Jet substructure measurements with small and large radius jets with ATLAS

Martin Rybar

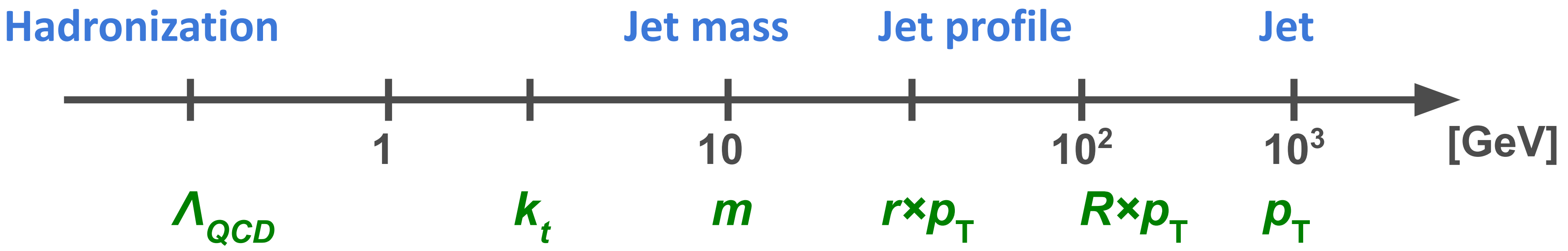
on behalf of ATLAS collaboration

Hard Probes 2024

23rd September 2024

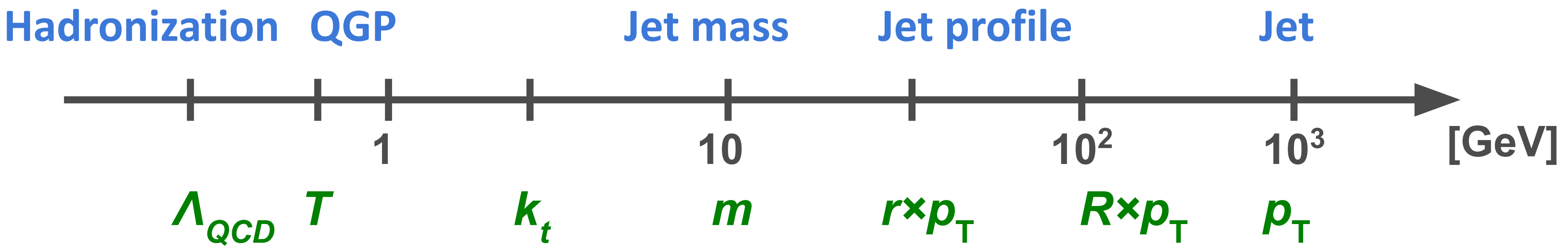
Why jet substructure?

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



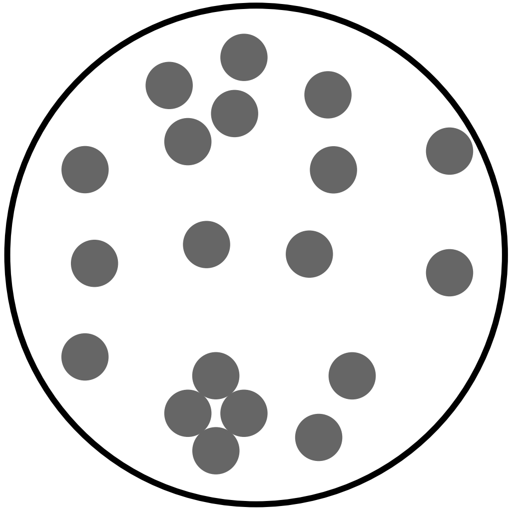
Why jet substructure in HI?

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



- 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?

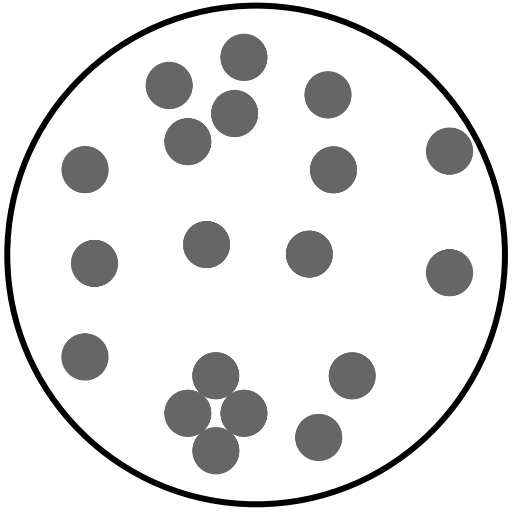
Jet definition & substructure



"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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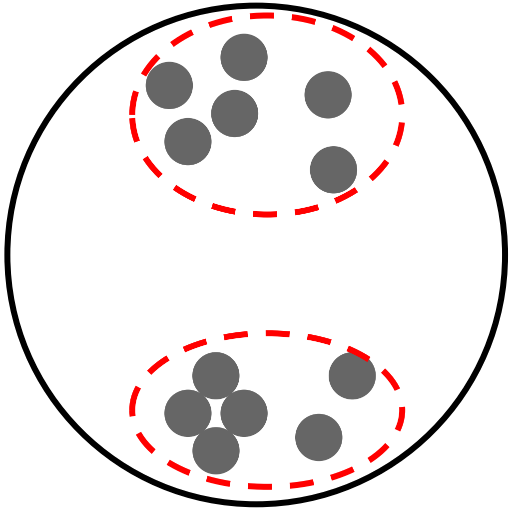


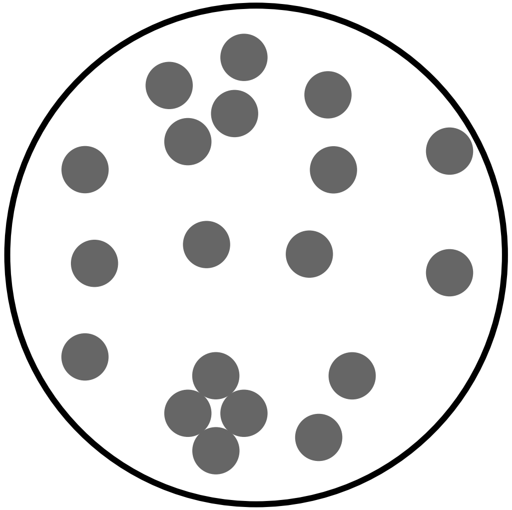
De-clustered & groomed jet with SoftDrop

Focusing on hard substructure…

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

Declustering follows the splitting evolution; grooming parameters ⇔ affects physics.

Jet definition & substructure



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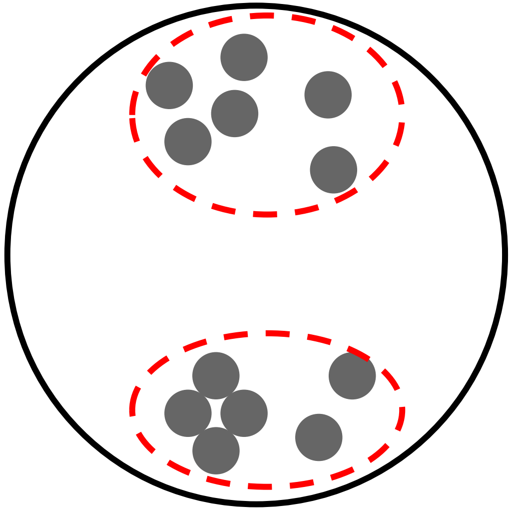

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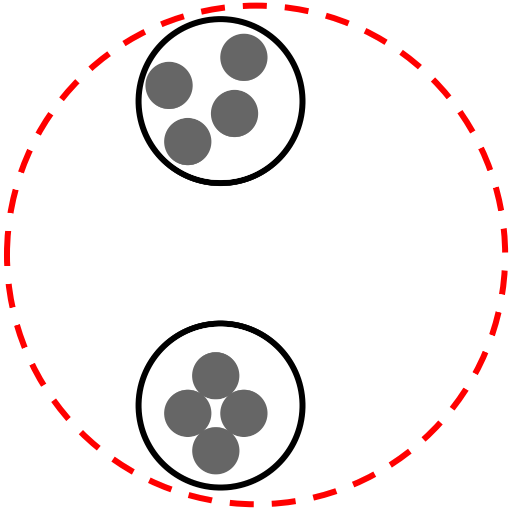


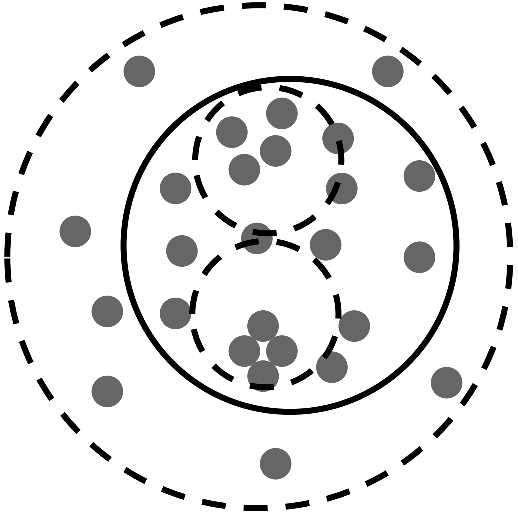
Re-clustered jet from smaller jets

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

Declustering follows the splitting evolution; grooming parameters ⇔ affects physics.

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

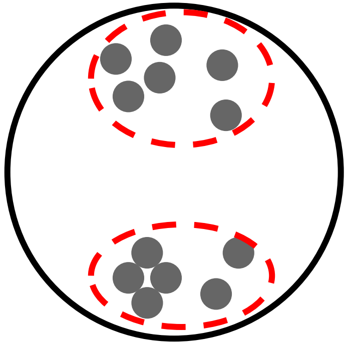
Jet definition & substructure



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

Radius dependence of dijet momentum balance

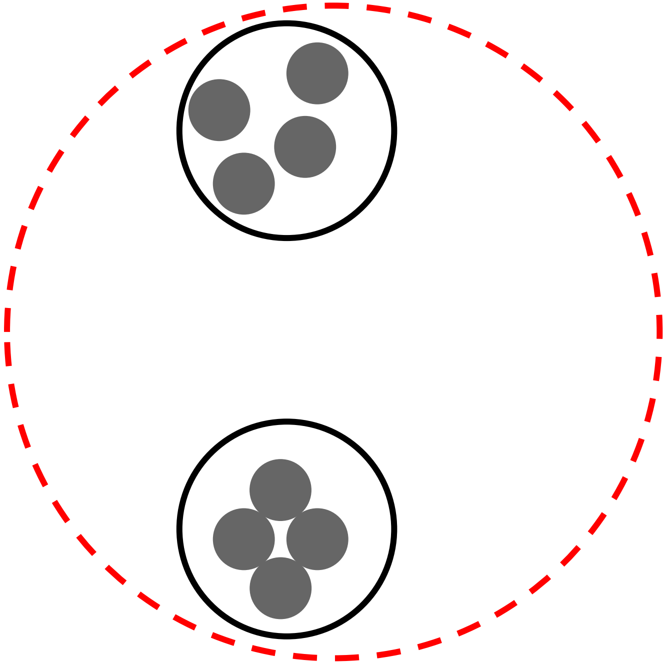
arXiv:2407.18796



De-clustered & groomed jet with SoftDrop

Substructure of *R*=0.4 jets

Phys. Rev. C 107 (2023) 054909

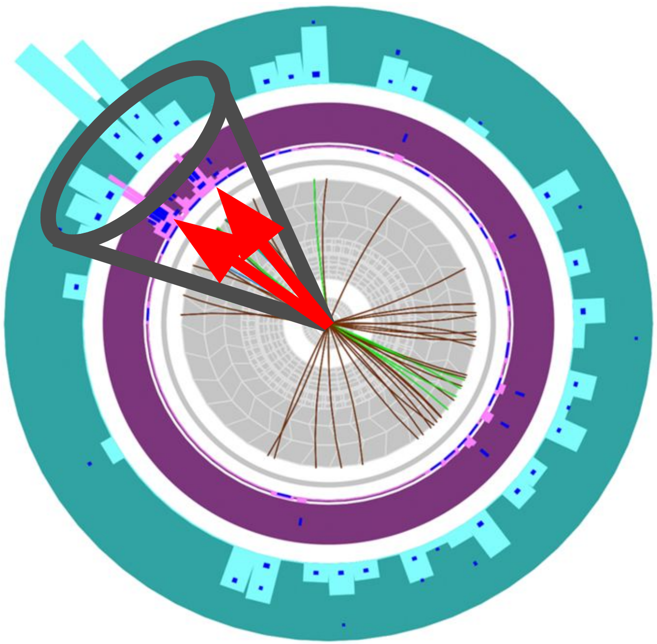


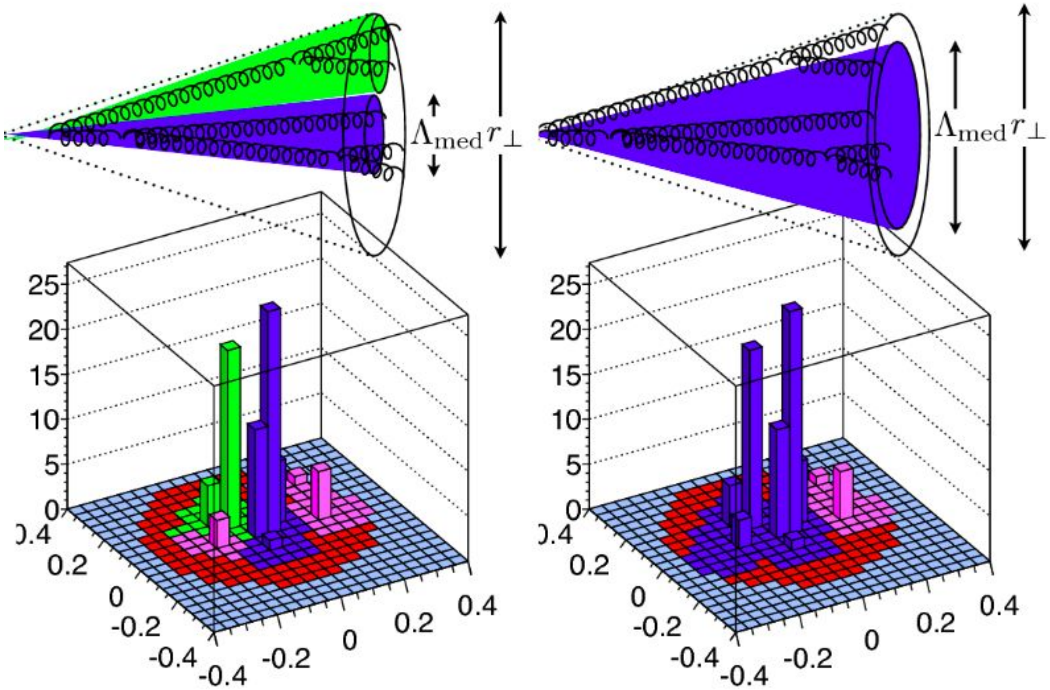
Re-clustered jet from smaller jets

Substructure of *R*=1.0 jets

Phys. Rev. Lett. 131 (2023) 172301

Dependence of suppression on jet structure?



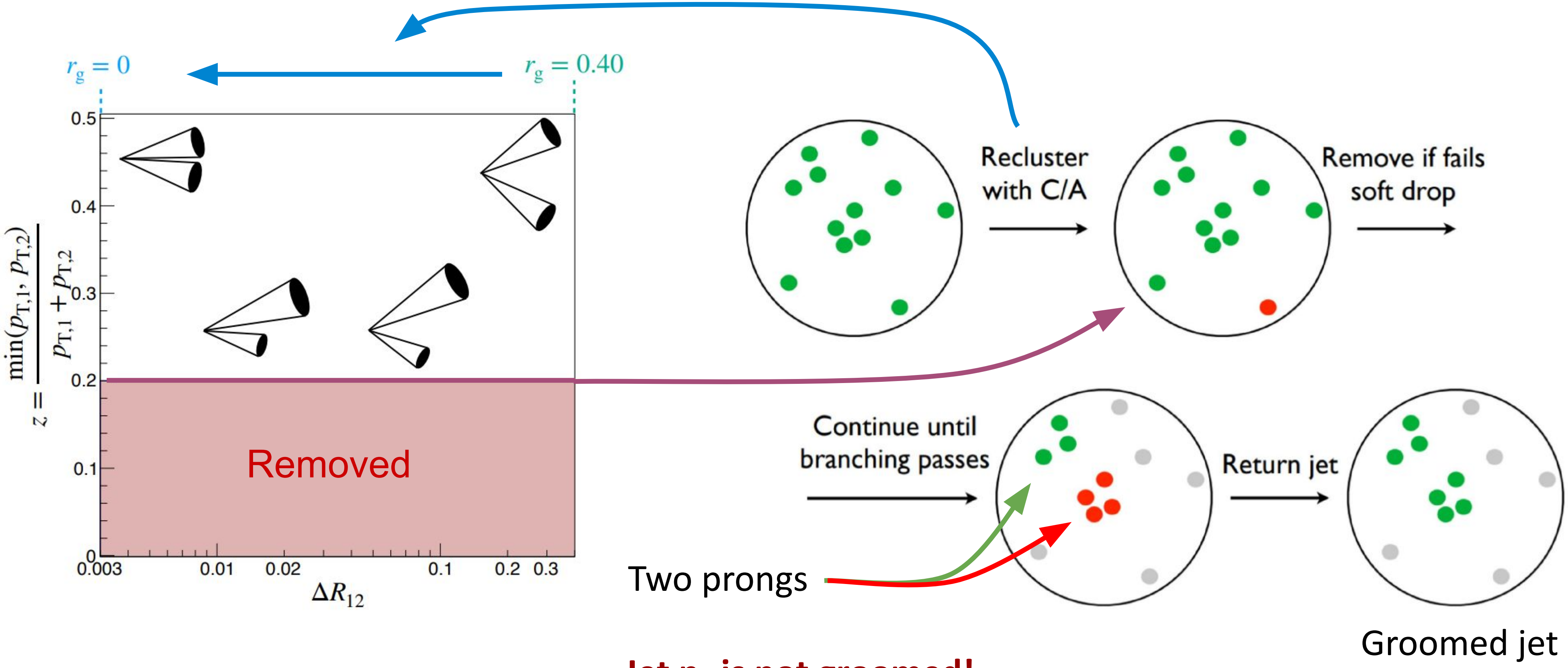


J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Lett. B725 (2013) 357

Can be addressed by measurement of jet R_{AA} as a function of their sub-structure.

Classifying parton splittings with Soft-Drop

- Classifying R =0.4 jets using angular separation of the hardest splitting

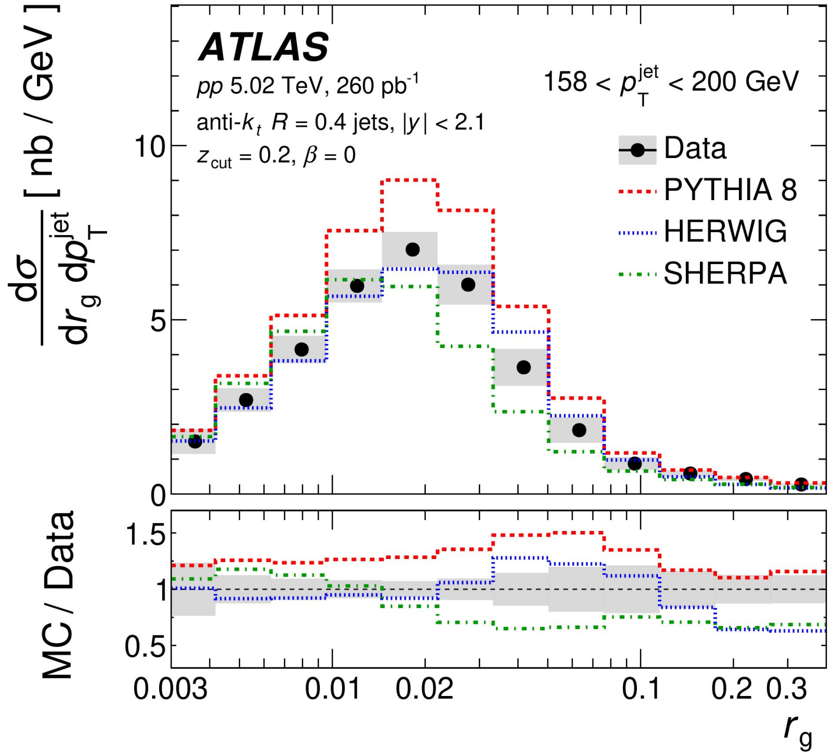


Drawing by Dhanush Hangal

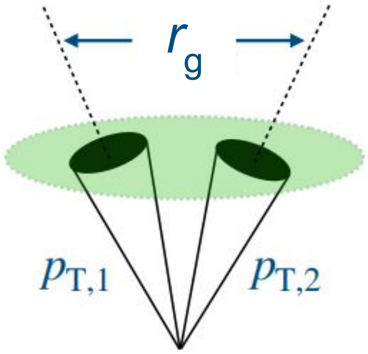
Jet p_T is not groomed!

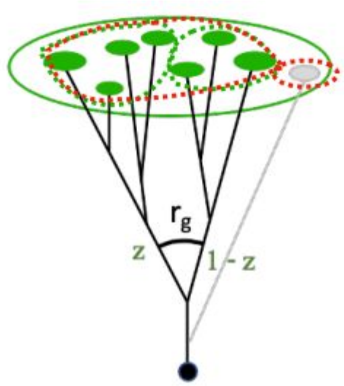
Classifying parton splittings with Soft-Drop

- Fully corrected & absolutely normalized cross-sections & yields.



Reference measurement in pp collisions at 5.02 TeV





r_g is ΔR_{12} between subjets when above SD condition is satisfied

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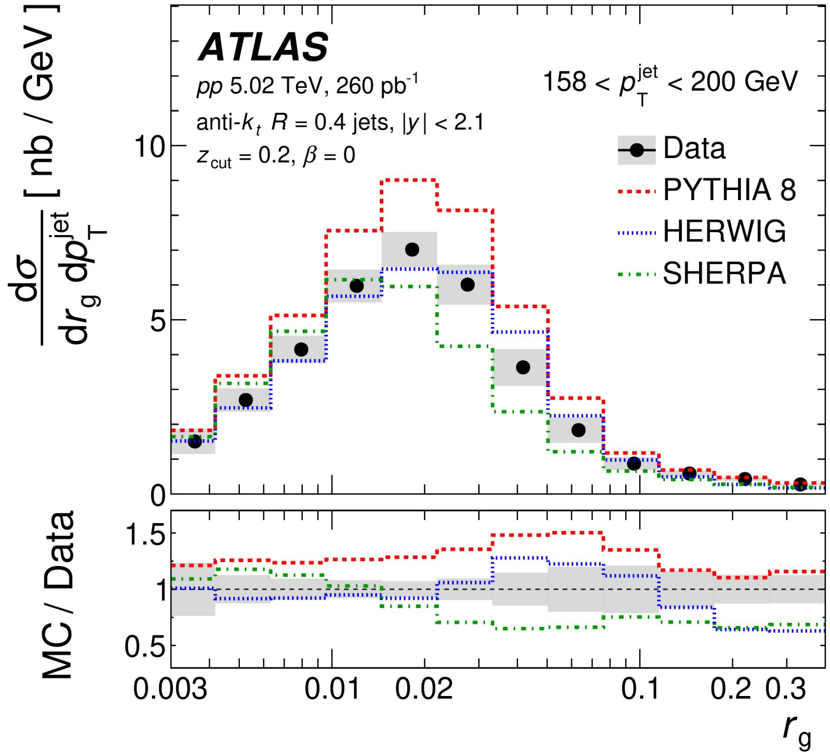
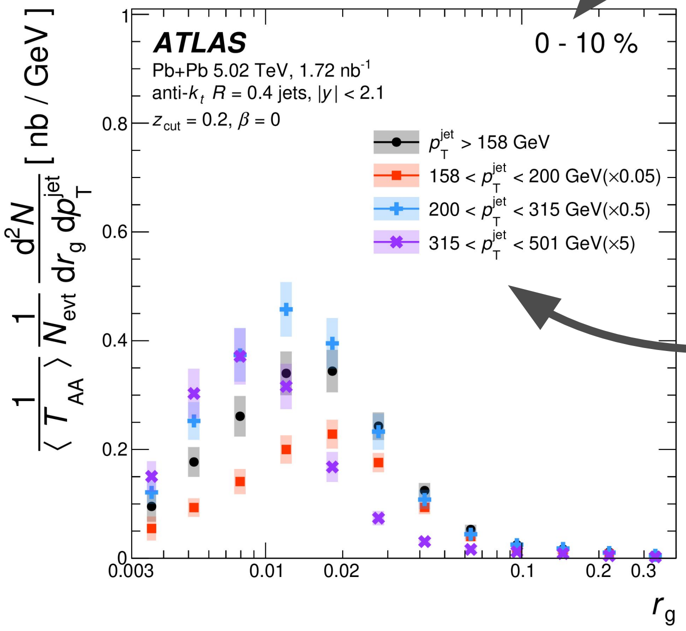
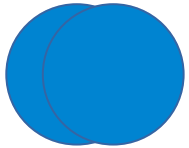
Classifying parton splittings with Soft-Drop

- Fully corrected & absolutely normalized cross-sections & yields.





Central "0-10%" Pb+Pb



Differential in jet p_T

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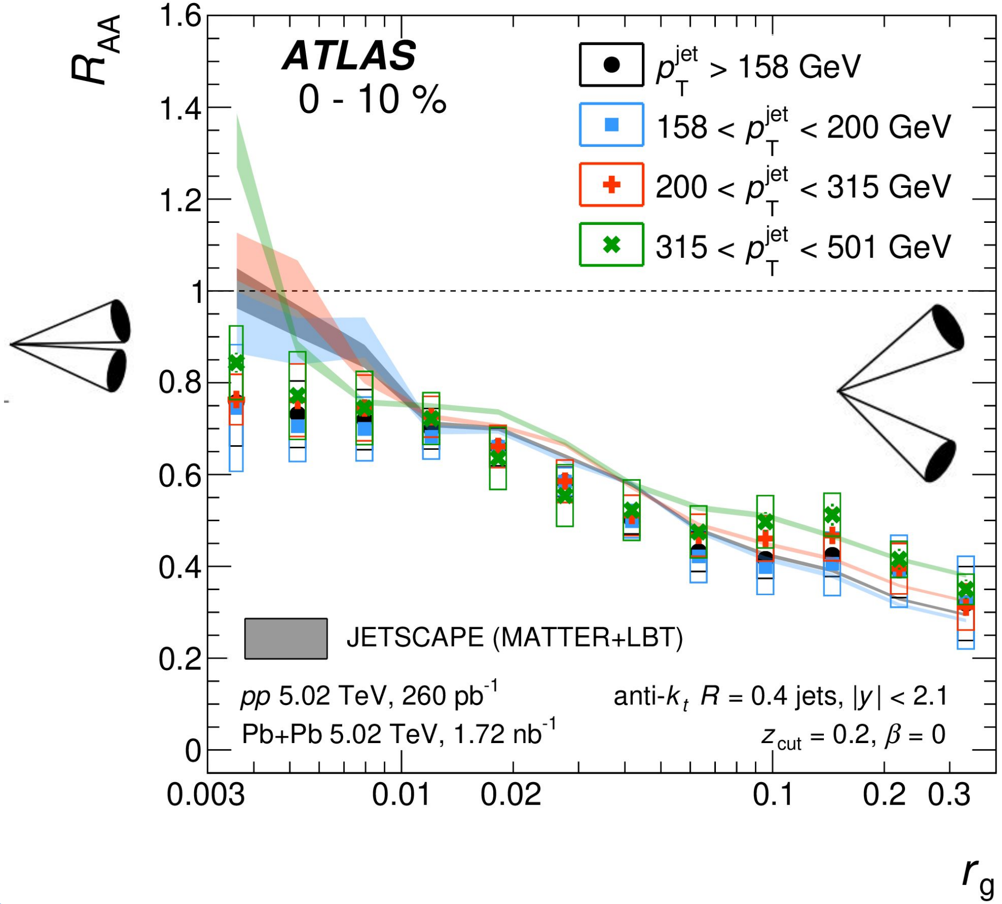
Suppression vs parton splittings



Strong dependence of jet suppression on r_g.

How can we understand the r_g vs p_T dependence?

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Jet p_T dependence of the suppression

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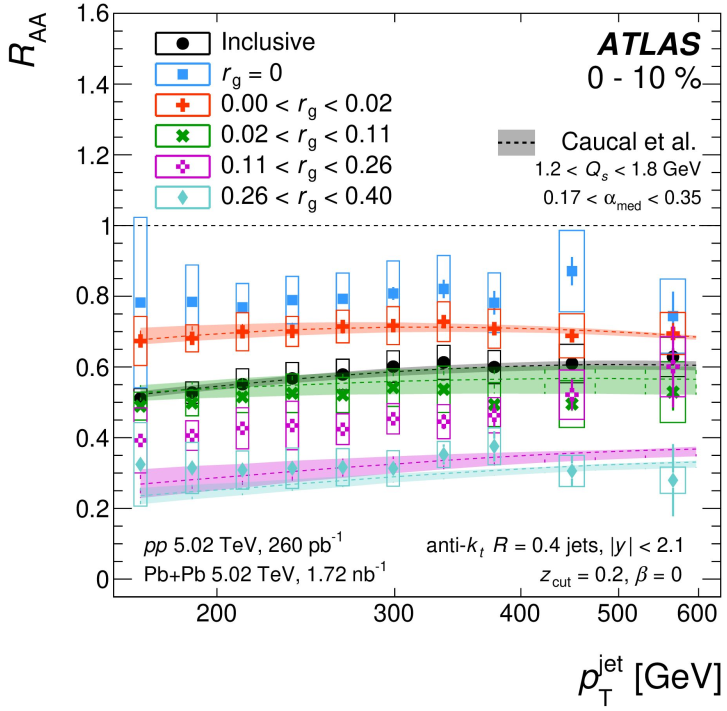

Lack of p_T dependence of R_{AA} for jets with similar structure

Jet p_T dependence of the suppression

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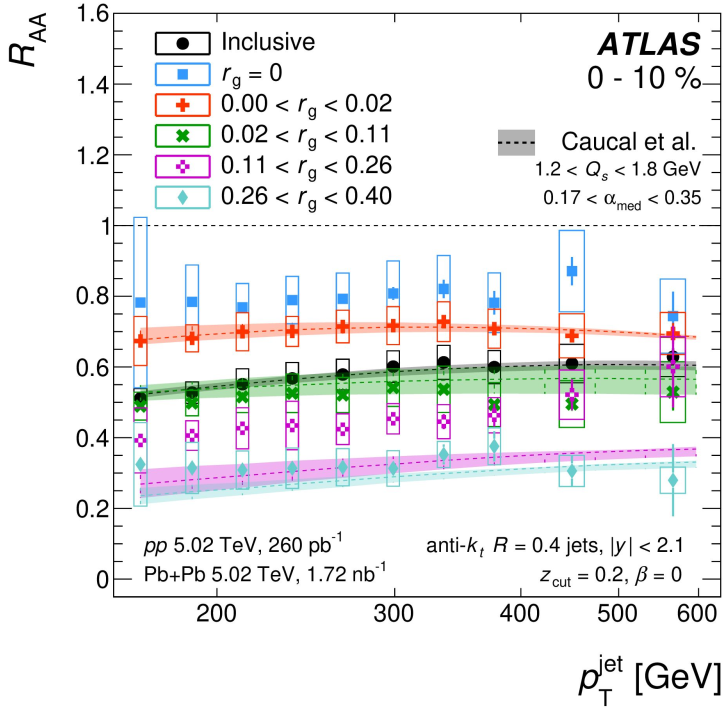
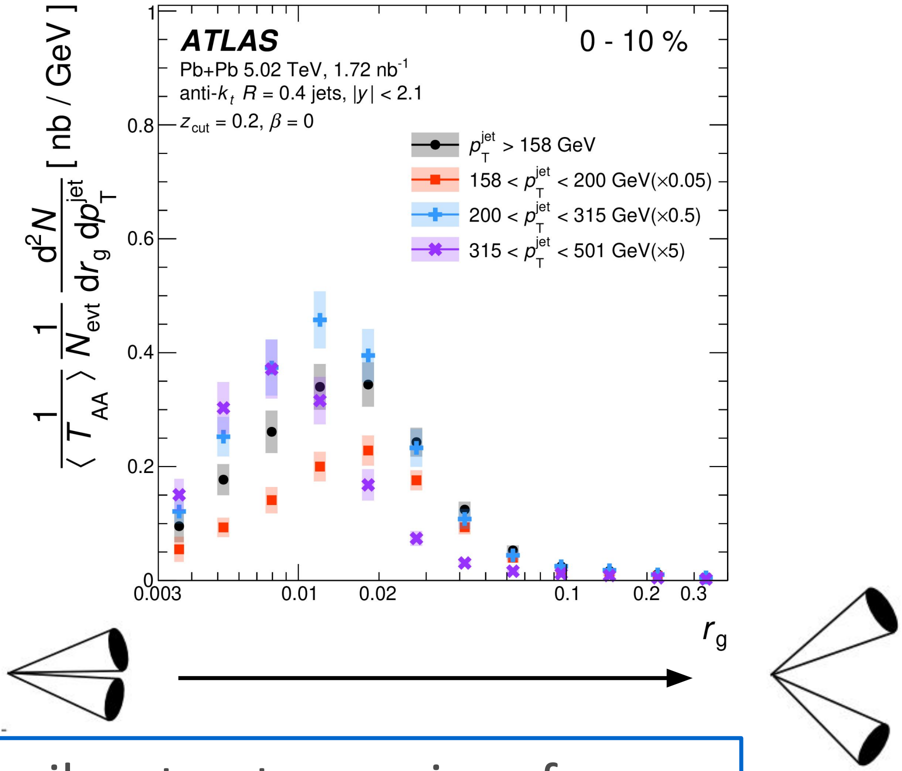
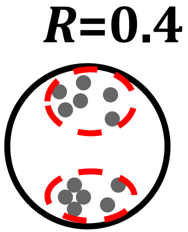


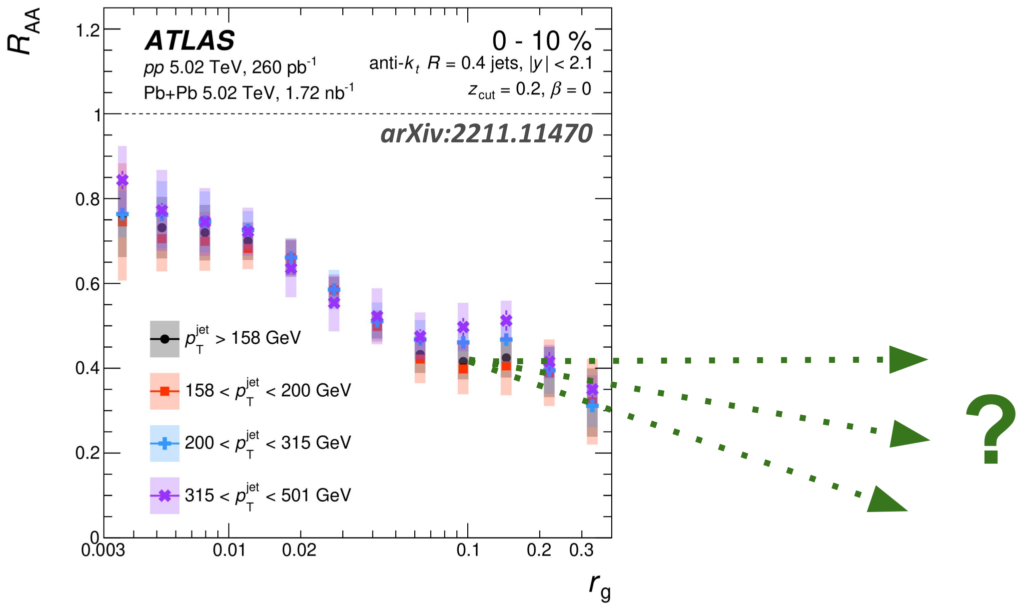


Lack of p_T dependence of R_{AA} for jets with similar structure + rise of inclusive R_{AA} ⇔ p_T dependence to r_g.

Full picture: small & large jets

- Addressing transition from color-coherence to decoherence…





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Re-clustered large-R jets

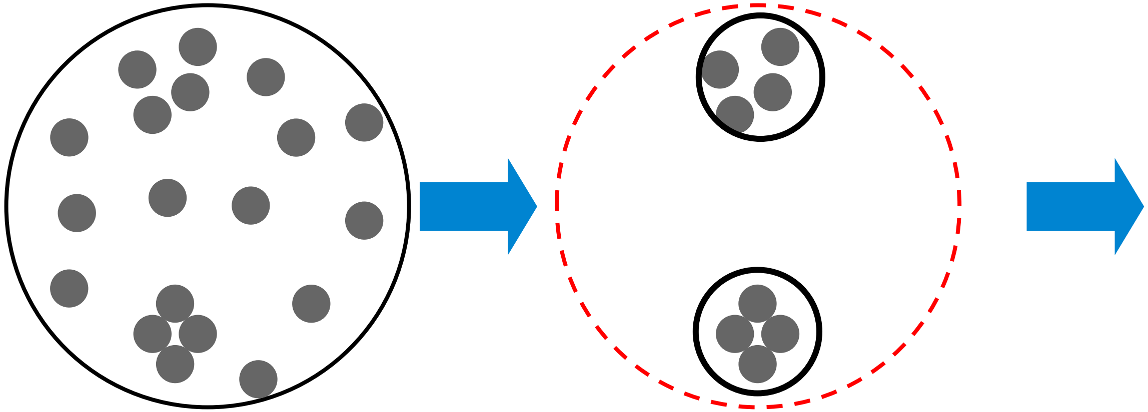
R=0.2 jets
p_T > 35 GeV

→ re-clustering with anti-k_t R=1.0

→ Sub-jets

→ re-clustering with k_t algorithm

→ $\sqrt{d_{12}}$ and ΔR_{12}



"Conventional" jet   Re-clustered jet

Different jets than the conventional R=1.0.
35 GeV threshold remove the soft component.

Observables and analysis procedure

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

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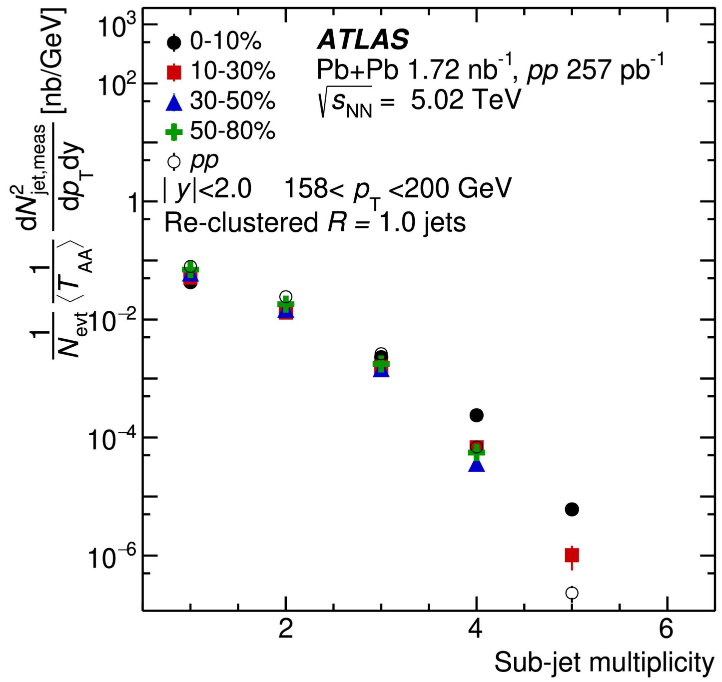
$$\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta\phi_{12}^2},\ \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$$

- Jet suppression is evaluated using modification factor R_{AA}.



Raw sub-jet multiplicity

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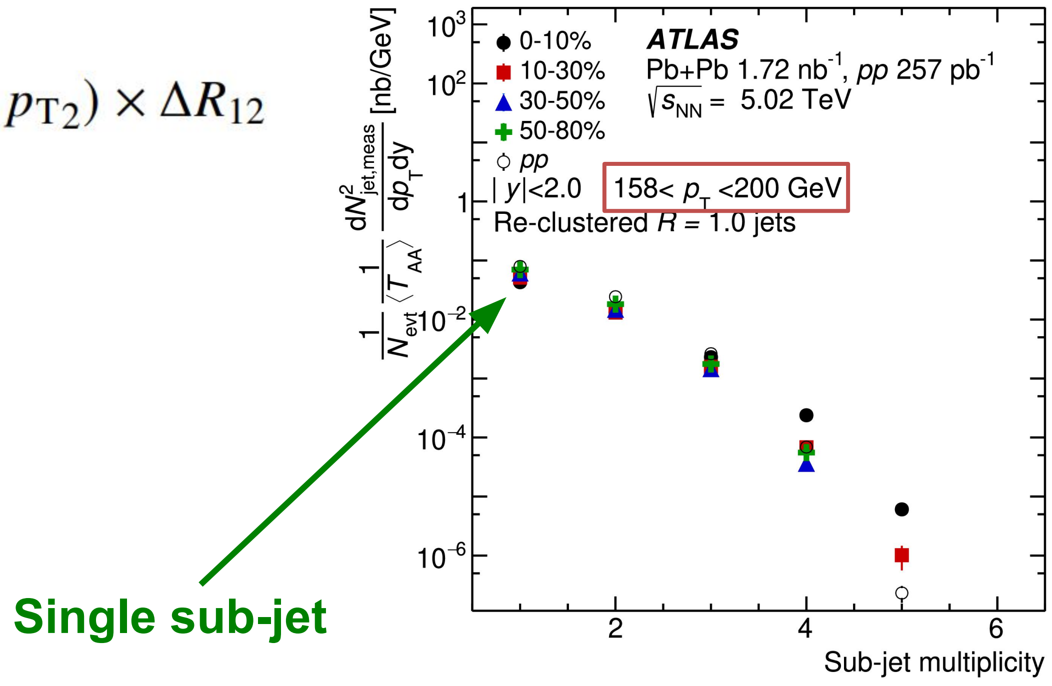

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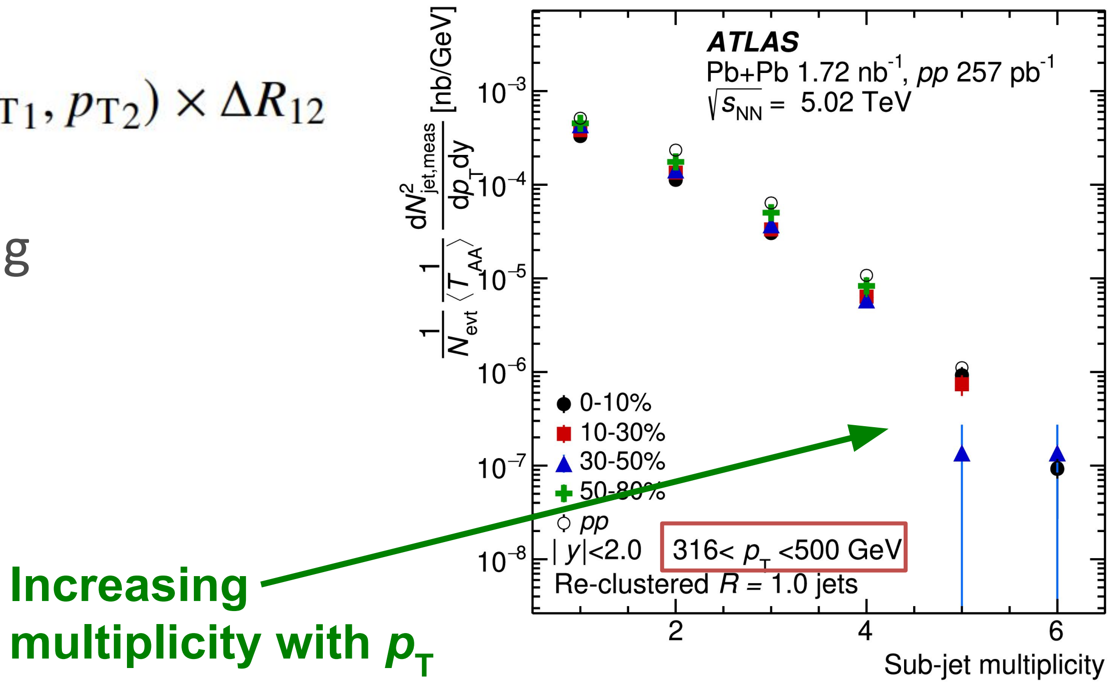
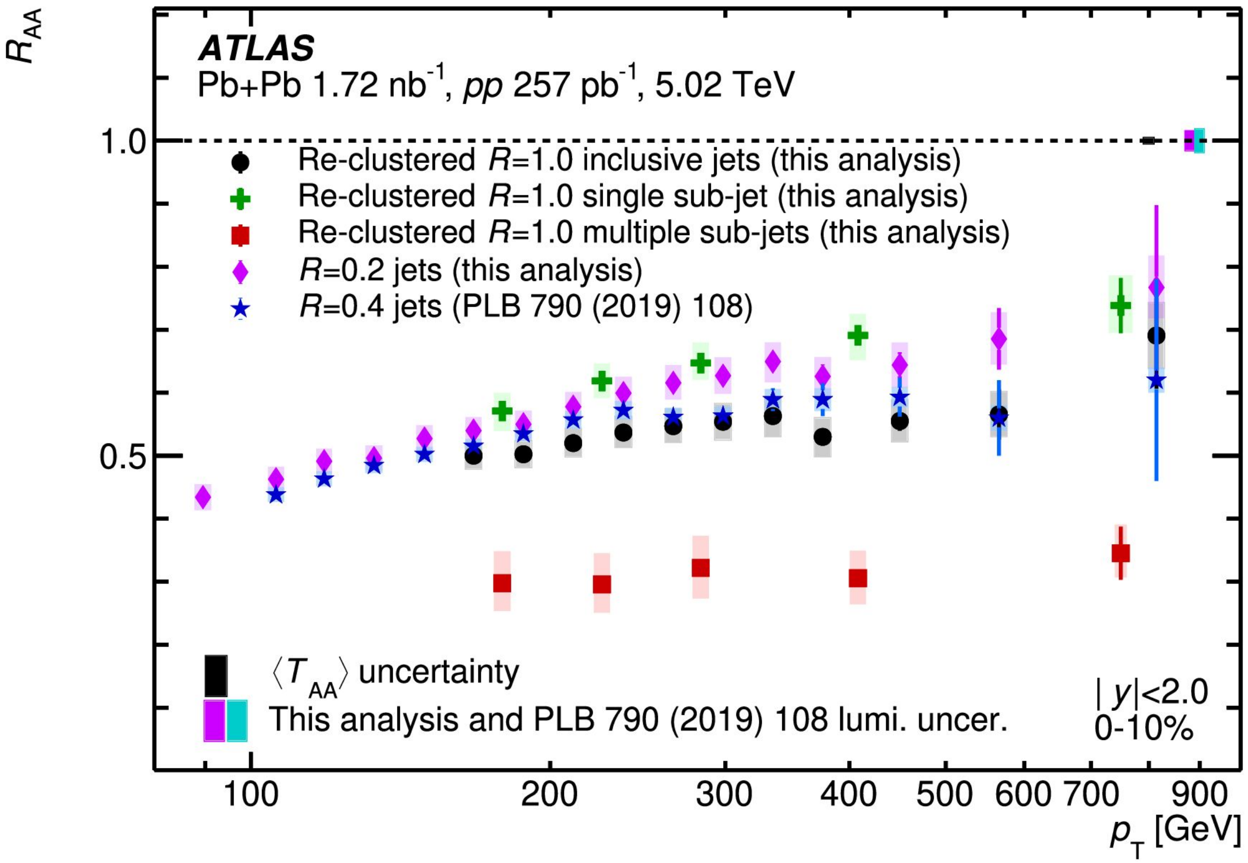


Raw sub-jet multiplicity

Jet suppression for different jet type



- Overall jets are suppressed by factor ~2 (except red points) in central Pb+Pb.

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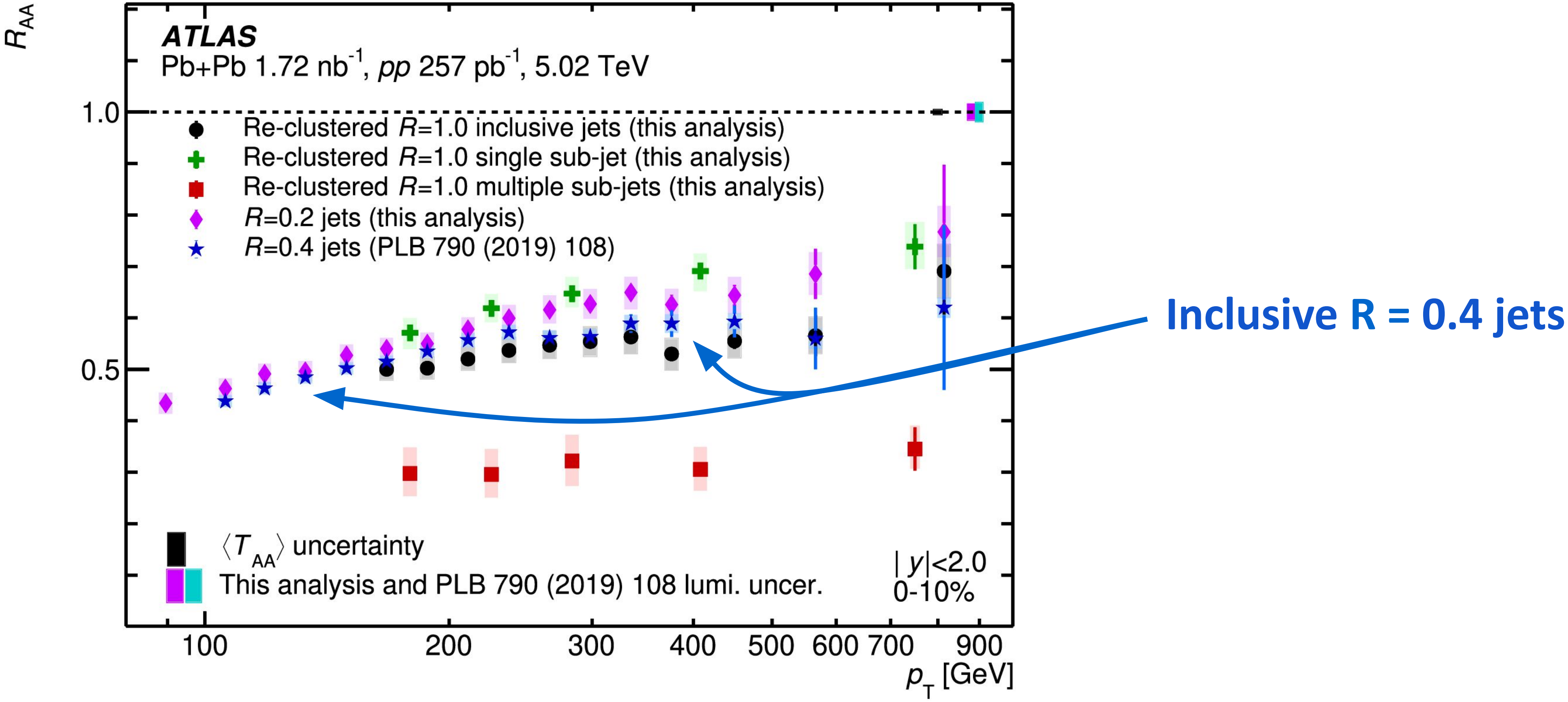
Jet suppression for different jet type



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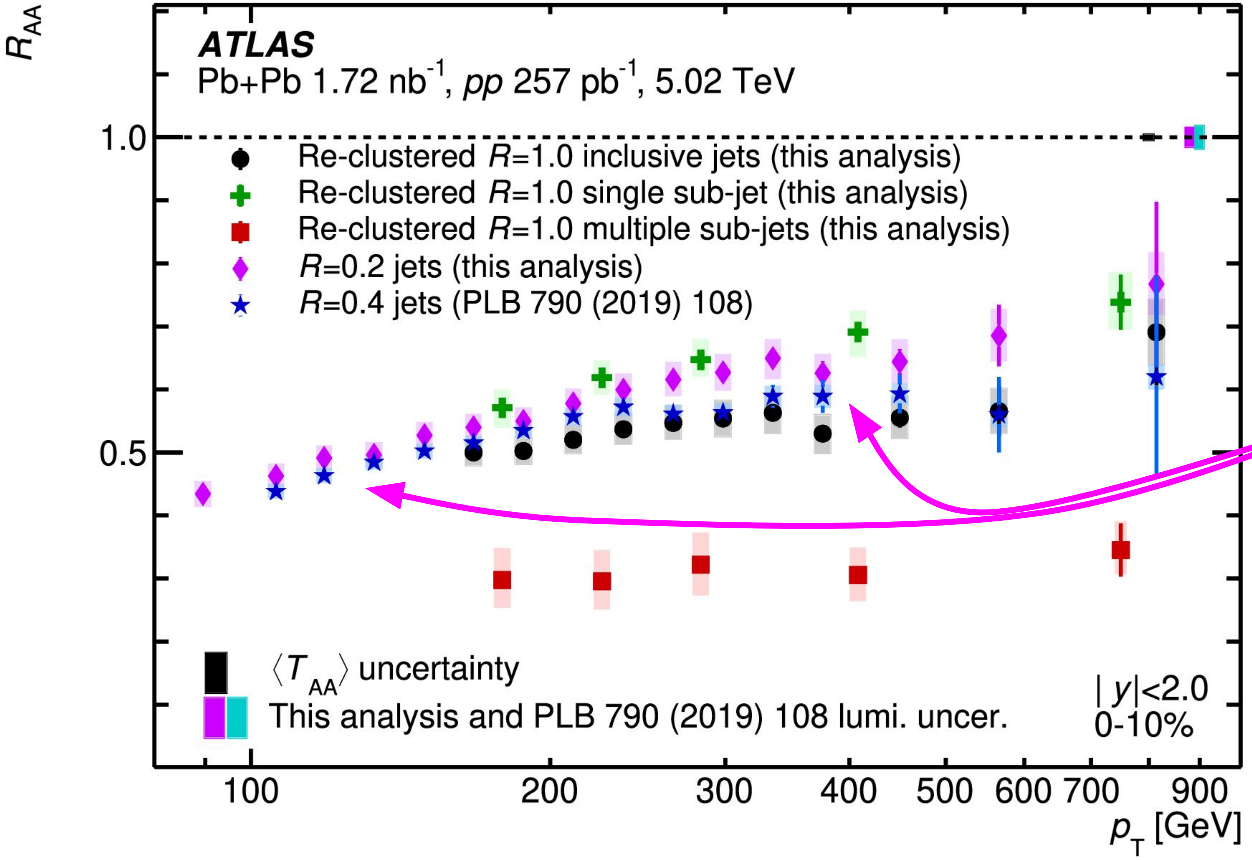

Inclusive R = 0.2 jets suppressed by a few % less wrt R = 0.4 (To be used in radial scan)

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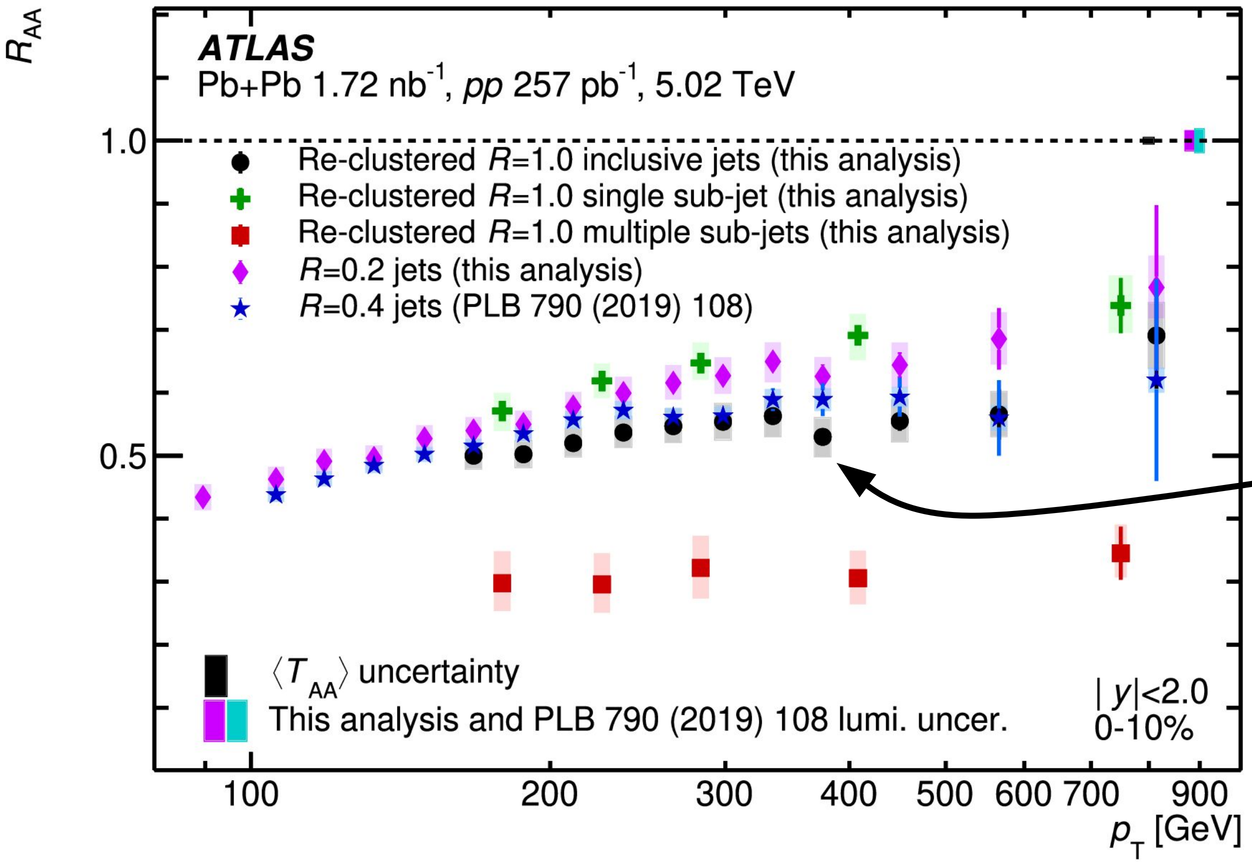
Jet suppression for different jet type



Inclusive re-clustered R=1.0 jets suppressed even more

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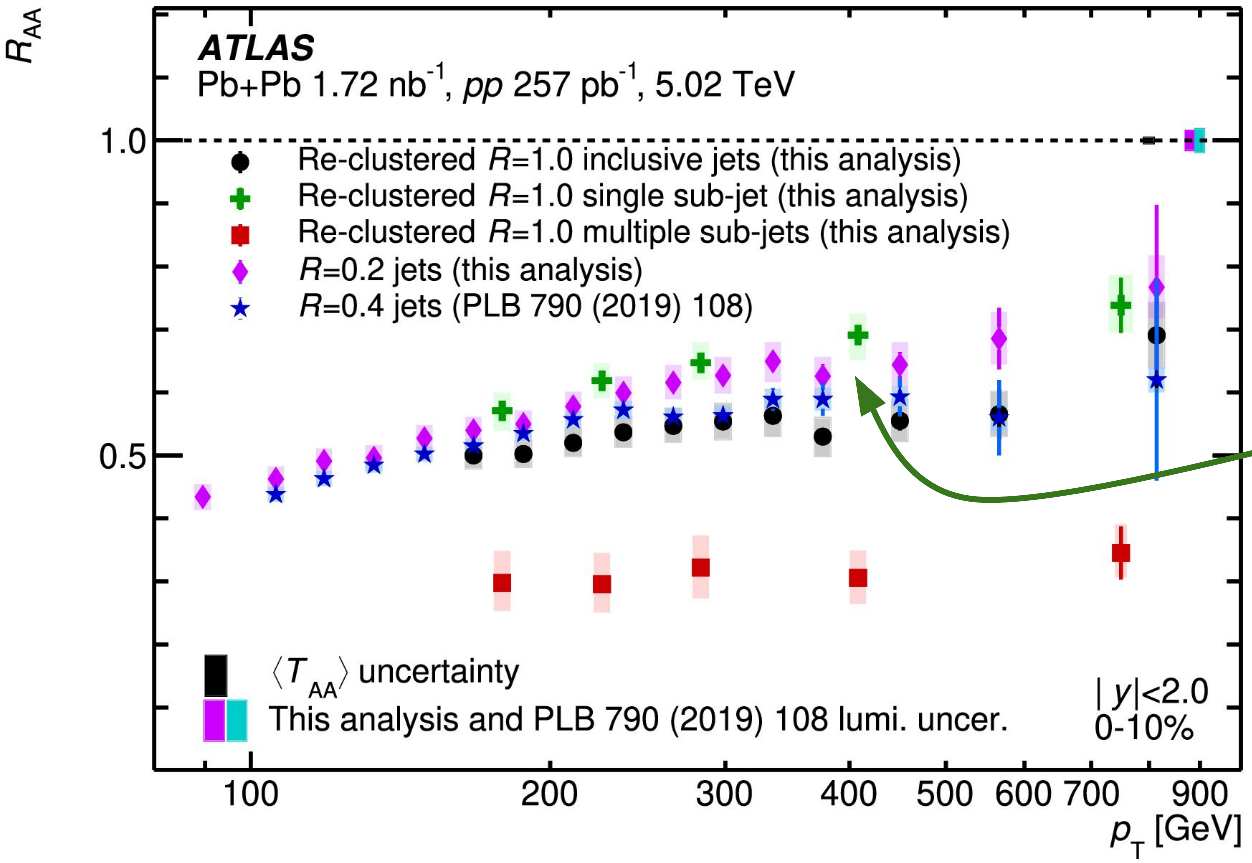
Jet suppression for different jet type



Two components:
single sub-jet *R*=1.0
suppressed the least

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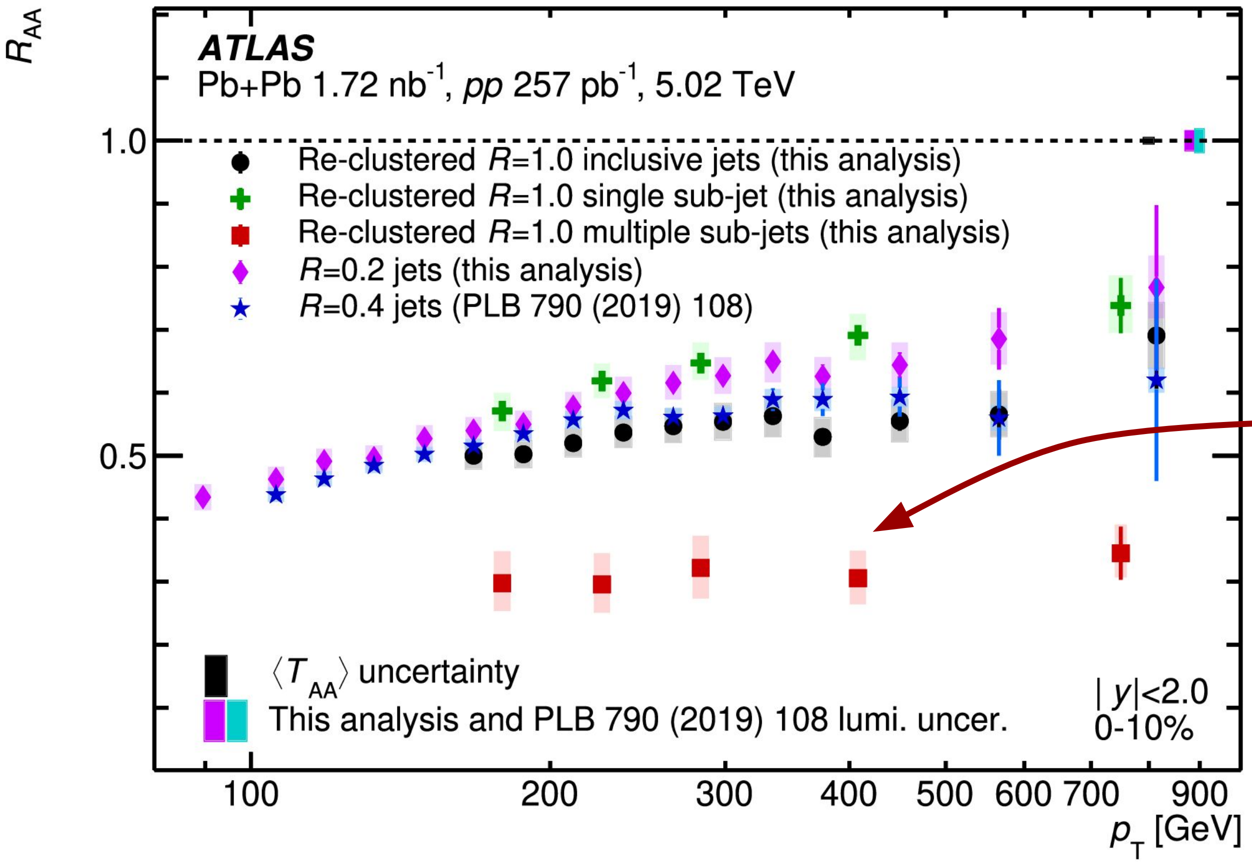
Jet suppression for different jet type



Two components:
multiple sub-jet *R*=1.0:
the largest suppression

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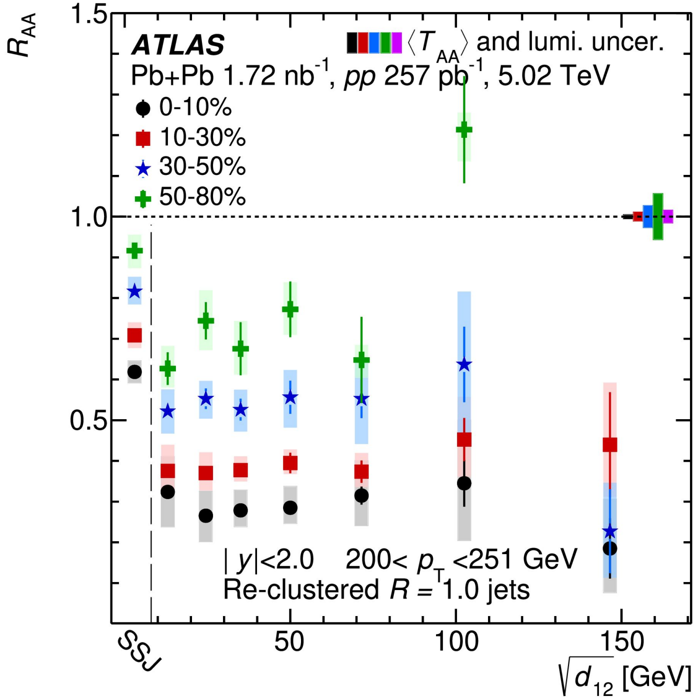
Re-clustered jets vs substructure



- 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 followed by flattening.

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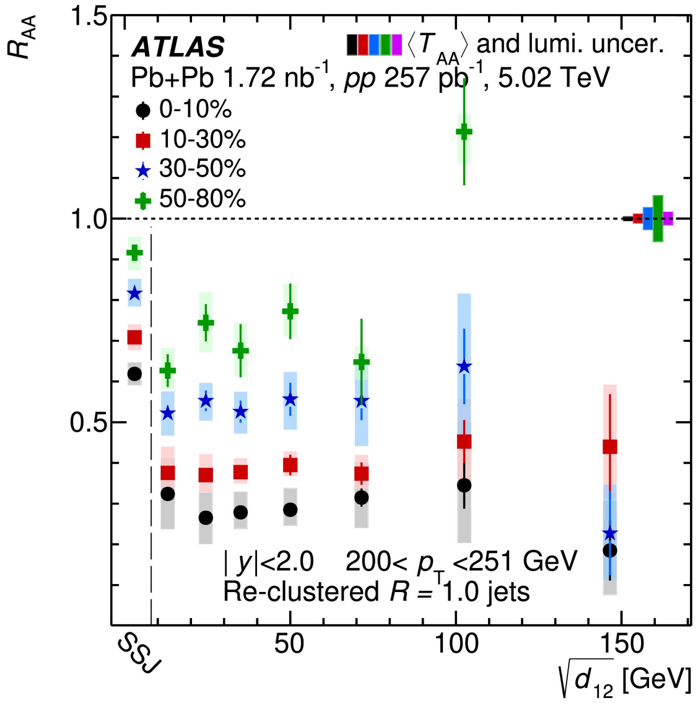
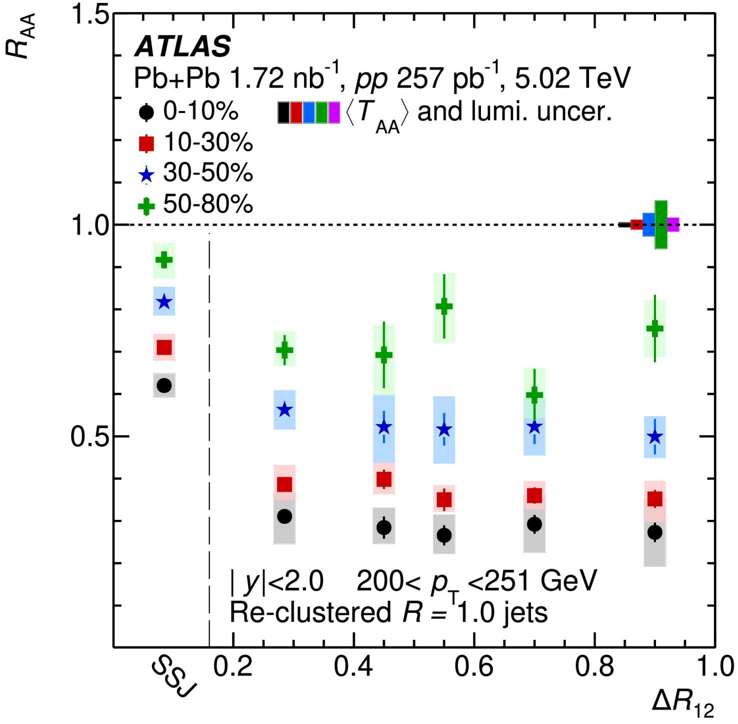
Re-clustered jets vs substructure





- The R_{AA} sharply decreases followed by flattening.
- Similar observation for suppression as function of angular separation.

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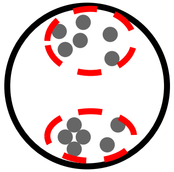
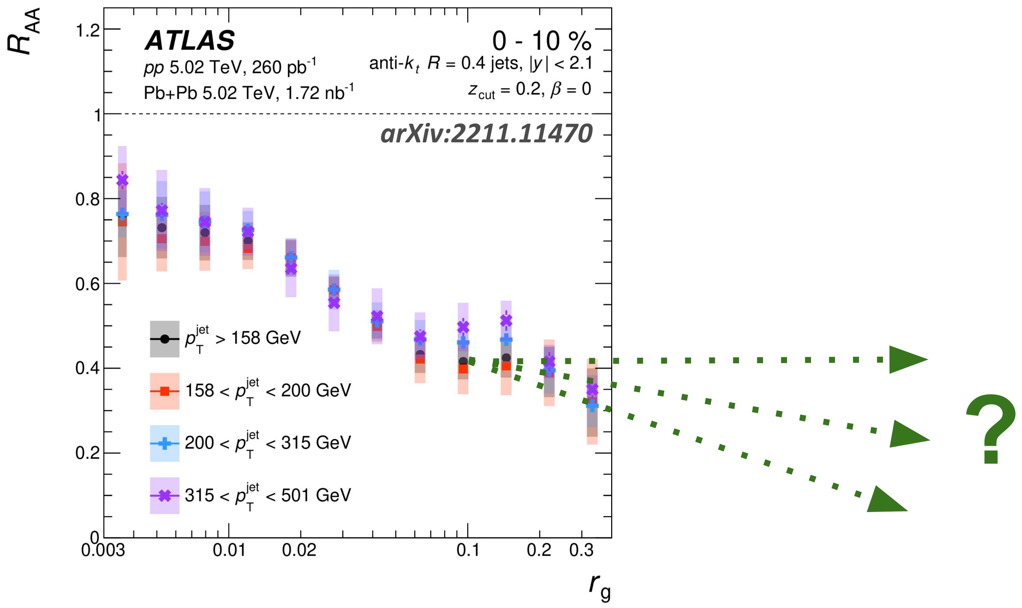
Full picture: small & large jets

- Addressing transition from color-coherence to decoherence…

R=0.4





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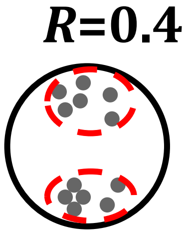
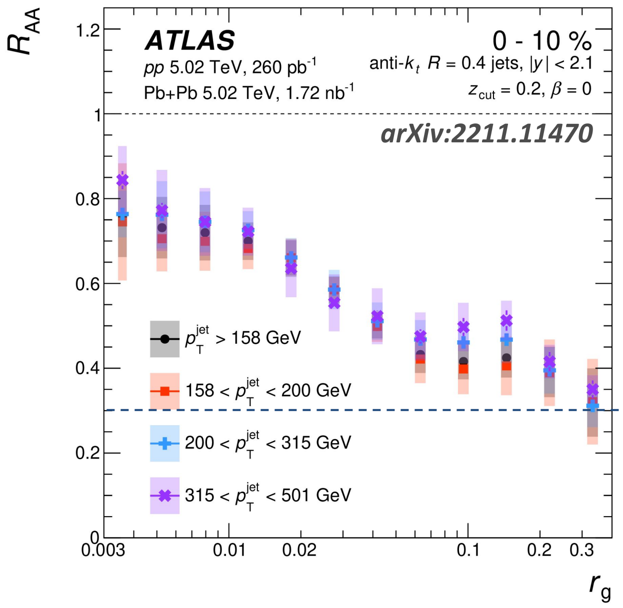
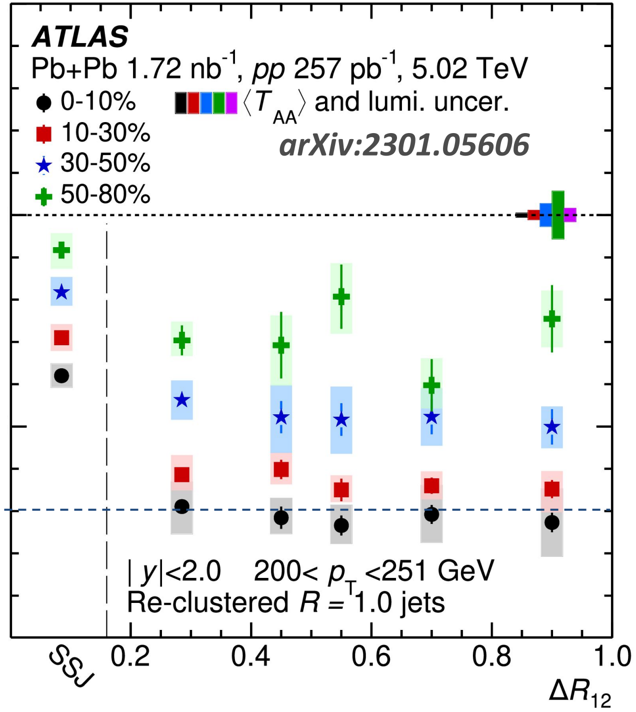
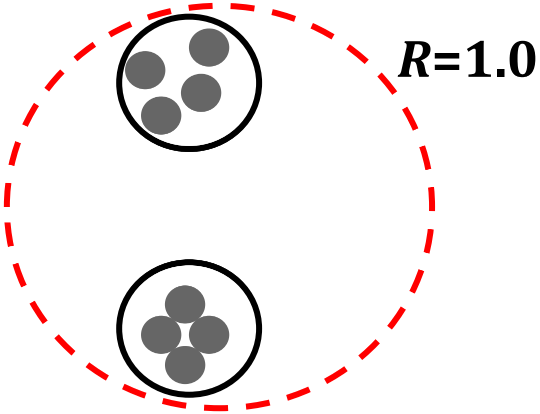






$$\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta \phi_{12}^2}$$



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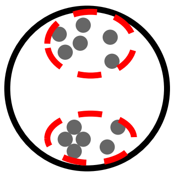

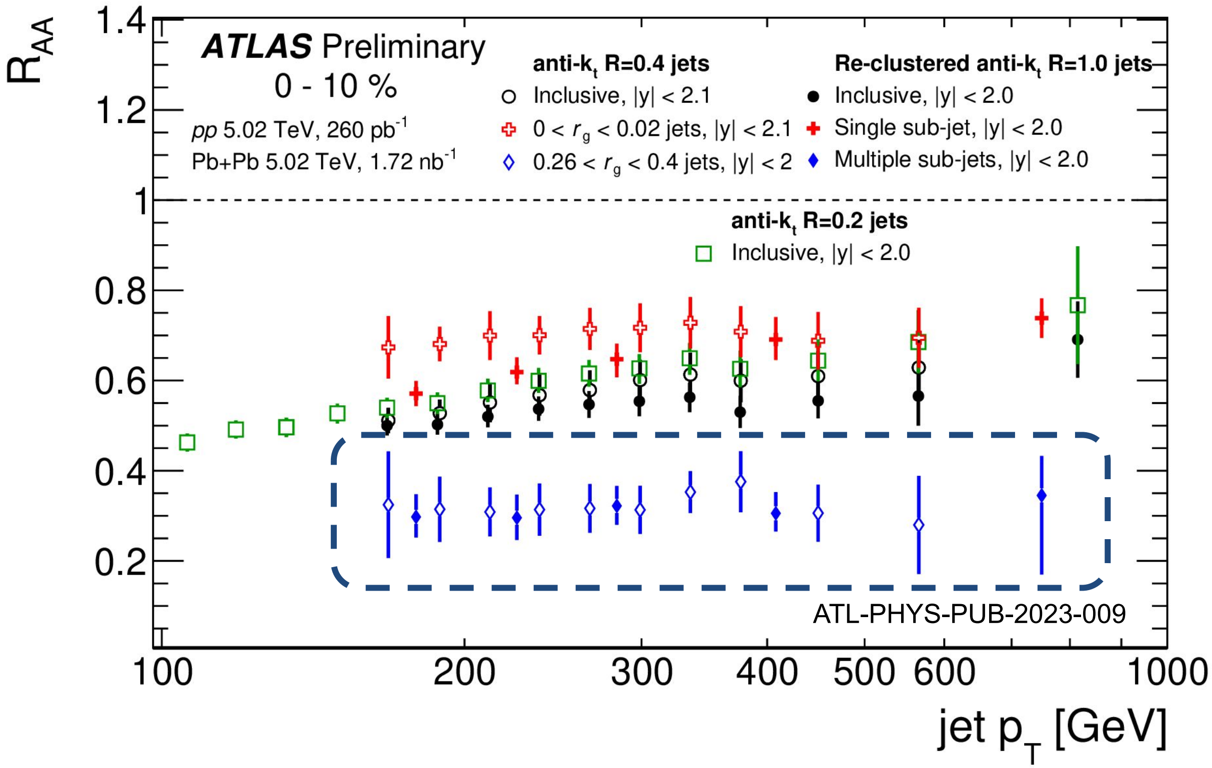

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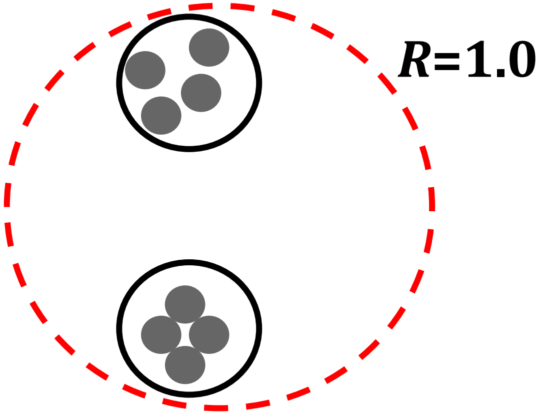
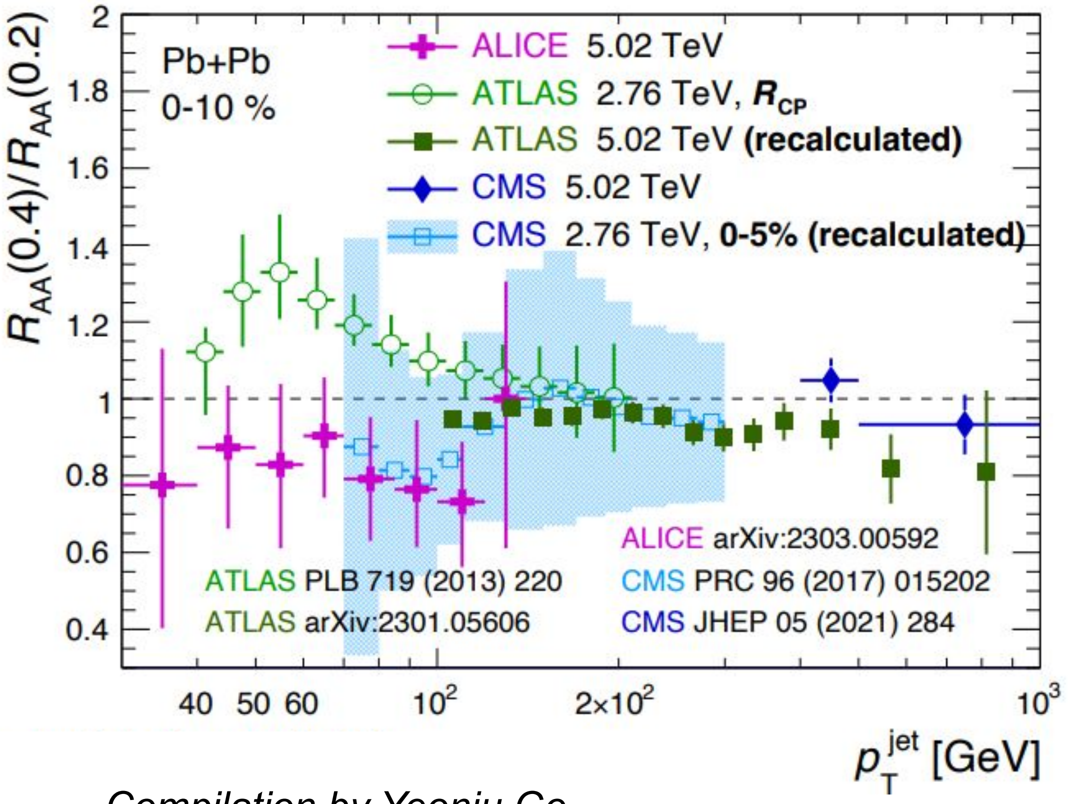


Radial scan

- Comparison of suppression of jets for different jet radii
  - Recovery + medium response ⇒ decrease of suppression with larger R
  - Difference in flavour fraction at same p_T ⇒ increase in suppression with larger R
  - Difference in spectral shape ⇒ increase in suppression with larger R
  - More resolved structure with larger R ⇒ increase in suppression with larger R

Radial scan

- Comparison of inclusive jets from different experiments.



Compilation by Yeonju Go

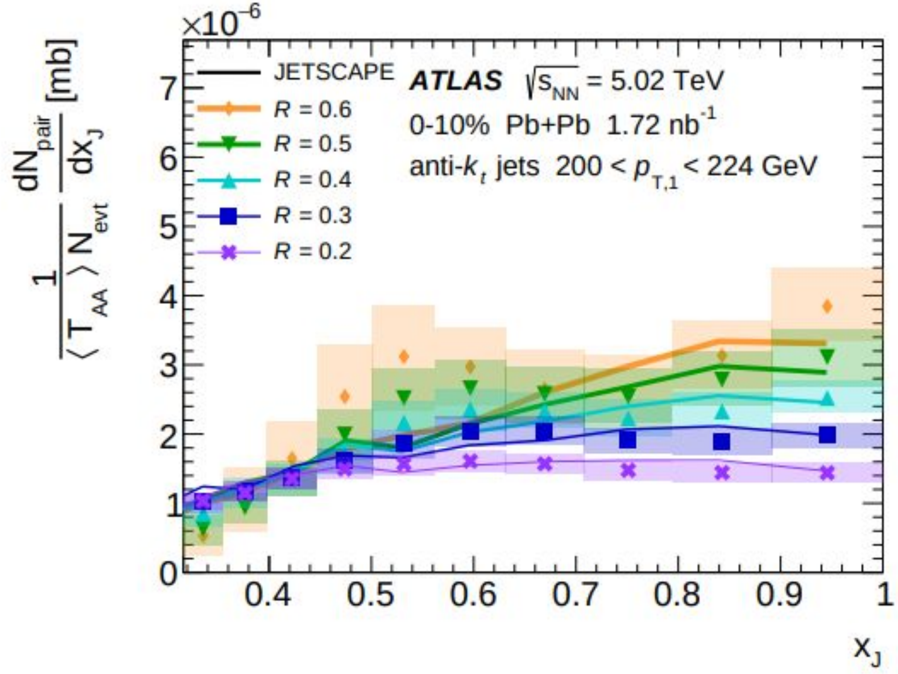
Tension between result…

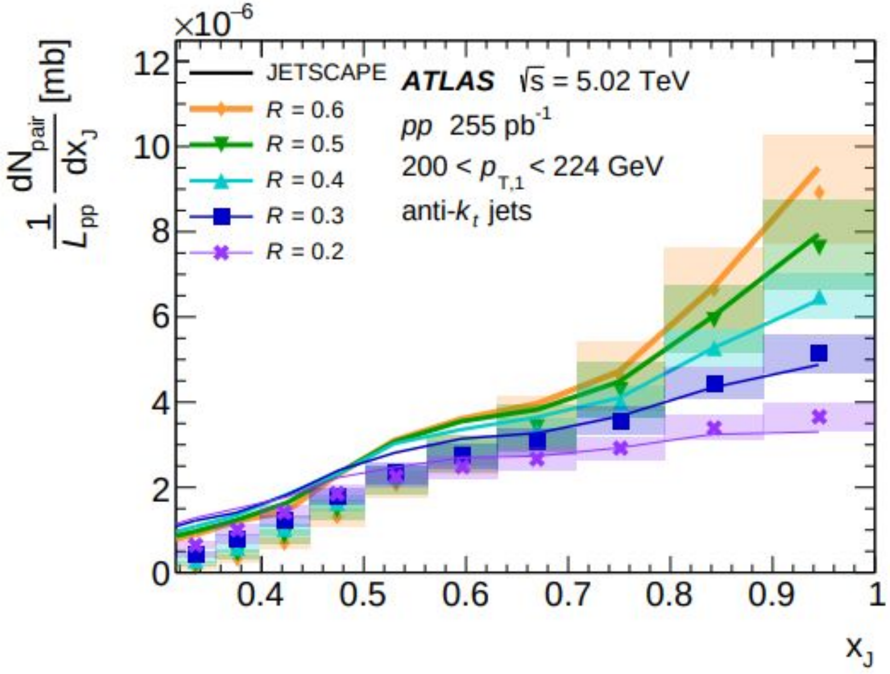
- Larger systematics
- Charged vs full jets
- 2.76 TeV vs 5.02 TeV & slightly different phase-space can not explain the difference.
- Lower-level details & comparison is needed.

R-dependence of dijet imbalance

- Characterized by $x_J = p_{T,2} / p_{T,1}$

More details in Anne's presentation





- Smaller modifications for imbalanced jets
- Larger dijets are more balanced in p_T.

arXiv:2407.18796

Summary

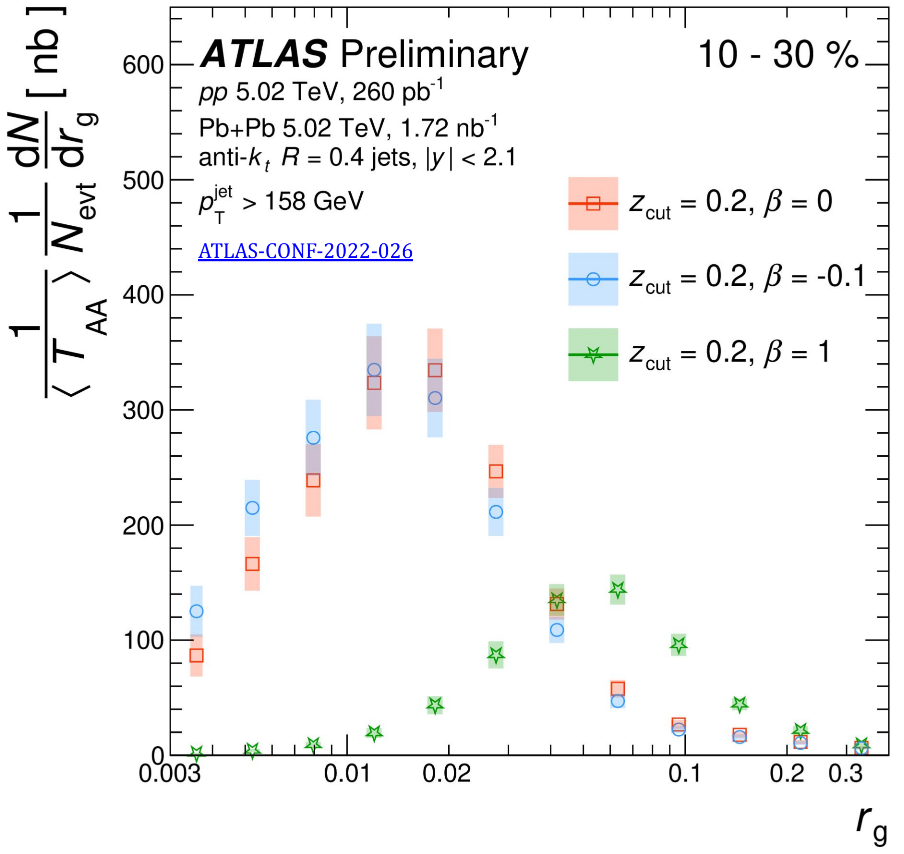
- **Jet substructure in HI is a rapidly developing area**
- **Two complementary measurement by ATLAS**
  - Jet suppression depends significantly on jet substructure.
  - Probing role on angular scale from distance 0.003 up to 1.0 ⇔ should help addressing color coherence phenomena.
  - Run 3 data should allow similar measurements in photon-tagged systems.

- **Weak dependence of suppression with R for inclusive jets > 100 GeV**
  - **Suppression of dijet pairs seen for imbalanced dijets**

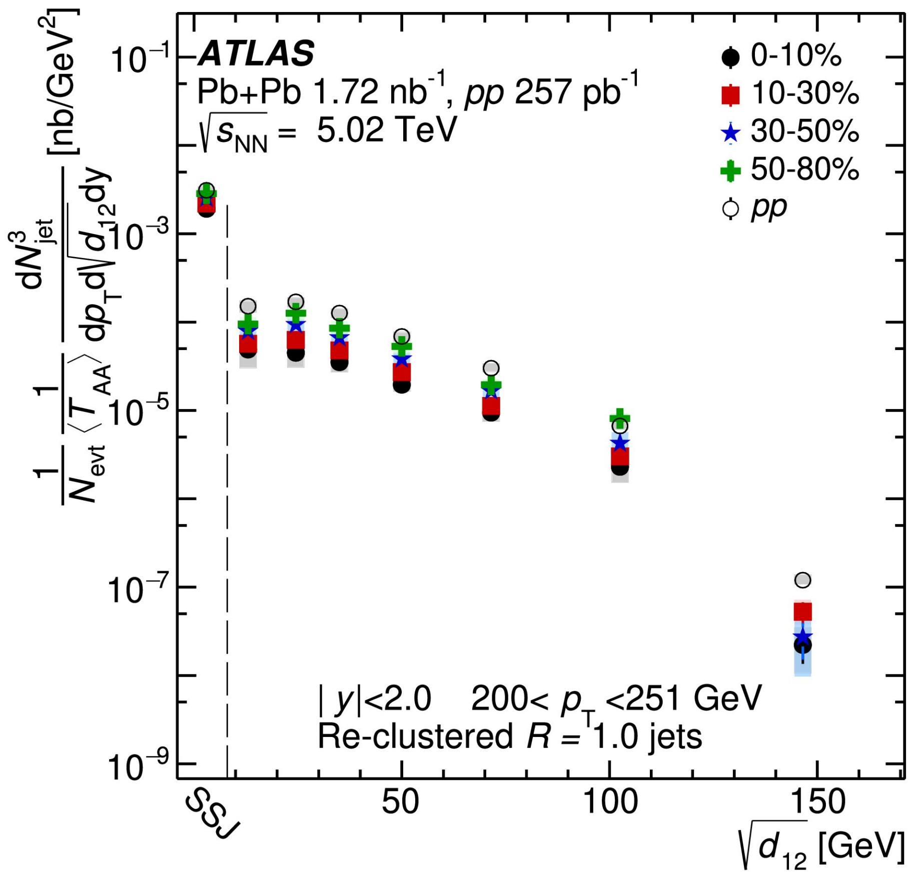
Backup

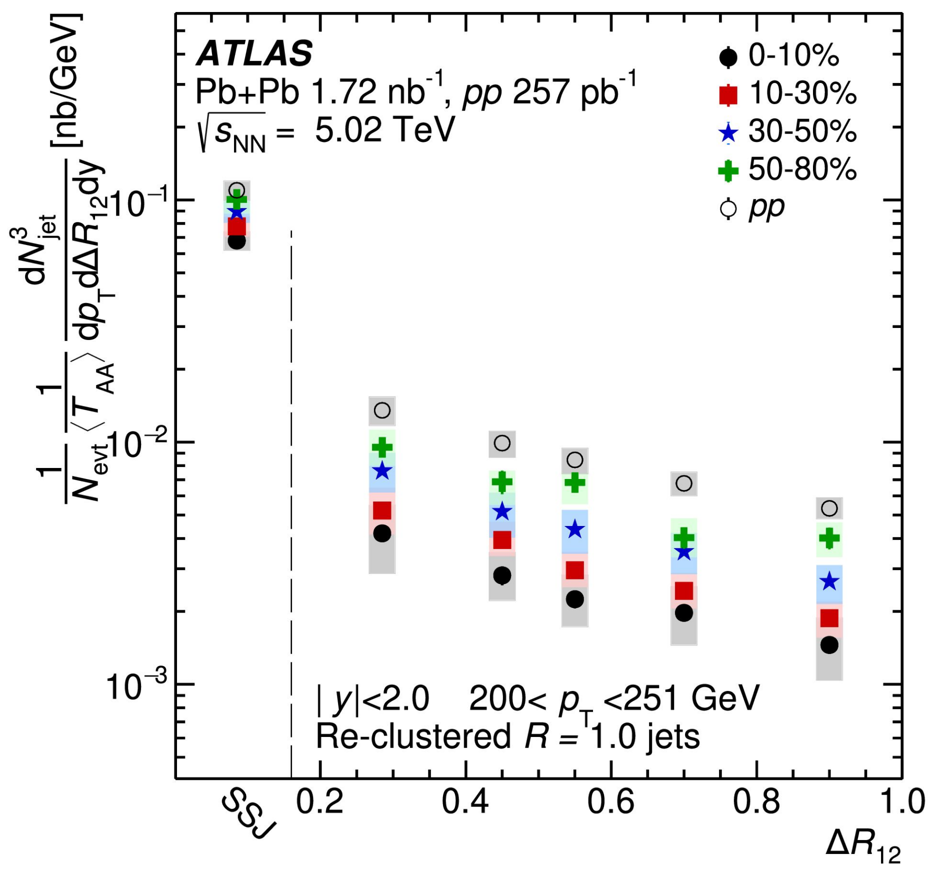
Challenges in jet structure measurements

- **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.
- Role of ISR@FSR
- Choice of setting in grooming…
  - Sensitive to modeling and subtraction.
  - Need to understand biases we introduce.

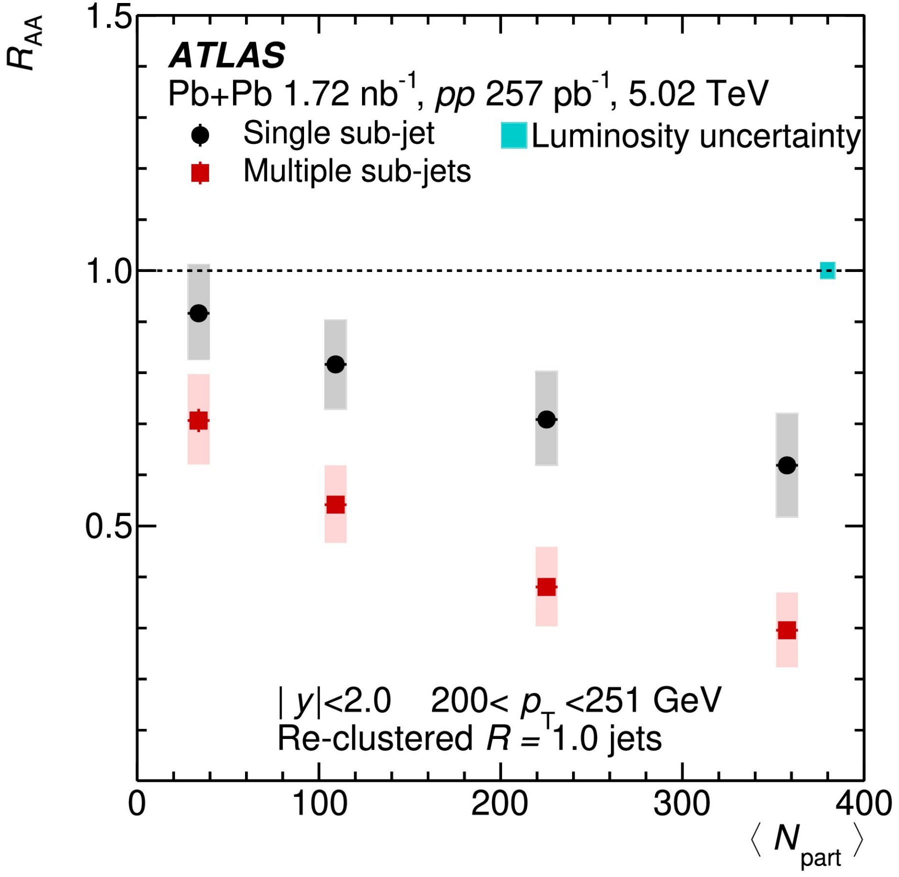


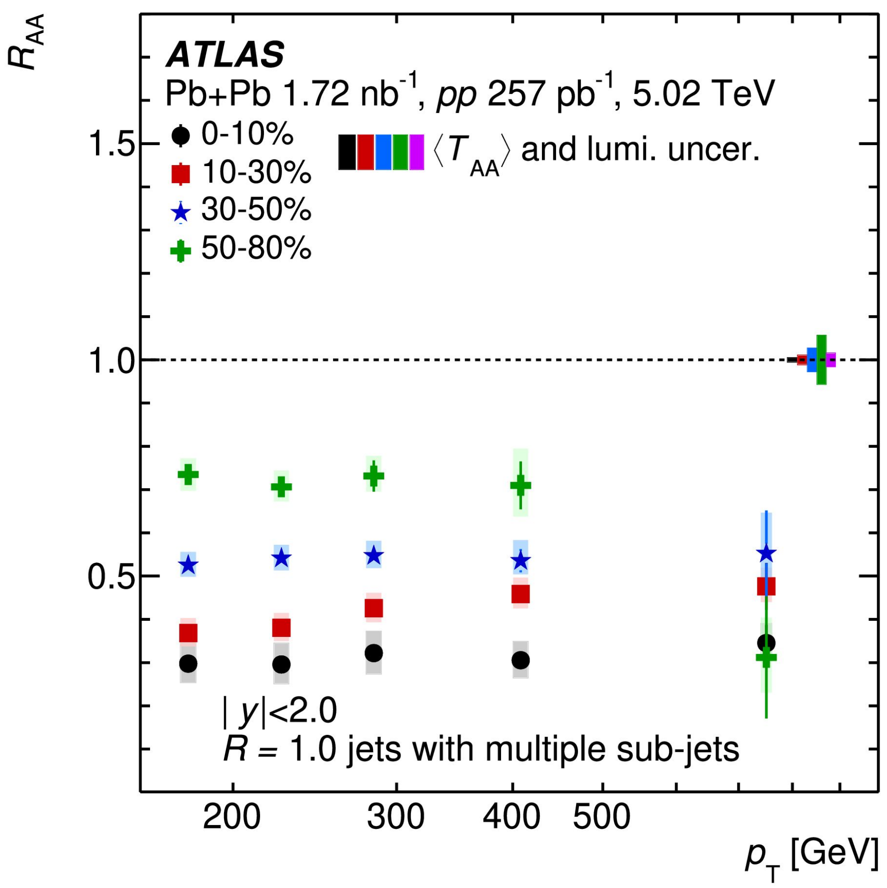
Splitting scale



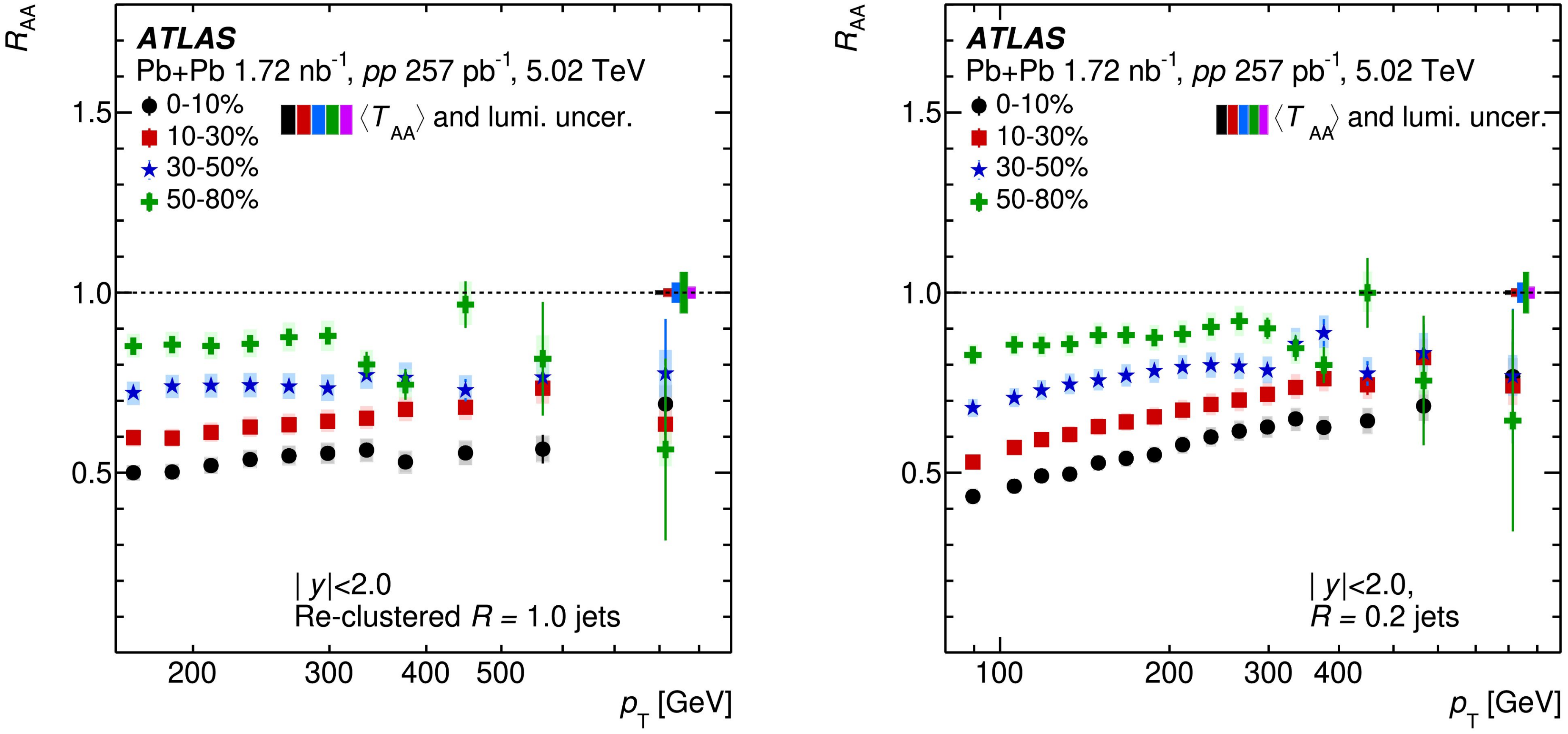


Clustered large-R jet RAA

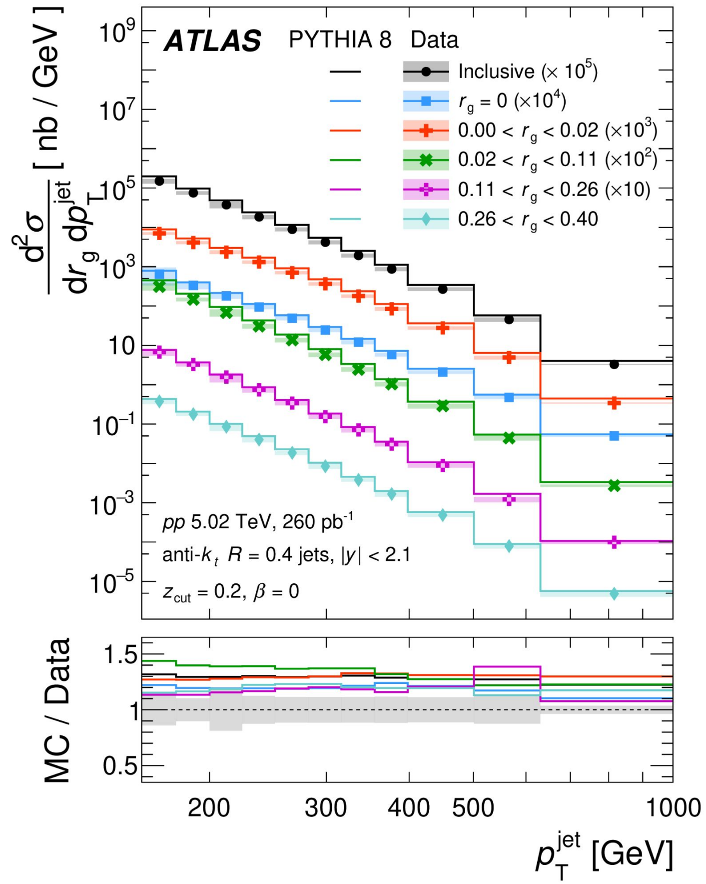


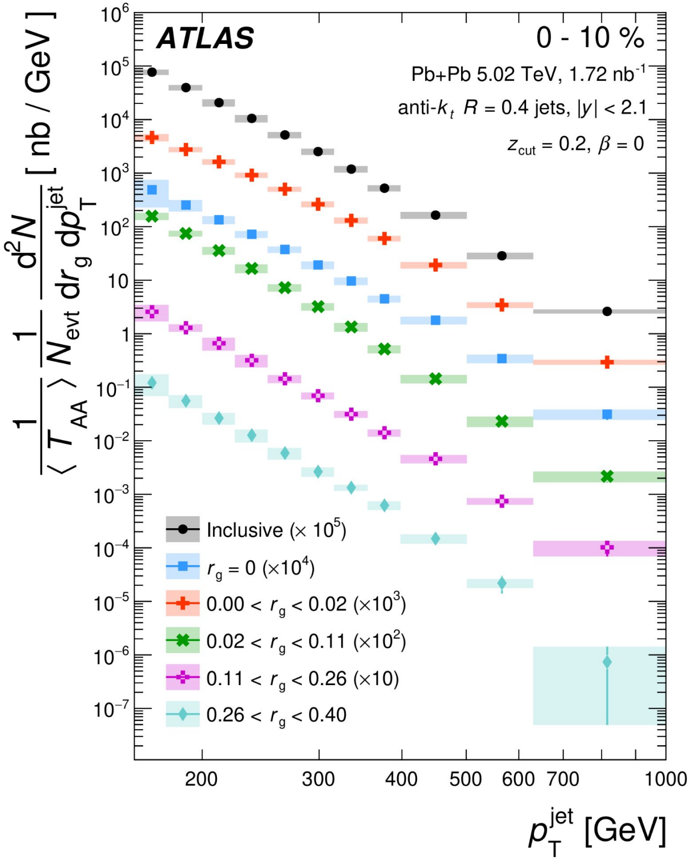


Inclusive je RAA



Additional material





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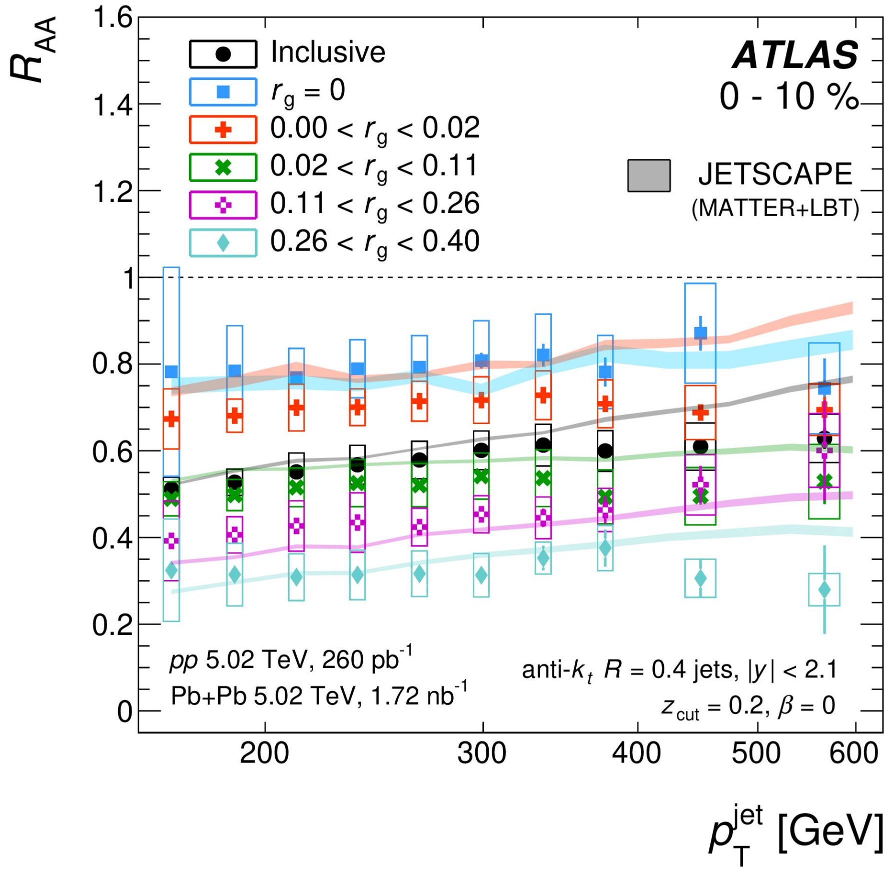

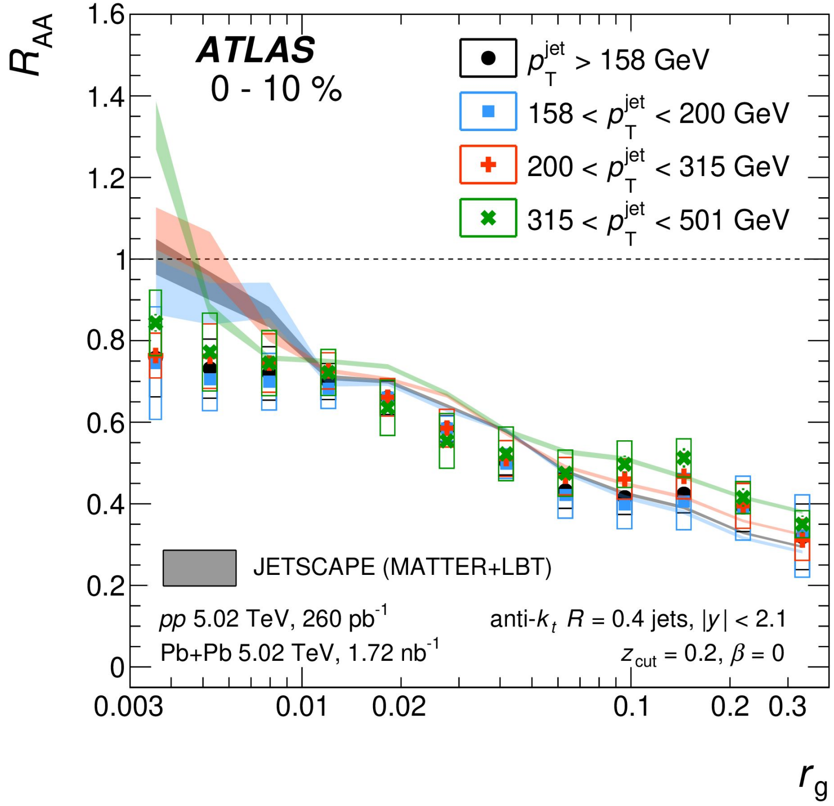

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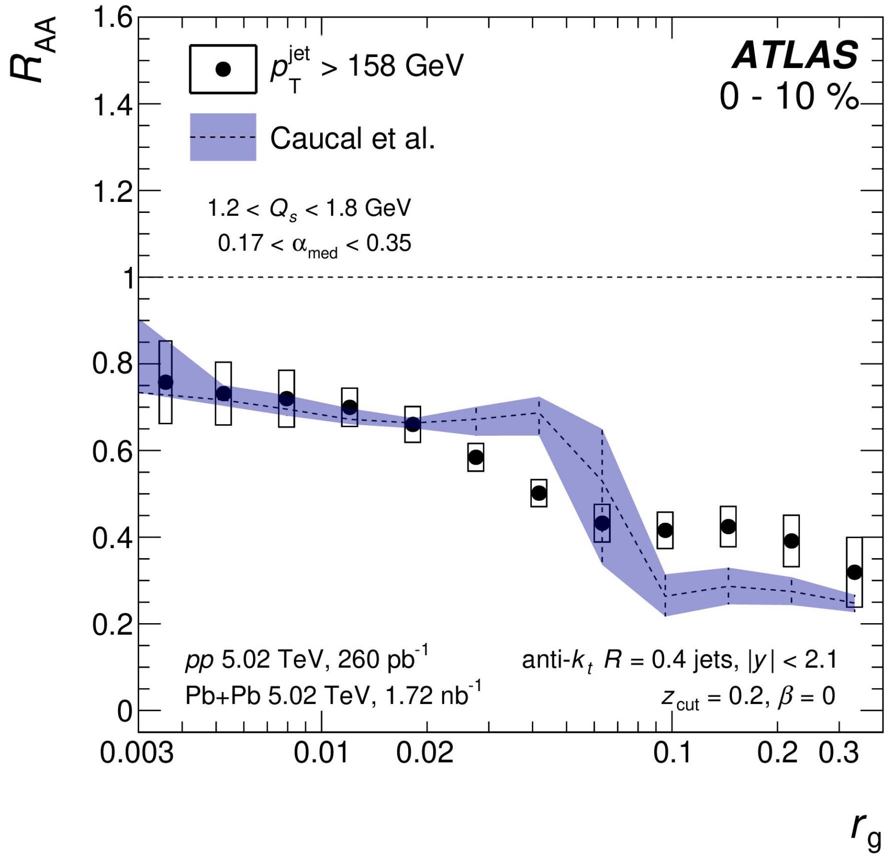
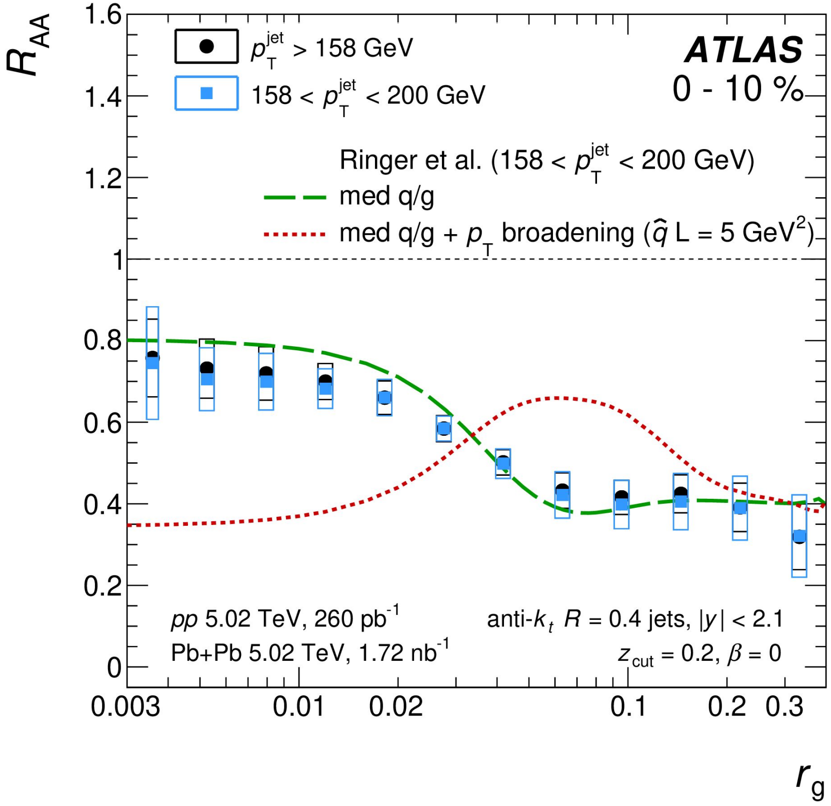
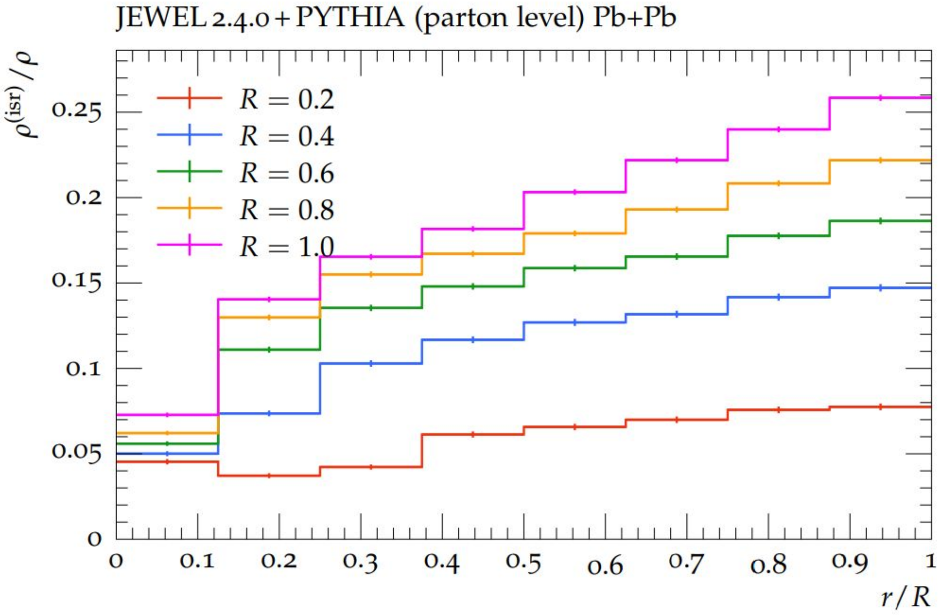




Challenges in these measurements

- **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.
  - Calibration of jet constituents.
- Role of ISR@FSR
  - Resembles medium response

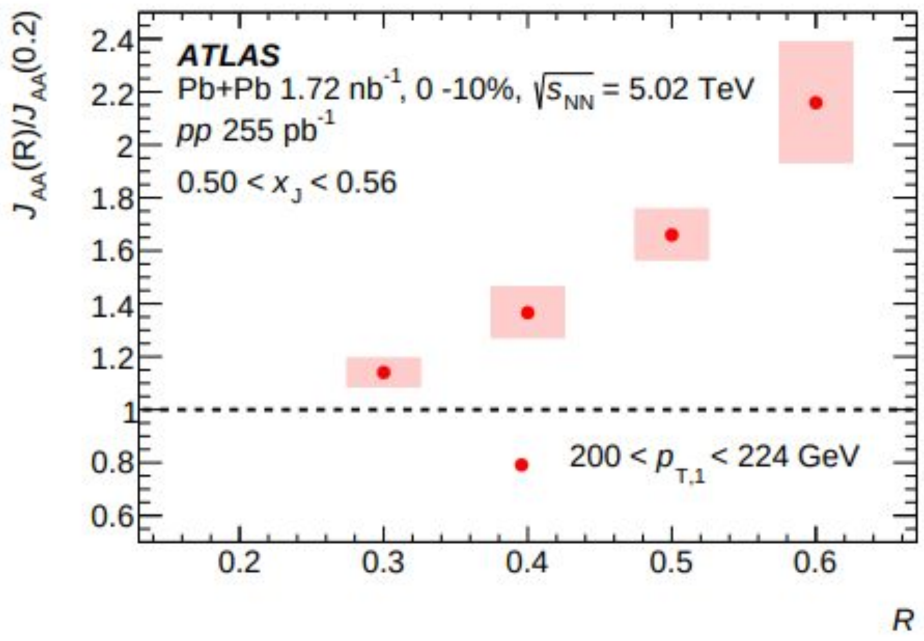


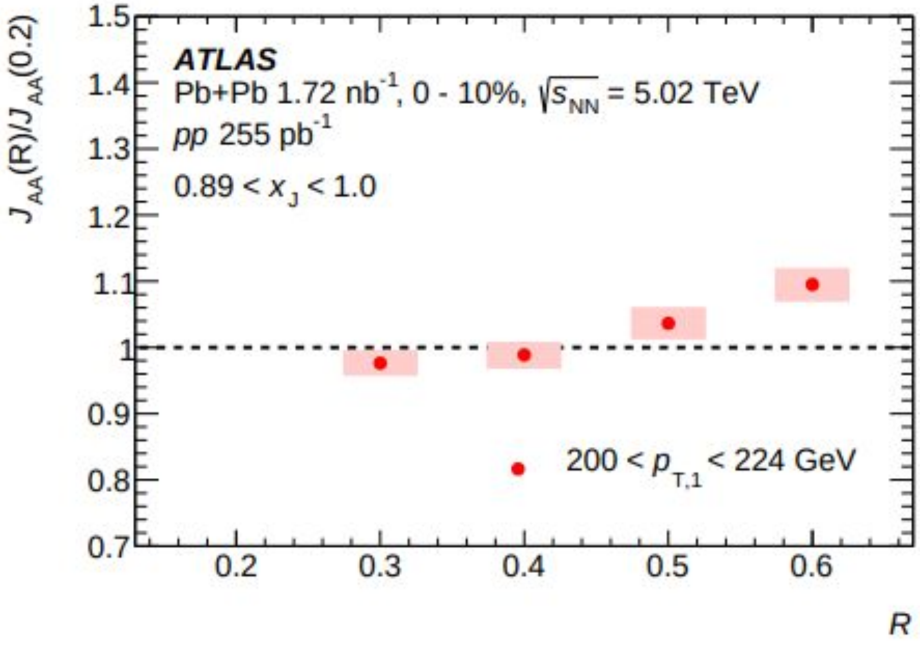
Impact of ISR on jet shape [by Korina](#)

R-dependence of dijet imbalance

$$J_{AA} \equiv \frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \frac{dN_{pair}^{AA}}{dx_J} \Bigg/ \left(\frac{1}{L_{pp}} \frac{dN_{pair}^{pp}}{dx_J} \right)$$

More details in Anne's presentation

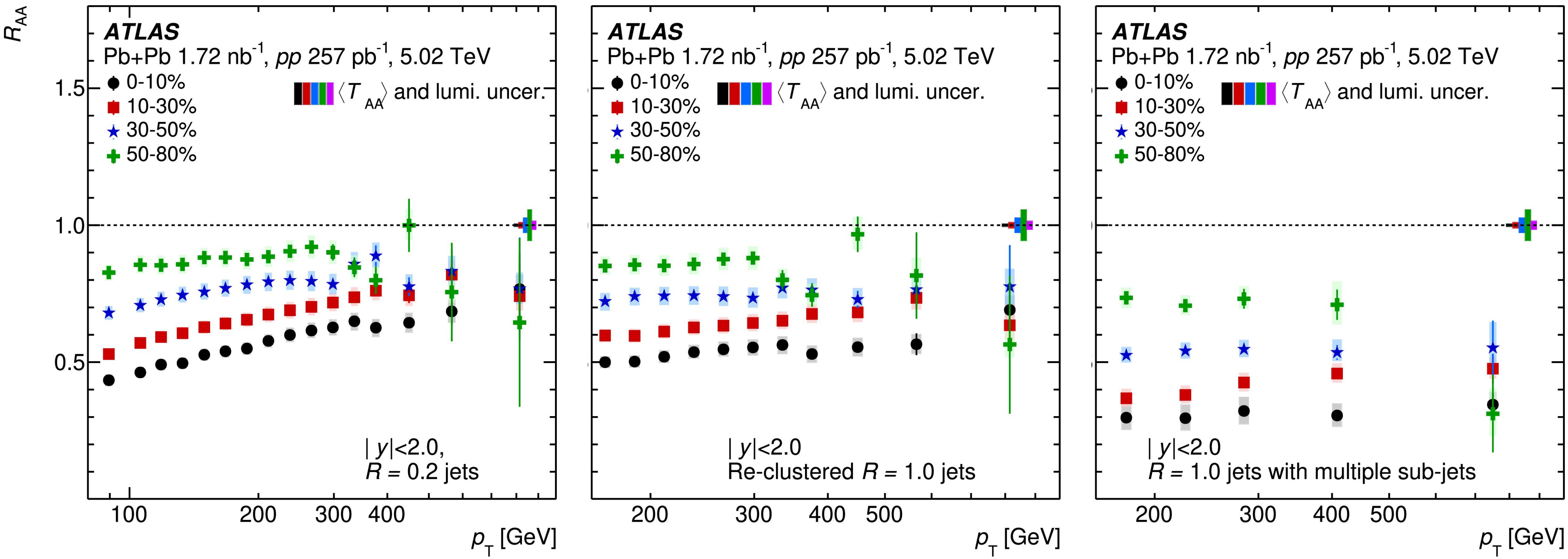




- R-dependent suppression primarily seen at low--x_J values.

arXiv:2407.18796

Jet suppression vs p_T



Inclusive R=0.2 *Re-clustered R=1.0* *Multiple sub-jet R=1.0*

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