Groomed jet substructure measurements in heavy-ion collisions

Dhanush Hangal (he/him)

September 3, 2022

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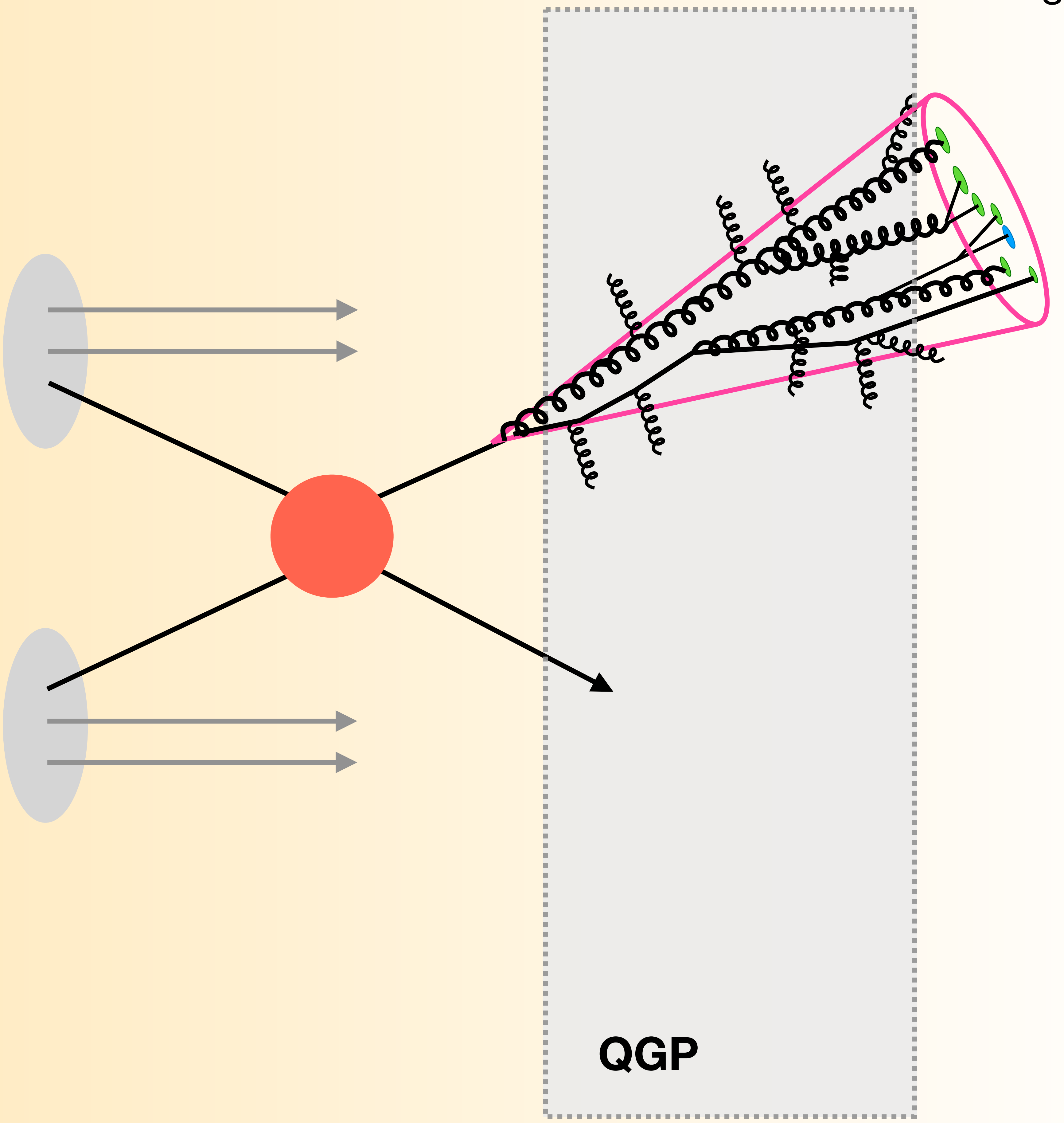
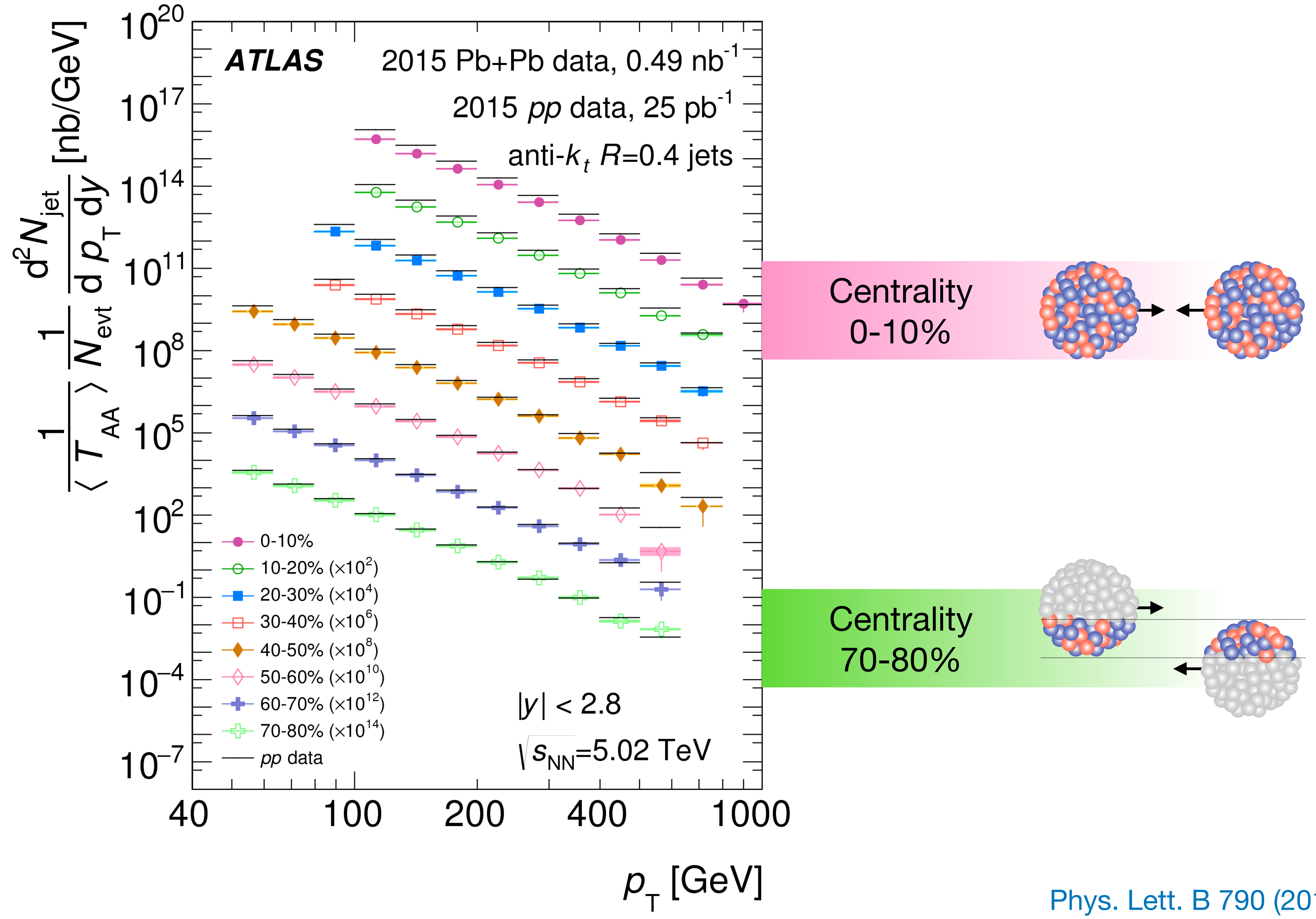
Jets in the Quark-Gluon Plasma



- Hard scattered partons undergo collisional and radiational energy loss in the QGP medium
- Jet yield is observed to be suppressed in heavy-ion collisions compared to pp baseline



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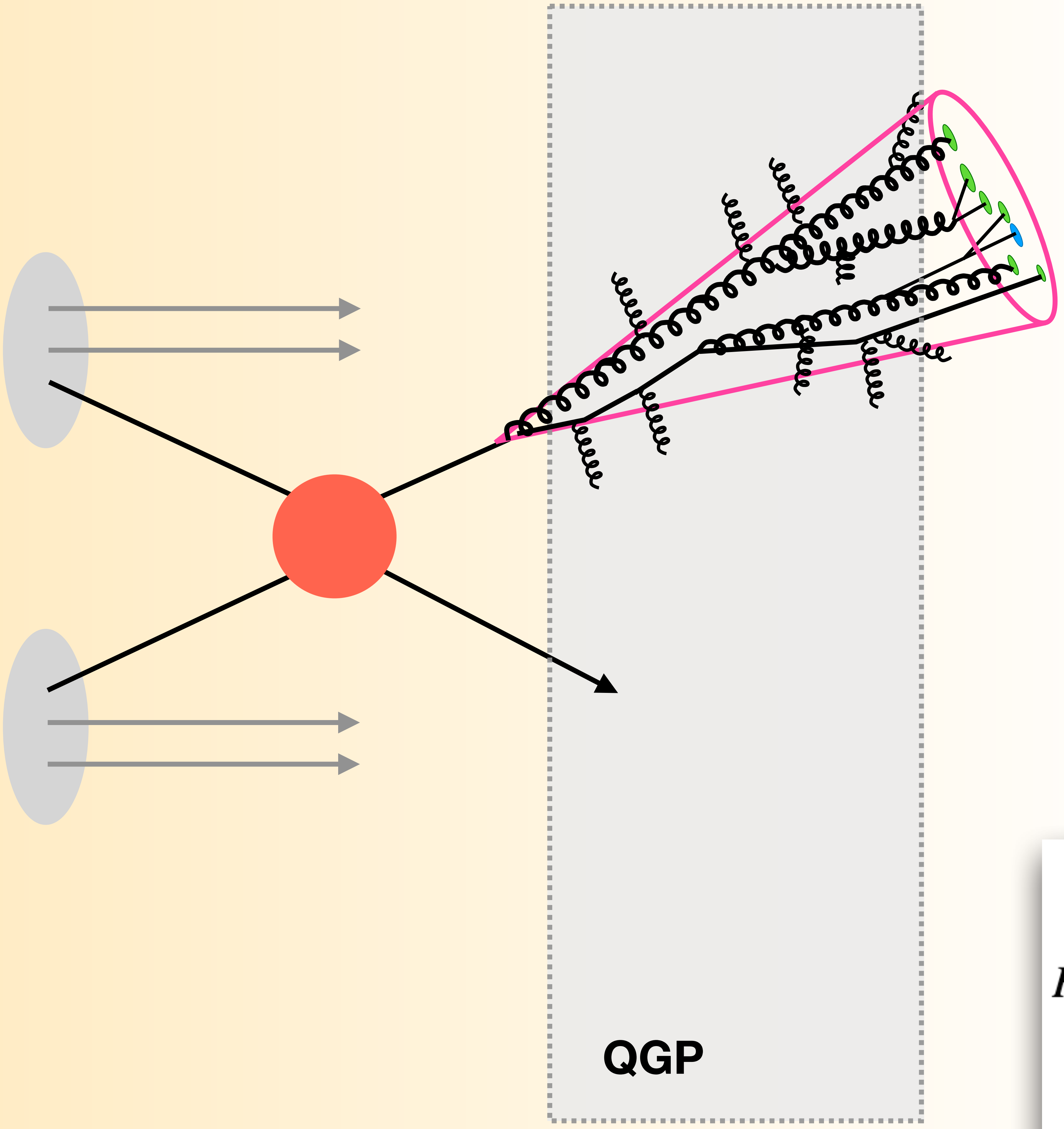
Jets in the QGP

- Jet energy loss or “quenching” in QGP characterized using nuclear modification factor (**R_{AA}**)

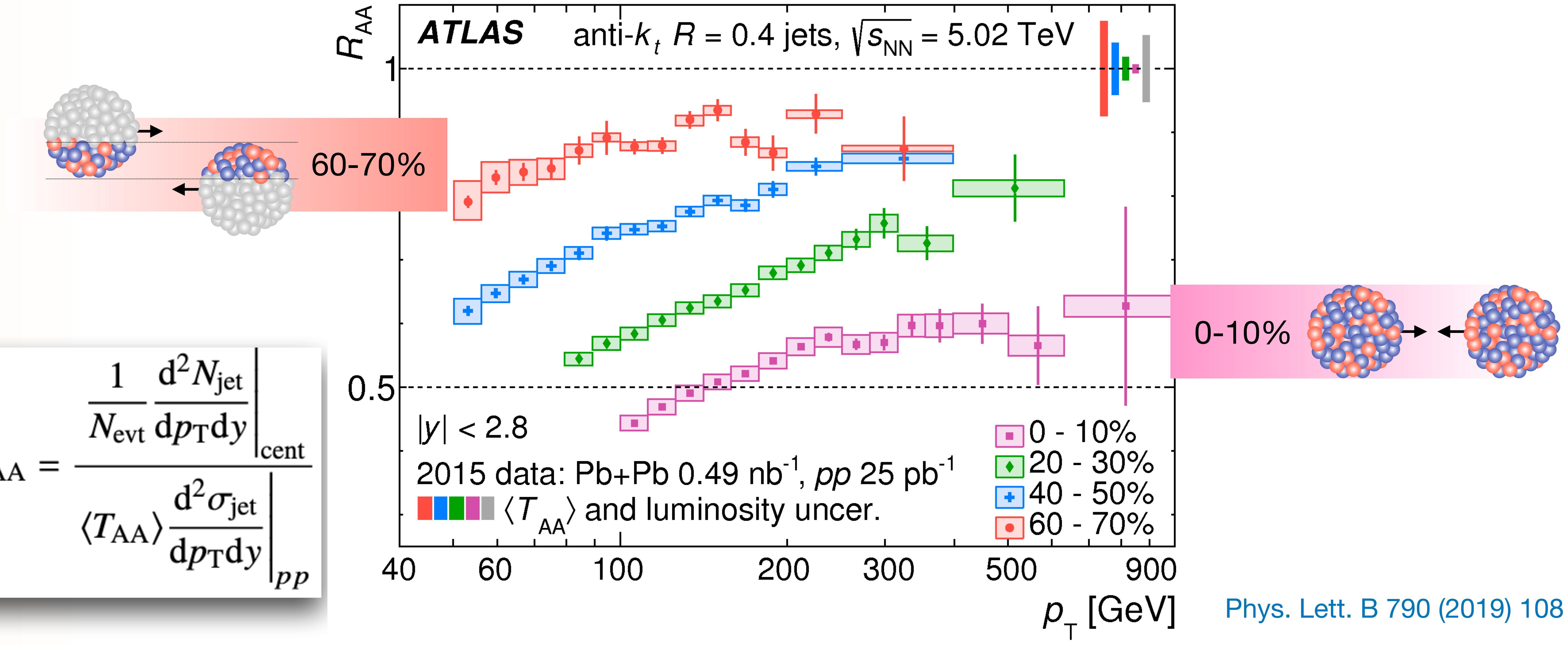


Jet production: heavy ion (**PbPb**) collisions vs. ***pp*** collisions

Nuclear modification factor

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

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



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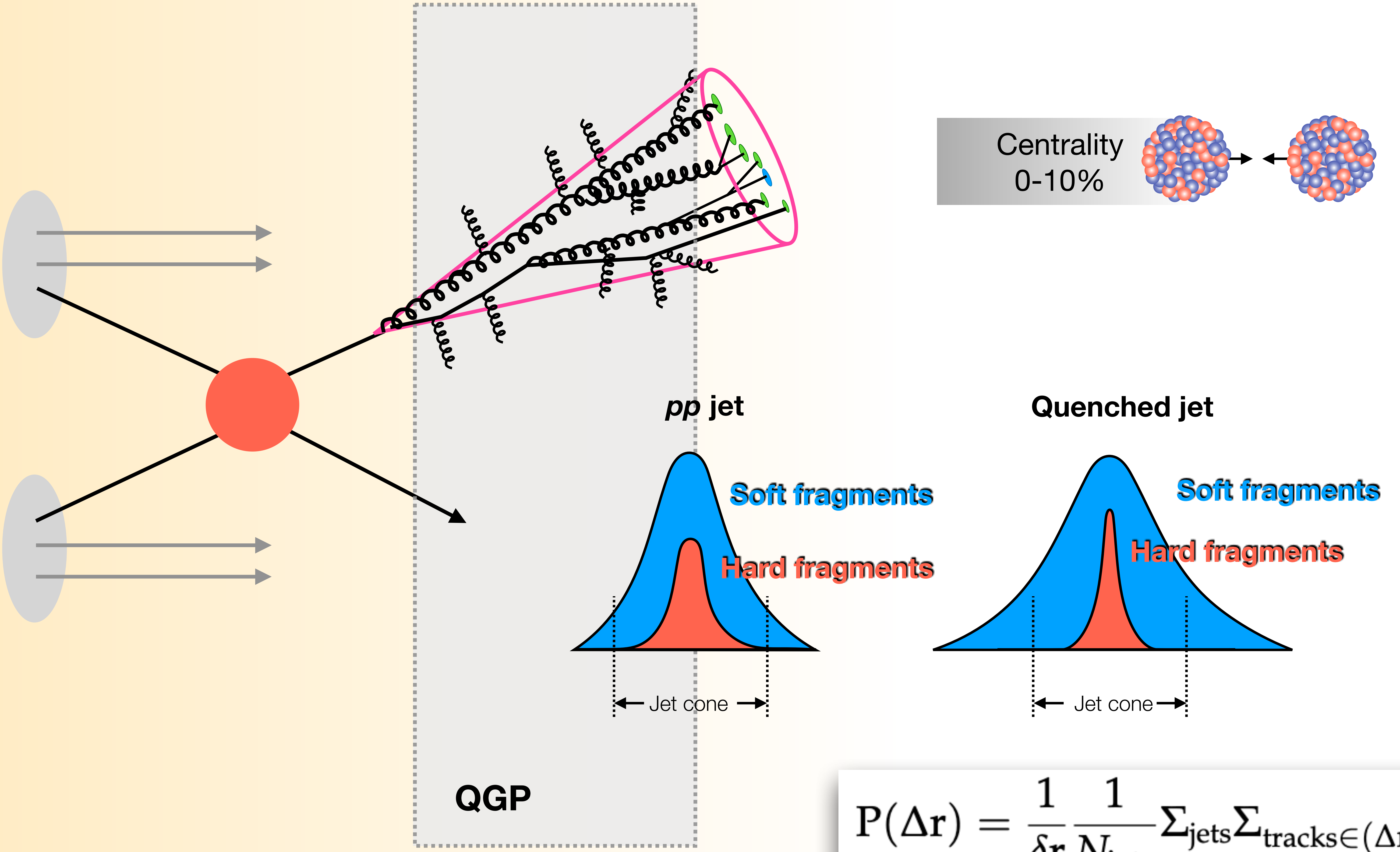
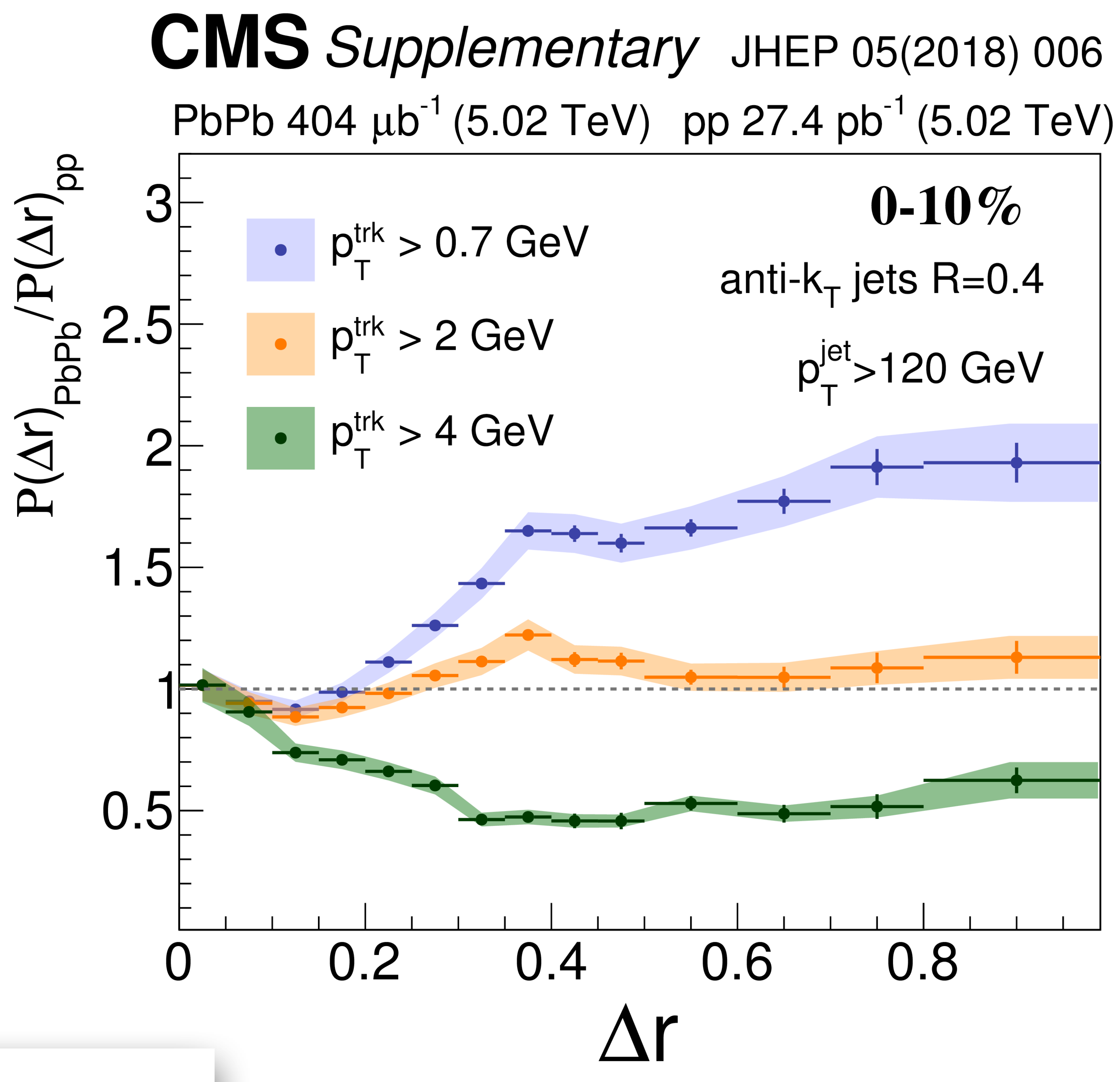
Jets in the QGP

- Depletion of hard fragments of a jet observed outside of the jet core
- Energy recovered via an excess of soft fragments at larger angles to the jet axis

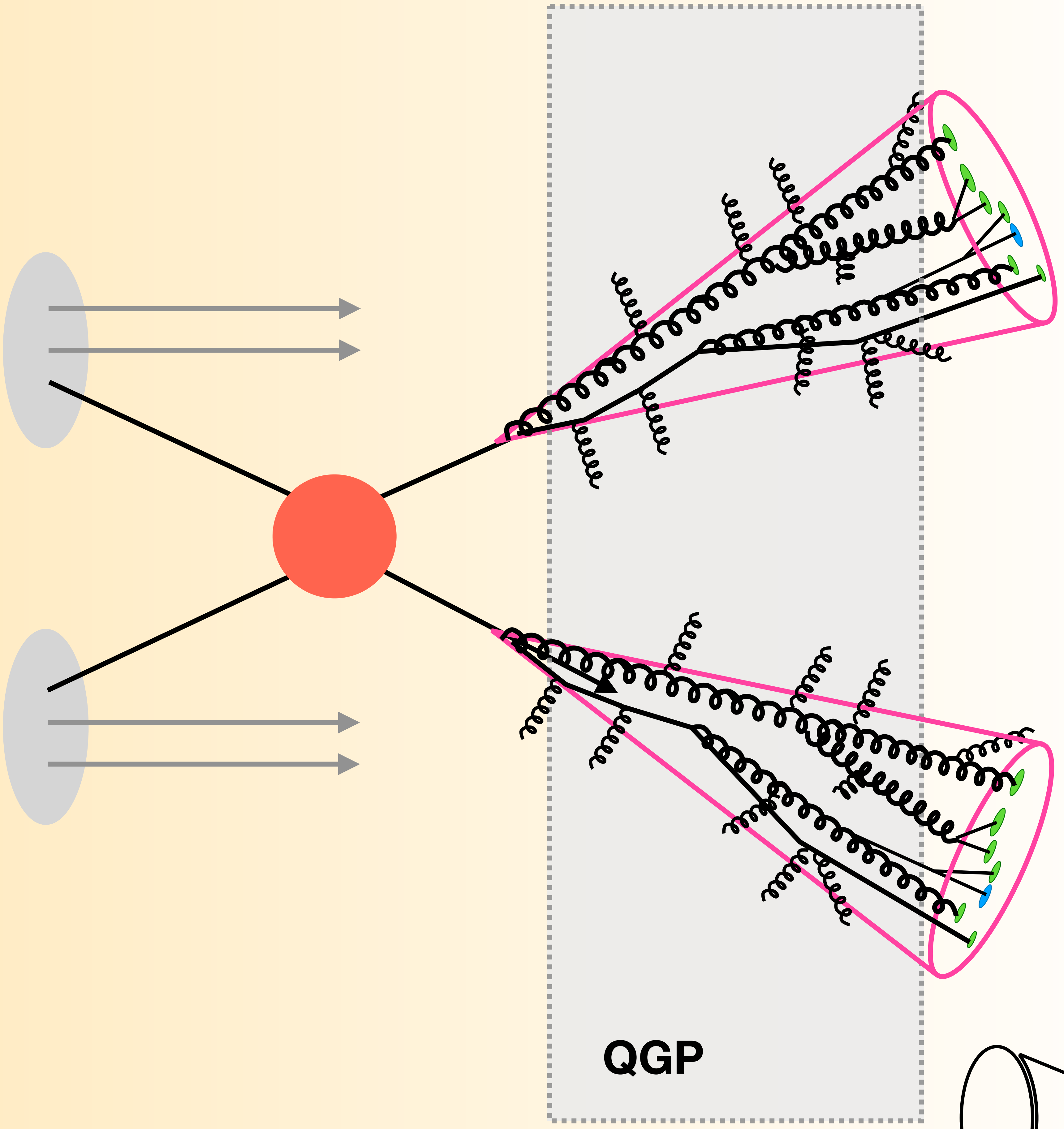




$$P(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{jets}}\Sigma_{jets}\Sigma_{tracks\in(\Delta r_a,\Delta r_b)}\,p_T^{trk}$$

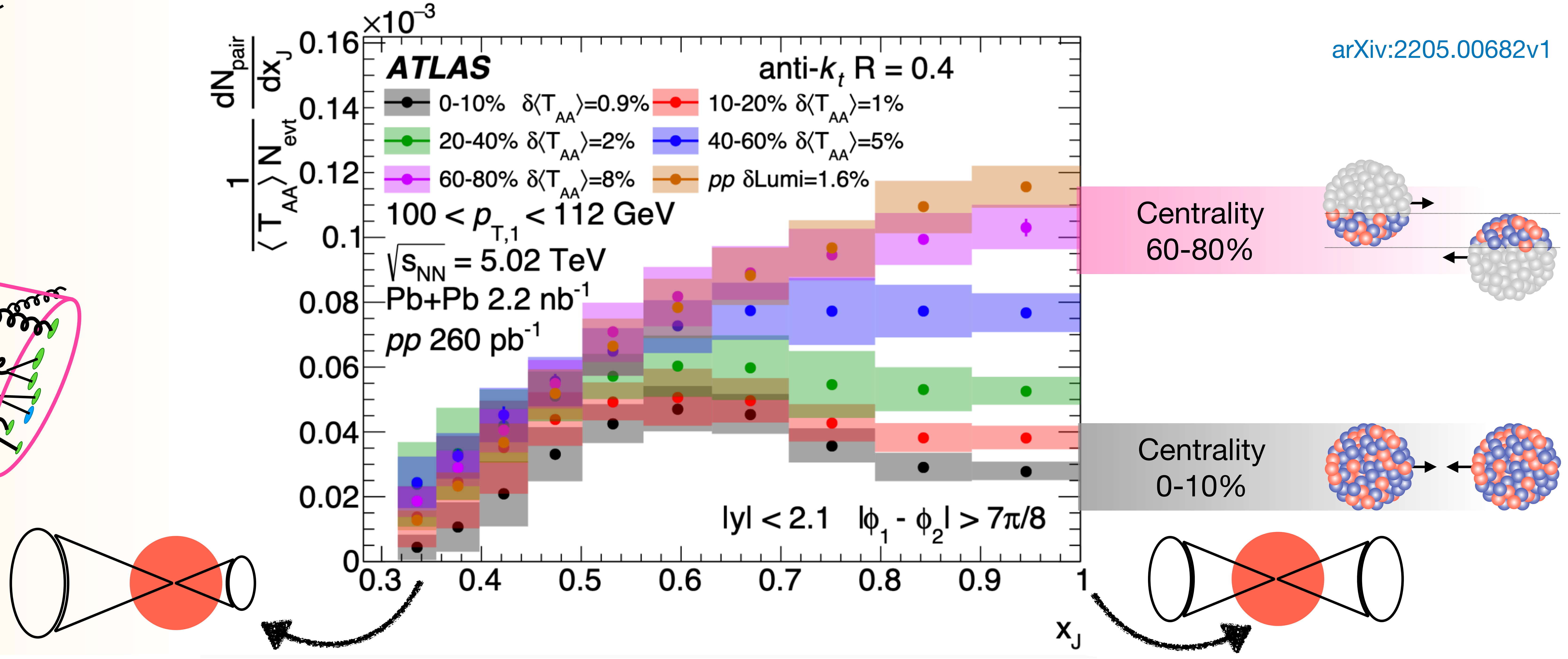
Jets in the QGP

- Back-to-back jets in observed to be much more asymmetric in central PbPb collisions
- Jet energy loss in the QGP observed to fluctuate -> **Need to measure it differentially**



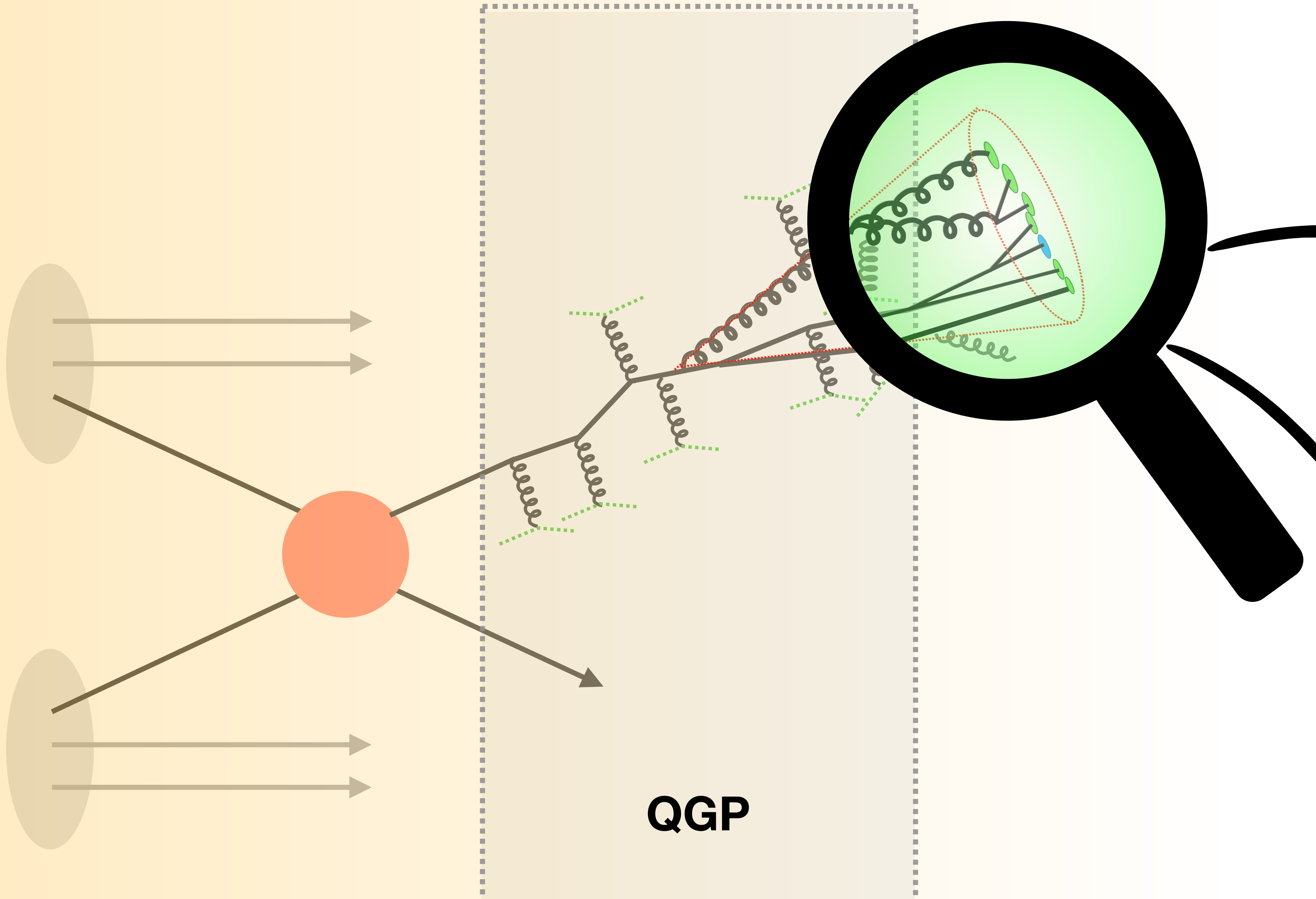
Dijet asymmetry $x_J \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}}}$

arXiv:2205.00682v1

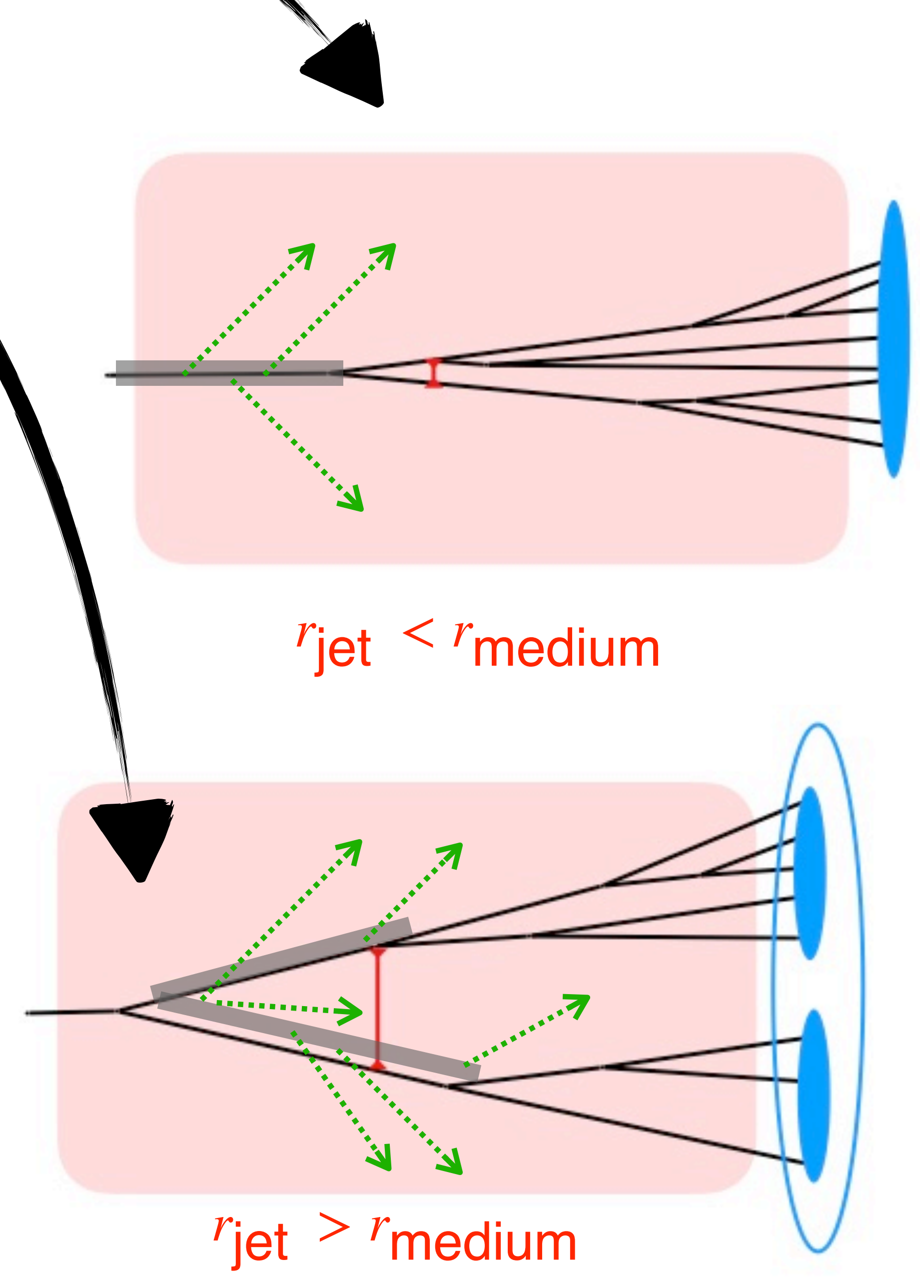


Jet substructure vs. suppression

- Does the jet energy loss in the QGP depend on its substructure?
- Does the QGP medium have an inherent angular scale beyond which it resolves the two prongs?



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



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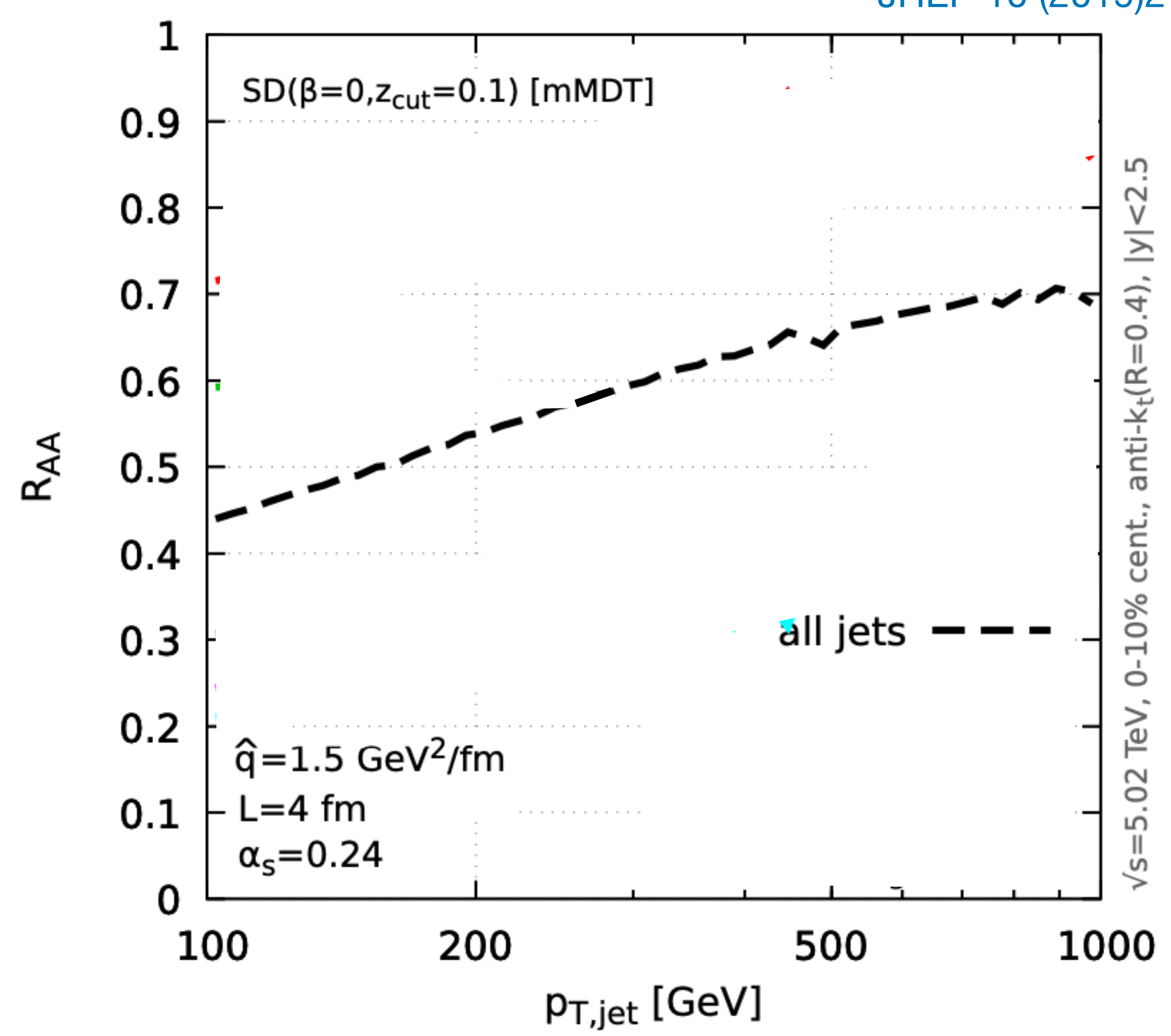

$$R_{AA}(p_T^{jet}, r_g) = \frac{1}{N_{evt}^{cent}} \frac{1}{\langle T_{AA} \rangle} \frac{\dfrac{d^2 N_{jet}^{cent}}{dp_T^{jet} dr_g}}{\dfrac{d^2 \sigma_{jet}}{dp_T^{jet} dr_g}},$$

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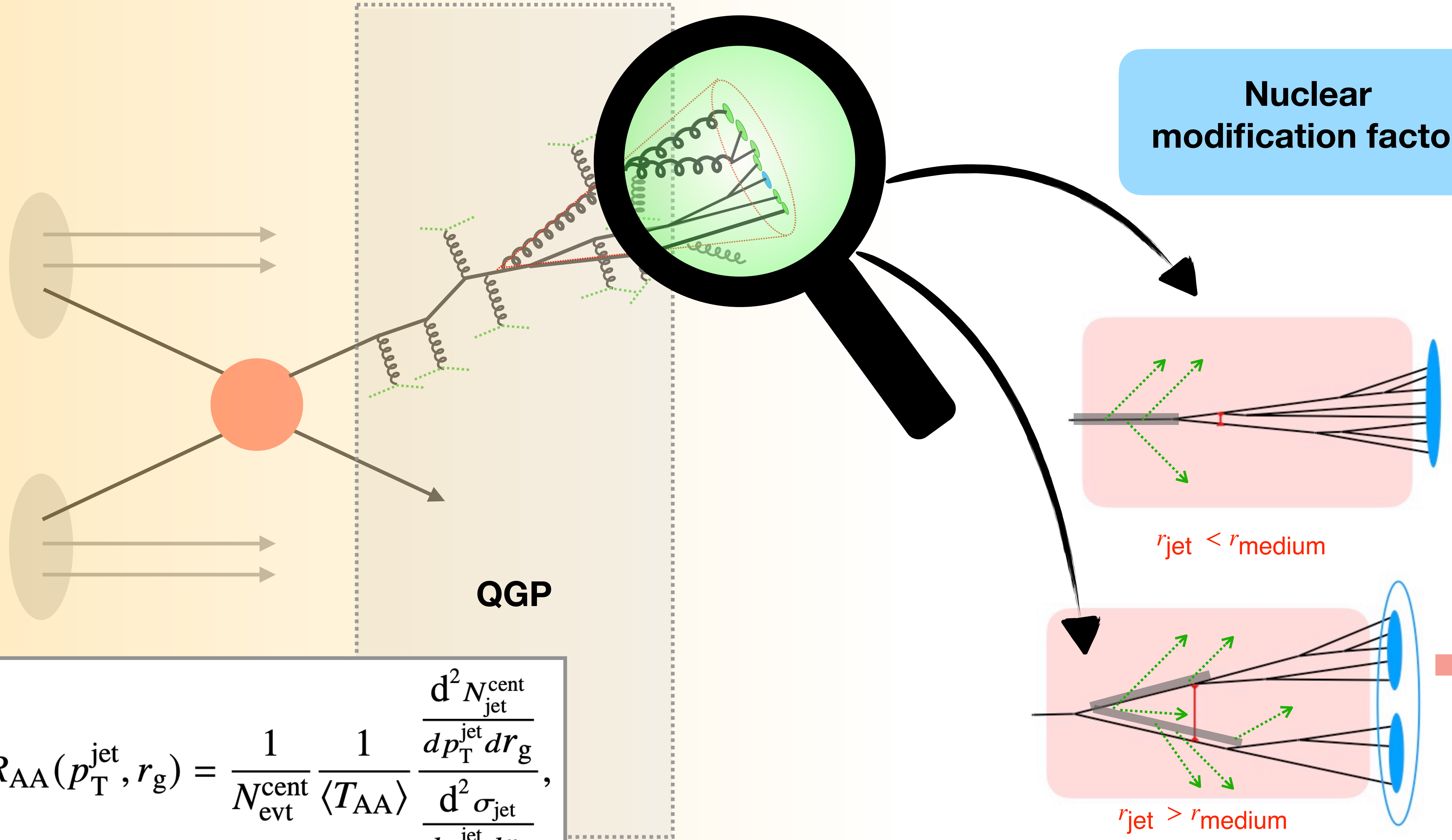

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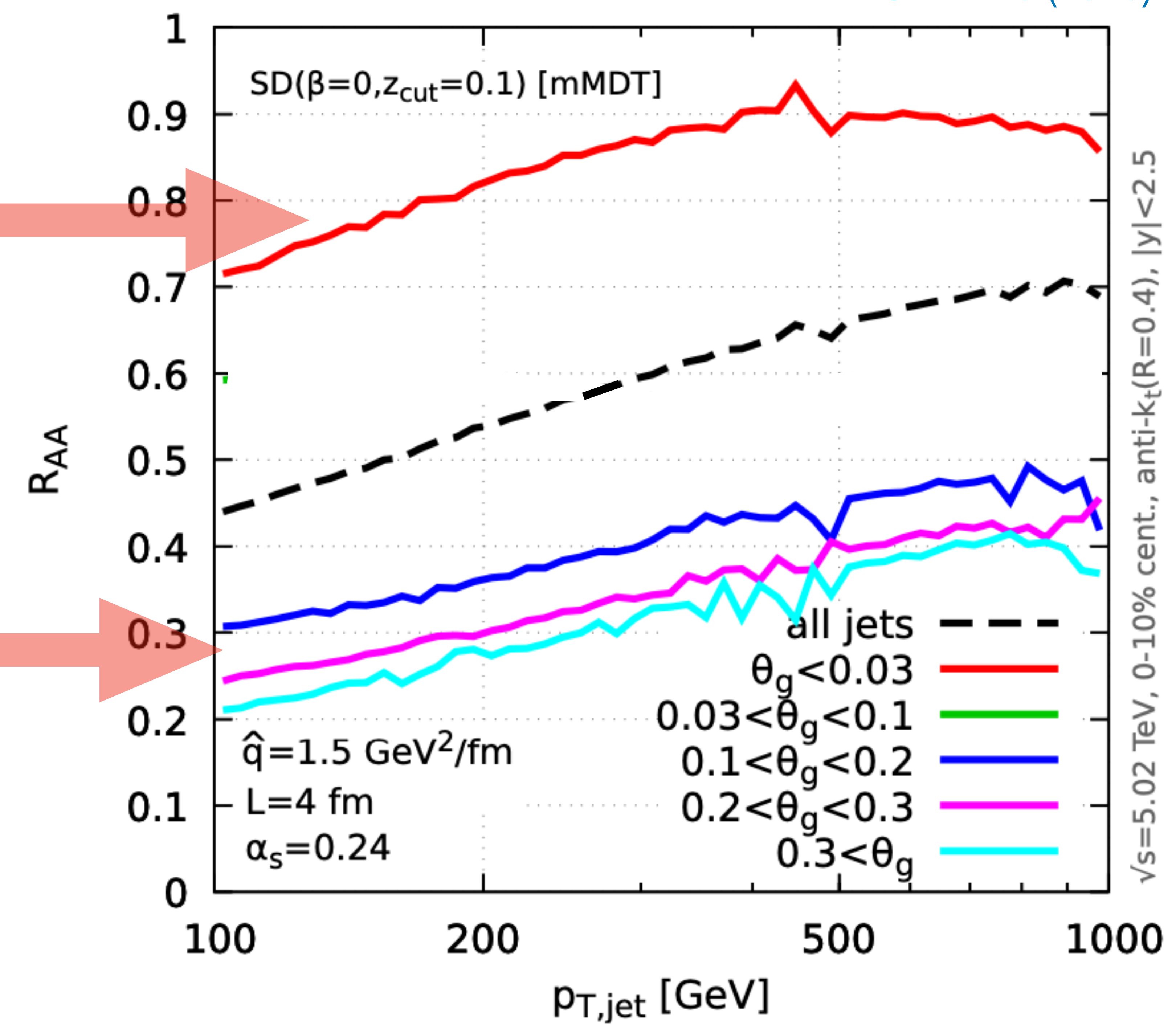
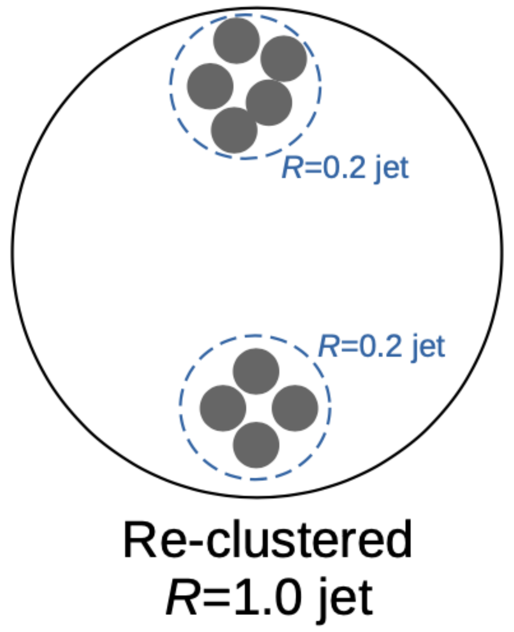
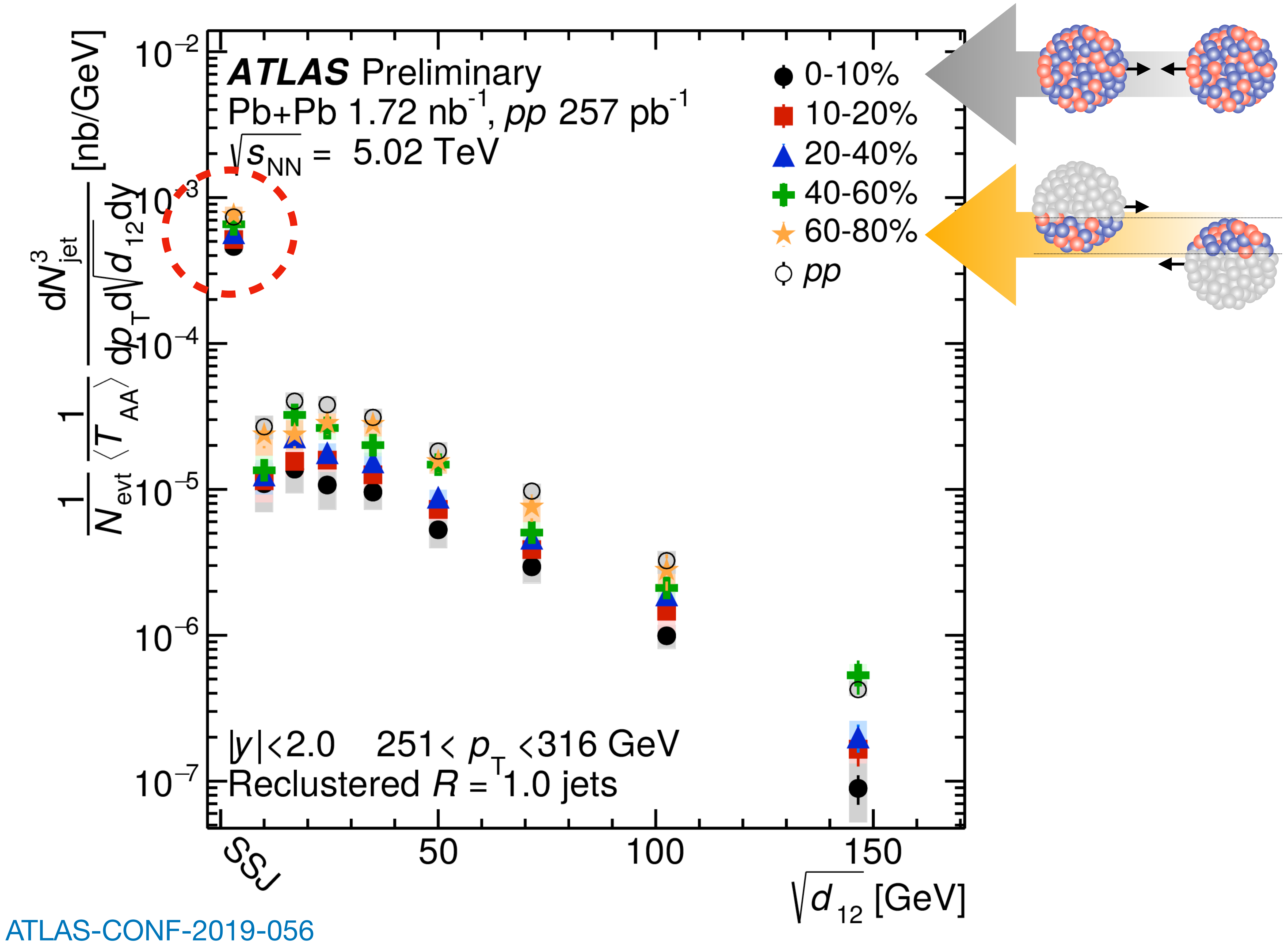


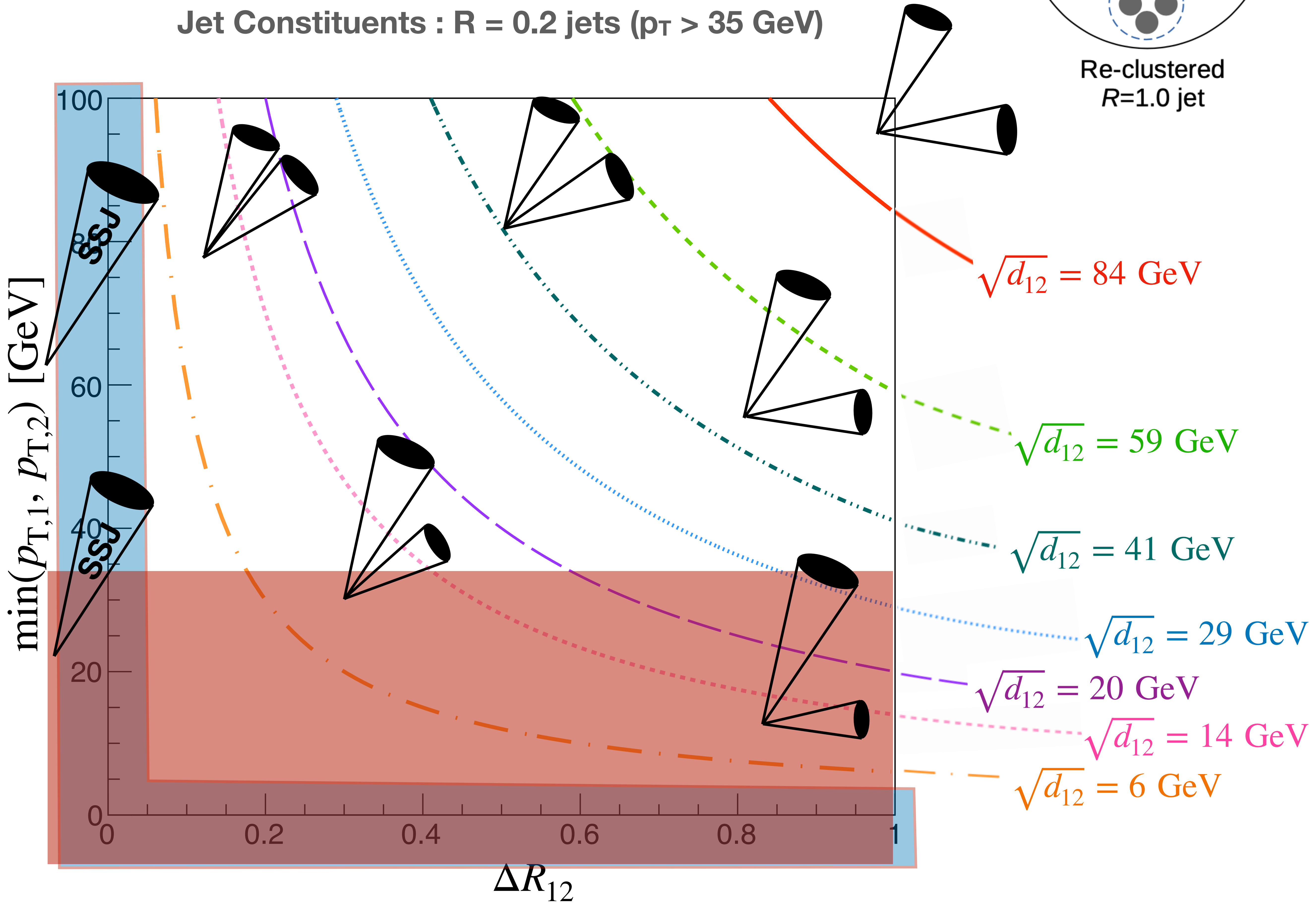
Splitting Scale ($\sqrt{d_{12}}$)

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



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





ATLAS-CONF-2019-056

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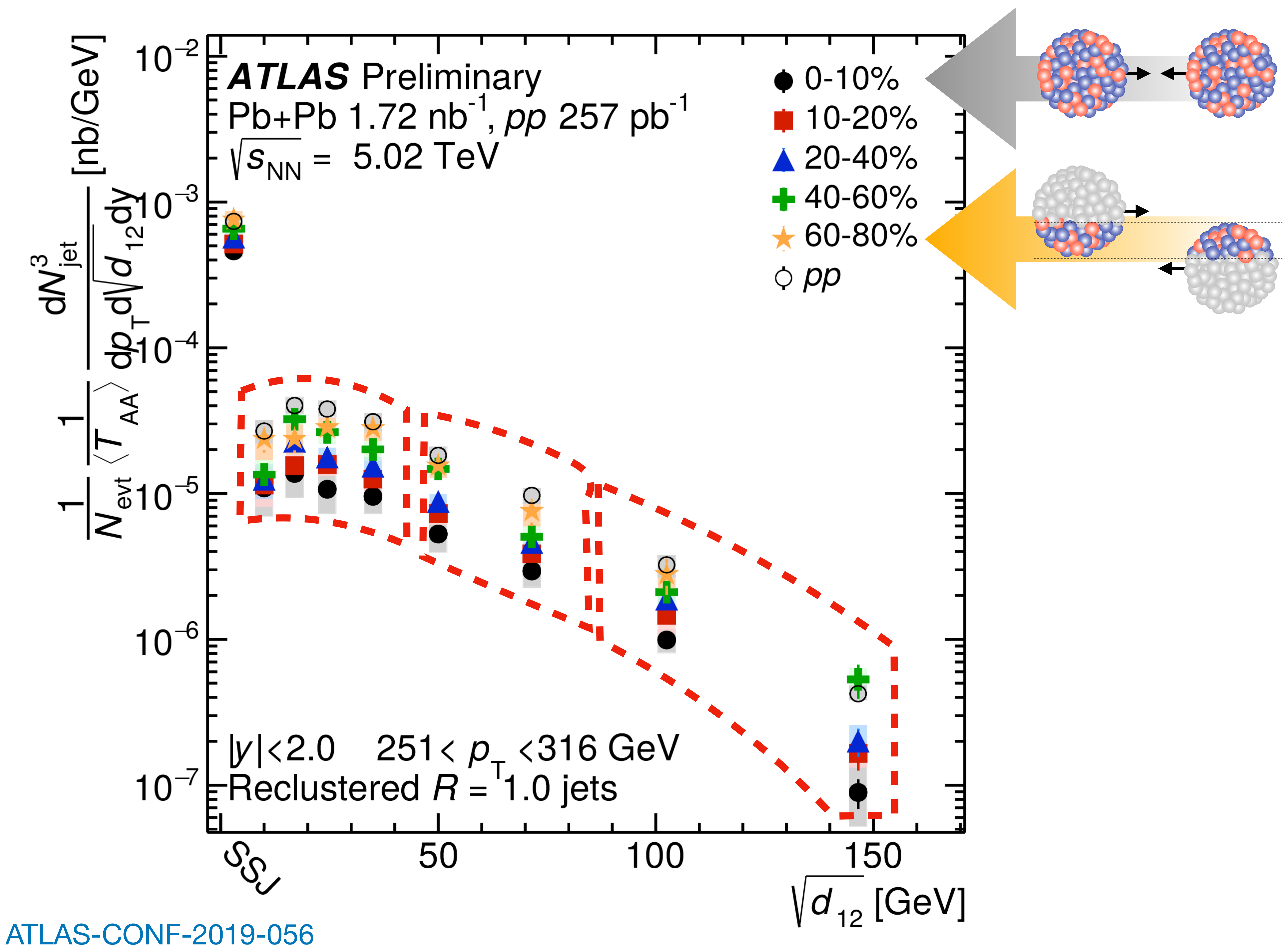

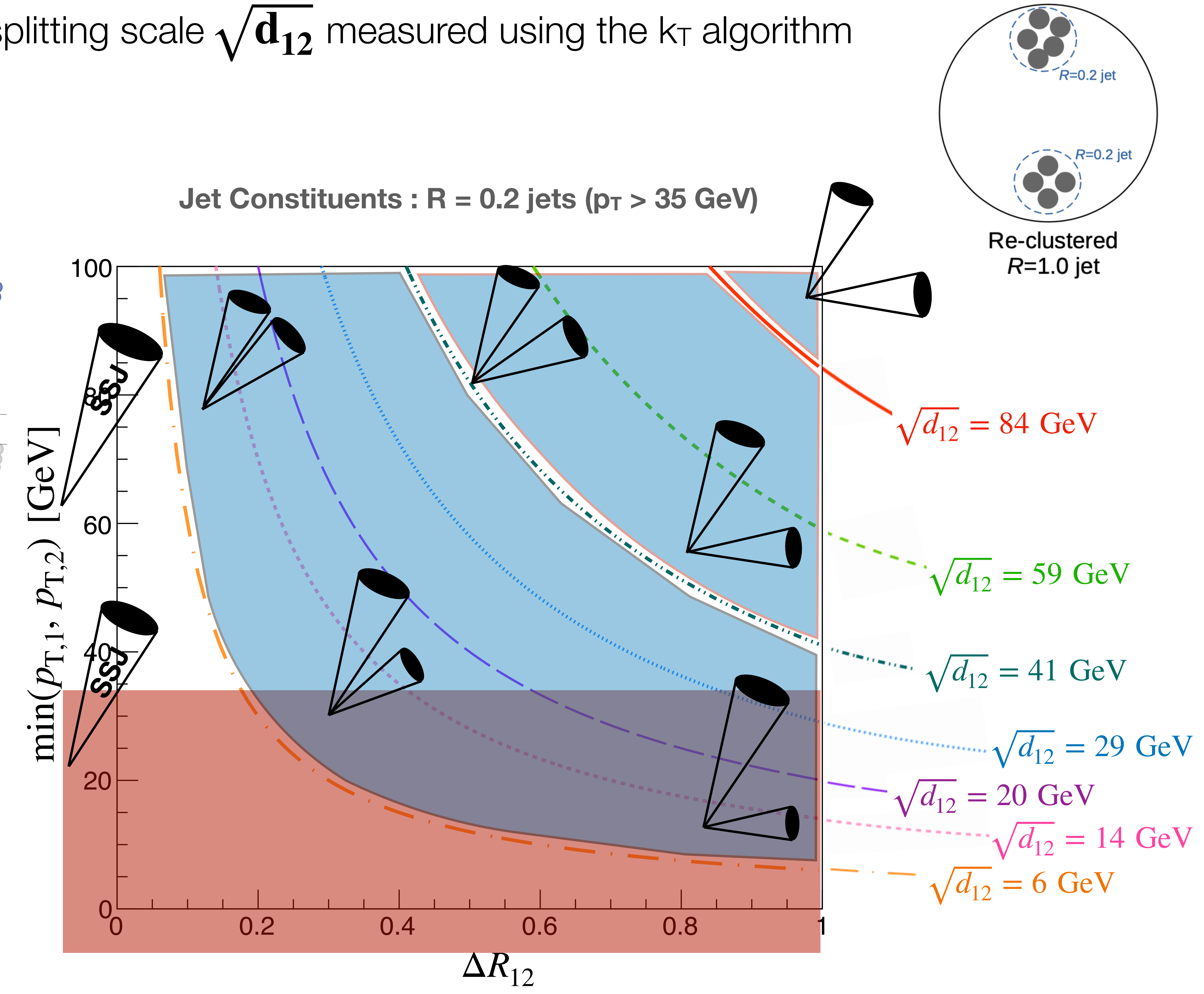

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Jet Suppression vs. $\sqrt{d_{12}}$

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

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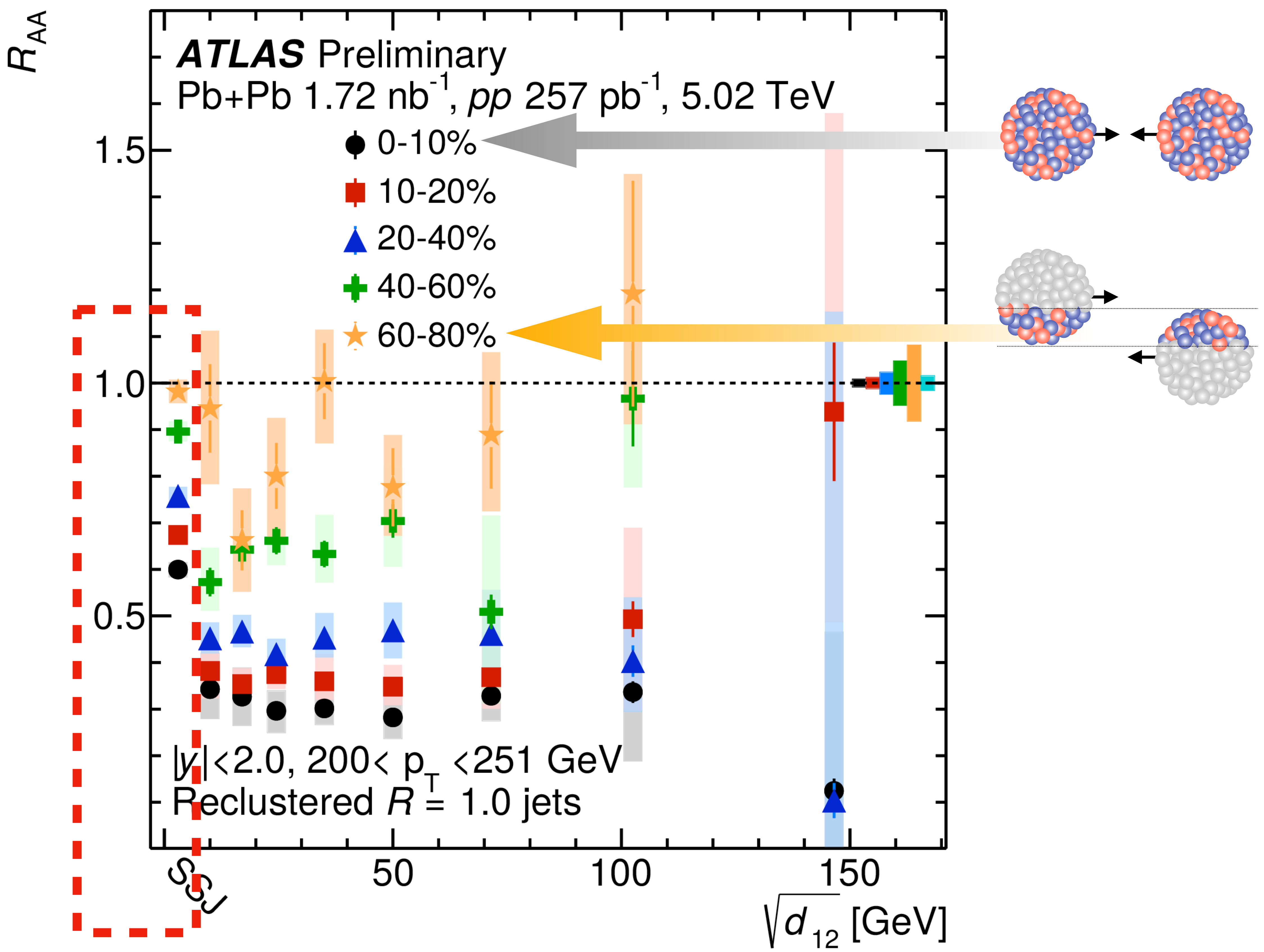

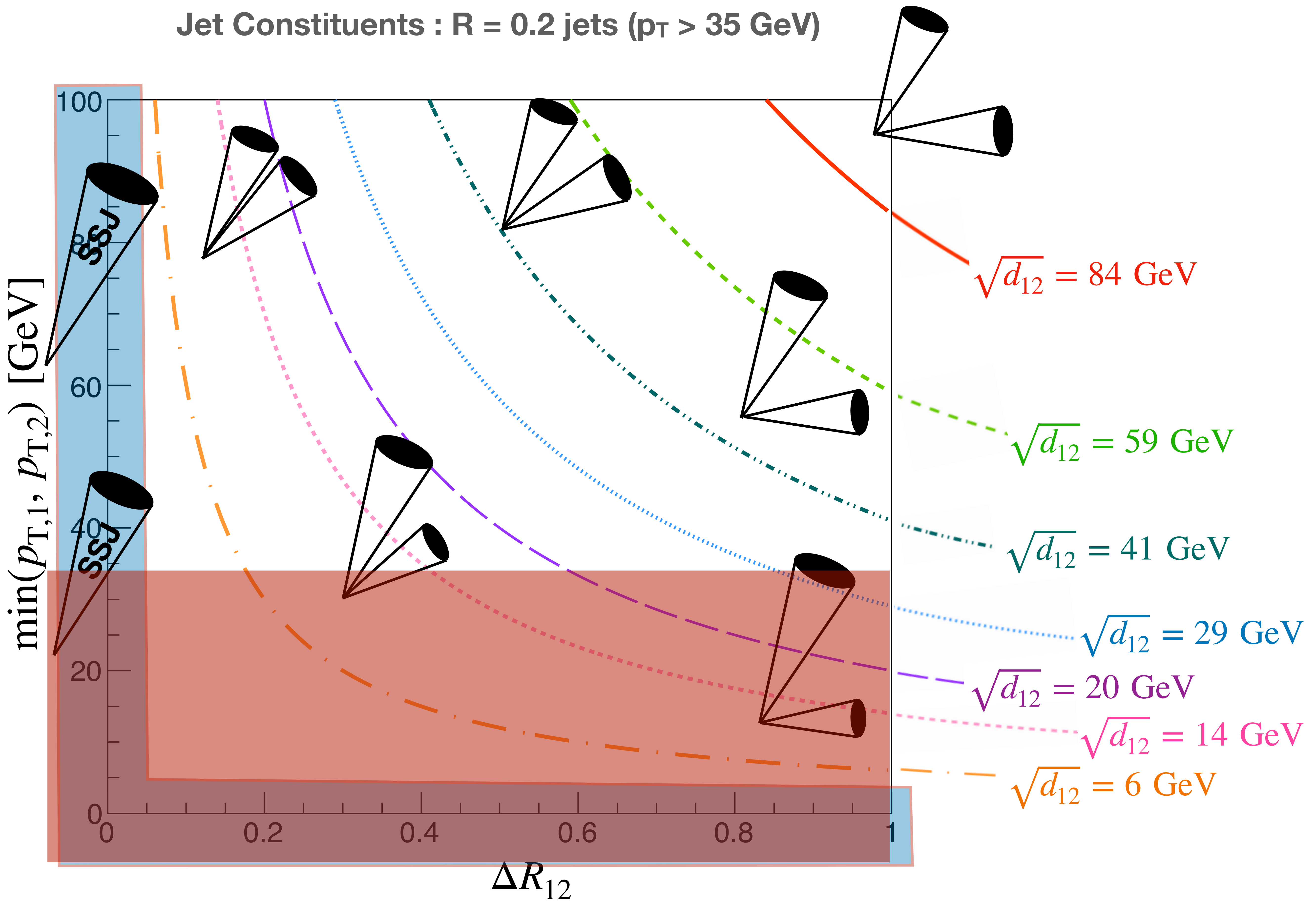

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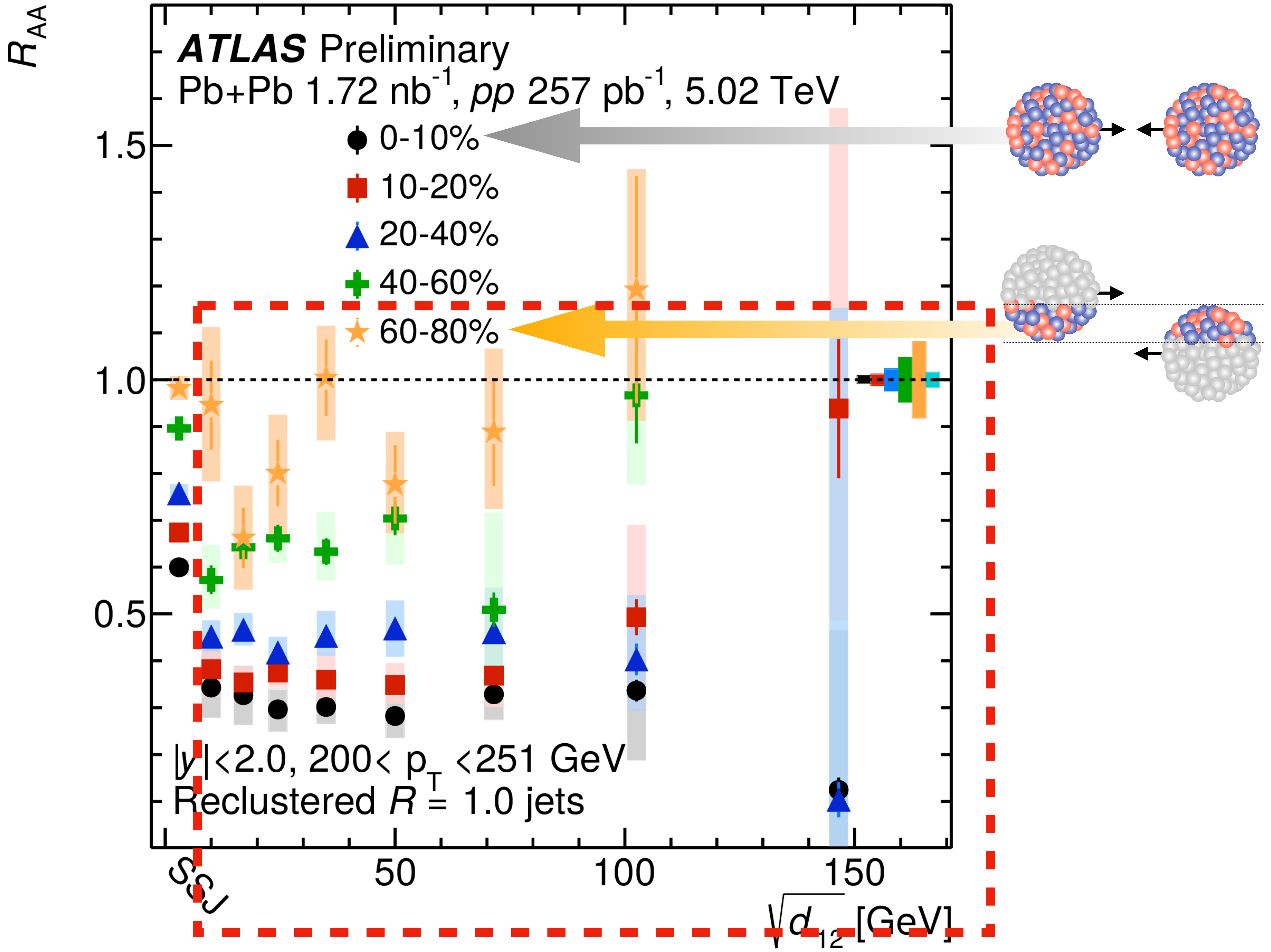
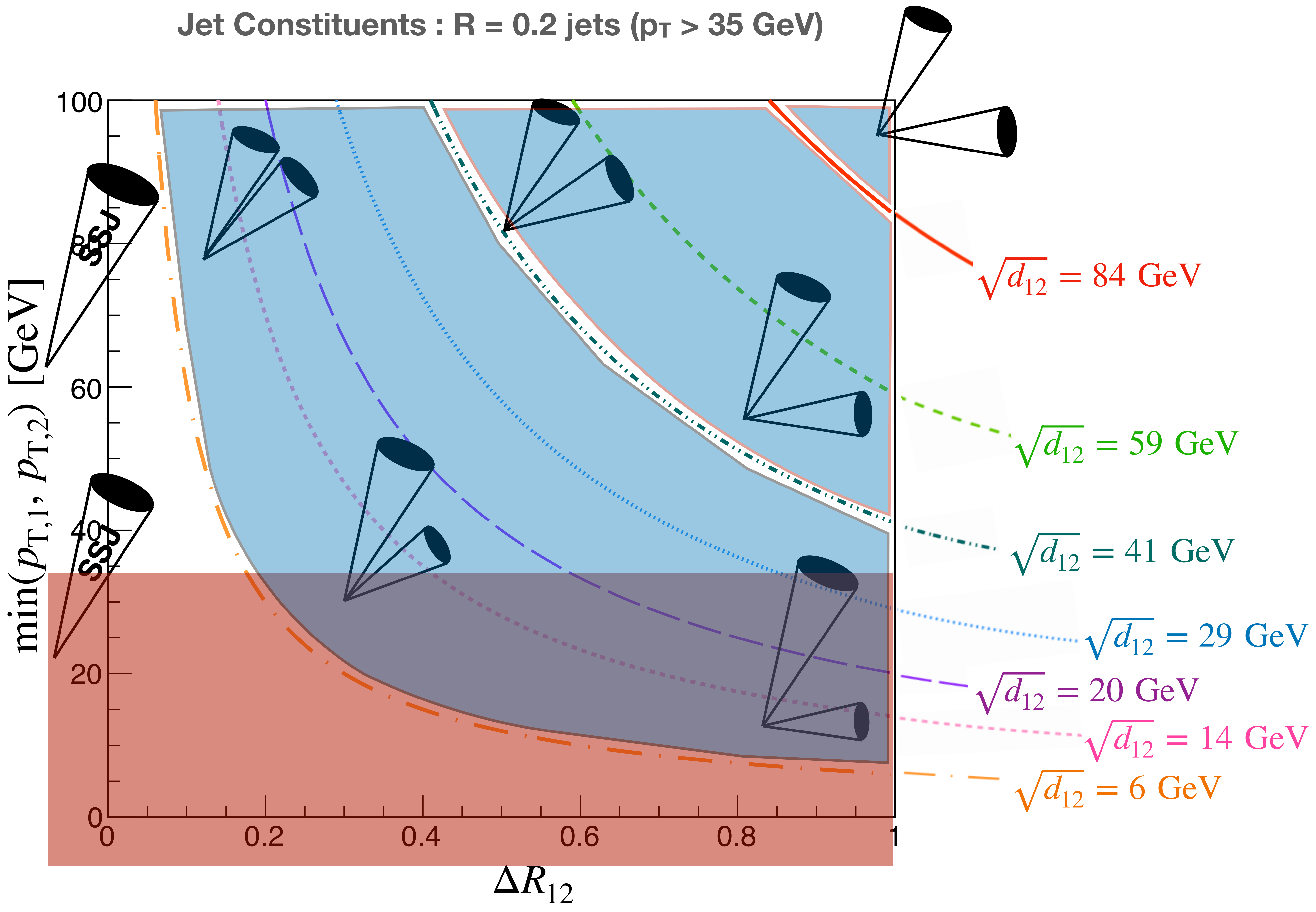
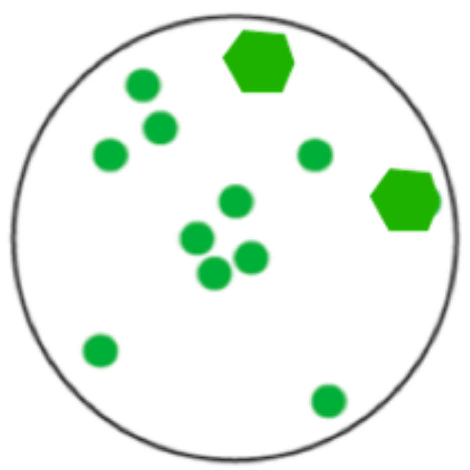


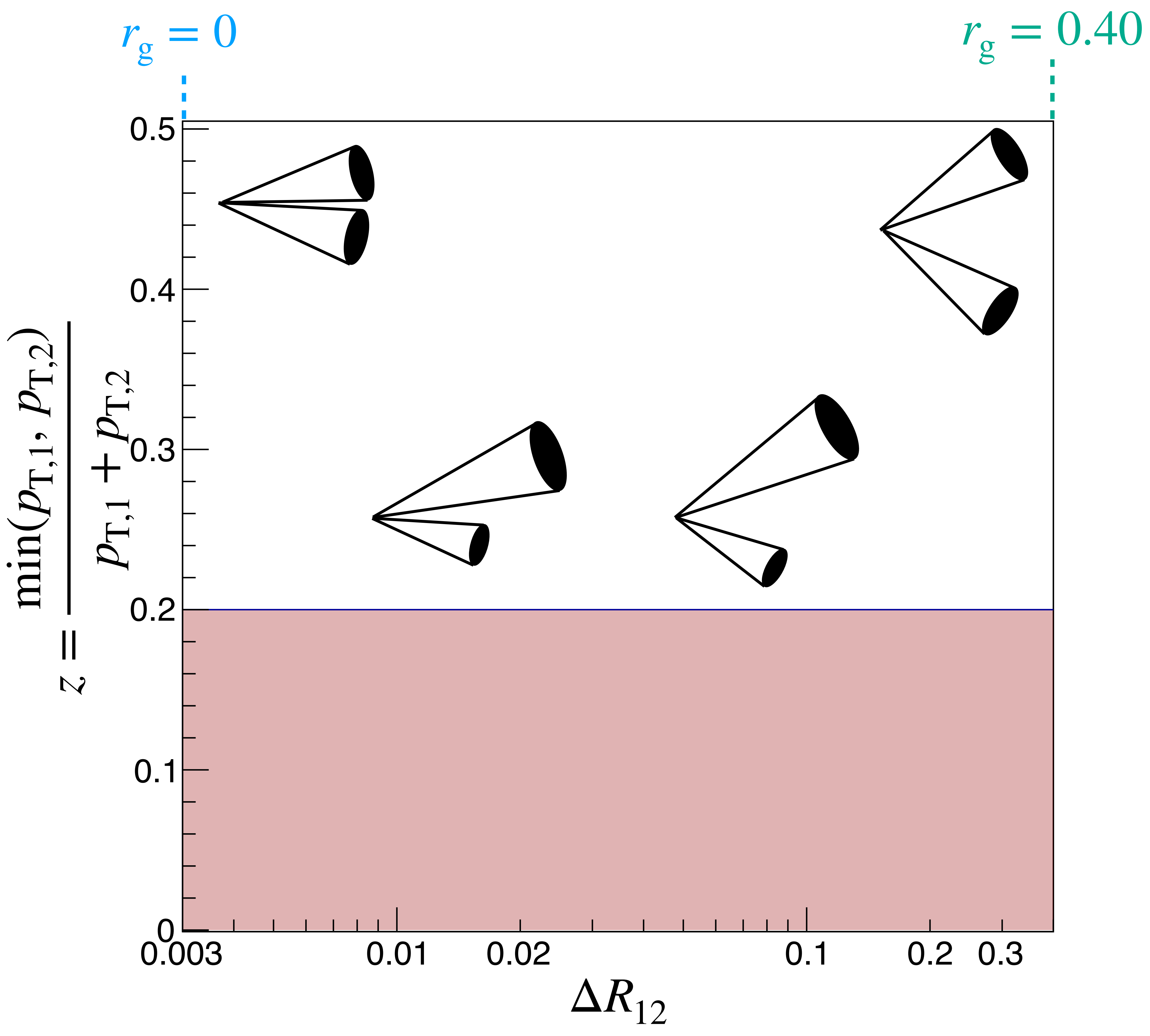


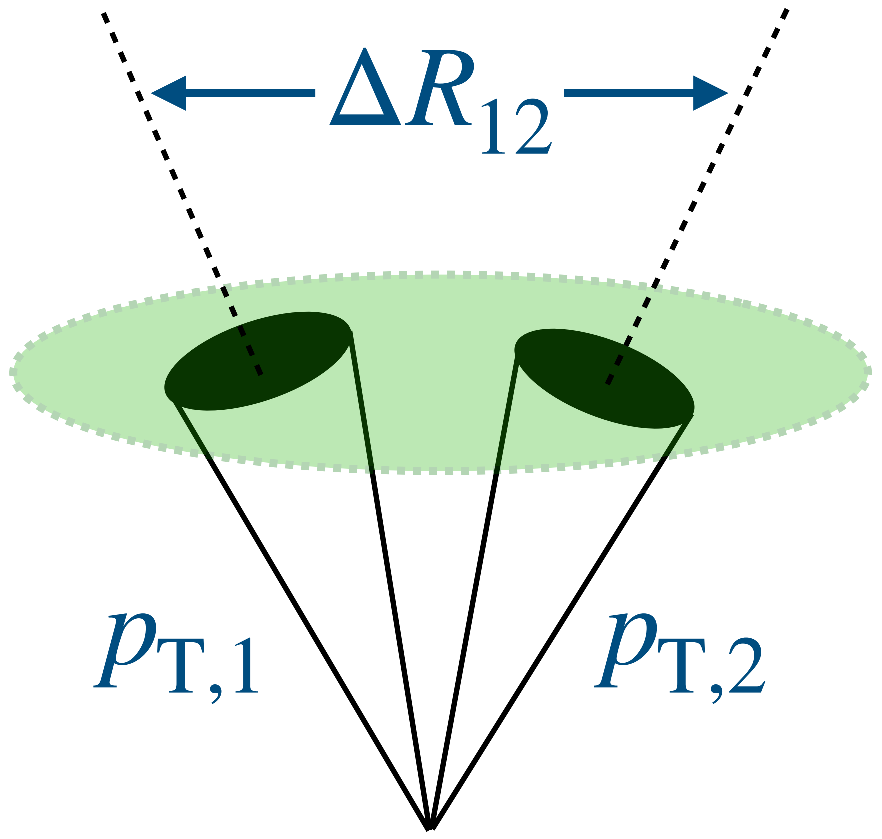
ATLAS-CONF-2019-056

Soft-Drop

- Characterize a jet using the energy imbalance of its **hardest splitting** (**z_g**)







$$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}}$$

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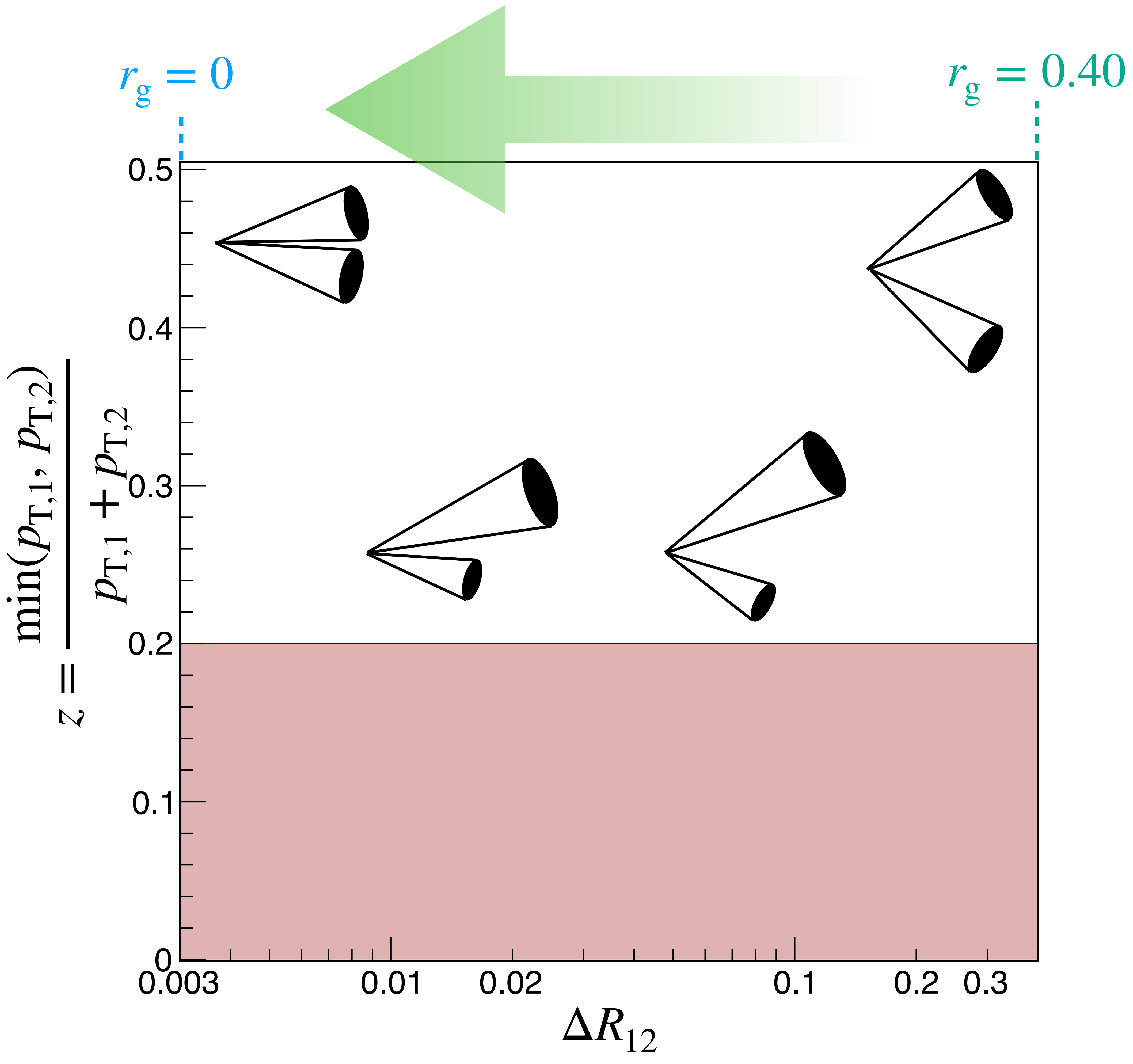
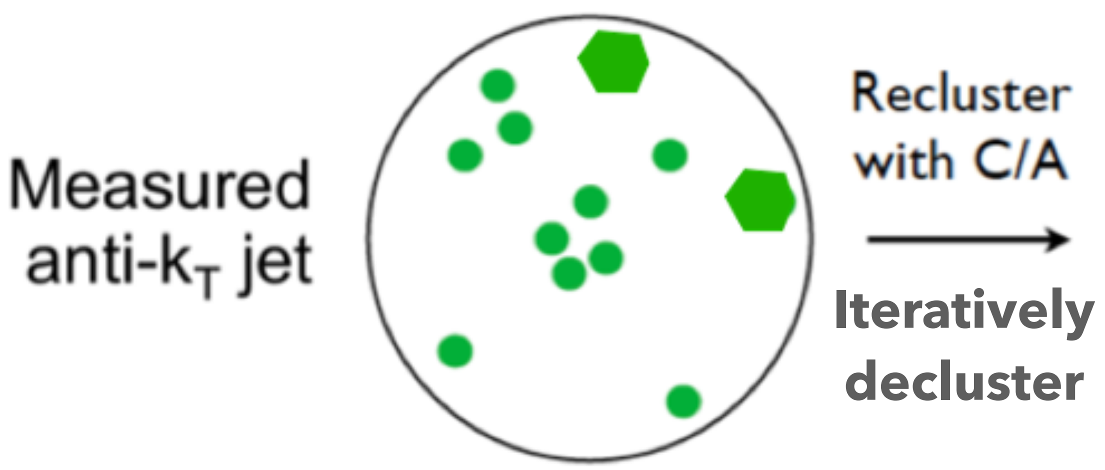
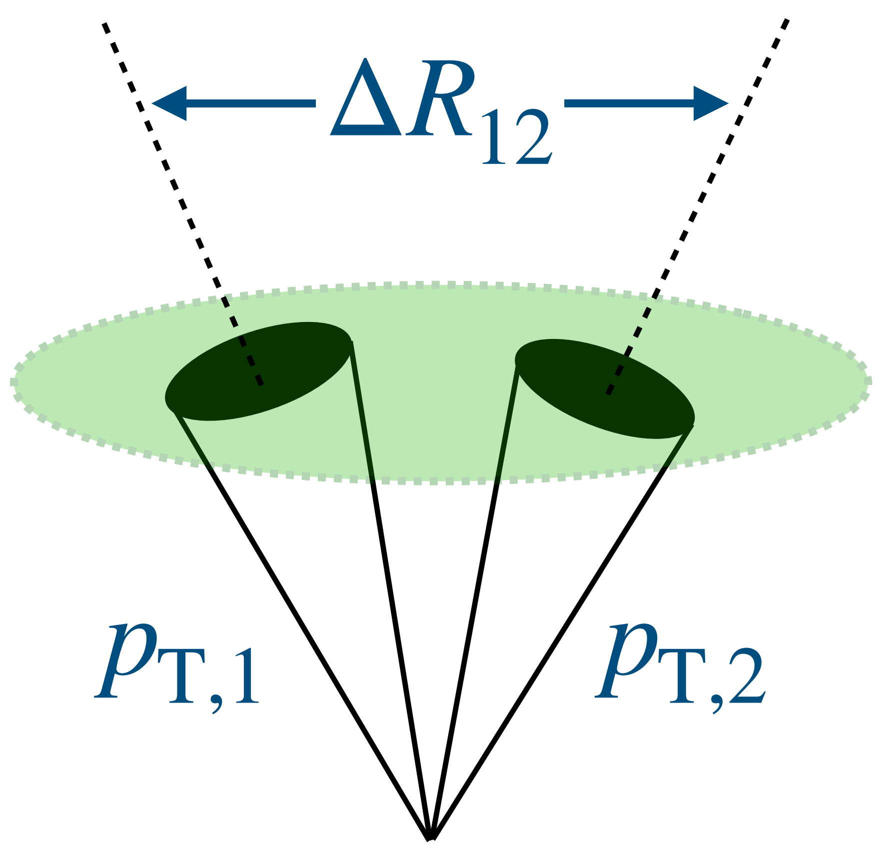




Cambridge/Aachen (C/A) is an angular-ordered clustering algorithm



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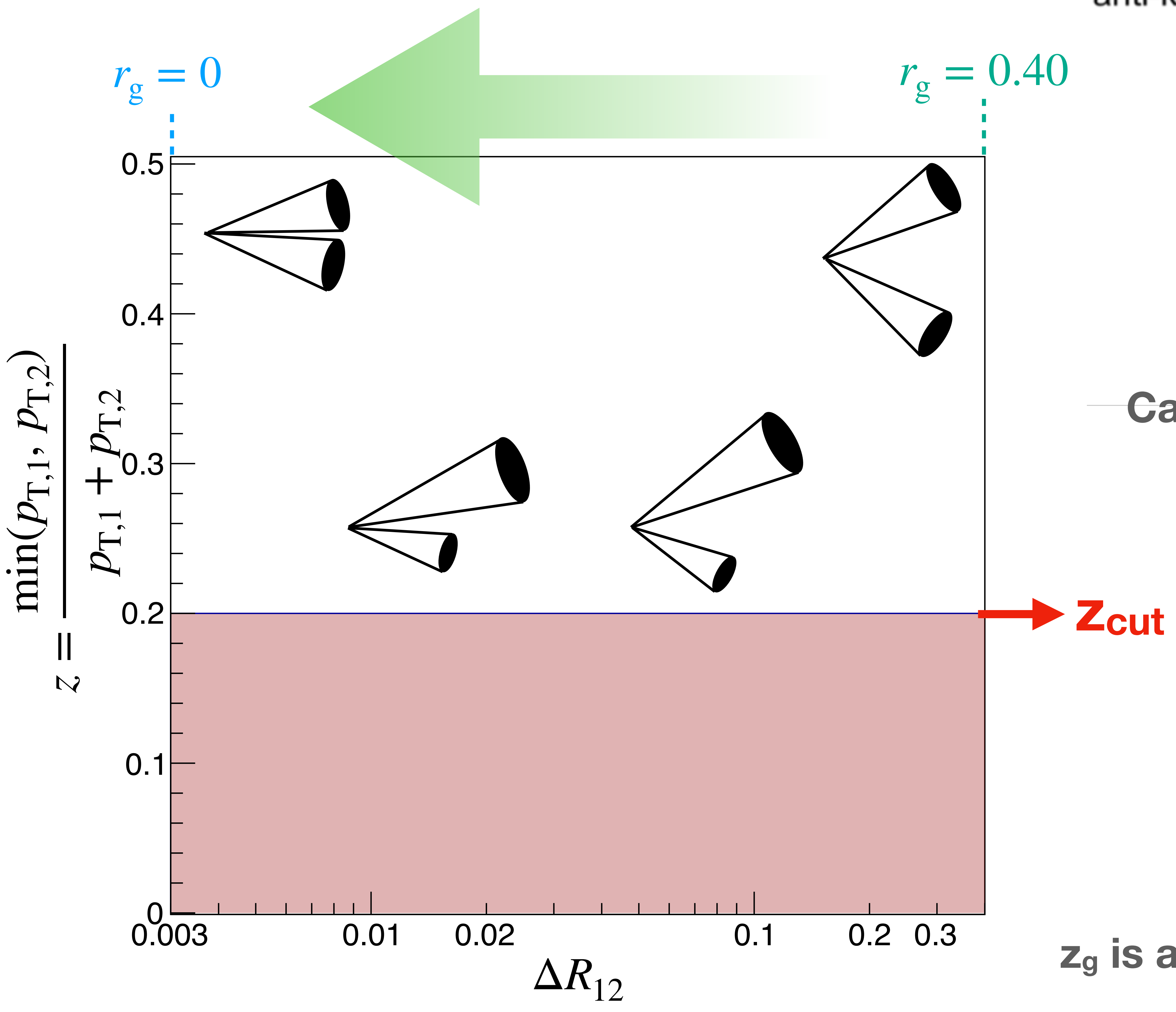

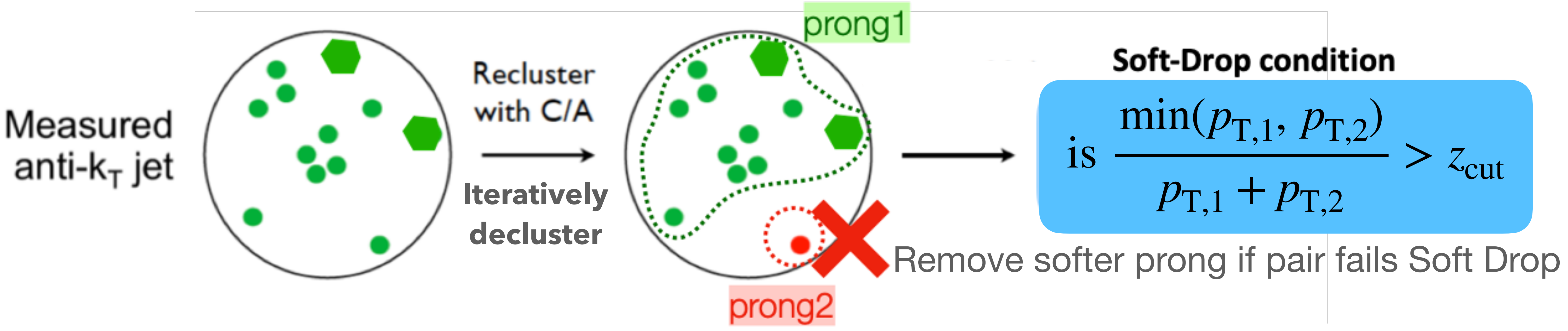

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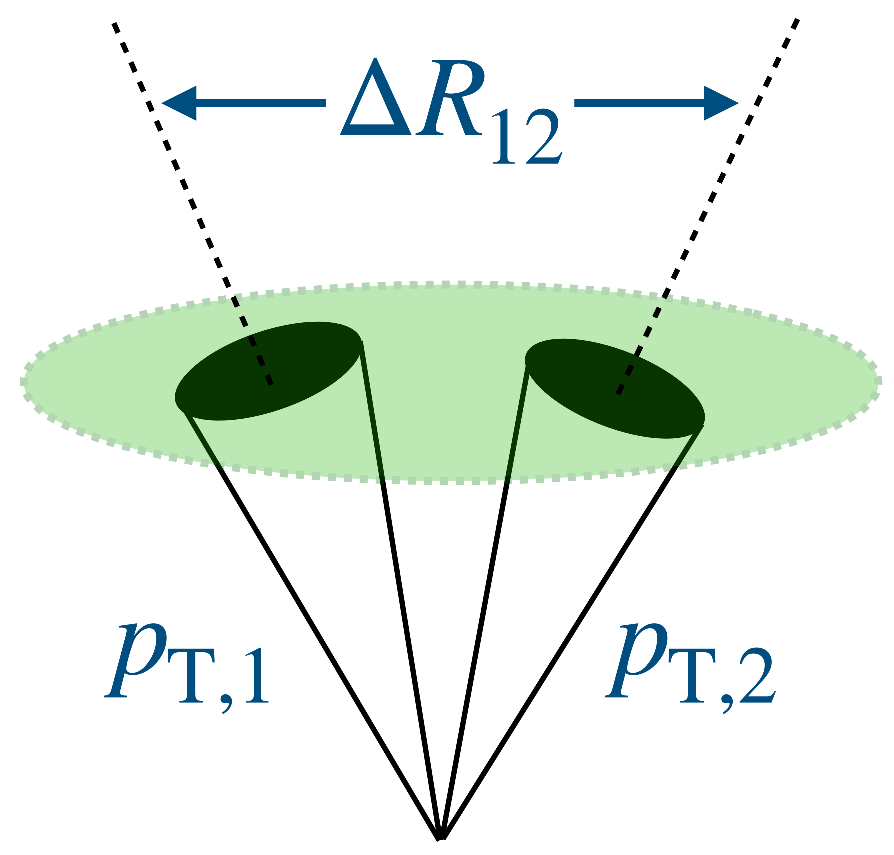

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z_g is a measure of subjet energy imbalance when SD condition is satisfied

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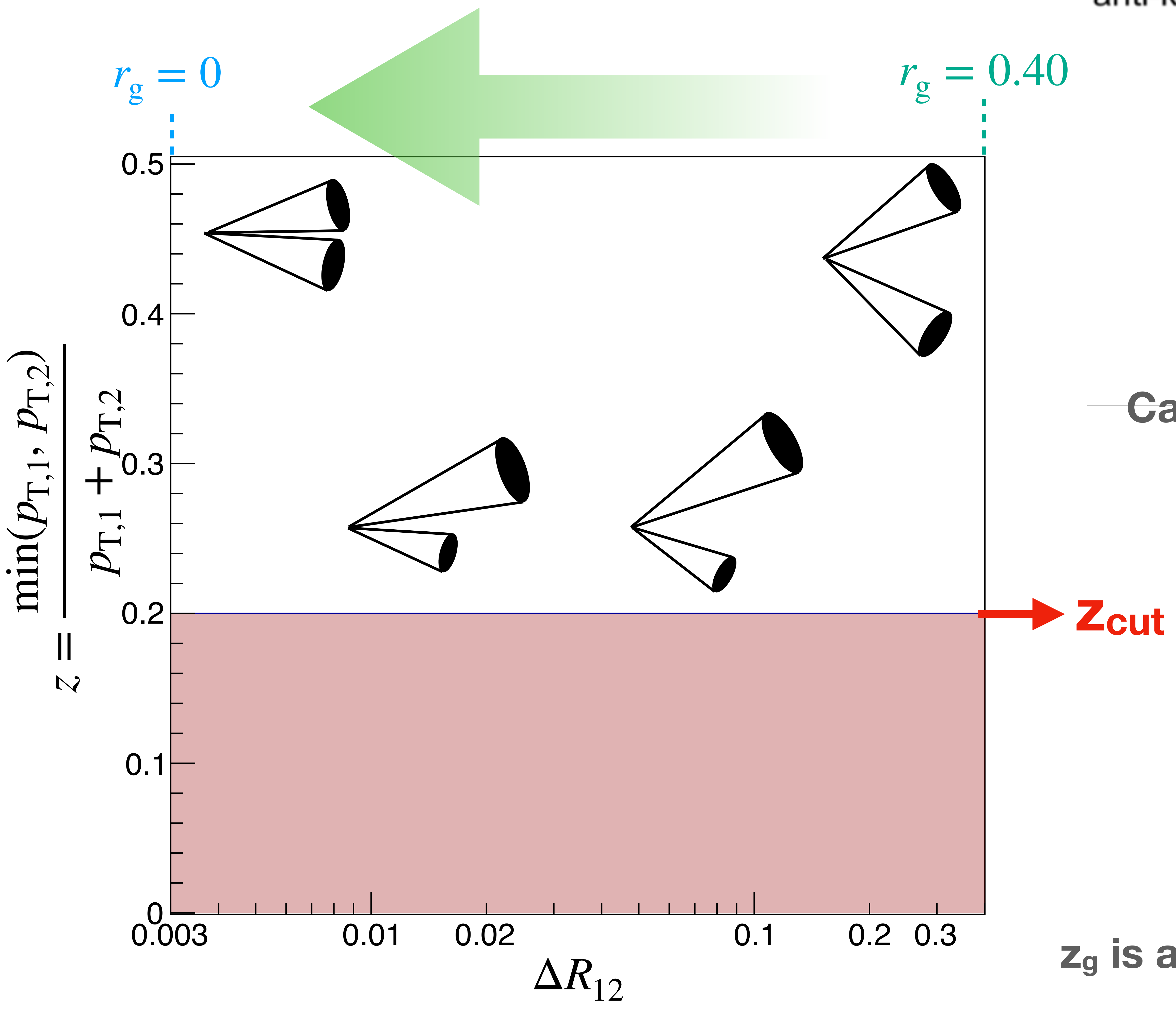

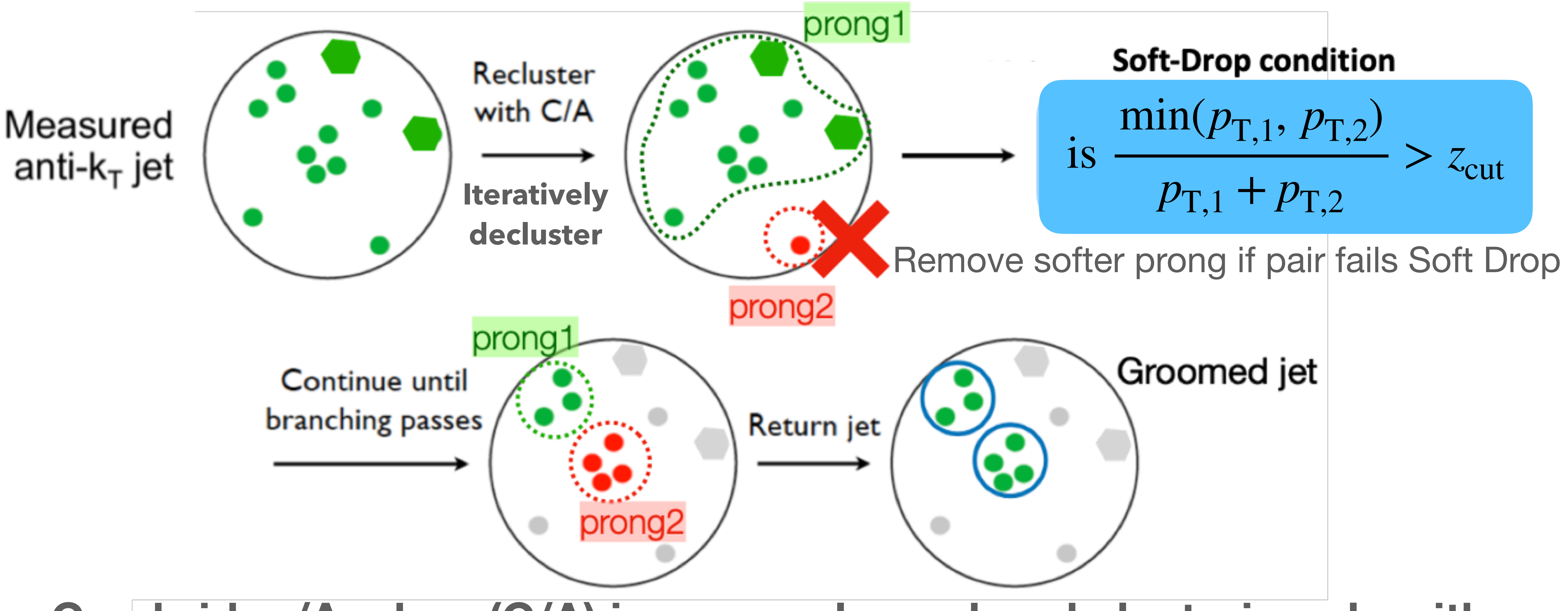

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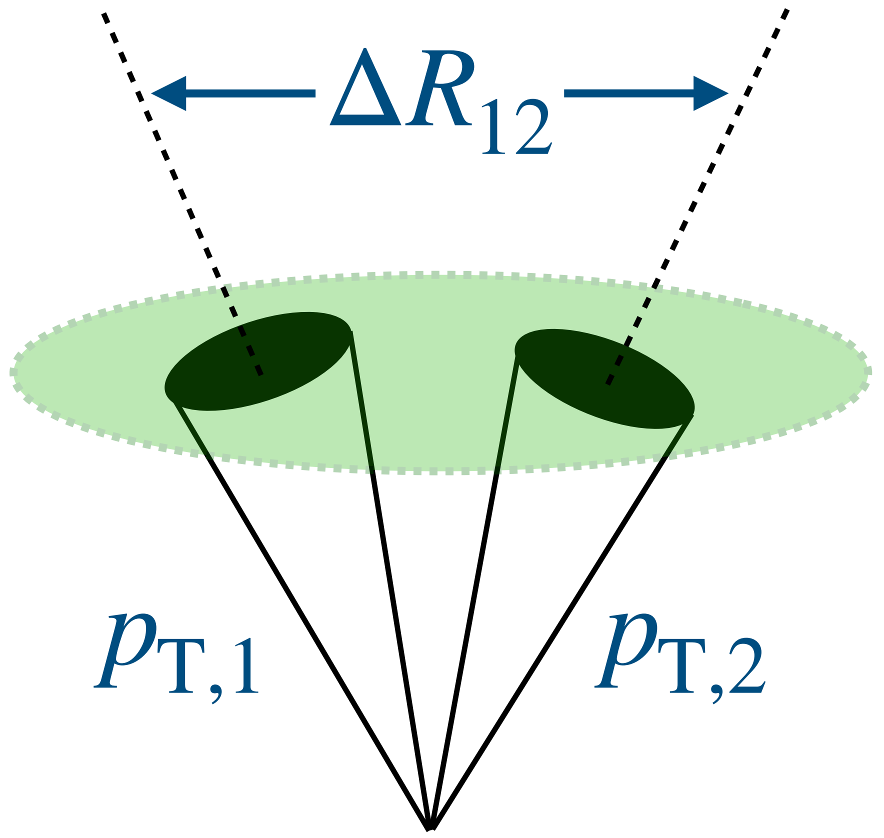

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z_g is a measure of subjet energy imbalance when SD condition is satisfied

Splitting function (CMS)

- z_g is a measure of energy imbalance of subjets corresponding to a jet's hard splitting
- Modification of self-normalized z_g observed in central PbPb collisions relative to pp

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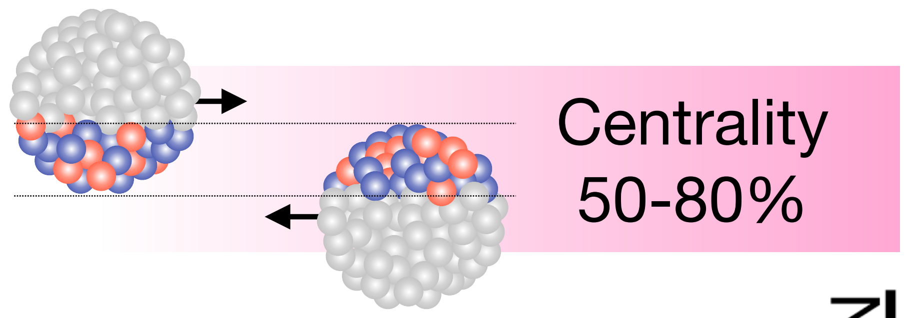

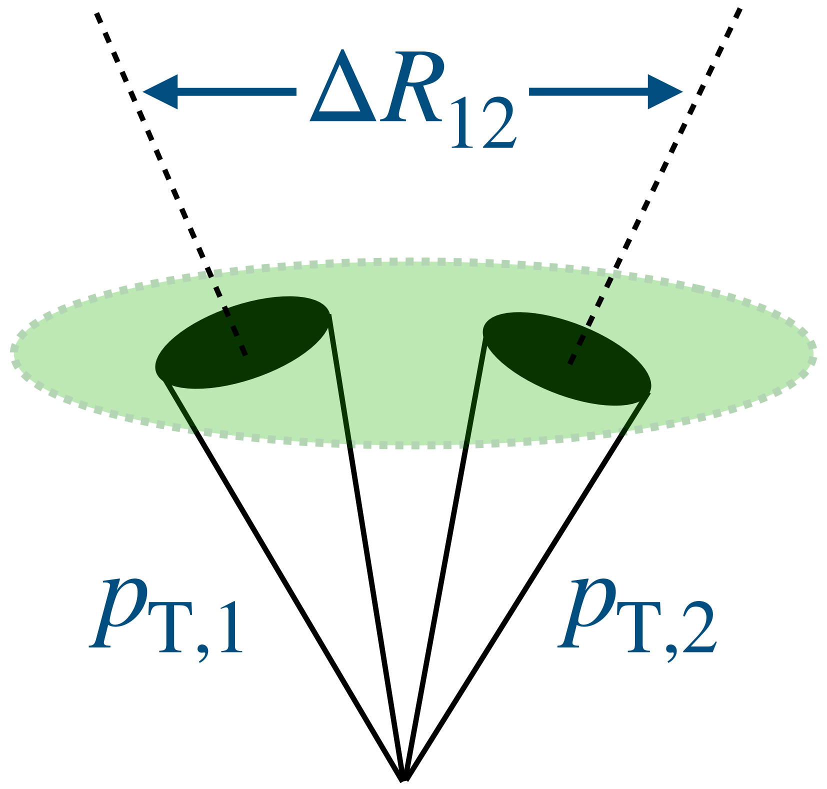

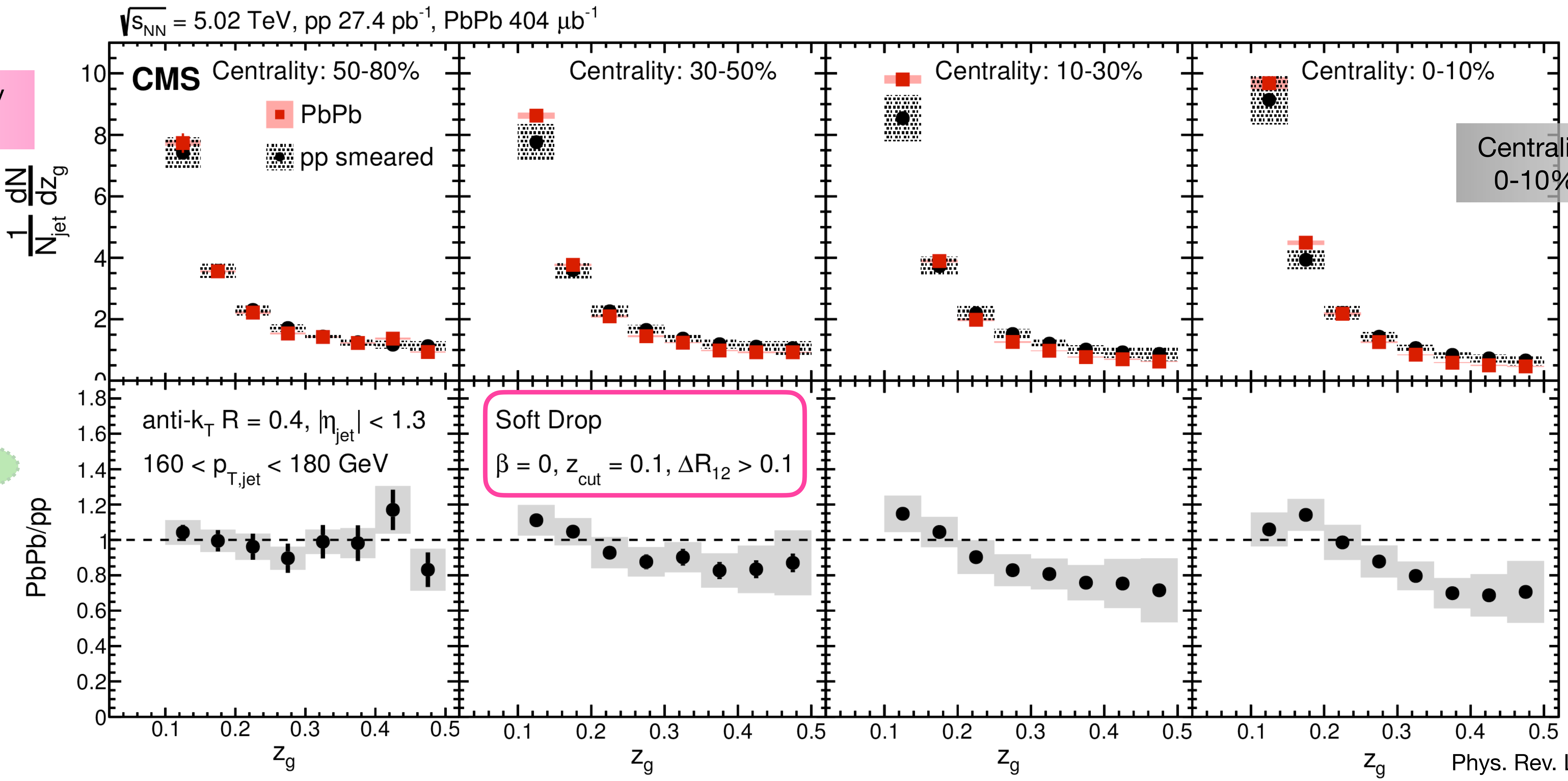

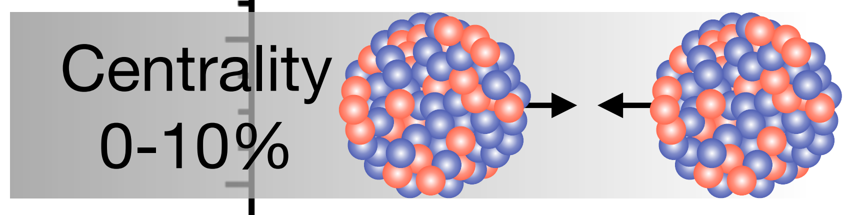

Phys. Rev. Lett. 120, 142302 (2018)

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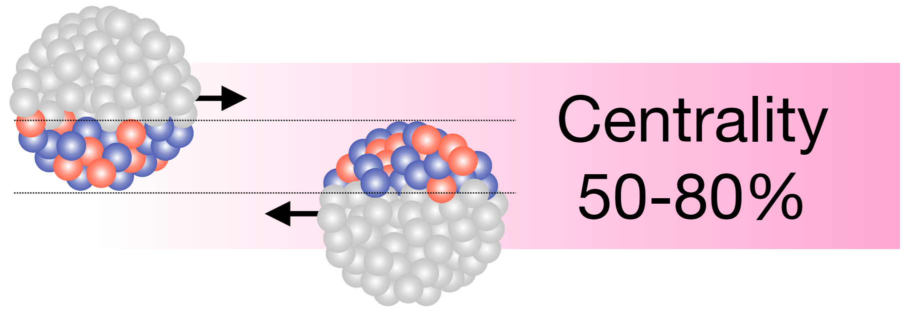

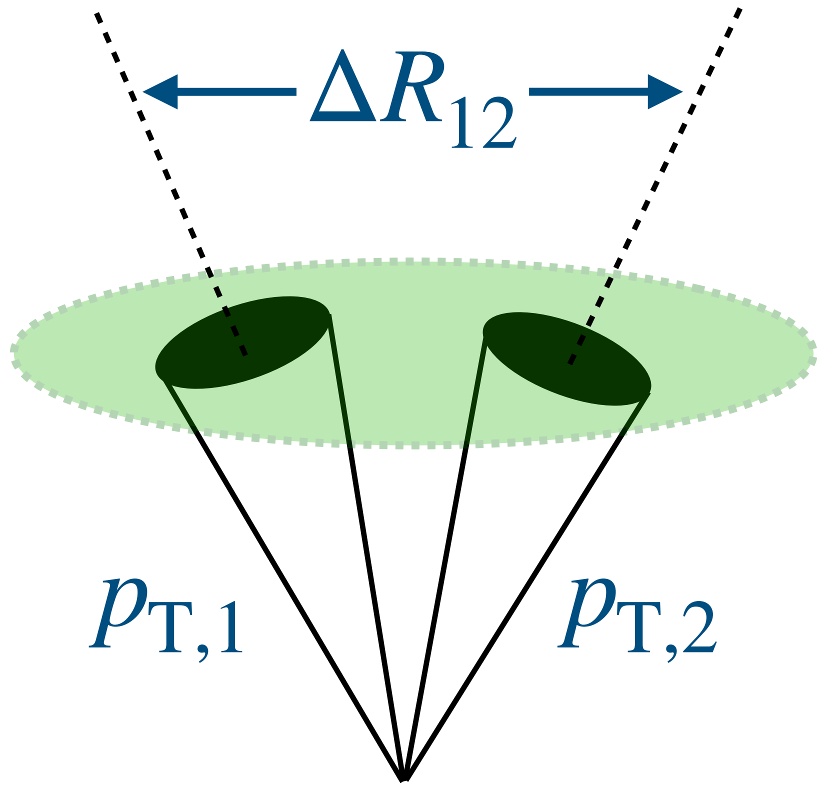

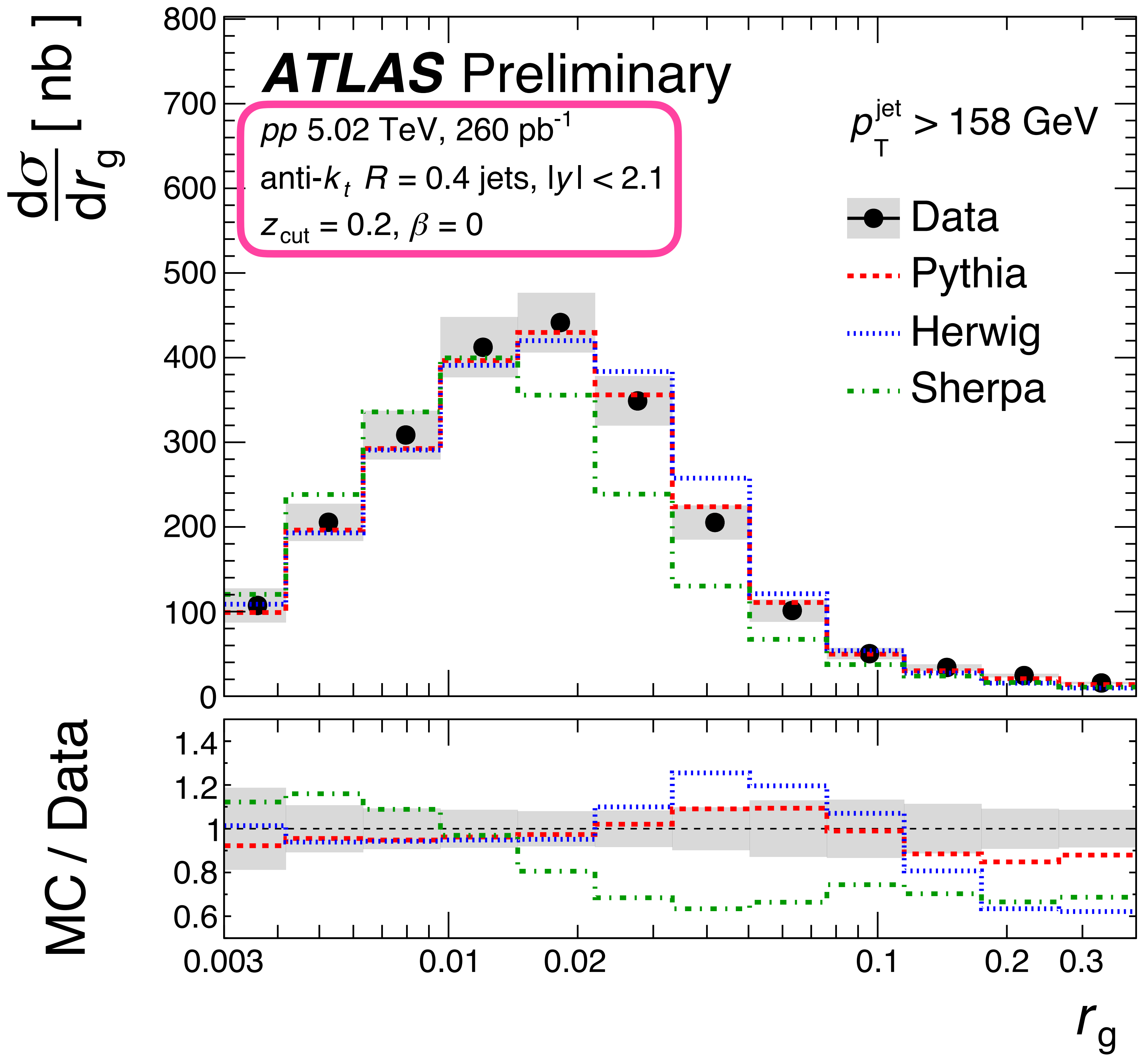

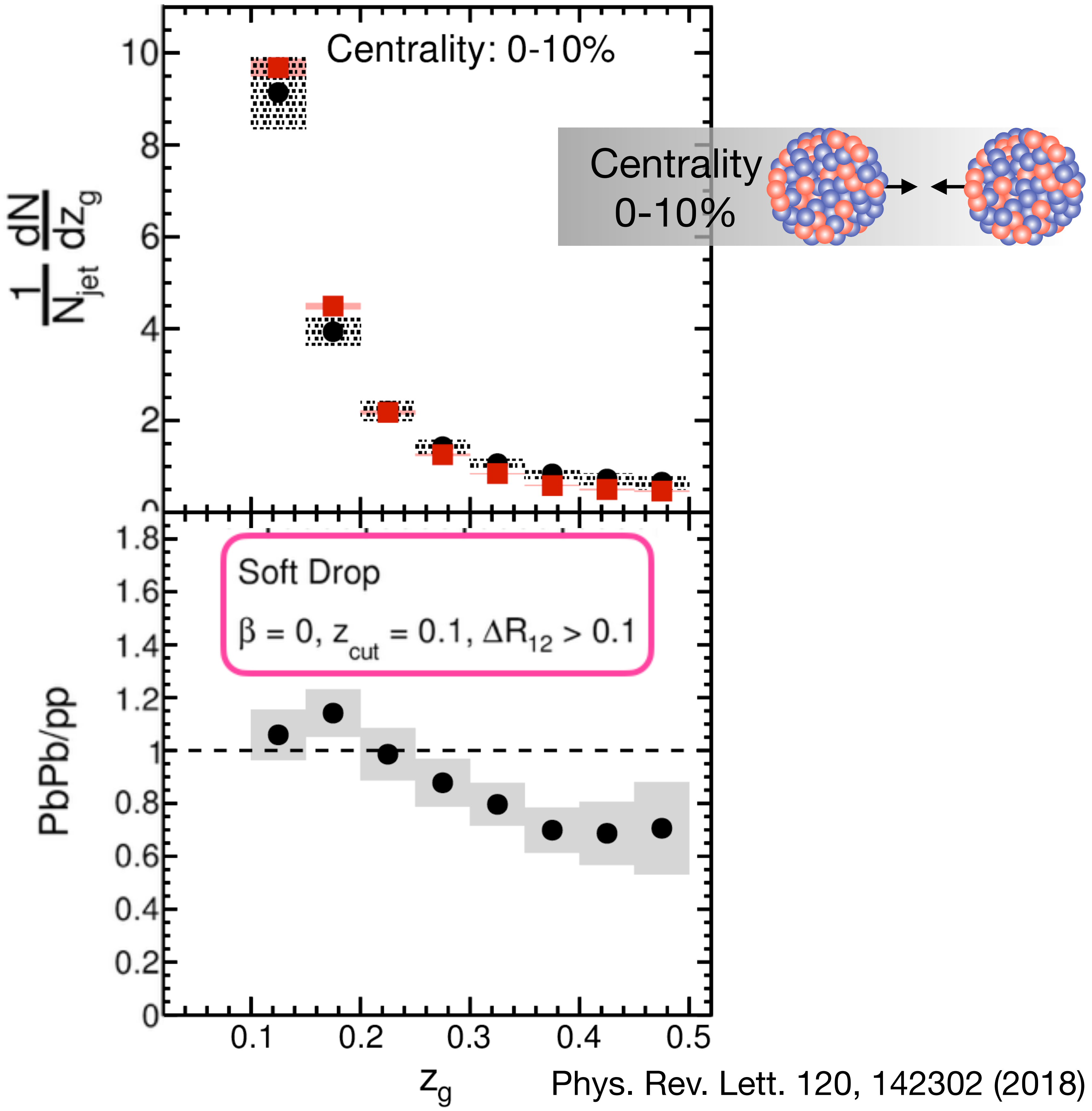

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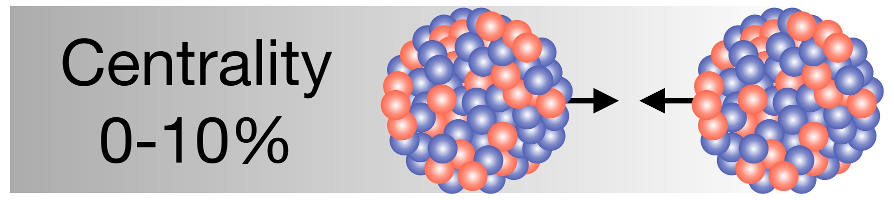
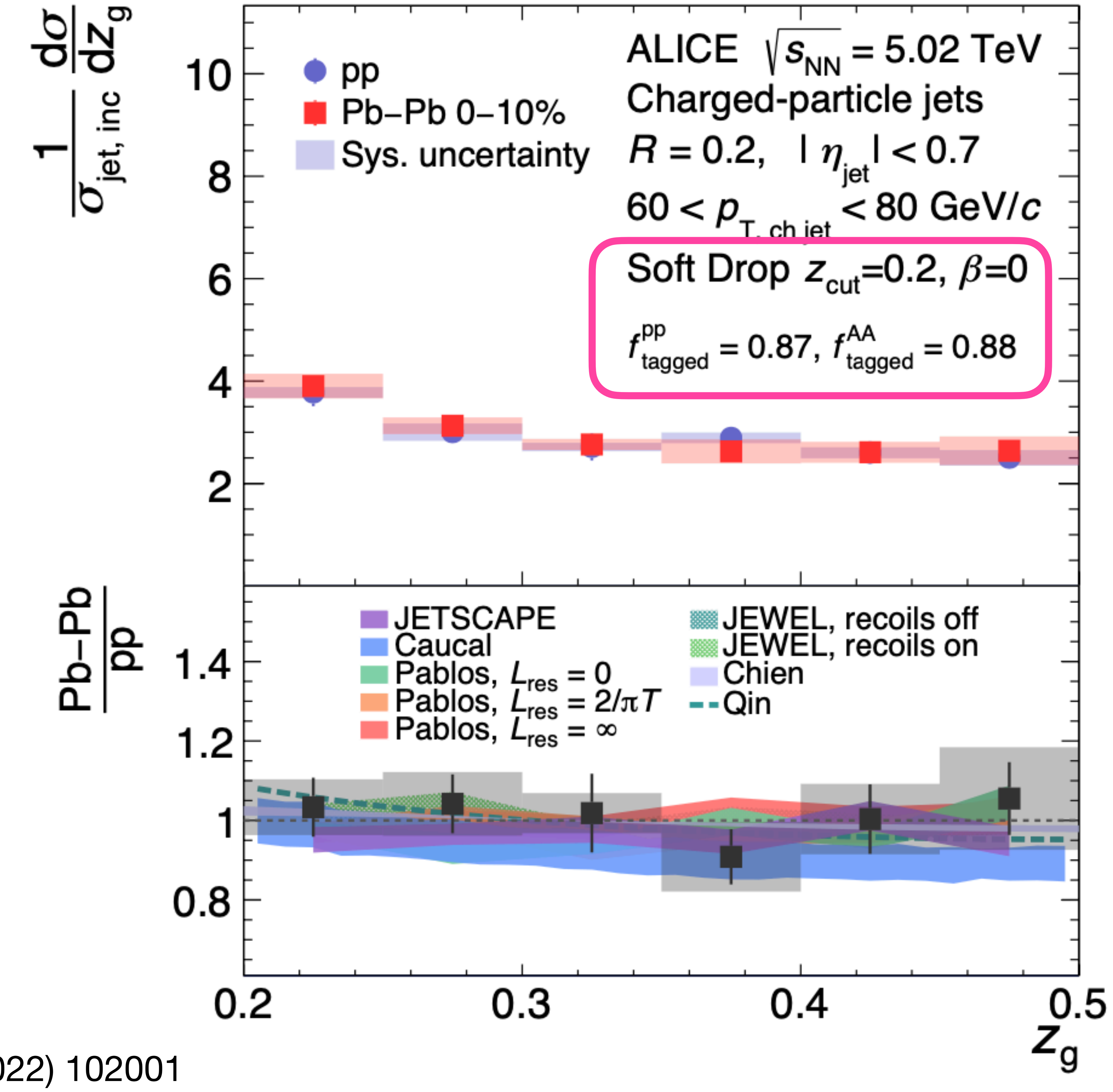
Splitting function (ALICE & STAR)

- z_g is a measure of energy imbalance of subjets corresponding to a jet's hard splitting
- No significant modification of z_g observed in central PbPb collisions relative to pp





PRL 128 (2022) 102001

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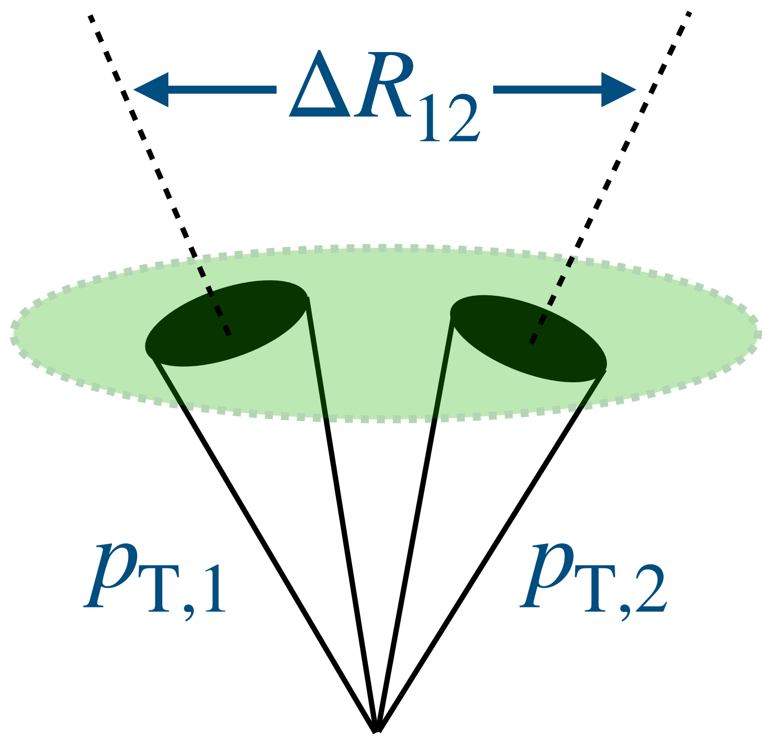

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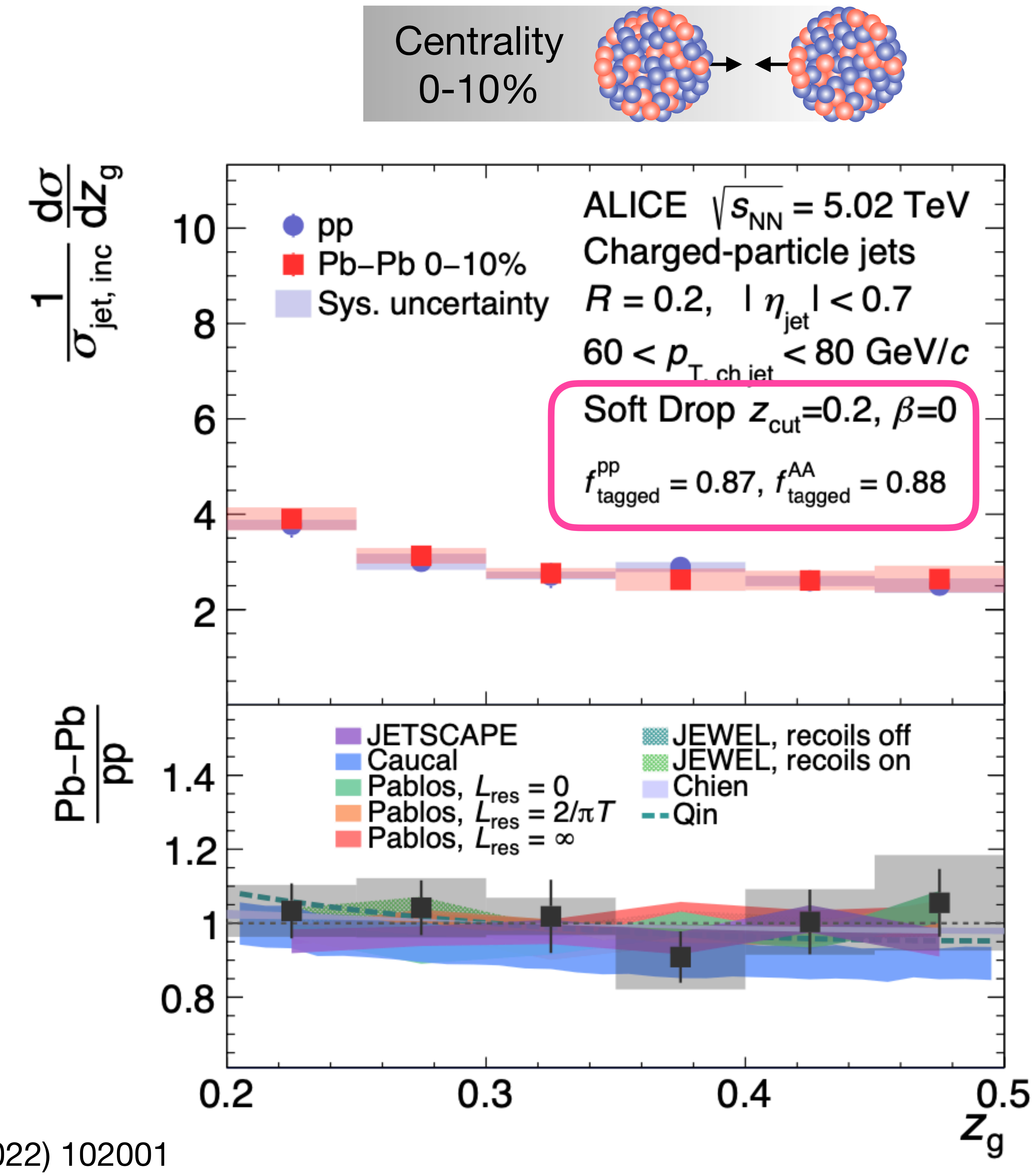
HardCore jet
$p_{T,\text{ constituent}} > 2$ GeV/c
Matched jet
$p_{T,\text{ constituent}} > 0.2$ GeV/c



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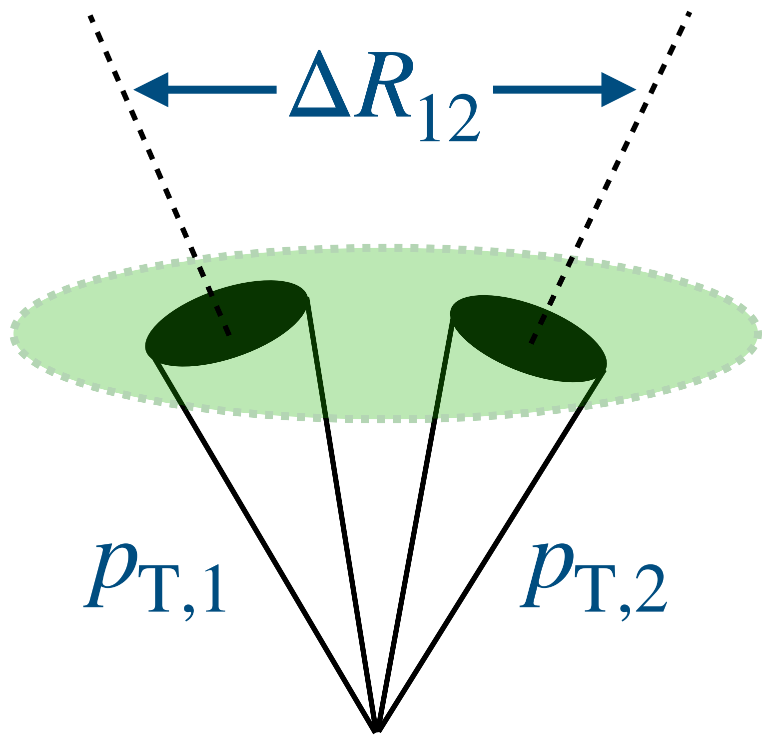
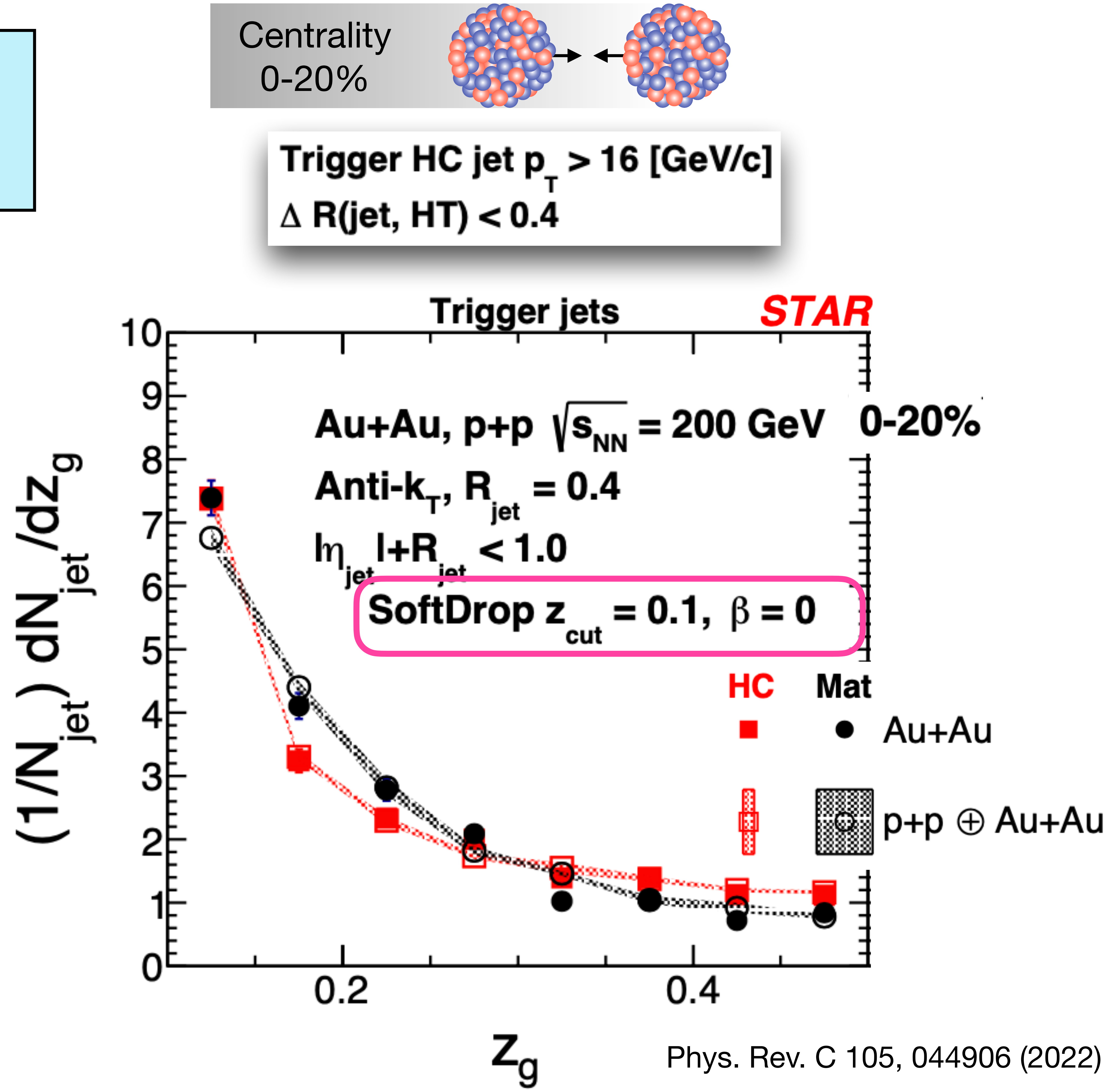


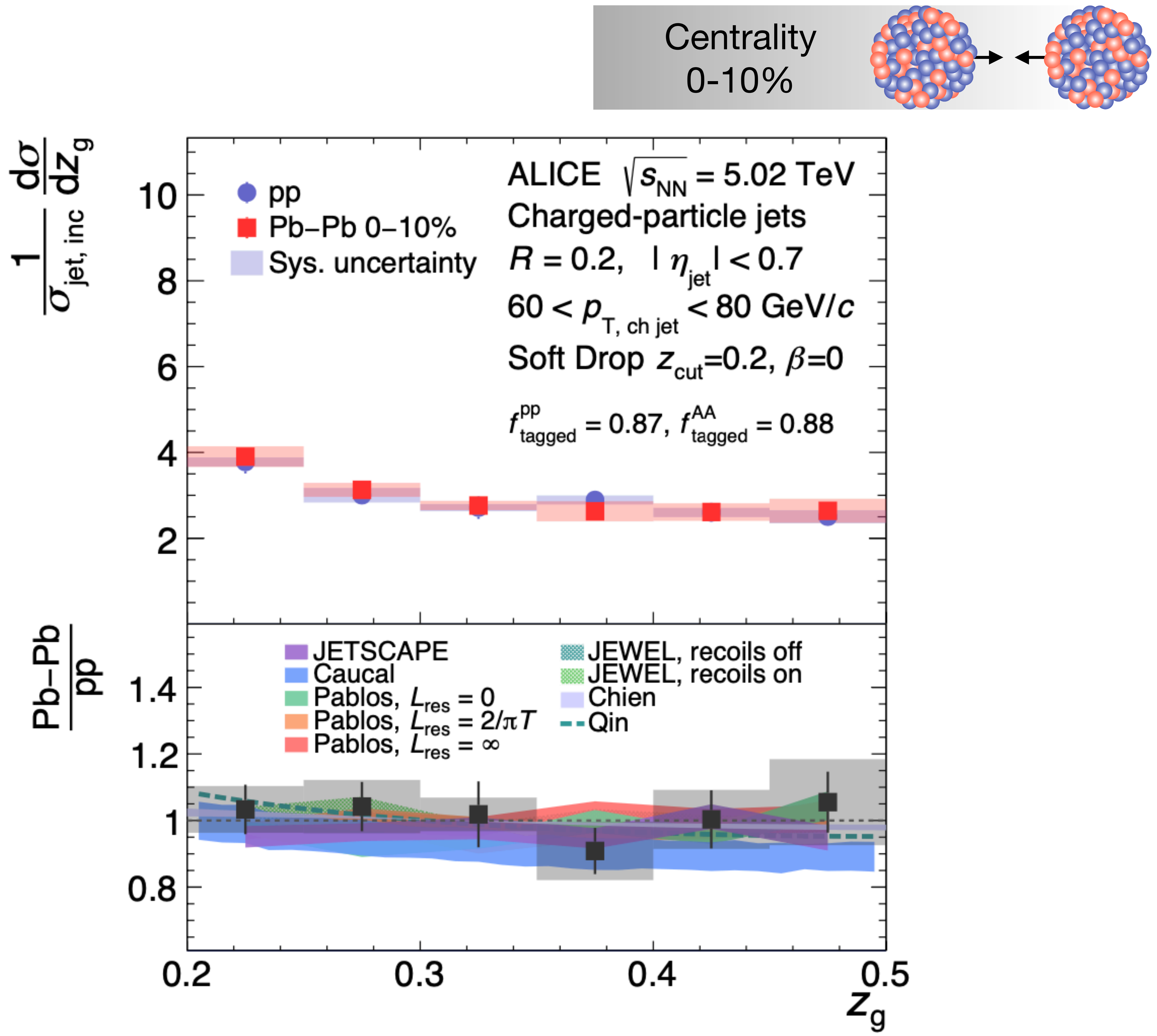


PRL 128 (2022) 102001

Phys. Rev. C 105, 044906 (2022)

Jet substructure interpretation

- Tension in self-normalized distributions of splitting function, z_g, between CMS vs. ALICE and STAR?



$$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}}$$

Is the jet's hard splitting being modified?

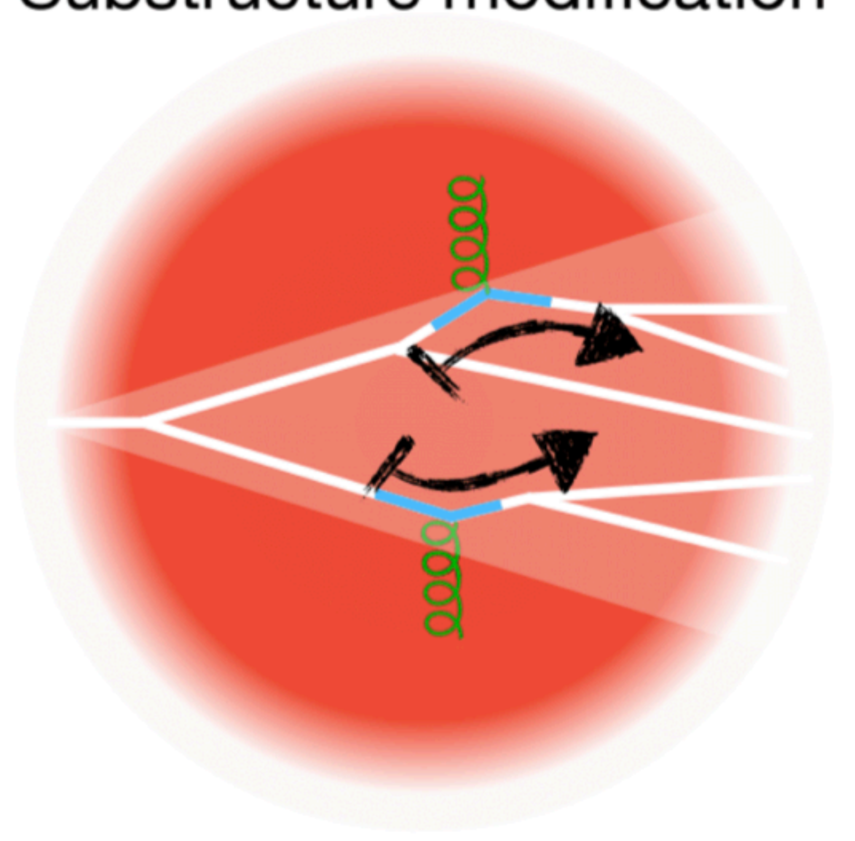


Figure from
Leticia Cunqueiro

PRL 128 (2022) 102001

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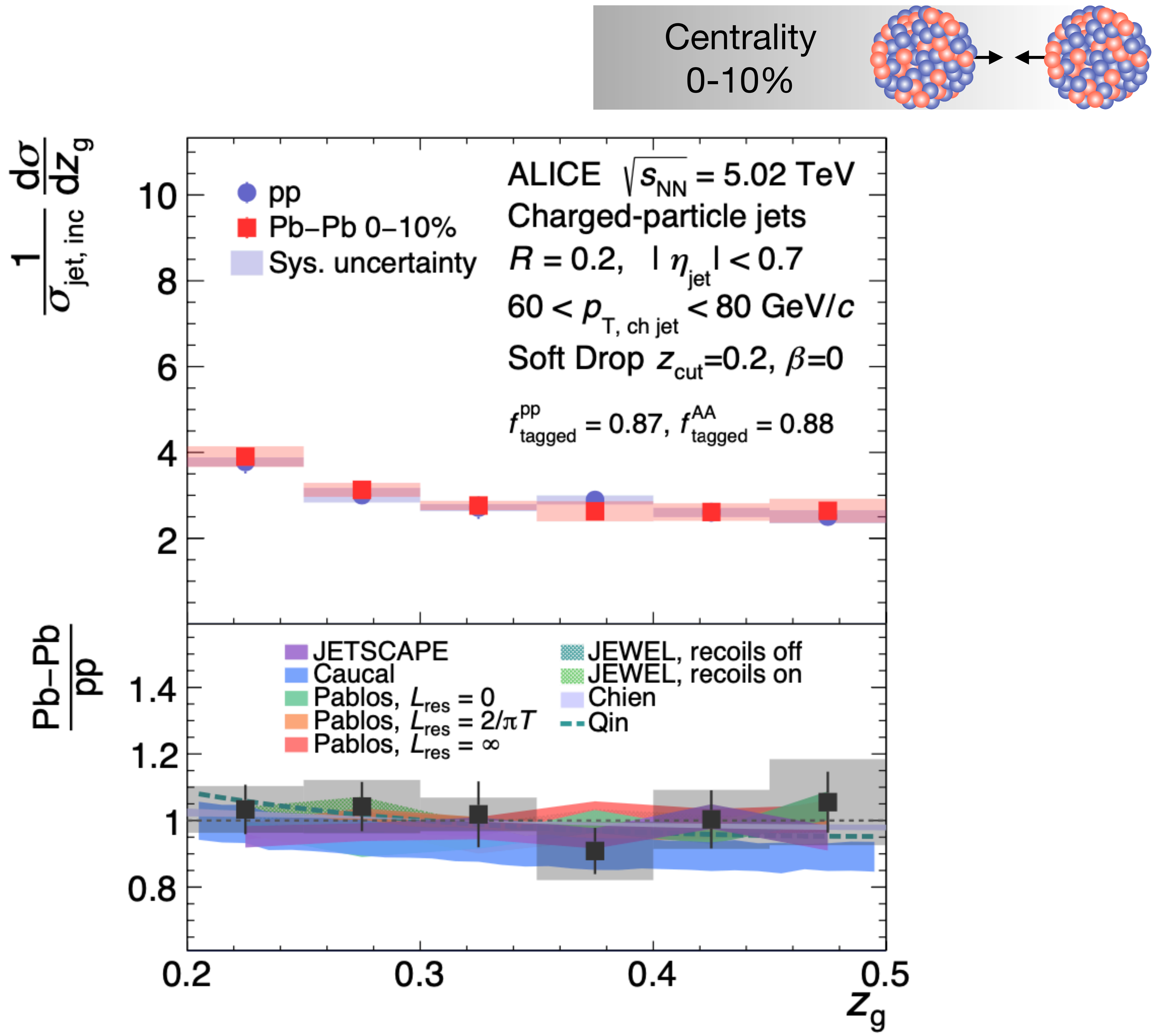

PRL 128 (2022) 102001

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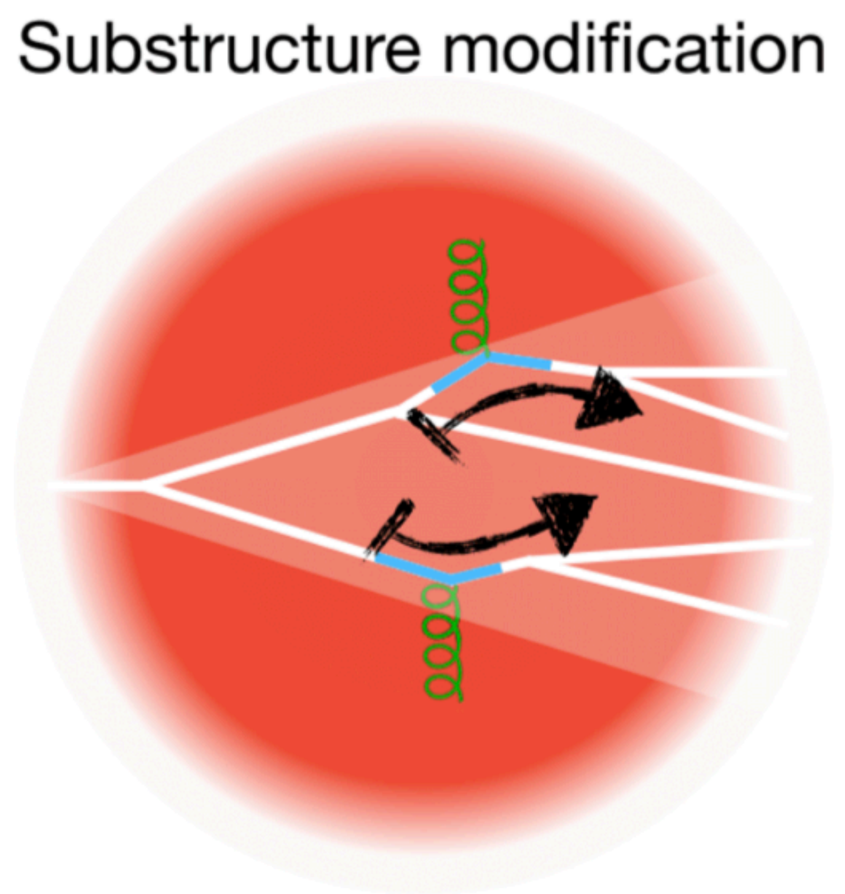

Figure from
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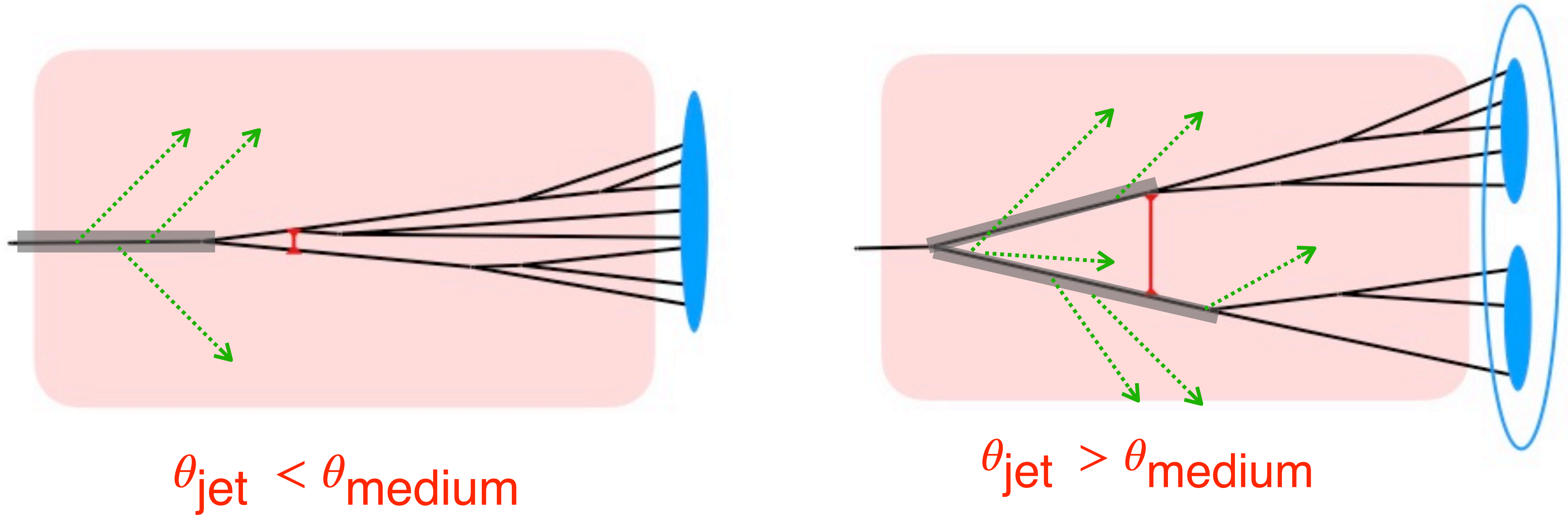
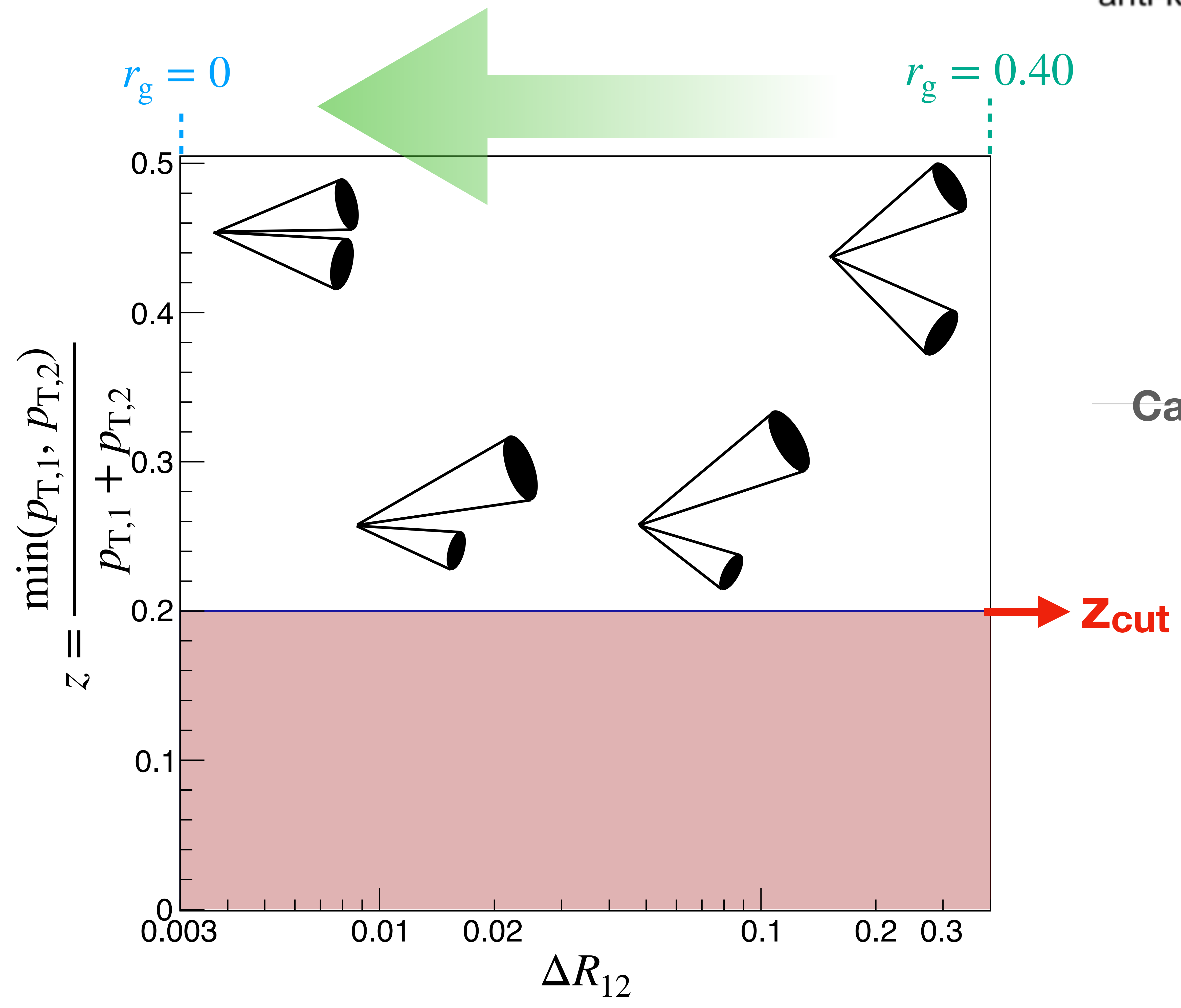
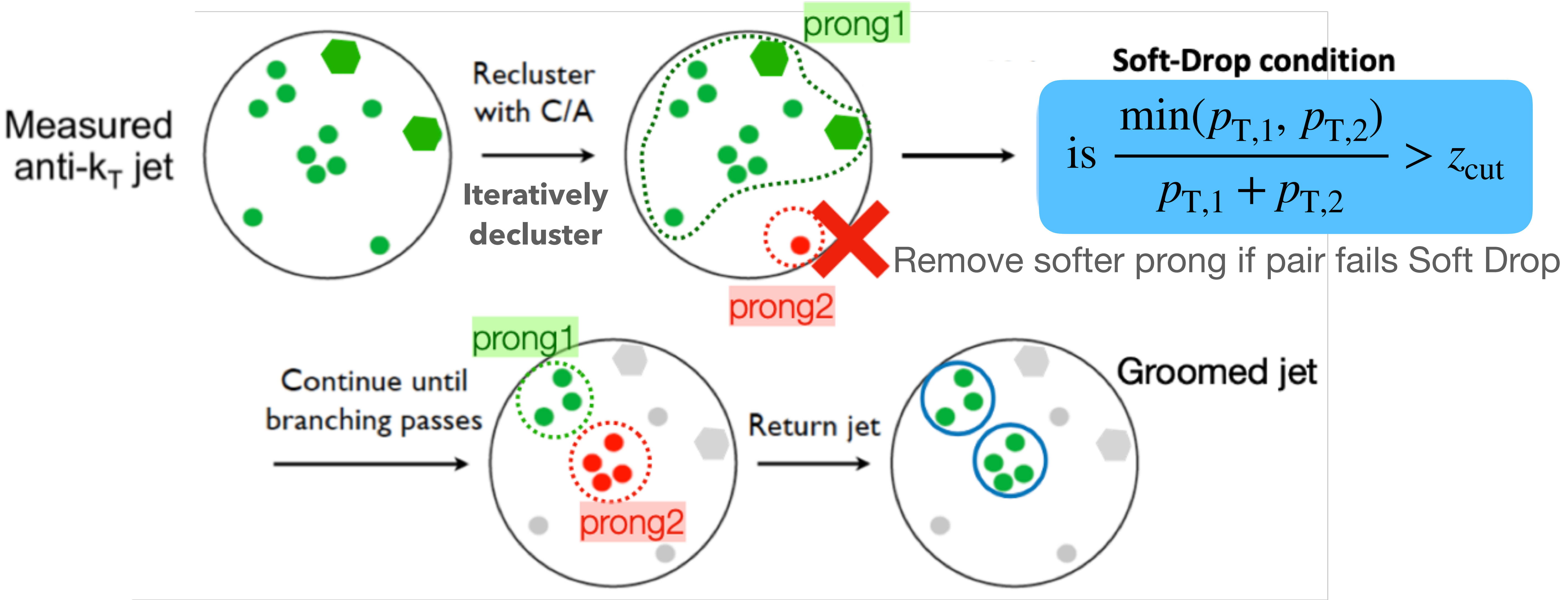
Or do jets with different splittings experience different quenching?



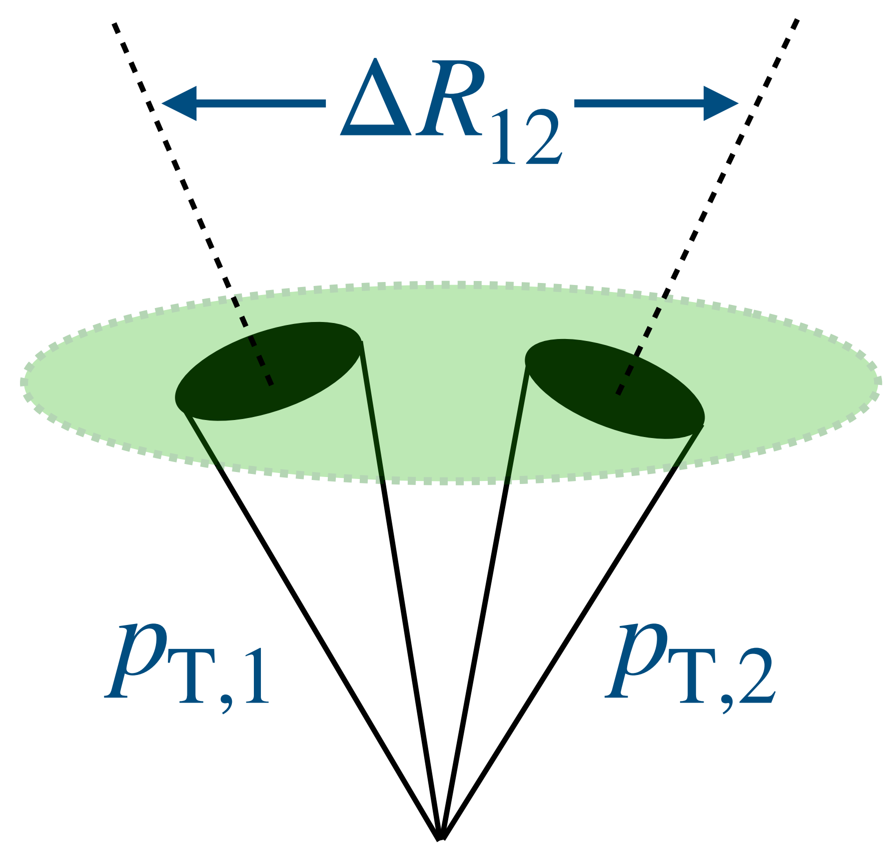
Soft-Drop

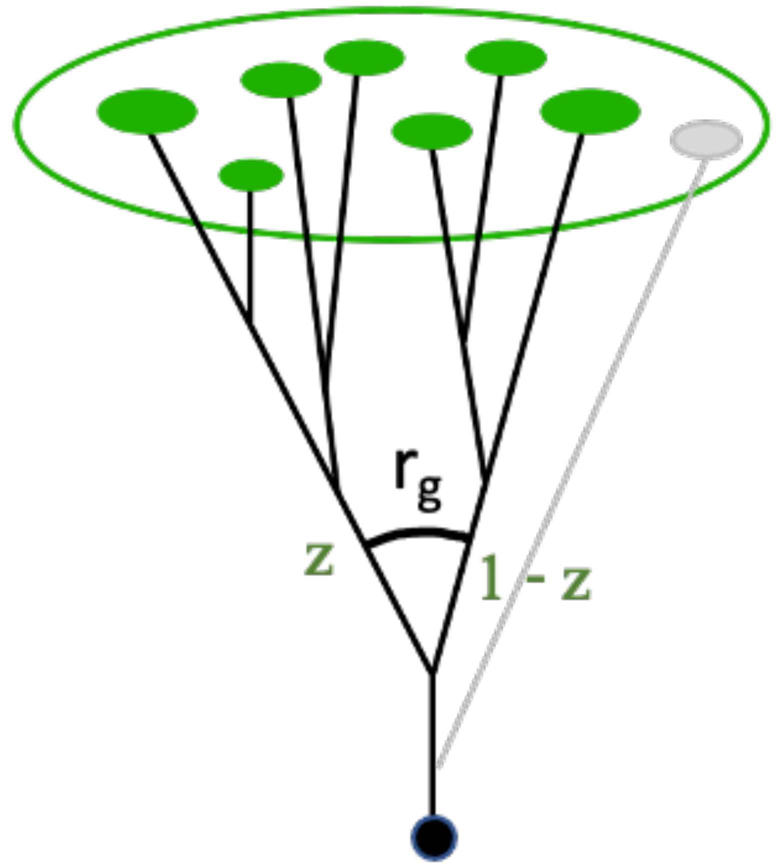
- Characterize a jet using the angular separation of its **hardest splitting (r_g)**





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

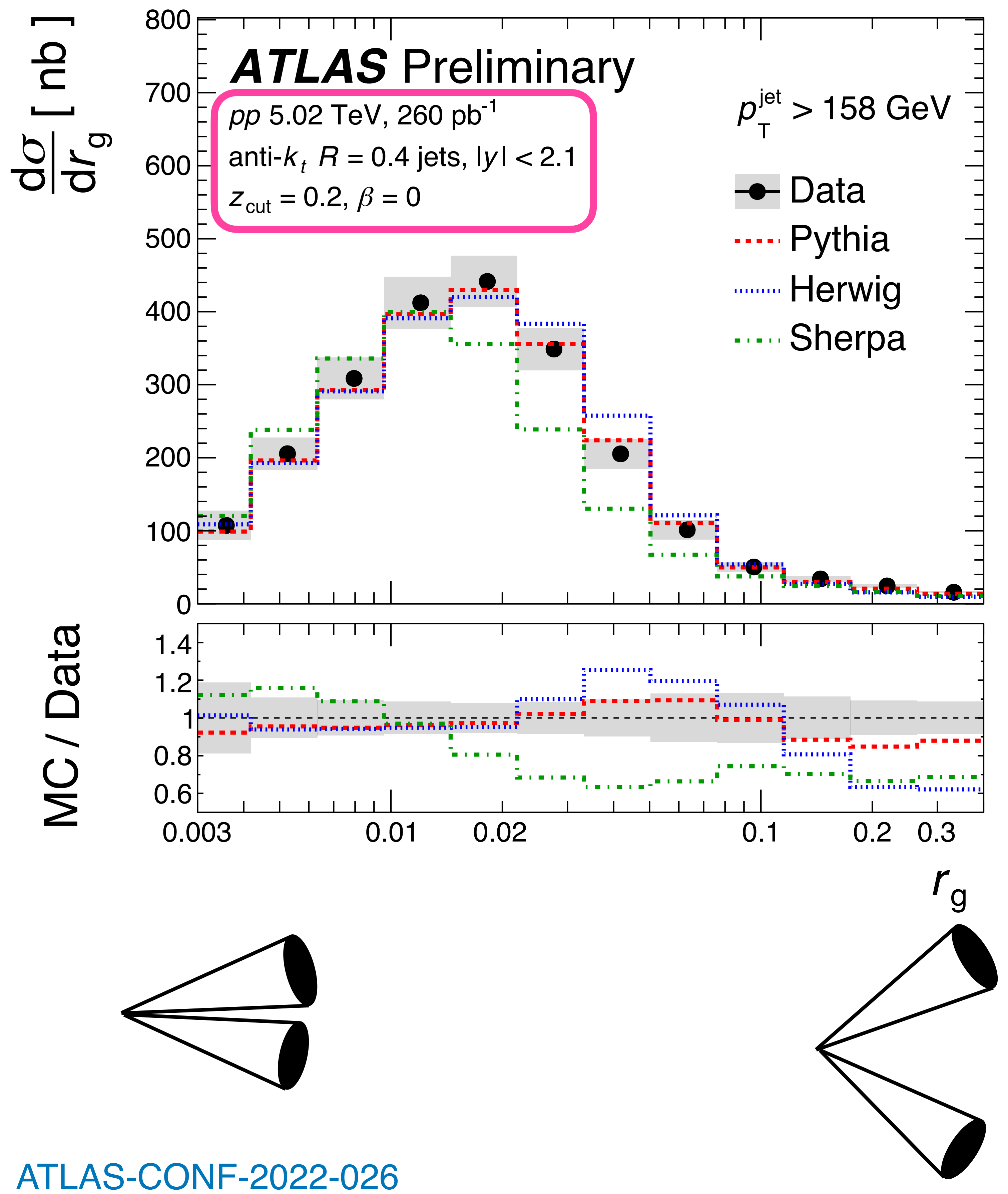


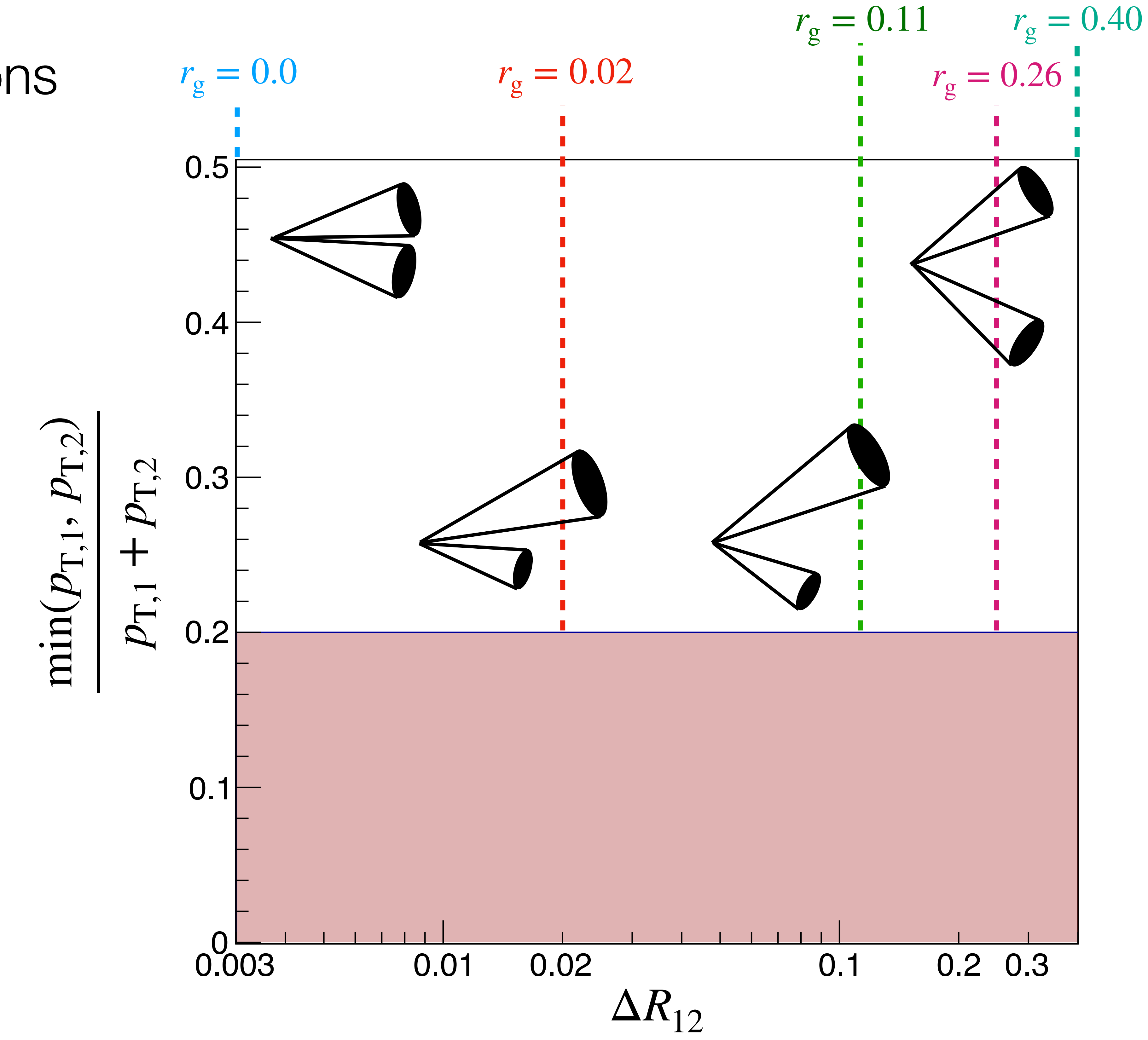


r_g is ΔR_{12} between subjets when SD condition is satisfied

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





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

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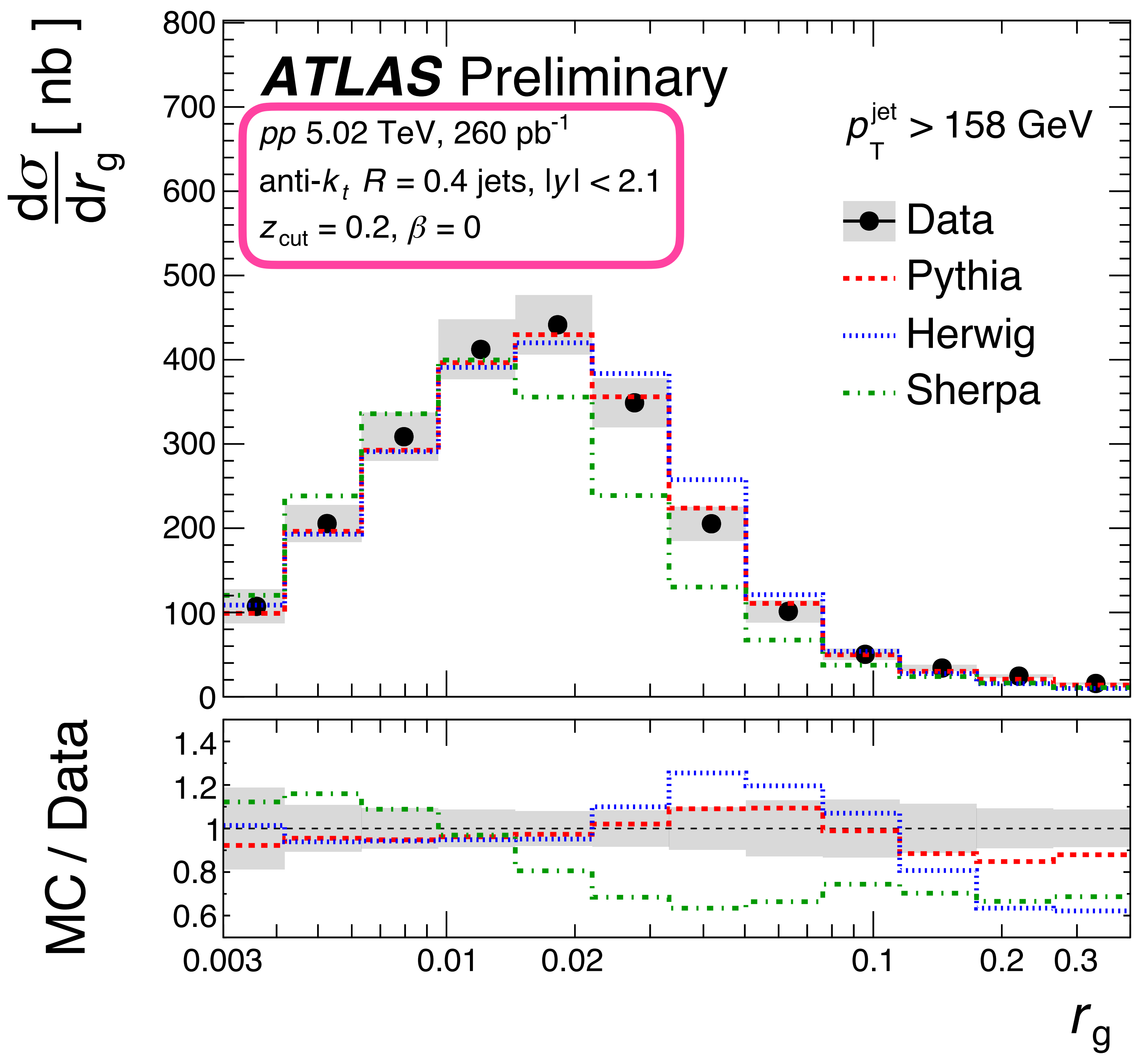

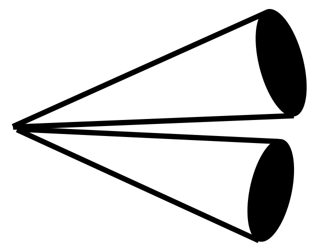

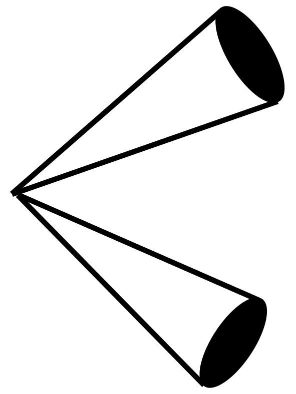

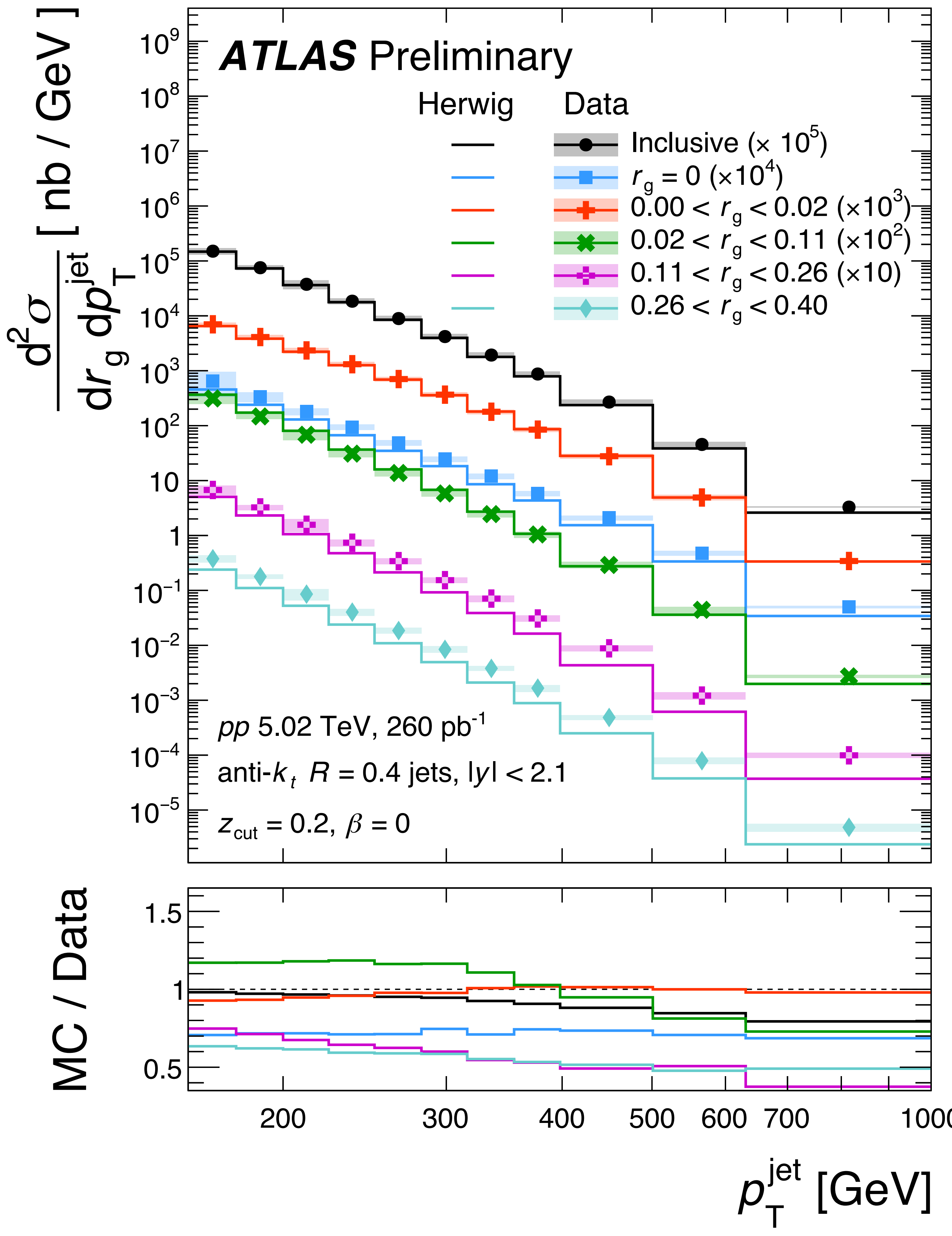

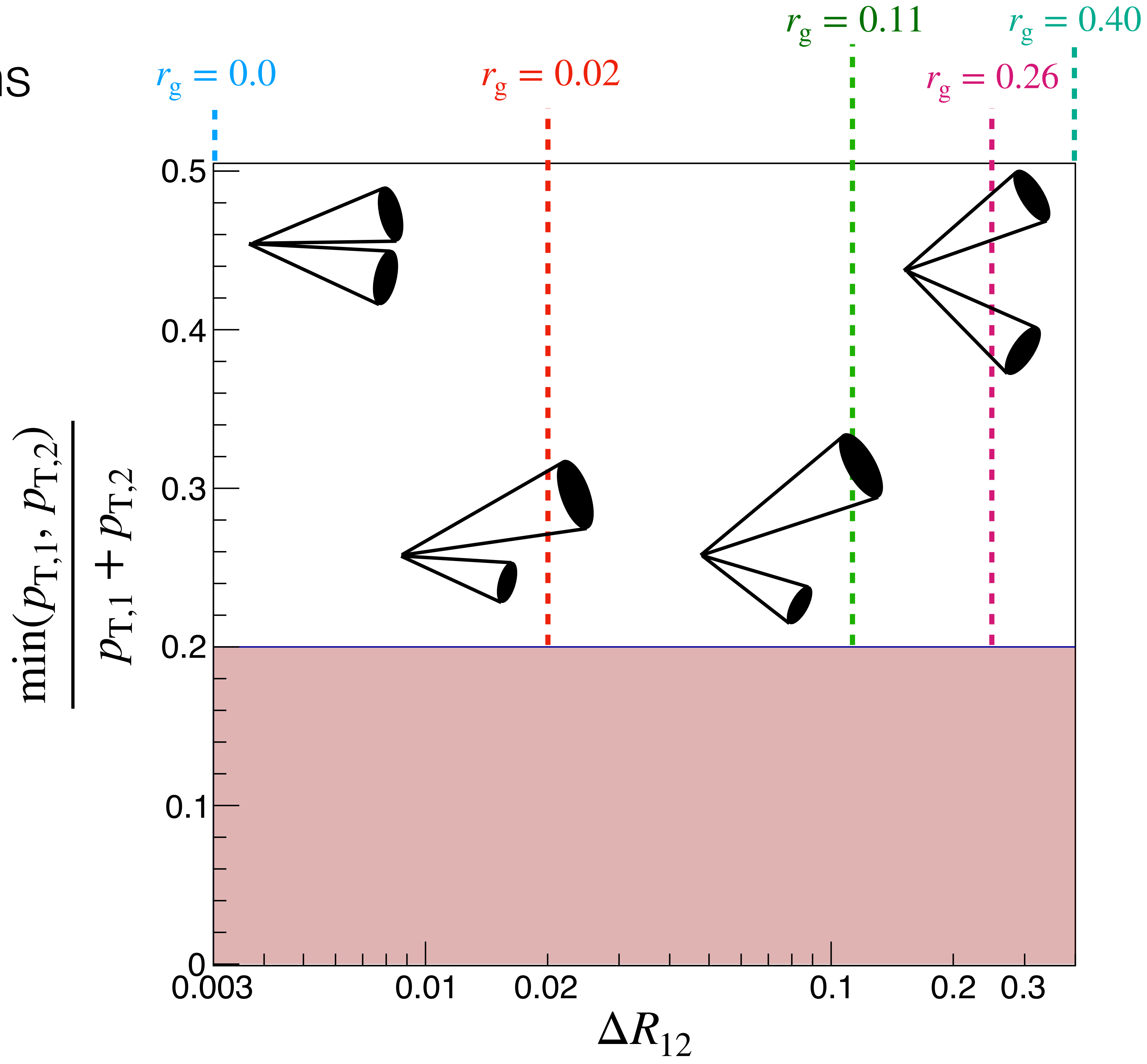

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(=0.2)$$

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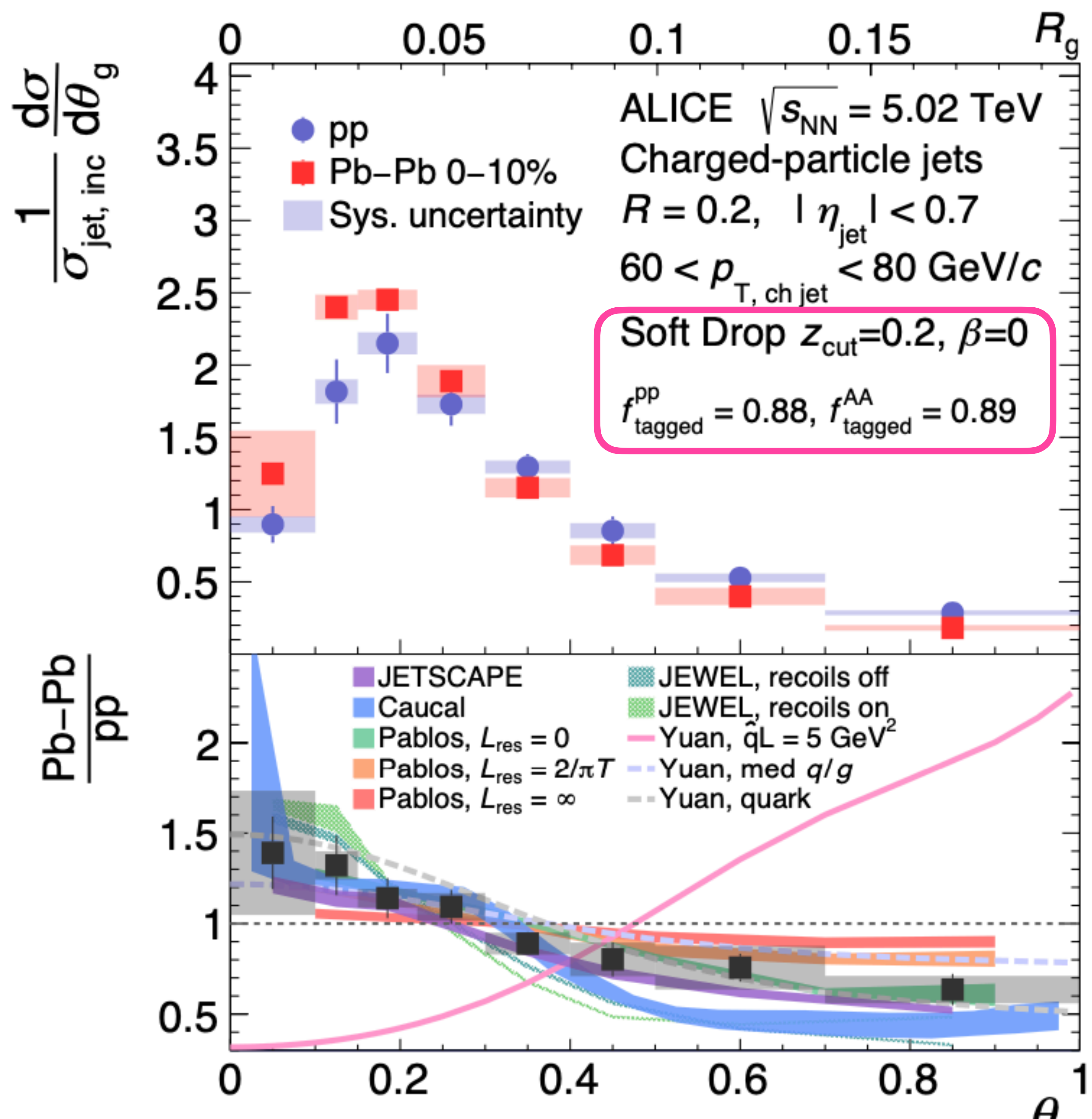
Angle of hardest splitting

- Modification of self-normalized distribution of angle of hardest splitting, θ_g, observed in central PbPb collisions



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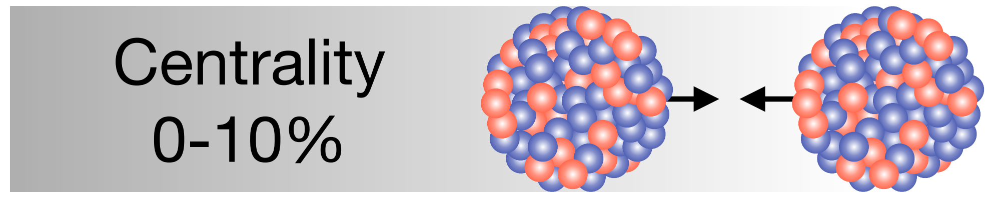


$$\theta_g = \frac{r_g}{R}$$

Substructure modification

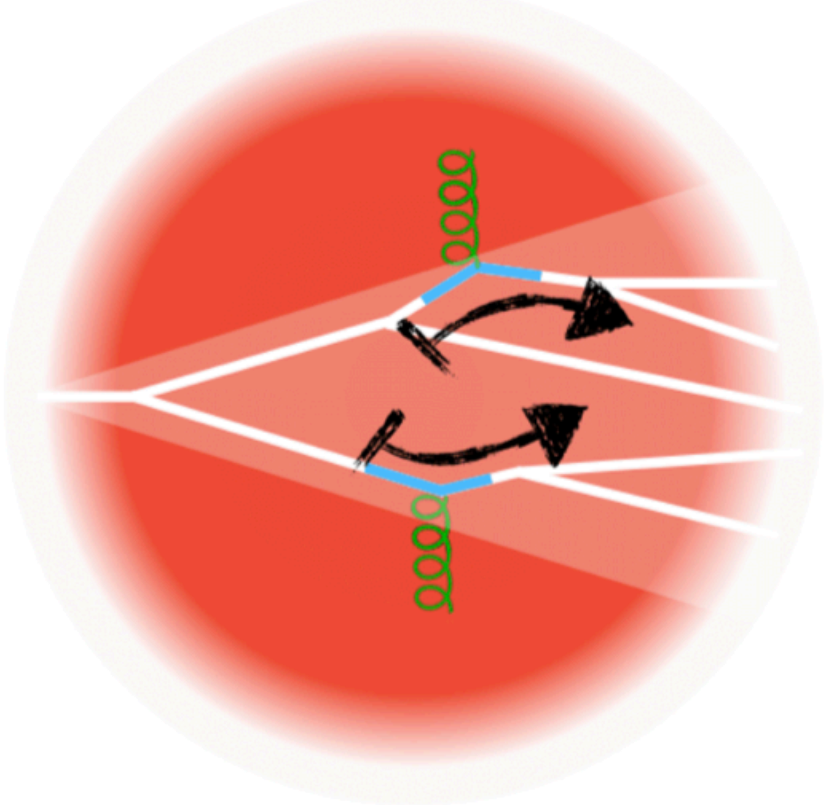
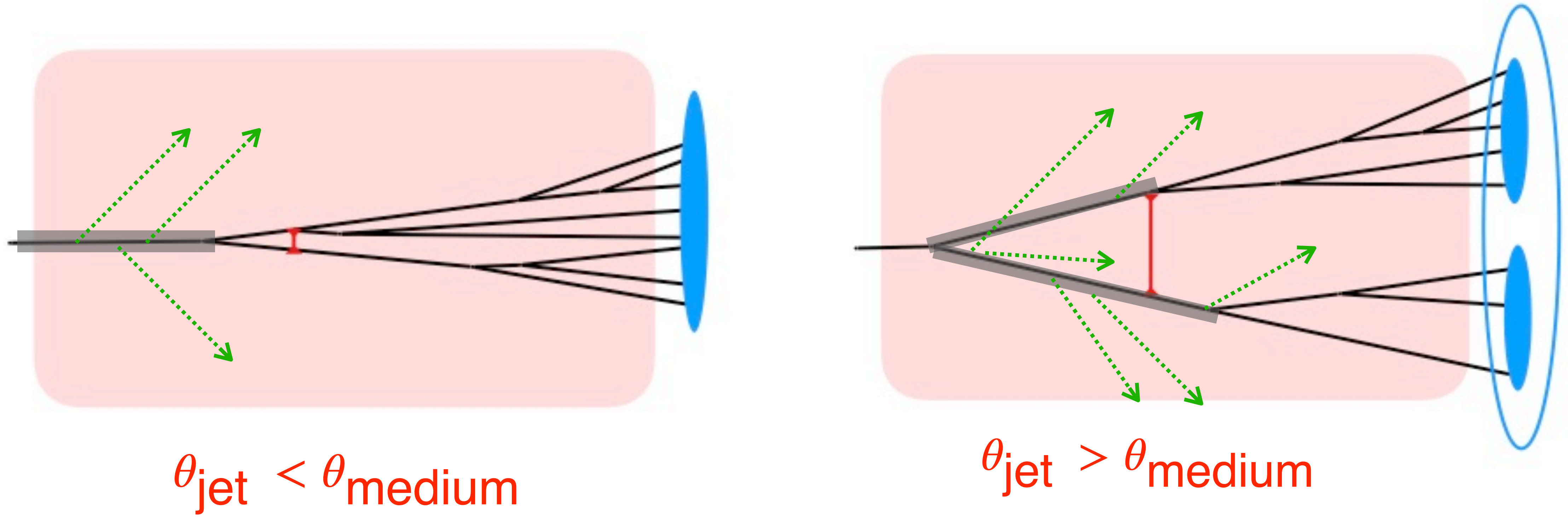


Figure from
Leticia Cunqueiro

Is the jet's hard splitting being modified?

Or do jets with different splittings experience different quenching?

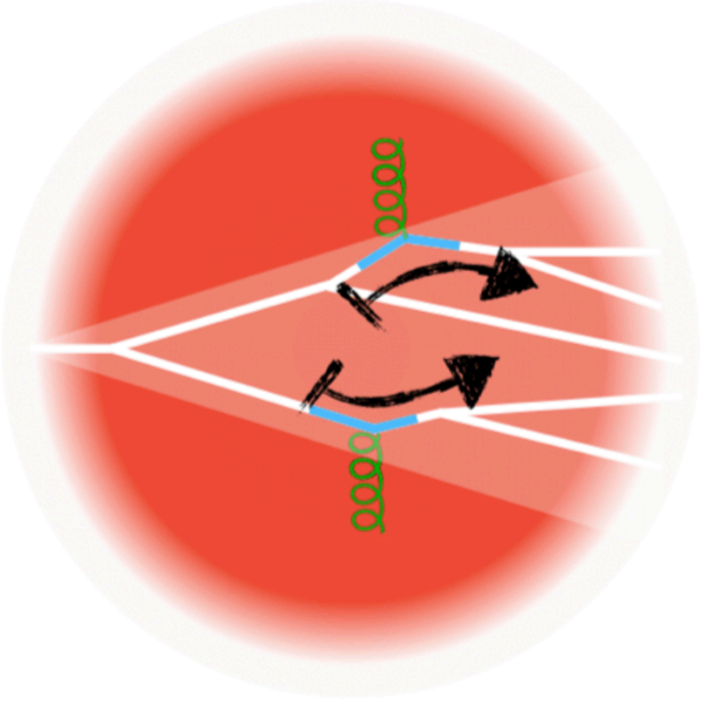


Angle of hardest splitting

- Modification of self-normalized distribution of angle of hardest splitting observed in central PbPb collisions
- Ratio of absolute cross-sections allows us to keep track of energy loss as a function of the substructure

$$\theta_g = \frac{r_g}{R}$$

Substructure modification



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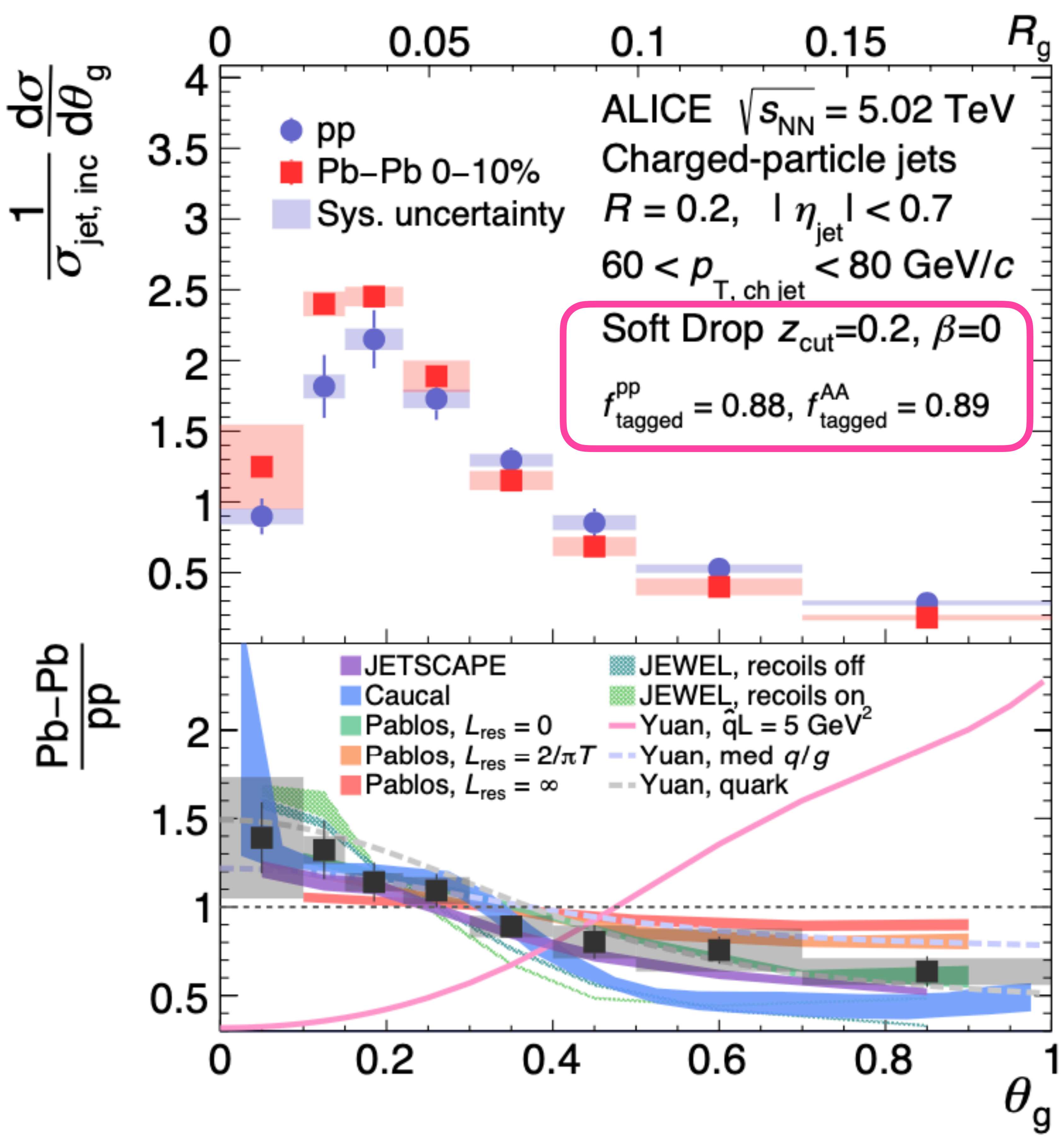

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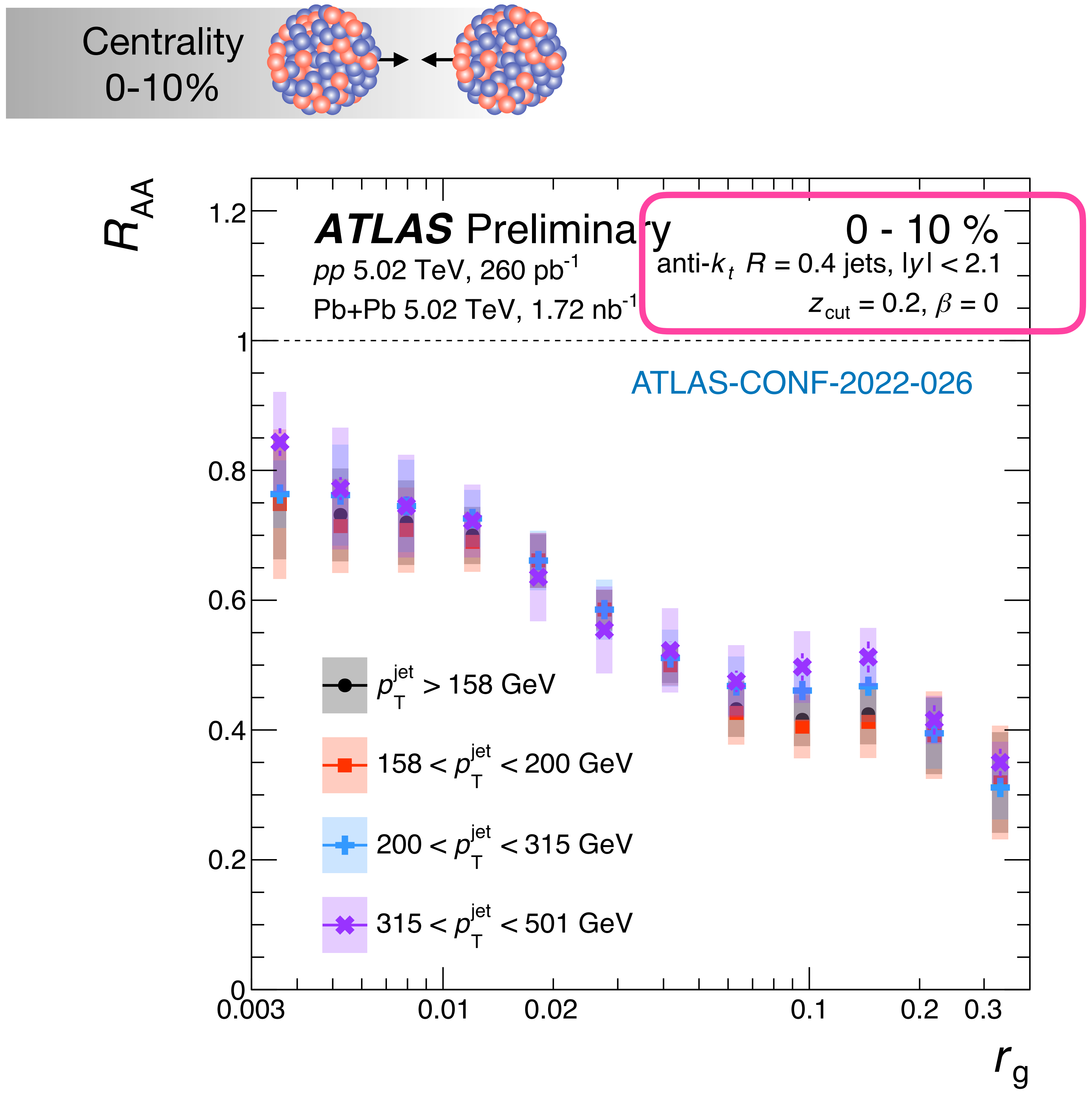

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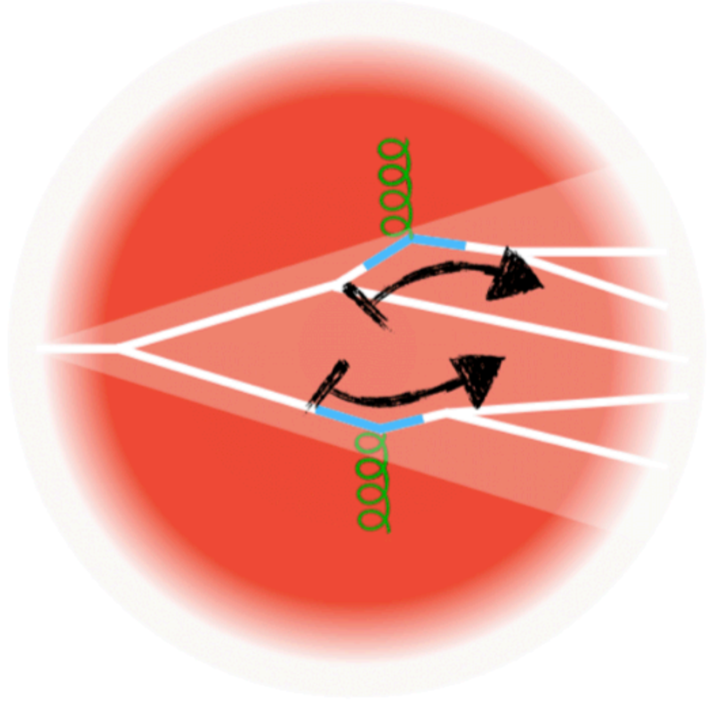

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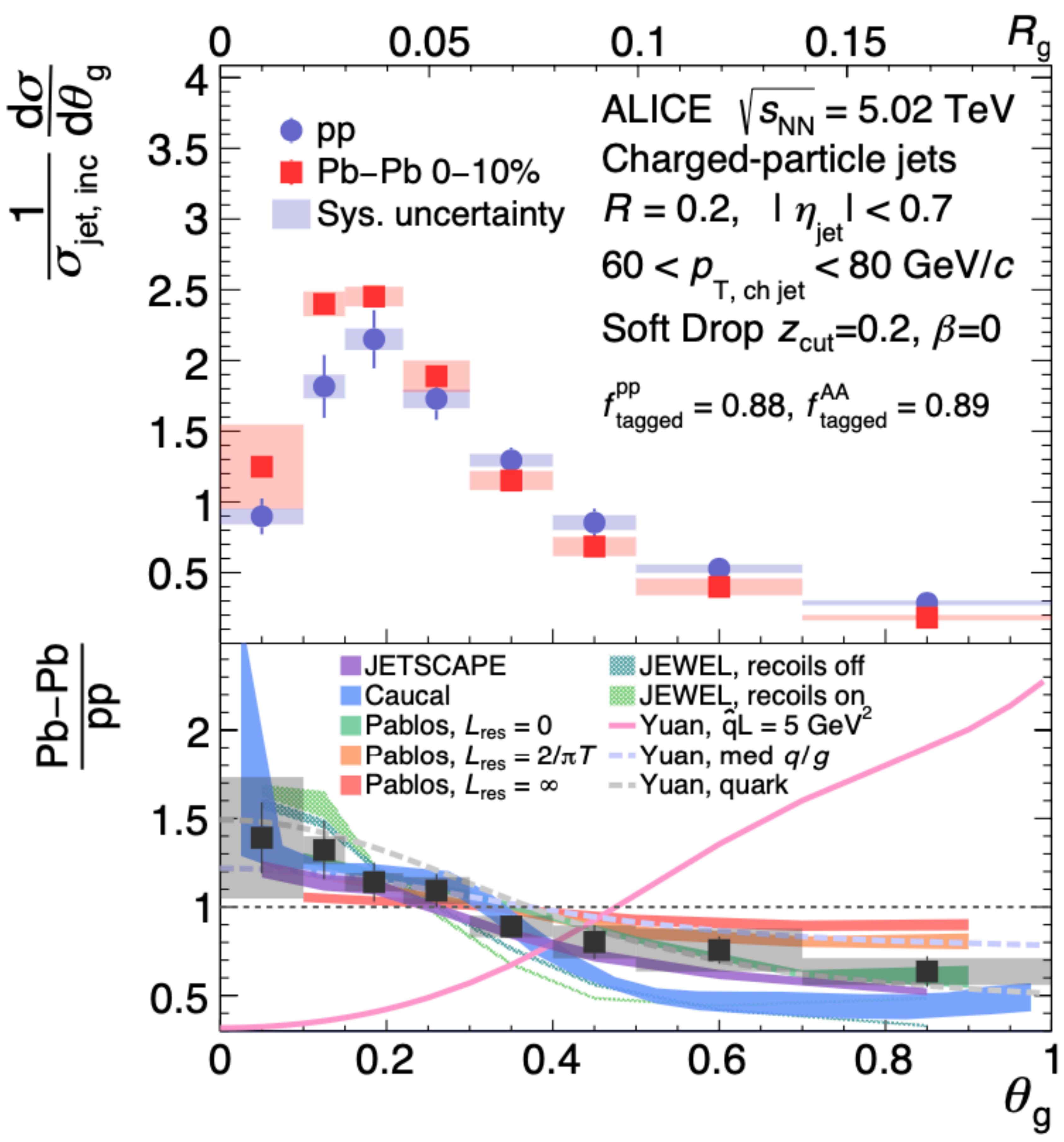
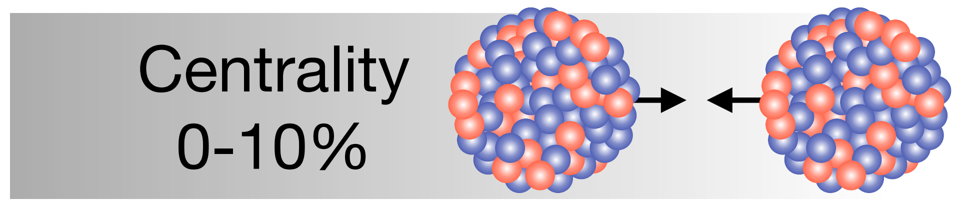
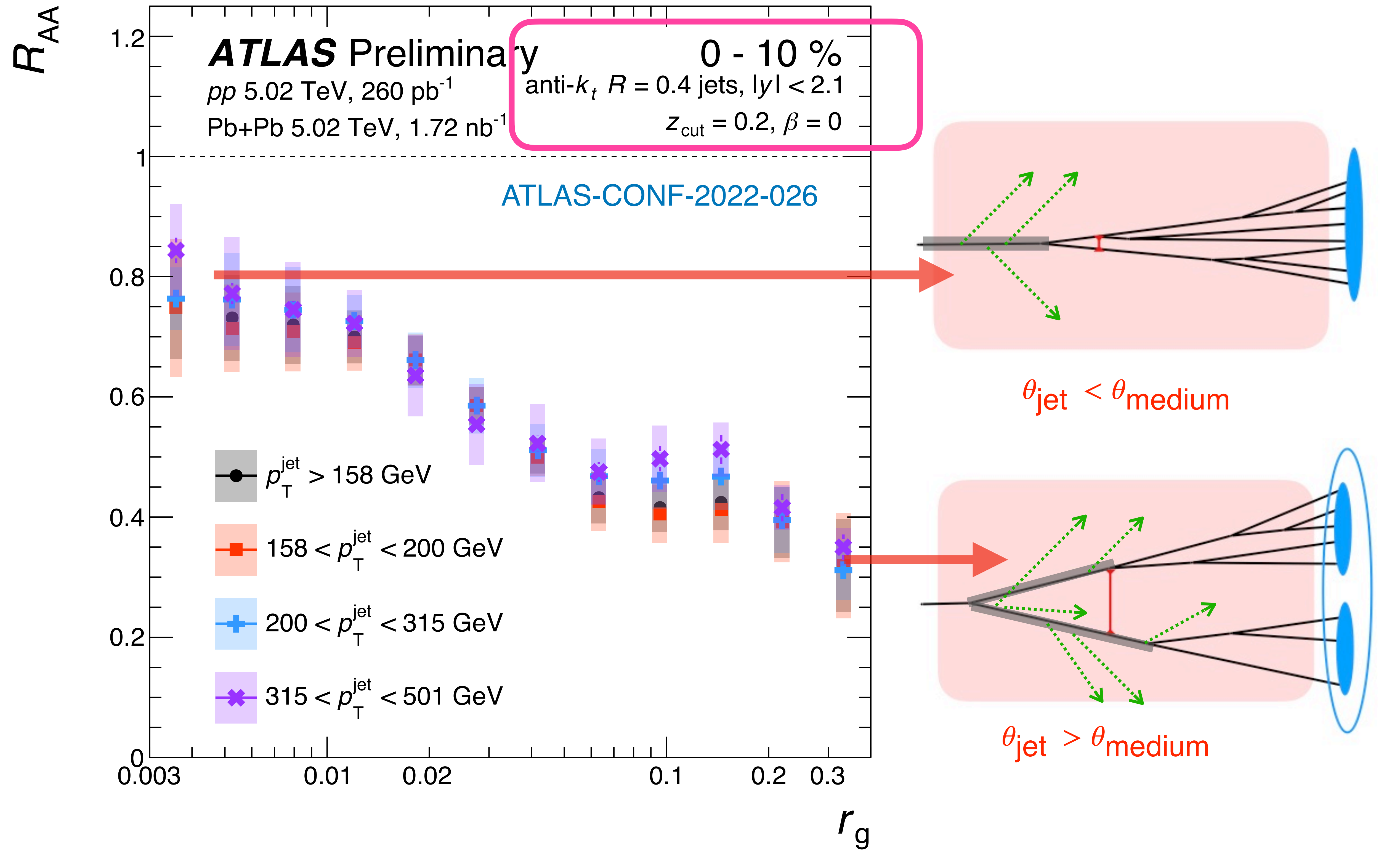


PRL 128 (2022) 102001

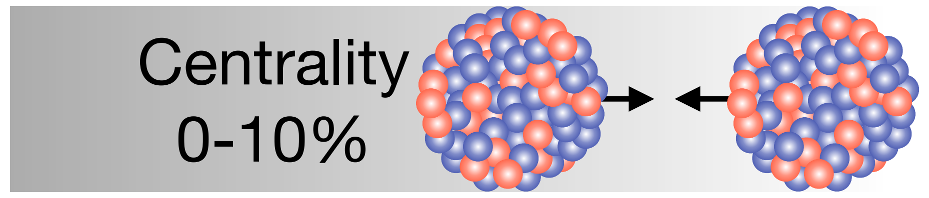


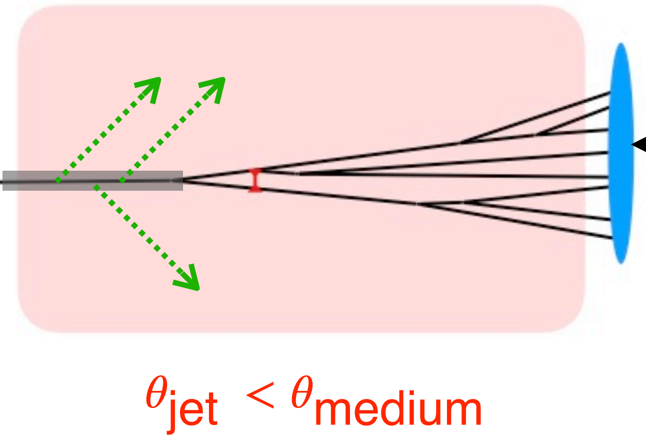


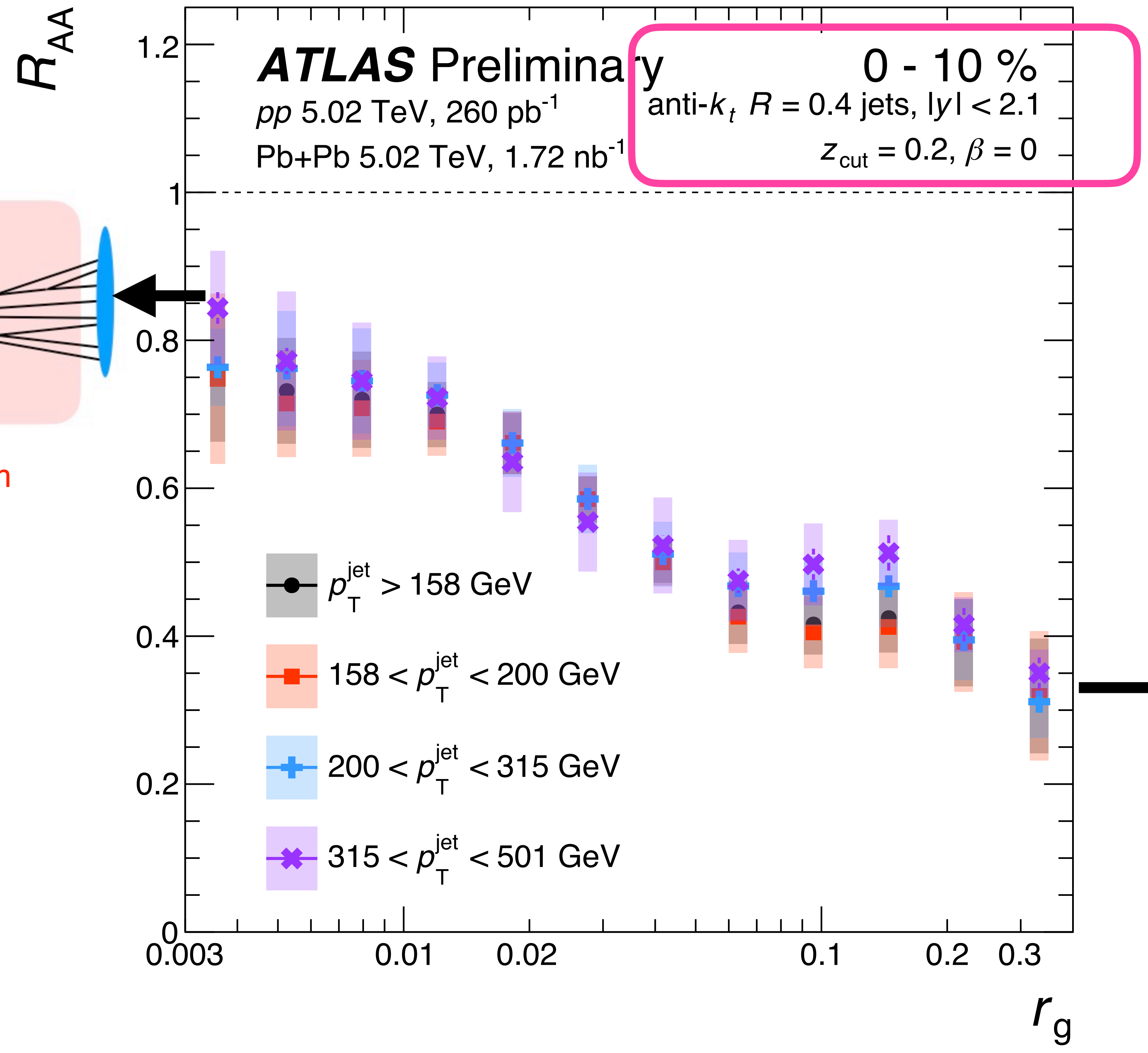
Jet suppression vs. splitting

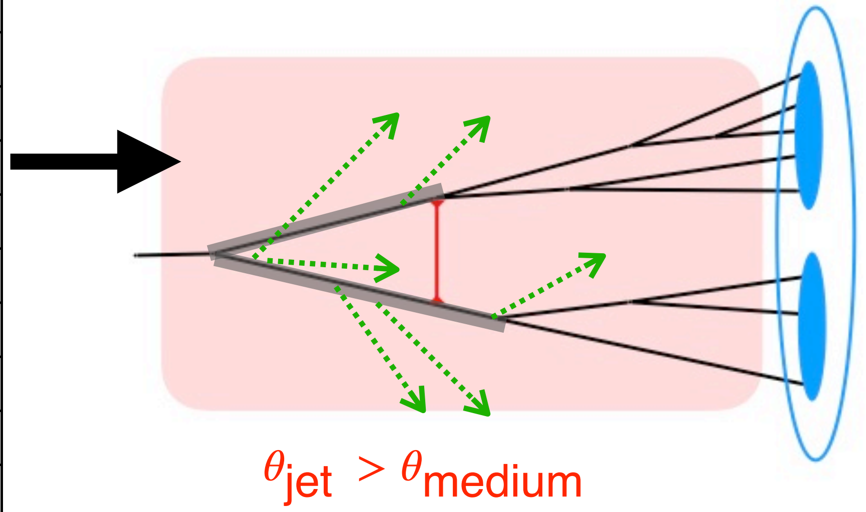
- Clear ordering observed in jet suppression vs. angle of hardest splitting (r_g)

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









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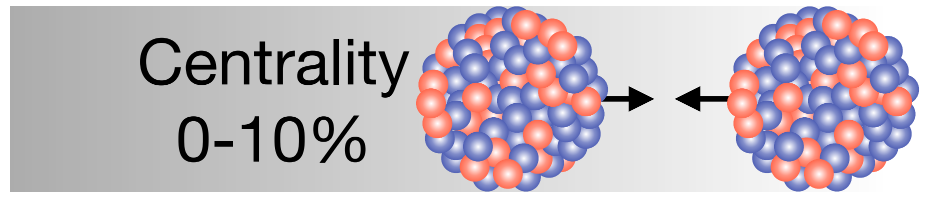
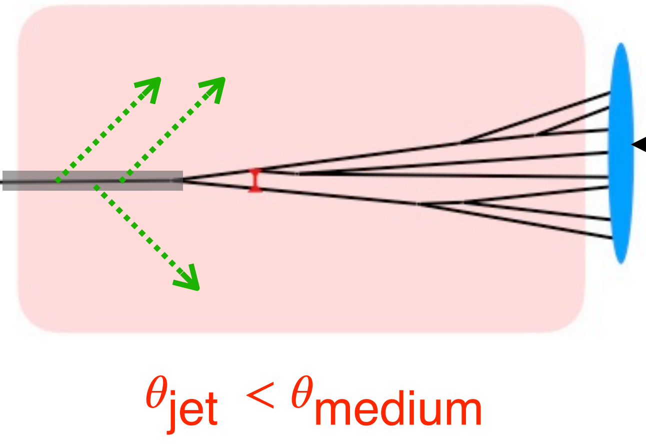
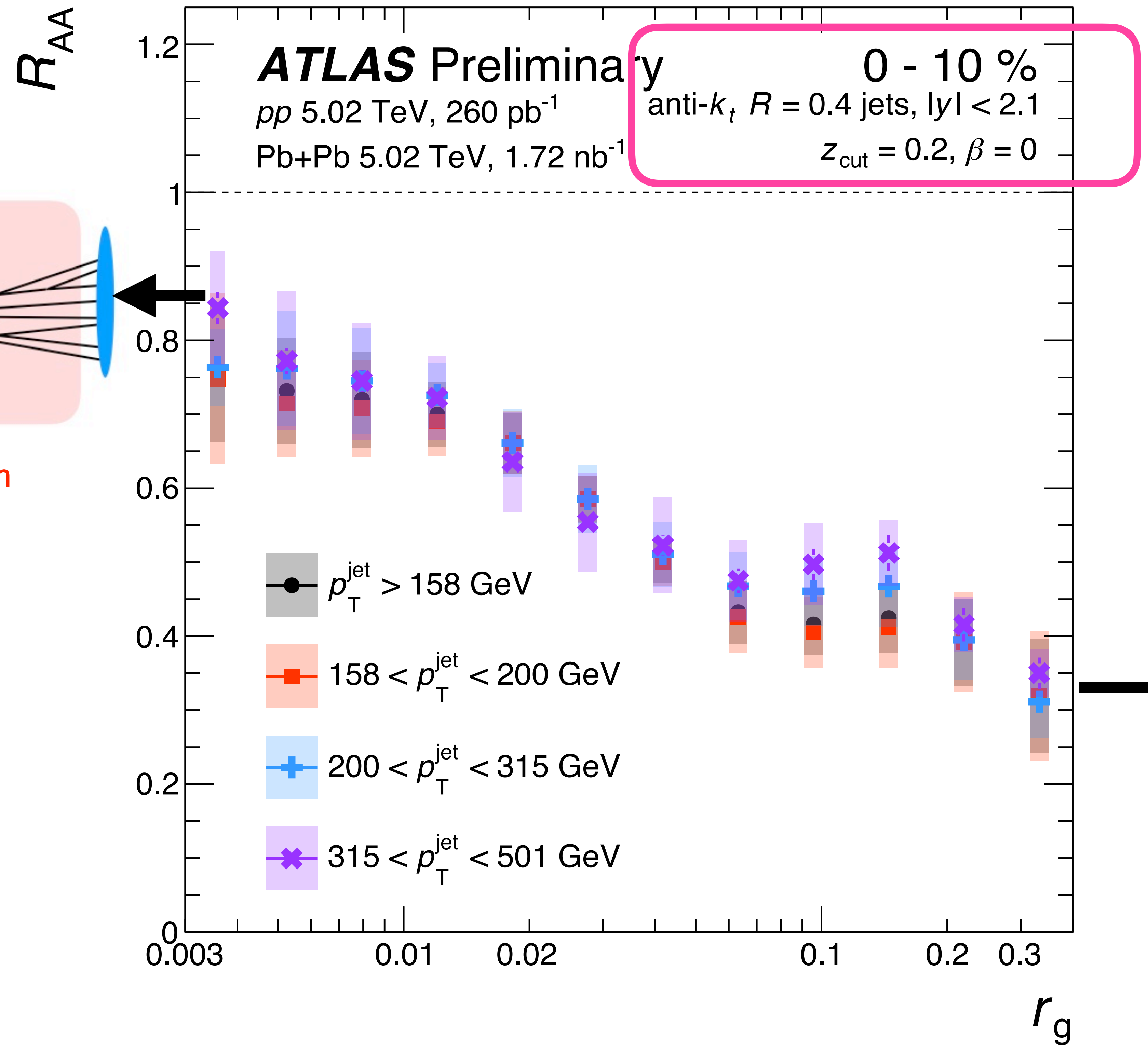
Jet suppression vs. splitting

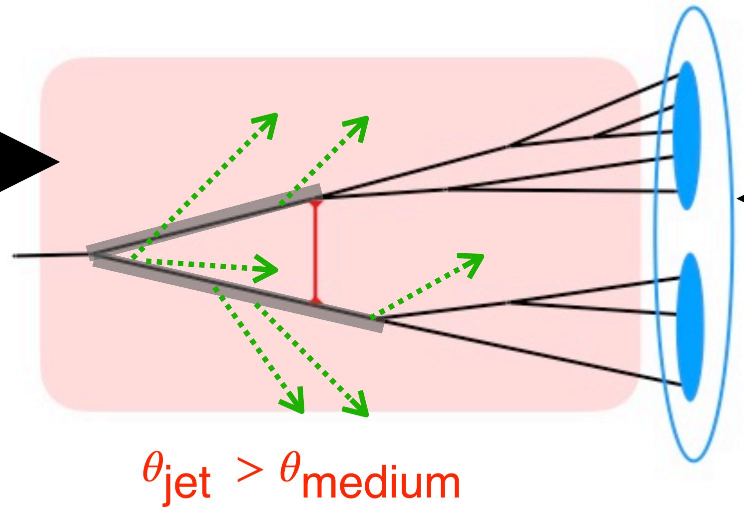
- Clear ordering observed in jet suppression vs. angle of hardest splitting (r_g)
- Jet R_{AA} vs. p_T is flatter in bins of r_g compared to rising trend of inclusive jets

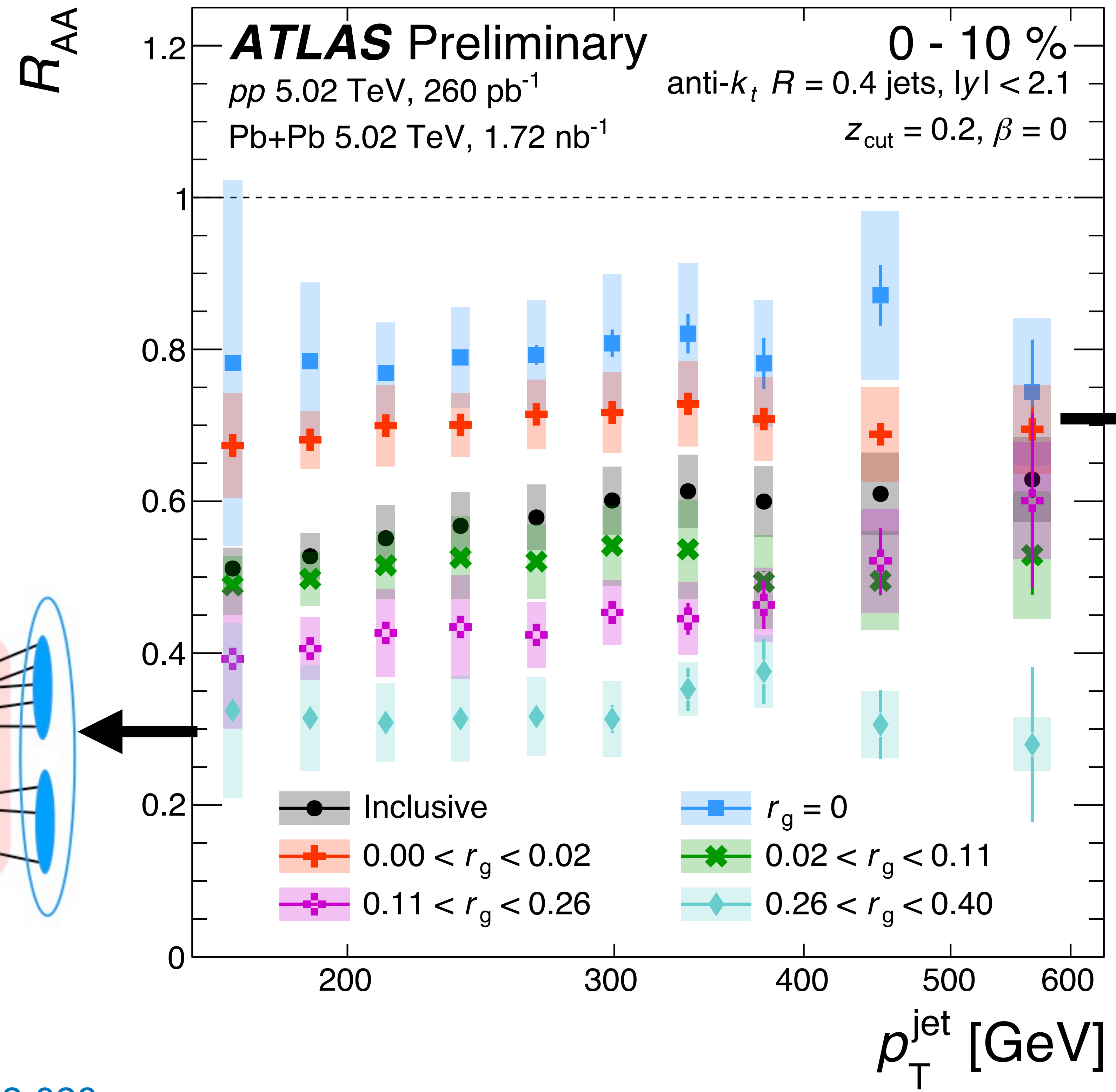
$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

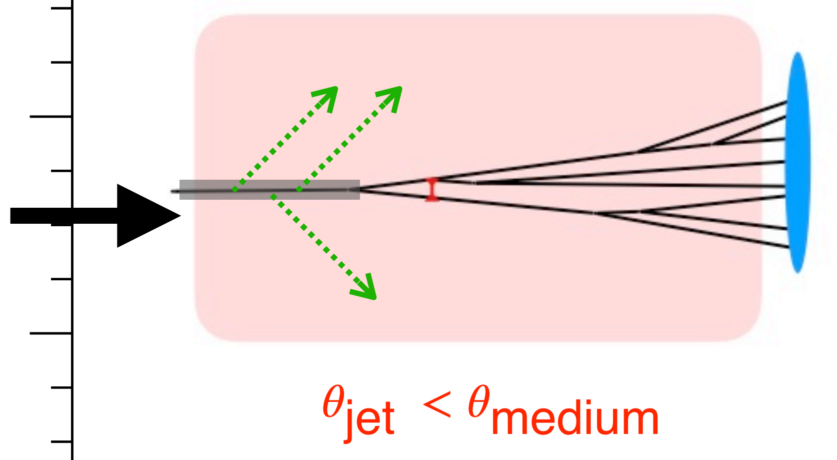












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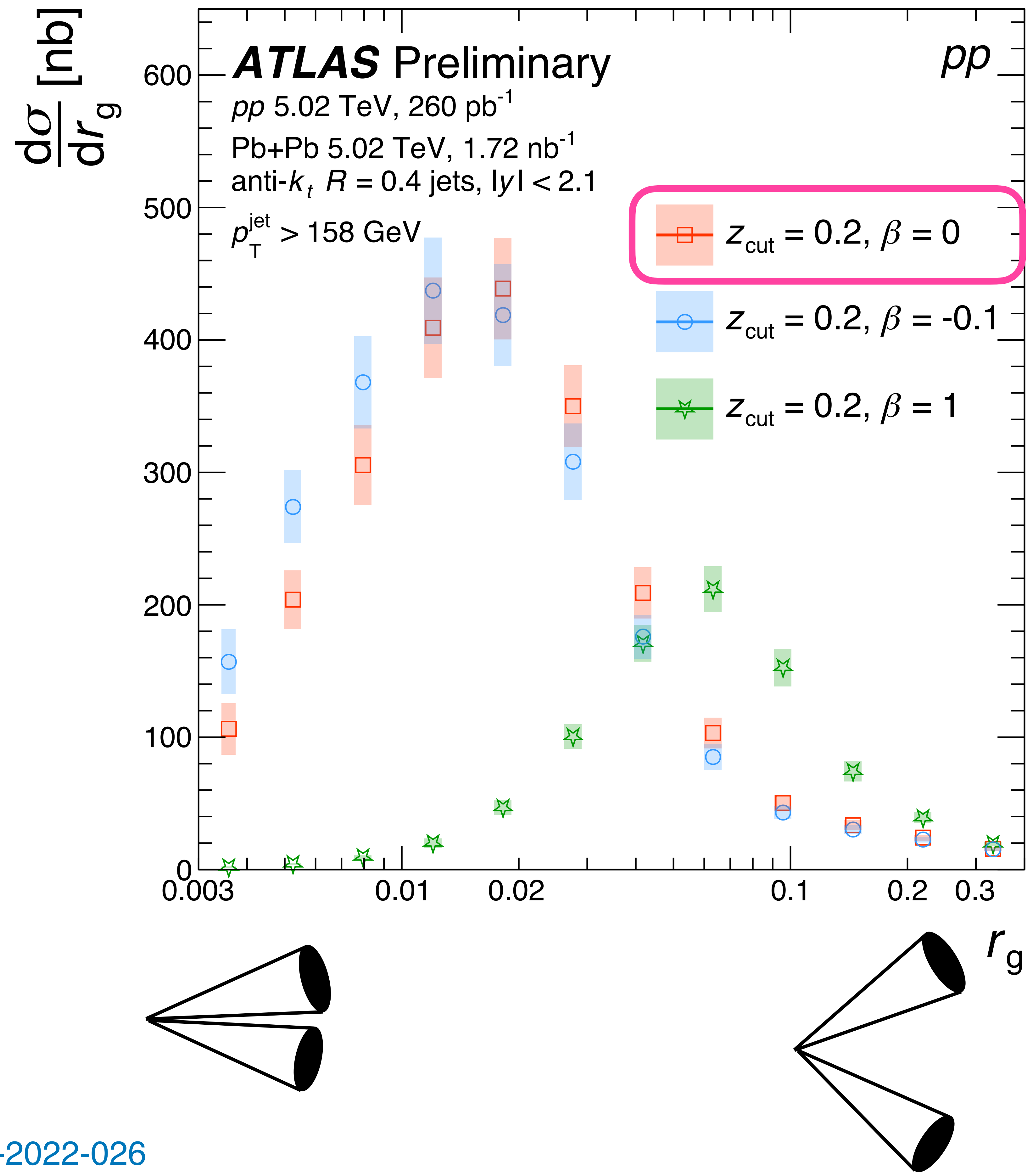
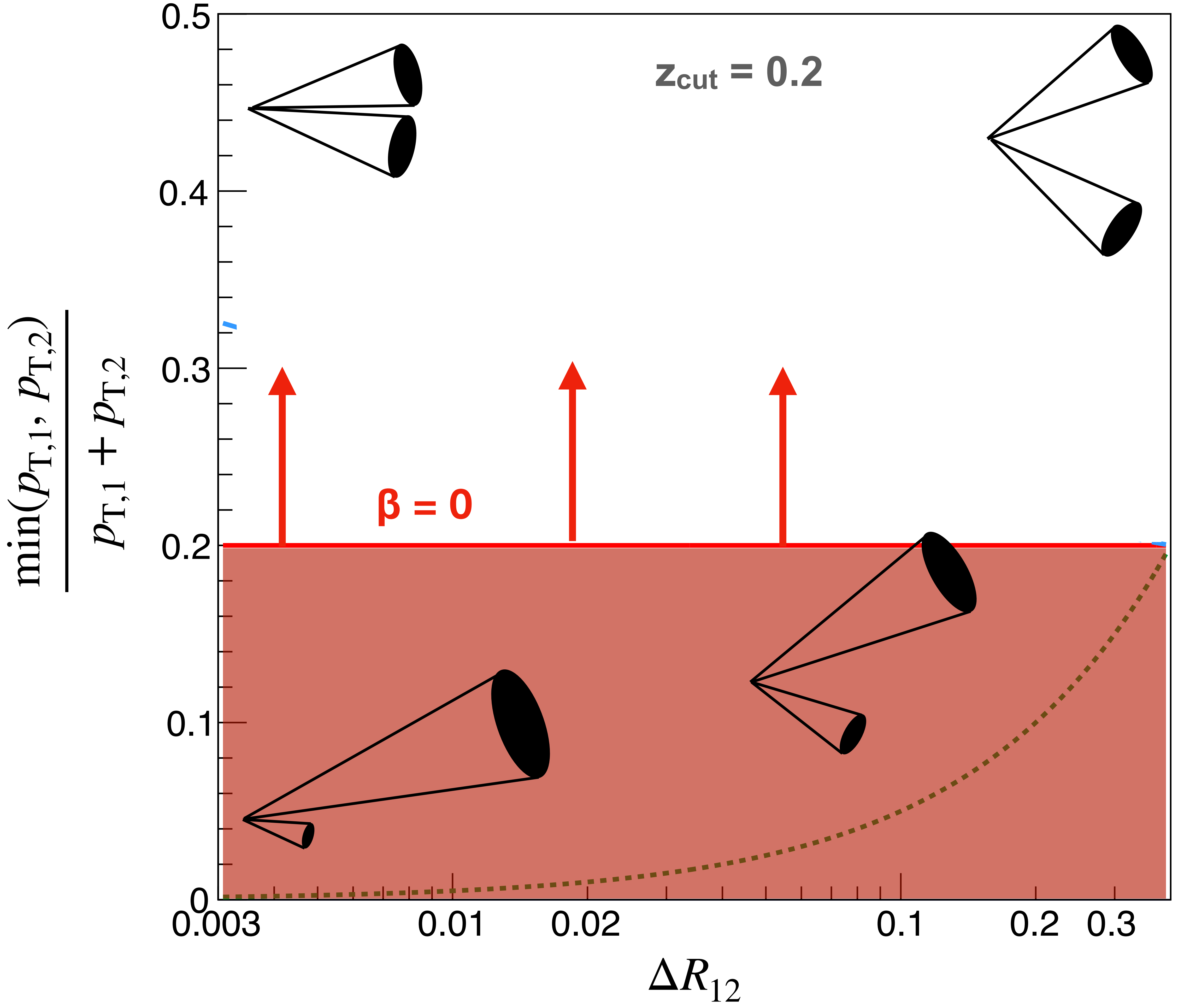
Soft Drop Parameters

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

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





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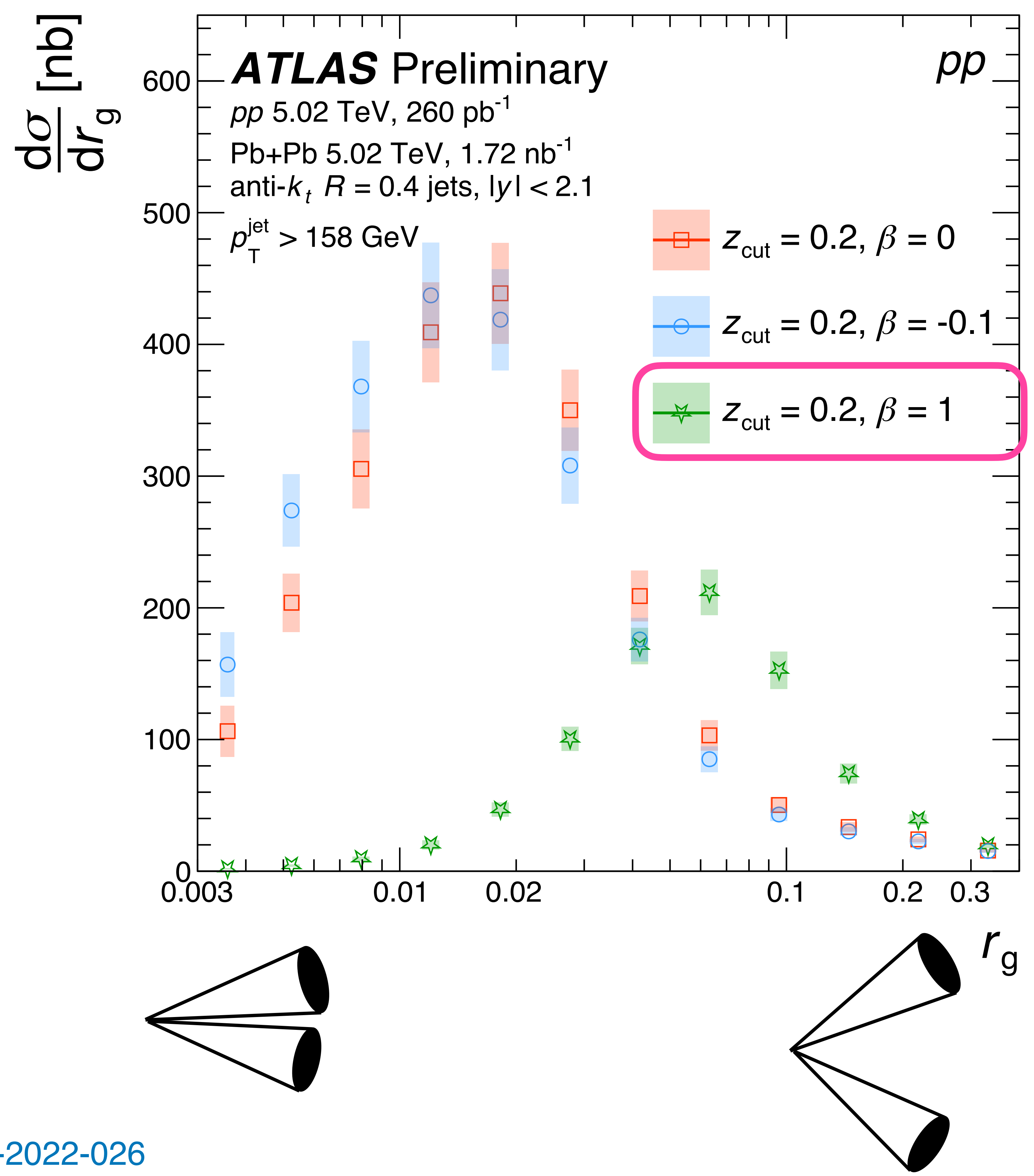

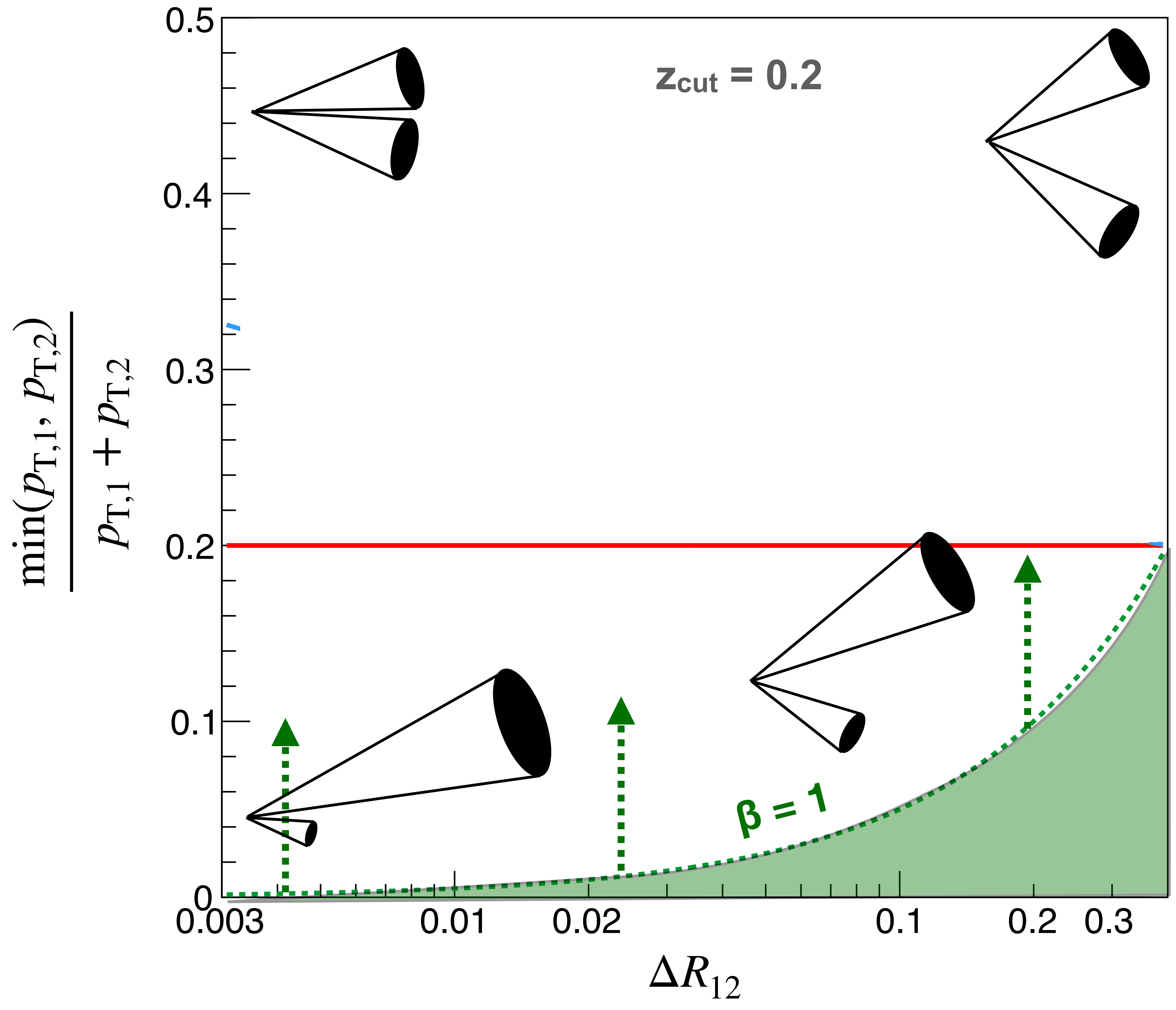

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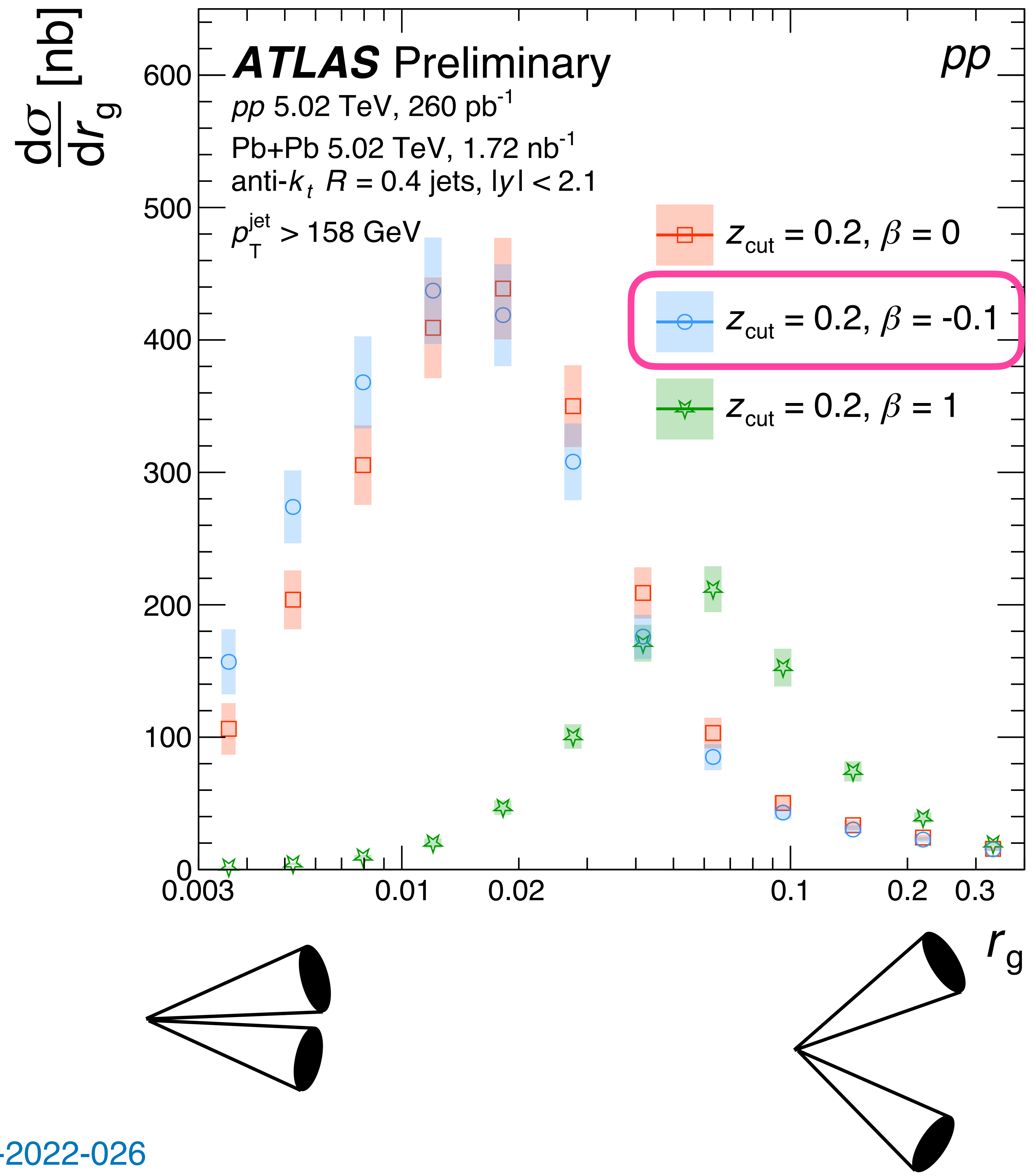

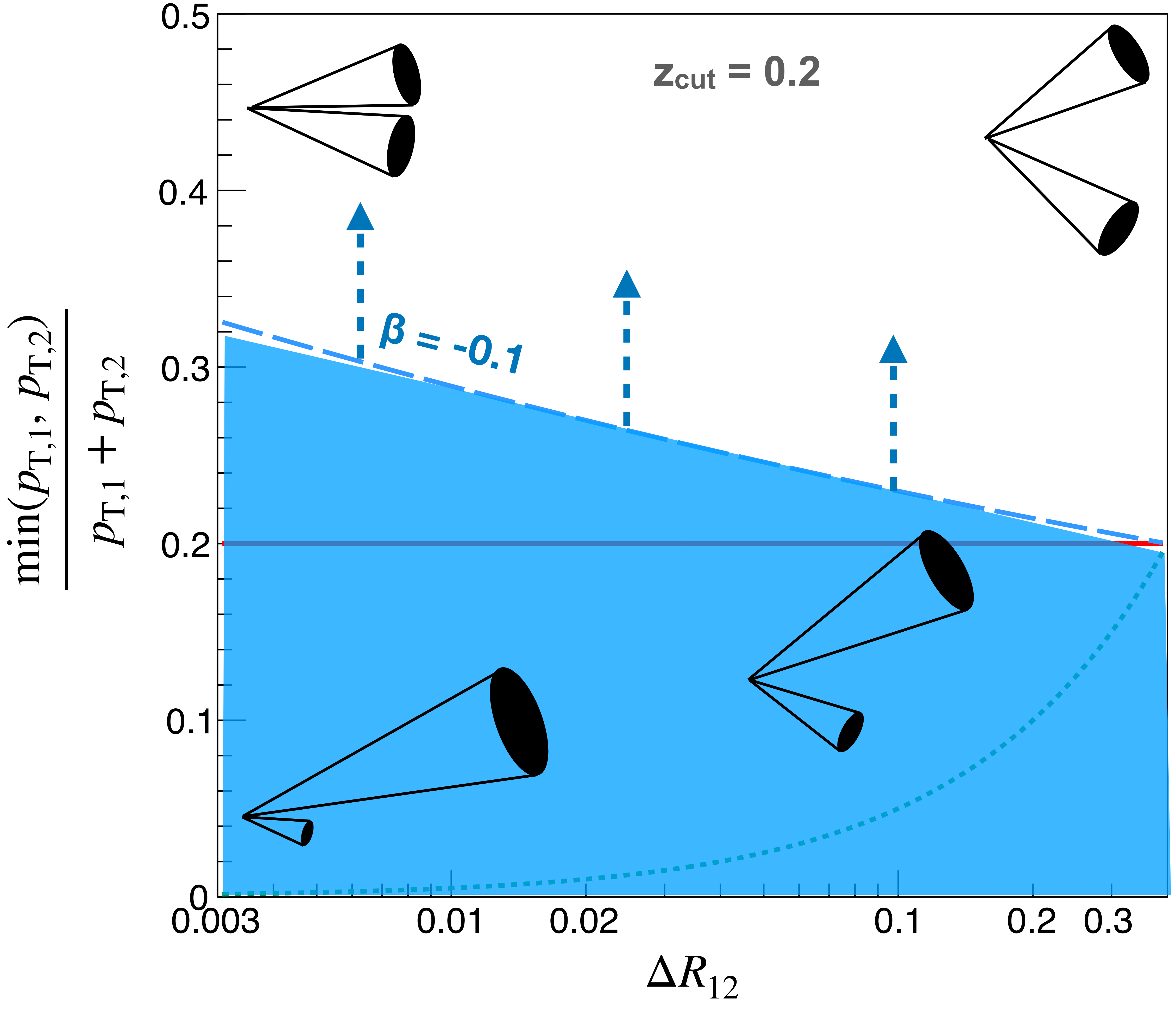

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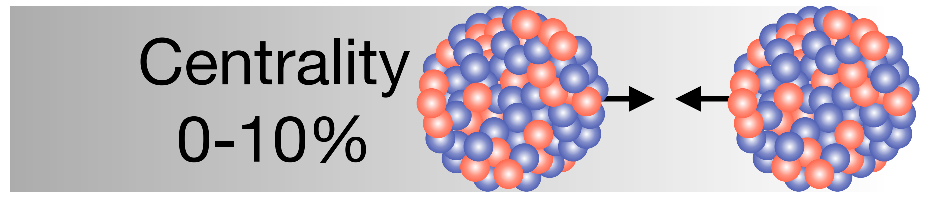
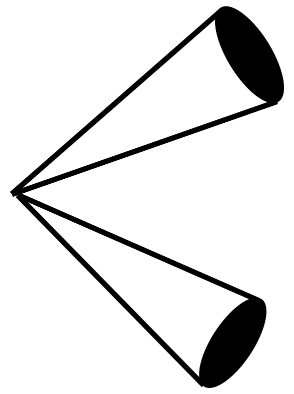
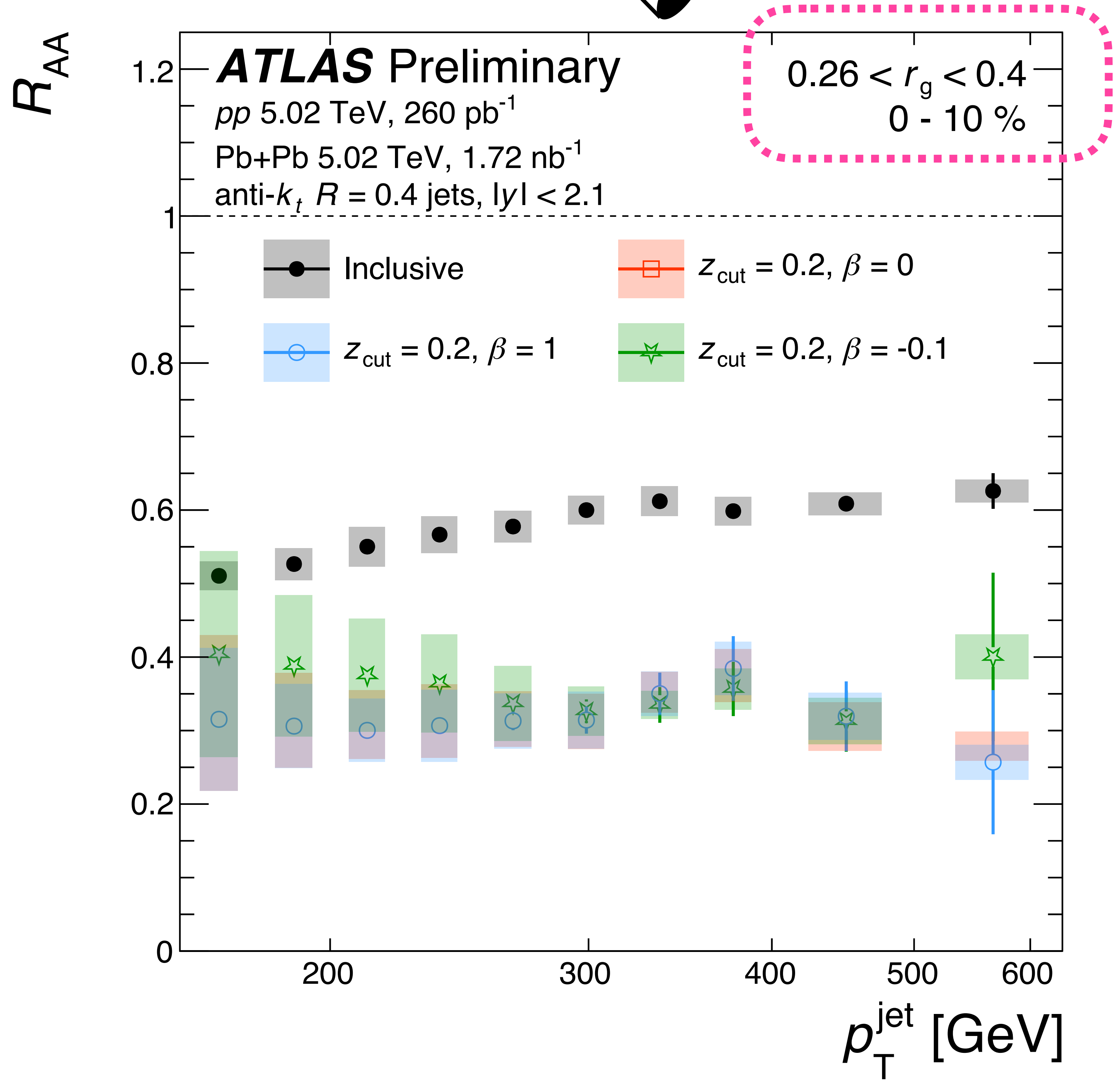
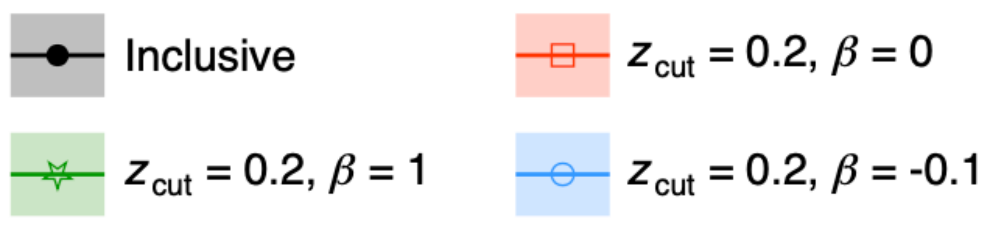
Jet Suppression vs. Substructure

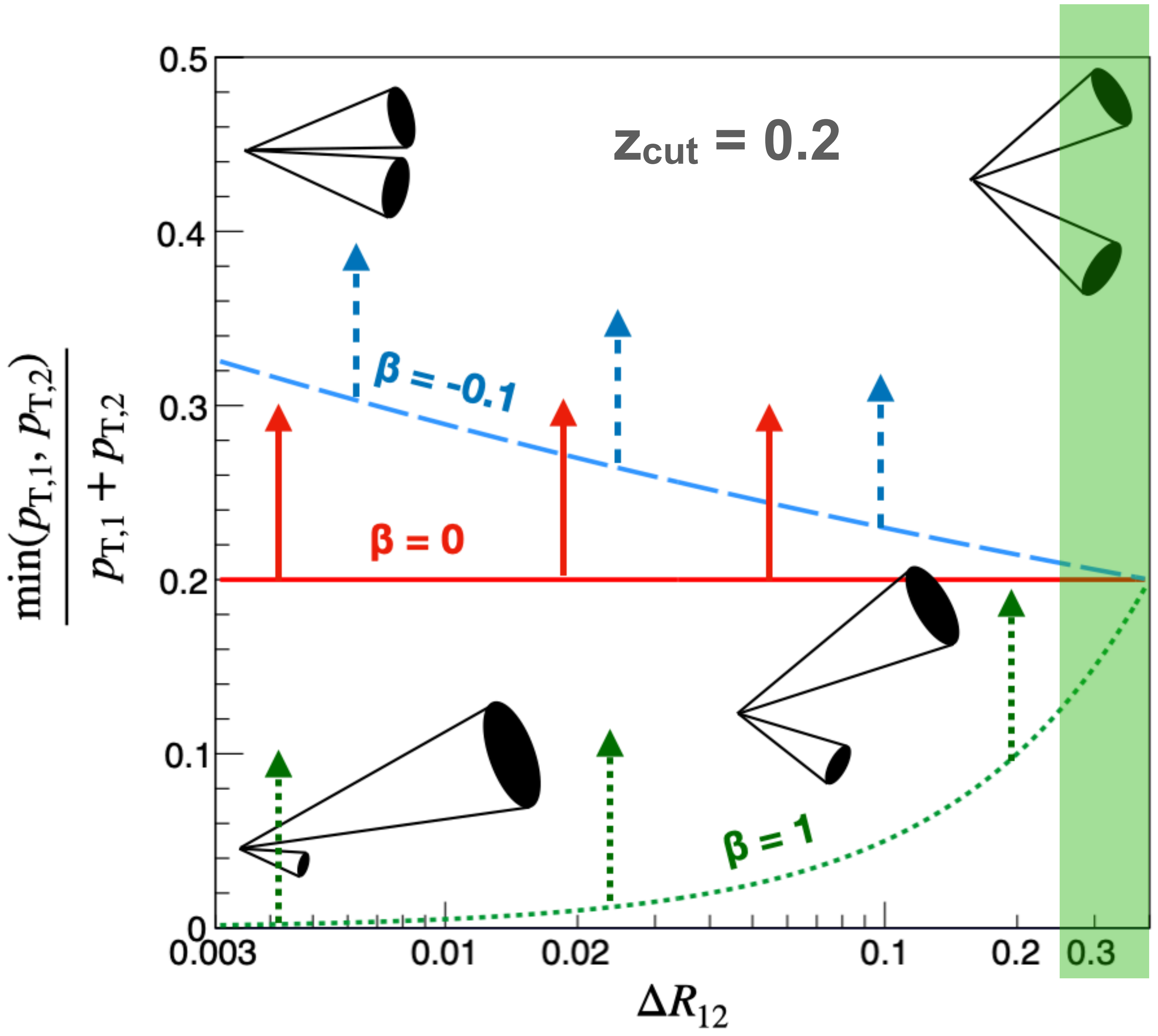
- Jet suppression vs. substructure measured using varied Soft-Drop parameters can be used to interpret modification of non-perturbative jet components











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

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

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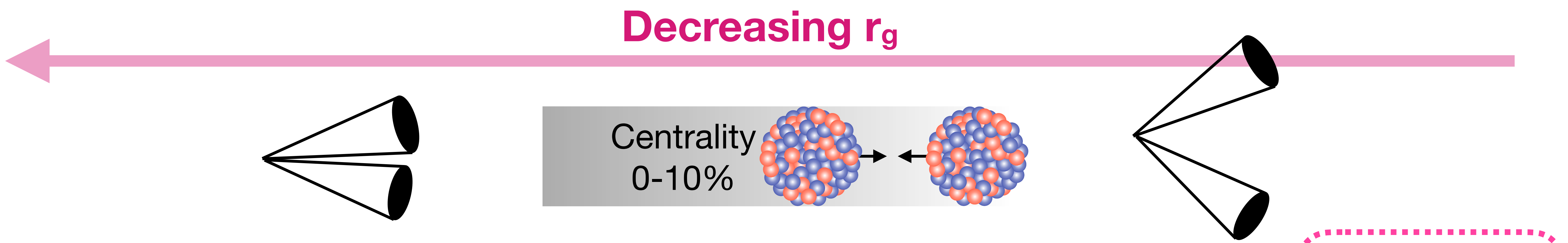

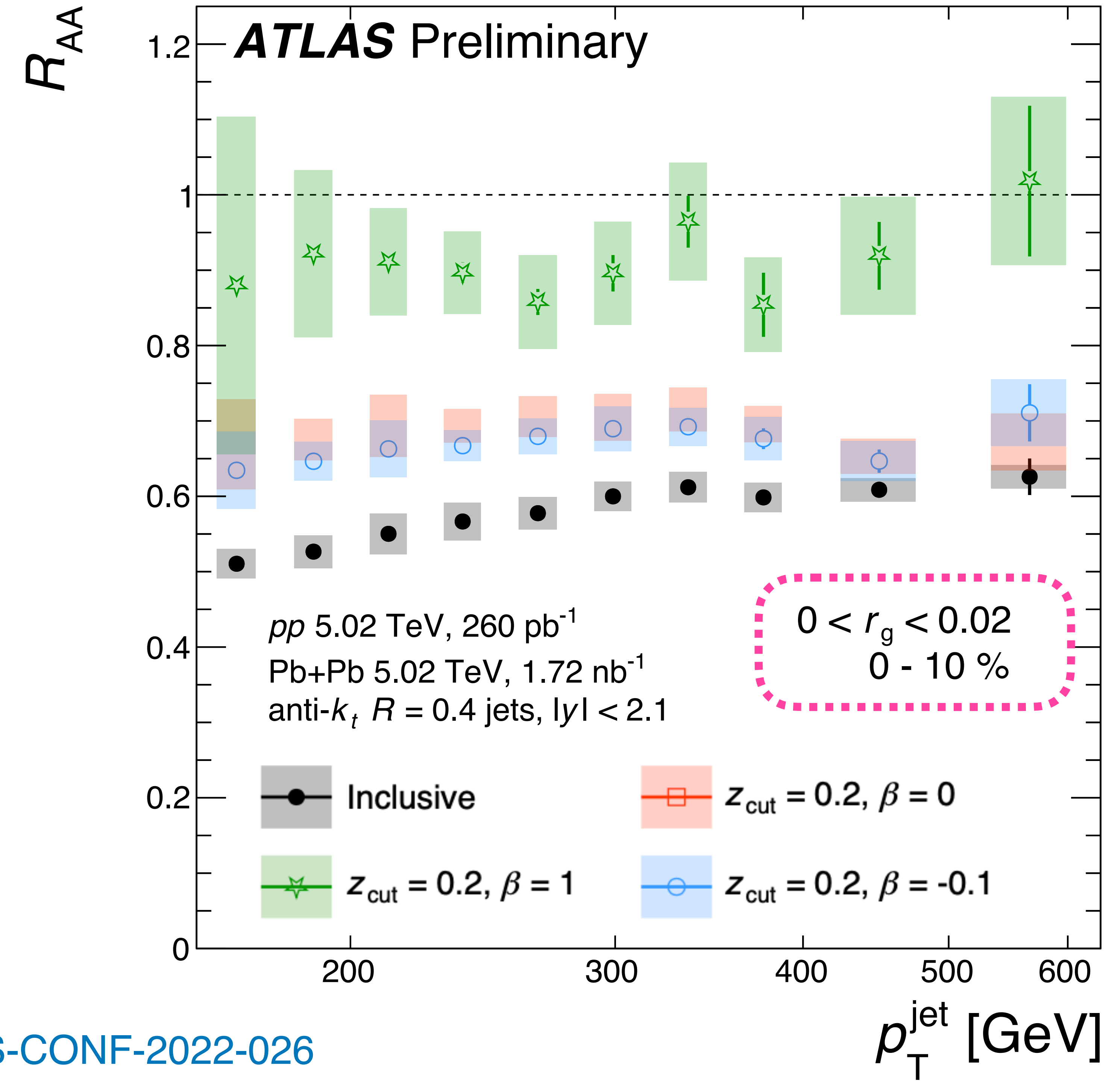

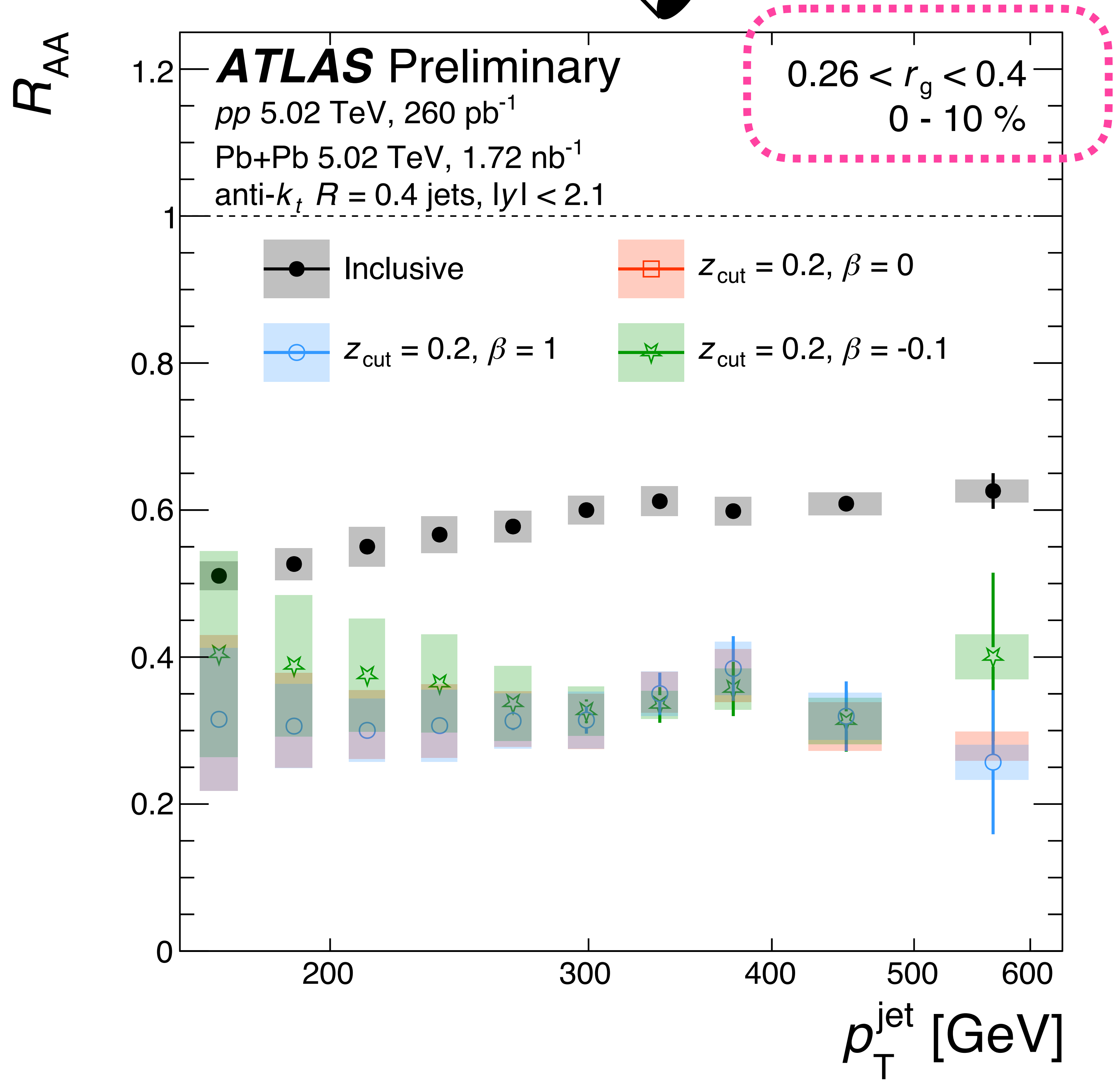

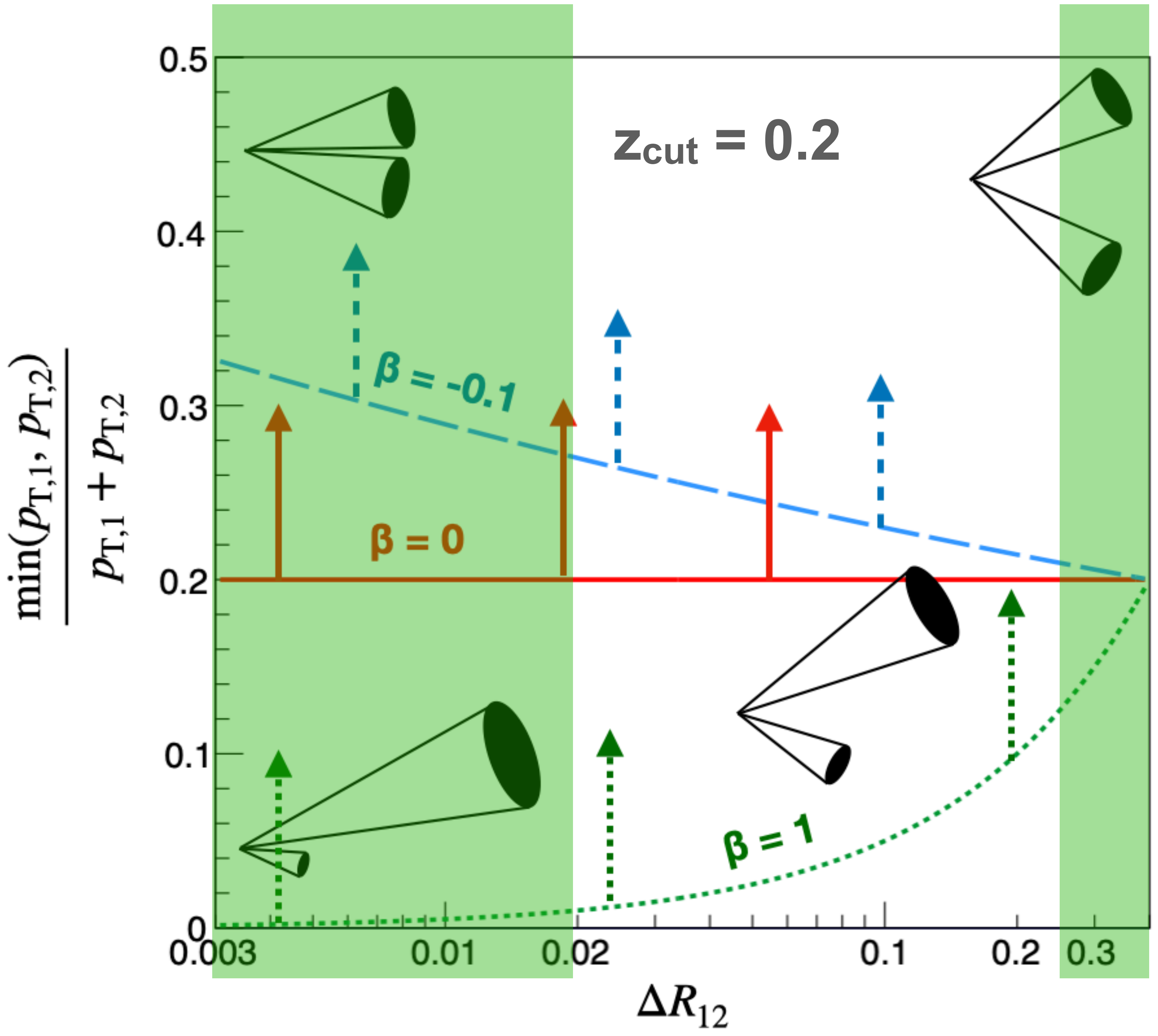

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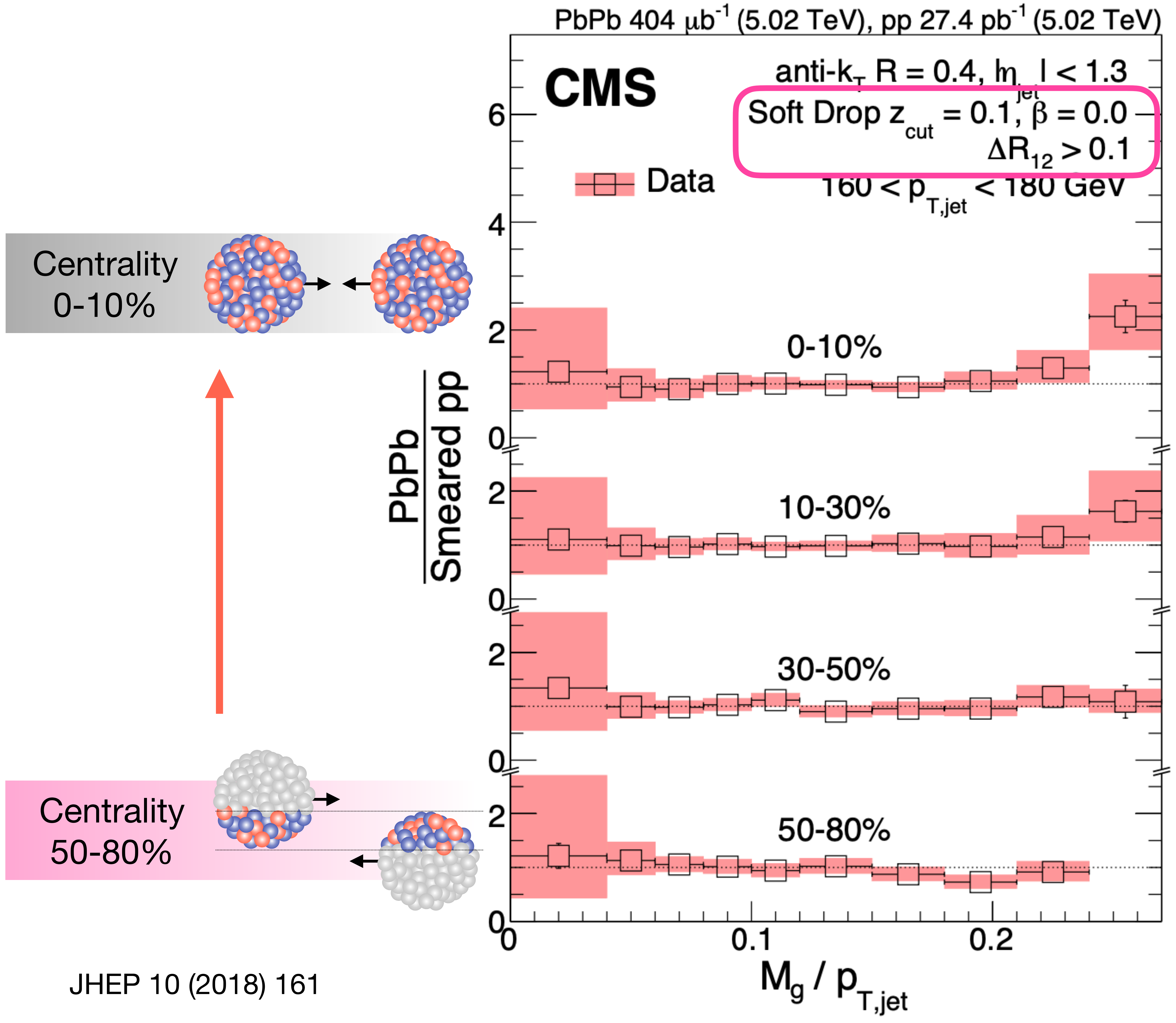
Jet Mass

- Opening angle of the parton splitting (r_g) is correlated with the jet mass (M_g)
- Minor modifications observed in central PbPb collisions relative to pp collisions

$$M_g \sim z\theta^2$$



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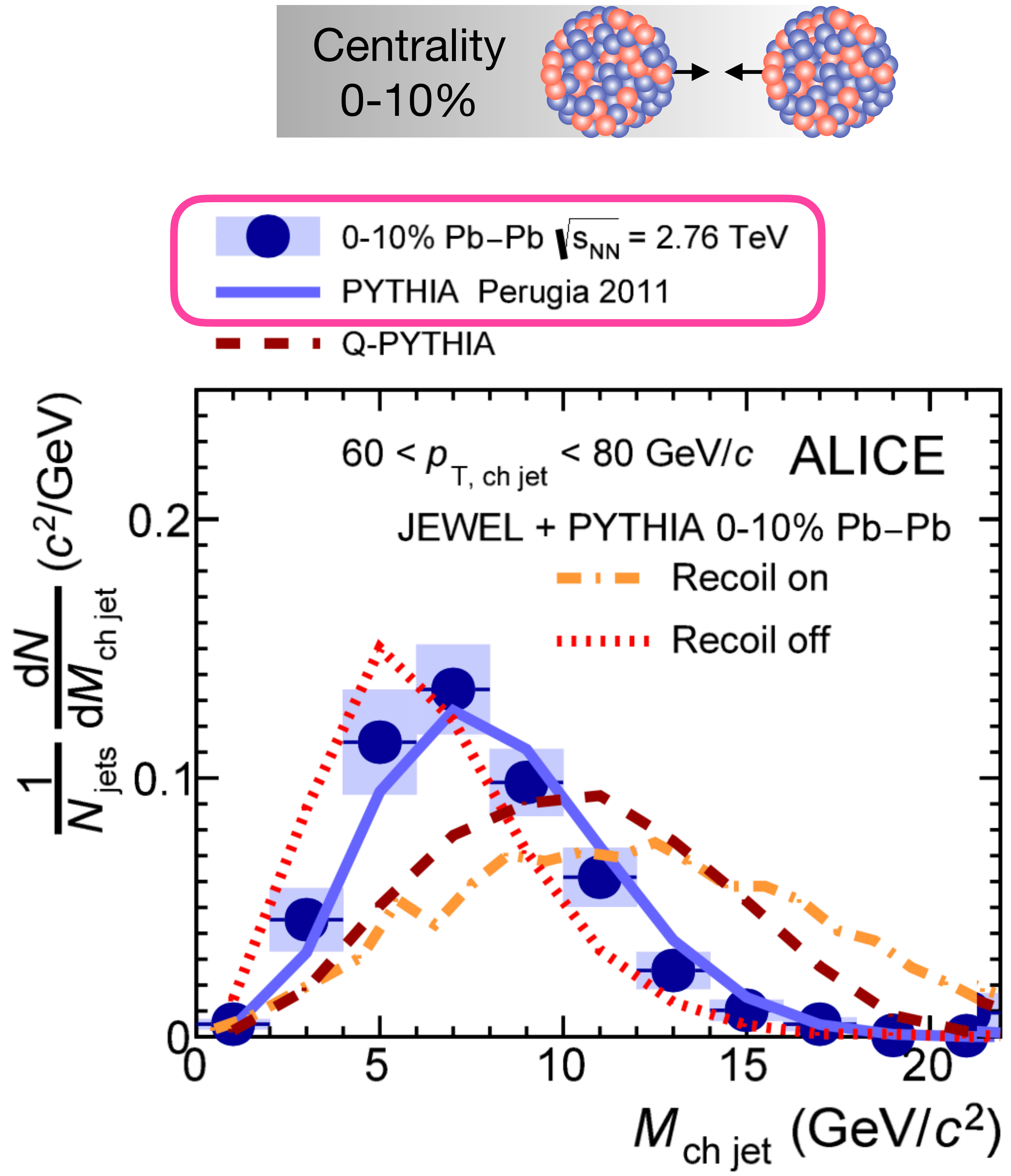
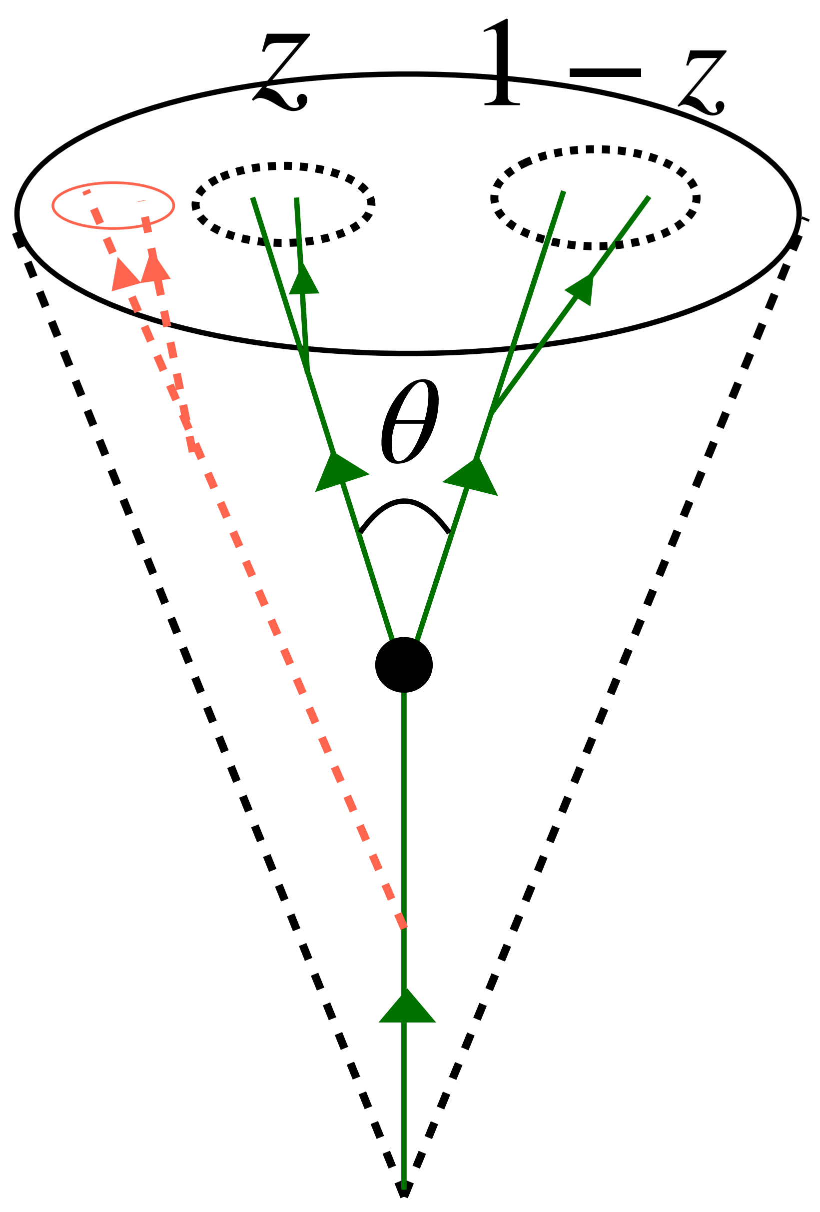


Phys. Lett. B776(2018) 249-264

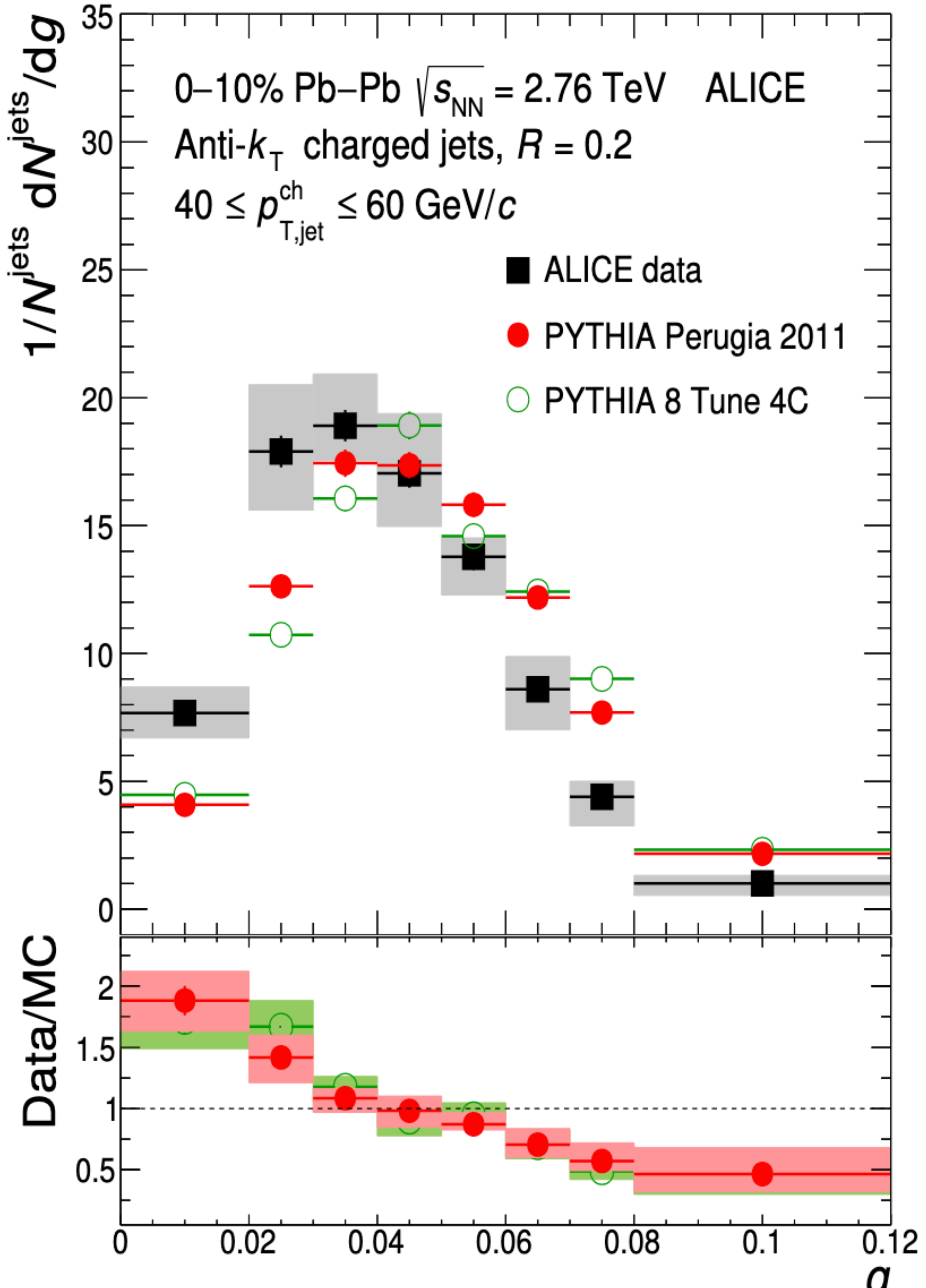


Jet Angularities

- Significant modification observed for jet girth in PbPb compared to Pythia, but not for jet mass (ungroomed jets)
- Non-perturbative components of the jet play a significant role in understanding the modification of jet substructure

$$g \sim z\theta$$

$$g = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \Delta R_{\mathrm{jet},i},$$



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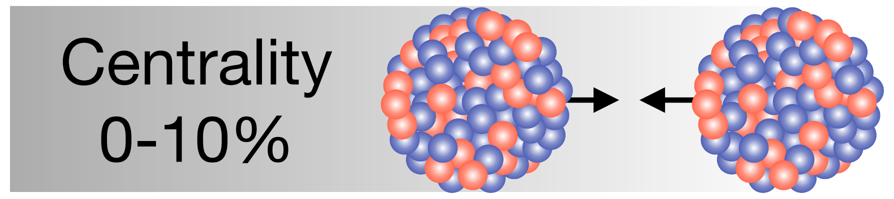

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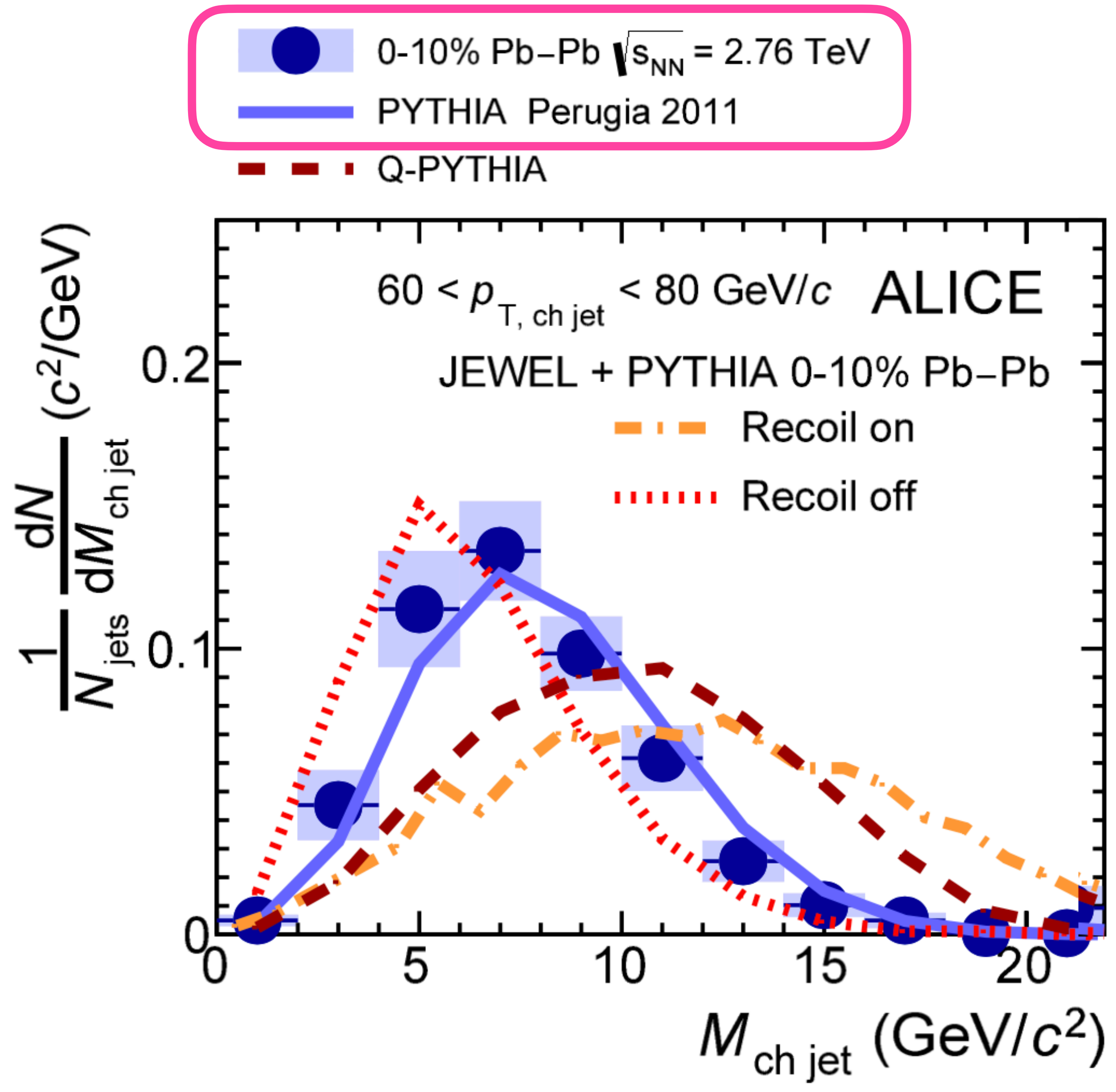

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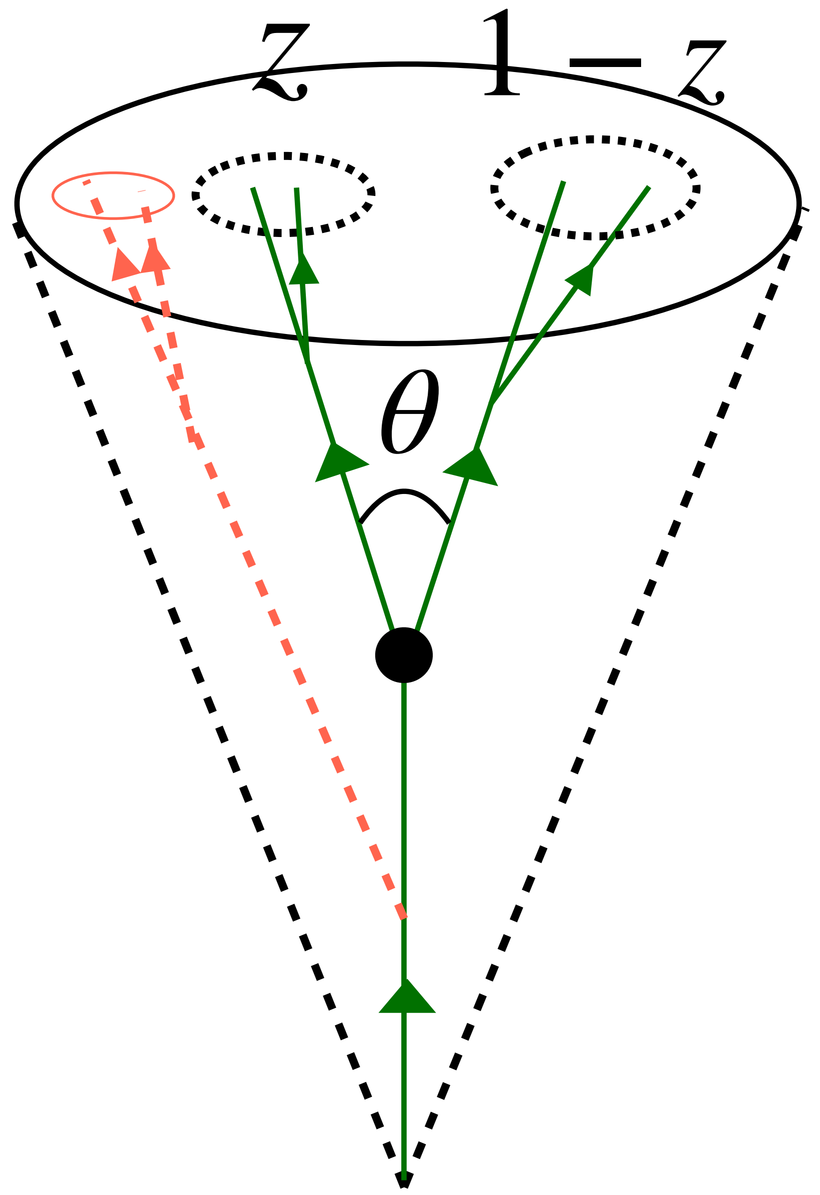
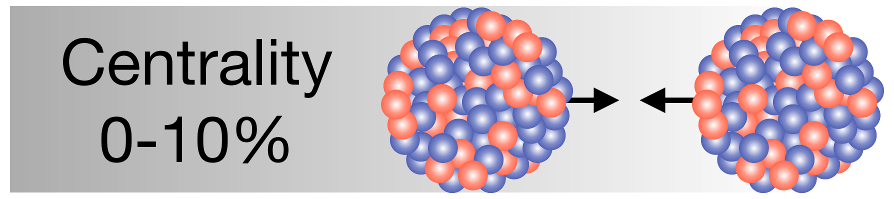
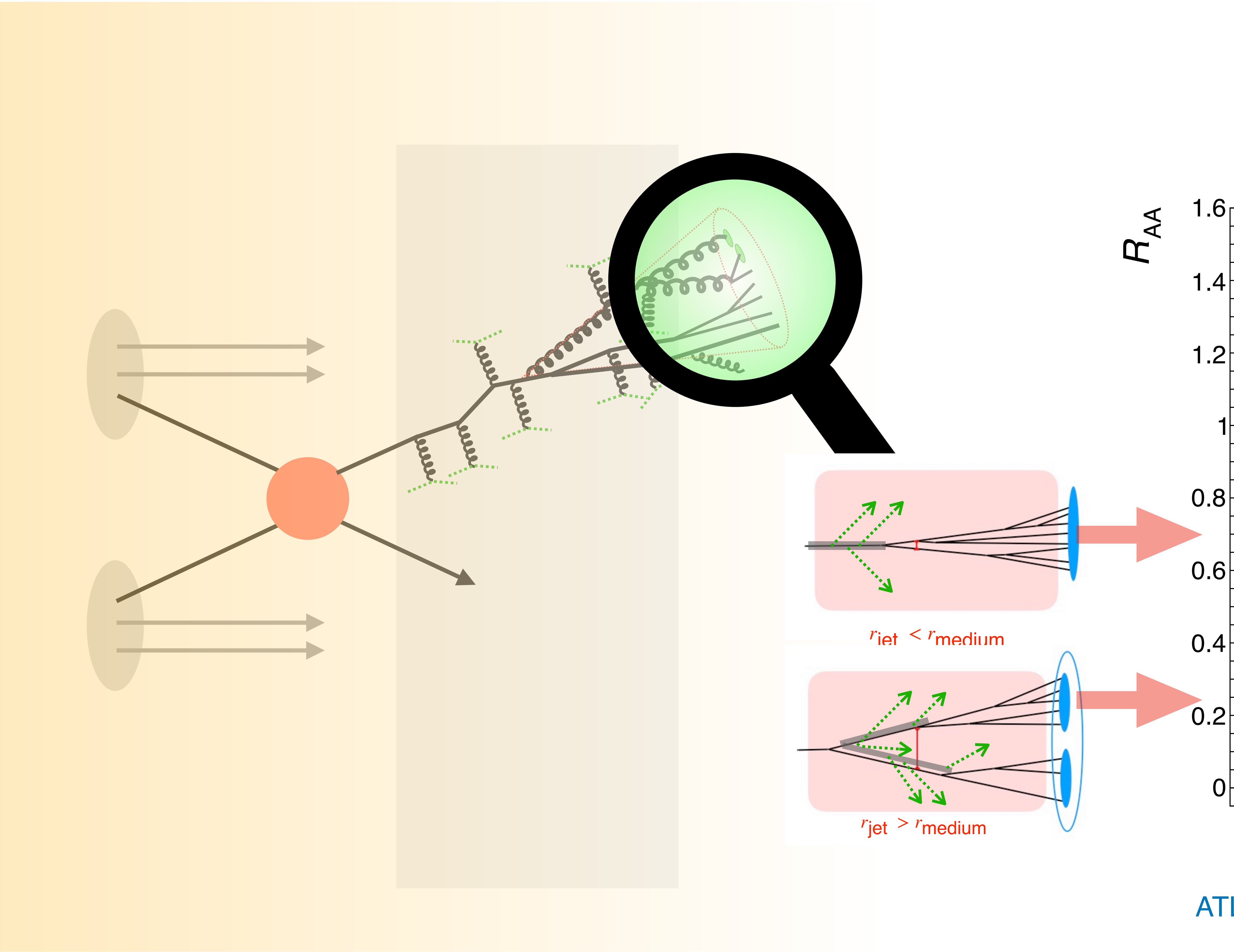
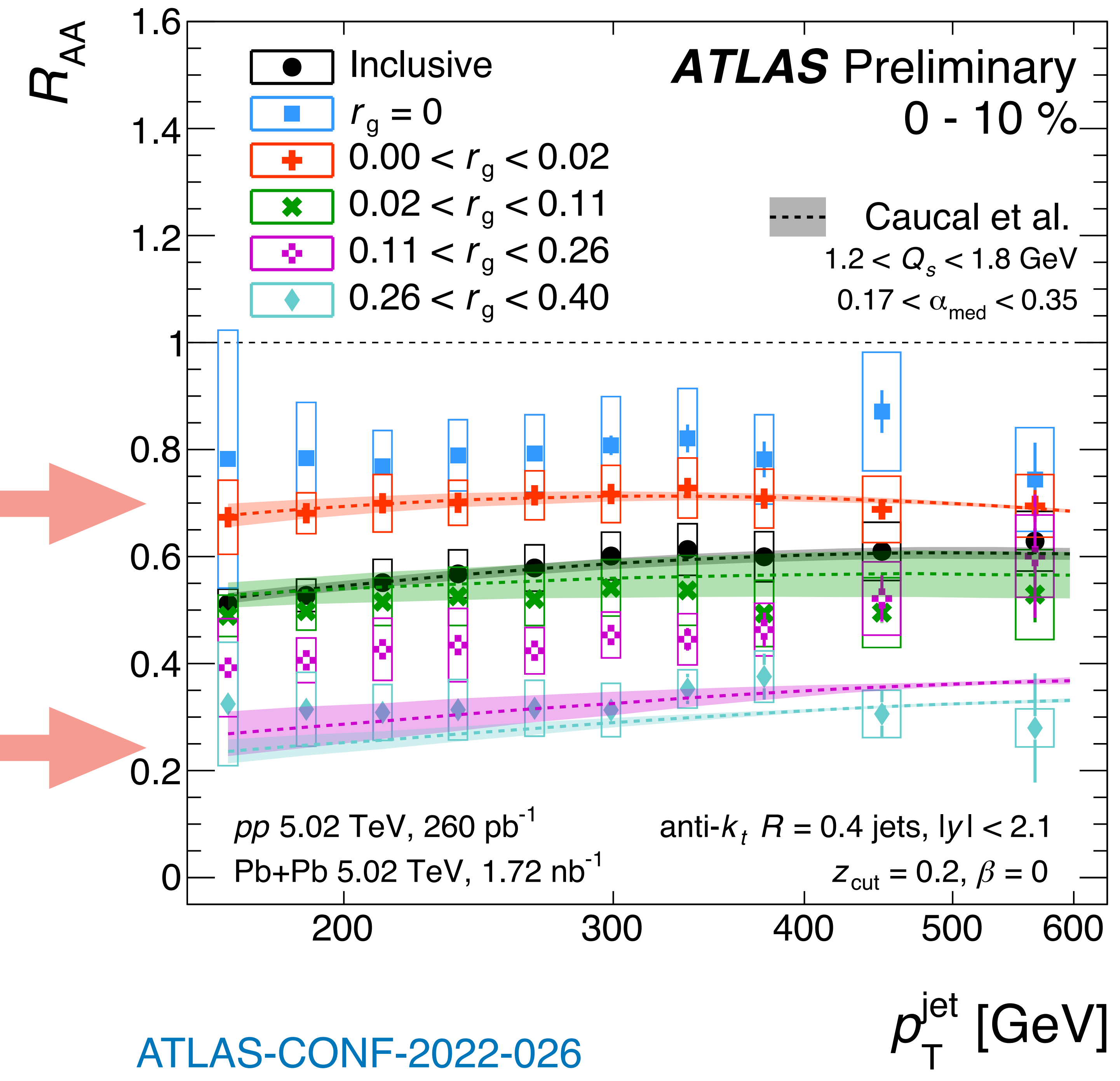


Summary

- Jet suppression in the QGP has been measured differentially using complementary substructure observables
- The jet R_{AA} is observed to depend significantly on many substructure observables
- Many more substructure observables like energy correlators yet to be explored to get a better handle on jet quenching







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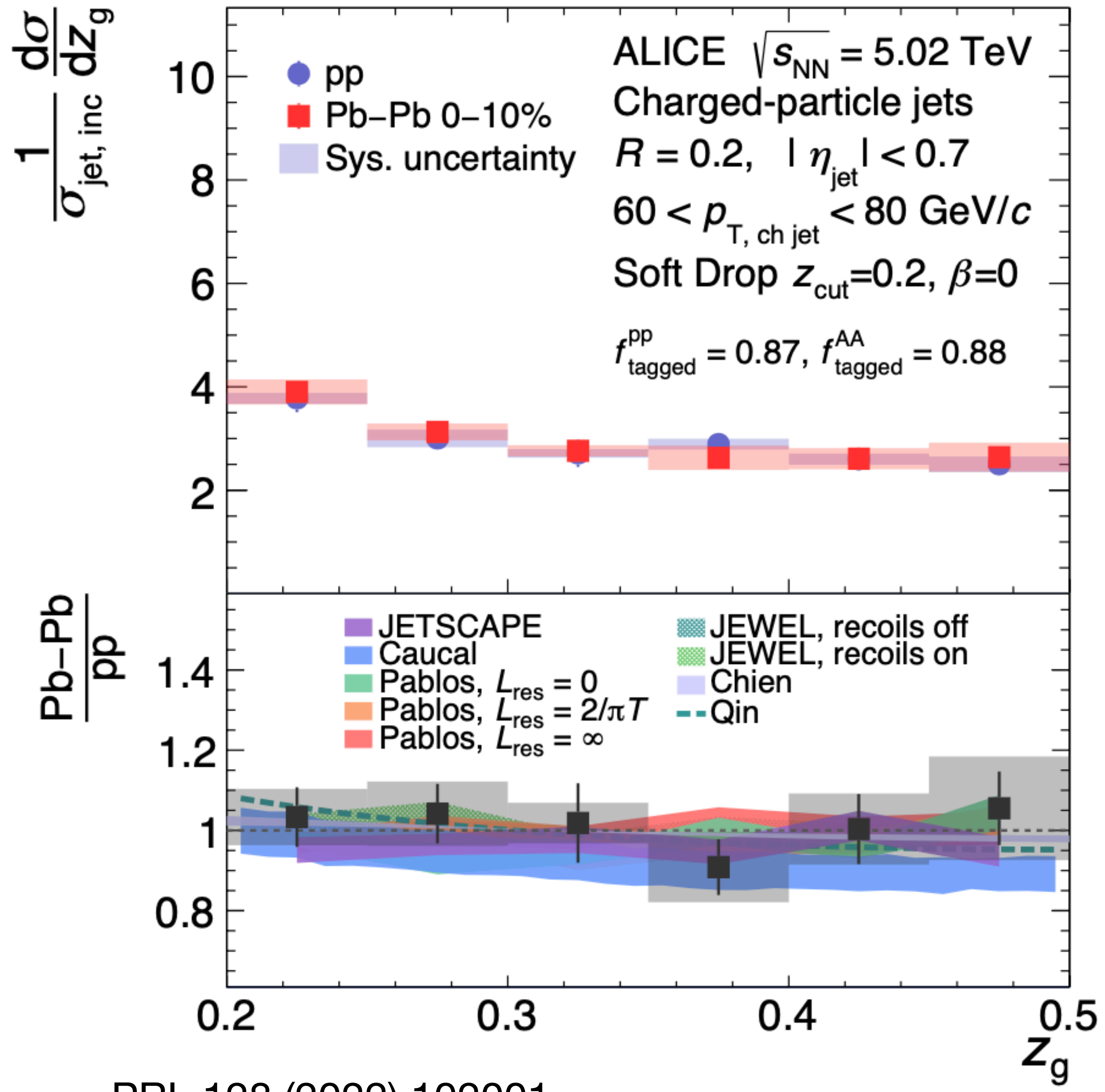
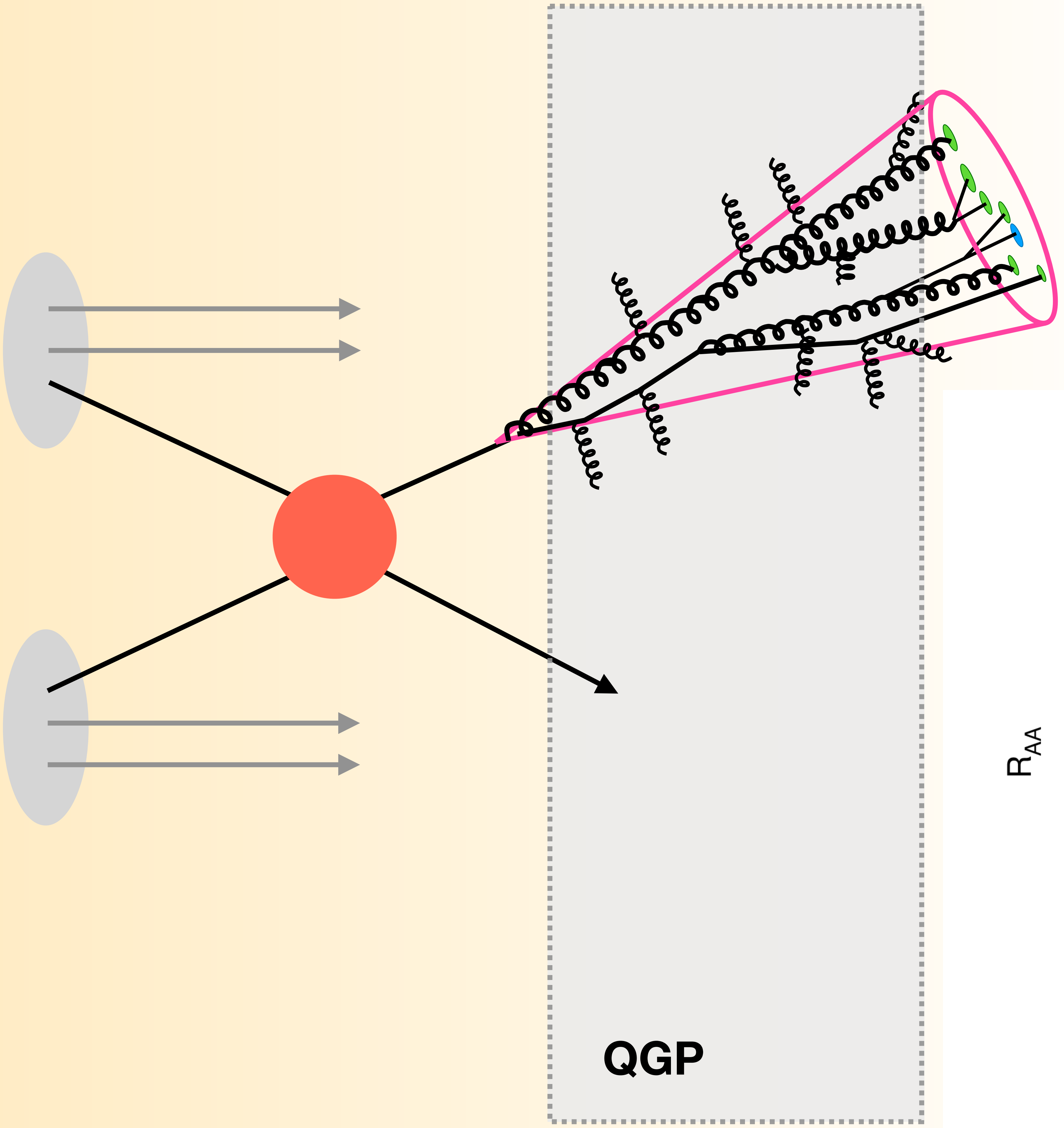


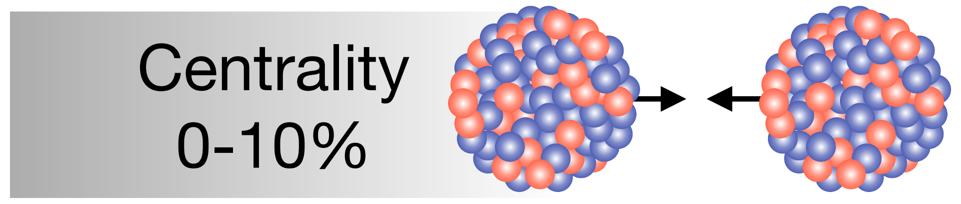
PRL 128 (2022) 102001

Backup

Jets in the QGP

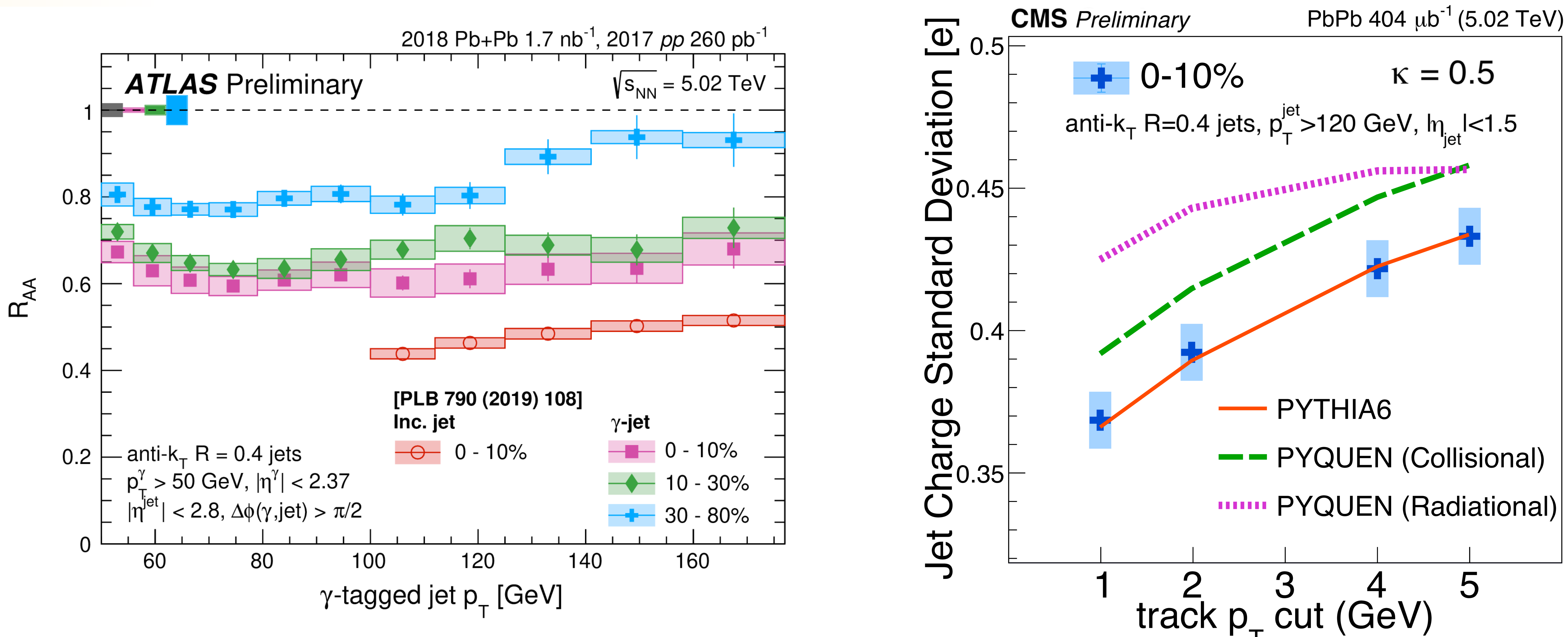


- Quark-initiated jets expected to lose lesser energy in the QGP due to color factor
- Jet charge in PbPb is consistent with quark-gluon fraction predictions from Pythia



Jet R_{AA} for γ - jets

Jet charge in PbPb



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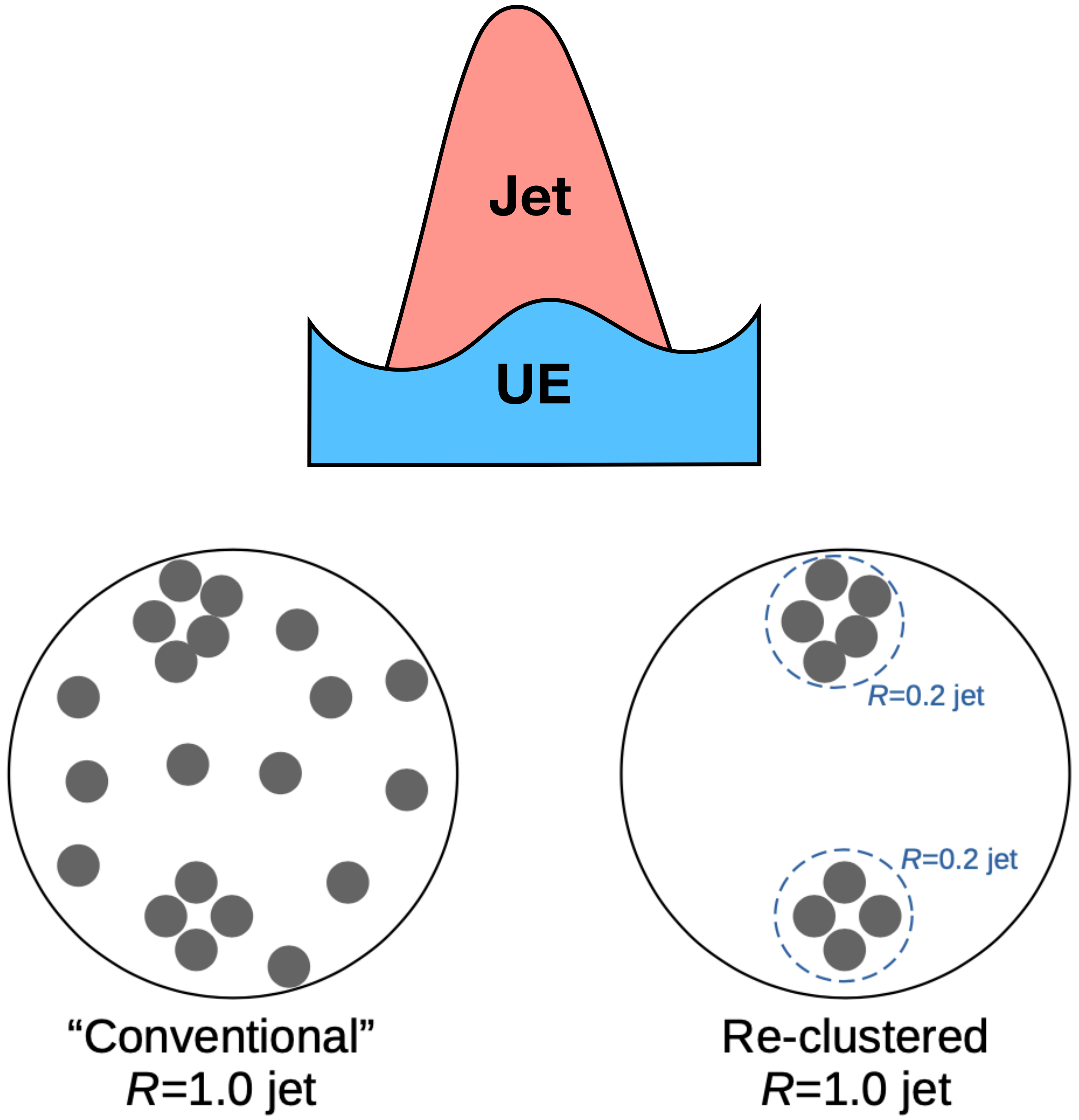
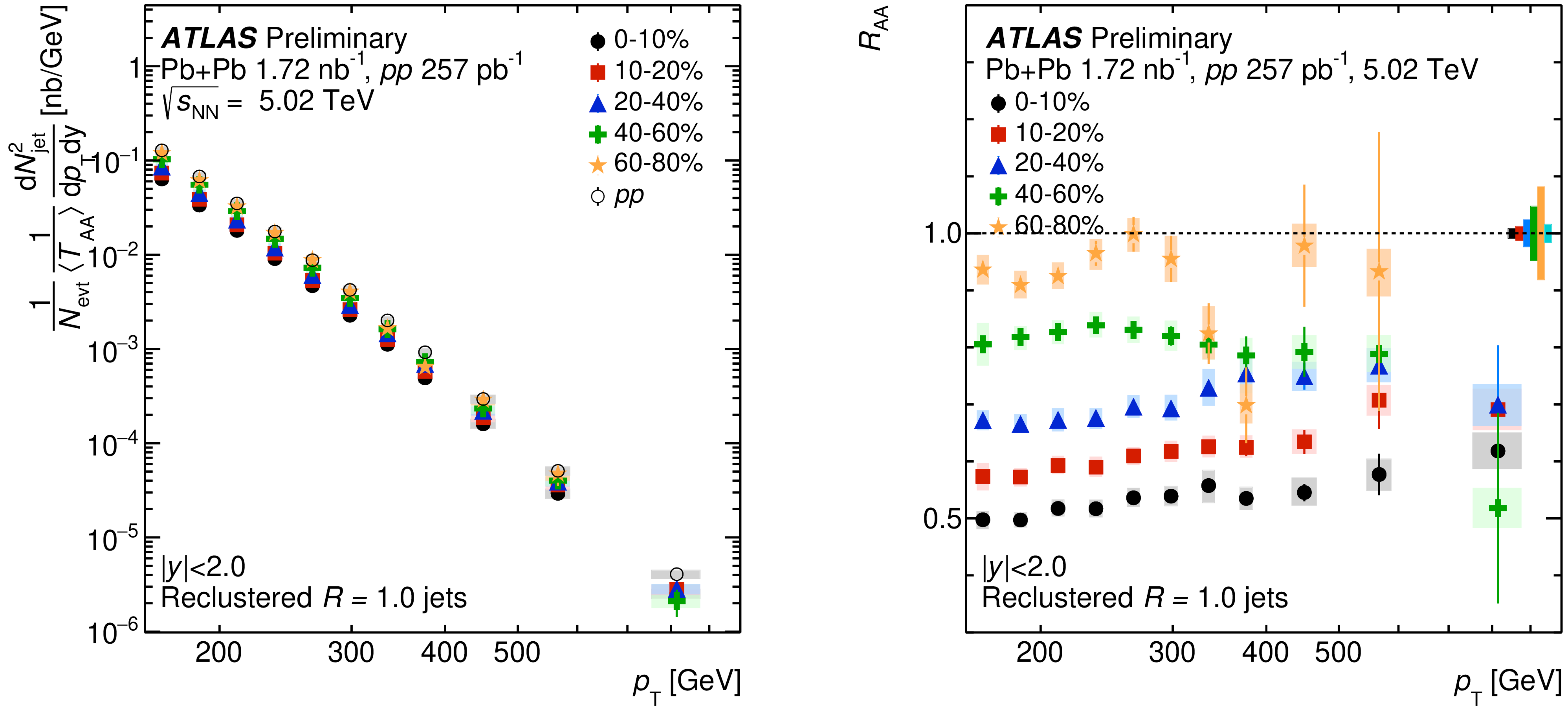
Large Radius Jets

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

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





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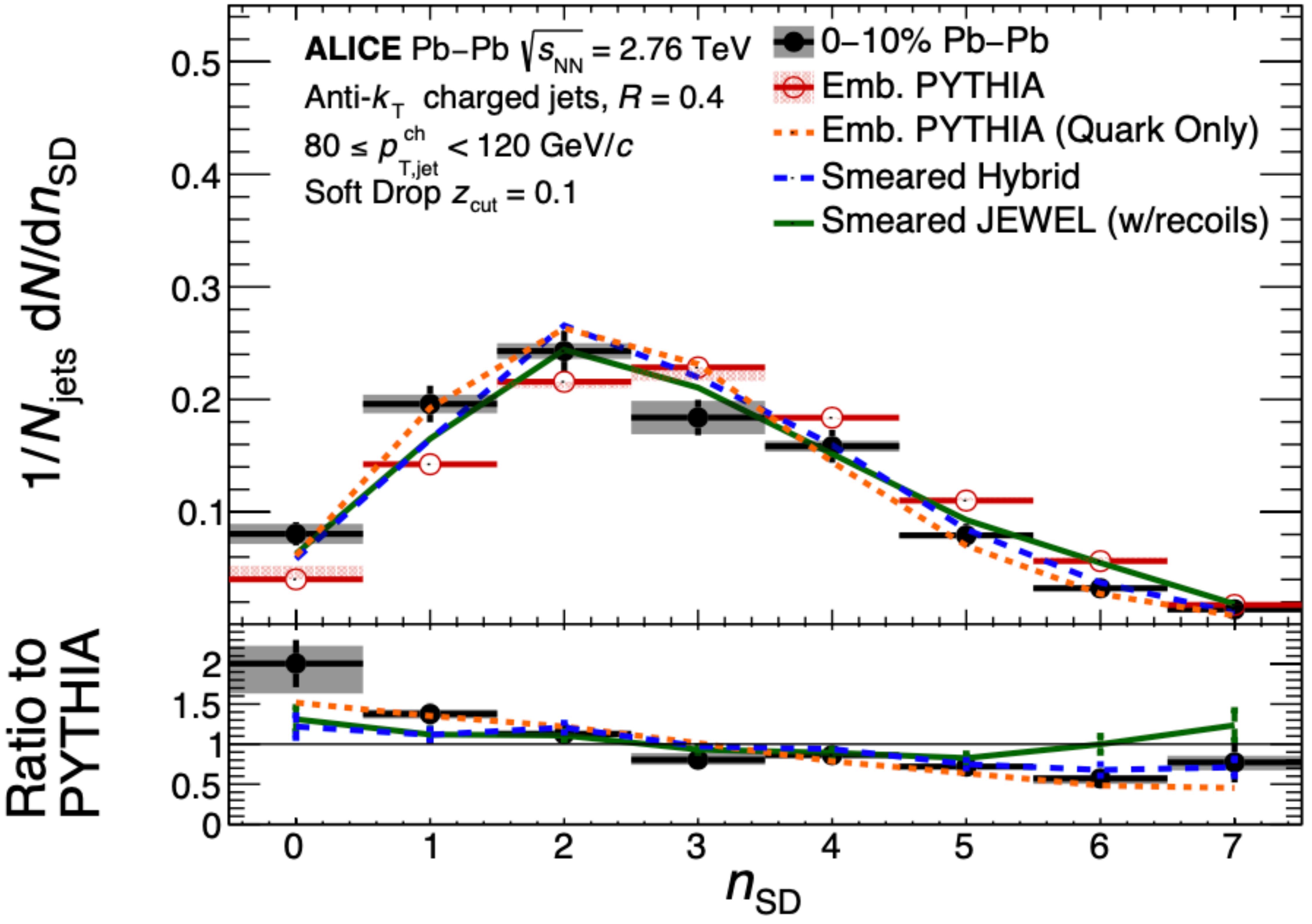
nSD splittings



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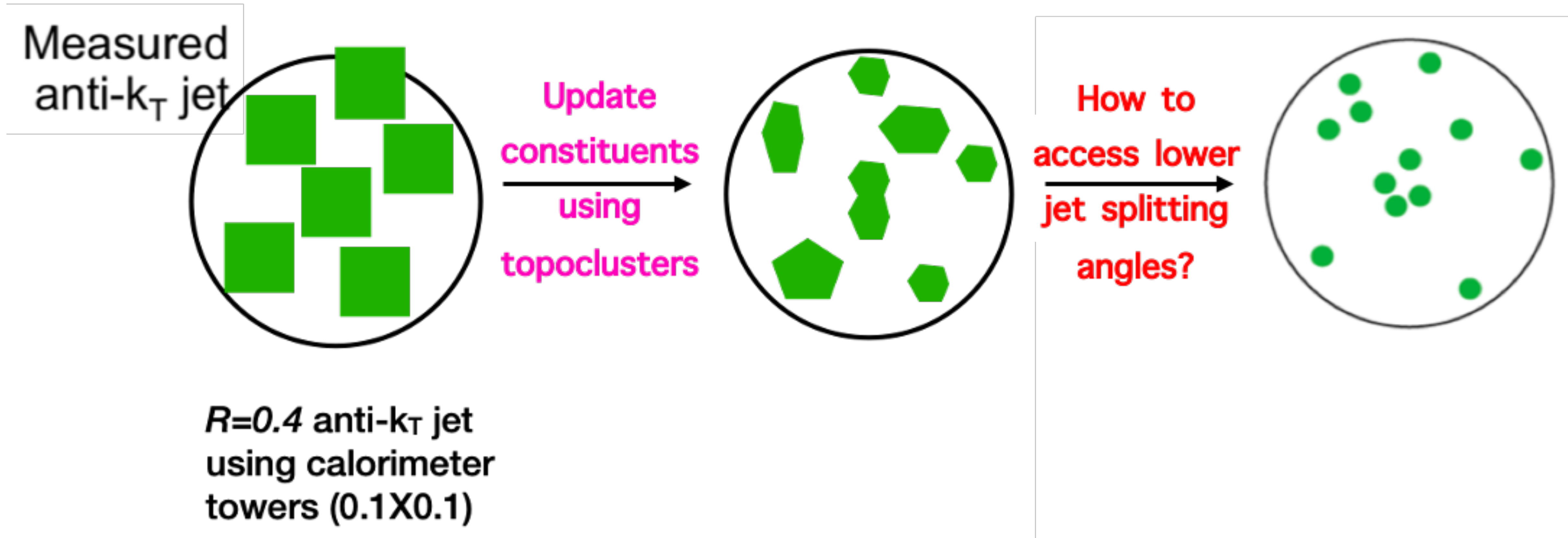
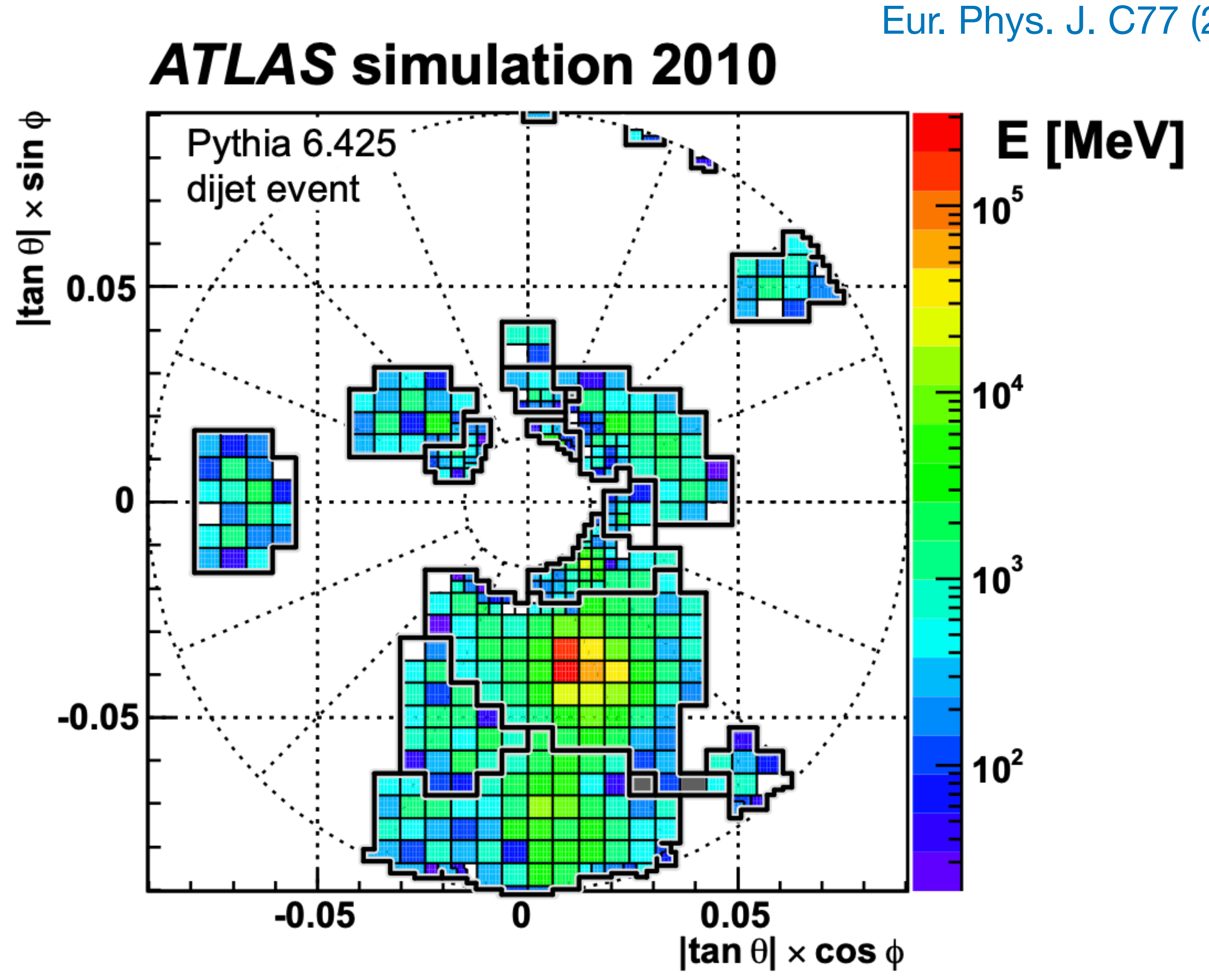
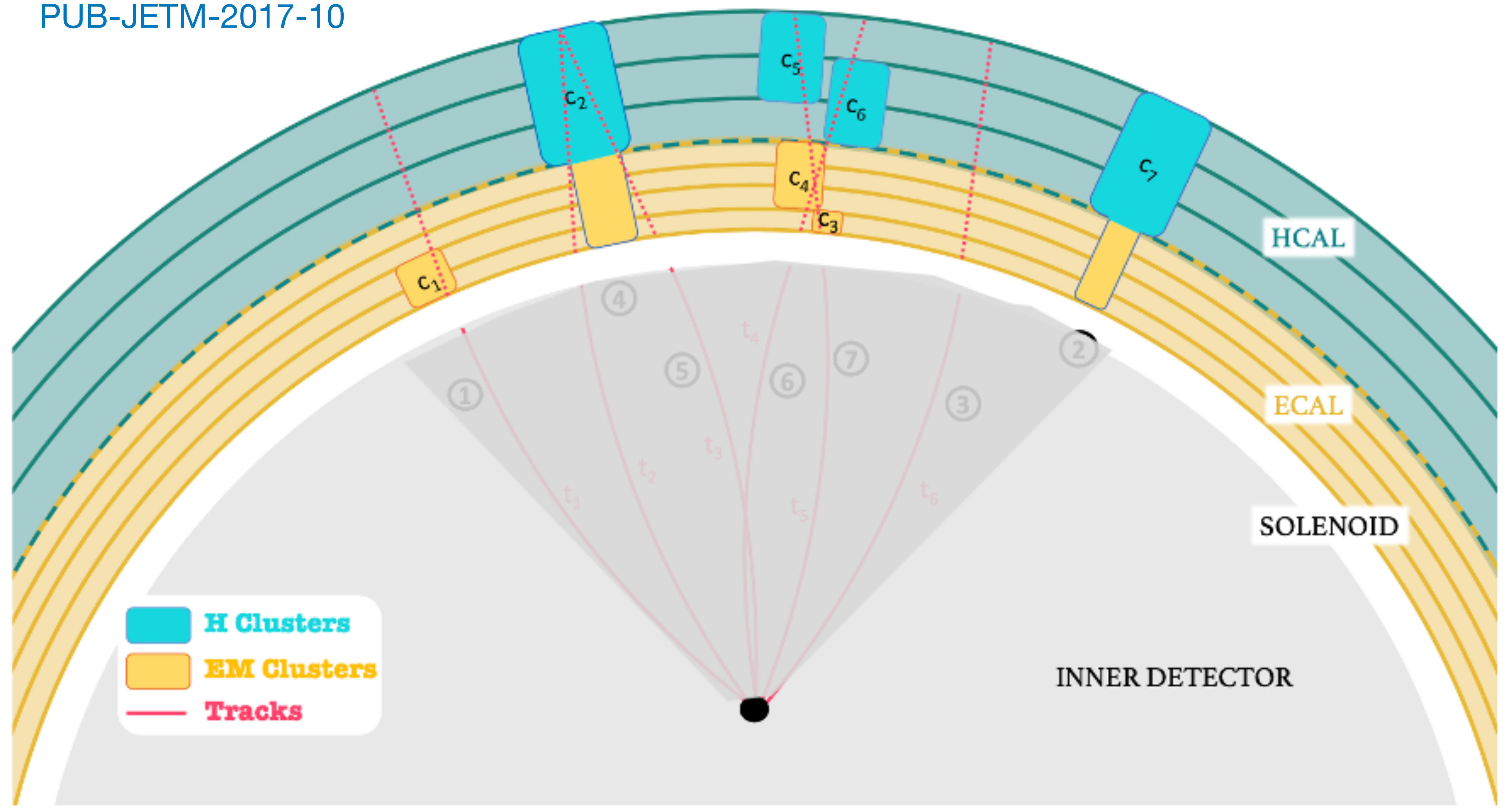
Topological Cell Clusters



Eur. Phys. J. C77 (2017) 490



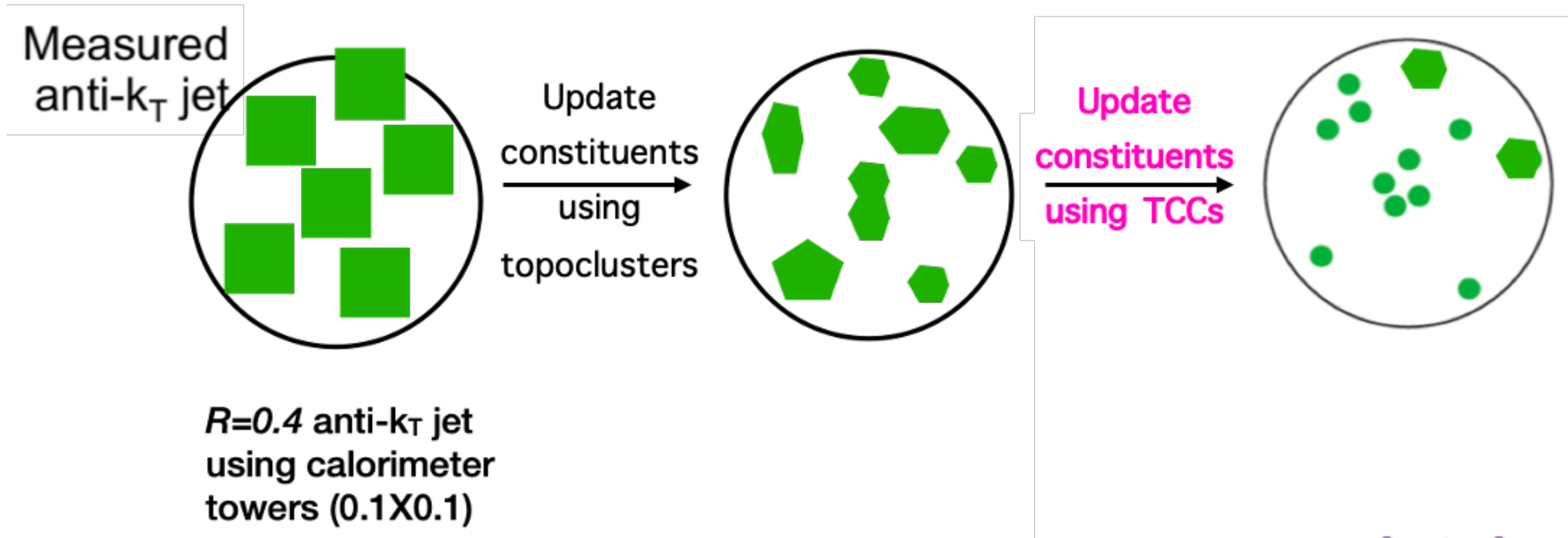
PUB-JETM-2017-10

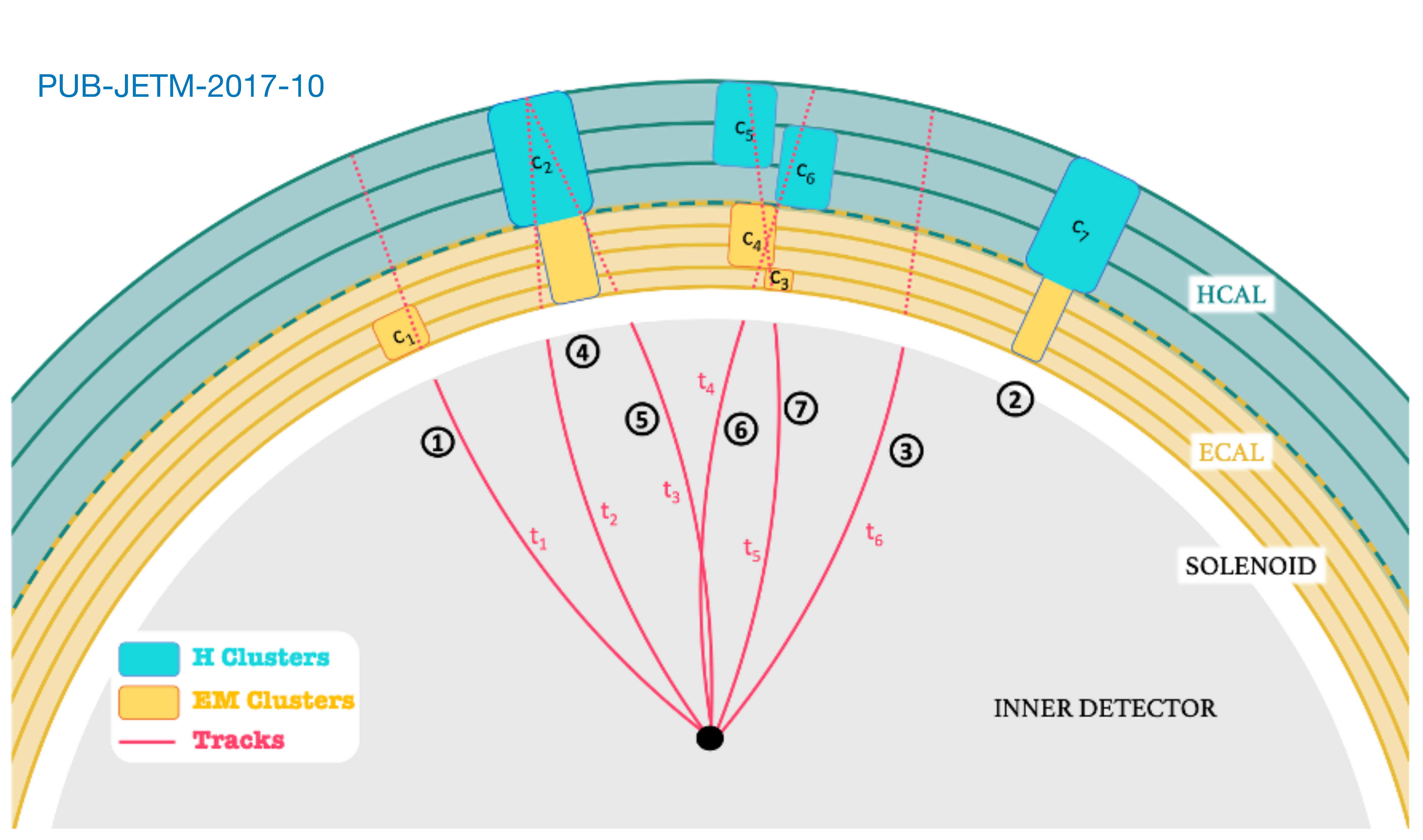


Topo-clusters

- 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)

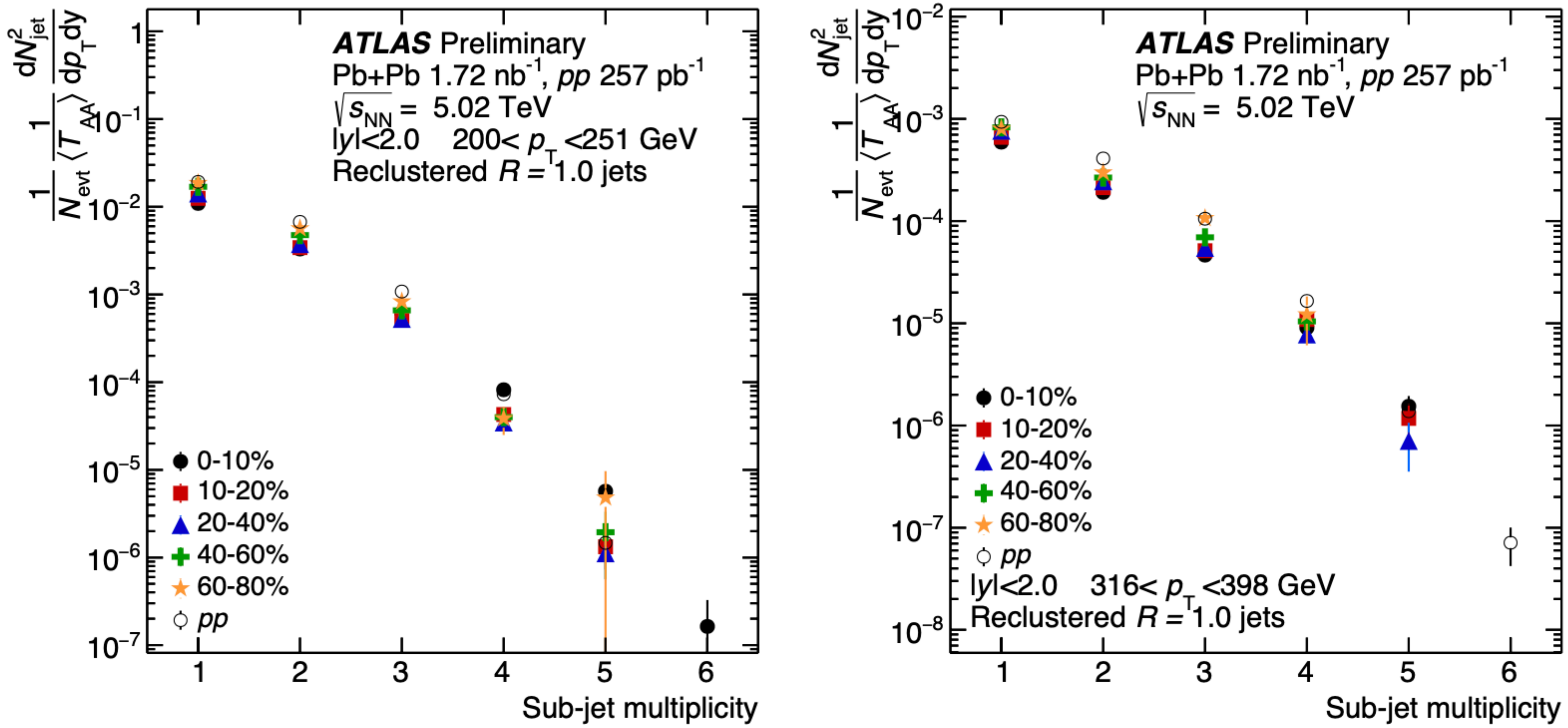




Track Calo-Clusters (TCCs)

- 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

Large R jet kinematics



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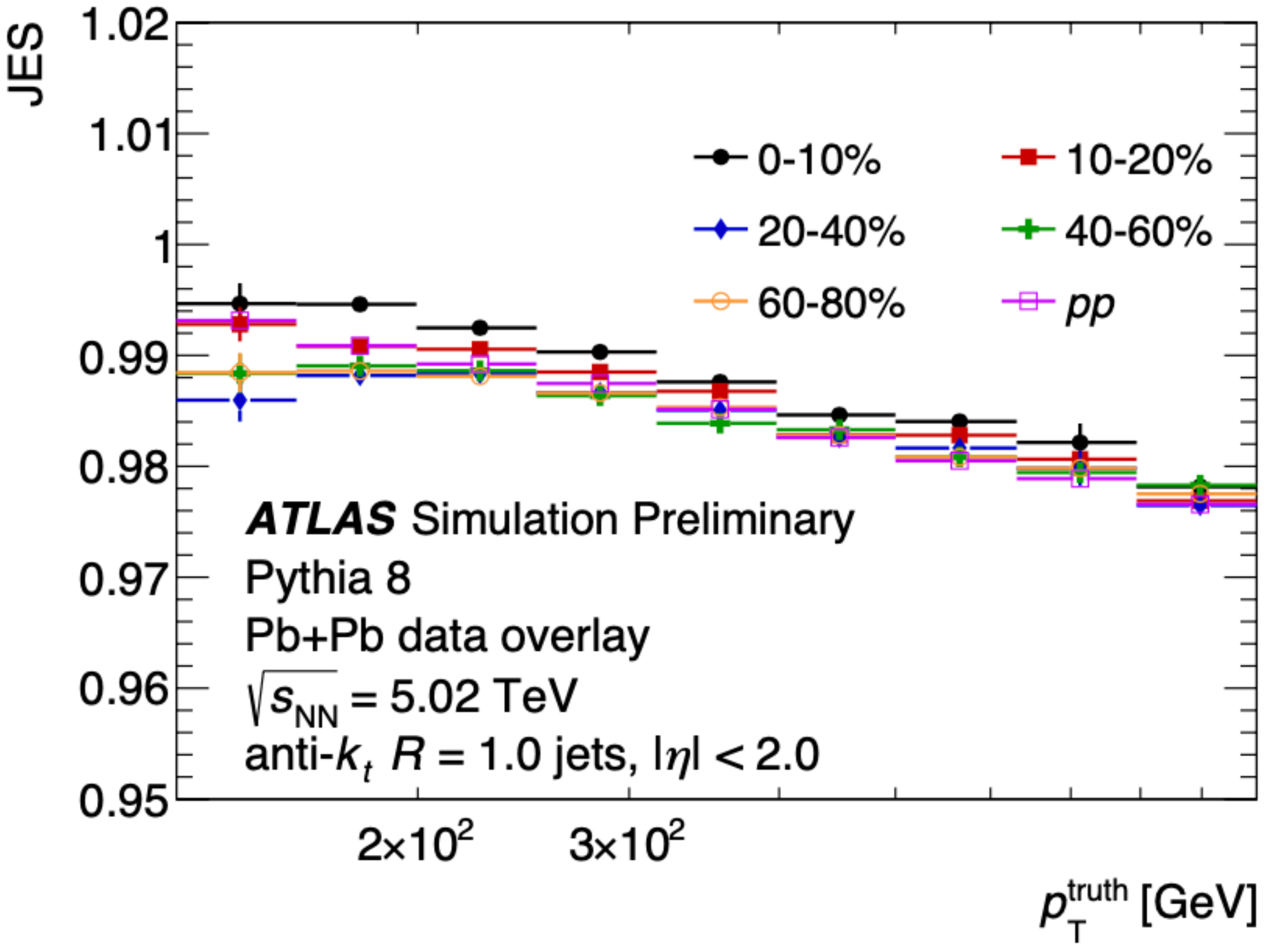
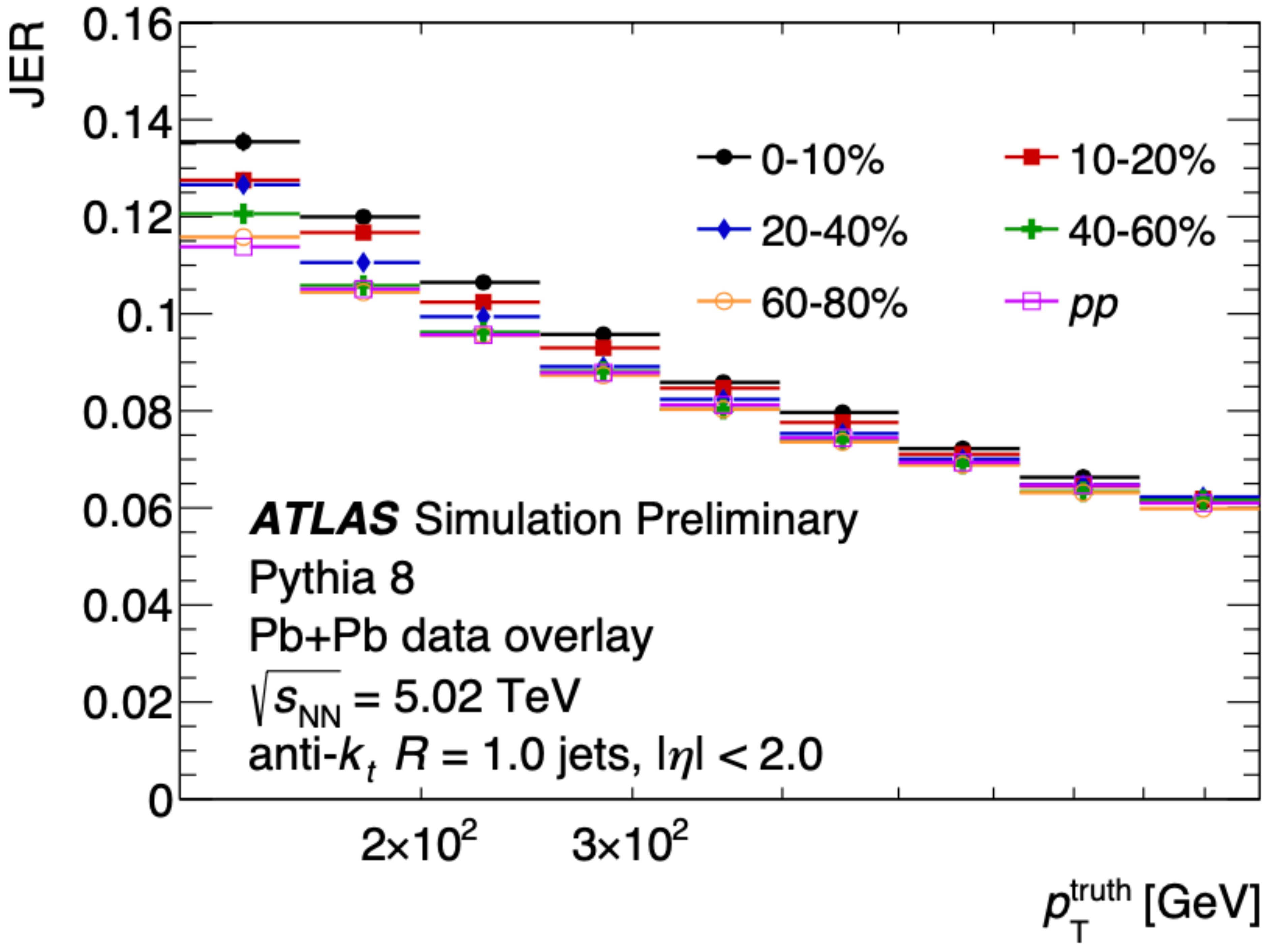
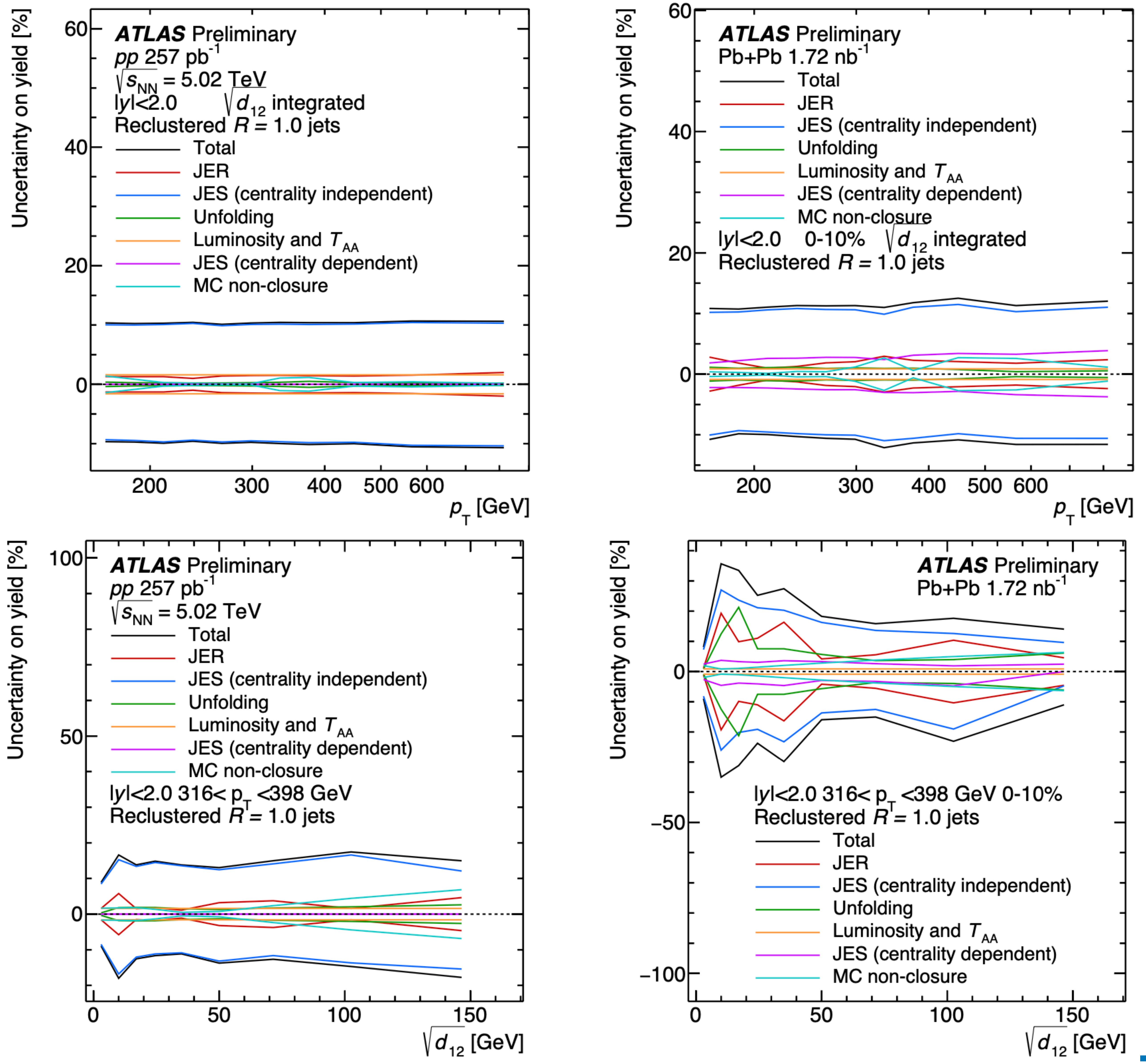
Large R jet kinematics





Large R jet systematics



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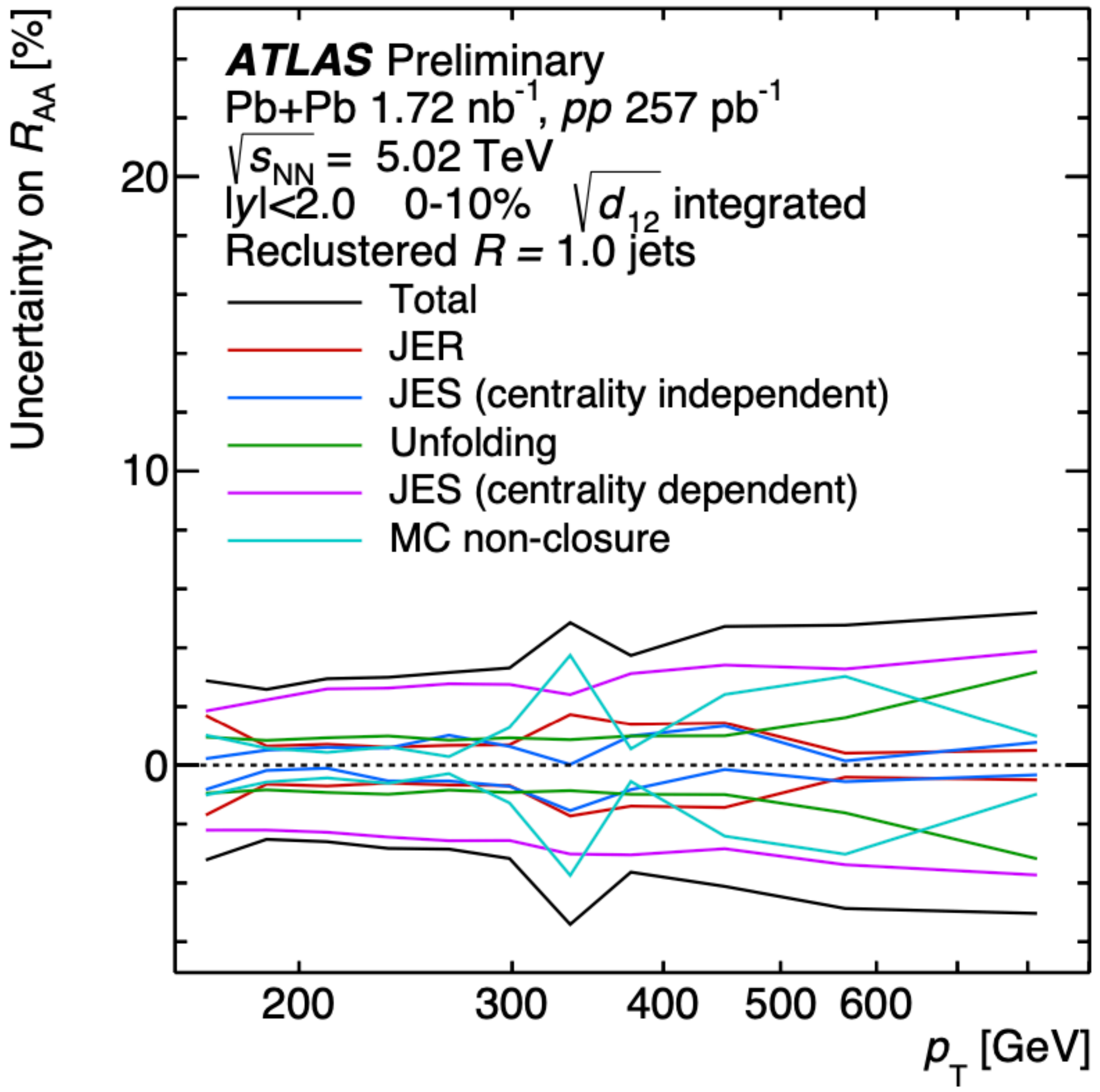
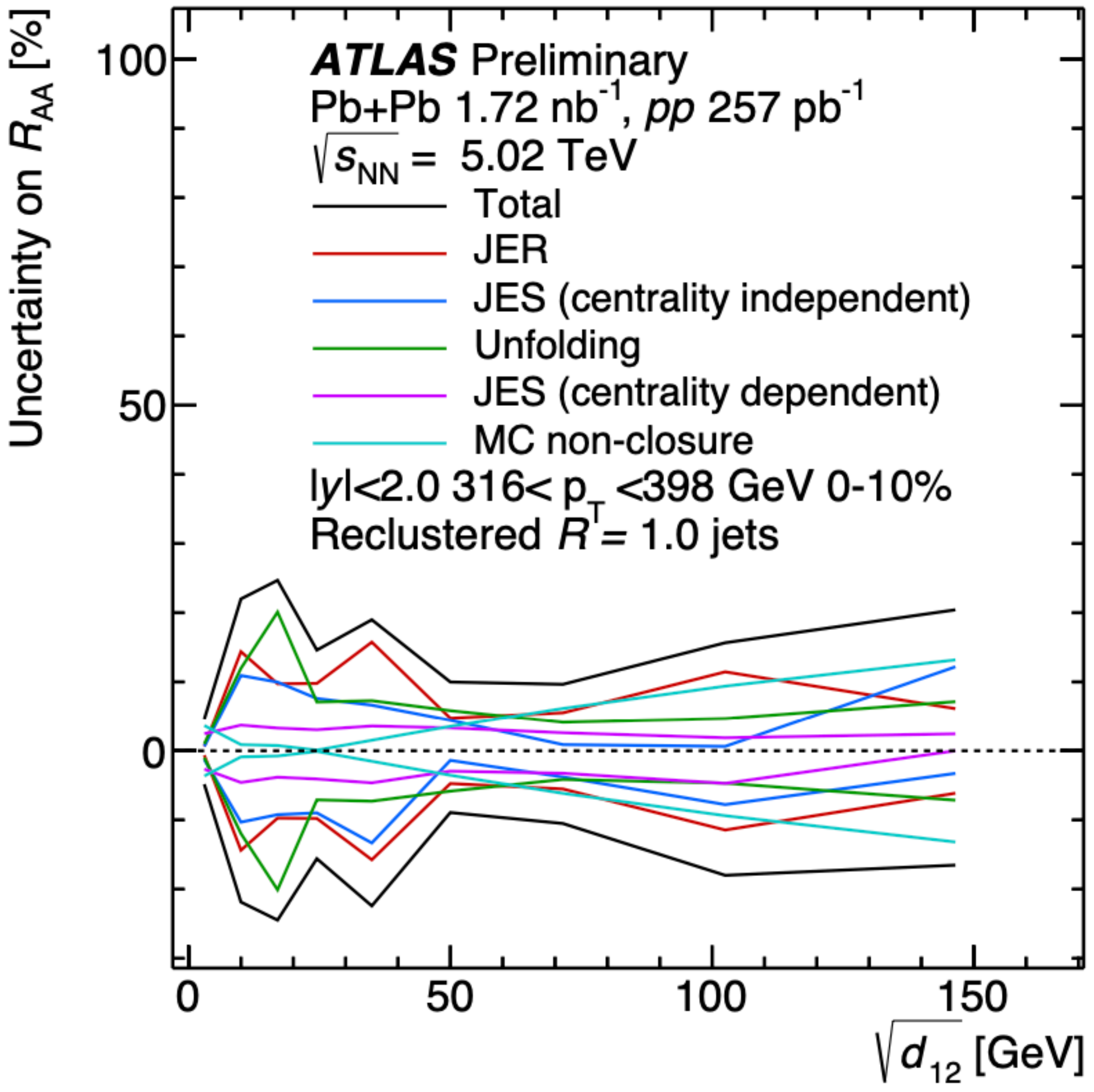
Large R jet systematics





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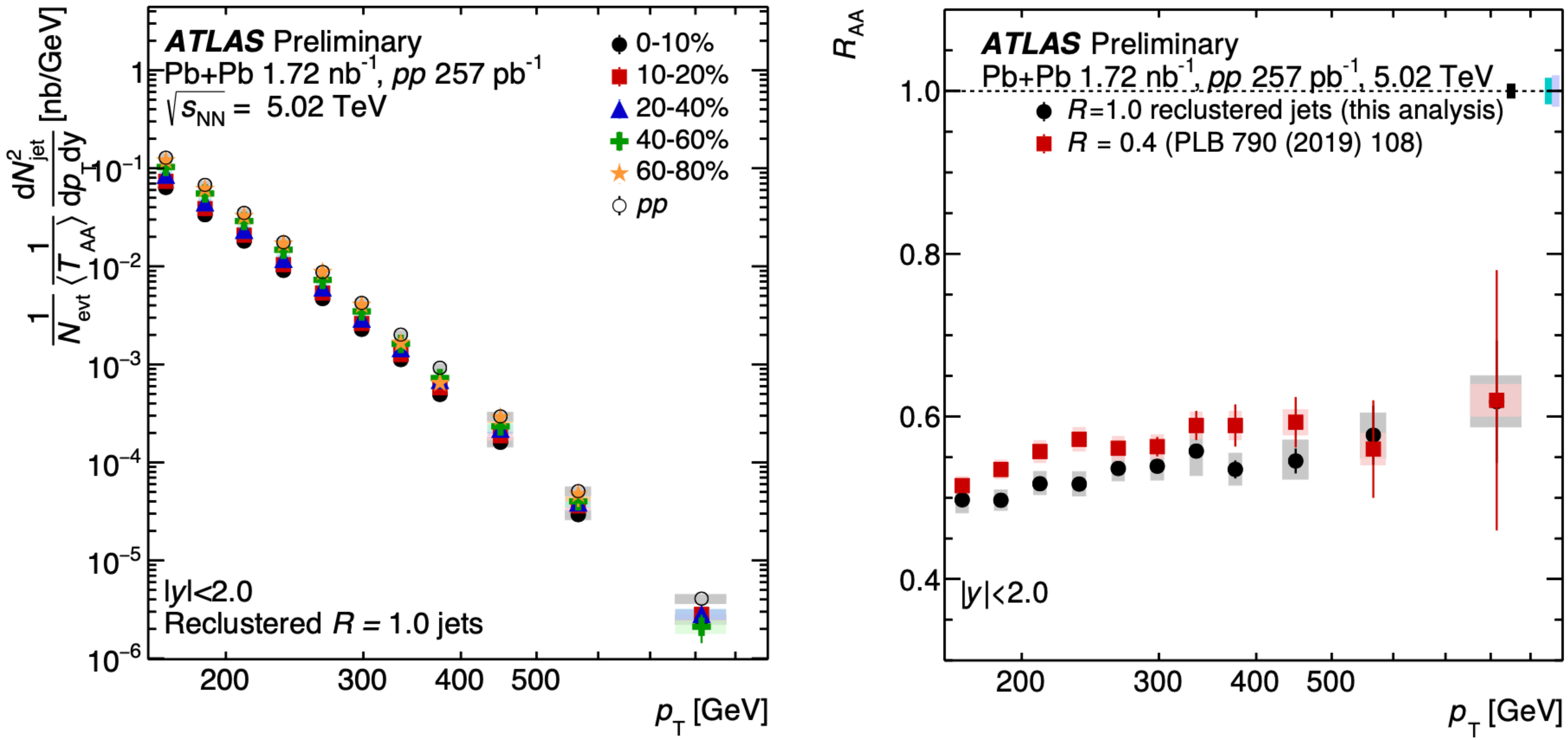
Large R jet R_{AA}



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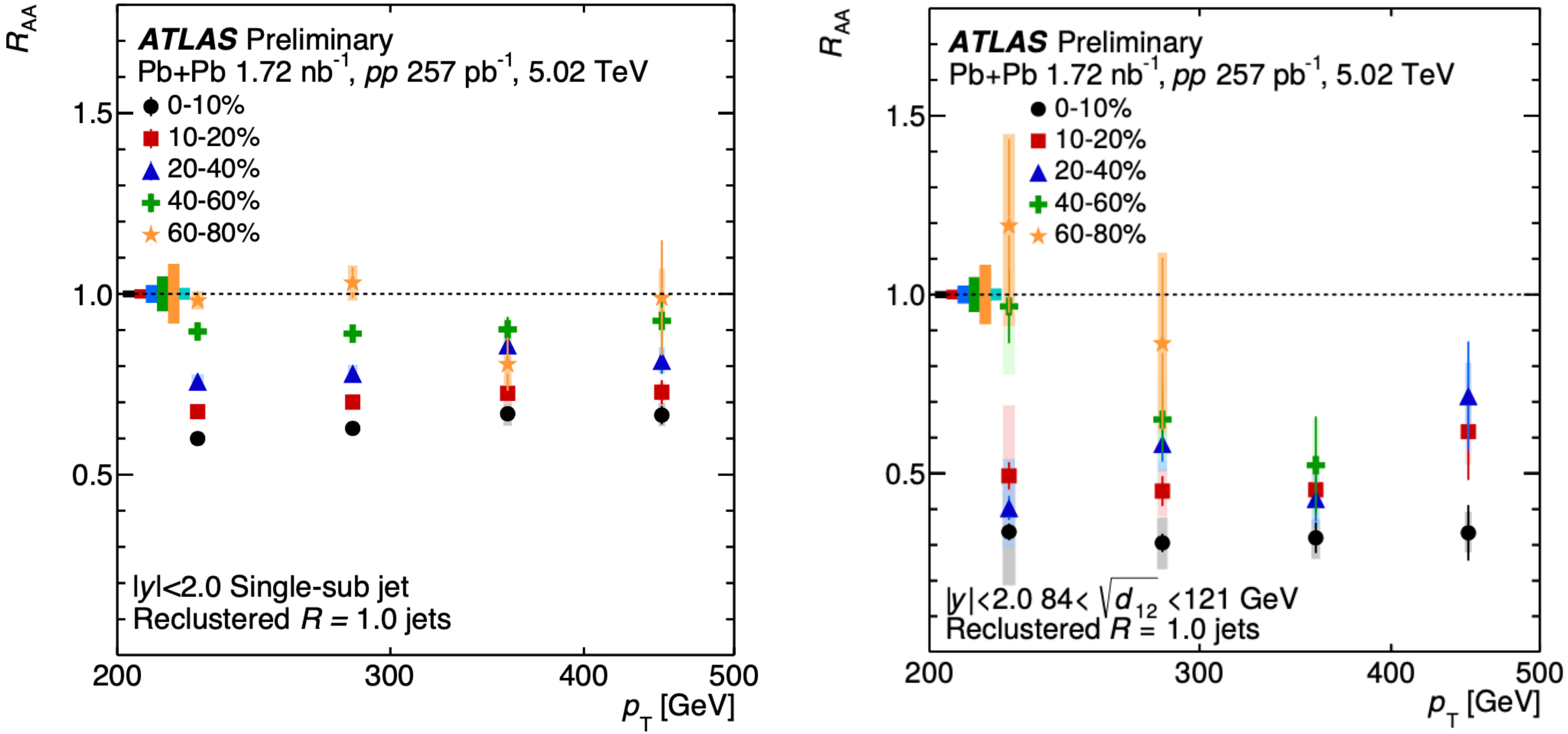
Large R jet R_{AA}



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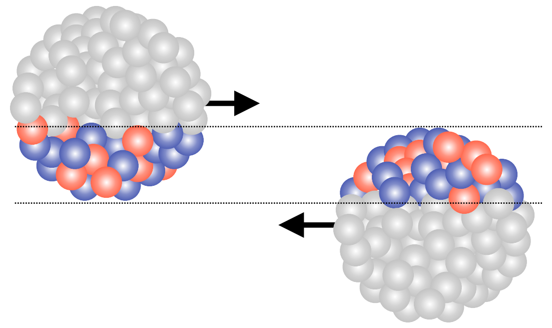
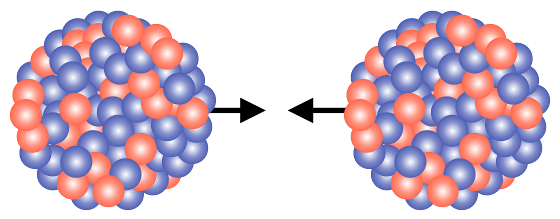
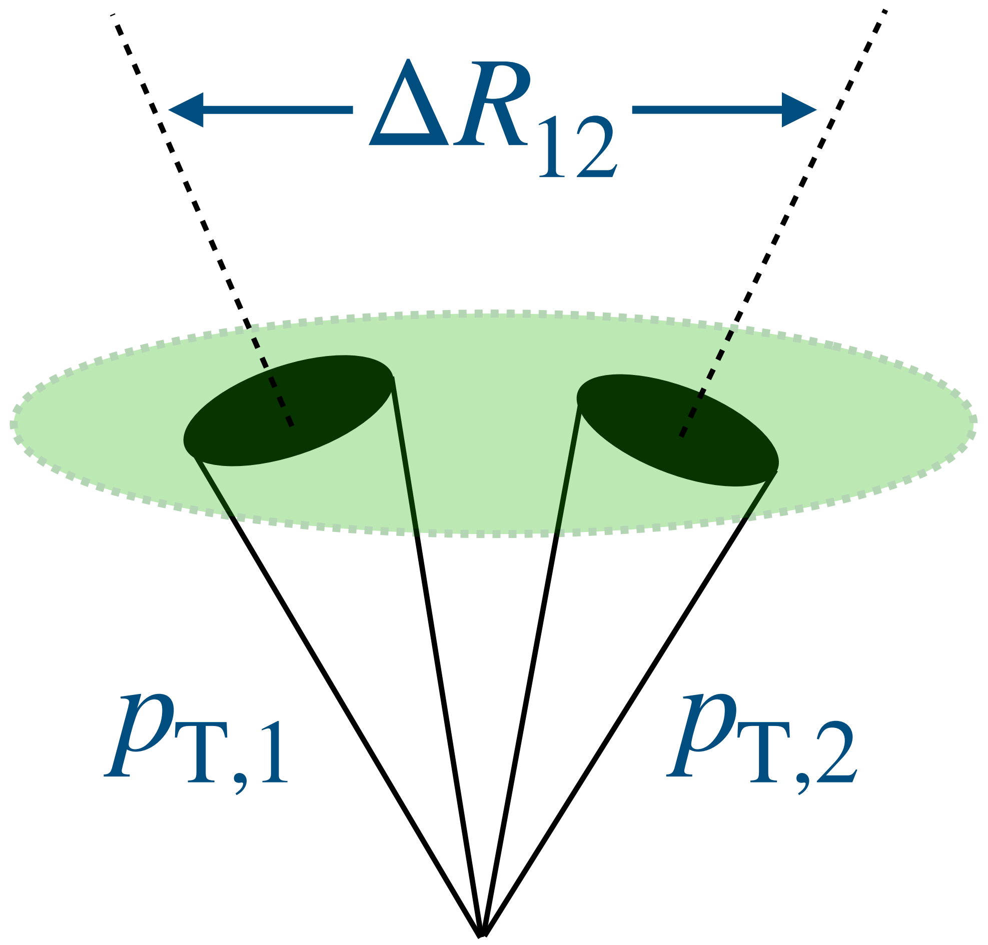
r_g with TCCs vs. Truth

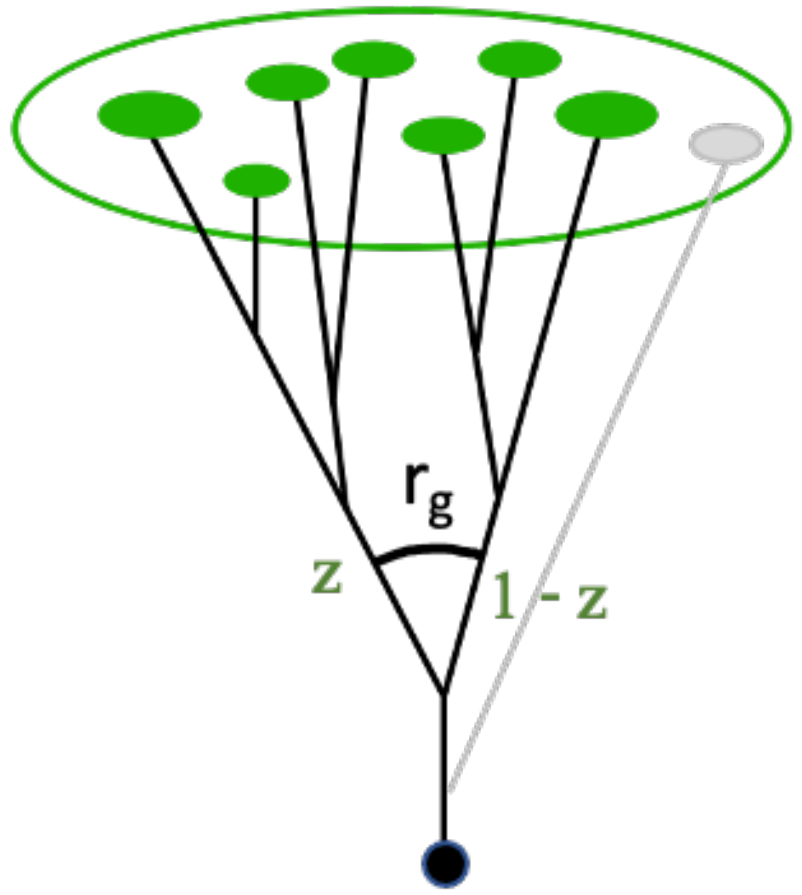
- Characterize a jet using the angular separation of its hardest splitting (r_g)
- TCCs show significantly improved performance in measuring r_g

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









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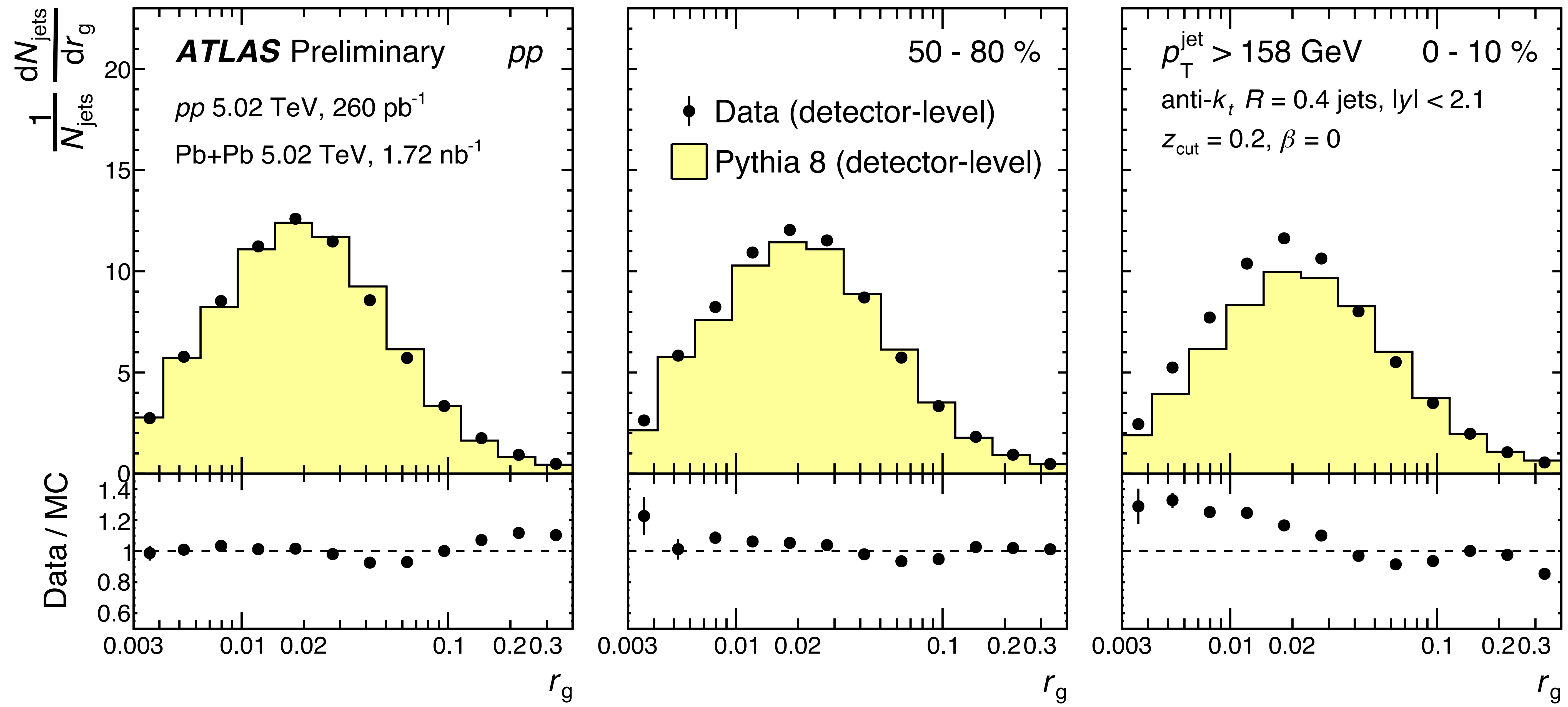
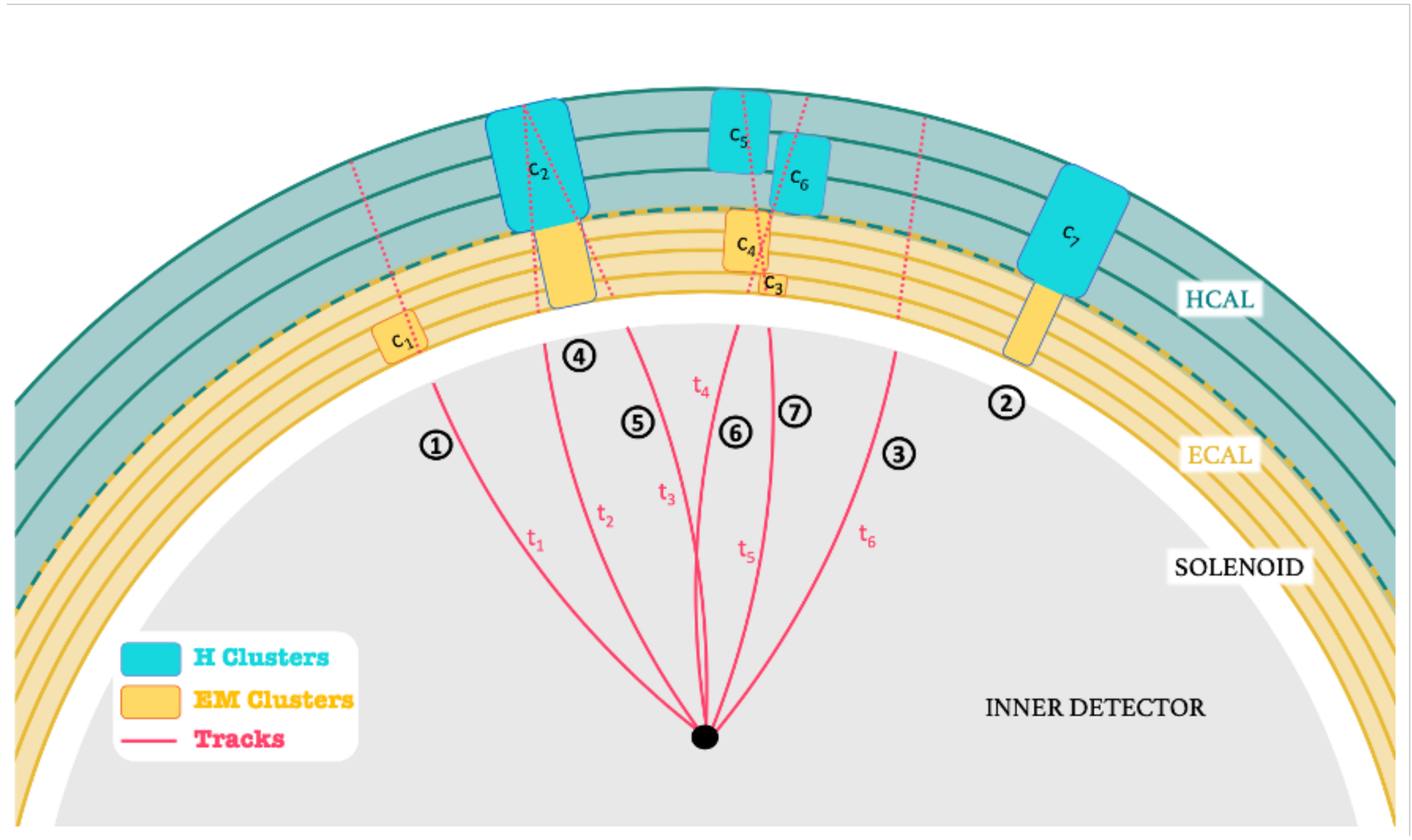
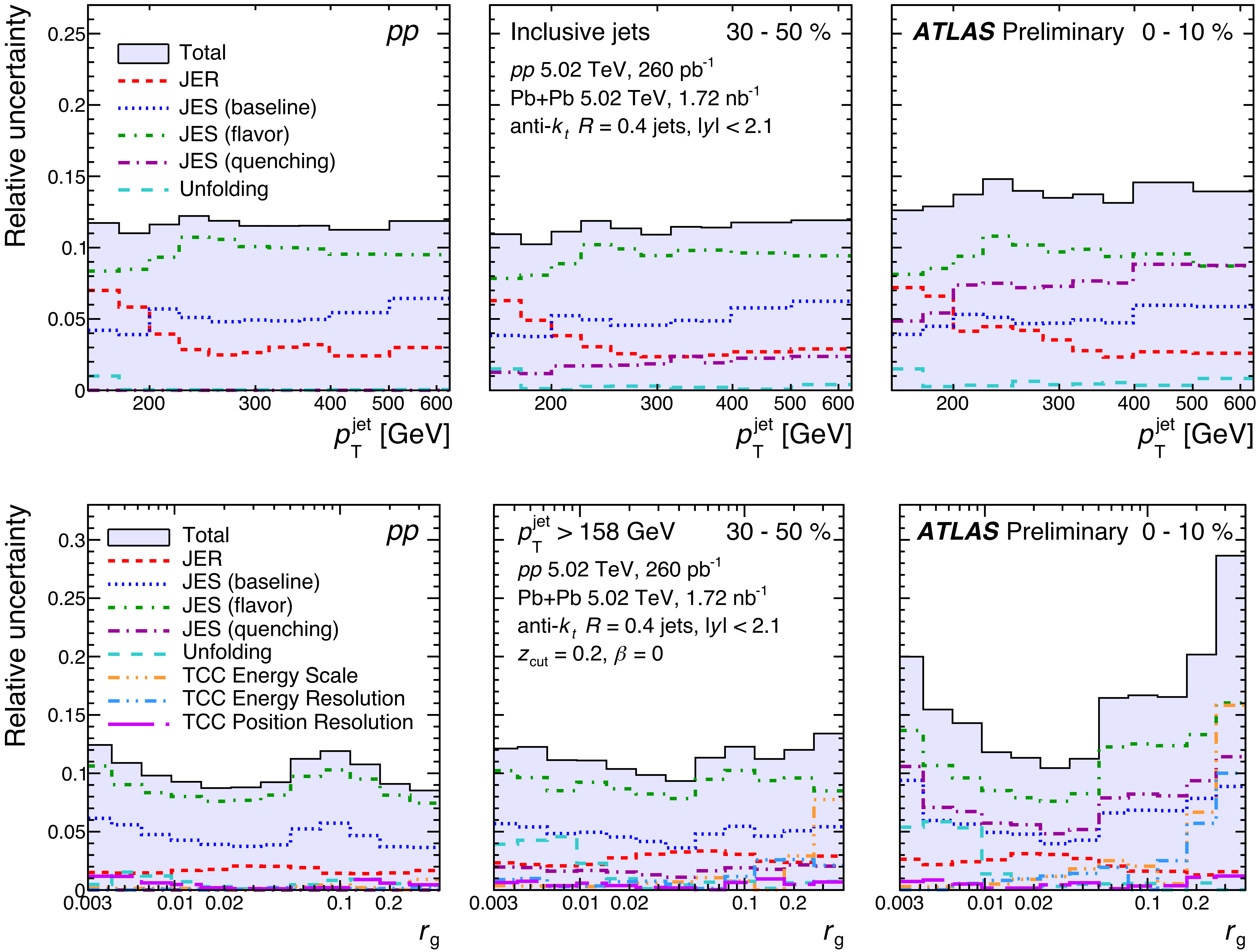


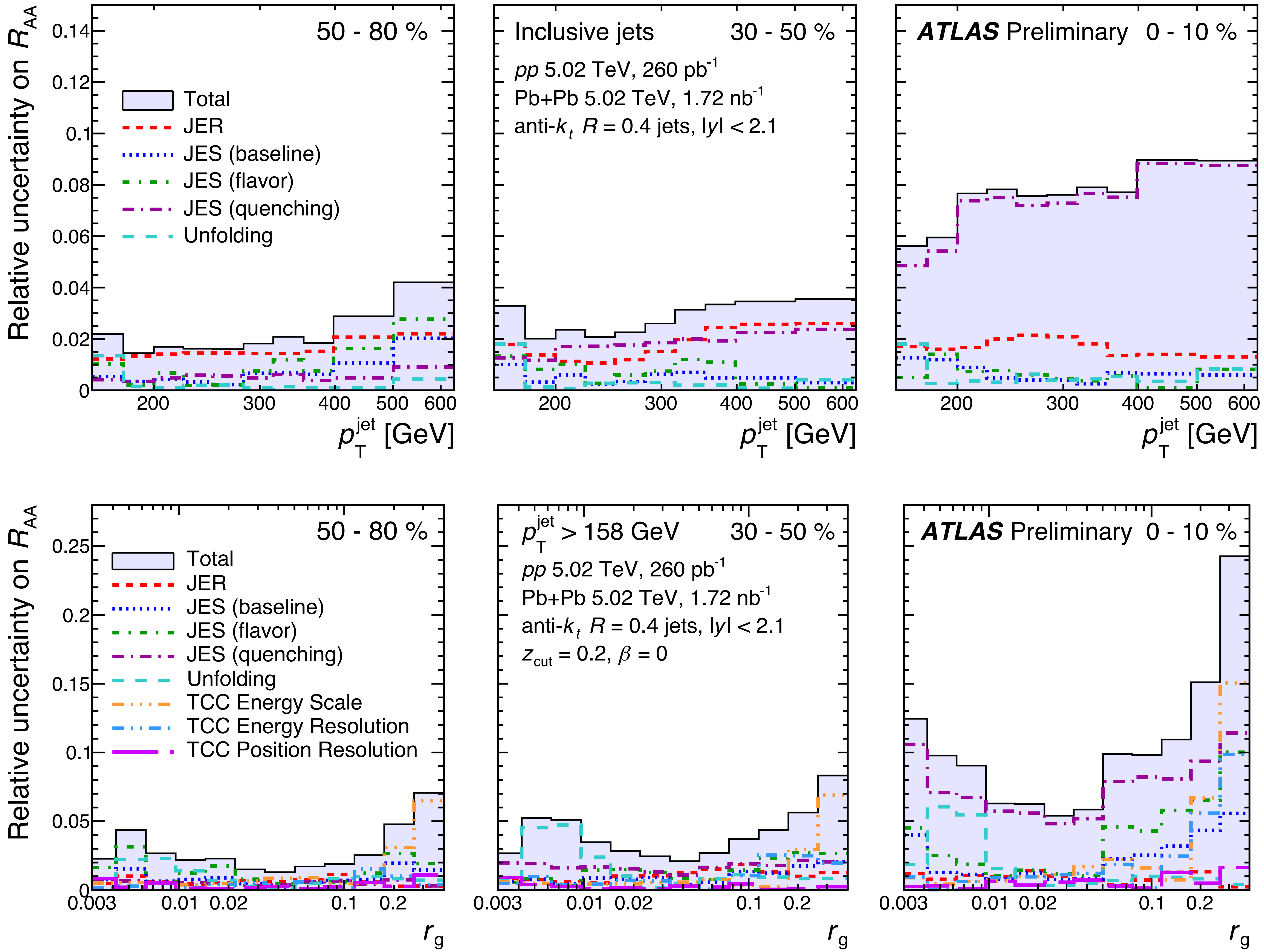


Systematic uncertainties



ATLAS-CONF-2022-026

Systematic uncertainties



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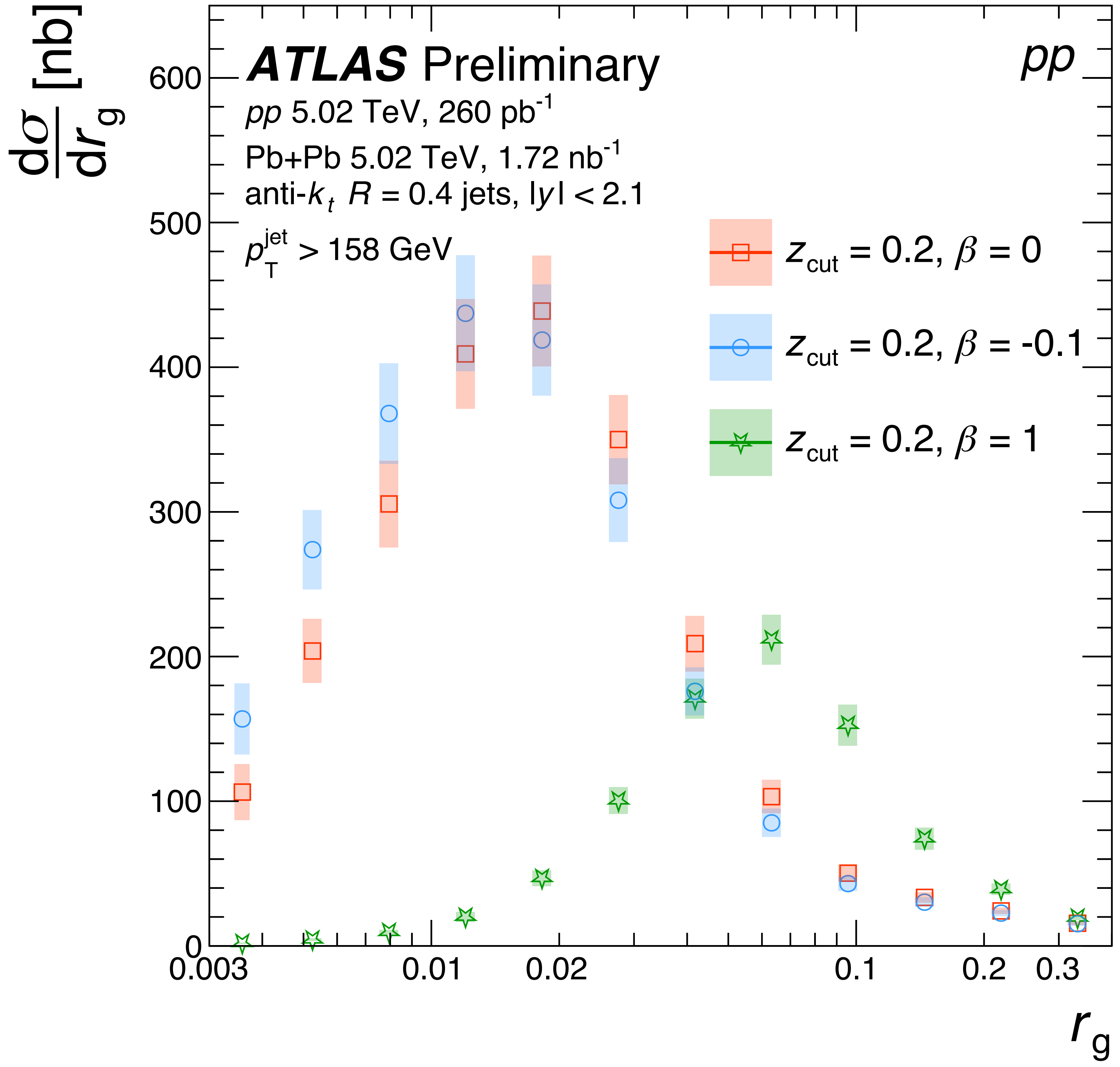
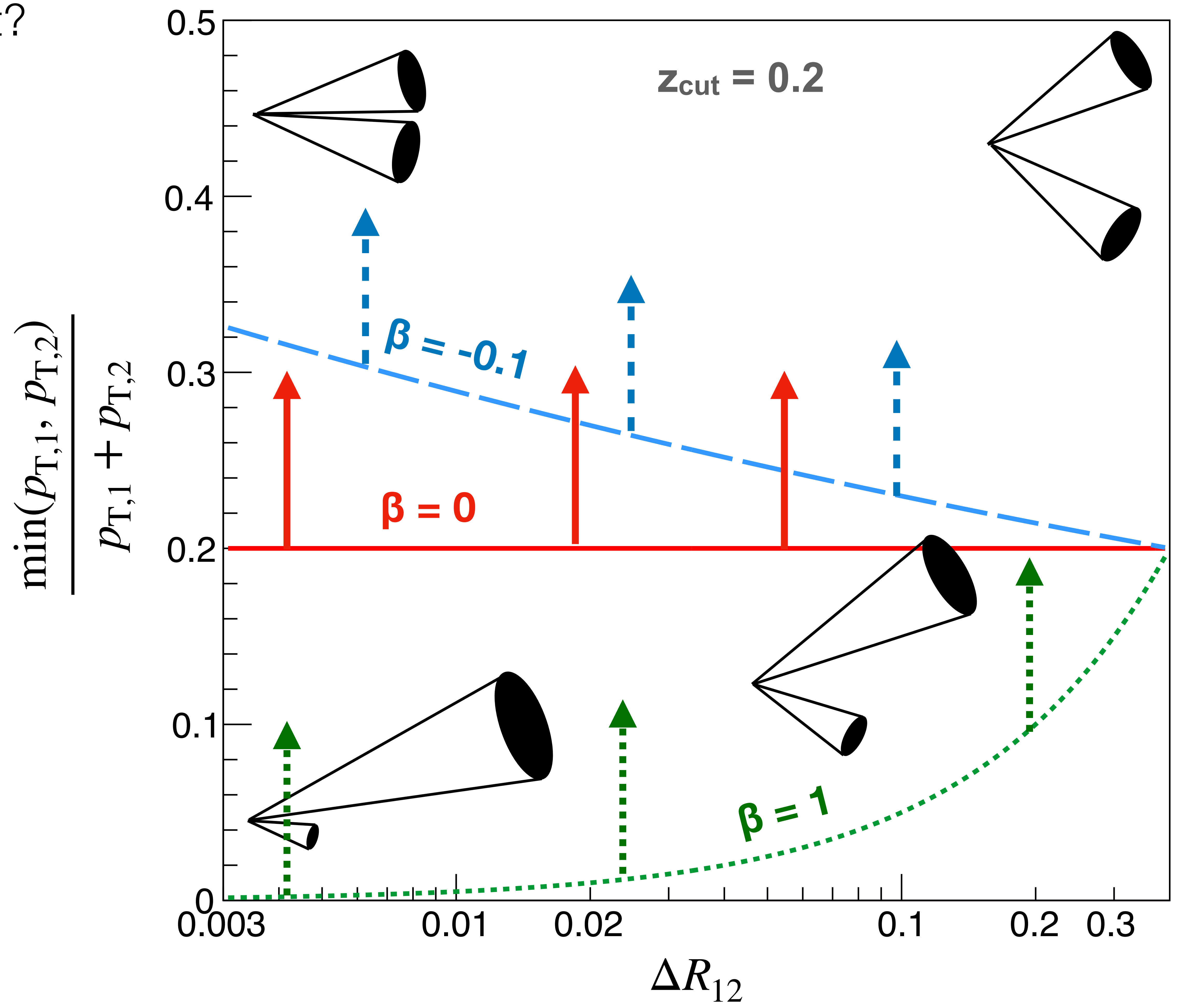
Soft Drop Parameters

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

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





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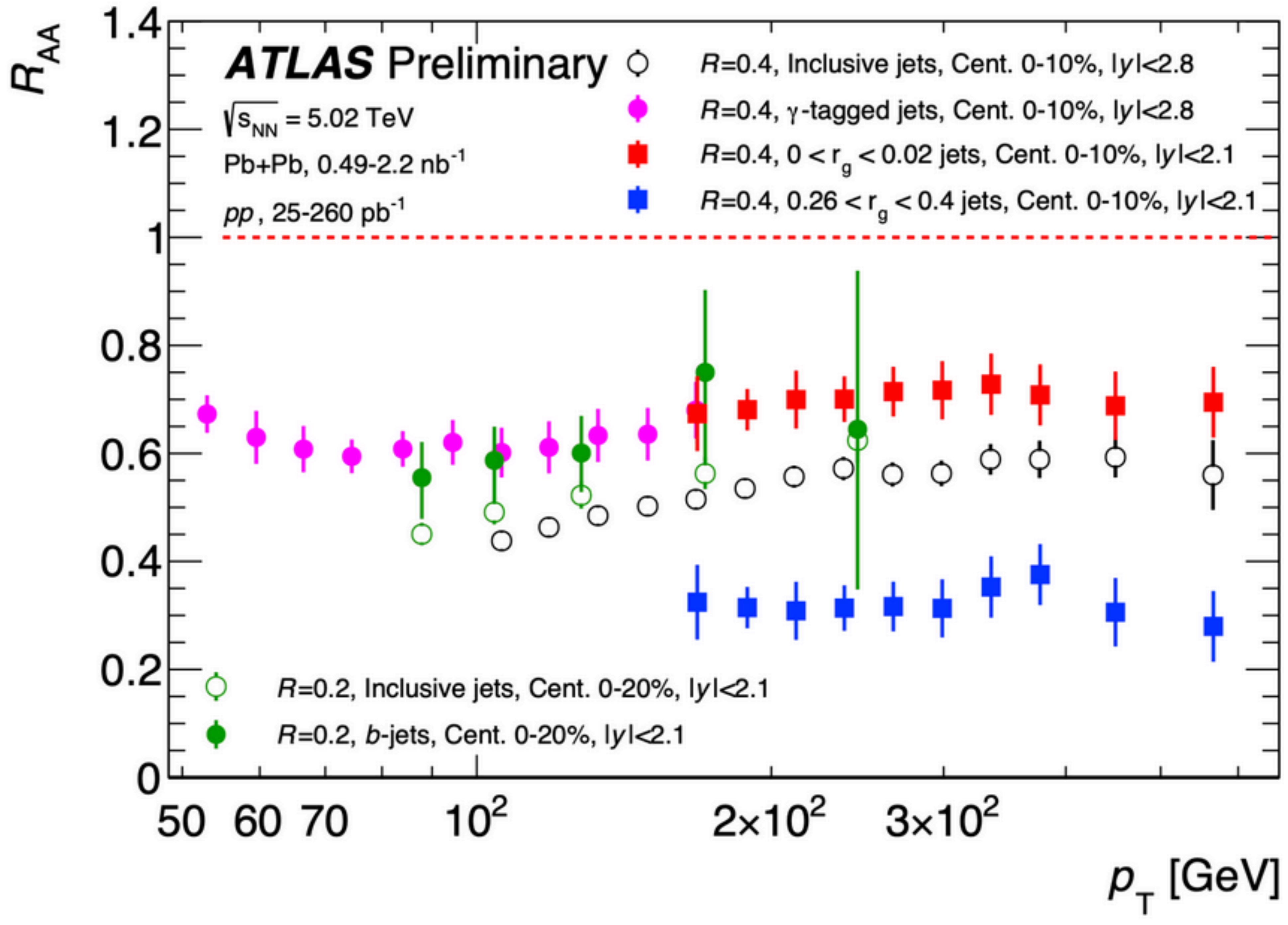
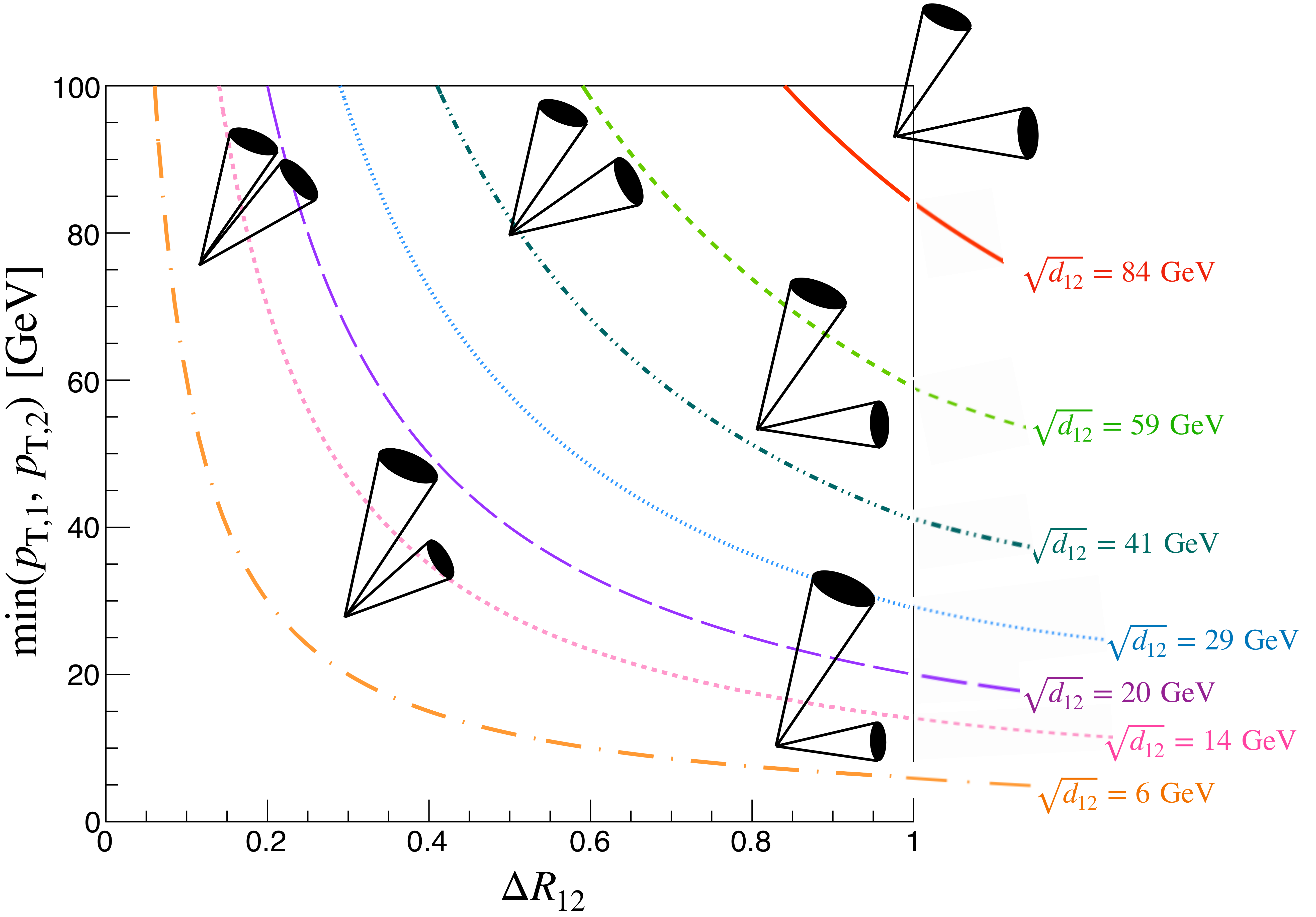
Backup



ATLAS Preliminary
$\sqrt{s_{NN}}$ = 5.02 TeV
Pb+Pb, 0.49-2.2 nb^{-1}
pp, 25-260 pb^{-1}
R=0.4, Inclusive jets, Cent. 0-10%, |y|<2.8
R=0.4, γ-tagged jets, Cent. 0-10%, |y|<2.8
R=0.4, 0 < r_g < 0.02 jets, Cent. 0-10%, |y|<2.1
R=0.4, 0.26 < r_g < 0.4 jets, Cent. 0-10%, |y|<2.1
R=0.2, Inclusive jets, Cent. 0-20%, |y|<2.1
R=0.2, b-jets, Cent. 0-20%, |y|<2.1
R_{AA}
p_T [GeV]

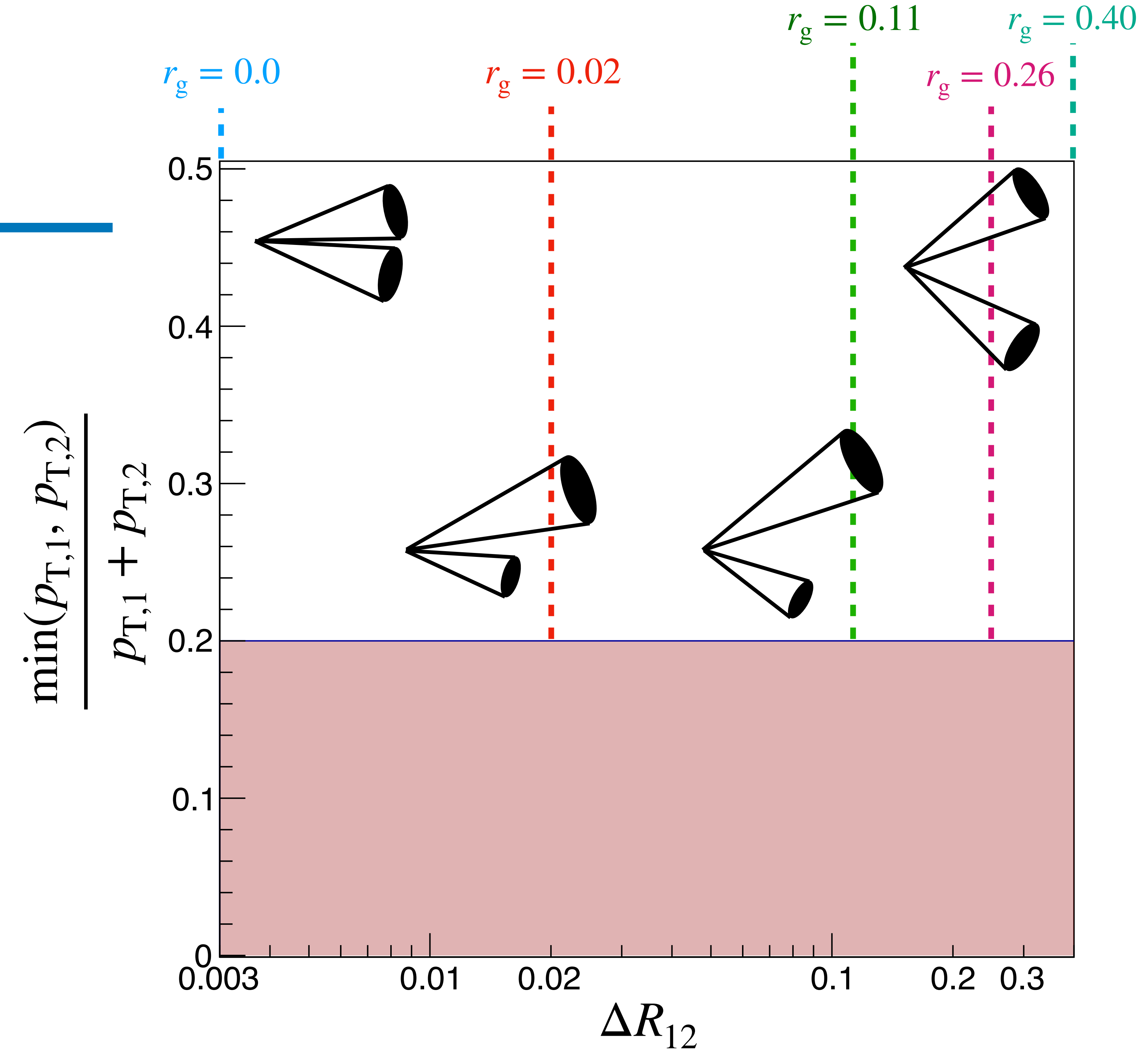


$\min(p_{T,1}, p_{T,2})$ [GeV]
ΔR_{12}
$\sqrt{d_{12}}$ = 84 GeV
$\sqrt{d_{12}}$ = 59 GeV
$\sqrt{d_{12}}$ = 41 GeV
$\sqrt{d_{12}}$ = 29 GeV
$\sqrt{d_{12}}$ = 20 GeV
$\sqrt{d_{12}}$ = 14 GeV
$\sqrt{d_{12}}$ = 6 GeV

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

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



Increasing jet p_T

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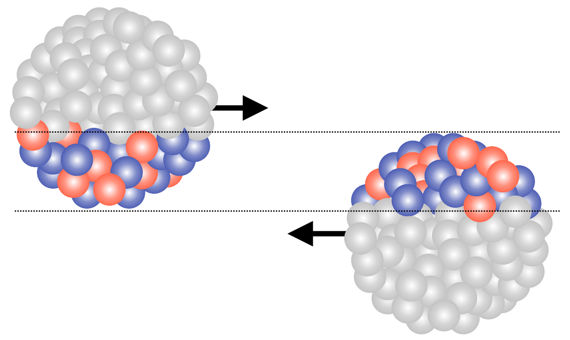
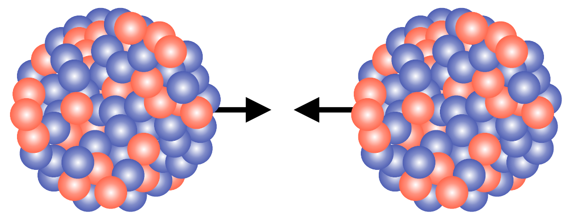
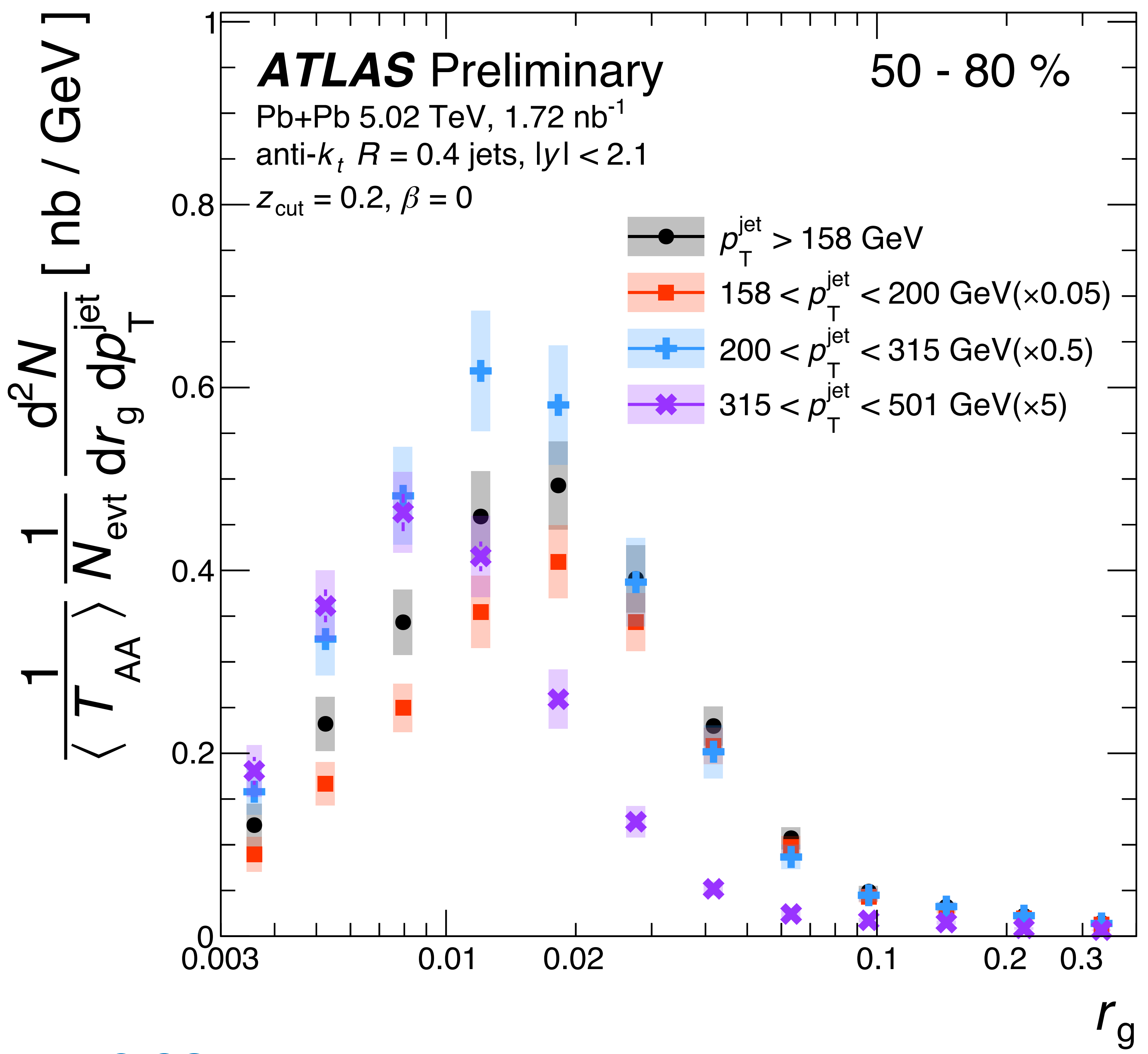
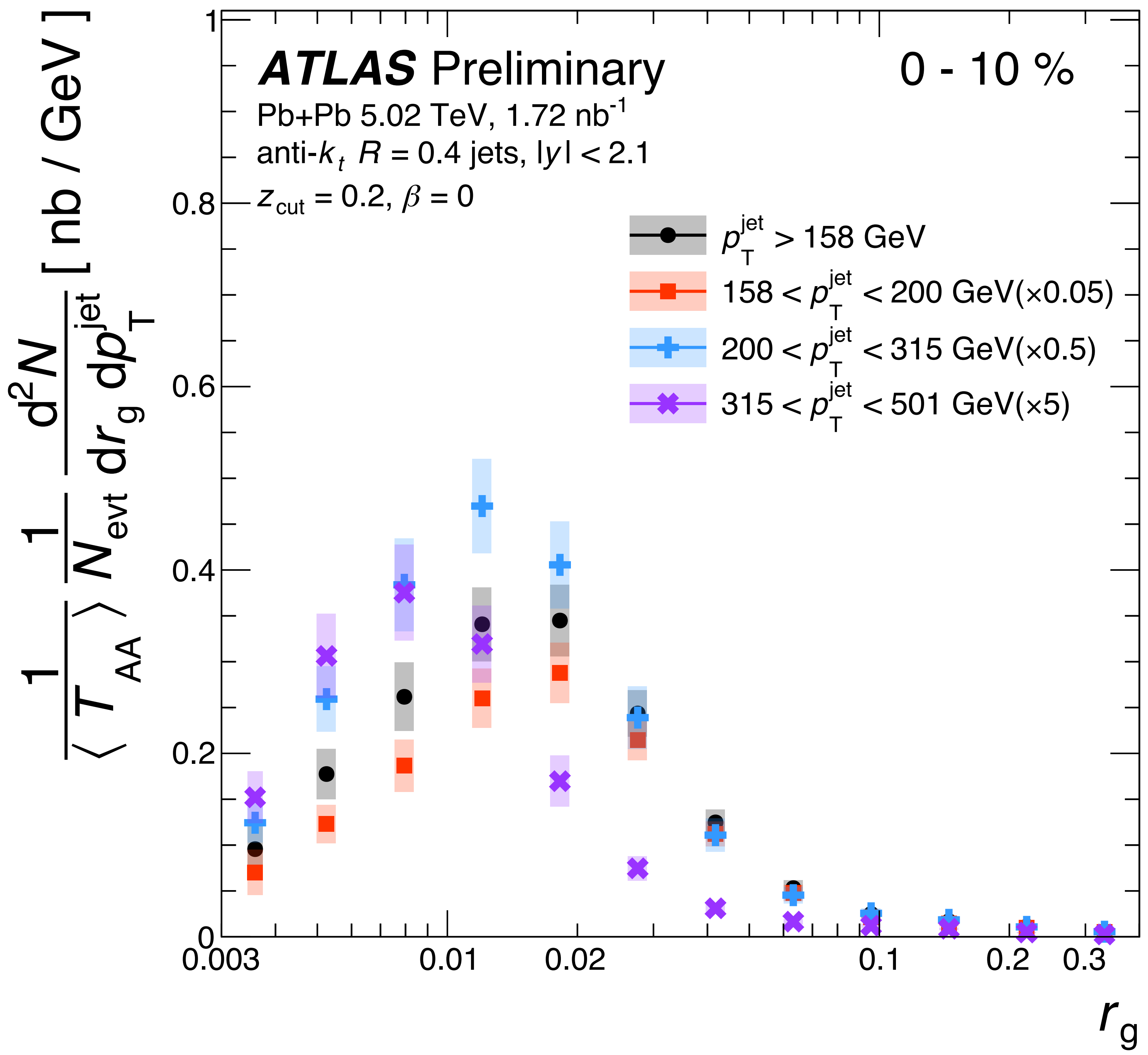
Unfolded jet r_g distributions

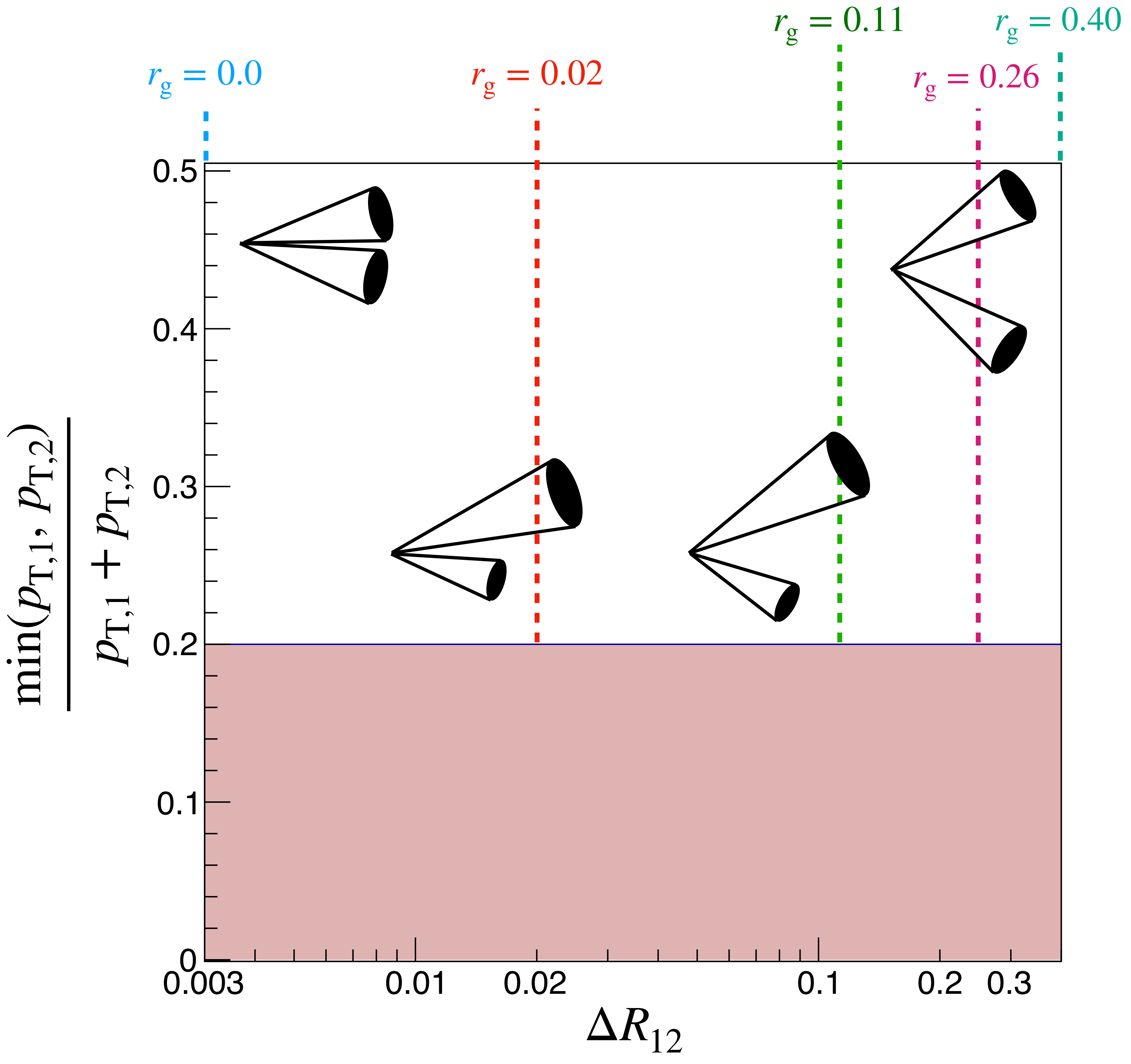
- Measurements of jet r_g unfolded to the truth hadron level for PbPb collisions
- Results shown differentially in event centrality and jet p_T intervals











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

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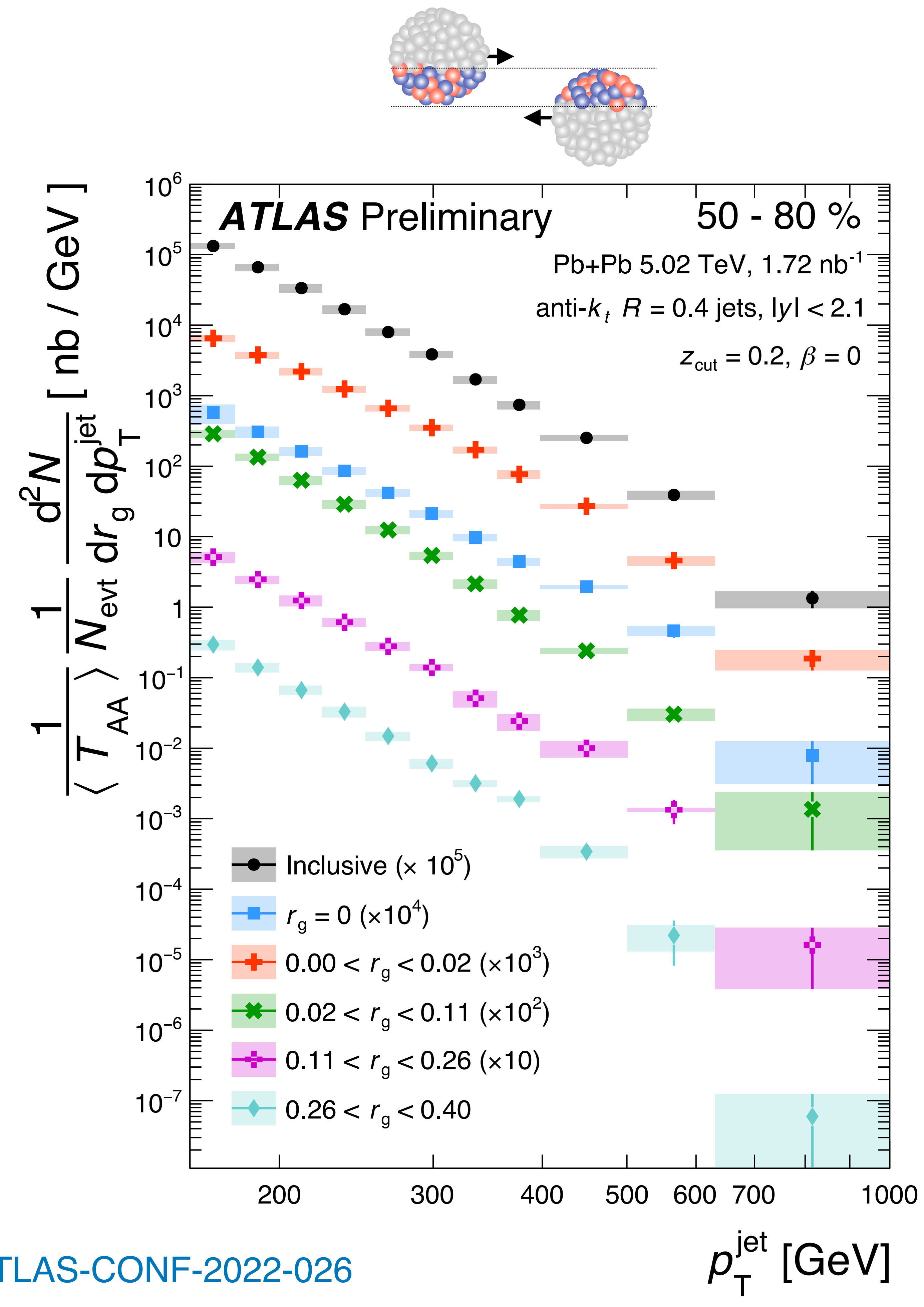
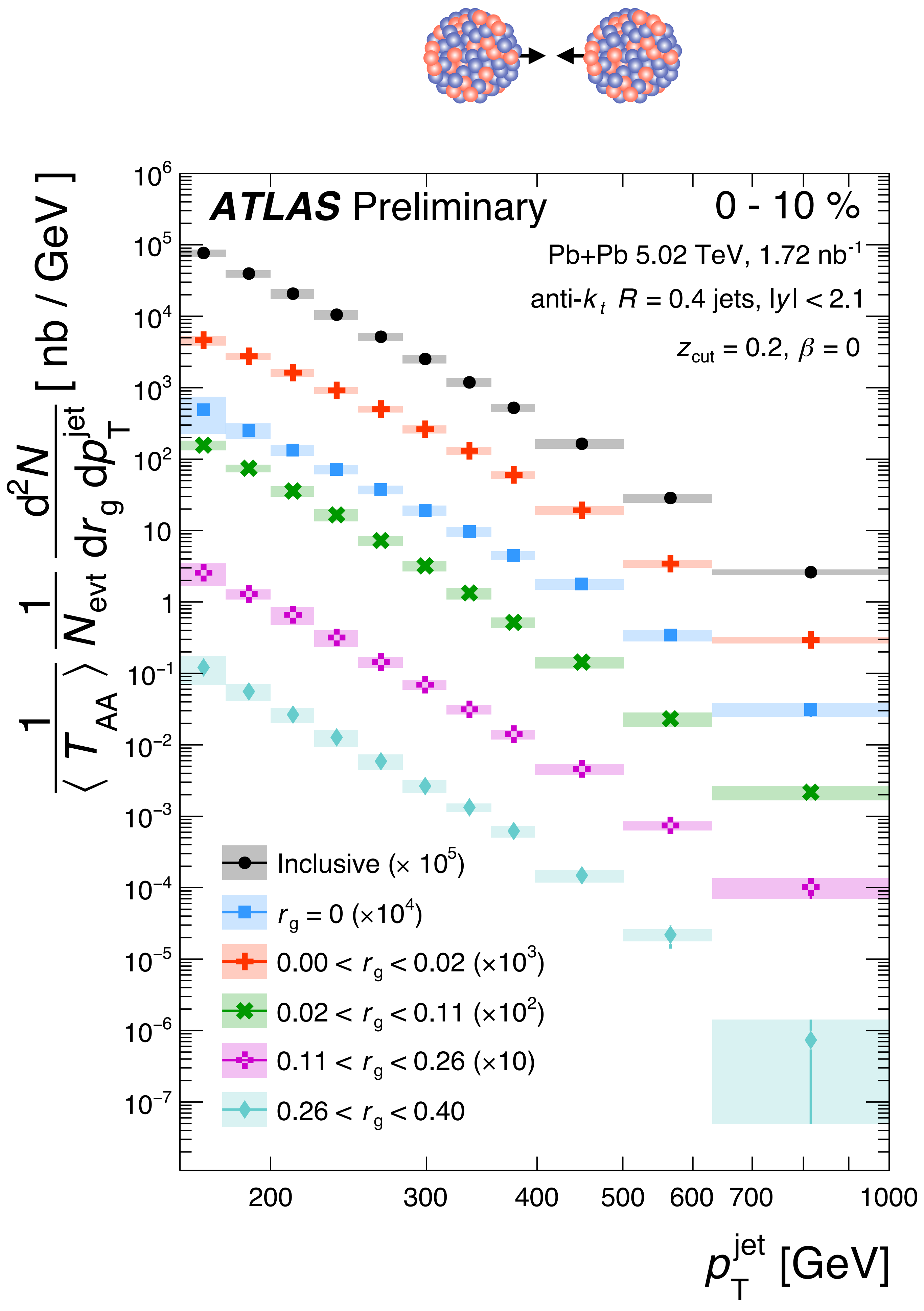
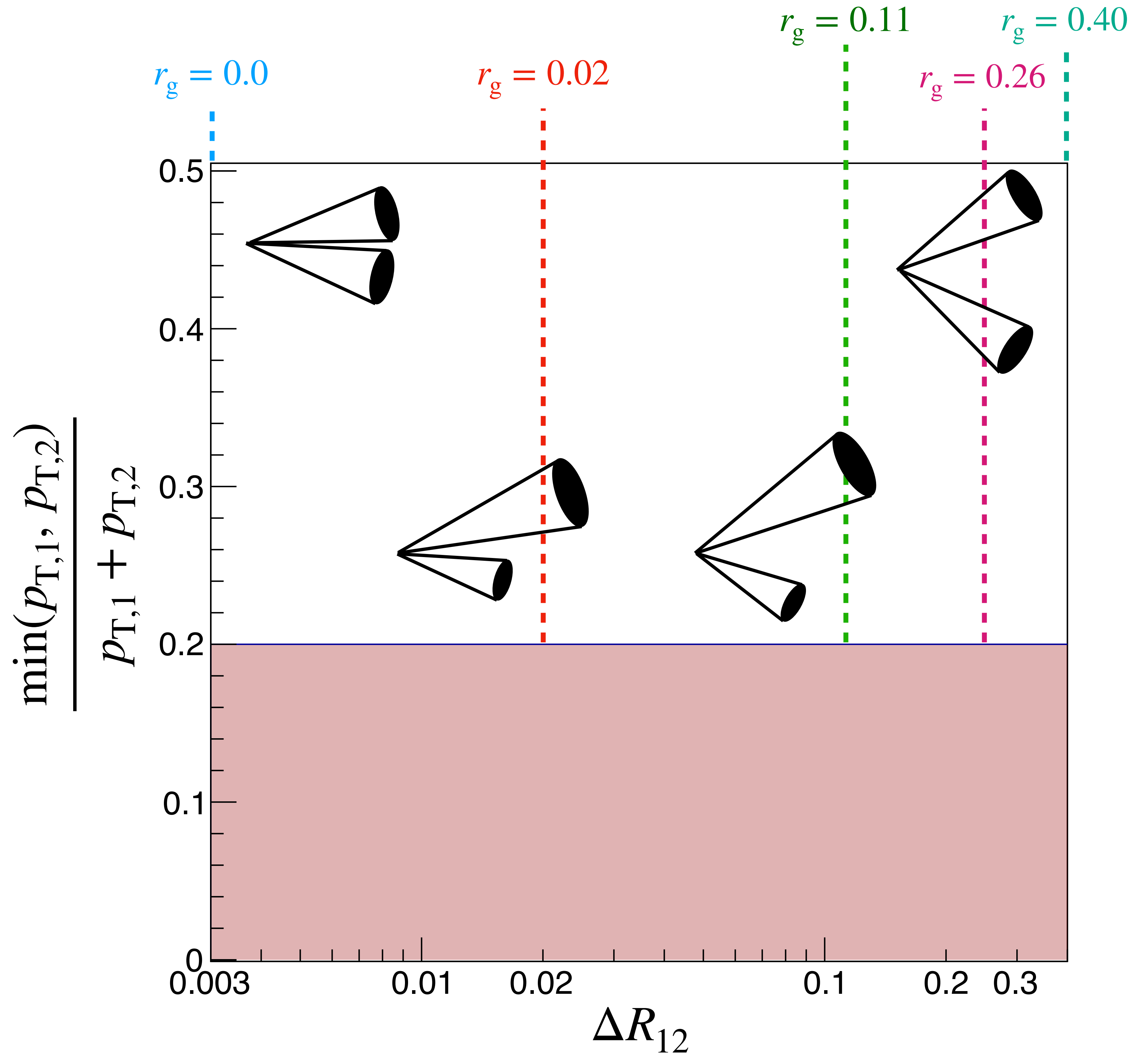
Unfolded jet p_T distributions

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







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

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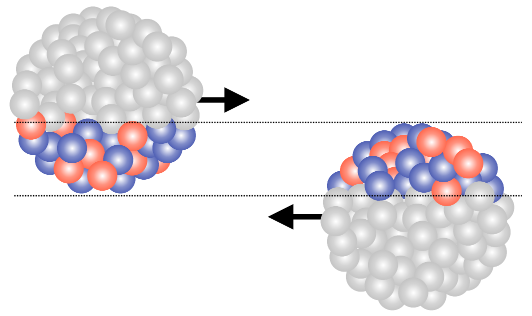
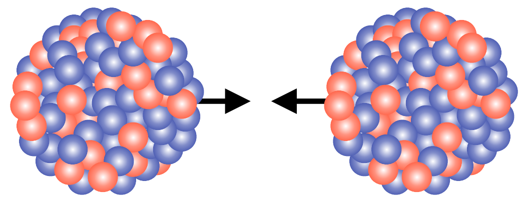
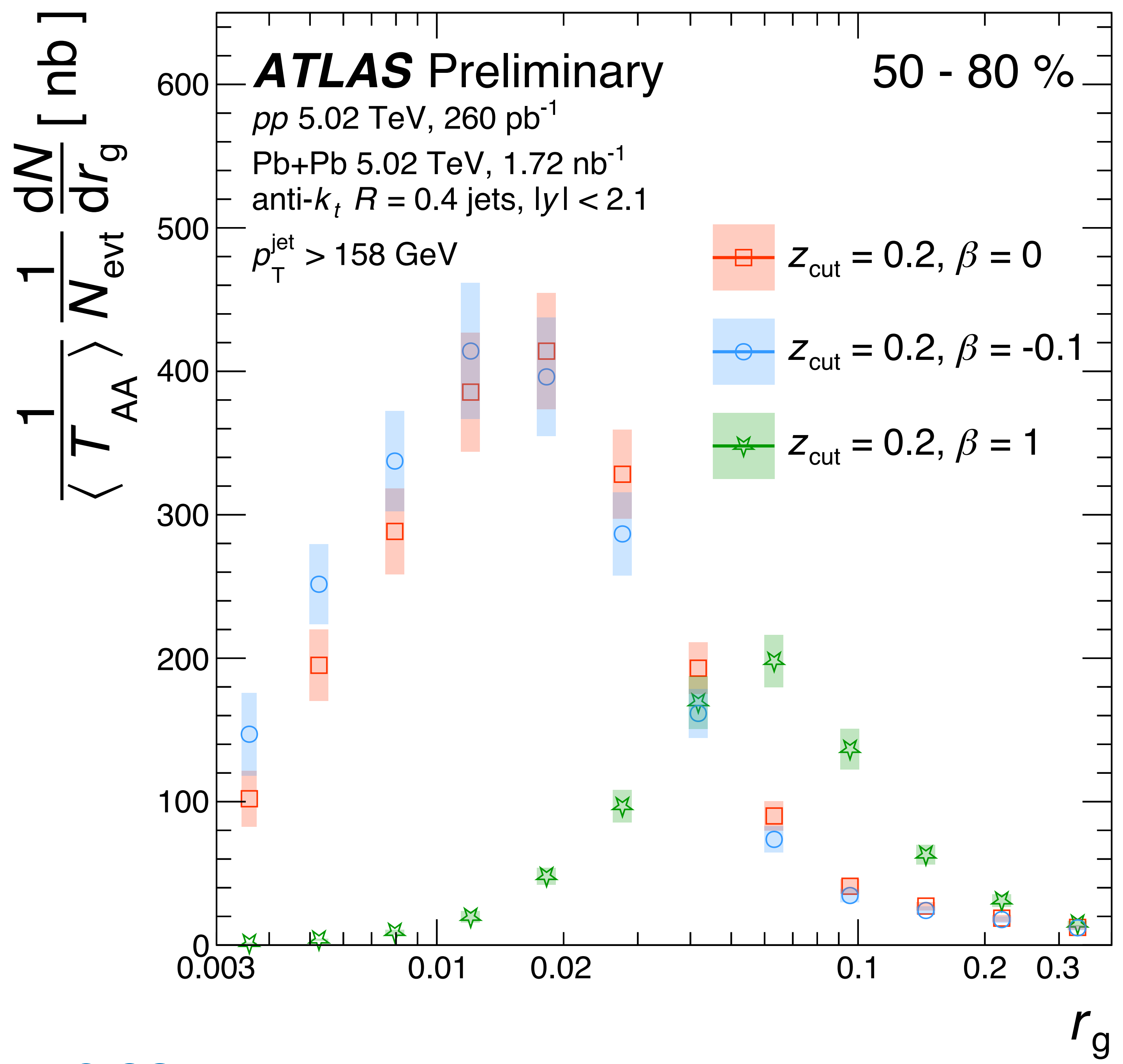
Soft Drop Parameters

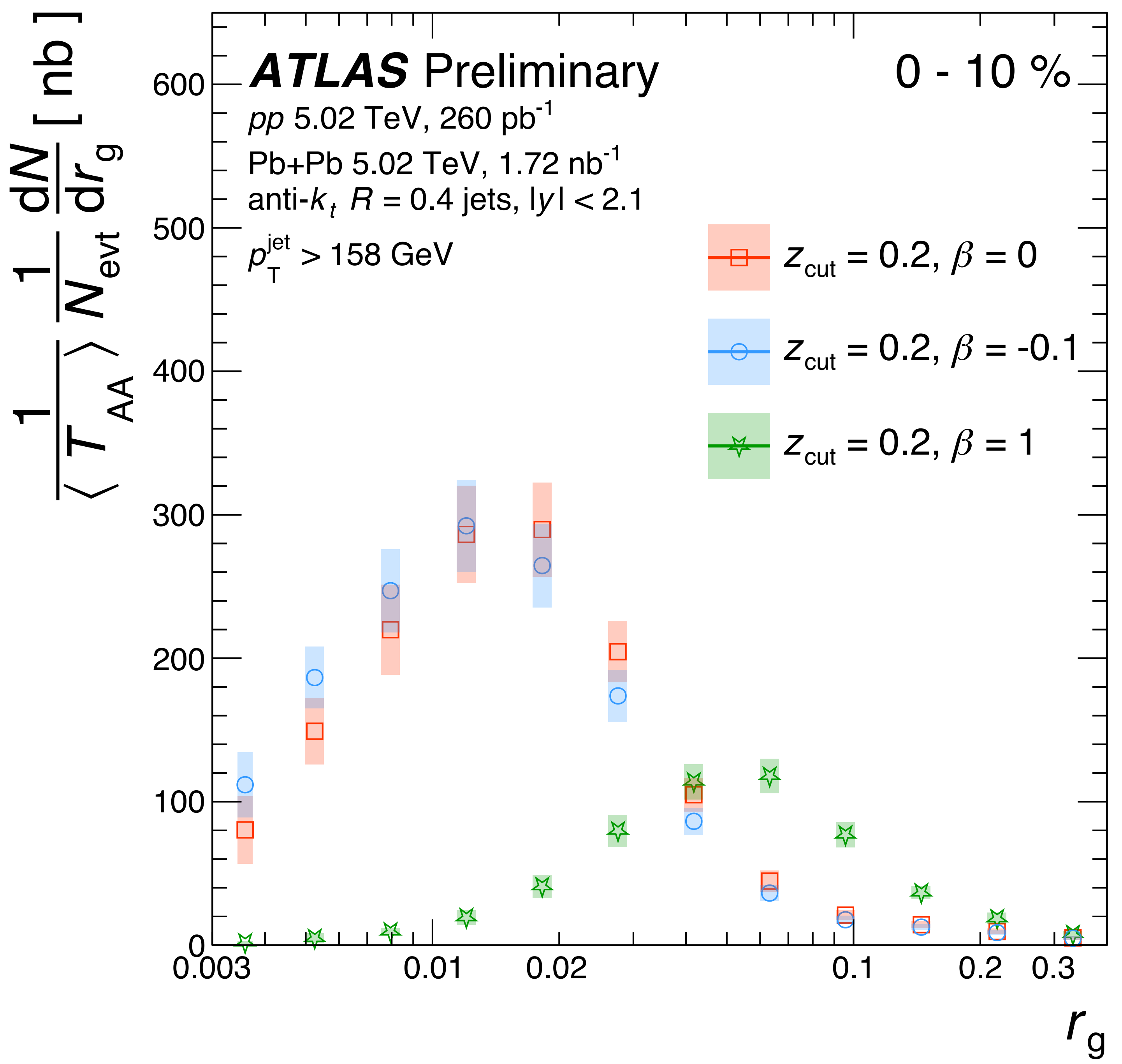
- What is the effect of including angle-dependent grooming in Soft-Drop on measuring the hardest splitting angle of a jet?
- How do we reconcile the measurement of r_g using varying Soft-Drop parameters with the observed modifications of the jet's fragmentation function in the QGP?

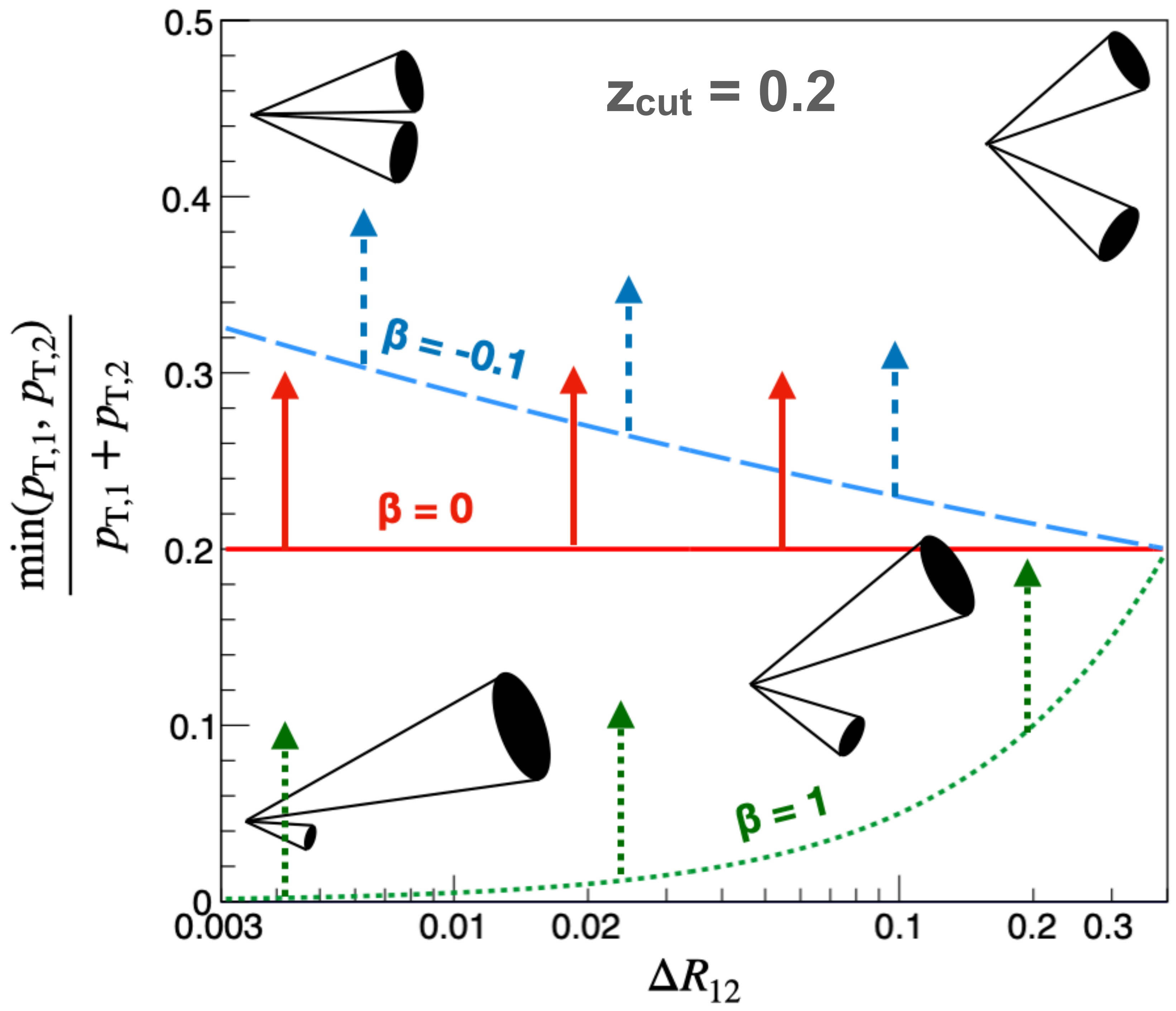




$$\frac{\min(p_{T,1},\, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{12}}{R(=0.4)} \right)^{\beta}$$







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