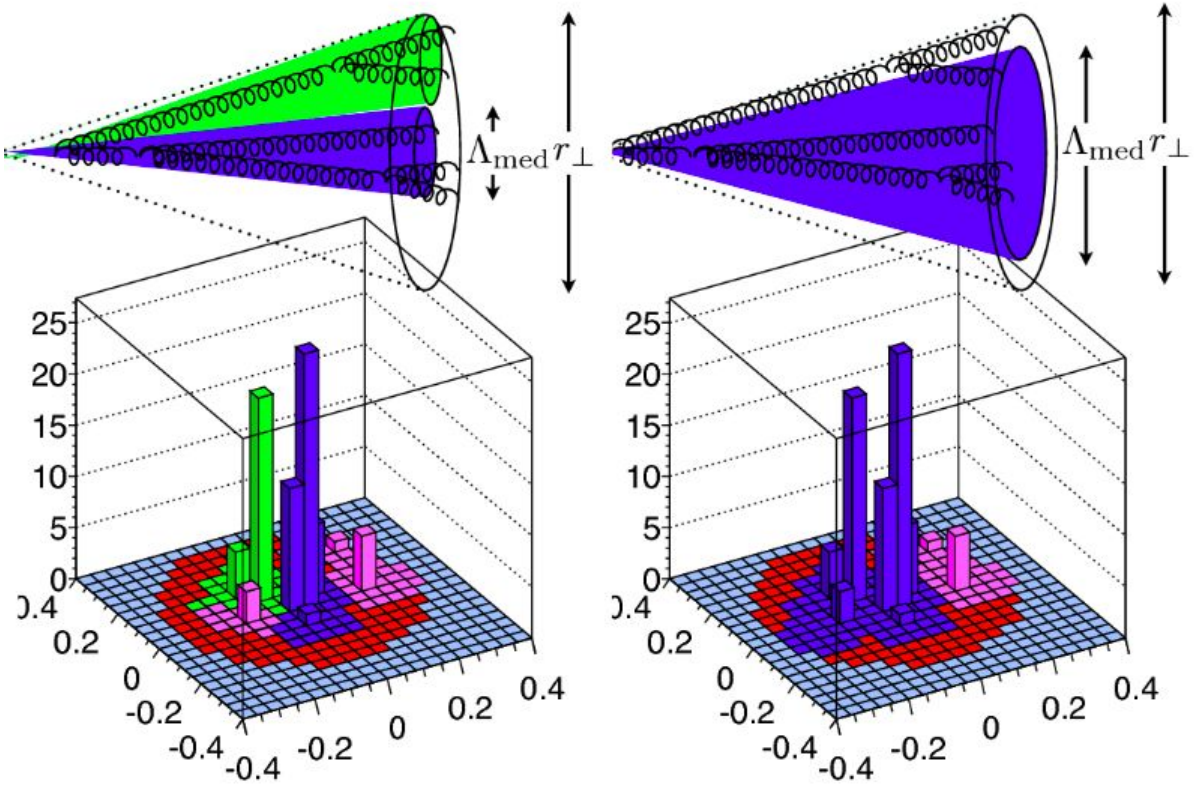
The absolute difference (#low p_T particles) is the highest inside the jet.

Can we see medium response in the jet p_T dependence?

Dependence of suppression on jet structure?



PRL 128, 102001 (2022)



J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Lett. B725 (2013) 357

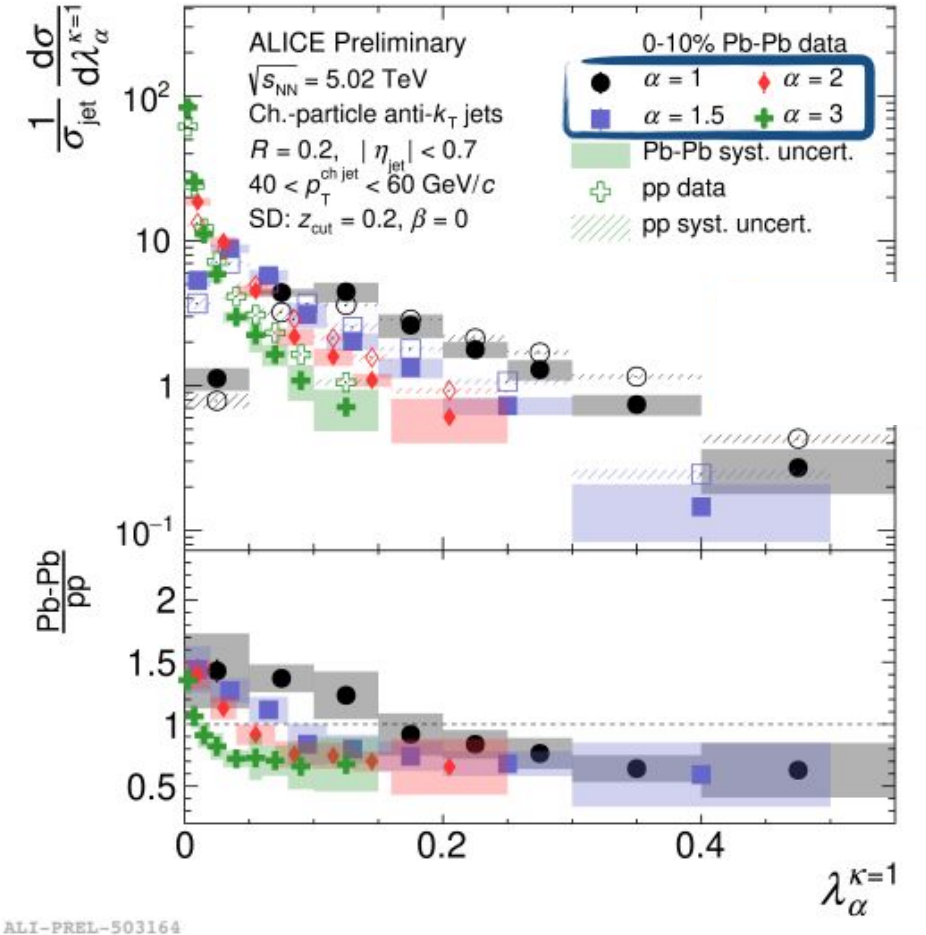
Jet angularities

$$\lambda_\alpha \equiv \sum_{i \in \text{jet}} z_i \theta_i^\alpha$$

$$z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}} \qquad \theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R}$$

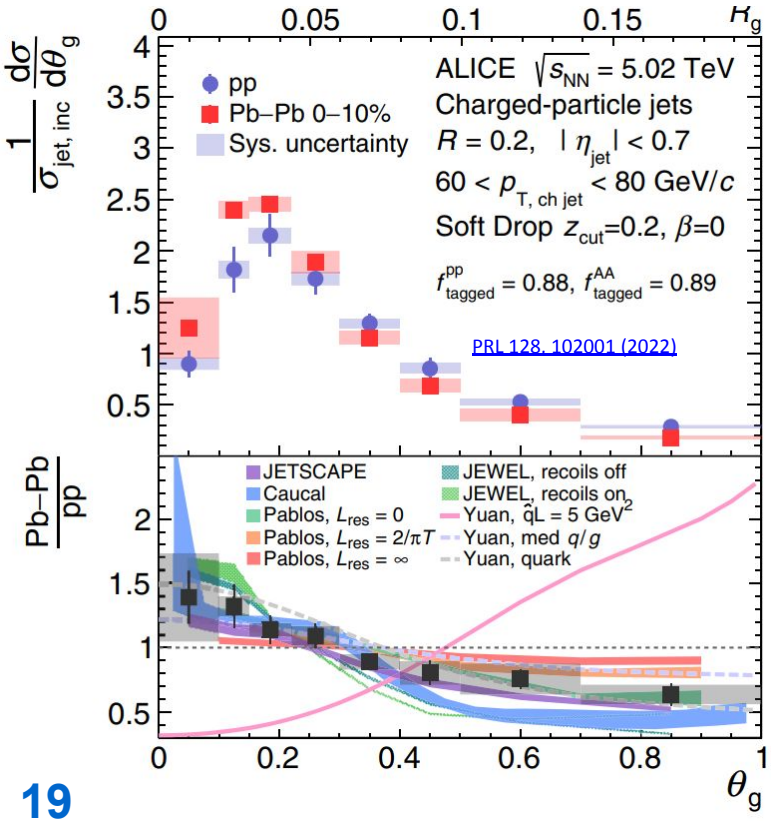
- ALICE systematic "scan" for $\alpha \in (1,3)$
  - $\alpha = 1 \Leftrightarrow$ width (girth)
  - $\alpha = 2 \sim (m/p_T)^2$

Groomed
Larger modifications in Pb+Pb wrt pp
Grooming remove in-jet broadening leaving the harder collimated part.
Ungroomed shows smaller modifications



Classifying parton splittings

- Focusing on hard substructure…
  → Study the modification to radiation pattern.

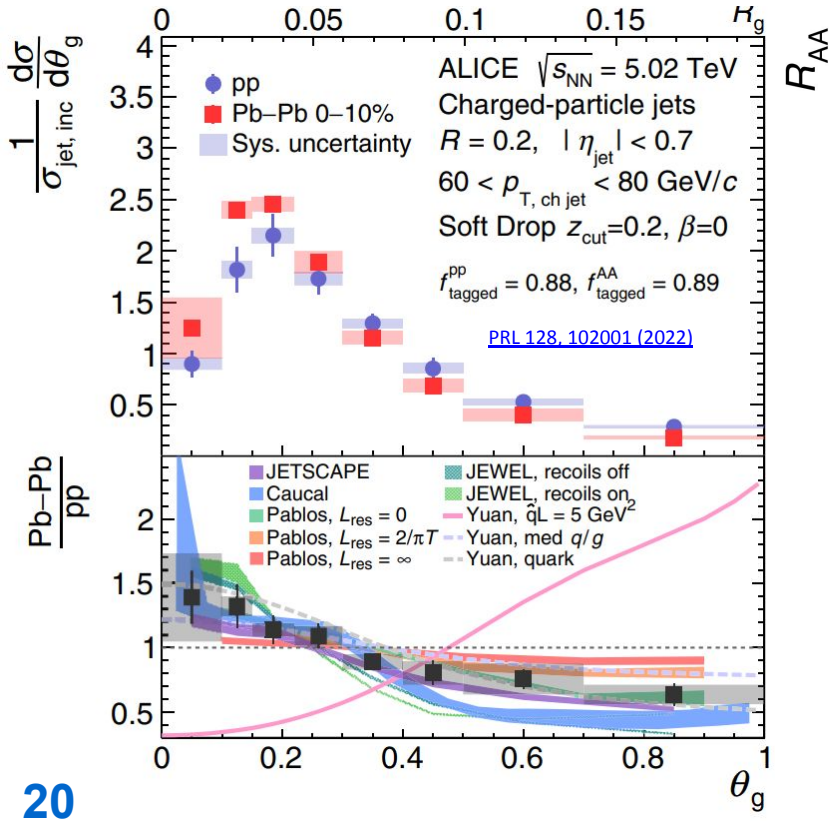


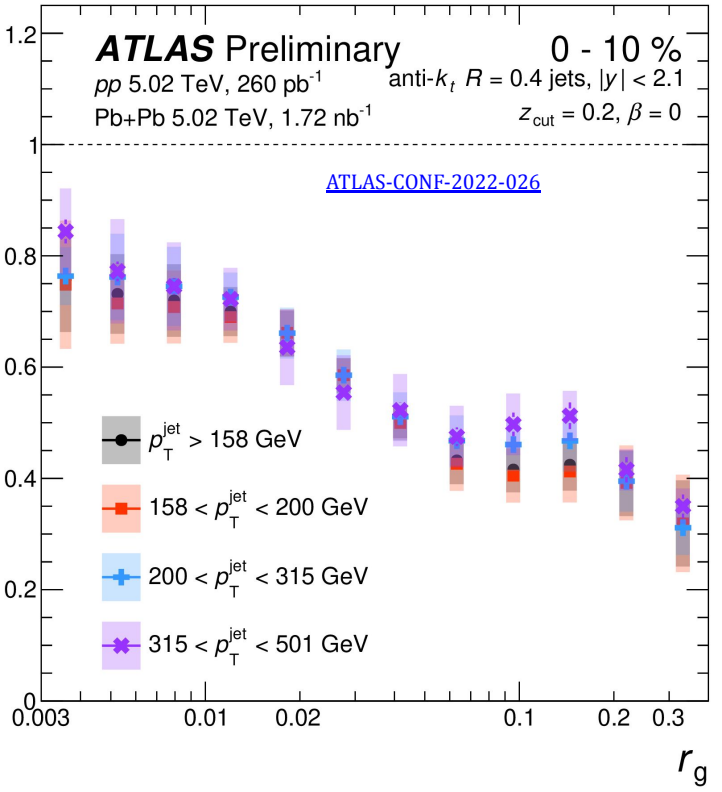
$$\theta_g = \frac{\Delta R_{1,2}}{R}$$

Jet narrowing
Selection bias?

Suppression vs parton splittings

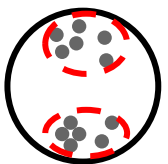
- Moving from per-jet -normalized to absolutely normalized measurement.
  → Role of jet structure in the supression process.





Strong dependence of jet suppression on r_g.

How can we understand the r_g dependence?

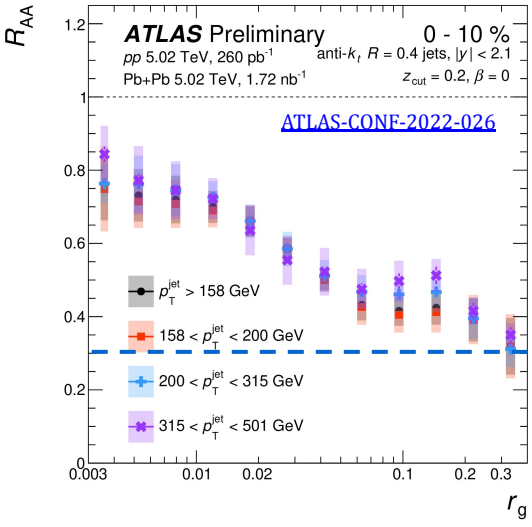


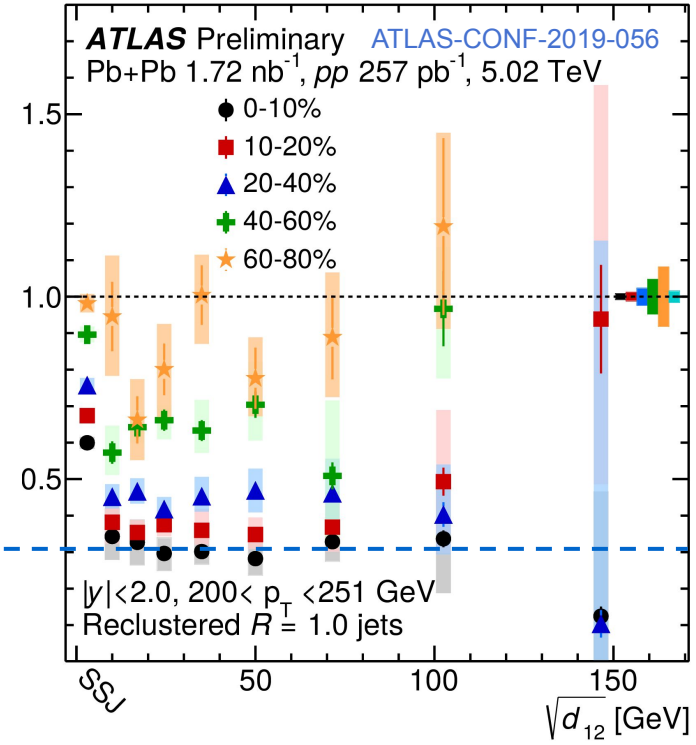
Suppression vs parton splittings

- Addressing transition from color-coherence to decoherence…

$$r_g = \theta_g = \frac{\Delta R_{1,2}}{R}$$

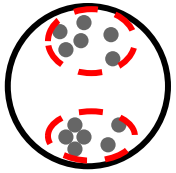
$r_g > \sim 0.2$



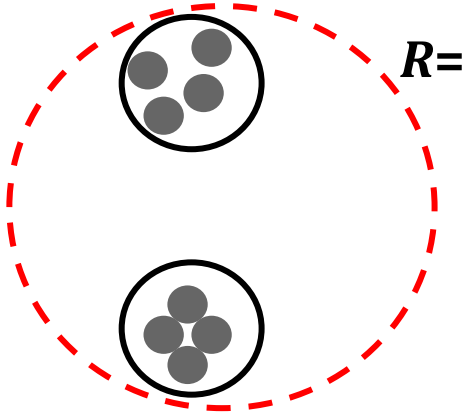


$$\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$$

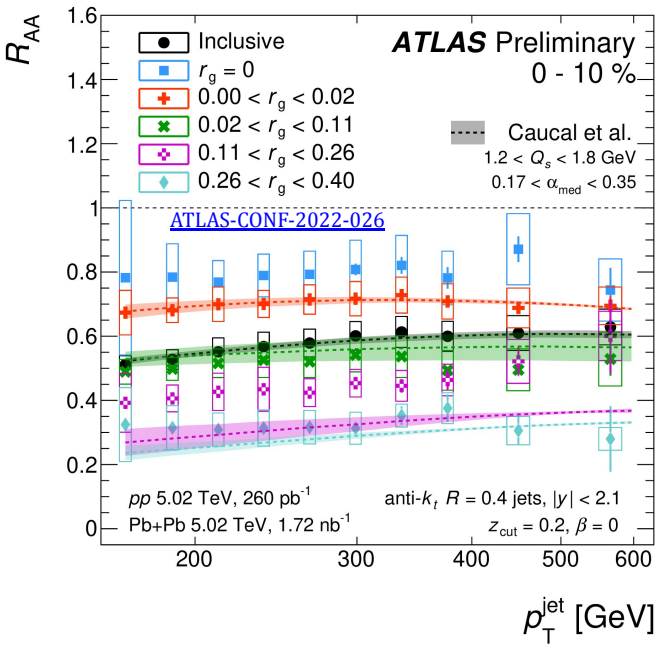
R=0.4

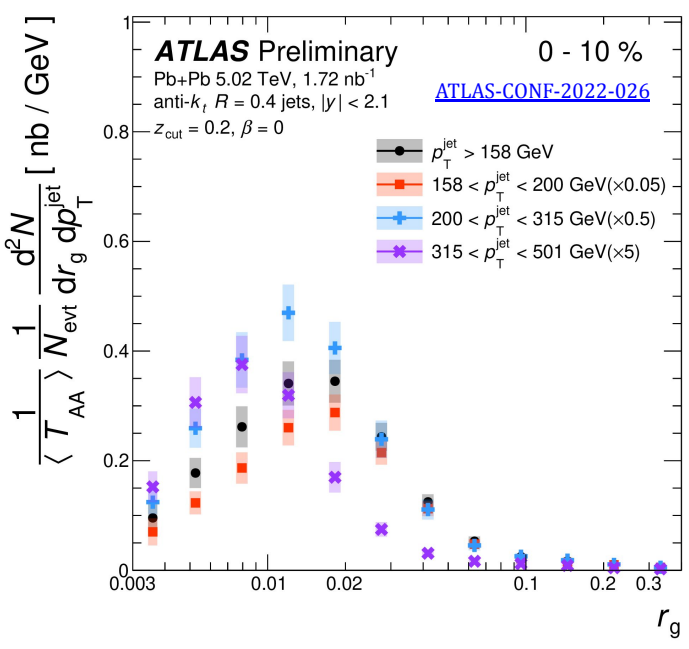


R=1.0



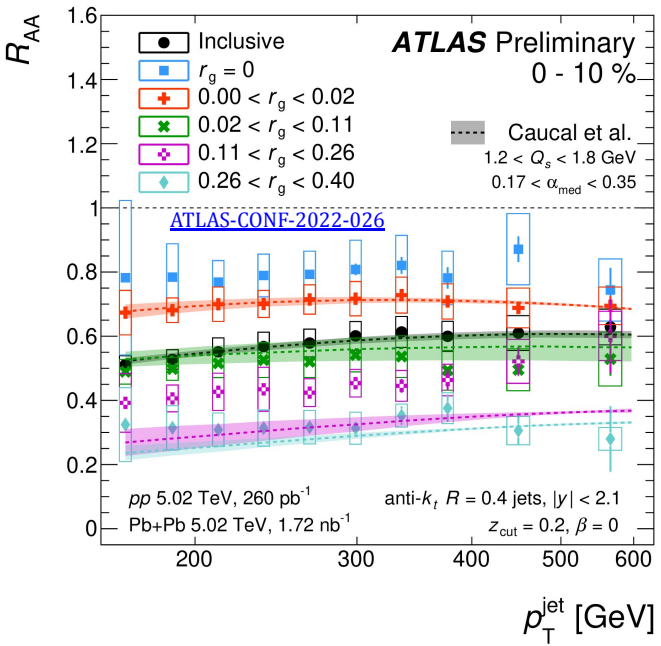
Suppression vs parton splittings

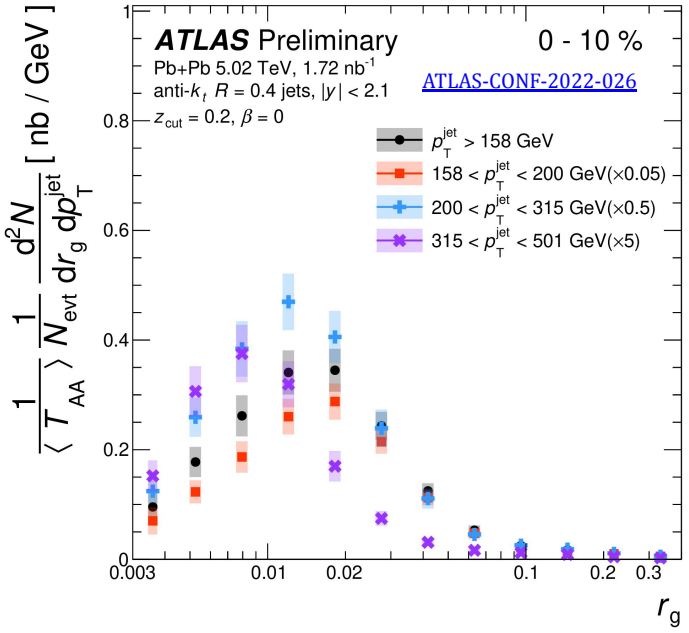


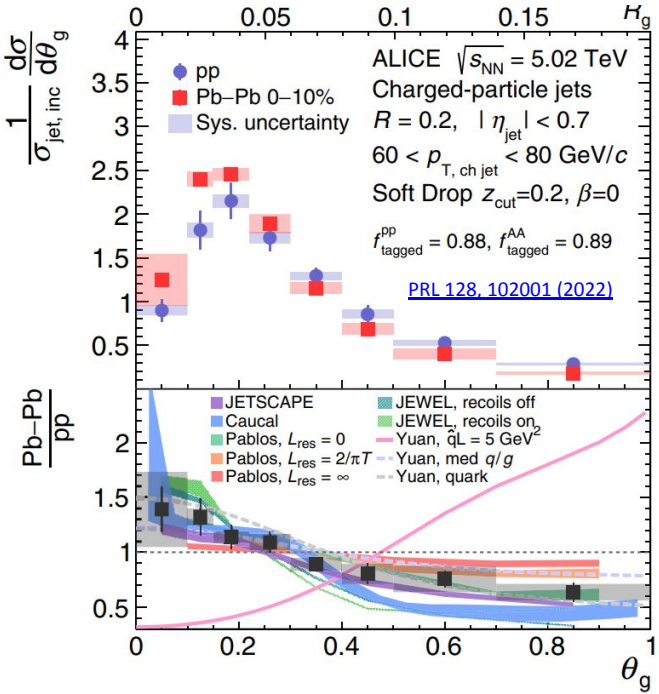


Lack of p_T dependence for R_{AA} for jets with similar structure + rise of inclusive $R_{AA} \Leftrightarrow p_T$ dependence to r_g.

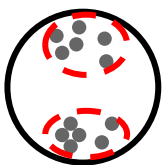
Classifying parton splittings





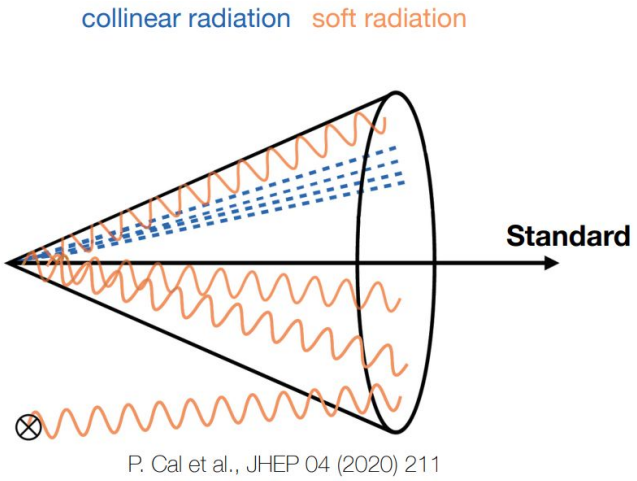


Lack of p_T dependence for R_{AA} for jets with similar structure + rise of inclusive $R_{AA} \Leftrightarrow p_T$ dependence to r_g.
More quantitative comparison between experiments is needed.



Jet acoplanarity

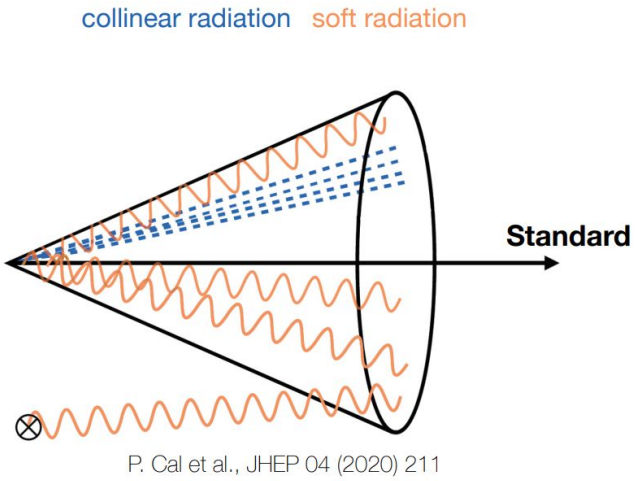
- Observable: angle between different jet axis:
  - Standard ungroomed axis



P. Cal et al., JHEP 04 (2020) 211

Jet acoplanarity

- Observable: angle between different jet axis:
  - Standard ungroomed axis
  - Groomed axis



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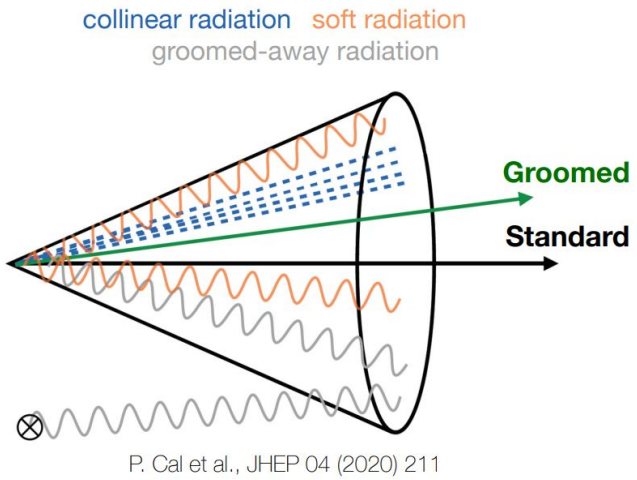
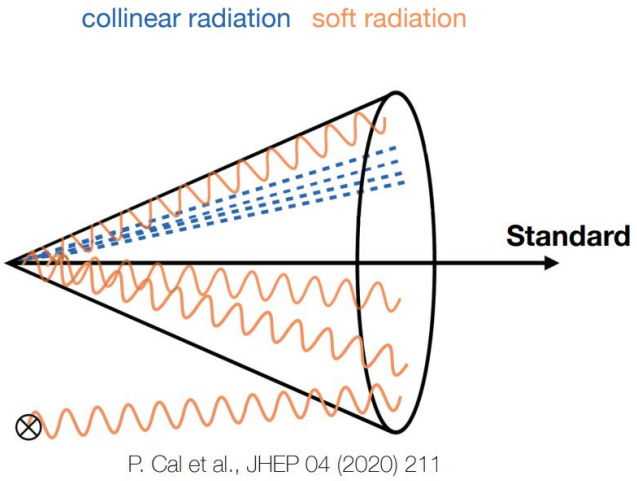


P. Cal et al., JHEP 04 (2020) 211

Jet acoplanarity

- Observable: angle between different jet axis:
  - Standard ungroomed axis
  - Groomed axis
  - The direction aligned ~with the hardest particle, "winner take all" (WTA)



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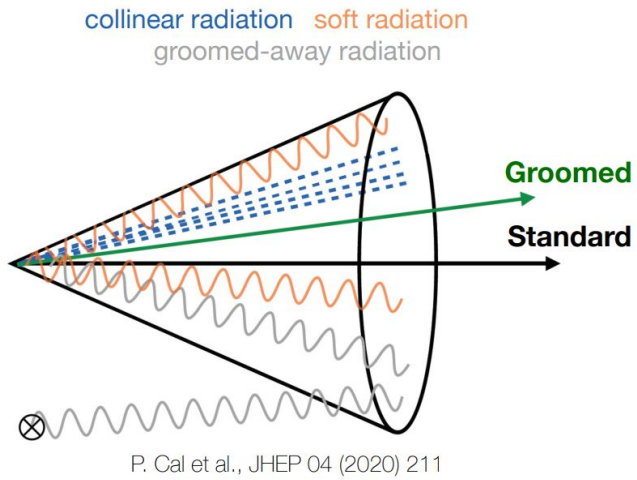
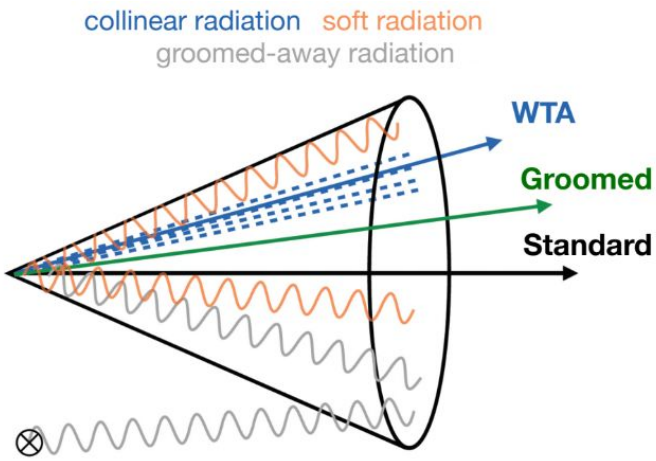


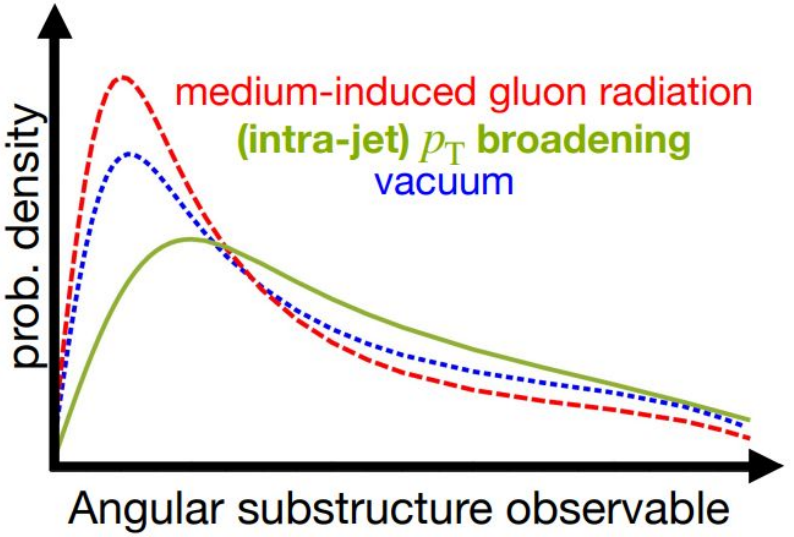
P. Cal et al., JHEP 04 (2020) 211



JHEP 04 (2020) 211

Jet acoplanarity

- Allows to study interplay between competing effects
  - Medium-induced gluon radiation
  - Multiple-scatterings-like (intra-jet) p_{T} broadening
- What is the effect of grooming?



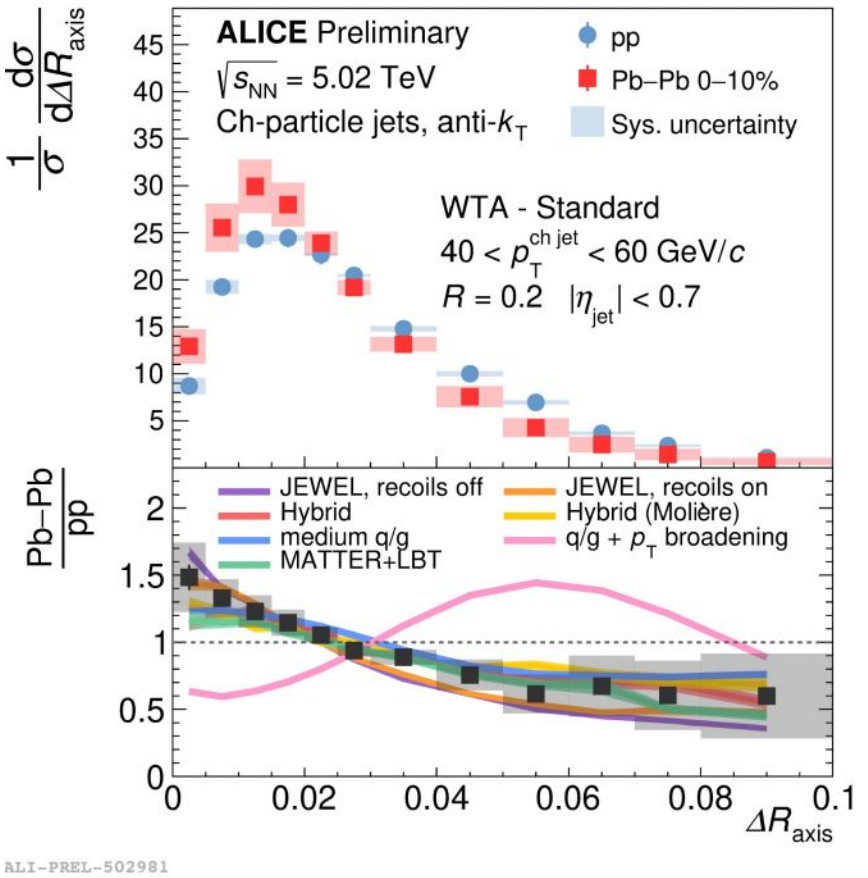
Ringer et al., PLB 808 (2020) 135634

Jet accoplanarity

- Allows to study interplay between competing effects
  - Medium-induced gluon radiation
  - Multiple-scatterings-like (intra-jet) p_{T} broadening
- What is the effect of grooming?

Overall no sensitive to grooming

Similar trend of narrowing as in other measurements.

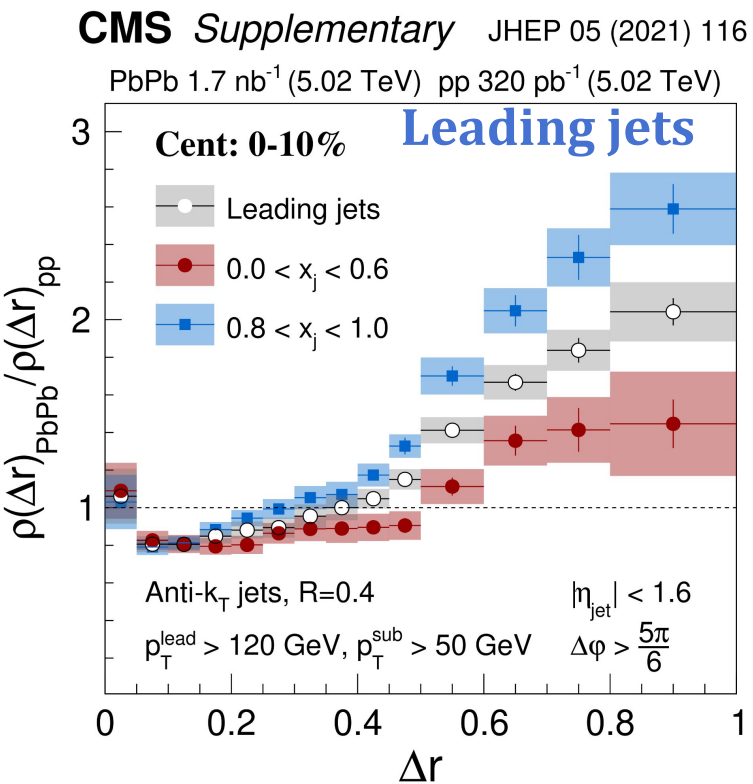


Summary

- **Jet substructure in HI is a rapidly developing area (and growing)… so exciting that many topics/results are not covered in this talk.**
  - Many new measurements → strong constraint on hypothesis about jet energy loss.
  - Experimental methods based on simulations for calibration & training → need for advances of MC modelling.
  - More & new data will allow precise EW boson-tagged measurements, study boosted tops, Z, W.
- **Main questions to be followed:**
  - Resolve tension in some measurements.
  - Isolate effects of color-charge, coherence, and medium response.
  - Quenching in small system? Substructure has potential to help.

Backup

Radial profile - leading/sub-leading

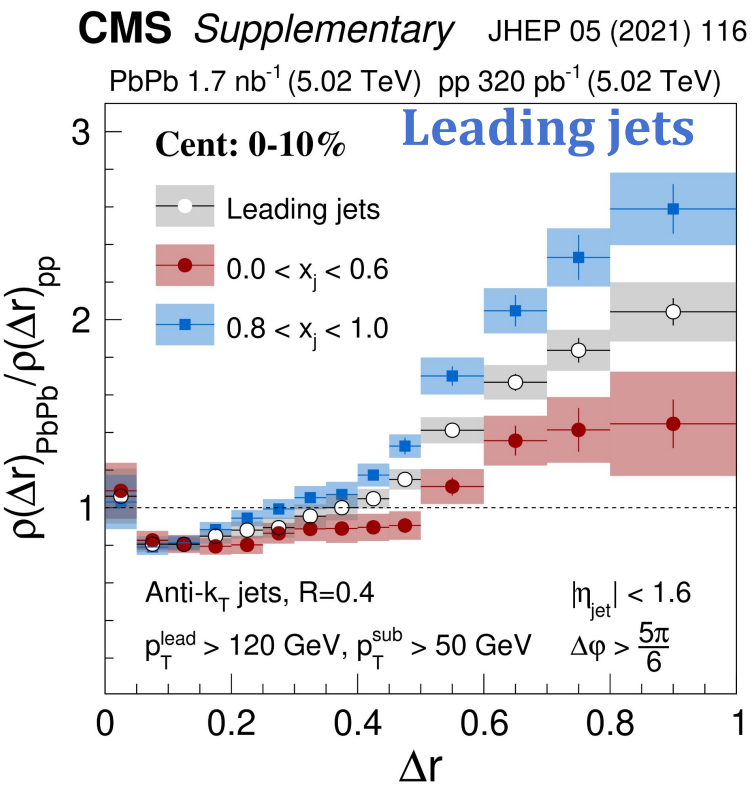


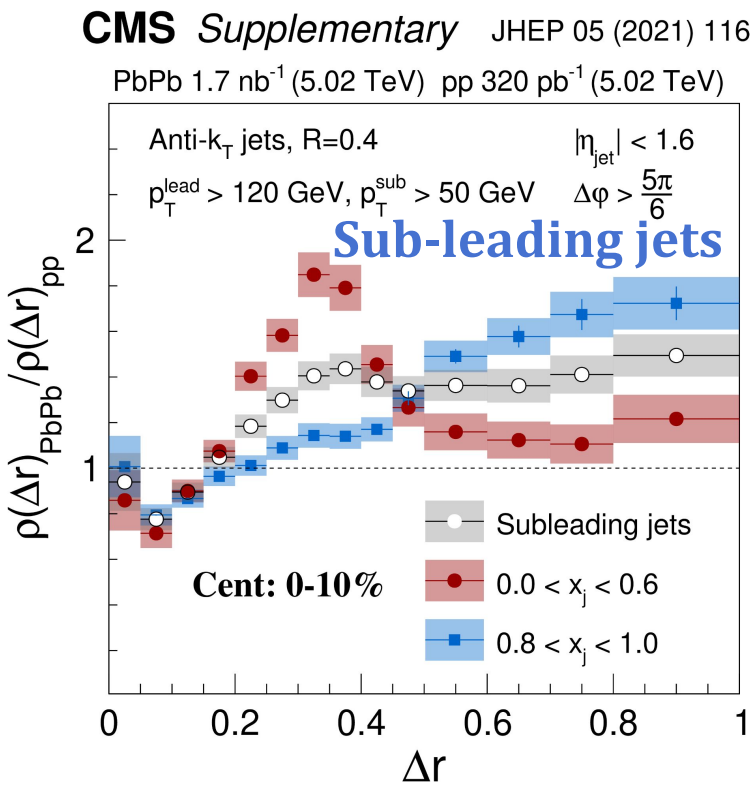
$$P(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{jets}}\Sigma_{jets}\Sigma_{tracks\in(\Delta r_a,\Delta r_b)}p_T^{ch}$$

$$\rho(\Delta r) = \frac{P(\Delta r)}{\Sigma_{jets}\Sigma_{tracks\in\Delta r<1}p_T^{ch}}$$

- Higher modifications of leading jet in balanced events ⇔ path-length dependence.

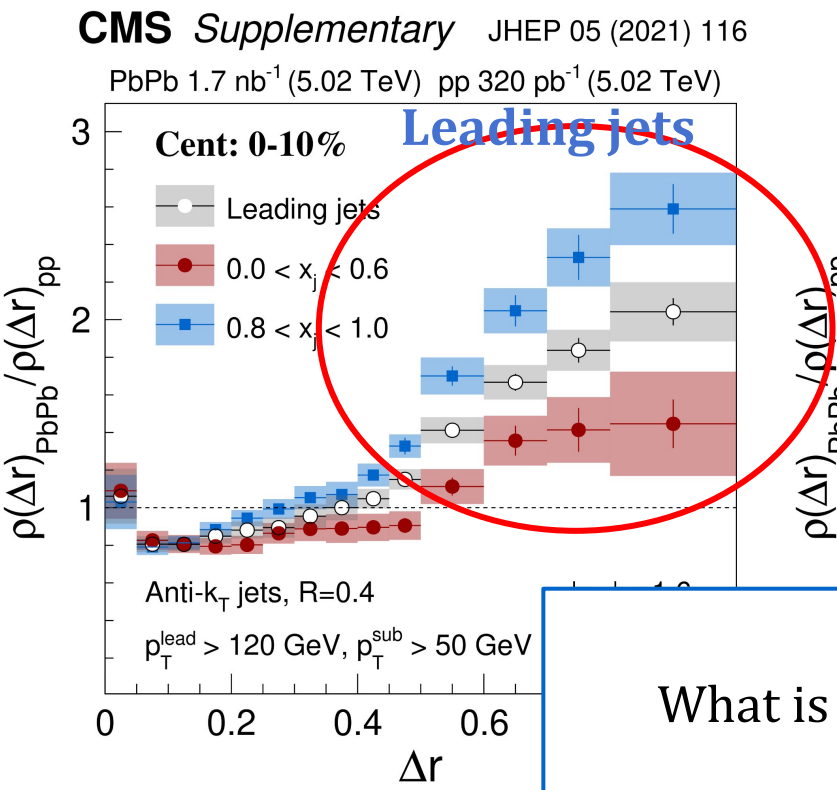
Radial profile - leading/sub-leading

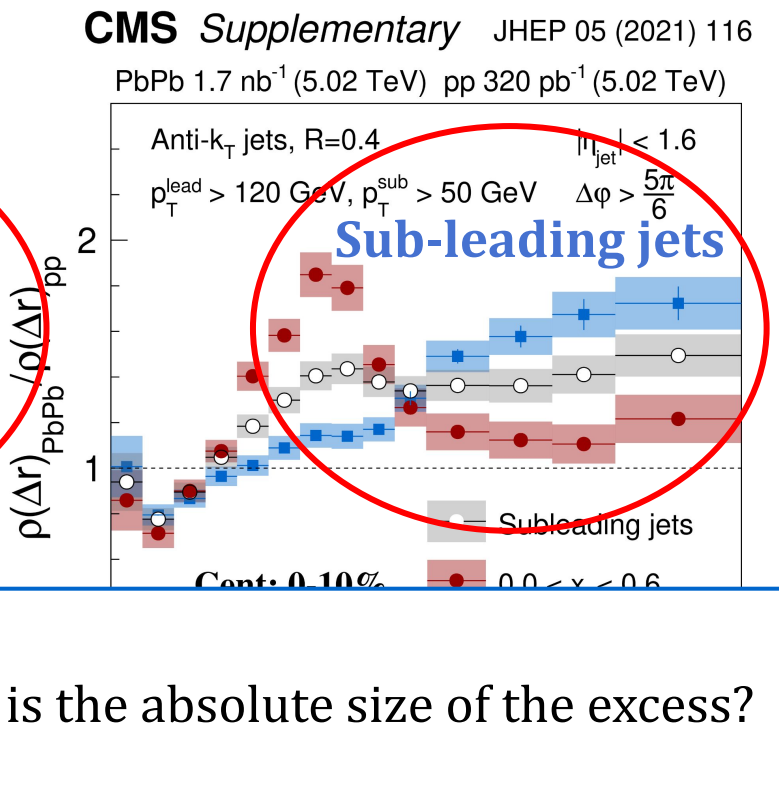




- Higher modifications of leading jet in unbalanced events
  - Drop expected from 3-jet event contribution in reference.

Radial profile - leading/sub-leading





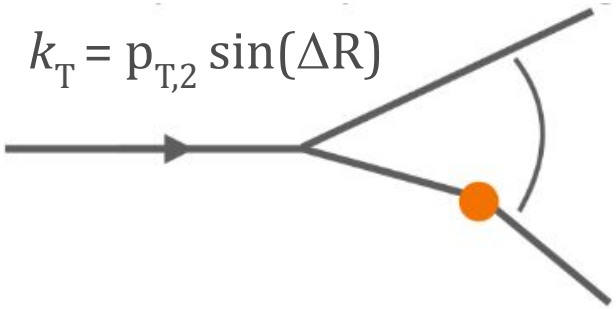
What is the absolute size of the excess?

- Higher modifications of leading jet in unbalanced events
  - Drop expected from 3-jet event contribution in reference.

Search for point like scattering using k_T

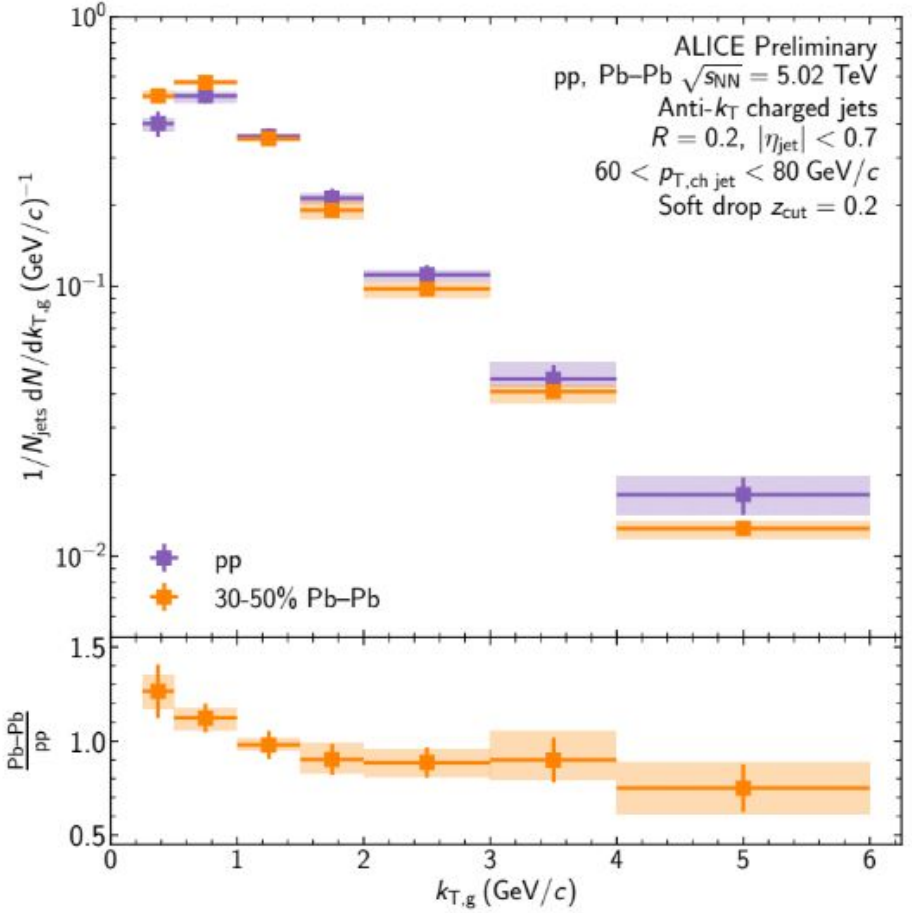
- Is there enhancement of large k_T splittings in Pb+Pb wrt pp?

$k_T = p_{T,2} \sin(\Delta R)$



- Using SoftDrop (dynamical grooming tested)

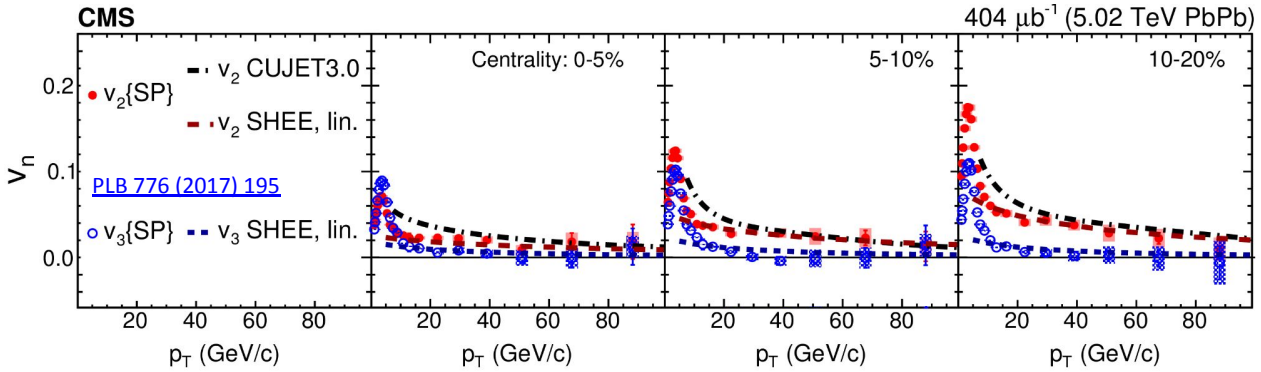
No modification at large k_T.
Hints of enhancement at low k_T.

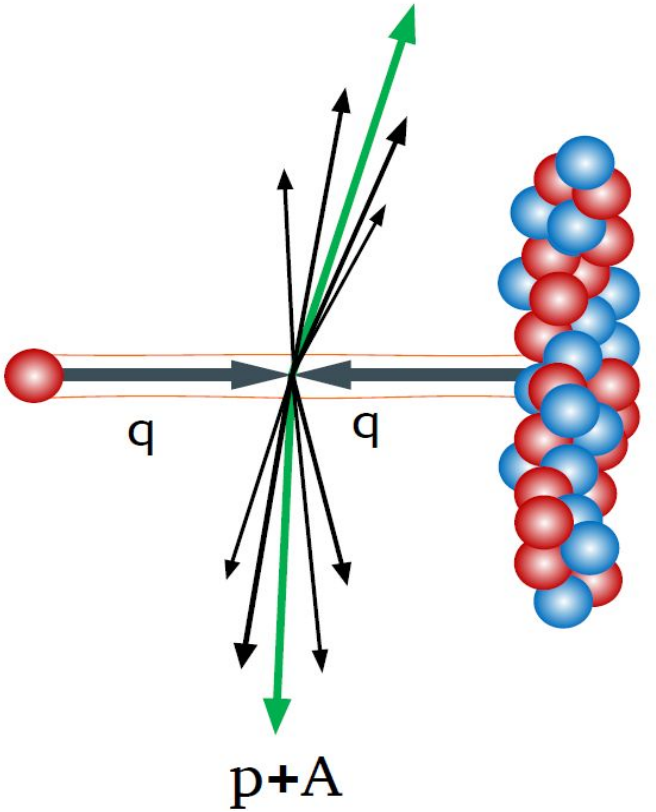


Talk by Hannah Bossi

Looking for jet quenching in small systems

- QGP signatures like (high) p_T flow seen in small systems.

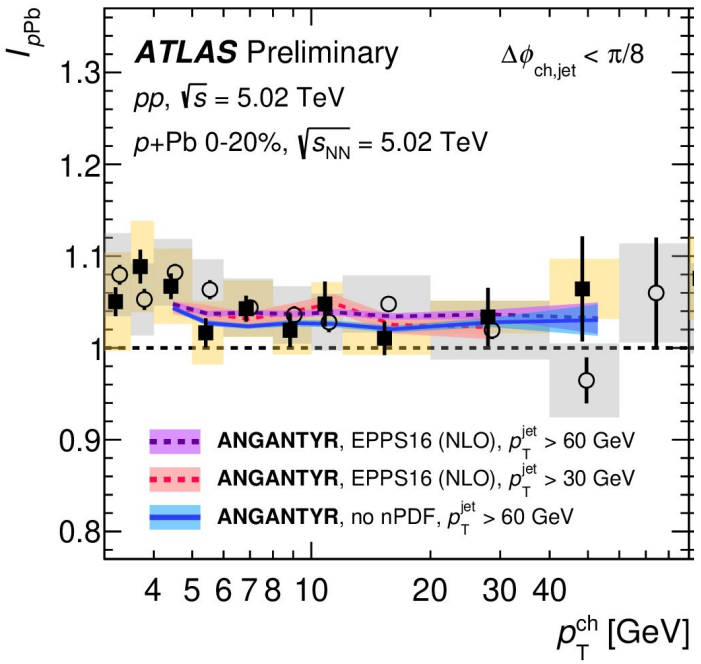


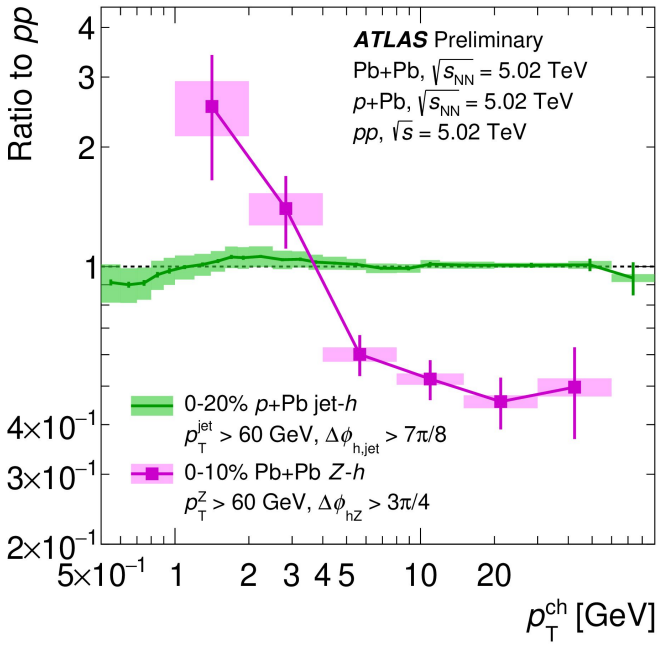


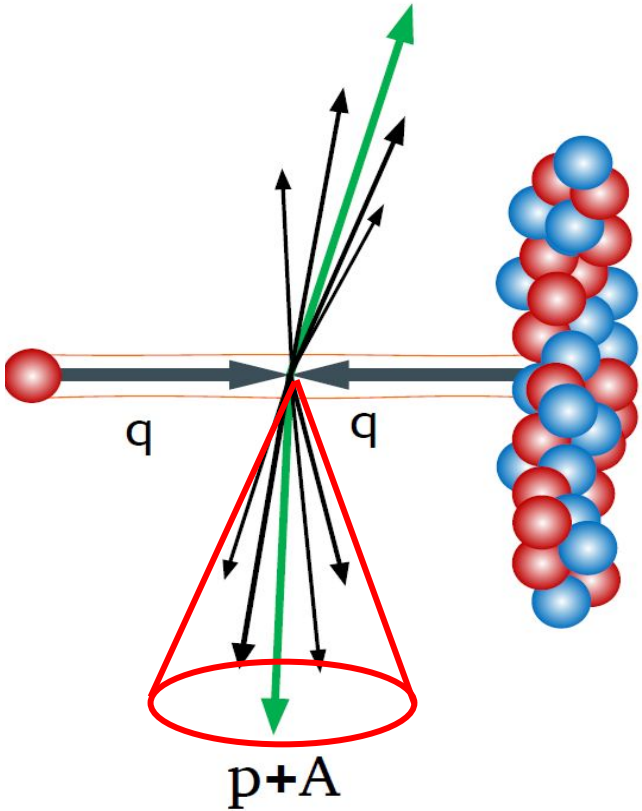
- Inclusive full jet measurements put limits on quenching → dominated by systematics uncertainties.
- Using jet substructure:
  - Per-jet quantities remove scaling uncertainties.
  - Need for robust centrality definition.

Looking for jet quenching in small systems

- Charged hadron yields within a jet:



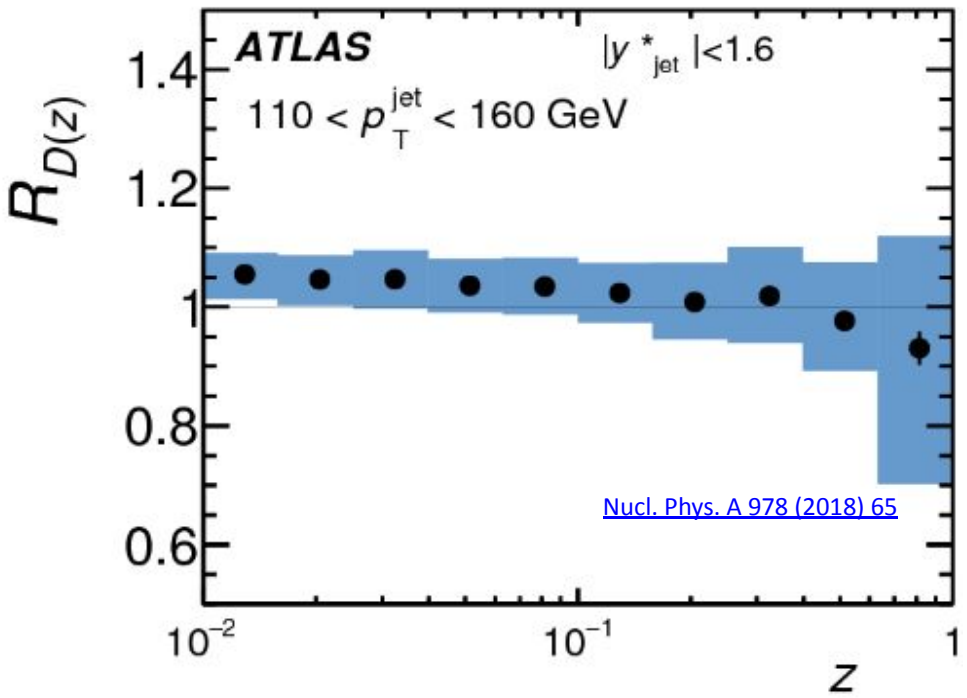


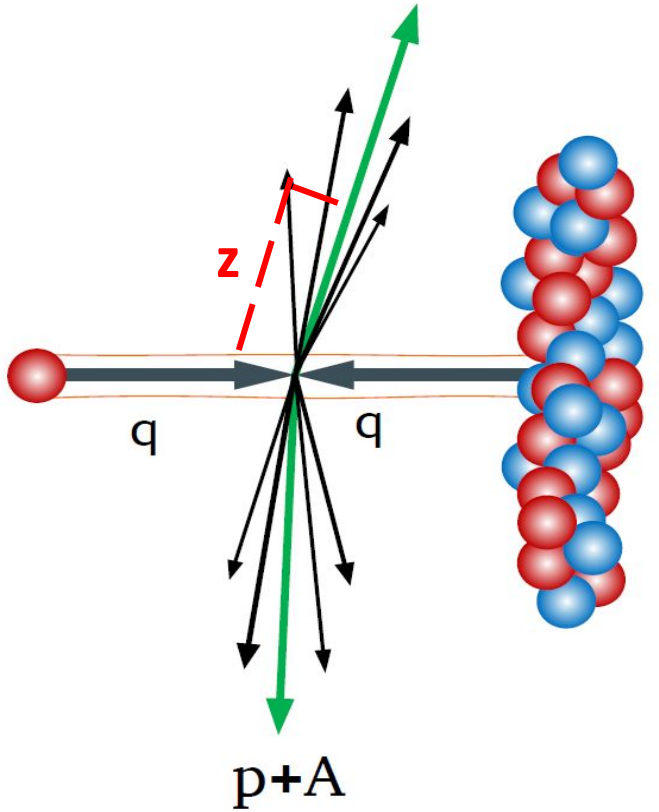


- Overall small excess but can be described without quenching.

Looking for jet quenching in small systems

Ratios of fragmentation functions in *p*+Pb and *pp*:

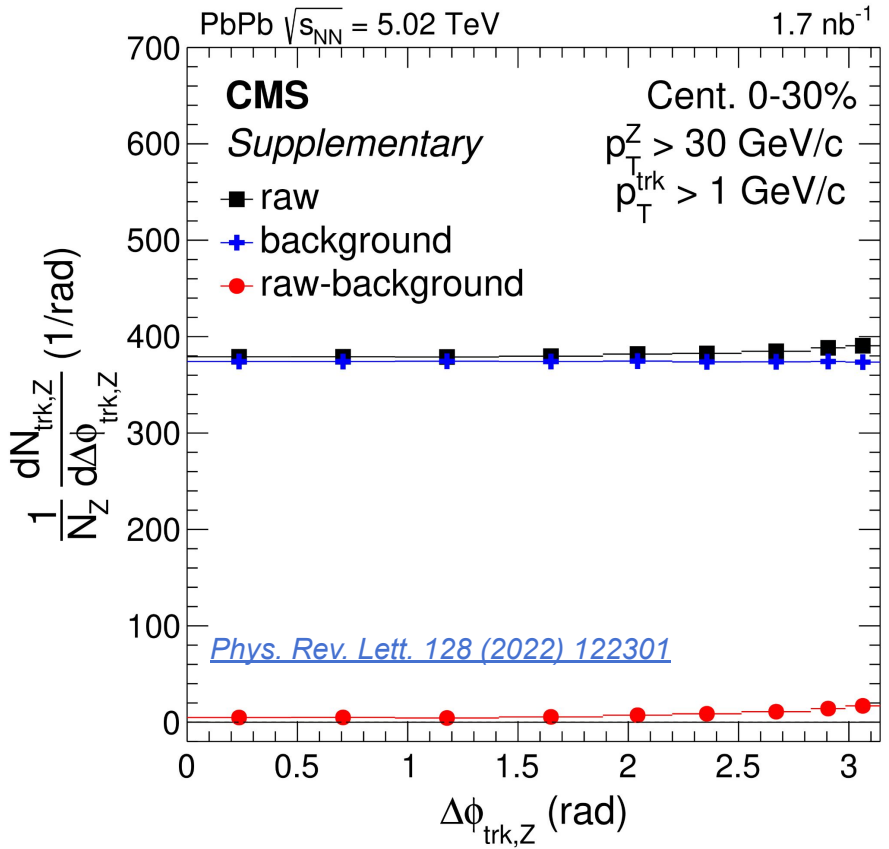




- No modification of parton shower is observed in *p*+Pb system.

Challenges in jet structure measurements

- **Push towards larger phase space: lower energy and various/larger radius.**
- Large UE contribution from soft particles.
- Combinatorial background from independent hard scatterings.
- For calorimetric measurement:
  - Jet energy calibration and uncertainties for every new jet "collection".... different radius, subjects, and constituents.



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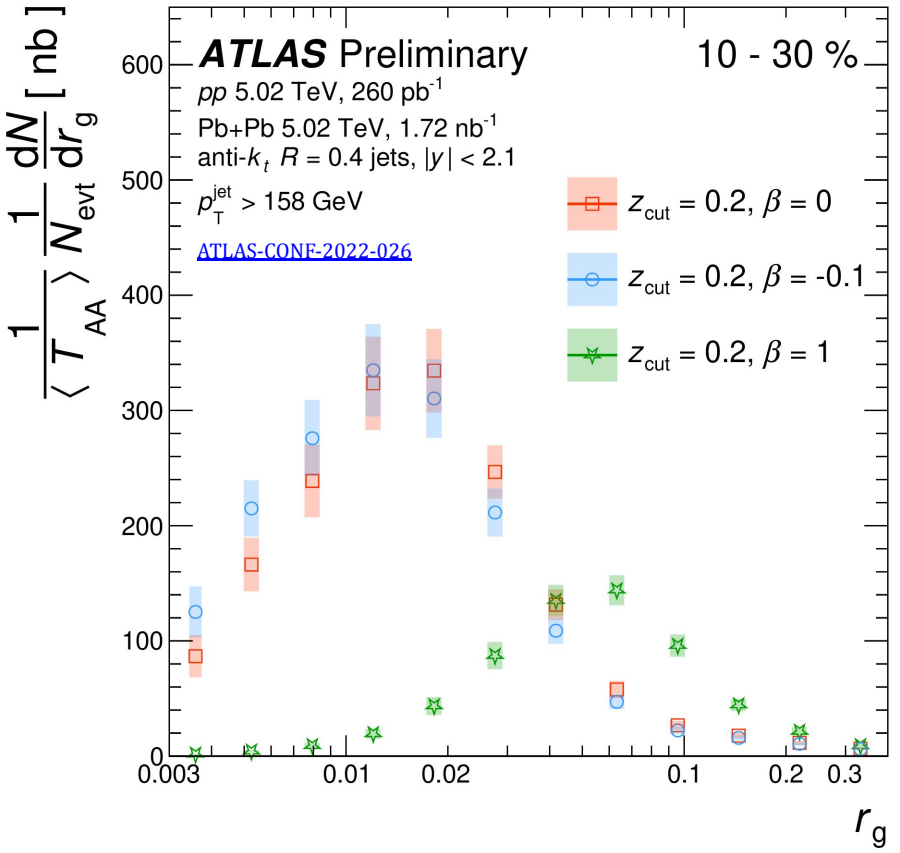
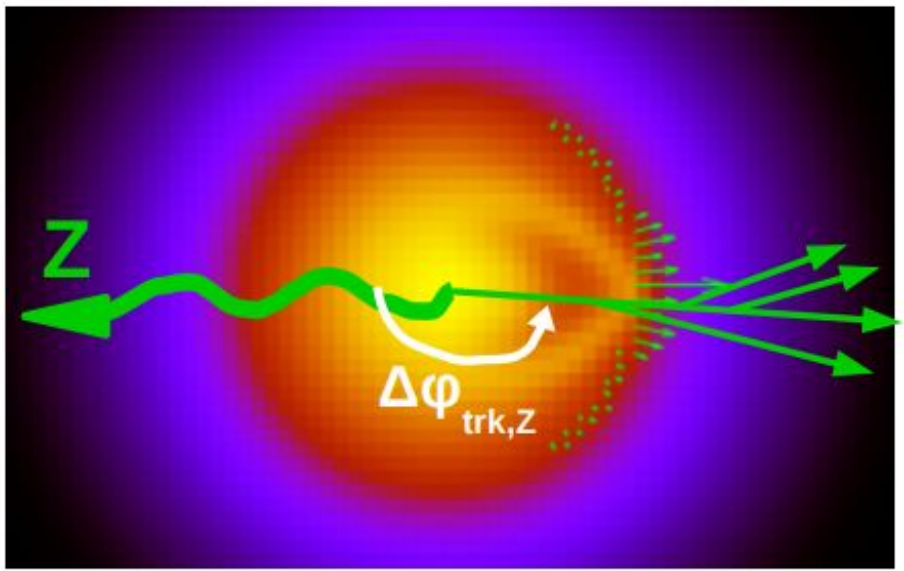
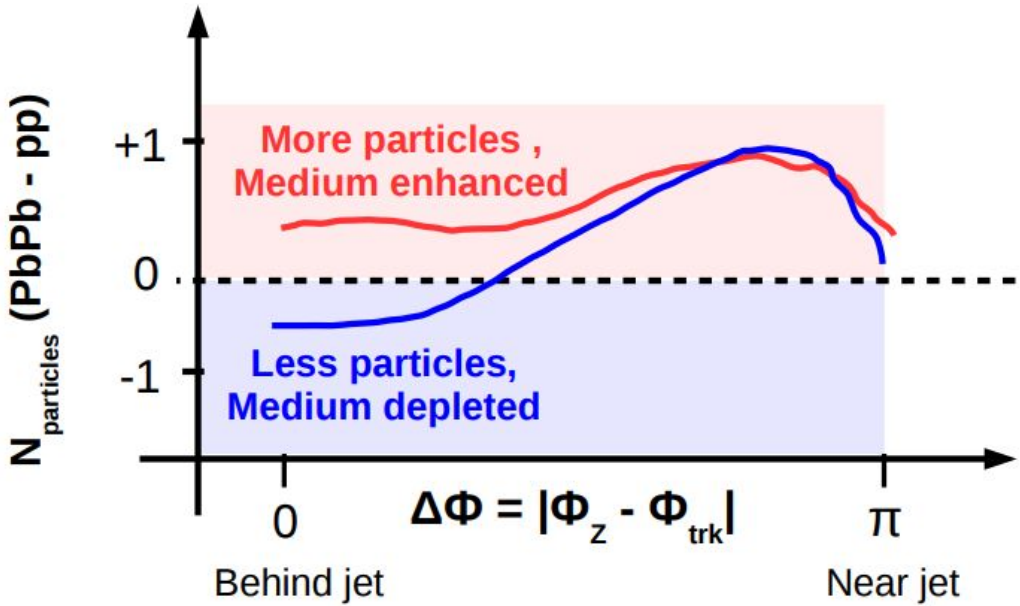
- Large UE contribution from soft particles.
- Combinatorial background from independent hard scatterings.
- For calorimetric measurement:
  - Jet energy calibration and uncertainties for every new jet “collection”.... different radius, subjects, and constituents.
- Role of ISR@FSR
- Choice of setting in grooming…
  - Sensitive to modeling and subtraction.
  - Need to understand biases we introduce.



Angular scan using EW boson tagged “jets”

- EW bosons tag the parton kinematics and flavour.
- Way to understand medium response.





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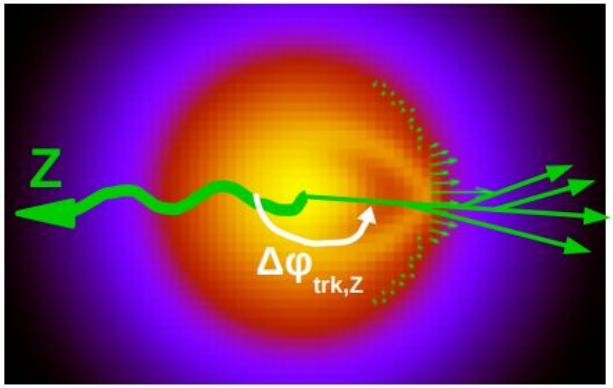
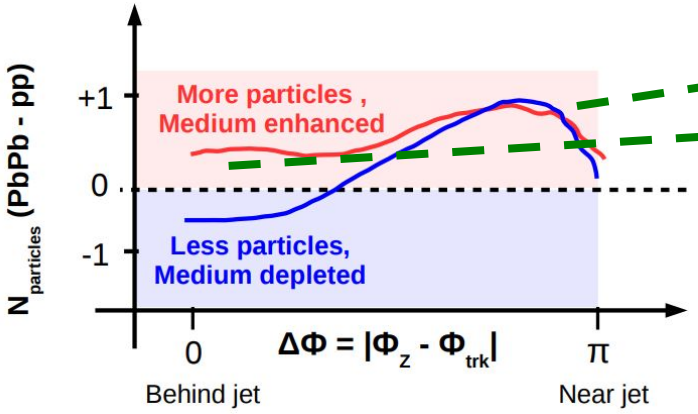
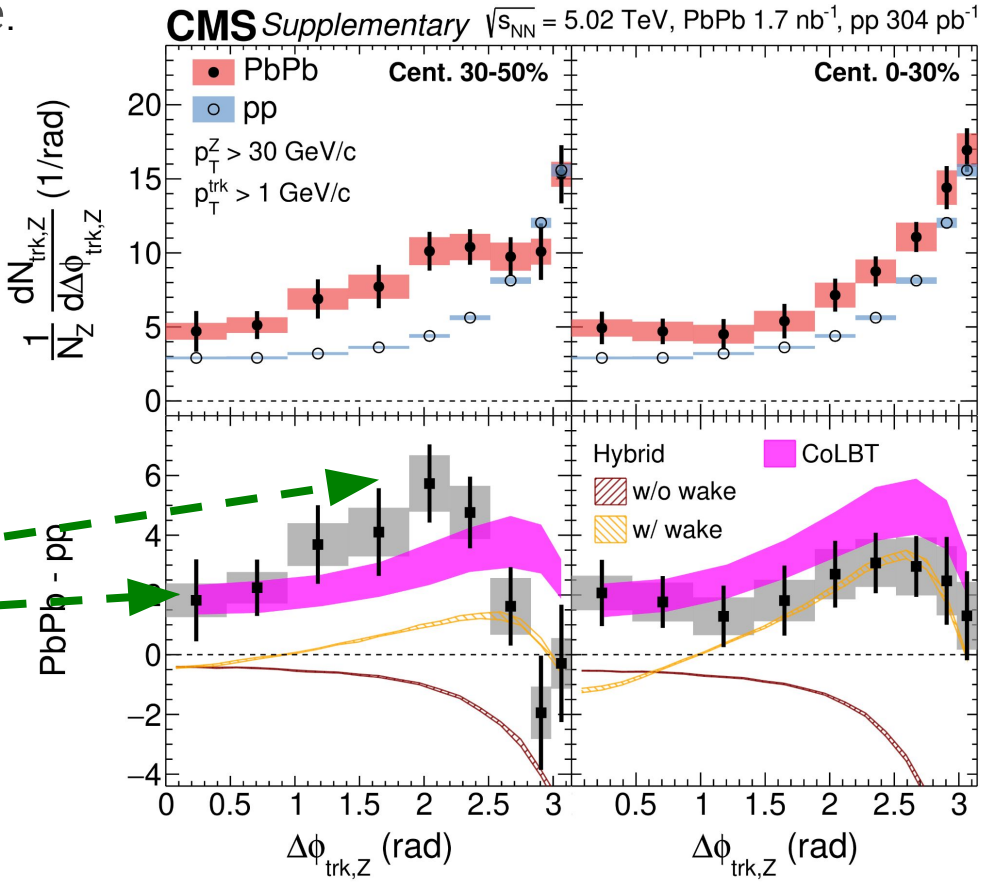




Phys. Rev. Lett. 128 (2022) 122301



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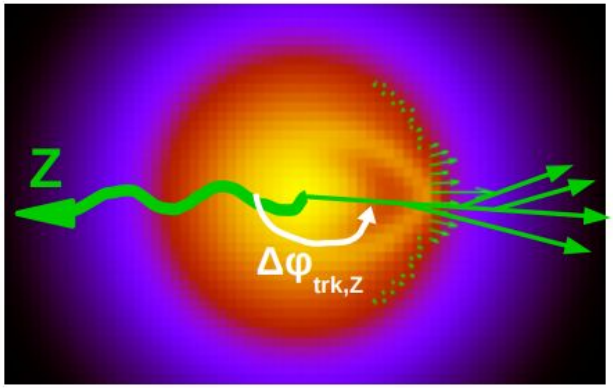

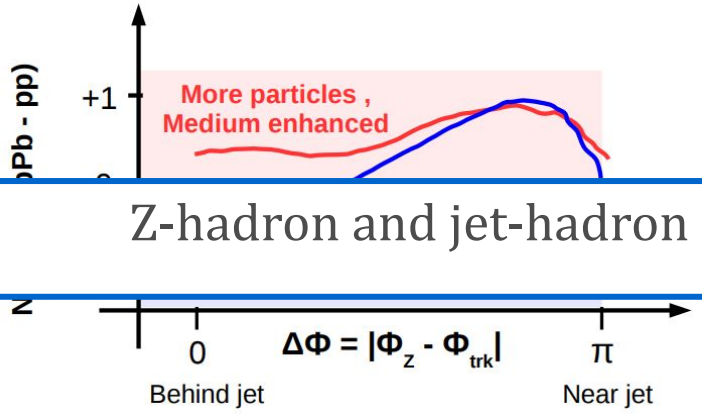

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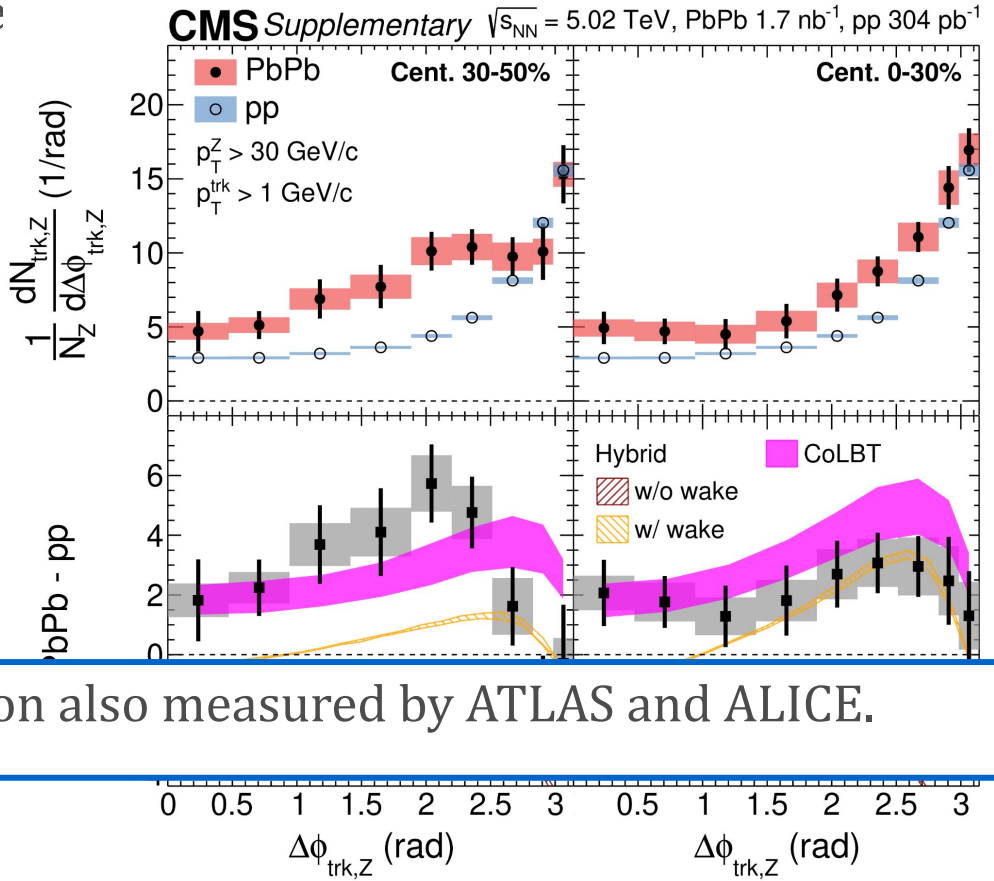

Z-hadron and jet-hadron correlation also measured by ATLAS and ALICE.