Inclusive jet measurements and jet substructure measurements with ALICE

James Mulligan for the ALICE Collaboration

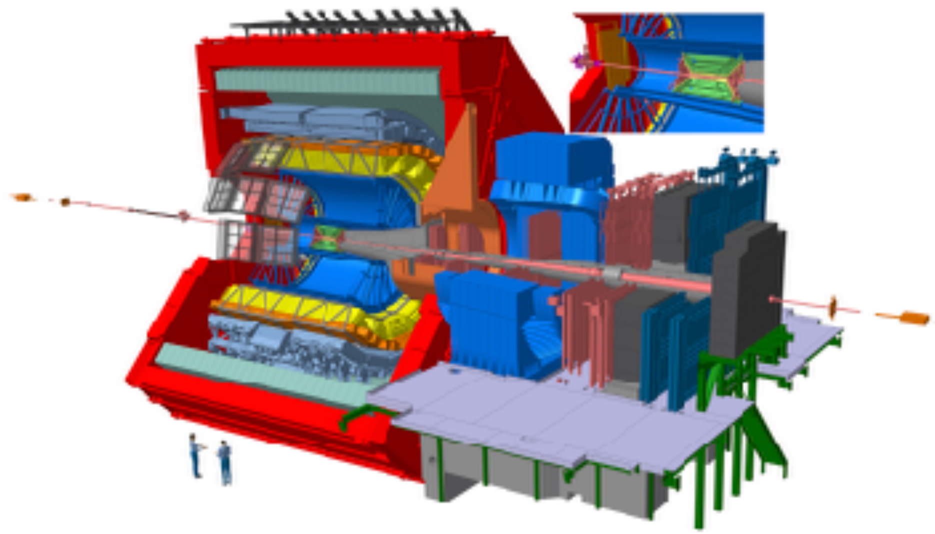
Workshop on Probing Quark-Gluon Matter with Jets, BNL
July 23, 2018

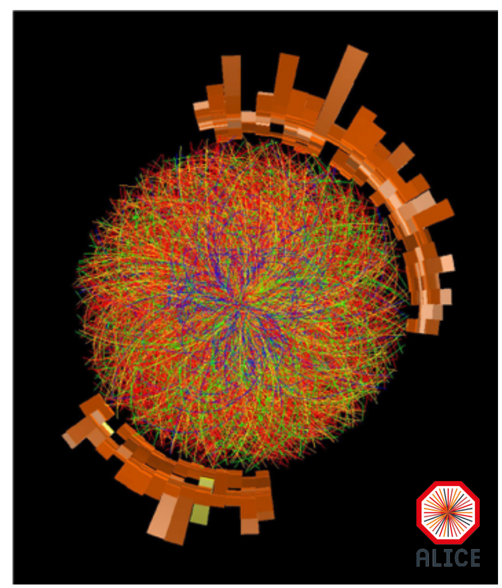
Jet reconstruction in ALICE

- ALICE reconstructs jets at mid-rapidity ($\eta < 0.7$) in pp, p-Pb, Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76 - 13$ TeV

- Charged particle jets (*charged jets*)
  - High-precision tracking down to $p_{\mathrm{T,track}} = 150$ MeV/c

- Jets (*full jets*)
  - Addition of particle information from the EM calorimeter down to $p_{\mathrm{T,cluster}} = 300$ MeV/c

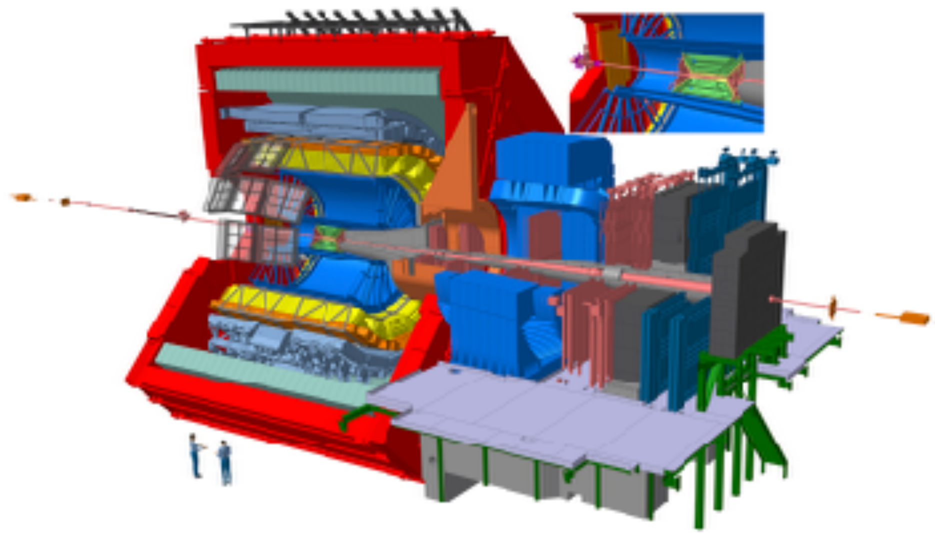




Jet reconstruction in ALICE

- ALICE's low-momentum constituent thresholds allow to measure:
  - Jets down to $p_{\mathrm{T}} \approx 40 - 100$ GeV/c
  - Modification to the soft components of jets
  - Medium recoil particles

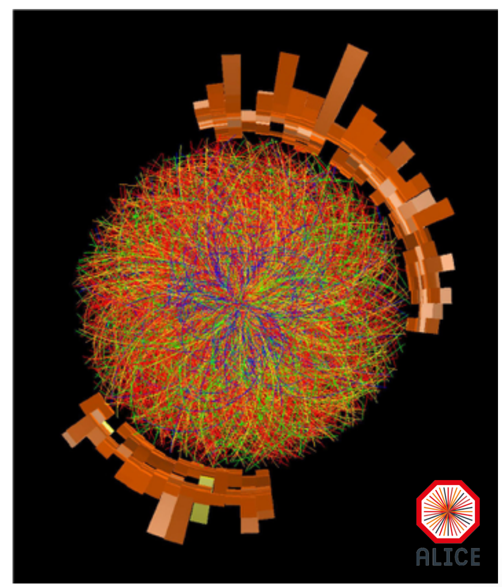
—> **Inclusive jet measurements**



- ALICE's tracking capabilities allow fine spatial resolution of single particles in jets

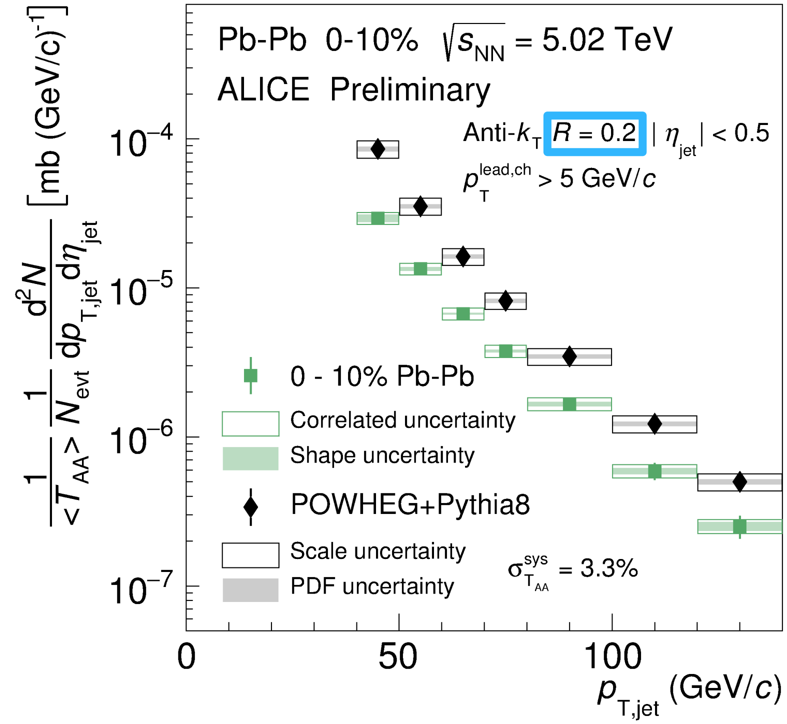
—> **Jet substructure measurements**

1. Constituent-based jet shapes
2. Groomed jet substructure

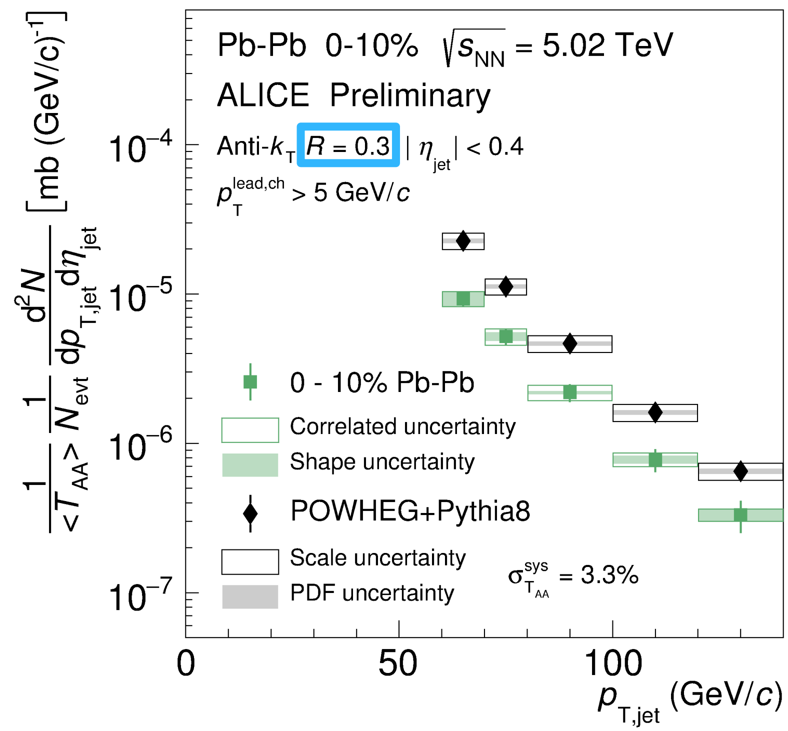


Inclusive jet spectra

- ALICE preliminary **full jet** measurement in **Pb-Pb** collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
  - 0-10% centrality
  - Jet p_{T} range: 40-140 GeV/c
  - Jet R: 0.2, 0.3
- The first Pb-Pb full jet measurement at **low transverse jet momentum** at this collision energy
- Reconstructed jets are required to have a p_{T} > 5 GeV/c leading charged particle
- The Pb-Pb spectra are unfolded for detector effects and background fluctuations by embedding Pythia8 events into Pb-Pb data



ALI-PREL-147150

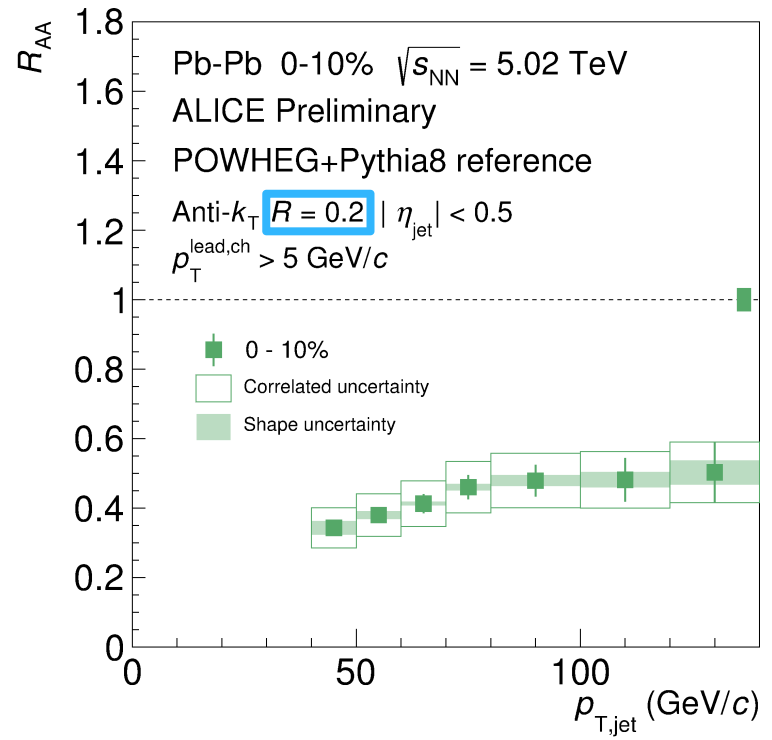


ALI-PREL-147154

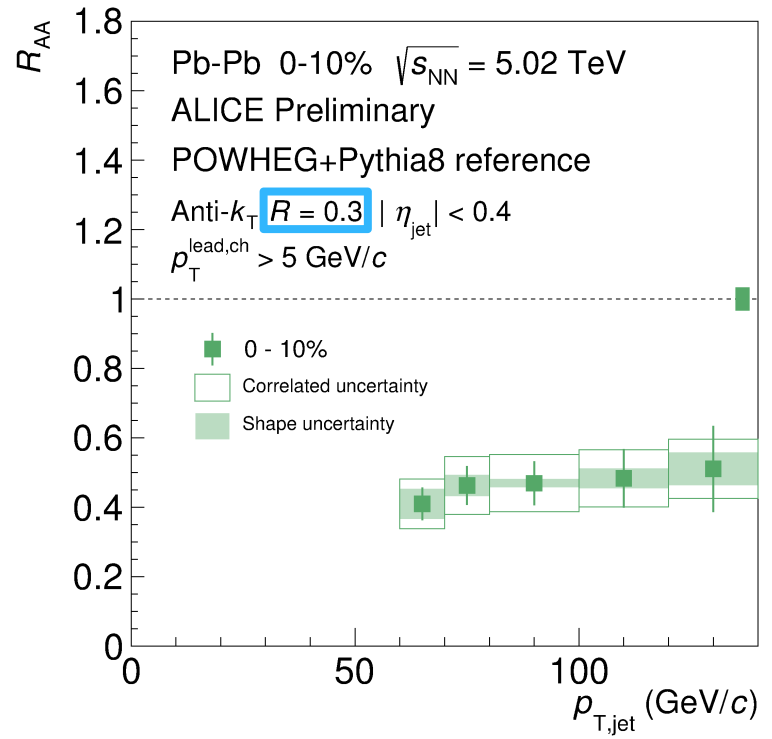
Jet R_{AA}

$$R_{AA} = \frac{\frac{1}{\langle T_{AA}\rangle}\frac{1}{N_{event}}\frac{d^2N}{dp_T\,d\eta}\Big|_{AA}}{\frac{d^2\sigma}{dp_T\,d\eta}\Big|_{pp}}$$

- Jet R_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV measured, using Pythia8 + POWHEG pp reference
- Similar suppression observed in R = 0.2 and R = 0.3; stronger suppression at low p_T



ALI-PREL-147158

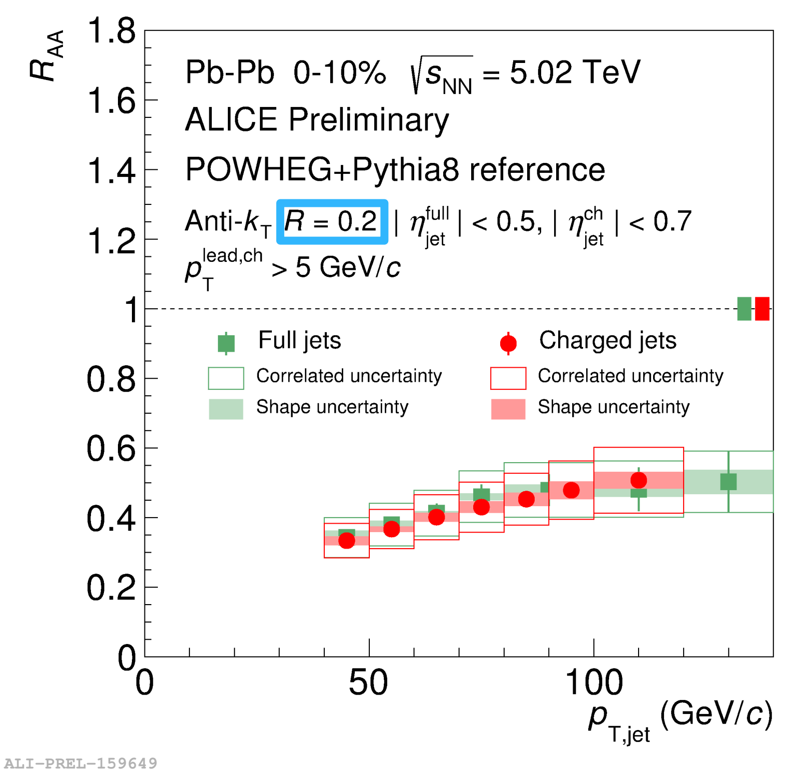


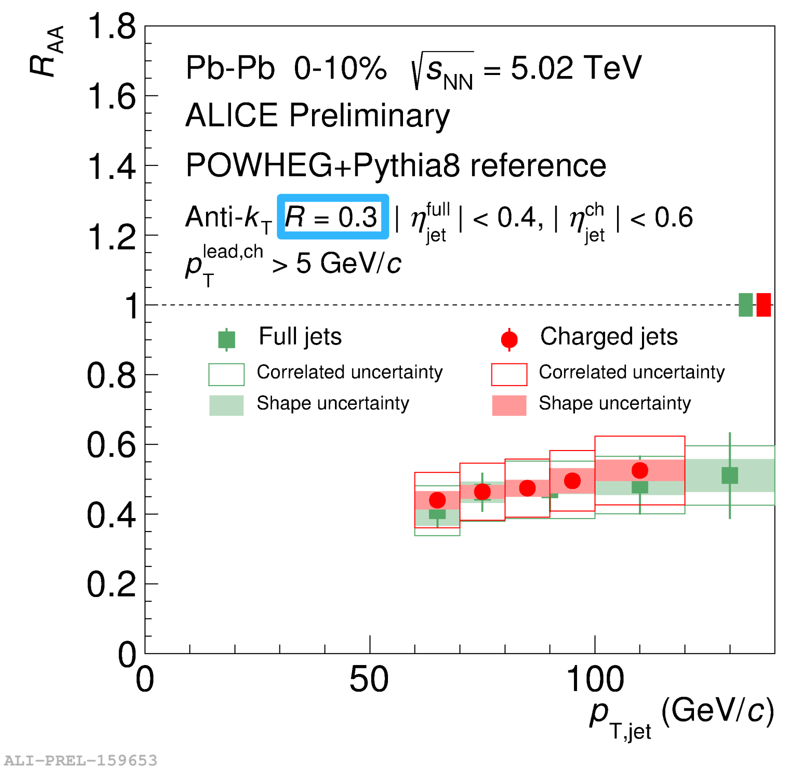
ALI-PREL-147162

Jet R_{AA}

$$R_{AA} = \frac{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{event}} \frac{d^2 N}{dp_T d\eta}\Big|_{AA}}{\frac{d^2\sigma}{dp_T d\eta}\Big|_{pp}}$$

- Jet R_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV measured, using Pythia8 + POWHEG pp reference
- Similar suppression observed in $R = 0.2$ and $R = 0.3$; stronger suppression at low p_T
- Charged particle jets and full jets are consistent

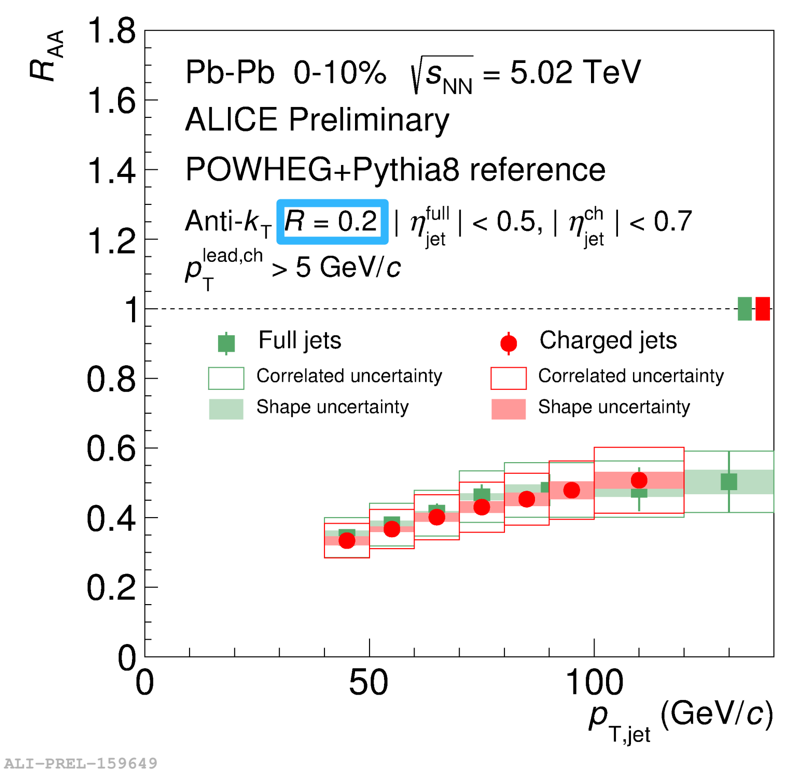


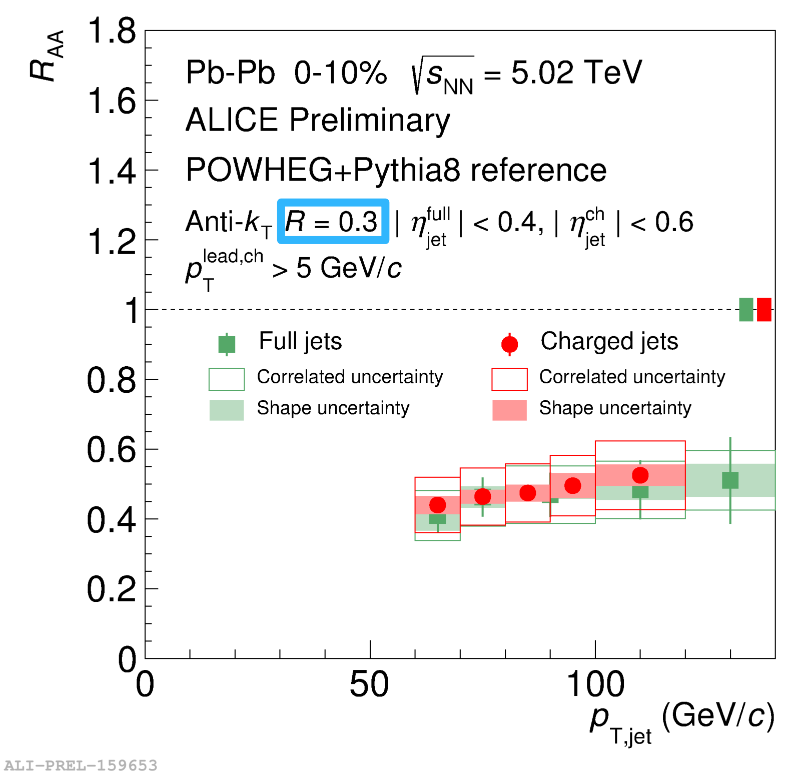


Jet R_{AA}

$$R_{AA} = \frac{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{event}} \frac{d^2 N}{d p_T d\eta}\Big|_{AA}}{\frac{d^2 \sigma}{d p_T d\eta}\Big|_{pp}}$$

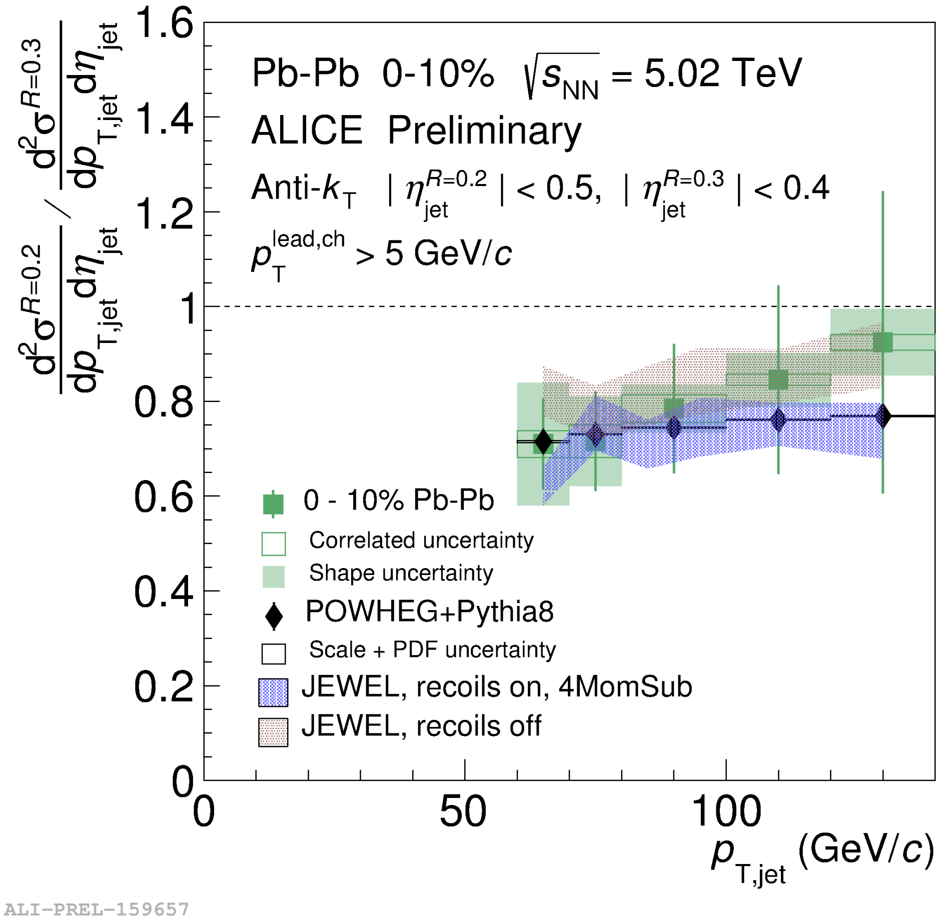
- Jet R_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV measured, using Pythia8 + POWHEG pp reference
- Similar suppression observed in $R = 0.2$ and $R = 0.3$; stronger suppression at low p_T
- pp reference measurement ongoing





Inclusive ratio: $R = 0.2$ / $R = 0.3$

- The ratio of jet cross-sections at different R is an inclusive **jet shape observable**, sensitive to the R-dependence of jet energy loss
- With the current precision, the Pb-Pb jet cross-section ratio $R = 0.2$ / $R = 0.3$ is consistent with POWHEG+Pythia8
- Extension to $R = 0.4$, lower p_T, and reduction of uncertainties in progress



Jet shapes

Final result!
arXiv 1807.06854

- Observables:
  - Radial moment, ***g***
  - Momentum dispersion, $\boldsymbol{p_T D}$

- The measurement:
  - Charged particle jets in pp ($\sqrt{s_{NN}} = 7$ TeV) and Pb-Pb ($\sqrt{s_{NN}} = 2.76$ TeV)
    - $p_{T,jet} = 40 - 60$ GeV/c
    - $R = 0.2$
  - Fully unfolded

Jet shapes

Final result!
arXiv 1807.06854

- Observables:
  - Radial moment, ***g***
  - Momentum dispersion, ***p***$\boldsymbol{p_{\mathrm{T}}}$**D**

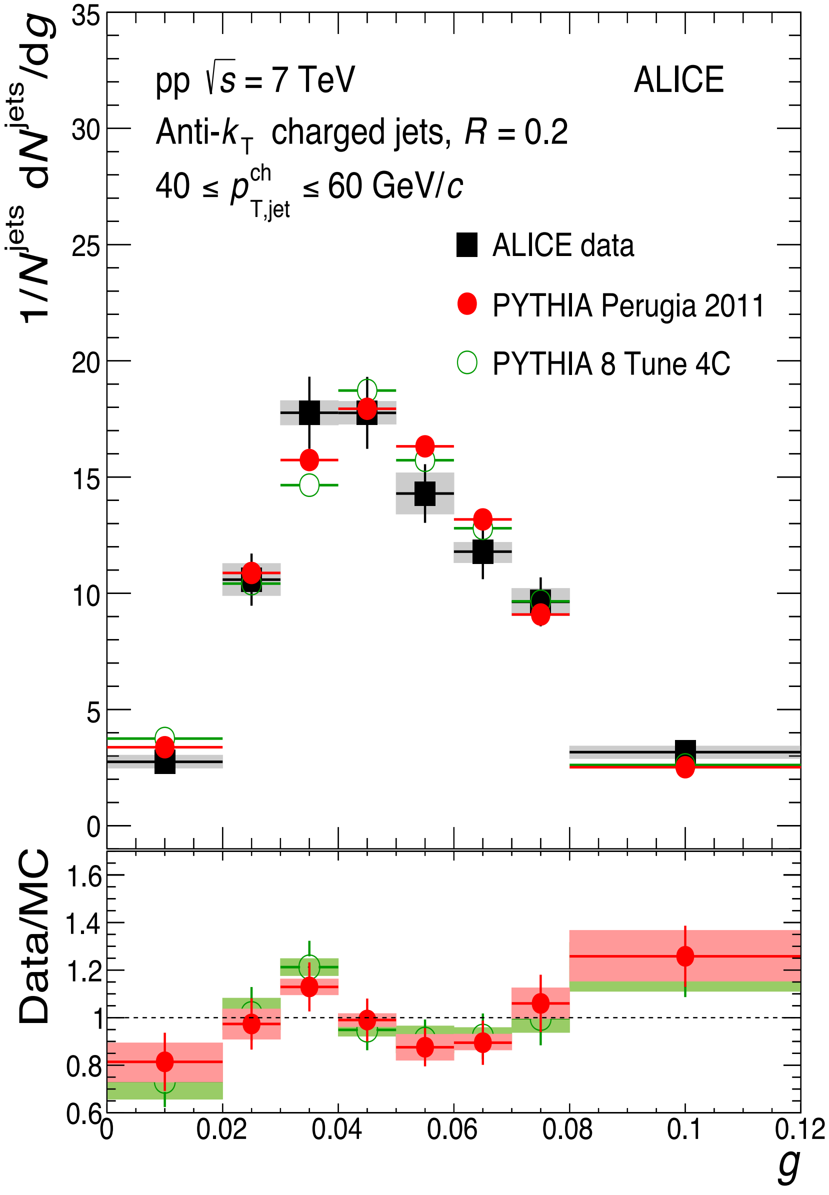
- The measurement:
  - Charged particle jets in pp ($\sqrt{s_{\mathrm{NN}}} = 7$ TeV) and Pb-Pb ($\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV)
    - $p_{\mathrm{T,jet}} = 40 - 60$ GeV/c
    - $R = 0.2$ → Small-radius jets: Useful to suppress effects that dominate at large-angle, such as medium recoil
  - Fully unfolded

Radial moment

Final result!
arXiv 1807.06854

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

- Measures a jet's radial momentum profile
- **pp** data agrees with Pythia within ≈ 20% at $\sqrt{s_{\text{NN}}} = 7$ TeV

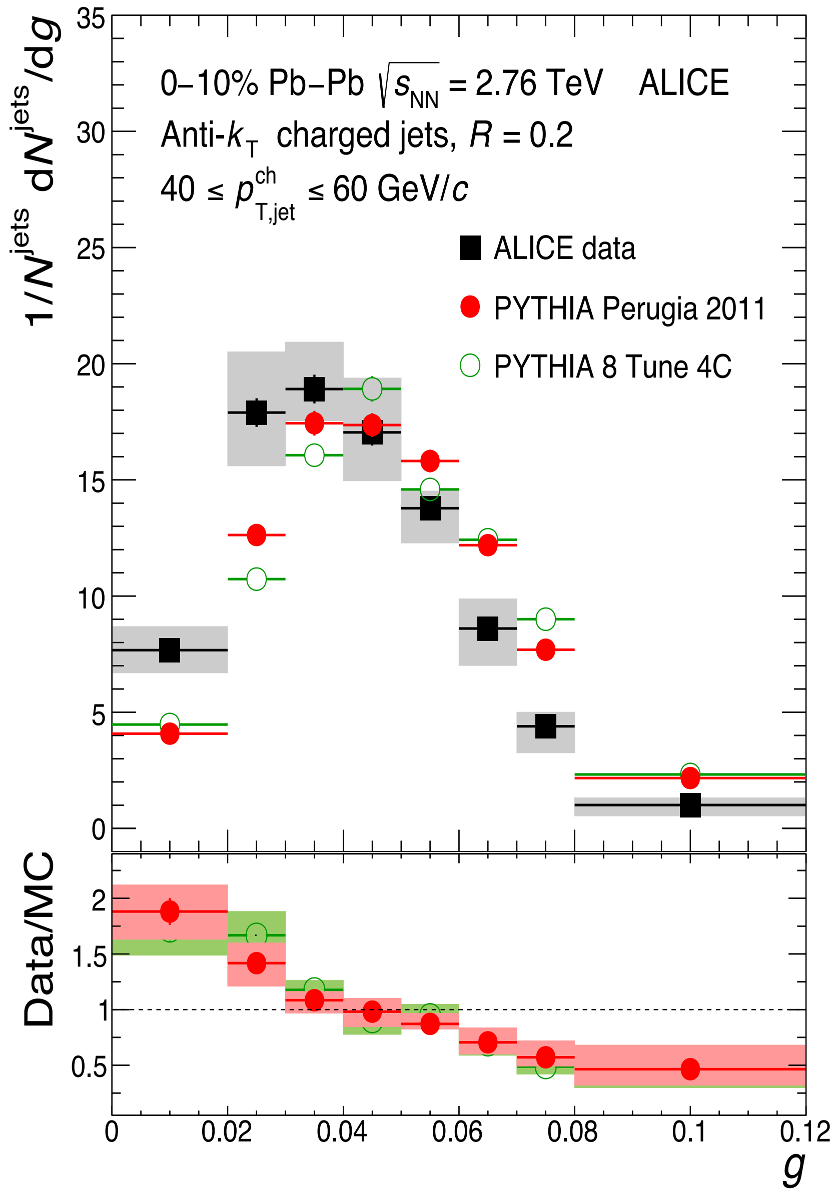


Radial moment

Final result!
arXiv 1807.06854

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

- Measures a jet's radial momentum profile
- pp data agrees with Pythia within ≈ 20% at $\sqrt{s_{\text{NN}}} = 7$ TeV
- In **Pb-Pb**, radial moment shifted to lower values
  - More collimated!

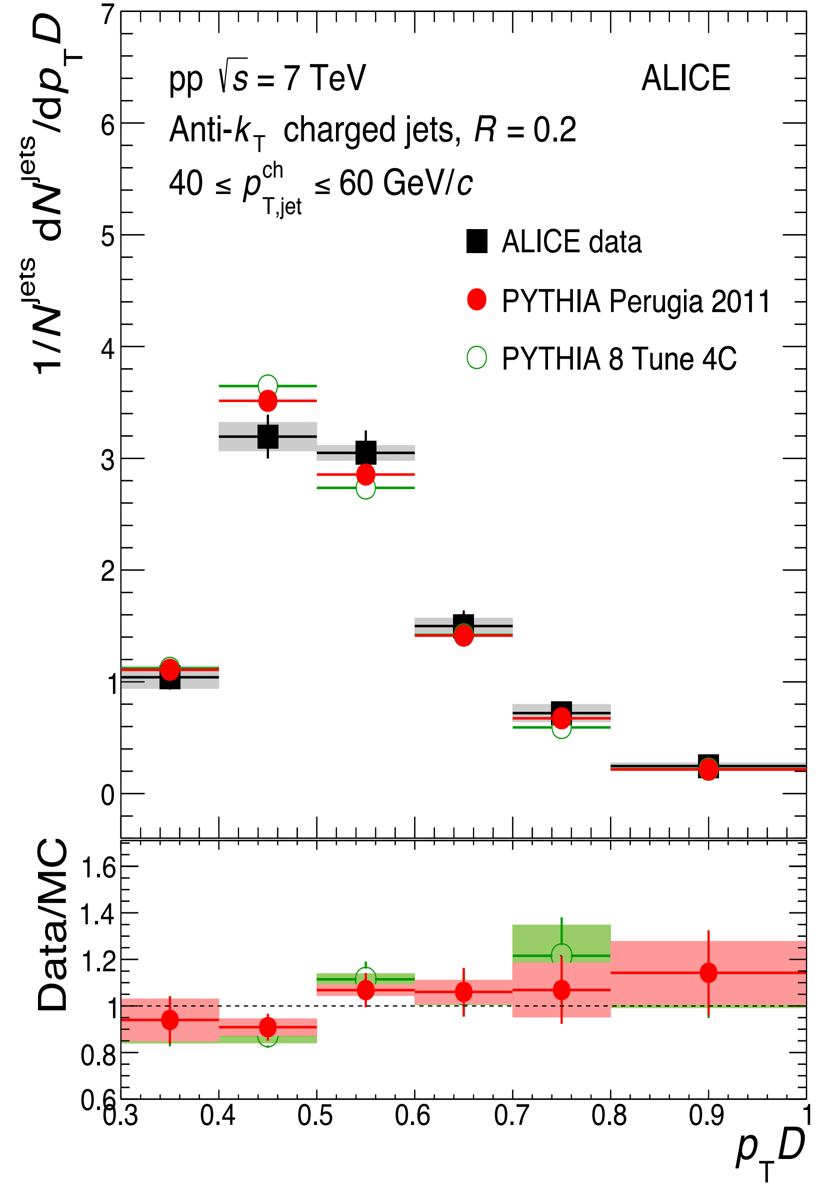


Momentum dispersion

Final result!
arXiv 1807.06854

$$p_{\mathrm{T}}D = \frac{\sqrt{\sum_{i\in\mathrm{jet}} p_{\mathrm{T},i}^2}}{\sum_{i\in\mathrm{jet}} p_{\mathrm{T},i}}$$

- Measures the dispersion of the constituent momentum inside a jet
  - $p_{\mathrm{T}}D \rightarrow 0$ for many constituents
  - $p_{\mathrm{T}}D \rightarrow 1$ for few constituents
- **pp** data agrees with Pythia within $\approx$ 20% at $\sqrt{s_{\mathrm{NN}}} = 7$ TeV

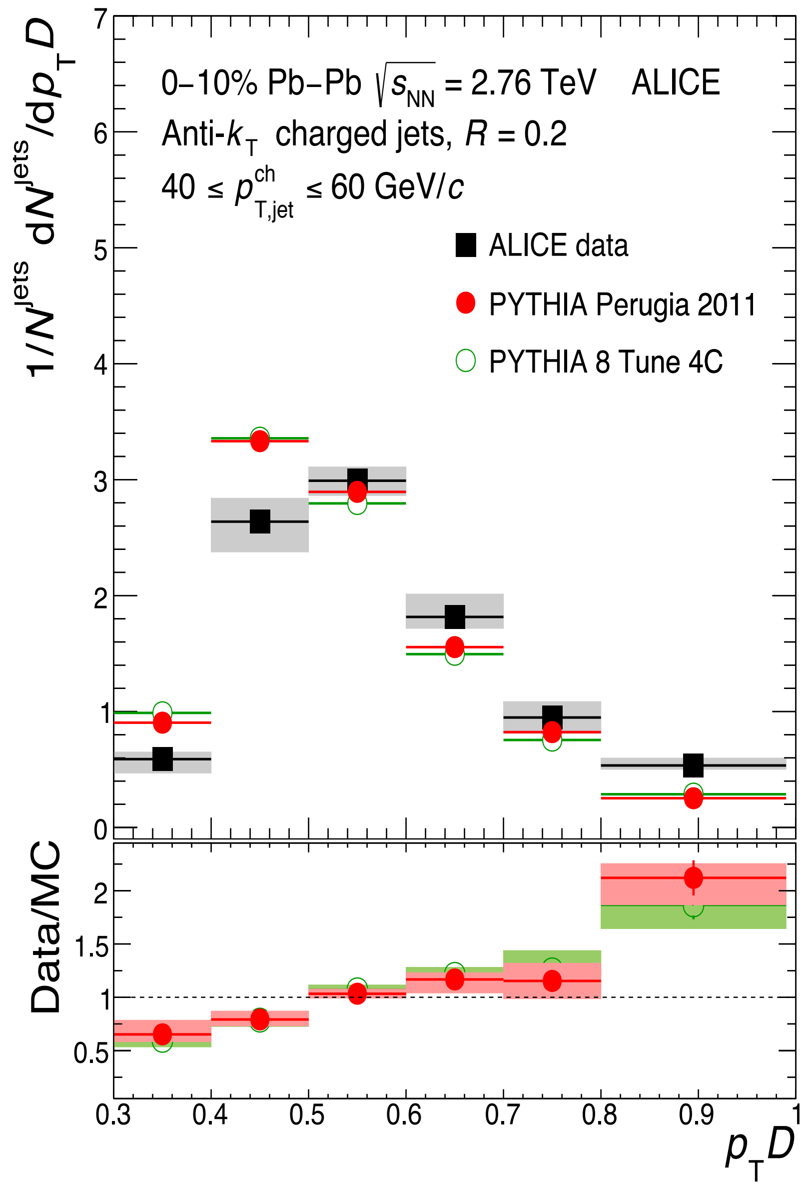


Momentum dispersion

Final result!
arXiv 1807.06854

$$p_{\mathrm{T}}D = \frac{\sqrt{\sum_{i\in\mathrm{jet}} p_{\mathrm{T},i}^2}}{\sum_{i\in\mathrm{jet}} p_{\mathrm{T},i}}$$

- Measures the dispersion of the constituent momentum inside a jet
  - $p_{\mathrm{T}}D \to 0$ for many constituents
  - $p_{\mathrm{T}}D \to 1$ for few constituents
- pp data agrees with Pythia within $\approx 20\%$ at $\sqrt{s_{\mathrm{NN}}} = 7$ TeV
- In **Pb-Pb**, $p_{\mathrm{T}}D$ is shifted to larger values
  - Harder fragmentation!



How is the jet core modified?

The modifications of g, $p_{\mathrm{T}}D$ in these R = 0.2 small-radius jets suggest that in Pb-Pb, **the jet core becomes more collimated and harder-fragmenting**

This is qualitatively consistent with the jet fragmentation function enhancement at large z

How much of the effect is due to:

Modification of the quark-gluon fraction?

(Quark jets are more collimated, harder fragmenting)

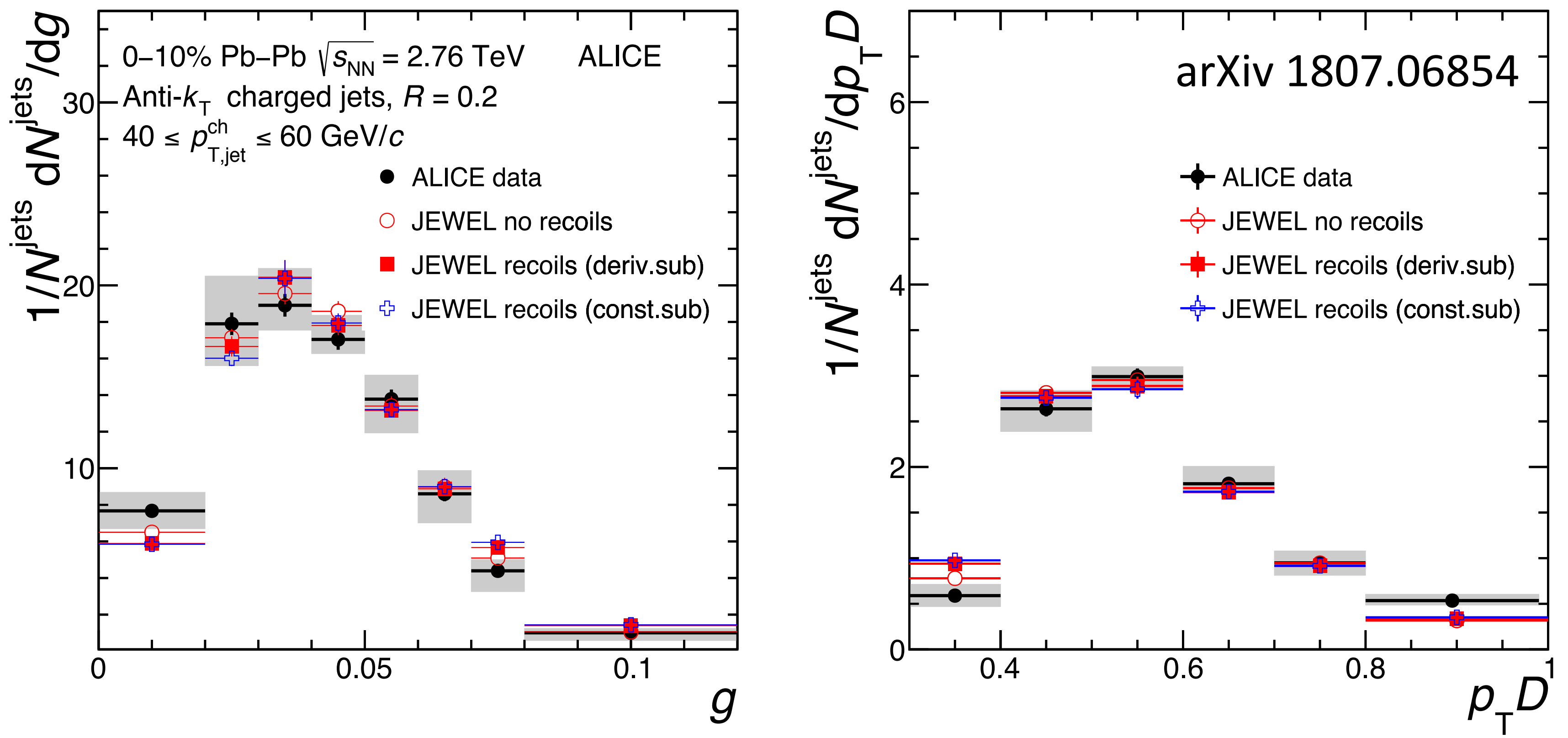
Shift of the jet p_{T} scale in Pb-Pb?

(In Pythia, as jet p_{T} increases, g decreases and $p_{\mathrm{T}}D$ decreases)

How is the jet core modified?

JEWEL agrees with the measured Pb-Pb distributions of g, $p_{\mathrm{T}}D$!

The impact of medium response is small



Groomed jet substructure

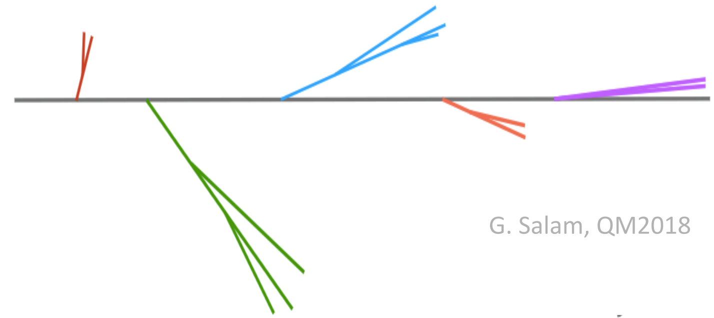
- Use the Soft Drop grooming algorithm to examine whether the hard splittings of jets are modified in Pb-Pb

M. Dasgupta et al. JHEP 1309 (2013) 029
A. Larkoski et al. JHEP 1405 (2014) 146

- The measurement:
  - Charged particle jets in pp (7 TeV) and Pb-Pb (2.76 TeV)
    - $p_{T,jet}$ = 40-60 GeV/c (pp), $p_{T,jet}$ = 80-120 GeV/c (Pb-Pb)
    - $R = 0.4$
  - pp: Fully unfolded
  - Pb-Pb: Detector-level, compared to embedded Pythia

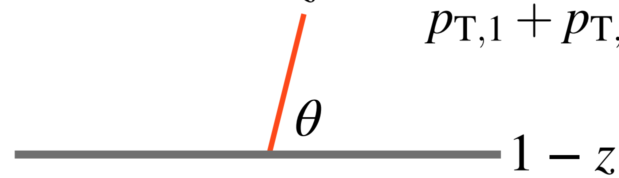
Groomed jet substructure

- Measurement procedure
  1. Cluster jets with the anti-k_T algorithm, then re-cluster each jet using the C/A algorithm
     - This produces an angularly ordered tree, similar to a parton shower
  2. Unwind the last clustering step and check the Soft Drop condition: $z > z_{\rm cut} \left(\frac{\Delta R}{R_0}\right)^{\beta}$
  3. Discard the softer sub-jet and repeat



G. Salam, QM2018

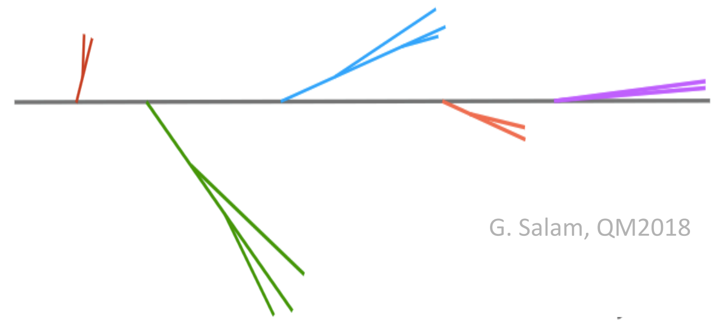
$$z = \frac{min(p_{\rm T,1}, p_{\rm T,2})}{p_{\rm T,1} + p_{\rm T,2}}$$



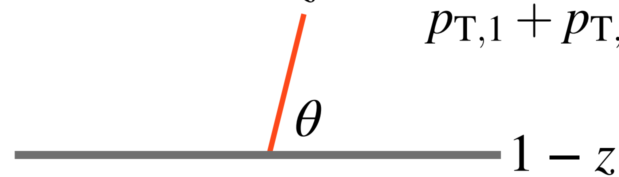
- The resulting hard splittings are described by:
  - $n_{\rm SD}$ is the number of splittings that pass the Soft Drop condition
  - $z_{\rm g}$, $R_{\rm g}$ describe the momentum fraction and angular separation of the **first** splitting

Groomed jet substructure

- Measurement procedure
  1. Cluster jets with the anti-k_T algorithm, then re-cluster each jet using the C/A algorithm
     - This produces an angularly ordered tree, similar to a parton shower
  2. Unwind the last clustering step and check the Soft Drop condition: $z > z_{\mathrm{cut}} \left(\frac{\Delta R}{R_0}\right)^{\beta}$
  3. Discard the softer sub-jet and repeat



$$z = \frac{min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}}$$

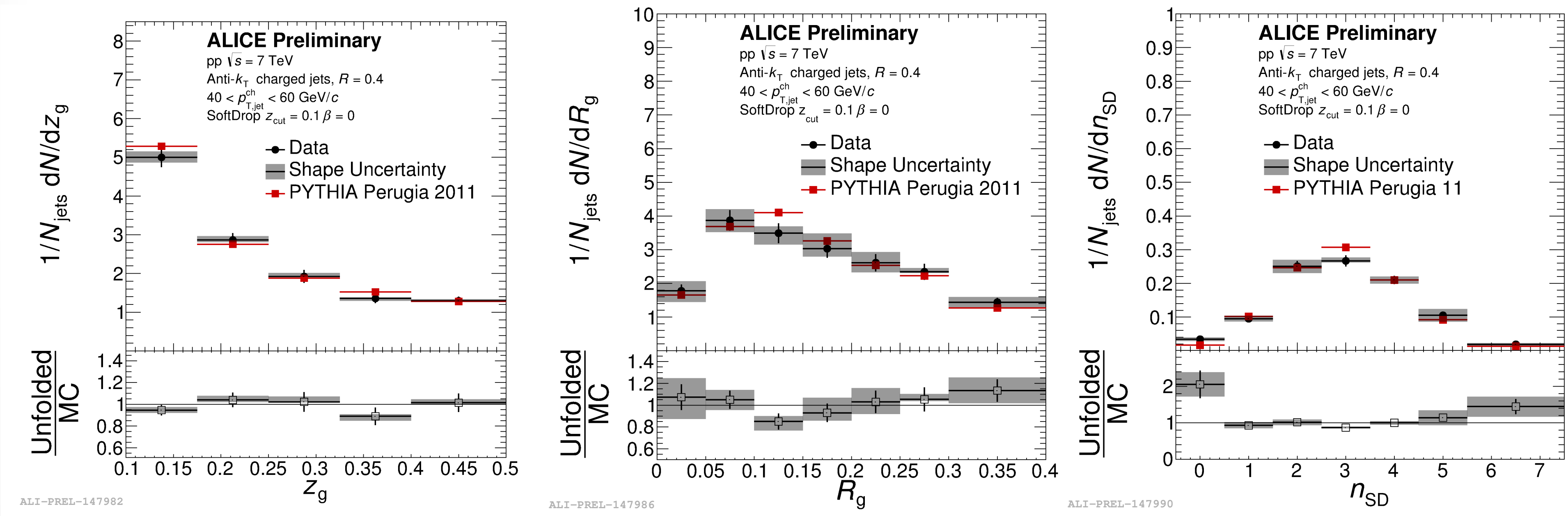


- The resulting hard splittings are described by:
  - n_{SD} is the number of splittings that pass the Soft Drop condition
  - z_{g}, R_{g} describe the momentum fraction and angular separation of the **first** splitting

We use $(z_{\mathrm{cut}}, \beta) = (0.1, 0)$

Groomed jet substructure – pp

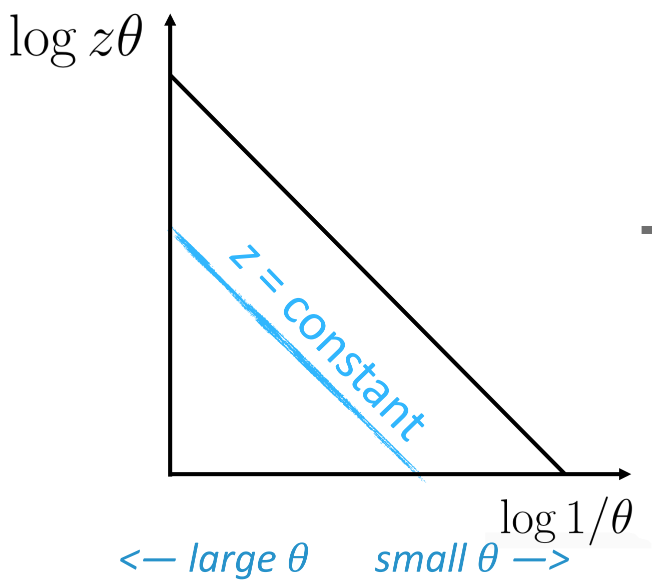
- pp measurement at $\sqrt{s_{\mathrm{NN}}} = 7\ \mathrm{TeV}$:
  - R = 0.4 jets, 40 < p_{T} < 60 GeV/c, $|\eta|$ < 0.5
  - Fully unfolded



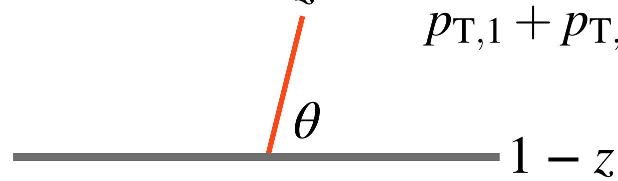
- z_{g}, R_{g}, n_{SD} are consistent with Pythia Perugia 2011

Groomed jet substructure

- Lund diagram:
  - Represents the phase-space density of 1—>2 splittings, described by (z,θ)



$$z = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

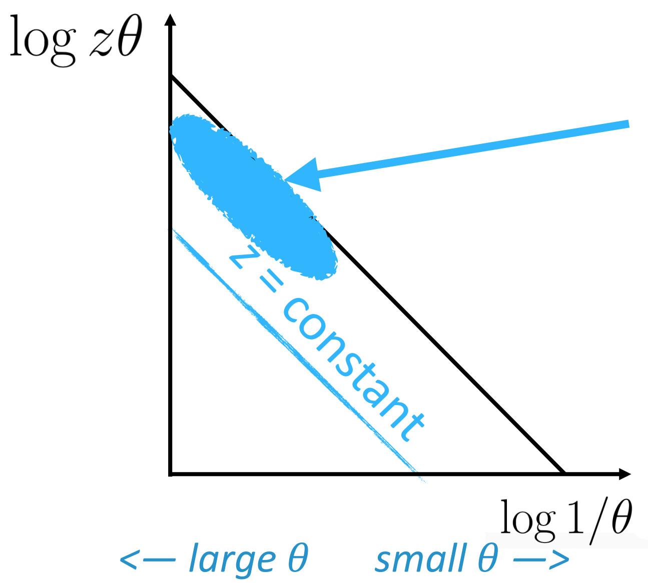


- By varying the Soft Drop parameters z_{cut}, β one can vary the phase space populated in the Lund diagram

$$z > z_{cut} \left(\frac{\Delta R}{R_0}\right)^{\beta}$$

Groomed jet substructure

- Lund diagram:
  - Represents the phase-space density of 1—>2 splittings, described by (z,θ)



Large θ hard splittings are predicted to be resolved by the medium and suppressed

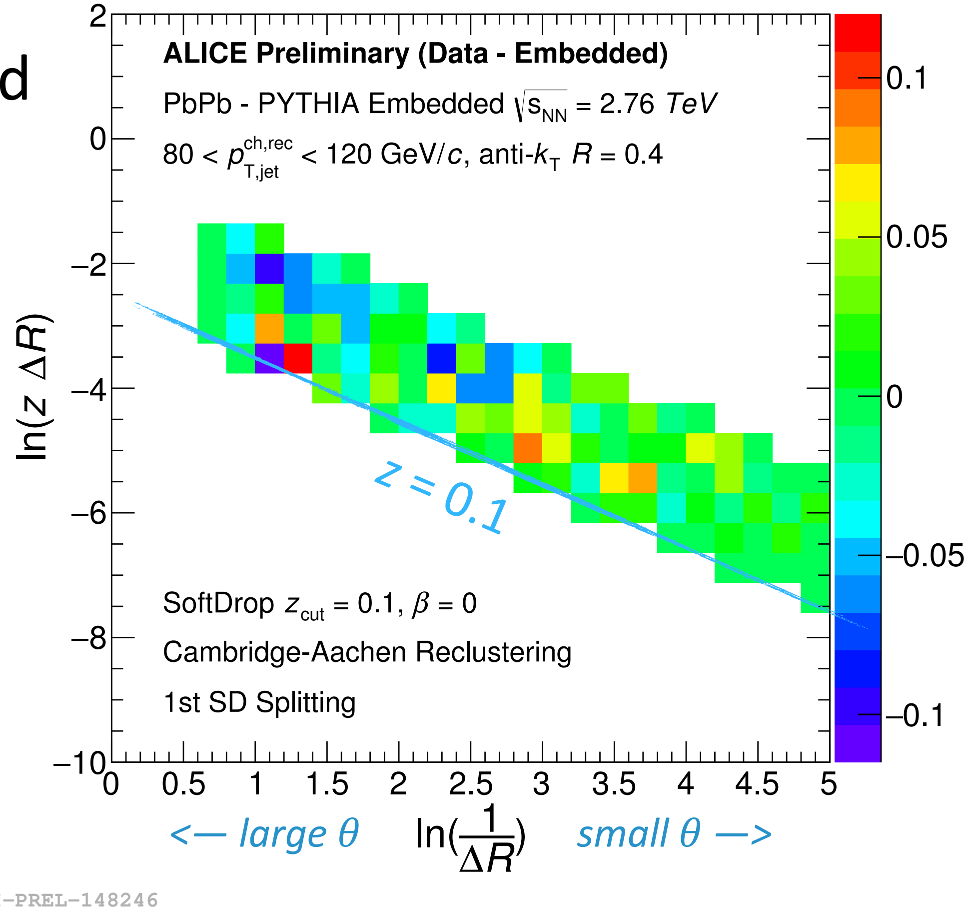
- By varying the Soft Drop parameters z_{cut}, β one can vary the phase space populated in the Lund diagram

$$z > z_{\text{cut}} \left(\frac{\Delta R}{R_0} \right)^{\beta}$$

Groomed jet substructure – Pb-Pb

- Pb-Pb measurement at $\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}$
  - $R = 0.4$, $p_{\mathrm{T}} = 80\text{-}120$ GeV/c, $|\eta| < 0.5$
  - Detector-level measurement, compared to Pythia embedded

Note: Soft Drop grooming removes below the constant diagonal line $z = 0.1$

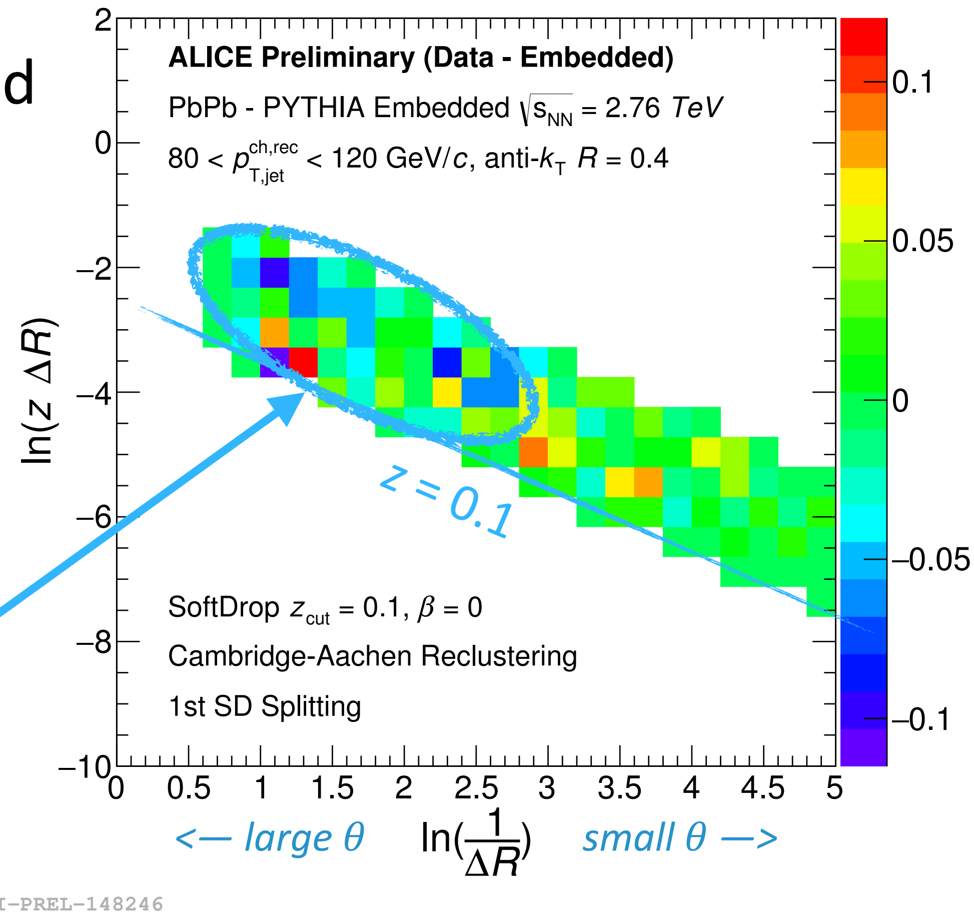


Groomed jet substructure – Pb-Pb

- Pb-Pb measurement at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV
  - $R = 0.4$, $p_{\mathrm{T}} = 80\text{-}120$ GeV/c, $|\eta| < 0.5$
  - Detector-level measurement, compared to Pythia embedded

Note: Soft Drop grooming removes below the constant diagonal line $z = 0.1$

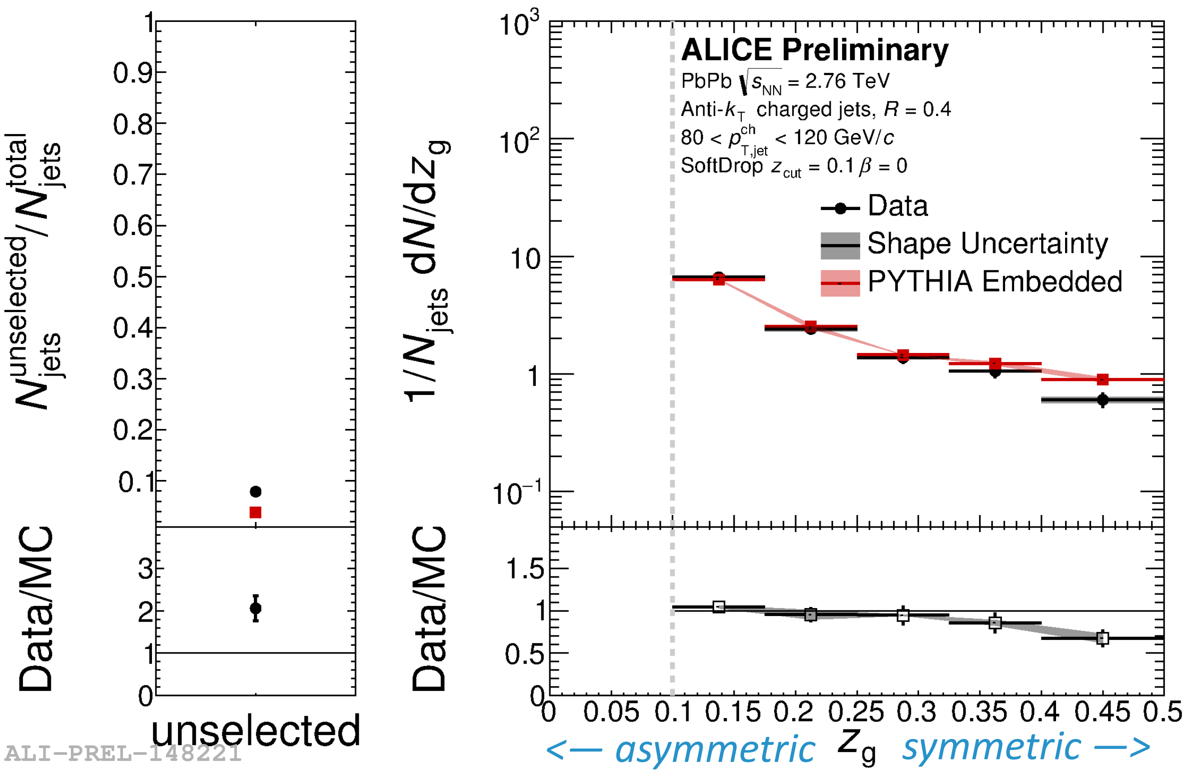
- There is a depletion of the large-angle splittings in Pb-Pb!



Groomed jet substructure – Pb-Pb

- The z_g distribution shows suppression at high z_g
  - That is, the hardest splittings are suppressed in Pb-Pb
- No enhancement at small z_g

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

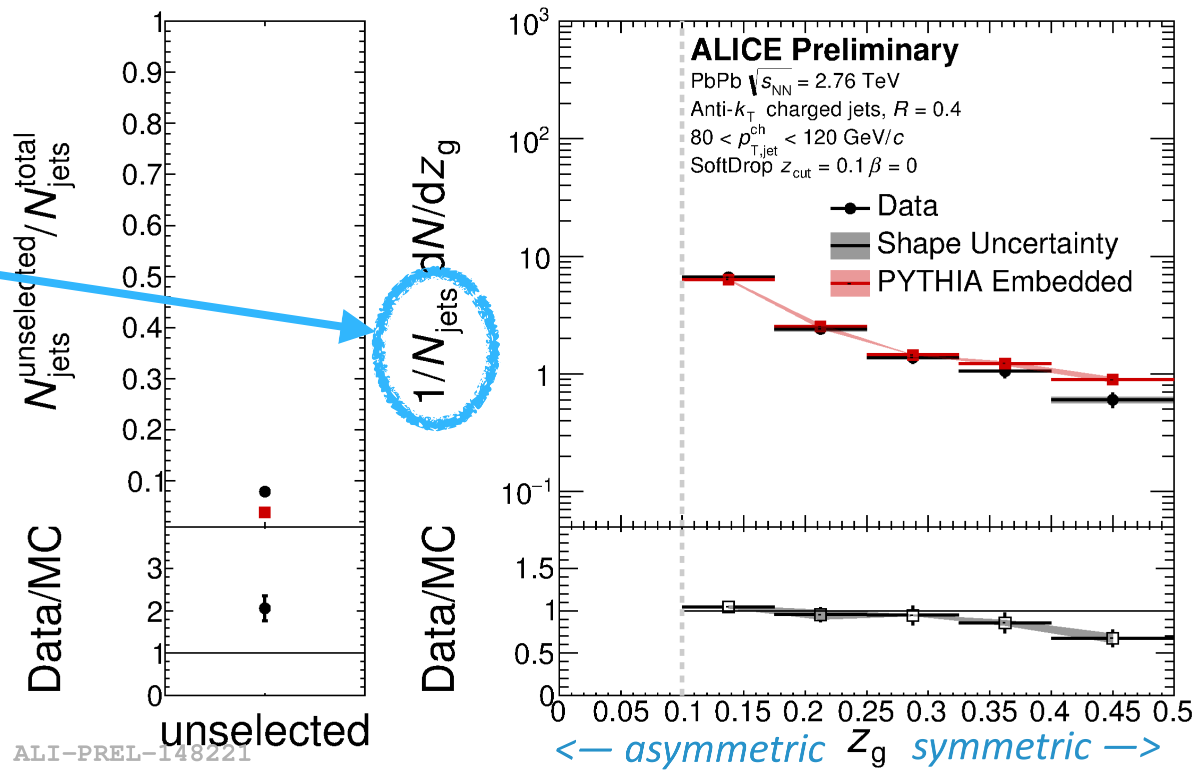


Groomed jet substructure – Pb-Pb

- The z_g distribution shows suppression at high z_g
  - That is, the hardest splittings are suppressed in Pb-Pb
- No enhancement at small z_g

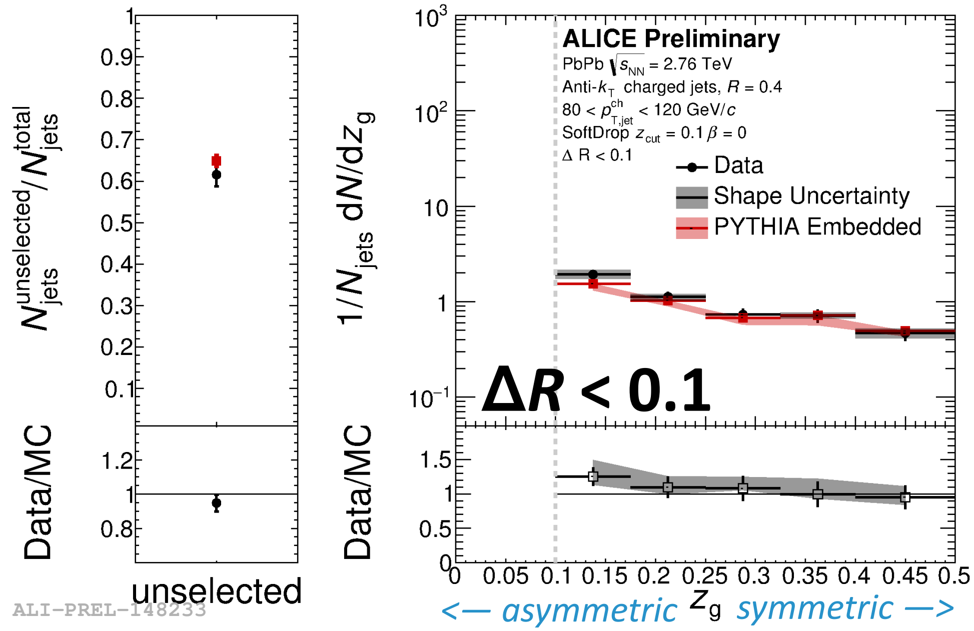
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

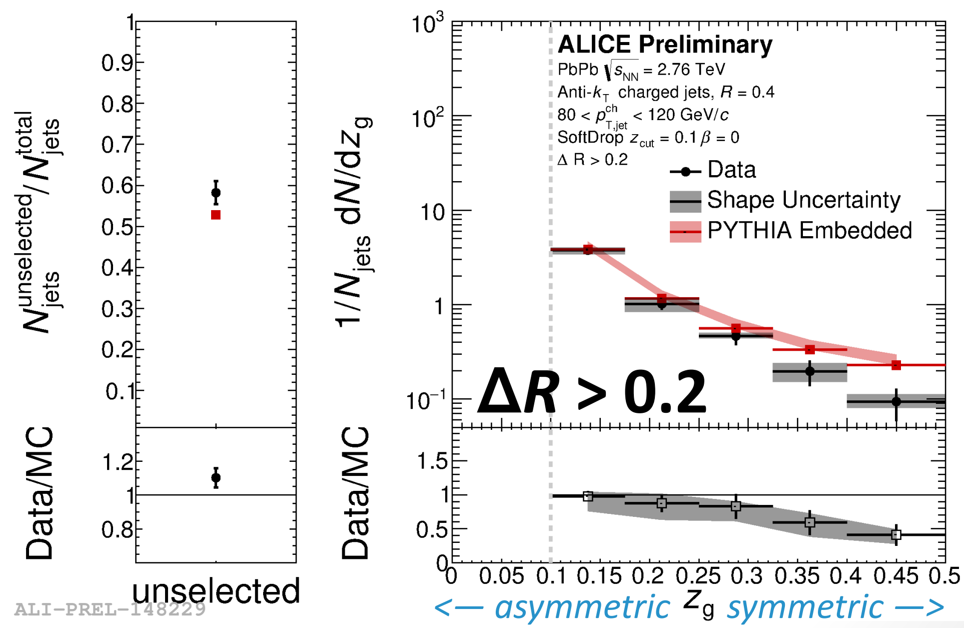
In order to interpret the results as absolute suppression/ enhancement, **must normalize by the number of inclusive jets**, including those that do not pass the Soft Drop condition



Groomed jet substructure – Pb-Pb

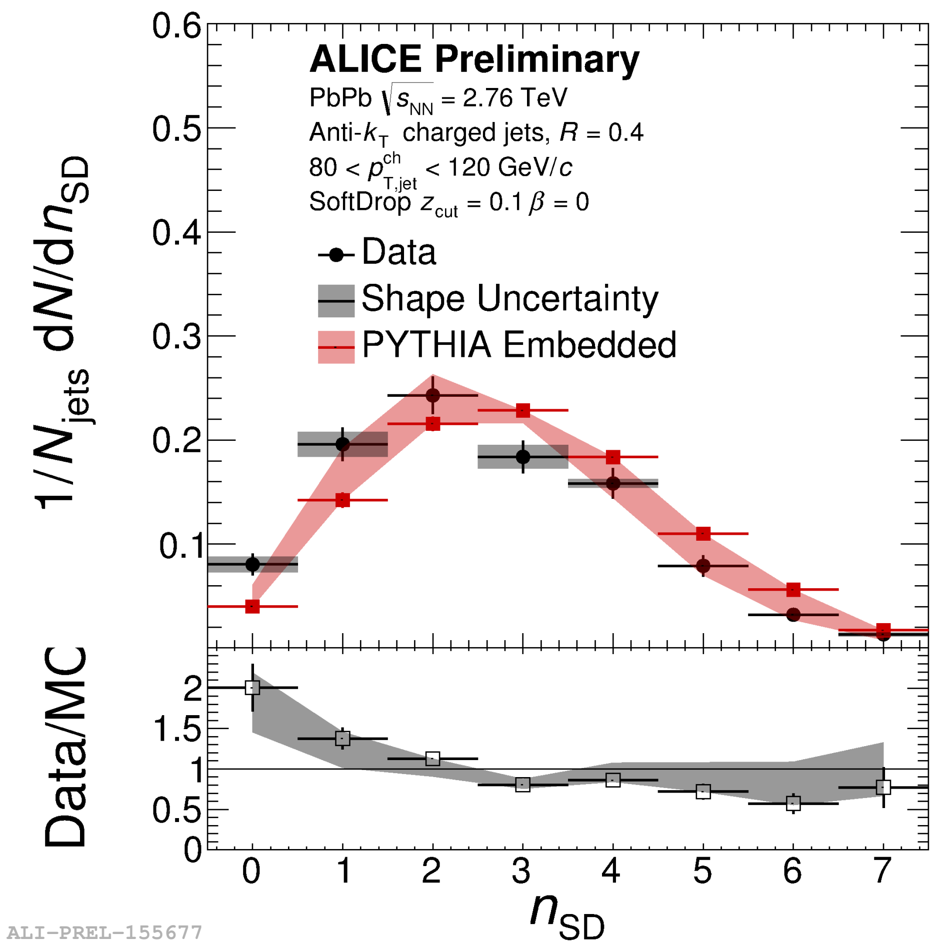
- The groomed sub-jet sample is then examined in two subsamples, depending on the ΔR between the two sub-jets
  - **Δ*R* < 0.1**: small enhancement of collinear splittings at small z_g
  - **Δ*R* > 0.2**: depletion of large-angle splittings at large z_g





Groomed jet substructure – Pb-Pb

- n_{SD} is the number of splittings that satisfy the Soft Drop condition
- For $1 \leq n_{SD} \leq 7$, there is no significant modification in Pb-Pb compared to embedded Pythia
- For $n_{SD} = 0$, there is slight enhancement in the number of jets that fail the Soft Drop condition



Summary

- ALICE preliminary result of jet R_{AA} at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV shows strong quenching, increasing at low p_{T}
- ALICE final result of constituent-based jet shapes g, $p_T D$ show collimation of jet core in Pb-Pb
- ALICE preliminary groomed jet substructure measurement with Soft Drop ($z_{\mathrm{cut}} = 0.1$, $\beta = 0$) in Pb-Pb shows:
    - Suppression of wide-angle, symmetric splittings
    - Slight enhancement of collinear, asymmetric splittings

Summary

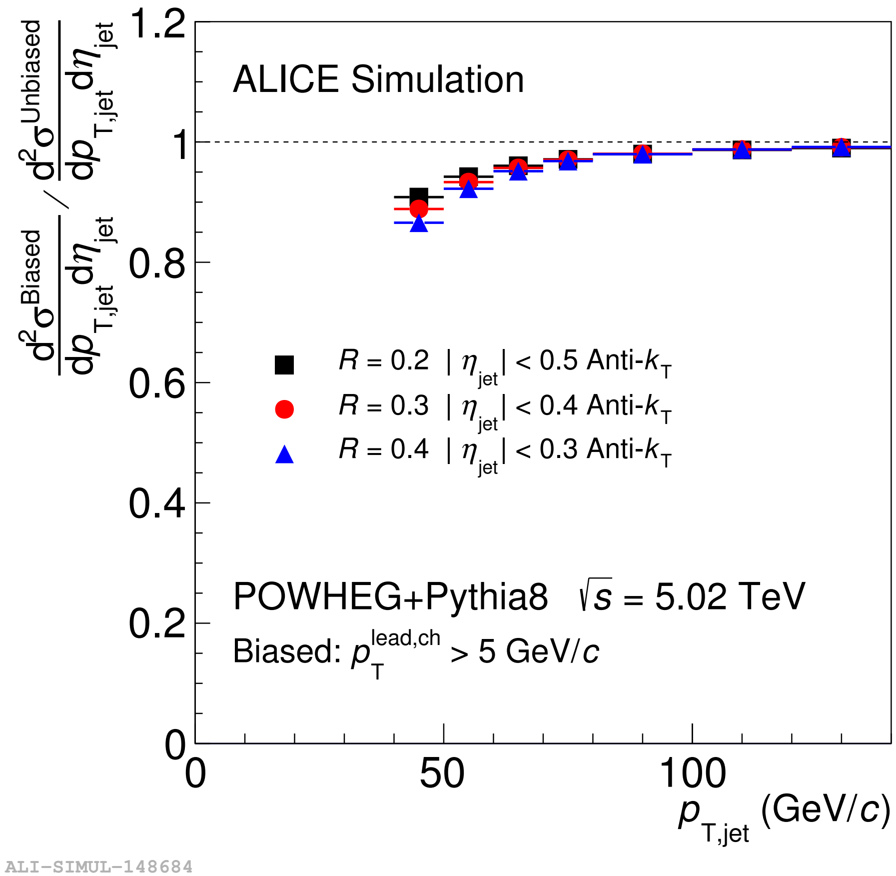
- ALICE preliminary result of jet R_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV shows strong quenching, increasing at low p_T
- ALICE final result of constituent-based jet shapes g, p_TD show collimation of jet core in Pb-Pb
- ALICE preliminary groomed jet substructure measurement with Soft Drop ($z_{cut} = 0.1$, $\beta = 0$) in Pb-Pb shows:
  - Suppression of wide-angle, symmetric splittings
  - Slight enhancement of collinear, asymmetric splittings

Multiple avenues to explore jet modification in greater detail, and more Pb-Pb statistics coming in 2018!

Thank you!

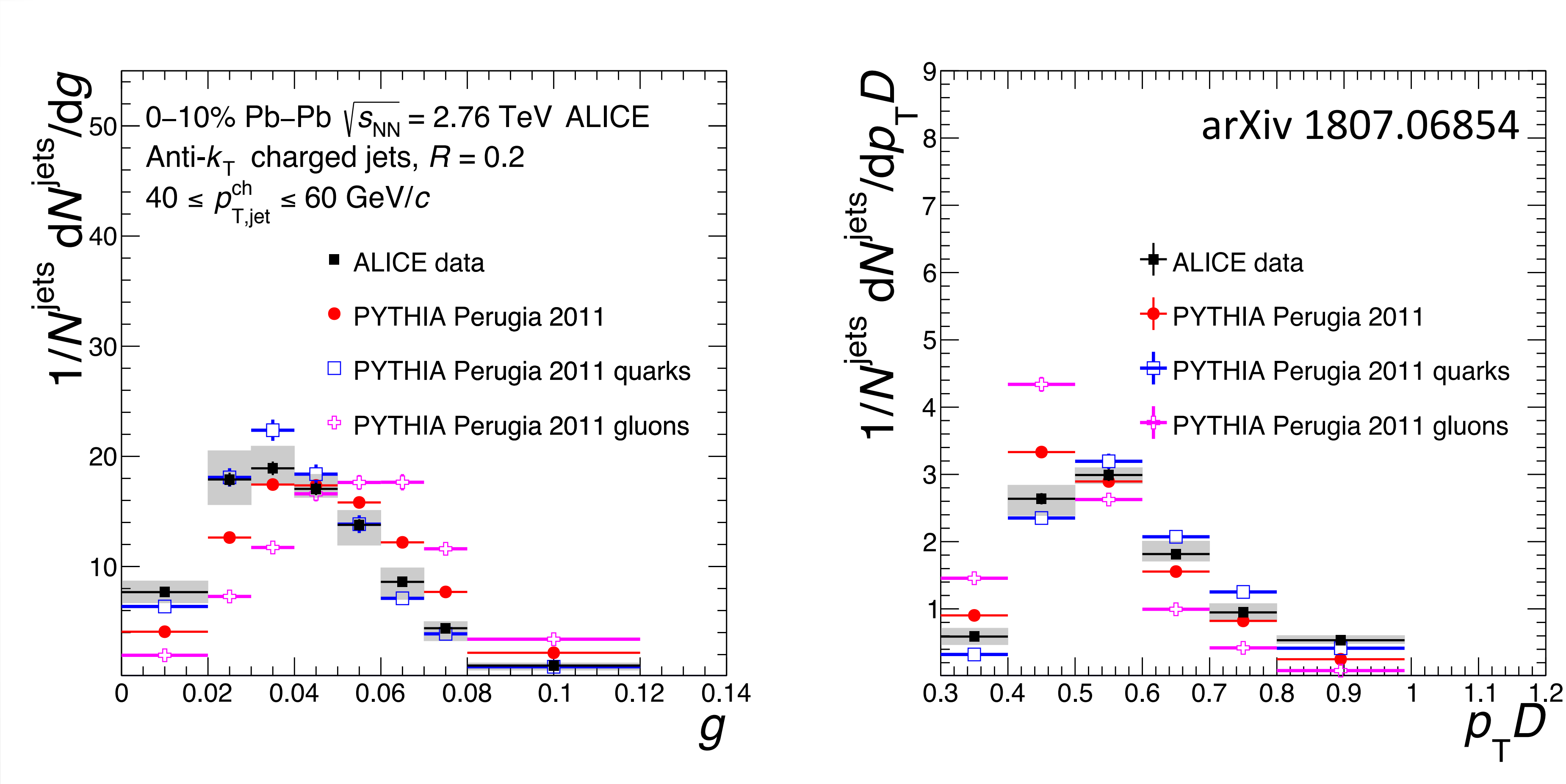
Backup

Leading track bias



How is the jet core modified?

The Pb-Pb results agree fairly well with Pythia quark jets



Jet mass

Phys. Lett. B776(2018) 249-264