



Measurements of the Substructure Dependence of Jet Quenching in PbPb collisions

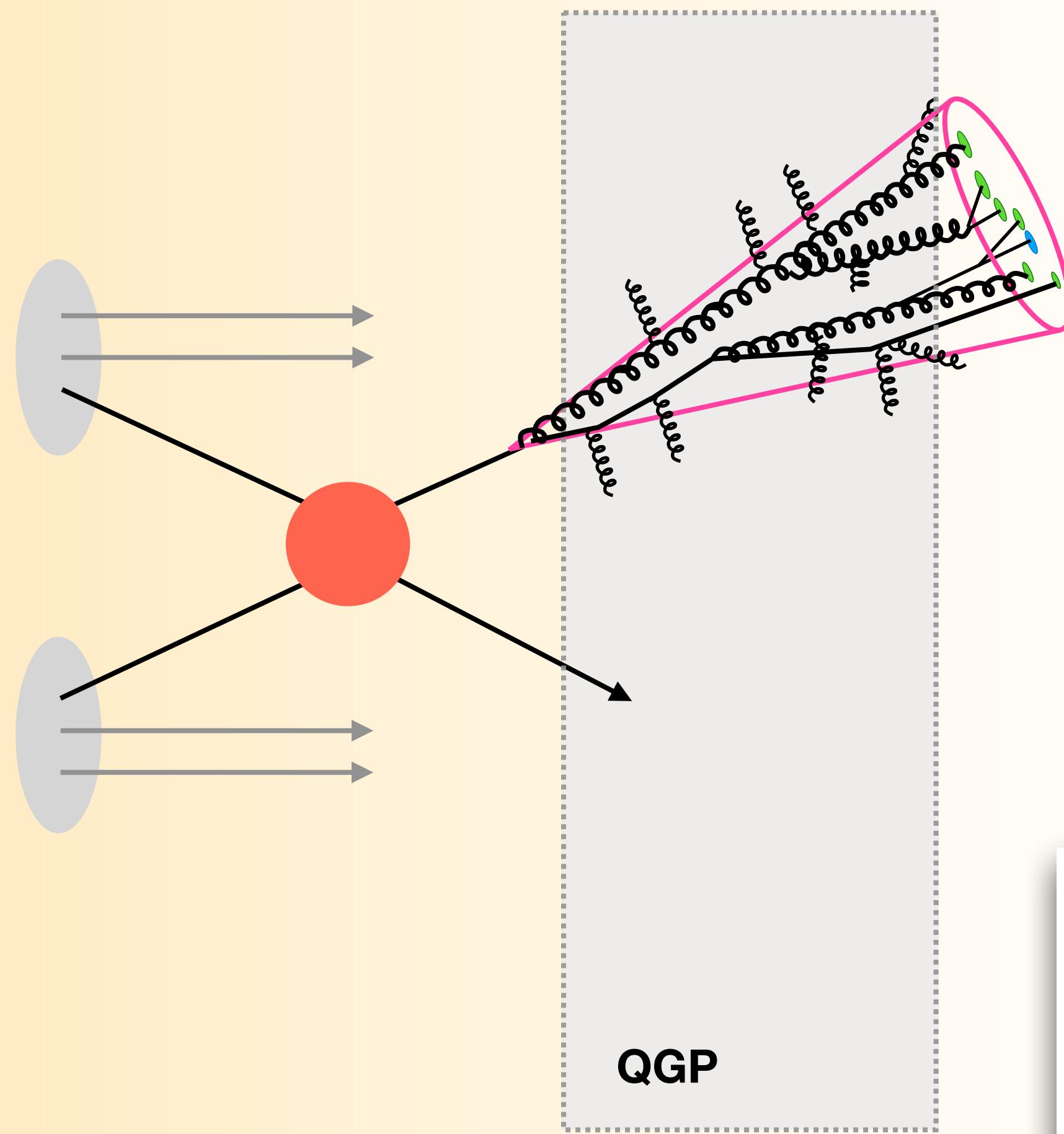
Dhanush Hangal (he/him)
On behalf of the ATLAS Collaboration
September 6, 2023

hangal1@lbl.gov



Jets in the Quark-Gluon Plasma

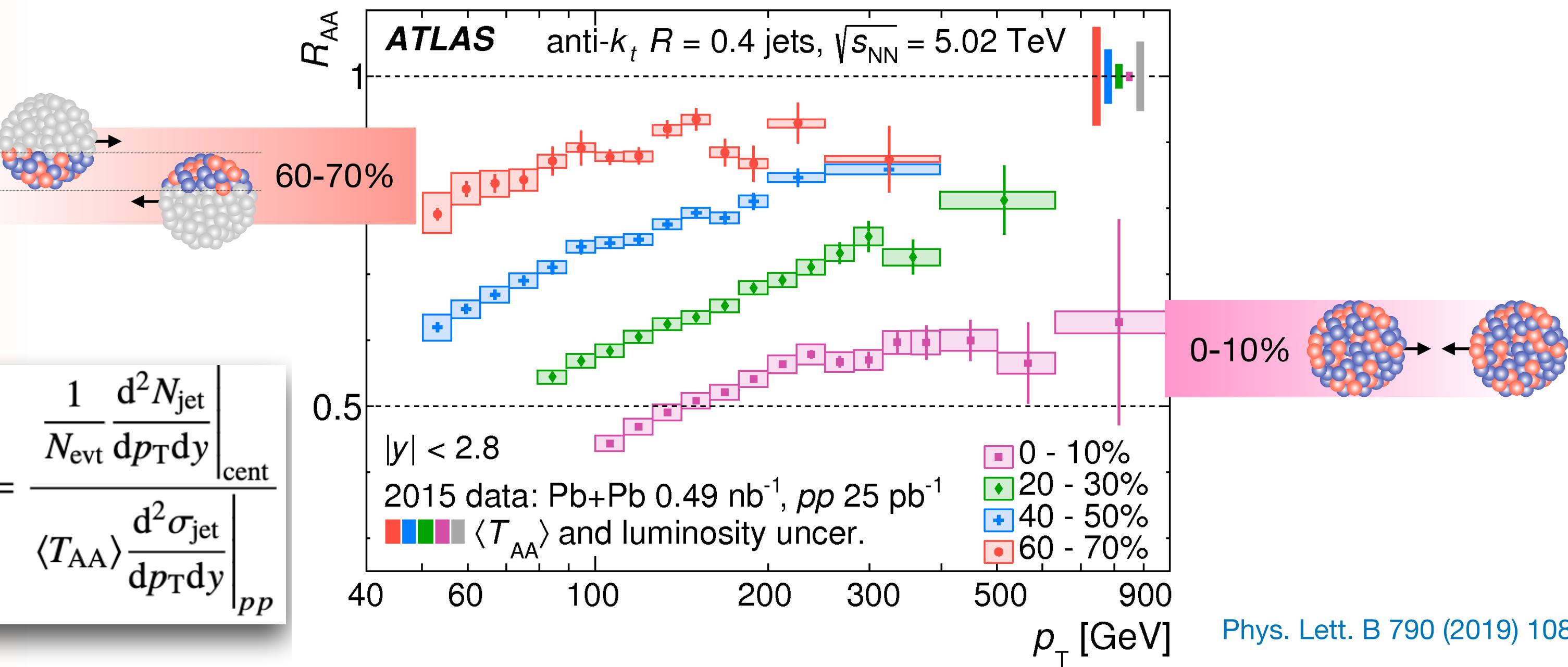
- Jet suppression and “quenching” in QGP characterized using nuclear modification factor (R_{AA})



$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{jet}}}{dp_T dy} \Big|_{\text{cent}}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \Big|_{pp}}$$

Jet production: heavy ion (**PbPb**) collisions vs. ***pp*** collisions

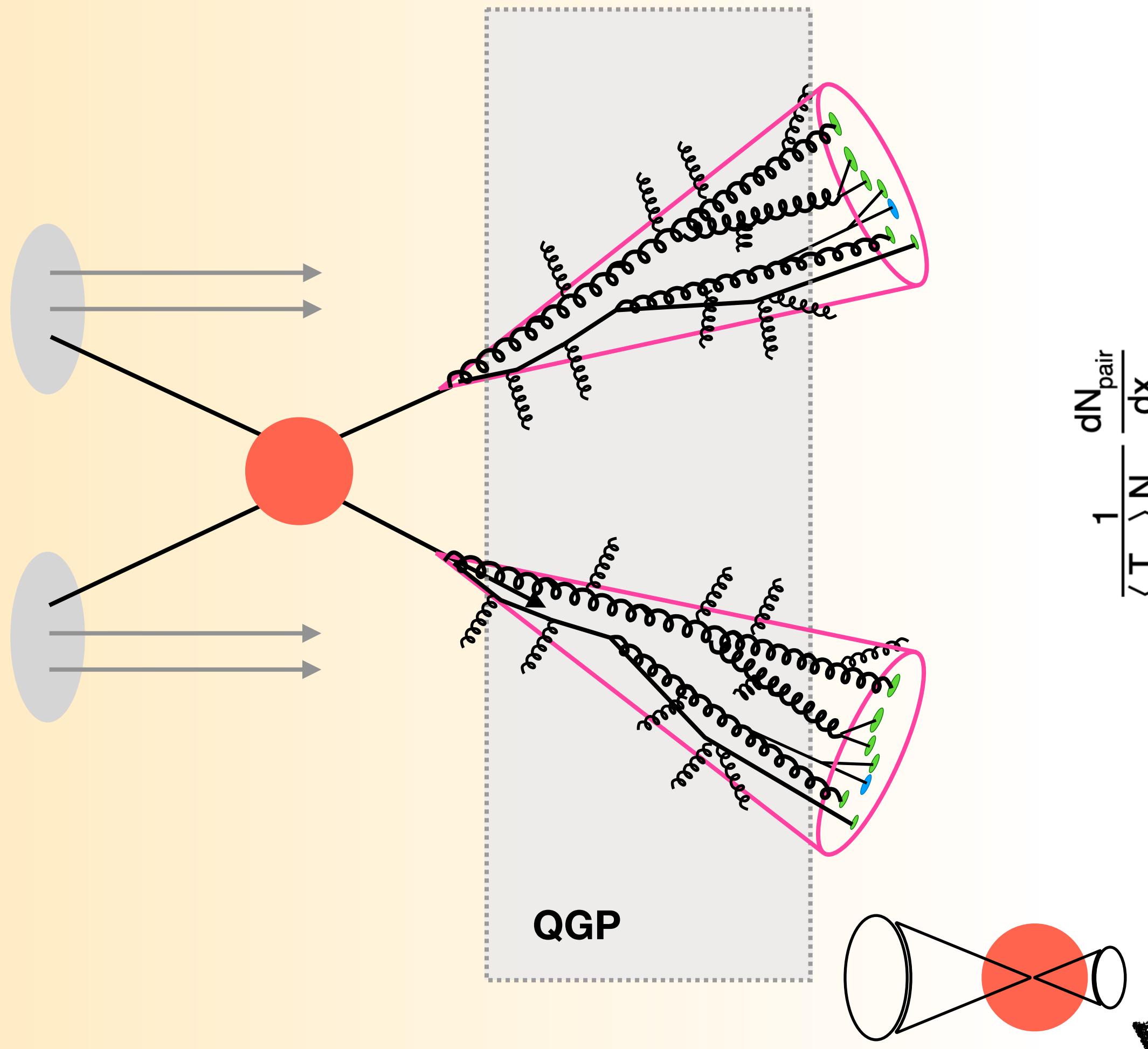
Nuclear modification factor $R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$



Phys. Lett. B 790 (2019) 108

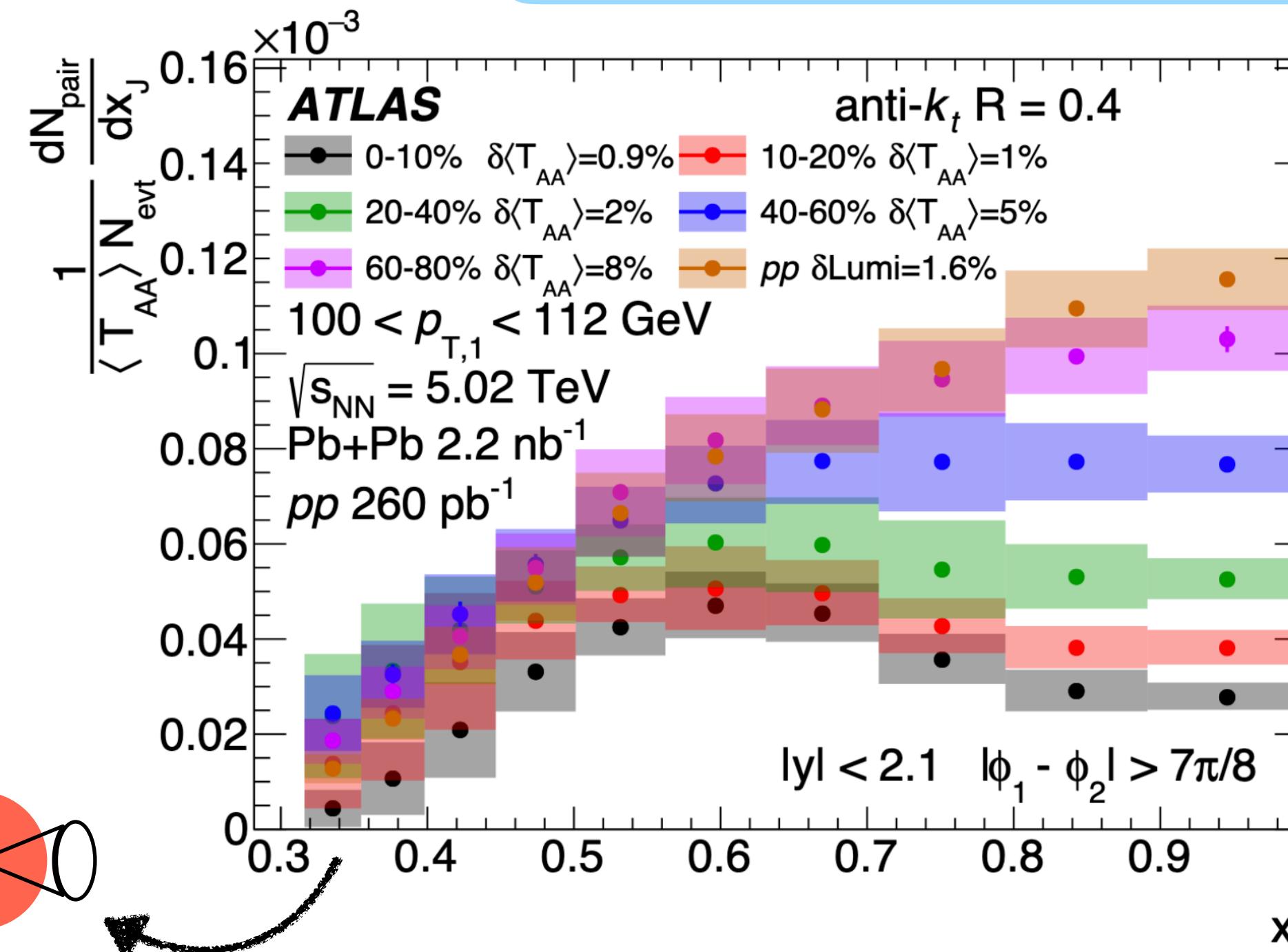
Jets in the QGP

- Jet suppression and “quenching” in QGP characterized using nuclear modification factor (R_{AA})
- Jet energy loss in the QGP observed to fluctuate -> **Need to measure it differentially**

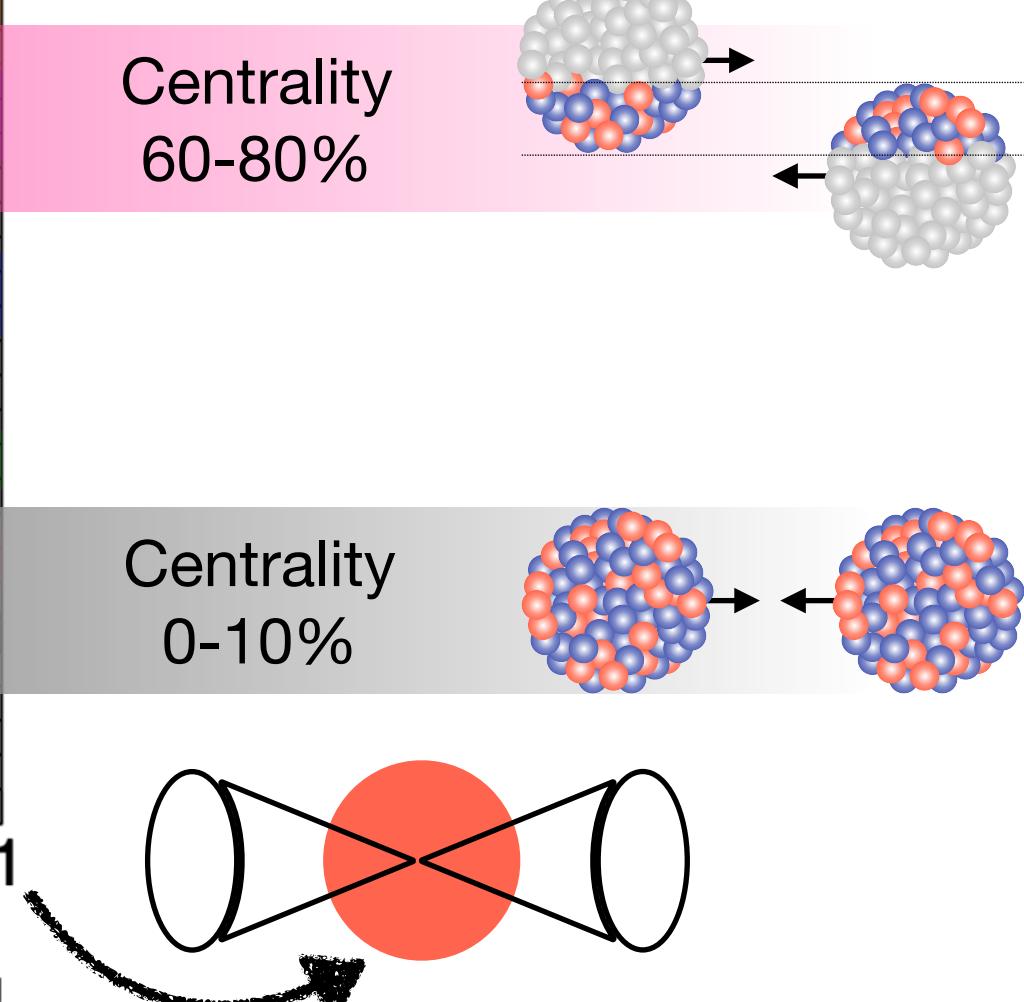


Jet production: heavy ion (**PbPb**) collisions vs. ***pp*** collisions

$$\text{Dijet asymmetry} \quad x_J \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}}}$$

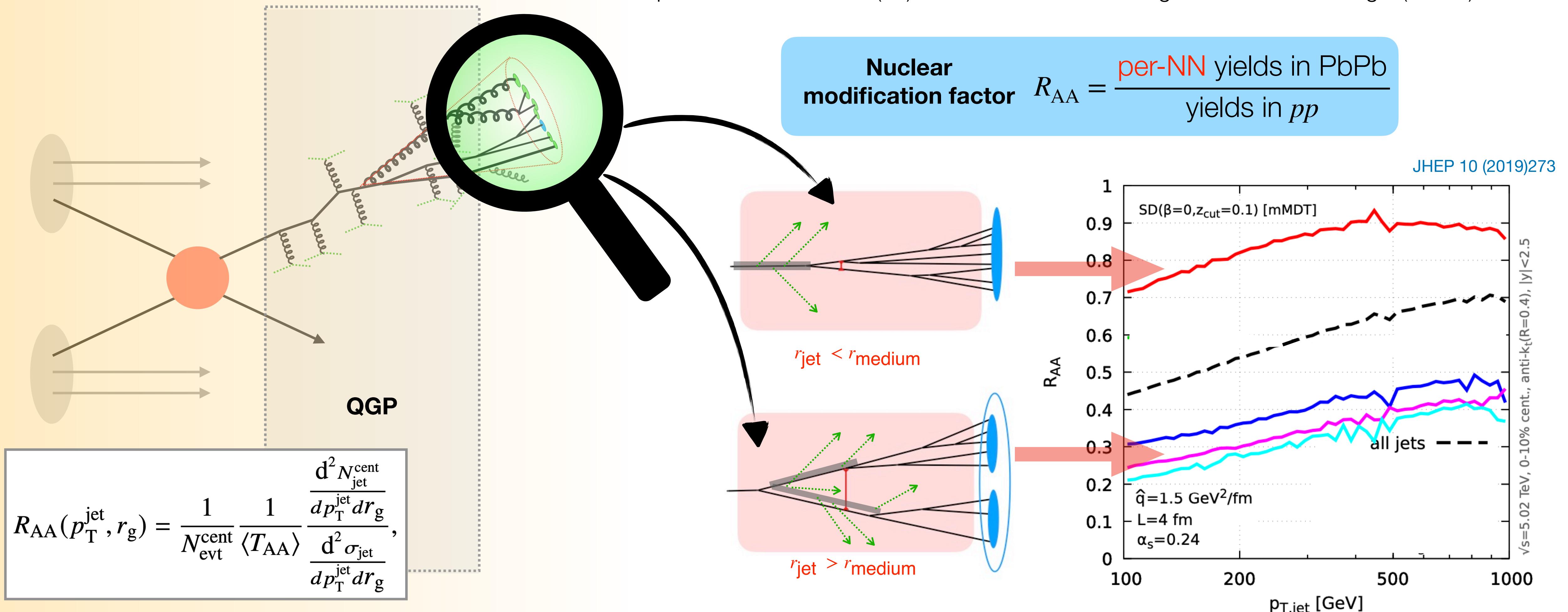


Phys. Rev. C. 107 (2023) 054908



Jet substructure vs. suppression

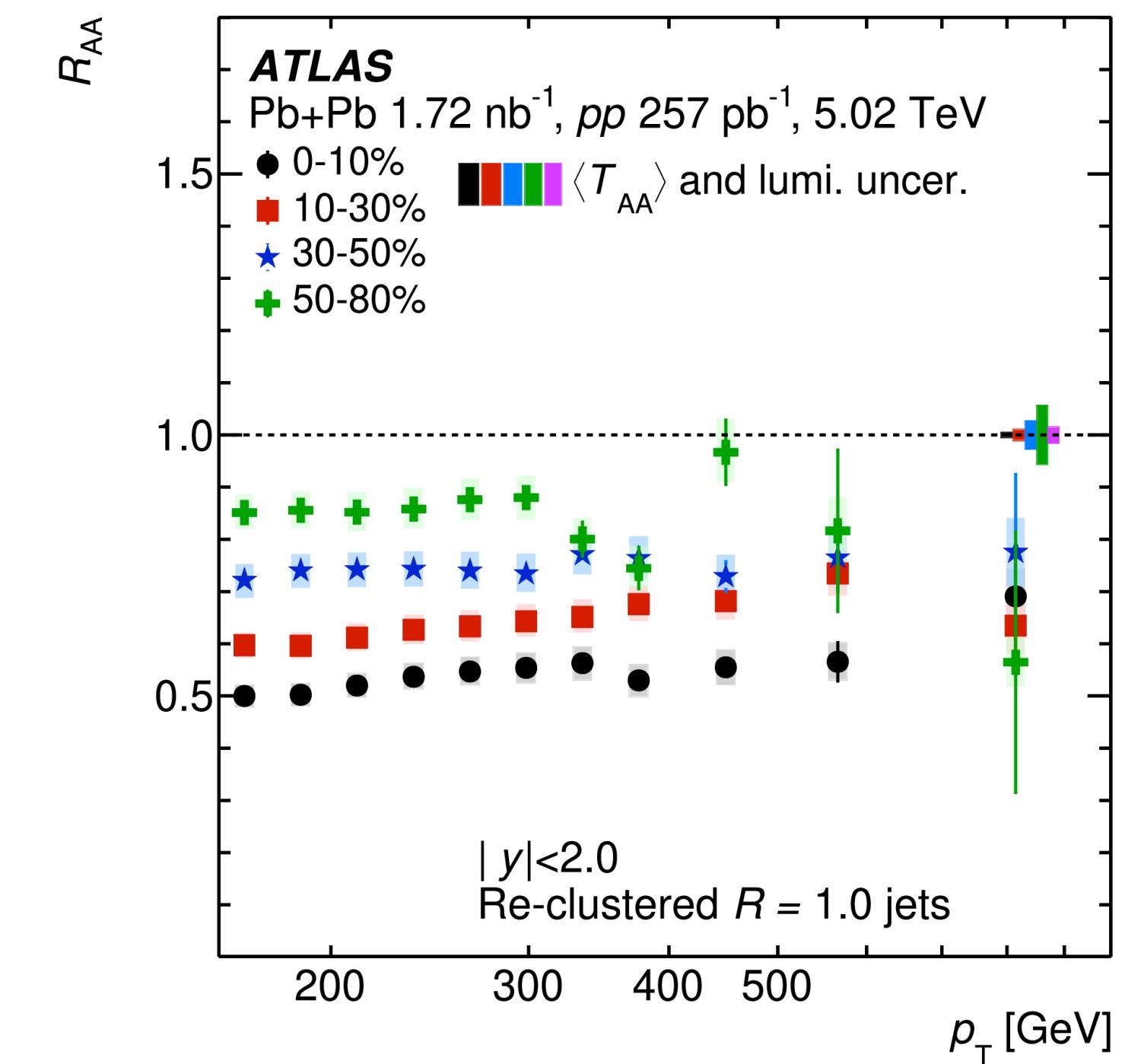
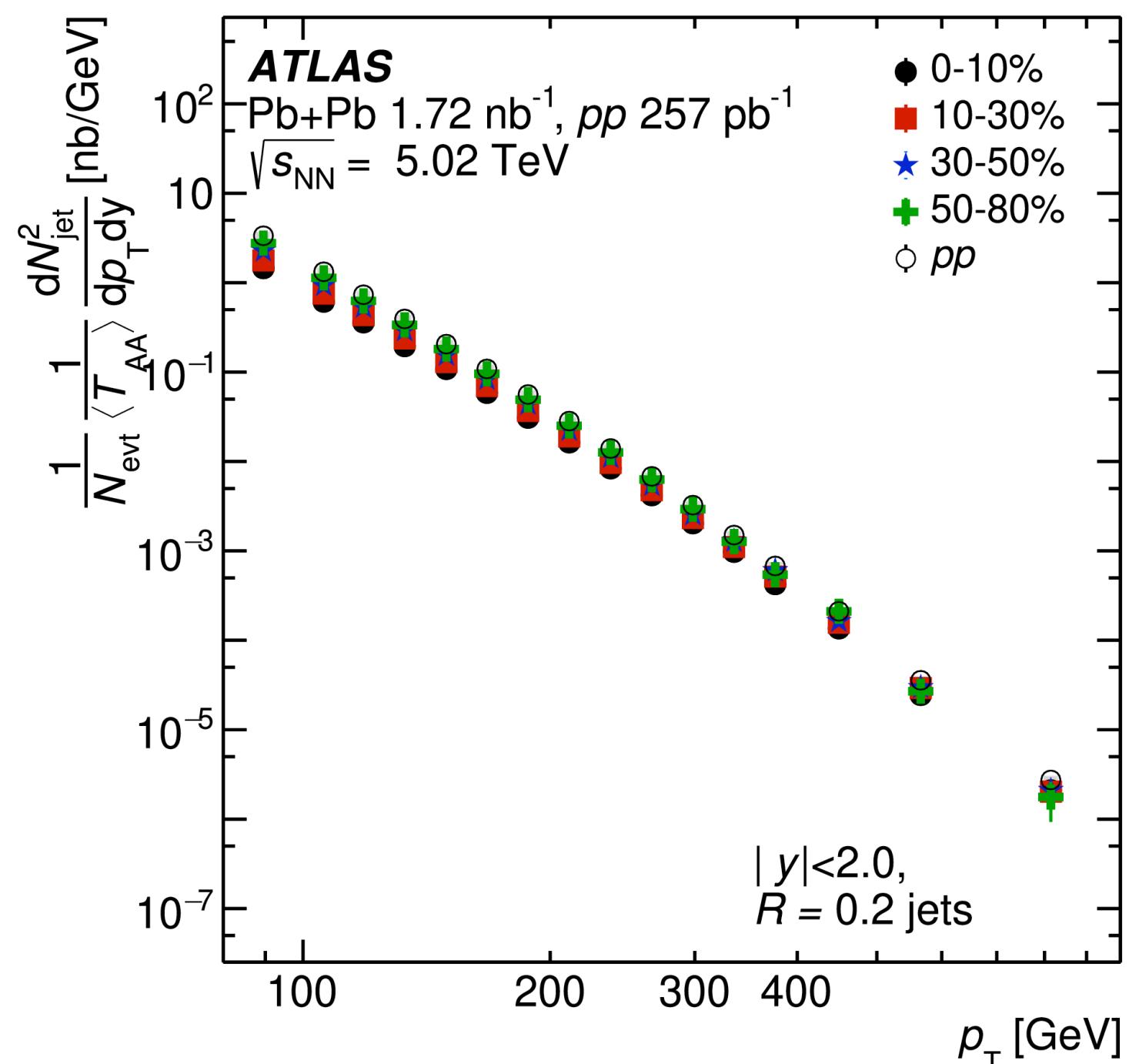
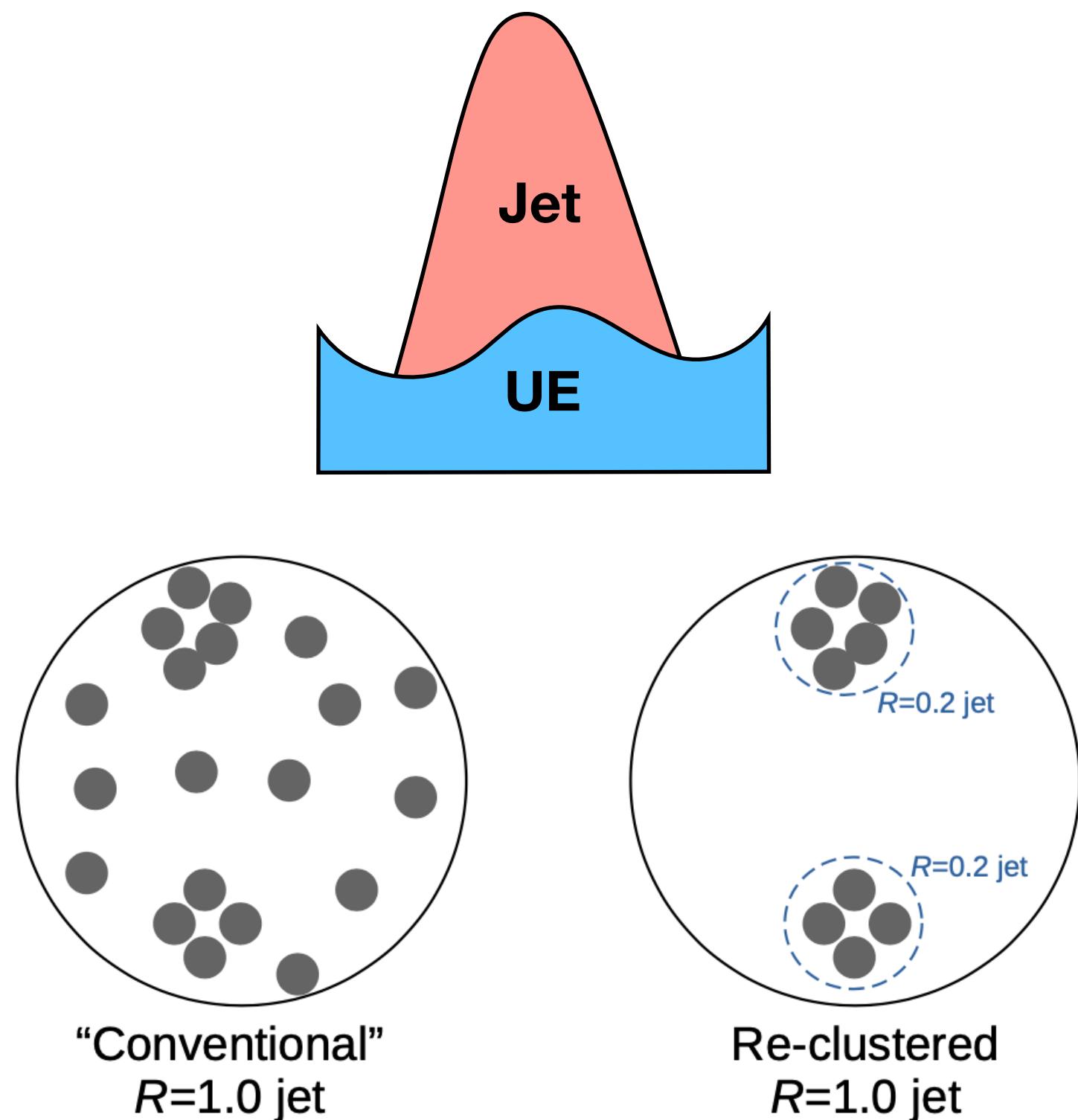
- Jet quenching in the QGP medium theorized to be dictated by color coherence picture
- Explore the role of color (de)coherence and the emergence of a critical angle (r_{medium})



Large Radius Jets

- Large radius jets ($R=1.0$) reconstructed by clustering $R=0.2$ jets using anti- k_T
- Background-subtracted $R=0.2$ jets used as constituents for **hard substructure measurement**
- Small R ($=0.2$) jets re-clustered using k_T algorithm, **hardest subjets clustered last**

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}} \frac{d^2 N_{\text{jet}}}{dp_T dy}} \Big|_{\text{cent}}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \Big|_{pp}}$$

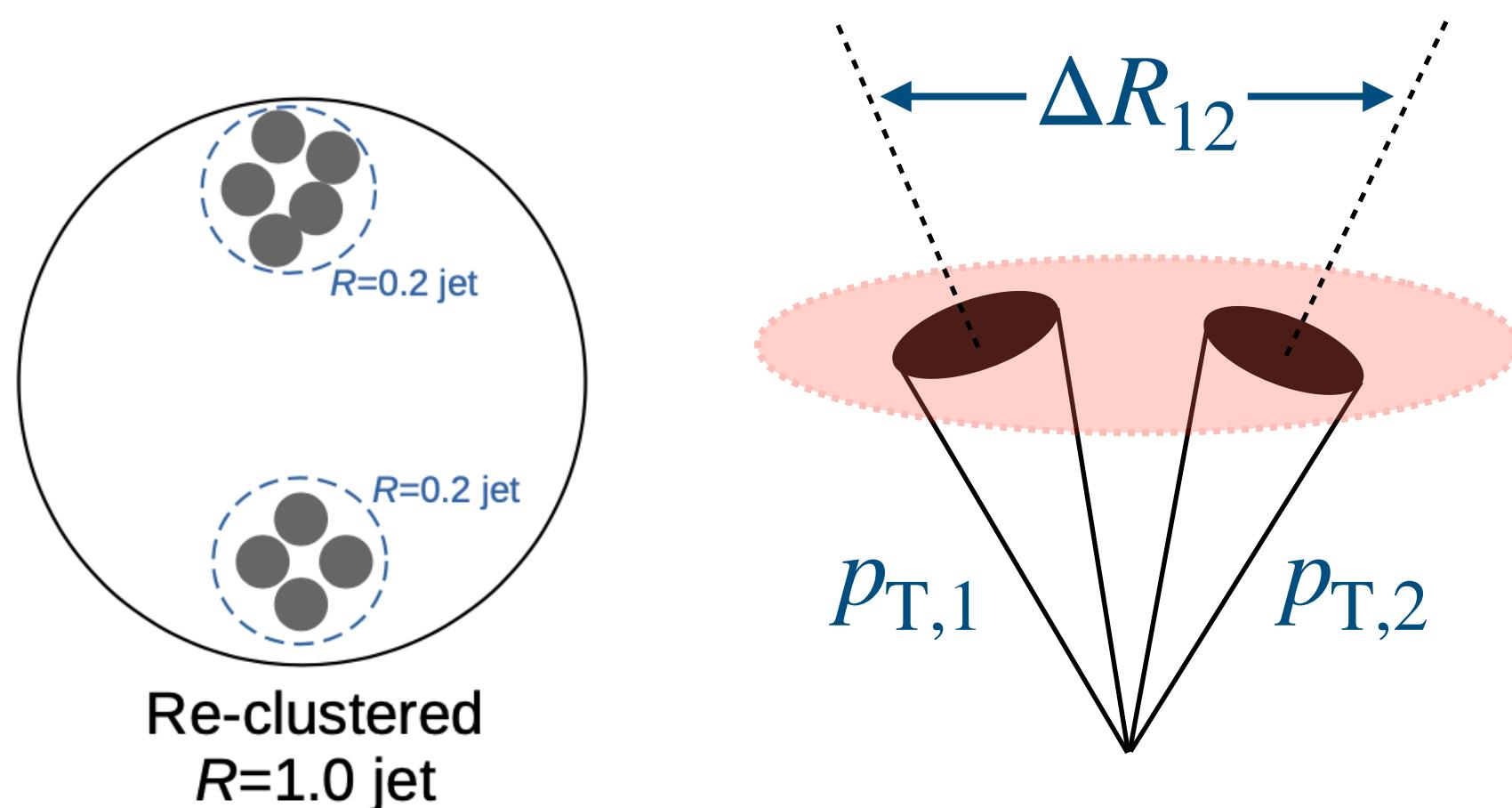


arXiv:2301.05606

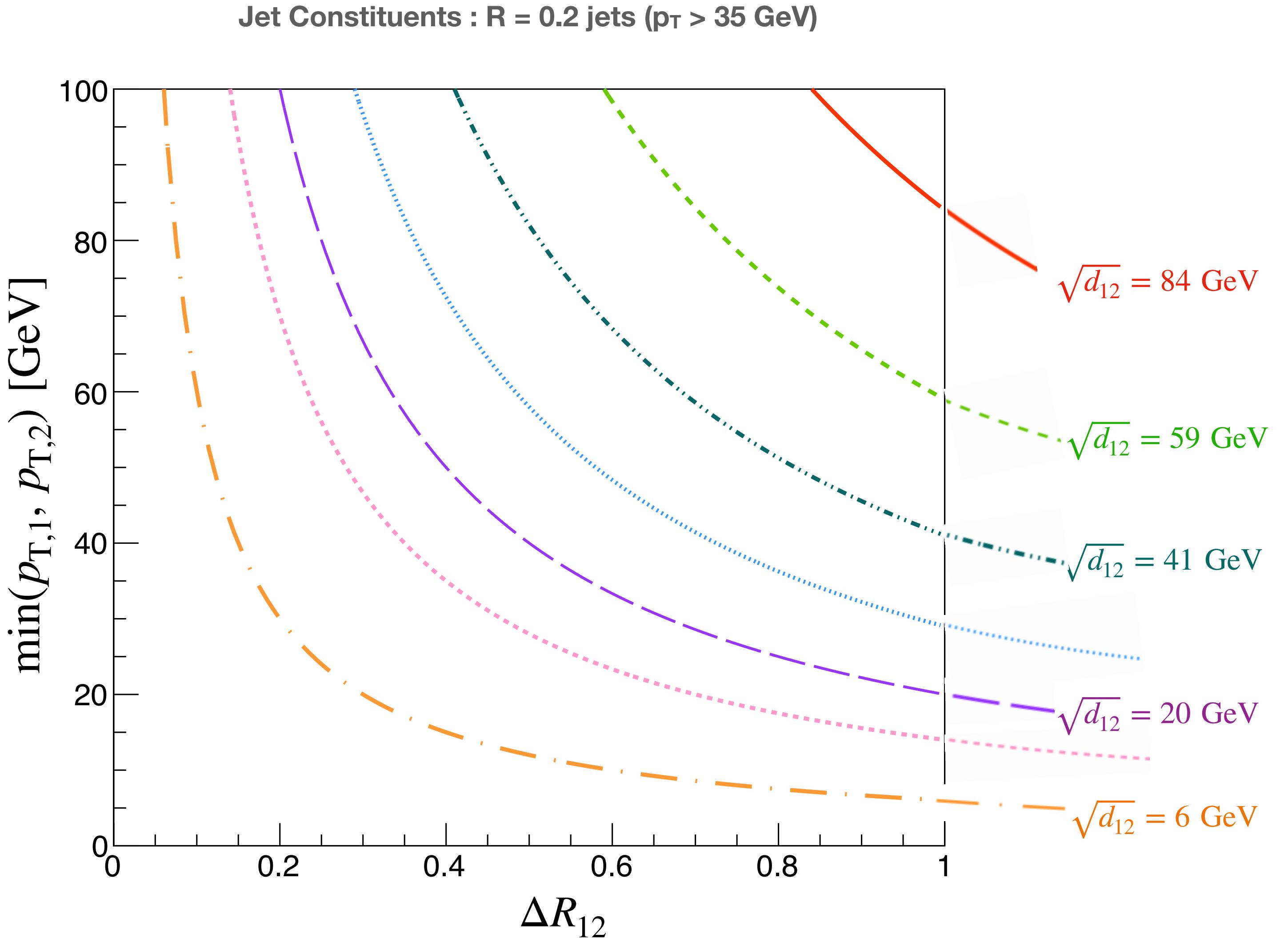
Splitting Scales ($\sqrt{d_{12}}$)

- Hard substructure of large-radius jet characterized using its splitting scale $\sqrt{d_{12}}$

- Two subjets from final k_T clustering step used in defining $\sqrt{d_{12}}$

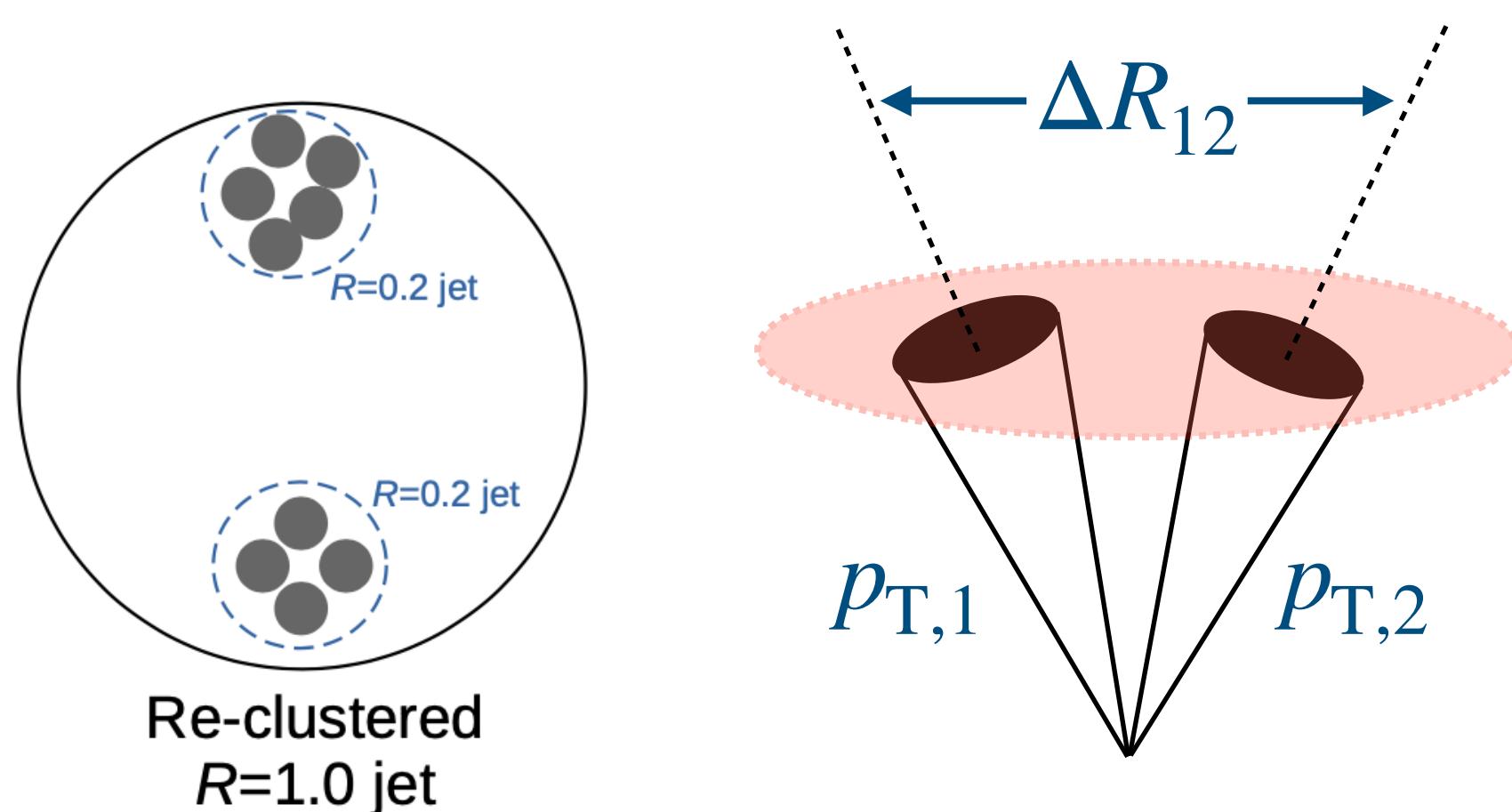


$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

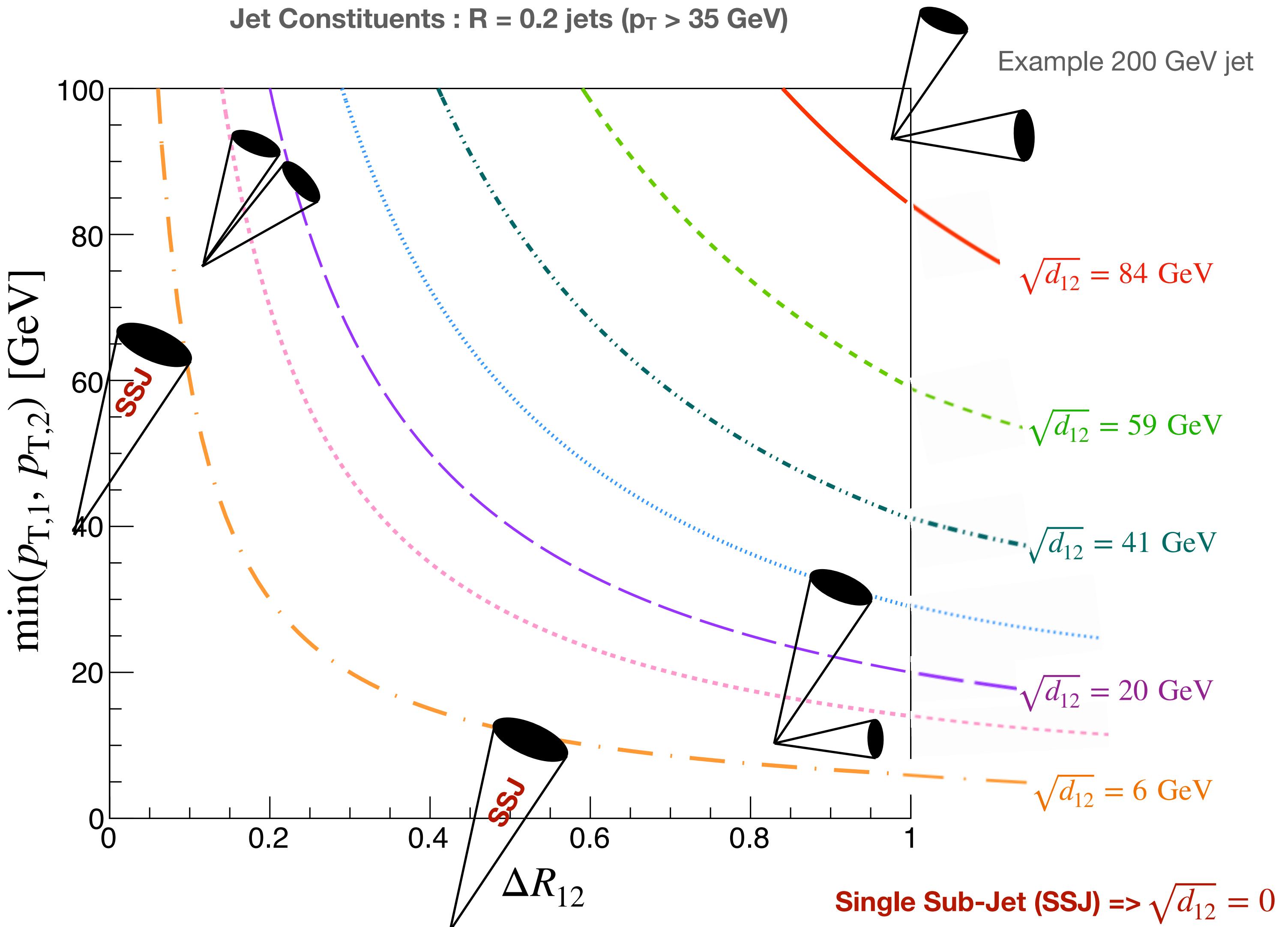


Splitting Scales ($\sqrt{d_{12}}$)

- Hard substructure of large-radius jet characterized using its splitting scale $\sqrt{d_{12}}$
- Two subjets from final k_T clustering step used in defining $\sqrt{d_{12}}$

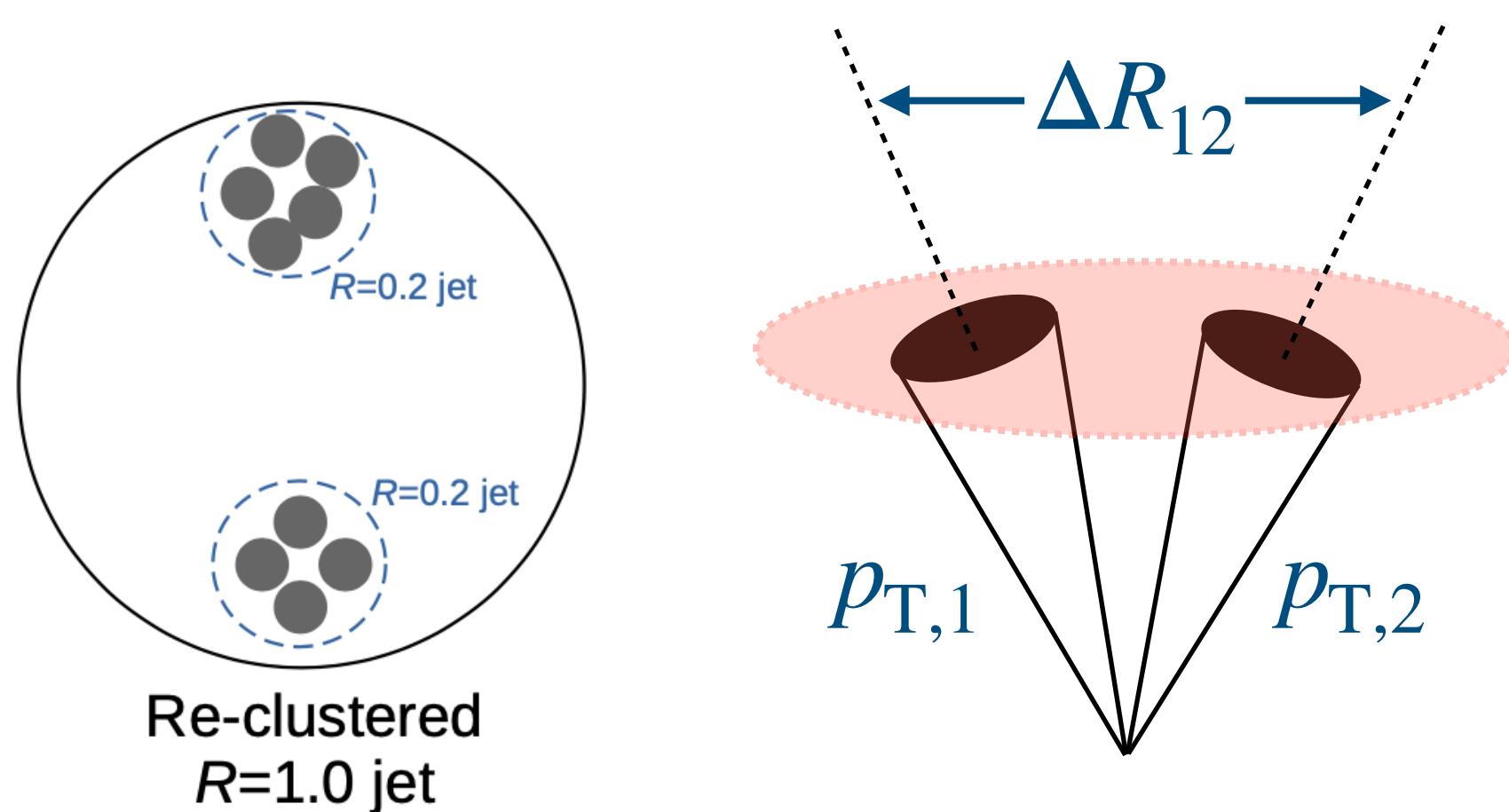


$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

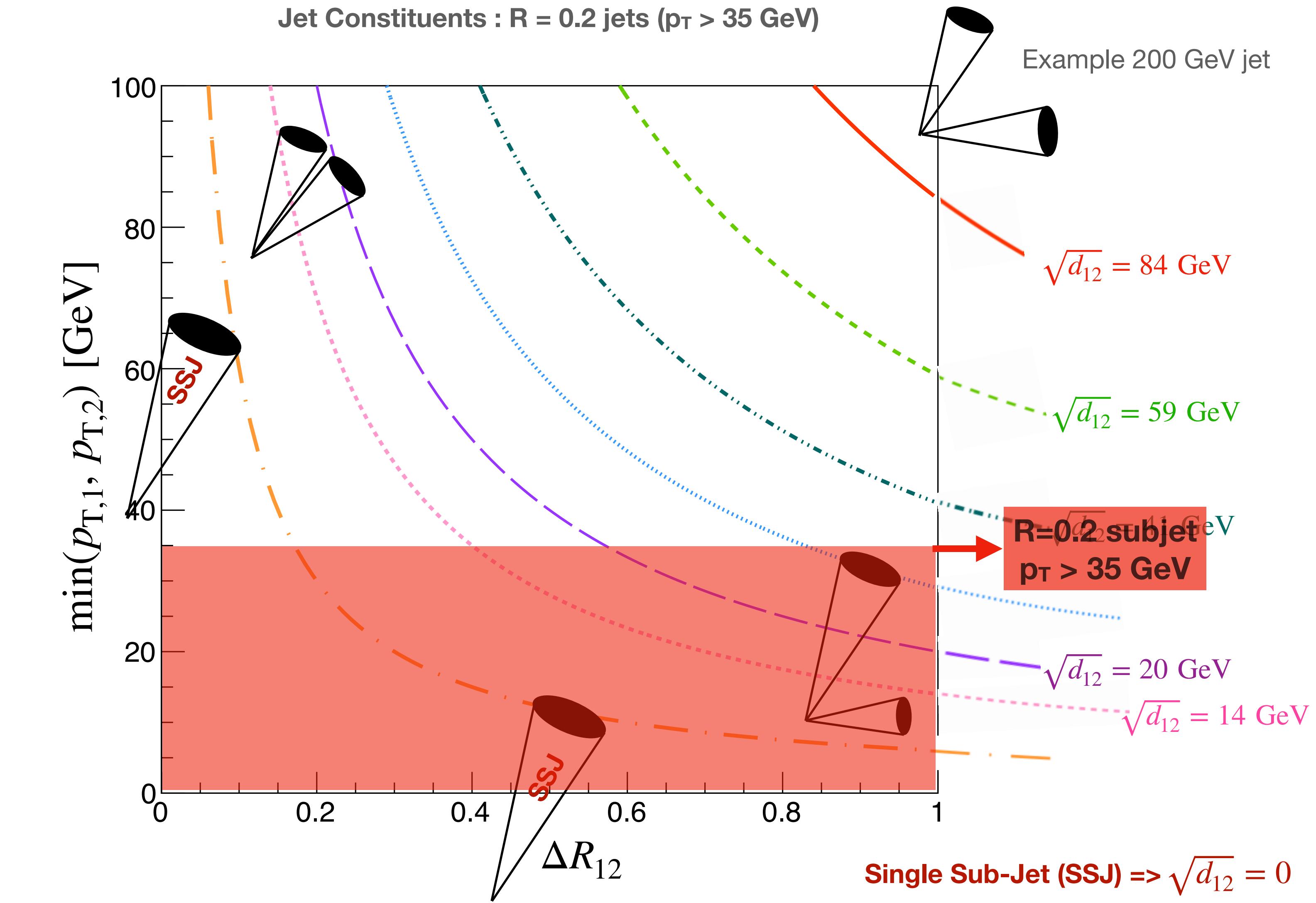


Splitting Scales ($\sqrt{d_{12}}$)

- Hard substructure of large-radius jet characterized using its splitting scale $\sqrt{d_{12}}$
- Two subjets from final k_T clustering step used in defining $\sqrt{d_{12}}$



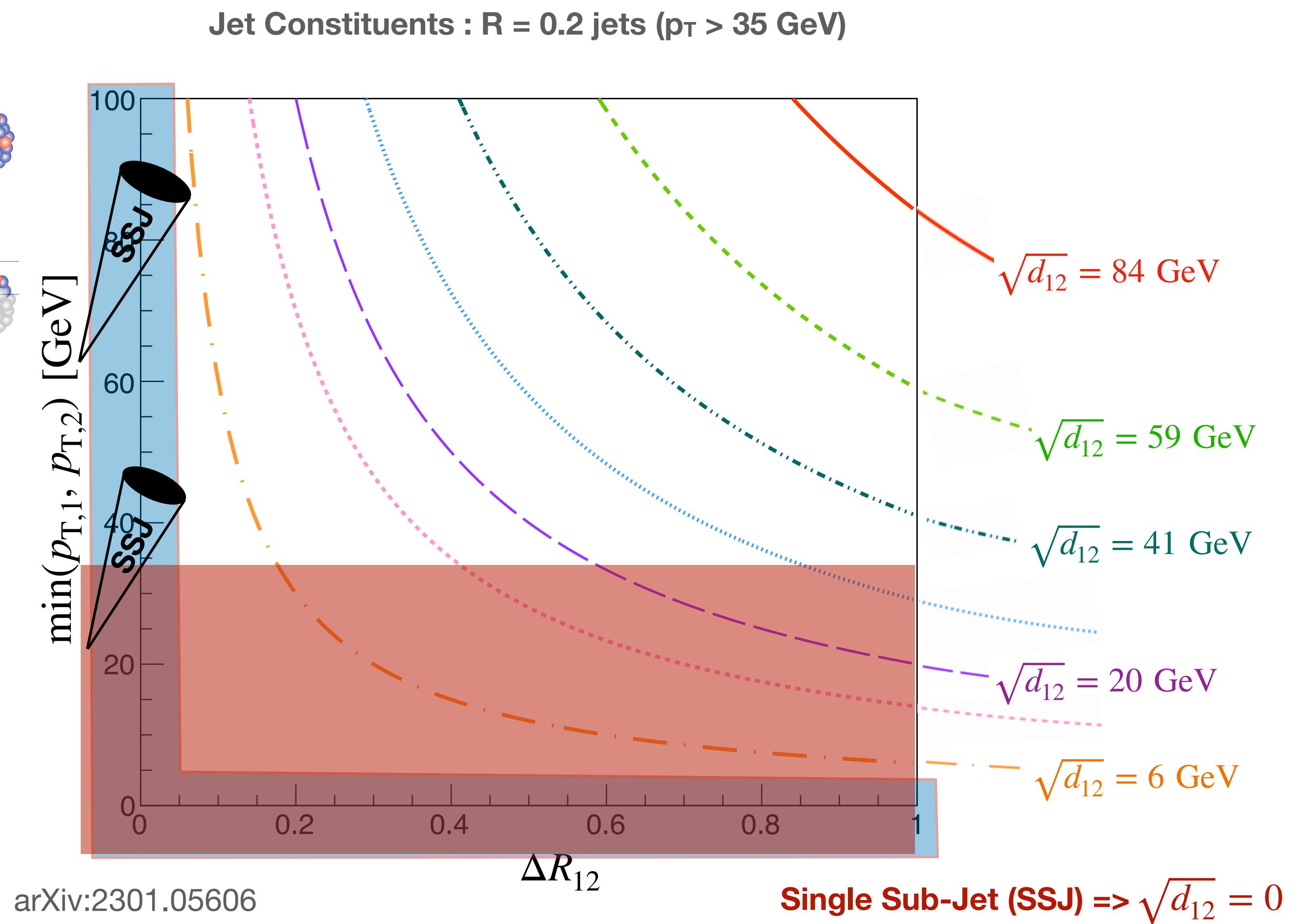
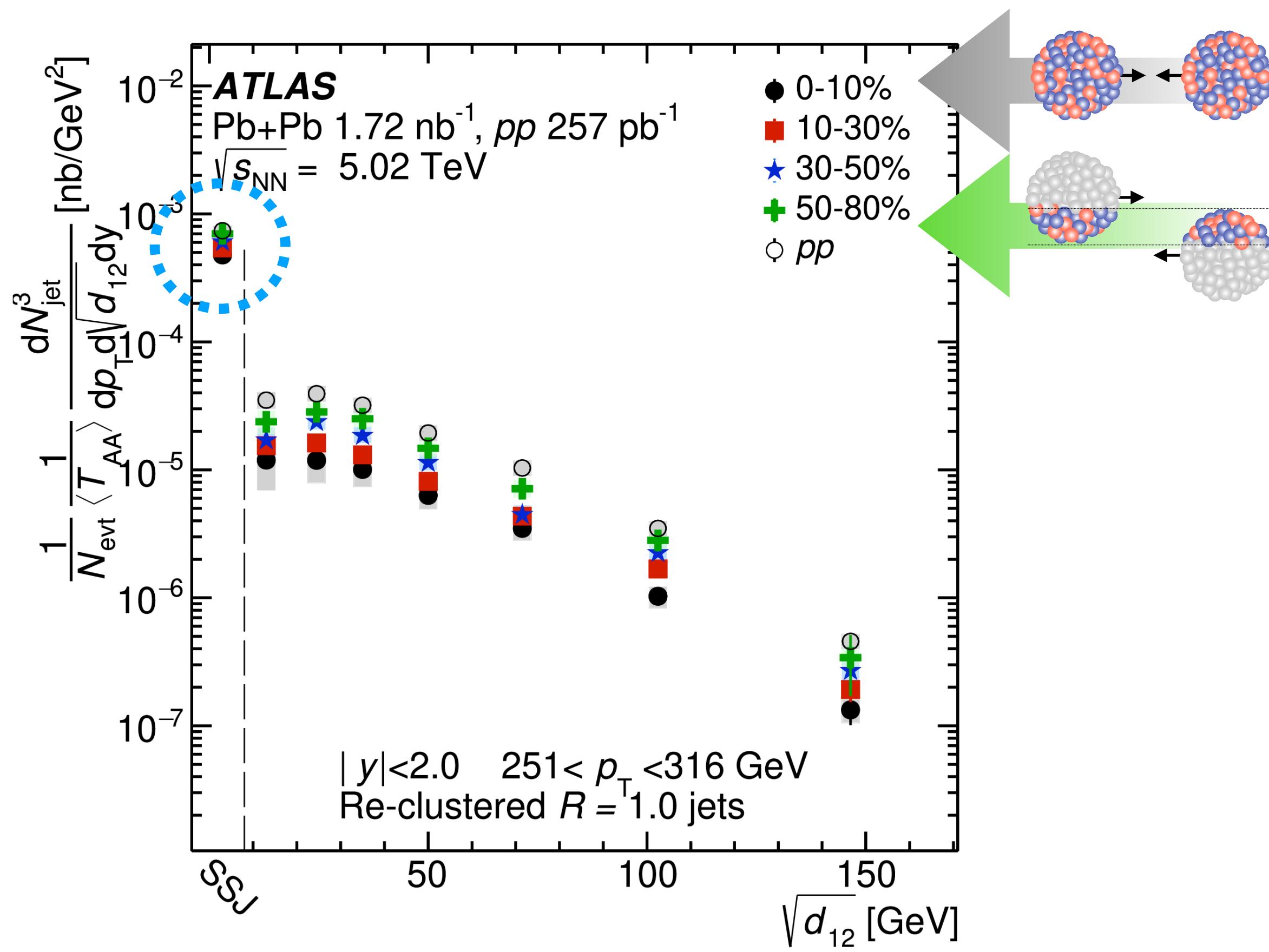
$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$



Splitting Scales ($\sqrt{d_{12}}$)

- Substructure of large-radius jet characterized using its splitting scale $\sqrt{d_{12}}$

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

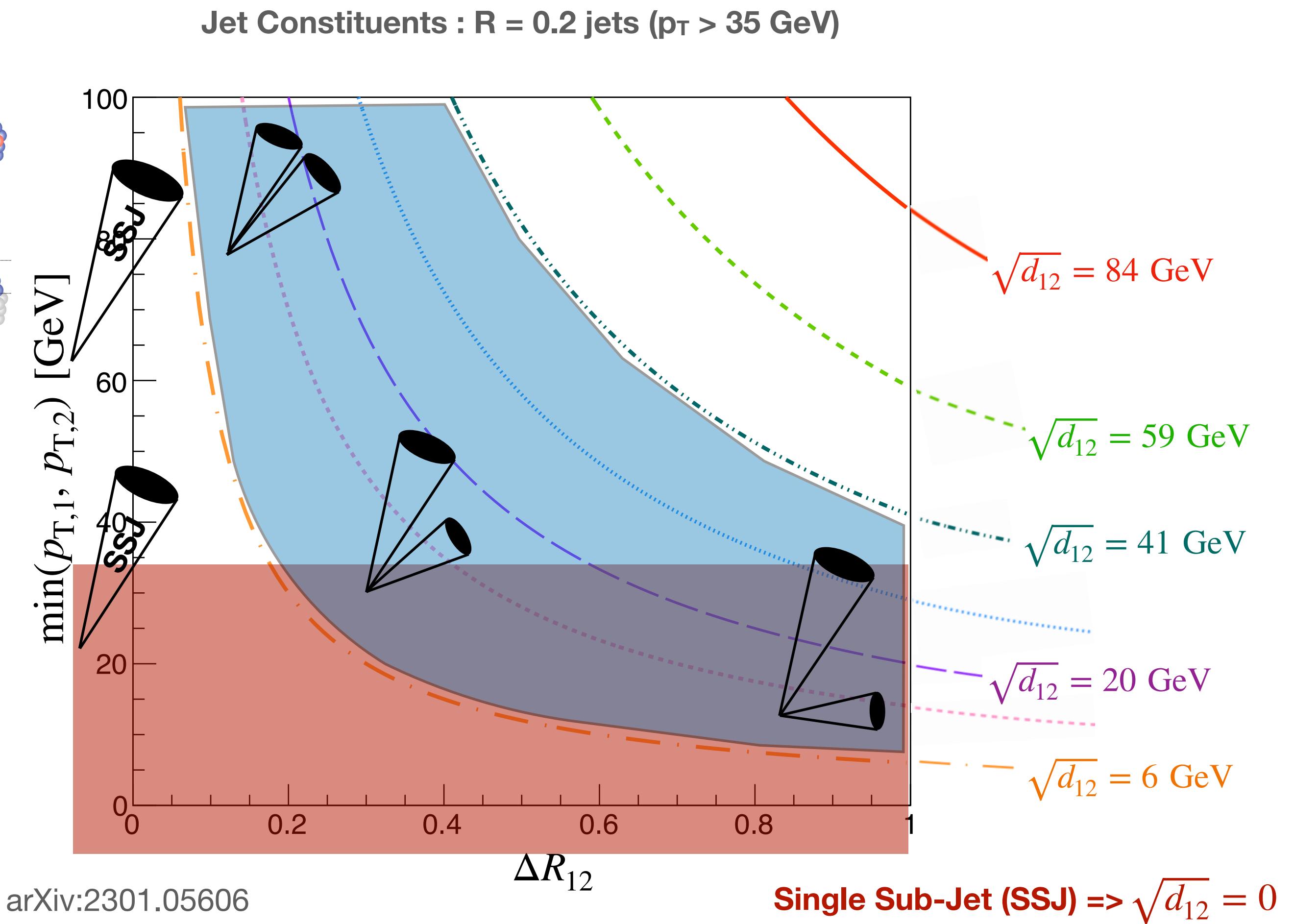
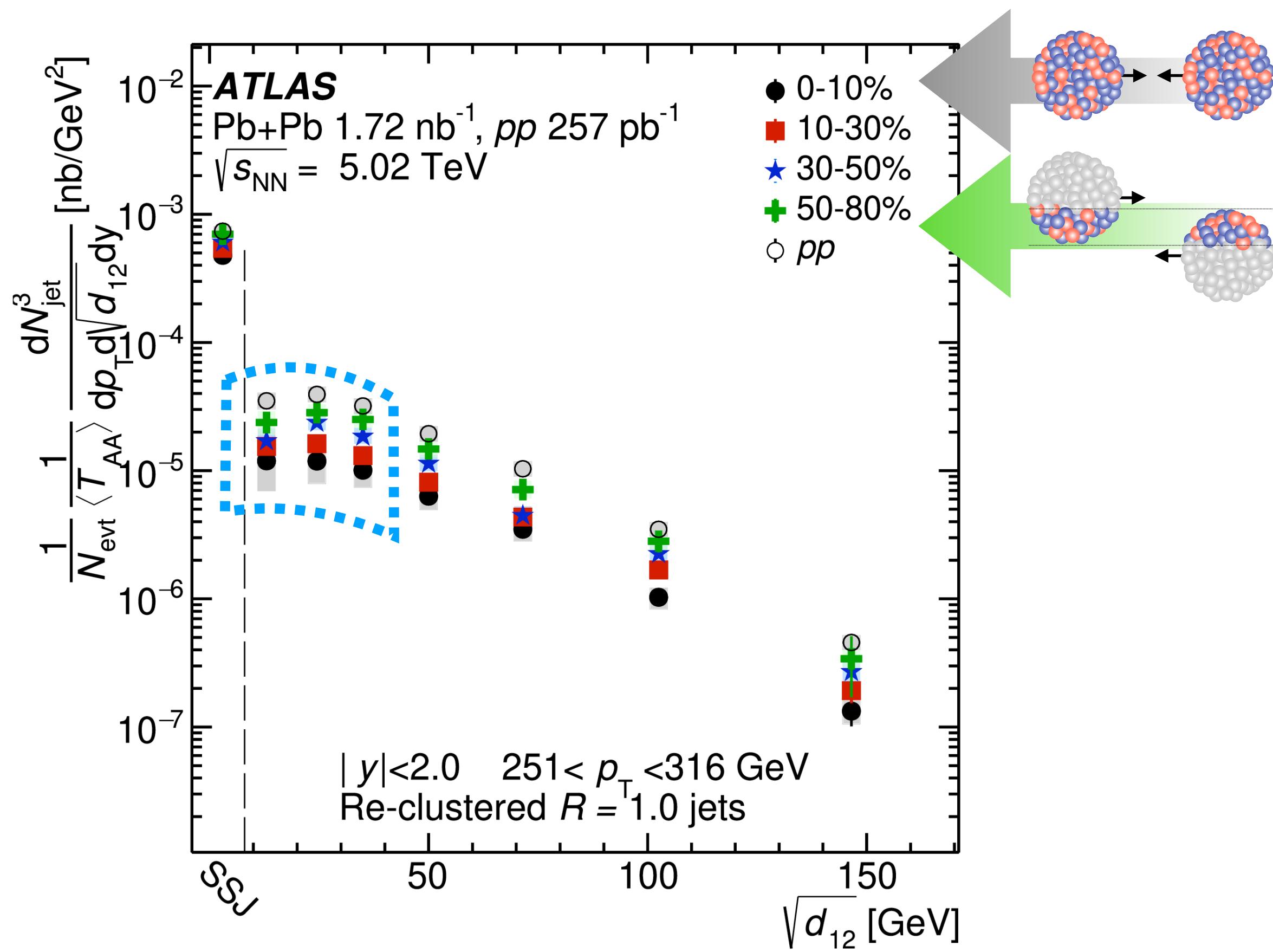


arXiv:2301.05606

Splitting Scales ($\sqrt{d_{12}}$)

- Substructure of large-radius jet characterized using its splitting scale $\sqrt{d_{12}}$

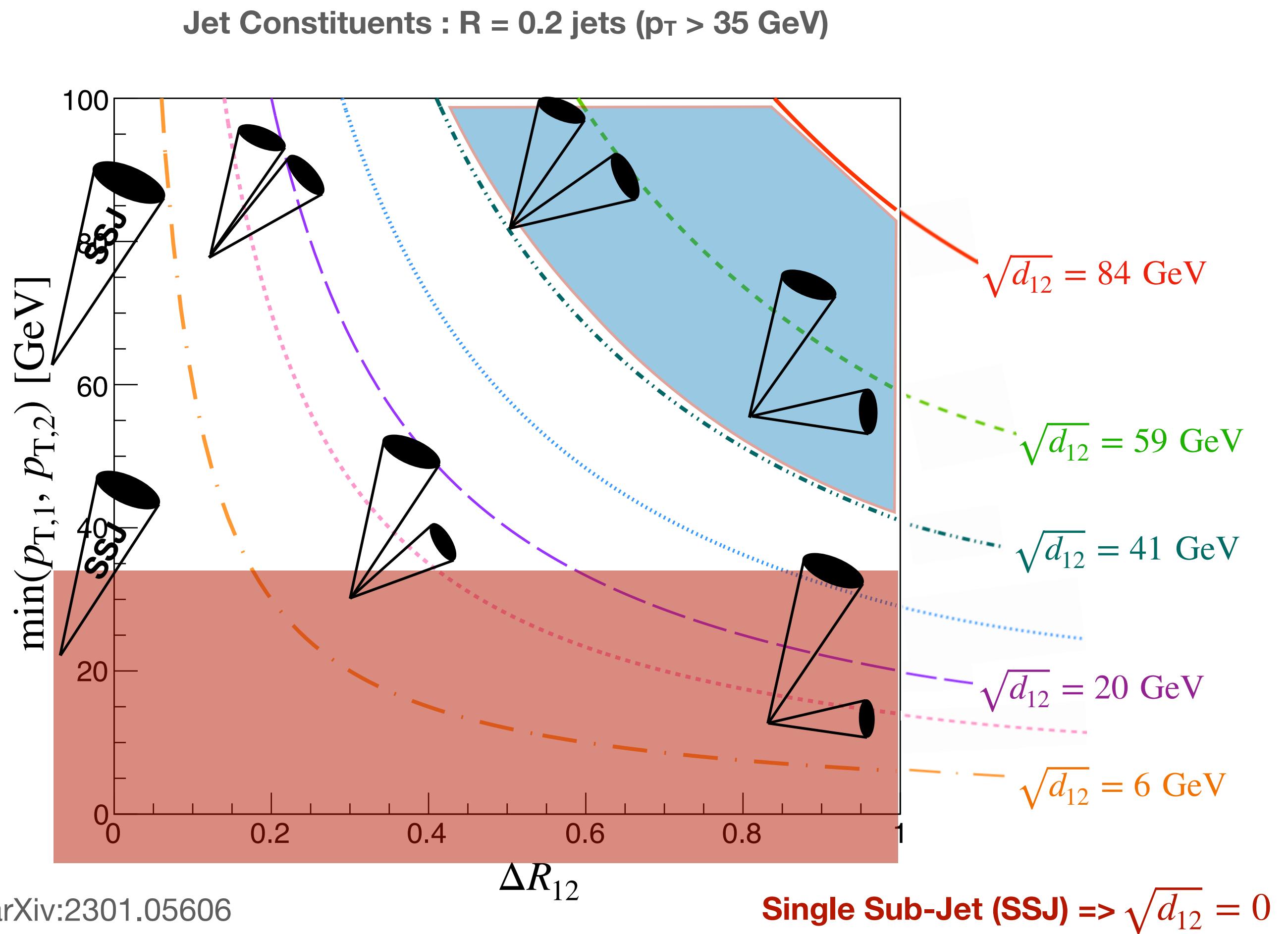
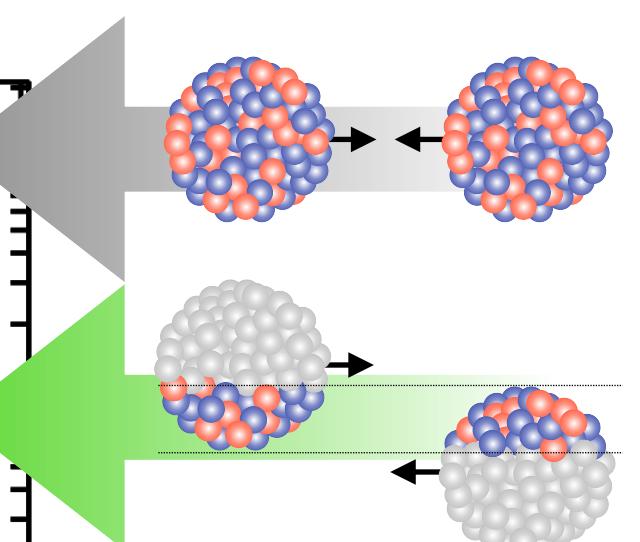
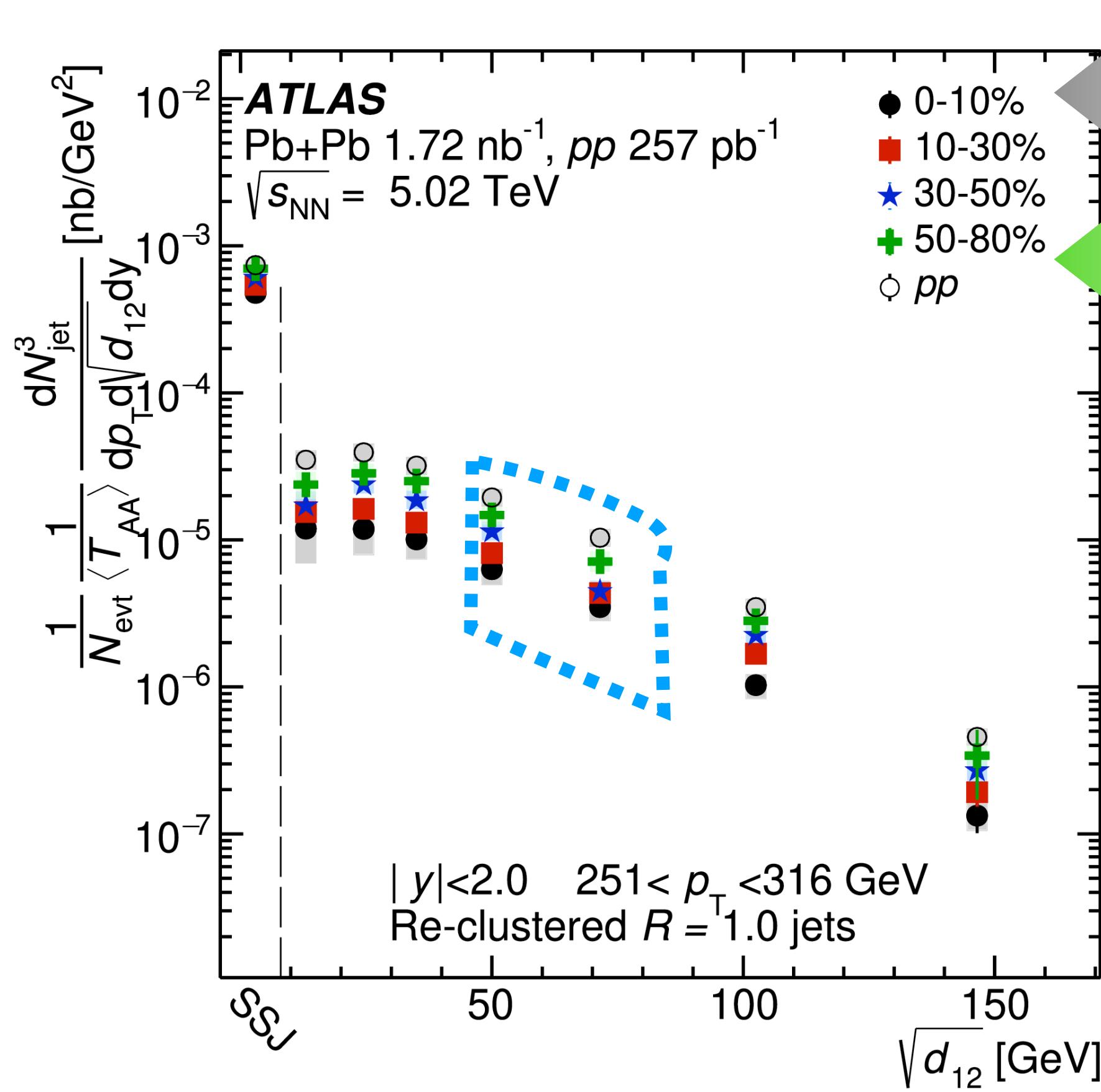
$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$



Splitting Scales ($\sqrt{d_{12}}$)

- Substructure of large-radius jet characterized using its splitting scale $\sqrt{d_{12}}$

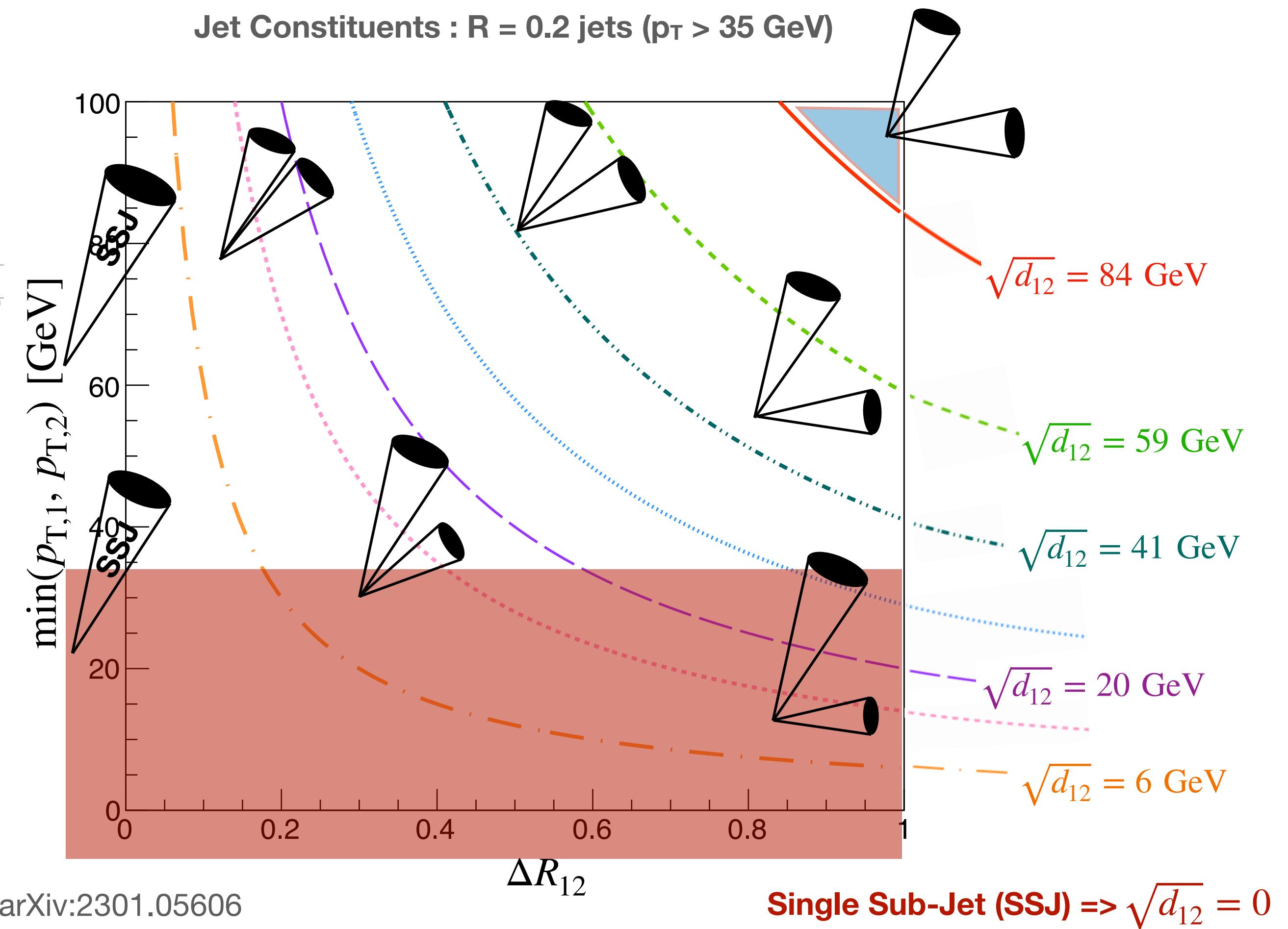
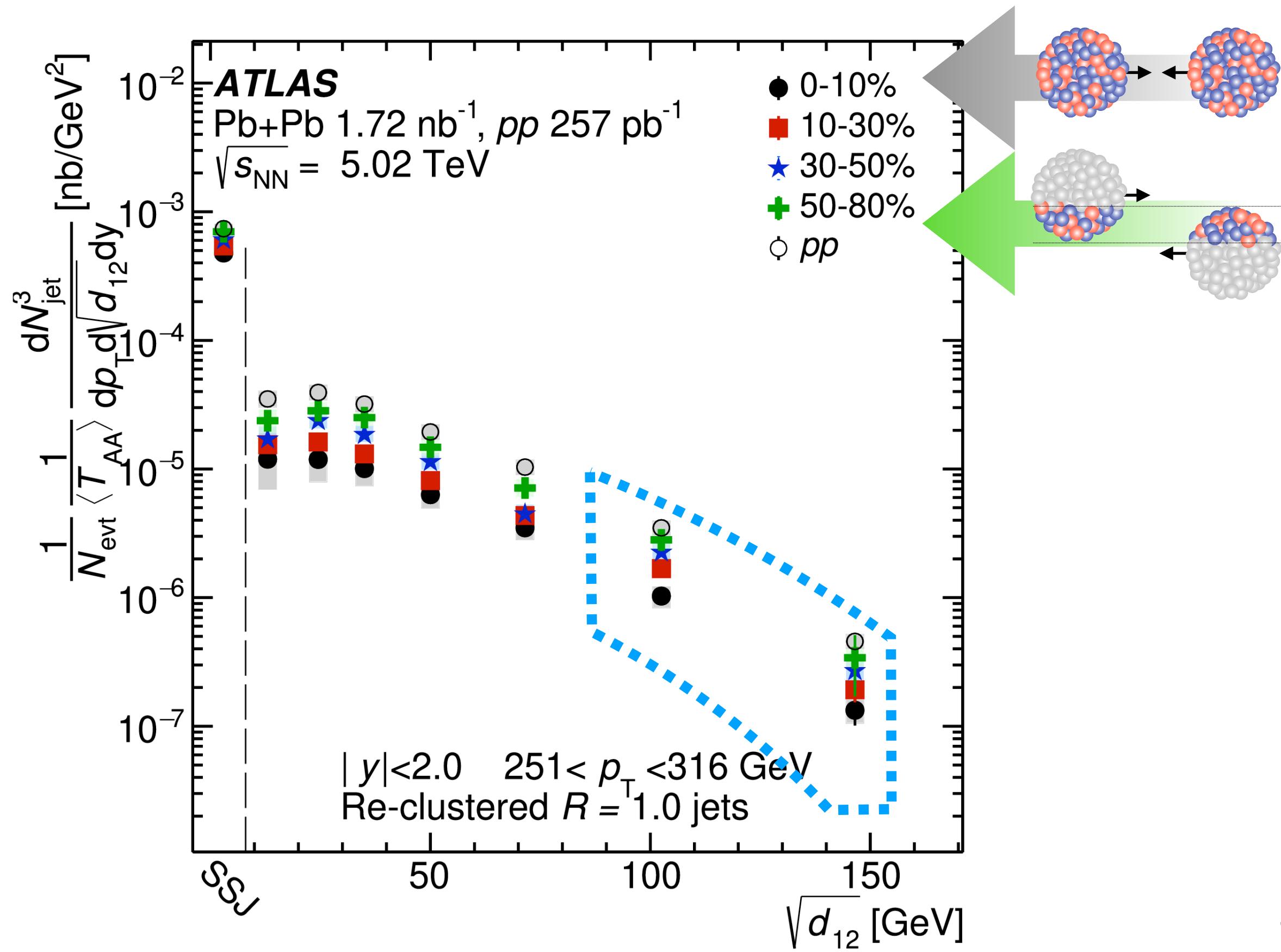
$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$



Splitting Scales ($\sqrt{d_{12}}$)

- Substructure of large-radius jet characterized using its splitting scale $\sqrt{d_{12}}$

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

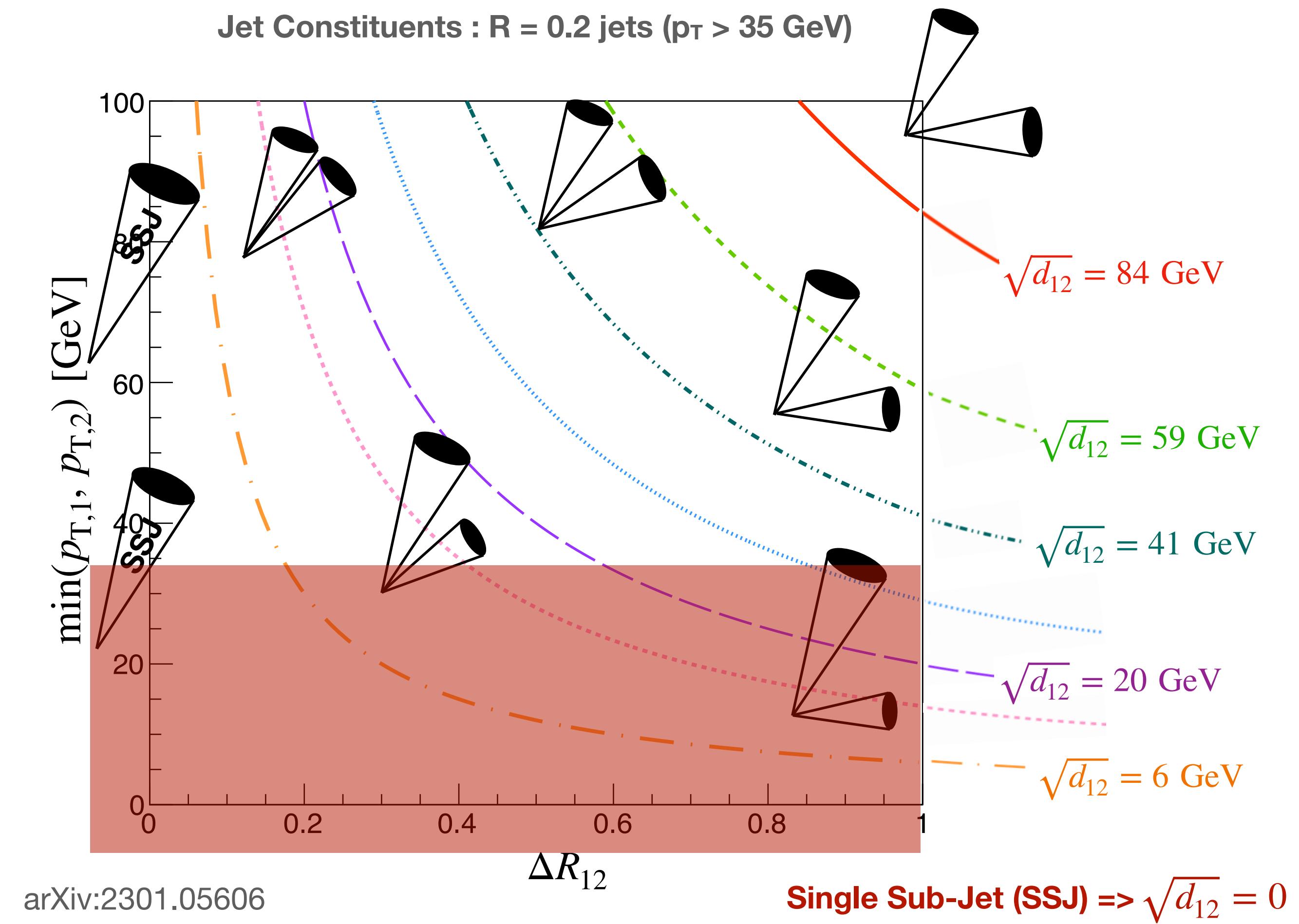
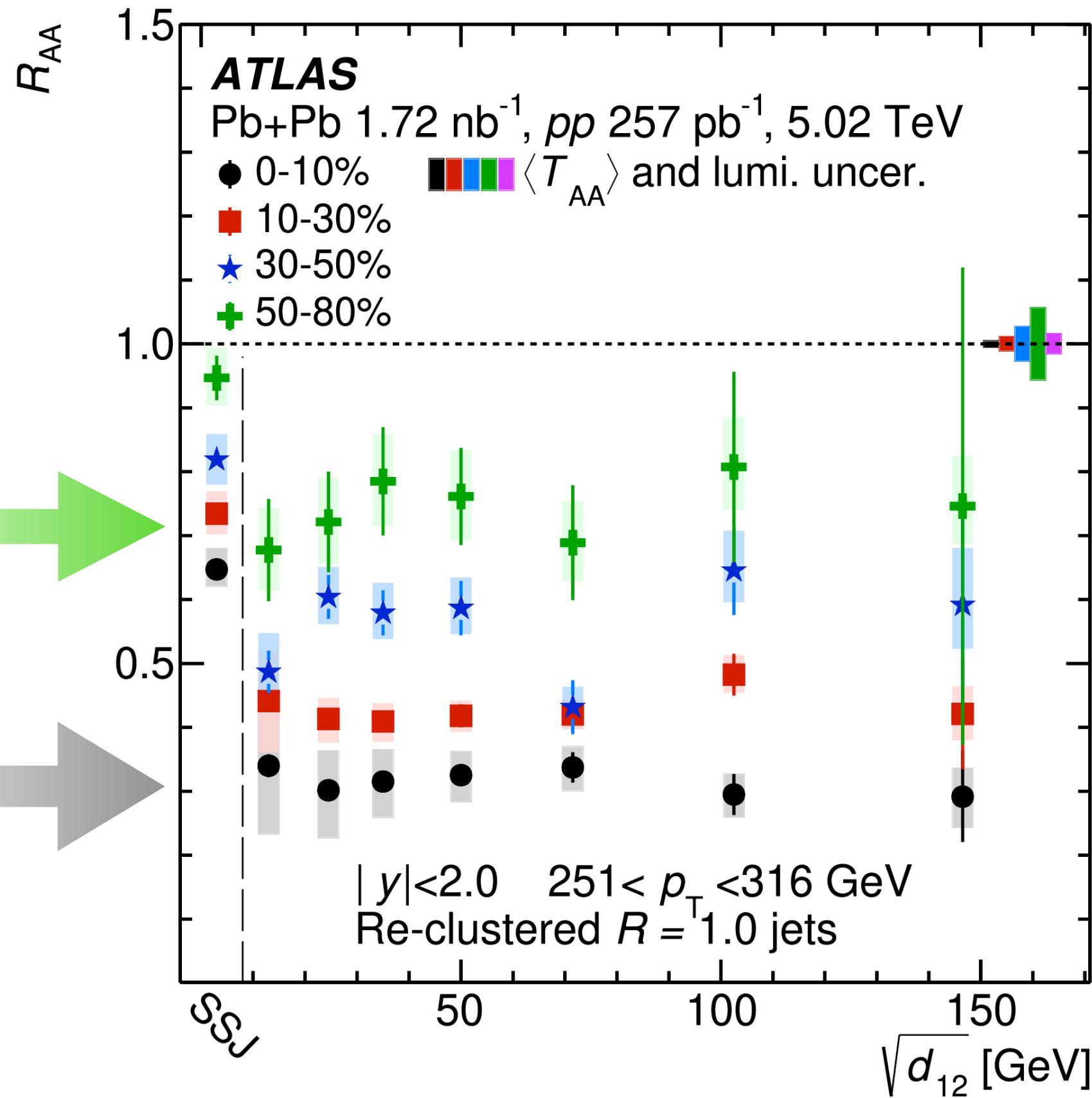


Jet Suppression vs. $\sqrt{d_{12}}$

- Suppression of large-radius jets in QGP characterized using its splitting scale $\sqrt{d_{12}}$

$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

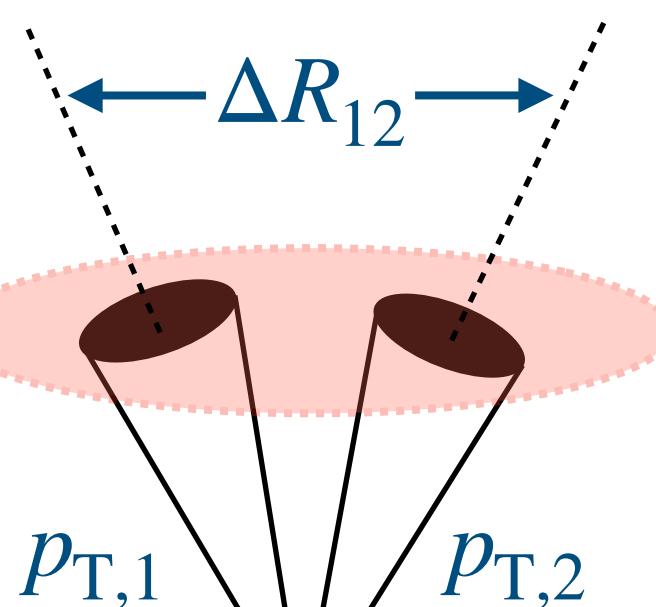
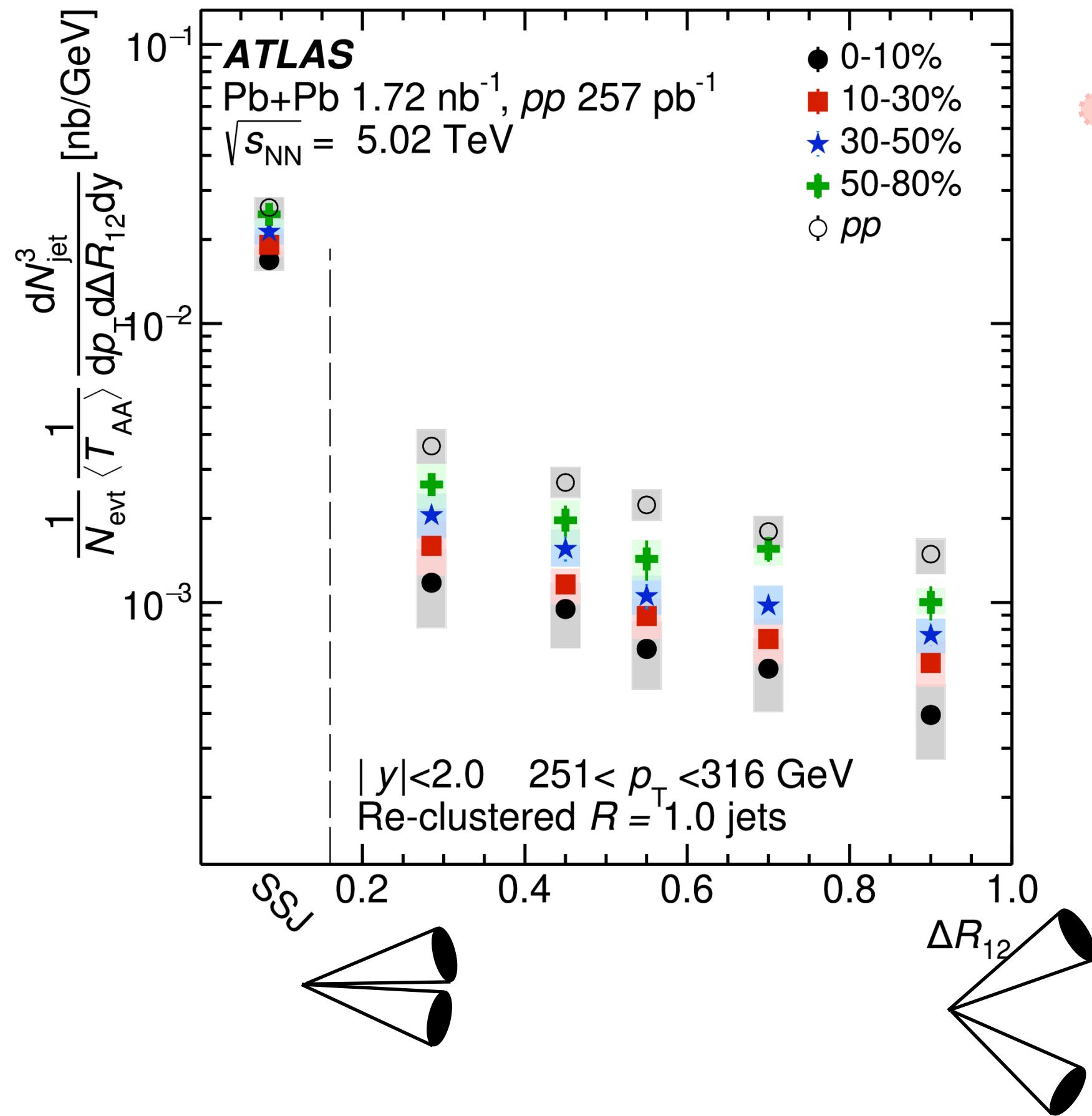
$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$



Jet Suppression vs. ΔR_{12}

- Two subjets from final k_T clustering step used in defining ΔR_{12}
- Suppression of large-radius jets in QGP characterized using its angular scale ΔR_{12}

$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

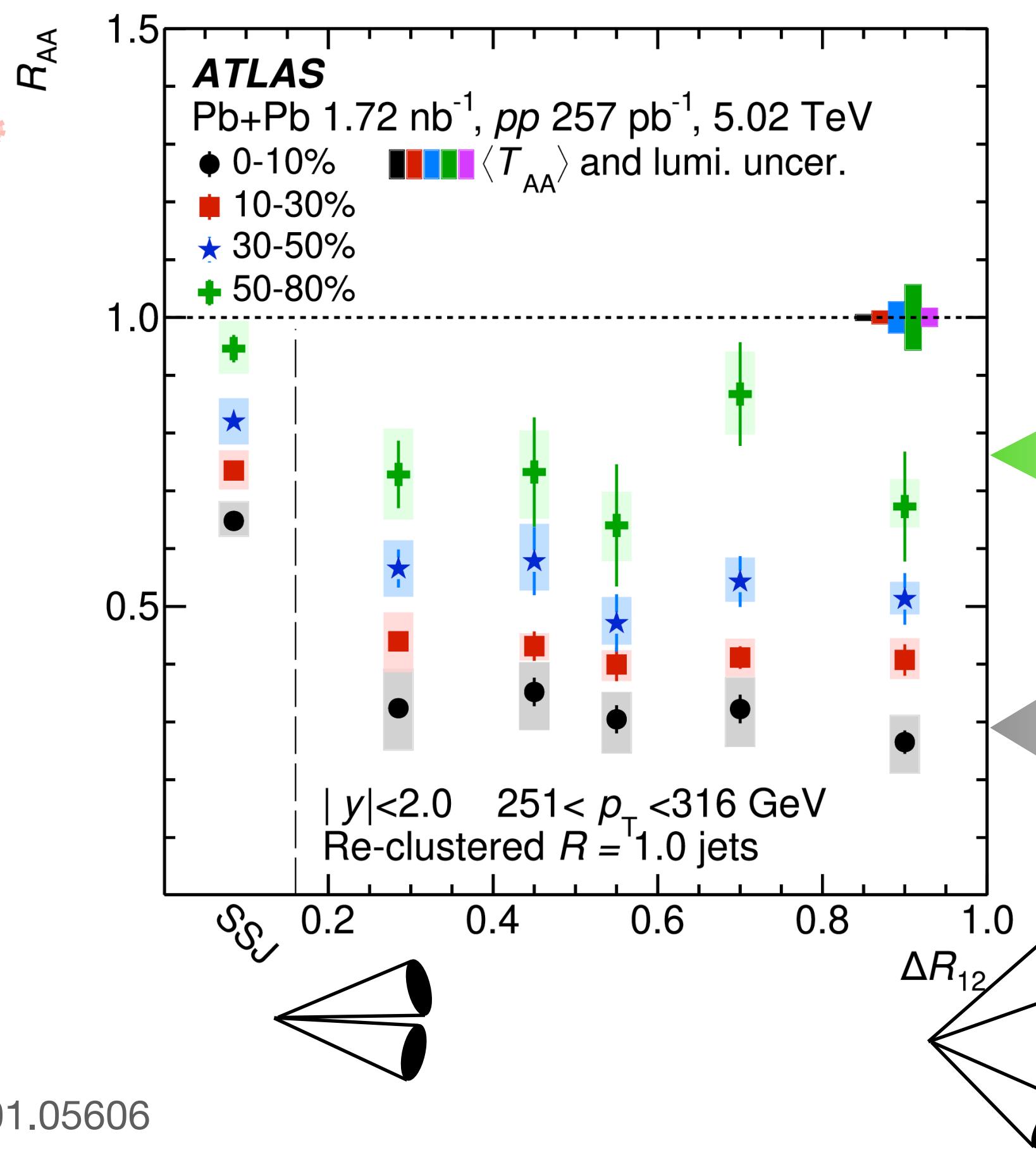
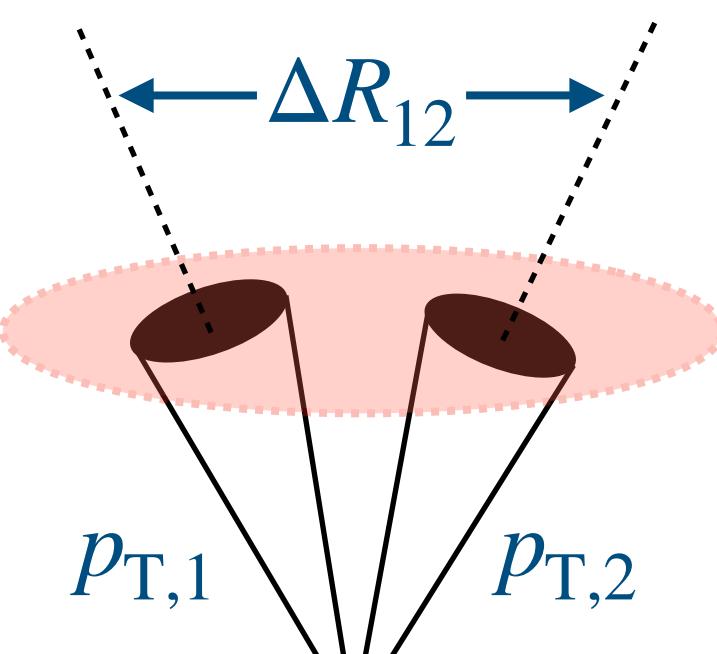
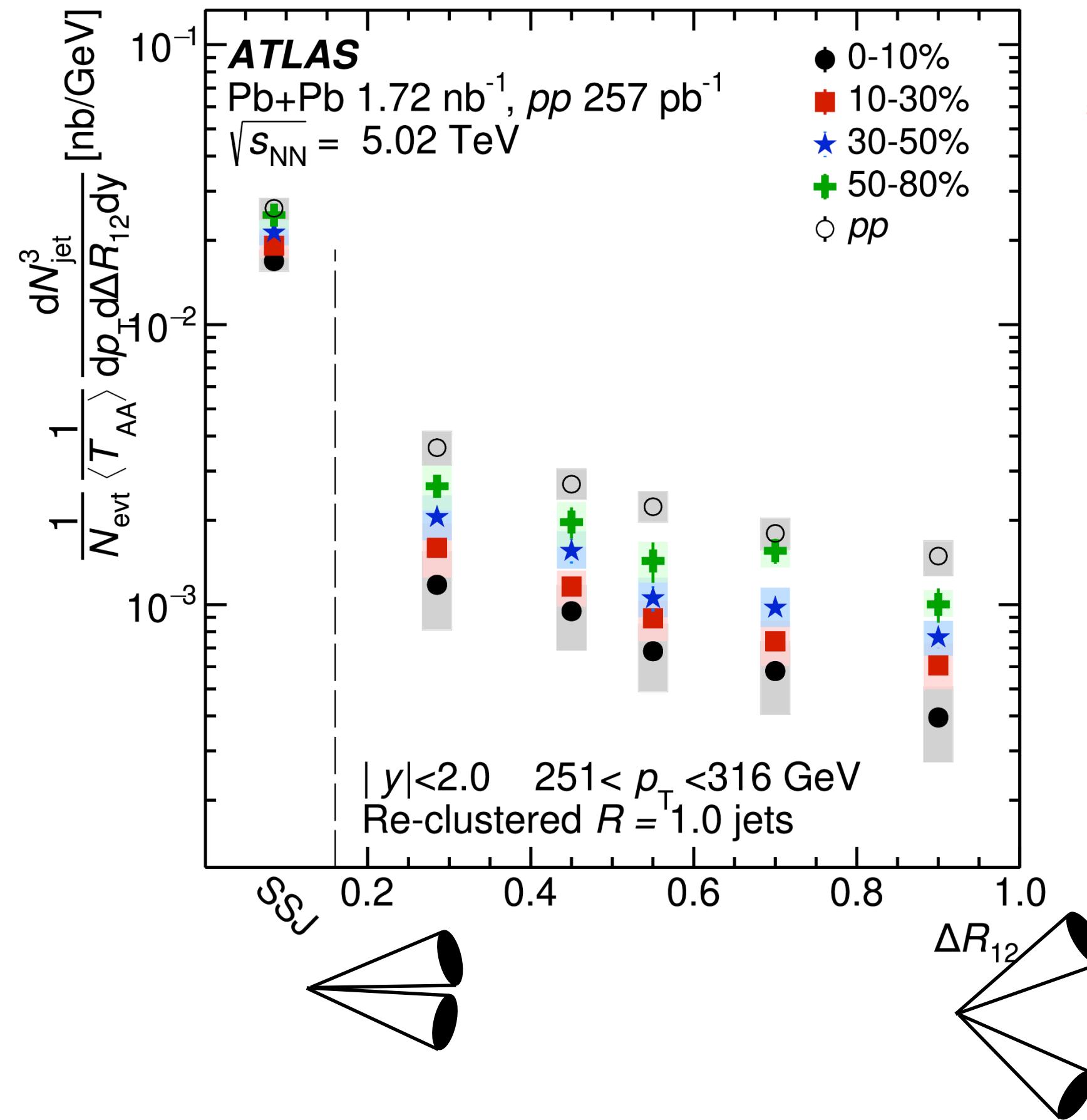


arXiv:2301.05606

Jet Suppression vs. ΔR_{12}

- Two subjets from final k_T clustering step used in defining ΔR_{12}
- Suppression of large-radius jets in QGP characterized using its angular scale ΔR_{12}

$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

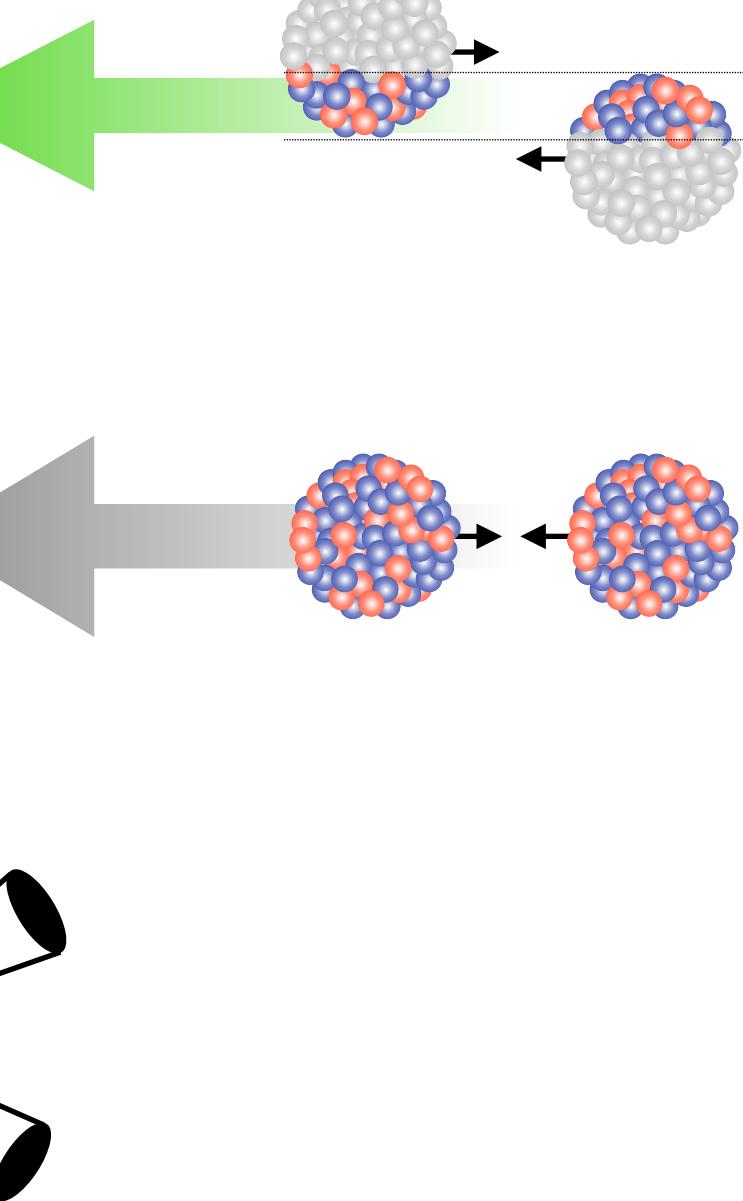
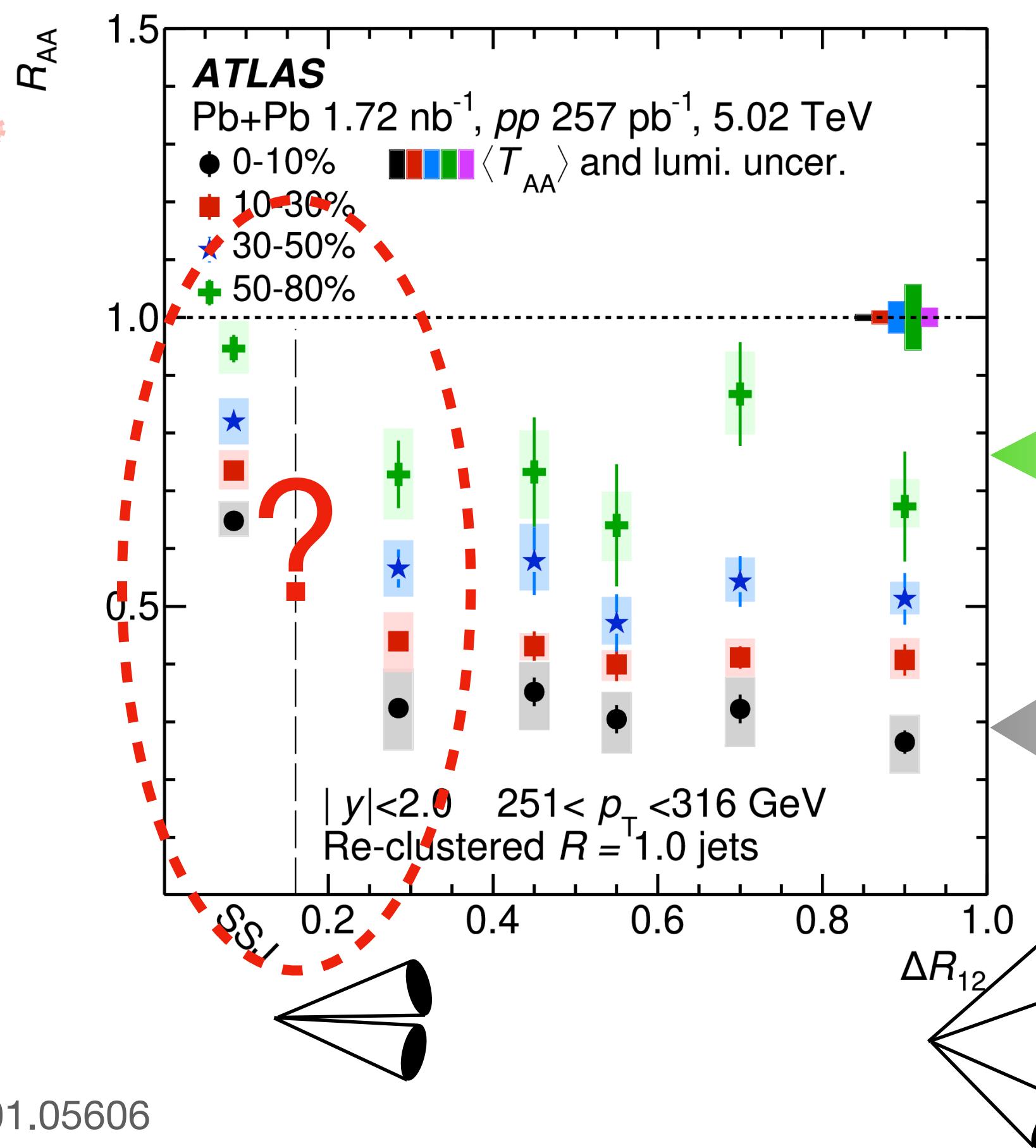
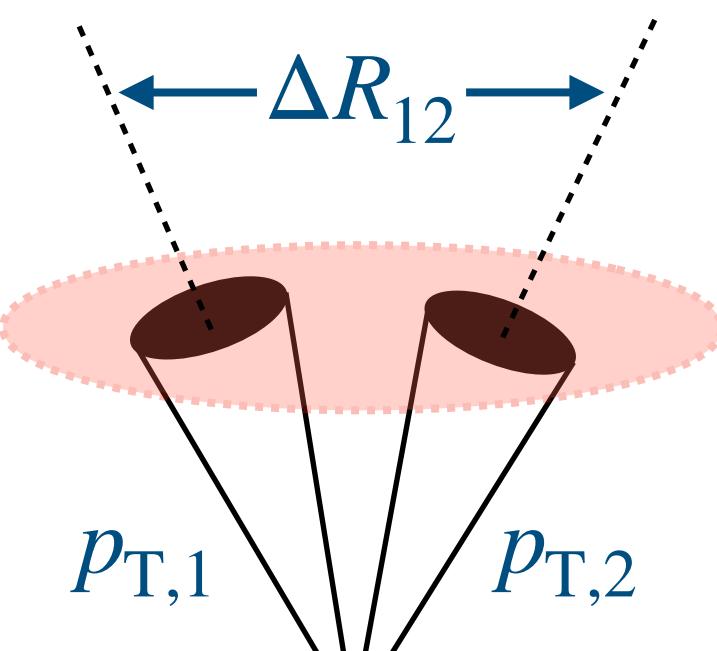
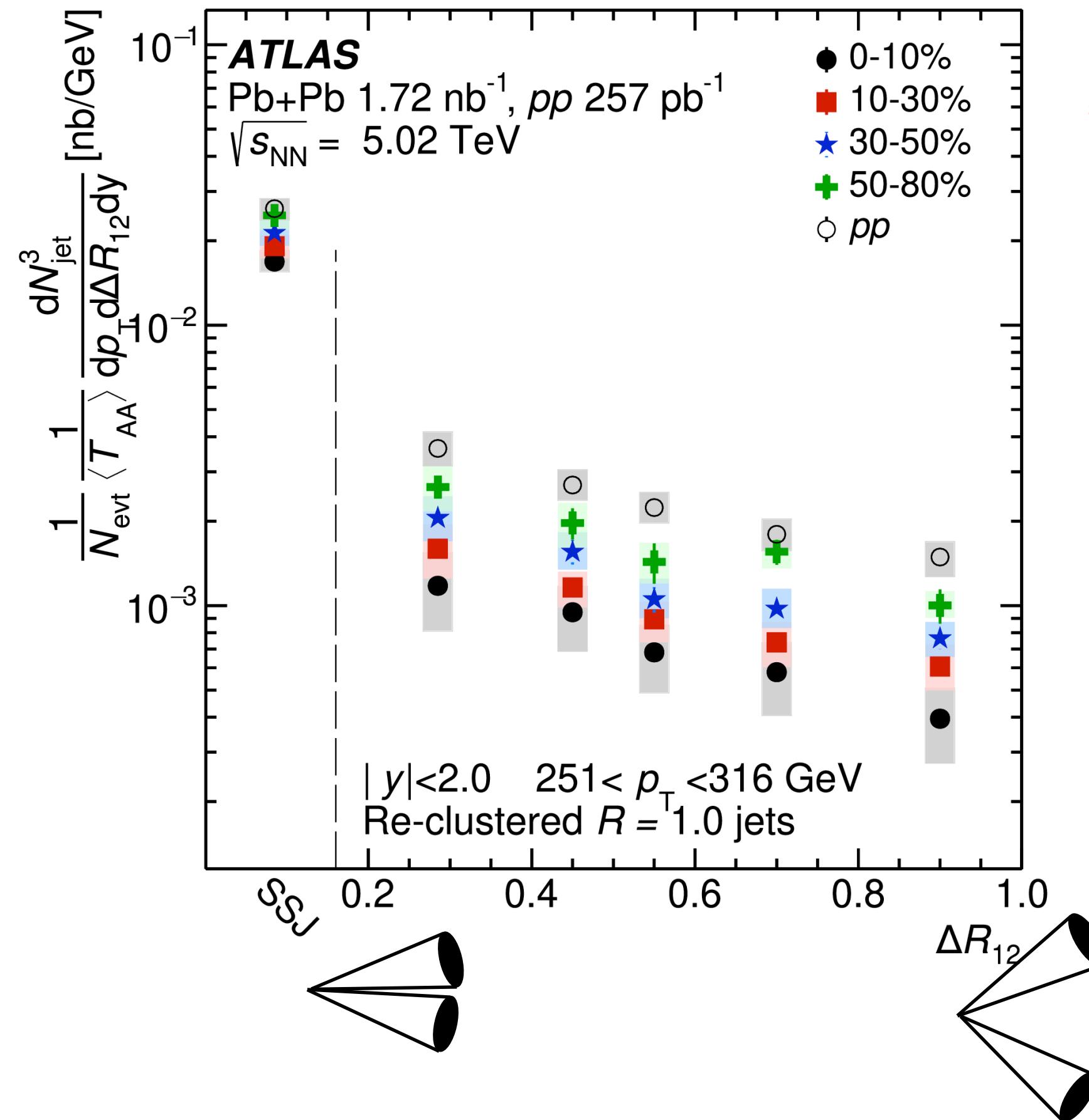


arXiv:2301.05606

Jet Suppression vs. ΔR_{12}

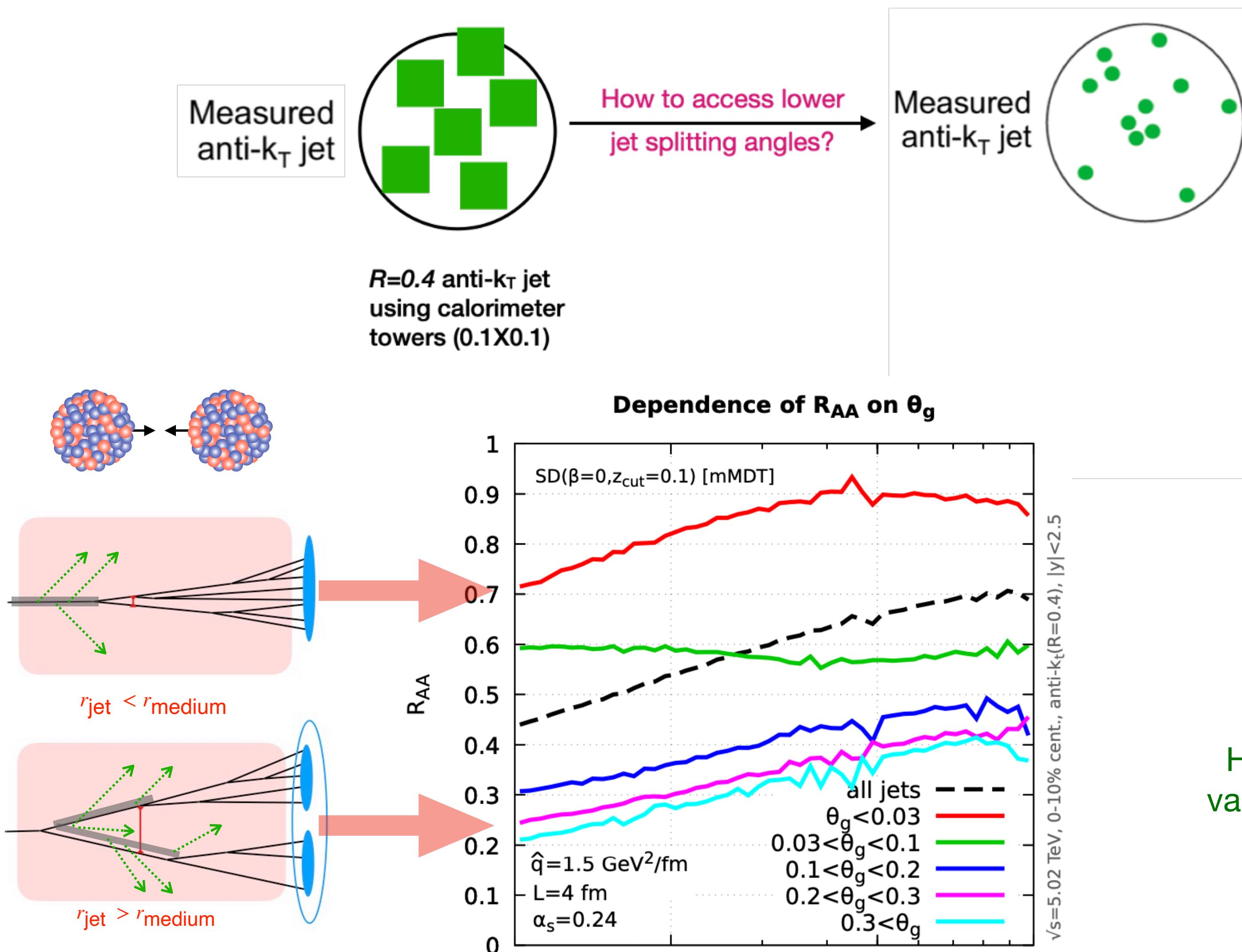
- Suppression of large-radius jets in QGP characterized using its angular scale ΔR_{12}
- Can we zoom into the low ΔR_{12} region to explore the (de)coherence effects?**

$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$



arXiv:2301.05606

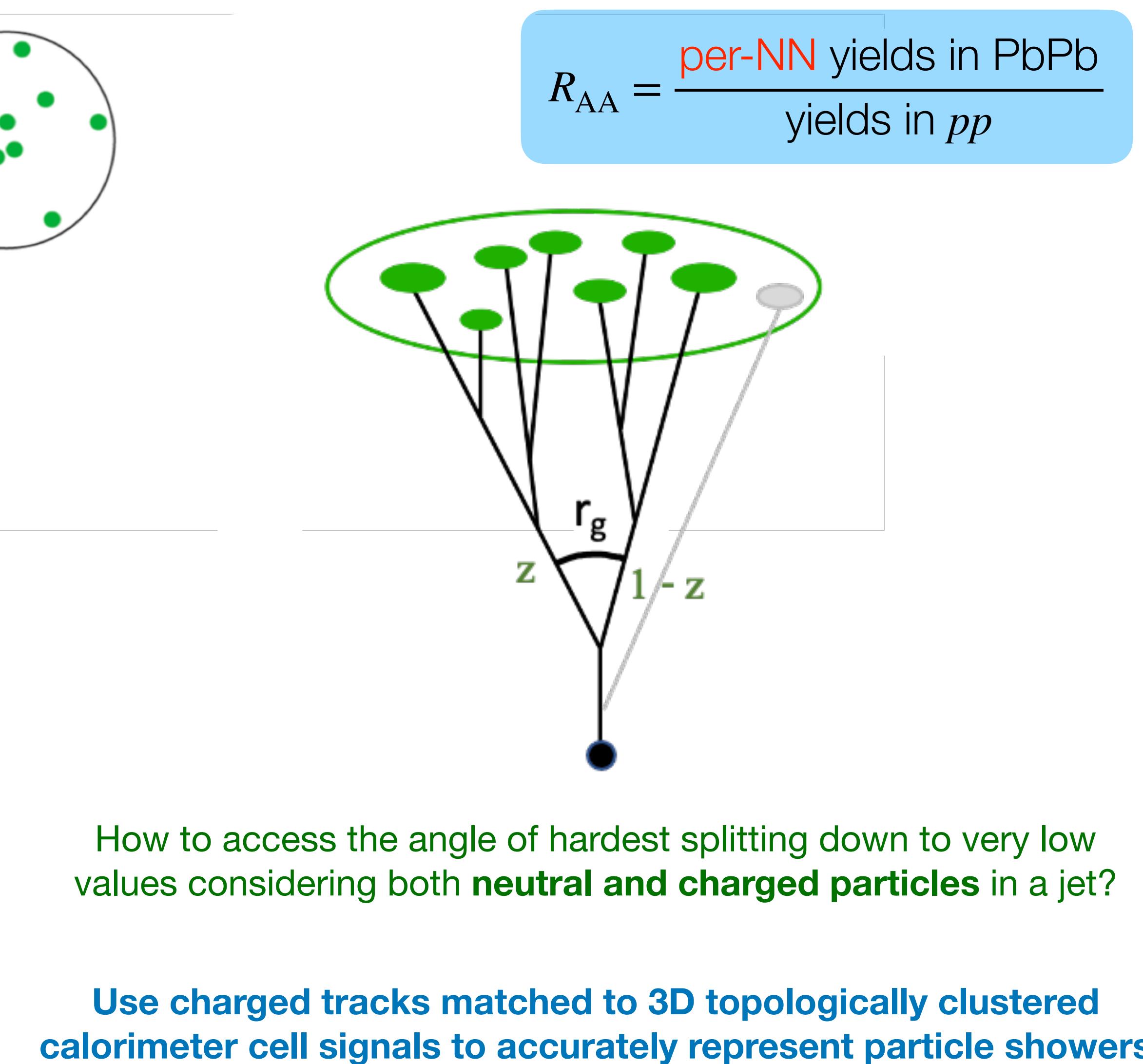
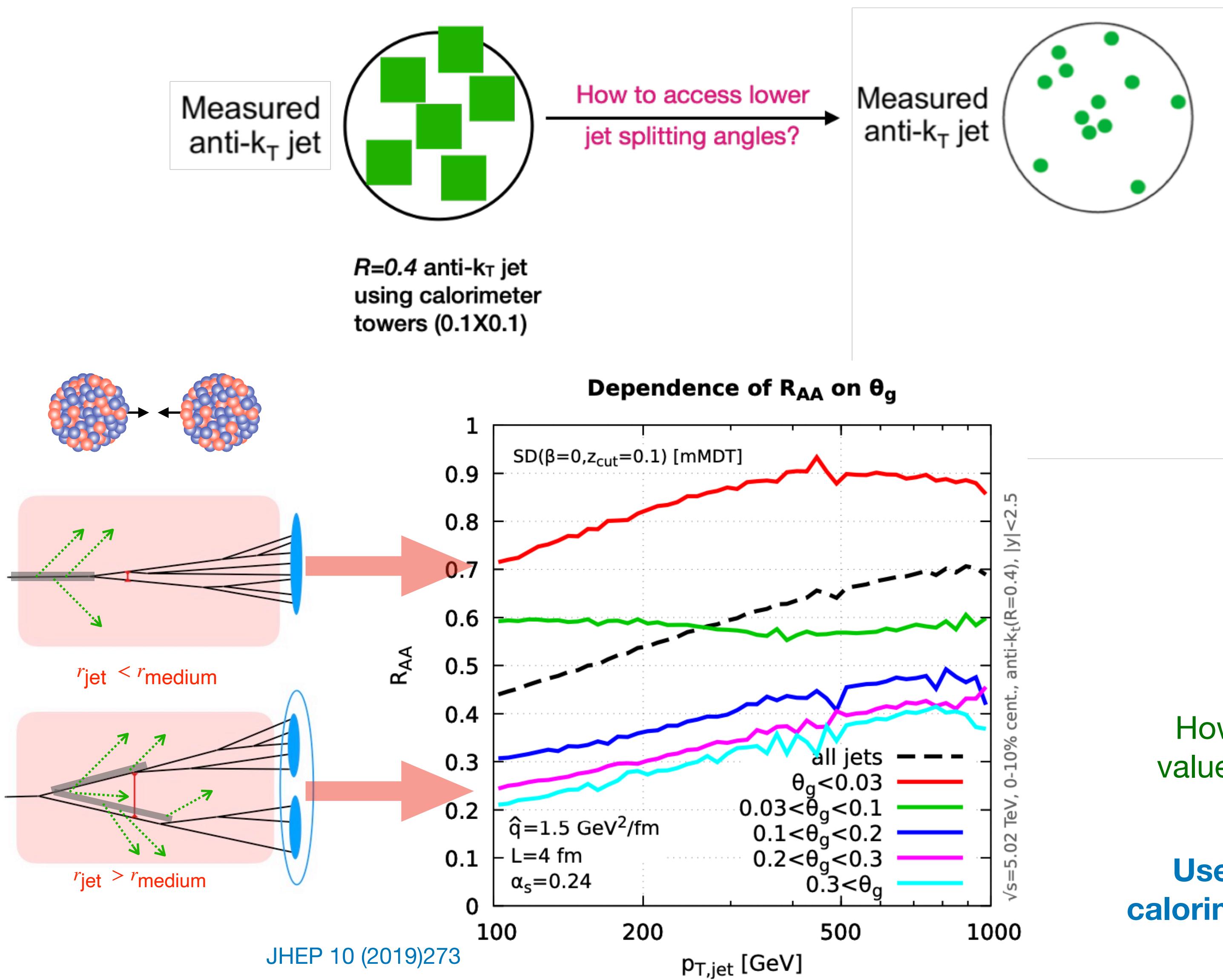
Hardest splitting in a Jet



$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

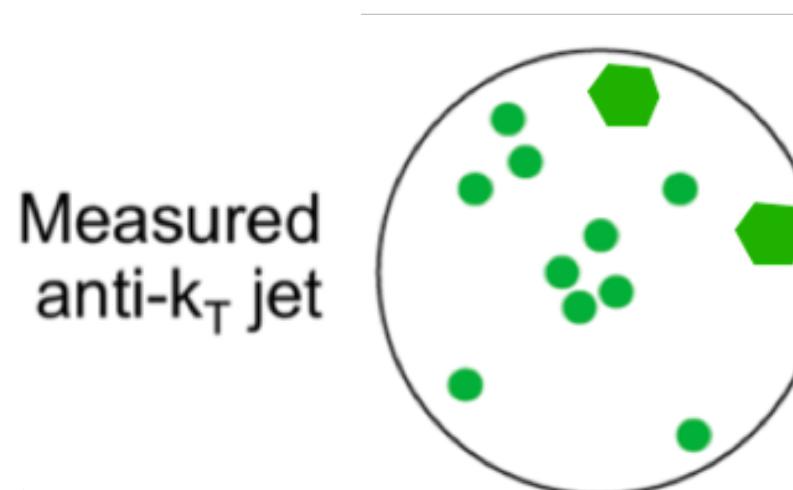
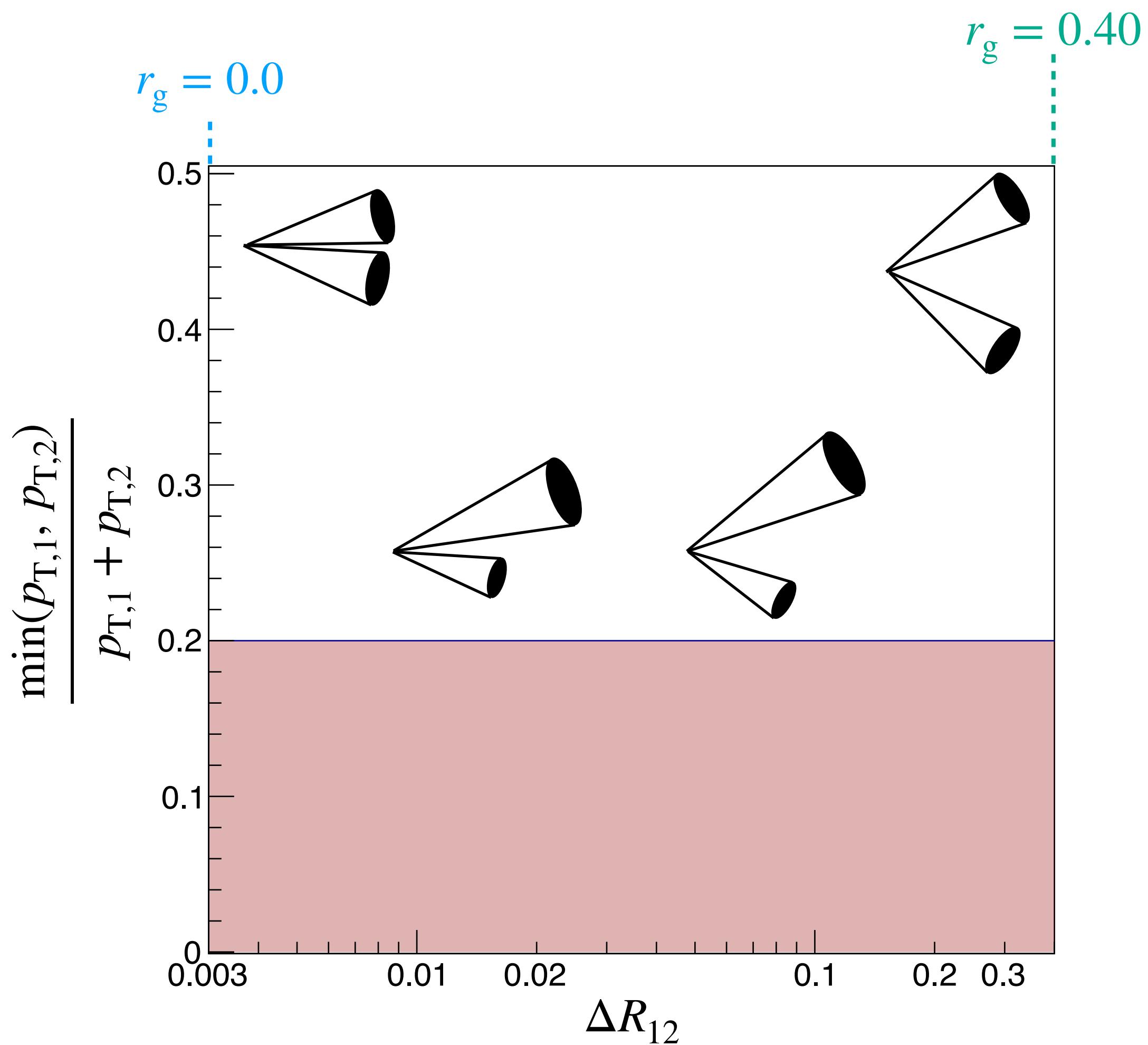
How to access the angle of hardest splitting down to very low values considering both **neutral and charged particles** in a jet?

Hardest splitting in a Jet

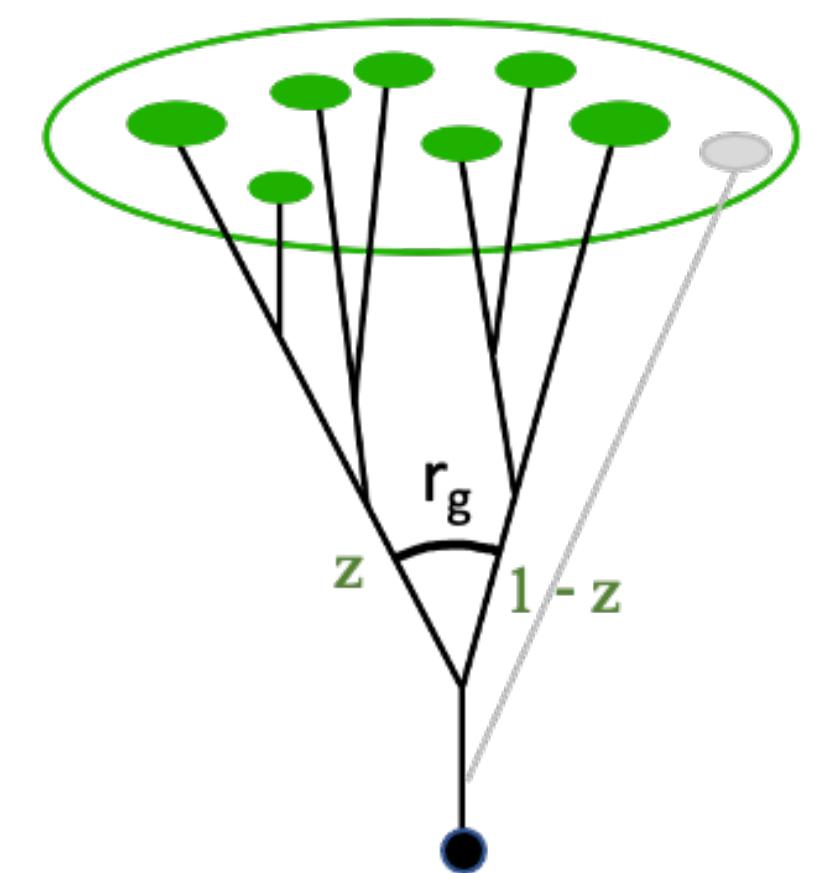


Soft-Drop and r_g

- Characterize a jet using the angular separation of its **hardest splitting** (r_g)

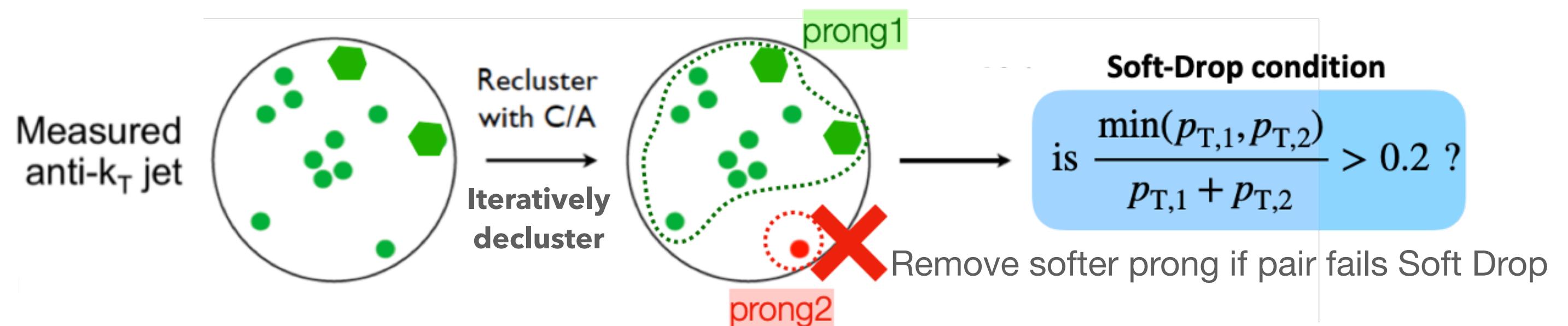
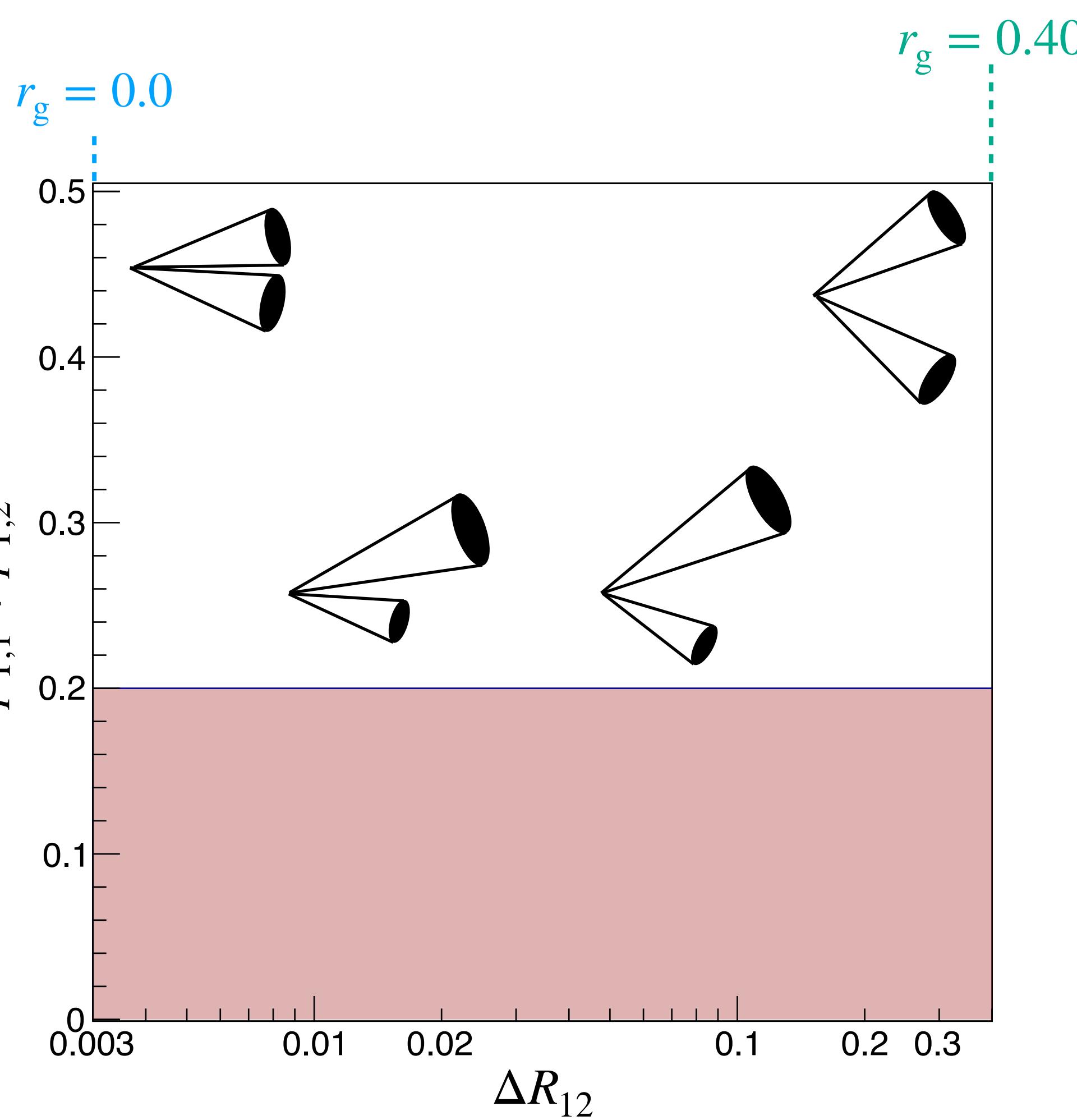


How to optimally tag the hardest splitting of a jet while not biasing the jet populations?

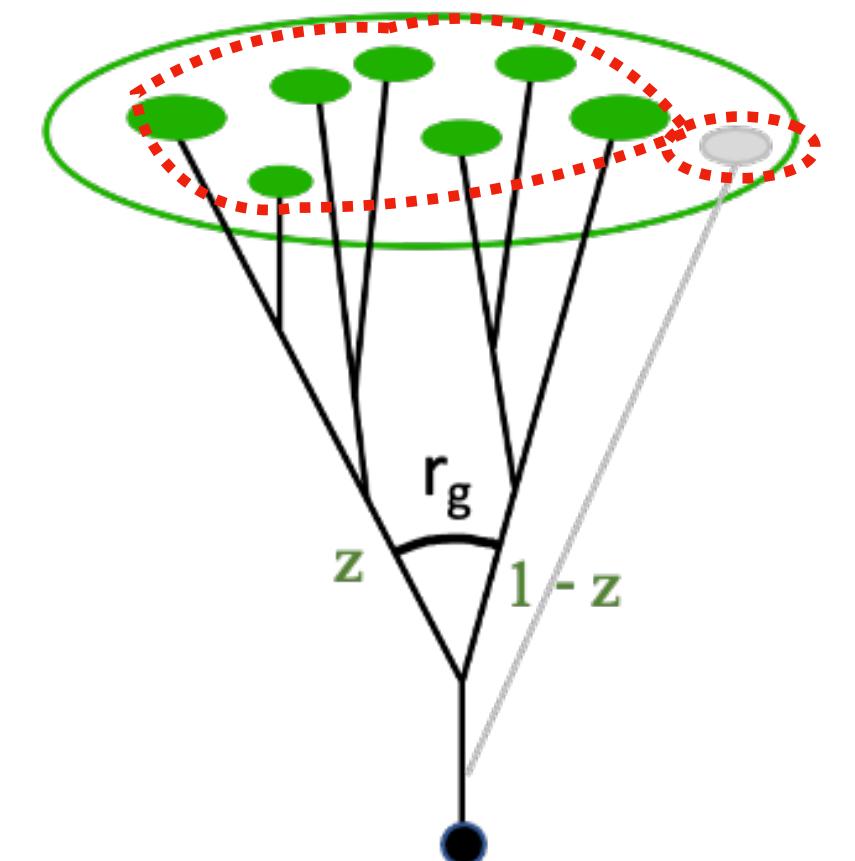


Soft-Drop and r_g

- Characterize a jet using the angular separation of its **hardest splitting** (r_g)

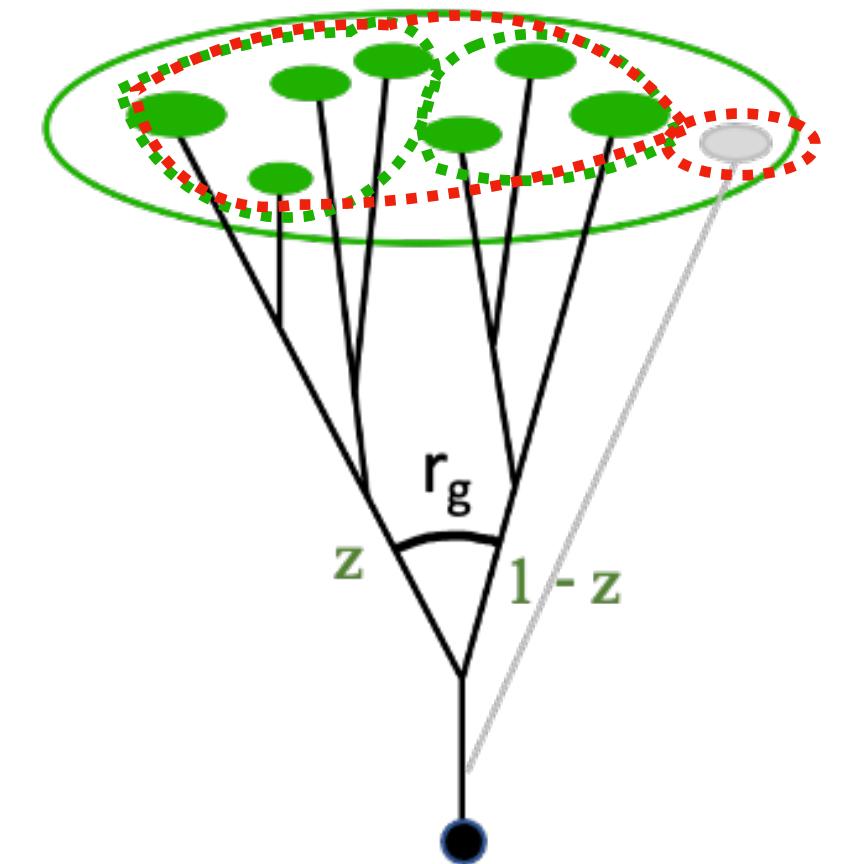
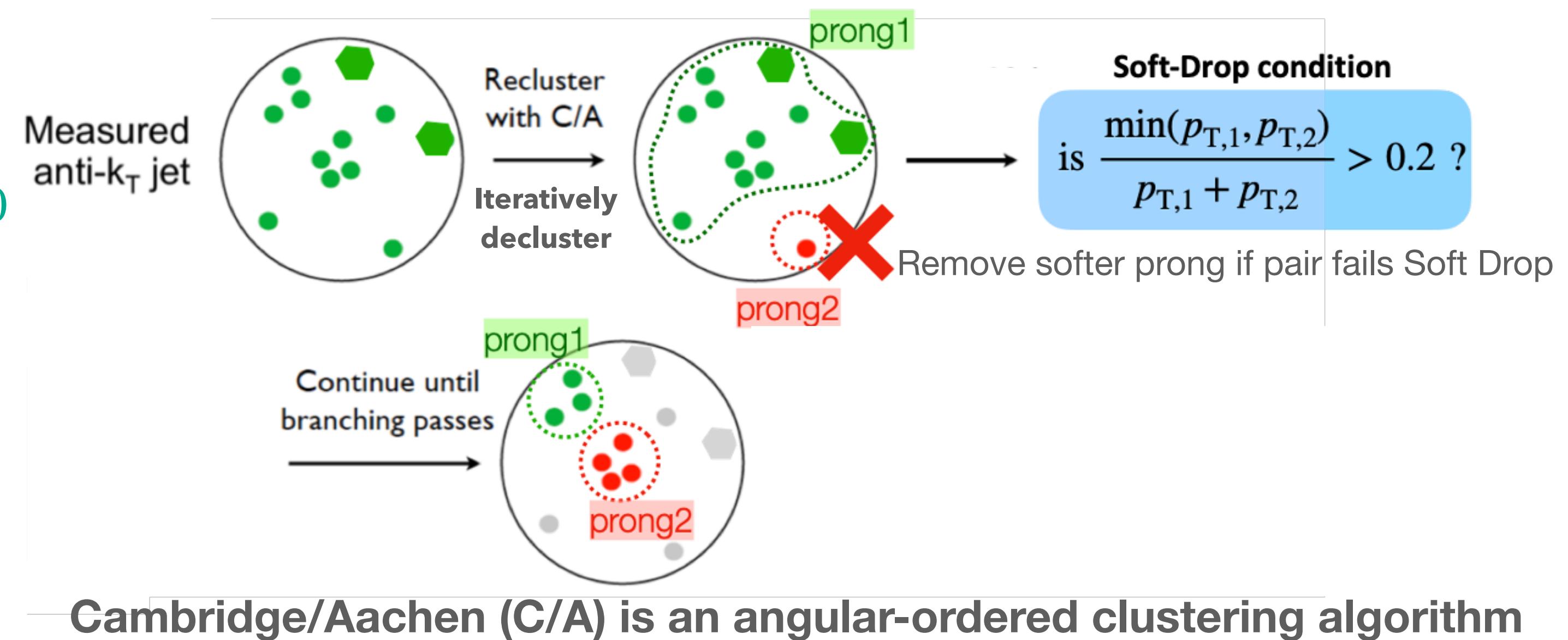
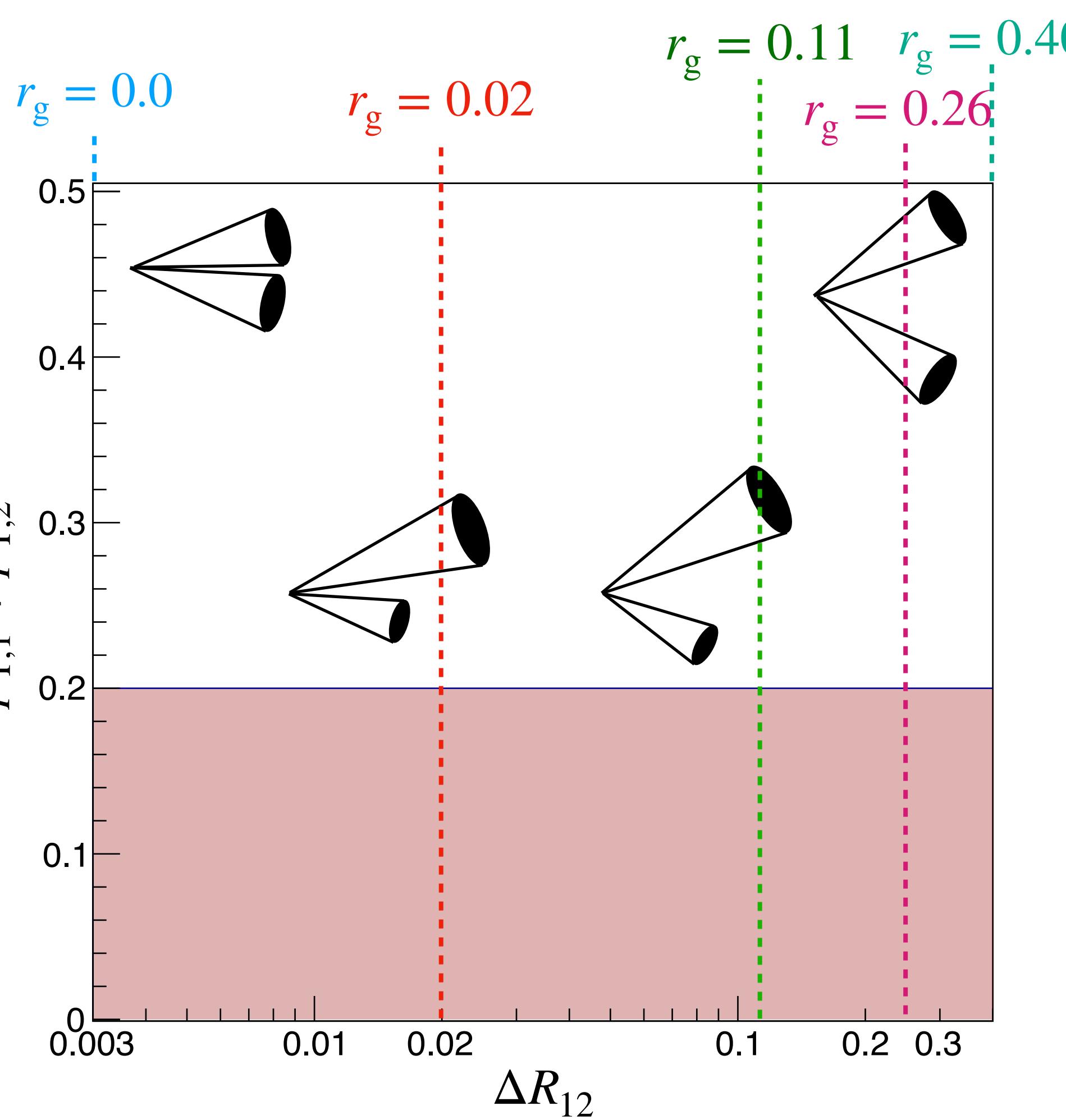


Cambridge/Aachen (C/A) is an angular-ordered clustering algorithm



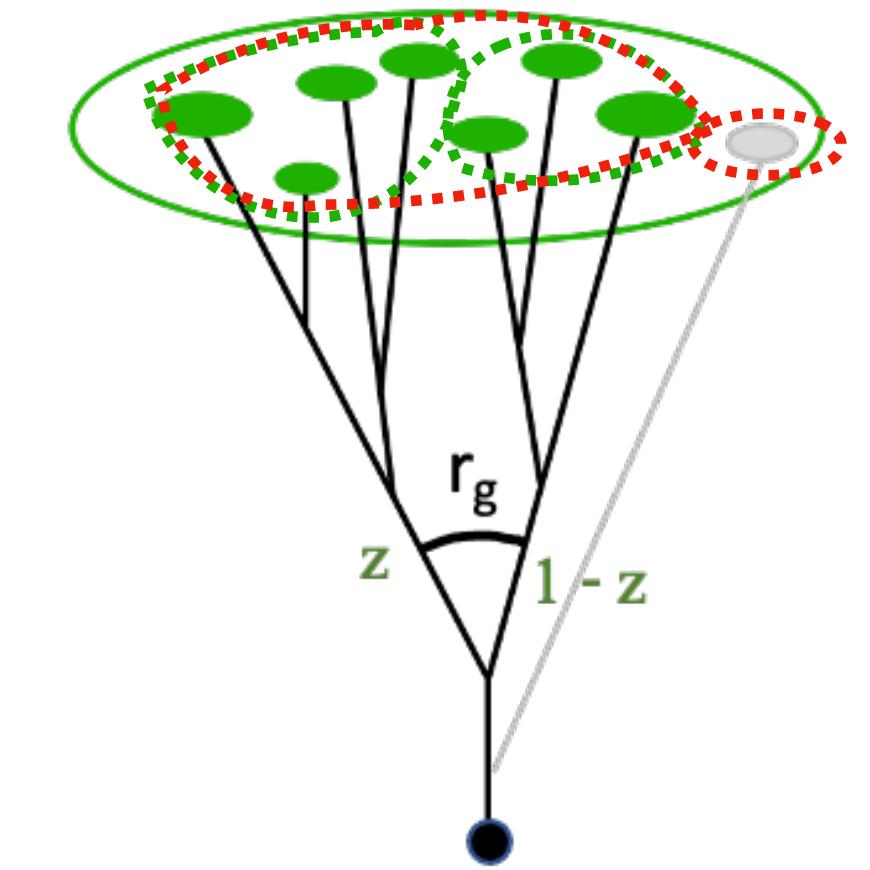
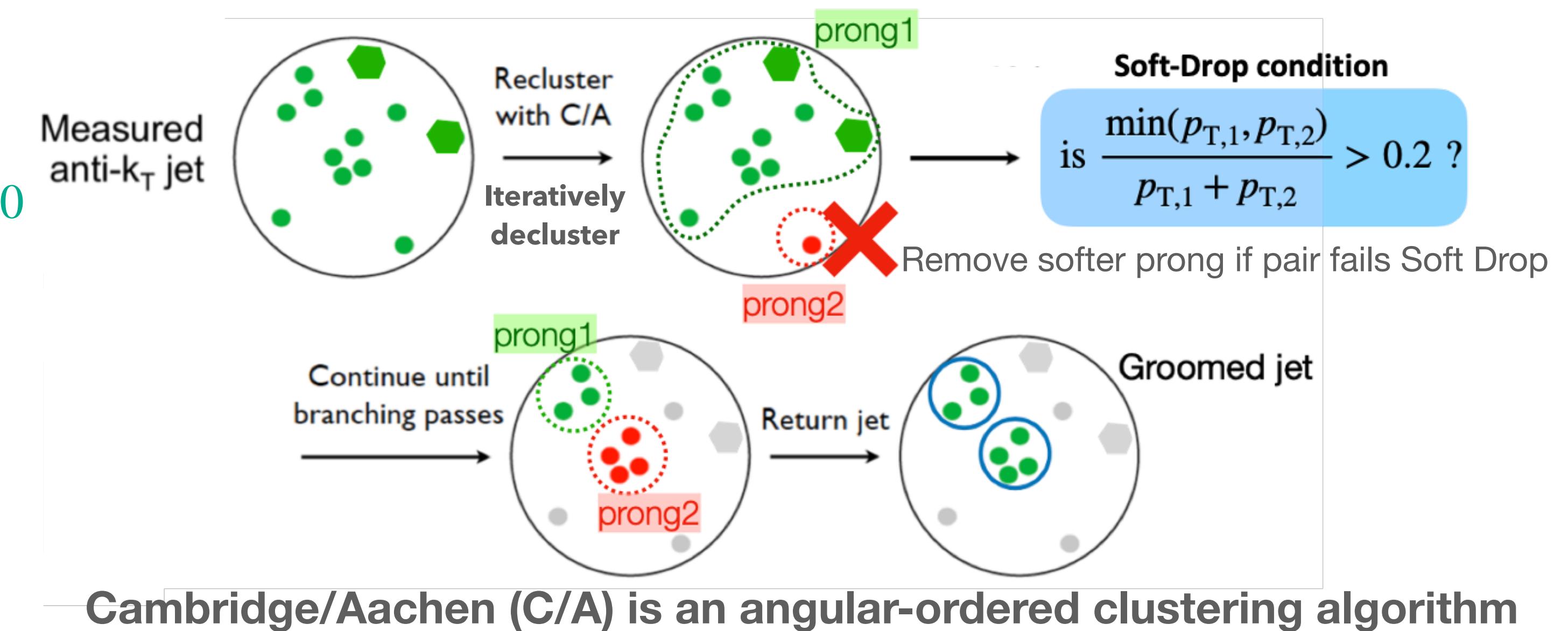
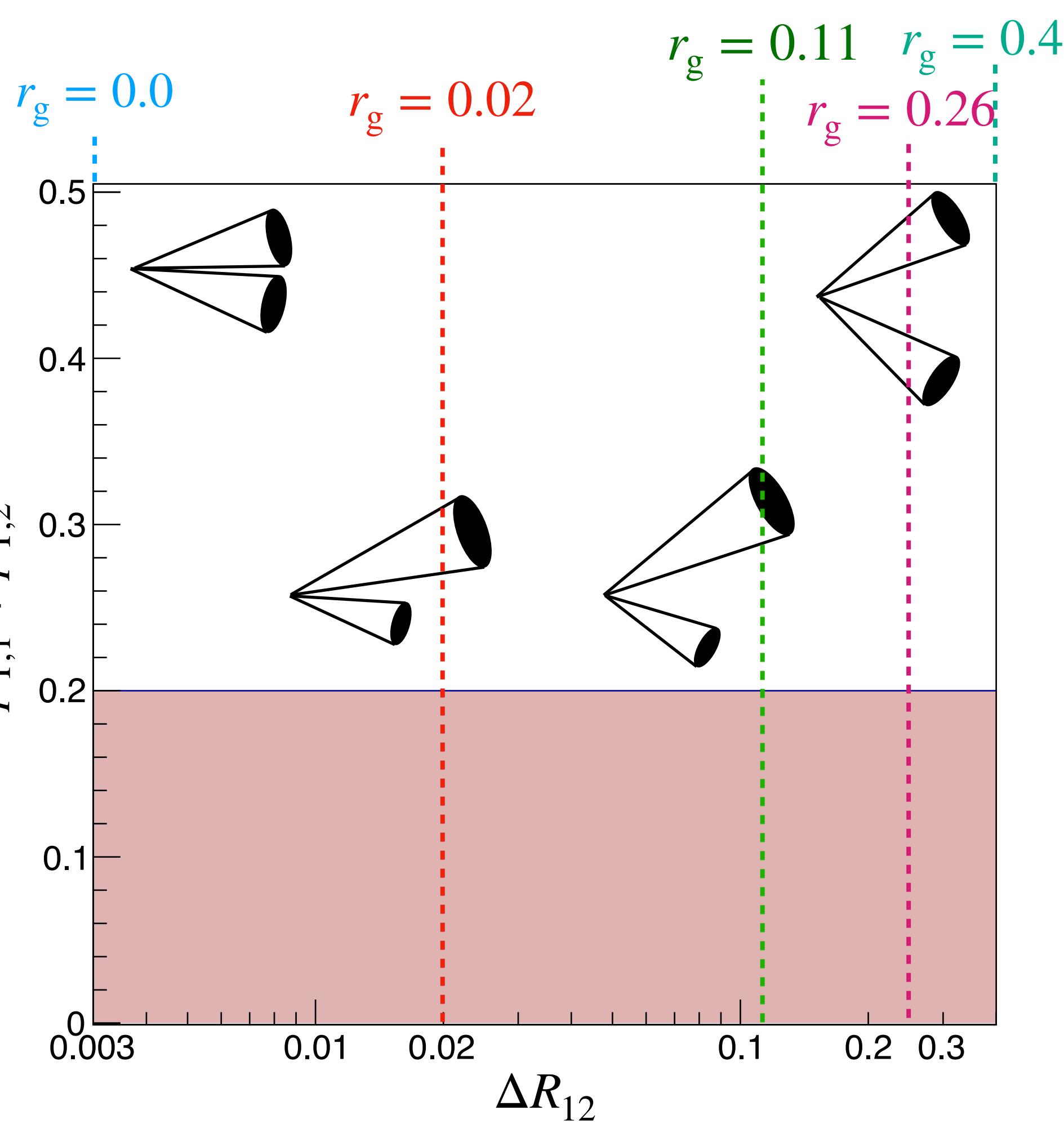
Soft-Drop and r_g

- Characterize a jet using the angular separation of its **hardest splitting** (r_g)



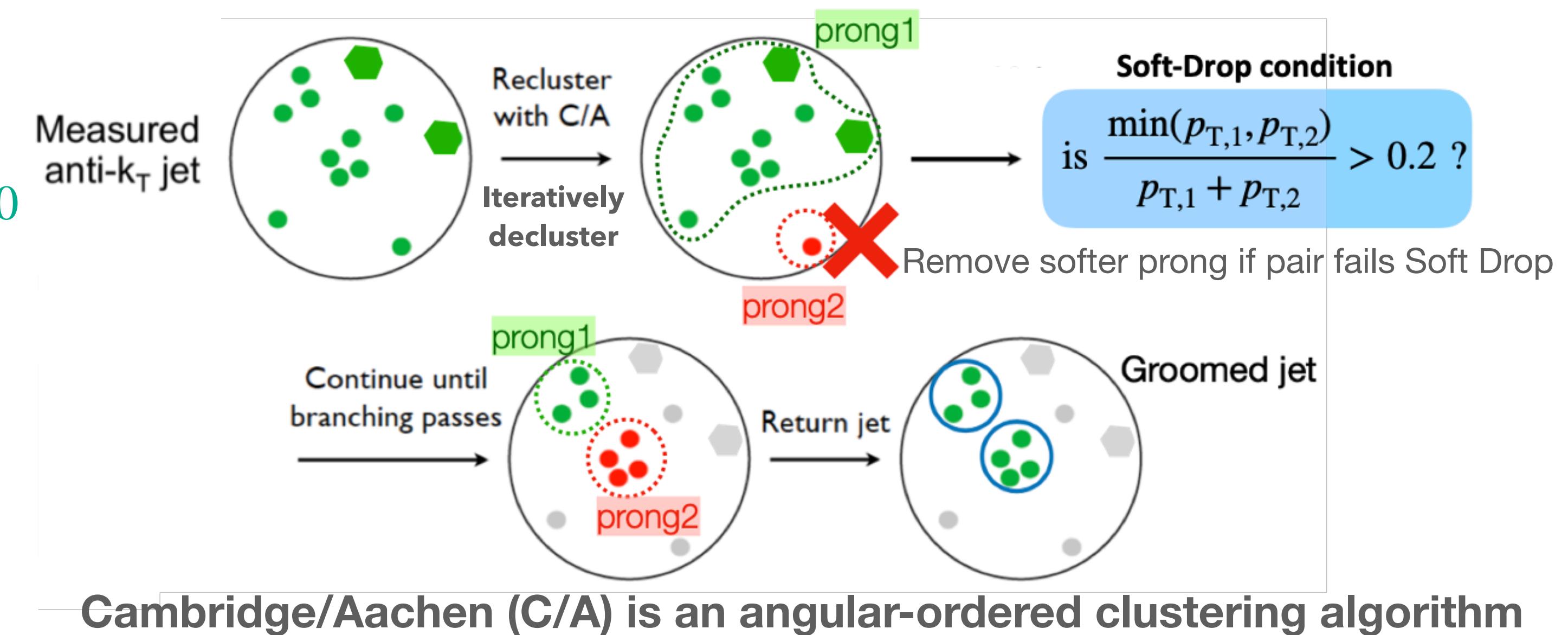
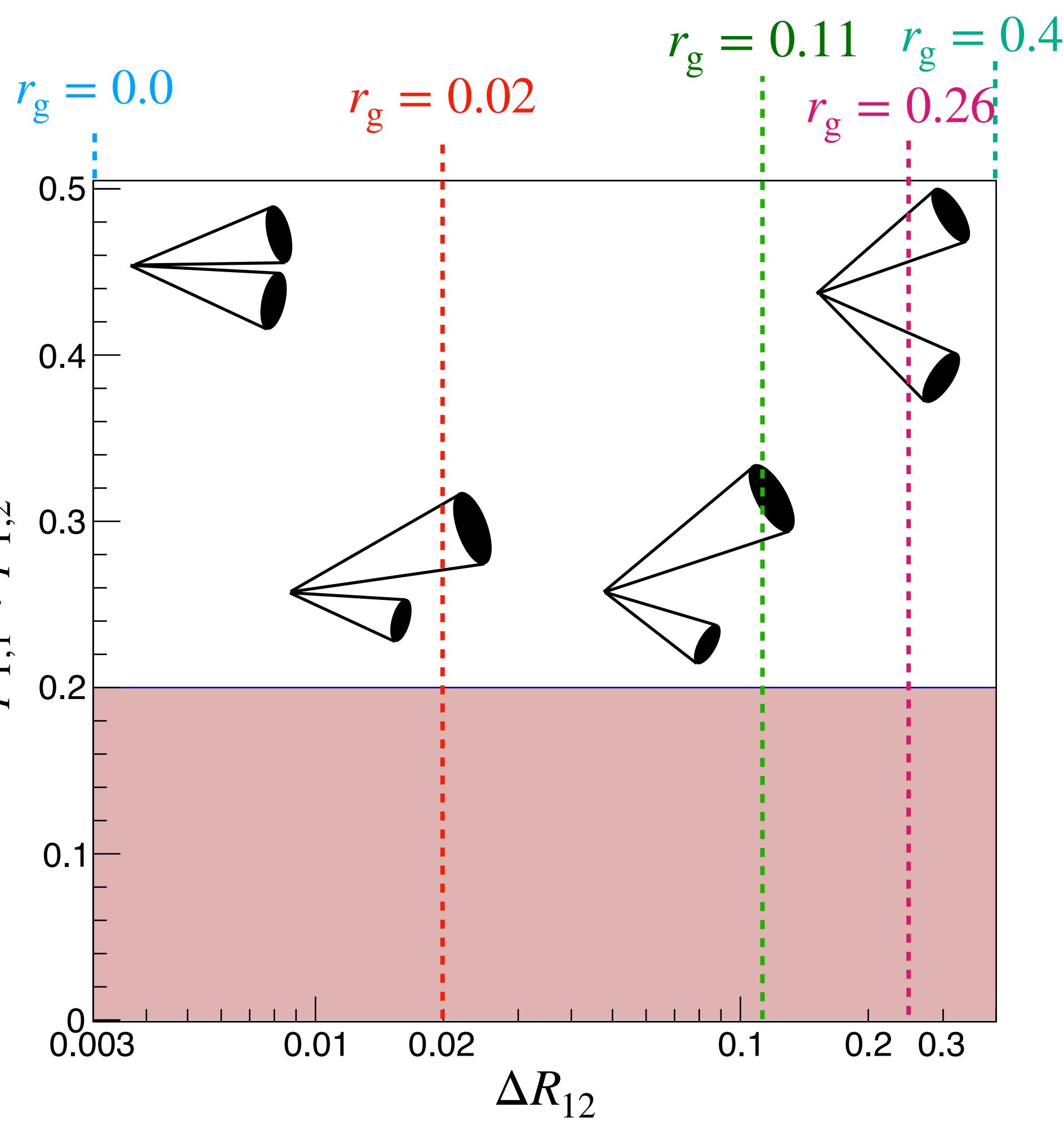
Soft-Drop and r_g

- Characterize a jet using the angular separation of its **hardest splitting** (r_g)

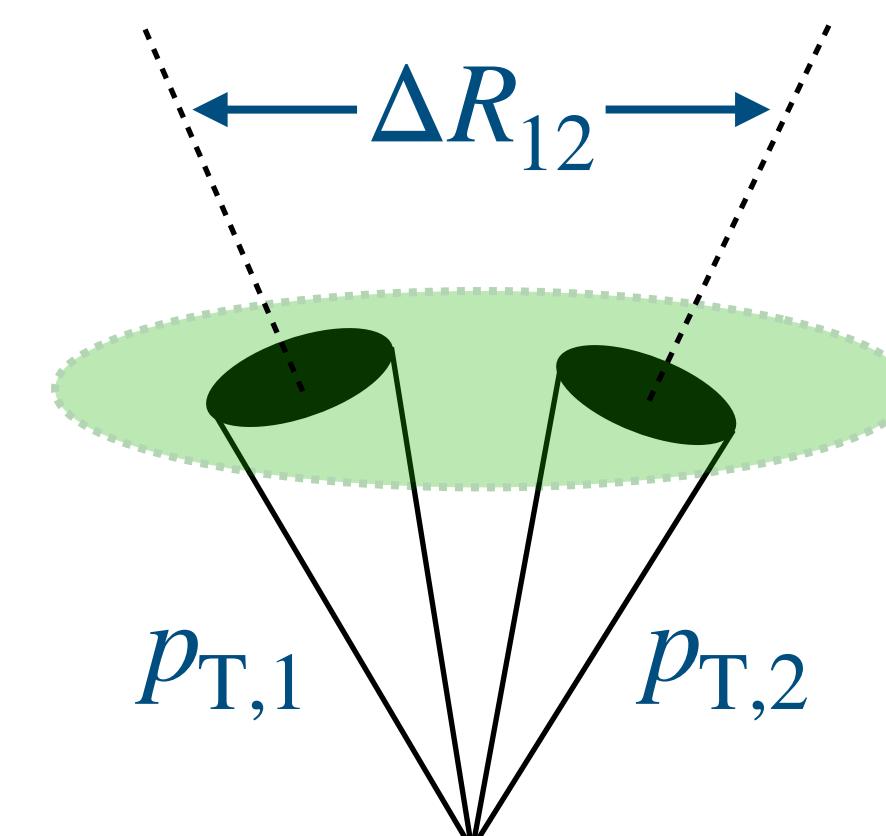


Soft-Drop and r_g

- Characterize a jet using the angular separation of its **hardest splitting** (r_g)



Cambridge/Aachen (C/A) is an angular-ordered clustering algorithm

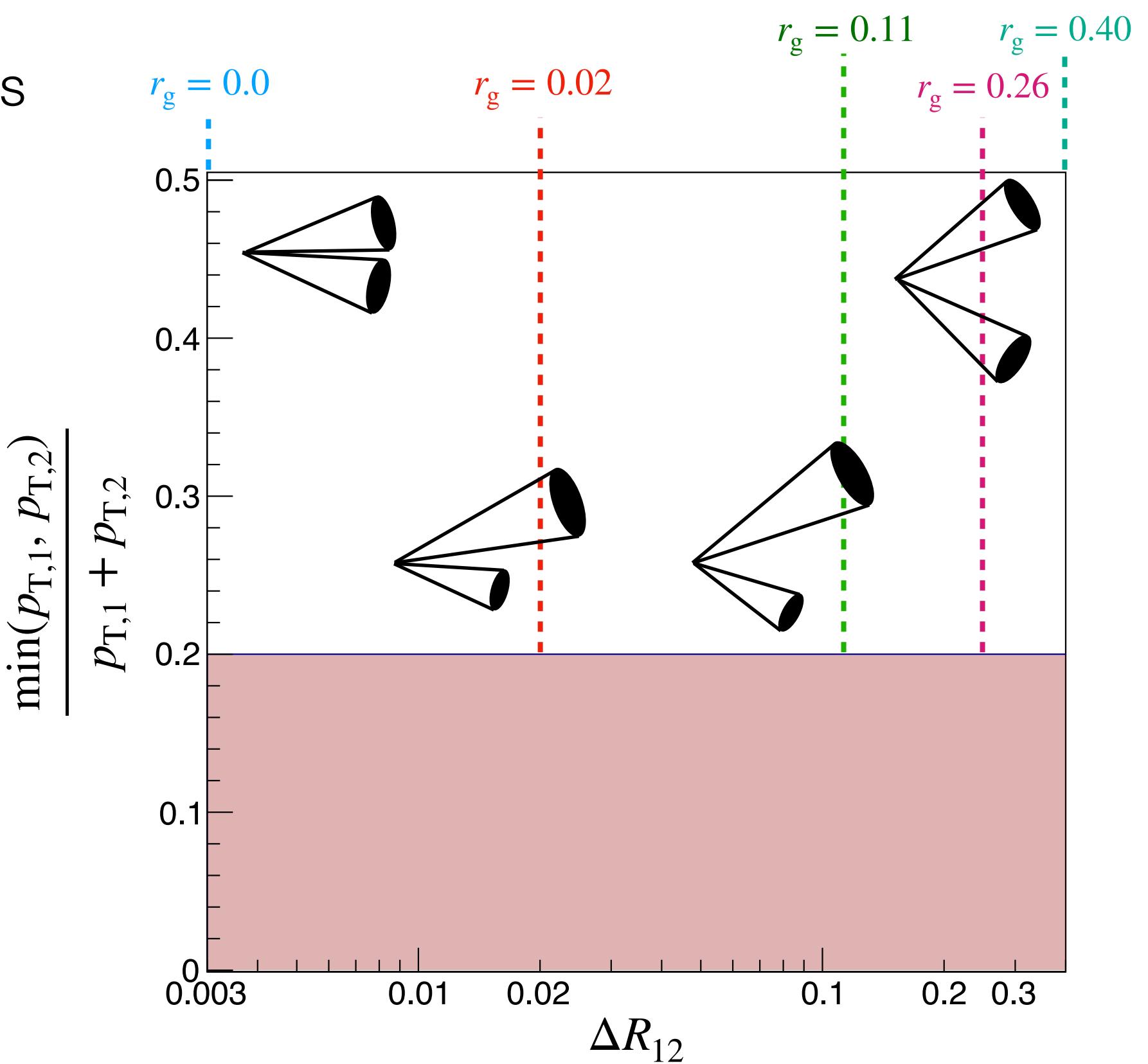
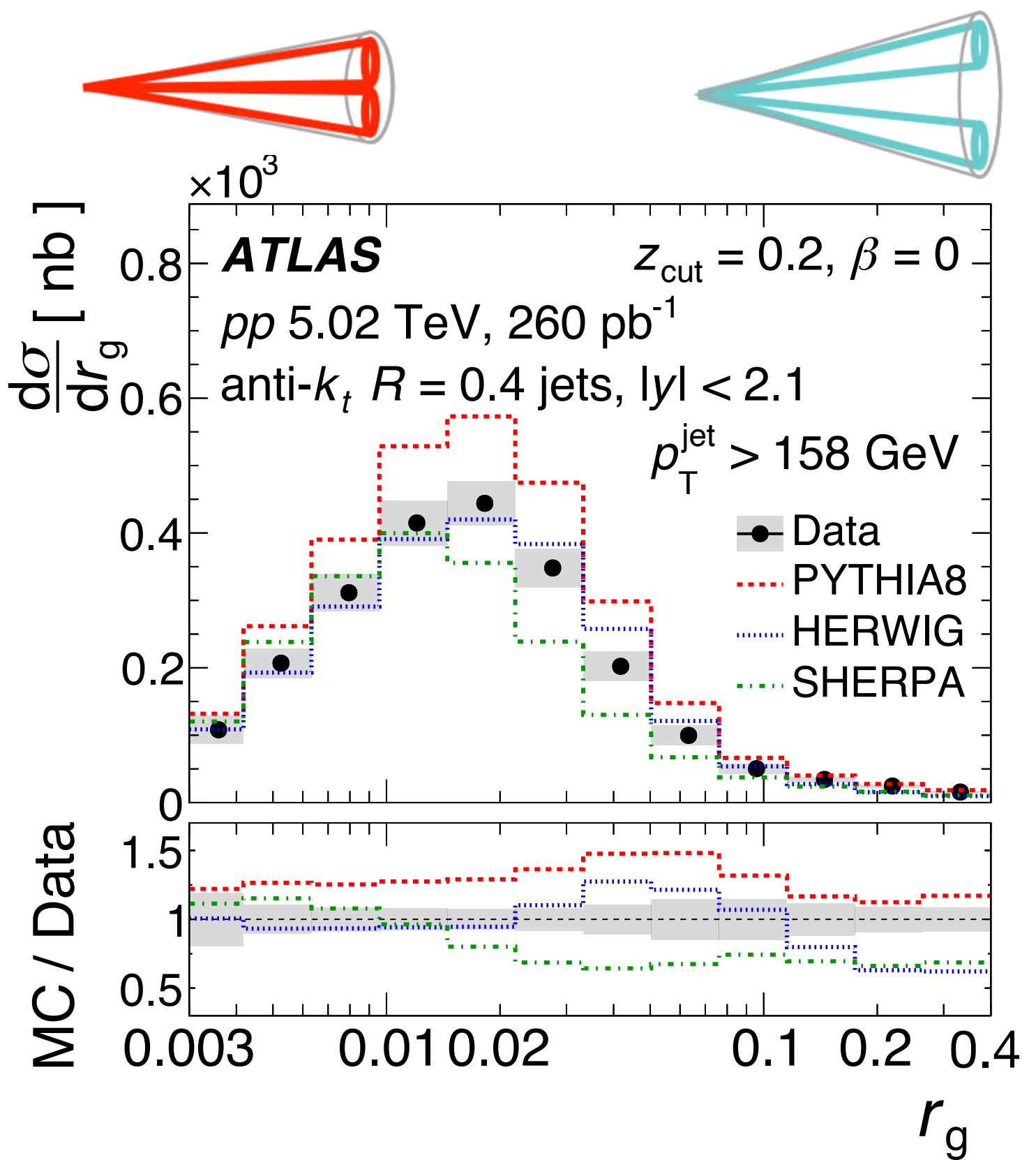


r_g is ΔR_{12} between subjets when above SD condition is satisfied

$$r_g = \Delta R_{12} \text{ when } \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > 0.2$$

Unfolded jet p_T & r_g distributions

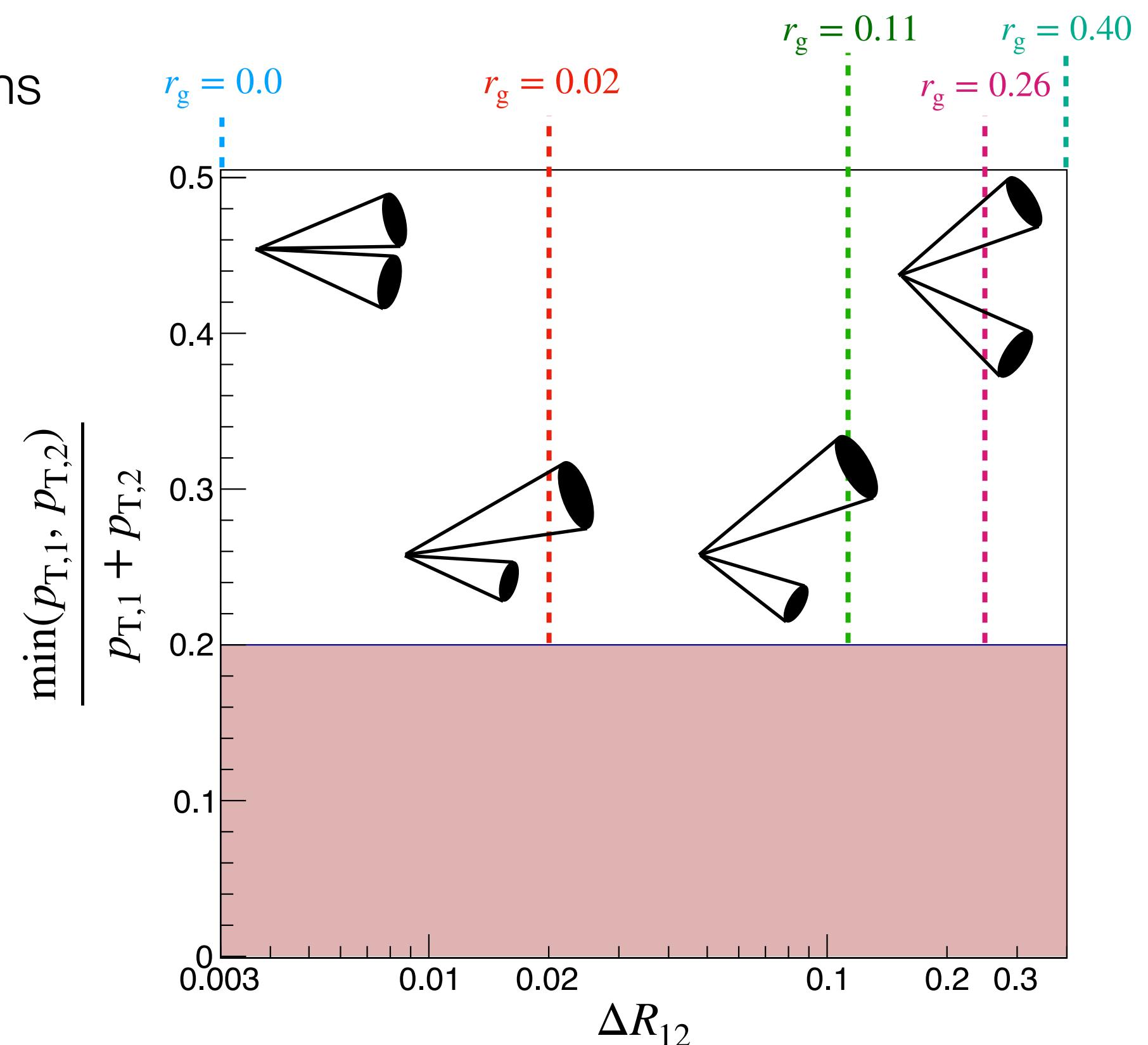
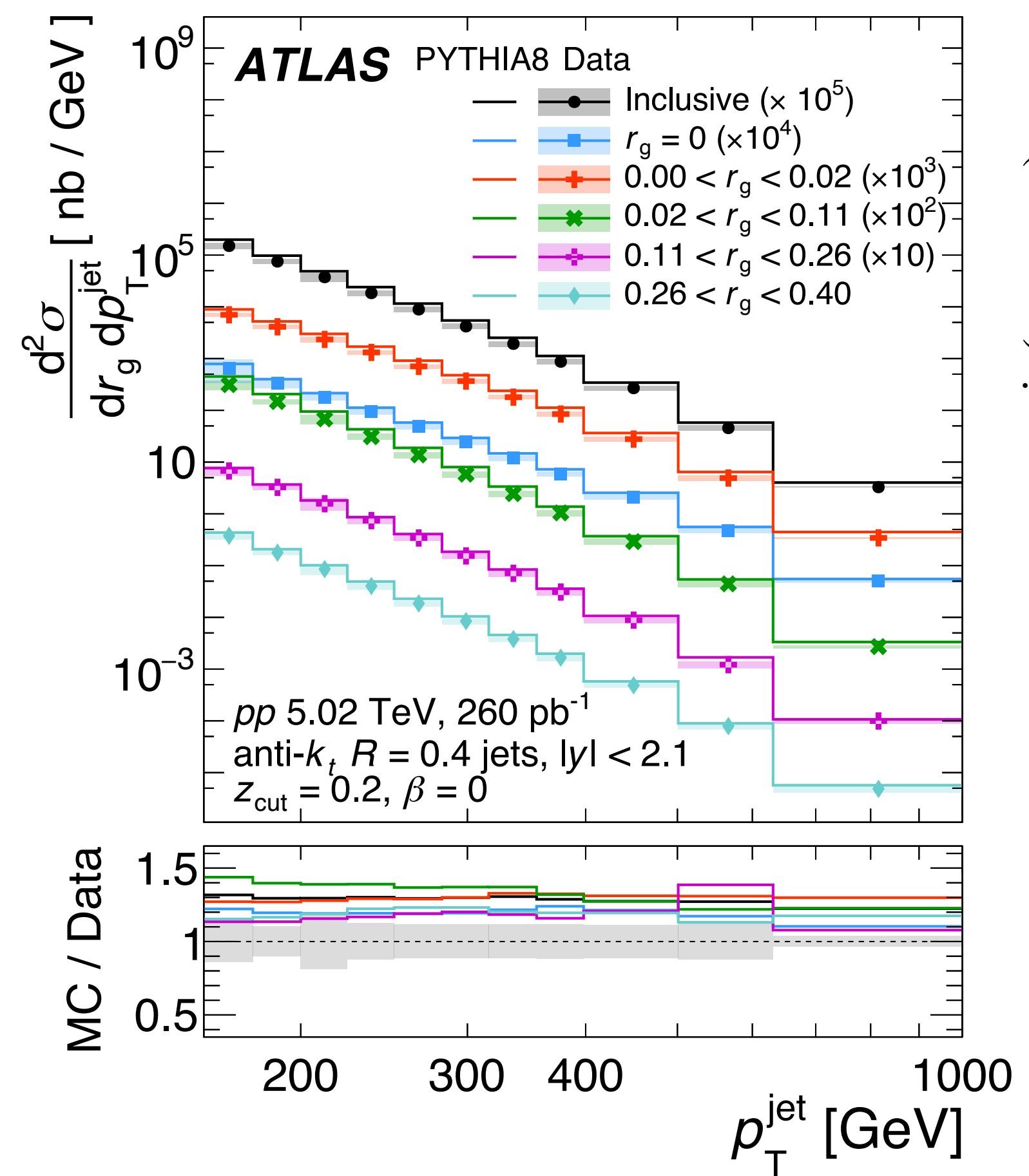
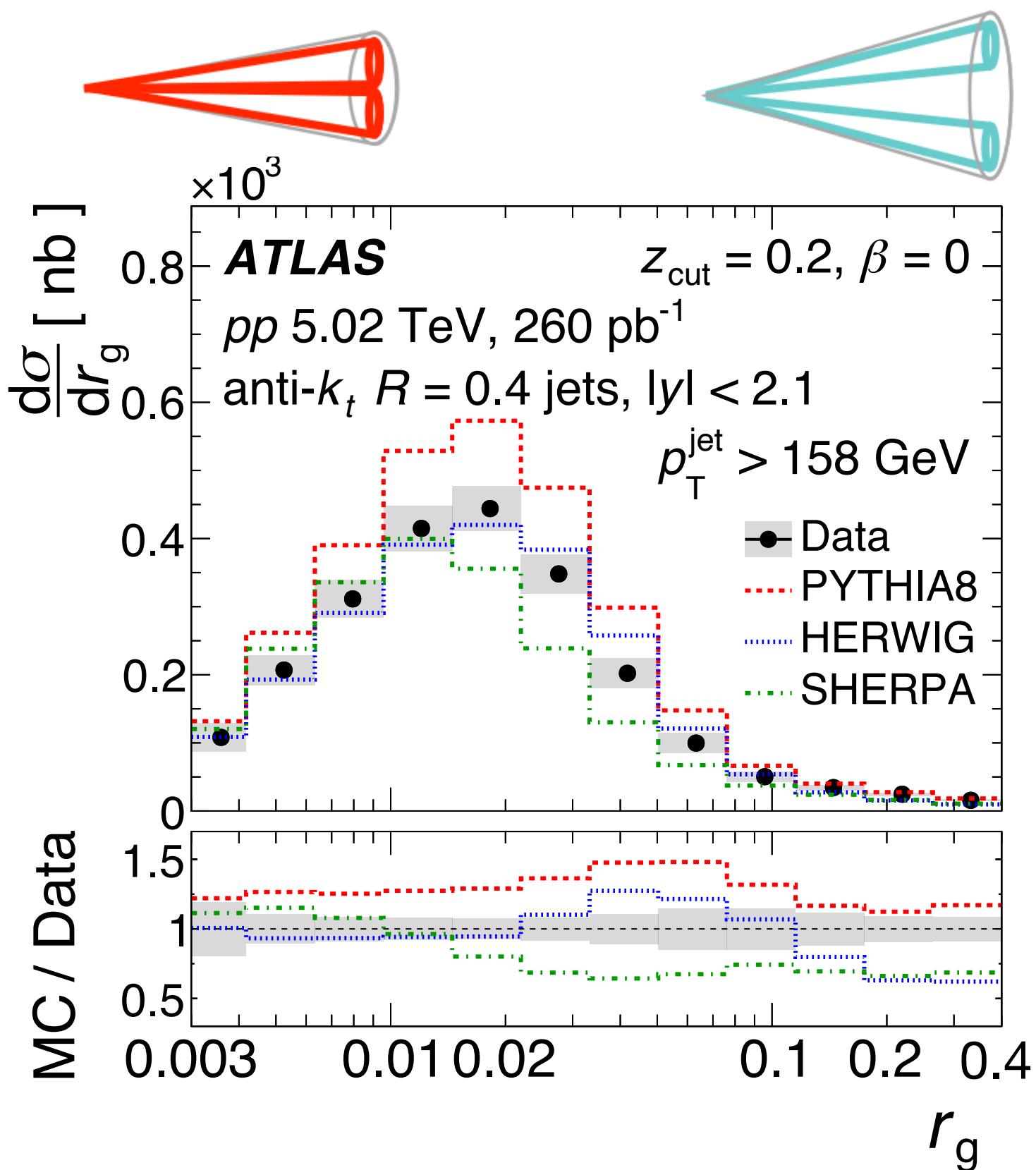
- Measurements of jet p_T and r_g unfolded to the truth hadron level for pp collisions
- Results shown differentially in jet r_g and p_T intervals, respectively



$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} (= 0.2)$$

Unfolded jet p_T & r_g distributions

- Measurements of jet p_T and r_g unfolded to the truth hadron level for pp collisions
- Results shown differentially in jet r_g and p_T intervals, respectively

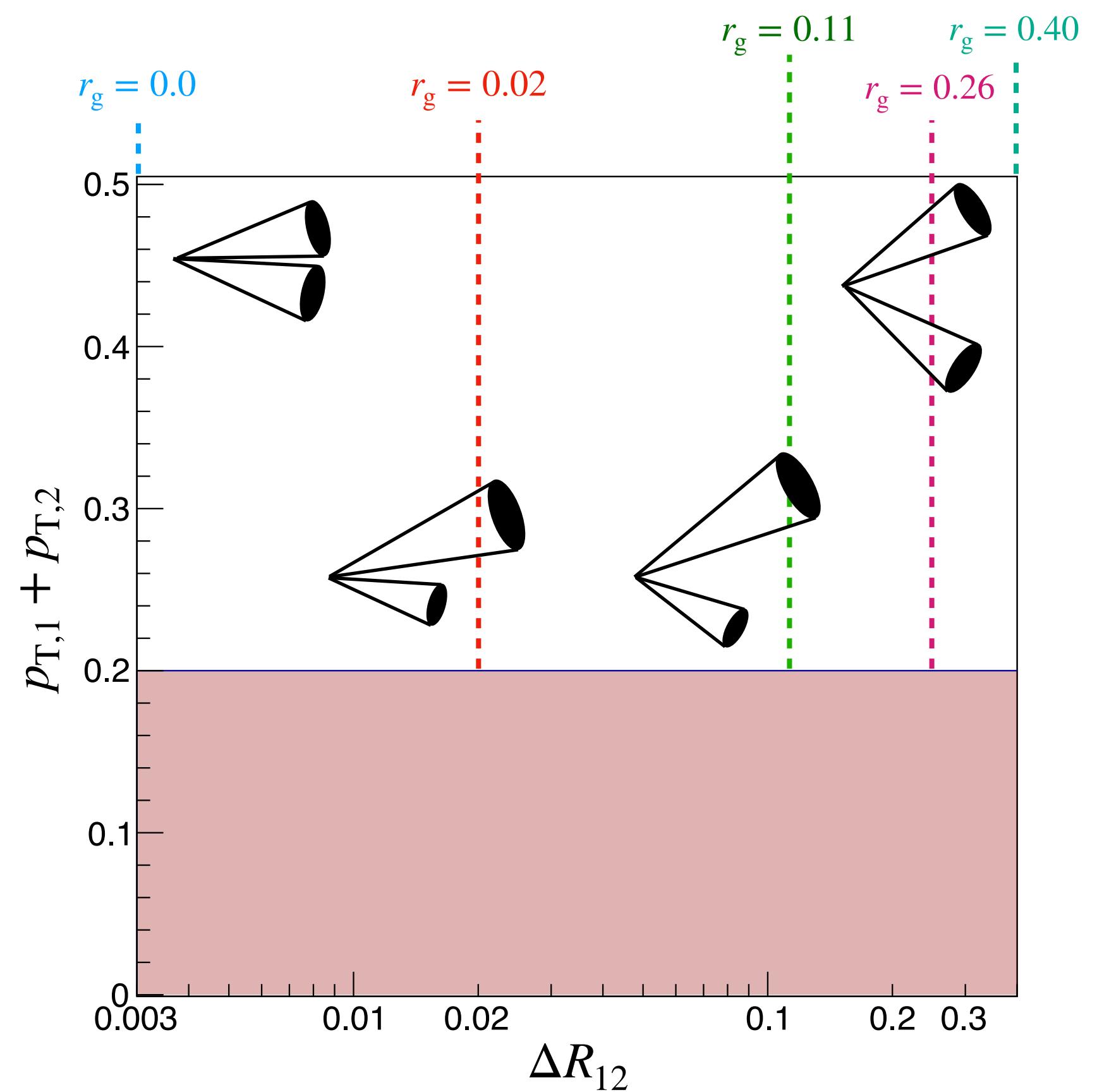
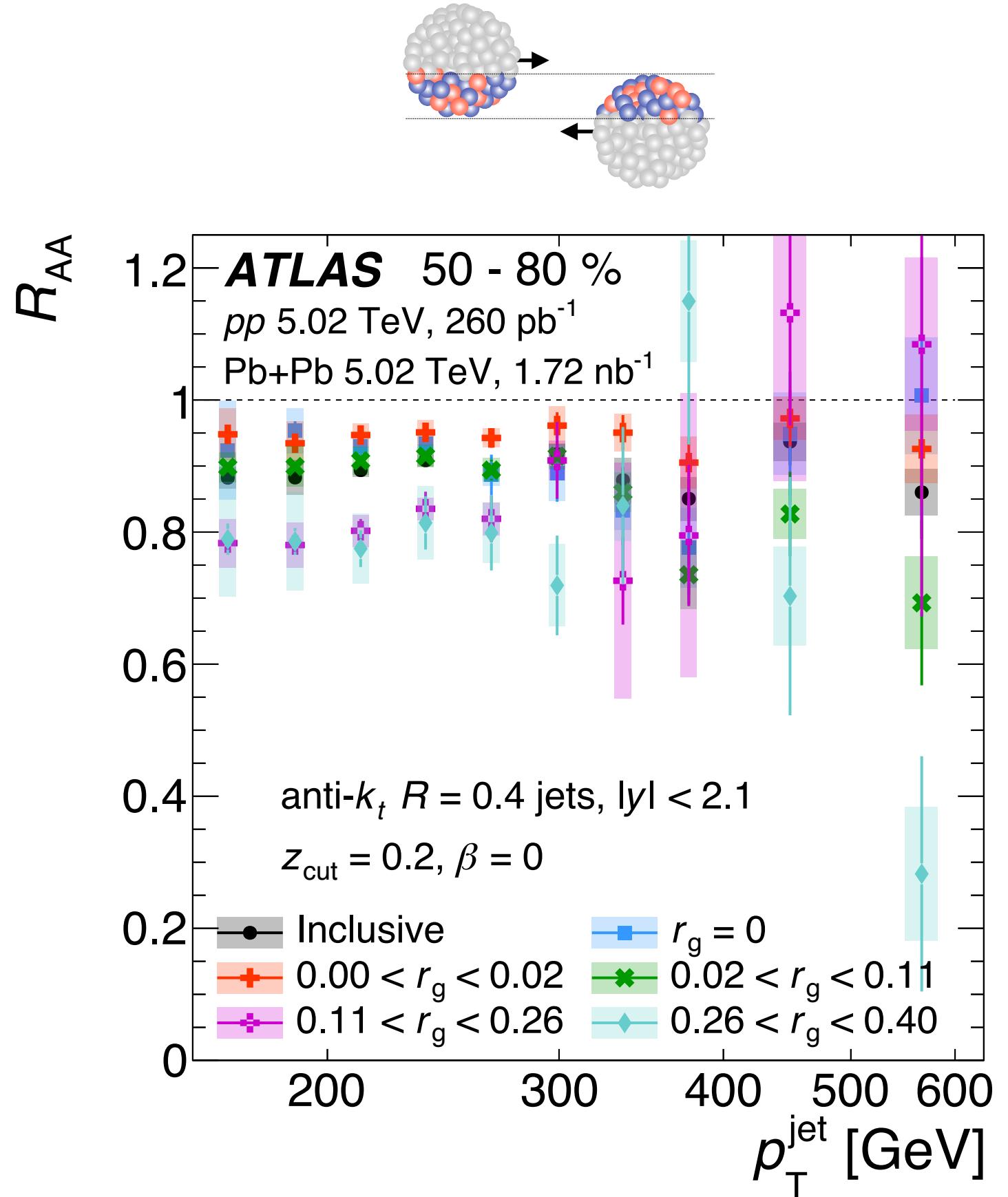


$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} (= 0.2)$$

$r_g = 0 \Rightarrow$ Jets failing SD condition (<5%)

Jet Suppression vs. p_T

- Jet suppression (R_{AA}) measured as a function of its hardest splitting angle (r_g)

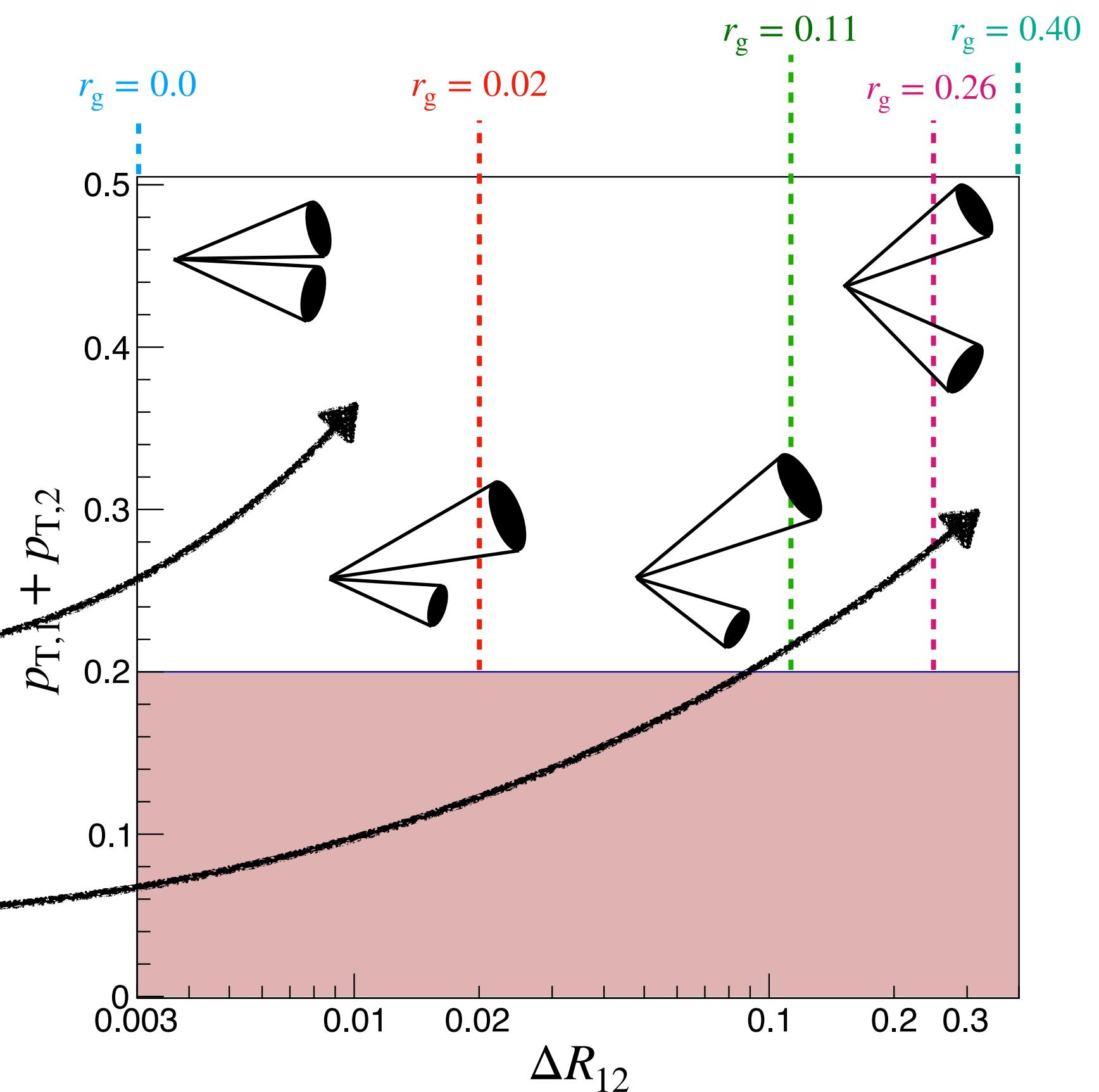
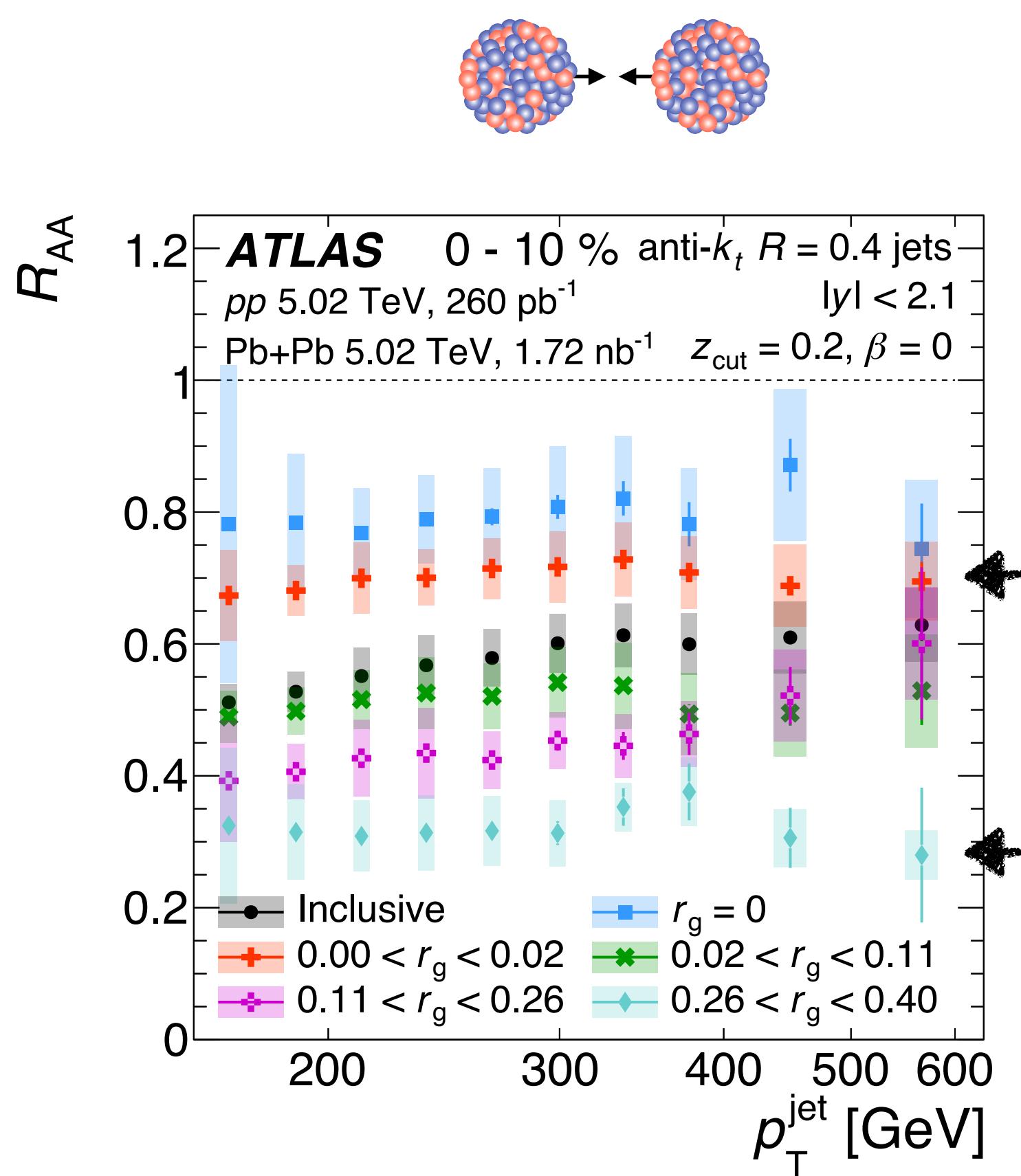
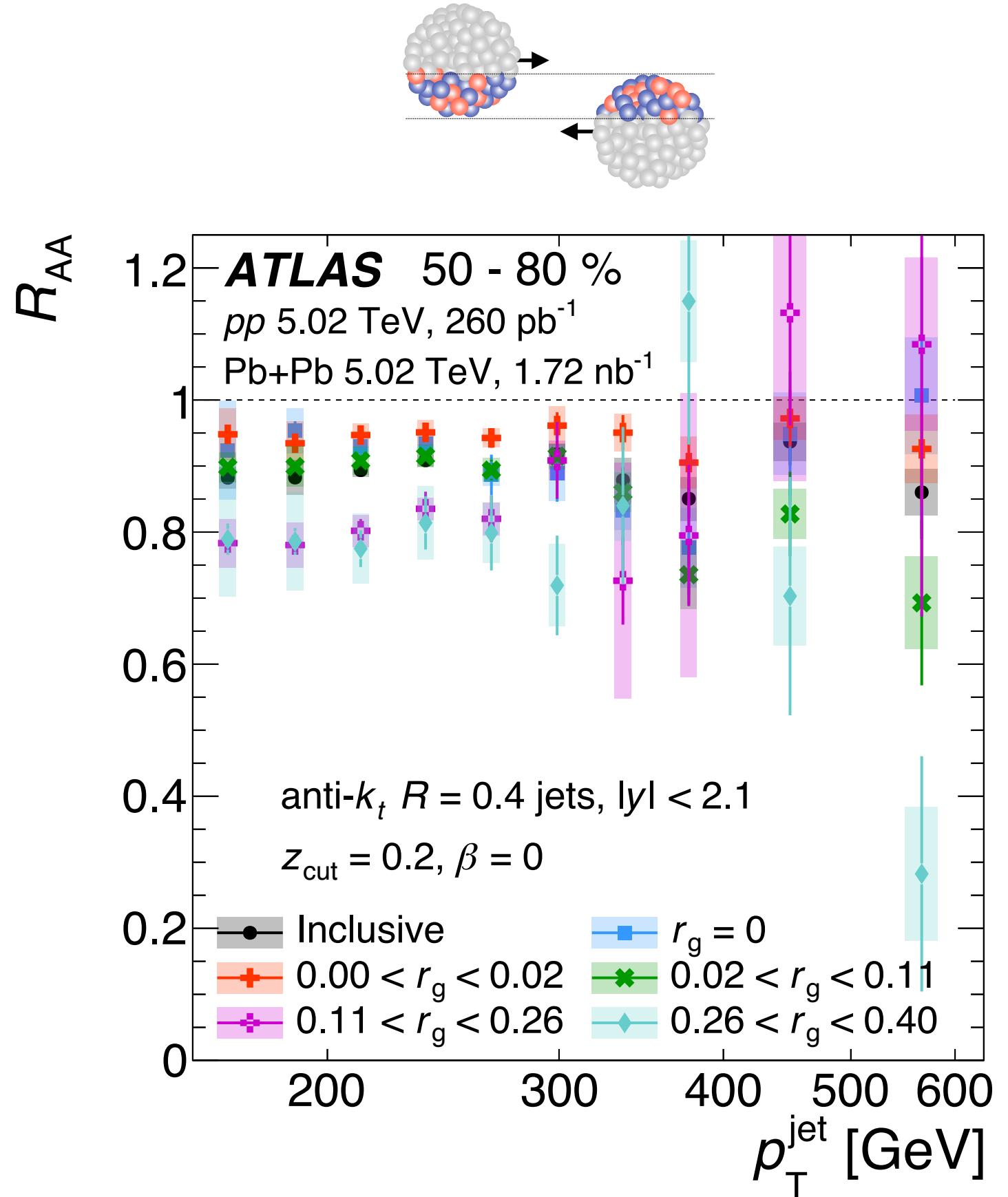


$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} (= 0.2)$$

$r_g = 0 \Rightarrow$ Jets failing SD condition (<5%)

Jet Suppression vs. p_T

- Jet suppression (R_{AA}) measured as a function of its hardest splitting angle (r_g)



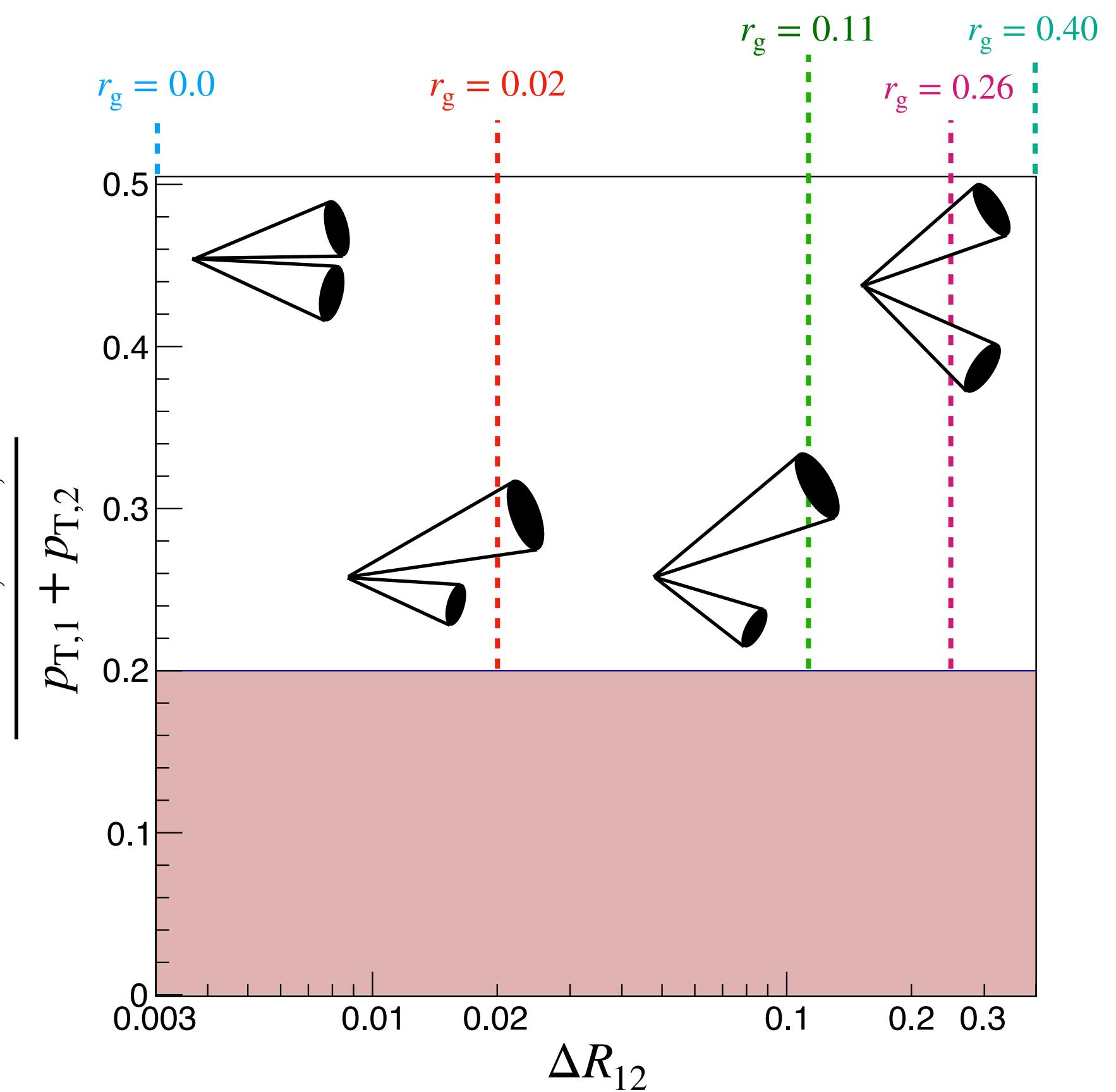
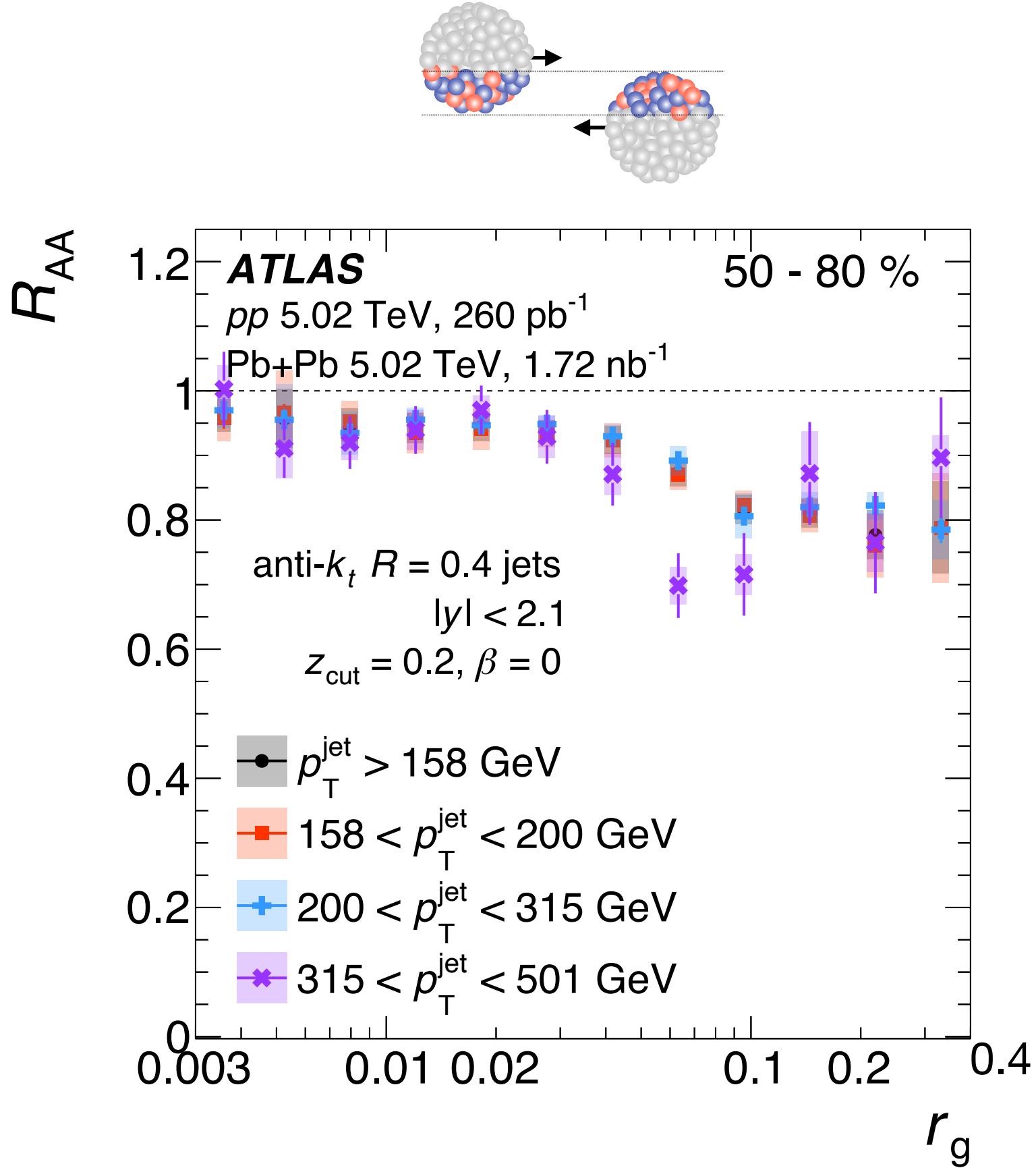
$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} (= 0.2)$$

Clear ordering in jet suppression vs. $r_g \rightarrow$ **Narrow jets less suppressed than wide jets**

$r_g = 0 \Rightarrow$ Jets failing SD condition (<5%)

Jet Suppression vs. r_g

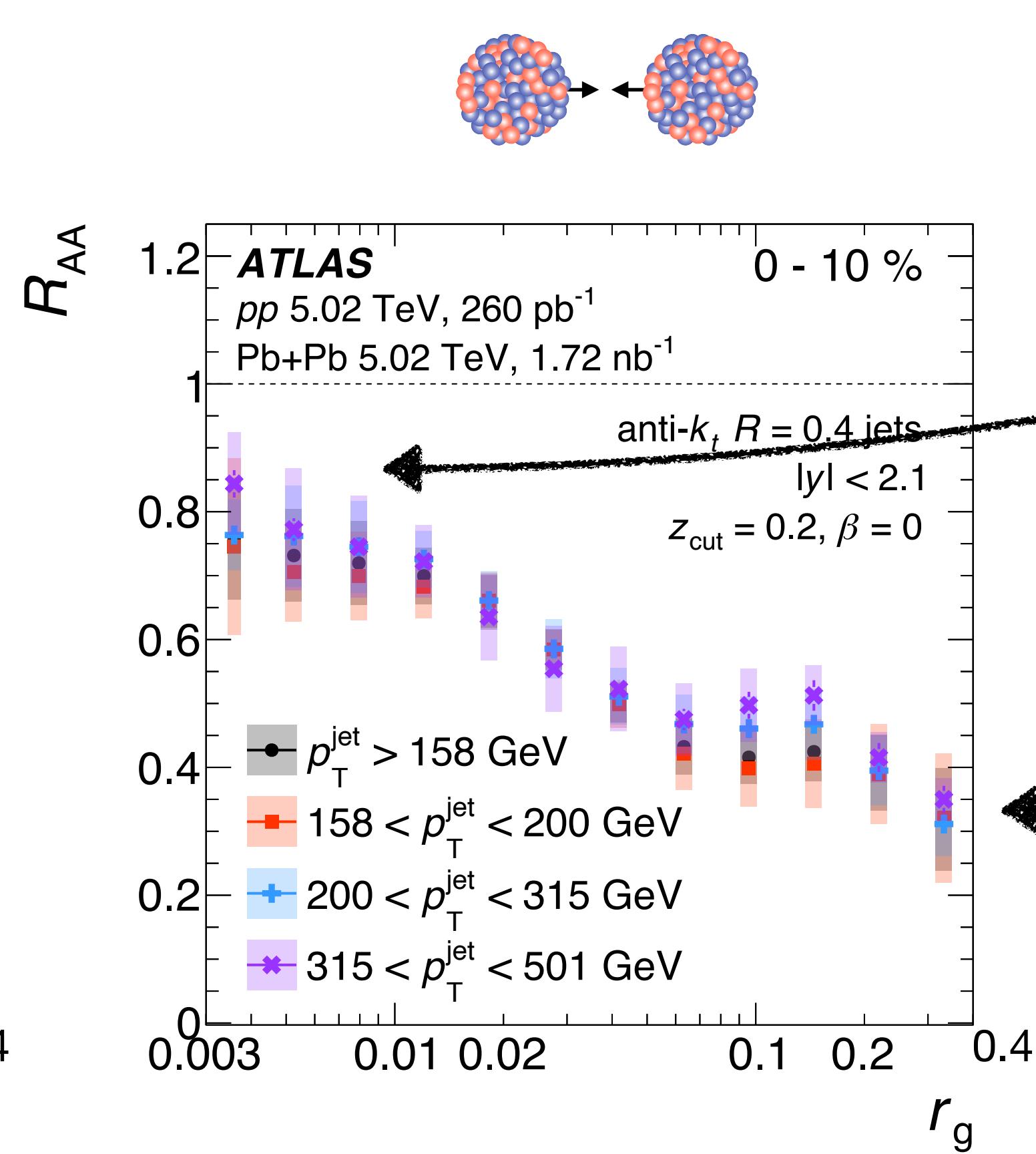
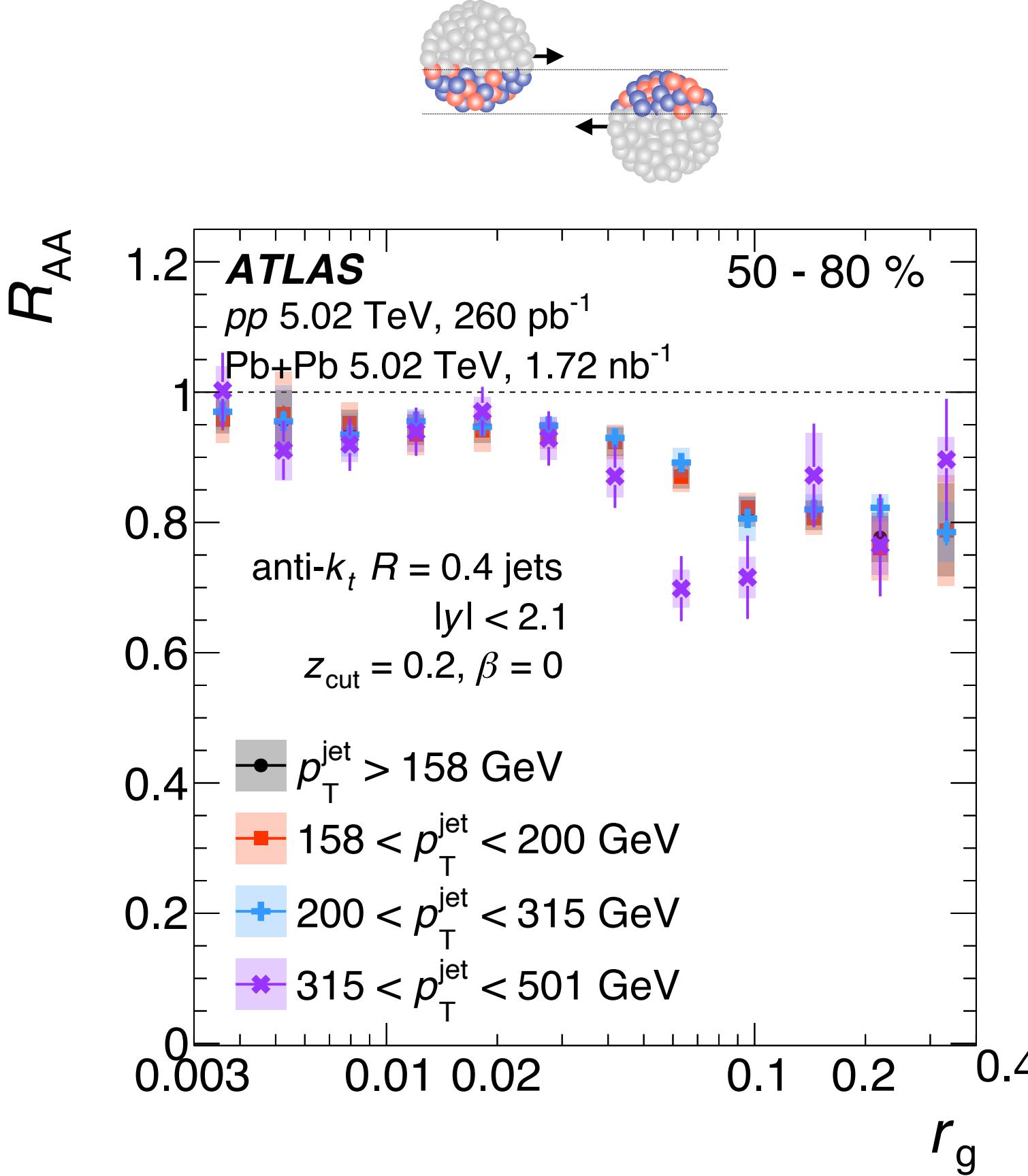
- Jet suppression (R_{AA}) measured as a function of its hardest splitting angle (r_g)



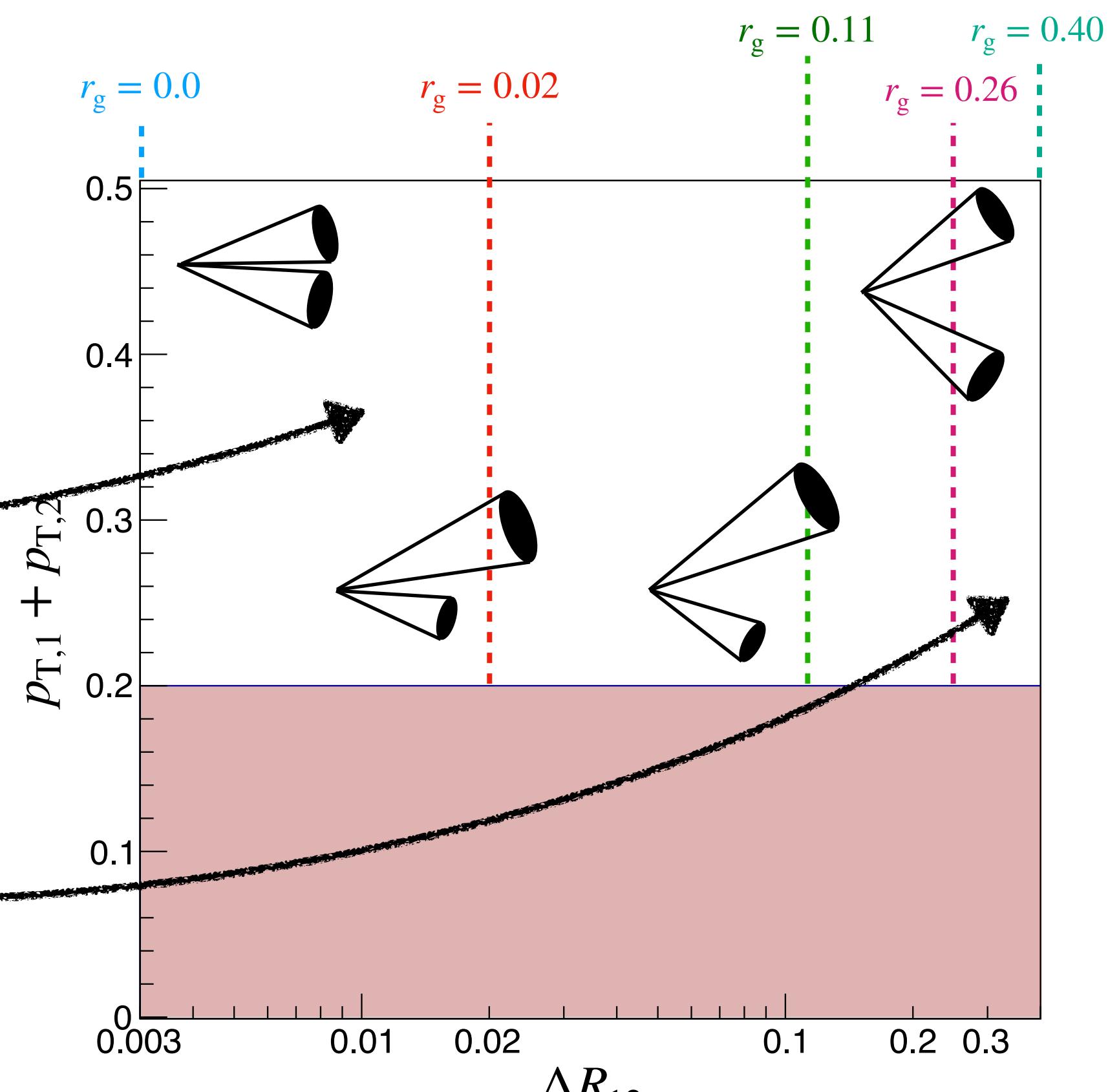
$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} (= 0.2)$$

Jet Suppression vs. r_g

- Jet suppression (R_{AA}) measured as a function of its hardest splitting angle (r_g)



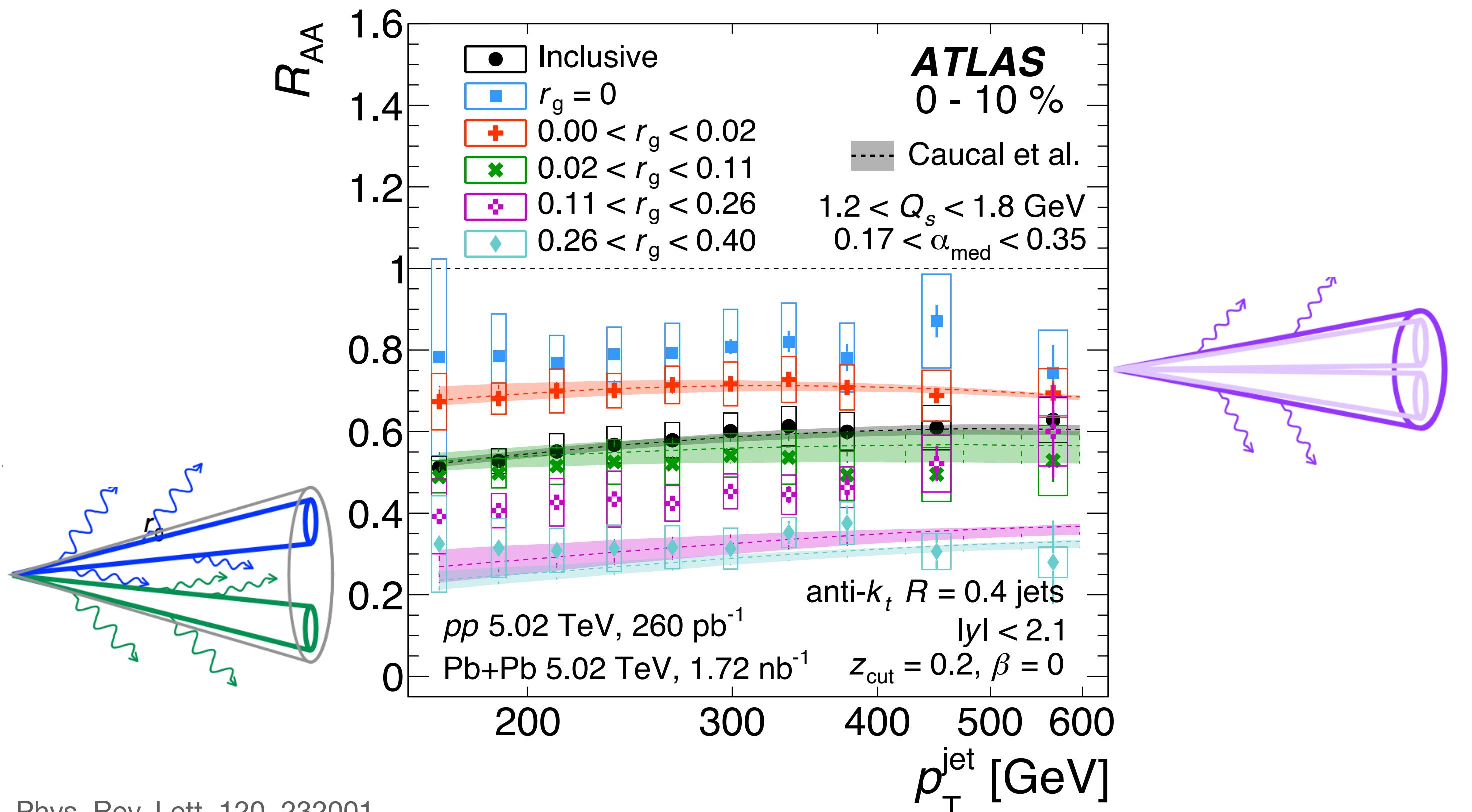
Significant drop in R_{AA} in $0.01 < r_g < 0.1$; **R_{AA} vs r_g exhibits little p_T dependence**



$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} (= 0.2)$$

Comparisons to Theory (Decoherence picture)

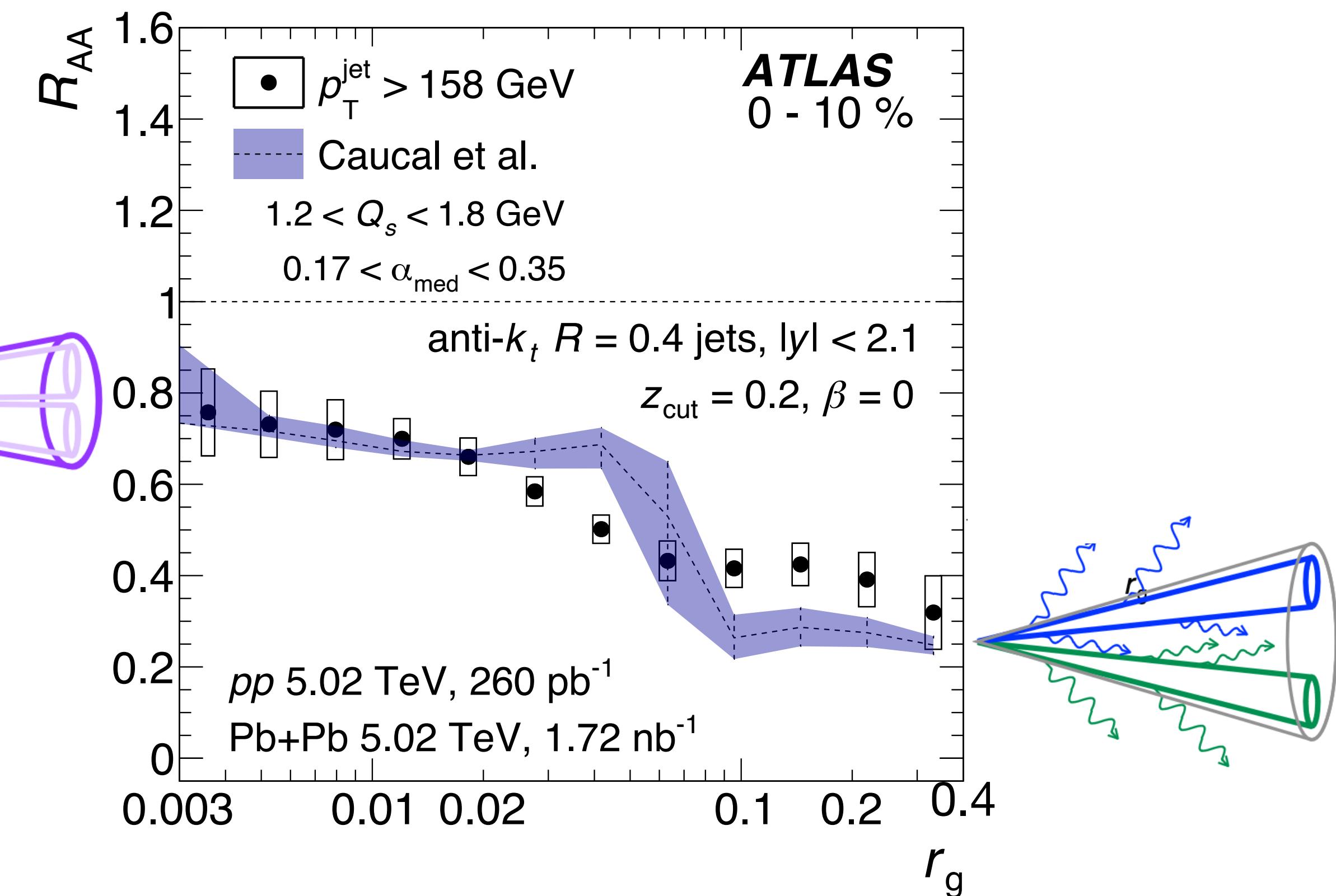
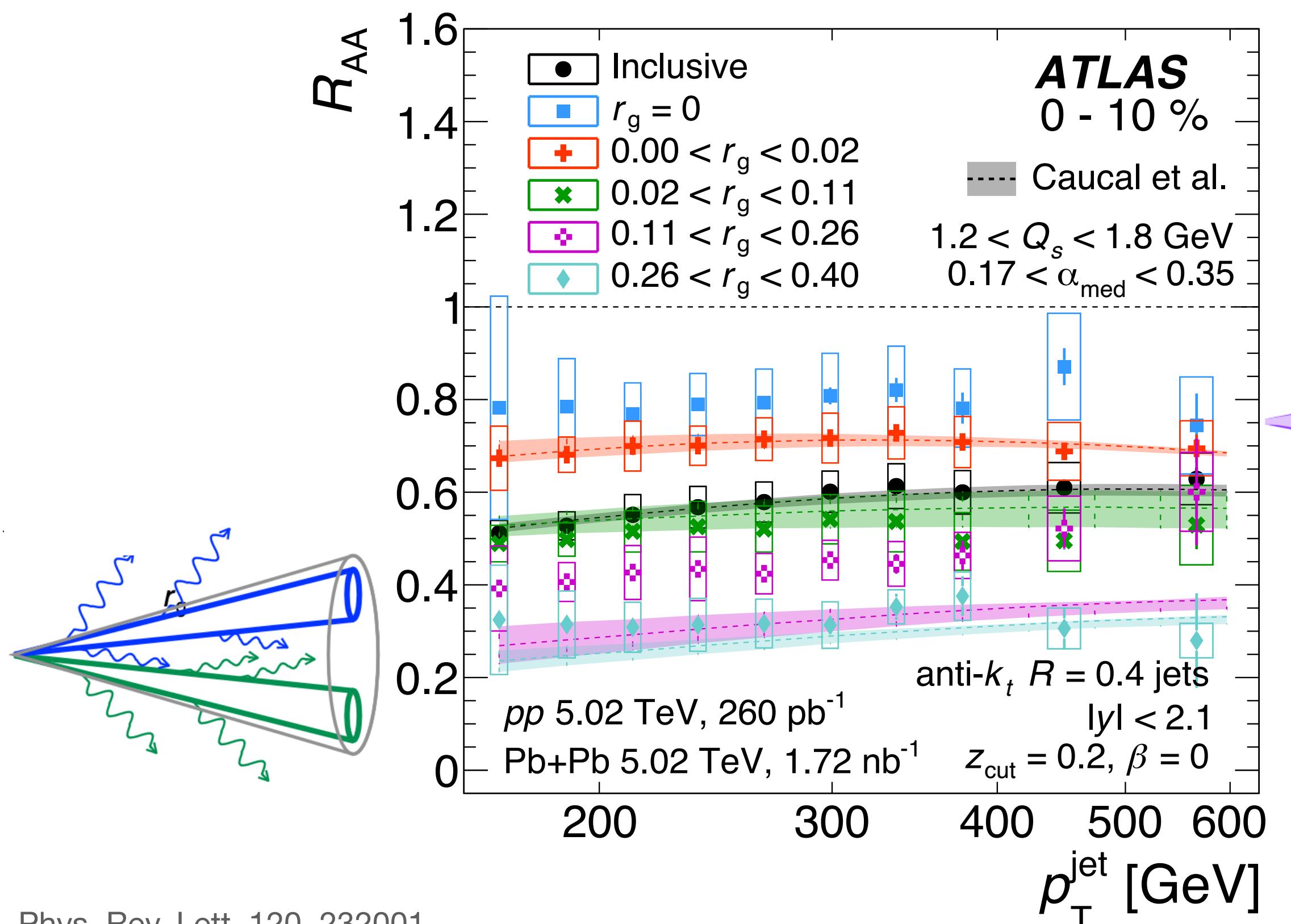
- Jet suppression (R_{AA}) as a function of its hardest splitting angle (r_g) compared to predictions from **decoherence model**



Phys. Rev. Lett. 120, 232001
JHEP 10 (2019) 273
JHEP 04 (2021) 209

Comparisons to Theory (Decoherence picture)

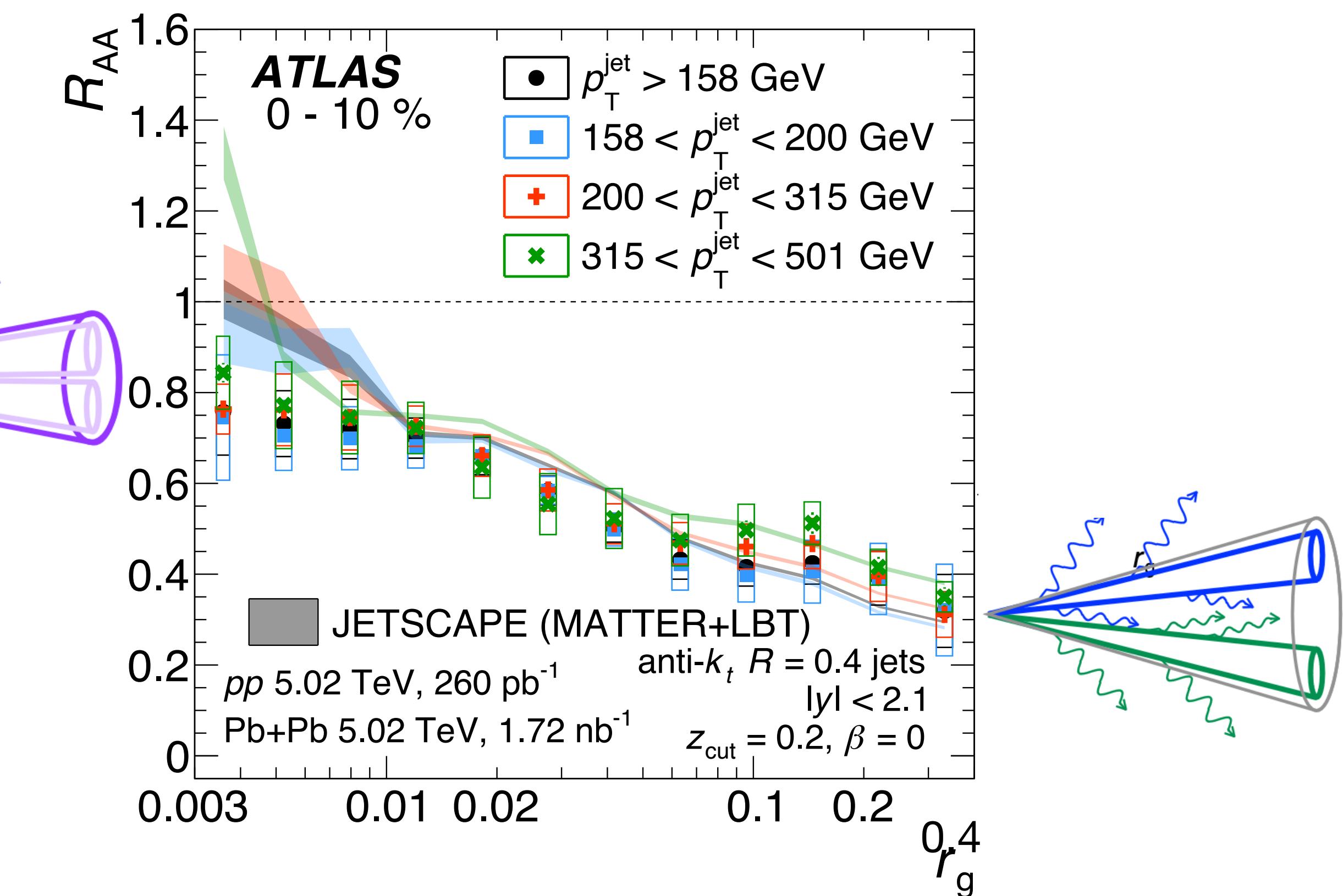
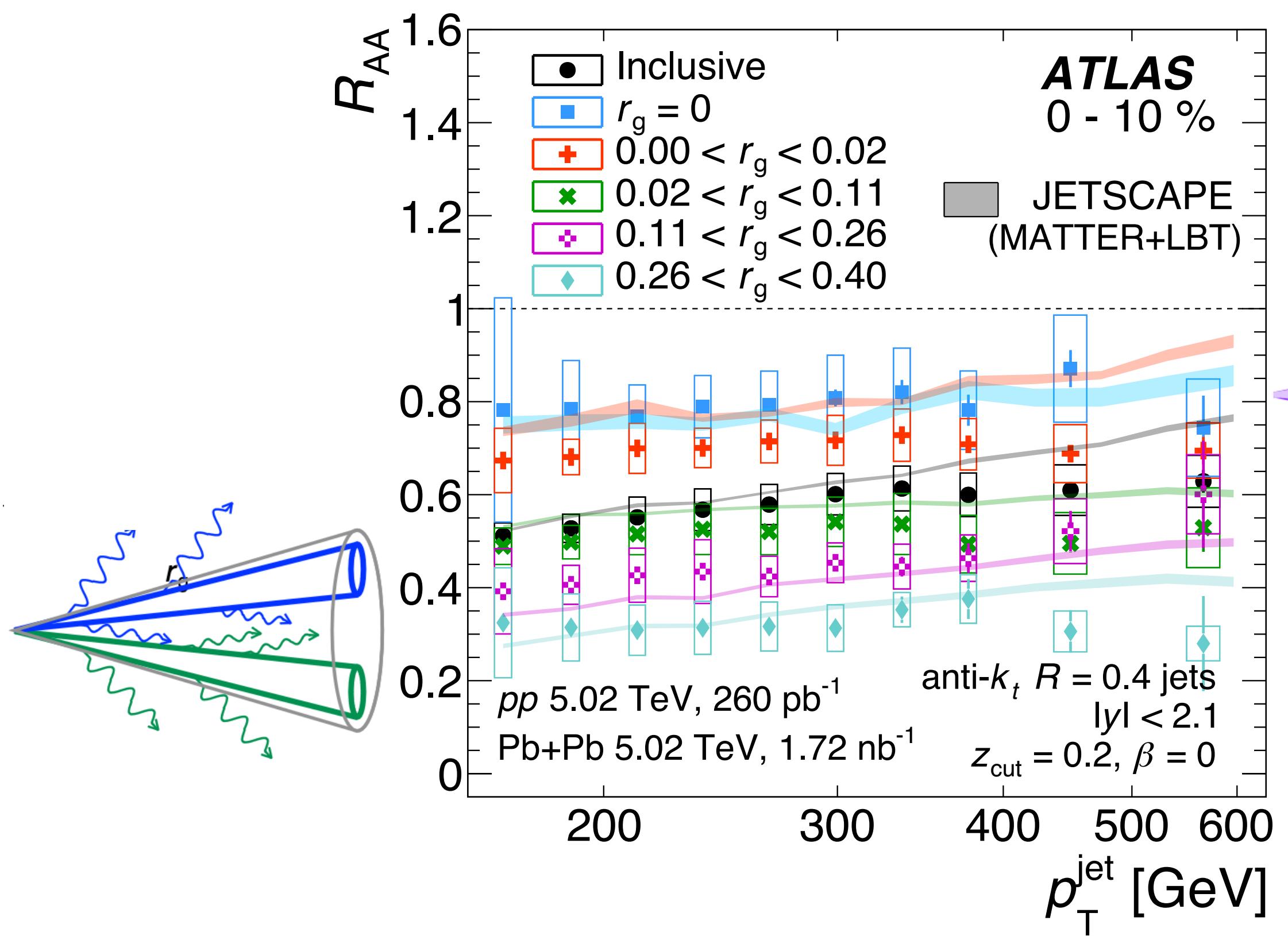
- Jet suppression (R_{AA}) as a function of its hardest splitting angle (r_g) compared to predictions from **decoherence model**
 - Dominant mechanism behind drop-off in R_{AA} vs r_g model predictions is colour decoherence and the associated critical angle



Phys. Rev. Lett. 120, 232001
JHEP 10 (2019) 273
JHEP 04 (2021) 209

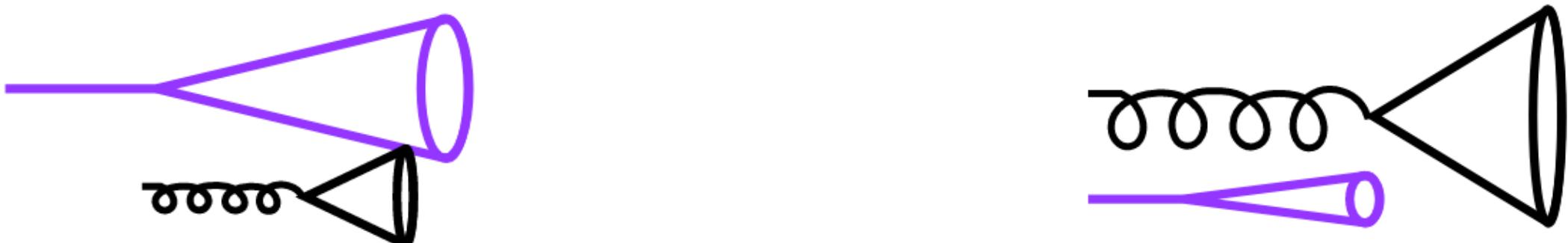
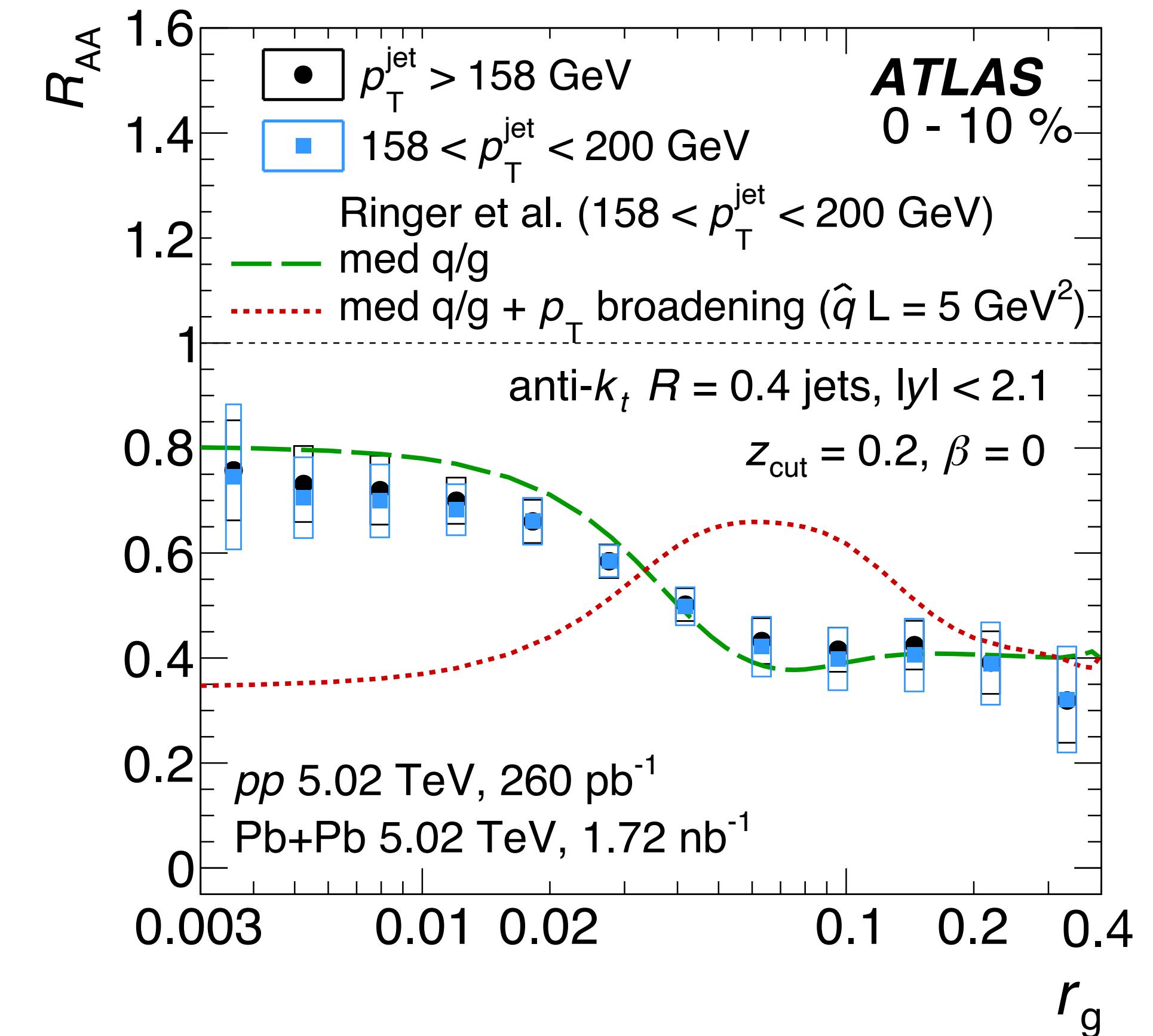
Comparisons to Theory (JETSCAPE)

- Jet suppression (R_{AA}) as a function of its hardest splitting angle (r_g) compared to predictions from **JETSCAPE**
- Recent JETSCAPE predictions strongly indicate that including virtuality-dependent coherence effects in energy loss is essential to describe the R_{AA} of single charged particles, inclusive jets and its substructure dependence.



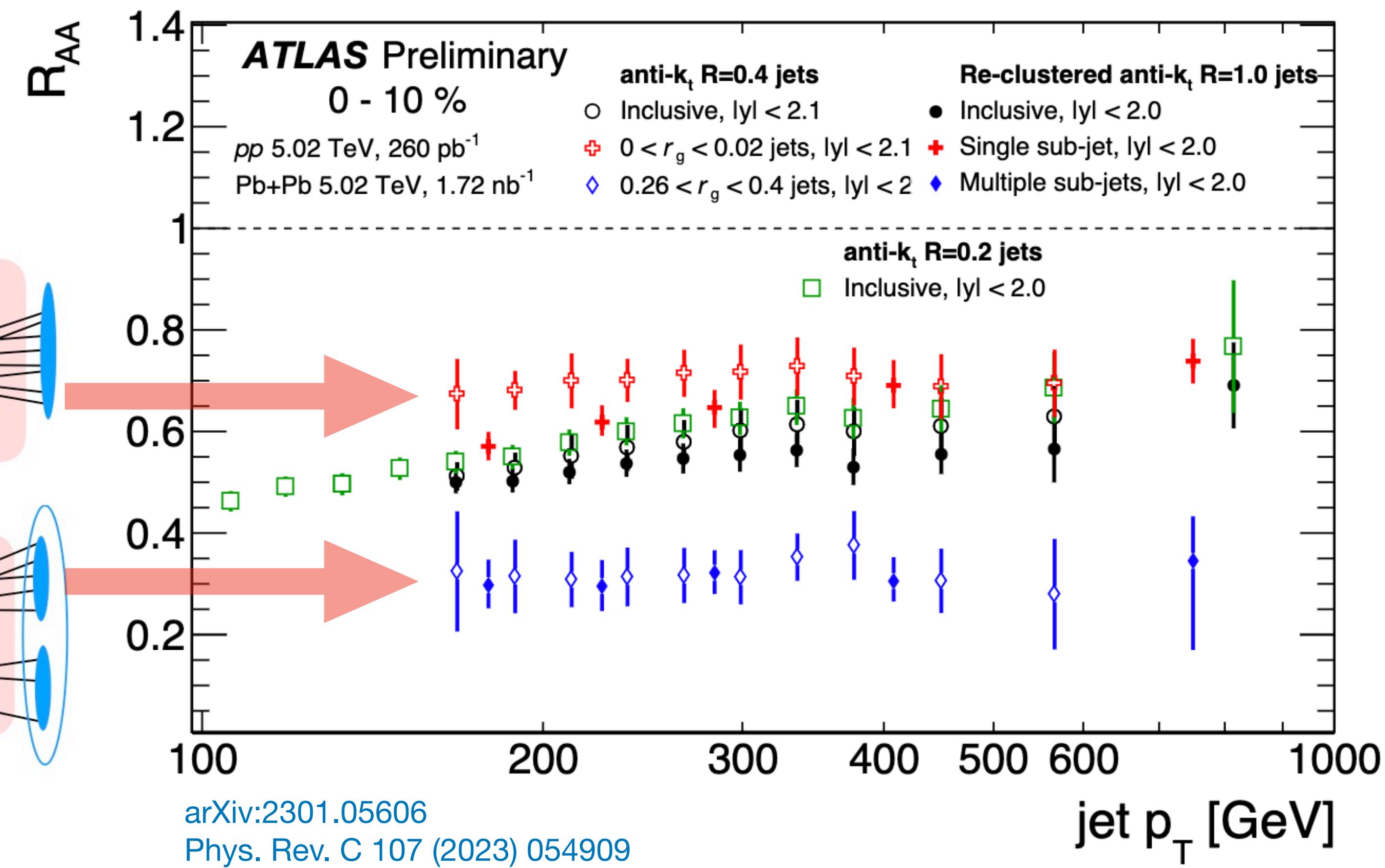
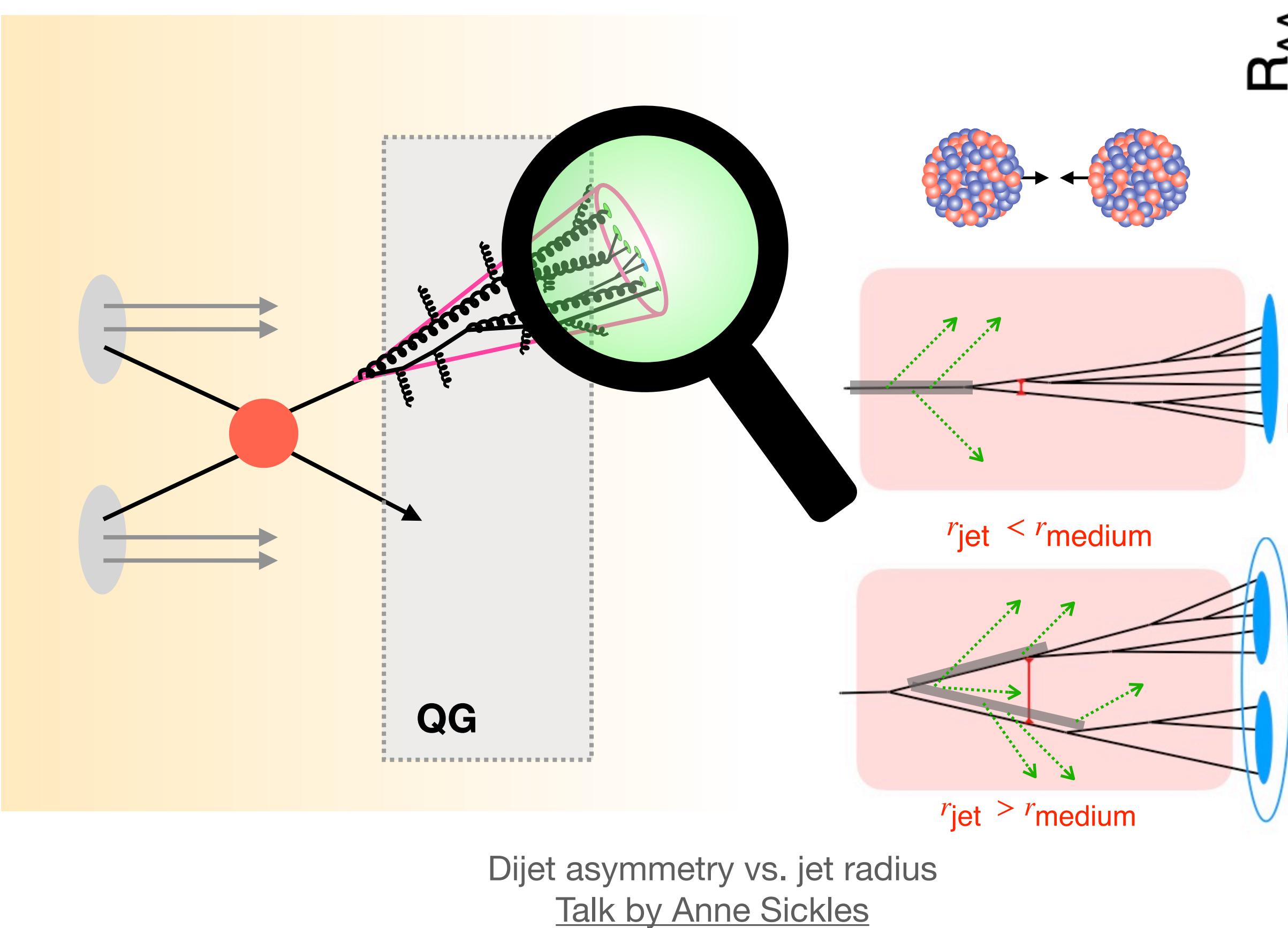
Comparisons to Theory (Quark vs. Gluon)

- Jet suppression (R_{AA}) as a function of its hardest splitting angle (r_g) compared to predictions from **q/g(+ p_T broadening) model**
- r_g -dependent R_{AA} behavior also described by model implementing empirical **quark vs. gluon energy loss**
- Empirically-driven quark vs. gluon energy loss model has (de)coherence effects built into the model predictions
- Adding p_T -broadening effects in the model results in features which not observed in r_g -dependent R_{AA} results



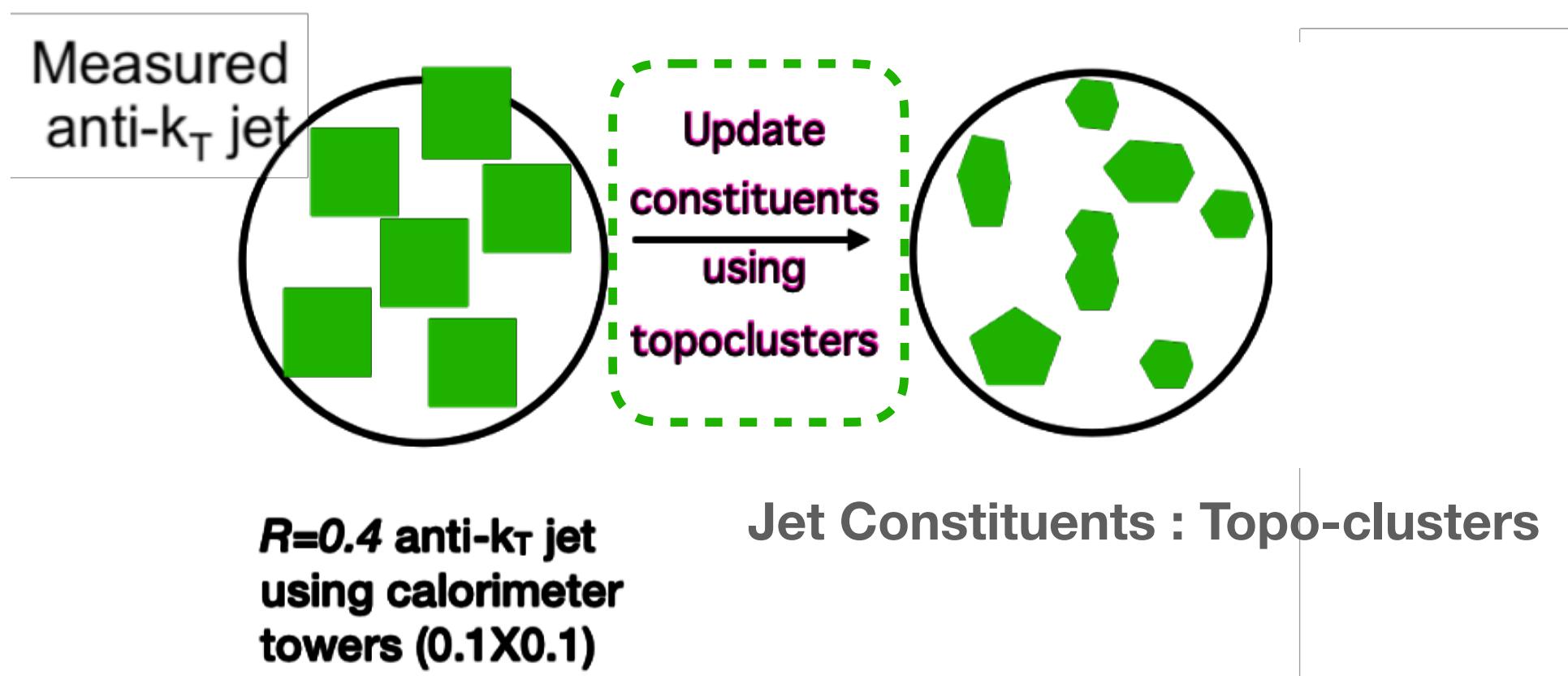
Summary

- Jet suppression measured as a function of the angle of its hardest splitting (r_g) and the splitting scale ($\sqrt{d_{12}}$)
- The R_{AA} is observed to depend significantly on its hardest splitting angle (r_g)
- Jet quenching in the QGP has been measured with many handles and much more remains to be explored!

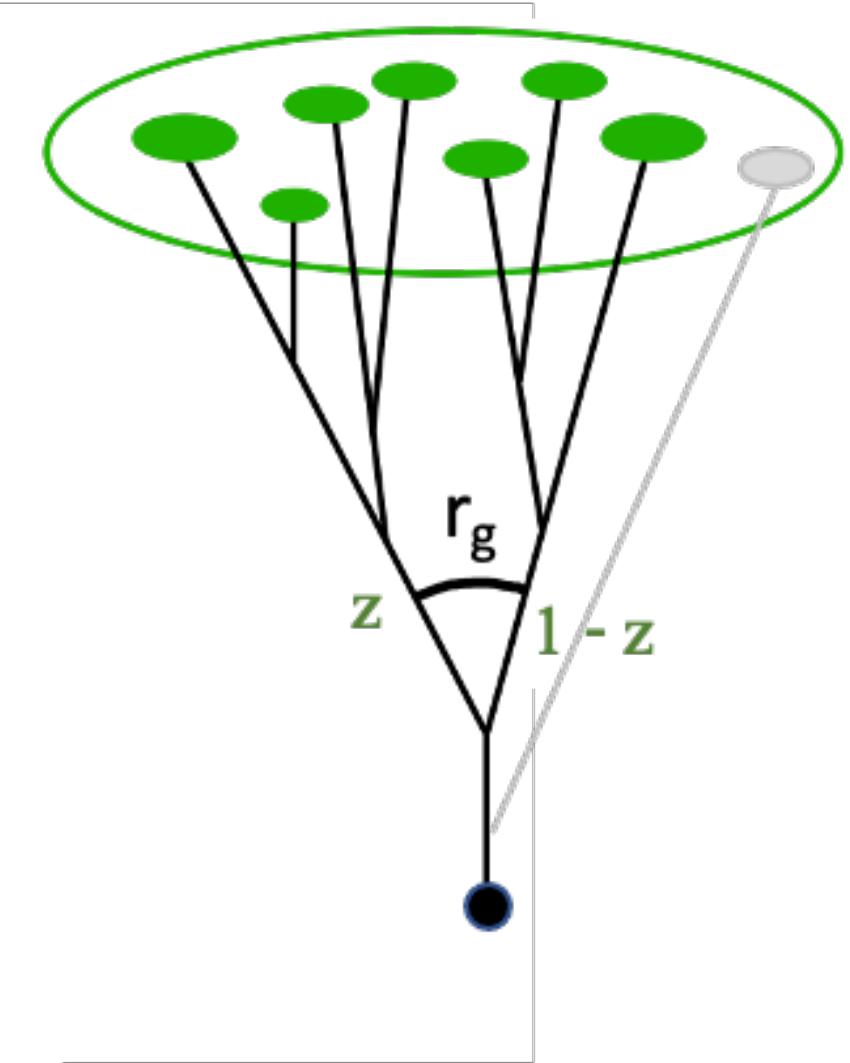


Backup

Jet Constituents



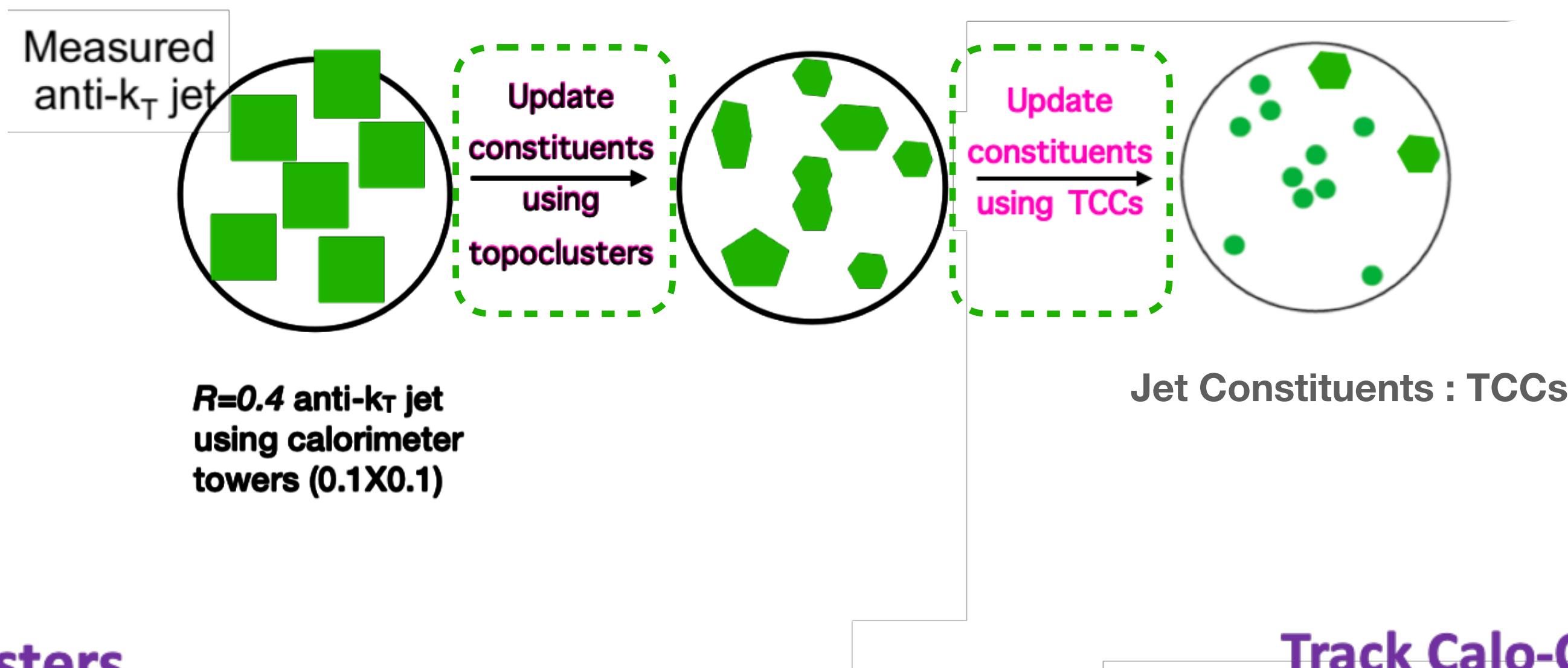
Jet Constituents : Topo-clusters



Topo-clusters

- 3D objects representing local particle showers in the detector
- ϕ - modulated background subtraction applied at cell-level in topo-cluster reconstruction in heavy-ion collisions

Jet Constituents

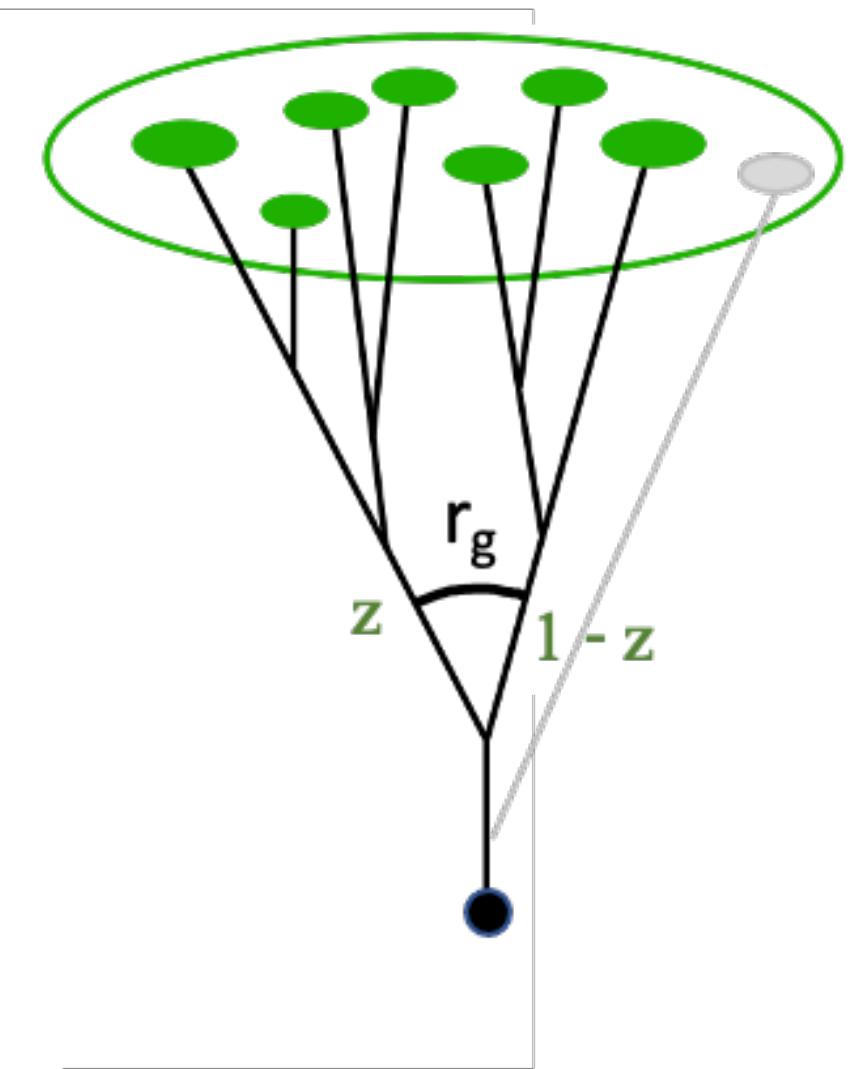


Topo-clusters

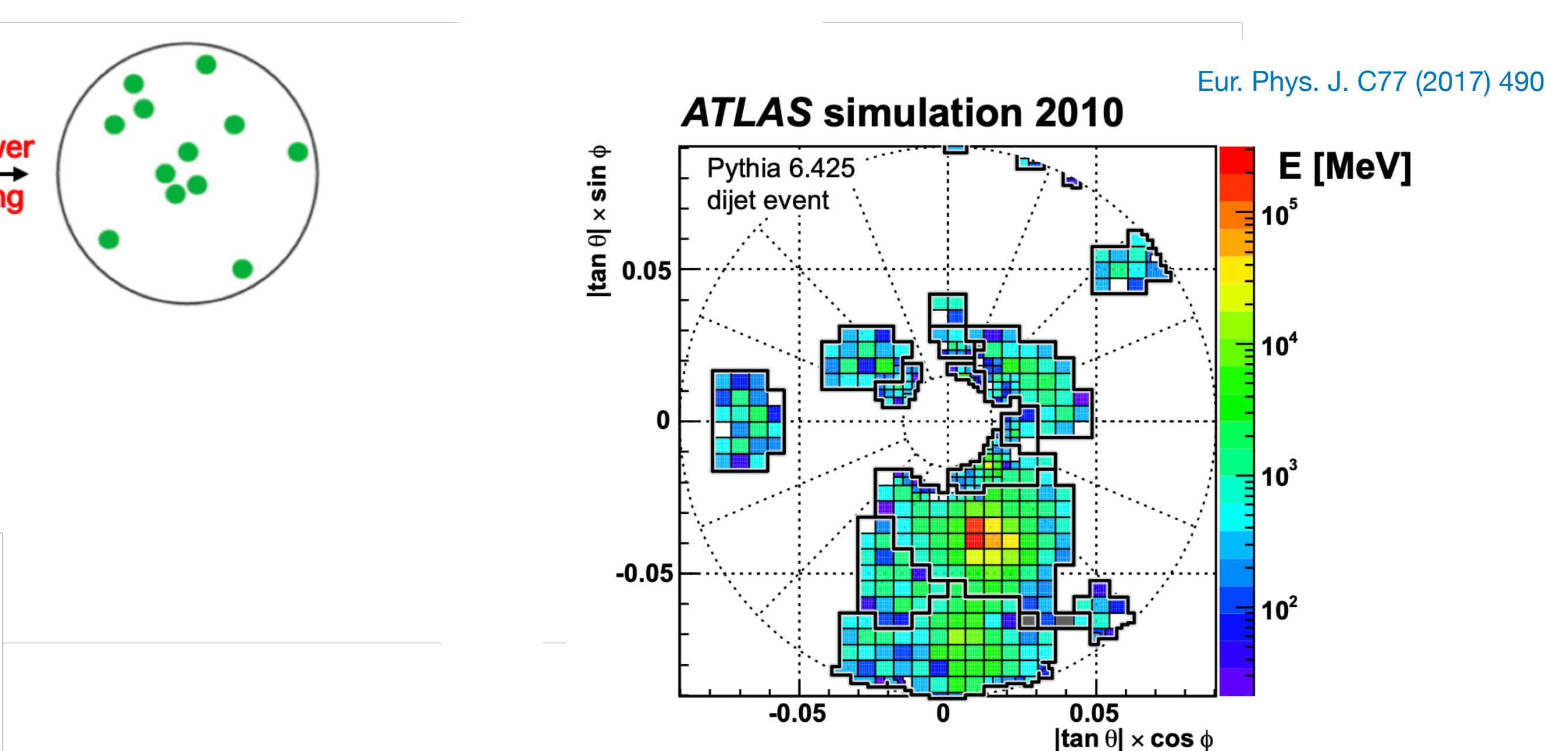
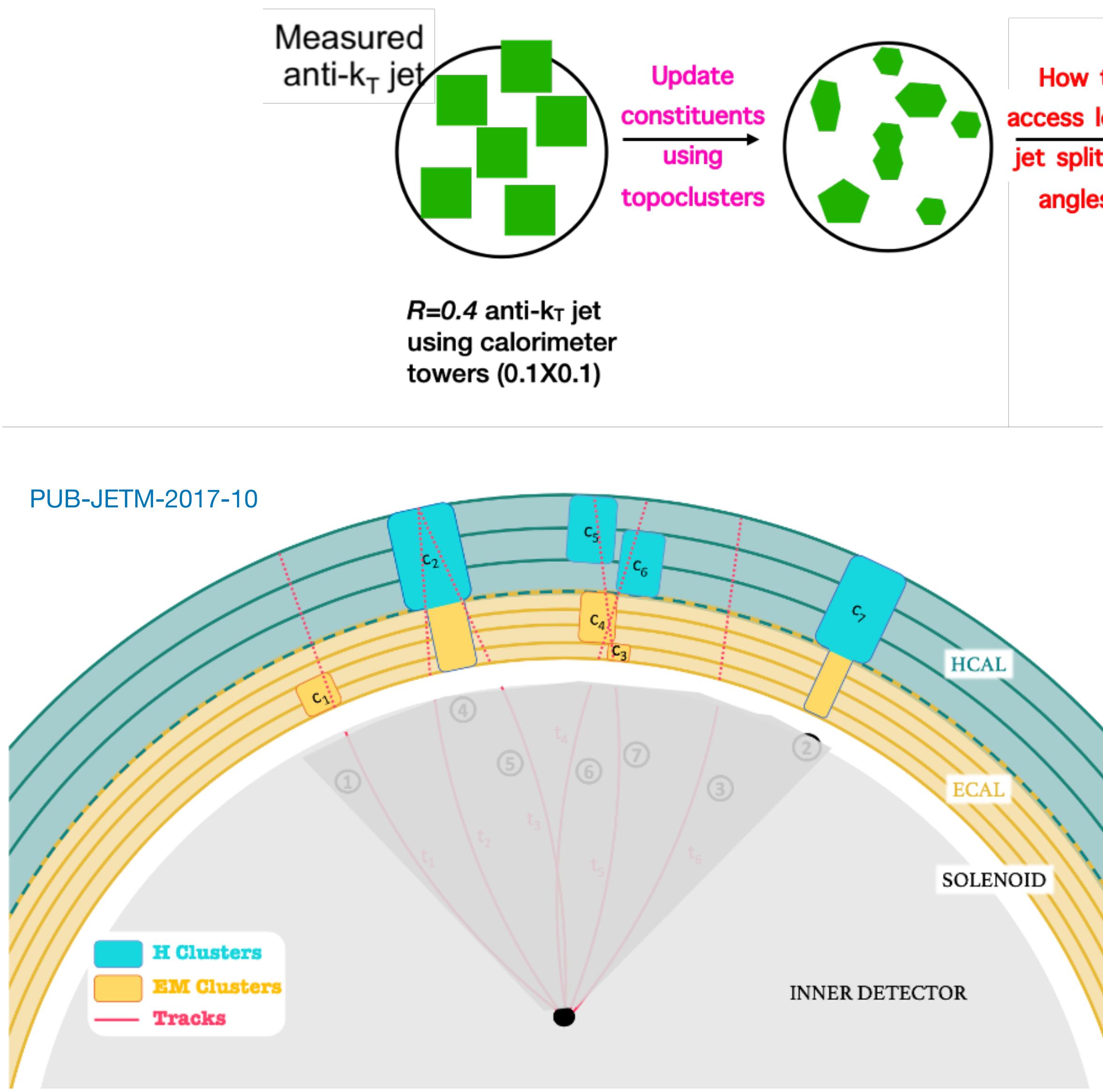
- 3D objects representing local particle showers in the detector
- ϕ - modulated background subtraction applied at cell-level in topo-cluster reconstruction in heavy-ion collisions

Track Calo-Clusters (TCCs)

- Objects built using tracks matched to topo-clusters
- Use angular information from charged tracks
- Energy information from topo-clusters, shared between TCCs
- ϕ - modulated background subtraction applied at cell-level in topo-cluster reconstruction in heavy-ion collisions



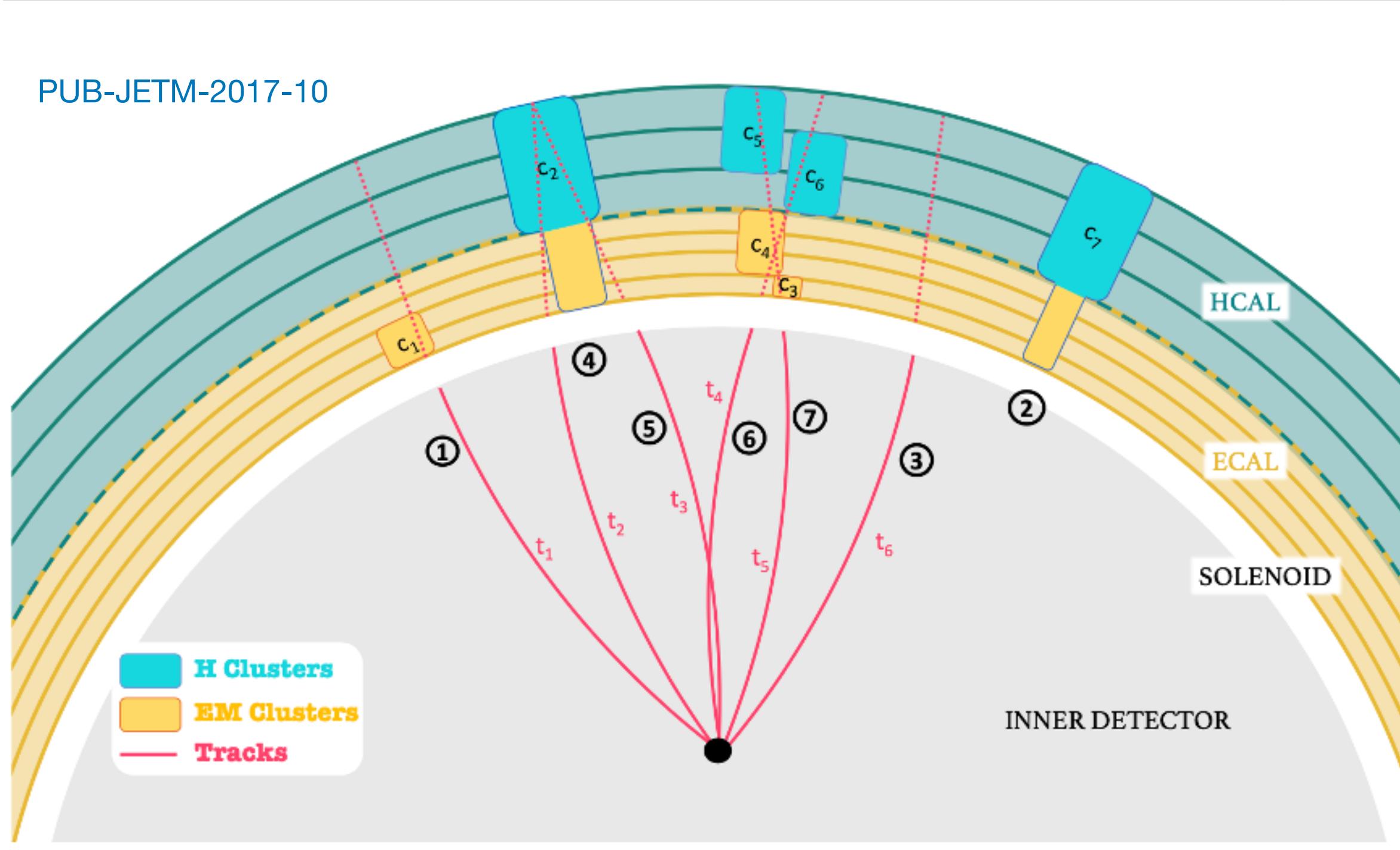
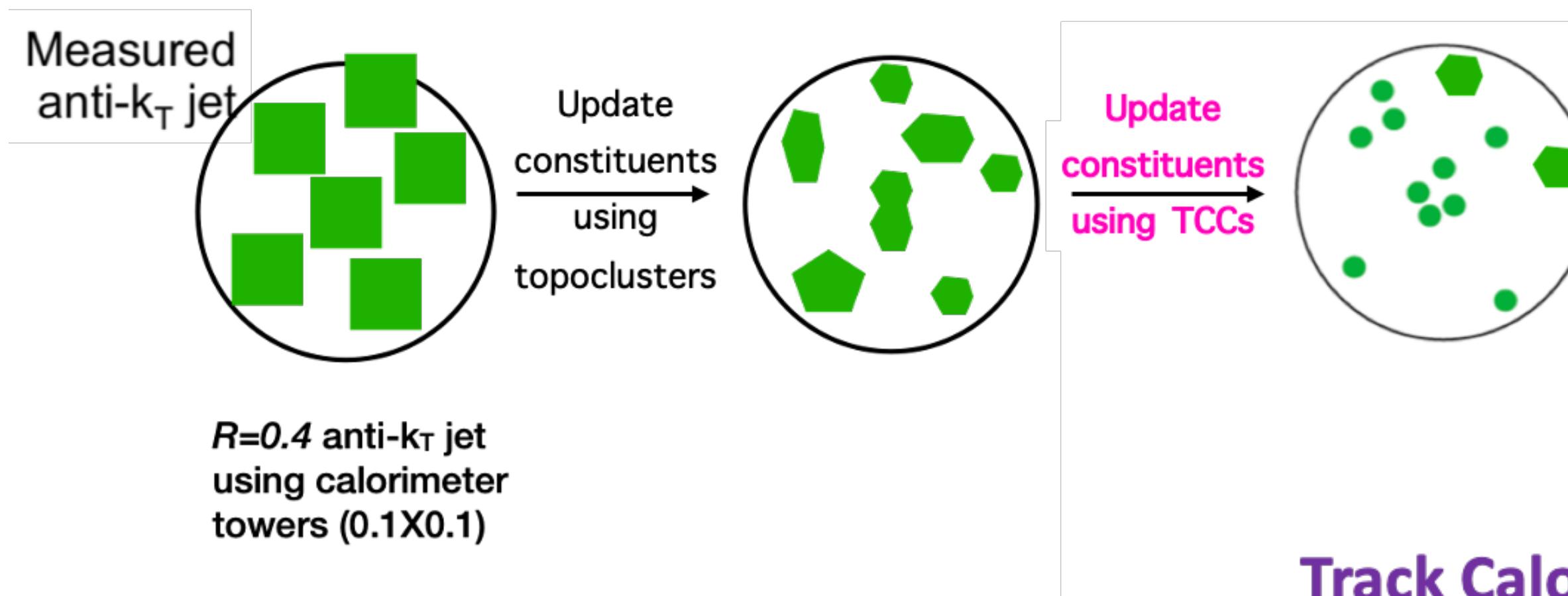
Topological Cell Clusters



Topo-clusters

- 3D objects representing local particle showers in the detector
- ϕ - modulated background subtraction applied at cell-level in topo-cluster reconstruction in heavy-ion collisions

Track Calo-Clusters (TCCs)



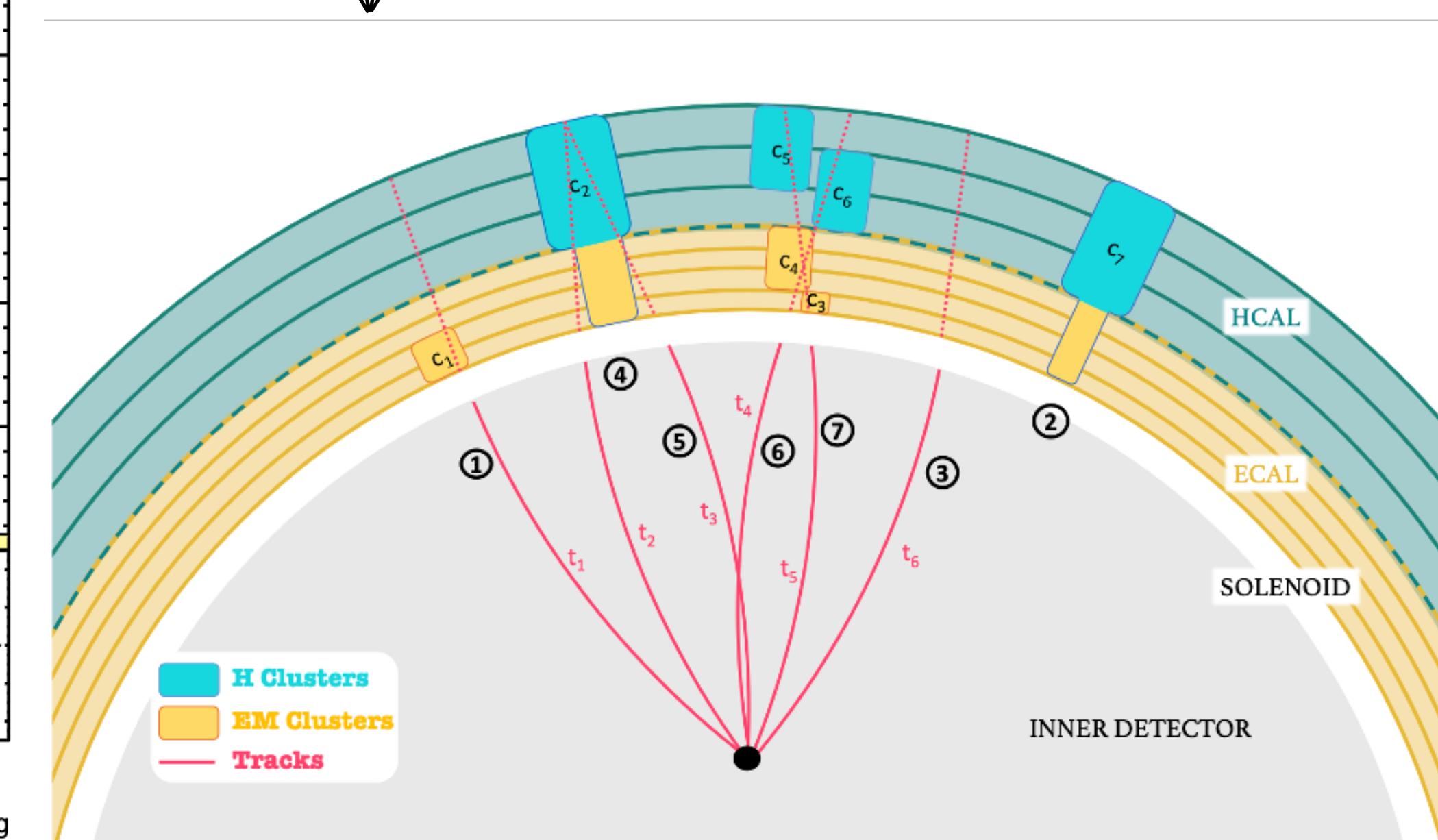
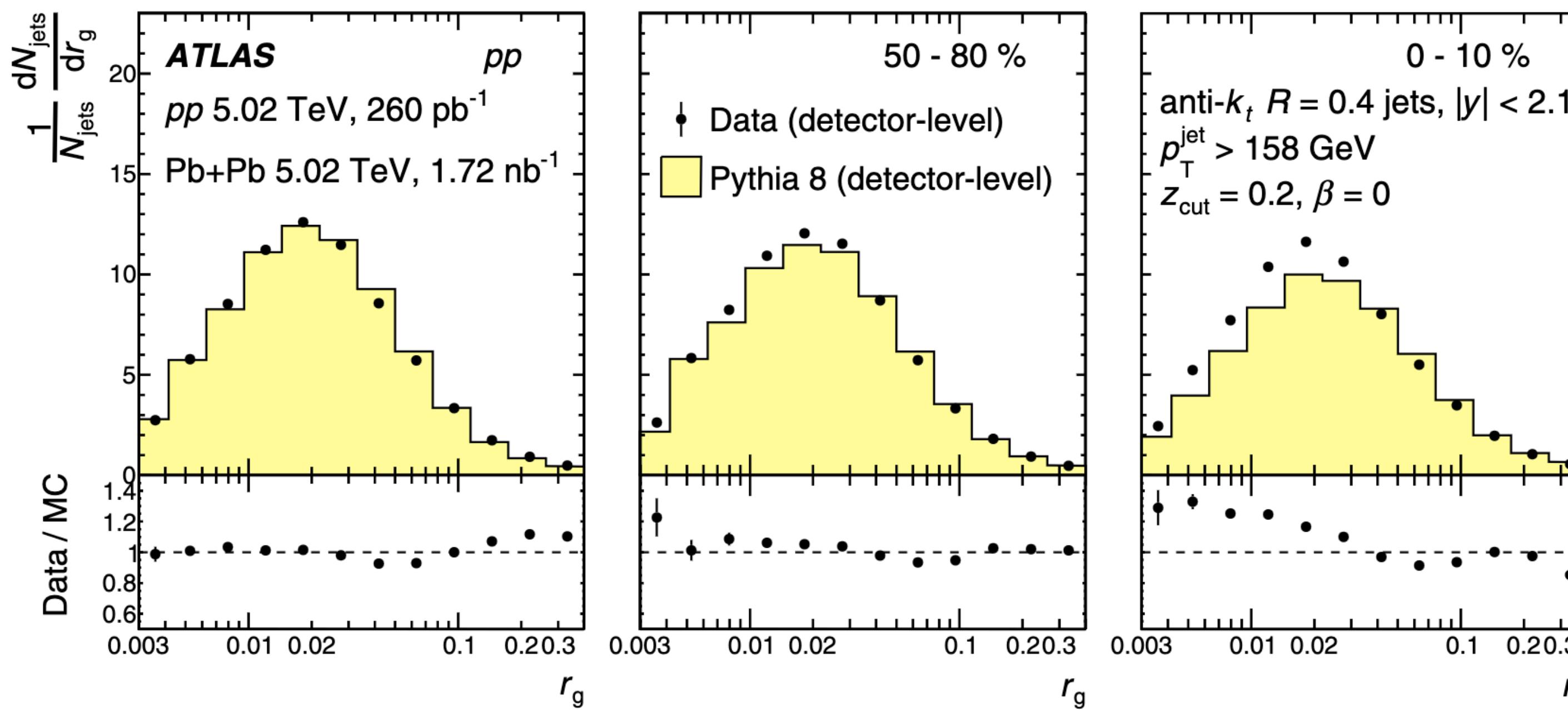
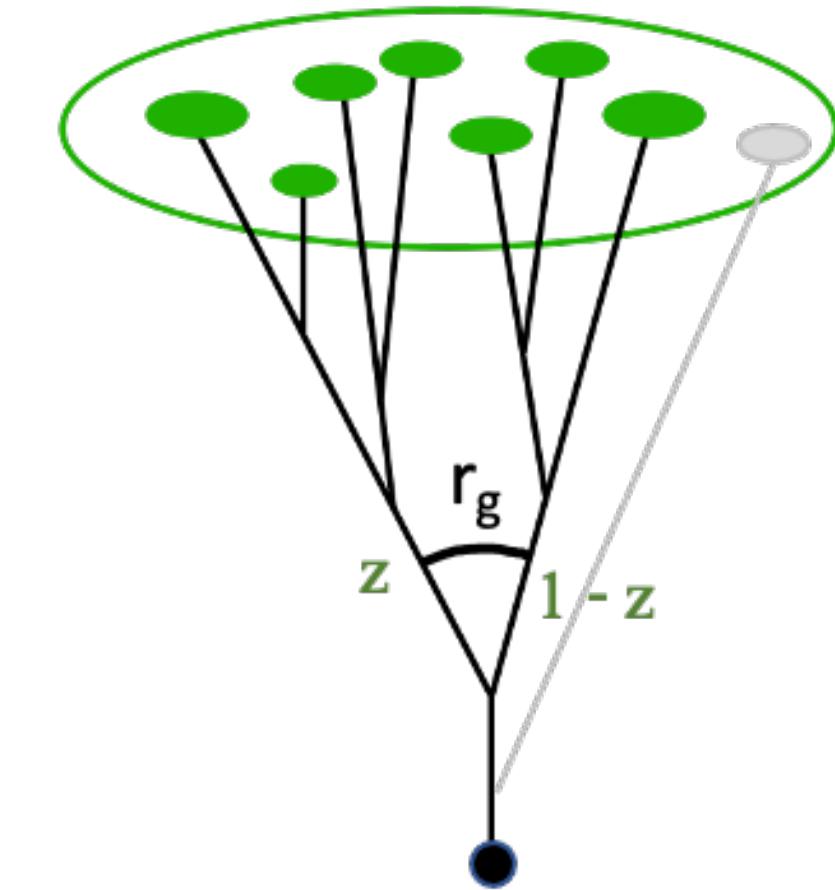
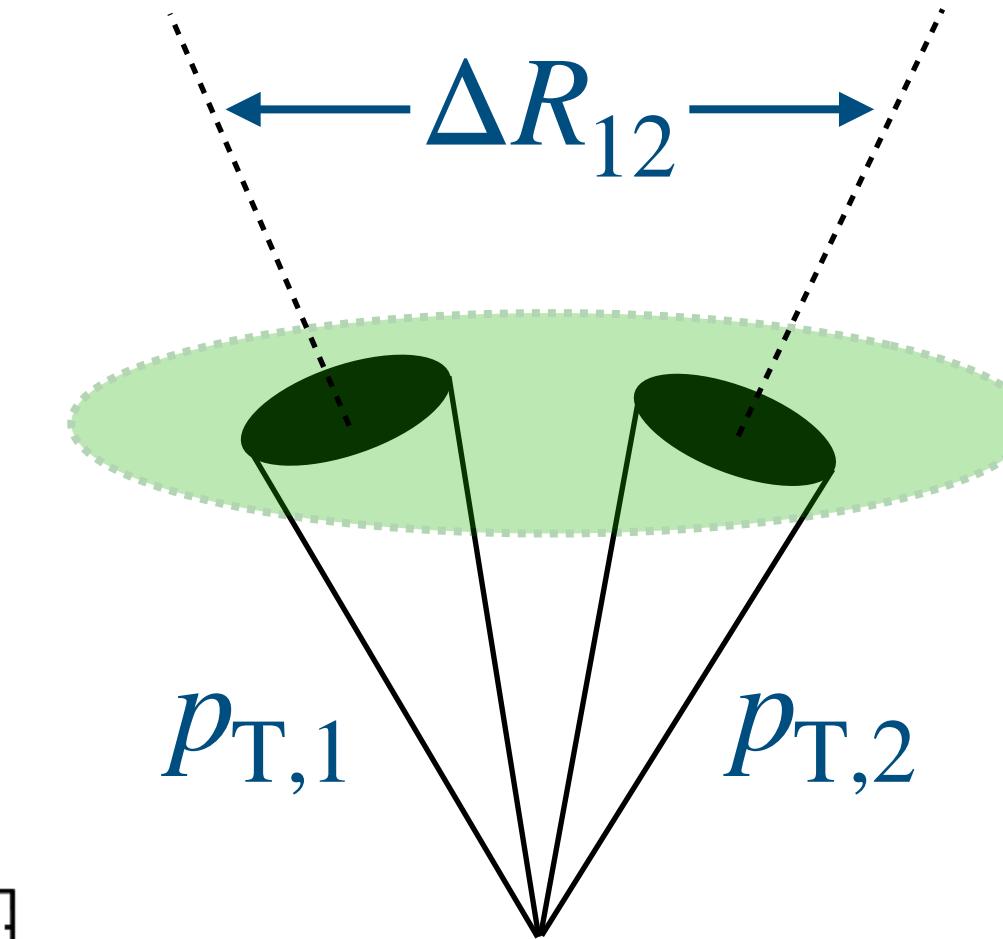
Track Calo-Clusters (TCCs)

- Objects built using tracks matched to topo-clusters
- Use angular information from charged tracks
- Energy information from topo-clusters, shared between TCCs
- ϕ - modulated background subtraction applied at cell-level in topo-cluster reconstruction in heavy-ion collisions

r_g with TCCs vs. Truth

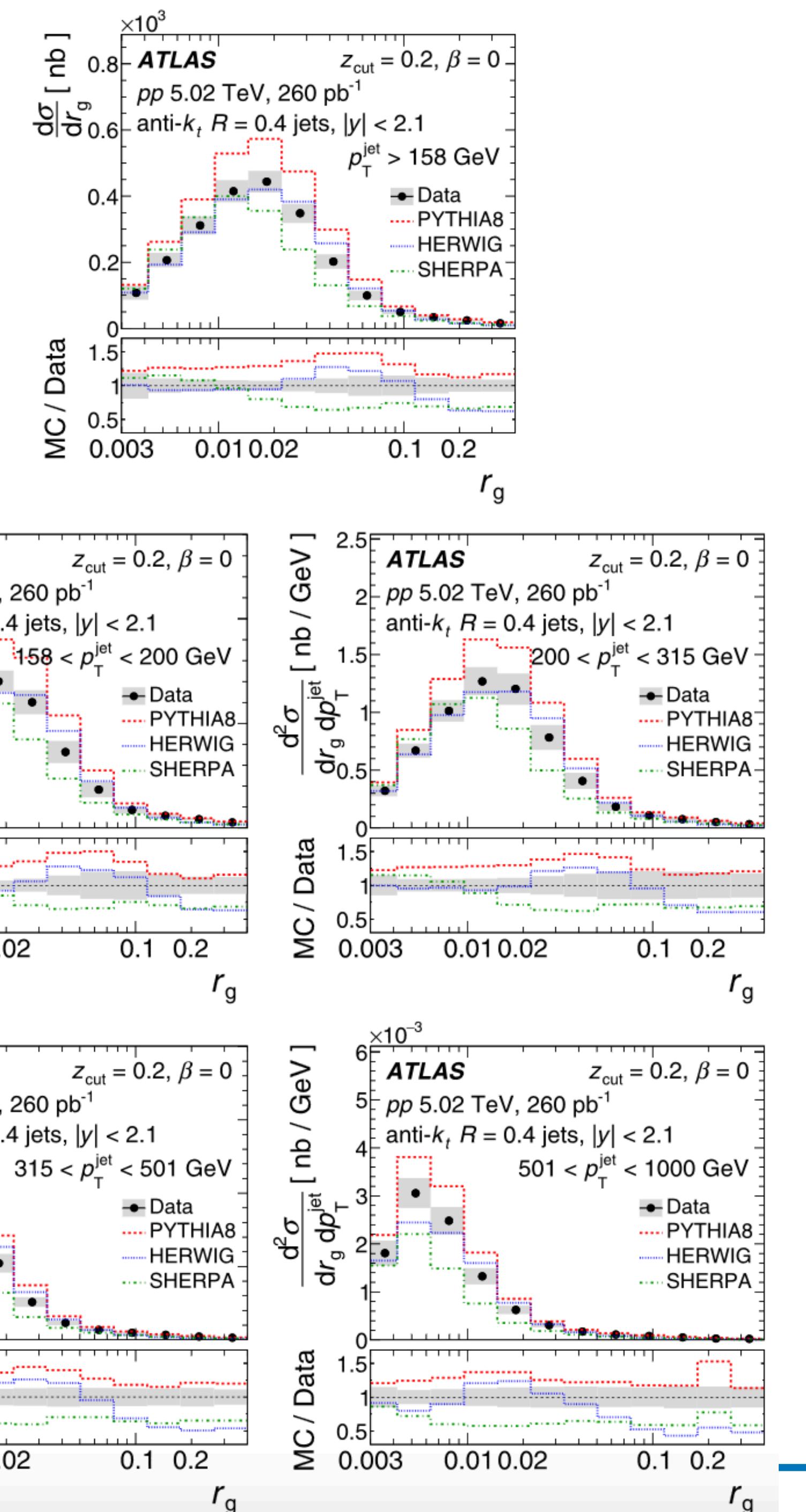
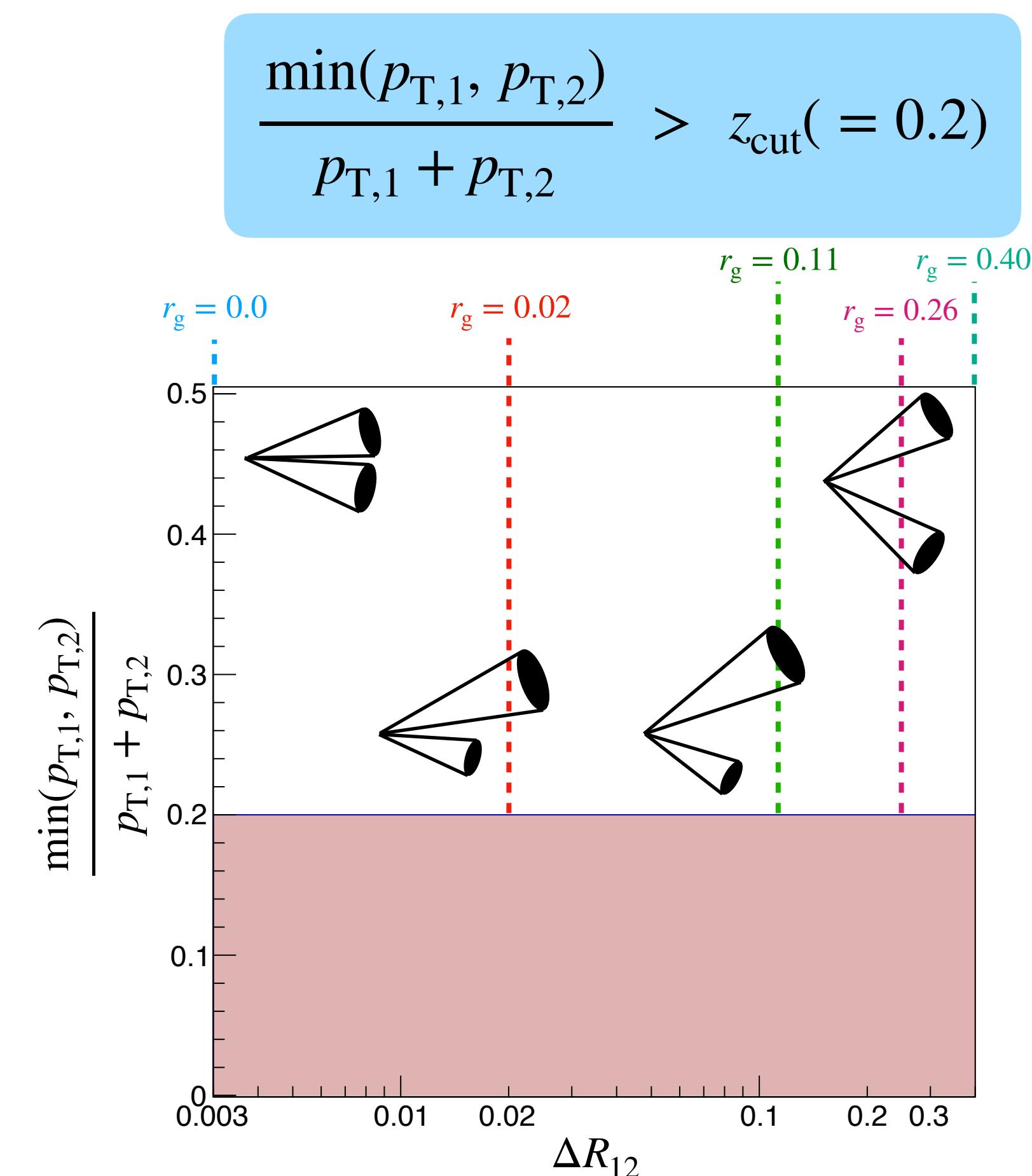
- Characterize a jet using the angular separation of its hardest splitting (r_g)
- TCCs show significantly improved performance in measuring r_g

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} (= 0.2)$$

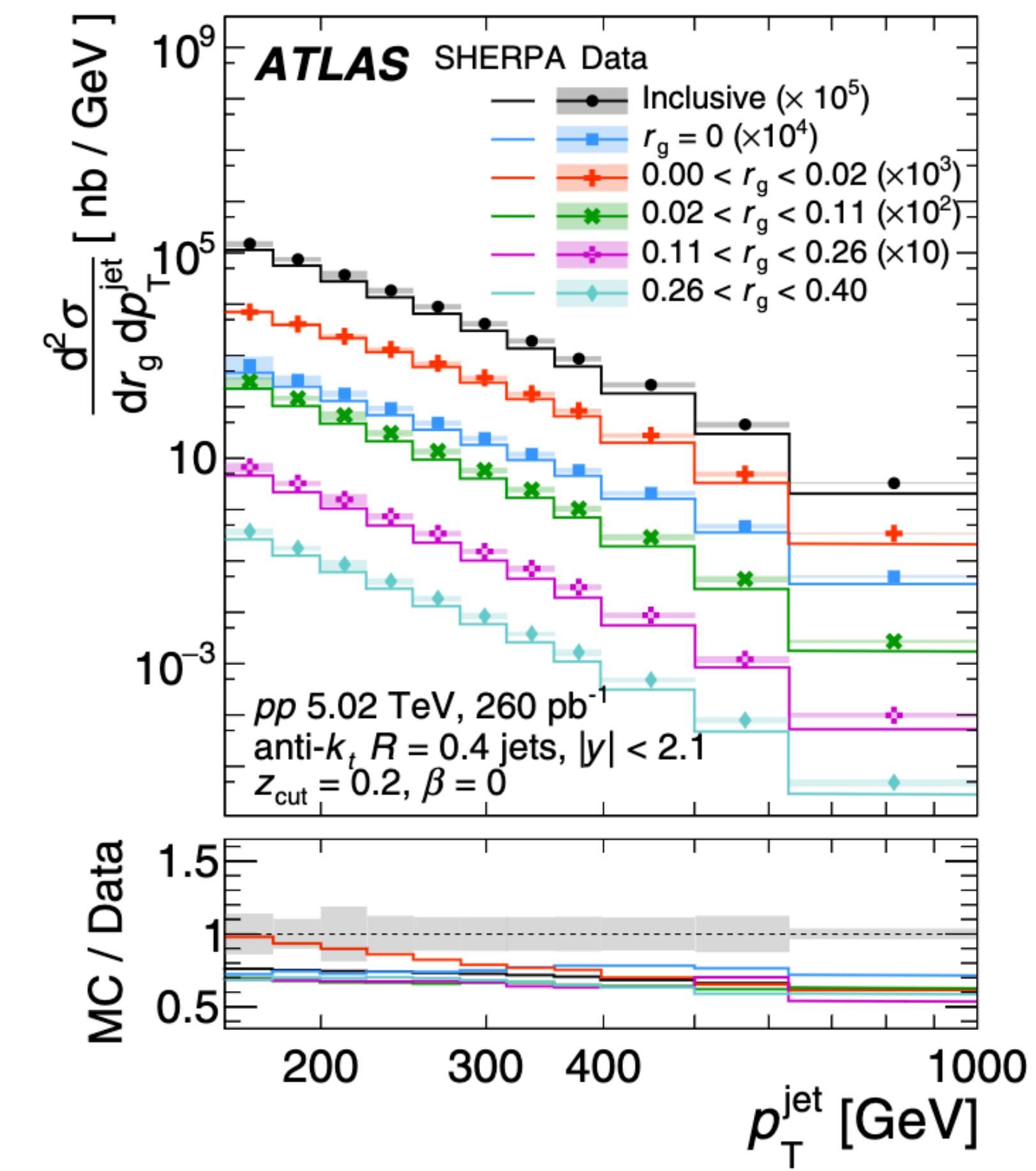
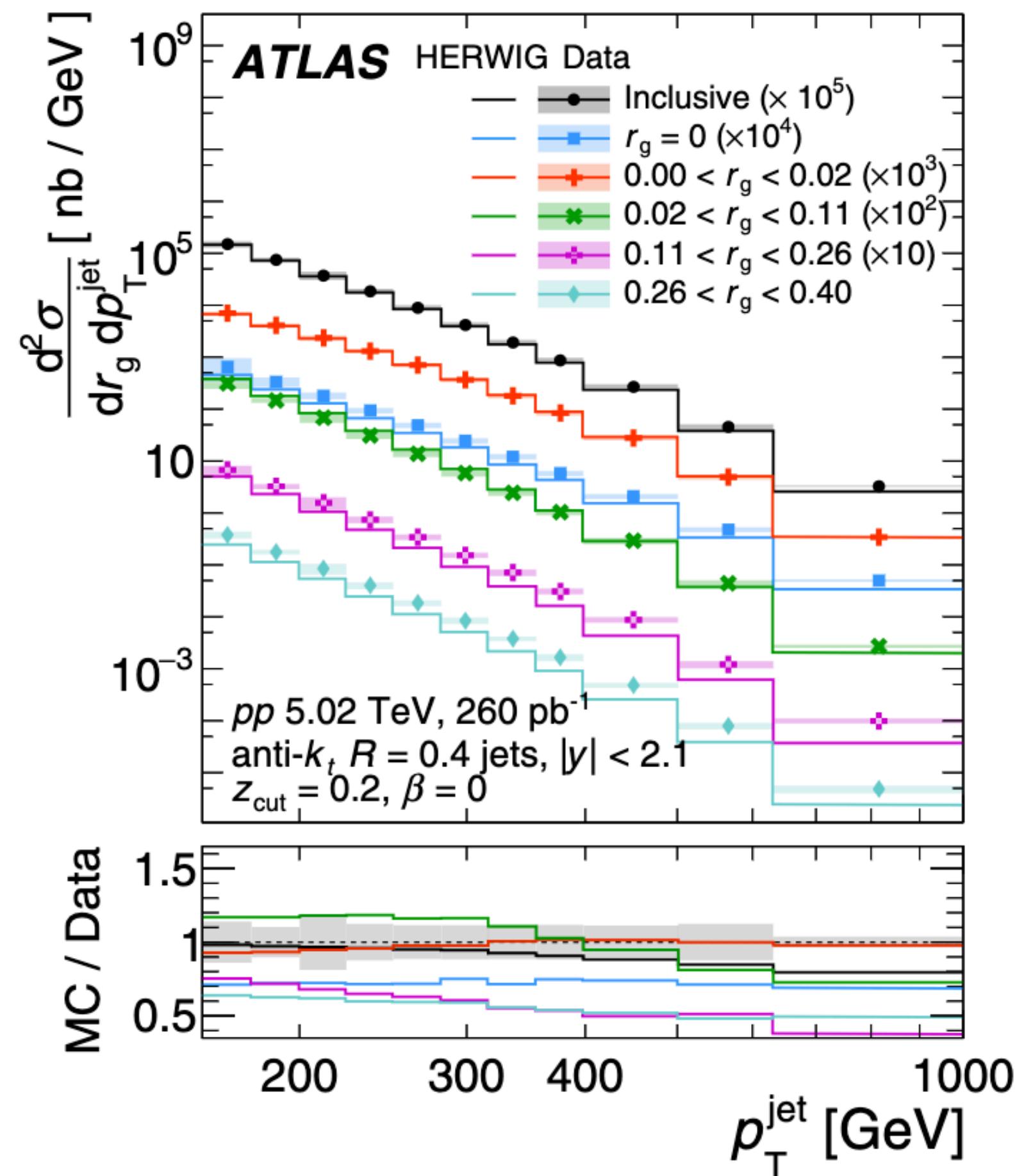
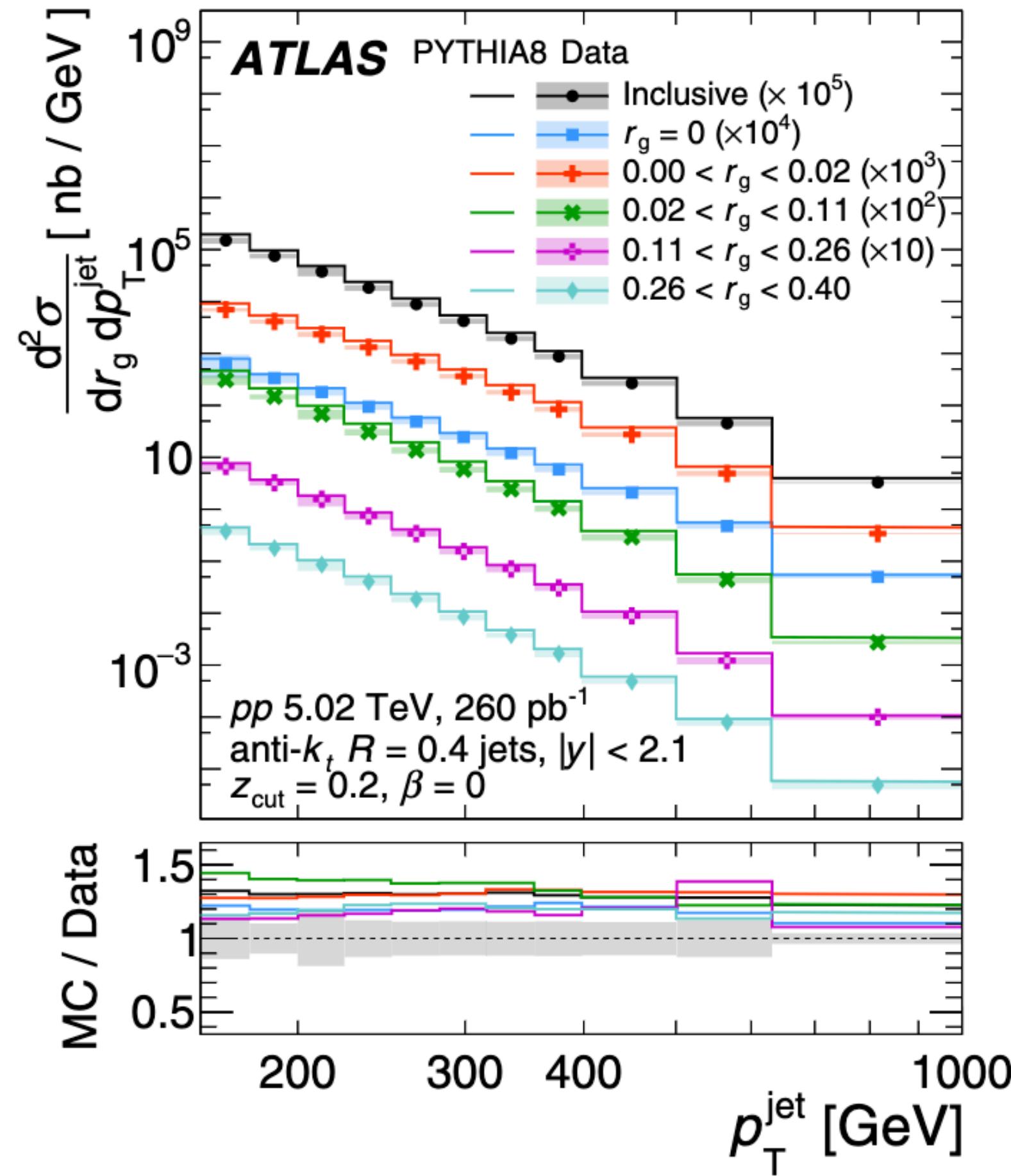


Unfolded jet r_g distributions

- Measurements of jet r_g unfolded to the truth hadron level for pp collisions
- r_g distributions get narrower with increasing jet p_T

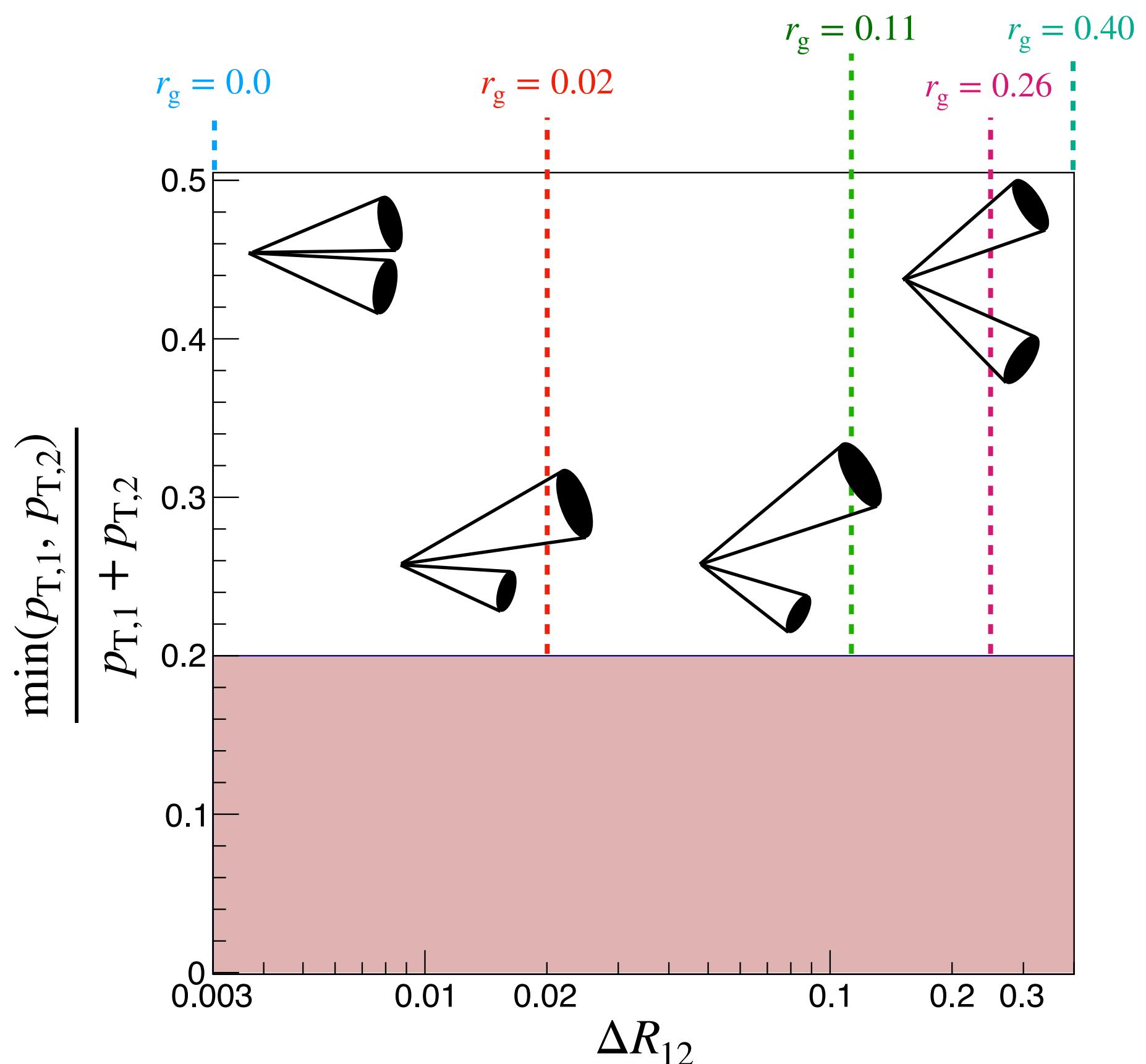
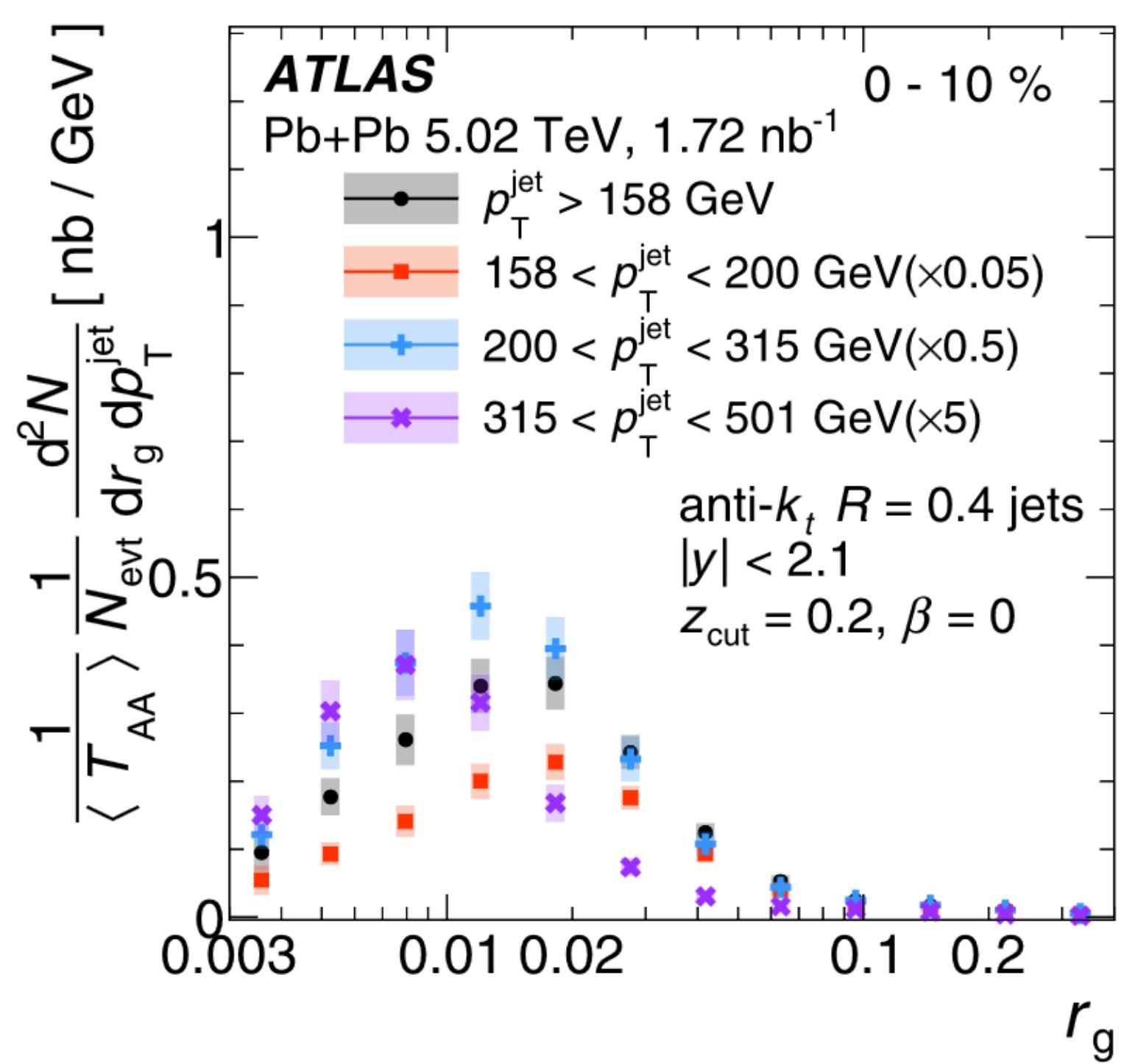
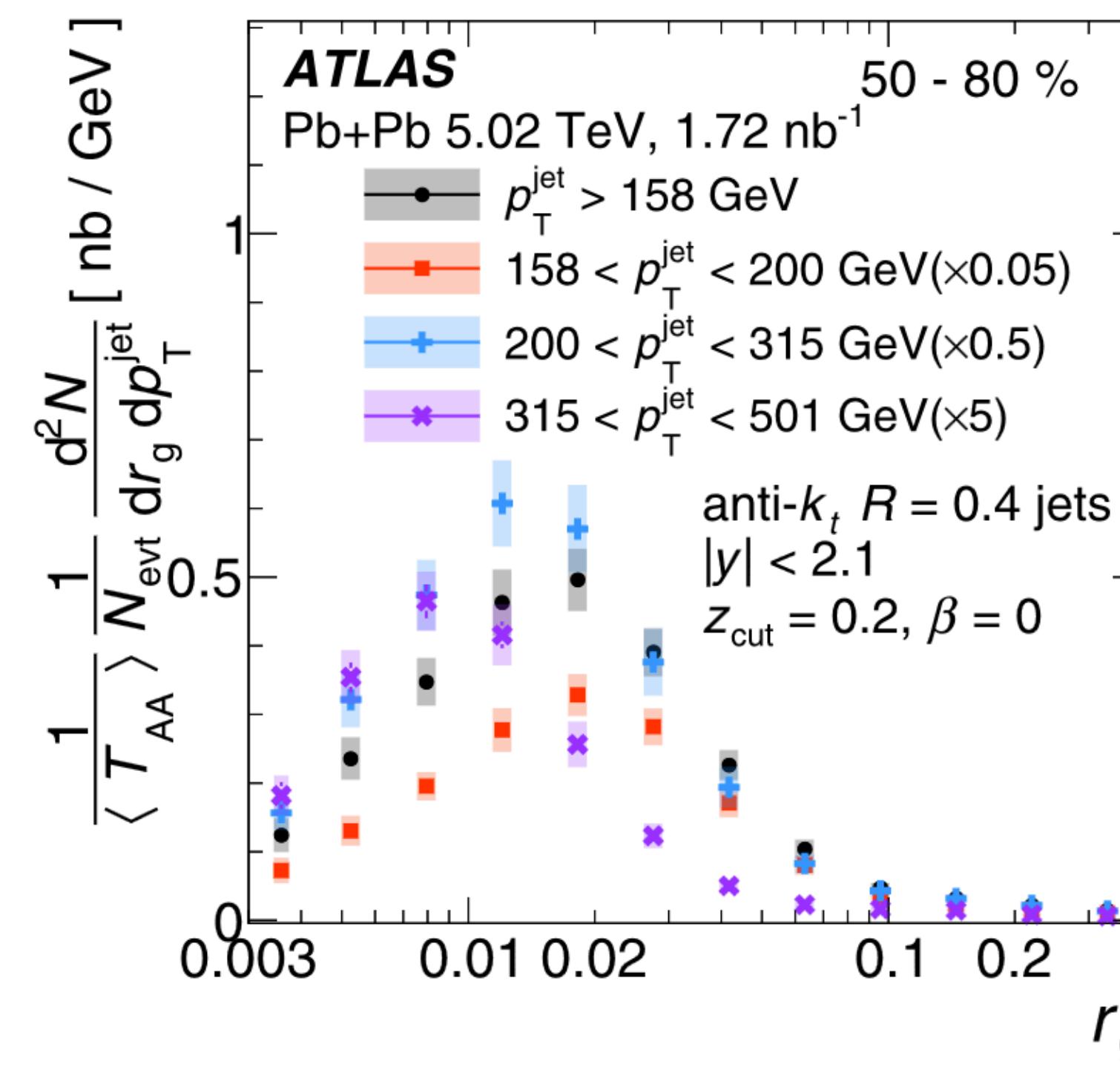
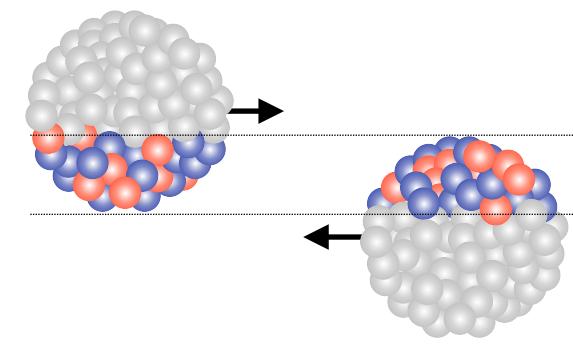


Unfolded jet p_T distributions



Unfolded jet r_g distributions

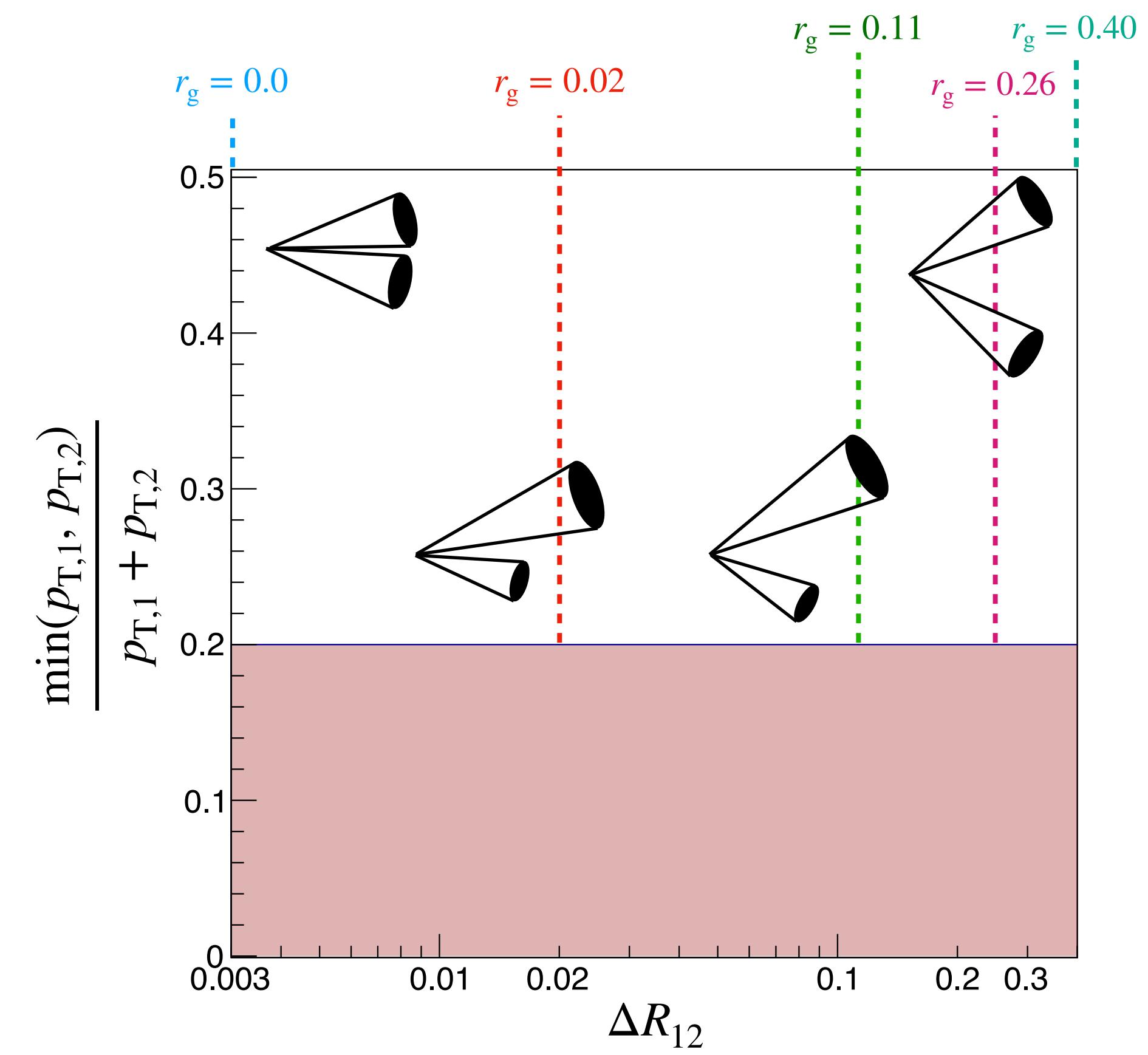
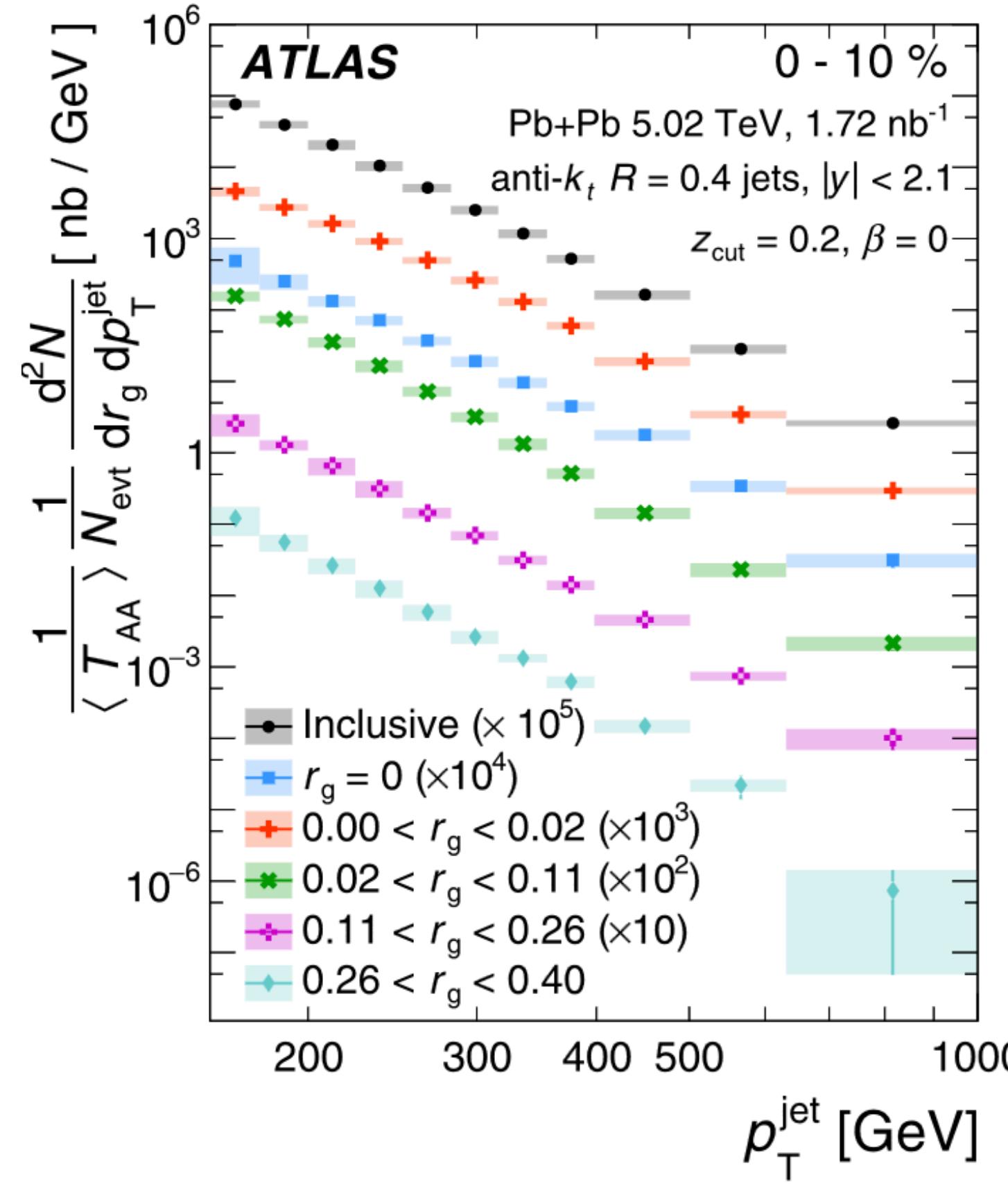
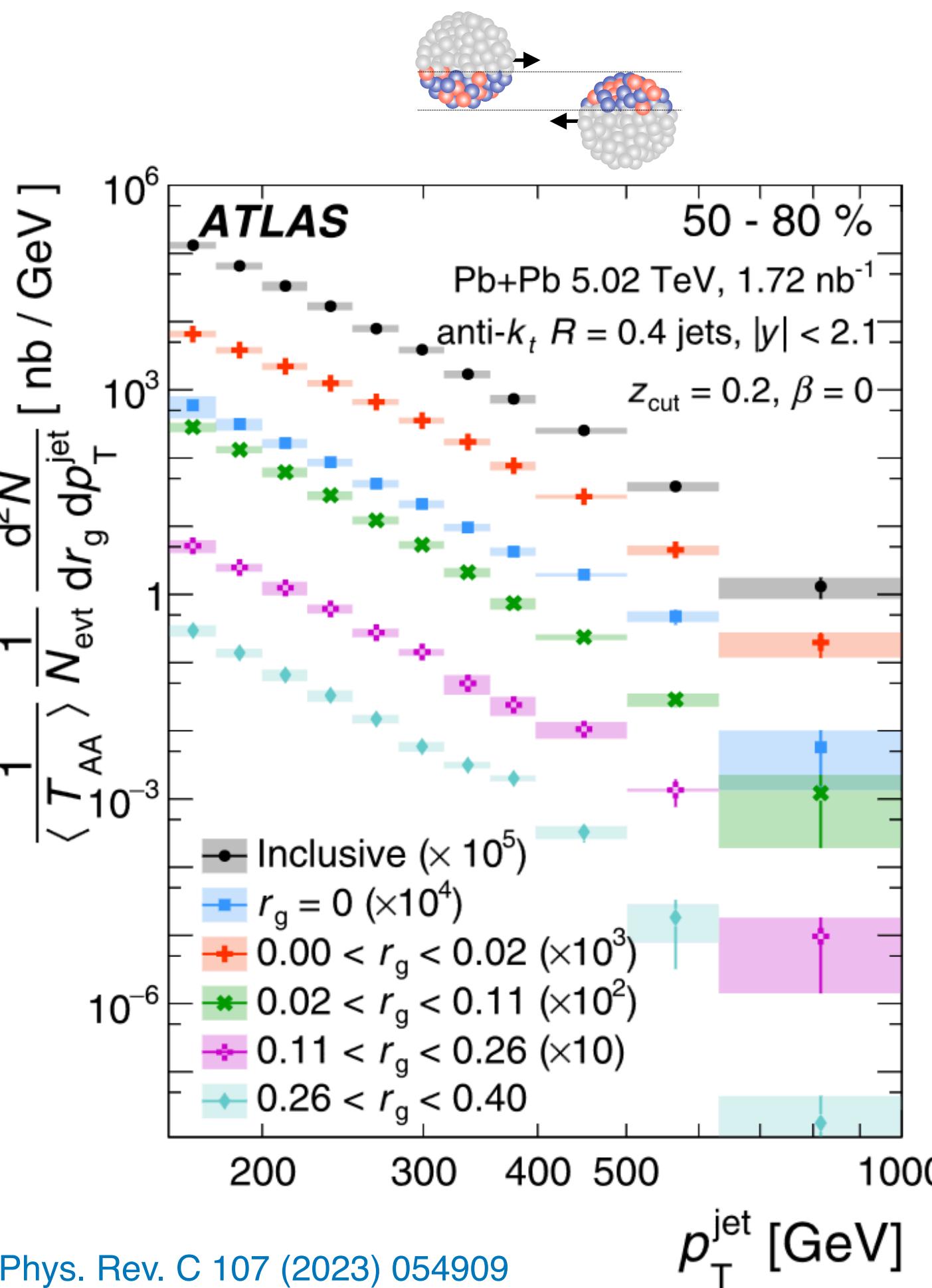
- Measurements of jet r_g unfolded to the truth hadron level for PbPb collisions
- Results shown differentially in event centrality and jet p_T intervals



$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} (= 0.2)$$

Unfolded jet p_T distributions

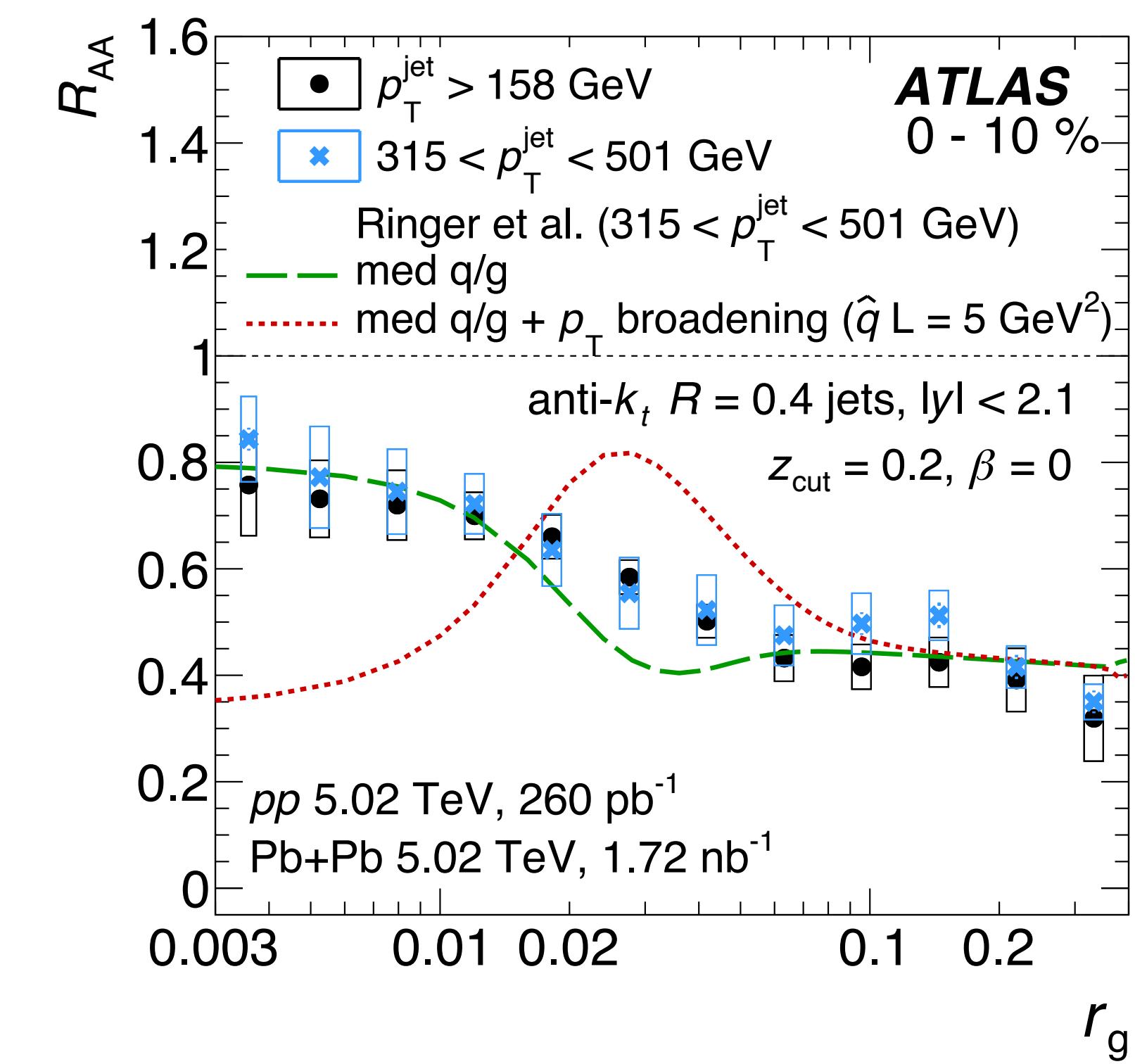
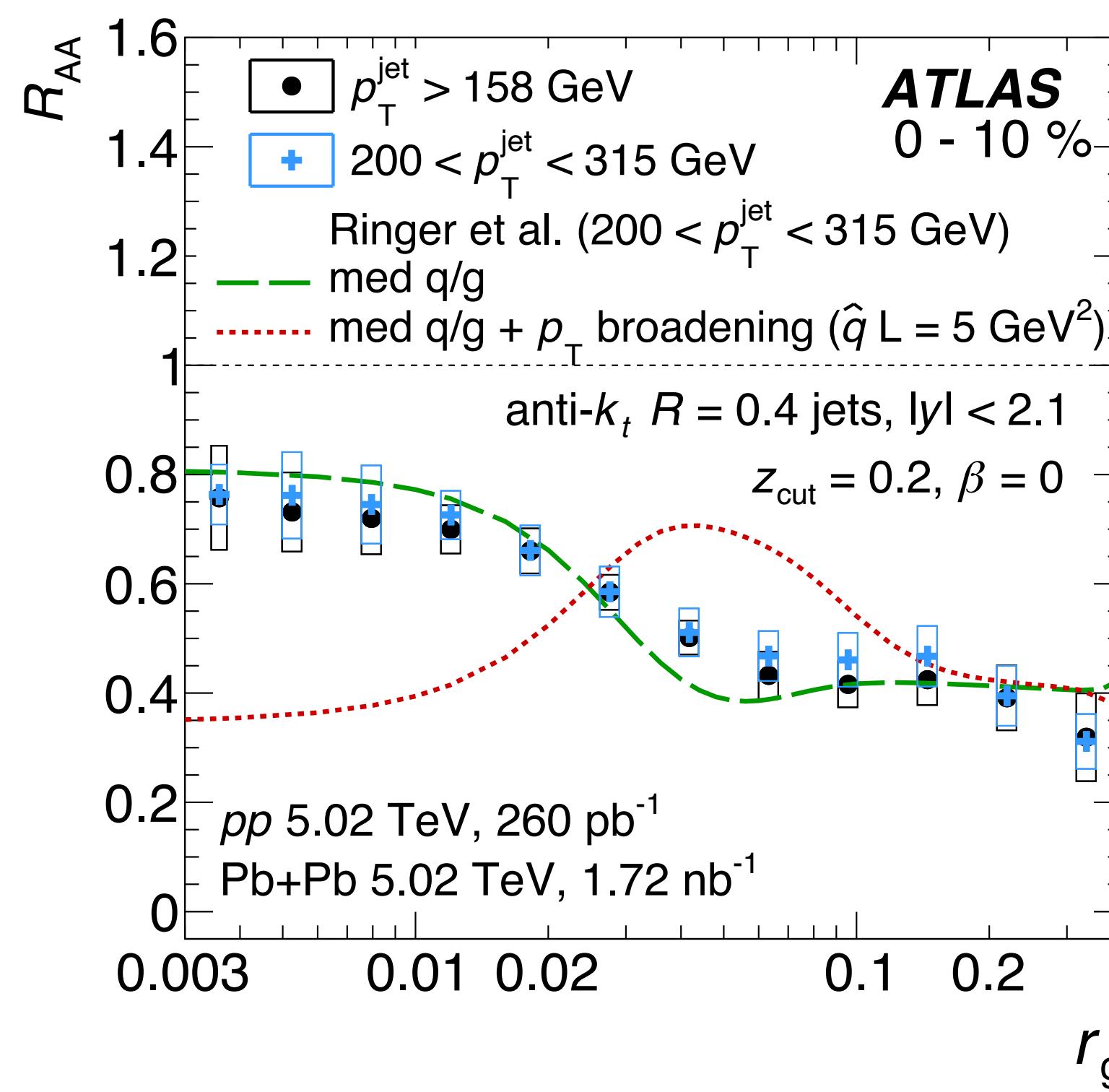
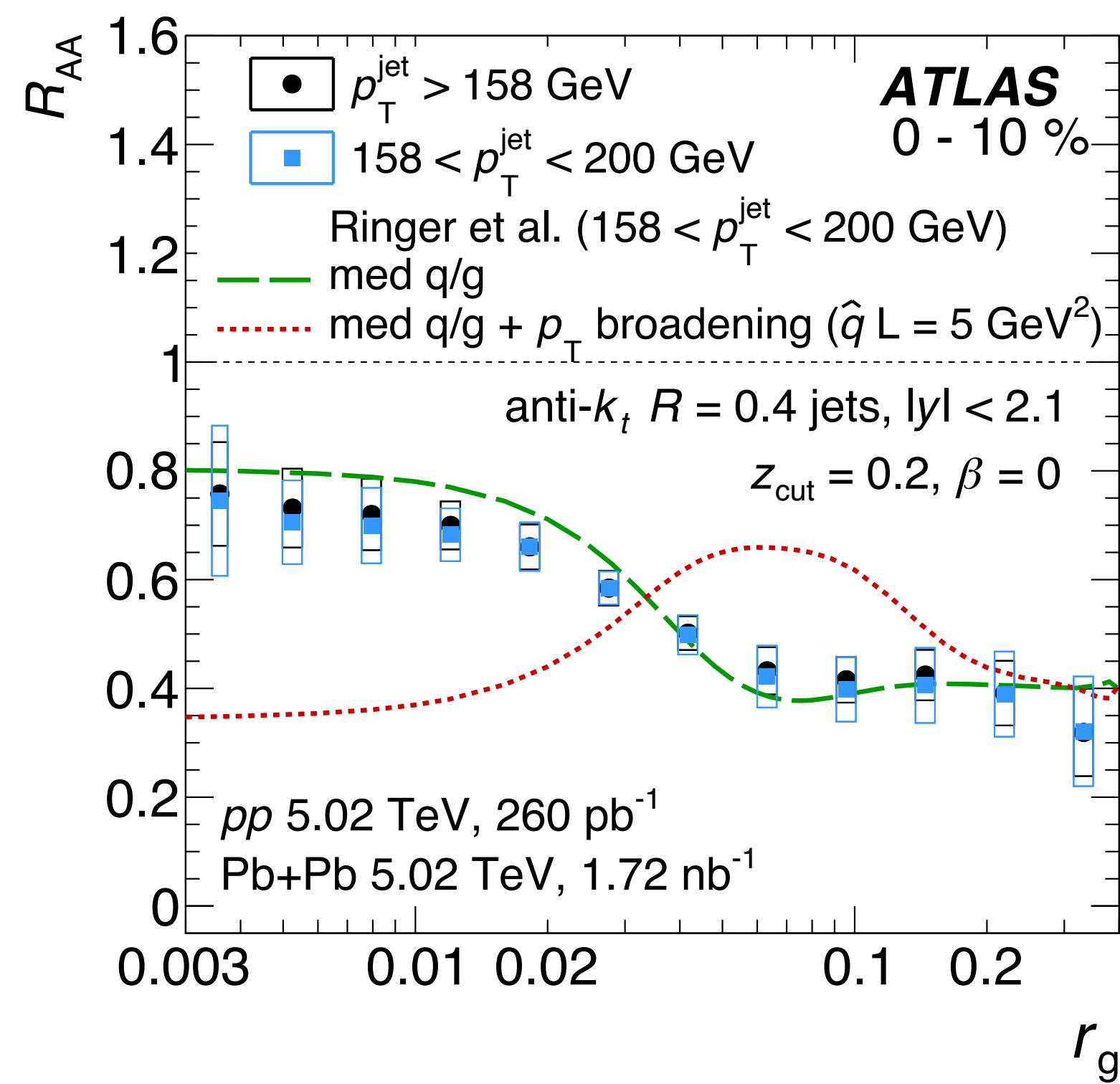
- Measurements of jet p_T unfolded to the truth hadron level for PbPb collisions
- Results shown differentially in jet r_g intervals



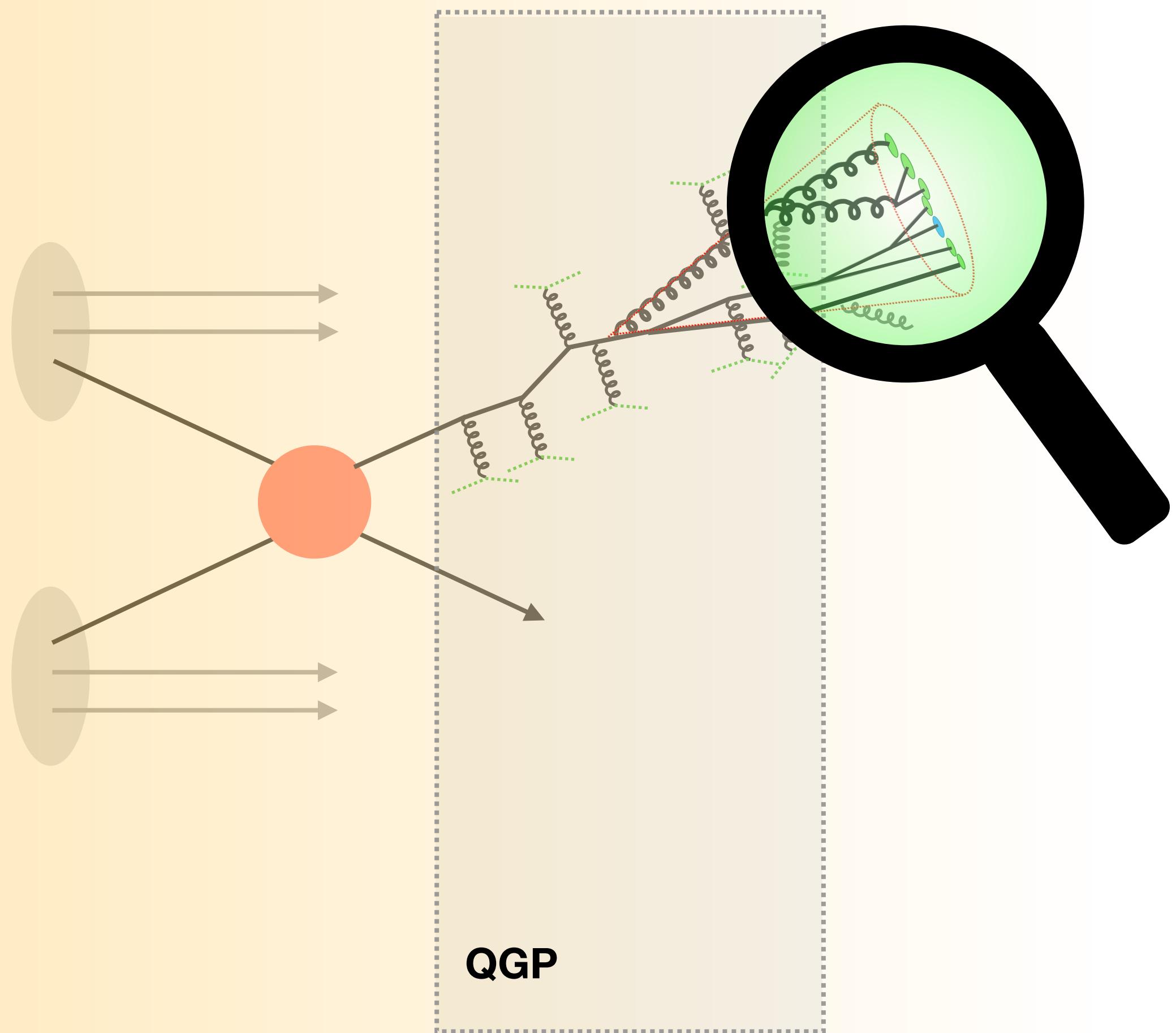
$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} (= 0.2)$$

Theory predictions

- Jet suppression (R_{AA}) as a function of its hardest splitting angle (r_g) compared to predictions from **q/g(+ p_T broadening) model**
- r_g -dependent R_{AA} behavior also described by model implementing empirical **quark vs. gluon energy loss**

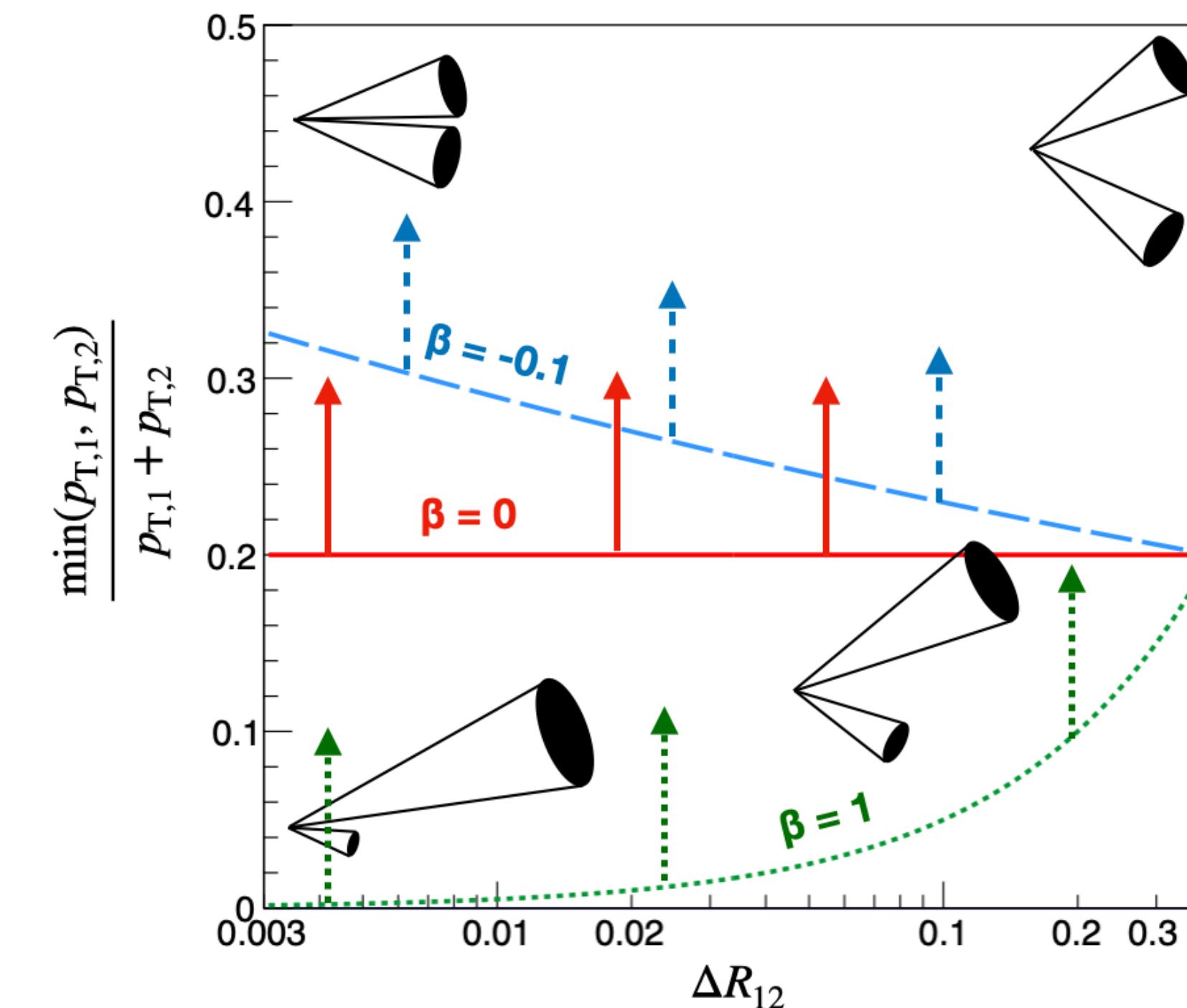


Jet substructure vs. suppression



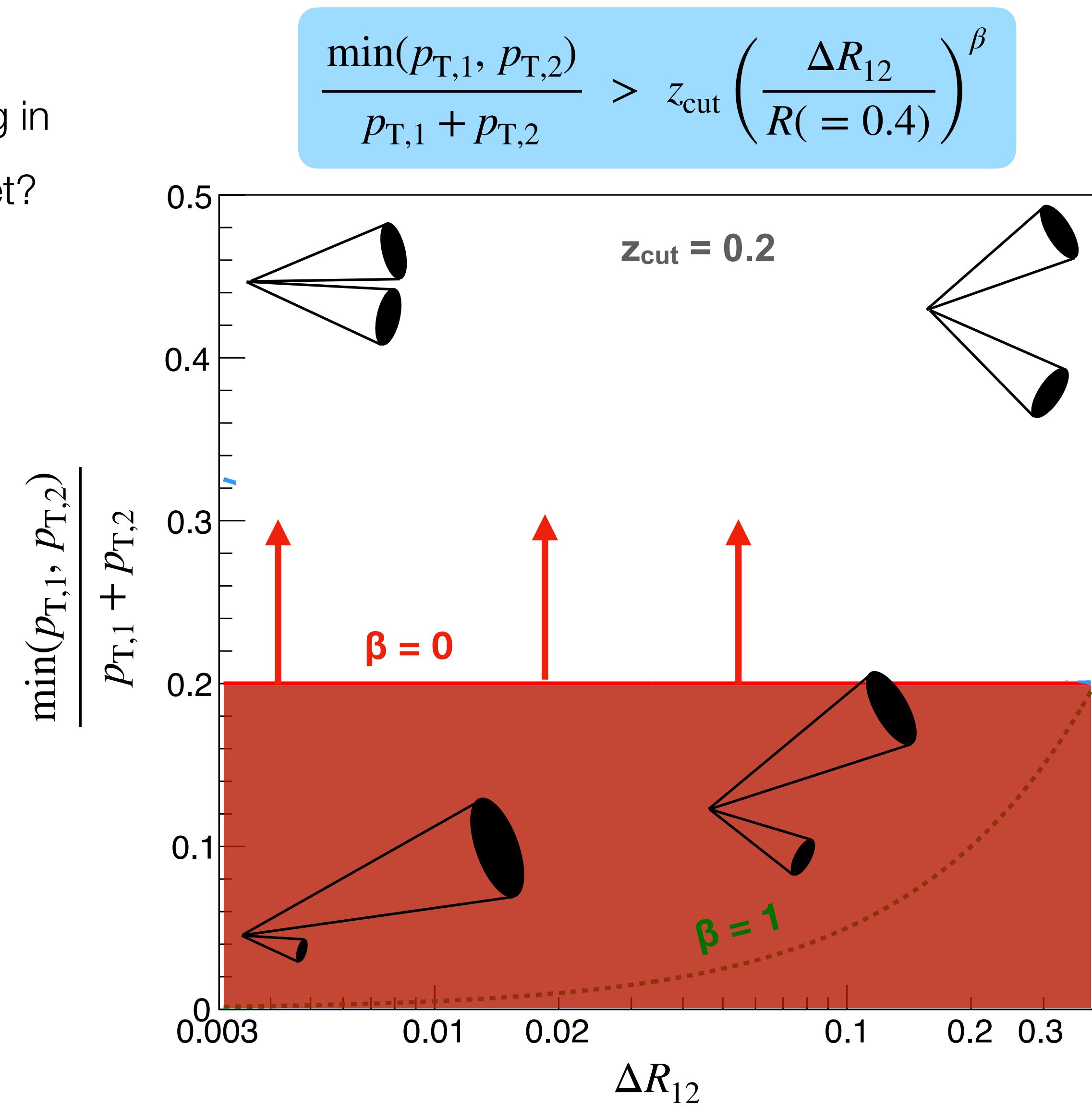
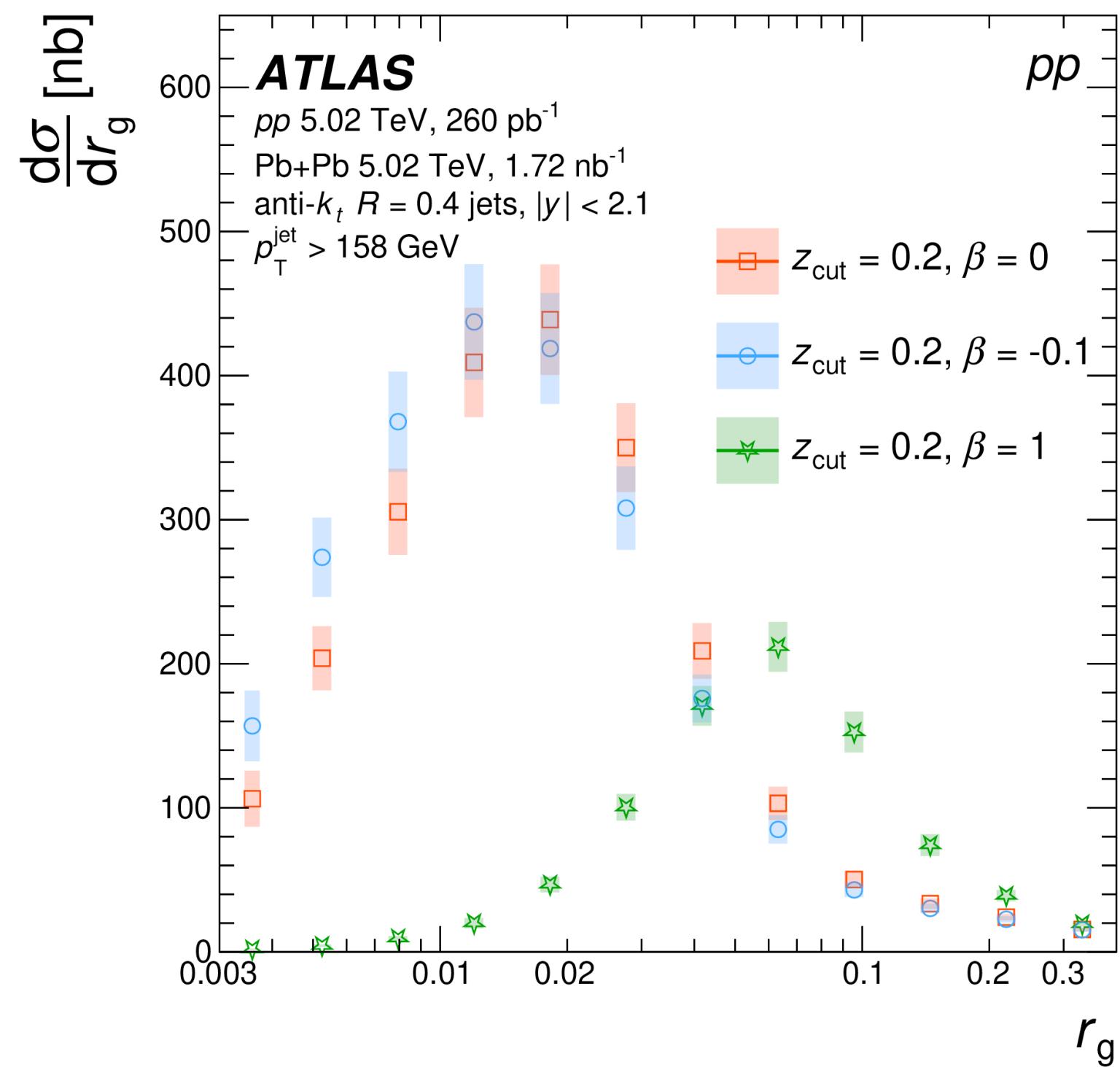
Soft Drop condition

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R(=0.4)} \right)^\beta$$



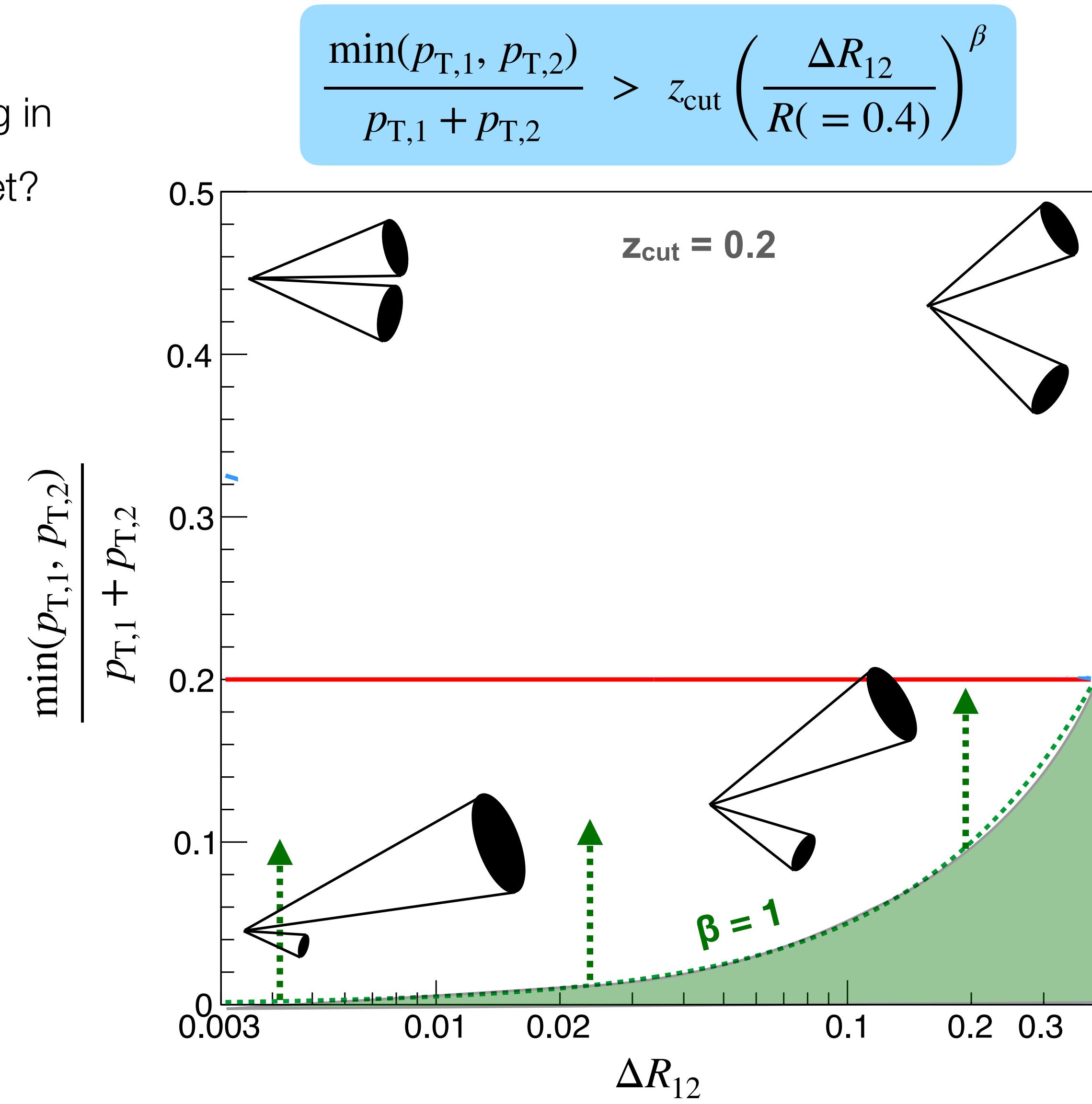
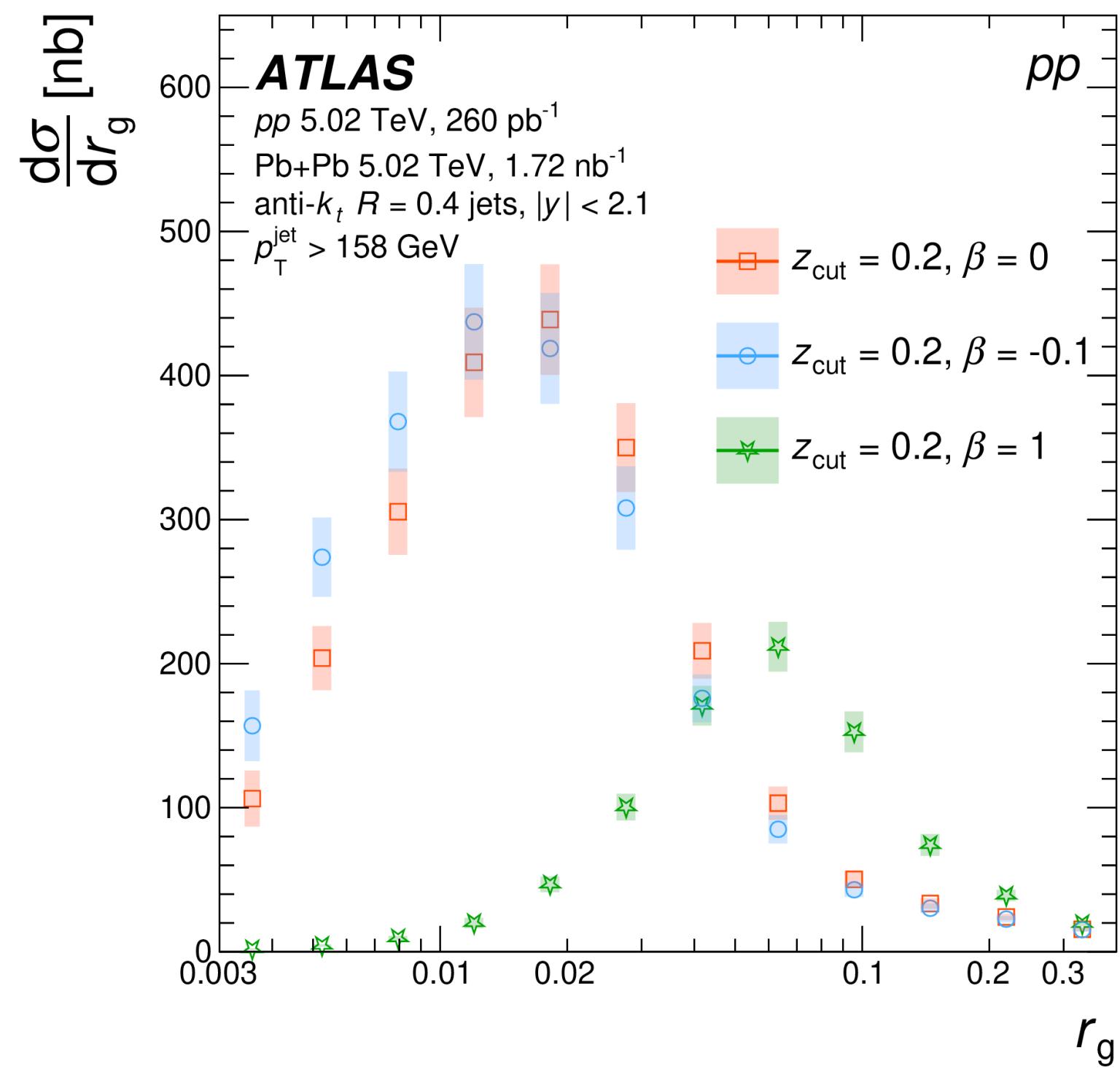
Soft Drop Parameters

- What is the effect of including angle-dependent grooming in Soft-Drop on measuring the hardest splitting angle of a jet?



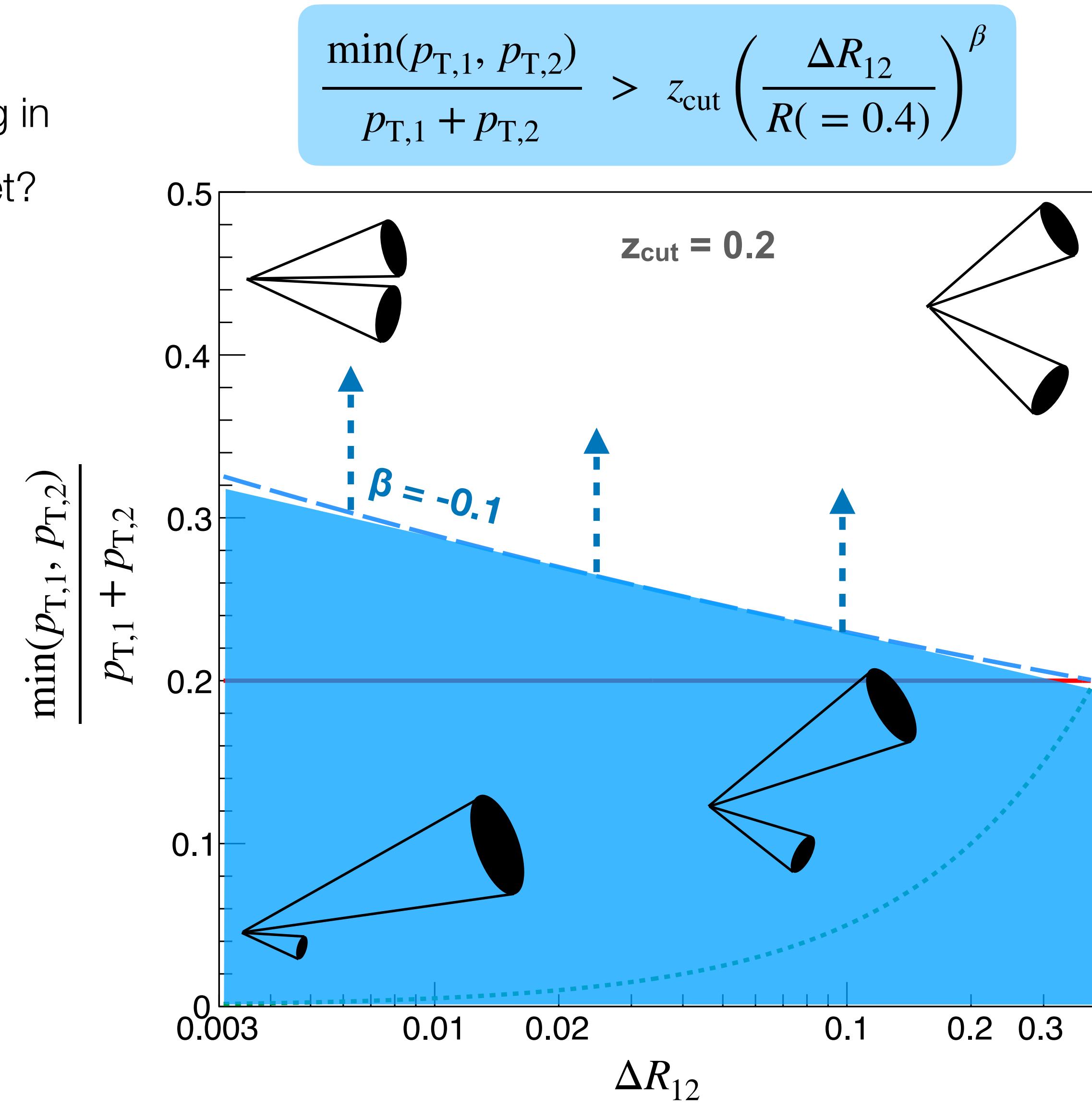
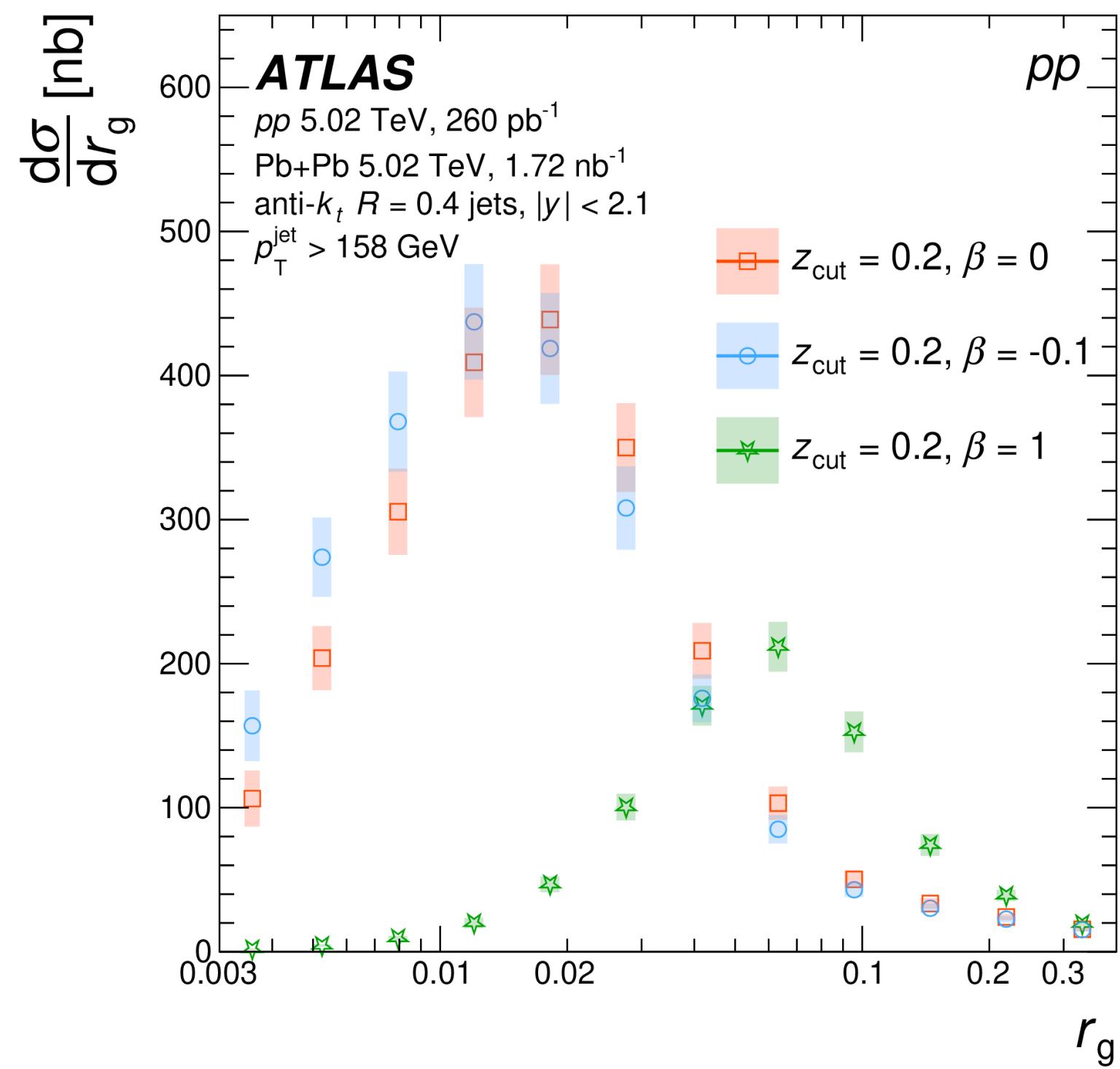
Soft Drop Parameters

- What is the effect of including angle-dependent grooming in Soft-Drop on measuring the hardest splitting angle of a jet?



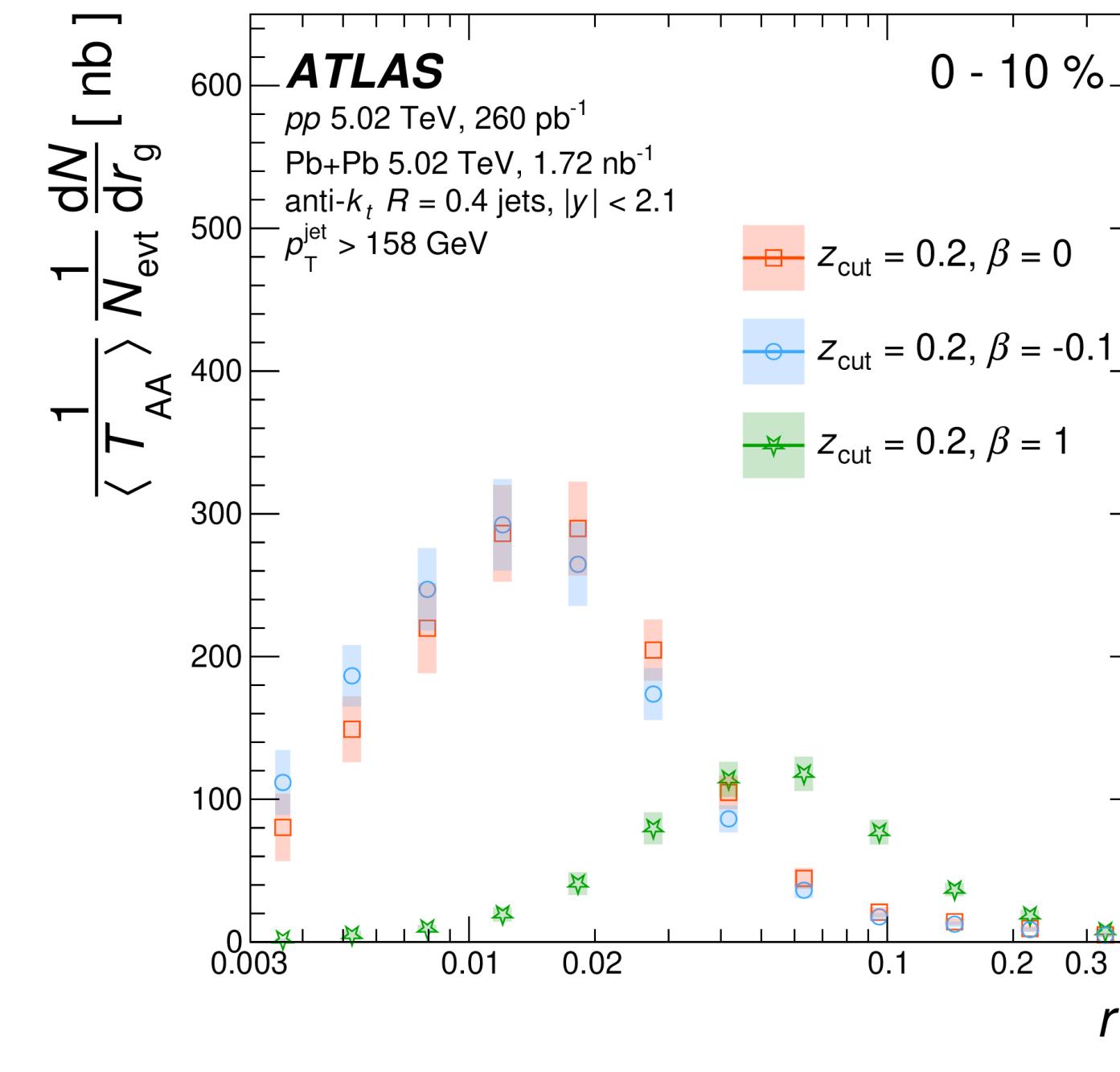
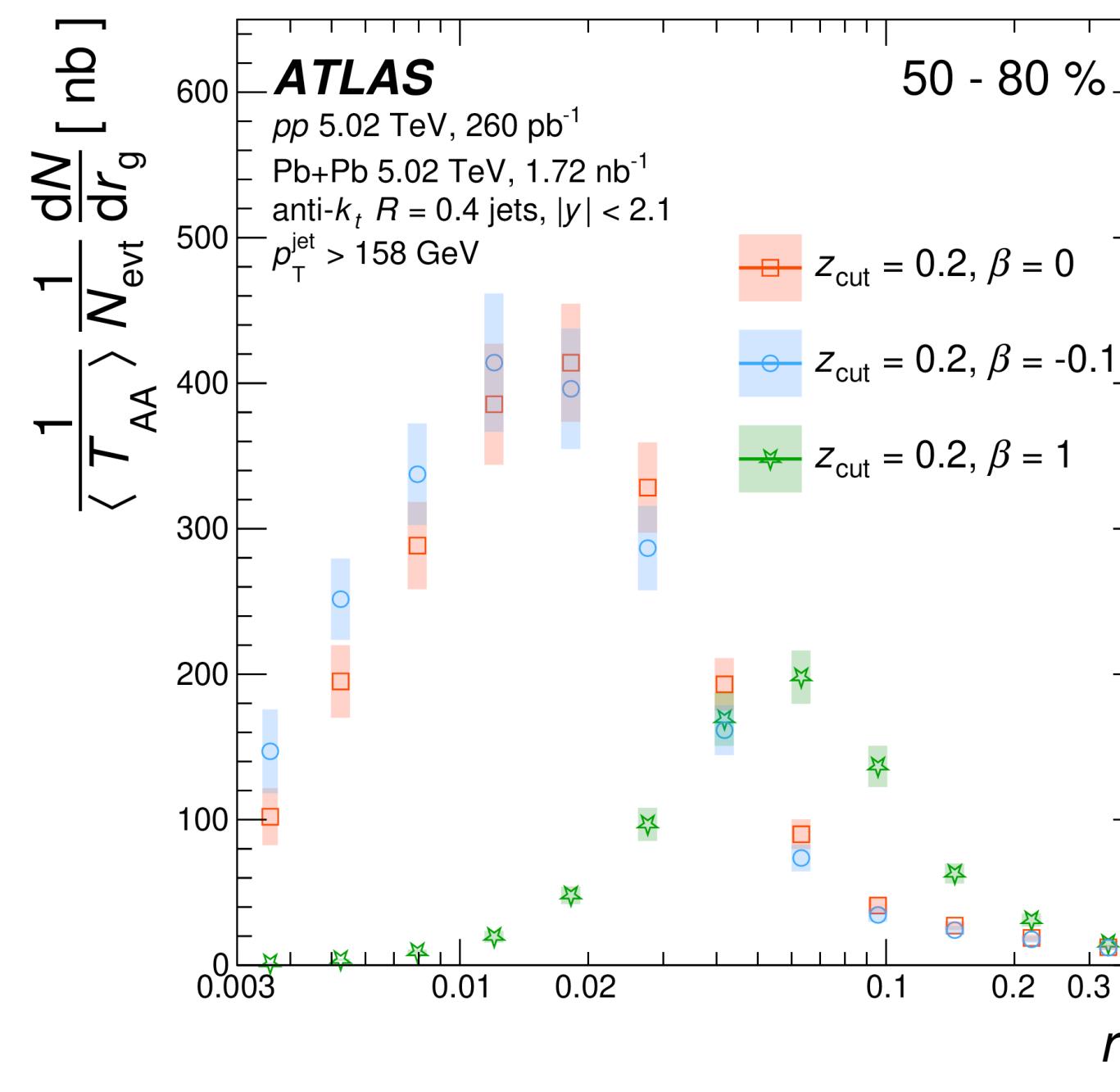
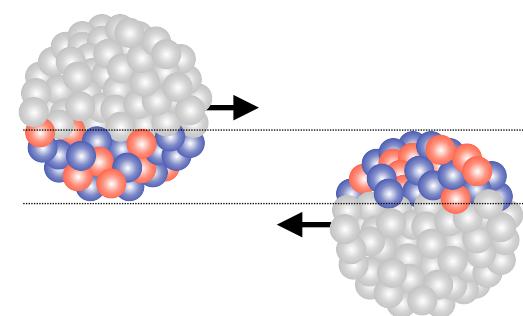
Soft Drop Parameters

- What is the effect of including angle-dependent grooming in Soft-Drop on measuring the hardest splitting angle of a jet?

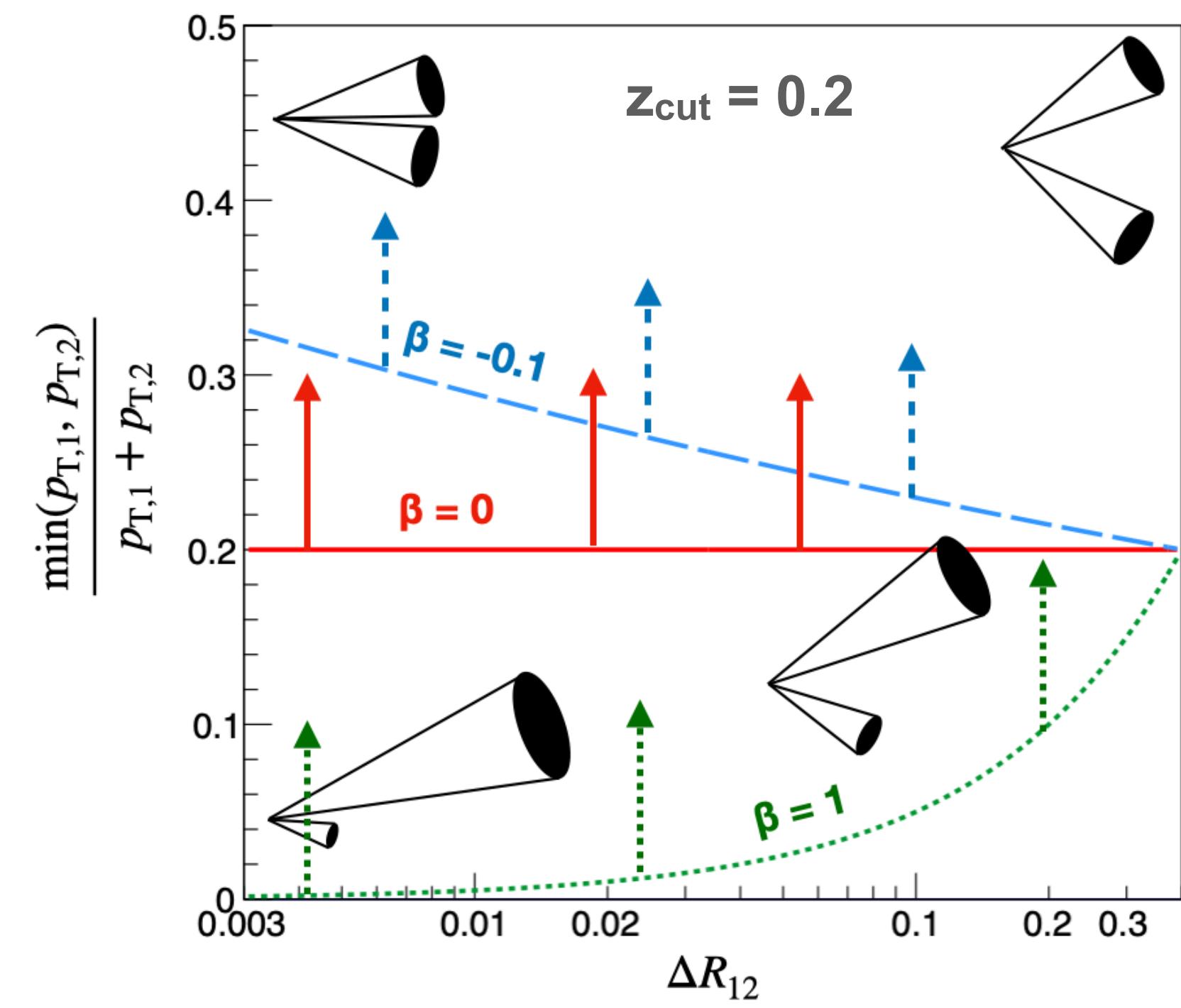


Soft Drop Parameters

- What is the effect of including angle-dependent grooming in Soft-Drop on measuring the hardest splitting angle of a jet?
- How do we reconcile the measurement of r_g using varying Soft-Drop parameters with the observed modifications of the jet's fragmentation function in the QGP?



$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R(=0.4)} \right)^\beta$$



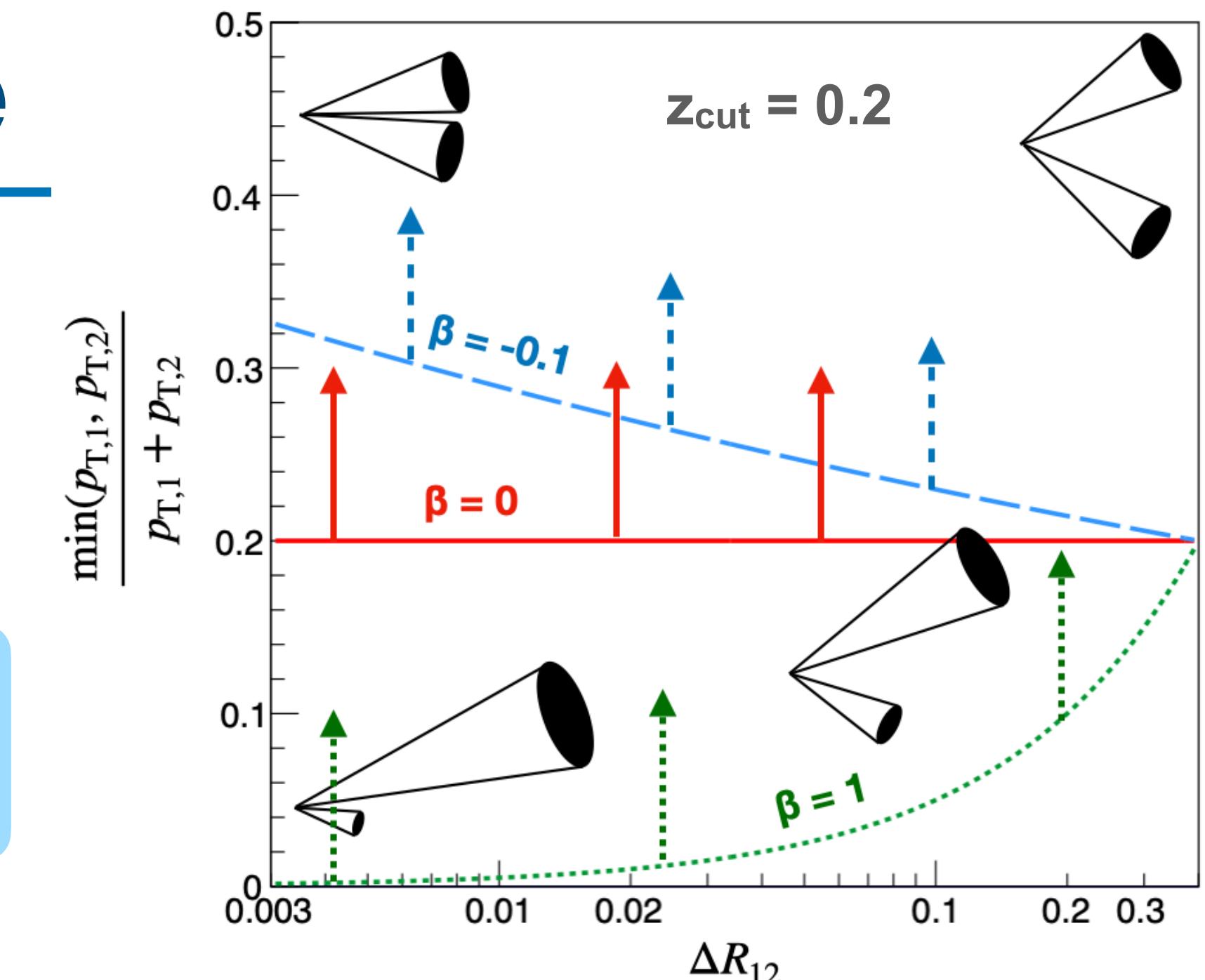
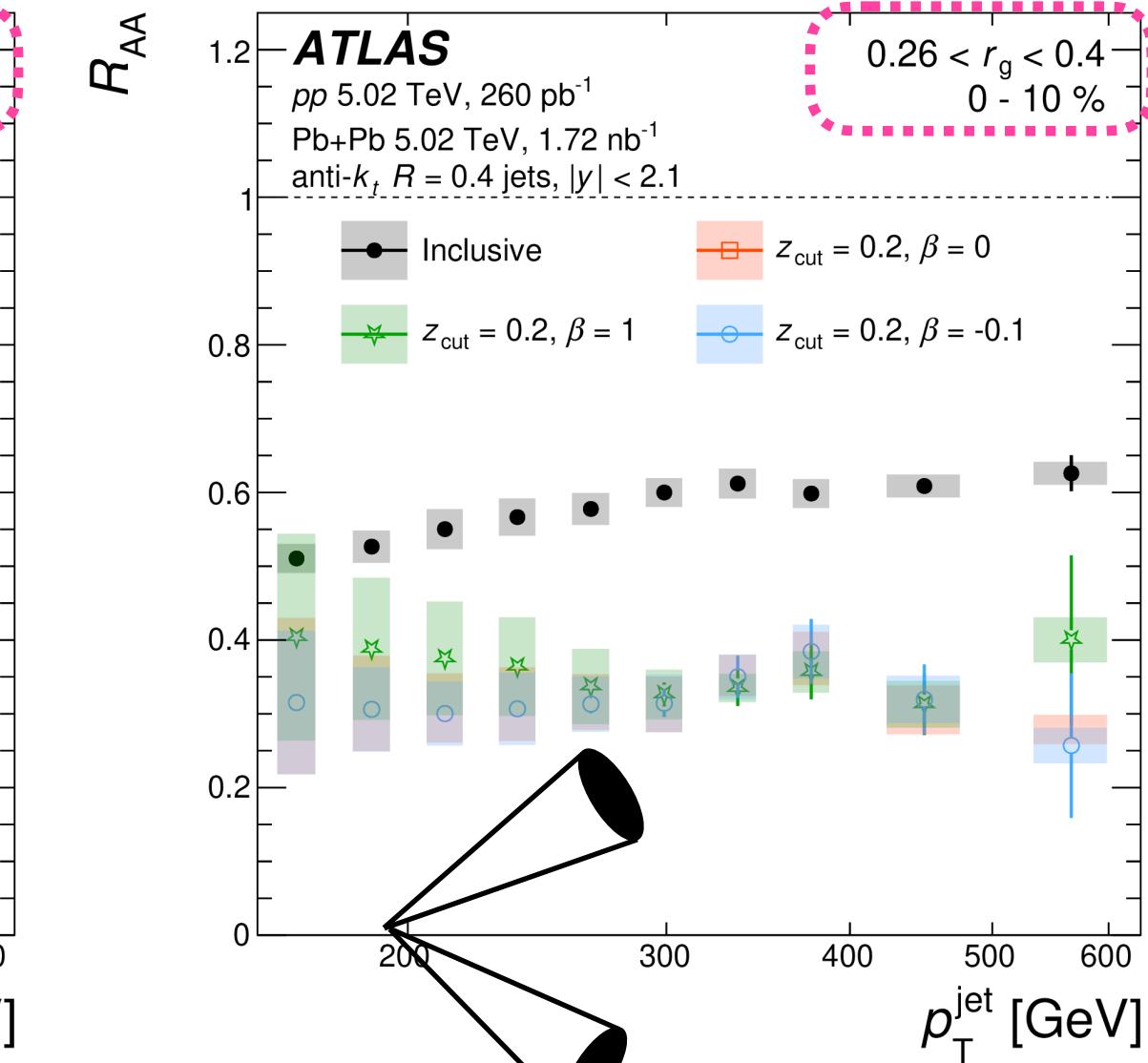
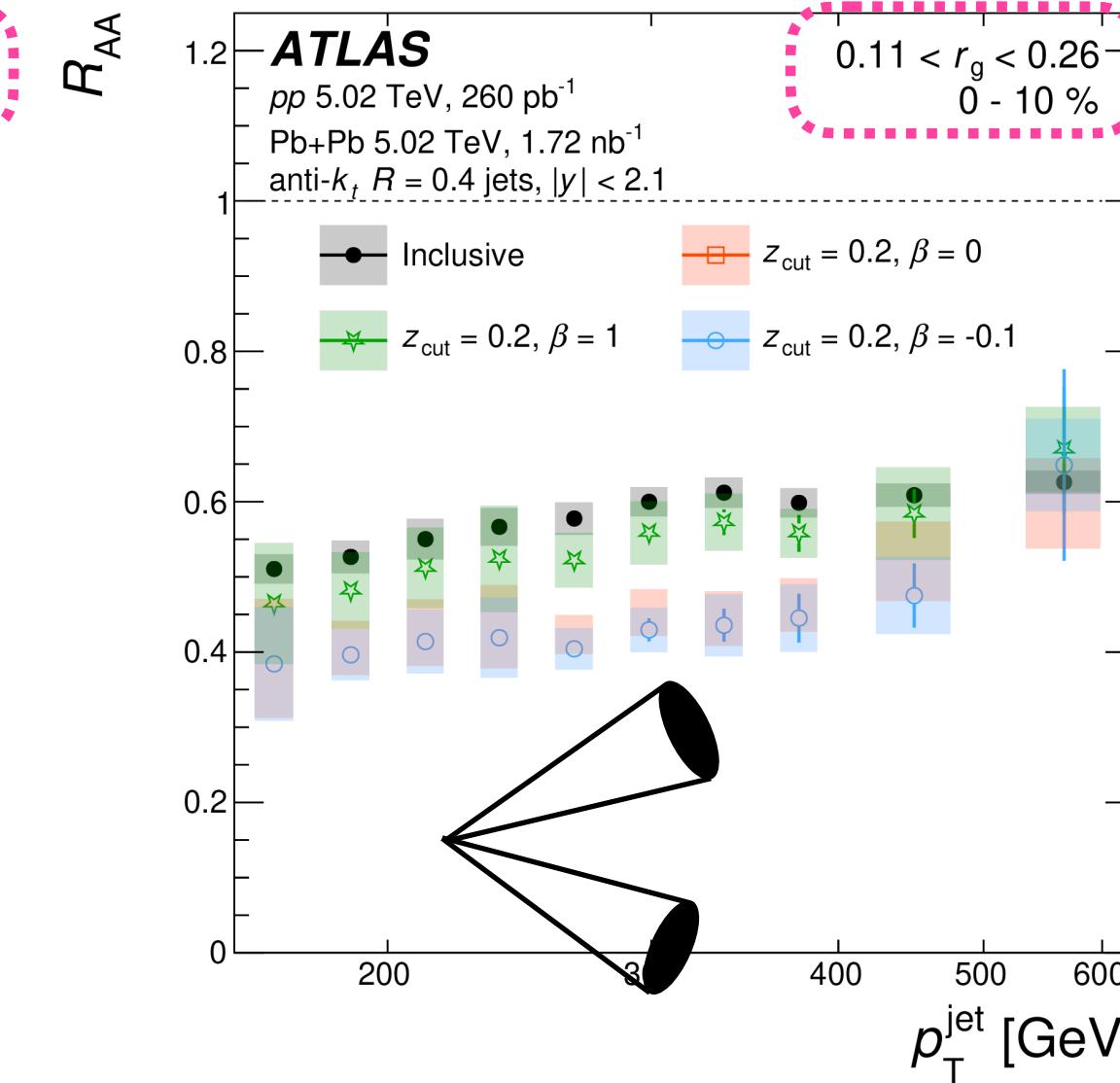
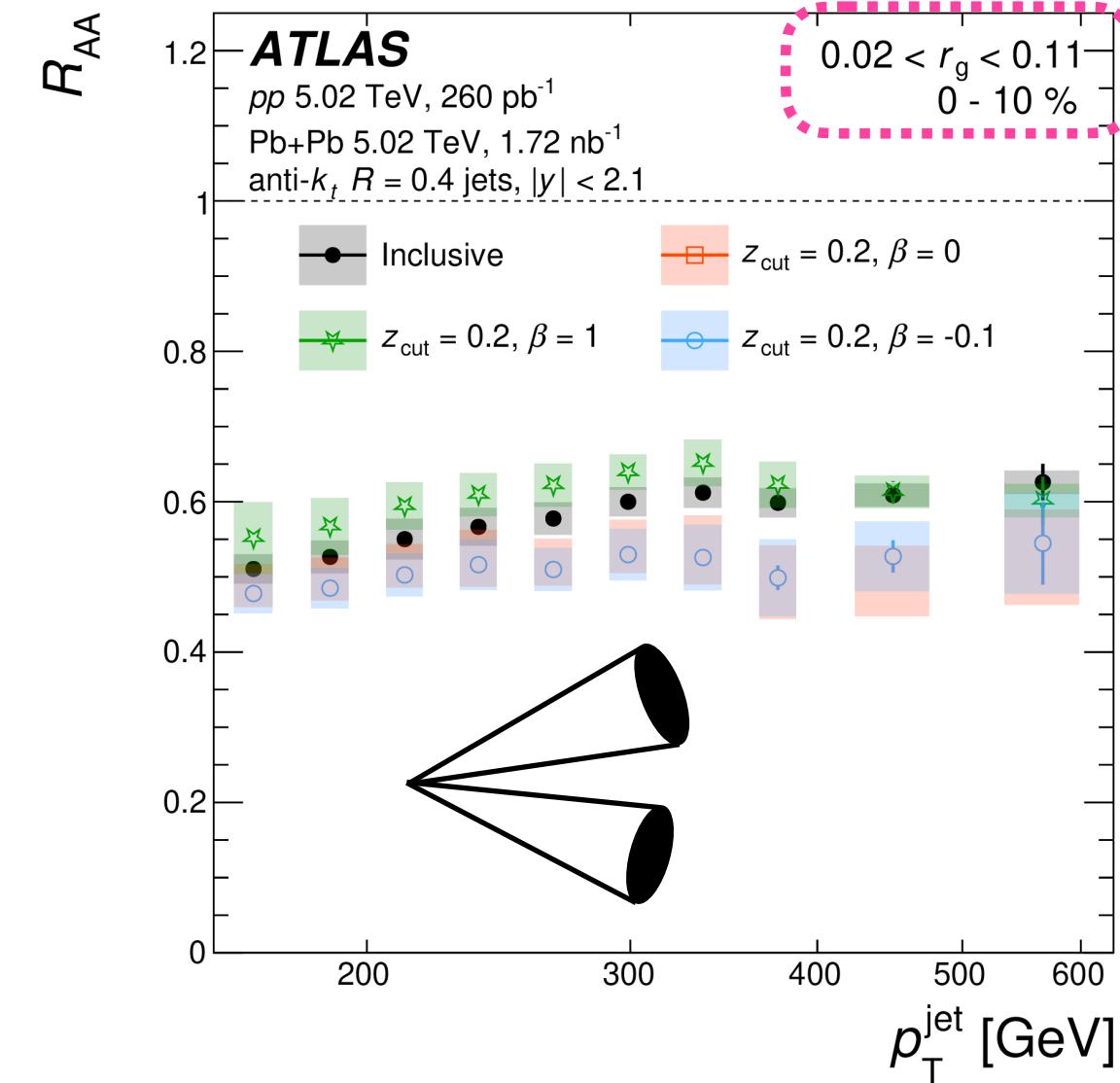
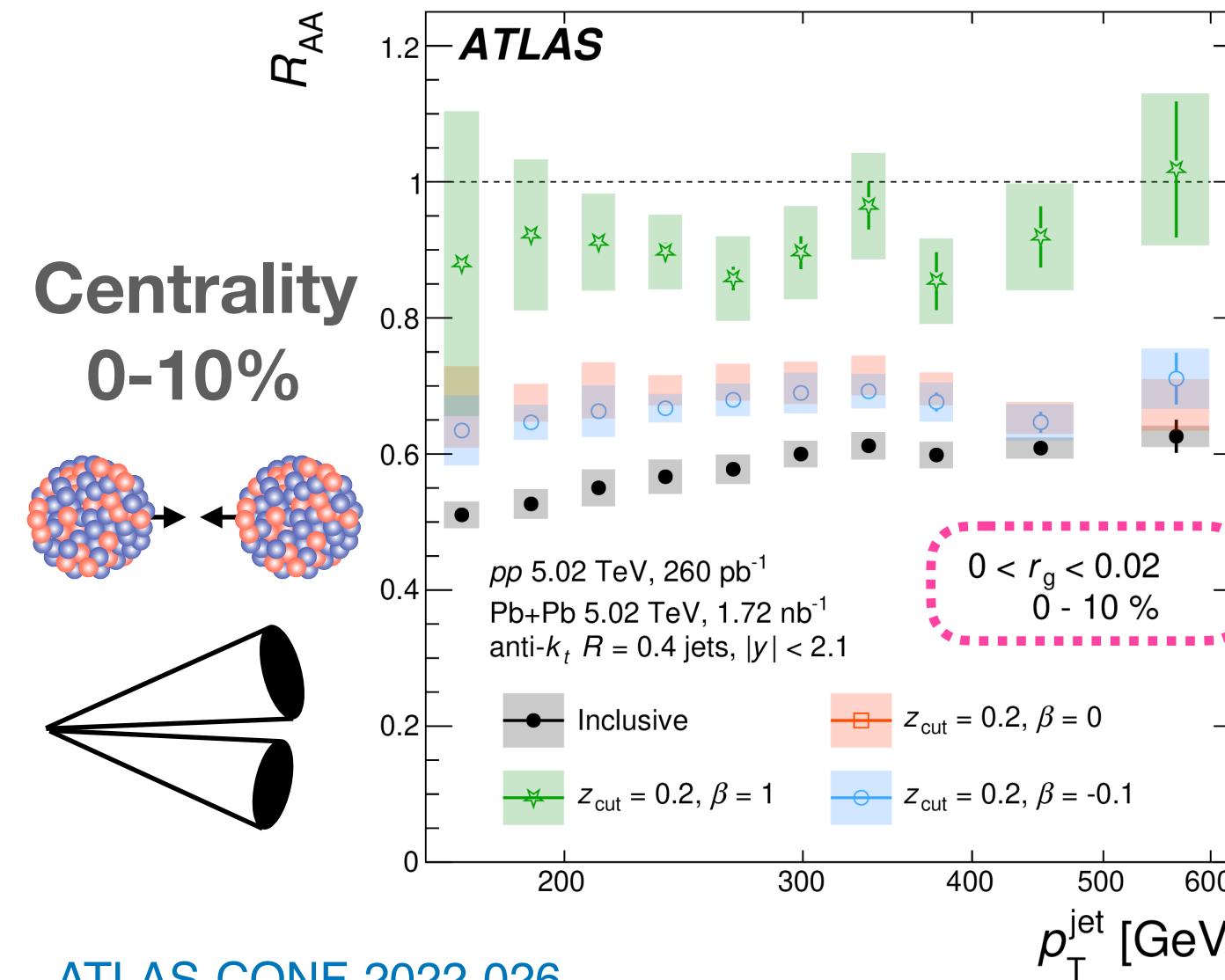
Jet Suppression vs. Substructure

- Jet suppression vs. substructure measured using varied Soft-Drop parameters can be used to interpret modification of non-perturbative jet components

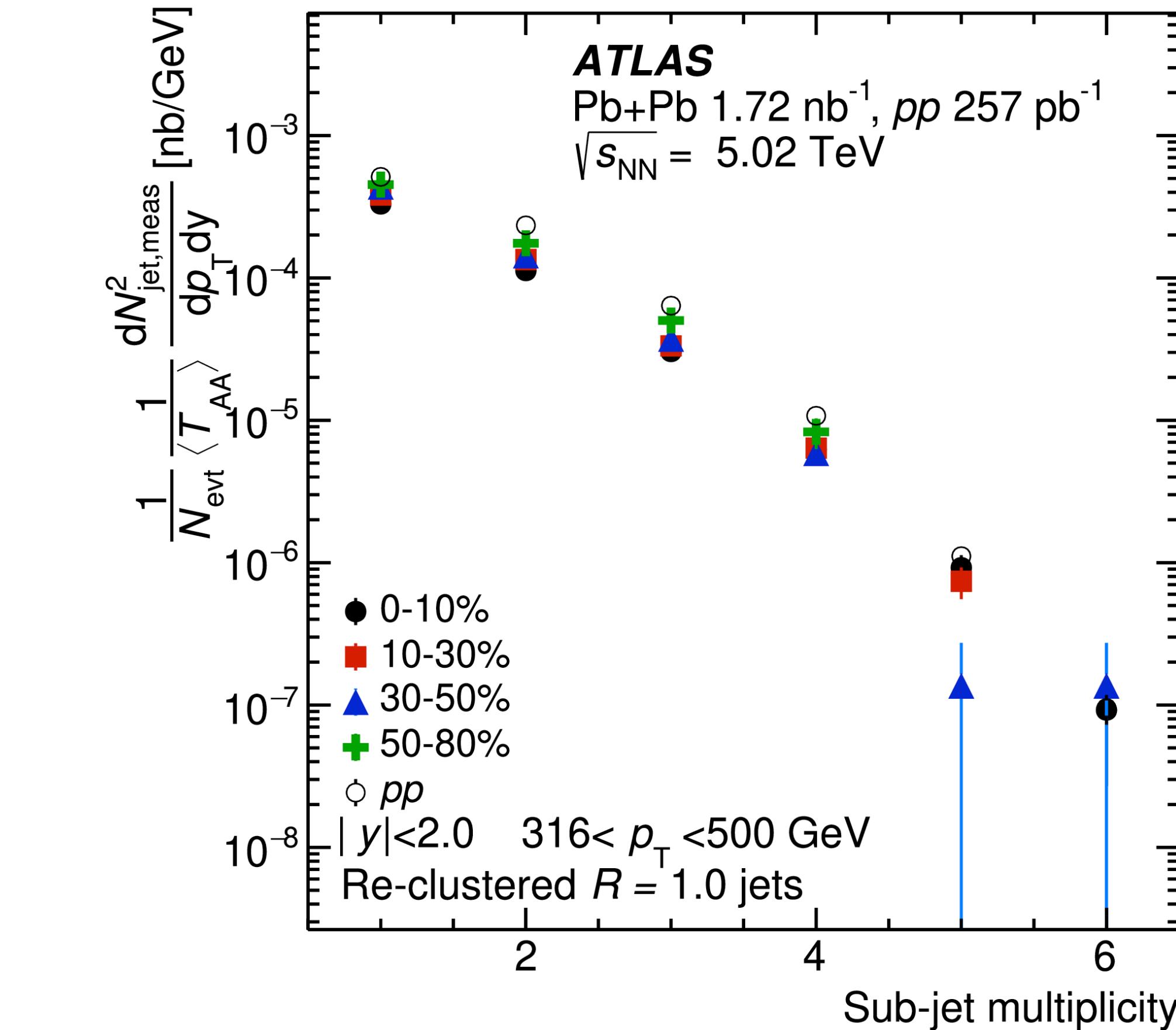
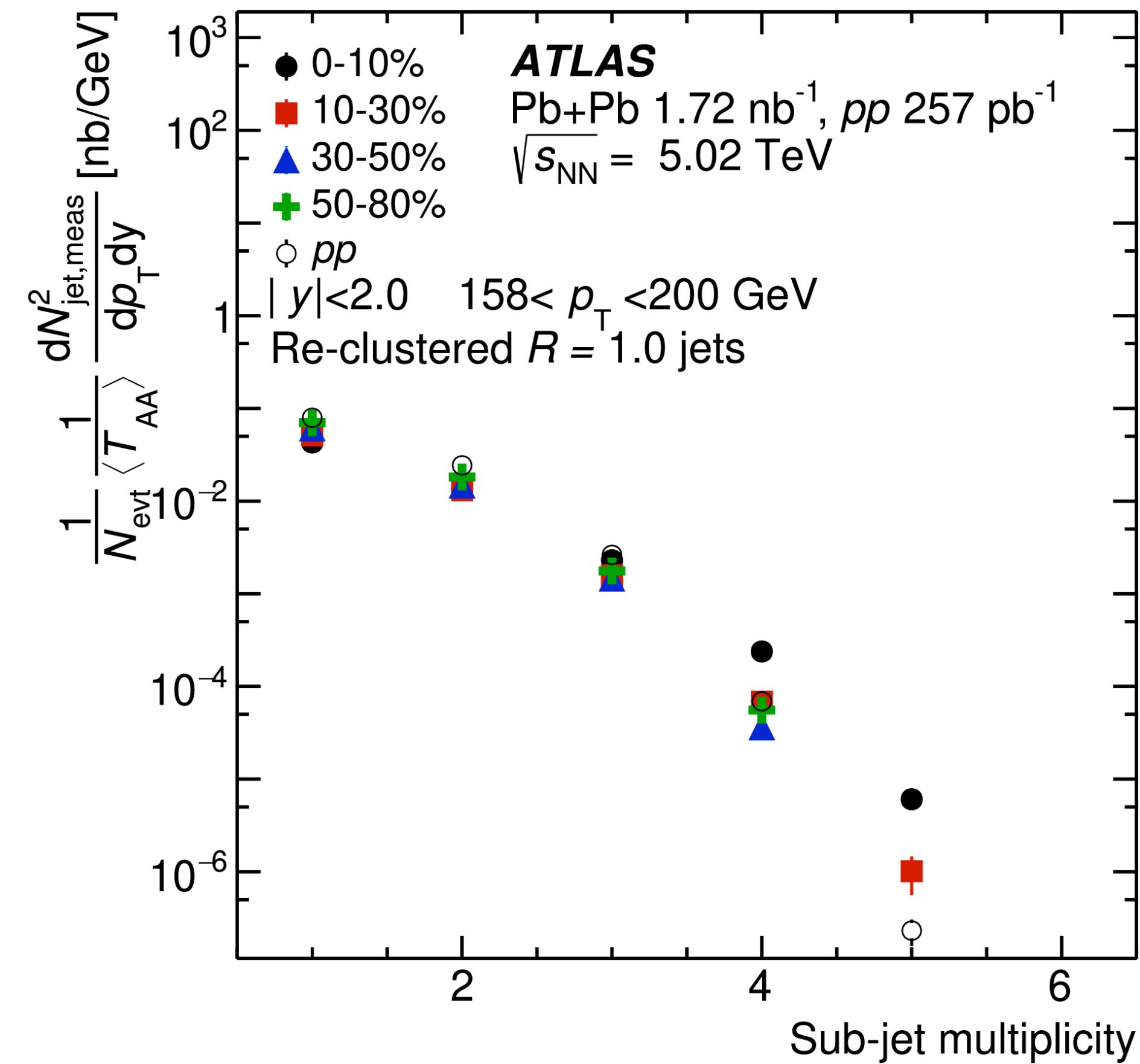
$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R(=0.4)} \right)^{\beta}$$

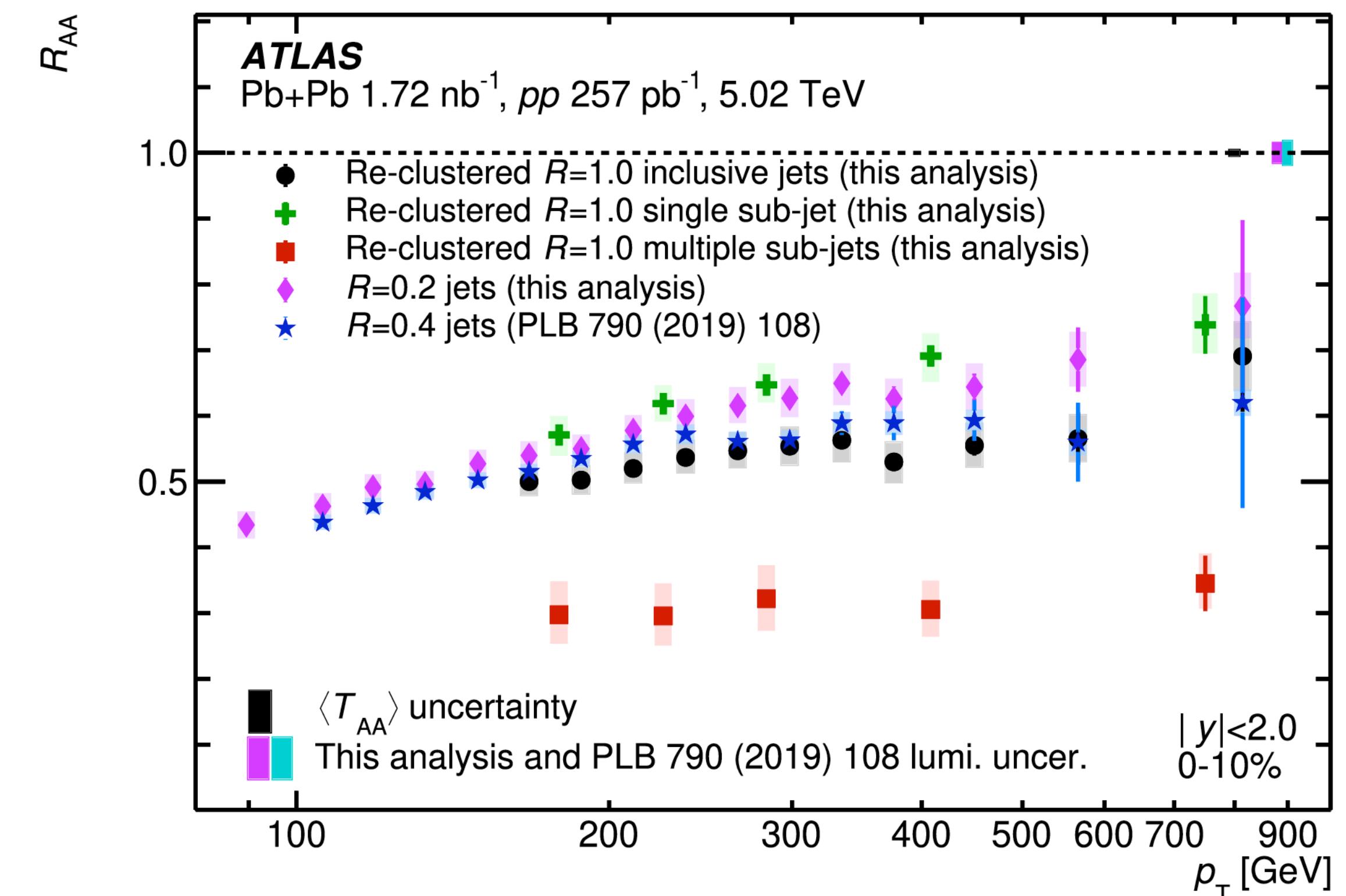
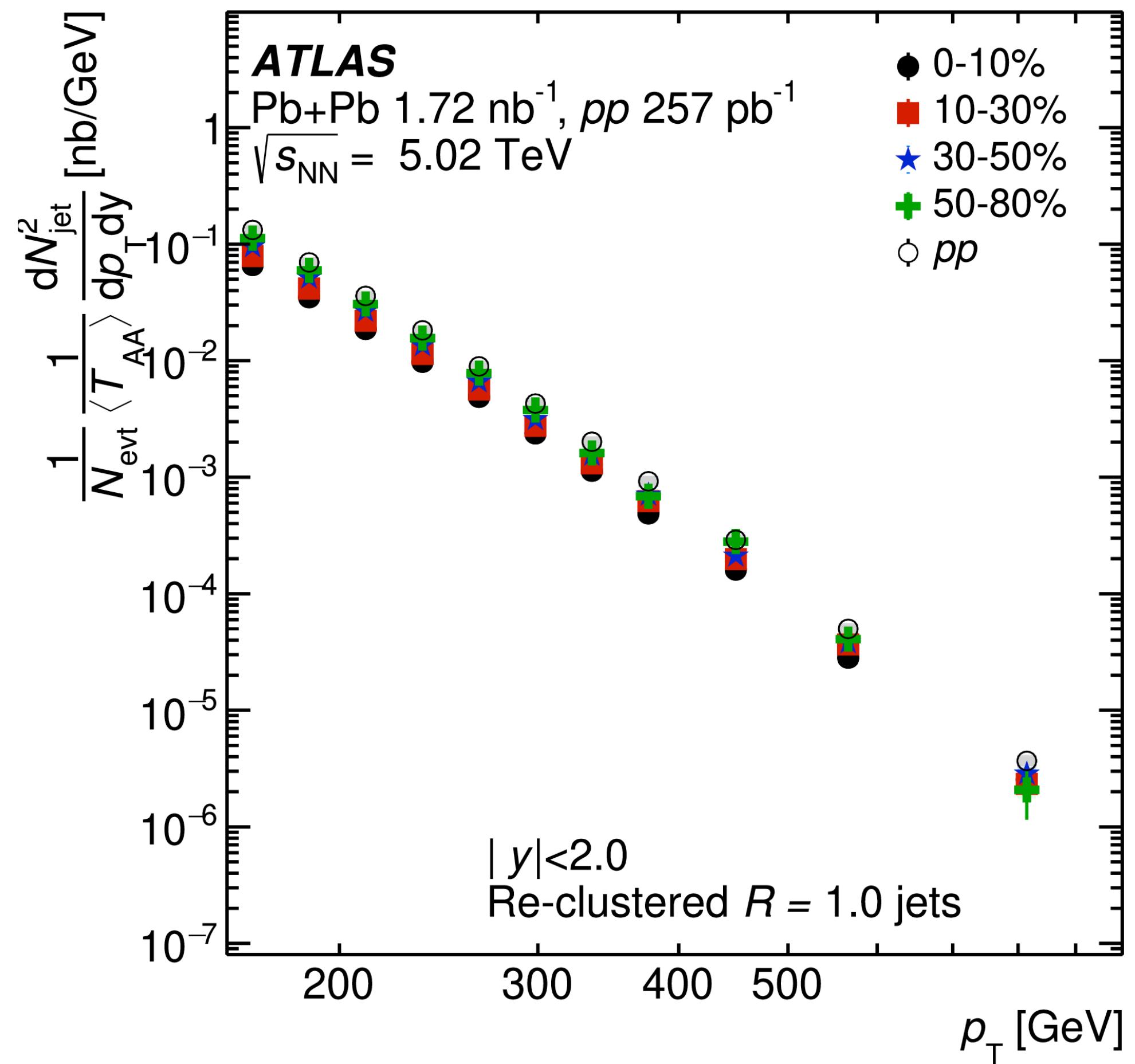
Decreasing r_g



Large R jet kinematics



Large R jet R_{AA}



arXiv:2301.05606

Jet Suppression vs. $\sqrt{d_{12}}$

- Suppression of large-radius jets in QGP very different for **SSJ** vs. $\sqrt{d_{12}} > 0$ cases

$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$

