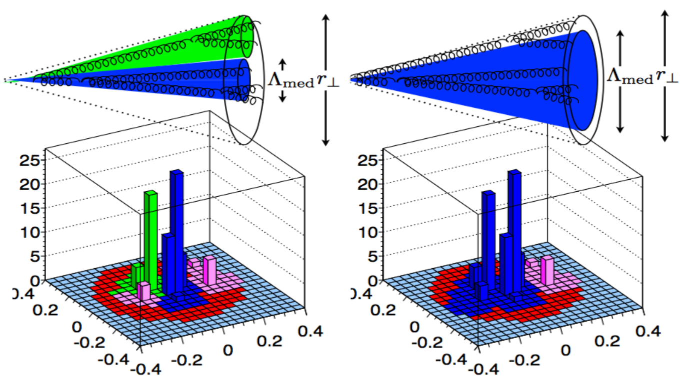
Investigating the Role of Coherence Effects on Jet Quenching in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV using Jet Substructure

Nima Zardoshti (Birmingham) for the ALICE Collaboration

Colour Coherence



Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk Phys.Lett.B ***725*** *(2013) 357–360*

Partons that are separated by less than the characteristic scale of the medium, Δ_{med}, won't be resolved as independent emitters.

$$\Delta_{med} \simeq 1 - e^{-\frac{1}{12}\hat{q}Lr_\perp^2} \equiv 1 - e^{-(\theta/\theta_c)^2}$$

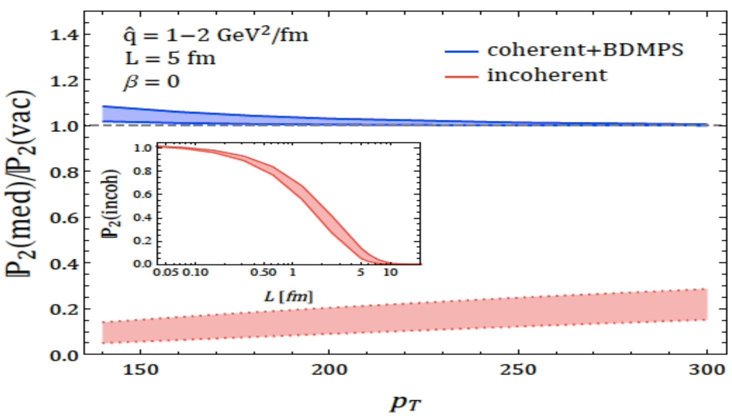
Where θ is the opening angle of the jet and θ_c is the characteristic scale determined by the medium.

The opening angle of the jet is defined by the largest antenna, given by the first splitting (in vacuum).

Two consequences if colour coherence is in effect:

- Non-resolved jets will radiate coherently as a colour singlet and substructure will be pp like (energy shifted).
- Resolved jet constituents will radiate incoherently resulting into a stronger energy loss.

Colour Coherence



[Mehtar-Tani, Tywoniuk, arXiv 1610.08930]

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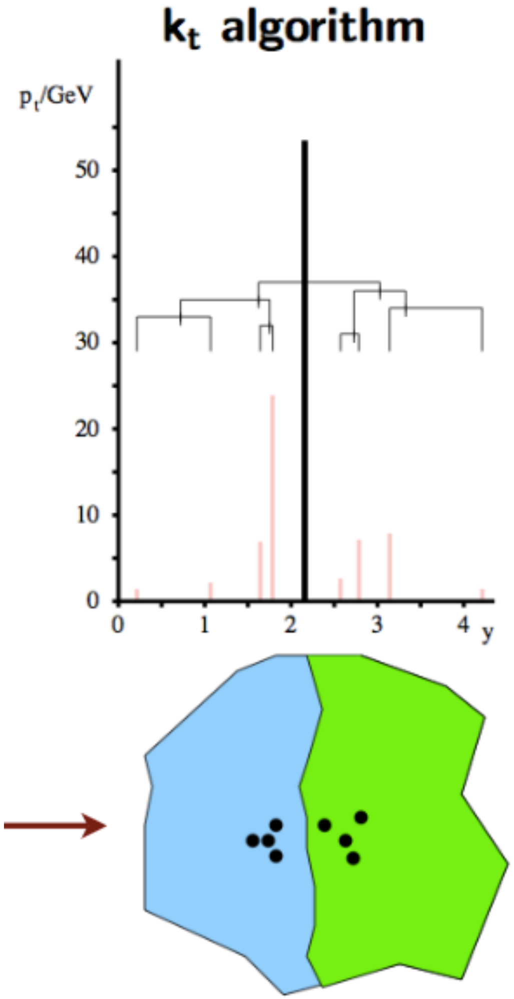
Theoretical calculations, using C/A and soft-drop at high p_T to define axes of first splitting, predict a sensitivity in the probability of 2-pronged jets to coherence effects.

In the case of incoherence the probability of 2-prongeness is dramatically suppressed.

In the coherent emission + hard BDMPS radiation case, an enhancement of the 2-pronged probability is expected.

Antenna Axes Calculation



- Recluster jet constituents with k_T algorithm in exclusive mode and $N_{subjets}$=2 .
- The two axes are the axes of the two subjets combined in the last step of the reclustering algorithm history.
- No angular or p_T cuts are introduced, no jets are rejected (only single track jets are rejected).
- We then measure jet shapes relative to these axes:

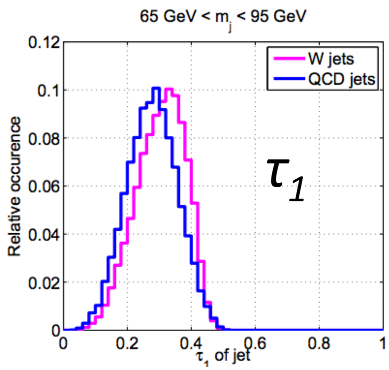
  * ΔR: aperture distance between the axes.

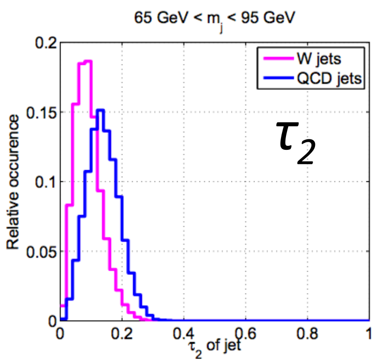
  * τ_2/τ_1: observable that measures how well the jet constituents are aligned with respect to the two axes.

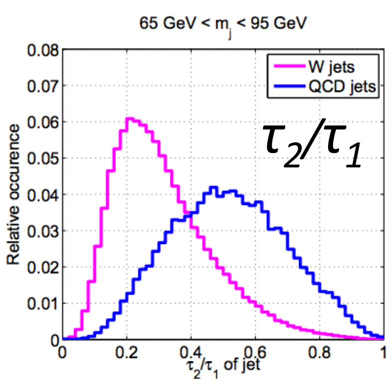
Fig. from M.Cacciari, https://indico.cern.ch/event/502239/contributions/2279351/

W jets
QCD jets

ΔR and Nsubjettiness







ΔR and τ_2/τ_1 are calculated relative to the two antenna axes.

- ΔR -> η-φ distance between axes.
- τ_2/τ_1 -> measures the two prongness of the jet.

-The Nsubjettiness, τ_N, jet shape (where *N* can be any positive integer) is a measure of how *N* pronged a jet's substructure is.

-Initially developed to tag jets from Higgs decays such as Higgs -> W^+W^-.

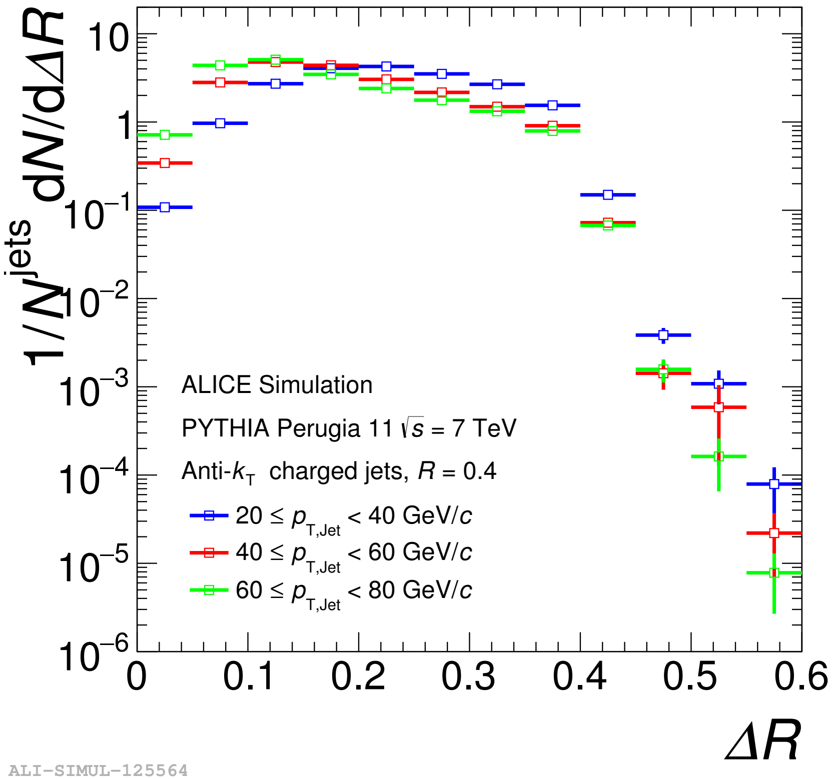
$$\tau_N = \frac{\sum_{i=1} p_{T,i} Min(\Delta R_{i,1}, \Delta R_{i,2}, ..., \Delta R_{i,N})}{R_0 \sum_{i=1} p_{T,i}}$$

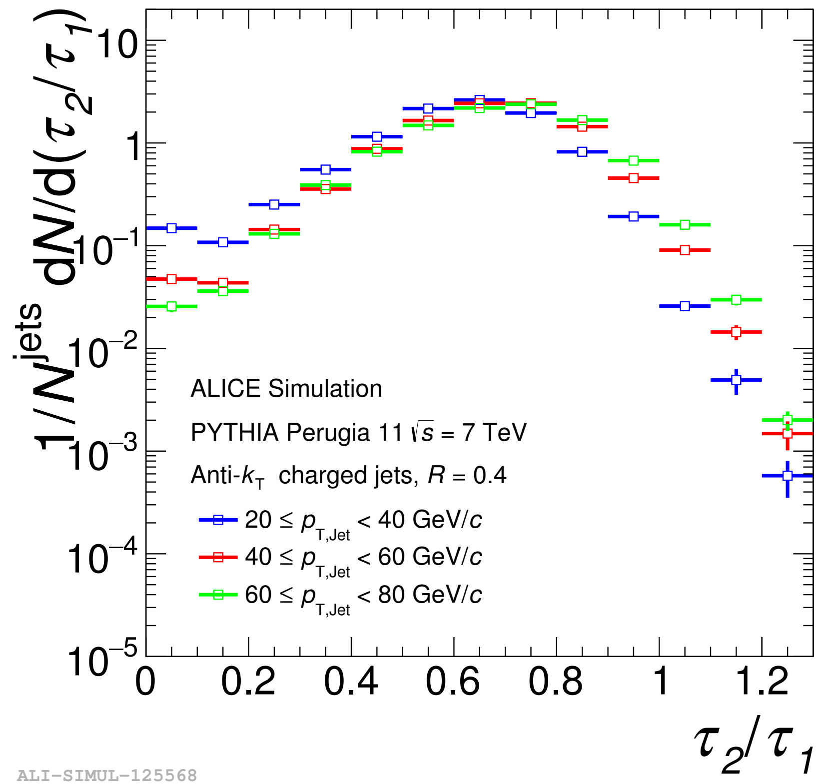
$\Delta R_{i,j}$ -> η-φ distance between track i and subjet j
$p_{T,i}$ -> p_T of i^{th} jet constituent
R_0 Jet resolution parameter

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 2 pronged

[J.Thaler et al,JHEP 1103:015,2011]

ΔR and τ_2/τ_1





- ΔR: opening angle between axes.
- τ_2/τ_1: by how much jet constituents are aligned with respect to those axes.
- Mild p_T dependence of the shapes.

Analysis Details and Correction Procedure

ALICE

Raw distributions:

Two systems: pp Minimum Bias at $\sqrt{s}$=7 TeV and Pb-Pb (0-10% central) at $\sqrt{s_{NN}}$=2.76 TeV

Charged particle tracks as input, p_T^{const} > 0.15 GeV/*c*

anti-k_T algorithm, *R*=0.4, E-scheme

Background subtraction:

Average background removal from shape observables event-by-event using new techniques:

Derivative (Area based) Subtraction *[G.Soyez et al, Phys.Rev.Lett 110 (2013) 16] .*

Constituent Subtraction *[P.Berta et al, JHEP 1406 (2014) 092]* ***(default method).***

Combinatorial background suppressed in Pb-Pb using hadron-jet coincidence technique.

Correction for residual background fluctuations and detector effects via unfolding:

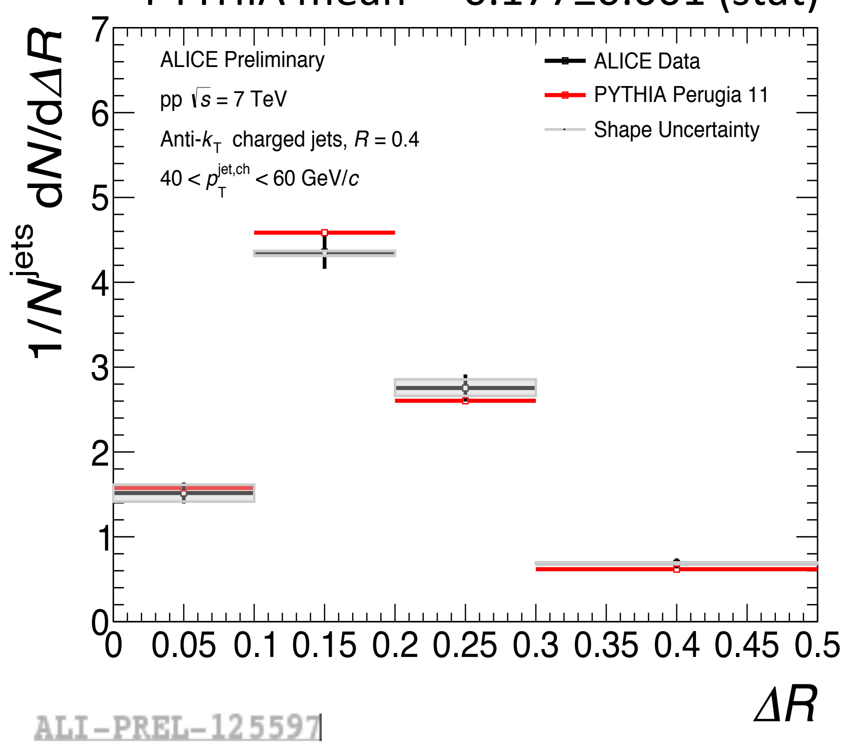
2D Bayesian techniques (*T.Adye, CERN-2011-006)2011) 13*).

are applied to unsmear the jet p_T and the shape simultaneously.

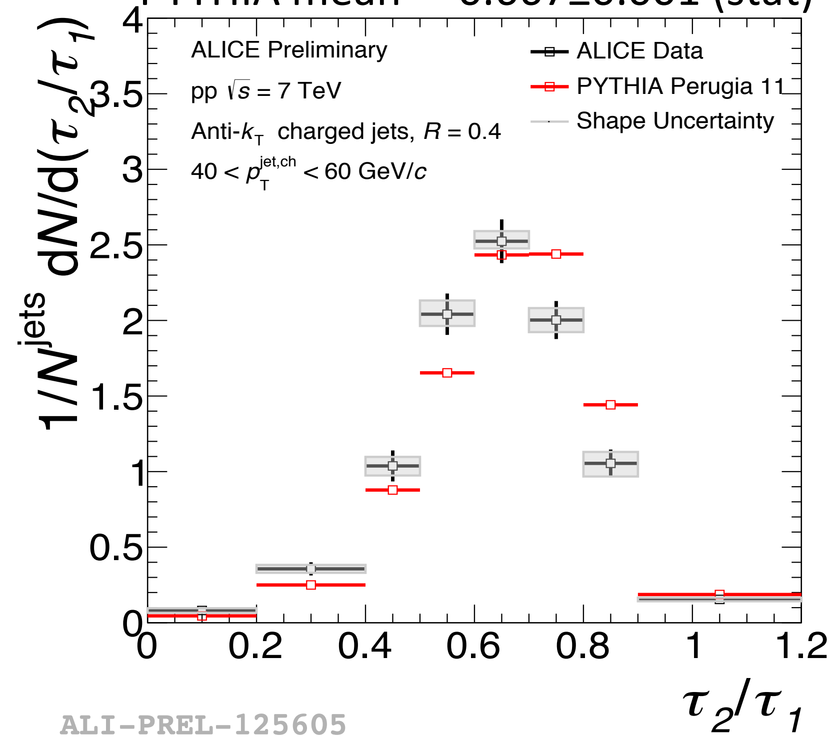
Reported results in p_T range: 40-60 GeV/*c* in both systems.

Fully Corrected pp Results

Data mean = 0.182±0.003 (stat)
PYTHIA mean = 0.177±0.001 (stat)



Data mean = 0.638±0.005 (stat)
PYTHIA mean = 0.667±0.001 (stat)



The systematic uncertainties include contributions from the tracking efficiency uncertainty (dominant), choice of the prior, regularization and truncation of the input

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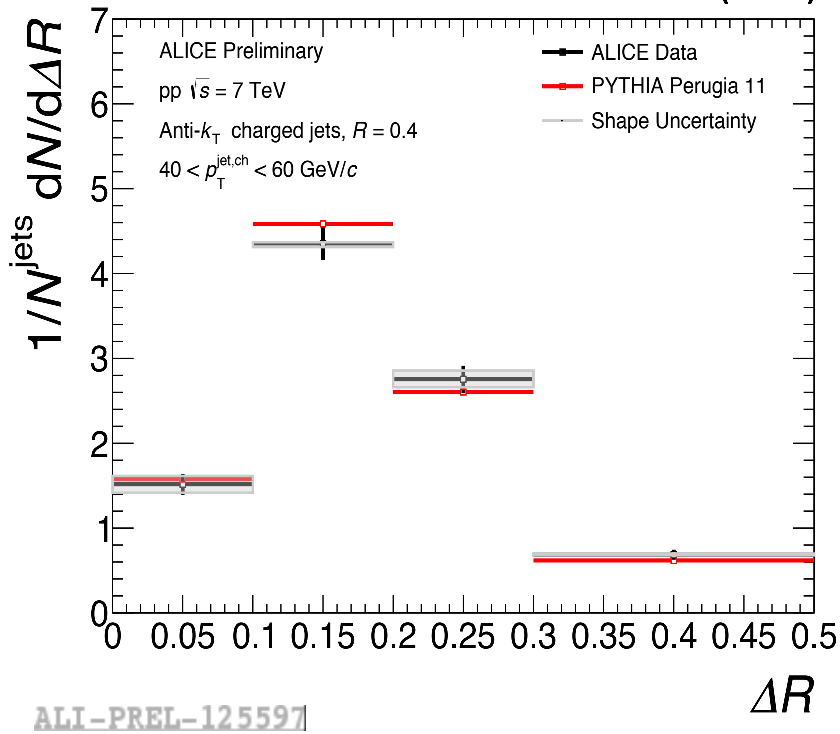

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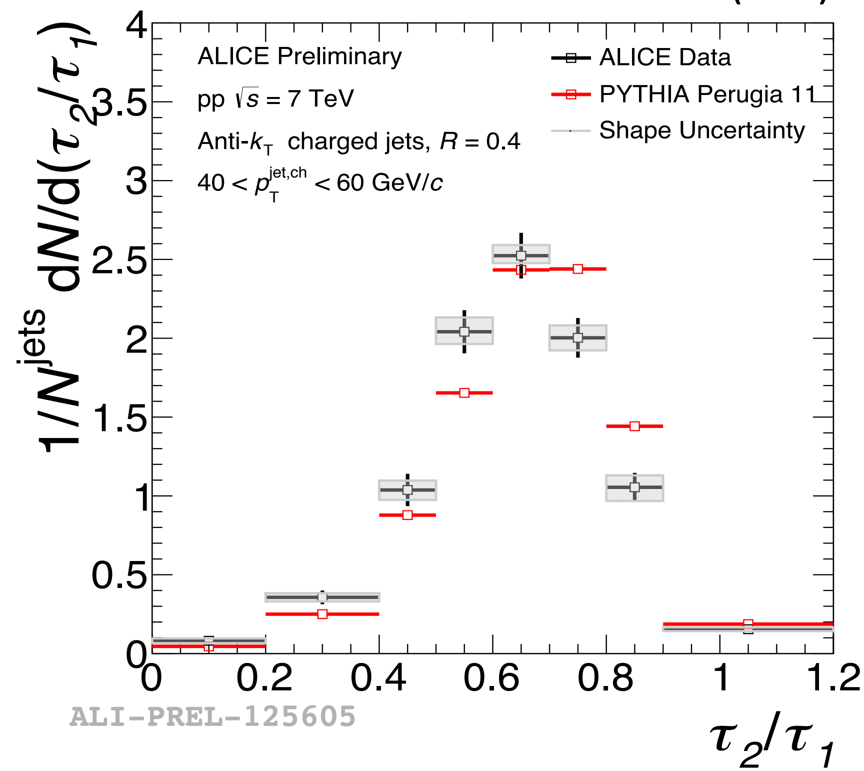
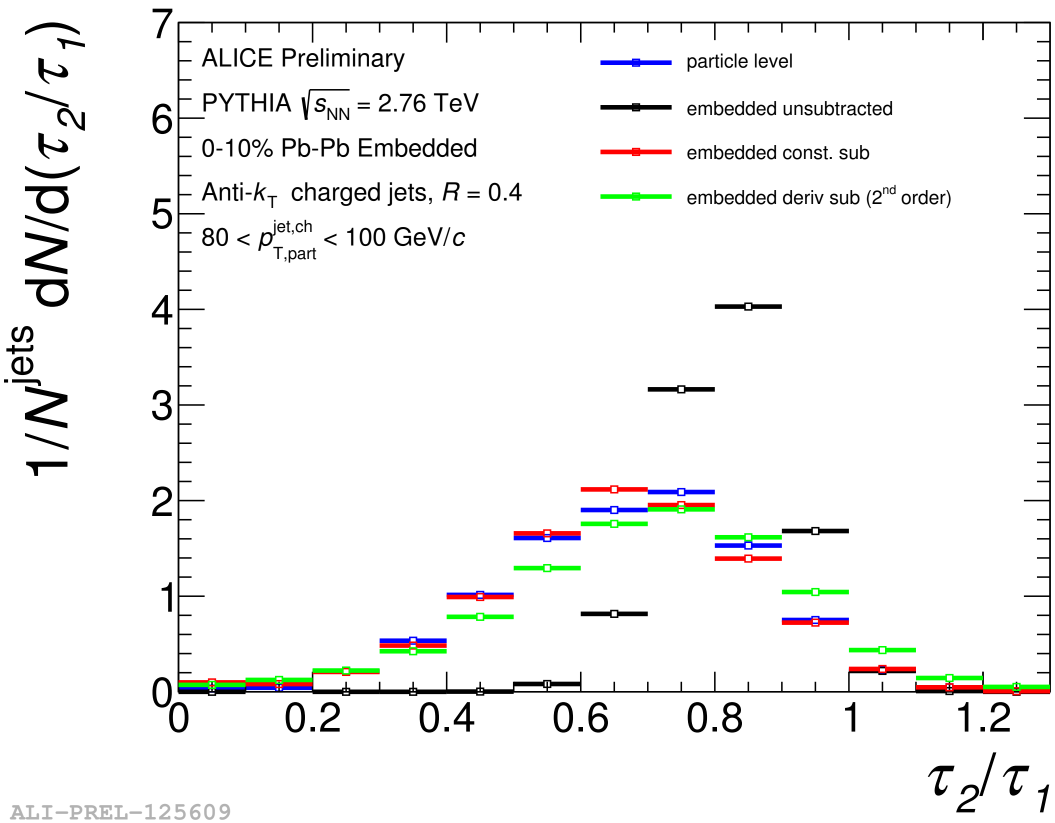


- ΔR well described by PYTHIA.
- Worse agreement for τ_2/τ_1, mean shifted by 0.029±0.005 (stat).

Subtraction Performance in Heavy Ion Background



ALI-PREL-125609

PYTHIA jets embedded in real 0-10% most central Pb-Pb events.

Embedded level reconstructed jets matched to PYTHIA level part jets to form response.

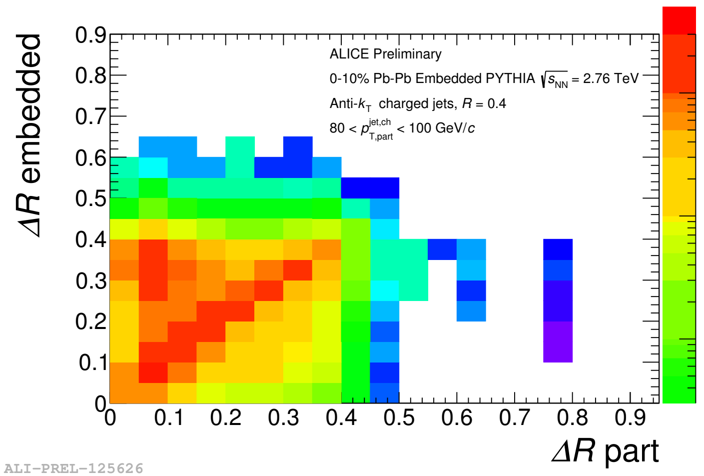
New subtraction methods applied to subtract the pedestal background per jet simultaneously from the shape and the p_T:

- Constituent Subtraction
- Derivative Subtraction

- Subtracted jet shape approaches that of original probe.
- Small Residual differences corrected via unfolding.

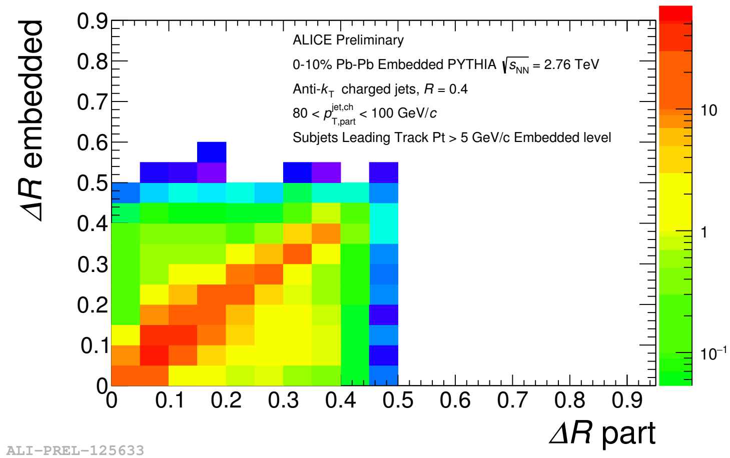
Heavy Ion Environment Background Response

ΔR is modified by background fluctuations
that replace a subleading axis at large angle.

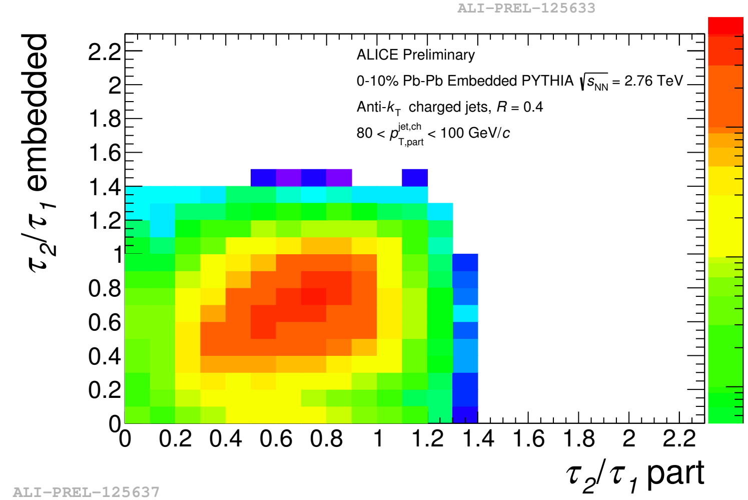


5 GeV/c cut on leading tracks in each subjet

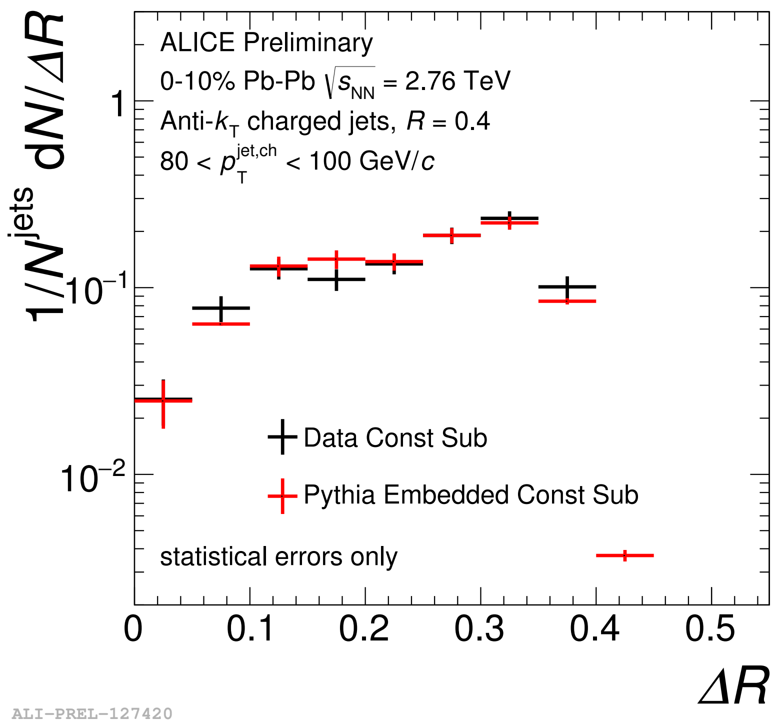
Suppresses shift in axes due to soft background

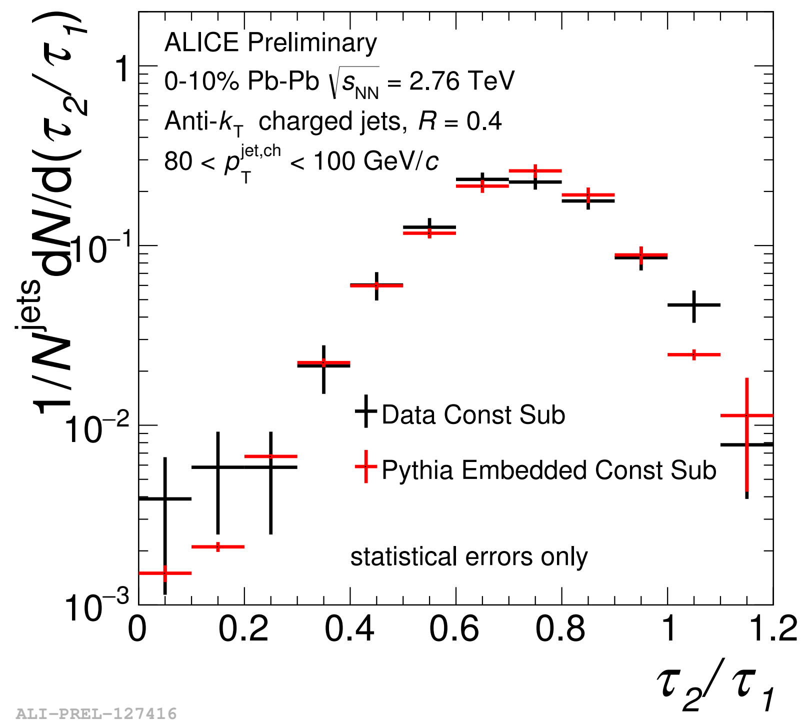


τ_2/τ_1 resilient to shift in axes due to soft/large angle background.
The background fluctuation needs to carry a significant fraction of the jet momentum to modify τ_2/τ_1.



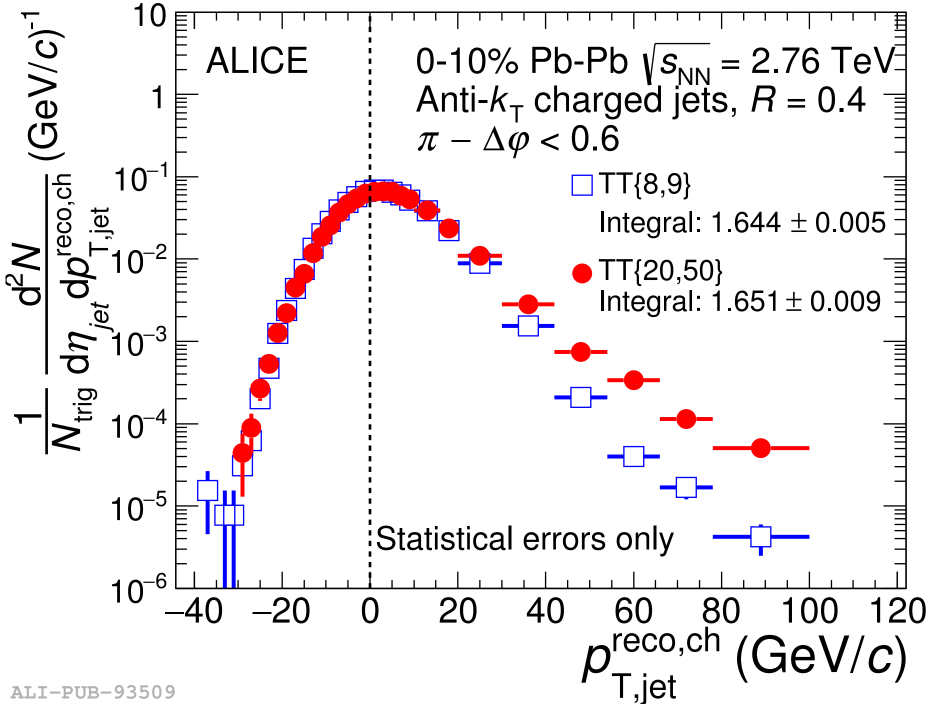
Comparison of Embedded PYTHIA and Raw Inclusive Pb-Pb Data



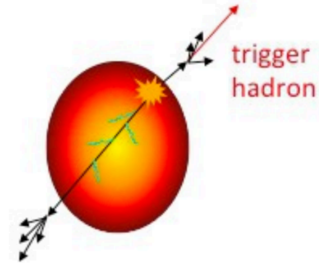


- Small differences between embedded PYTHIA and raw data point to small quenching effects.
- If jets were “resolved” a suppression of large *ΔR* jets would be expected – No Suppression observed.
- ->However there is a strong contamination of fake axes at large angles, due to background fluctuations. Needs full correction.

Substructure of Recoil Jets



ALICE,JHEP09(2015)170



Use semi inclusive hadron-jet coincidence measurements to suppress combinatorial background and to measure jets and jet substructure down to low p_T and large *R*.

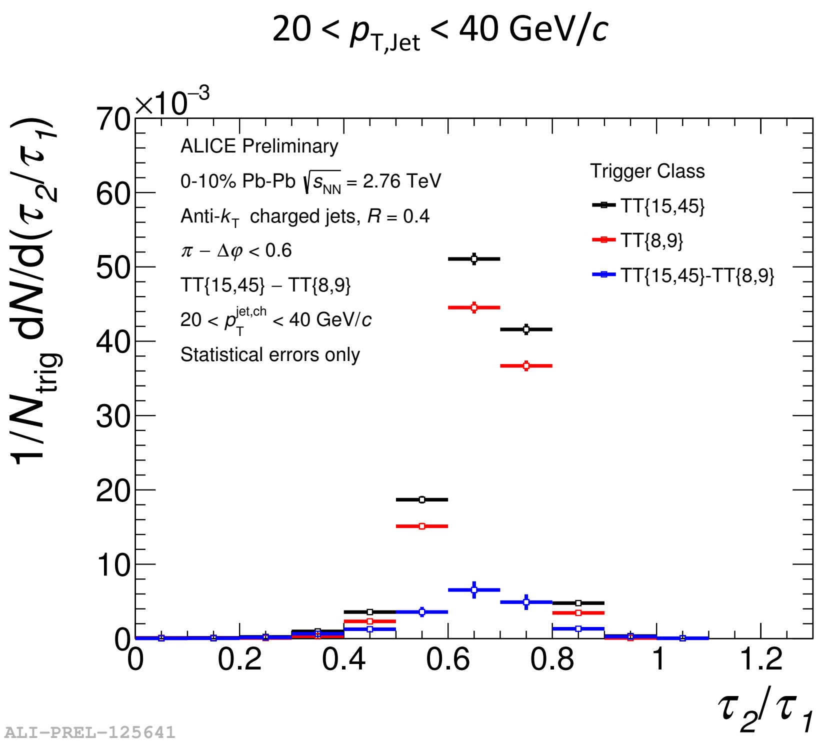
The yield of jets recoiling from two exclusive high p_T trigger classes is measured.

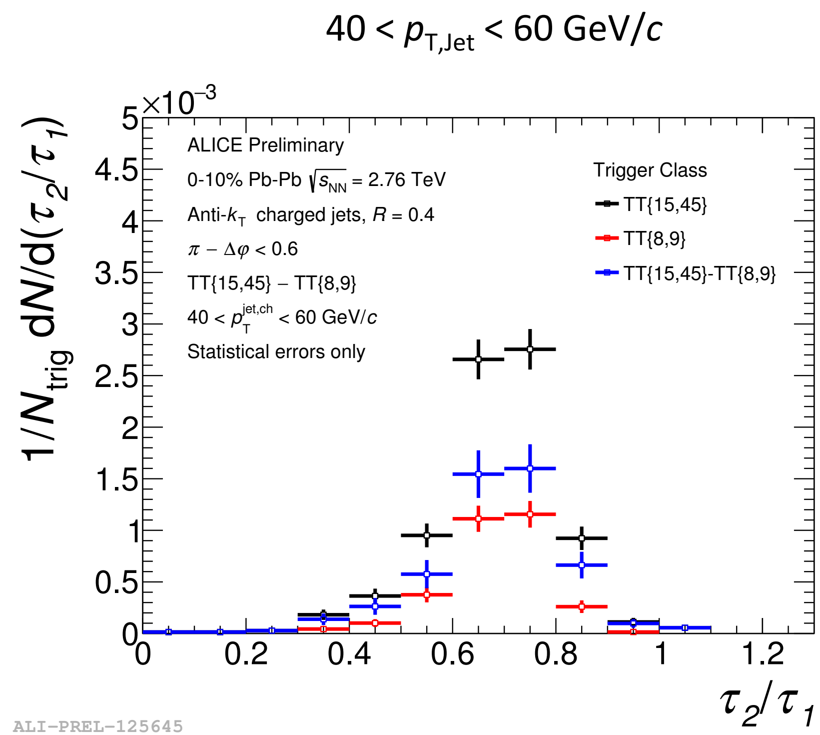
The difference in yield of the two classes provides an IRC-safe and combinatorial free jet sample that can be unfolded.

Extension of technique to 2D:

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

Raw Substructure of Recoil Jets

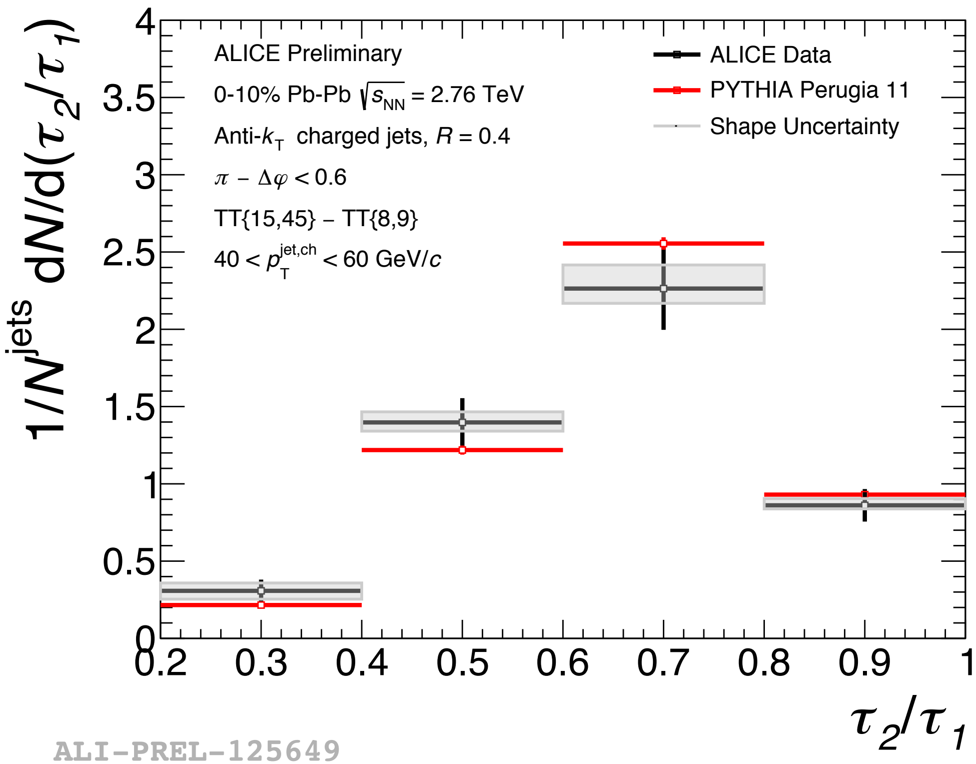




Difference yield approaches signal yield with increasing $p_{T,jet}$.

Fully Corrected Recoil Jet Shape in Pb-Pb

Data mean = 0.652±0.011 (stat)
PYTHIA mean = 0.670±0.002 (stat)



In addition to the systematic variations done in pp, the Pb-Pb analysis also considers the uncertainties due to:

- The choice of the subtraction method.
- The uncertainty due to the EP bias induced by the trigger track.

- Alignment of radiation relative to the two k_T axes is similar in Pb-Pb and PYTHIA
- Full correction of *ΔR* ongoing.

Alternative Axes Finding Strategies

The axes obtained by different strategies can be sensitive to processes of different scales

Axes finding strategies under investigation:

- k_T exclusive with N=2
- Minimisation (Multi-pass axes)
- C\A on soft dropped jets (Axes finding done post grooming)
- Other strategies of interest

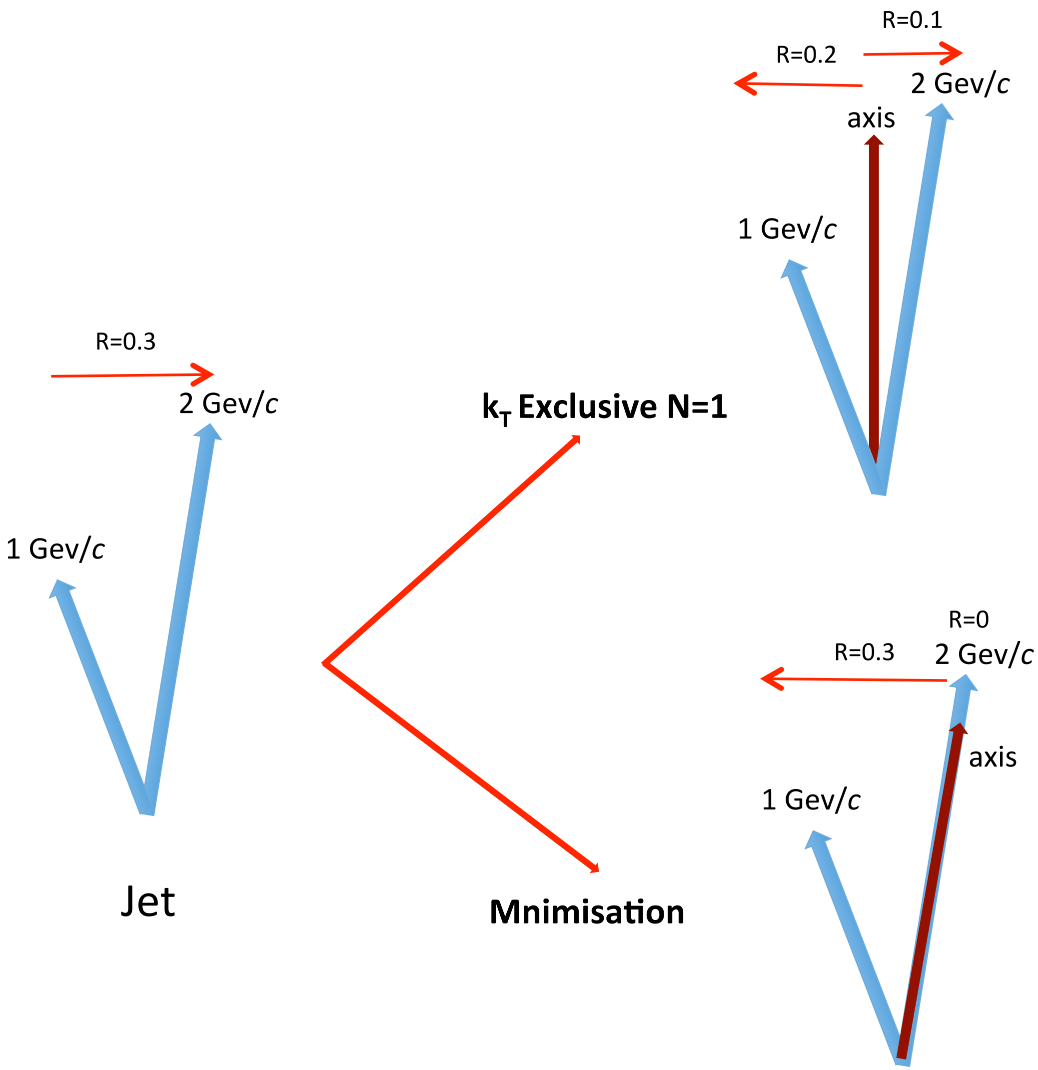
Minimisation Strategy

To find N axes:

- Pick N random starting axes
- Perform an iterative minimisation procedure to determine a local minimum for N-subjettines
- Repeat process X (X=100 for this analysis) times with different random starting axes
- Pick the final axes that give the lowest minimum value (out of the X times performed)
- These axes are the best guess of the global minimum
- Calculate jet shapes using these axes

Choice of number of possible axes is not constrained by the number of jet constituents

Differences in Axes Finding Strategies



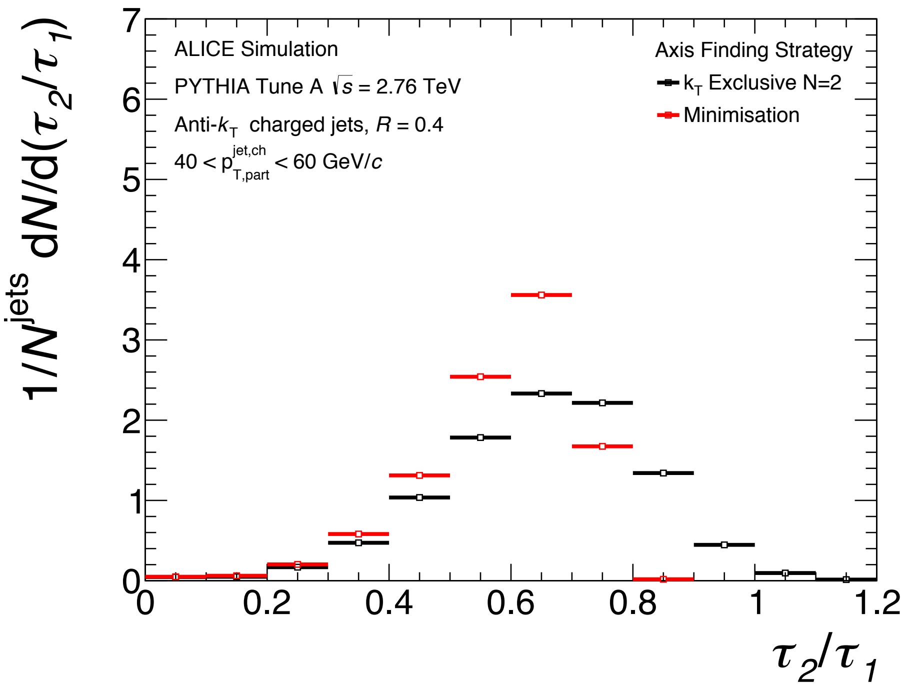
τ_1 numerator = $\sum_{i=0}^{N} p_{T,i} \Delta R_{i,1}$

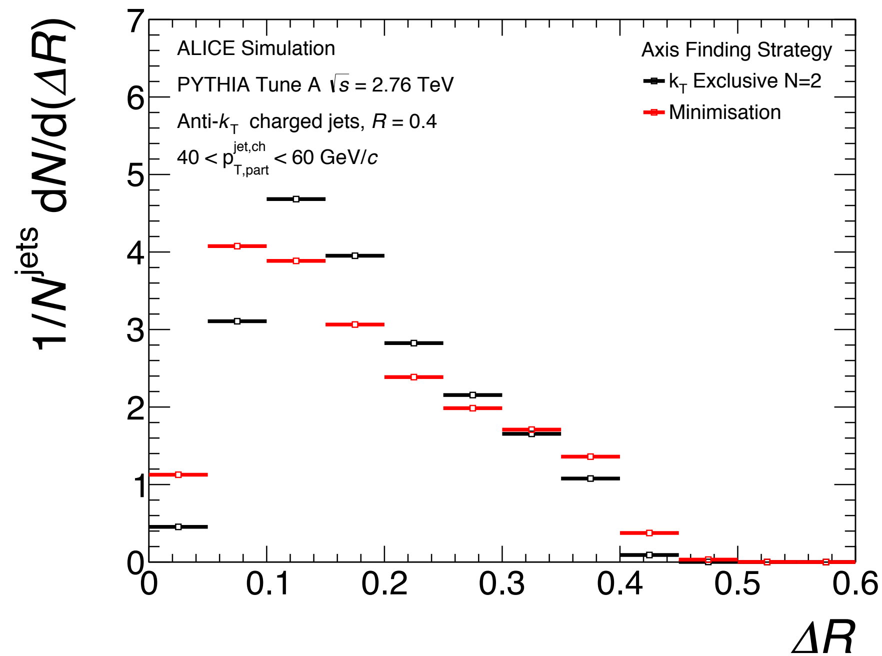
(1 x 0.2) + (2 x 0.1) = 0.2 + 0.2 = 0.4

In some cases the different strategies can have different results

(1 x 0.3) + (2 x 0) = 0.3 + 0 = 0.3

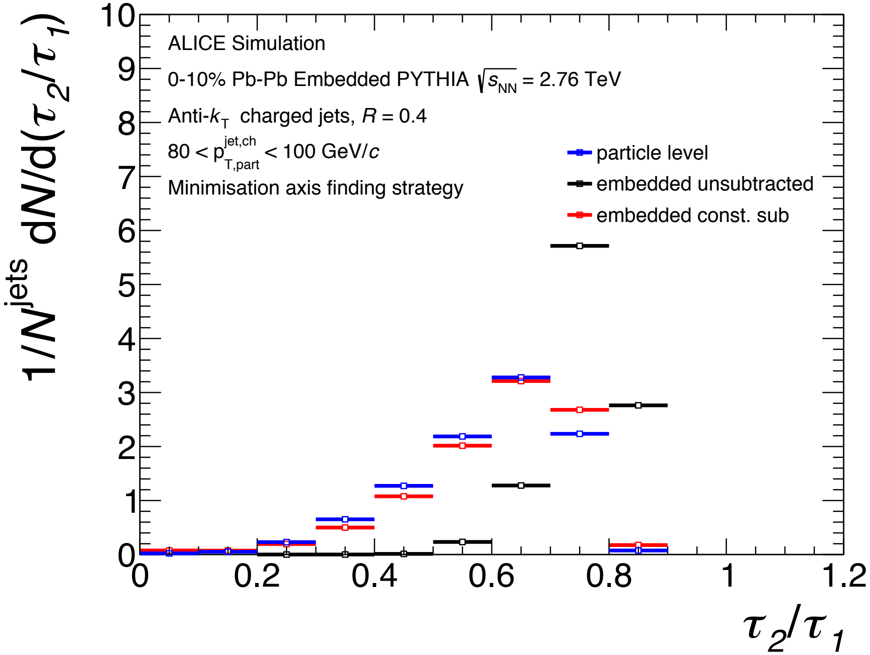
PYTHIA comparisons of the strategies

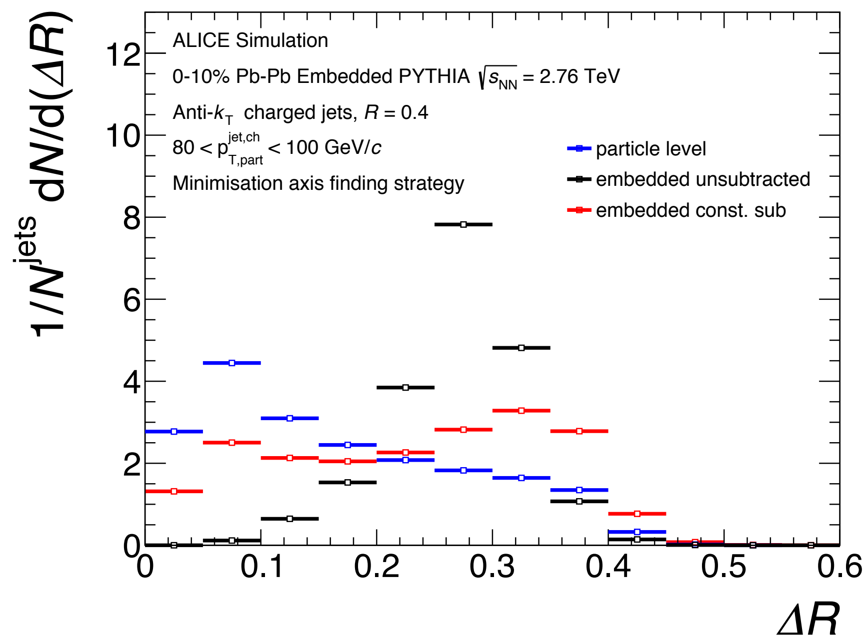




- Minimisation axes finding strategy shifts both shapes to lower values
- Shift expected in τ_2/τ_1 due to nature of minimisation (attempt to find global minimum)
- Minimisation of τ_2/τ_1 leads to enhancements at either end of the ΔR shape

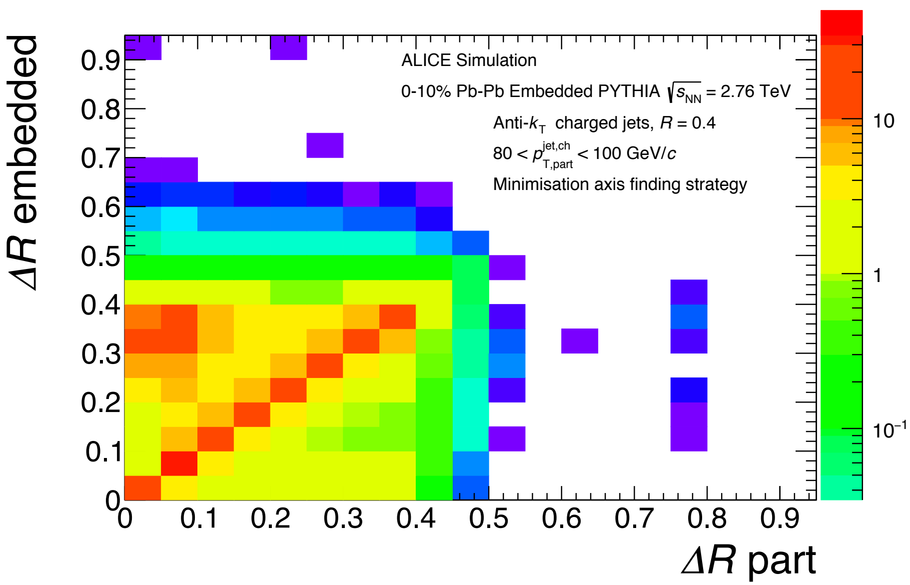
Subtraction Performance in Minimisation Strategy

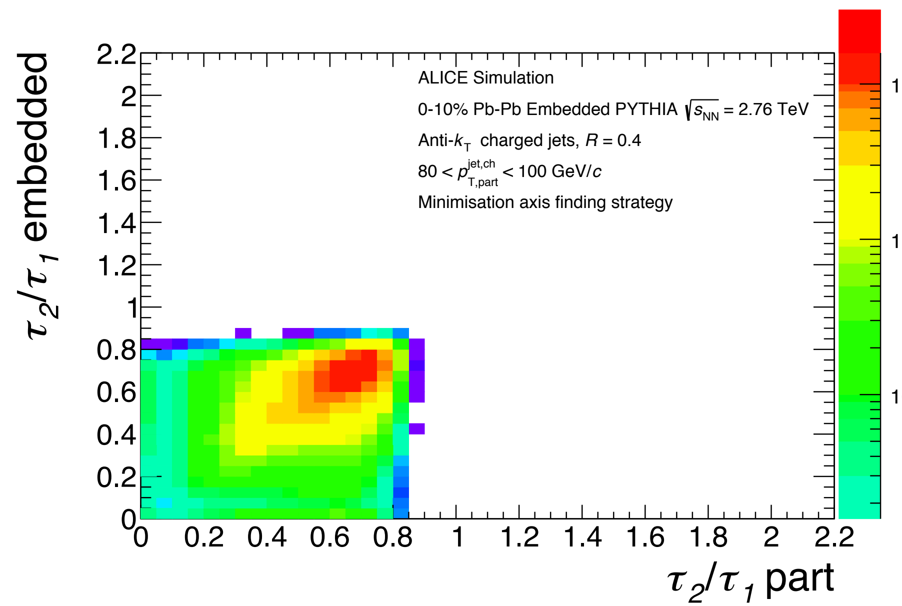




- Constituent subtraction corrects the shapes back to particle level well for τ_2/τ_1
- ΔR shape not well corrected for all jets. **Low p_T large angle** background remnants responsible for large effects?

Responses Obtained from Embedding with Minimisation Strategy





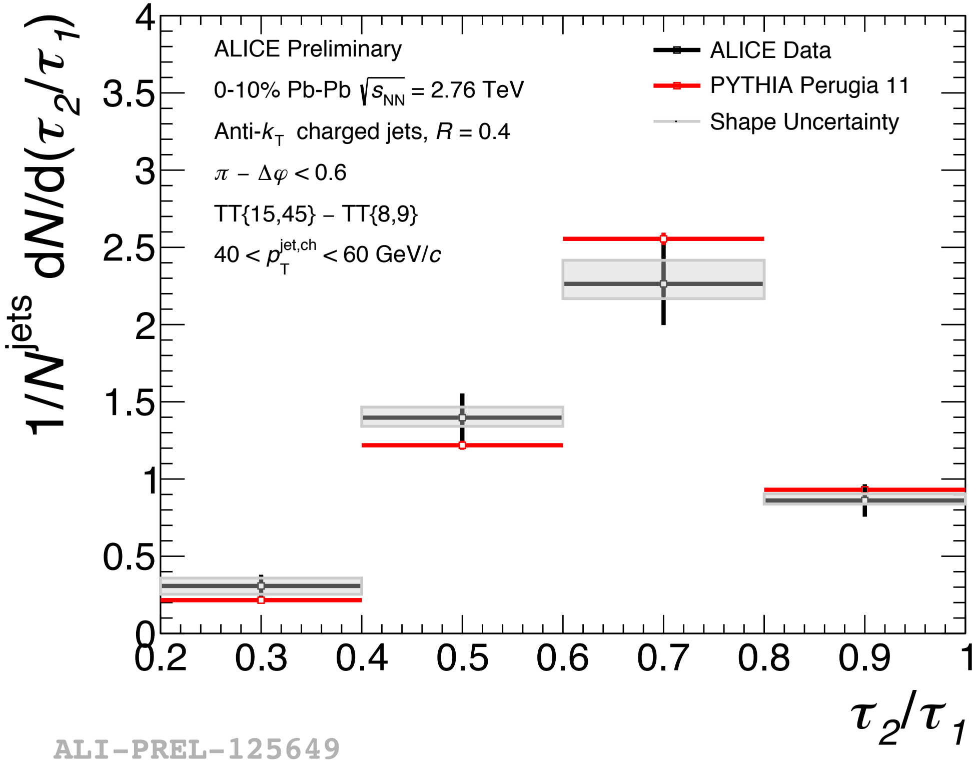
- Both shapes have a more diagonal response compared to the k_T exclusive N=2 case
- 2nd peak still present in ΔR - constituent subtraction does not fully correct the variable
- These responses will be used as input to the unfolding of the recoil data

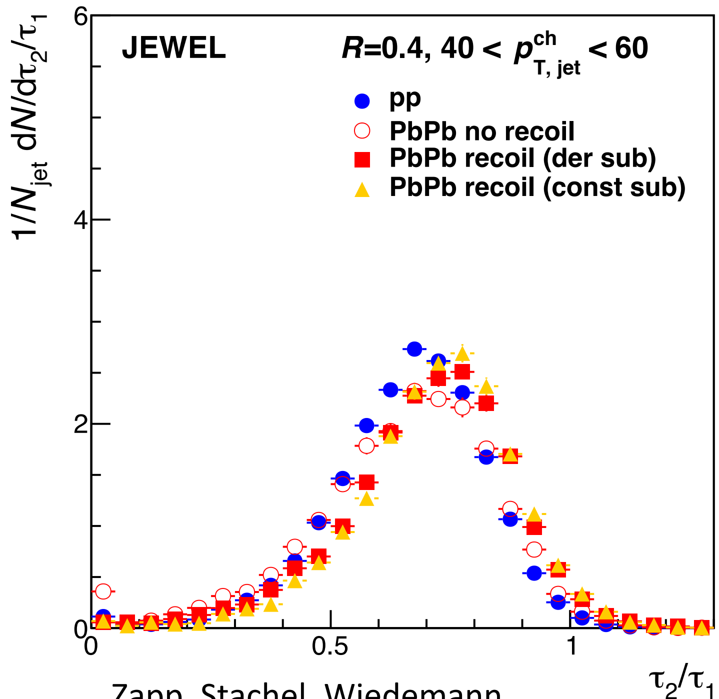
Conclusions

- Measurement of new shapes sensitive to coherence effects by exploiting the **jet clustering history.**
- First fully corrected jet shape measurement at **large resolution R and low jet p_T** using the hadron-jet coincidence technique.
- Fully corrected τ_2/τ_1 jet shape for recoil jets of 40-60 GeV/*c* presented. Structure appears unmodified in medium compared to PYTHIA. **Rare BDMPS gluon emissions within the cone are expected to make the jets less 2-subjetty** in this jet p_T range.
- Will explore the feasibility of **3D unfolding** in order to study the angular separation (ΔR) of tagged two-pronged jets (τ_2/τ_1)
- These **exploratory measurements** pave the way for more systematic and detailed studies of jet substructure to probe key aspects of jet quenching such as rare semi-hard BDMPS gluons and colour coherence.

BACKUP

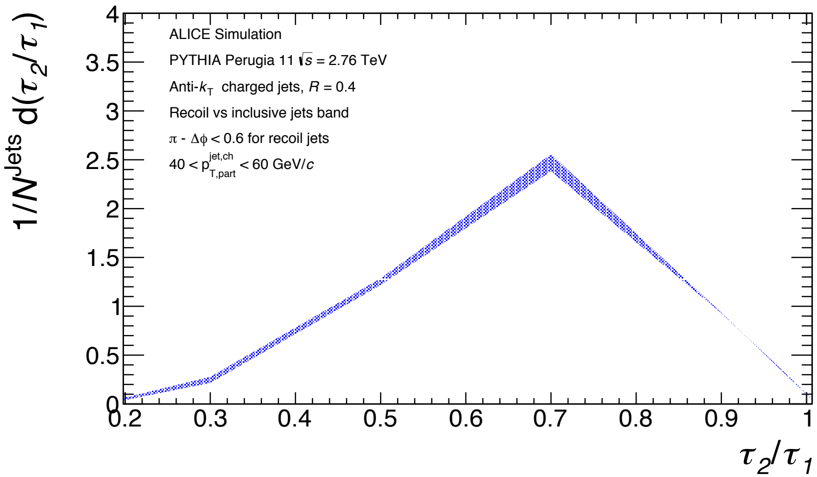
Model Comparison





Zapp, Stachel, Wiedemann, PoS High-pTphysics09:022,2009

Incoherent radiation as modelled by JEWEL shifts the τ_2/τ_1 distribution towards less 2-pronged jets possibly due to back-reaction and semi-hard gluon radiation.



Recoil vs Inclusive PYTHIA band