Measurement of jet structure and substructure in heavy ion collisions with ATLAS

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for the ATLAS collaboration

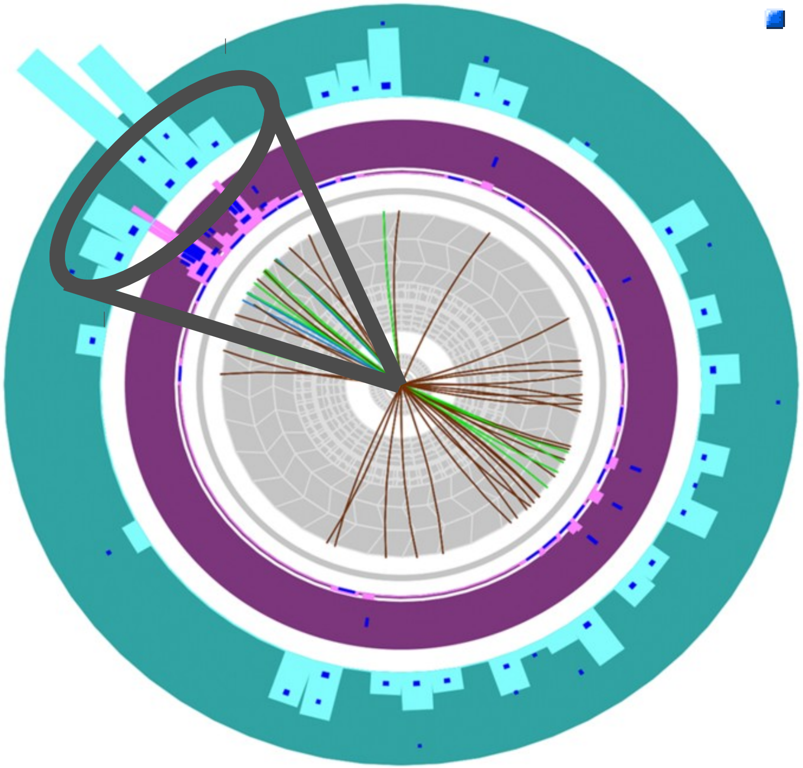
Quark Matter 2019 *November 6, 2019*

Jet splitting and parton shower in QGP

- How is the parton shower modified in the deconfined medium?
  - Is the fragmentation process modified?
  - What is the role of jet momentum?
  - Can we see medium response to the fast partons?
  - Previous jet measurements suggest transfer energy out-of the jet cone.

- How does jets with multi-pronged structure loose energy?
  - Can we see color coherence/decoherence effects?
  - It may help to disentangle the contributions of path length and fluctuations to the quenching.

Jet fragmentation



- Measurement of fragmentation functions and their ratios:

$$D(p_{\mathrm{T}}) \equiv \frac{1}{N_{\mathrm{jet}}}\frac{\mathrm{d}n_{\mathrm{ch}}}{\mathrm{d}p_{\mathrm{T}}} \qquad D(z) \equiv \frac{1}{N_{\mathrm{jet}}}\frac{\mathrm{d}n_{\mathrm{ch}}}{\mathrm{d}z}$$

$$z \equiv p_{\mathrm{T}} \cos \Delta R \,/\, p_{\mathrm{T}}^{\mathrm{jet}}$$

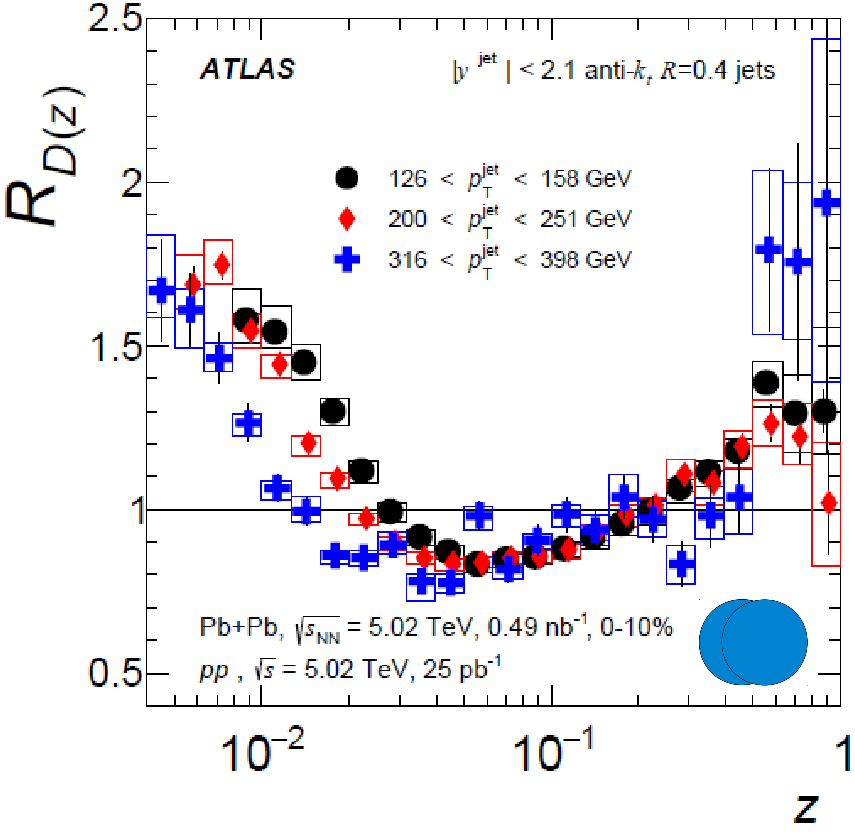
Shower in medium

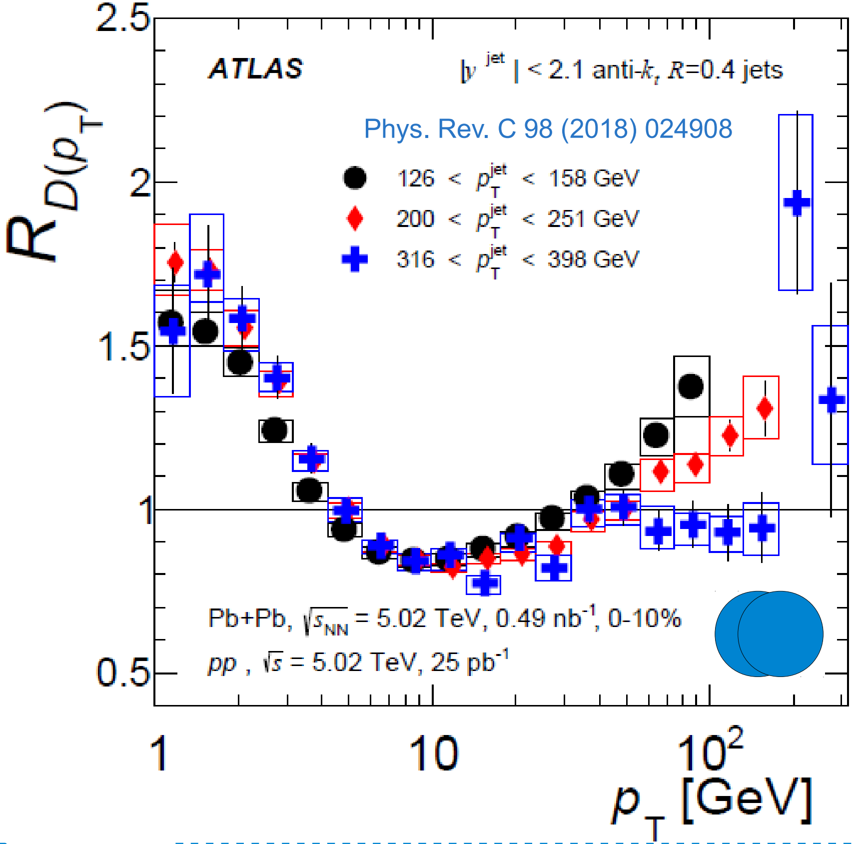
$$R_{D(z)} \equiv \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{pp}}$$

Shower in vacuum

- Fully corrected for detector effects.

Jet p_T dependence to the FF modification

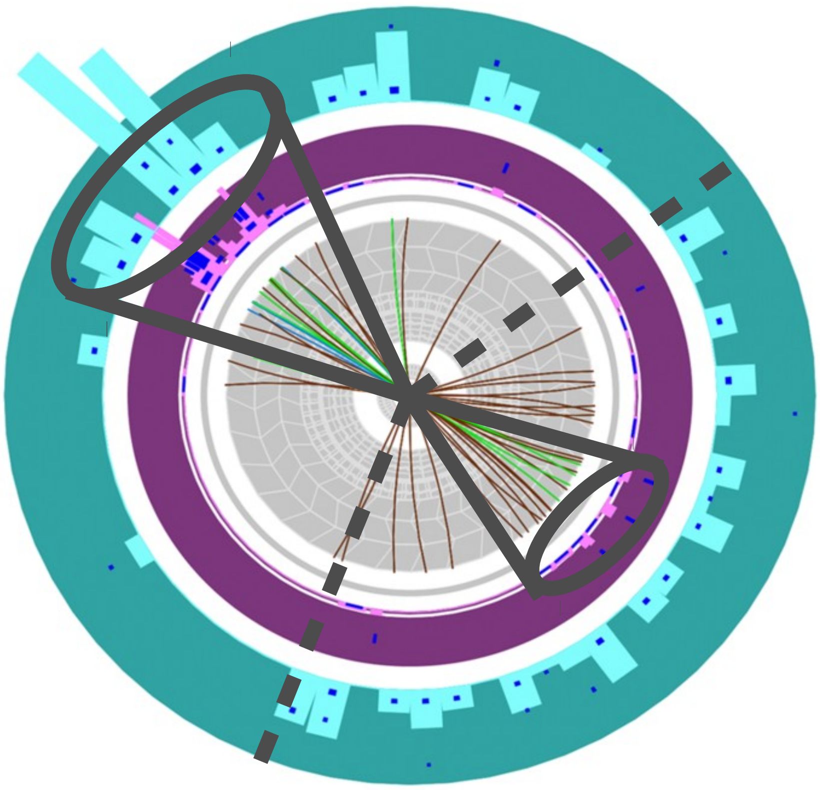




No dependence on jet p_T observed at high z for jets up to 400 GeV.

Enhancement of soft fragments increases for high p_T jets.

Expanding the measurement to large angles



$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{\mathrm{d}r\,\mathrm{d}p_{\mathrm{T}}}$$

where $r < 0.8$ with respect to jet axis

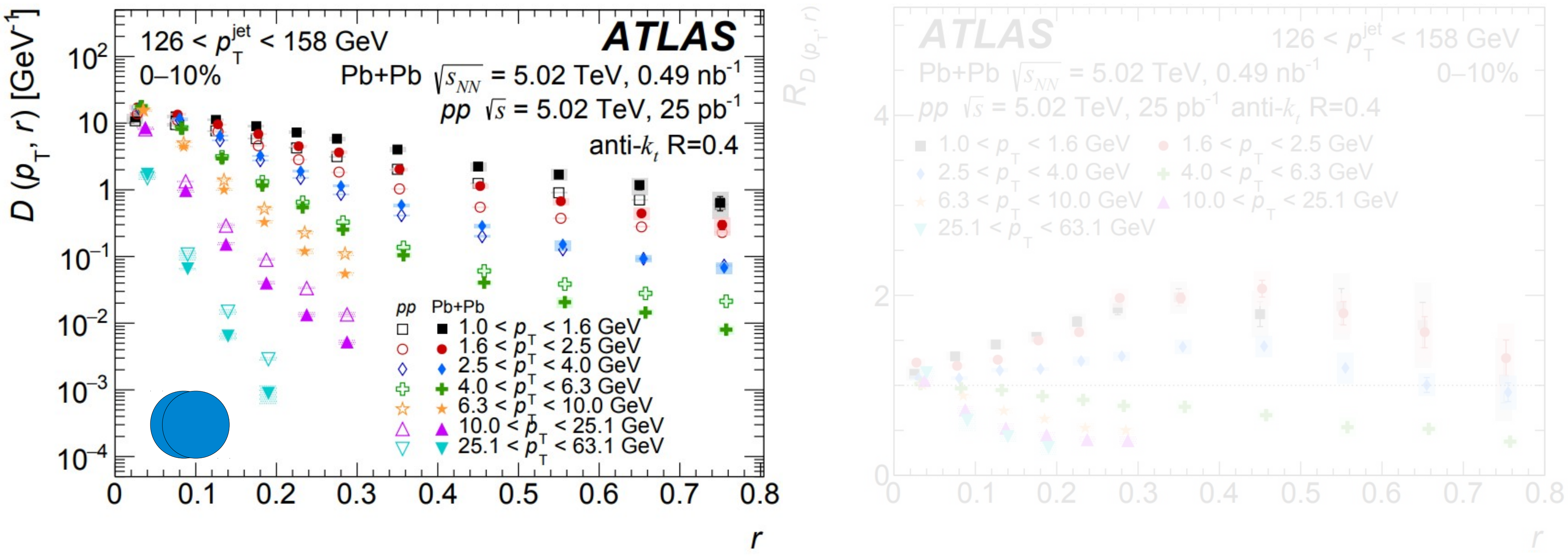
- Ratios and differences are evaluated:

$$R_{D(p_{\mathrm{T}},r)} = \frac{D(p_{\mathrm{T}}, r)_{\mathrm{Pb+Pb}}}{D(p_{\mathrm{T}}, r)_{pp}}$$

$$\Delta D(p_{\mathrm{T}}, r) = D(p_{\mathrm{T}}, r)_{\mathrm{Pb+Pb}} - D(p_{\mathrm{T}}, r)_{pp}$$

- Measurement corrected for UE contributions and for track and jet momentum and angular resolutions.

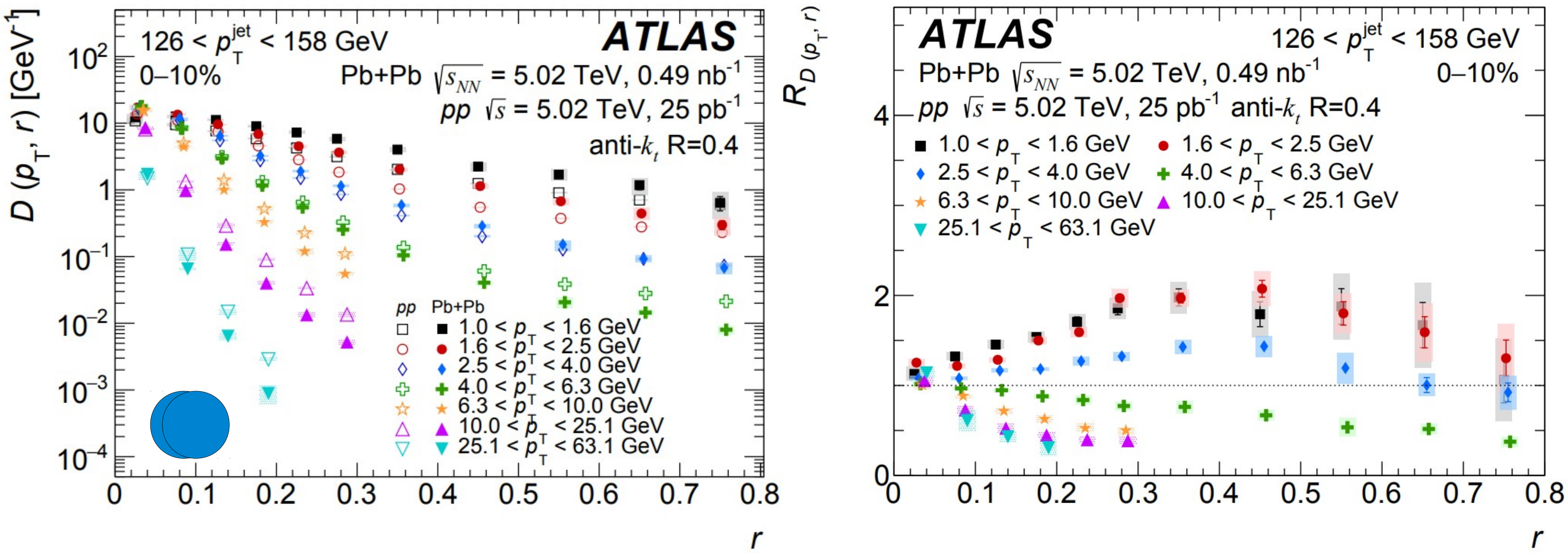
Radial profile



- Sharp fall-of with r with increasing track p_T.
- Change of shapes in central Pb+Pb collisions compared to *pp* reference.

arXiv:1908.05264

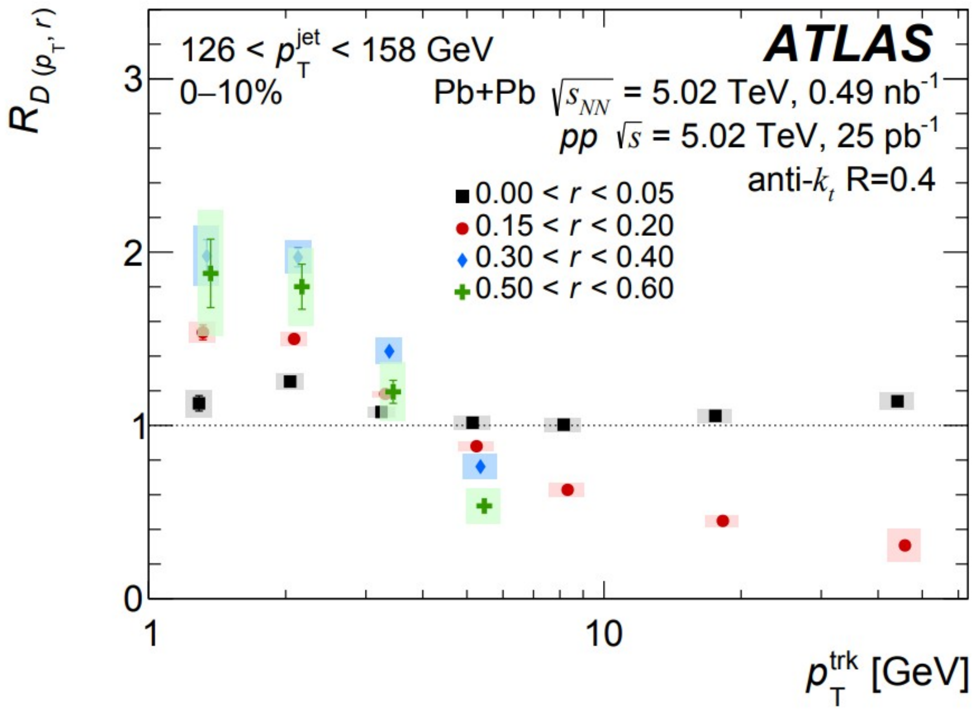
Radial profile

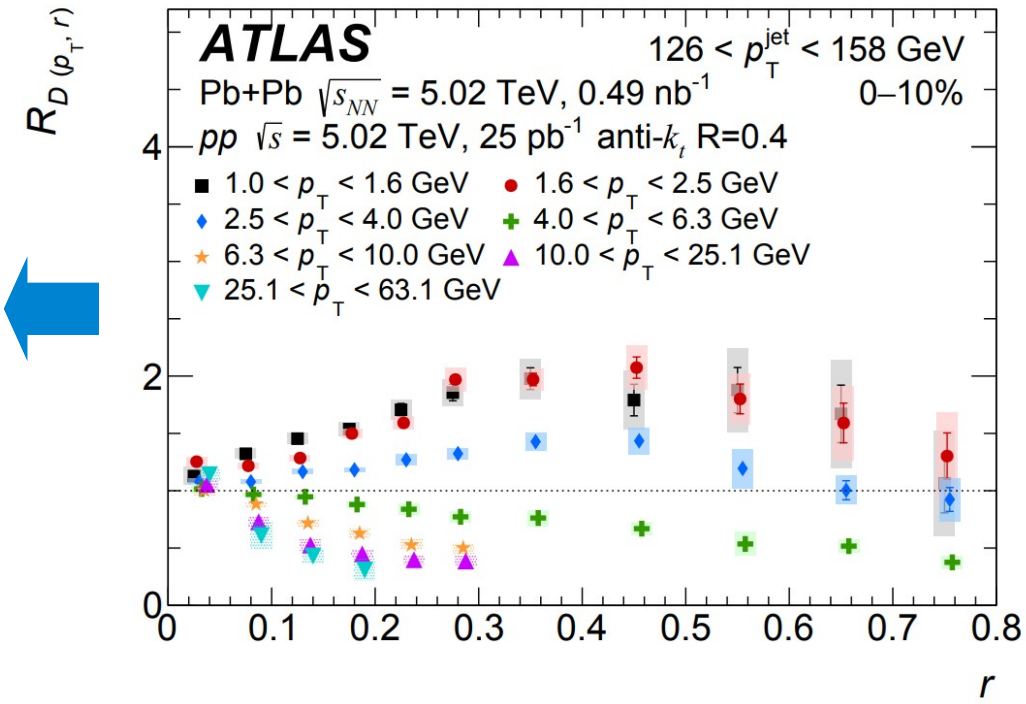


- Jets are broader in more central collisions at low p_T.
- Significant suppression of yields of particles p_T > 4 GeV outside the jet core.

arXiv:1908.05264

Radial profile

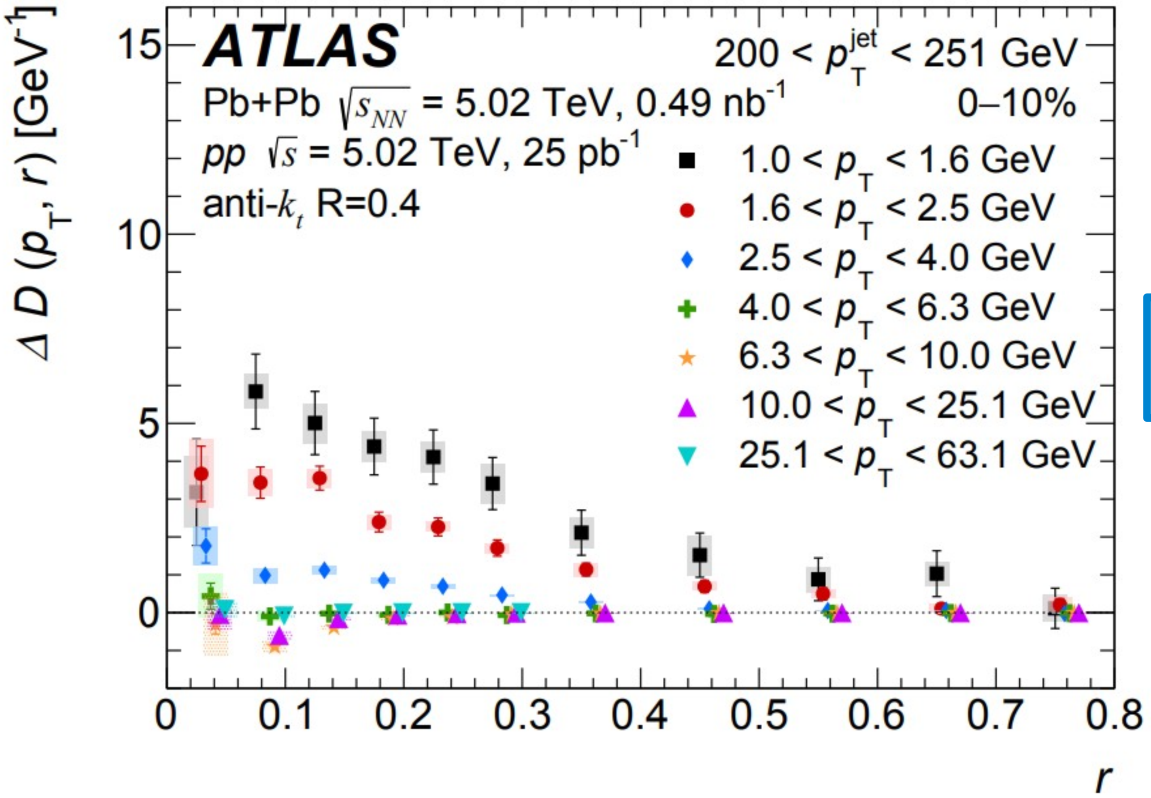




- Smallest modification seen in the jet core.
- The enhancement increases with decreasing p_T.
- The suppression decreases with increasing p_T.
- Minimal modification for particles with p_T of ~4 GeV.

arXiv:1908.05264

Absolute size of modifications

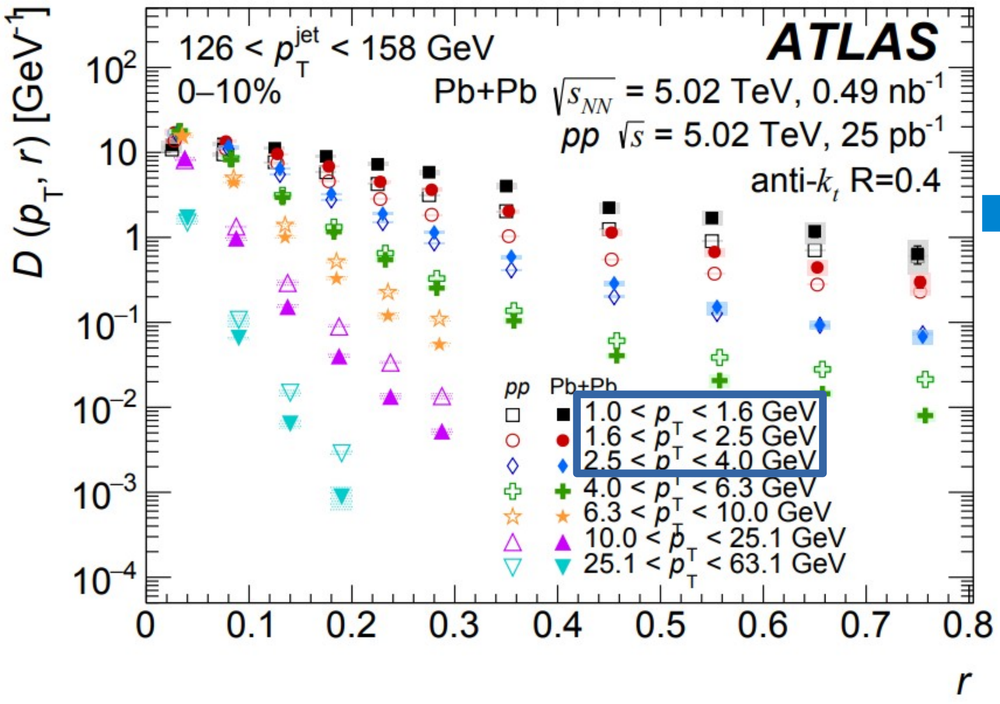


$$\Delta D(p_{\mathrm{T}}, r) = D(p_{\mathrm{T}}, r)_{\mathrm{Pb+Pb}} - D(p_{\mathrm{T}}, r)_{pp}$$

- The largest excess in terms of number of extra particles is in the cone!
  - Up to ~5 extra particles per unit area per GeV.

arXiv:1908.05264

Integrals of $D(p_T, r)$ distributions



$$\Theta(r) = \int_{1\ \mathrm{GeV}}^{4\ \mathrm{GeV}} D(p_\mathrm{T}, r)\, dp_\mathrm{T}$$

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

arXiv:1908.05264

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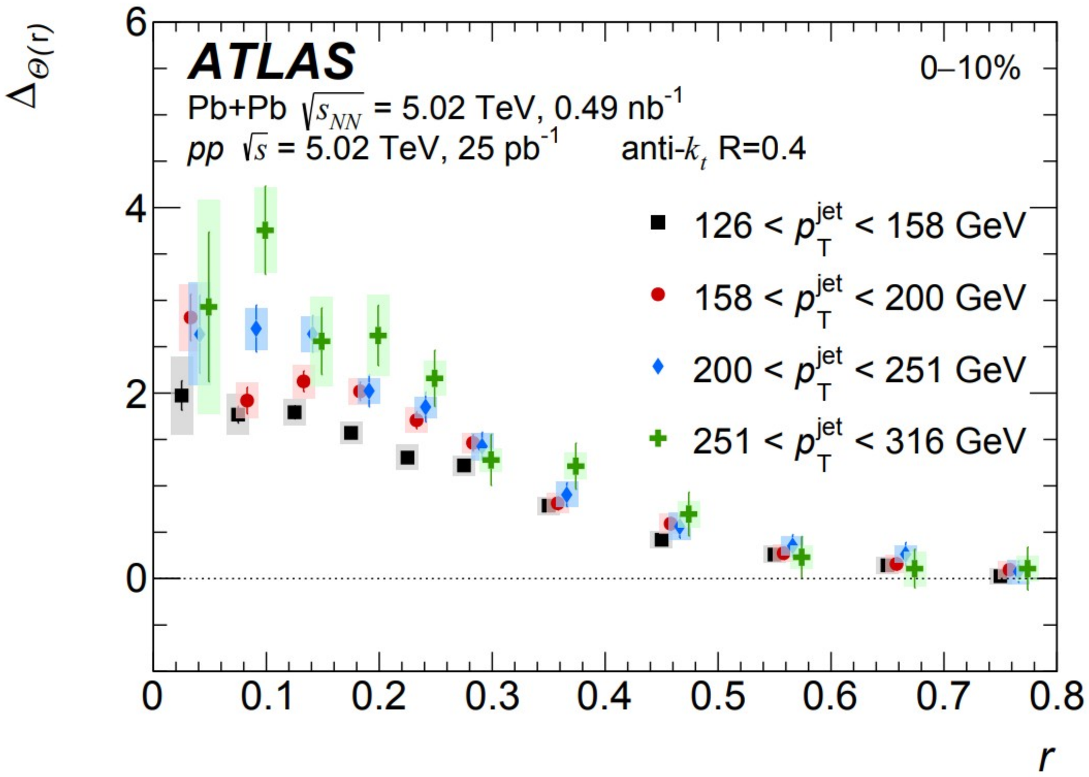

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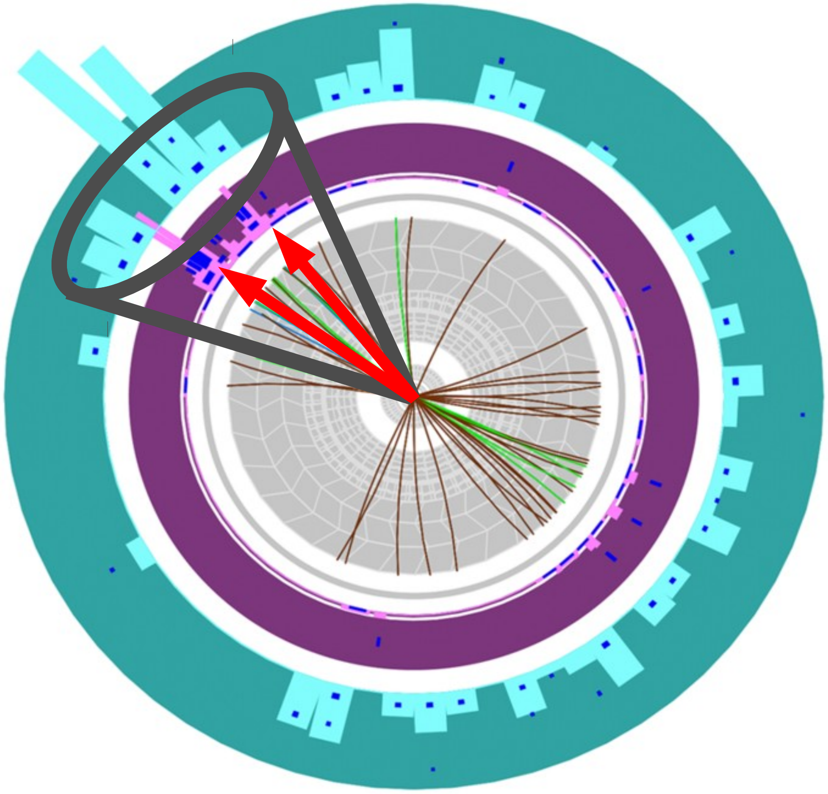
$$\Delta_{\Theta(r)} = \Theta(r)_{\text{Pb+Pb}} - \Theta(r)_{pp}$$

- Significant jet p_T dependence to the enhancement is observed

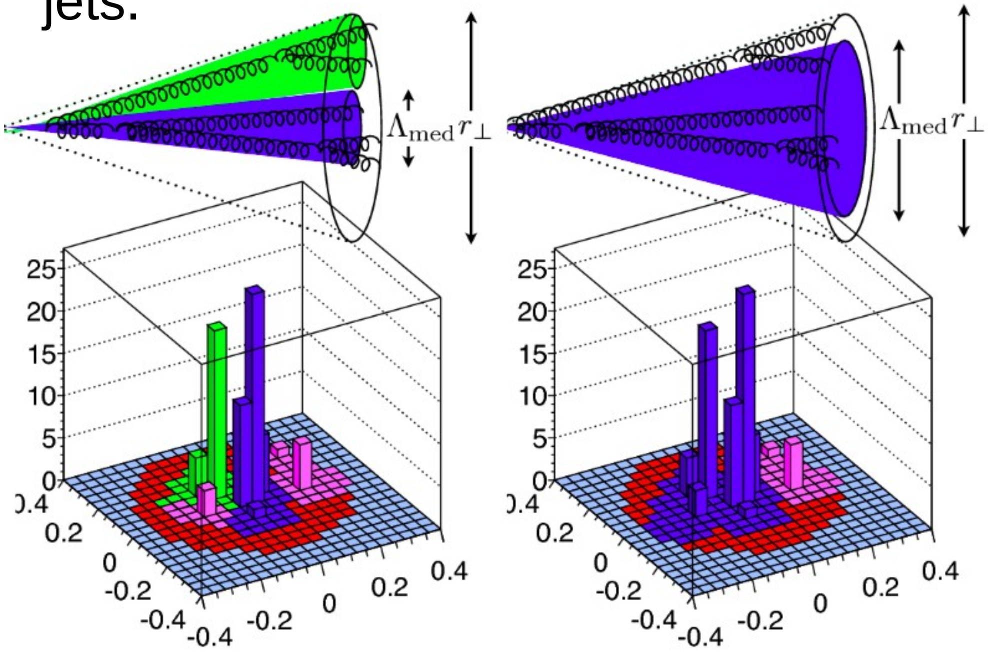
➡ Consistent with inclusive jet fragmentation measurement.

arXiv:1908.05264

Expanding the measurement to large angles



- Does the jet suppression depend on jet structure?
- Can be addressed by measurement of jet R_{AA} as a function of their sub-structure using sub-jets.



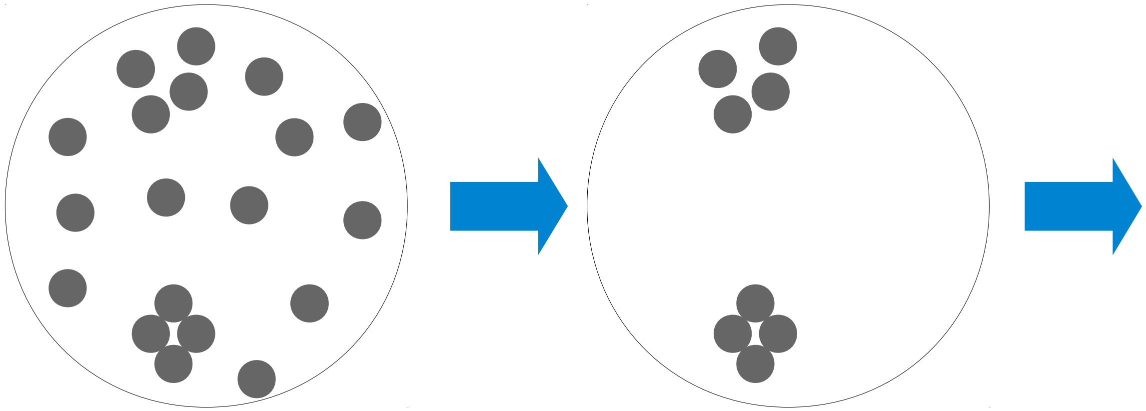
J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Lett. B725 (2013) 357

Reclustered large-R jets

Cal. towers & UE subtraction → R=0.2 jets p_T > 35 GeV → re-clustering with anti-k_t R=1.0

↓

Sub-jets → re-clustering with k_t algorithm → Splitting scale $\sqrt{d_{12}}$



"Conventional" jet → Re-clustered jet

Different jets than the conventional R=1.0.

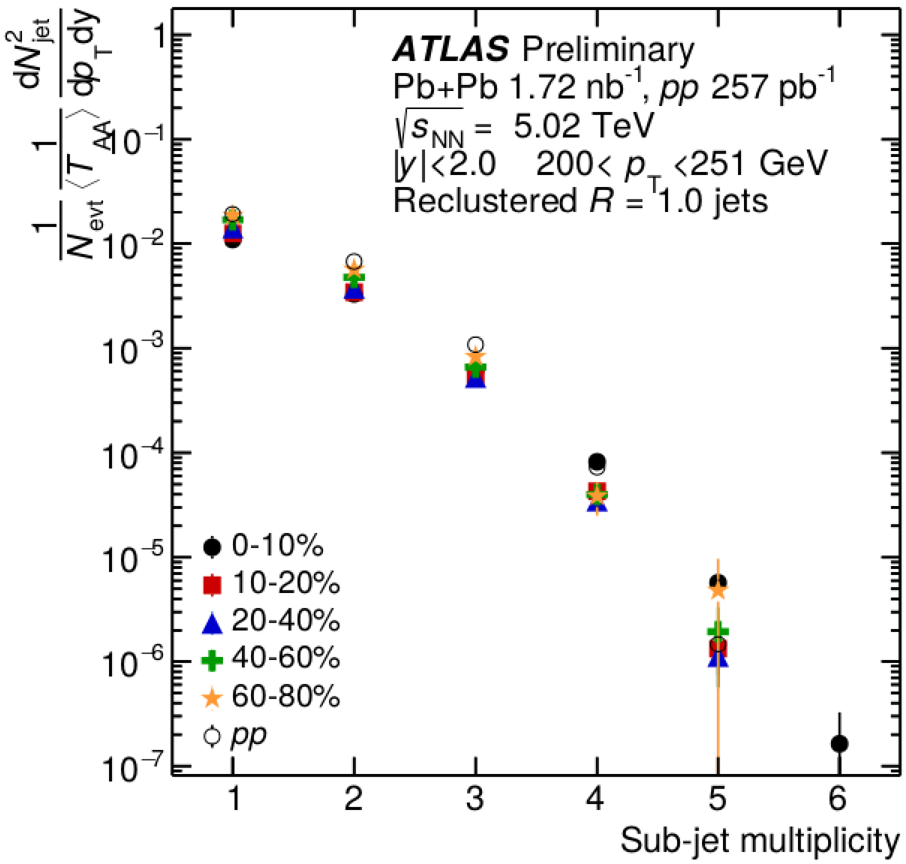
Trimming & 35 GeV threshold remove all the soft component.

Observables and analysis procedure

- Measurement of yields of re-clustered R=1.0 jets as function of p_T and and k_t splitting scale:

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

- Jet supression is evaluated using nuclear modification factor R_{AA}
- Yields are corrected for detector effects using 2D Bayesian unfolding.
  - Corrects also for presence of the combinatorial contribution.



Raw sub-jet multiplicity

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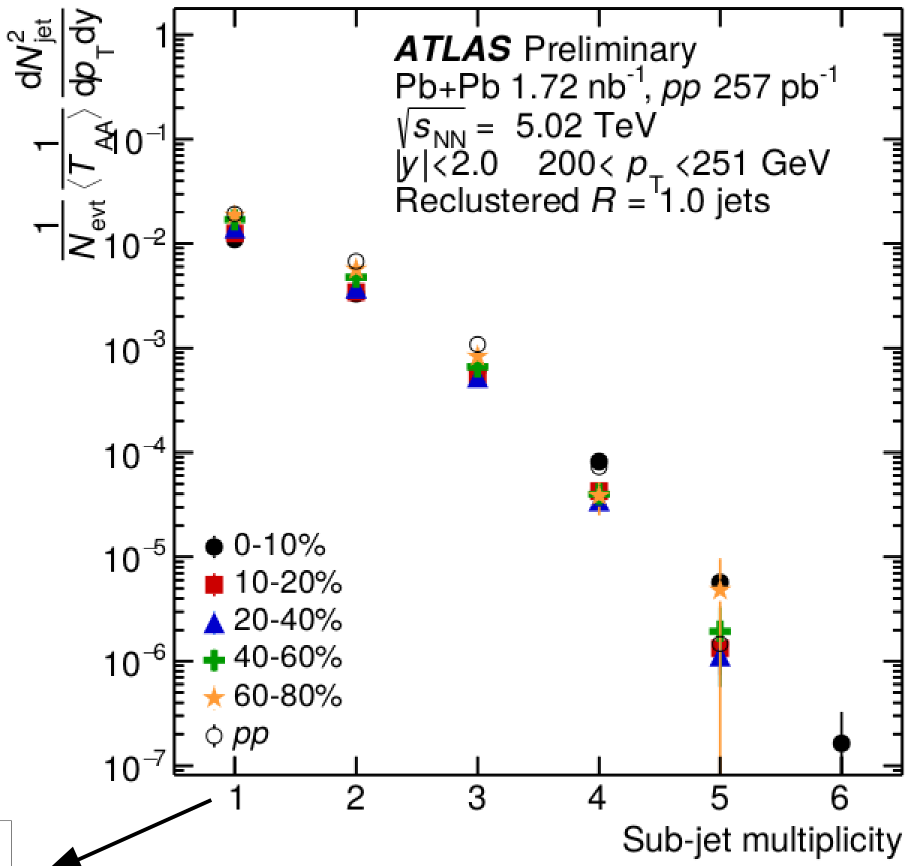
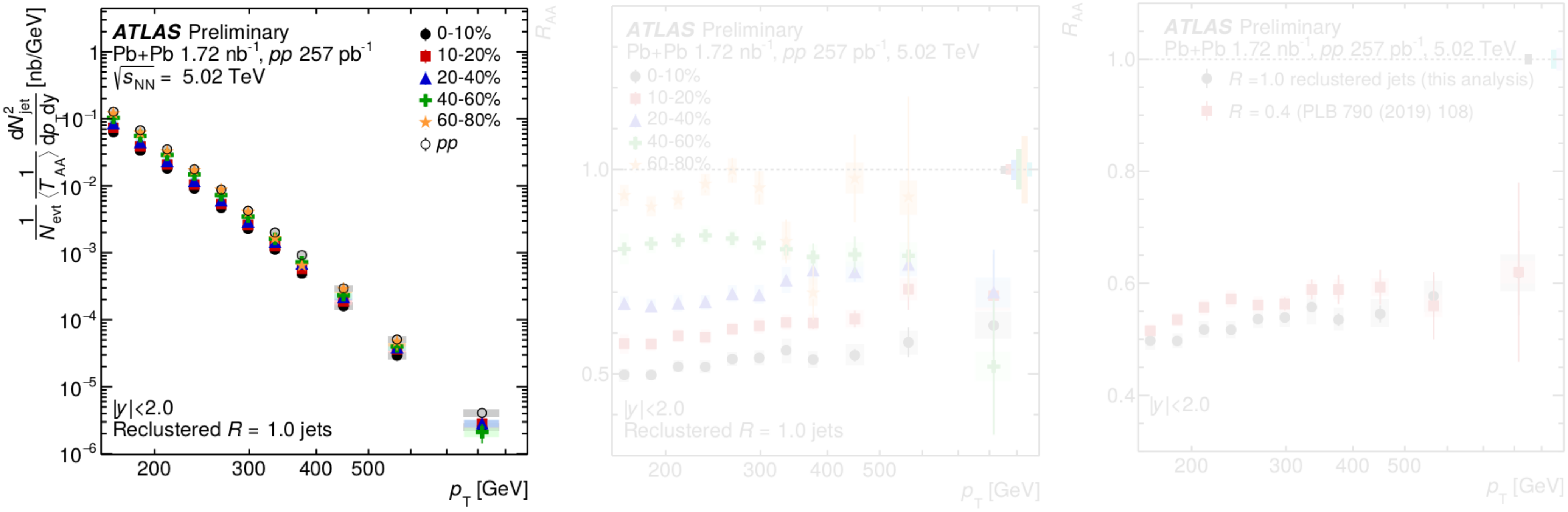


Raw sub-jet multiplicity

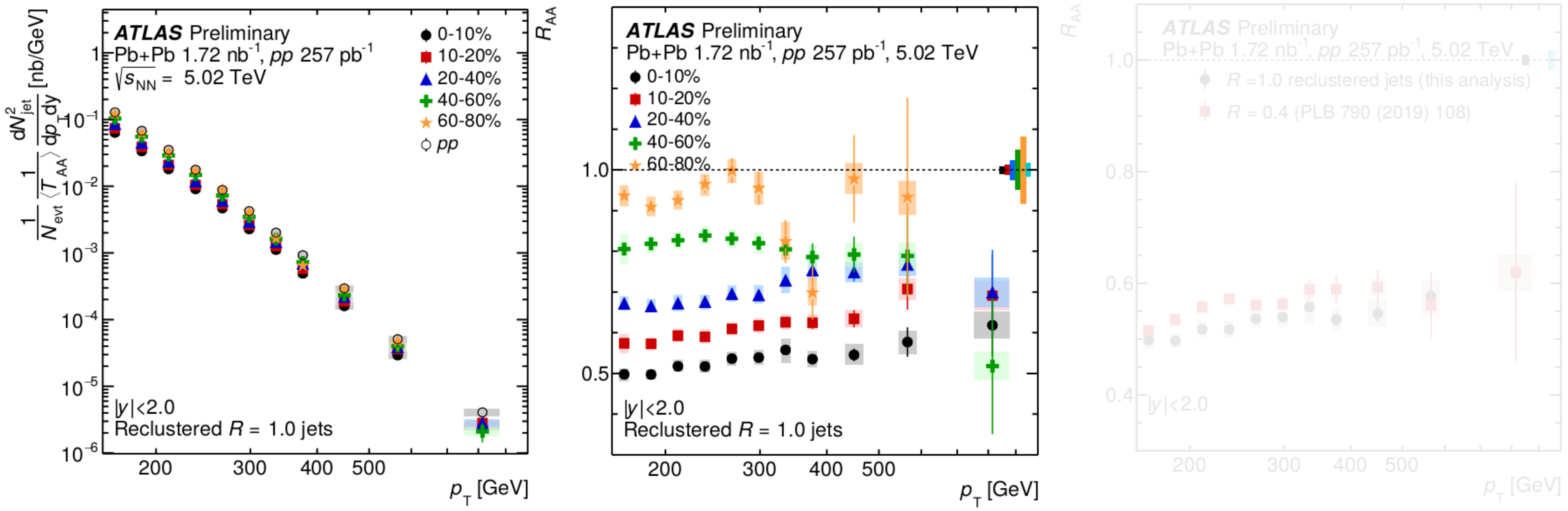
Single sub-jet: $\sqrt{d_{12}}=0$

Inclusive yields



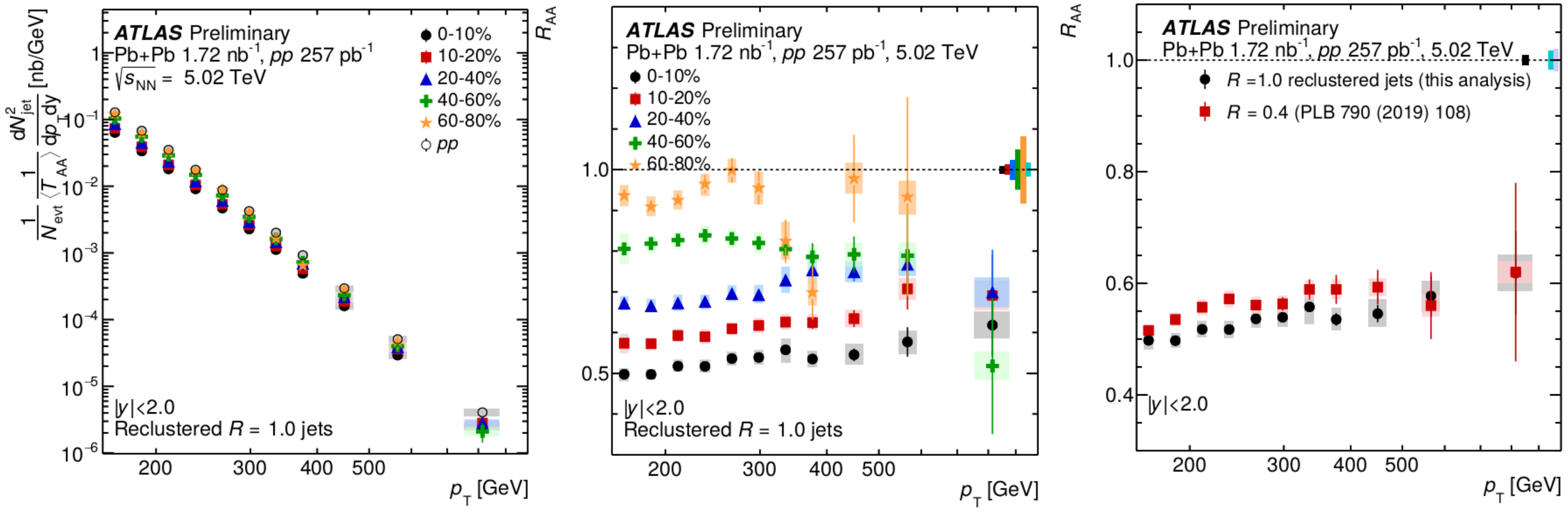
- Clear centrality dependence of the yields and suppression with respect to *pp* cross-section.

R_{AA} of Inclusive yields



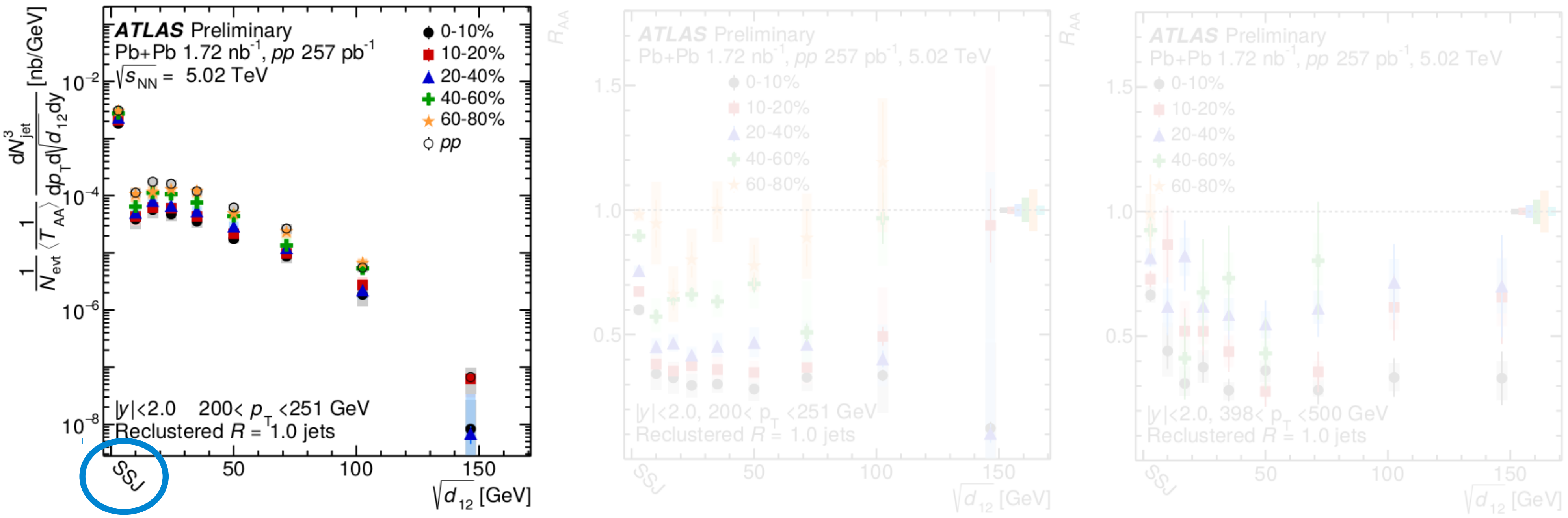
- Suppression by factor of 2 in the most central collisions.
- Small but continuous increase of the R_{AA} with p_T.

R_{AA} of Inclusive yields



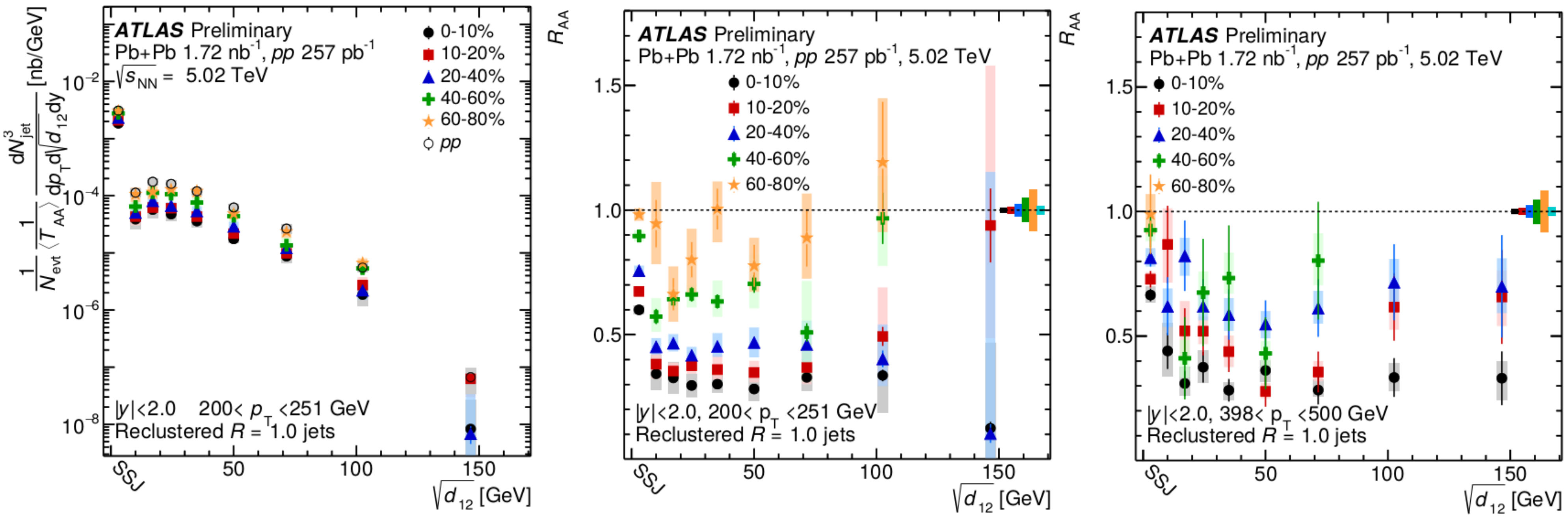
- Qualitatively similar to suppression of conventional R=0.4 jets but a larger suppression.
- Models predict a smaller suppression for larger R jets.
- Re-clustering remove the energy radiated between R=0.2 sub-jets.

Yields of re-clustered jets vs splitting scale



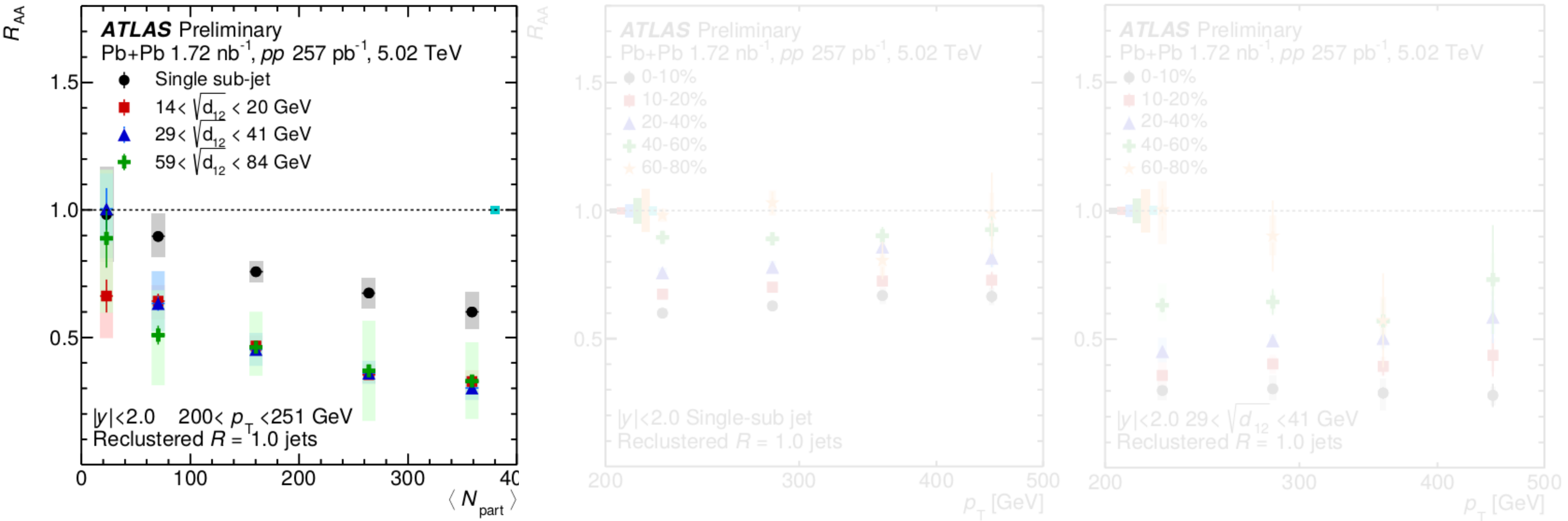
- The lowest $\sqrt{d_{12}}$ interval populated by jets with single "isolated" sub-jet.
- Yields suppressed in more central collisions with respect to *pp* collisions.

Yields of re-clustered jets vs splitting scale



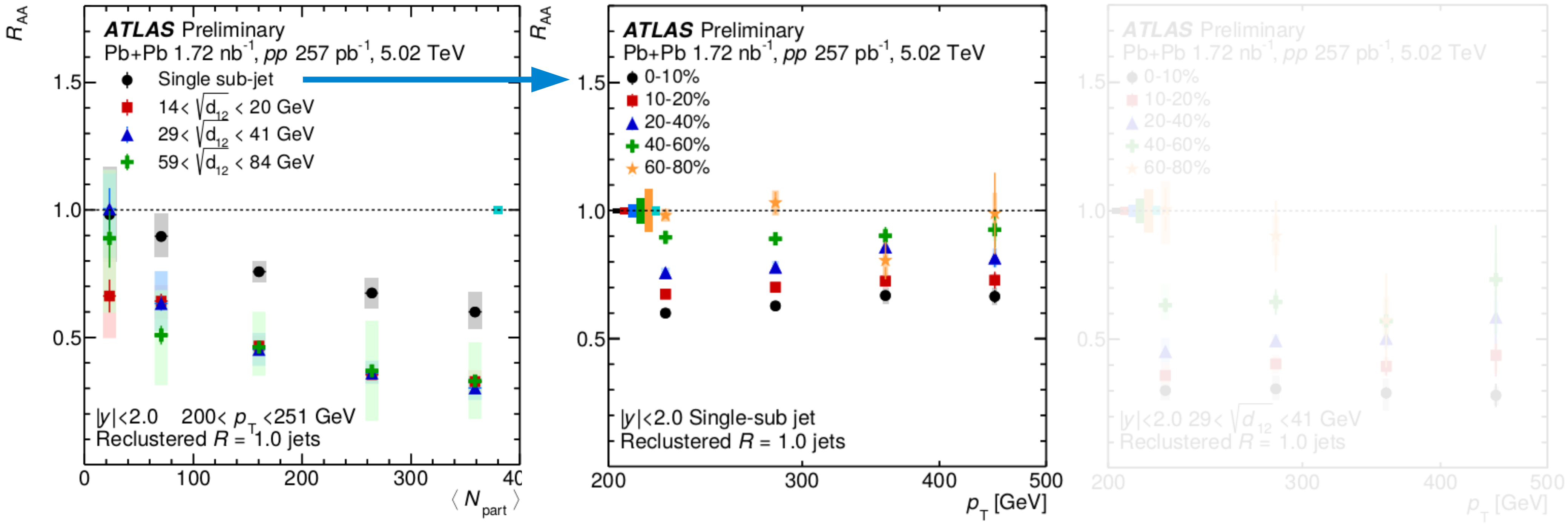
- Significant change of the R_{AA} magnitude between jets with single sub-jet and and those with more complex substructure.
- The R_{AA} sharply decreases with increasing $\sqrt{d_{12}}$ followed by flattening.

Centrality dependence



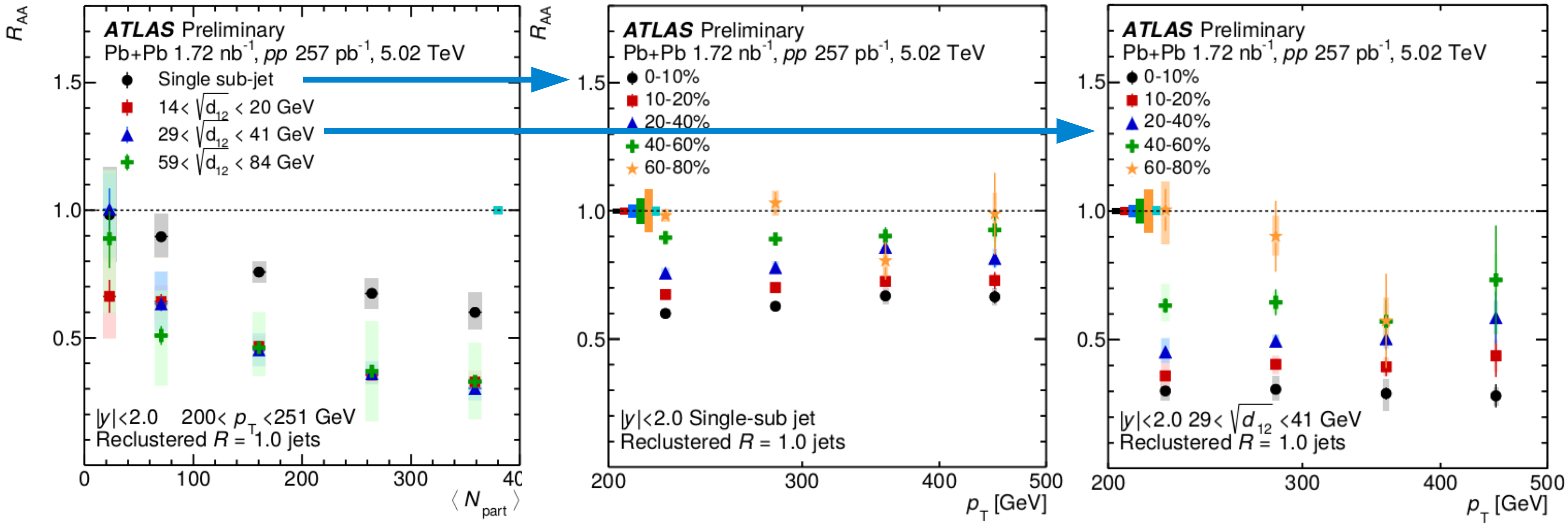
- A continuous increase of the suppression with increasing centrality.
- The jets with single sub-jet are less suppressed with respect to those with higher sub-jet multiplicity.
- In agreement with previous measurements if suppression of nearby jets.

Jet p_T dependence



- R=1.0 with a single "isolated" sub-jet shows similar trends as inclusive measurement but smaller suppression.

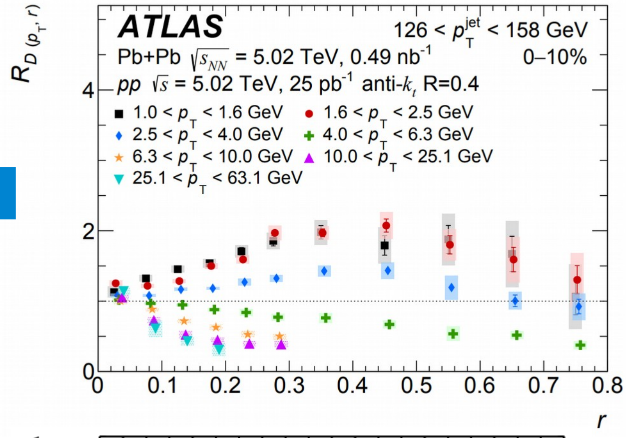
Jet p_T dependence



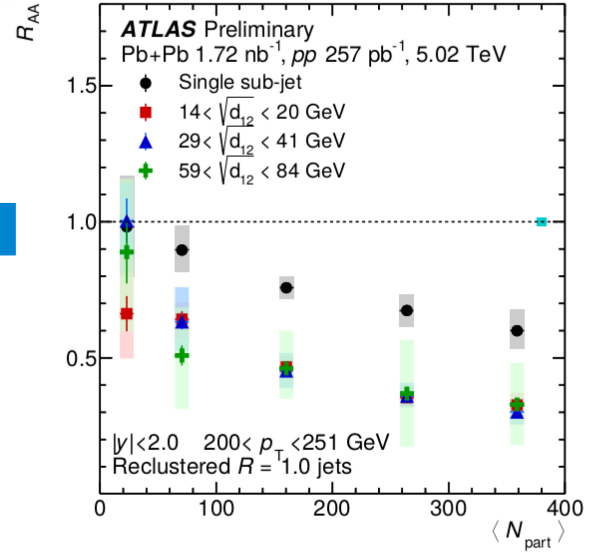
- Less p_T dependence seen for R_{AA} for re-clustered jets with a complex substructure.
- Both spectra shapes and quenching affects the R_{AA}.

Conclusions

- Jet broadening for low p_T particles in central Pb+Pb collisions.
- Suppression of higher p_T particles outside the jet core.
- The largest excess in terms of number of extra particles is in the cone.



- Measurement of re-clustered R=1.0 jets shows significant variation of R_{AA} with the p_T scale of the hardest splitting.
- Significance difference in quenching or jets with multi-prong structure compared to those with single sub-jet.

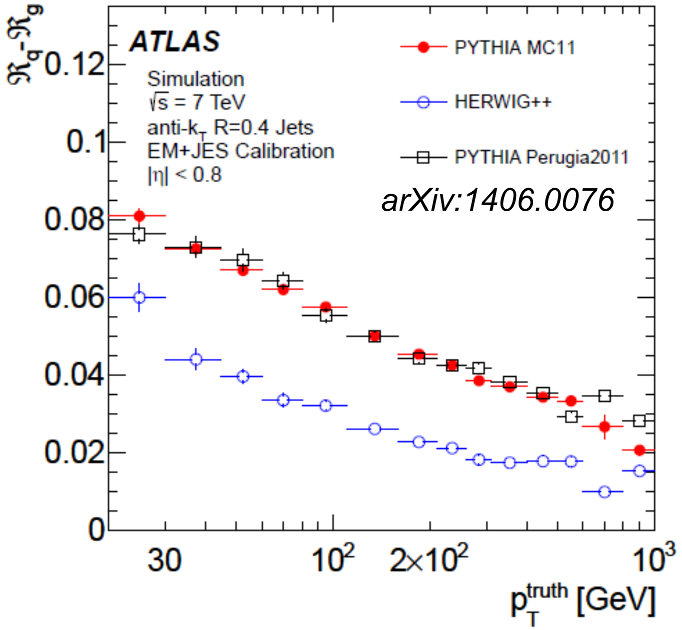


ATLAS HI Public results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Aspects of measurement @ high-p_T

- Jet response depends on parton flavour.
- Steeper FF when approaching the z~1.
- Worsening of track momentum resolution at high p_T.
- Difference in the jet energy resolution in *pp* and Pb+Pb at lower p_T.

Difference in response for quark and gluon jets:



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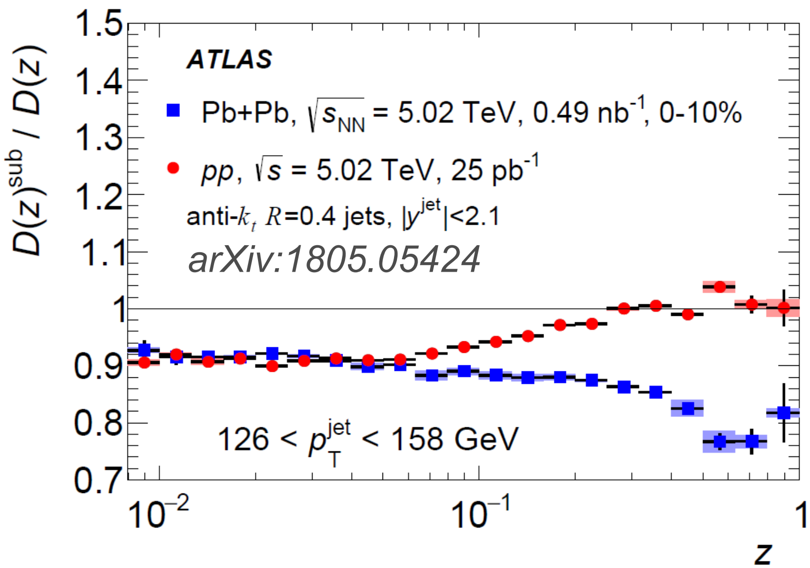
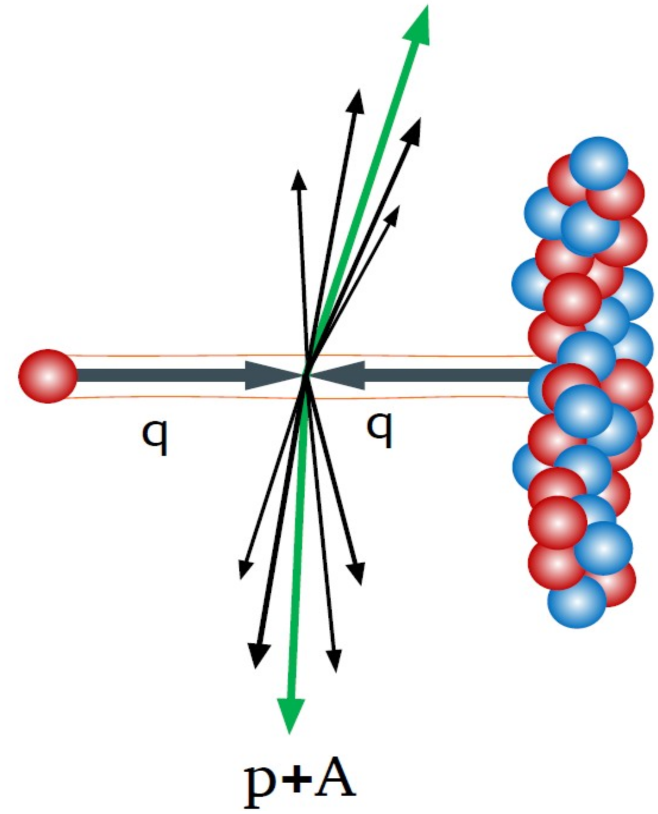
Need for 2D unfolding

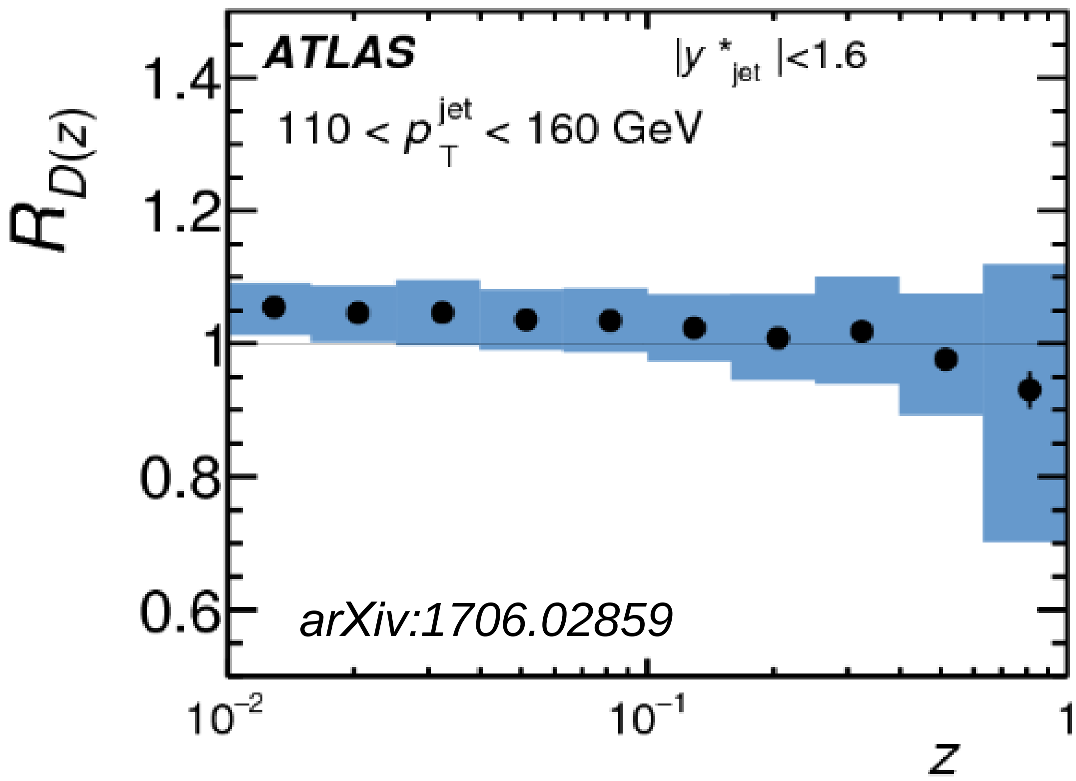
Impact of the unfolding



- The $D(p_T, r)$ are further corrected for position resolution by bin-by-bin correction.

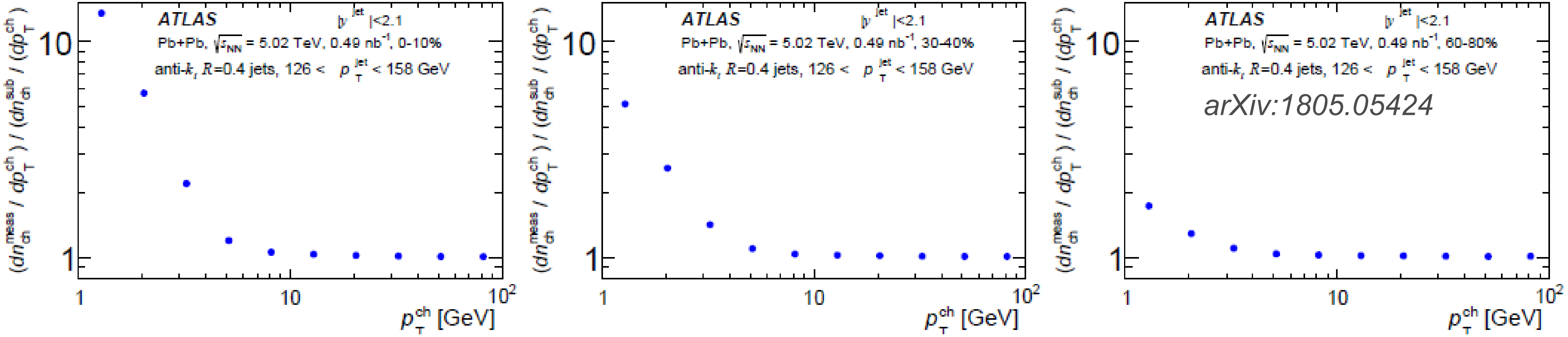
Shower modifications in p+Pb collisions?



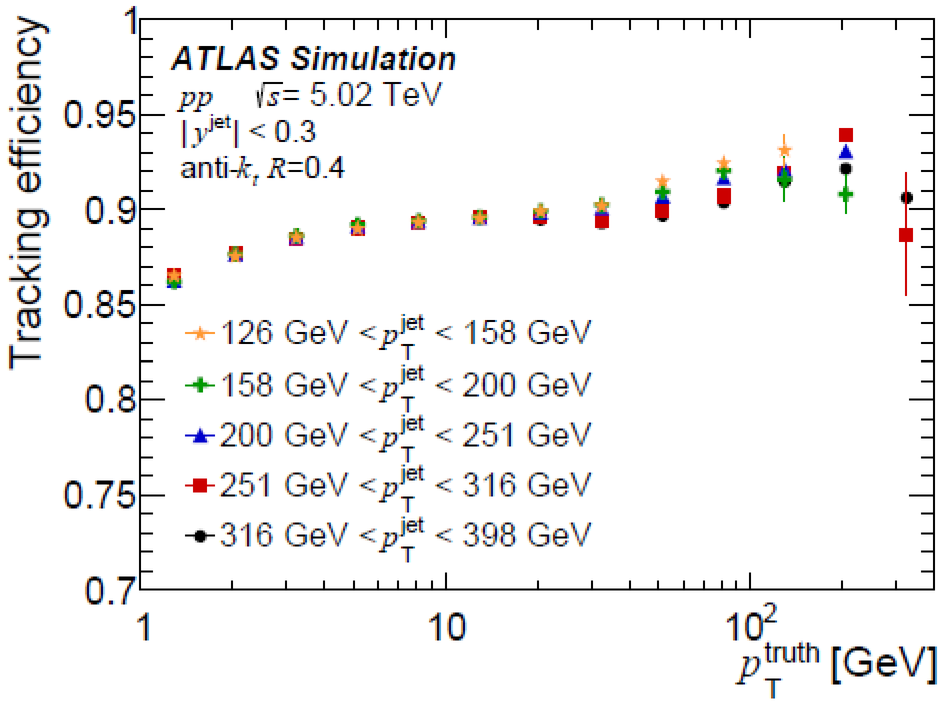


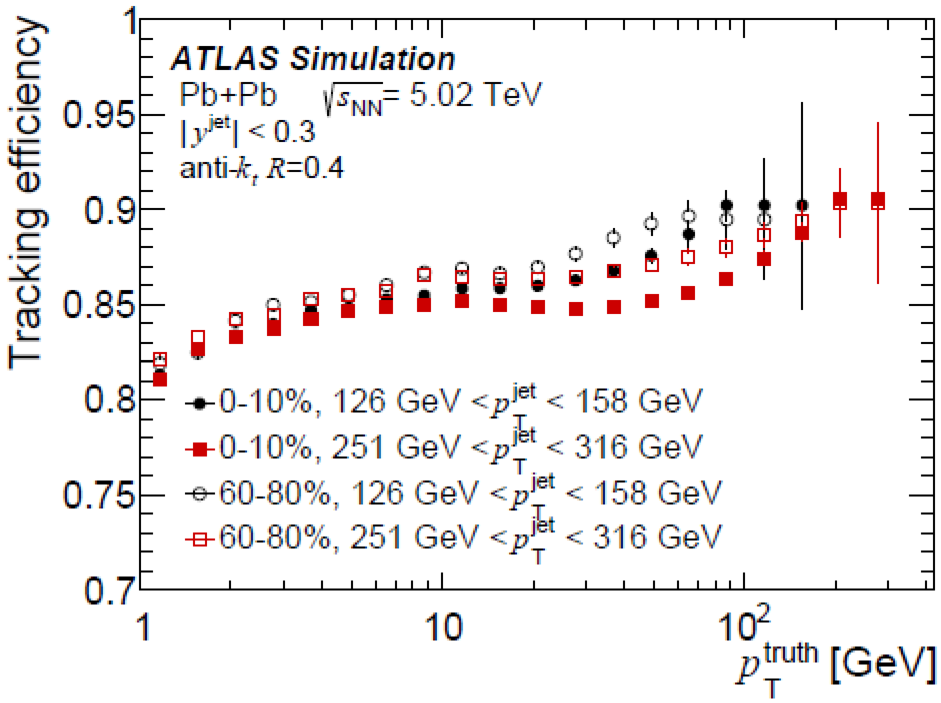
No modification of parton shower is observed in p+Pb system.

UE in FF measurement



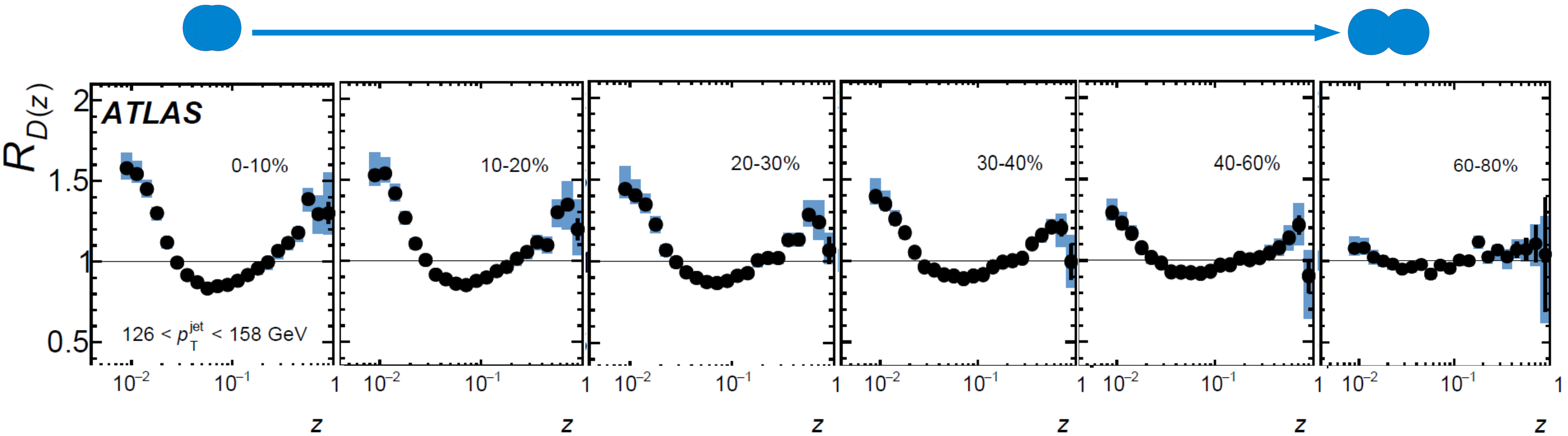
Tracking efficiency





arXiv:1805.05424

Modification of jet fragmentation in Pb+Pb

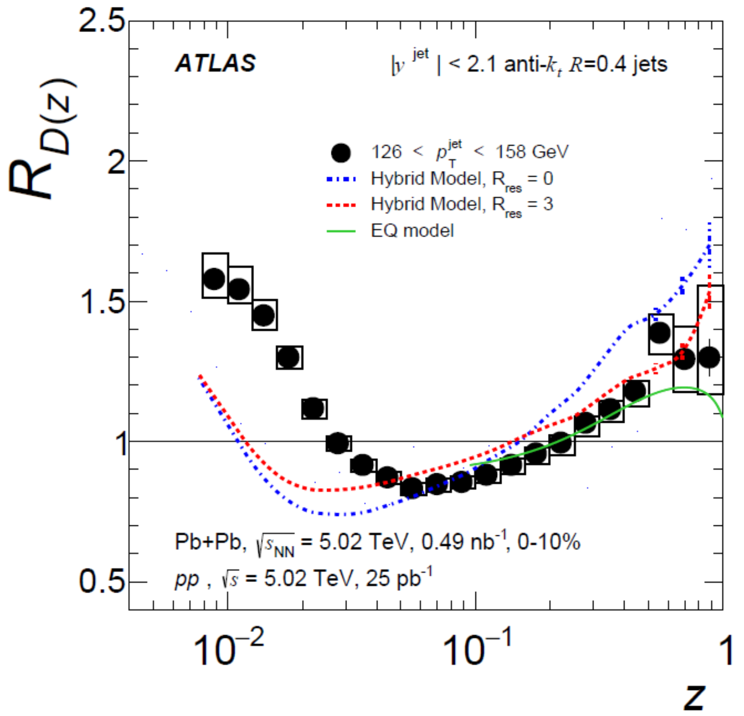


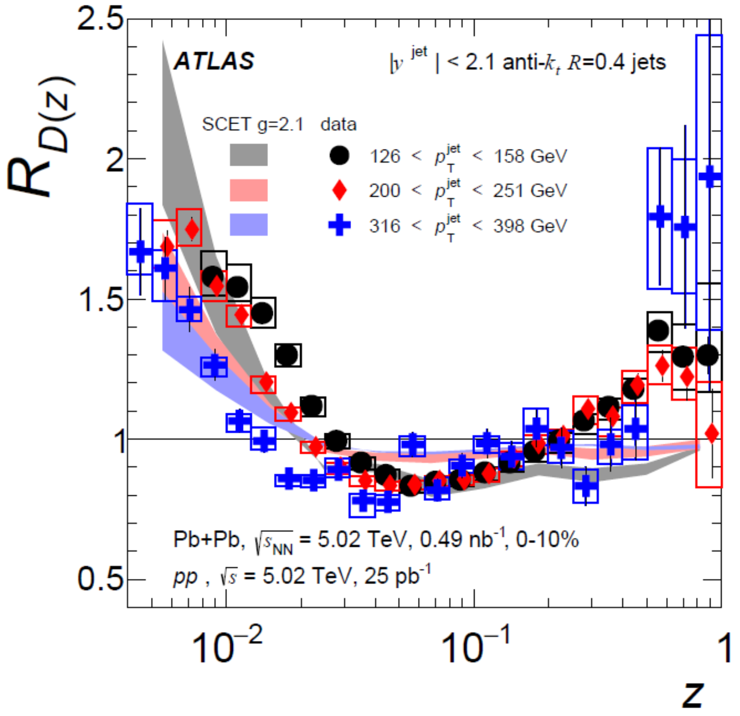
Increasing modification to FF with increasing centrality.

Enhancements of yields of hard and soft fragments.

arXiv:1805.05424

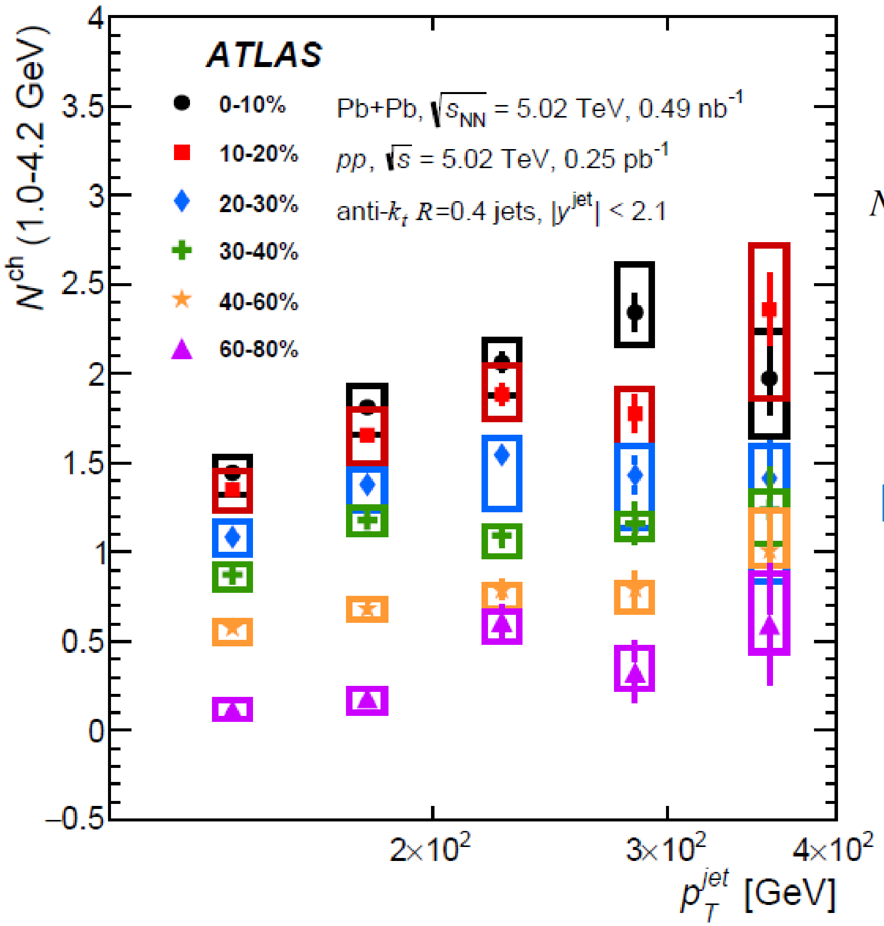
Can theory describe the measurement?



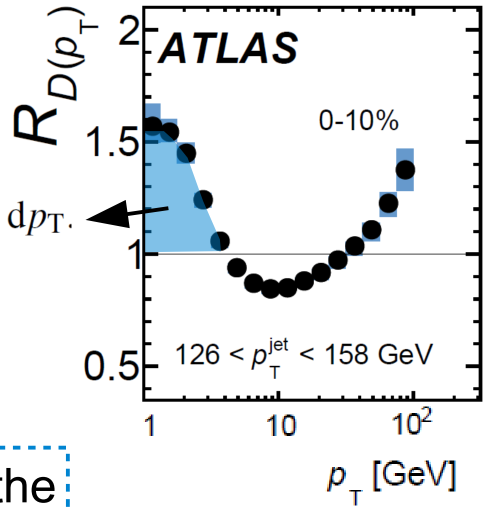


- Hybrid model (arXiv:1707.05245) consistent at high *z*, disagreement at low *z* due to simplistic medium response modeling.
- EQ model is able to describe the high-*z* excess.
- SCETg model is able to qualitatively described the low-*z* excess.

Integrals of $D(p_T)$ distributions



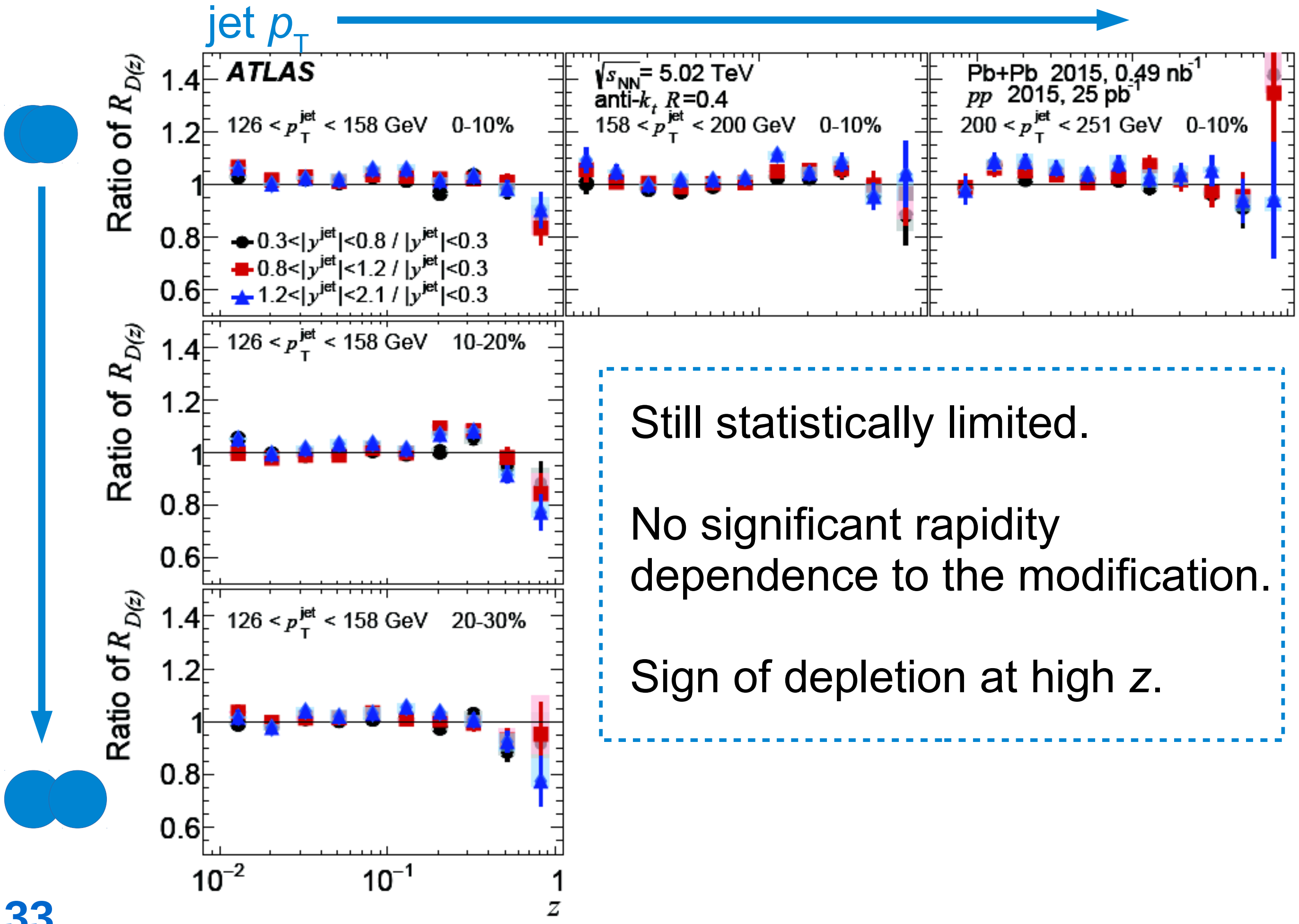
$$N^{\mathrm{ch}} \equiv \int_{p_{\mathrm{T,min}}}^{p_{\mathrm{T,max}}} \left(D(p_{\mathrm{T}})|_{\mathrm{cent}} - D(p_{\mathrm{T}})|_{\mathrm{pp}} \right) \mathrm{d}p_{\mathrm{T}}.$$



Jet p_T dependence to the enhancement.

arXiv:1805.05424

Rapidity dependence



- Measured as ratio of $R_{D(z)}$ in different jet y bins to the $R_{D(z)}$ in $|y|$<0.3.

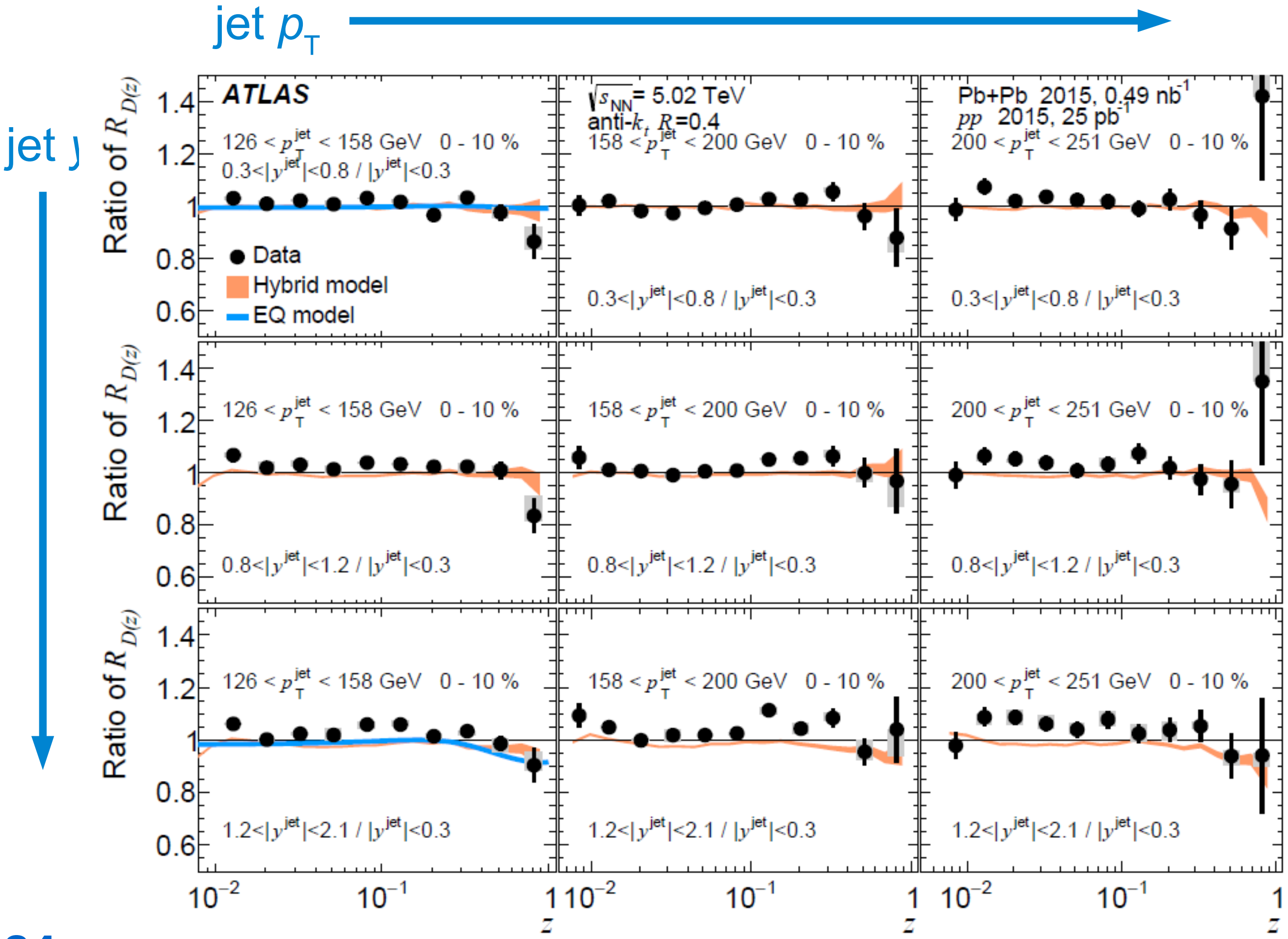
Still statistically limited.

No significant rapidity dependence to the modification.

Sign of depletion at high z.

arXiv:1805.05424

Rapidity dependence



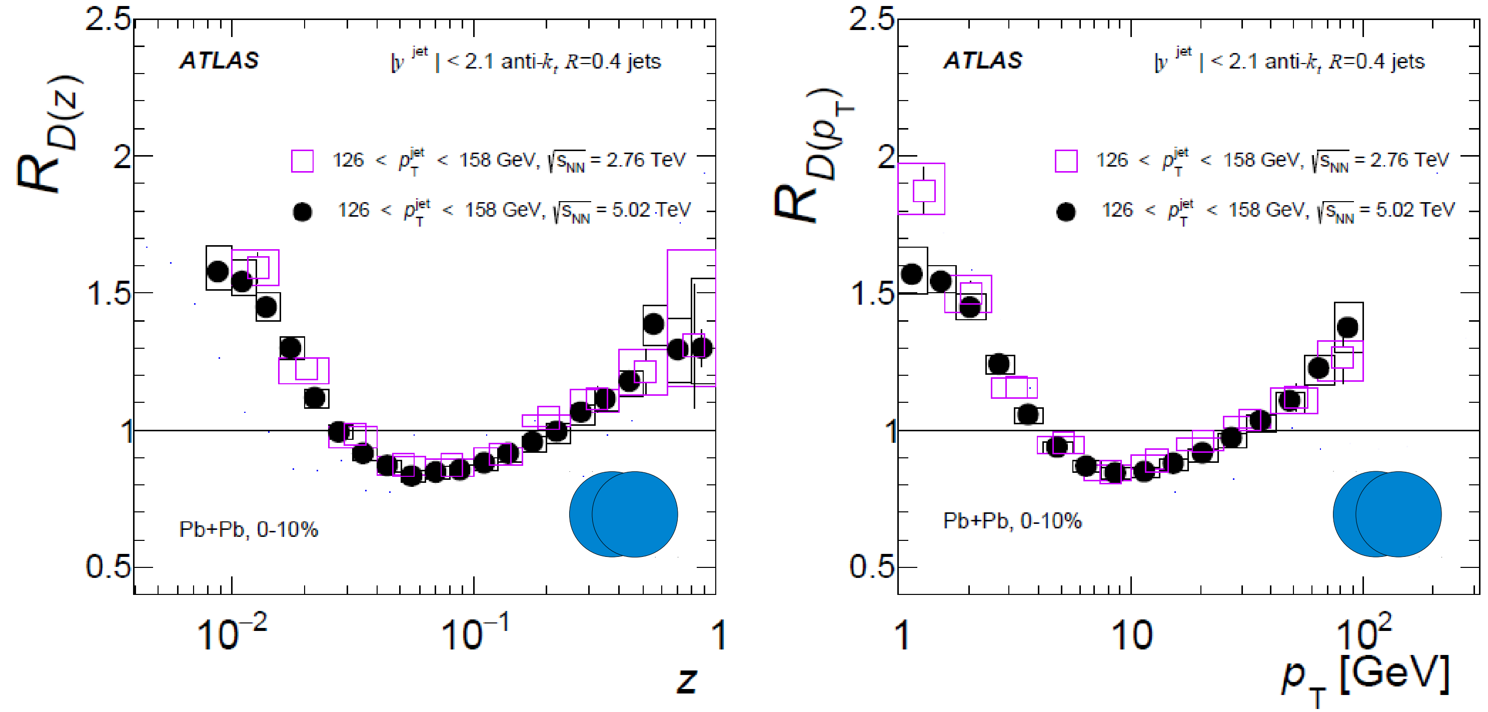
- Comparison to EQ and Hybrid model.

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

arXiv:1805.05424

Is there dependence on collision energy?

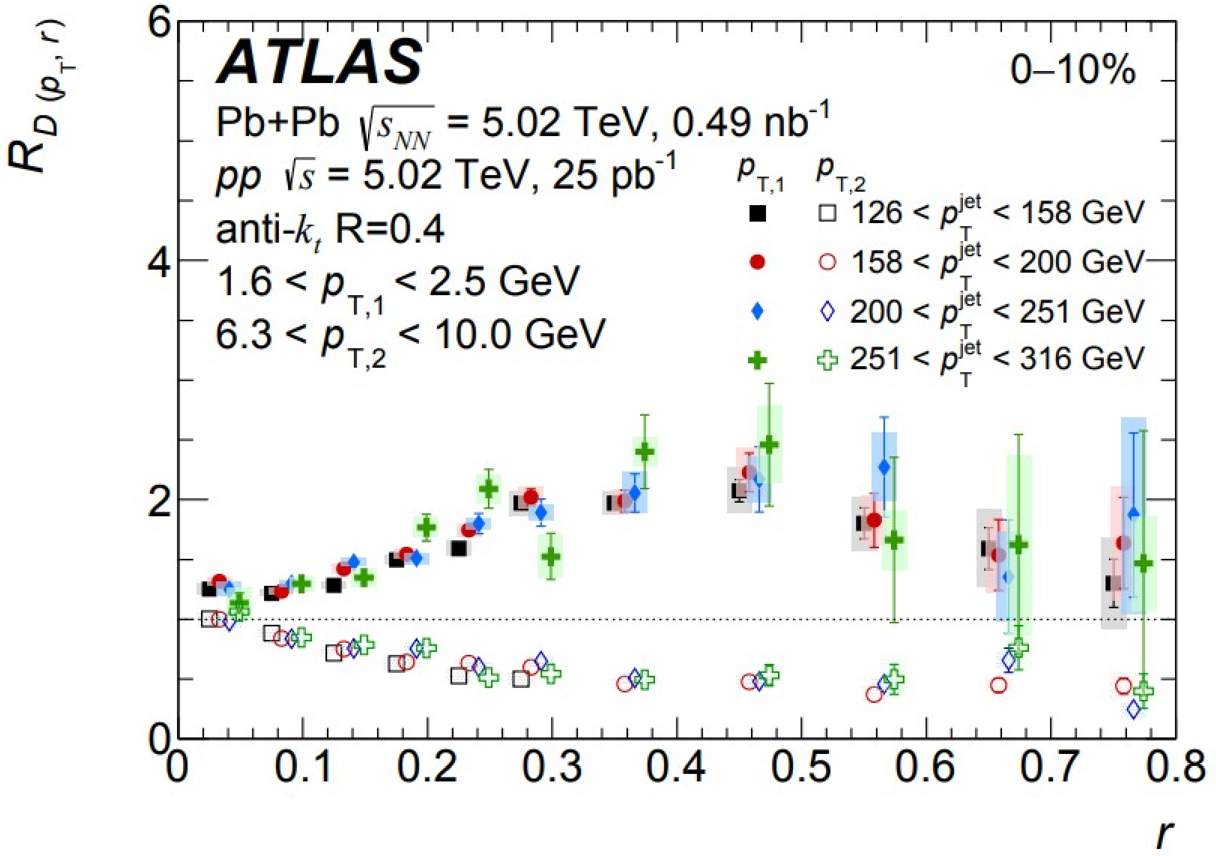
- Comparison to the result at 2.76 TeV.



No dependence on the collision energy.
Similar to other jet observables.

arXiv:1805.05424

Jet p_T dependence of $R_{D(pT,r)}$

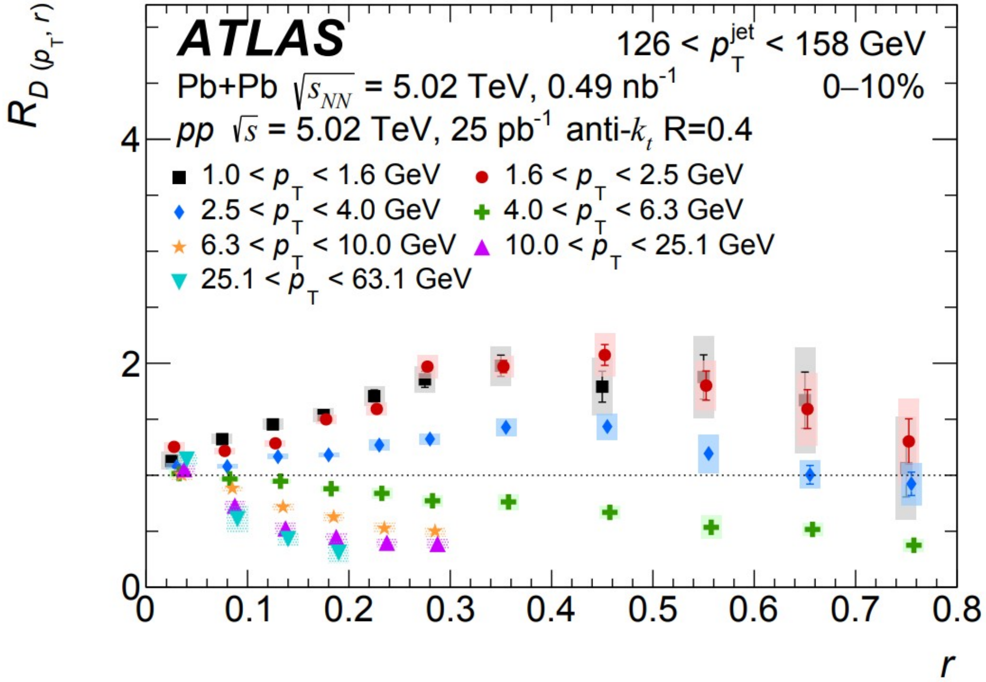


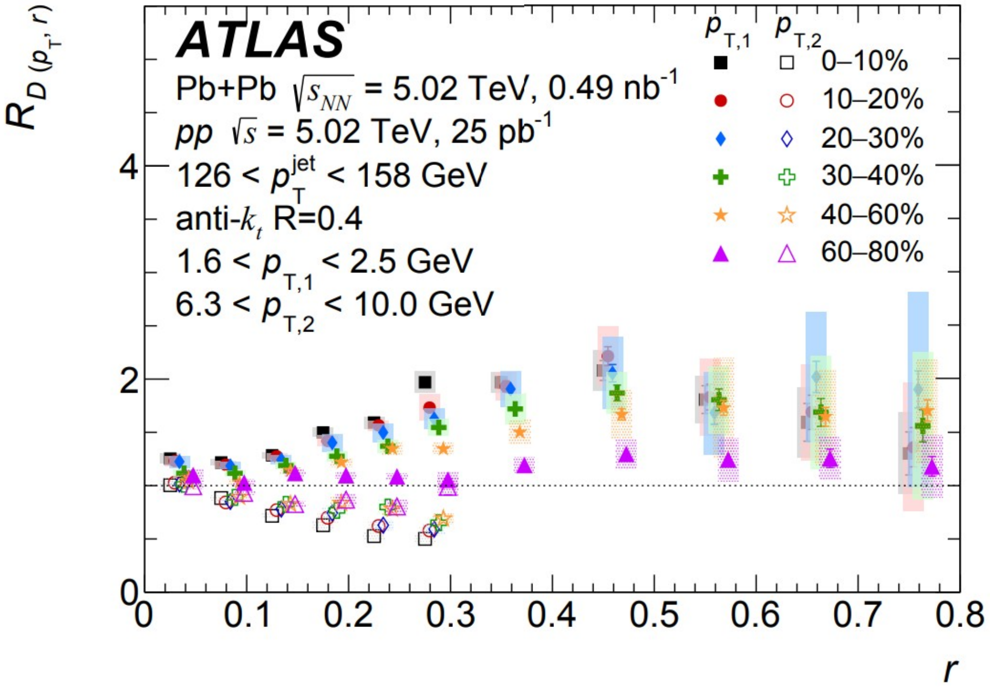
Similar observation as for r-inclusive measurement:

Yield of soft fragments more enhanced for higher p_T jets.

No significant dependence of yields for fragments with intermediate p_T.

Modification of Radial Profile

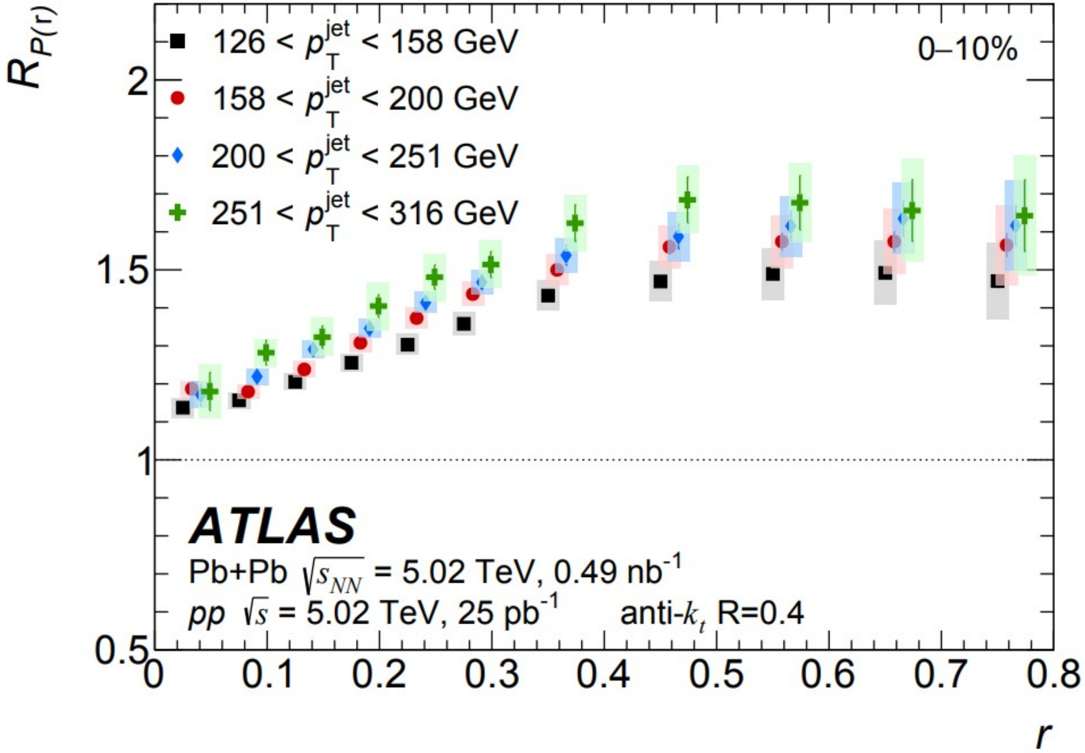




Jets are broader in more central collisions at low p_T.
Significant suppression of yileds of particles > 4 GeV outside the jet core.

Continuous modifications with centrality: Increase of yields of soft fragments with *r*. Decrease of yields of higher-p_T particles with *r*.

Integrals of $D(p_T,r)$ distributions



Integrated "jet shape"

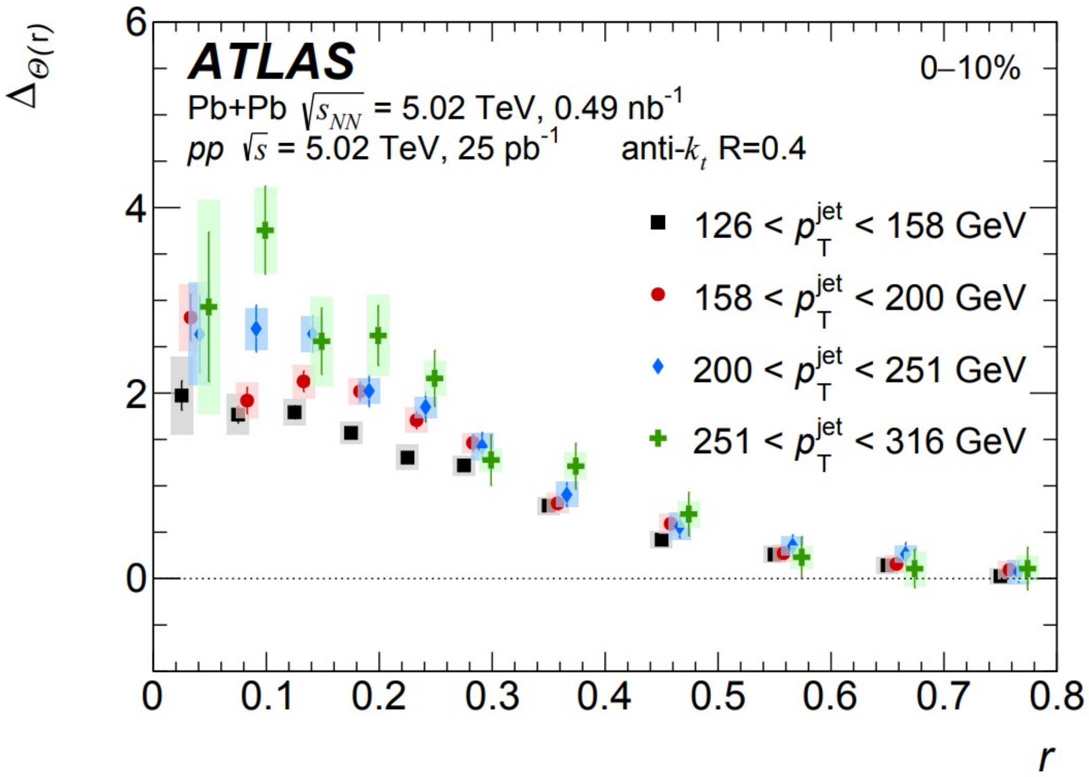
$$P(r) = \int_0^r \int_{1\ \mathrm{GeV}}^{4\ \mathrm{GeV}} D(p_\mathrm{T}, r')dp_\mathrm{T}dr'$$

$$R_{P(r)} = \frac{P(r)_{\mathrm{Pb+Pb}}}{P(r)_{pp}}$$

- Linear increase of the excess with r towards r = 0.5 with flattening at larger radial distances.
- Significant jet p_T dependence to the enhancement is observed.

arXiv:1908.05264

Integrals of $D(p_T,r)$ distributions



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

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

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  ➡ Consistent with inclusive jet fragmentation measurement.

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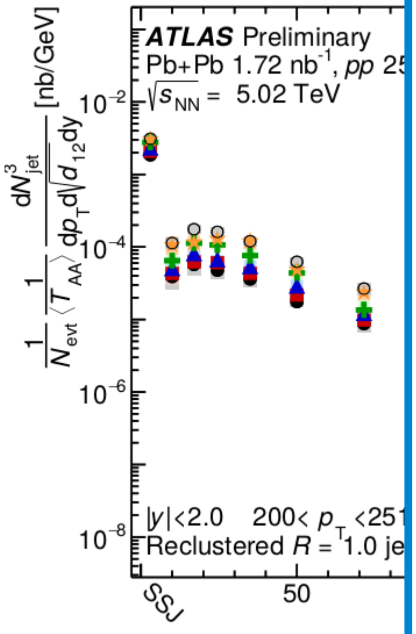
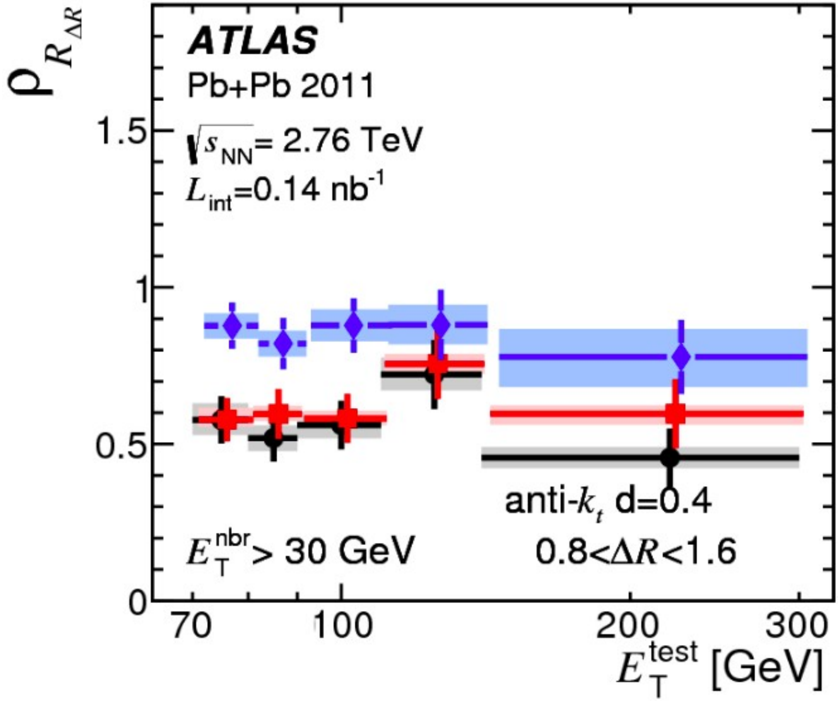
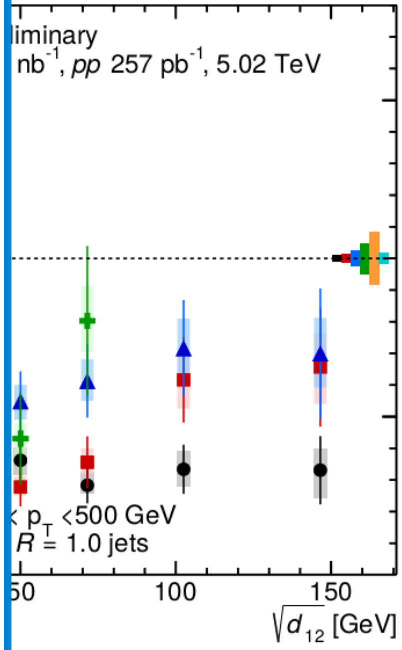
Yields of Re-clustered jets vs splitting scale



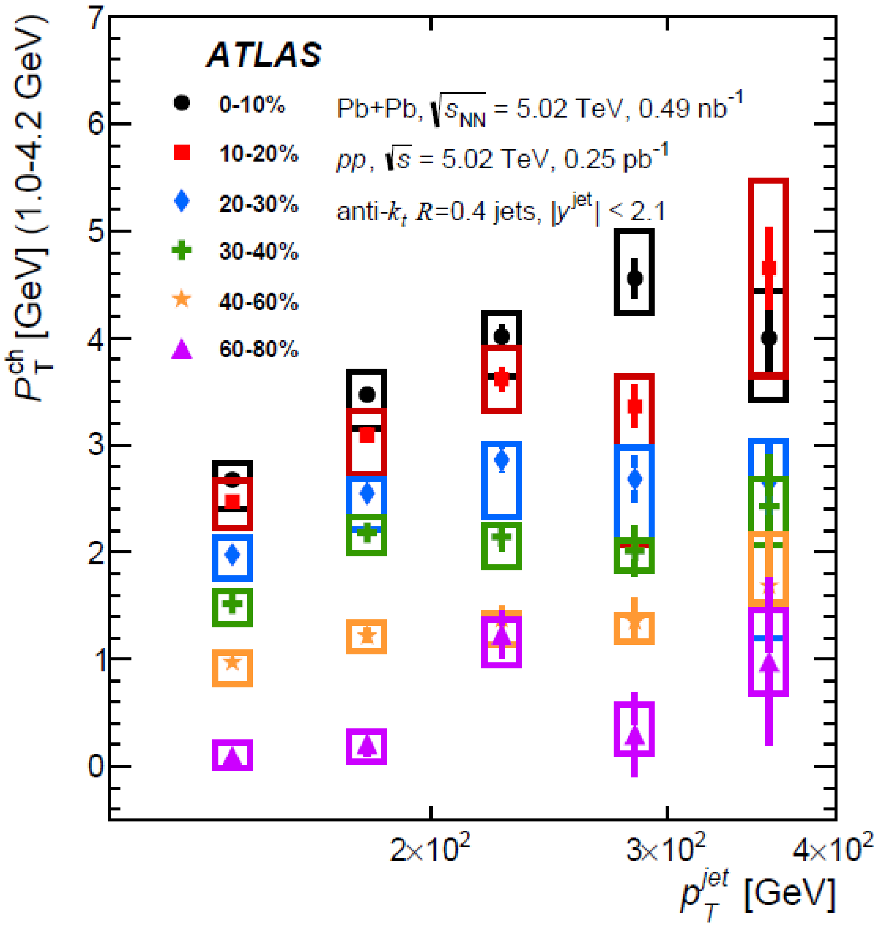
Consistent with previous ATLAS result reporting supression to conditional yileds of nerby jets.



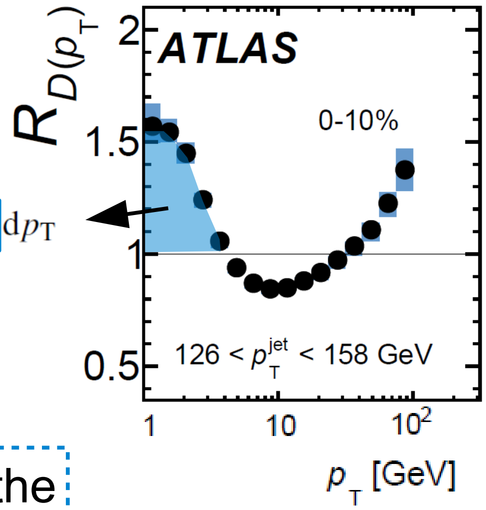


- Significant ch … e sub-jet and and those with m…
- The R_{AA} shar … ening.

Integrals of $D(p_T)$ distributions



$$P_T^{ch} \equiv \int_{p_{T,min}}^{p_{T,max}} \left(D(p_T)|_{cent} - D(p_T)|_{pp} \right) p_T \, dp_T$$



Jet p_T dependence to the enhancement.

Response of the medium to the high-p_T parton?

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