ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

Experimental results on intra-jet softening and large-angle energy flow

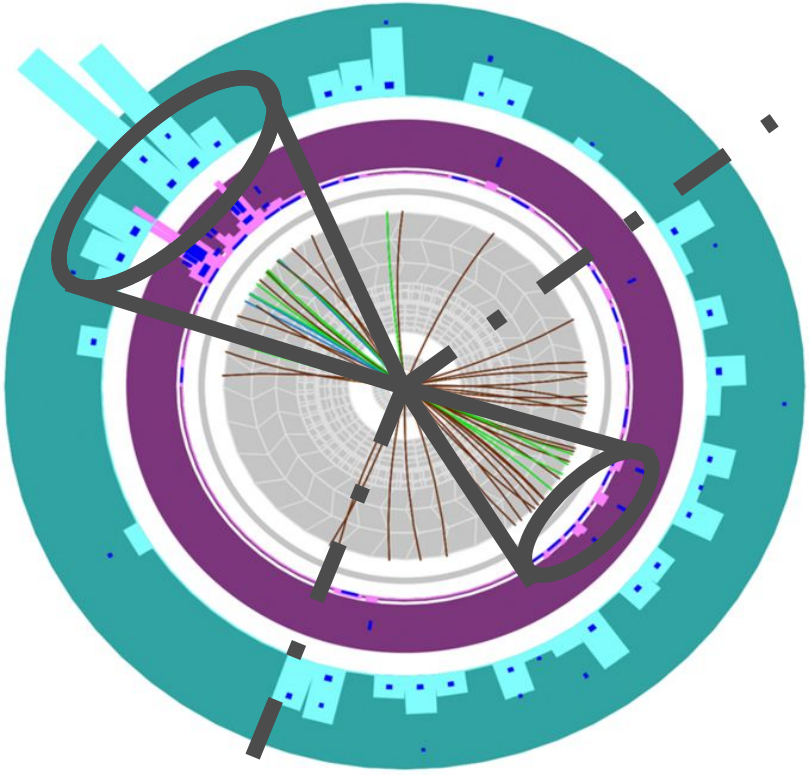
Martin Rybar

ECT Jet quenching workshop*

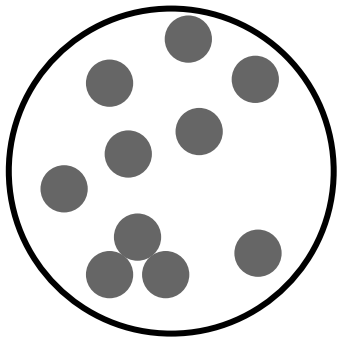
15th June 2022

Parton shower in QGP

- How is the fragmentation process modified?
- Where is the energy transported?
  - How much energy is transported out-of the jet cone?
- What are the effective scales of the interactions determining the energy loss?
  - What is the role of jet momentum, flavour and mass?
  - Can we see medium response to the fast partons?
- How does the hadronization process work?



What do we measure?



Full jet made of particles/tracks/towers/clusters

Fragmentation functions, track-jet correlations and jet shapes.

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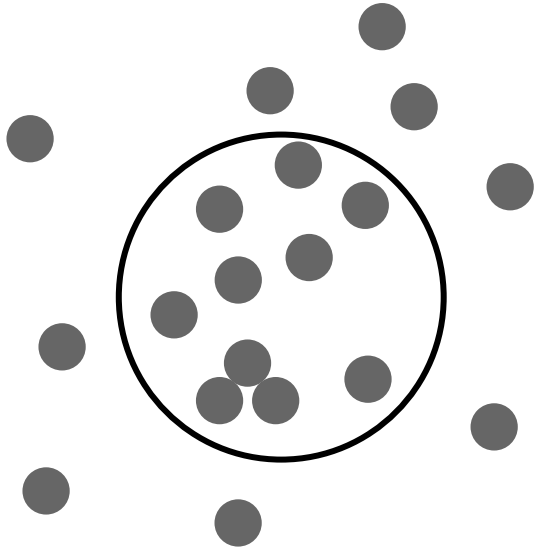

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Can be extended to large angles

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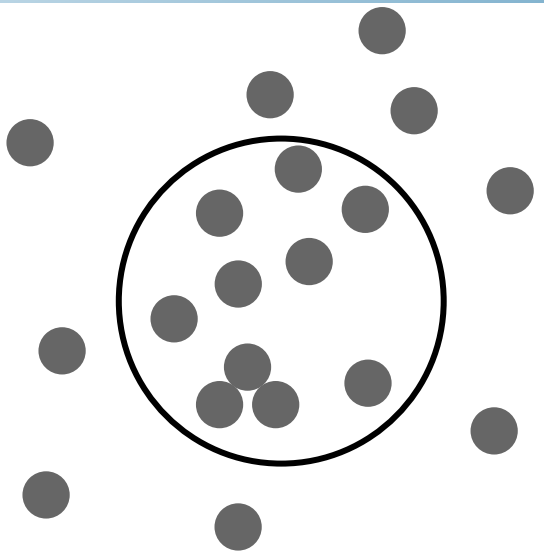

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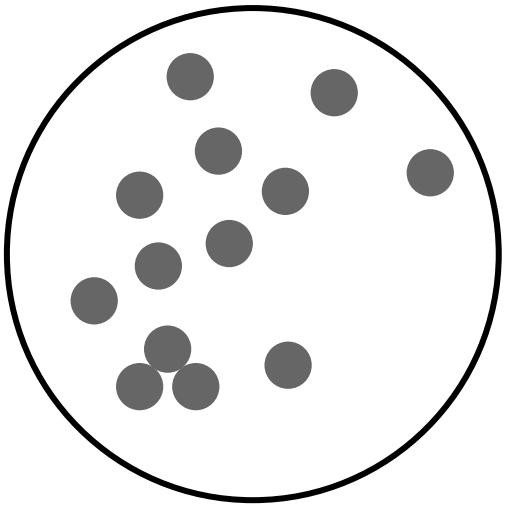

Jets made of particles/tracks/towers/clusters with different *R*.

Comparison of RAA for different jet sizes

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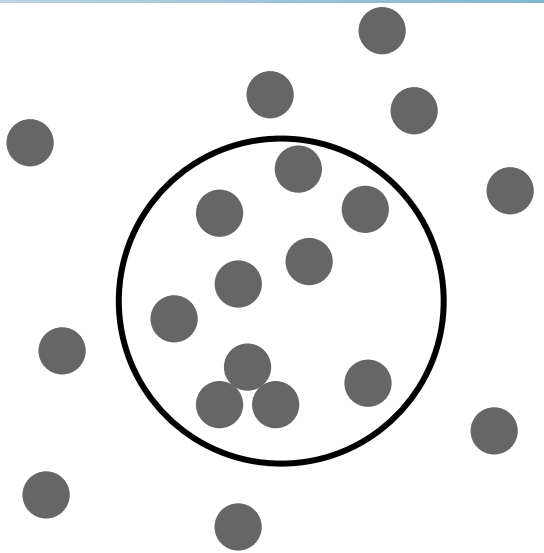

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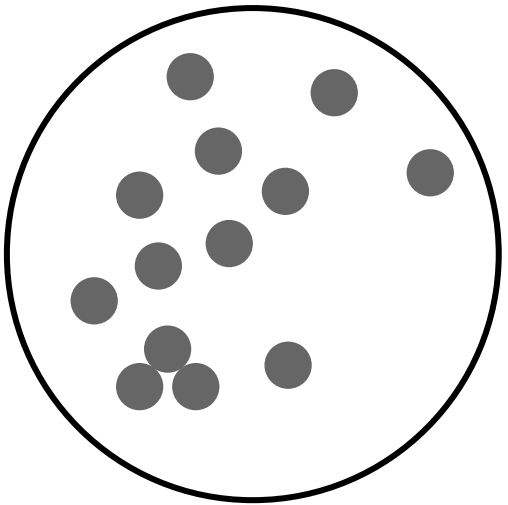

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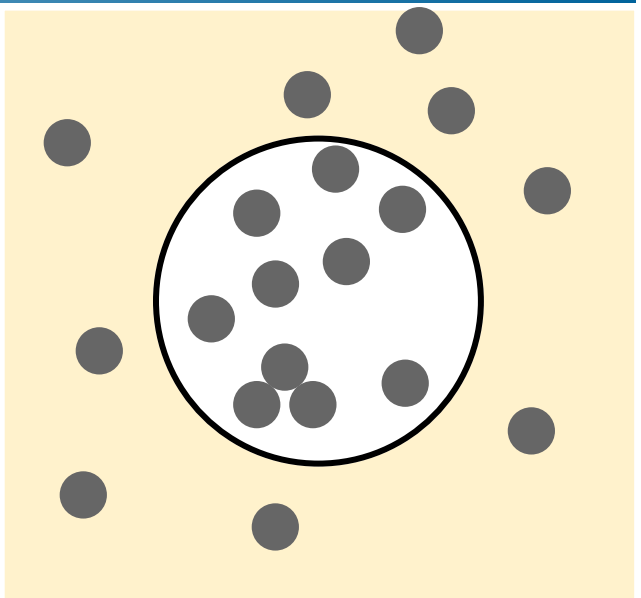
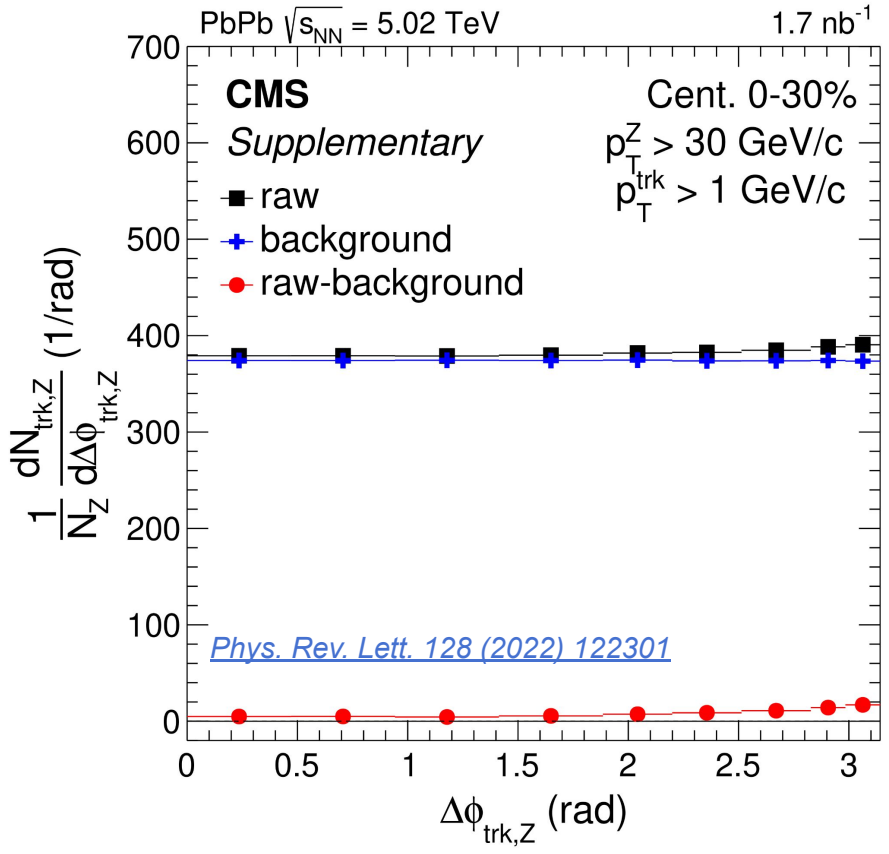


jet and some global event property

Missing transverse momentum calculculated in jet events.

Challenges in these measurements

- **Push towards larger phase space: lower energy and various/larger radius.**
- Large UE contribution from soft particles.
- For calorimetric measurement:
  - Jet energy calibration and uncertainties for every new jet "collection".... different radius, subjects, and constituents.
  - Jet response depends on jet fragmentation/flavour.



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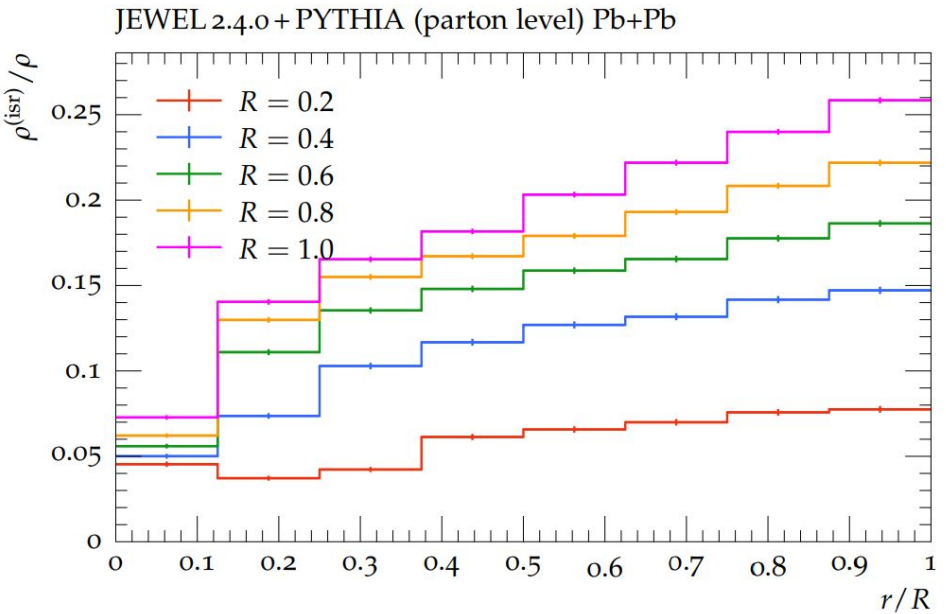
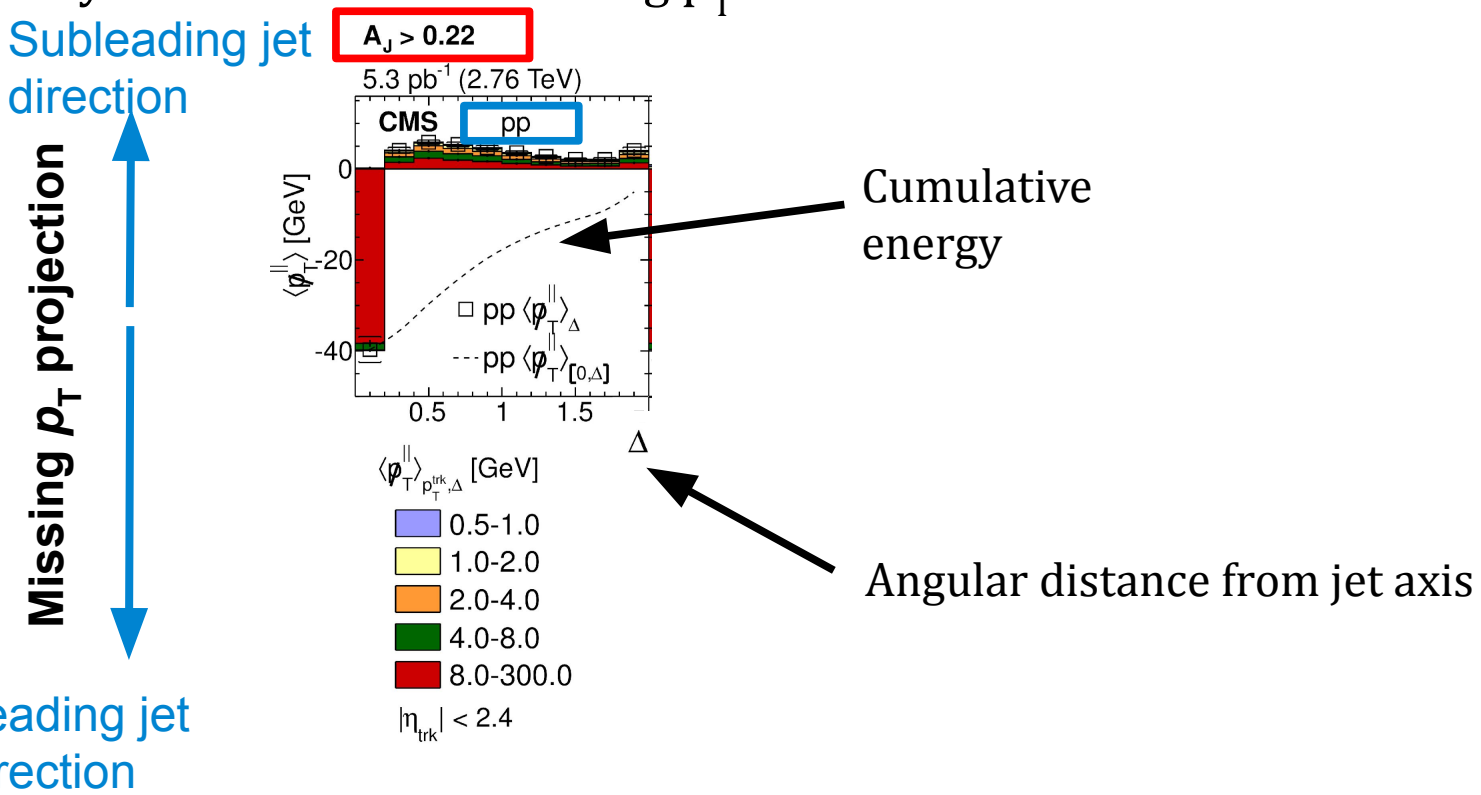
  - Jet response depends on jet fragmentation/flavour.
- Role of ISR@FSR
  - Resembles medium response



Impact of ISR on jet shape by Korina

Where does the energy flows?

- Study of correlation of missing p_T evaluated with tracks in various p_T bins with jets.



JHEP 01 (2016) 006

Where does the energy flows?

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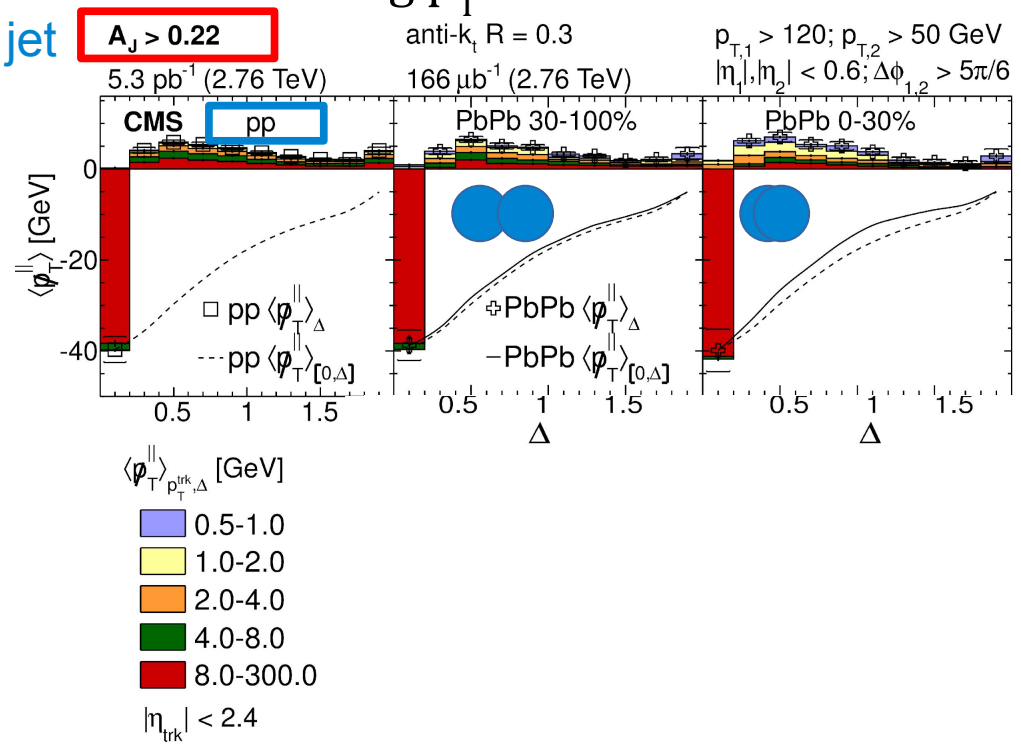
Subleading jet direction

Missing p_T projection

Leading jet direction



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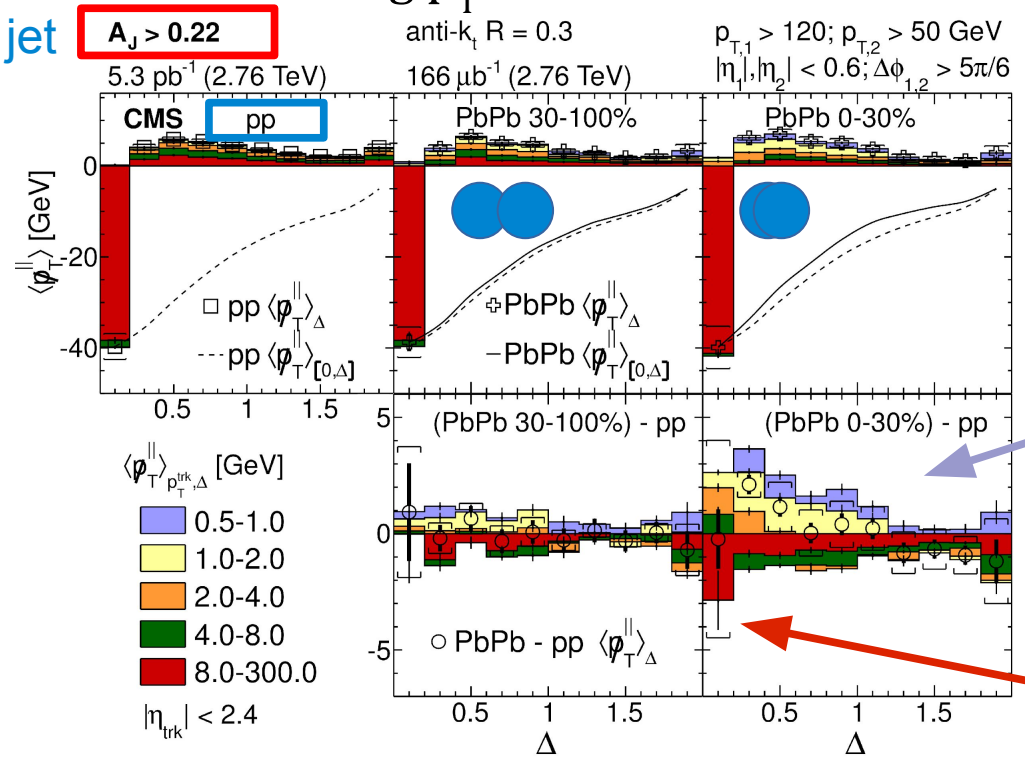


JHEP 01 (2016) 006

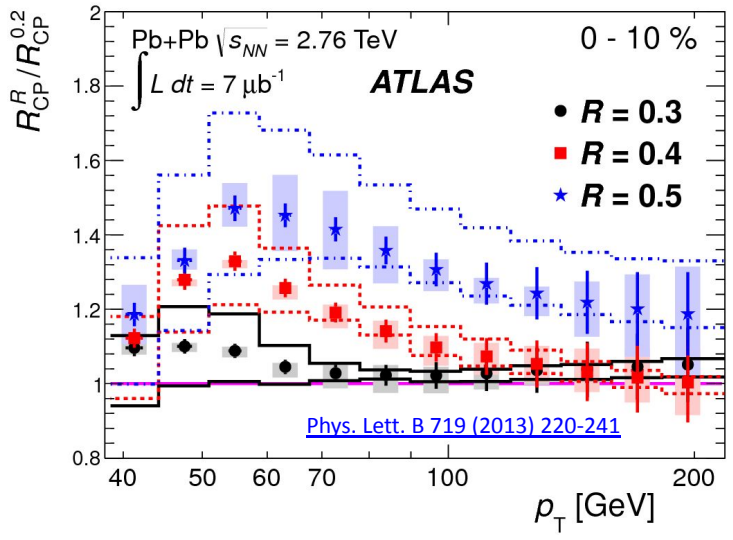
Balanced at large angles by soft particles

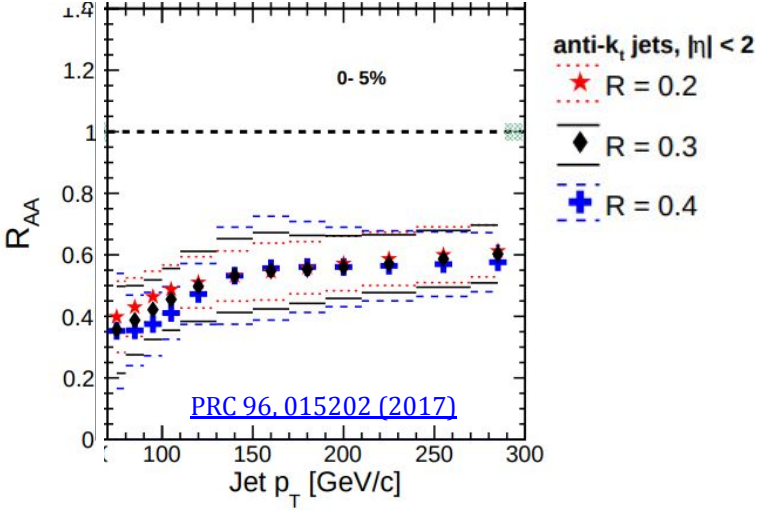
High-p_T imbalance at small angles

Radial scan

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

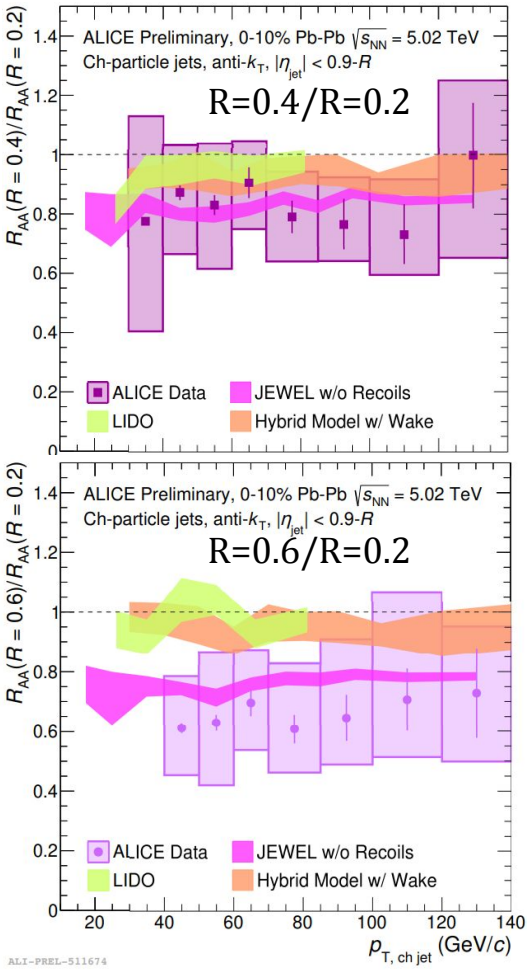
What we know from past measurements…





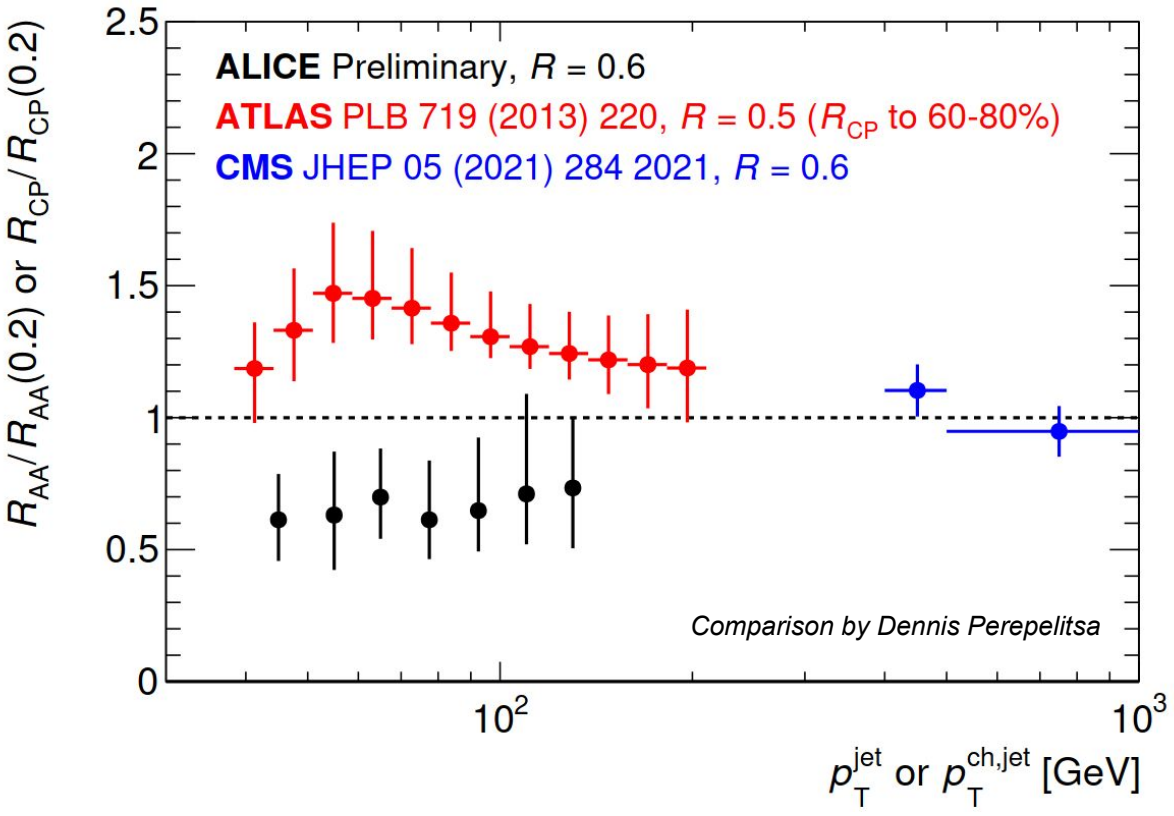
- The increase in RAA with jet *R* expected from theory: JHEP 0811:093,2008 and PLB 713 (2012) 224-232

Radial scan



Suggests increasing suppression for larger R.

Radial scan

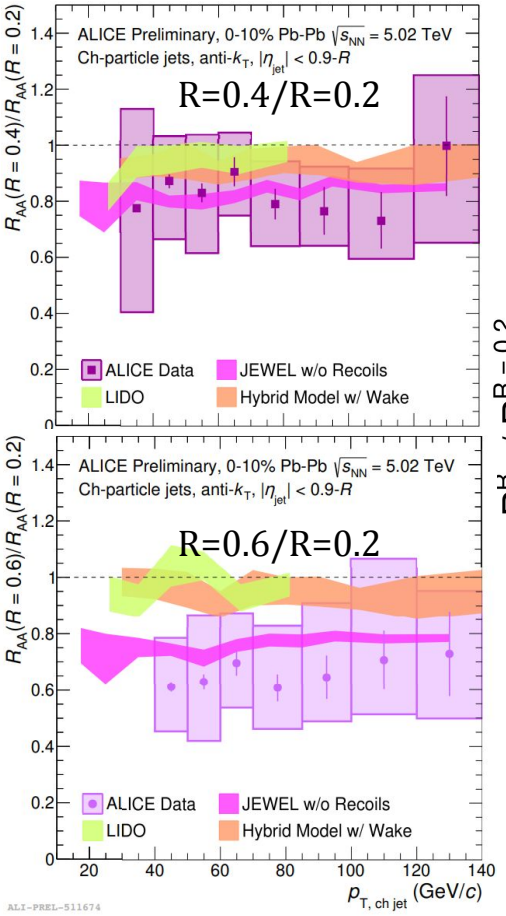


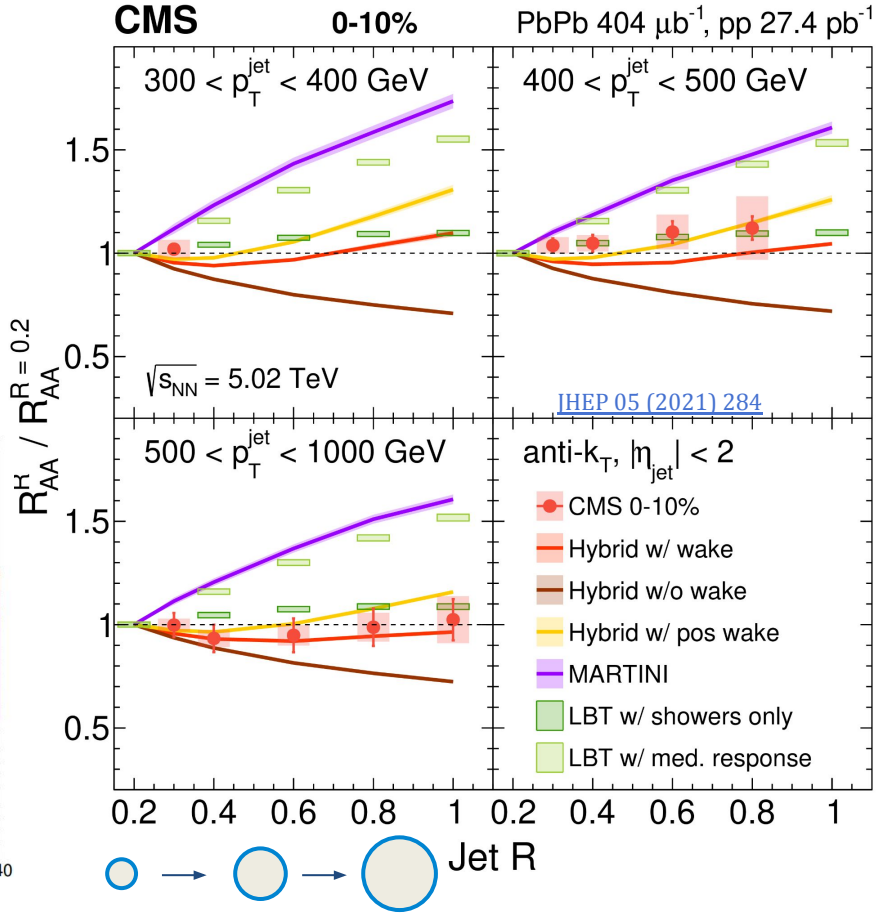
Tension with ATLAS result

- Charged vs full jet? (3/2 in the energy scales)
- ALICE: cluster in track > 150 MeV
- ATLAS: ~700 MeV tracks do not reach calorimeter.
- 2.76 TeV vs 5.02 TeV & slightly different phase-space
- Lower-level details & comparison is needed.

Radial scan

- Many competing effect when changing the jet size.





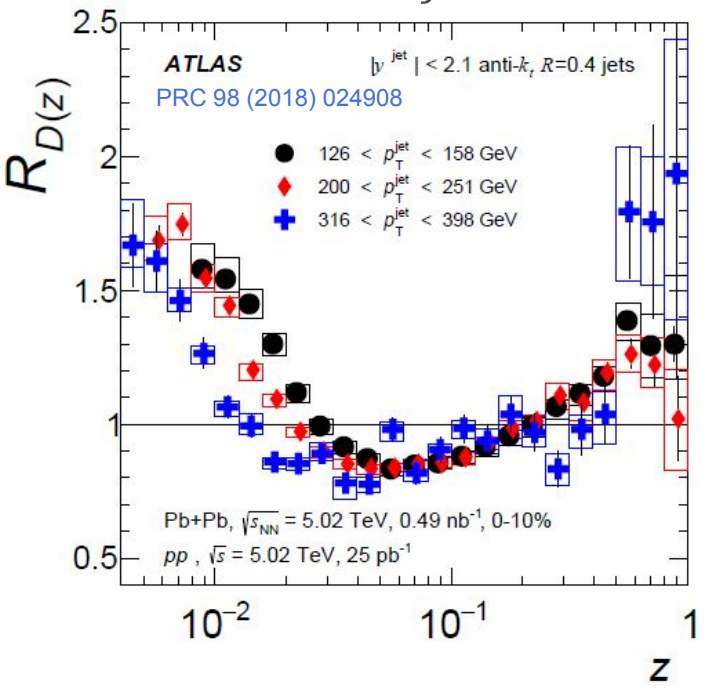
No significant R dependence at high p_T seen by CMS.

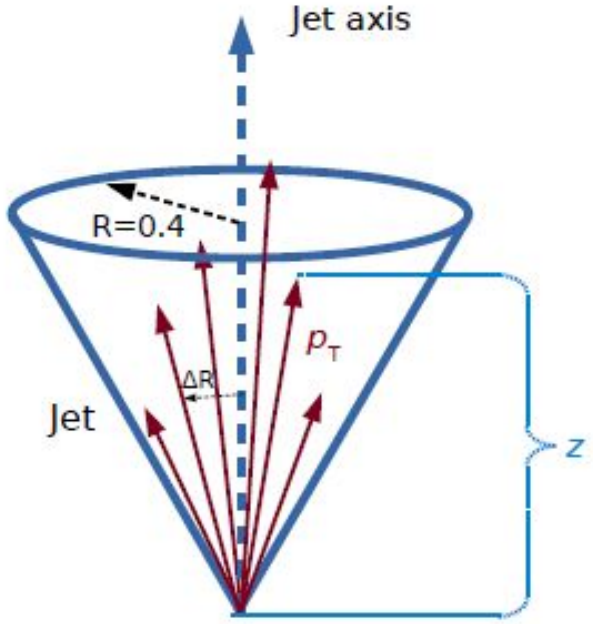
Different phase space & relatively large uncertainties.

Models going in both directions.

Jet fragmentation

Inclusive jets FF





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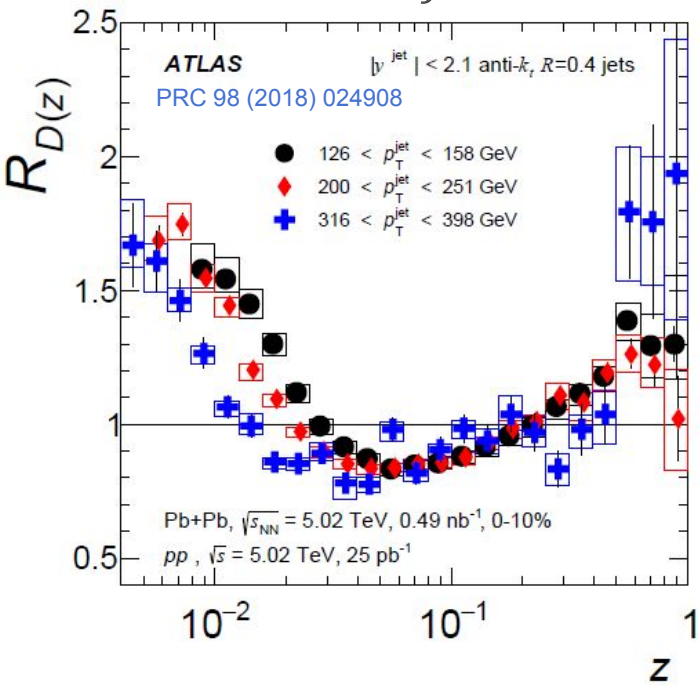
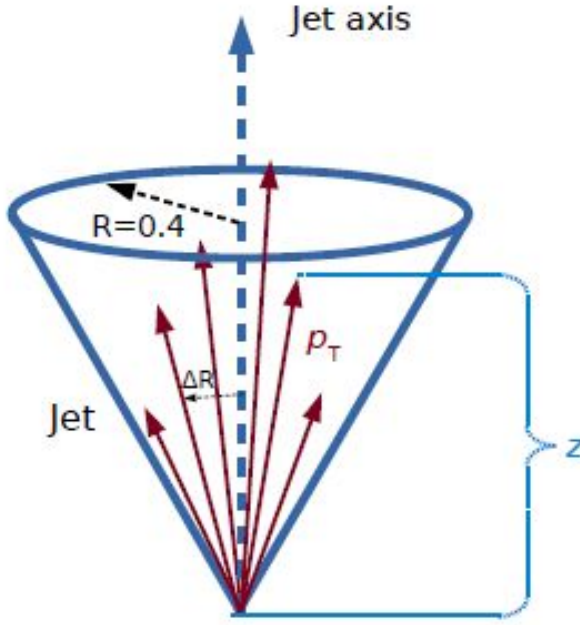
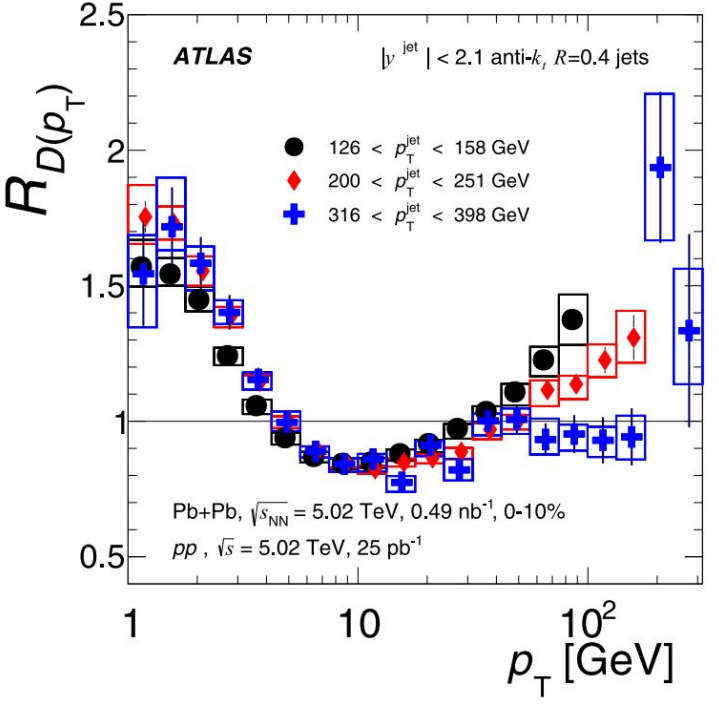
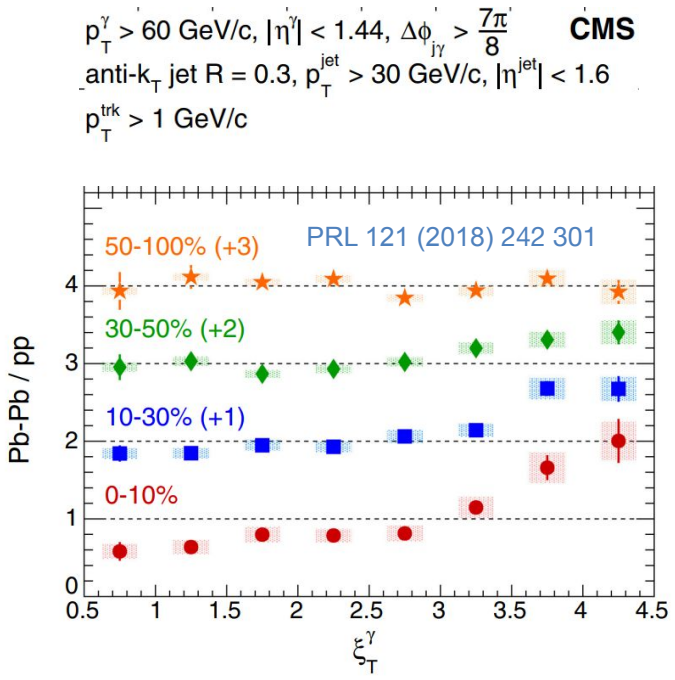




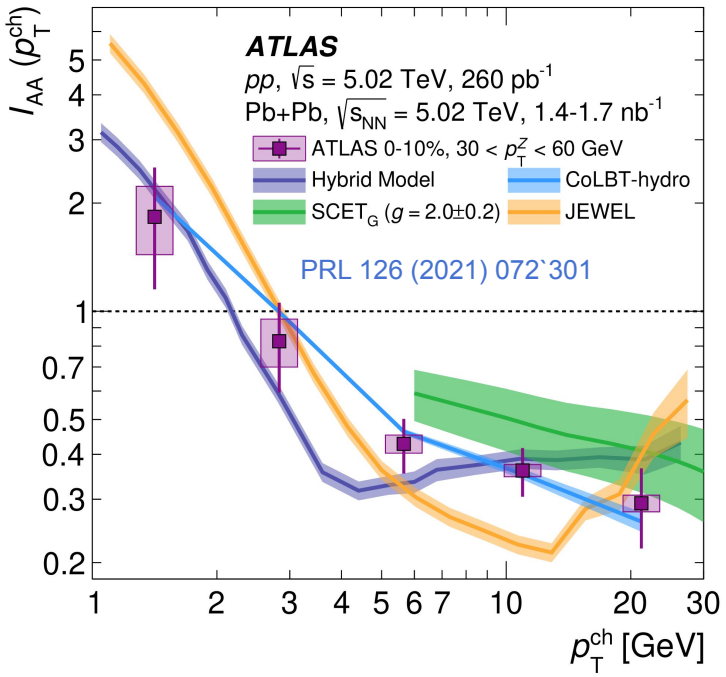


Jet fragmentation

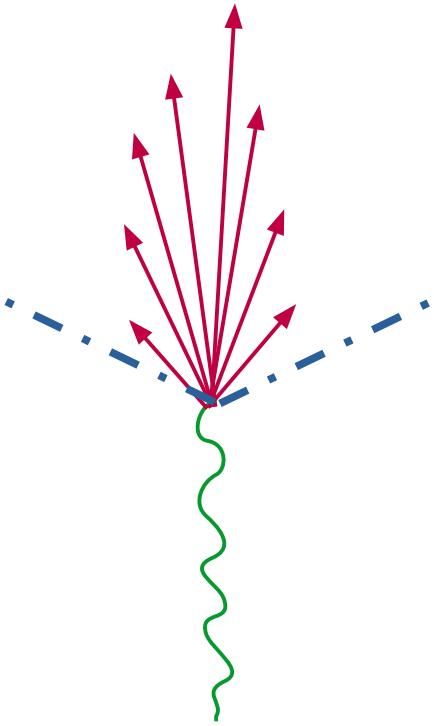
γ-tagged yields



Z- tagged yields



What is the new information compared to the inclusive measurement?



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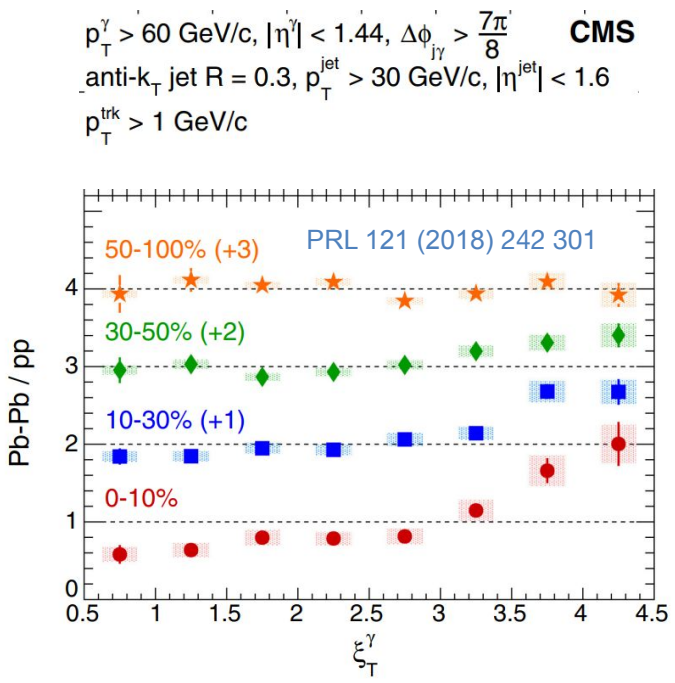

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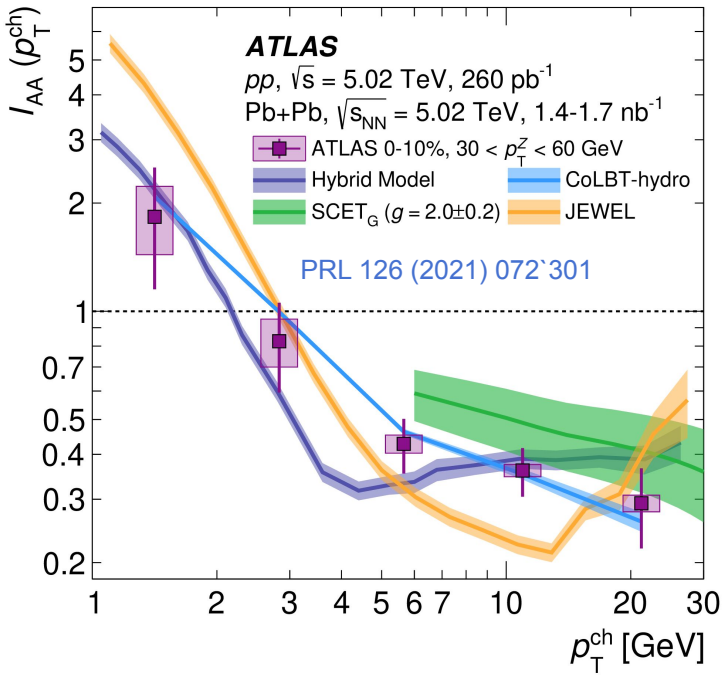
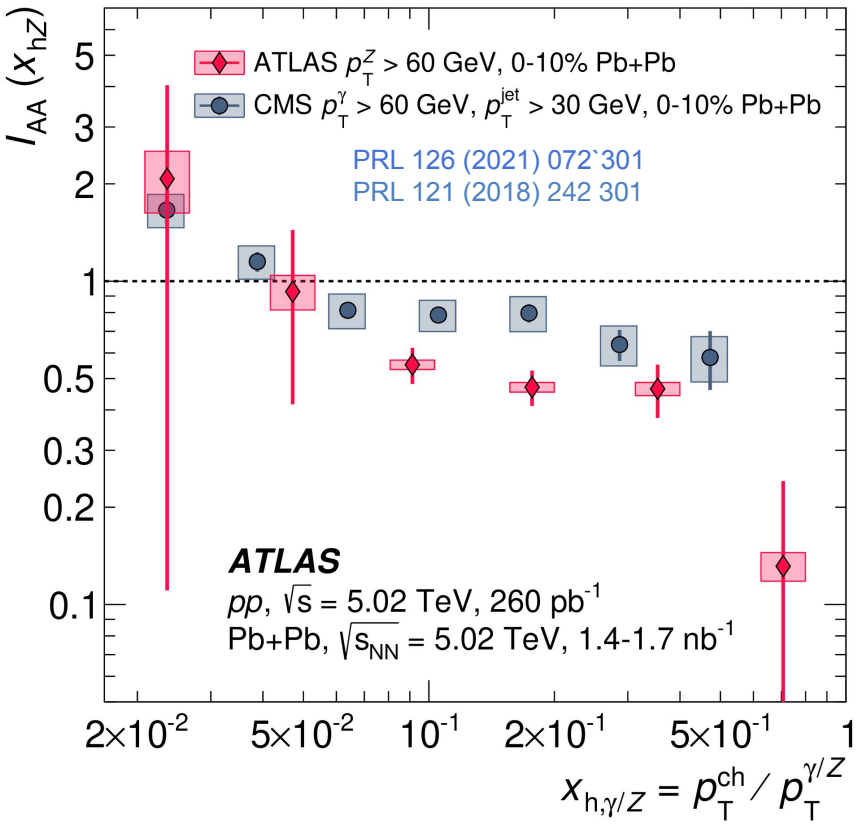


What is the new information compared to the inclusive measurement?

- Quark dominated jet sample.
- Access to low p_T (jet) region.
- Suppressing selection bias.
- Extra enhancement & suppression wrt inclusive

Jet fragmentation

Z- and γ-tagged yields

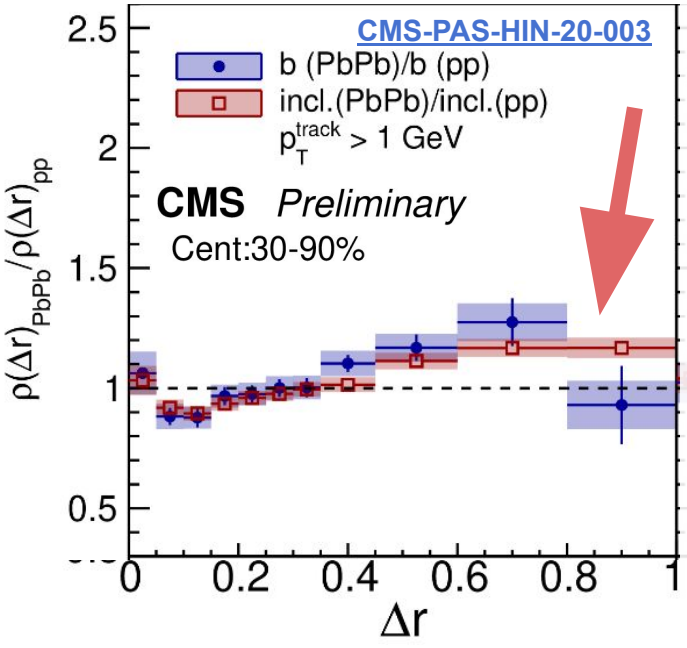


Comparing Z- and ϒ-tagged measurements.

- Testing role of parton virtuality.
- Access to low p_T (jet) region.
- ϒ-tagged measurements differs in kinematic region → large quenched jets not included.

Radial profile - inclusive jets

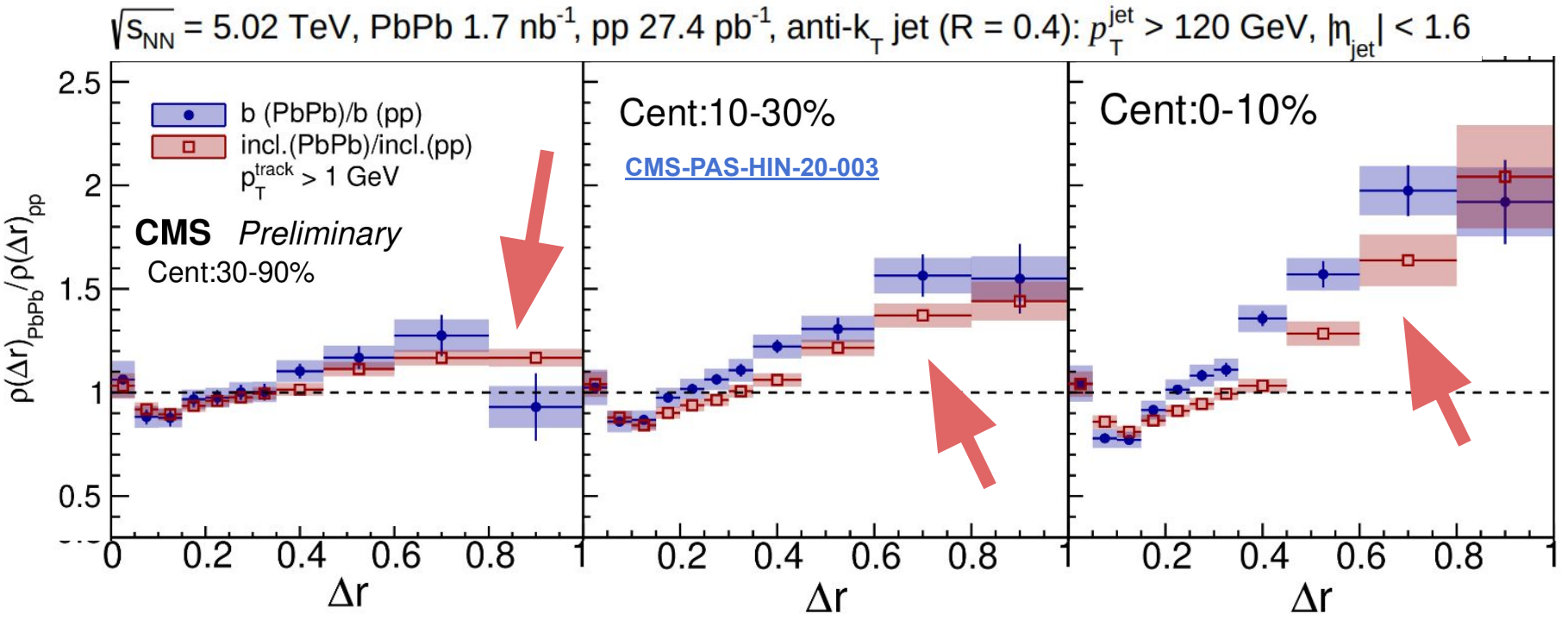
$\sqrt{s_{NN}}$ = 5.02 TeV, PbPb 1.7 nb^{-1}, pp 27.4 pb^{-1}, anti-k$_T$ jet (R = 0.4): p_T^{jet} > 120 GeV, $|\eta_{jet}|$ < 1.6



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

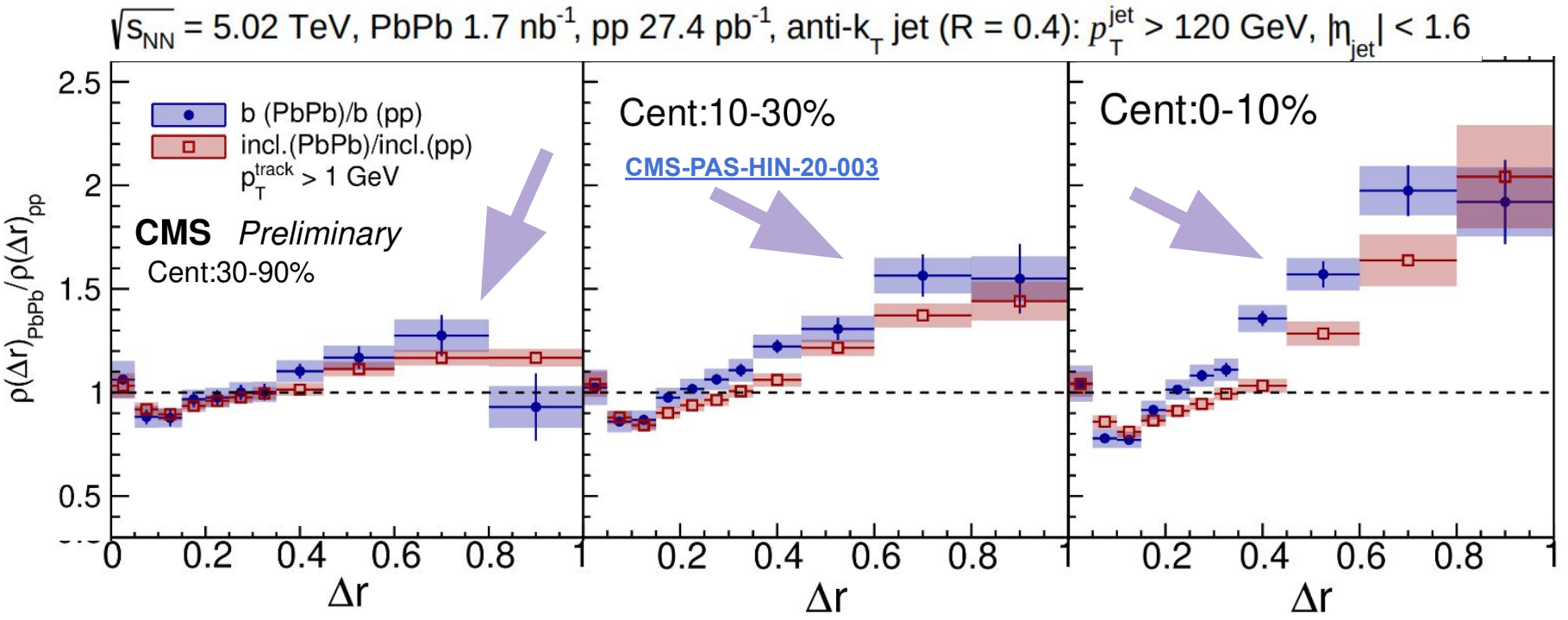
$$\rho(\Delta r) = \frac{P(\Delta r)}{\Sigma_{jets}\Sigma_{tracks\in\Delta r<1}p_T^{ch}}$$

Radial profile - inclusive jets



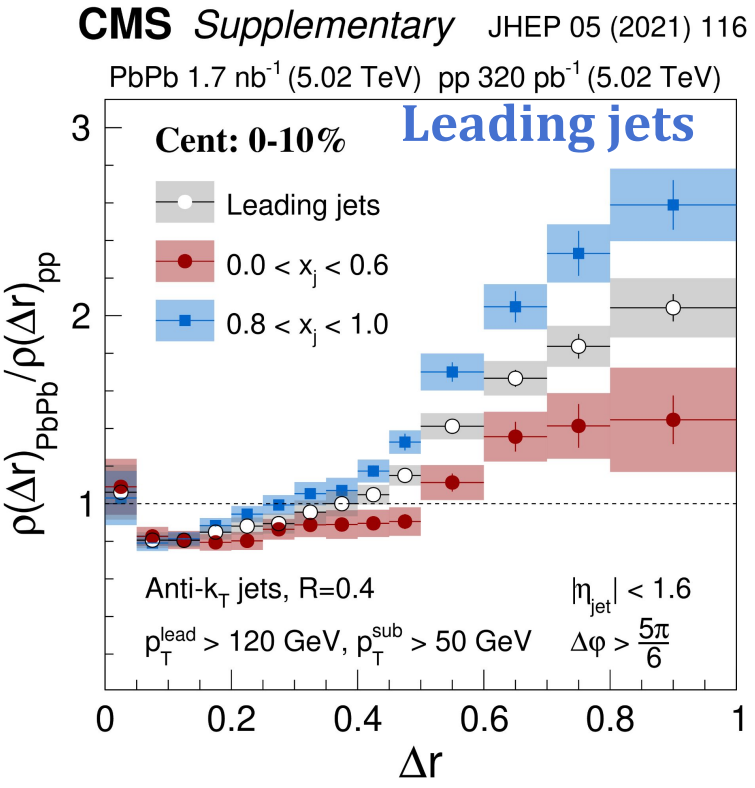
- Core largely unmodified; but jets are broader in more central Pb+Pb.
- Energy re-distributed toward and behind the jet edge in low p_T particles.
- More differential studies…

Radial profile - b-jets



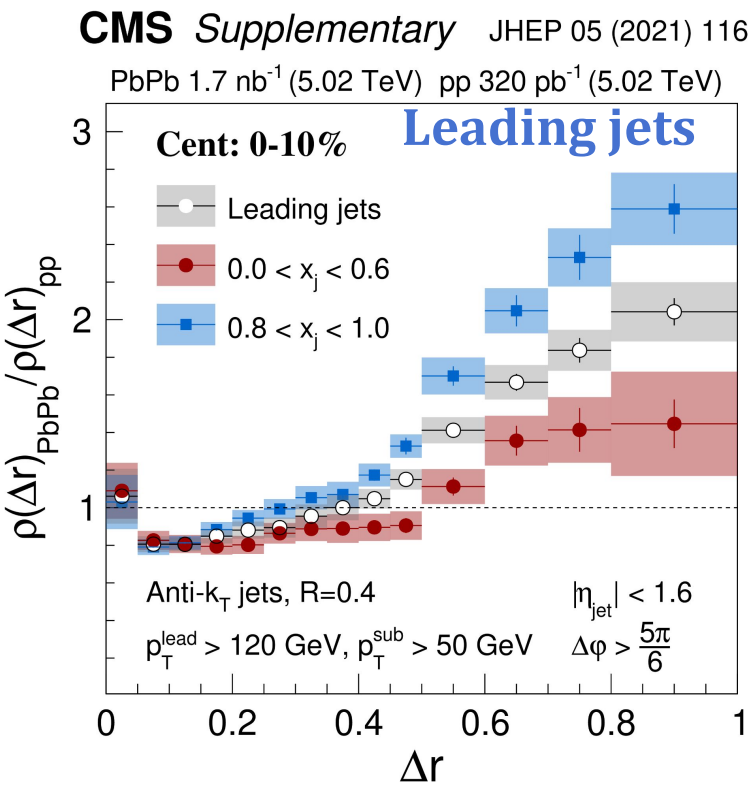
- Similar pattern as for inclusive jets but quantitatively larger
- Do we see effect of flavour or mass (dead cone)?
    - Model comparison is needed.

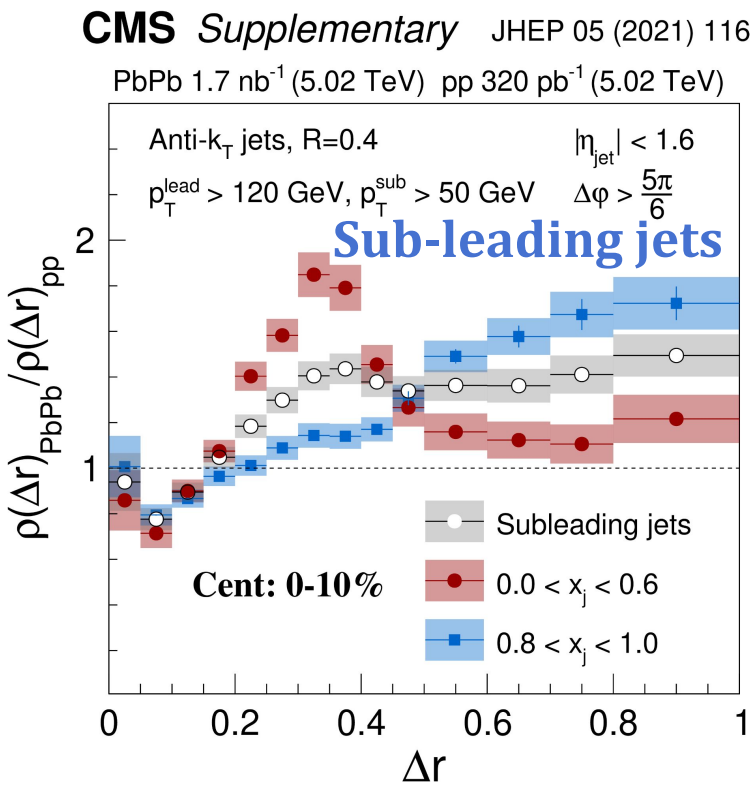
Radial profile - leading/sub-leading



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

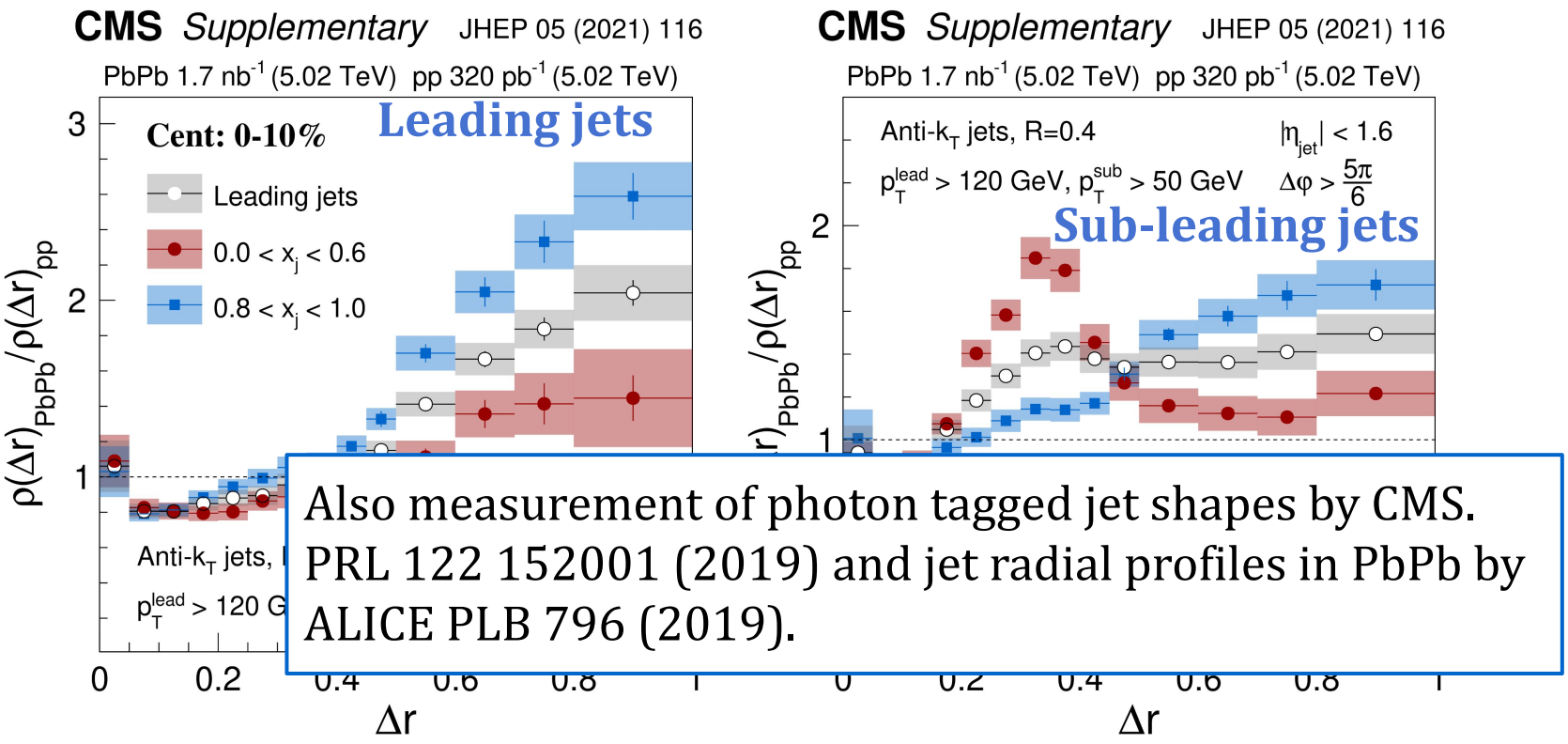
Radial profile - leading/sub-leading





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

Radial profile - leading/sub-leading



Also measurement of photon tagged jet shapes by CMS. PRL 122 152001 (2019) and jet radial profiles in PbPb by ALICE PLB 796 (2019).

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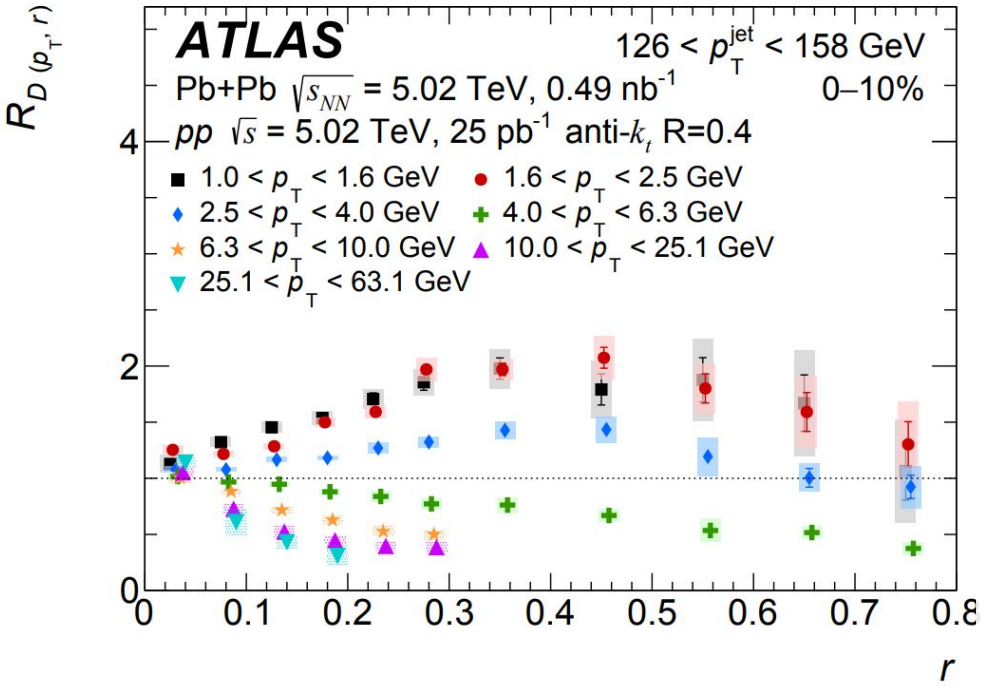
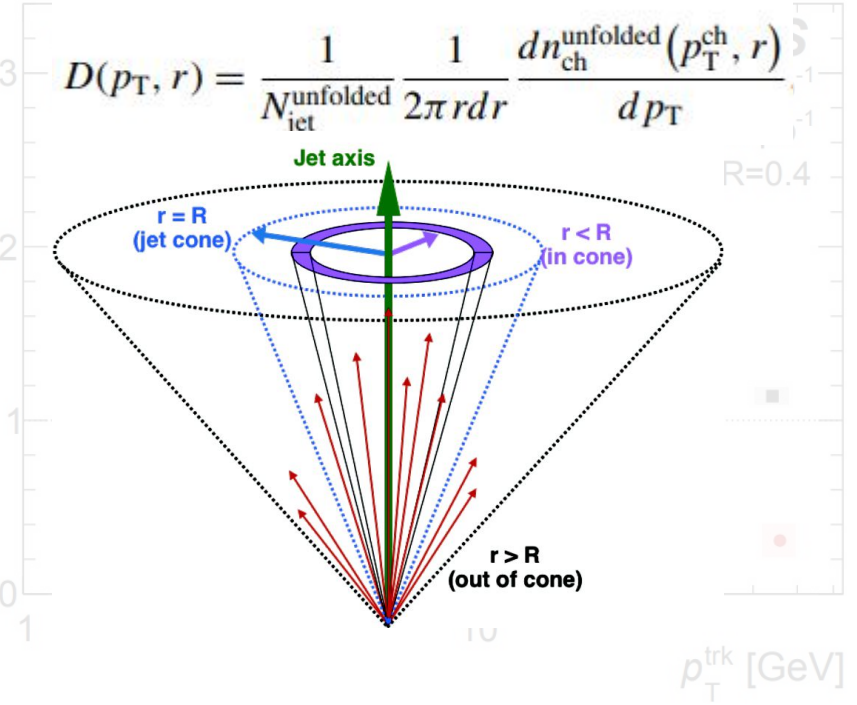
Modification of Radial Profile

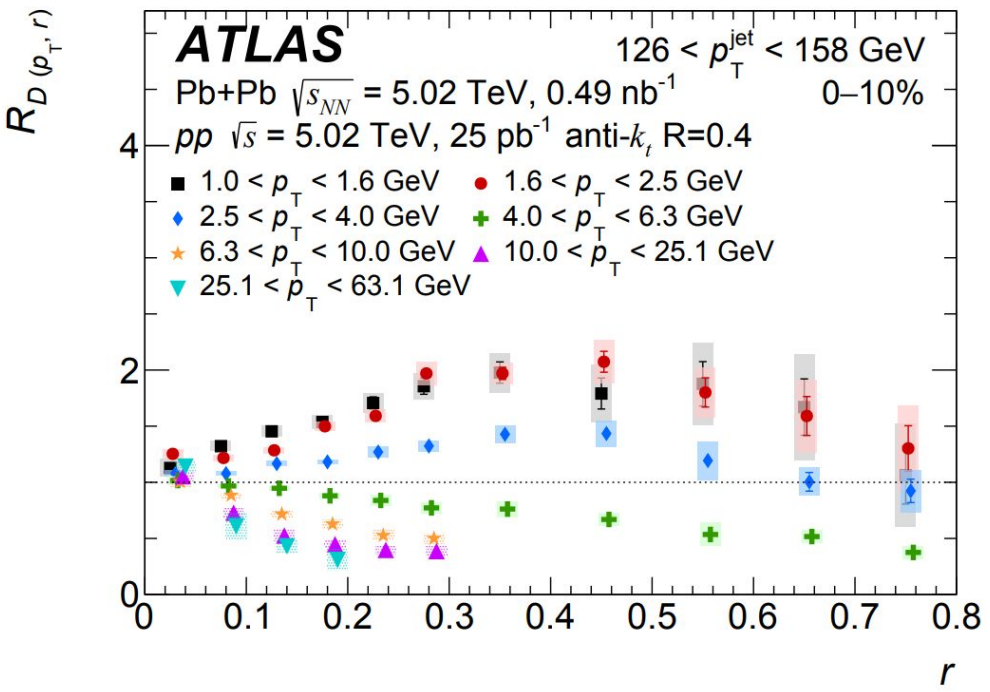


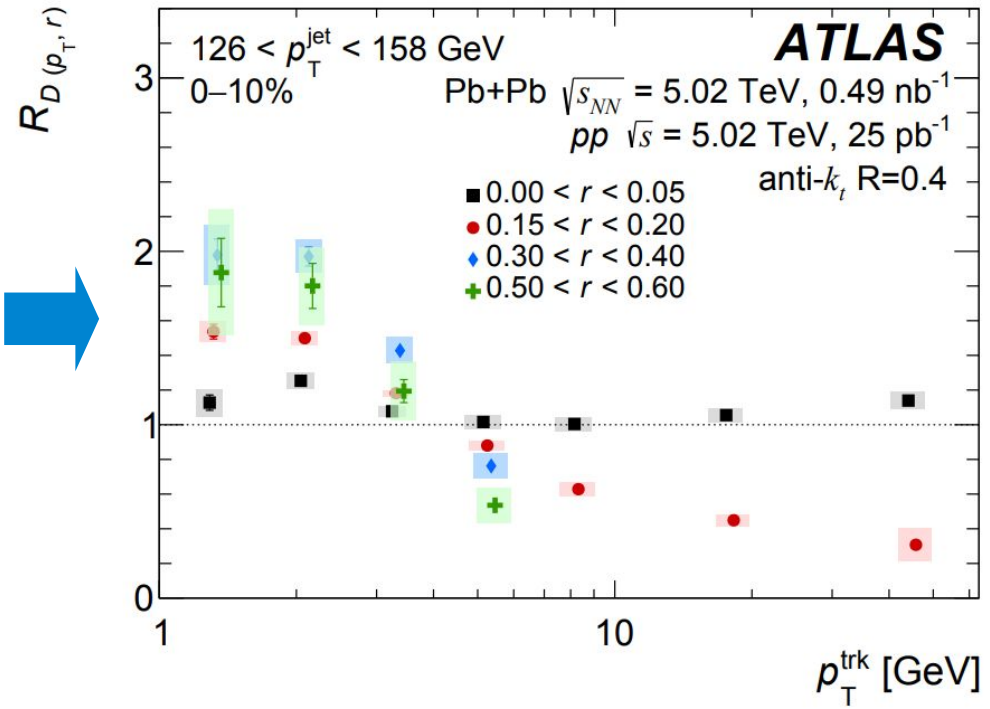


- Jets are broader in more central collisions at low p_T.
- Significant suppression of yields of particles p_T > 4 GeV outside the jet core.

arXiv:1908.05264

Modification of Radial Profile

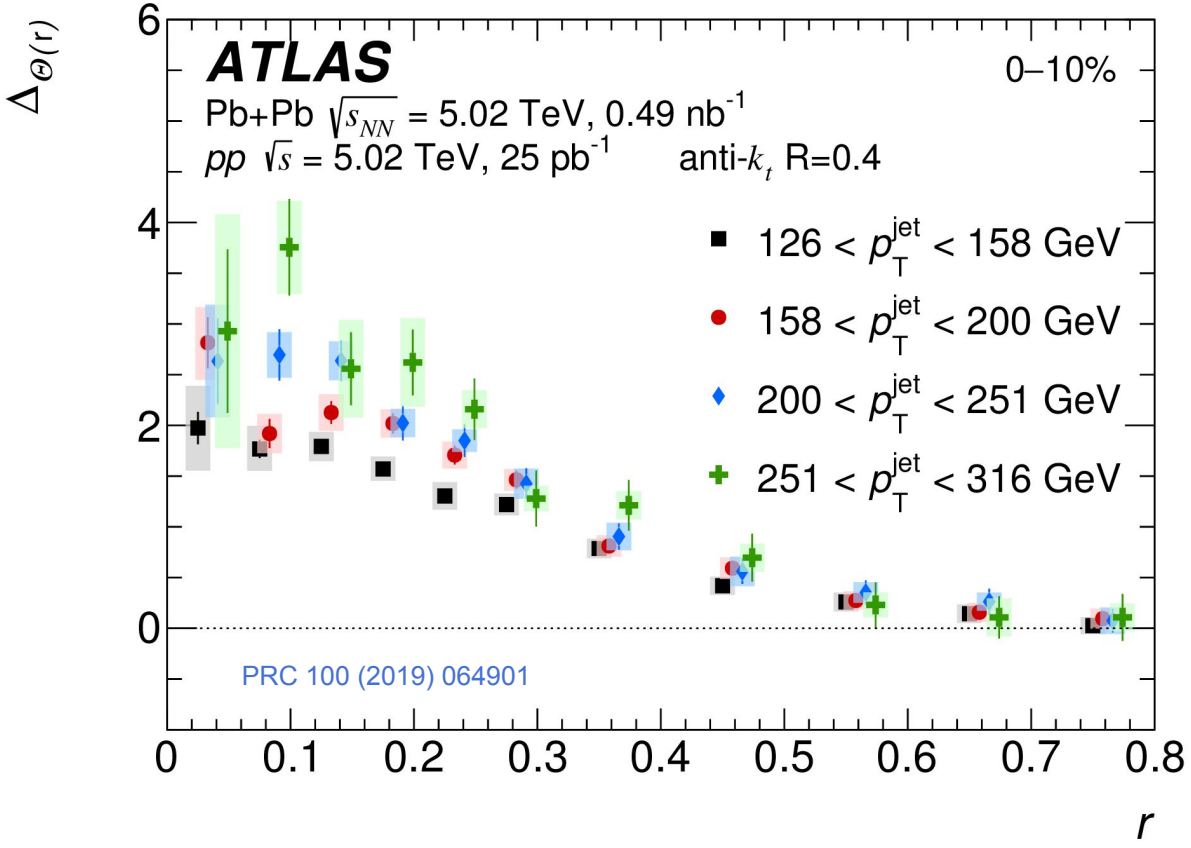




- Smallest modification seen in the jet core.
- The enhancement increases with decreasing p_T.

arXiv:1908.05264

Radial profile



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

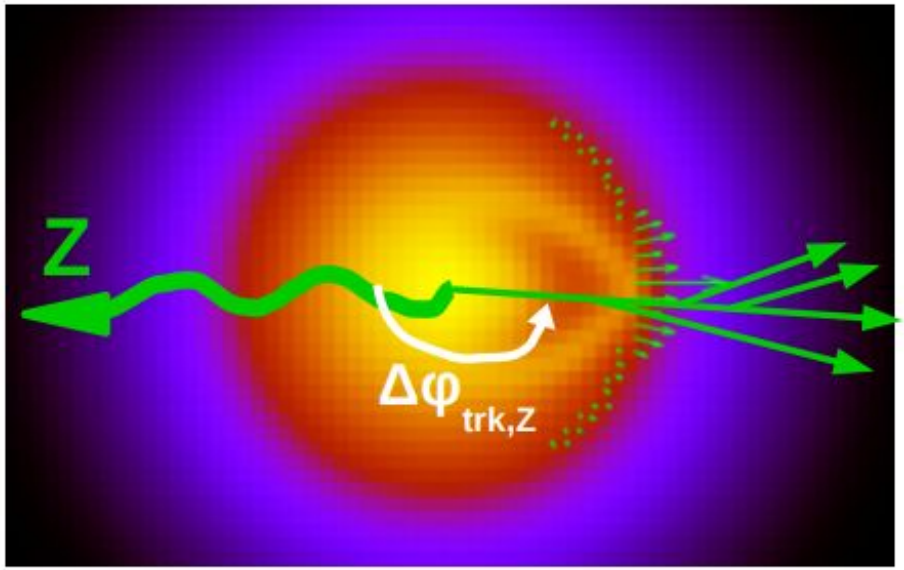
$$\Delta_{\Theta(r)} = \Theta(r)_{\mathrm{Pb+Pb}} - \Theta(r)_{pp}$$

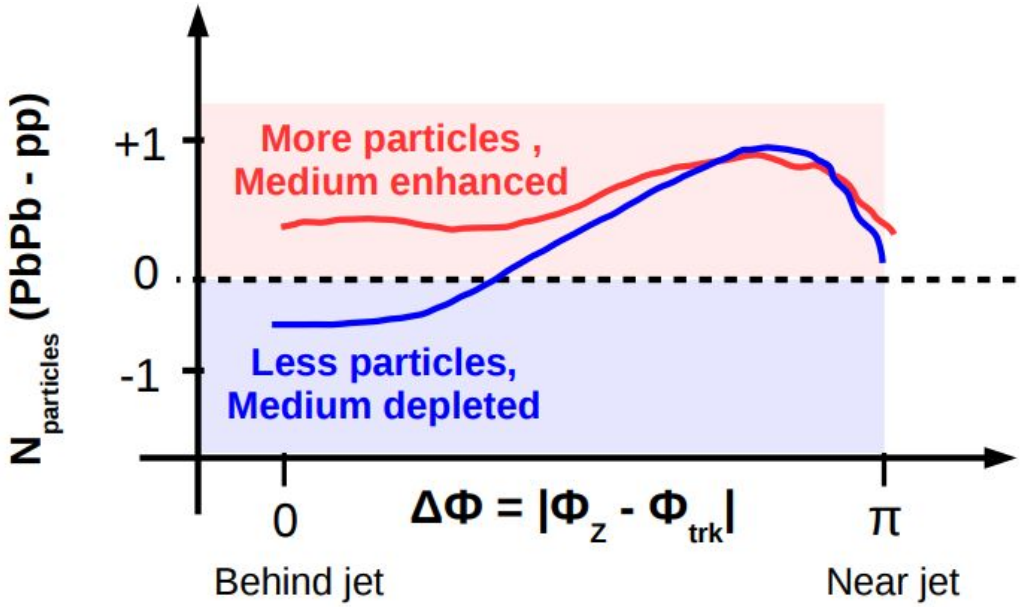
The absolute difference (#low p_T particles) is the highest inside the jet.

Can we see medium response in the jet p_T dependence?

Angular scan using EW boson tagged “jets”

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





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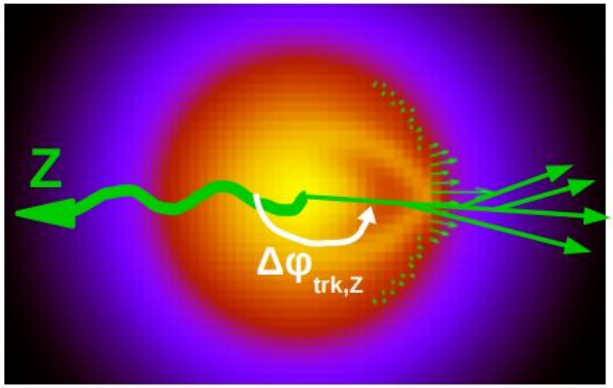
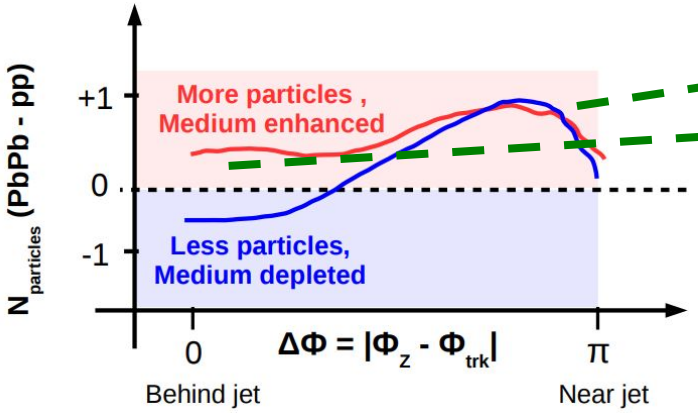
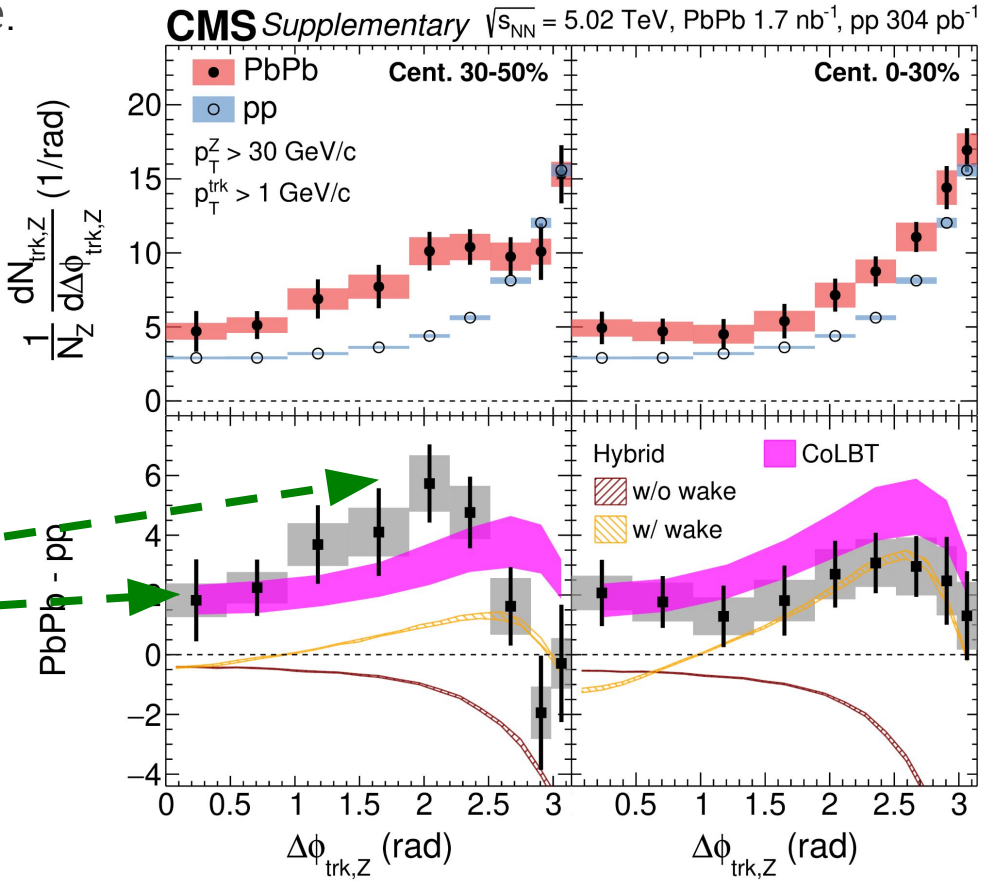


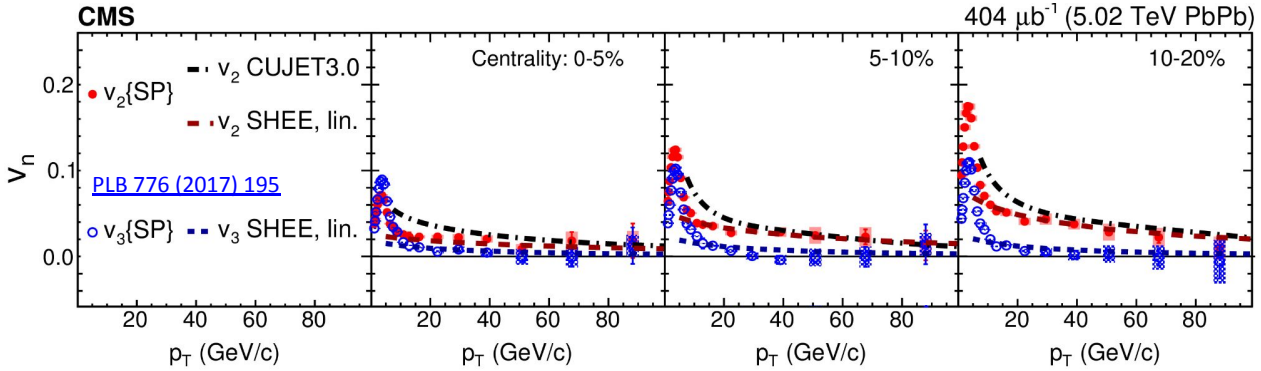


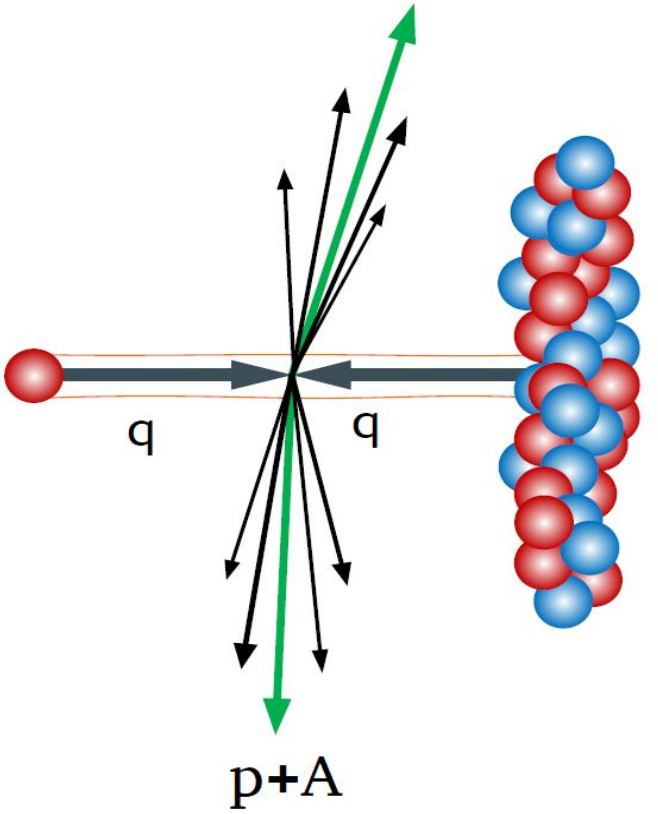
Phys. Rev. Lett. 128 (2022) 122301



Looking for jet quenching in small systems

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

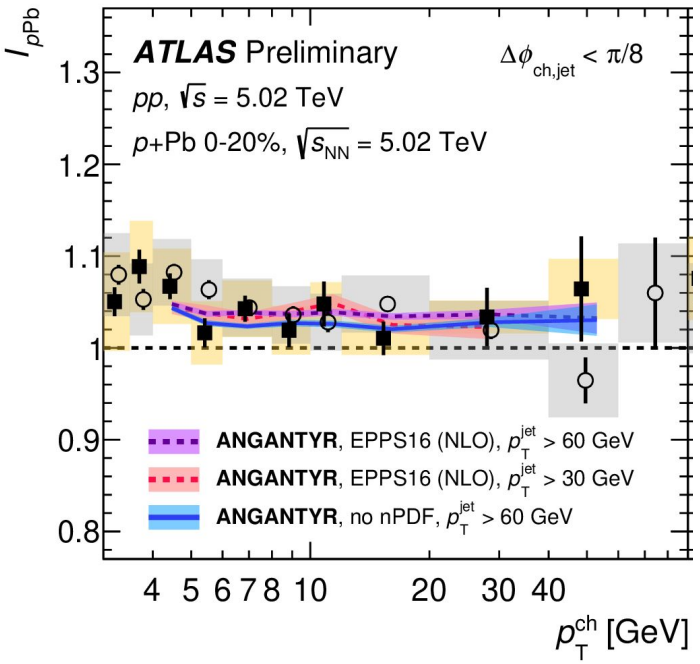


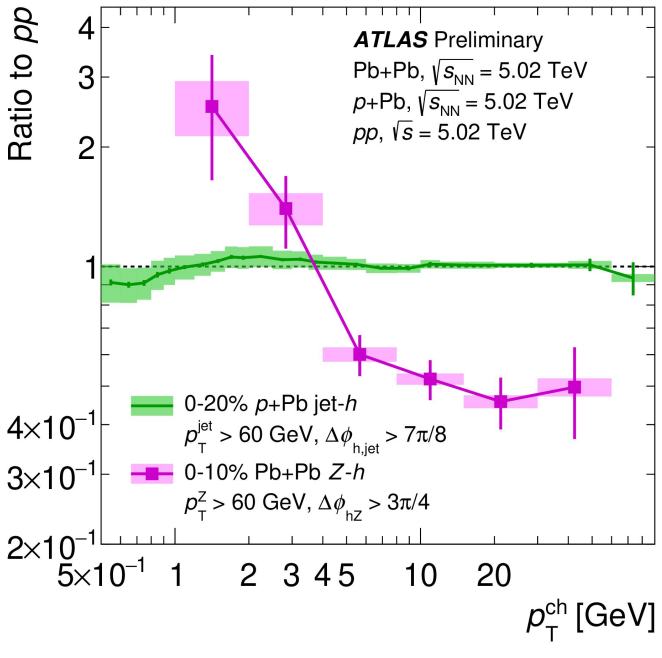


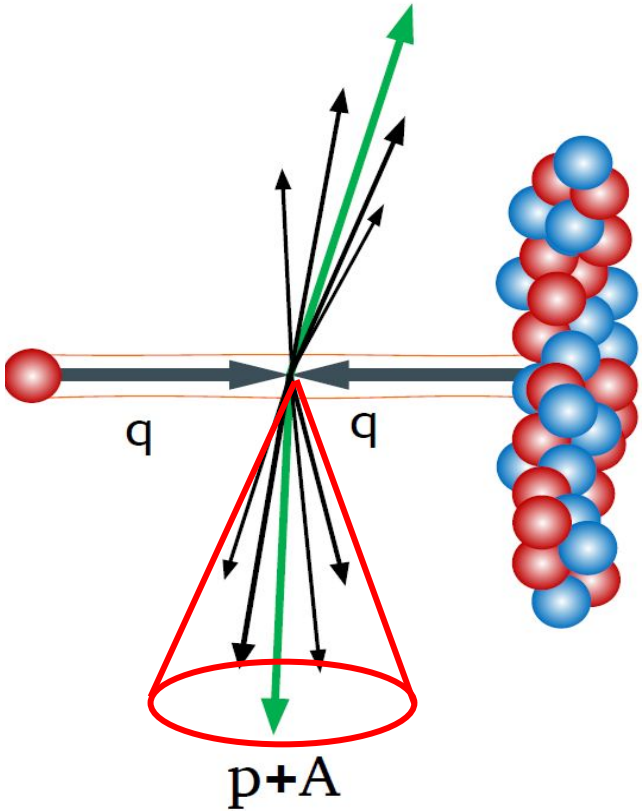
- Inclusive full jet measurements put limits on quenching → dominated by systematics uncertainties.
- Using jet substructure:
  - Per-jet quantities remove scaling uncertainties.
  - Need for robust centrality definition.

Looking for jet quenching in small systems

- Charged hadron yields within a jet:



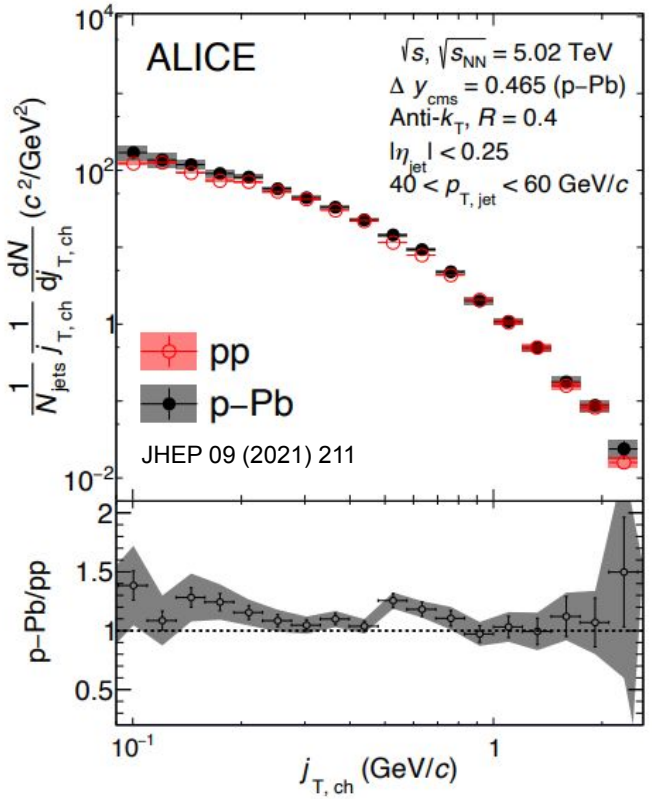


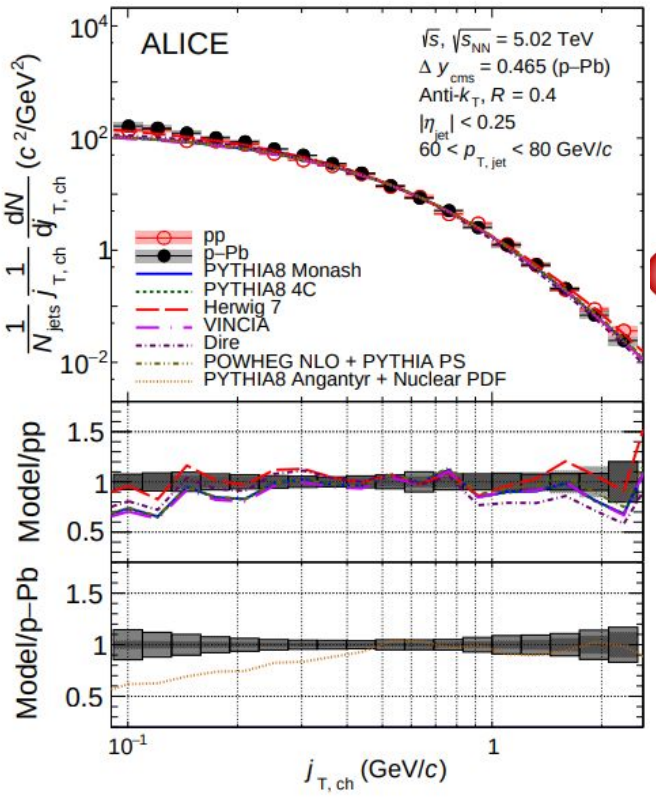


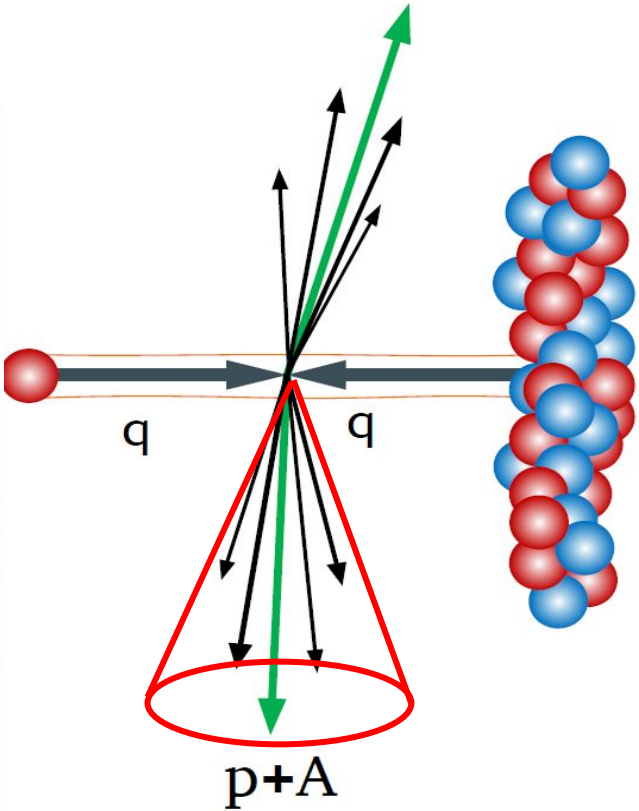
- Overall small excess but can be described without quenching.

Looking for jet quenching in small systems

- Charged hadron within a jet: transverse structure





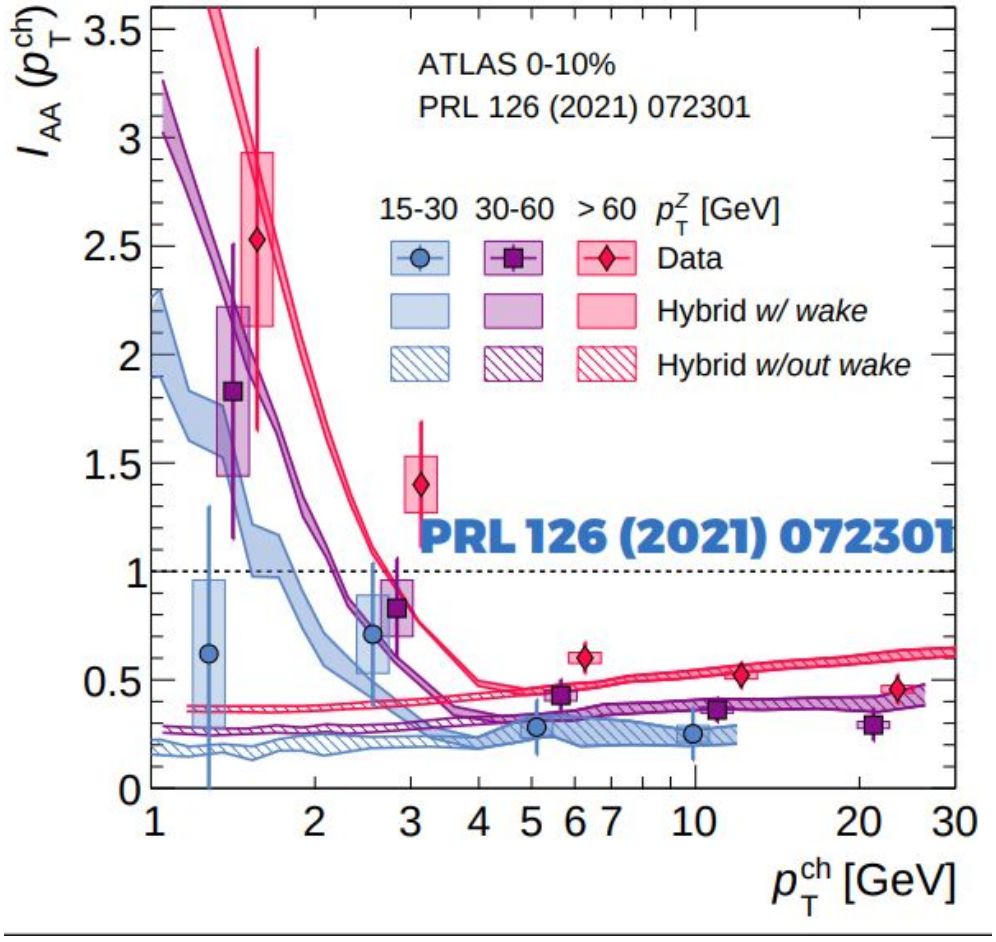


Summary

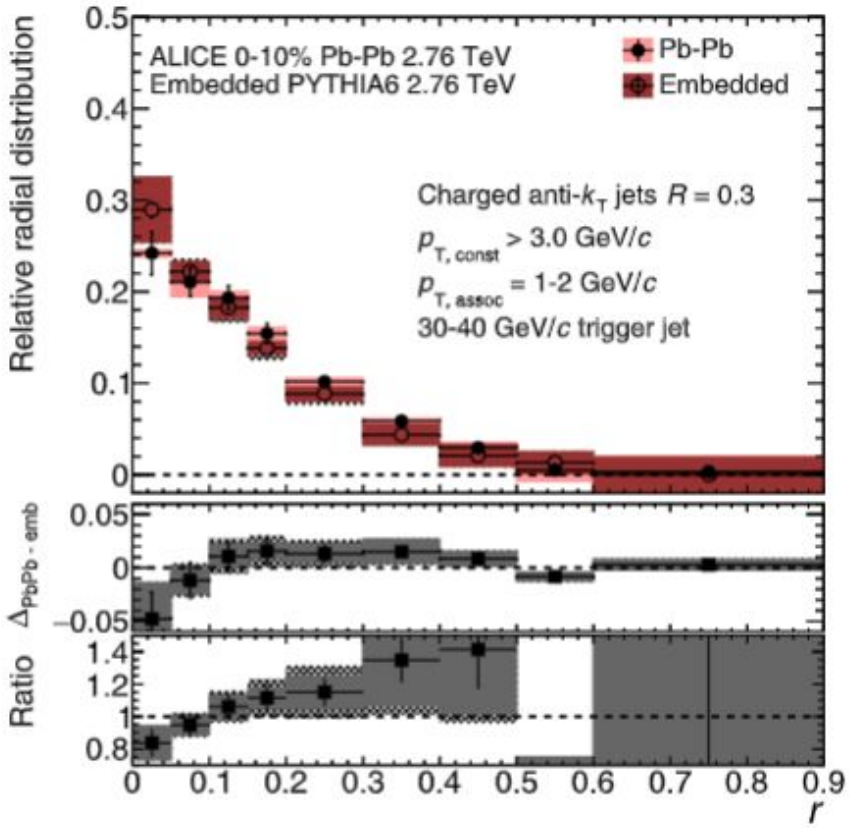
- **“Average” jet energy distributions, i.e. jet shape and fragmentation function fully established**
  - Constrainting features implemented in theoretical models.
  - Experimental methods based on simulations for calibration & training → need for advances of MC modelling.
  - More & new data will allow precise EW boson-tagged measurements
  - Study energy flow wrt number of radiators.
- Need to resolve tension in some measurements.
- Isolate effect of medium response.
  - Can we do some “chemistry” measurement of the soft component?
- Quenching in small system?

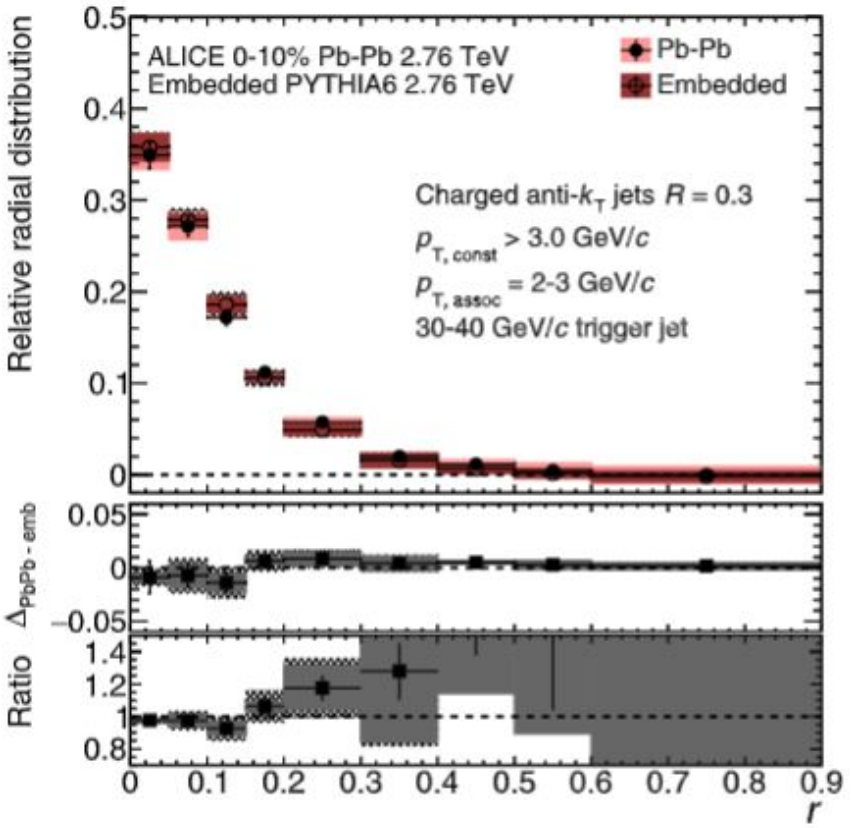
Backup

Z-hadron

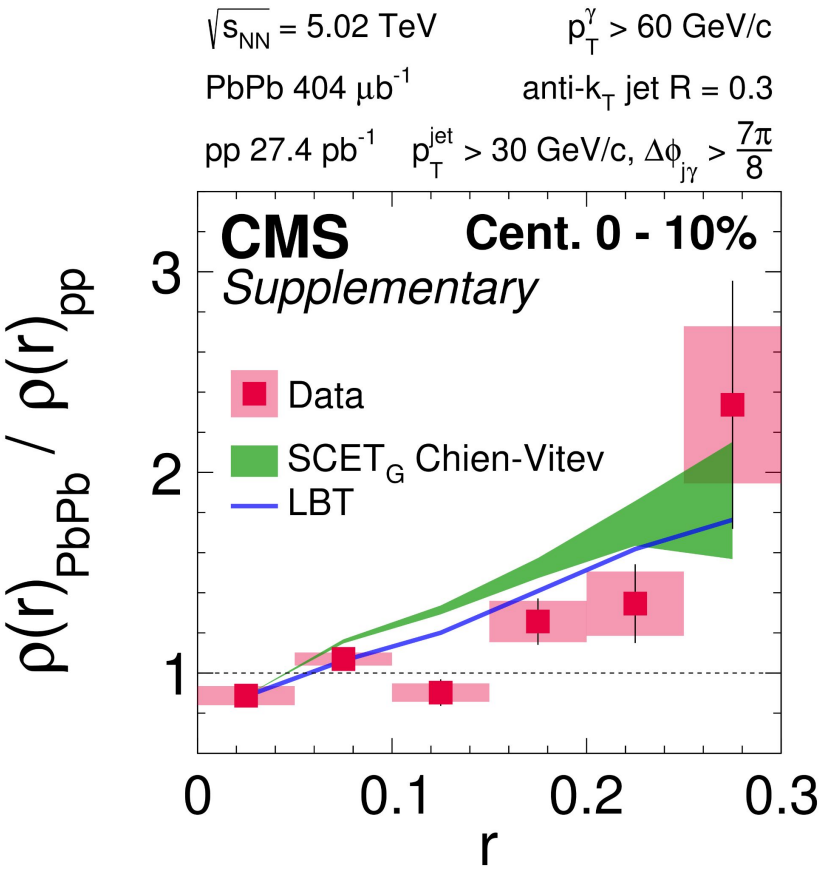

ATLAS 0-10%
PRL 126 (2021) 072301
15-30 30-60 > 60 p_T^Z [GeV]
Data
Hybrid w/ wake
Hybrid w/out wake
PRL 126 (2021) 072301
I_{AA} (p_T^{ch})
p_T^{ch} [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
5
6
7
10
20
30

ALICE radial profile



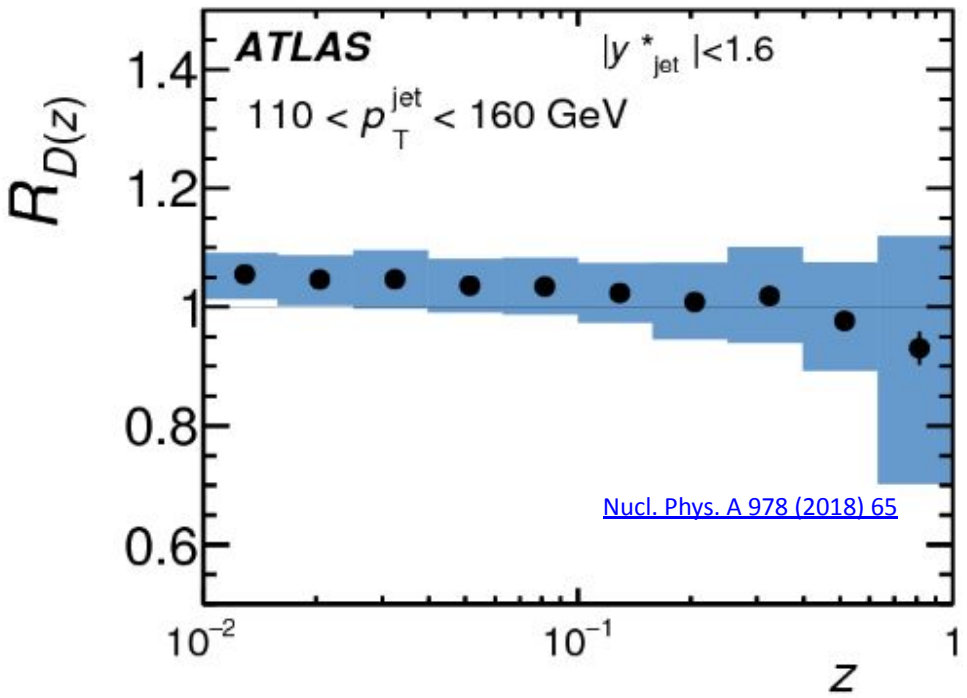


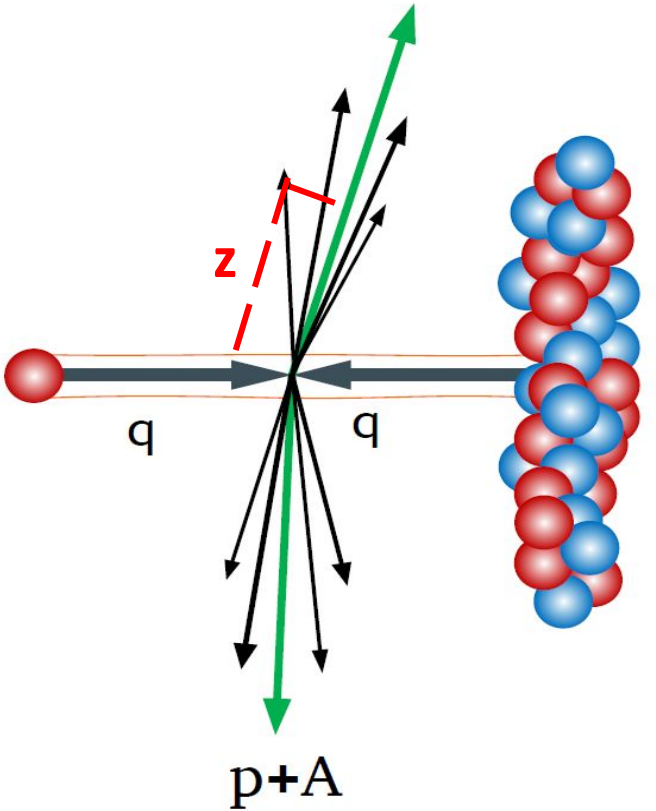
Radial profile - photon-tagged



Looking for jet quenching in small systems

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





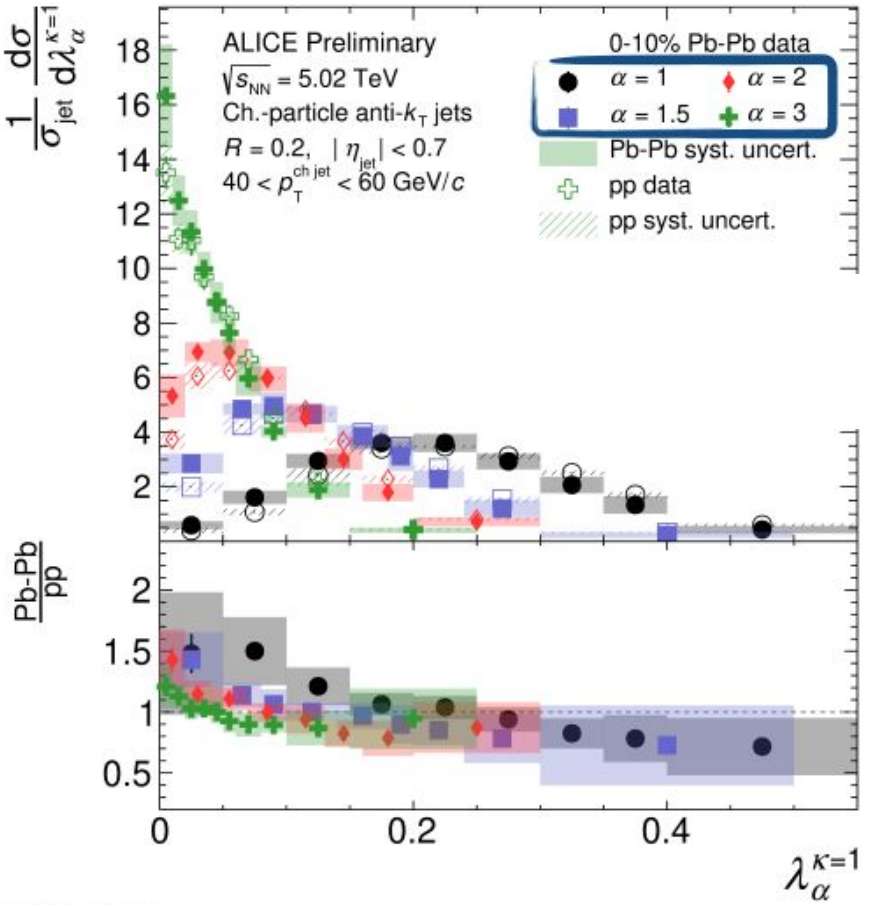
- No modification of parton shower is observed in *p*+Pb system.

Jet angularities

$$\lambda_\alpha \equiv \sum_{i \in \text{jet}} z_i \theta_i^\alpha \qquad z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}} \qquad \theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R}$$

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

Ungroomed
Mild to no modifications in Pb+Pb wrt *pp*.



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