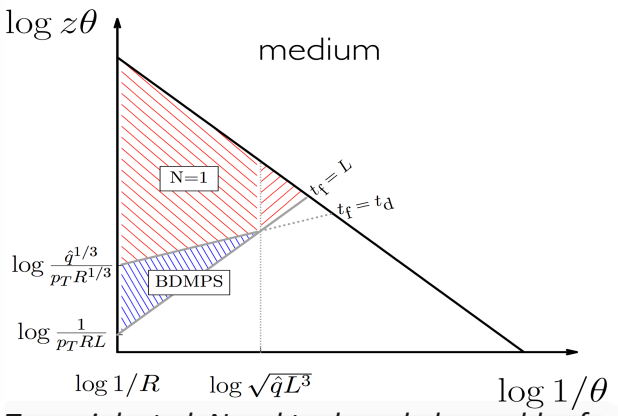
Exploring the Phase Space of Jet Splittings at ALICE

Nima Zardoshti

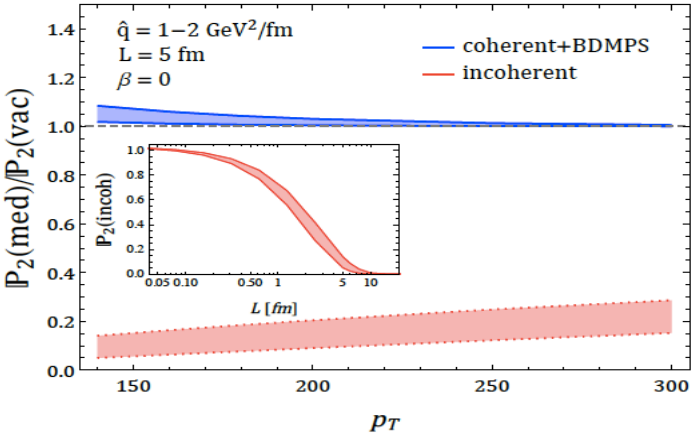
Motivation : Jet Splittings

- Systematically investigate jet splittings at different scales.
- Utilise different reclustering algorithms and grooming procedures.
- In pp collisions: Expected to be sensitive to fundamental QCD parameters.
- In Pb-Pb collisions: Expected to be sensitive to quenching effects such as coherence and medium induced semi-hard radiation.



Tywoniuk et al. Novel tools and observables for jet physics in heavy-ion collisions

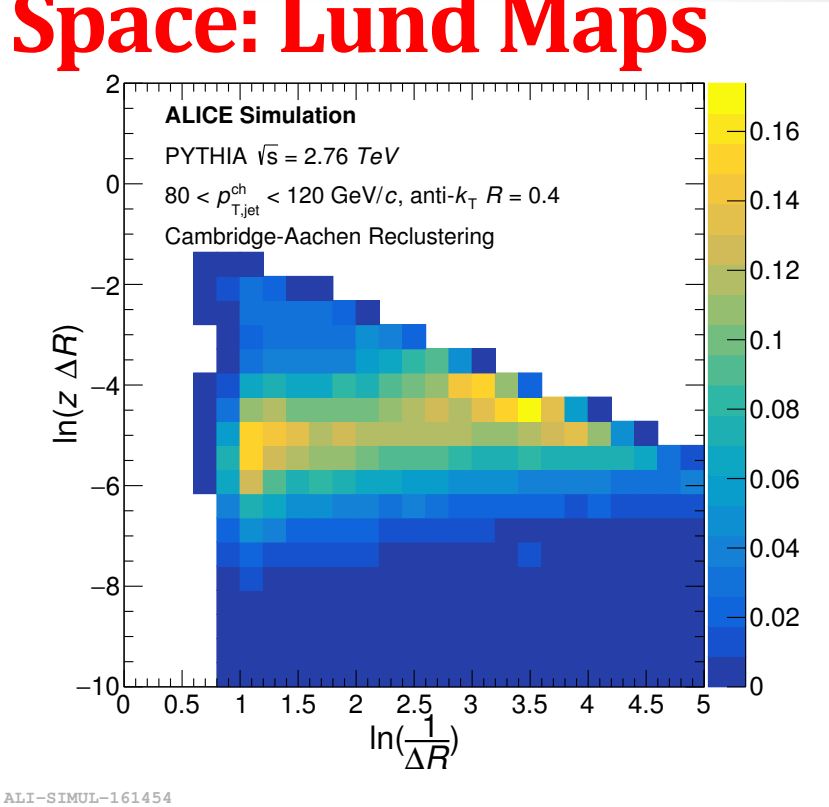
Rate of change of two-pronged probability (P_2)



Mehtar-Tani et al, JHEP 1704 (2017) 125

Exploring the Phase Space: Lund Maps

- Lund maps are 2D maps of jet splittings.
- Derived from pQCD splitting functions.
- Powerful tools for controlling the phase space.
- Flexible metric : Can be filled in a variety of ways.
- Multi-dimensional realisation of jet shapes.



$$P = \frac{1}{N_{splittings}} \frac{dN}{d\ln(z\Delta R)\ln(1/\Delta R)}$$

Based on method from Salam et al, arXiv: 1807.04758

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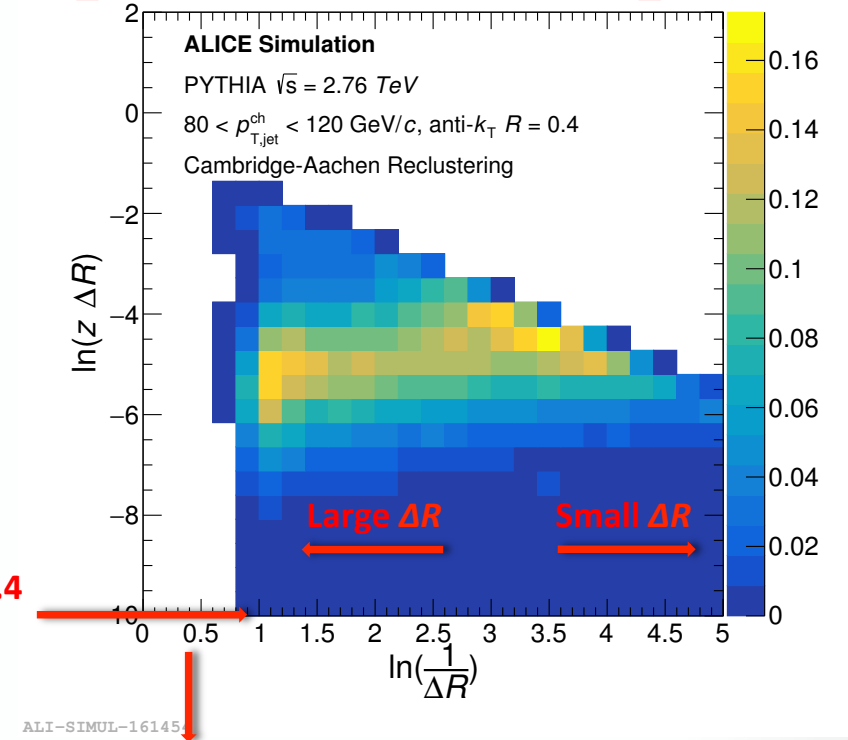

Limited by R=0.4 jet radius

Projection of x-axis

ΔR : η-φ distance between subjets

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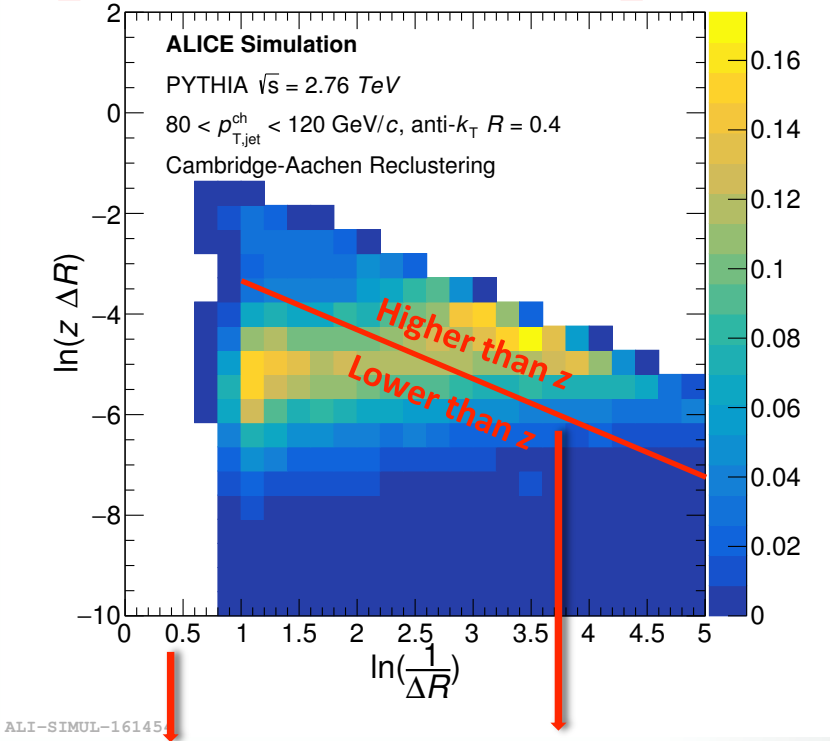

Projection of x-axis
ΔR : η-φ distance between subjets

Straight Line
z : momentum fraction of subleading prong

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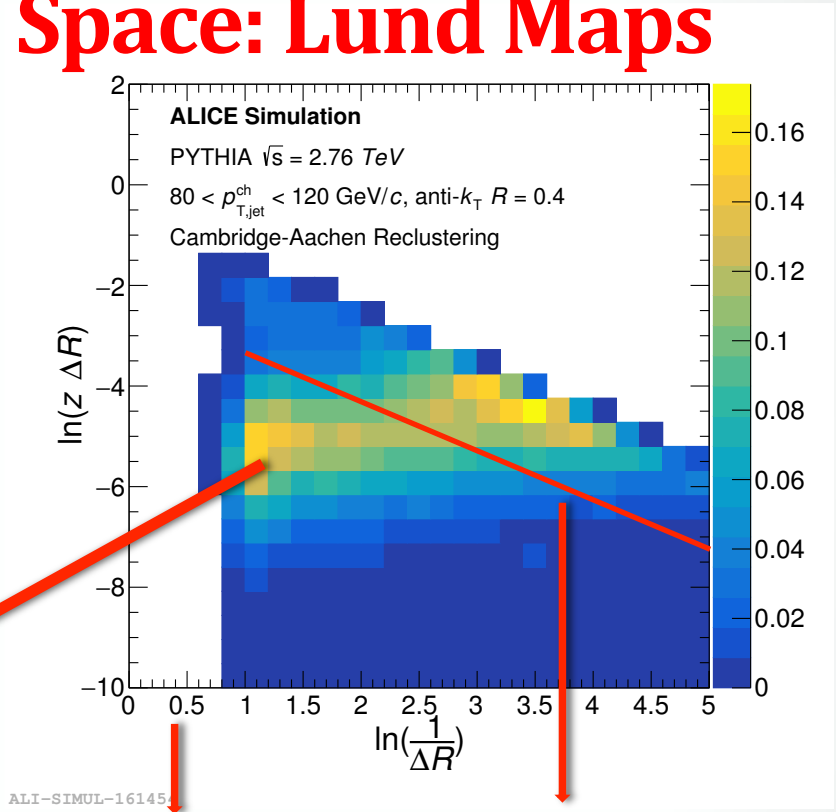

Number of entries:
n : number of splittings obtained by iteratively unclustering and following the hardest subjet

Projection of x-axis
ΔR : η-φ distance between subjets

Straight Line
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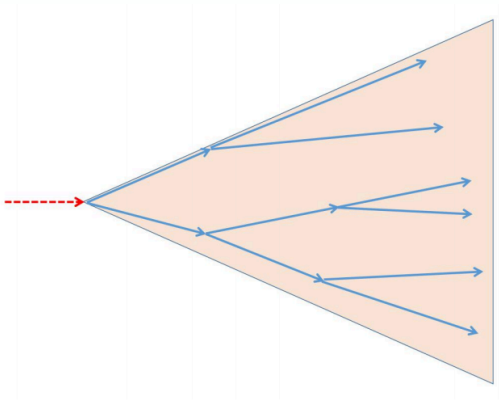
Experimental Access to Splittings: Reclustering Jets



- Recluster jet constituents with a variety of algorithms.
- Reclustering history is unwound to access the axes that were brought together in the final steps.
- Reclustered axes give experimental access to splittings.
- We then measure jet shapes relative to these axes.
- We also define variables to scan the iterative reclustering itself → fill Lund diagram.

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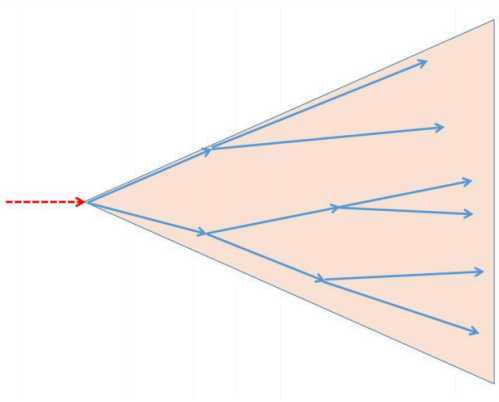

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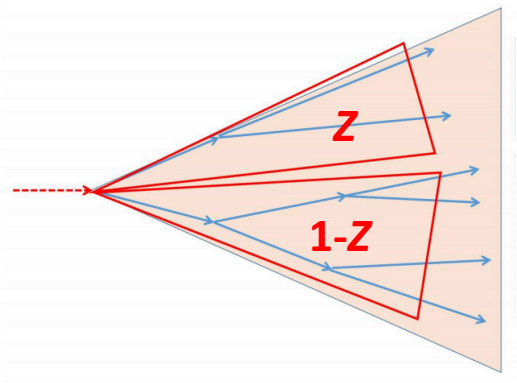
Reclustering Algorithms

- **k_T** p_T sensitive → returns axes of hard splittings.
- **Cambridge/Aachen (C/A)** No p_T dependence → sensitive to largest splitting.
- **C/A + minimisation of τ_N** Expected to reduce sensitivity to uncorrelated soft radiation.
- **Soft Drop (C/A)** Large angle soft structures groomed → sensitive to hard splittings.

Experimental Access to Splittings: Reclustering Jets



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Dasgupta et al, JHEP 1309 (2013) 029
Larkoski et al, JHEP 1405 (2014) 146

Soft Drop condition: $z > z_{\rm cut}\,\theta^{\beta}$ Default values: $z_{\rm cut} = 0.1$ $\beta = 0$

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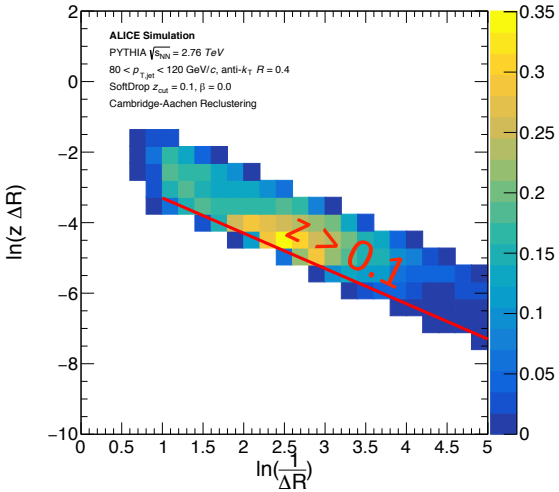

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- We then measure jet shapes relative to these axes.
- We also define variables to scan the iterative reclustering itself → fill Lund diagram.

- Lund diagram filled with only the first splitting which passes Soft Drop.

Soft Drop condition: $z > z_{\mathrm{cut}}\,\theta^{\beta}$ Default values: $z_{\mathrm{cut}} = 0.1$ $\beta = 0$

Reclustering Algorithms

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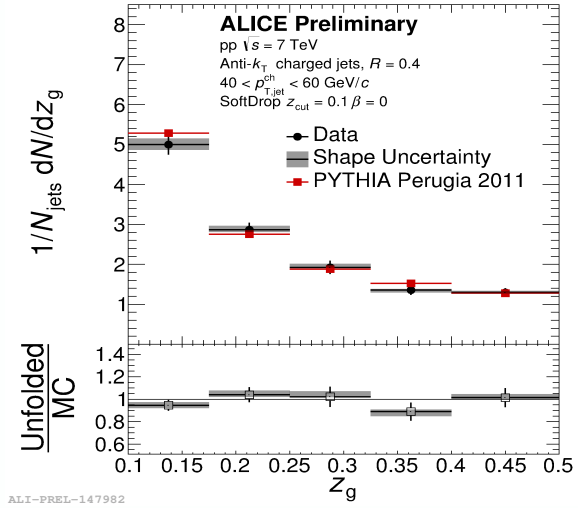
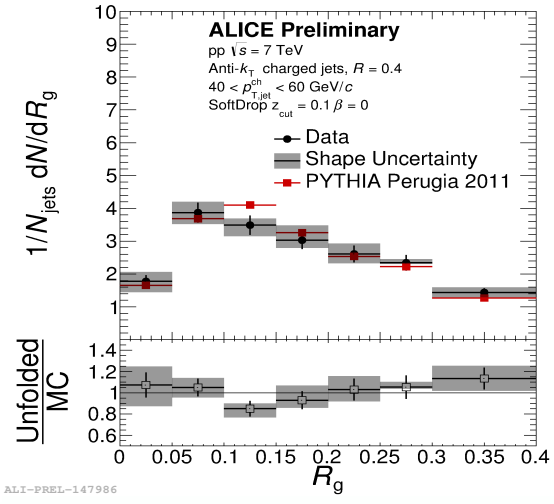
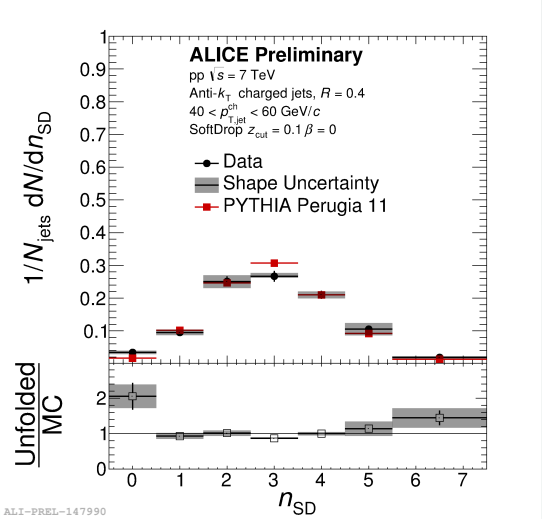
Fully Corrected Soft Drop Shapes in pp







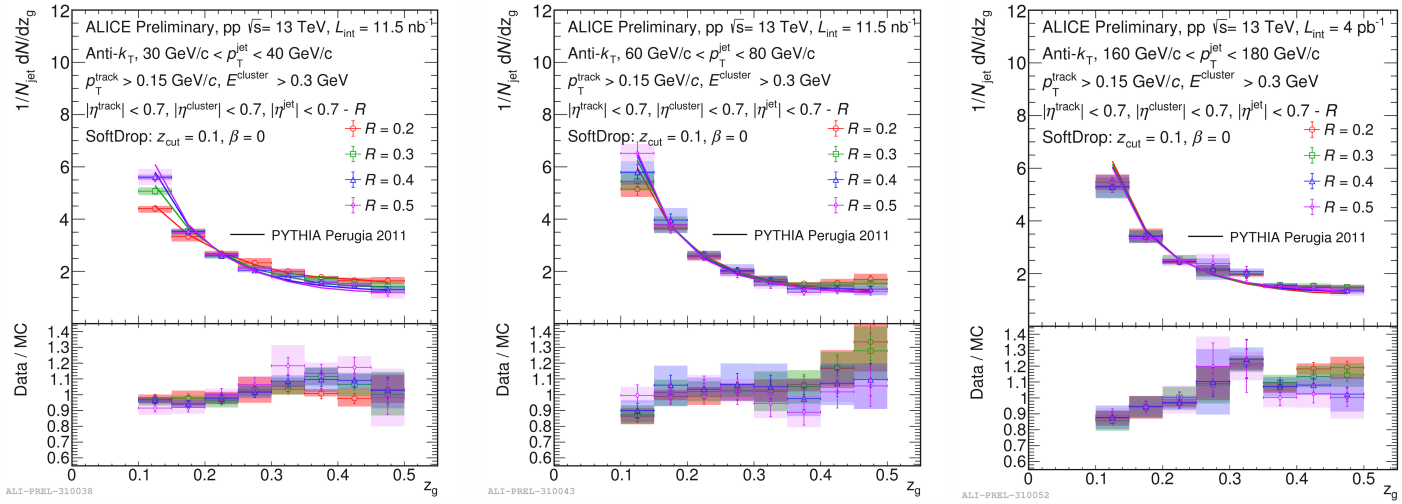
- Soft Drop variables are projections of the Lund map.
- For z_g and R_g the Lund map is only filled with the first splitting satisfying Soft Drop.
- Pythia describes all three measured variables well.
- Fully corrected with 2D Bayesian Unfolding:
  → directly comparable to particle level

- Normalising to the total number of jets in the reconstructed $p_{T,jet}$ bin.

Jets satifying $z > z_{cut} = 0.1$
- Data : 97.3(0.5)%
- PYTHIA : 98.9(0.1)%

Full Jets : z_g Measurements in Differential p_T^{jet} and Jet Resolution Bins in pp

$30 < p_{T,jet} < 40$ GeV/c $\quad$ $60 < p_{T,jet} < 80$ GeV/c $\quad$ $160 < p_{T,jet} < 180$ GeV/c



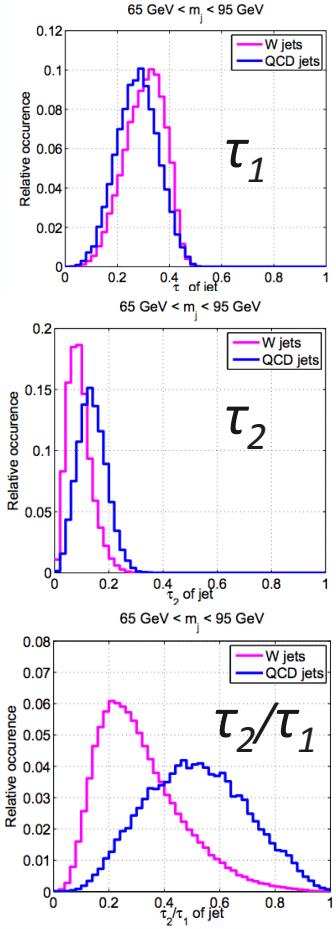
New Result!

Talk by M. Fasel

- Larger data set at $\sqrt{s}$ = 13 TeV : L_{int} = 11.5 nb^{-1} (Min Bias) L_{int} = 4 pb^{-1} (Triggered)
- Extending data set further by measuring full jets: Charged tracking + EMCal towers.

  - Allows for a more **detailed probing of QCD**:
    Can help constrain non-perturbative effects?

W jets
QCD jets



[Thaler et al, JHEP 1103 (2011) 015]

N-subjettiness

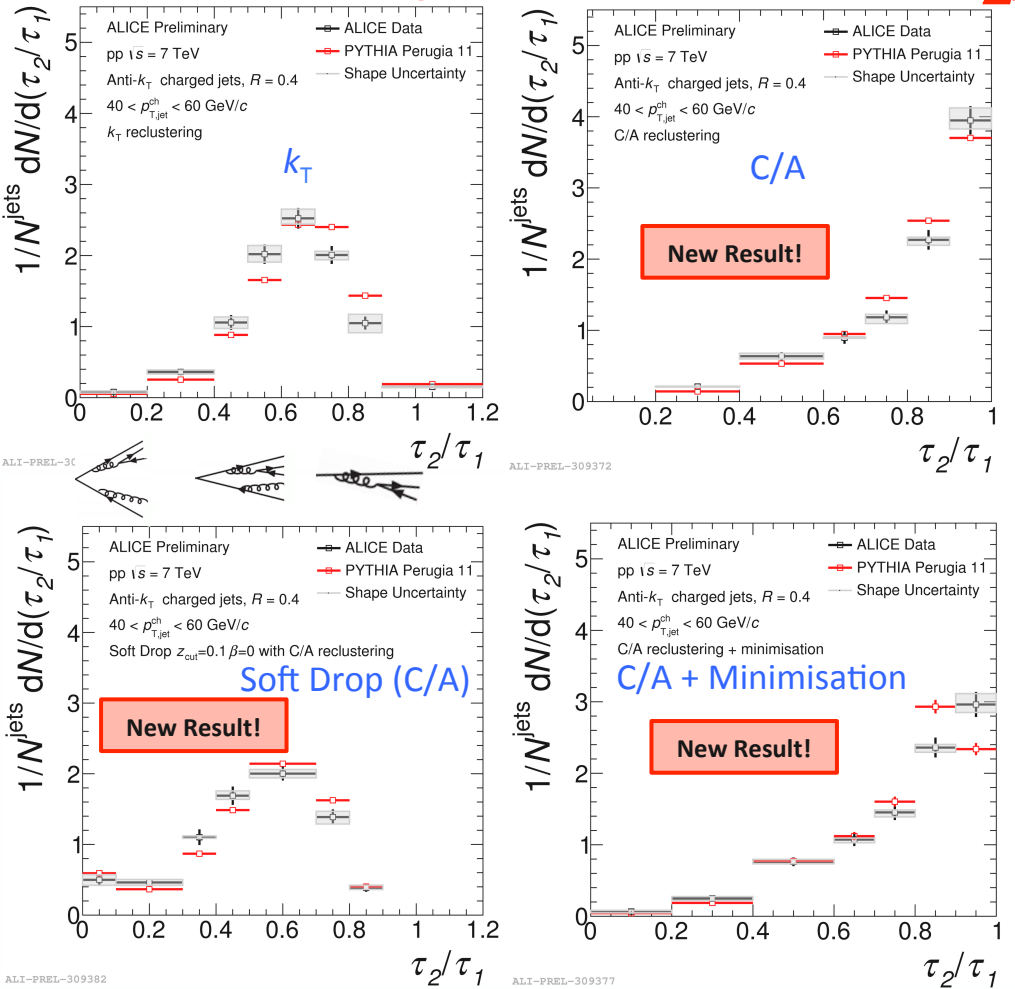
- The N-subjettiness, τ_N , jet shape is a measure of how *N*-pronged a jet's substructure is.
- τ_N is calculated relative to the *N* returned axes.
- Initially developed to tag jets from Higgs decays such as Higgs -> W^+W^-.

$$\tau_N = \frac{\sum_{i=1} p_{T,i} Min(\Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N})}{R_0 \sum_{i=1} p_{T,i}}$$

$\Delta R_{i,j}$ -> η-φ distance between track *i* and subjet *j*
$p_{T,i}$ -> p_T of ith jet constituent
R_0 : Jet resolution parameter

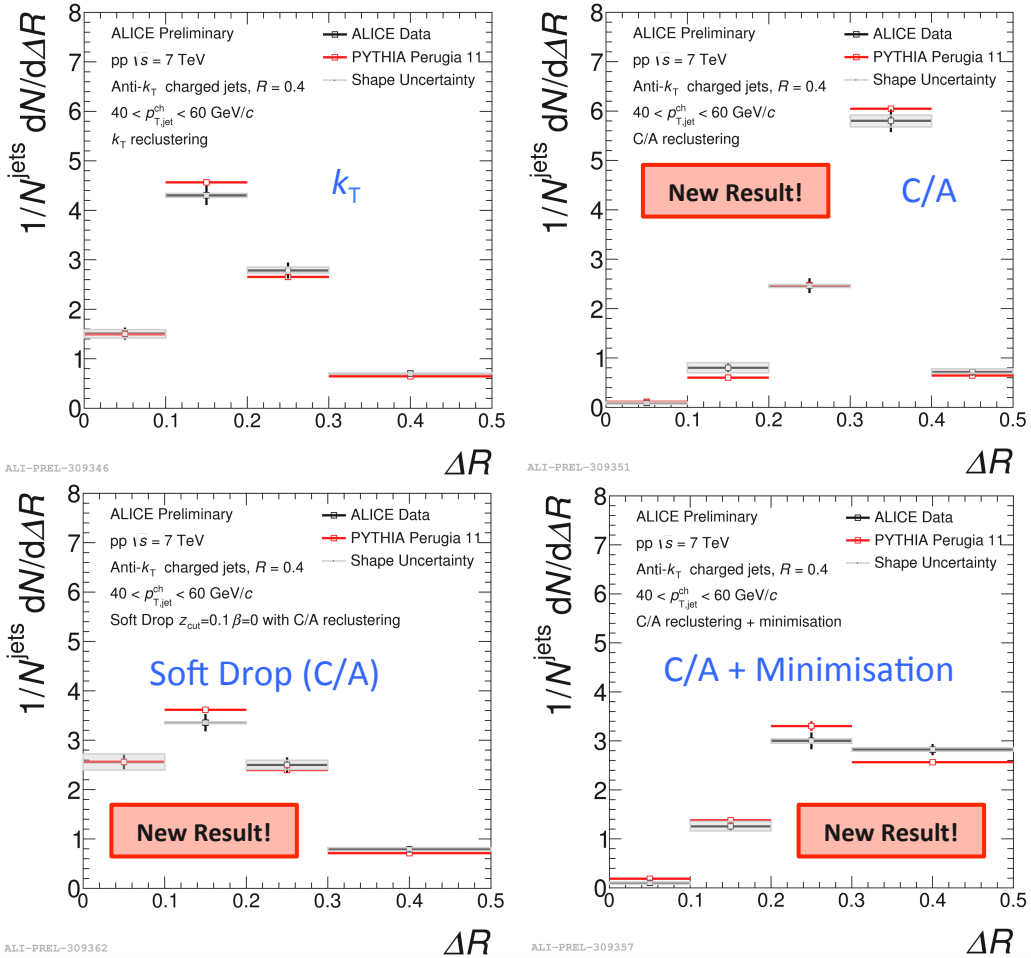
- τ_N -> 0 Jet has *N* or fewer well defined cores
- τ_N -> 1 Jet has at least *N*+1 cores
- τ_N/τ_{N-1} -> 0 Jet has *N* cores
- τ_2/τ_1 -> 0 Jet is two-pronged

Fully Corrected τ_2/τ_1 Shape in pp



- Alignment of radiation relative to returned axes (τ_2/τ_1) **reasonably well** described by PYTHIA.
- Additional information compared to Lund map: subleading subjet.
- Subleading C/A axis follows soft radiation : jet not expected to be two-pronged relative to this axis.
- The Soft Drop groomer increases the p_T sensitivity of the subleading axis.

Fully Corrected ΔR Shape in pp



- Clean observable describing the distance between different types of splittings in the jet.
- Returned axes (ΔR) **well described** by PYTHIA.
- C/A : soft scale acts at large distances from the jet core.
- k_T and Soft Drop: hard splittings primarily in jet core.

Accounting for the Heavy Ion Background: Embedding

- PYTHIA jets embedded in real 0-10% most central Pb-Pb events.
- Embedded level reconstructed jets matched to PYTHIA level jets.
- **Background** and **detector effects** reproduced at embedded level.

Subtraction methods applied to subtract the pedestal background per jet simultaneously from the shape and the p_T:

- Constituent Subtraction
  Berta et al, JHEP 1406 (2014) 092
- Derivative Subtraction
  Soyez et al, Phys.Rev.Lett 110 (2013) 16

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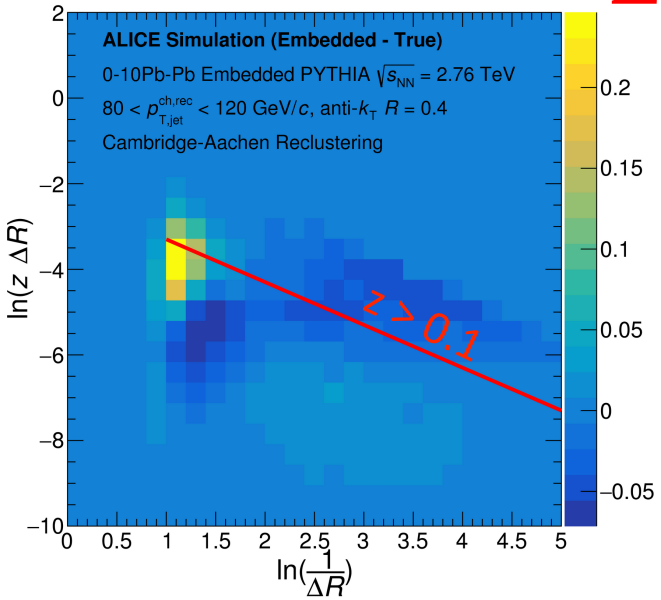

- Lund diagram can be used to isolate the background contribution.
- Enhancement of splittings at low z_g
  → **purely background effect**.

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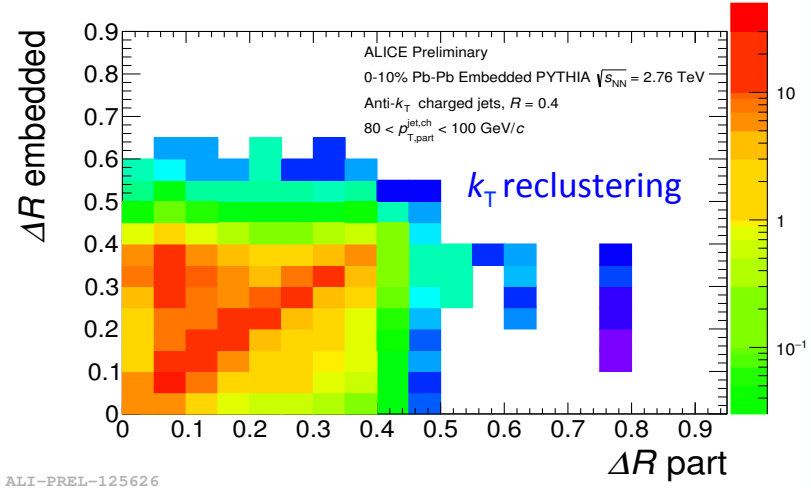
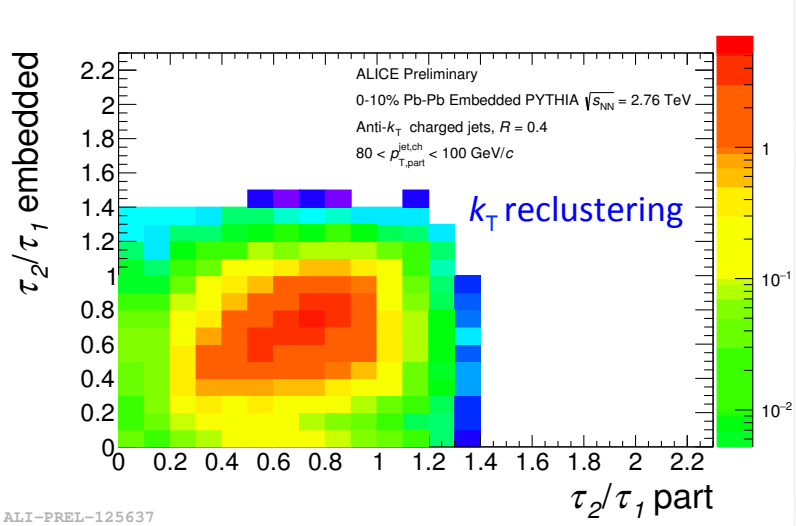
Sensitivity of Jet Shapes to the Background



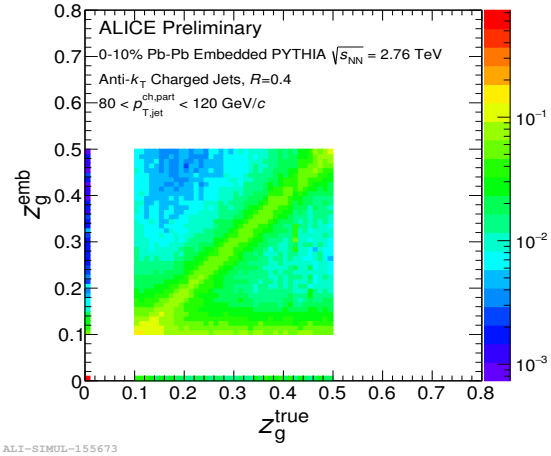


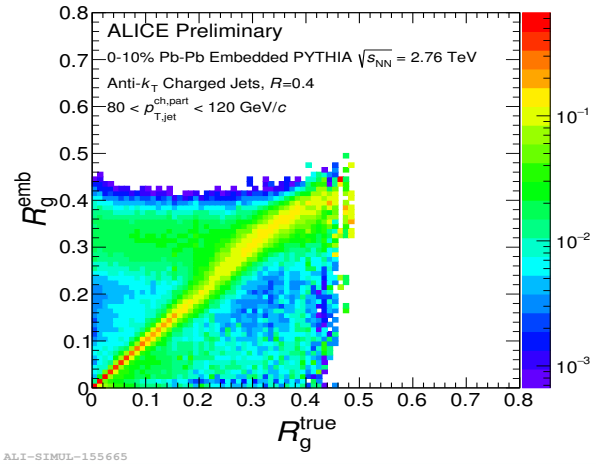
- **ΔR sensitive to background fluctuations at large angles which replace subleading axis (fake splittings).**
  Double peak structure of response inhibits unfolding.

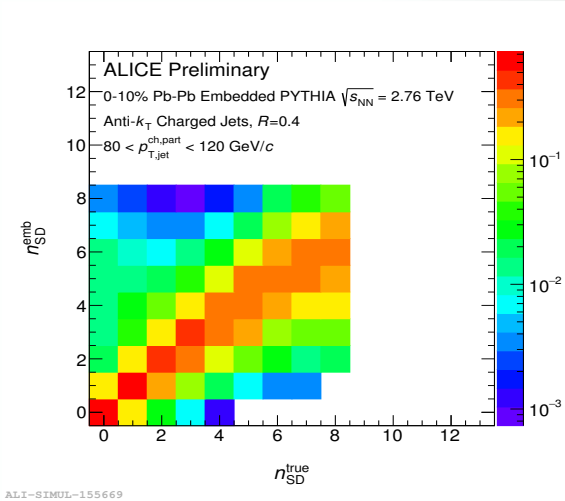
- **τ_2/τ_1 resilient to shift in axes due to soft/large angle background.**

  The background fluctuation needs to carry a significant fraction of the jet momentum to modify τ_2/τ_1.

Sensitivity of Jet Shapes to the Background





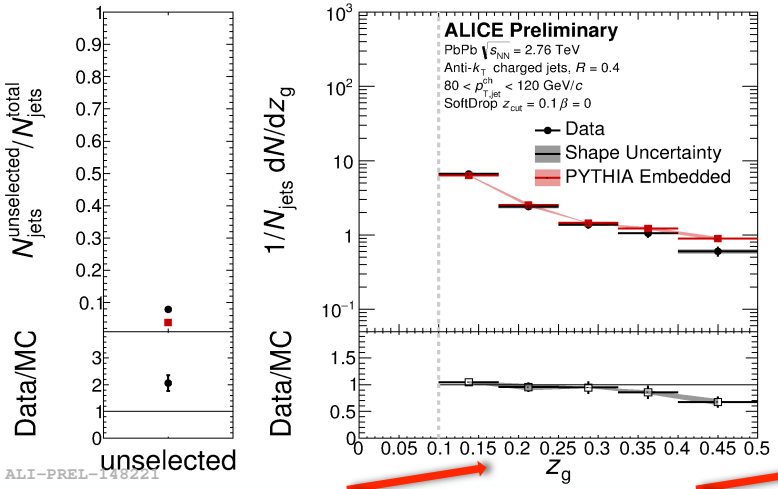


- Uncorrelated background **adds splittings** at **low z_g**.
- Fake splittings **appear** at **large R_g** due to the background.
- n_{SD} appears relatively robust to the presence of background.

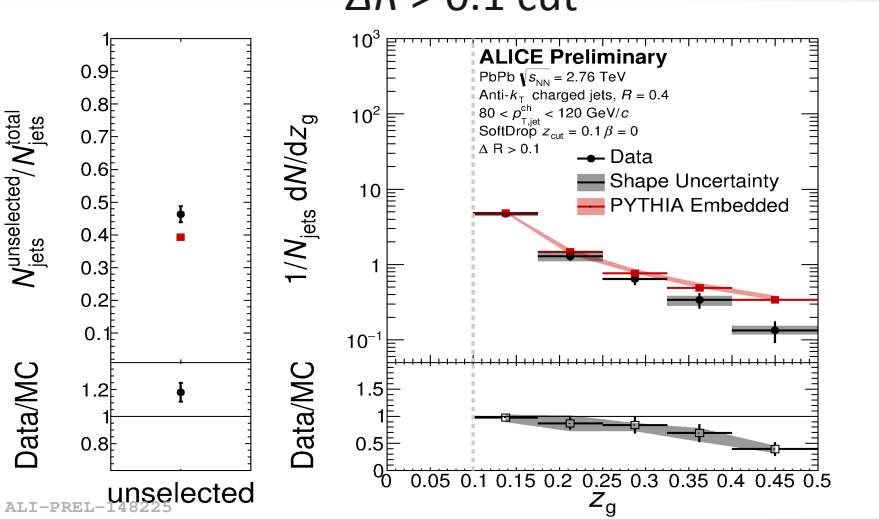
- Embedding accounts for background effects (fake splittings etc): **Allows for direct comparison with uncorrected data**.

Inclusive z_g Shape in Pb-Pb

No ΔR cut



$\Delta R > 0.1$ cut



Asymmetric splittings

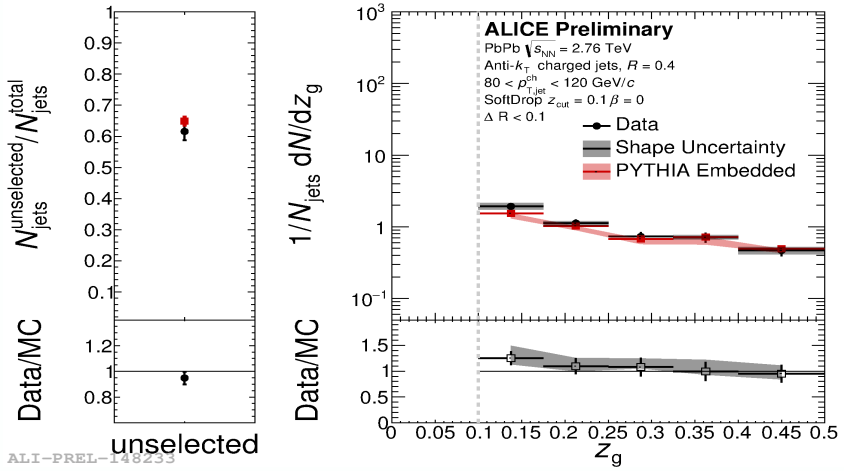
Symmetric splittings

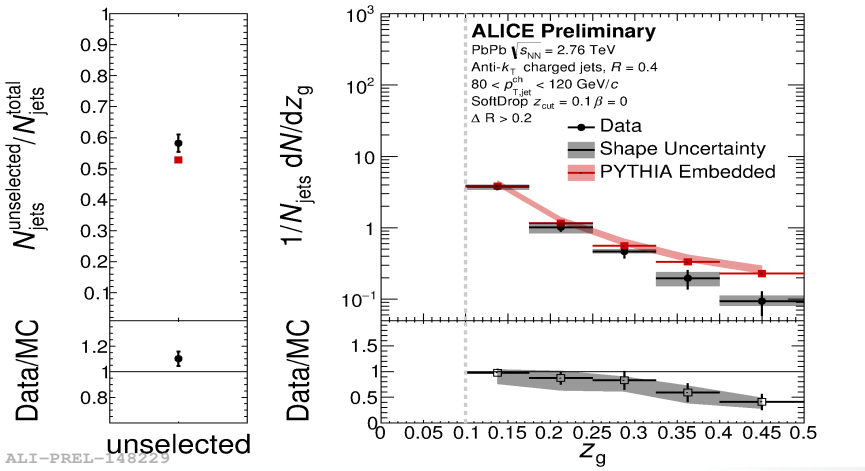
- **No net enhancement** of splittings passing the Soft Drop criteria observed at $\Delta R > 0.1$.
- ~ 10 % **reduction** in the number of jets with a splitting that passes Soft Drop.

Inclusive z_g Shape in Pb-Pb

$\Delta R < 0.1$ cut → Collimated splittings

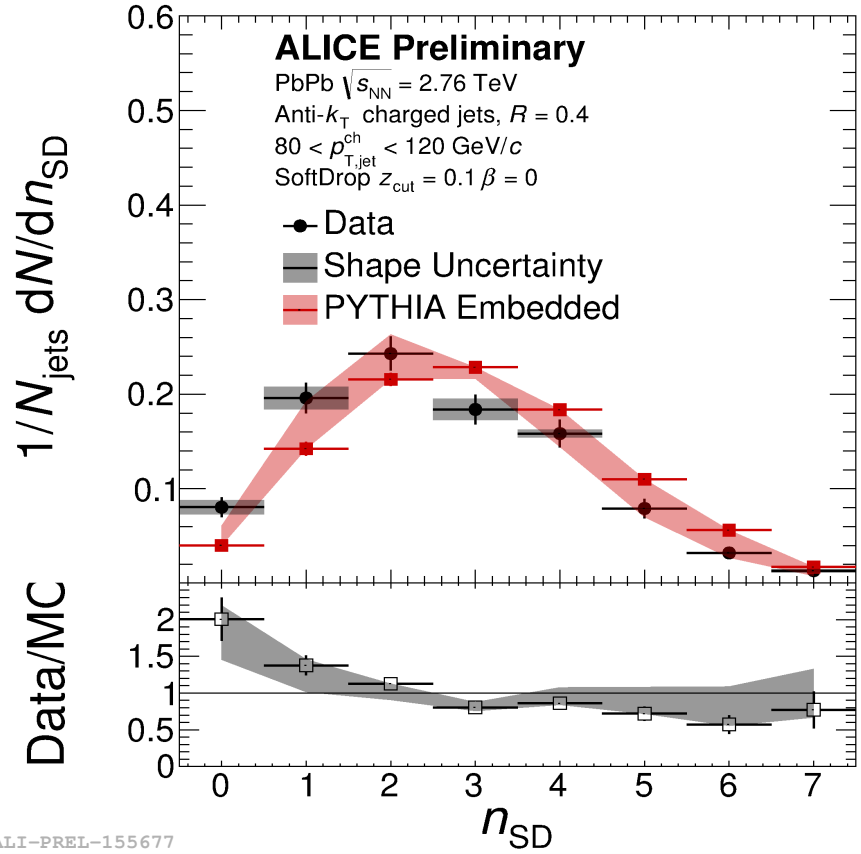
$\Delta R > 0.2$ cut → Large Angle splittings





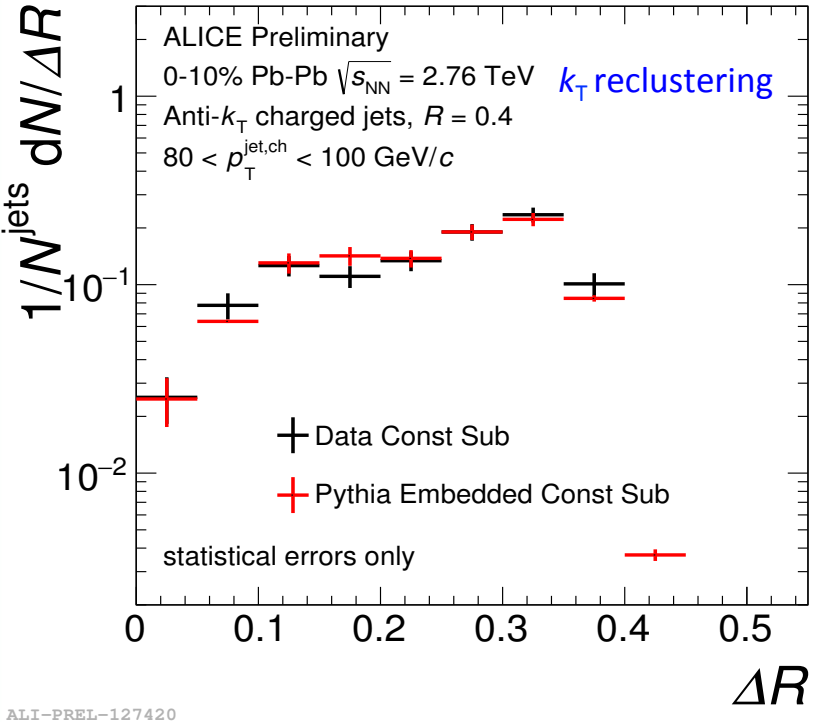
- **Collimated** splittings **enhanced**.
- **Large angle** splittings **suppressed**.
- No low z_g enhancement observed at large angles.

Number of Splittings in the Jet that Satisfying the Soft Drop Condition in Pb-Pb



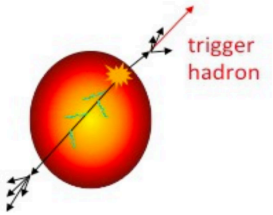
- **No enhancement** in number of splittings passing Soft Drop.
- Enhancement in number of untagged jets (first bin).
- In contrast to expected correlated medium response or coherent collinear emissions.

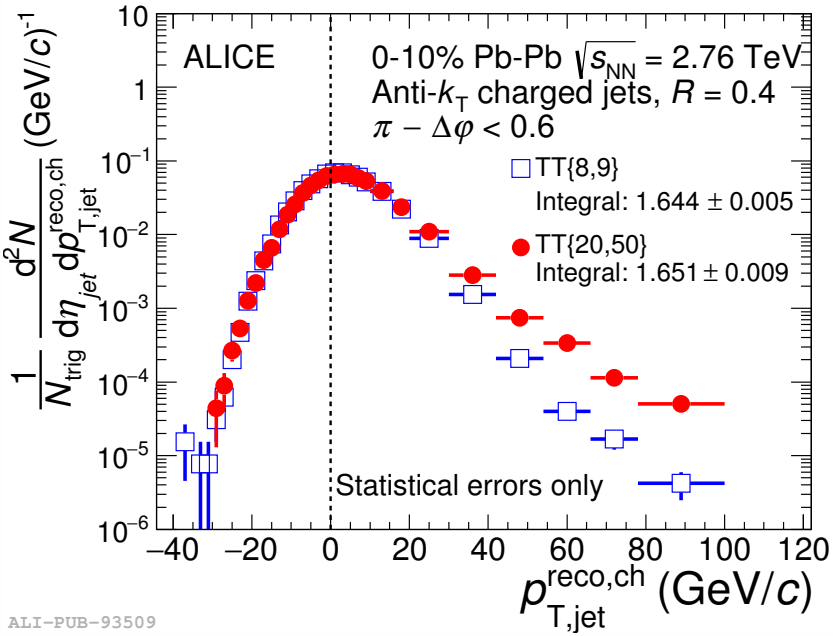
Inclusive ΔR Shape in Pb-Pb



- **No modification** observed within statistical limits.
- Suppression of large ΔR would be expected for "resolved" jets.
- Enhancement of low ΔR would be expected with medium induced semi-hard radiation.
- Possible modifications can be smeared by the **fake splittings** → reduction of signal to background ratio.
- Need to **reject fake splittings** to uncover potential physics signal.

Probing Lower p_T Jets : Recoil Jets





ALICE, JHEP09(2015)170

- Combinatorial jets dominant at **low p_T** and **large jet resolution**.
- Unfolding requires a combinatorial free input ⟶ leads to a fully corrected measurement which is directly comparable to particle level.

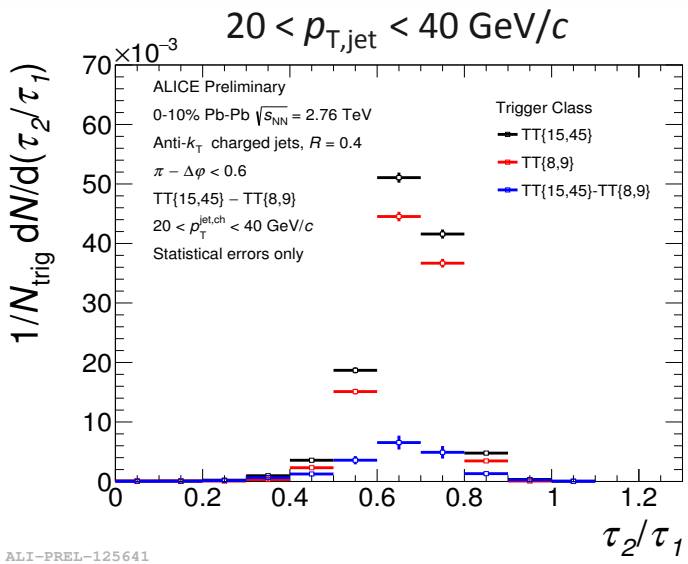
Use semi-inclusive hadron-jet coincidence measurements to suppress combinatorial background:

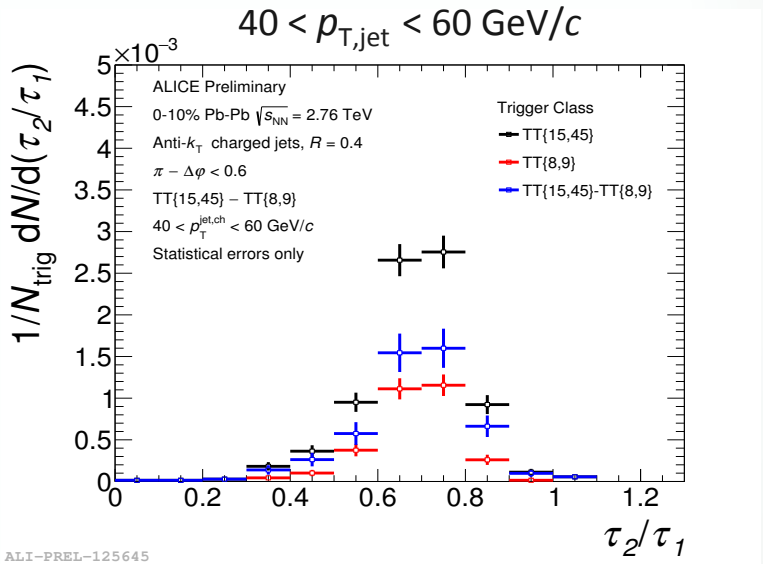
- The yield of jets recoiling from two exclusive high p_T trigger classes is measured.
- The **difference in yield** of the two classes provides an IRC-safe and combinatorial free jet distribution that can be unfolded.

Recoil Jets in 2D : Raw Recoil Jet Shapes

Extension of technique to 2D:

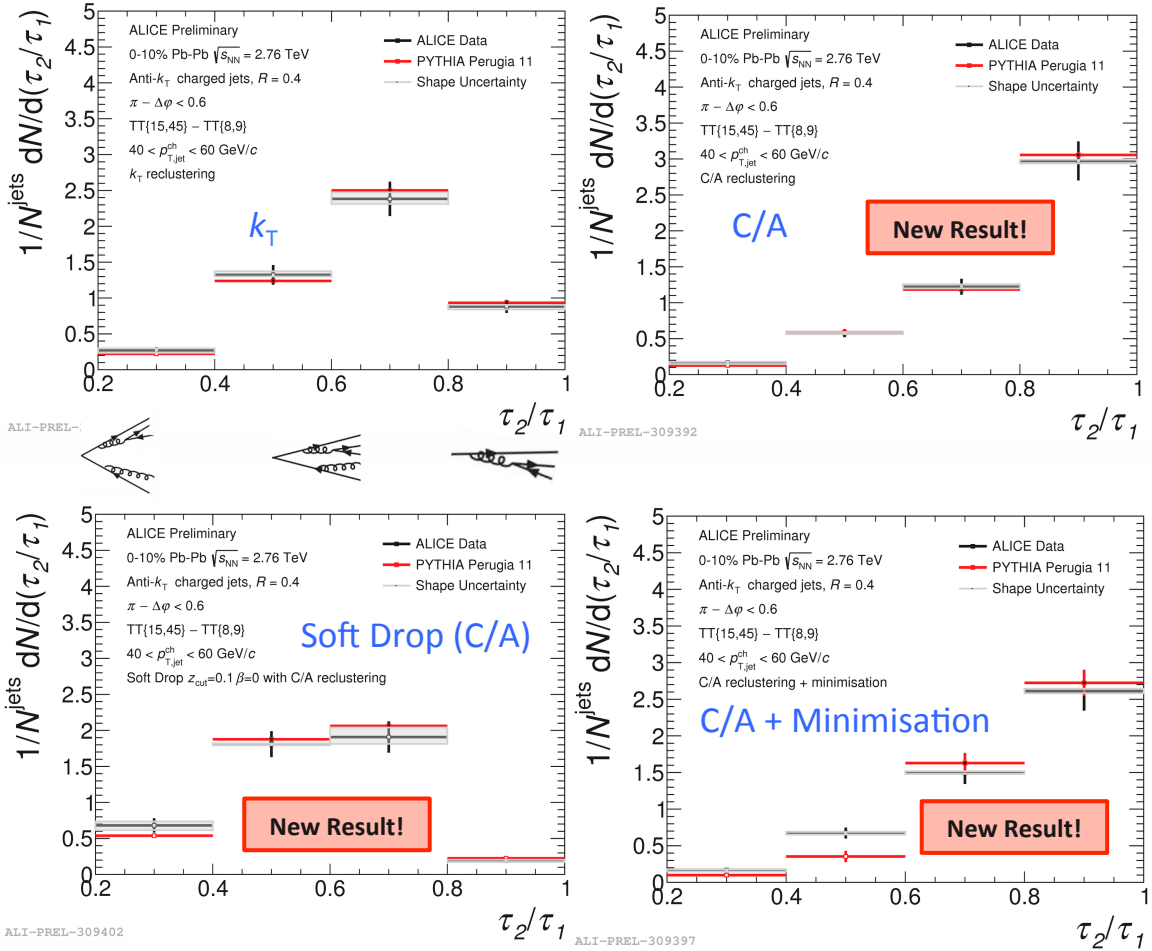
$$\text{Difference} = \left(\frac{1}{N_{\text{trig}}} \cdot \frac{dN_{\text{jet}}}{d(\text{shape})dp_{\text{T,jet}}}\right)_{\text{TT}_{\text{signal}}} - \left(\frac{1}{N_{\text{trig}}} \cdot \frac{dN_{\text{jet}}}{d(\text{shape})dp_{\text{T,jet}}}\right)_{\text{TT}_{\text{reference}}}$$





- Difference yield approaches signal yield with **increasing** $p_{T,jet}$.
- Raw uncorrected distributions.

Fully Corrected τ_2/τ_1 Recoil Shape in Pb-Pb



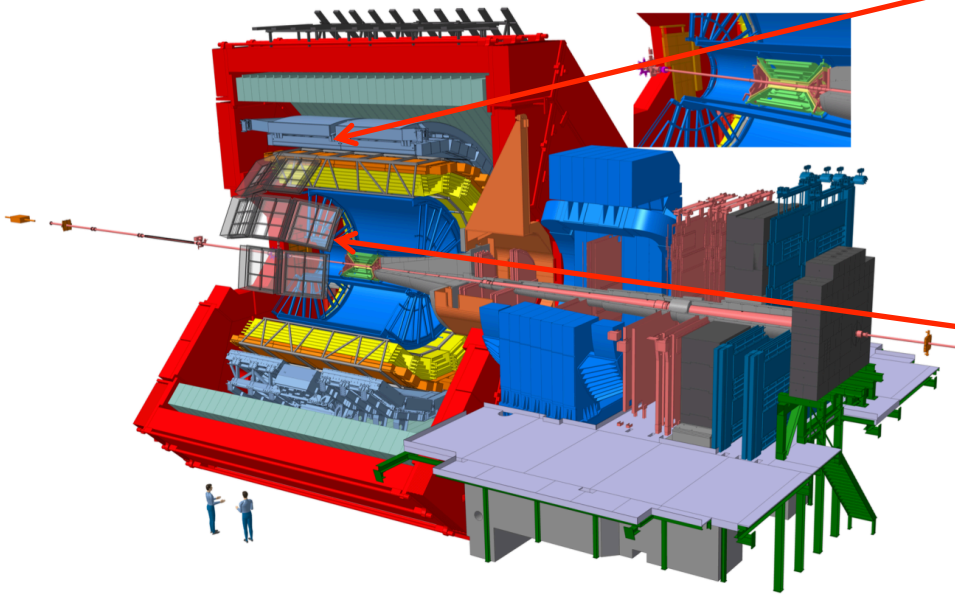
- Alignment of radiation relative to returned axes is similar in Pb-Pb and PYTHIA.
- **No quenching modifications** observed in a variety of different types of splittings.
- k_T and Soft Drop :
  - A shift to larger values expected if jets are "resolved".
  - A shift to lower values expected with medium induced semi-hard radiation.

Conclusions

- Reclustering algorithms varied to probe **different scales** in the splittings.
- **No modification** of the the **two-pronged substructure** of jets observed in the medium.
- A **significant modification** of the z_g **distribution** observed in the medium.
- **Large angle splittings** appear **suppressed** in data.
- The **number of hard splittings** are **not enhanced** in data.
- These measurements represent an ongoing effort to systematically investigate jet substructure at ALICE.

BACKUP

ALICE Detector



- **EMCal** : neutral constituents

  $p_{T,cutoff} = 300$ MeV/c

  $|\eta| < 0.7$

  $1.4 < \varphi < 3.1$

  Jet trigger

- **ITS + TPC** : charged constituents

  $p_{T,cutoff} = 150$ MeV/c

  $|\eta| < 0.9$