

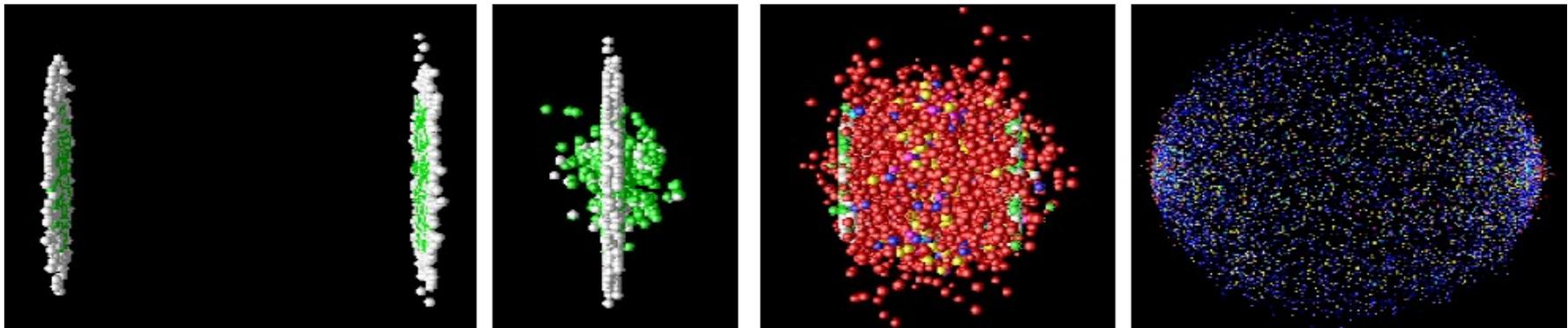


Latest results on jet suppression and jet substructure in heavy-ion collisions with ATLAS

Martin Rybar
for the ATLAS collaboration

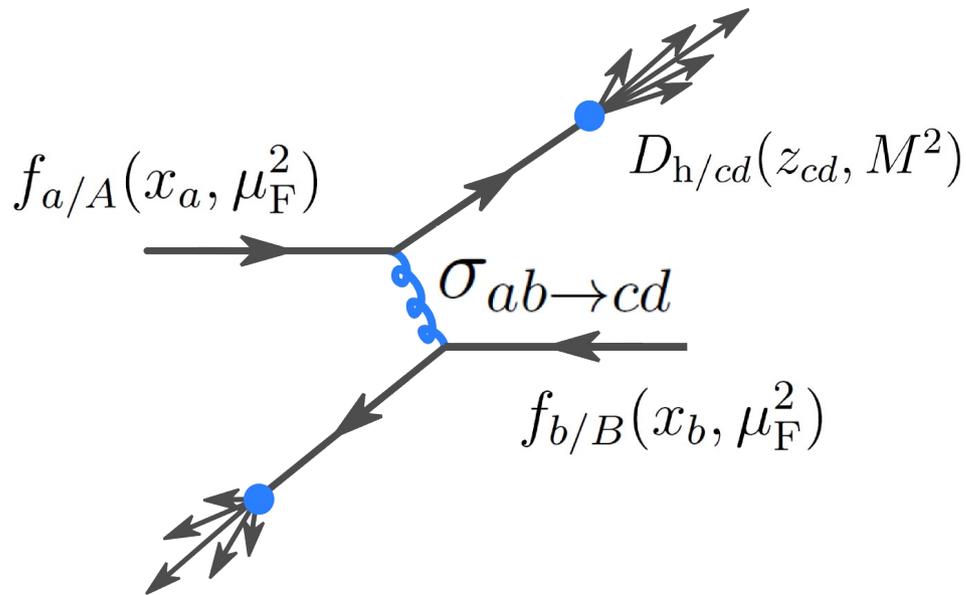
QCD matter at high temperatures

- In HI collisions we want to:
 - Study parton dynamics underlying QGP properties.
 - Characterize macroscopic long-wavelength QGP properties.
 - Understand particle production mechanism both in small and larger systems.
 - Understand the initial state effects and study nPDF effects
- We can achieve that **by using (hard) probes of different scales...**

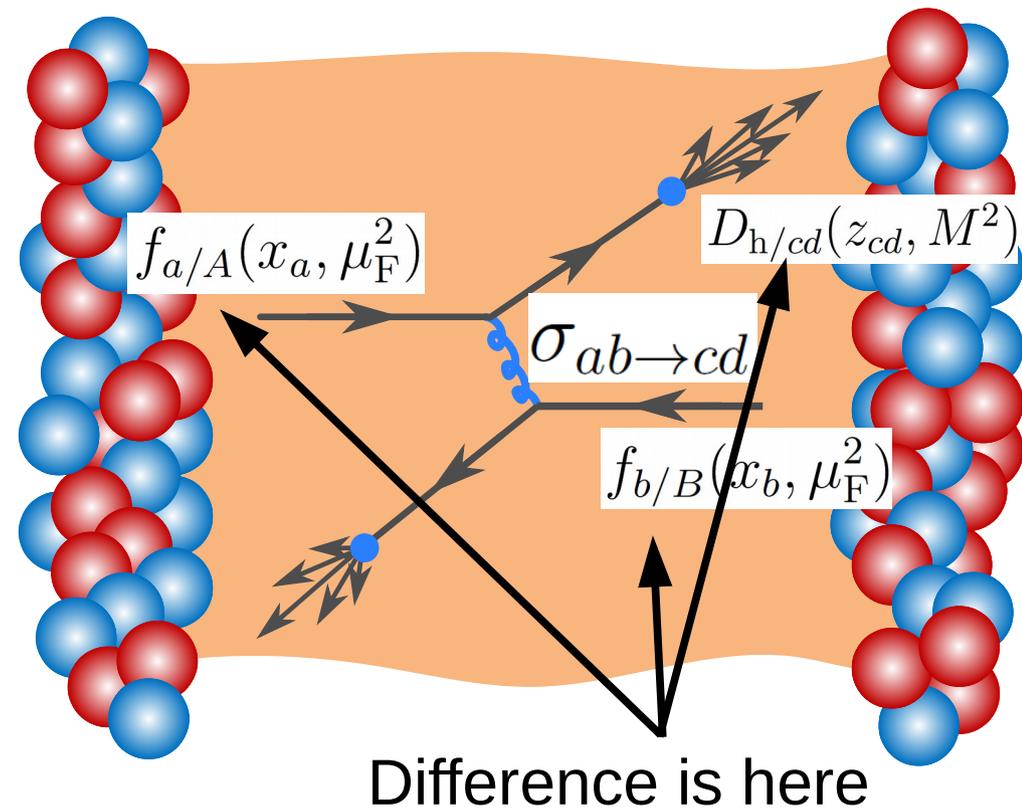


Jets in quark-gluon plasma

hadron-hadron



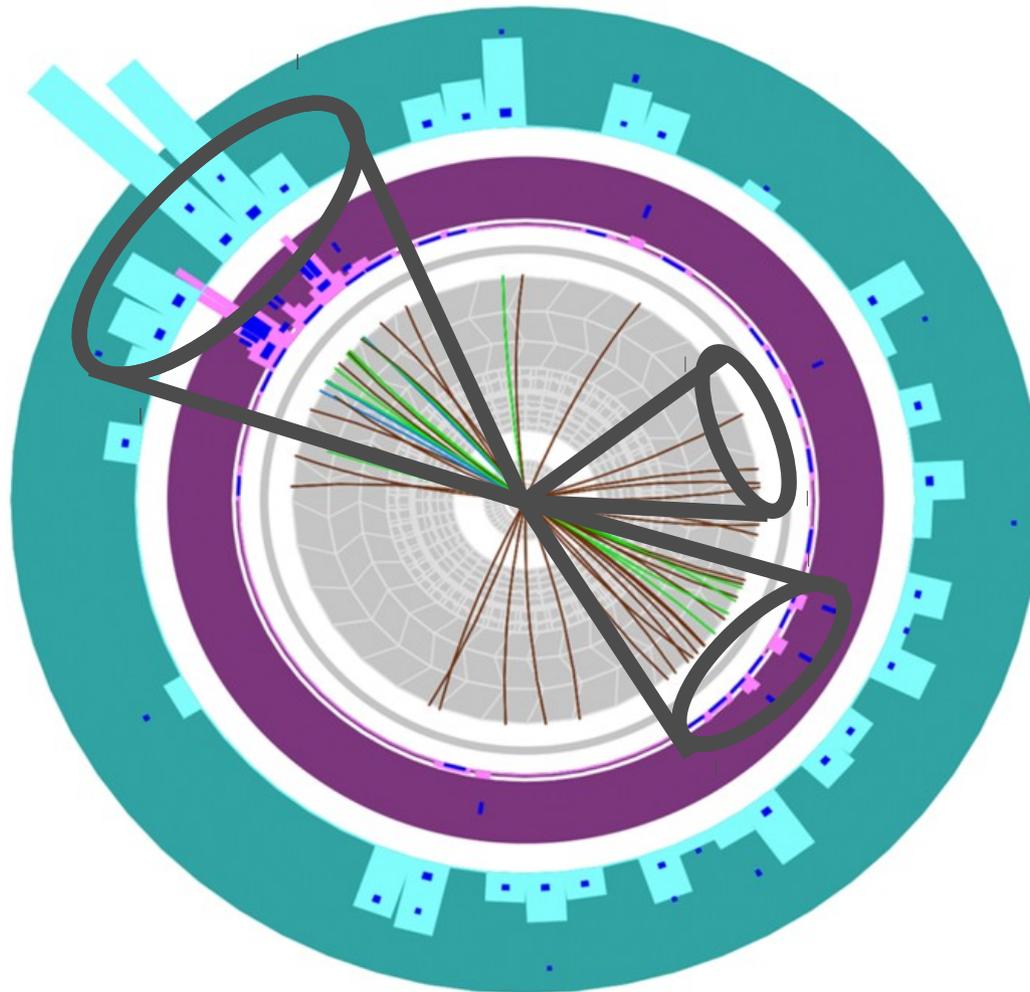
nucleus-nucleus



- How much modification is from different initial state like nPDFs?
- Parton shower is affected by the medium.

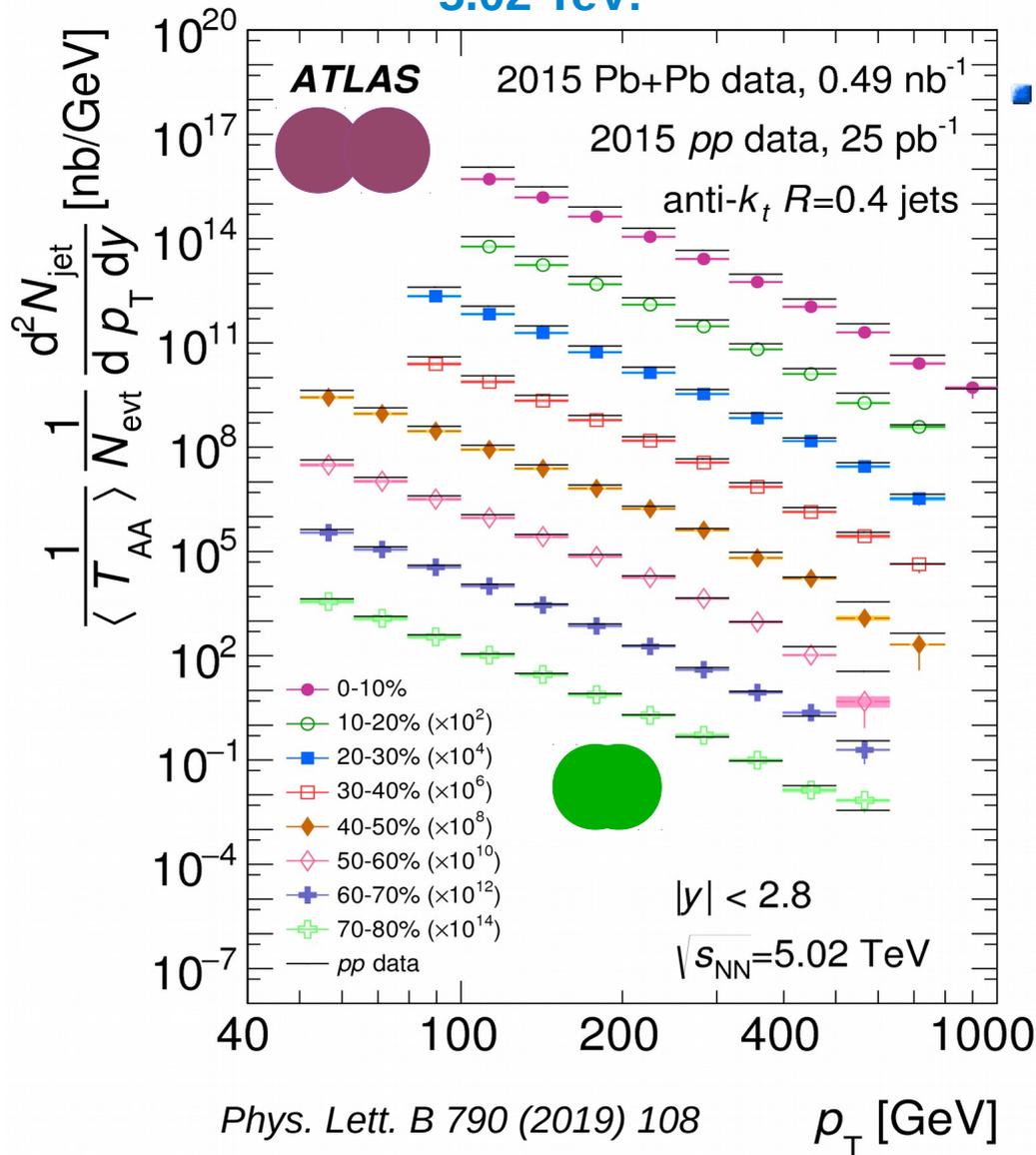
Jet quenching measurement

Inclusive jet spectra



Inclusive jet spectra in pp and Pb+Pb collisions

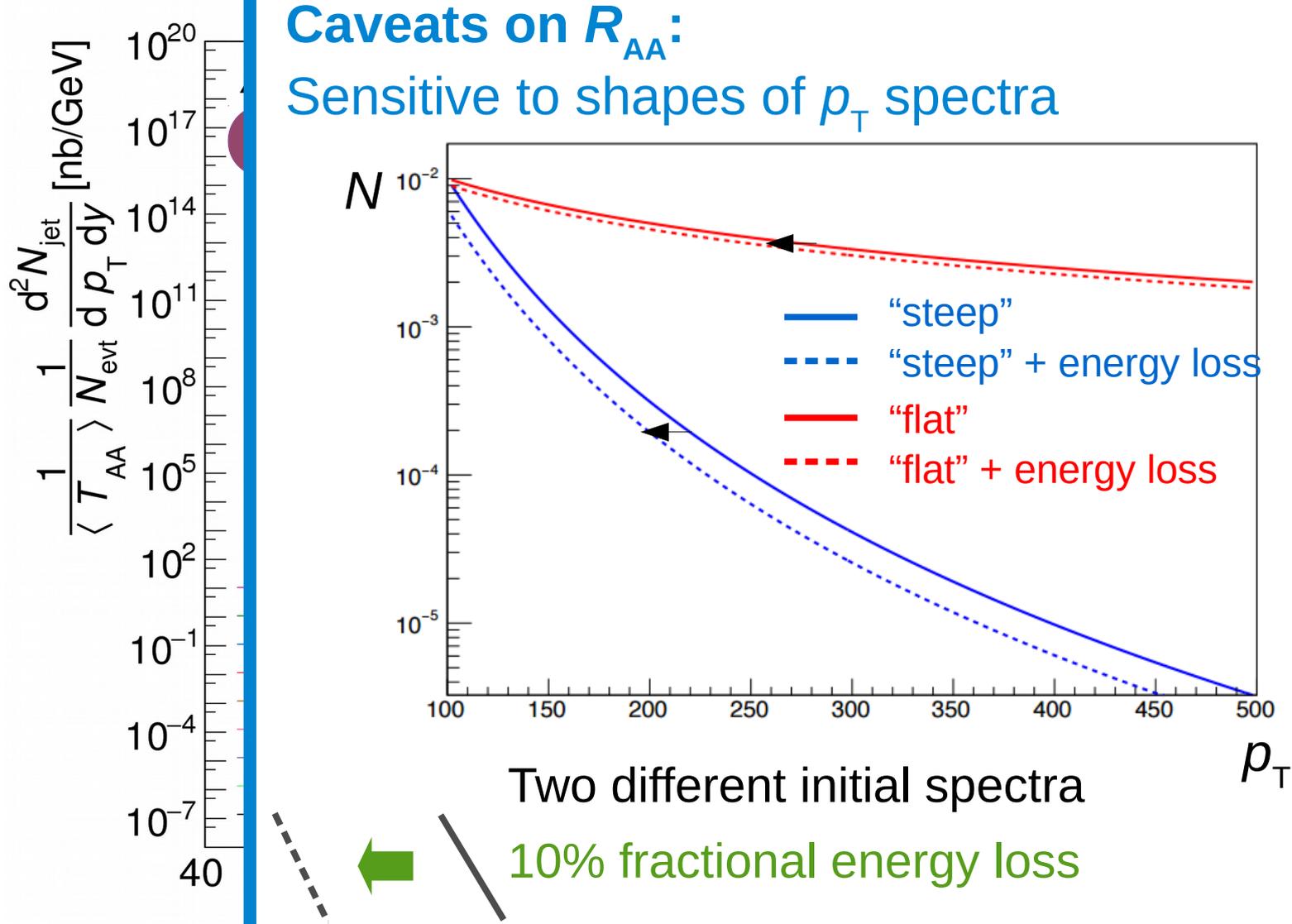
5.02 TeV:



- Comparison of HI and pp collisions through nuclear modification factor

$$R_{AA} = \frac{1}{N_{\text{coll}}} \frac{\text{Scaled A+A}}{\text{pp}} = \frac{1}{N_{\text{coll}}} \frac{\frac{dN_{AA}}{dp_T}}{\frac{dN_{pp}}{dp_T}}$$

Inclusive jet spectra in pp and Pb+Pb collisions



pp collisions
Nucleon-Nucleon
interaction factor

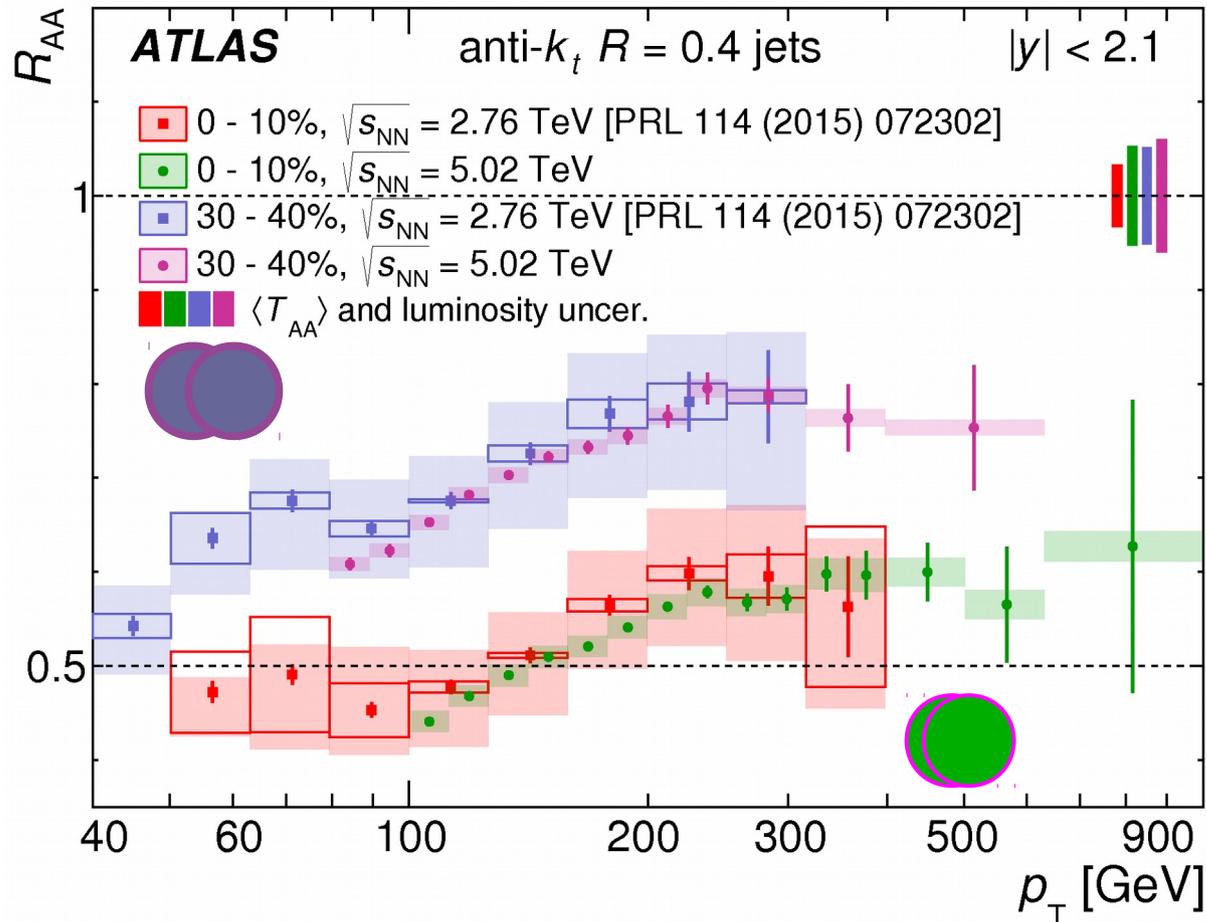
Scaled A+A

$$\frac{1}{N_{coll}} \frac{dN_{AA}}{dp_T}$$

$$\frac{dN_{pp}}{dp_T}$$

pp

Suppression of single jet spectra



- R_{AA} exhibits weak p_T dependence.
- Same magnitude of R_{AA} seen between 2.76 TeV and 5.02 TeV.
- Access to jet p_T up to 1 TeV and improved systematic uncertainties at 5.02 TeV.

What about rapidity dependence?

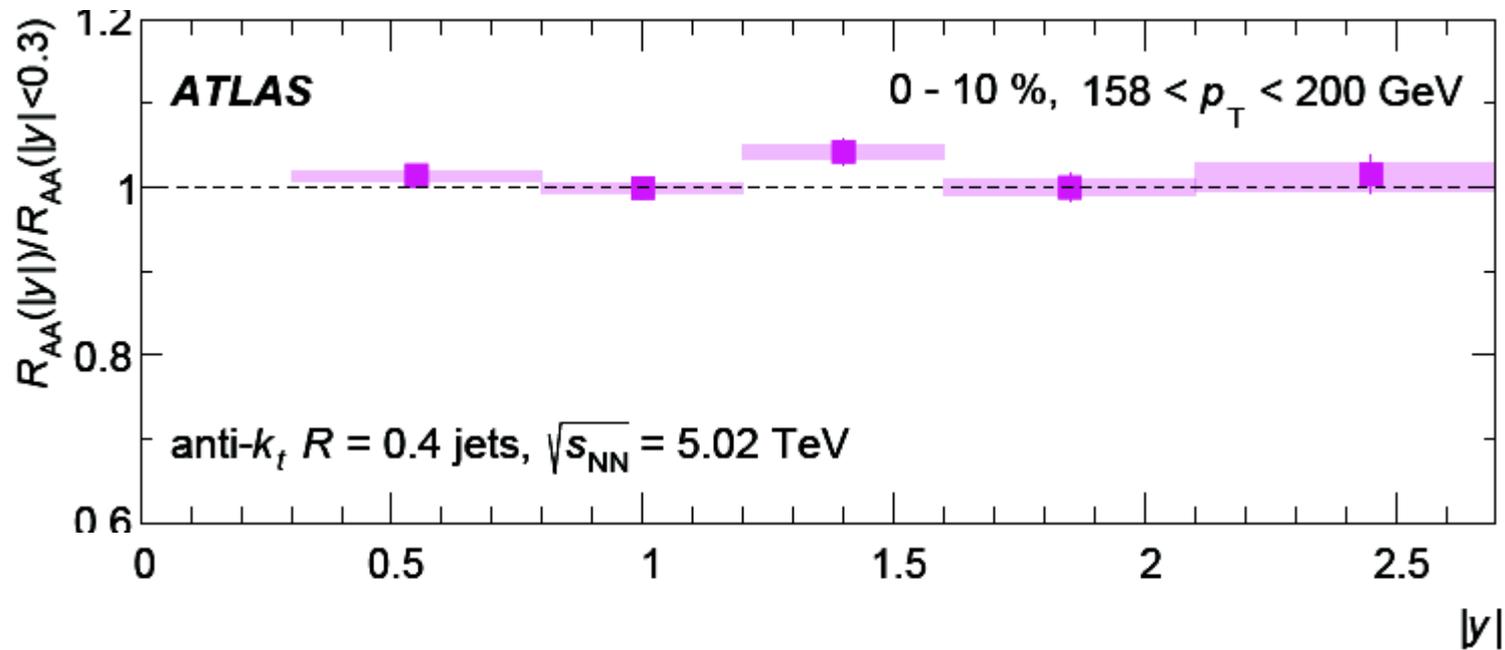
Two competing effects:

- Increasing rapidity → steeper spectrum → decrease of R_{AA}
- Increasing rapidity → higher quark fraction → increase of R_{AA}

What about rapidity dependence?

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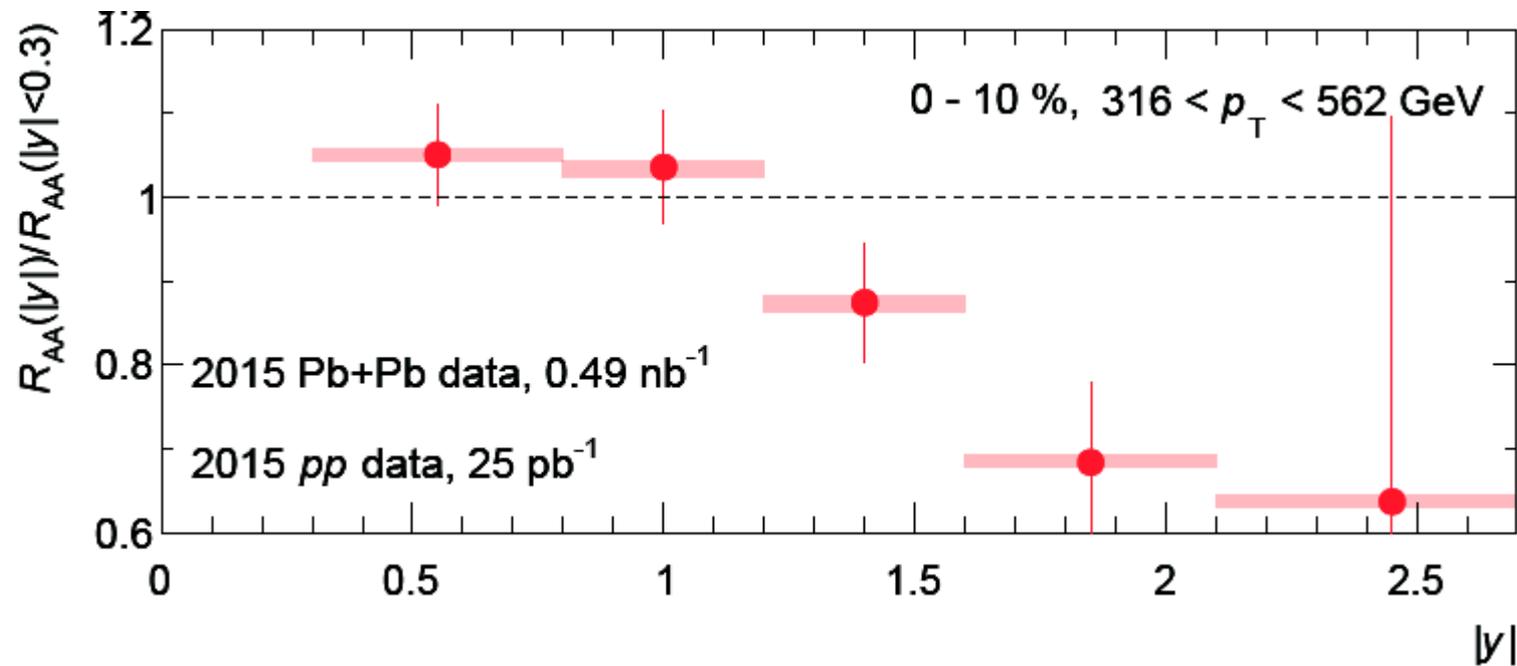


\rightarrow Effects seems to cancel at low and intermediate p_T .

What about rapidity dependence?

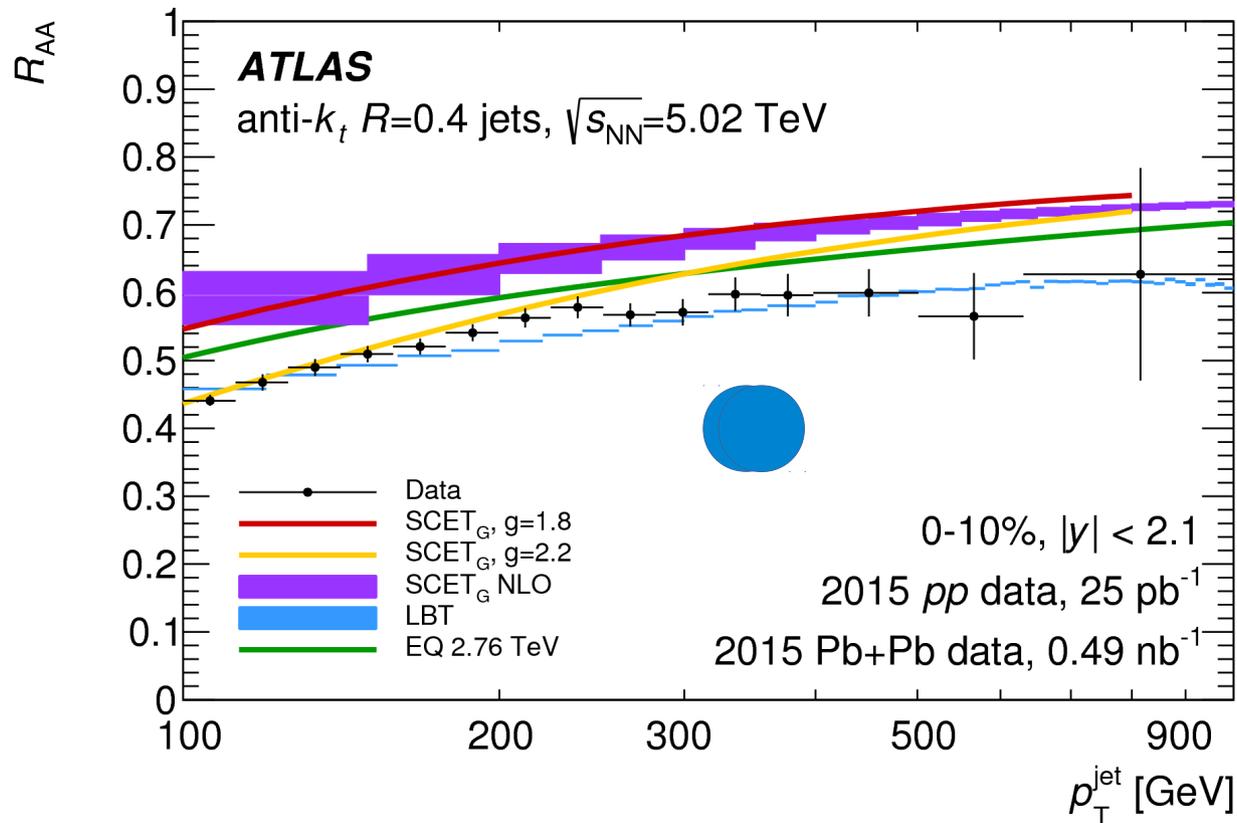
Two competing effects:

- Increasing rapidity \rightarrow steeper spectrum \rightarrow decrease of R_{AA}
- Increasing rapidity \rightarrow higher quark fraction \rightarrow increase of R_{AA}



\rightarrow Larger suppression in forward region at high p_T likely dominated by steepness of spectra.

Theoretical descriptions



Lorentz Boltzmann Transport (LBT) model (arXiv:1503.03313)

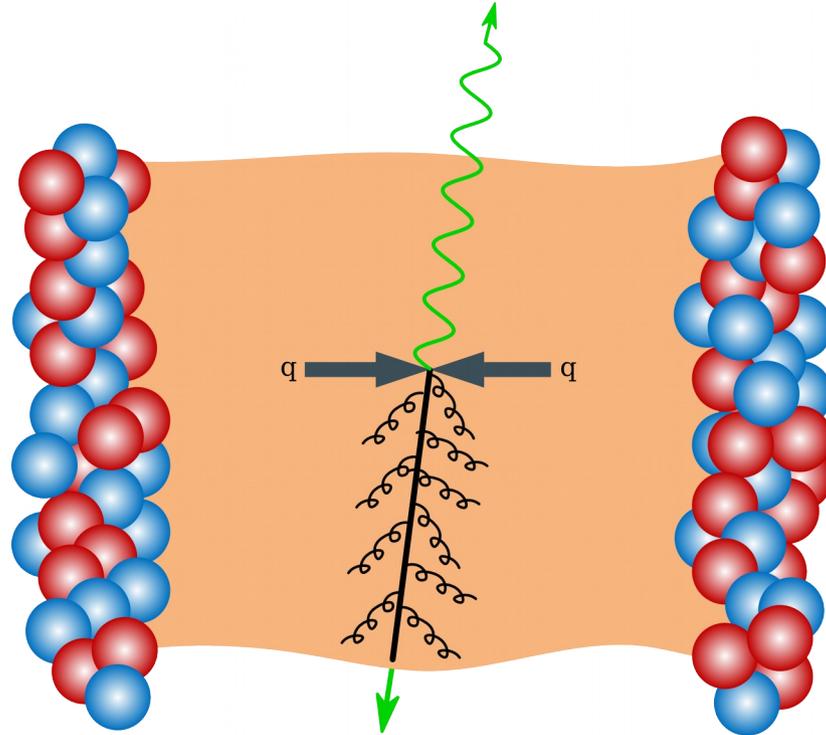
Soft Collinear Effective Field Theory (SCETg) (arXiv:1509.02936)

Effective Quenching (EQ) model (arXiv:1504.05169)

- Models are able to describe trends in the data.

Jets + vector bosons

- Different hard probes interact with medium differently.

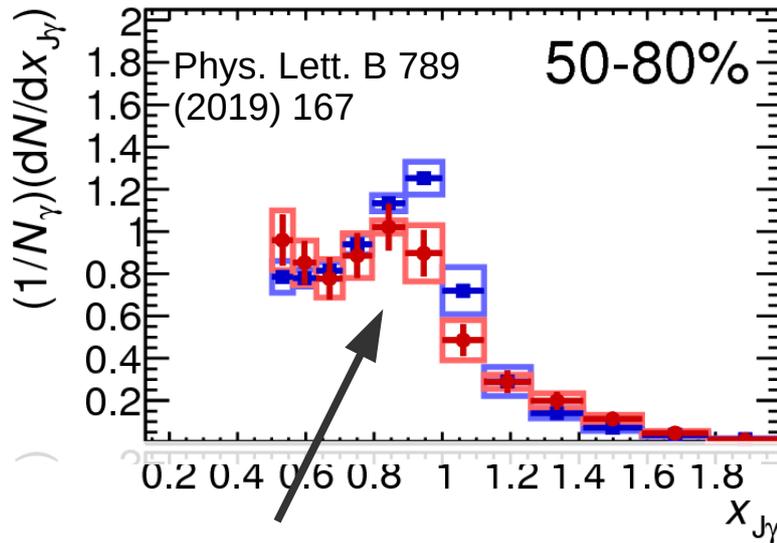


- Photons and Z's calibrate the parton energy.
- Flavor fraction differs compared to di-jets.

Photon-jet correlations

- What is the absolute amount of energy lost in QGP?

➔ Measurement of balance in photon-jet system $x_{J\gamma} = p_T^{\text{jet}} / p_T^{\gamma}$



ATLAS

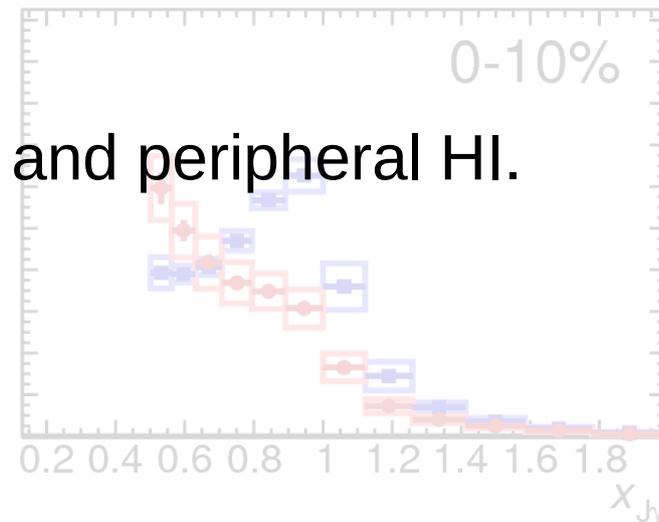
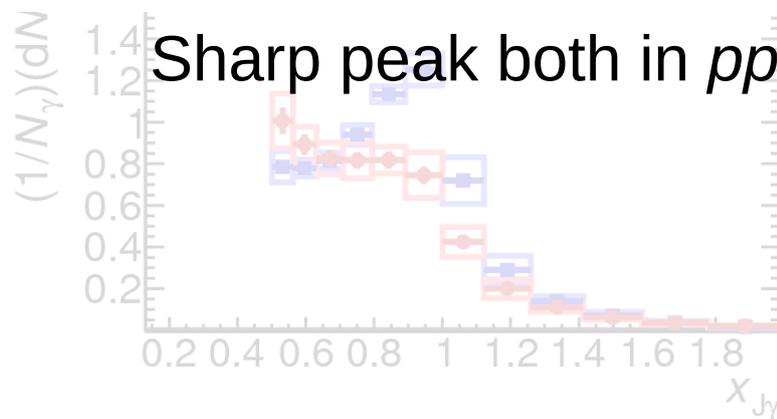
pp 5.02 TeV, 25 pb⁻¹

Pb+Pb 5.02 TeV, 0.49 nb⁻¹

$p_T^{\gamma} = 63.1-79.6$ GeV

■ pp (same each panel)

■ Pb+Pb

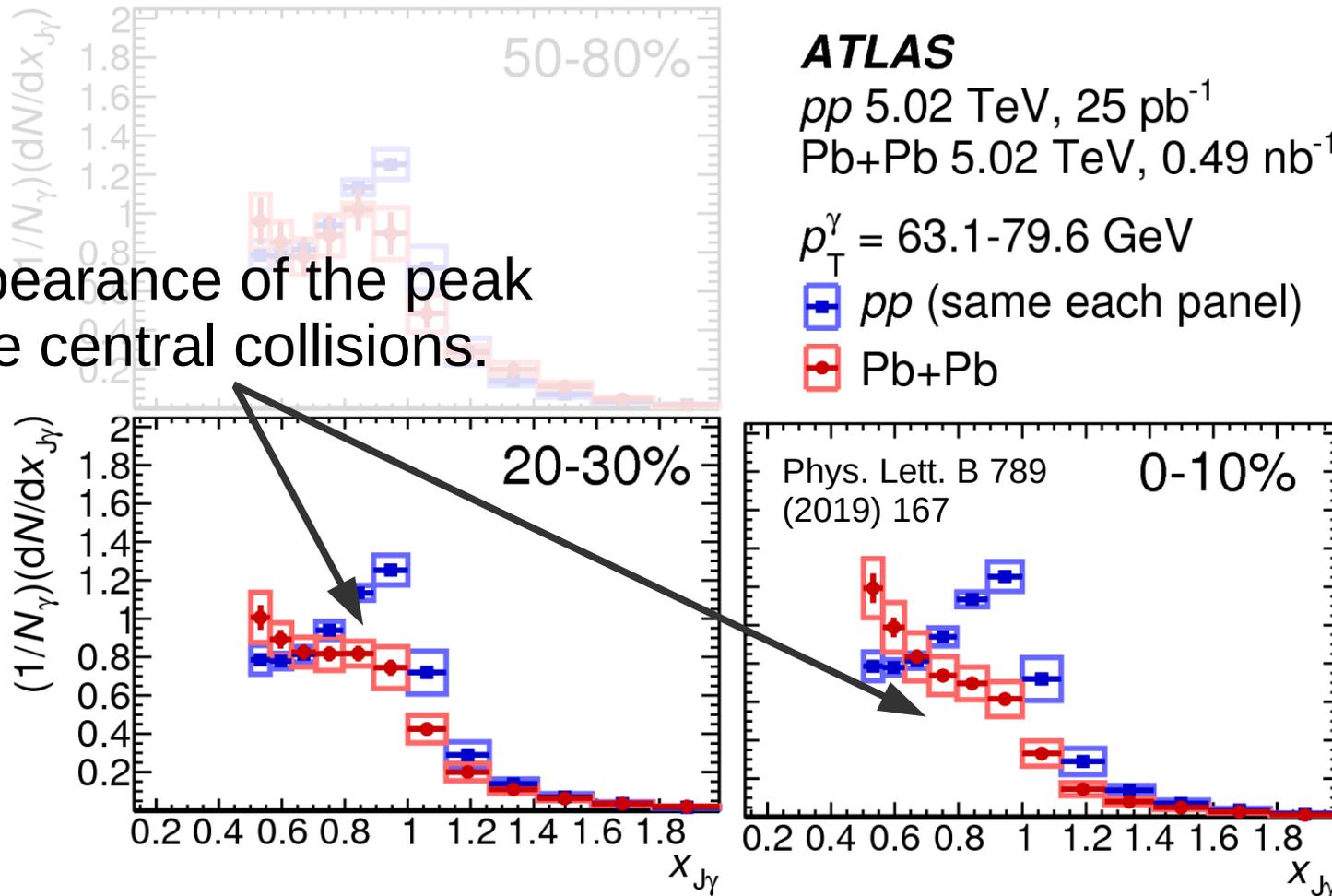


Photon-jet correlations

- What is the absolute amount of energy lost in QGP?

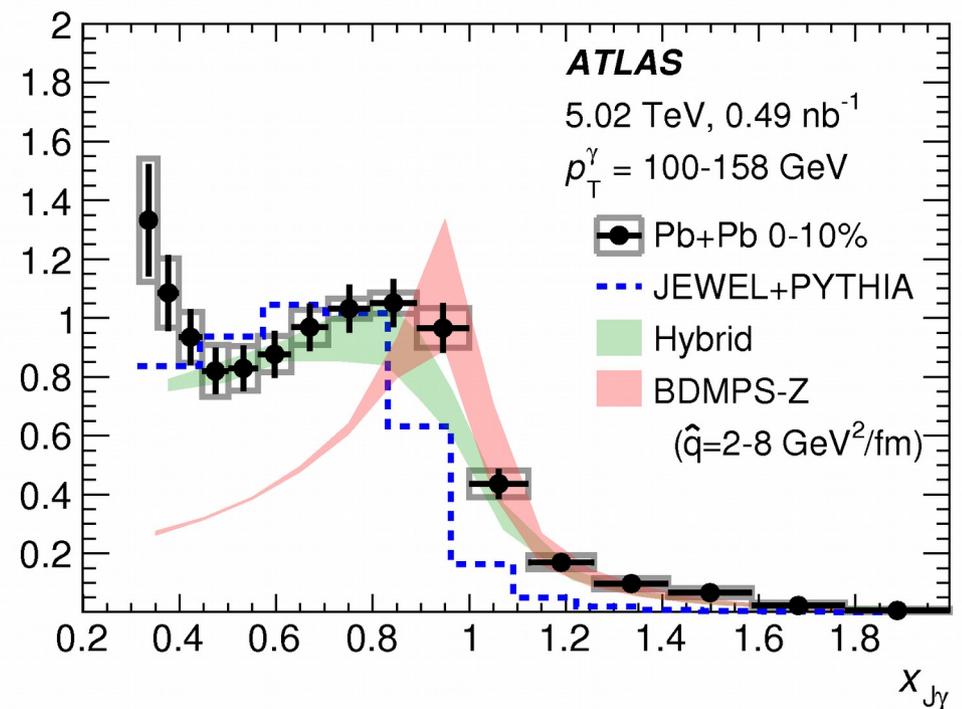
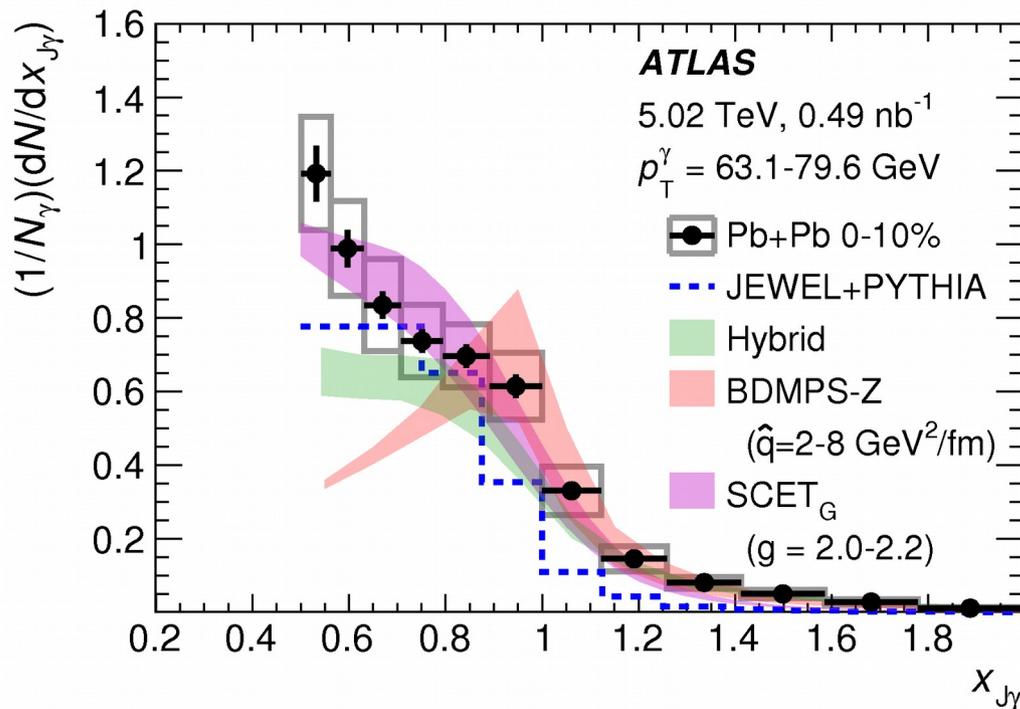
➔ Measurement of balance in photon-jet system $x_{J\gamma} = p_T^{\text{jet}} / p_T^{\gamma}$

Disappearance of the peak
in more central collisions.



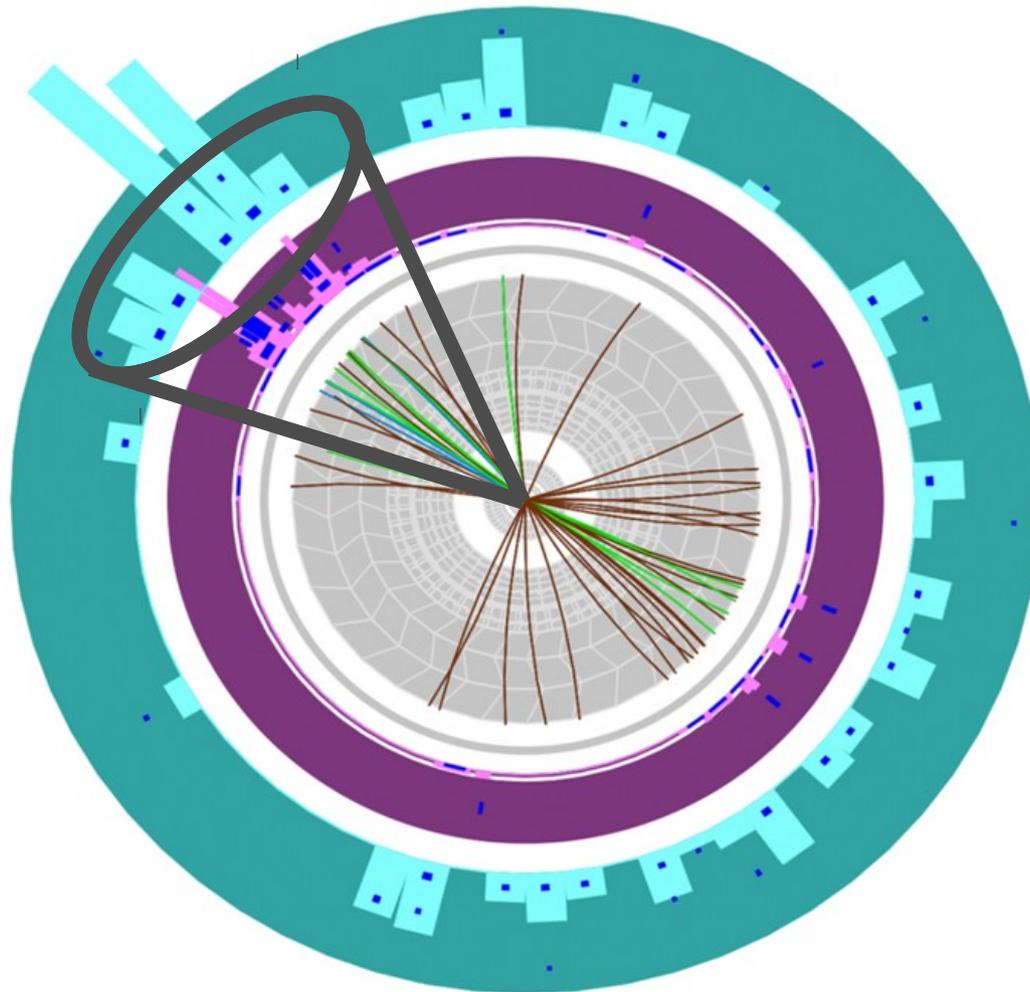
Can theory describe observed trends?

Increasing photon p_T →



- Comparison to SCETg, Hybrid model, BDMPS-Z ([arXiv1803.10533](https://arxiv.org/abs/1803.10533)), and JEWEL MC ([arXiv:1608.03099](https://arxiv.org/abs/1608.03099))
- Some models able to describe basic features.
- Difficult to describe the detailed behavior of the distribution.

Jet structure in Pb+Pb collisions



How much is the jet structure modified in Pb+Pb?

- Measurement of fragmentation functions

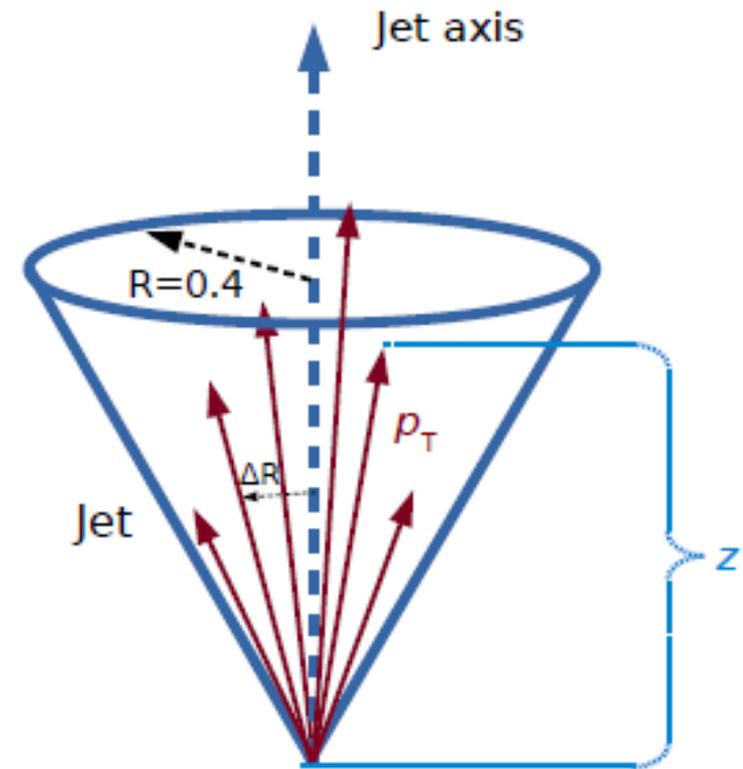
$$D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{dn_{\text{ch}}}{dz}, \text{ where } z \equiv p_T \cos \Delta R / p_T^{\text{jet}} \quad D(p_T) \equiv \frac{1}{N_{\text{jet}}} \frac{dn_{\text{ch}}}{dp_T}$$

Shower in medium

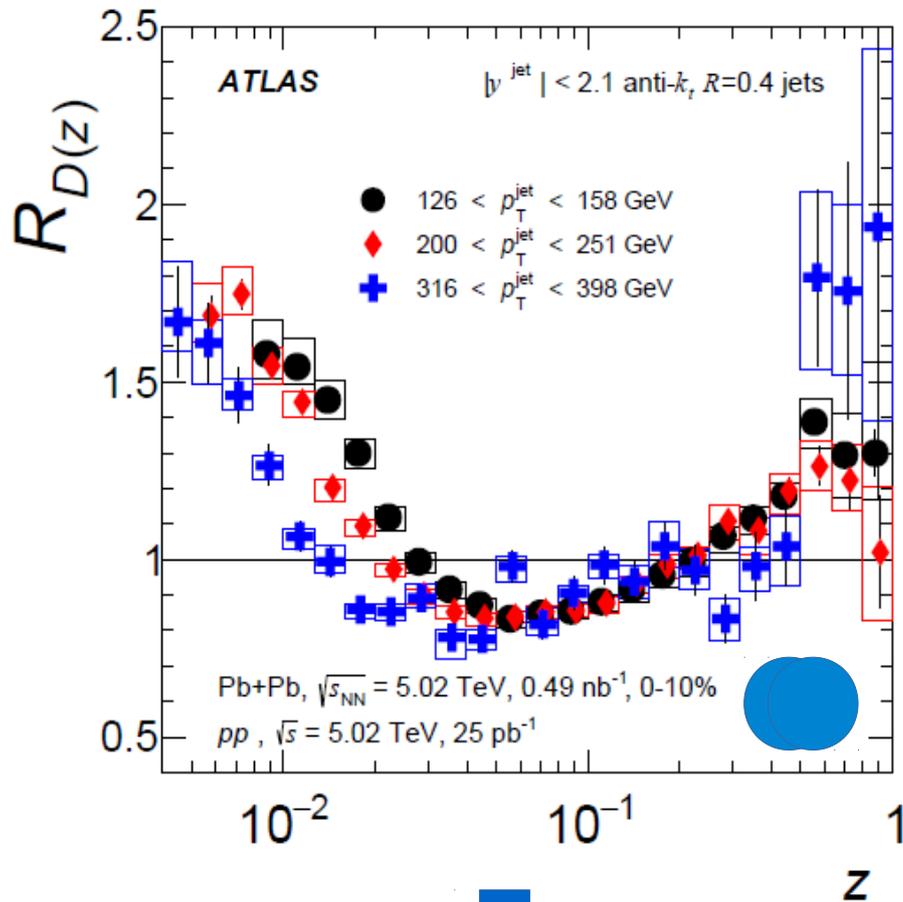
$$R_D(z) \equiv \frac{D(z)_{\text{PbPb}}}{D(z)_{\text{pp}}}$$

Shower in vacuum

- Corrected by 2D unfolding to particle level.

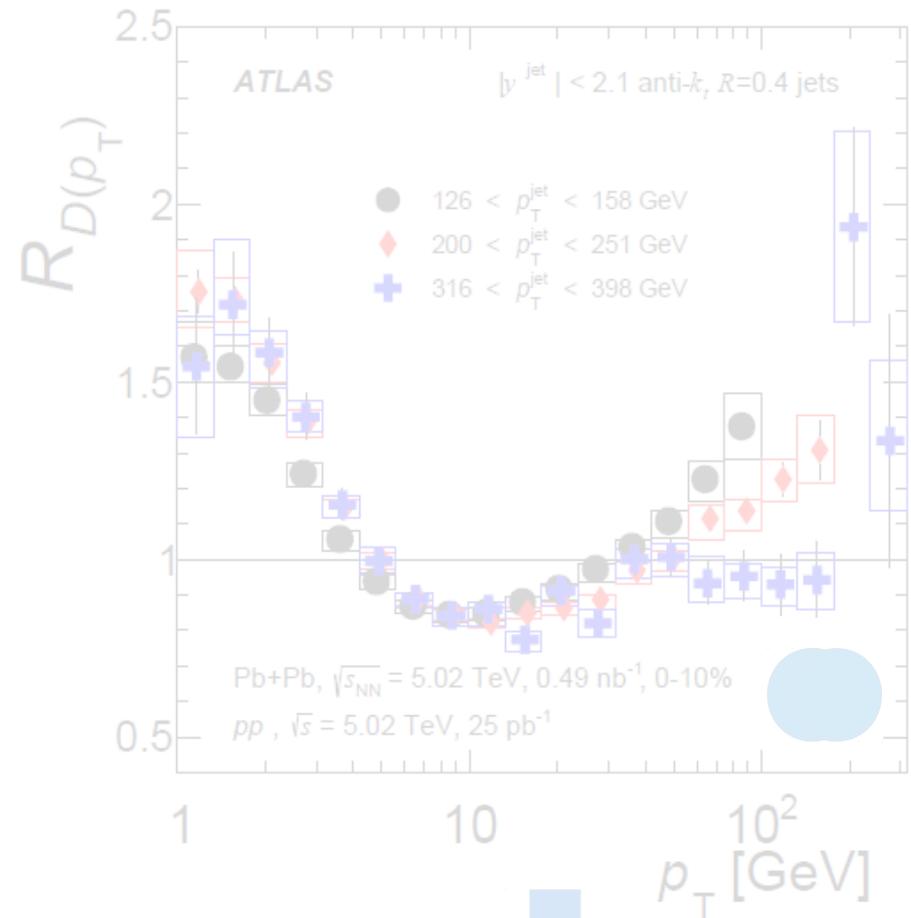


Modification in central collisions



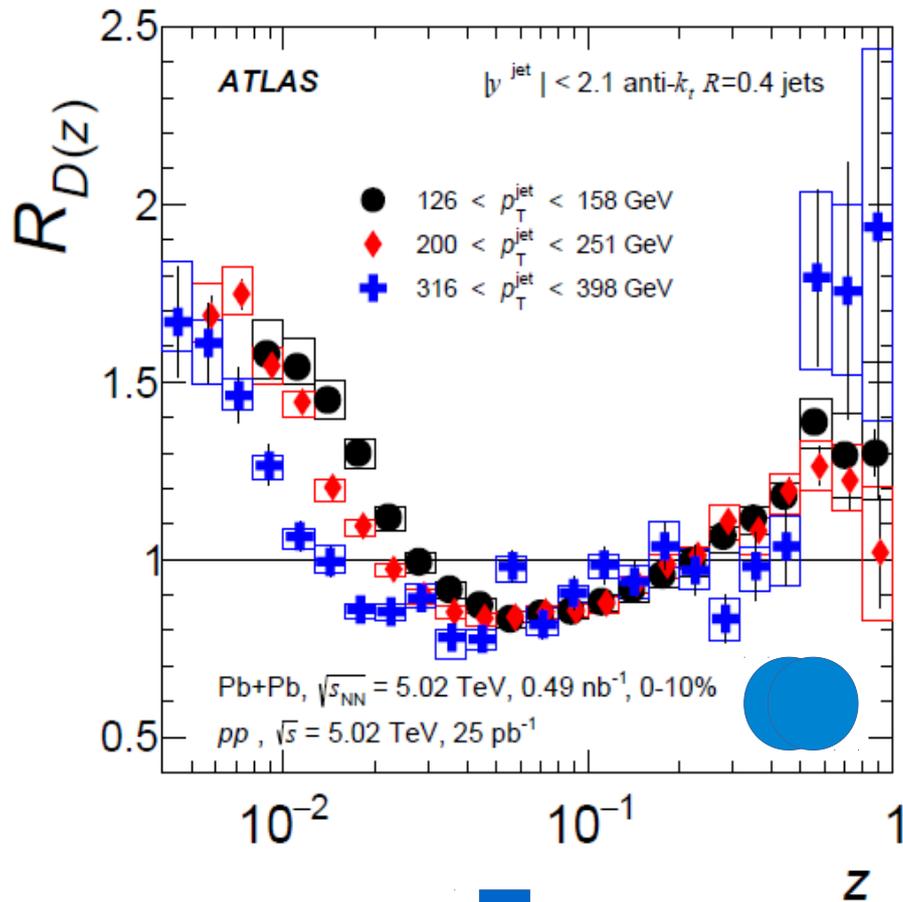
Enhancement of hard fragments.

No dependence on jet p_T observed at high z for jets up to 400 GeV.



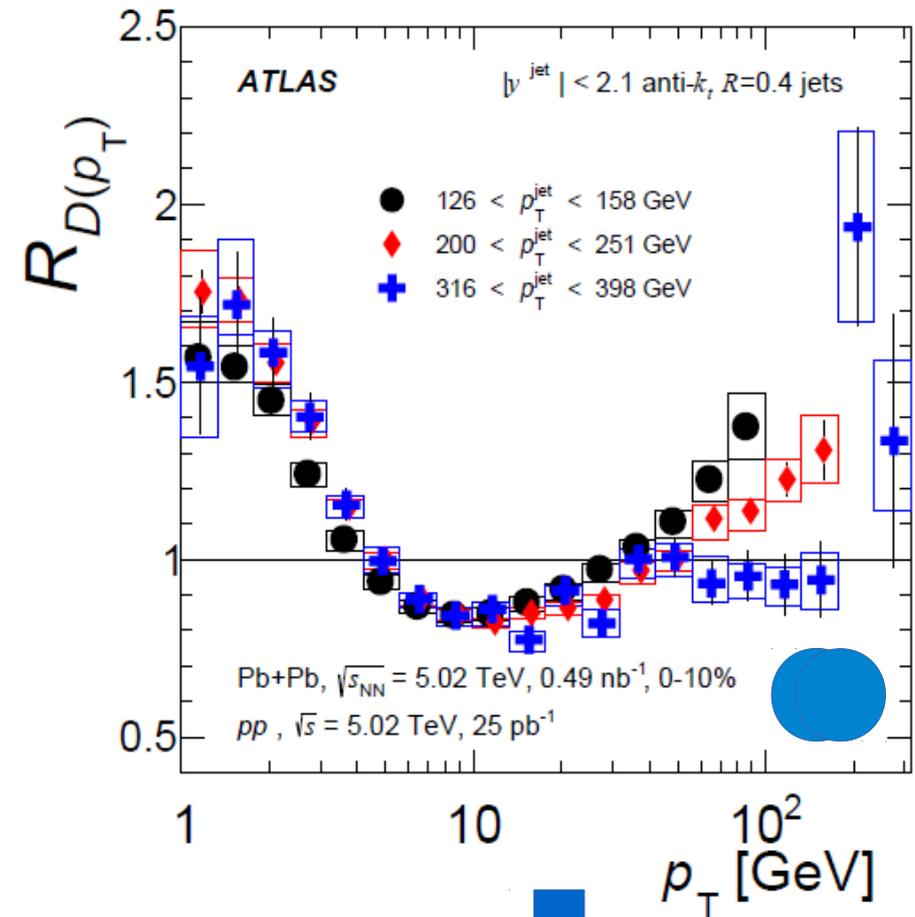
Enhancement of soft fragments.

Modification in central collisions



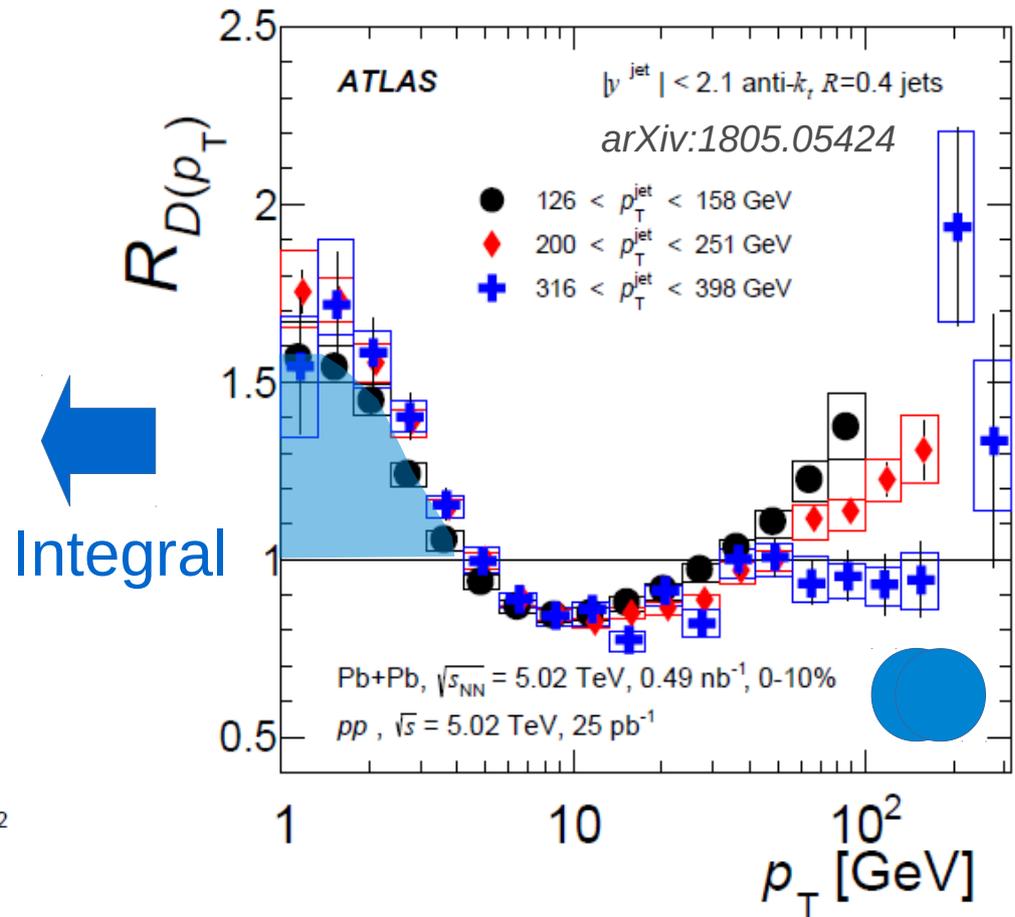
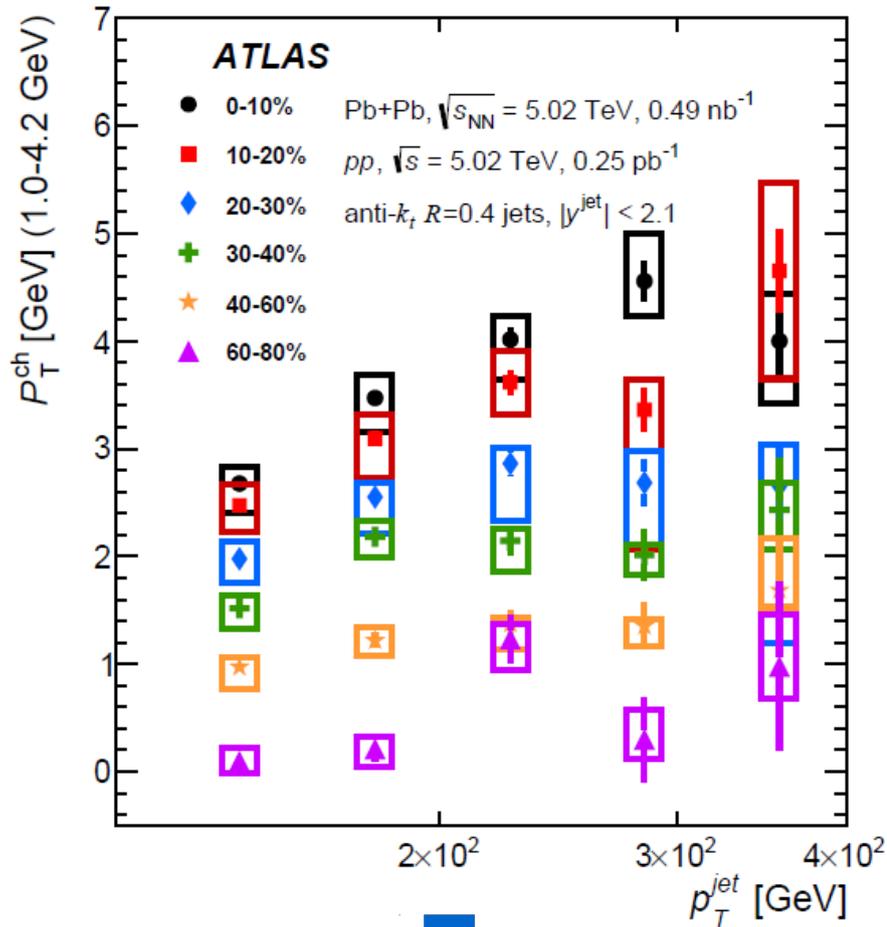
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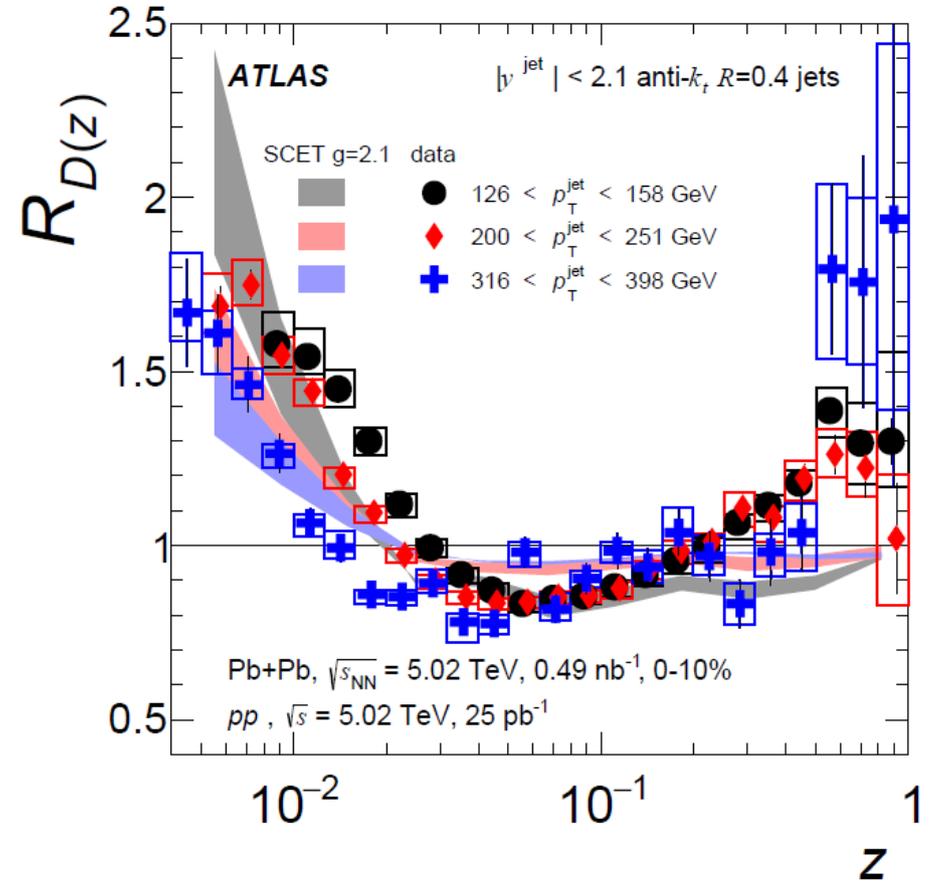
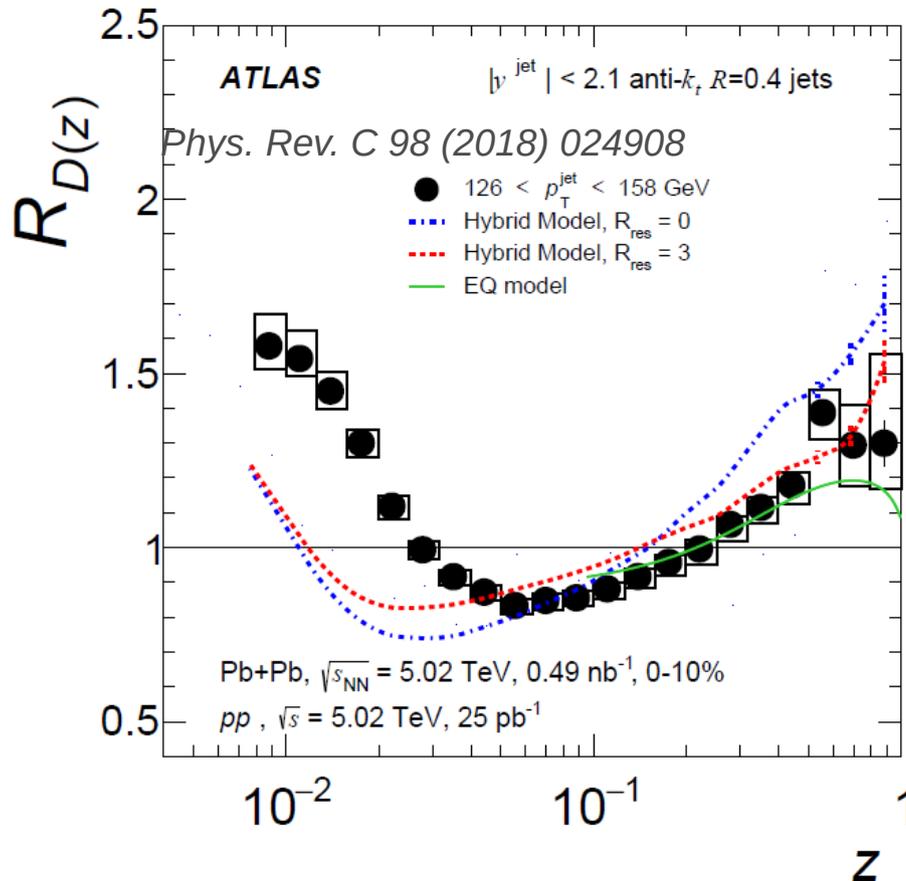
Modification in central collisions



Integral

- Jet p_T dependence to the enhancement.
- Response of the medium to the high- p_T parton?

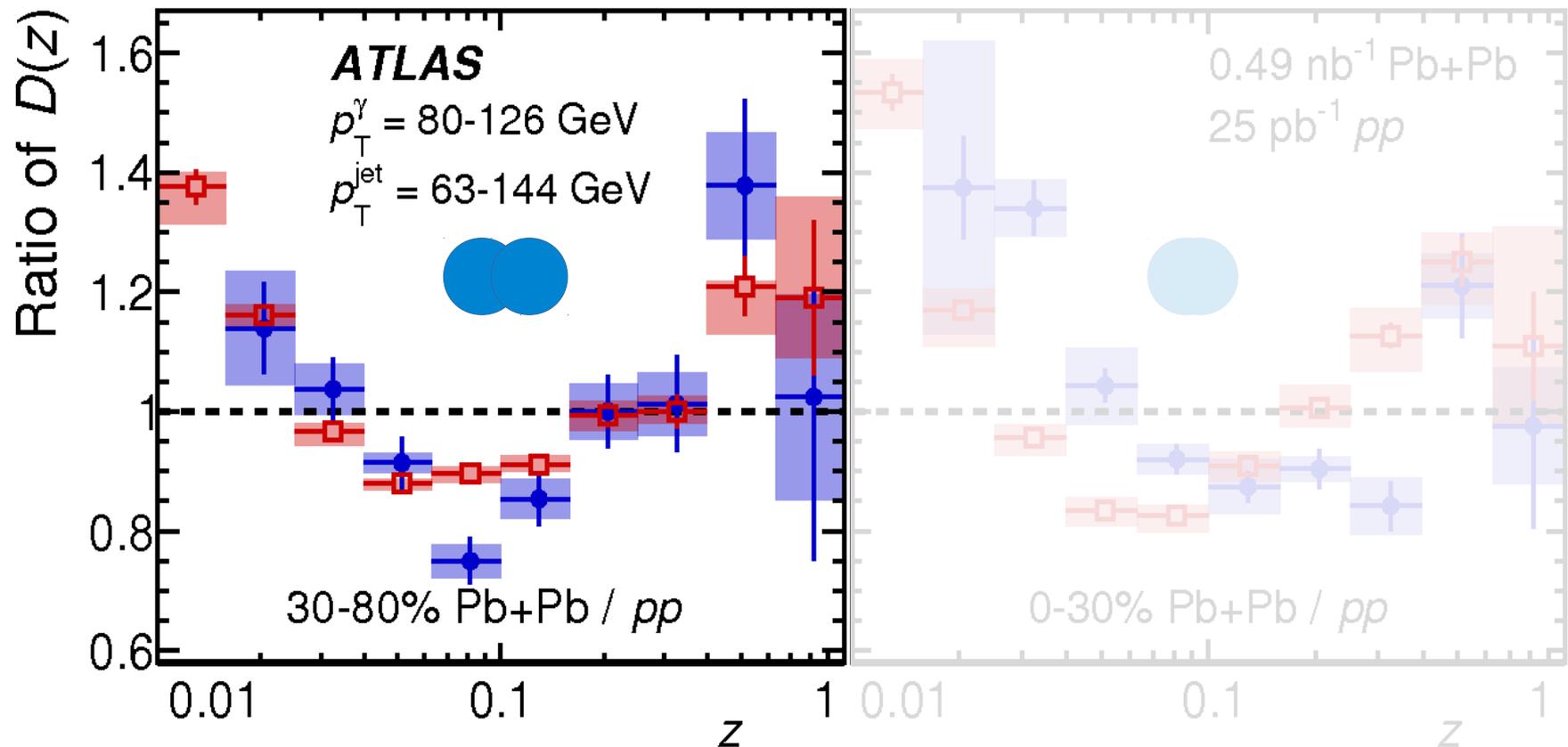
Can theory describe measurement?



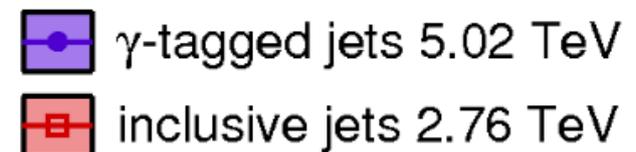
- **Hybrid model** ([arXiv:1707.05245](https://arxiv.org/abs/1707.05245)) consistent at high z , disagreement at low z due to simplistic medium response modeling.
- **EQ model** ([arXiv:1504.05169](https://arxiv.org/abs/1504.05169)) is able to describe the high- z excess.
- **SCETg** ([arXiv:1509.02936](https://arxiv.org/abs/1509.02936)) model is able to qualitatively described the low- z excess.

Photon-tagged jet fragmentation

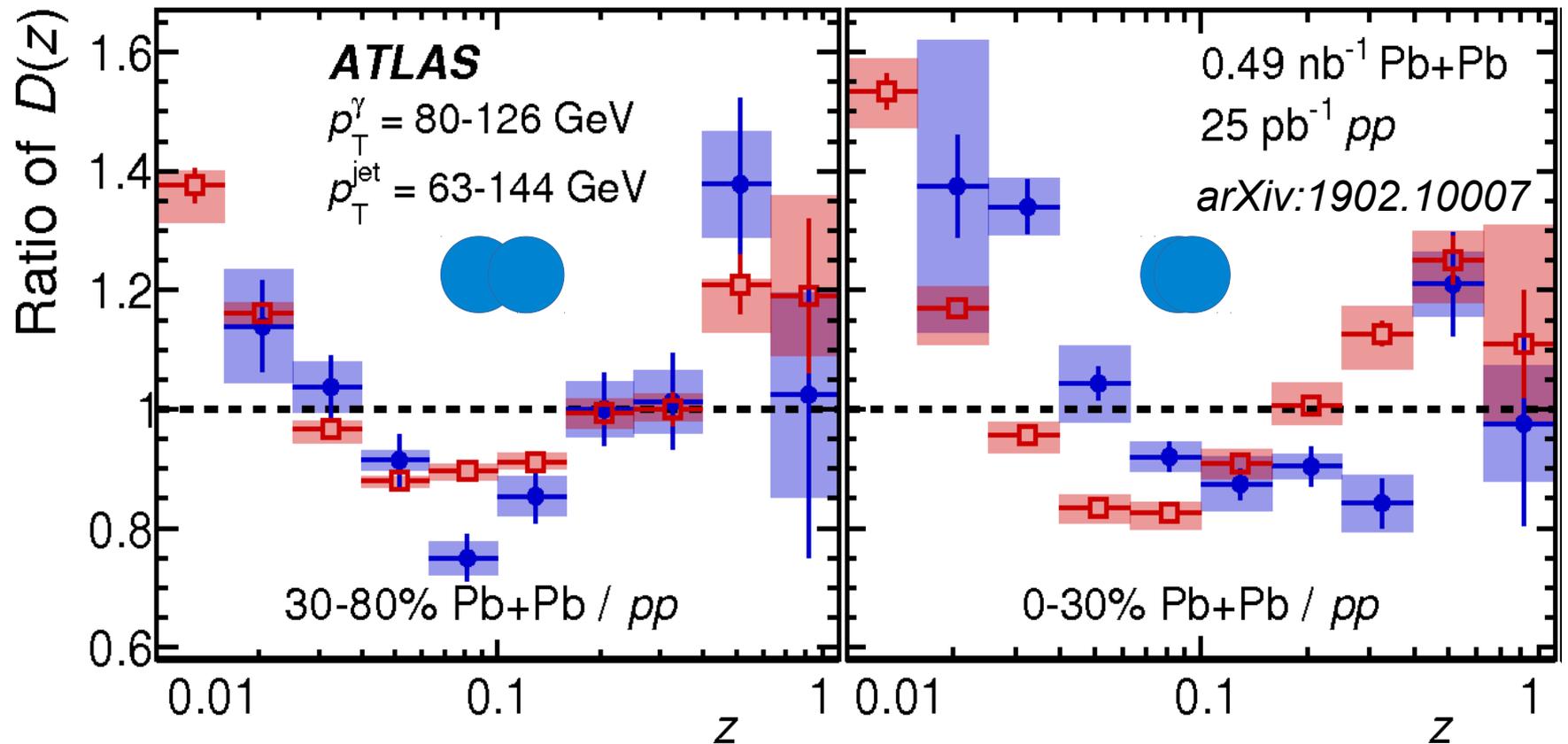
- Enhanced quark jet contribution compared to inclusive jets.
- flavor dependence of quenching.



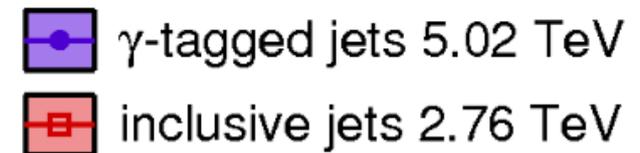
- Statistically limited.
- Same pattern as for inclusive jets.
- Ratios similar in peripheral collisions.



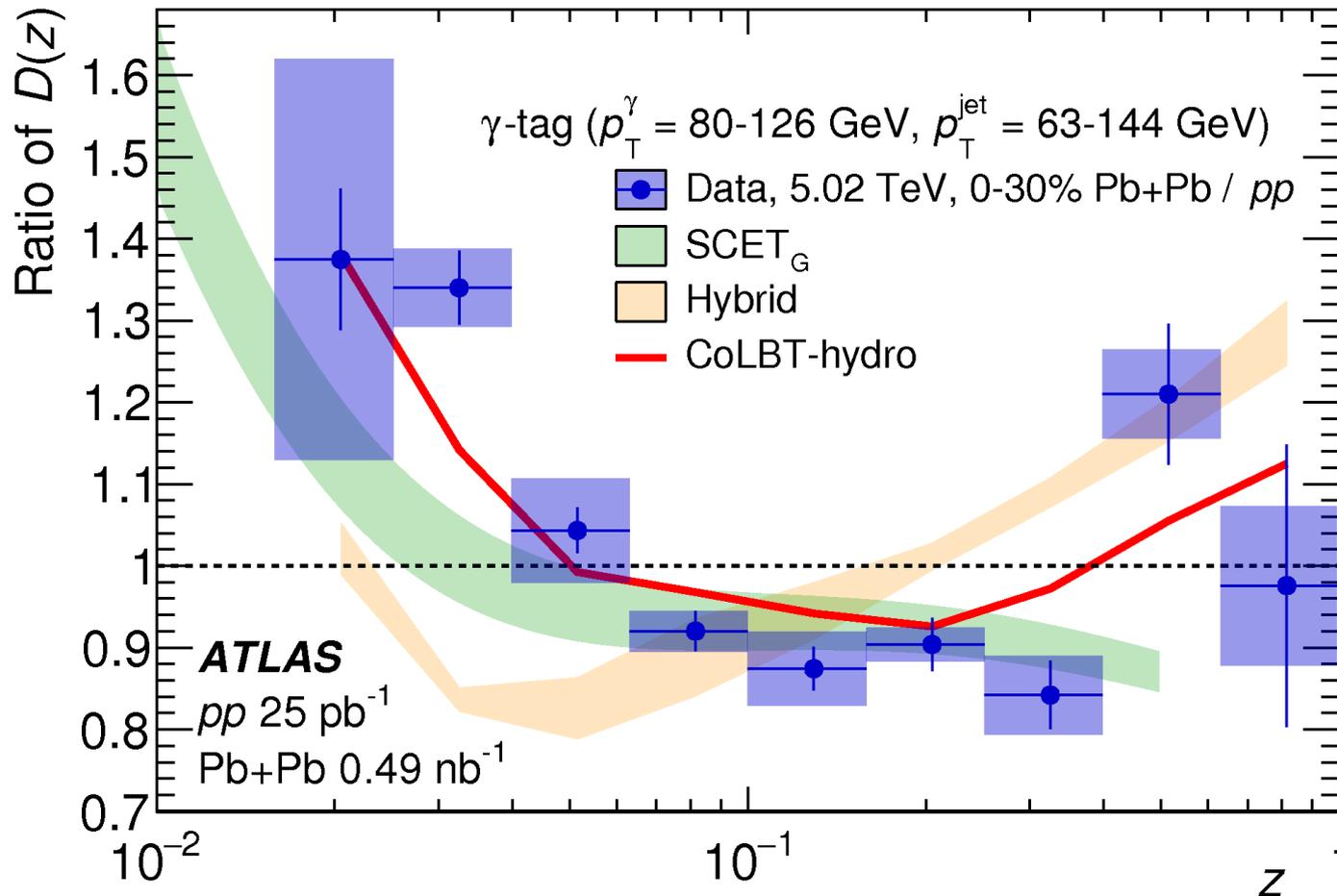
Photon-tagged jet fragmentation



- Extra enhancement/suppression seen in photon-tagged FF in central collisions.
- Color factor dependence competing with surface bias effects?



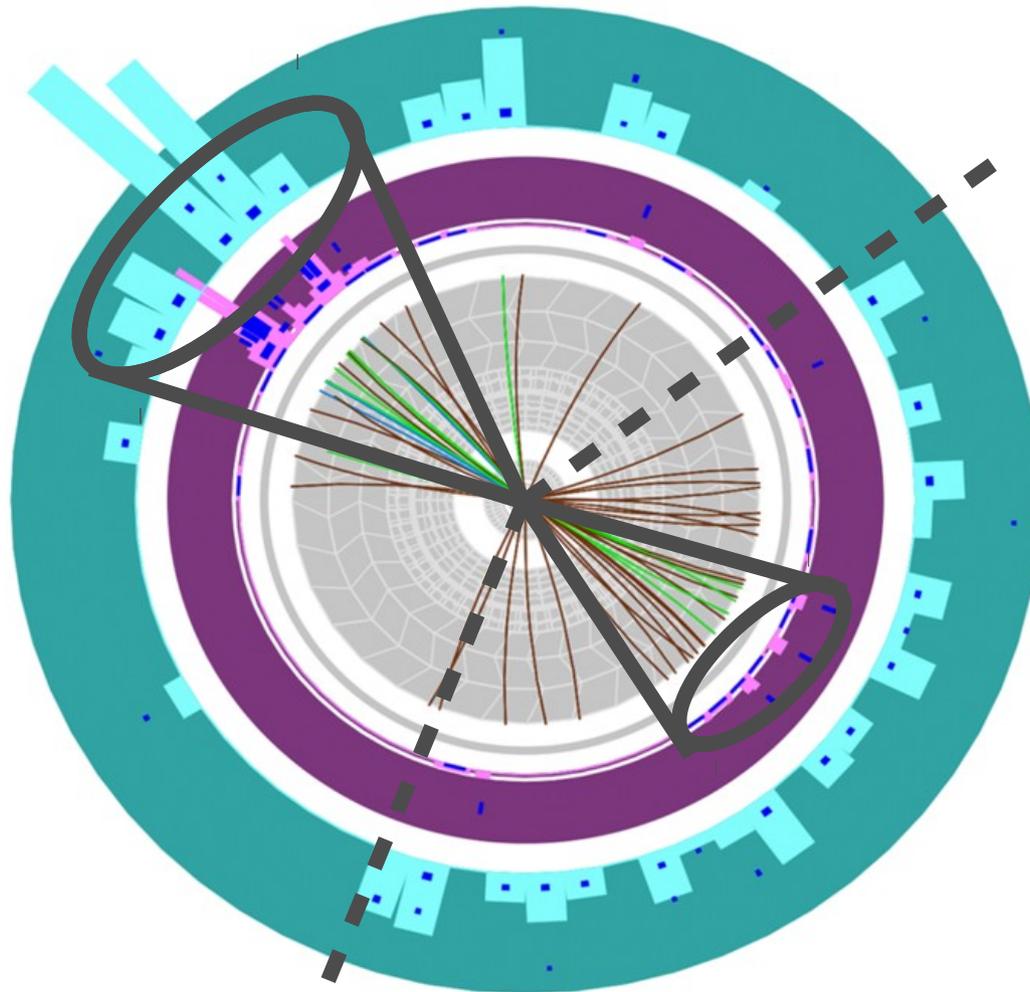
Photon-tagged jet fragmentation vs theory



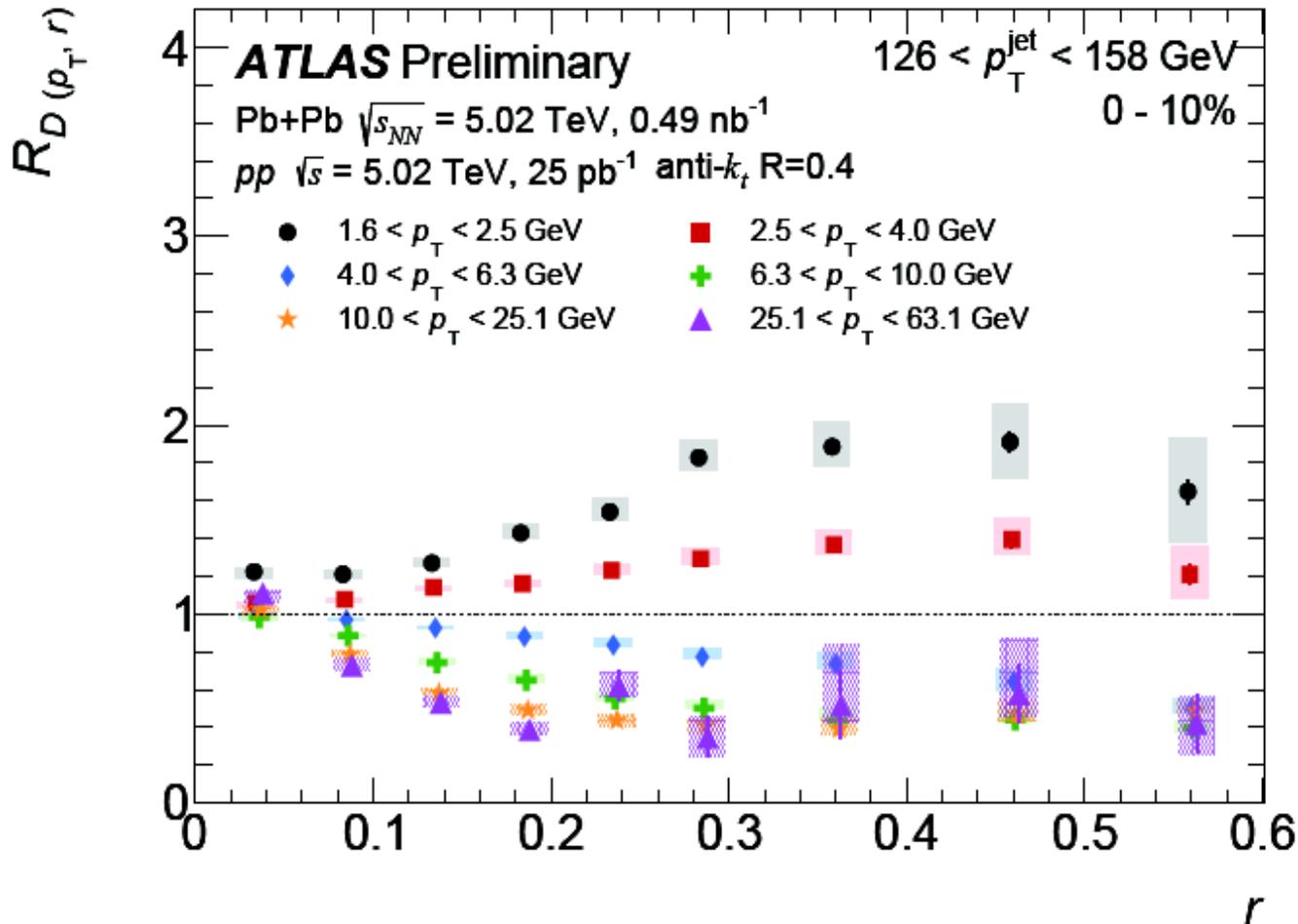
- The SCET_G calculation and the CoLBT-hydro model is able to describe the key features of the data.

Jet quenching measurement

Track-jet correlations at large angles

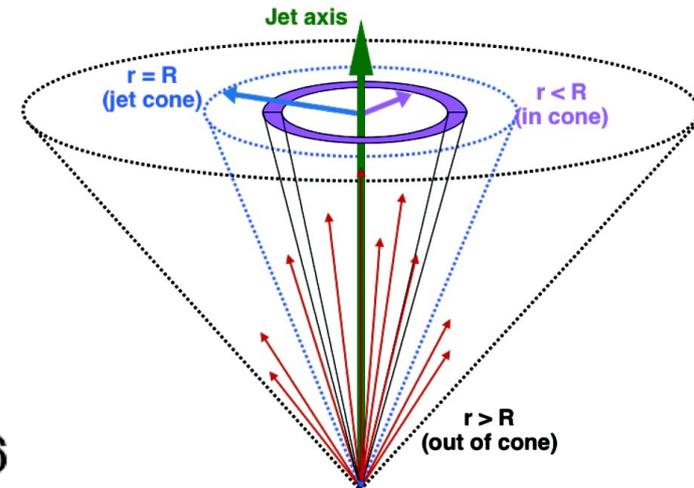


Let's look around jet....



$$D(p_T, r) = \frac{1}{N_{\text{jet}}} \frac{1}{2\pi r} \frac{d^2 n_{\text{ch}}(r)}{dr dp_T}$$

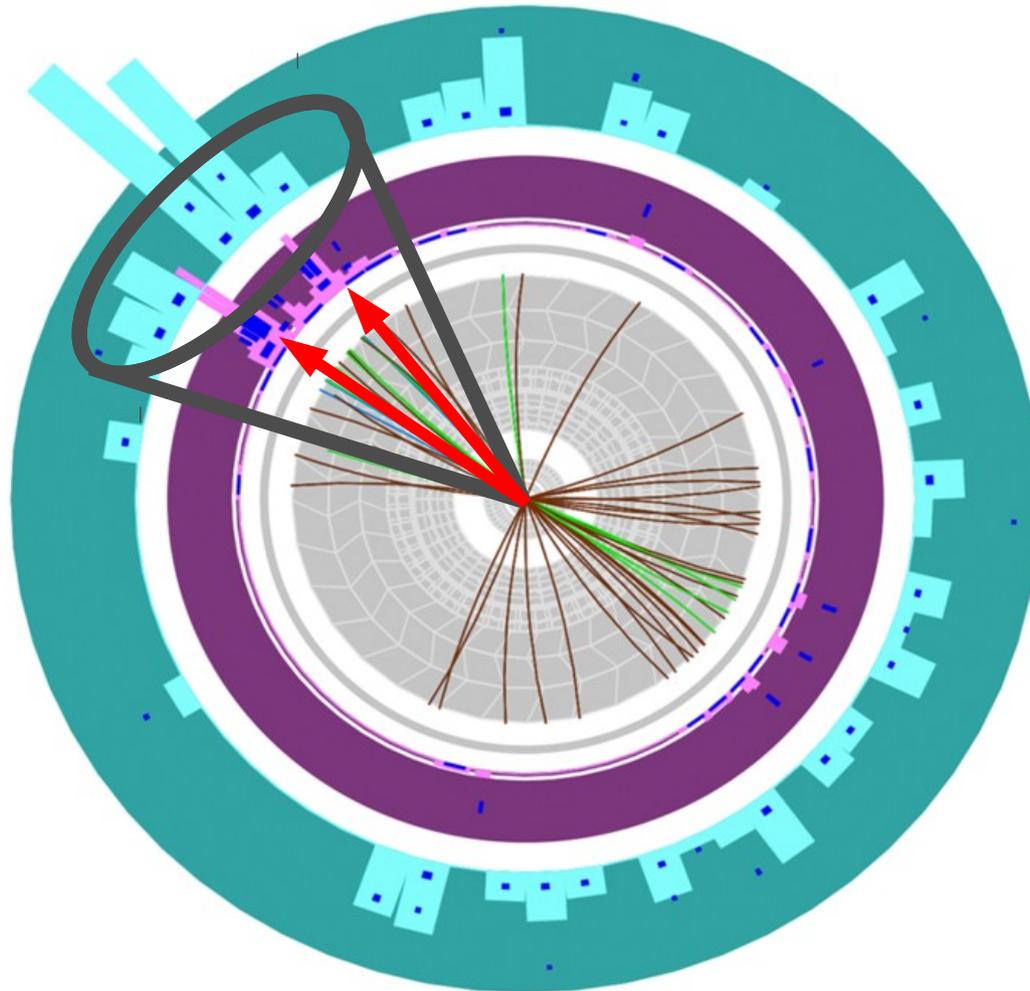
where $r < 0.6$



- Jets are broader in central collisions compared to pp .
 - But decrease of yields of intermediate p_T particles with r .
- Smallest modification seen in the jet core.

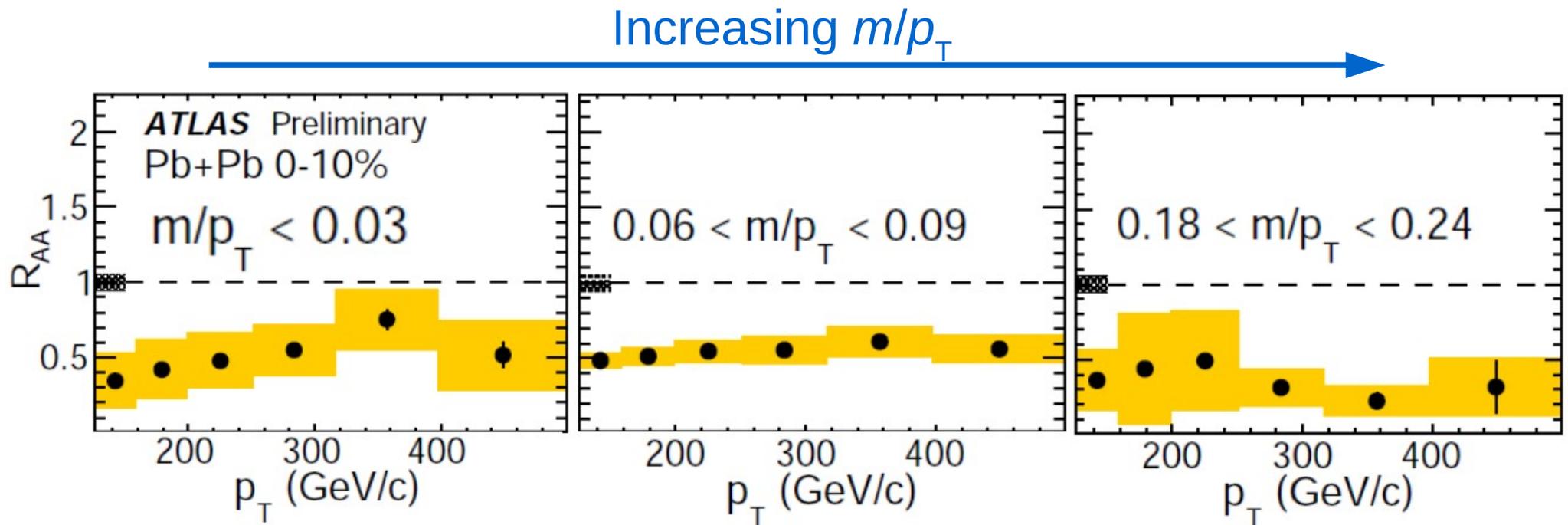
Jet quenching measurement

Jet substructure



Jet substructure in HI collisions

- Does the jet suppression depend on jet structure?
- Jet mass carries information about transverse structure of jet.
 - connection to virtuality of initial parton.



- No significant change of R_{AA} with mass
→ consistent with inclusive jet R_{AA} .

Summary

- Using high statistics LHC data and new techniques bring us to era of precise measurements in heavy-ion collisions
 - Different jet observables sensitive to different aspect of probing the QGP.
 - New probes like give new perspective on QCD and QGP.
 - Complementary measurements of jet structure put strong constraints on theoretical models.

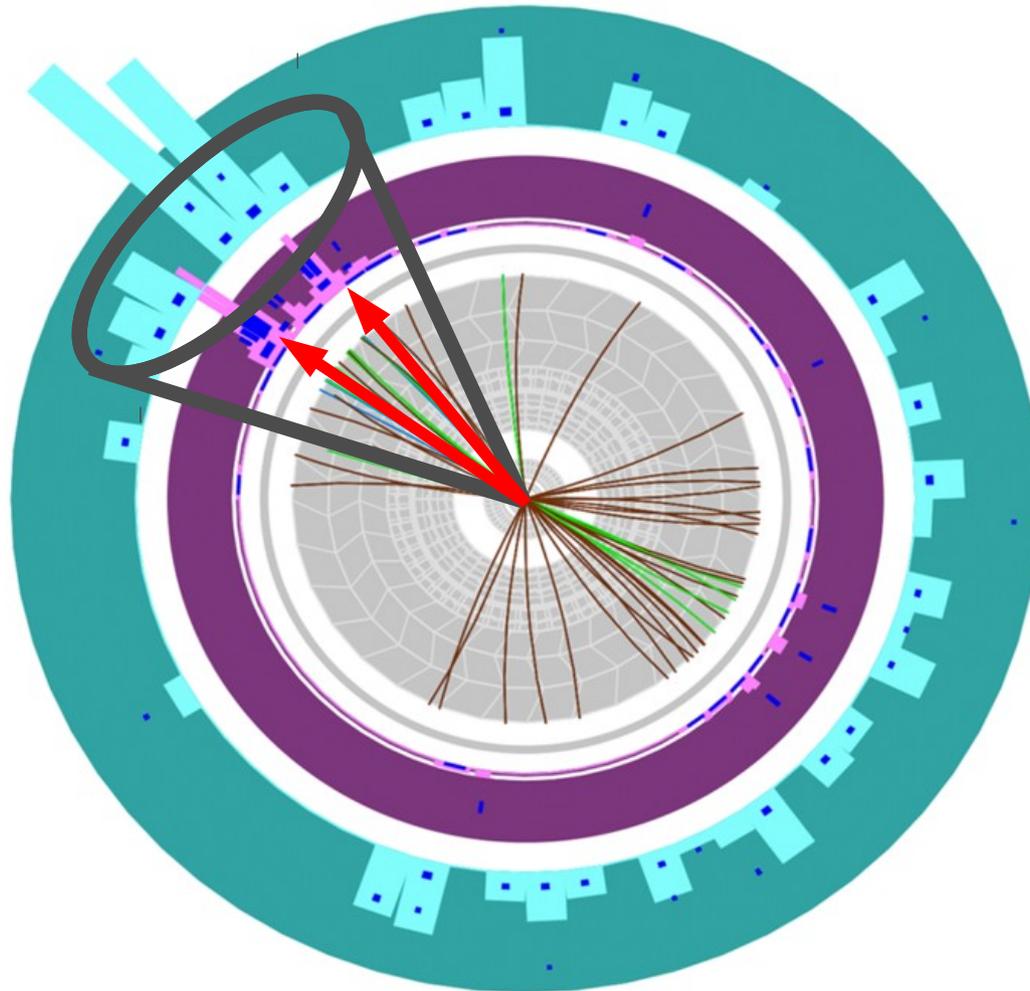
All ATLAS Heavy Ion public results:

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults>

Backup

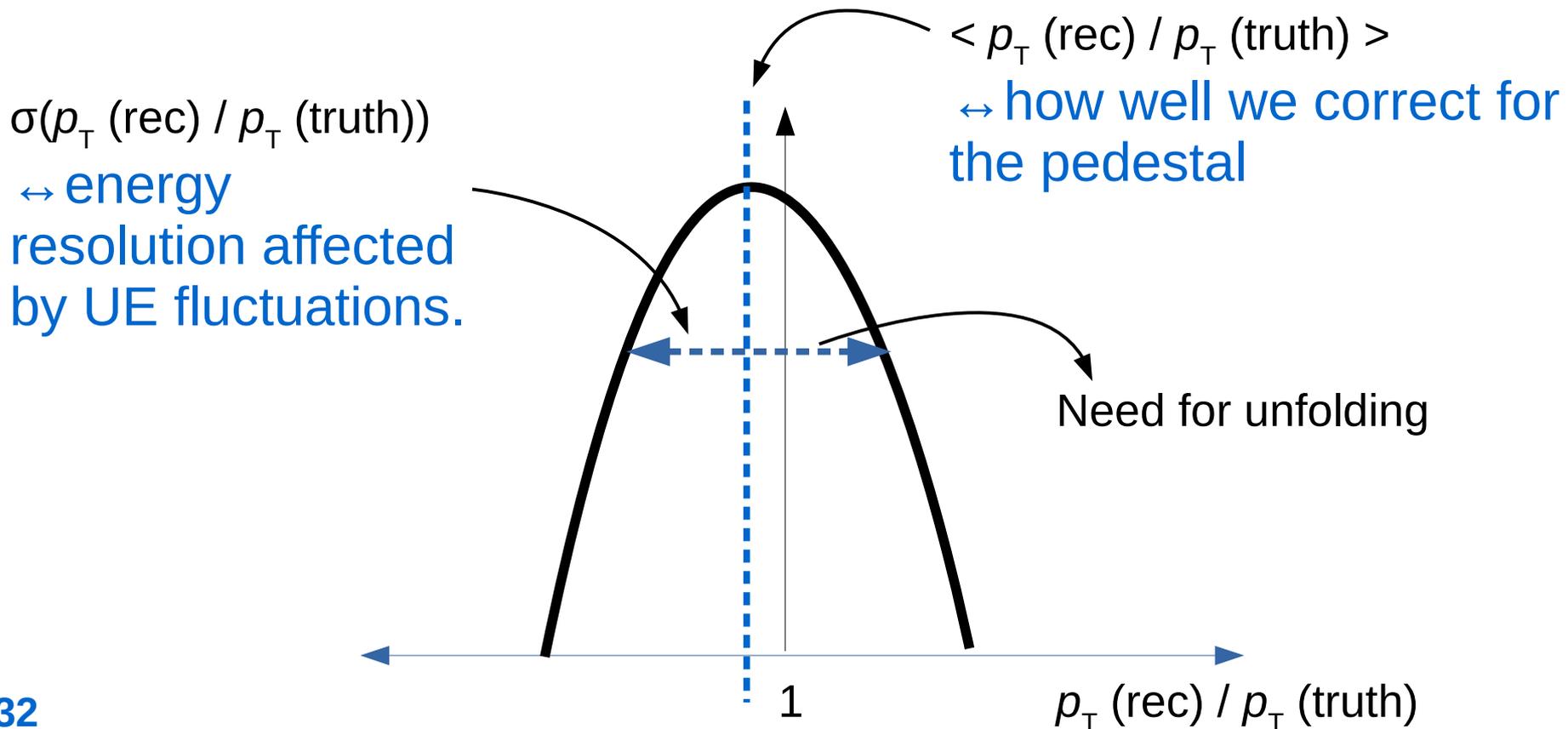
Jet quenching measurement

Jet substructure

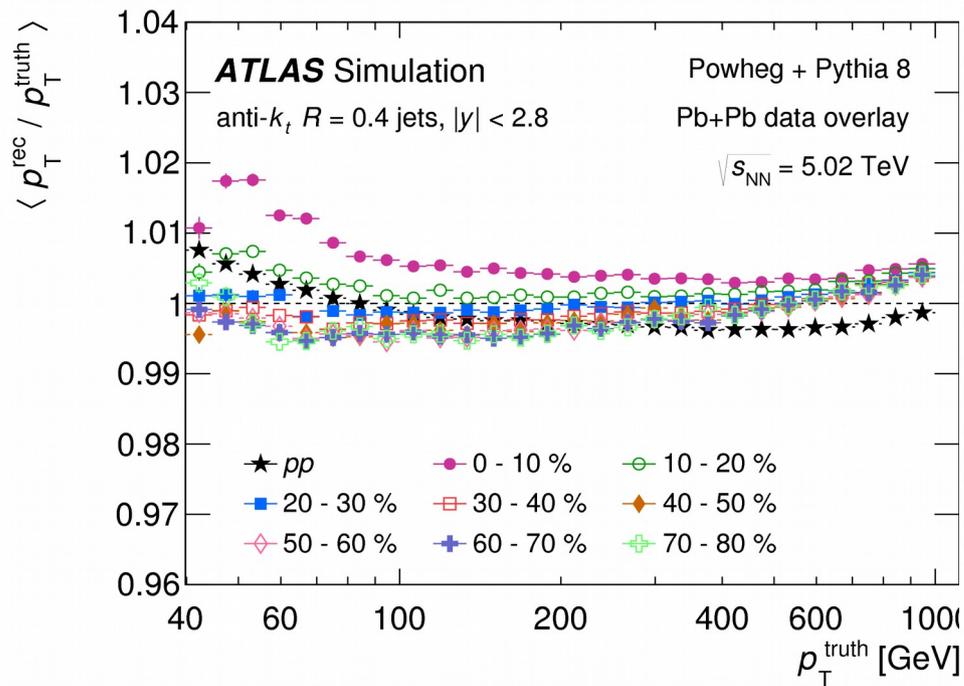


Jet reconstruction

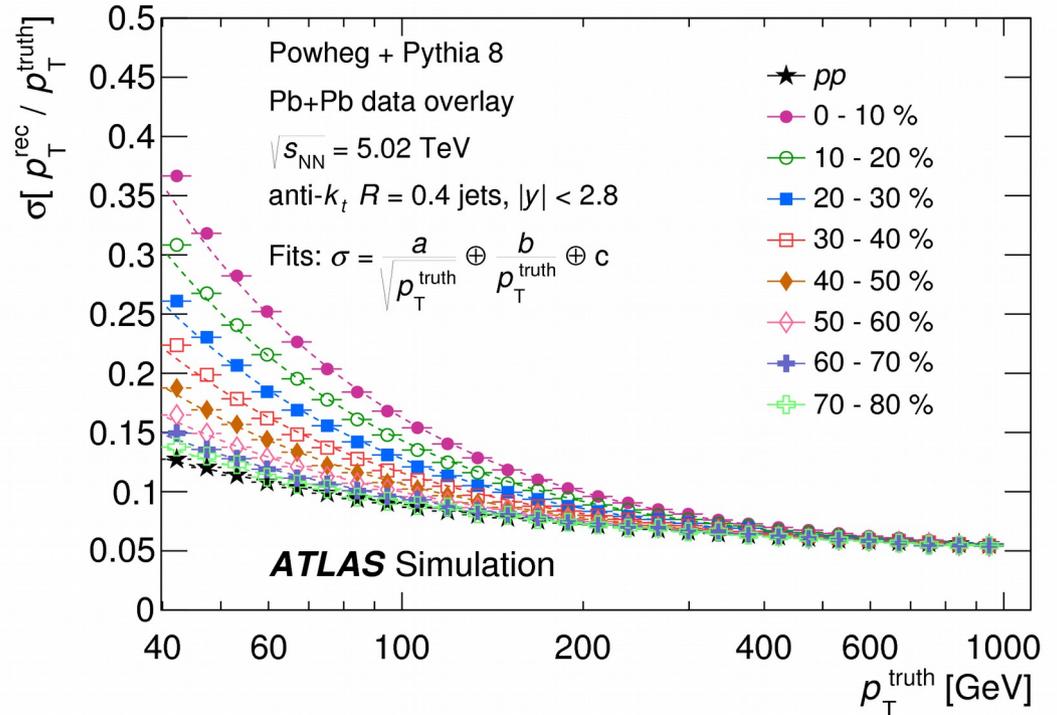
- Jets reconstructed with Anti- k_t with $R=0.4$ and underlying event (UE) subtraction.
- Mean UE, up to 150 GeV for 0.4 jet, estimated event-by-event as a function of pseudorapidity and corrected for v_n modulation.



Jet reconstruction

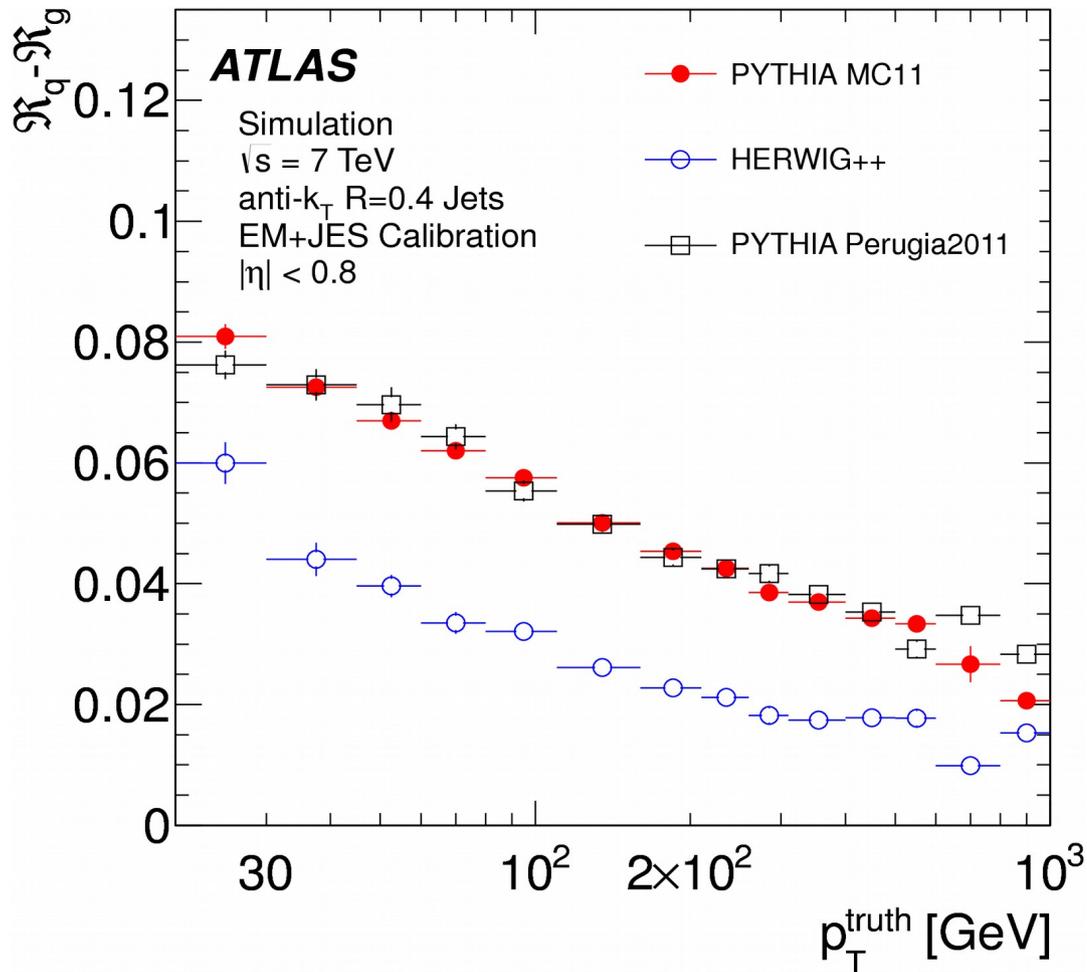


Average responses within 1% from unity almost independent of centrality.



Jet energy resolution dominated by UE fluctuations.

Jet response vs observable

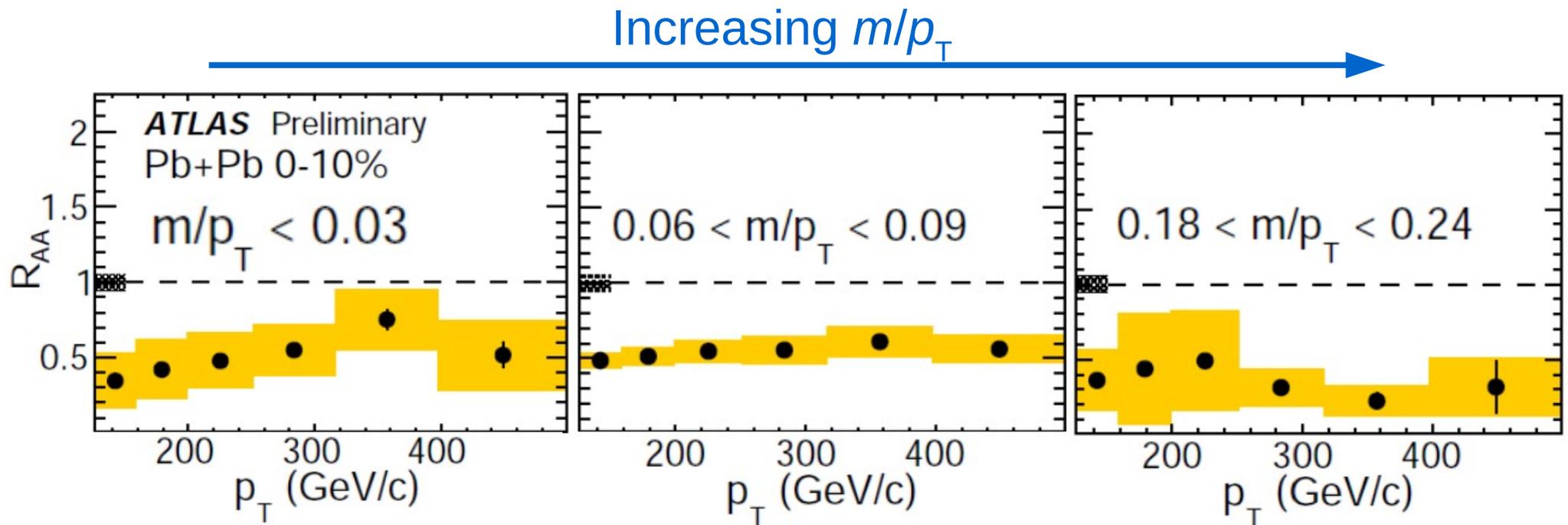


Response (and resolution) depends on the jet appearance.

Difference in response between quark and gluon jets in 7 TeV pp data.

Jet substructure in HI collisions

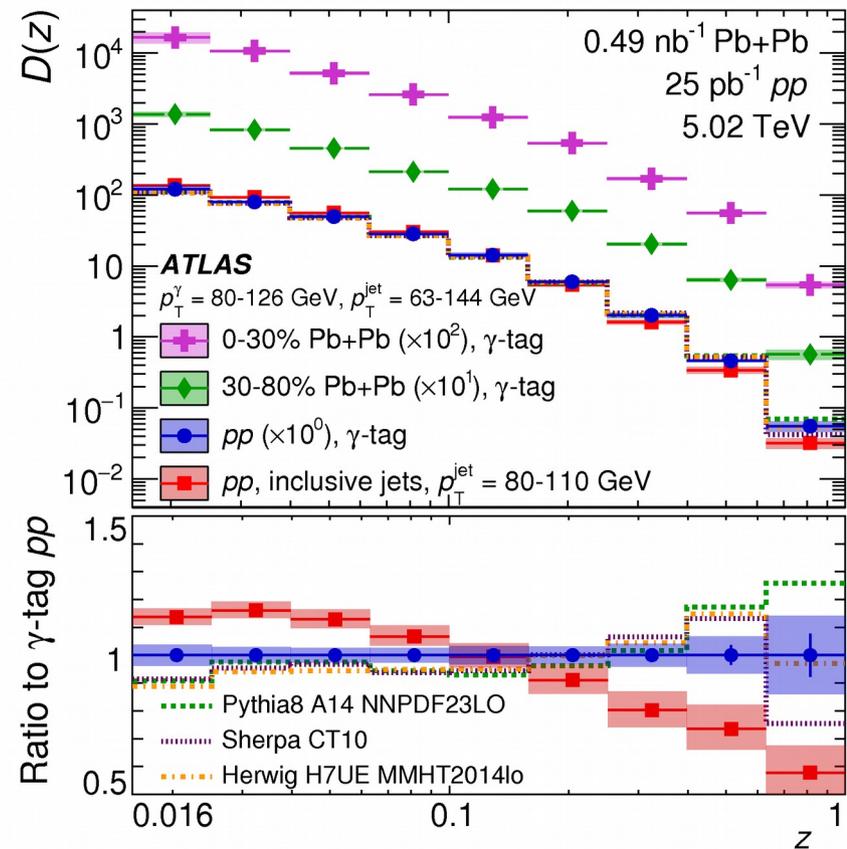
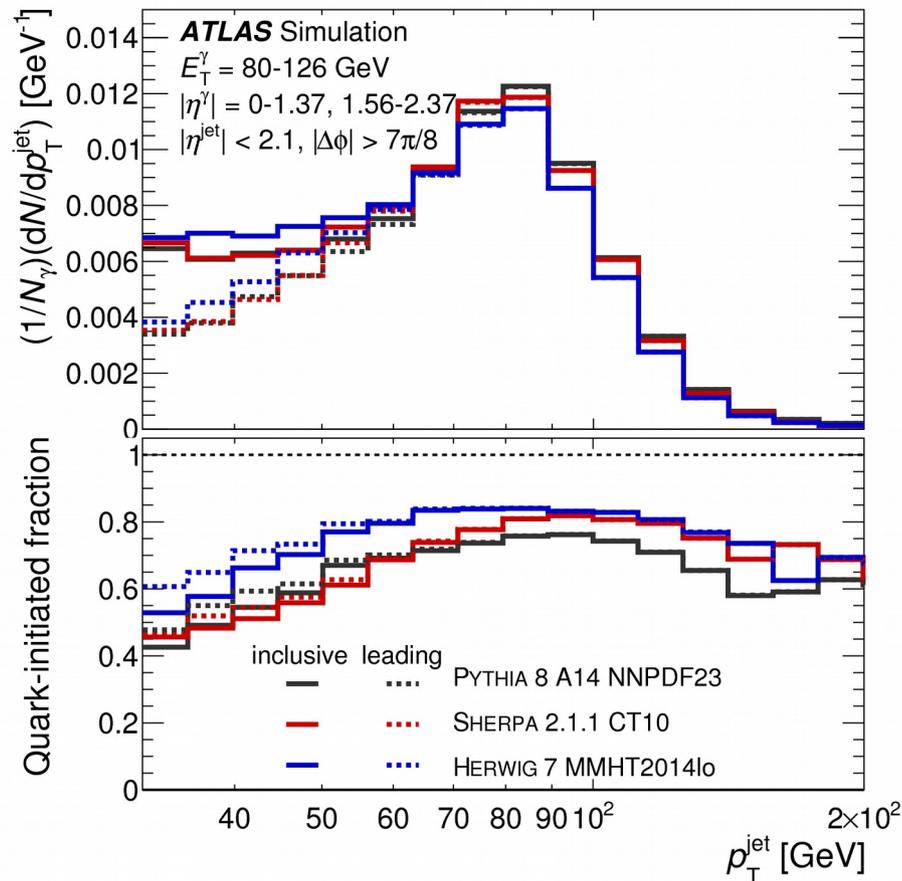
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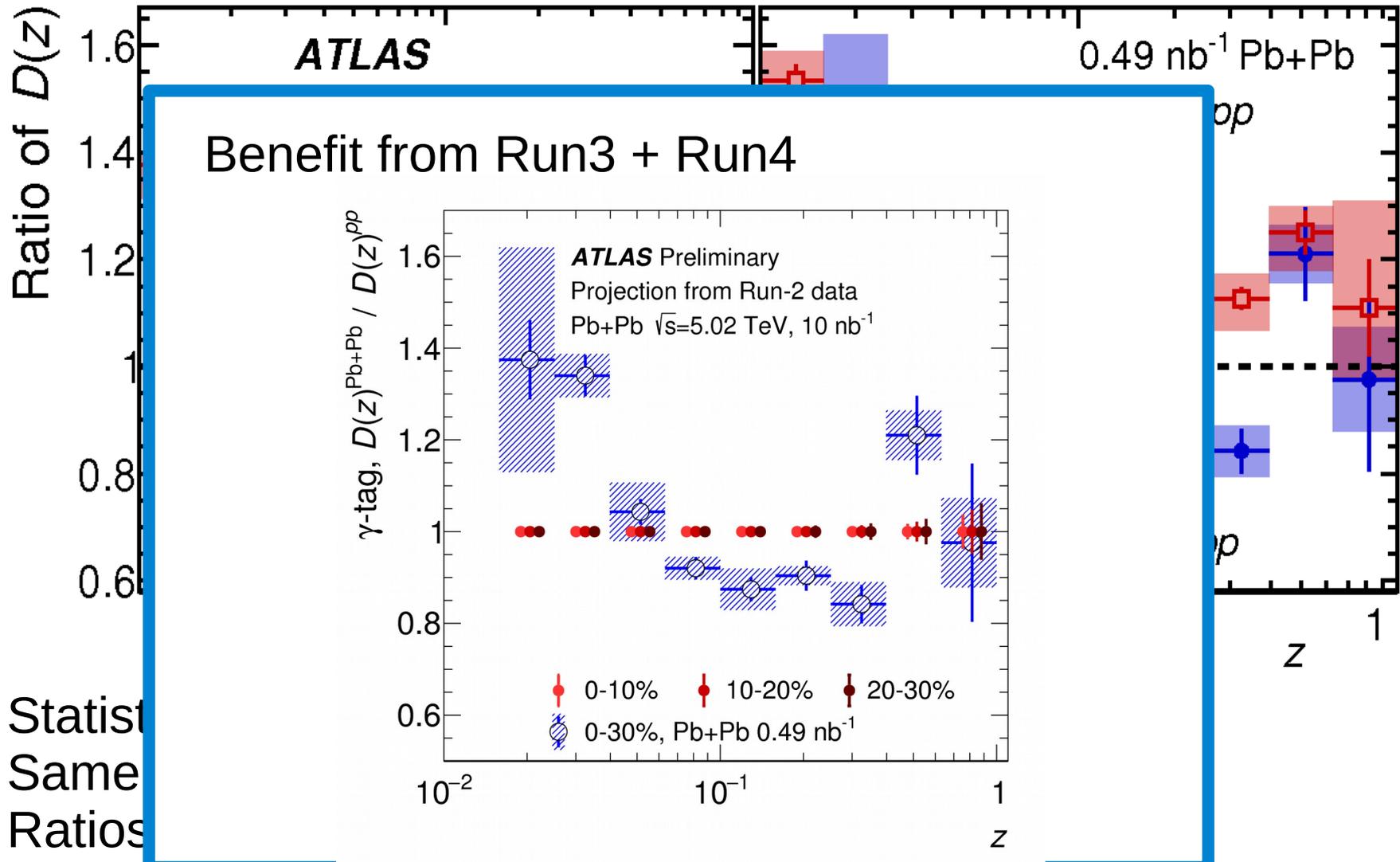
Photon-tagged jet fragmentation

- Enhanced quark jet contribution compared to inclusive jets.
- flavor dependence of quenching.



Steeper FF in photon-tagged jets.

Photon-tagged jet fragmentation



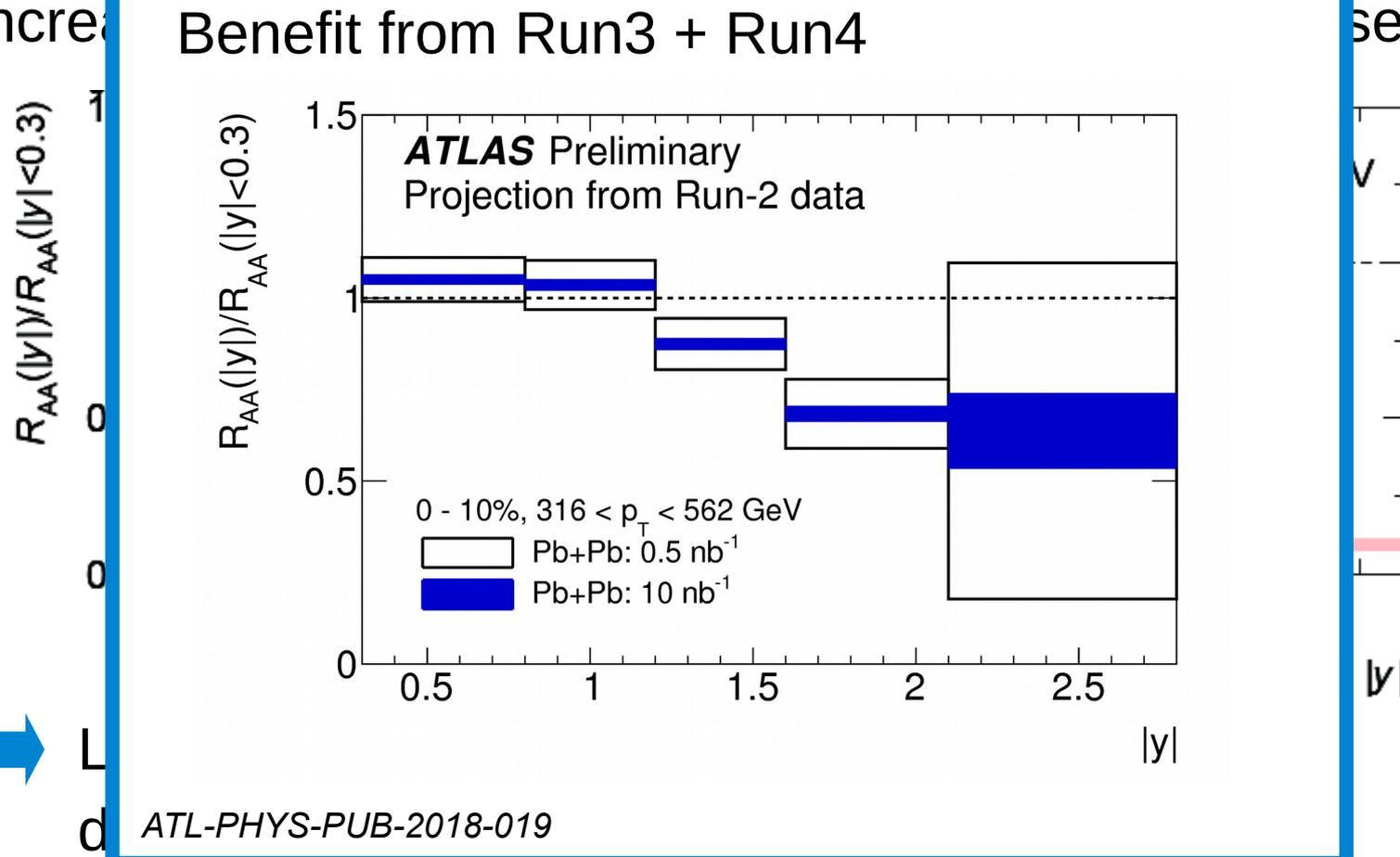
- Statist
- Same
- Ratios

■ Extra enhancement/suppression seen in photon-tagged FF in central collisions.

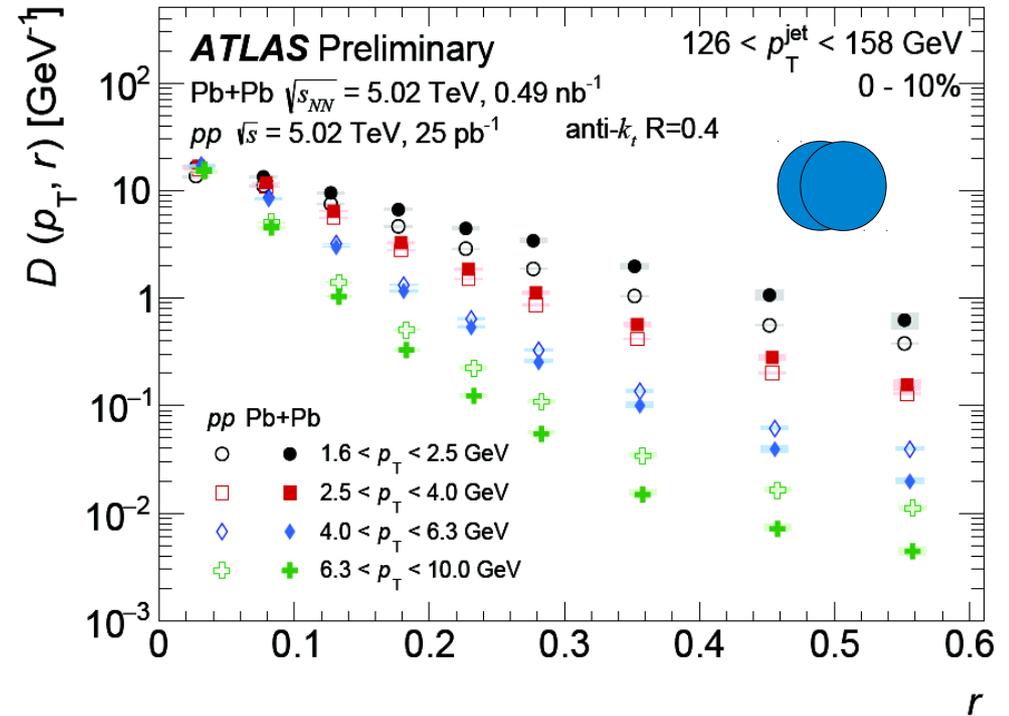
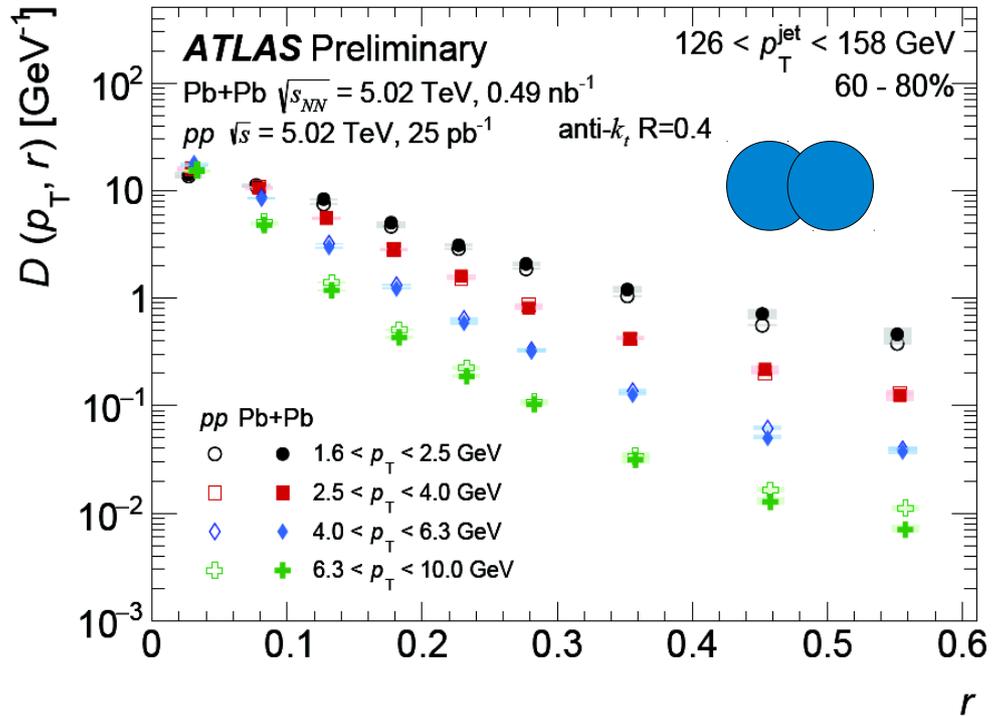
What about rapidity dependence?

Two competing effects:

- Increasing rapidity → steeper spectrum → decrease of R_{AA}
- Increasing rapidity → increase of R_{AA}



Radial Profile



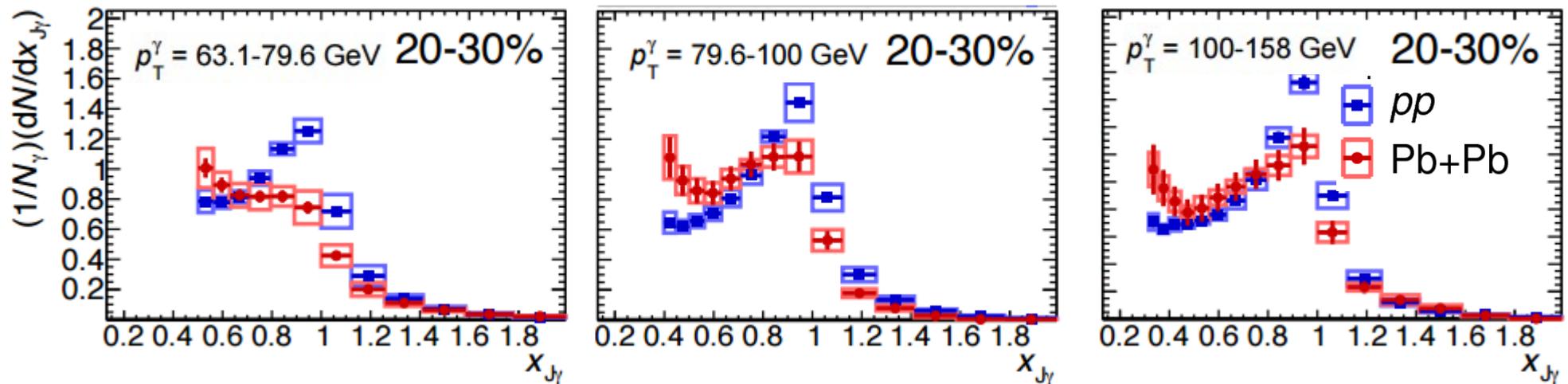
Change of shapes in central Pb+Pb collisions compared to pp reference.

Photon-jet correlations

- What is the absolute amount of energy lost in QGP?

➔ Measurement of balance in photon-jet system $x_{J\gamma} = p_T^{\text{jet}} / p_T^\gamma$

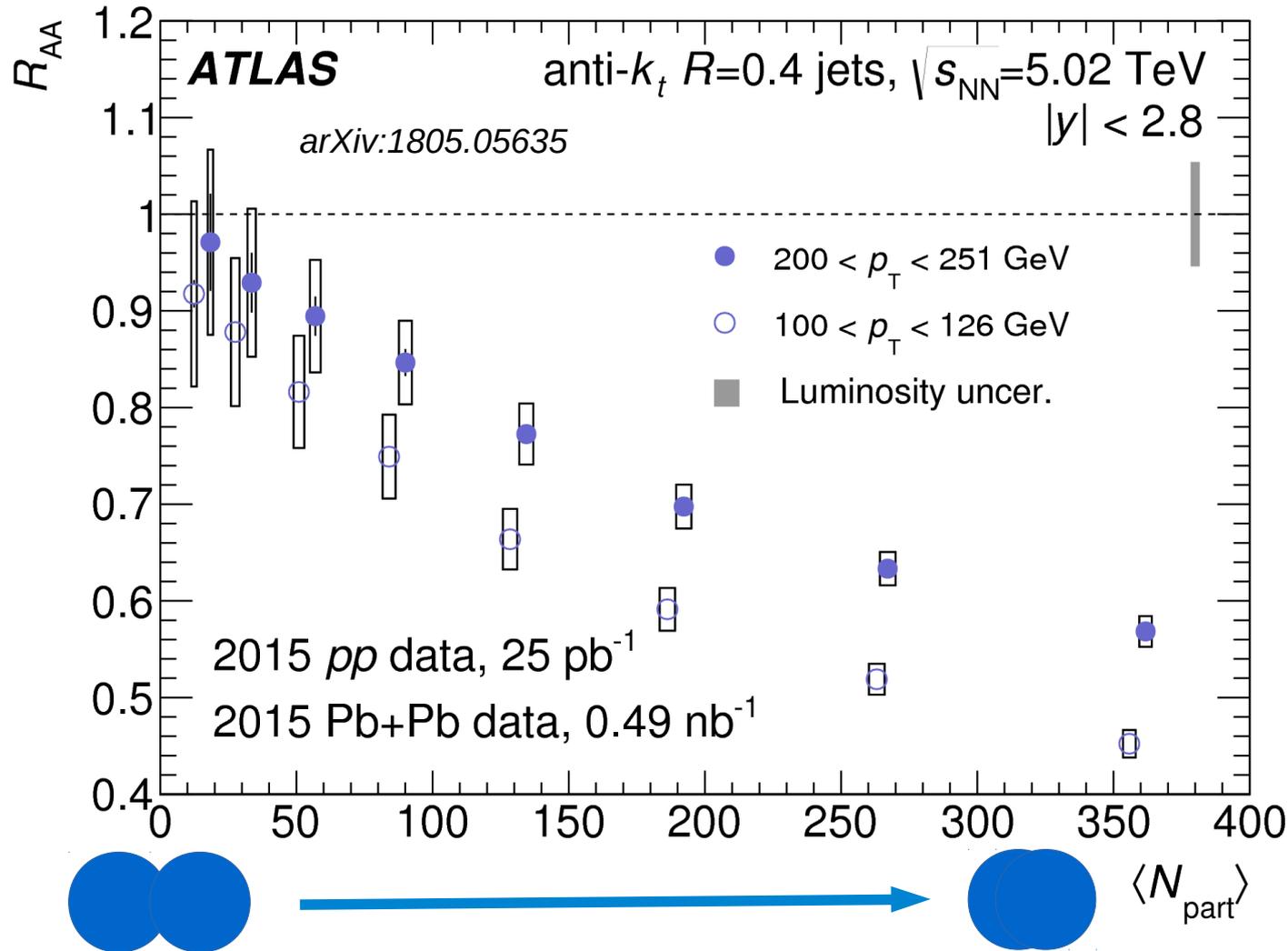
Increasing photon p_T



- Peak reappears at higher p_T .
- Contribution from jets without energy loss?

Suppression of single jet spectra

R_{AA} @5.02 TeV:



41 ■ Increasing suppression w.r.t. pp reference with increasing centrality.

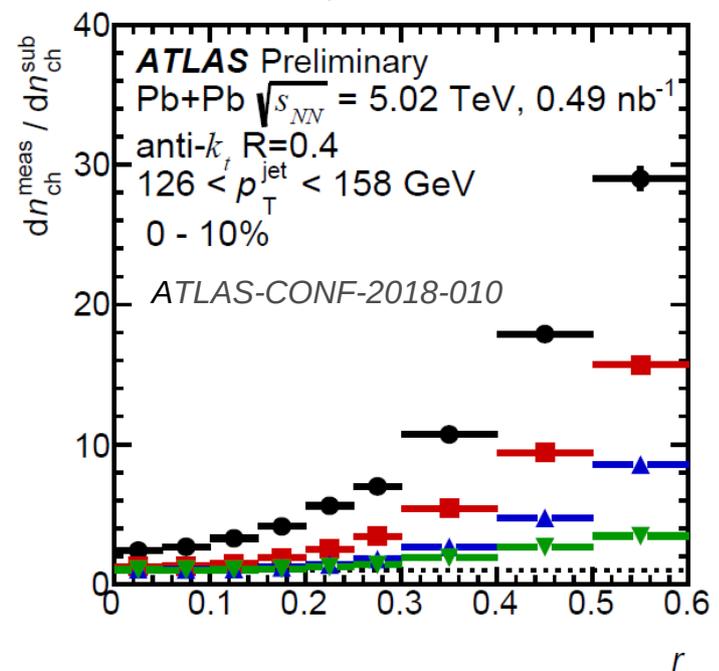
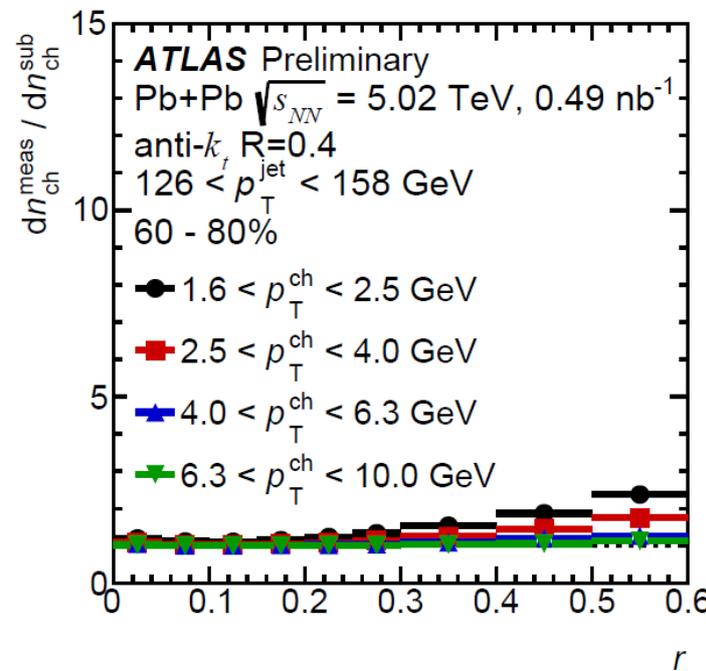
Aspects of measurement @ low- p_T

- Significant contribution of background from underlying event (UE).

more central collisions

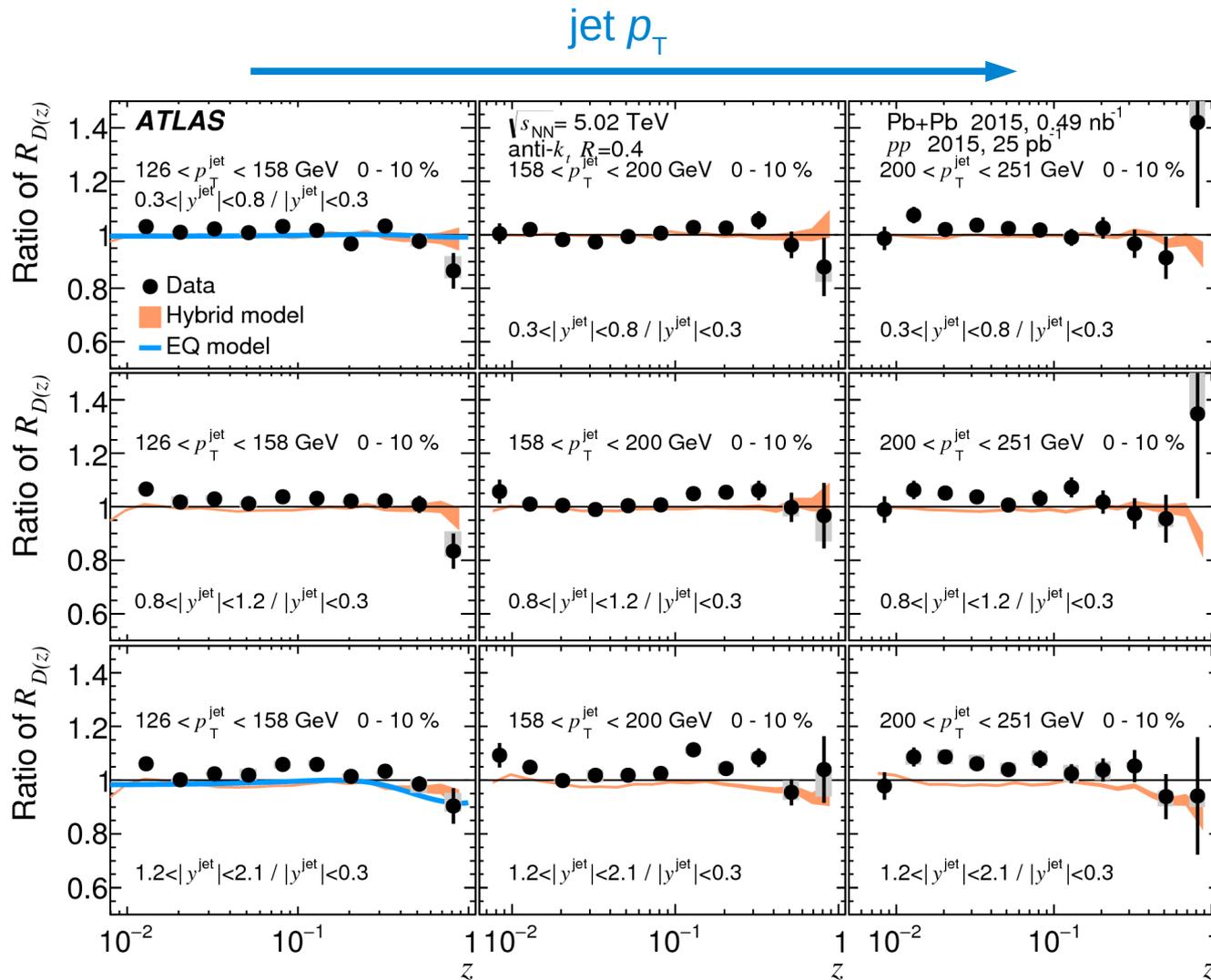
Signal + Background

Signal



- Signal-to-background ratio decreasing with increasing centrality, increasing r , and decreasing p_T .
- Various properties of UE are taken into account in subtraction method: η -dependence, flow variation, correlation of UE and jet energy resolution.

Rapidity dependence



- $R_{D(z)}$ in central region is compared to that in forward.
- No significant rapidity dependence to the modification.
- Sign of depletion at high z .
- Comparison to EQ and Hybrid model.

➡ Both models are able to describe the rapidity dependence in data.