Nikhef

CIPANP 2018: May 29 – June 3, 2018 Palm Springs, CA

ALICE

Parton shower modification studied with jet substructure in ALICE

Davide Caffarri (NIKHEF), for the ALICE Collaboration

In-medium energy loss

- Partons with high energy and virtuality lose energy through the medium
  - at large angle → jet not modified “pp-like”
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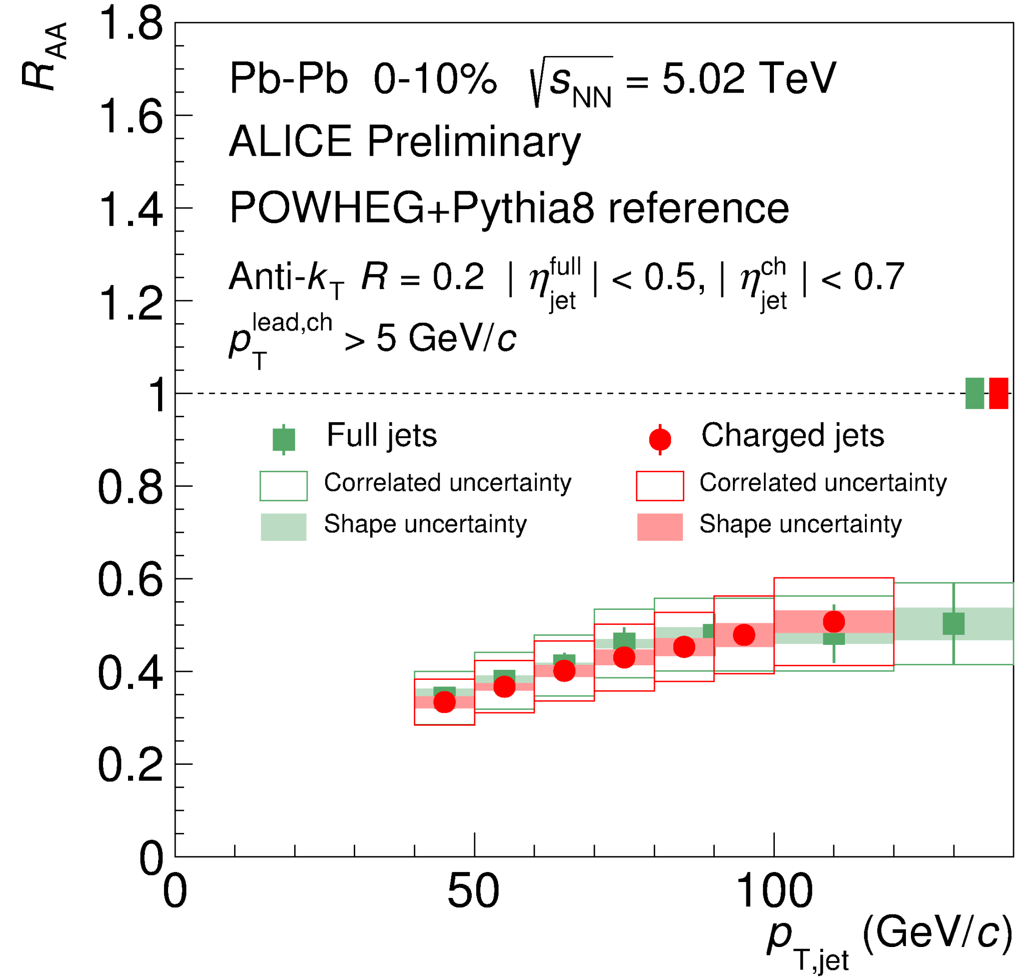
$$R_{\mathrm{AA}} = \frac{1}{< T_{AA} >} \frac{\mathrm{d}^2\mathrm{N}_{\mathrm{jet,ch}}/\mathrm{d}p_T\, d\eta|_{\mathrm{Pb-Pb}}}{\mathrm{d}^2\sigma_{\mathrm{jet,ch}}/\mathrm{d}p_T\, d\eta|_{\mathrm{pp}}}$$



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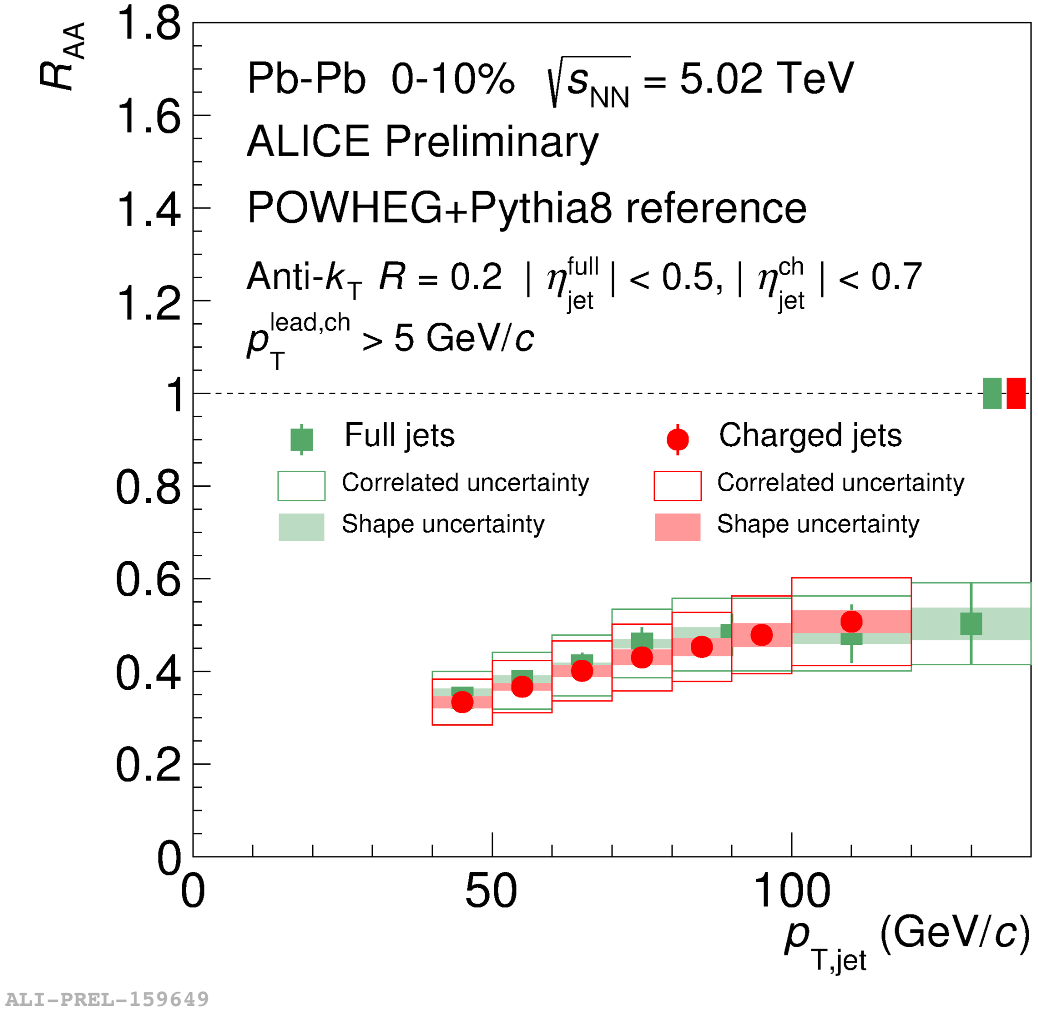
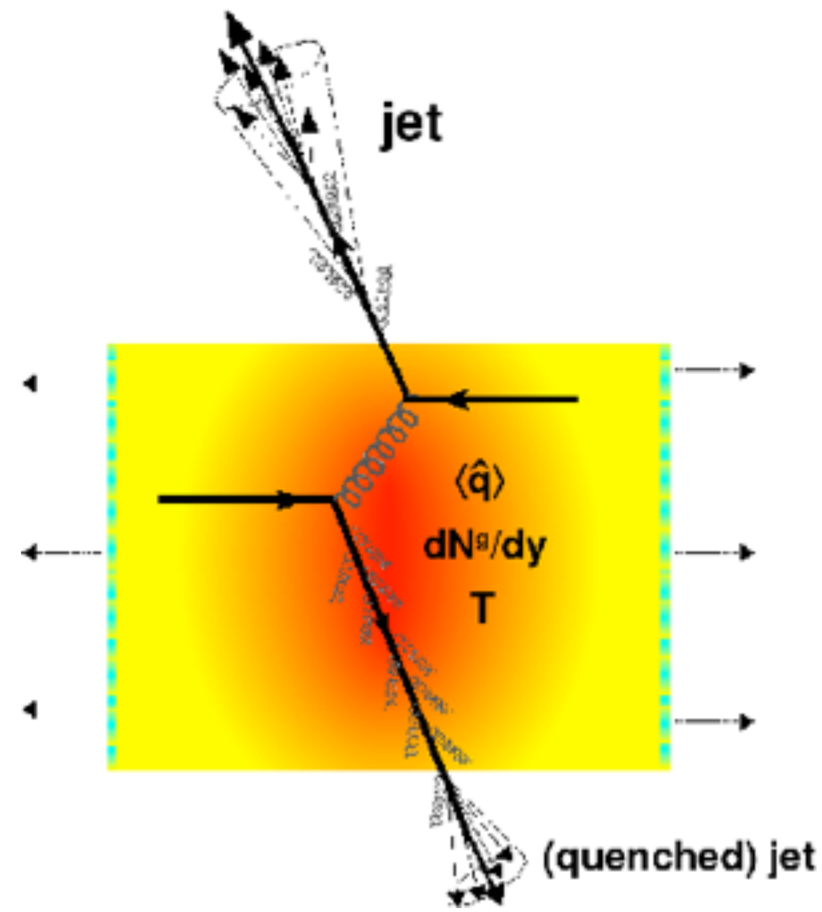
- Jet substructure allows to study:
  - **detailed mechanisms** of energy loss and splitting
  - modification of the **fragmentation**
  - **fundamental properties** of the medium (density, degree of freedom, …)

$$R_{AA} = \frac{1}{< T_{AA} >} \frac{d^2 N_{jet,ch}/dp_T d\eta|_{Pb-Pb}}{d^2\sigma_{jet,ch}/dp_T d\eta|_{pp}}$$



Jet substructure in ALICE

- ALICE has developed a program on jet substructure studies:
  - to establish a clean connection to theory
  - to probe different aspects of jet quenching:
    - energy redistribution
    - intra-jet broadening/collimation
    - enhanced splitting
    - mass hierarchy
    - colour coherence
  - focused on **low/intermediate p_T jet**:
    - stronger quenching effects expected
    - larger background to deal with
    - exploiting ALICE very good tracking resolution capabilities



D. d'Enterria, Nucl Phys A827 (2009) 365

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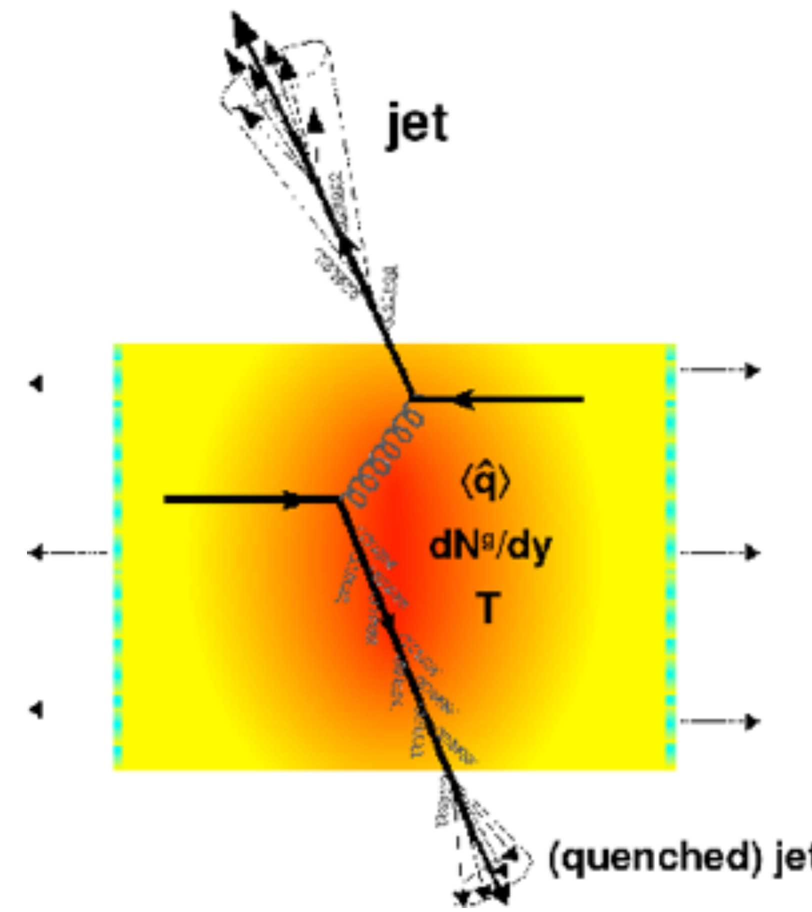

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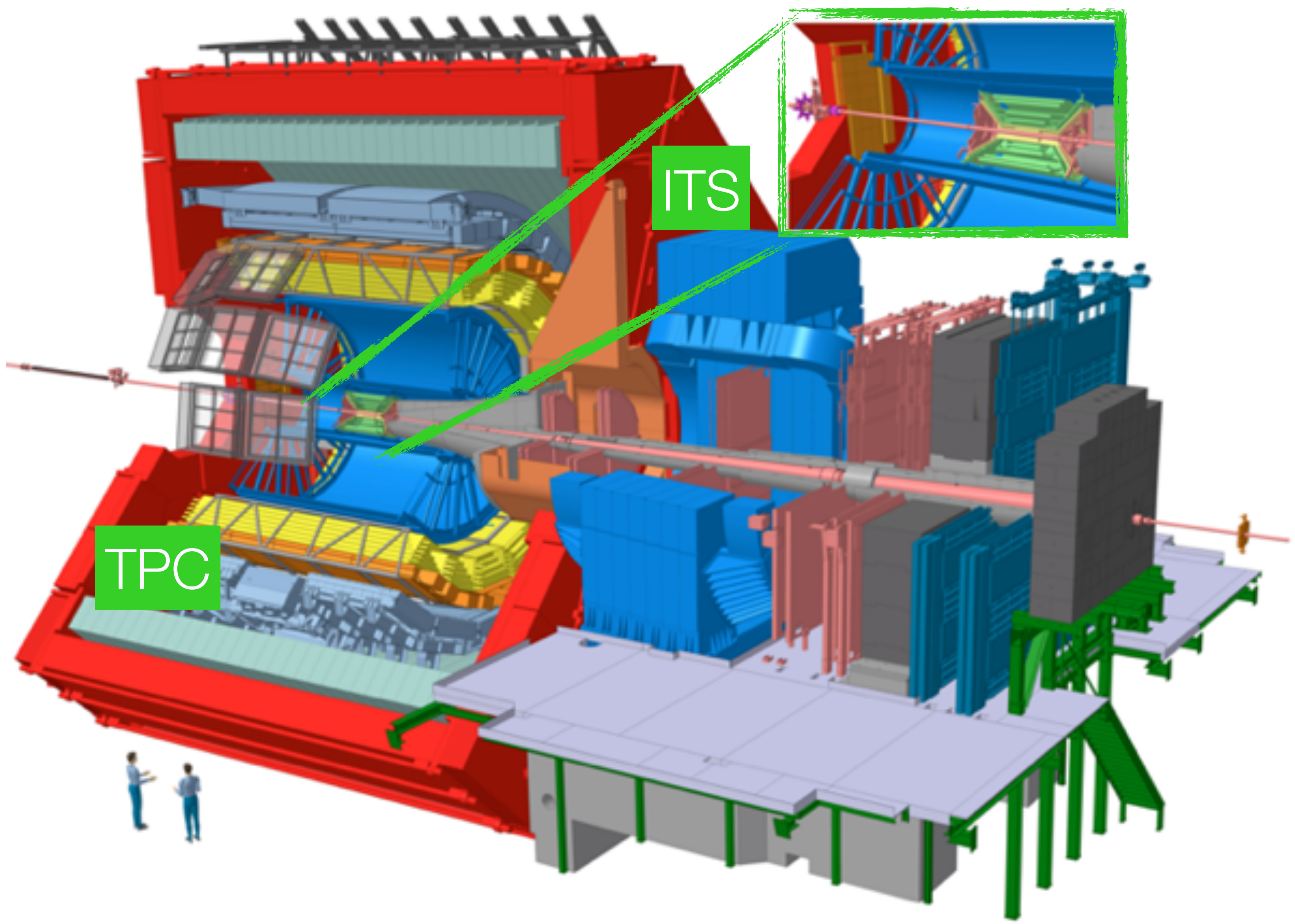
Disclaimer: due to time-limit, today I will show only Pb-Pb results.
pp results are agreement within ~20% with PYTHIA, used as reference (see back up slides)

Jet reconstruction in ALICE



$|\eta| < 0.9$, $0 < \varphi < 2\pi$

ITS: Inner Tracking System (silicon)

TPC: Time Projection Chamber

Track $p_T > 150$ MeV/c

Charged constituent jets (jet^{ch})

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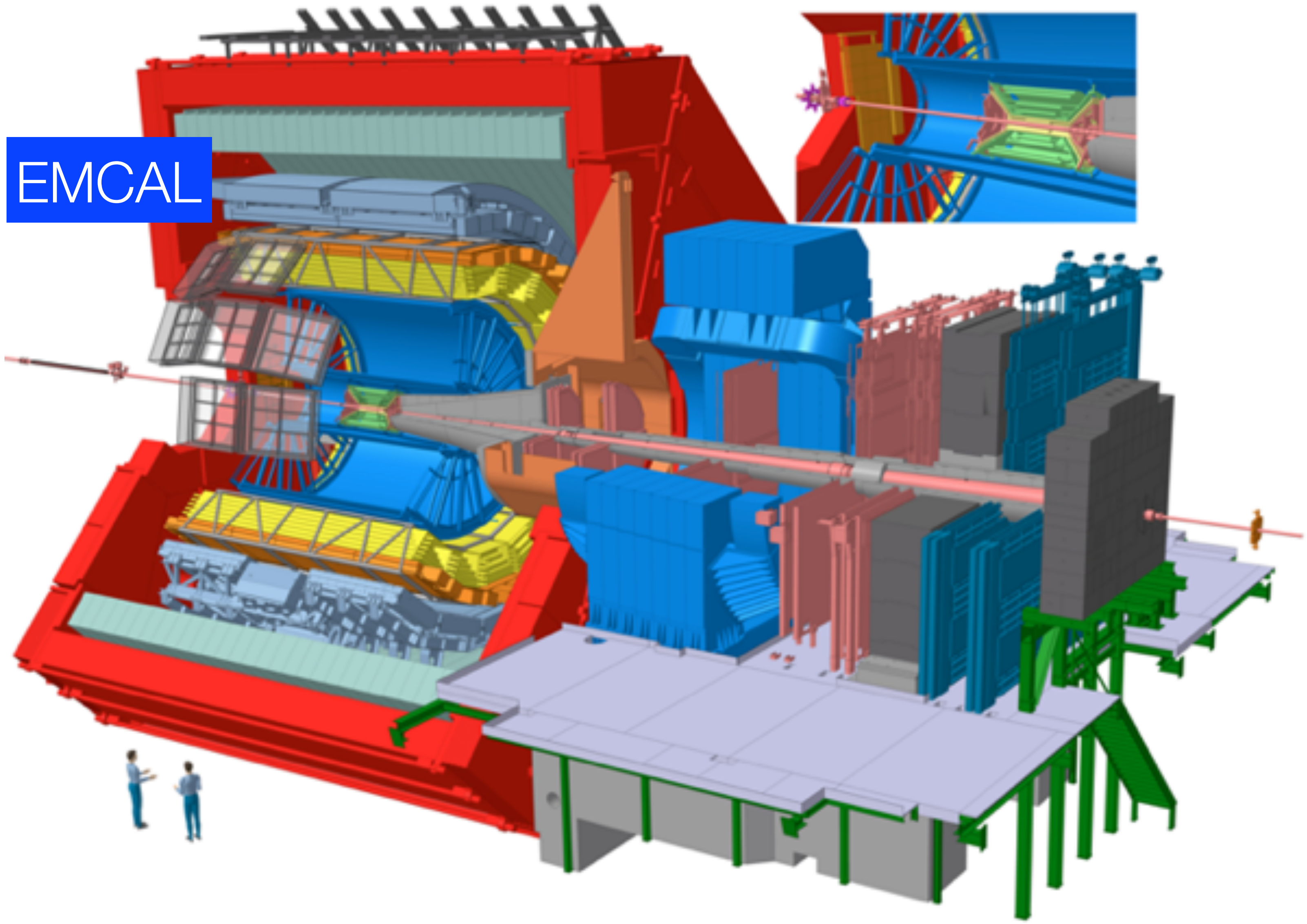

EMCAL: Pb scintillator sampling calorimeter
$|\eta| < 0.7$, $1.4 < \varphi < \pi$
$\Delta\eta = \Delta\varphi \approx 0.014$
Cluster $E_T > 300$ MeV

Neutral constituent jets

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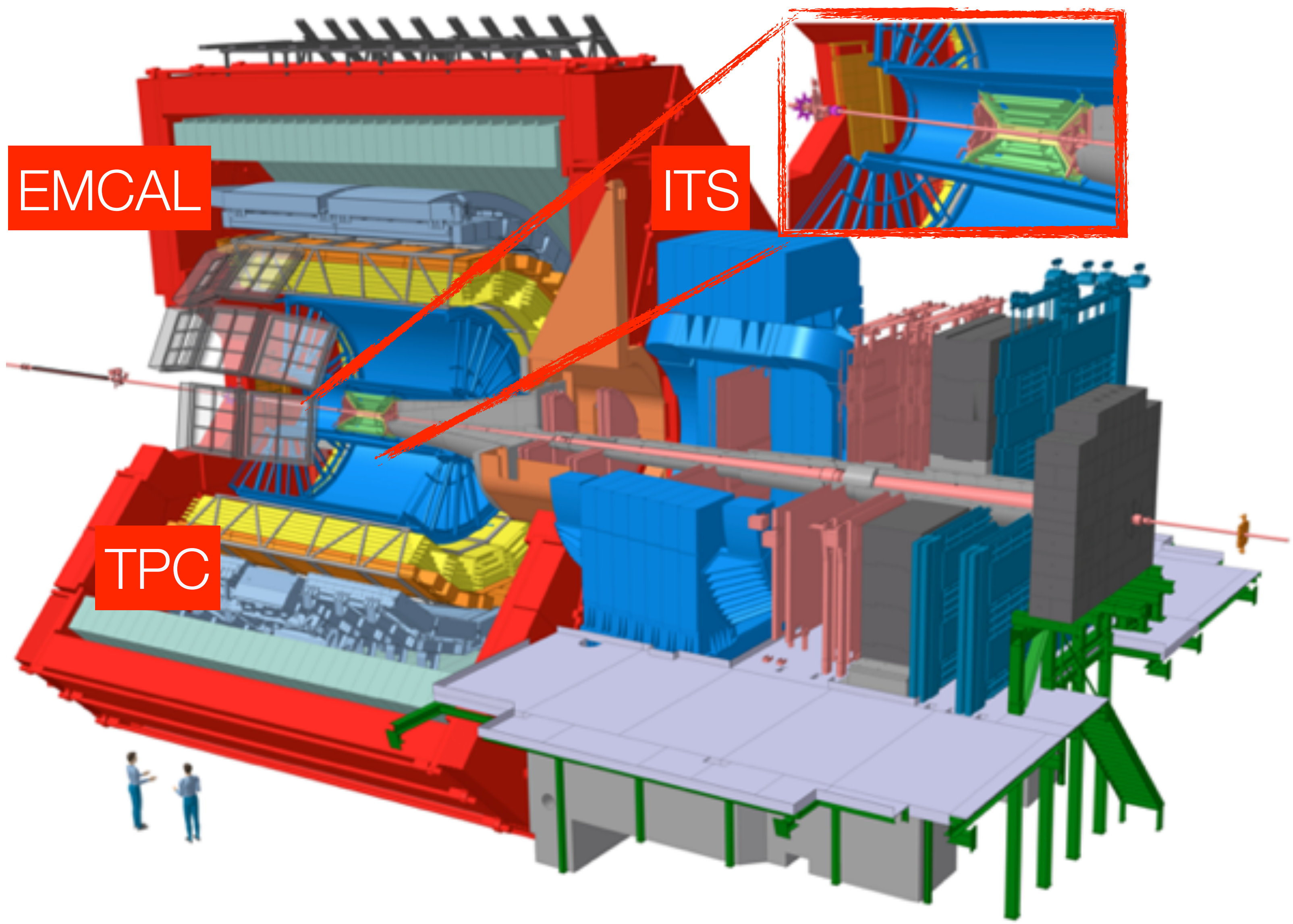

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Full jet reconstruction
matching the neutral and charged constituents

Jet shapes definitions

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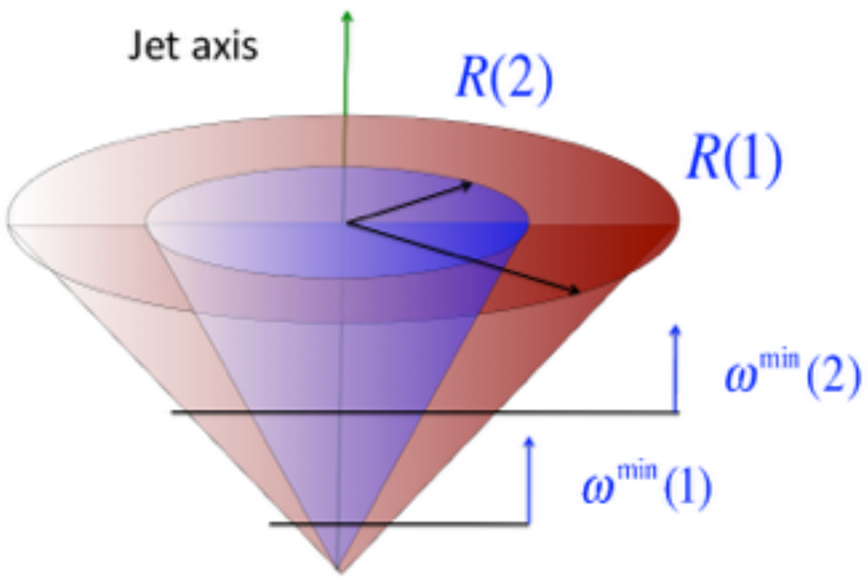
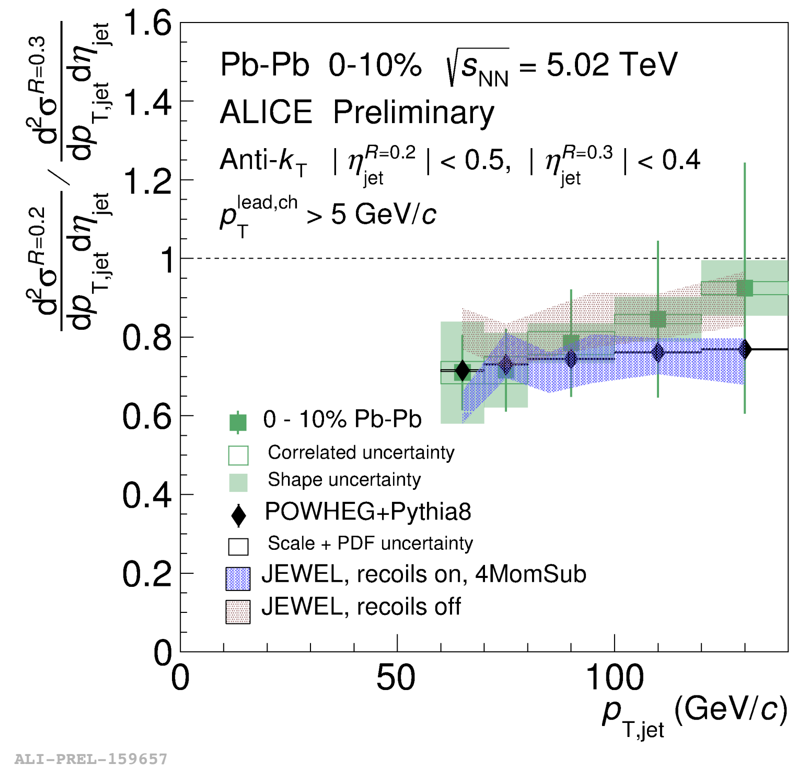
  - **Ratio of jet yields for different R**
    - sensitive to transverse energy profile of the jet
    - energy lost recovered at larger angle?
    - observable calculable in pQCD Soyez, Phys. Lett. B698 (2011) 59-62



Inclusive jet cross section ratios

- ALICE measured the inclusive jet spectra in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV for both charged and full jets for *R*=0.2, *R*=0.3



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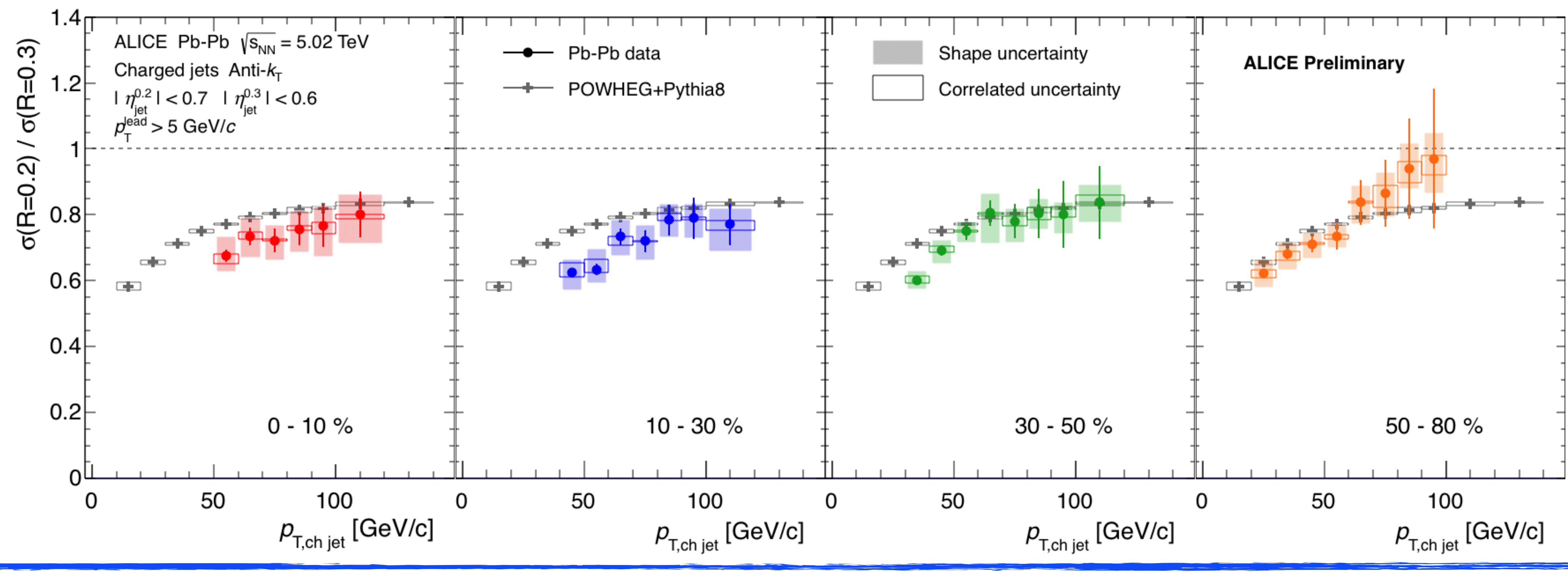
- **No significant difference with respect to jet fragmentation in vacuum** (POWEG + PYTHIA8 reference)



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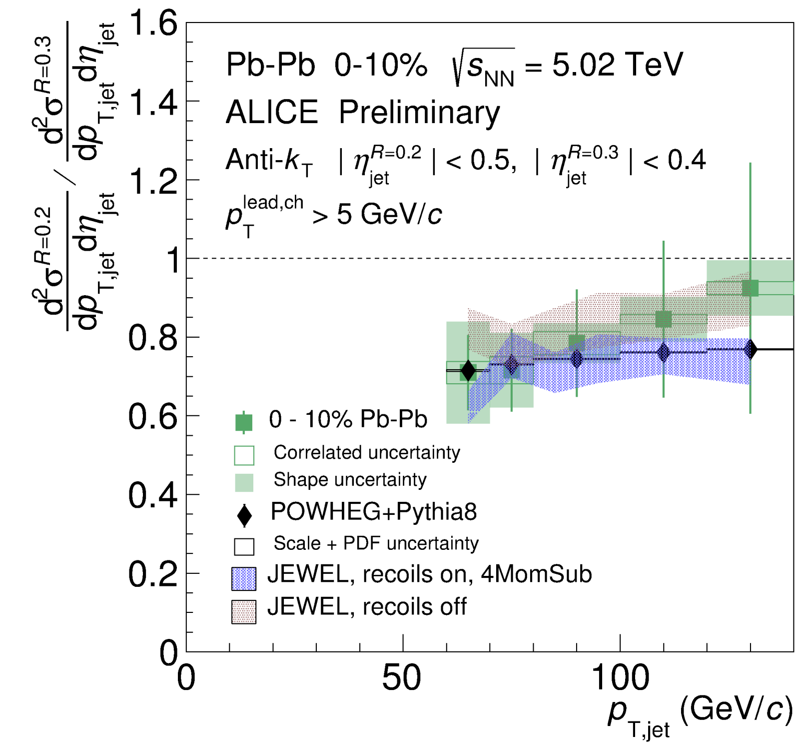

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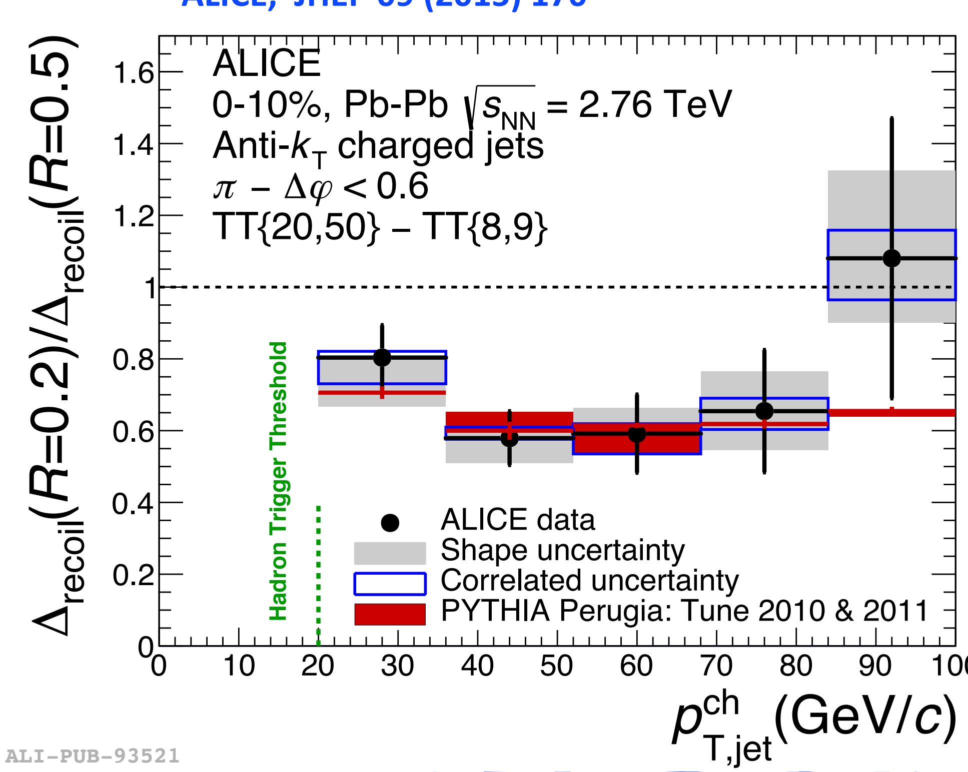
ALICE, JHEP 09 (2015) 170

- Also extending the measurement up to R=0.5 with semi-inclusive h-jet coincidence technique, no significant difference observed
- Lost energy must reappear in at large angle outside the jet cone



Jet shapes definitions

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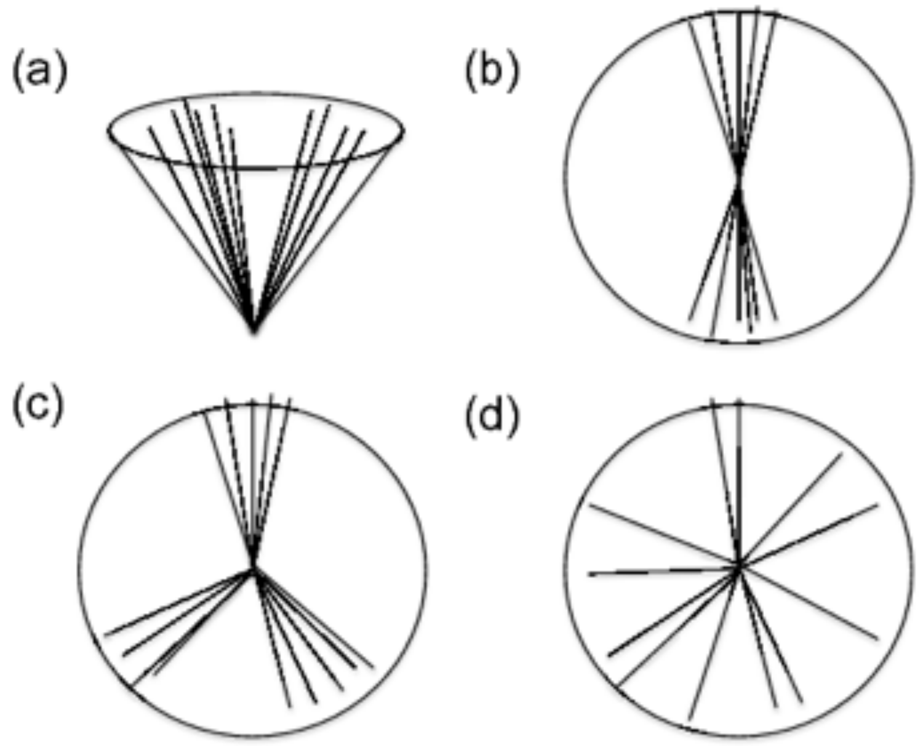
  - **Shapes built as a jet-by-jet function of the jet constituents 4-momenta**



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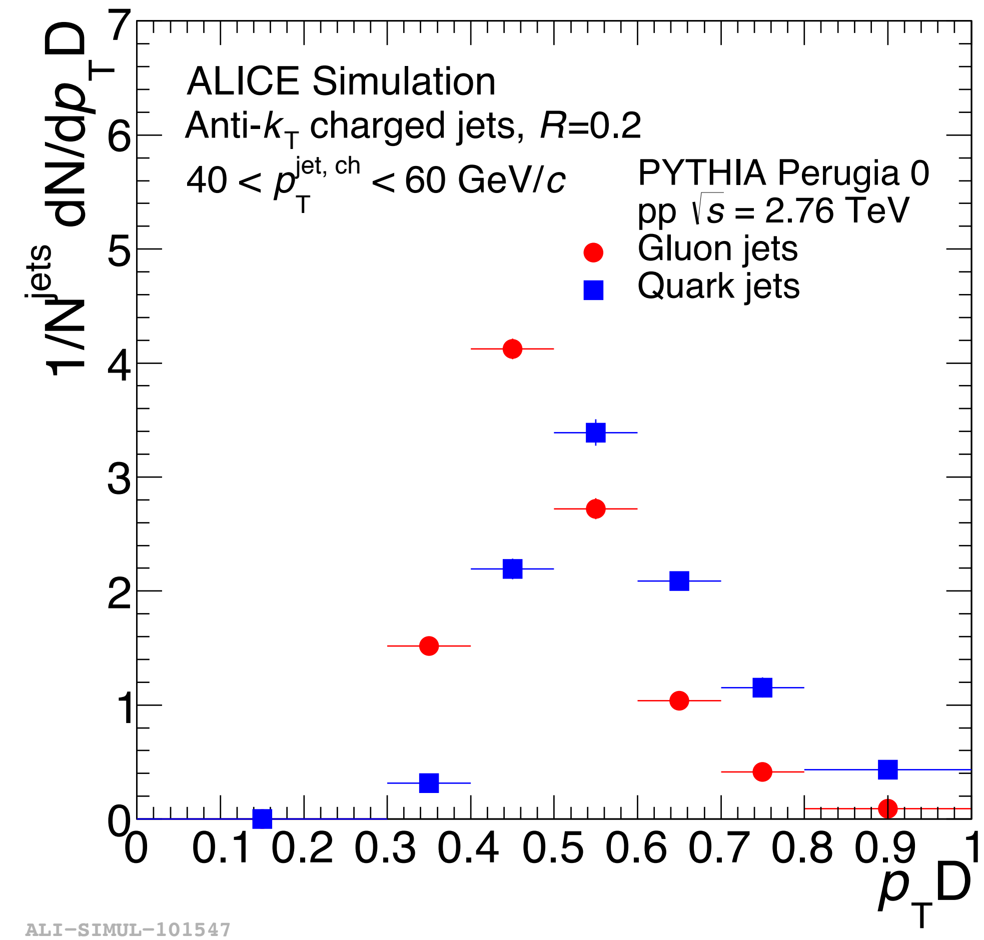
    - **Momentum dispersion (p_TD)**:
      - Measures the fractions of the jet momentum distributed in its constituents
      - jets with few hard constituents have higher p_TD
      - different p_TD expected for **quark/gluon** jets due to the different fragmentation



$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

J. Gallicchio, M.D. Schwartz, PRL 107 (2011) 172001

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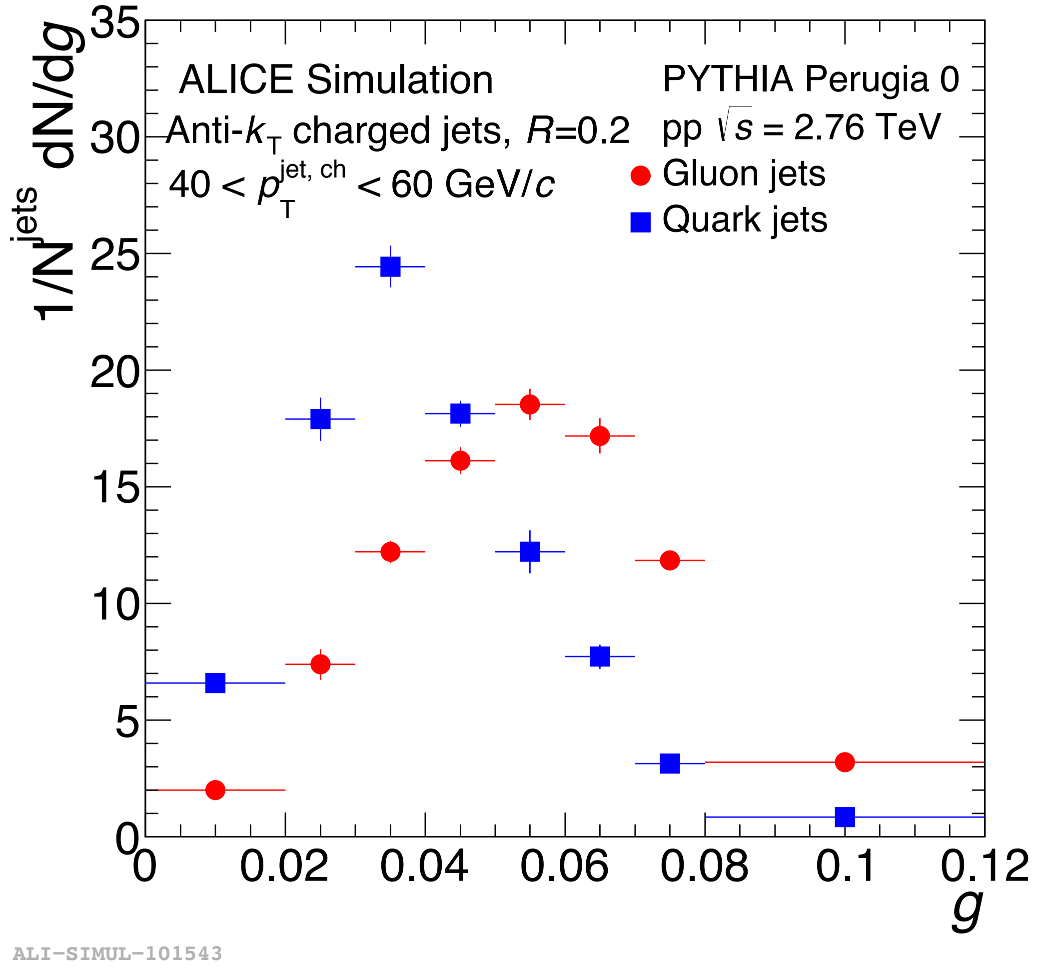
    - **Radial moment (*g*)**:
      - Measures the momentum re-distribution of jet constituents weighted by their distance from the jet axis

$$g = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T}}^{i}}{p_{\mathrm{T}}^{\mathrm{jet}}} |r_i|$$



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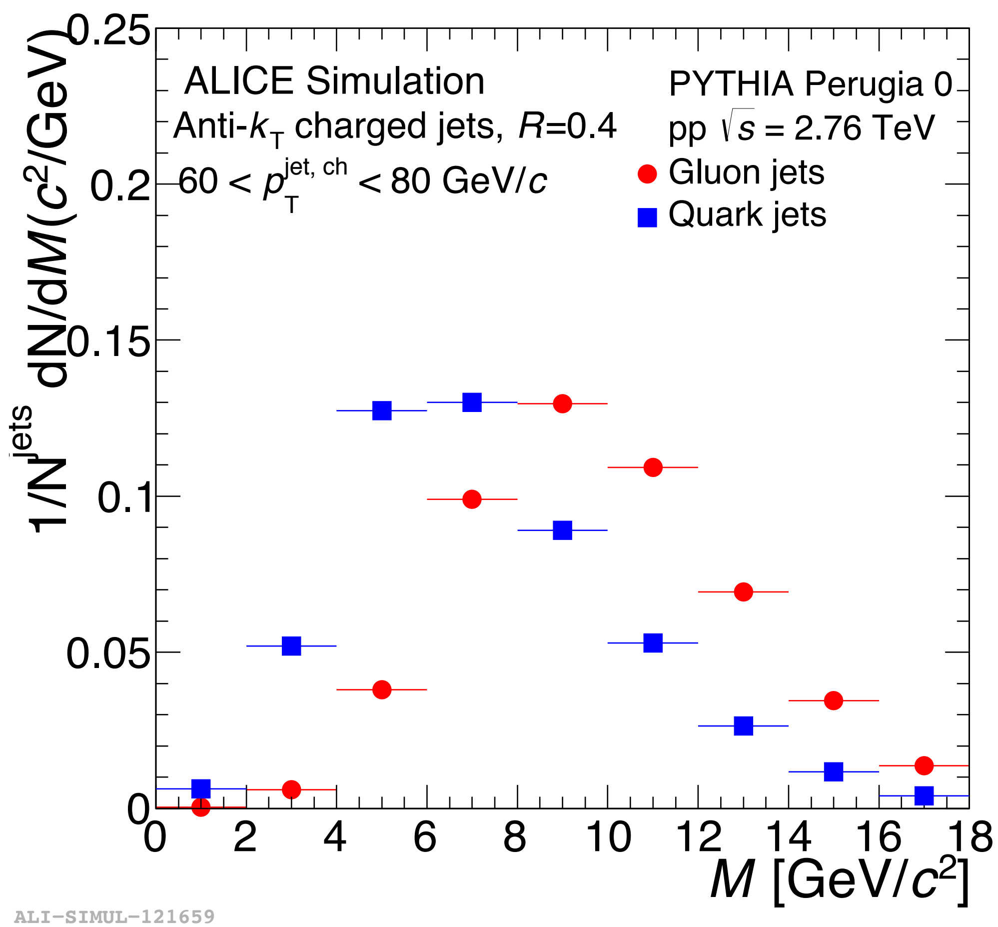
    - **Jet Mass (*M*)**
      - Difference of the momentum of the jets and the energy of its constituents weighted by their pseudo-rapidity.
      - Related to the virtuality of the parton traversing the medium

$$M = \sqrt{p^2 - p_T^2 - p_z^2}.$$

$$p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i, \quad p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i.$$

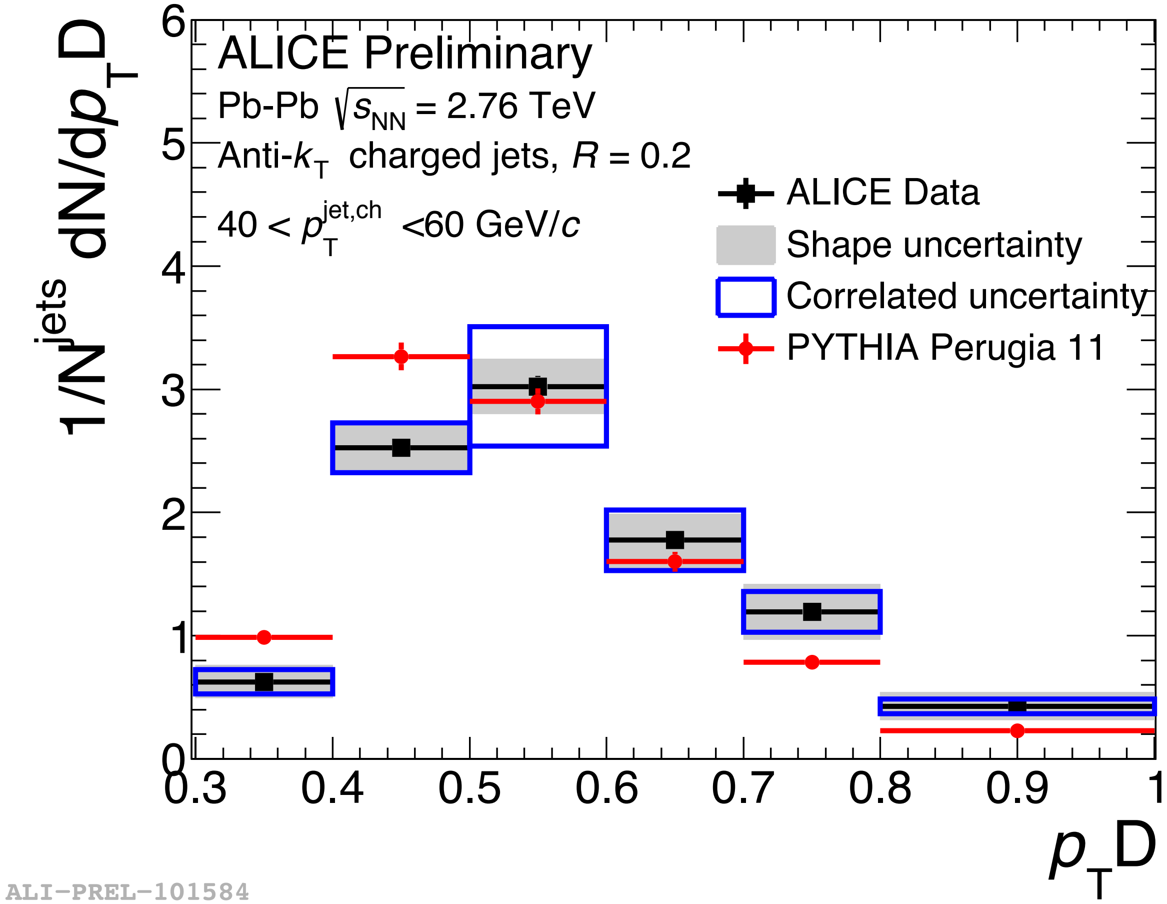


J. Gallicchio, M.D. Schwartz, PRL 107 (2011) 172001   A. Majumder and J. Putschke. Phys. Rev. C 93, 054909

Charged jet shapes in Pb-Pb collisions

- $p_T D$ shifted to higher values in Pb-Pb collisions relative to PYTHIA Perugia11

Charged jets, R = 0.2, 40 < p_T < 60 GeV/c



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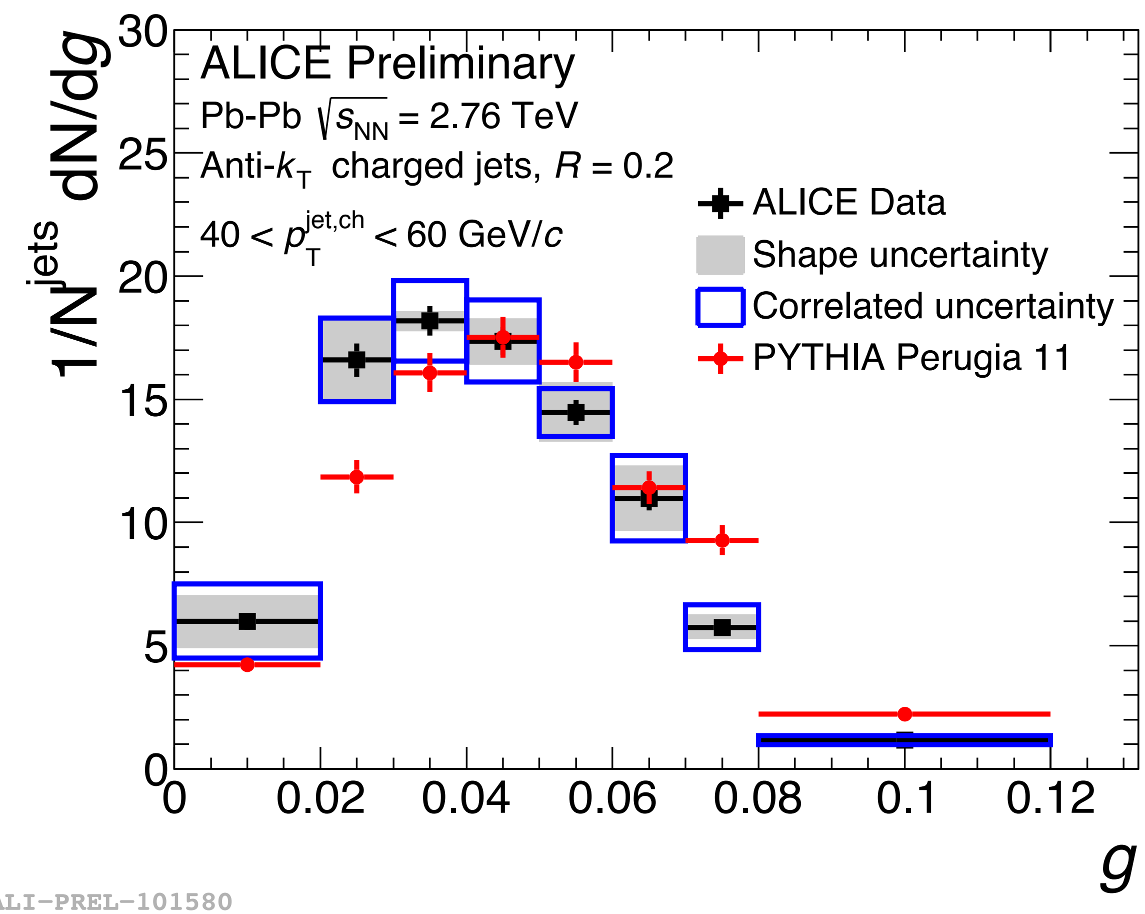

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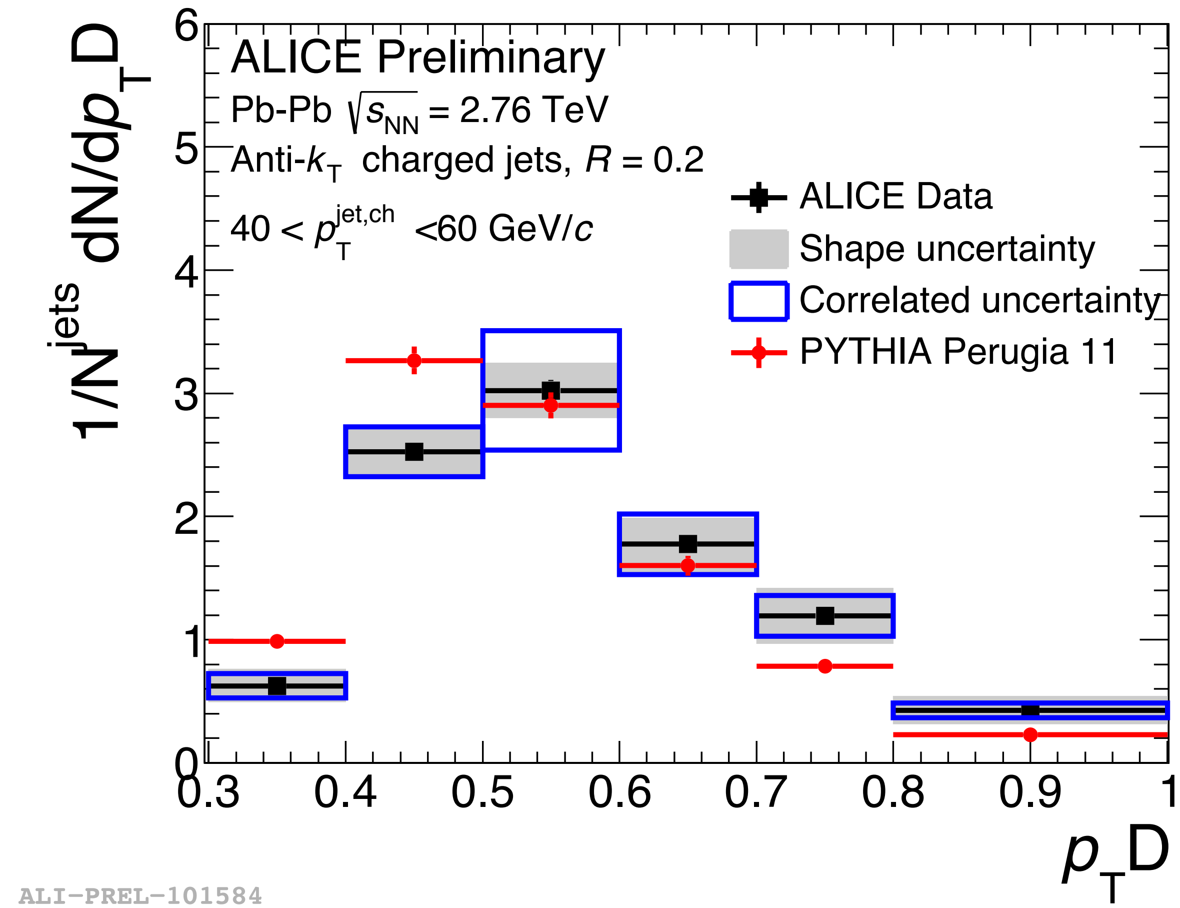

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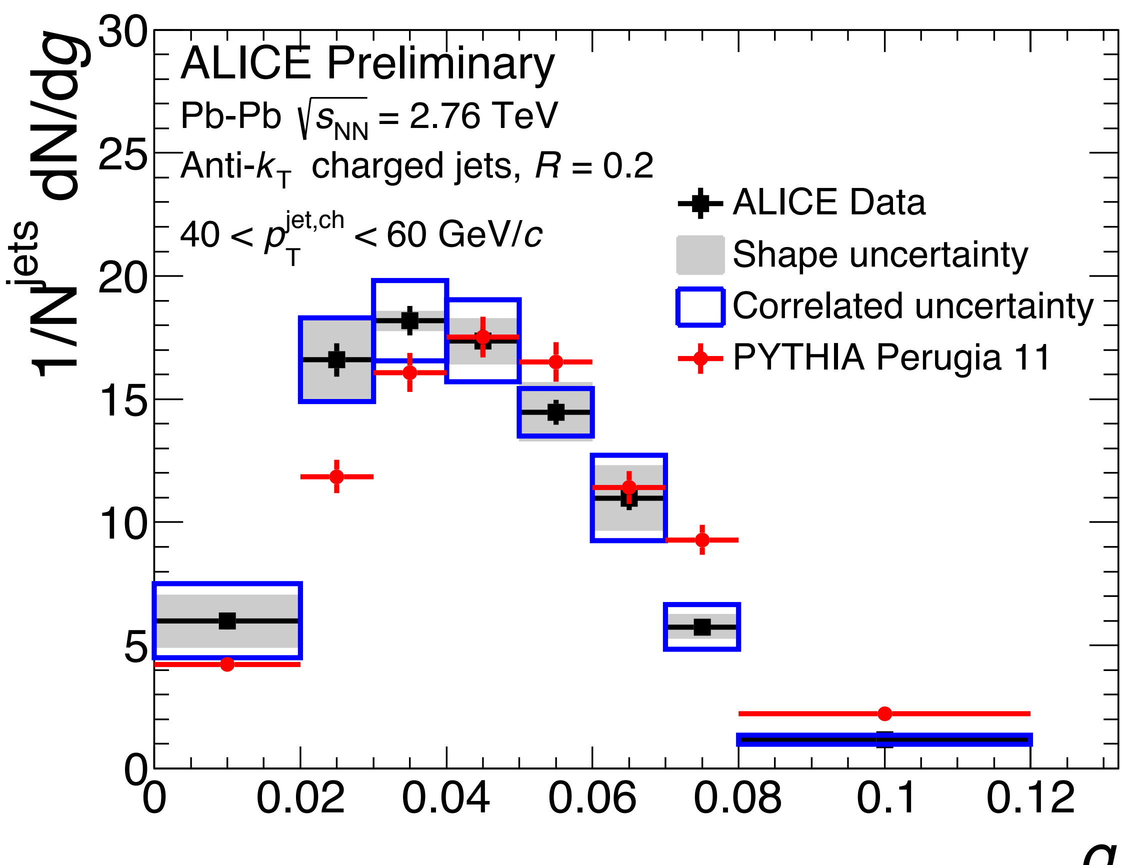
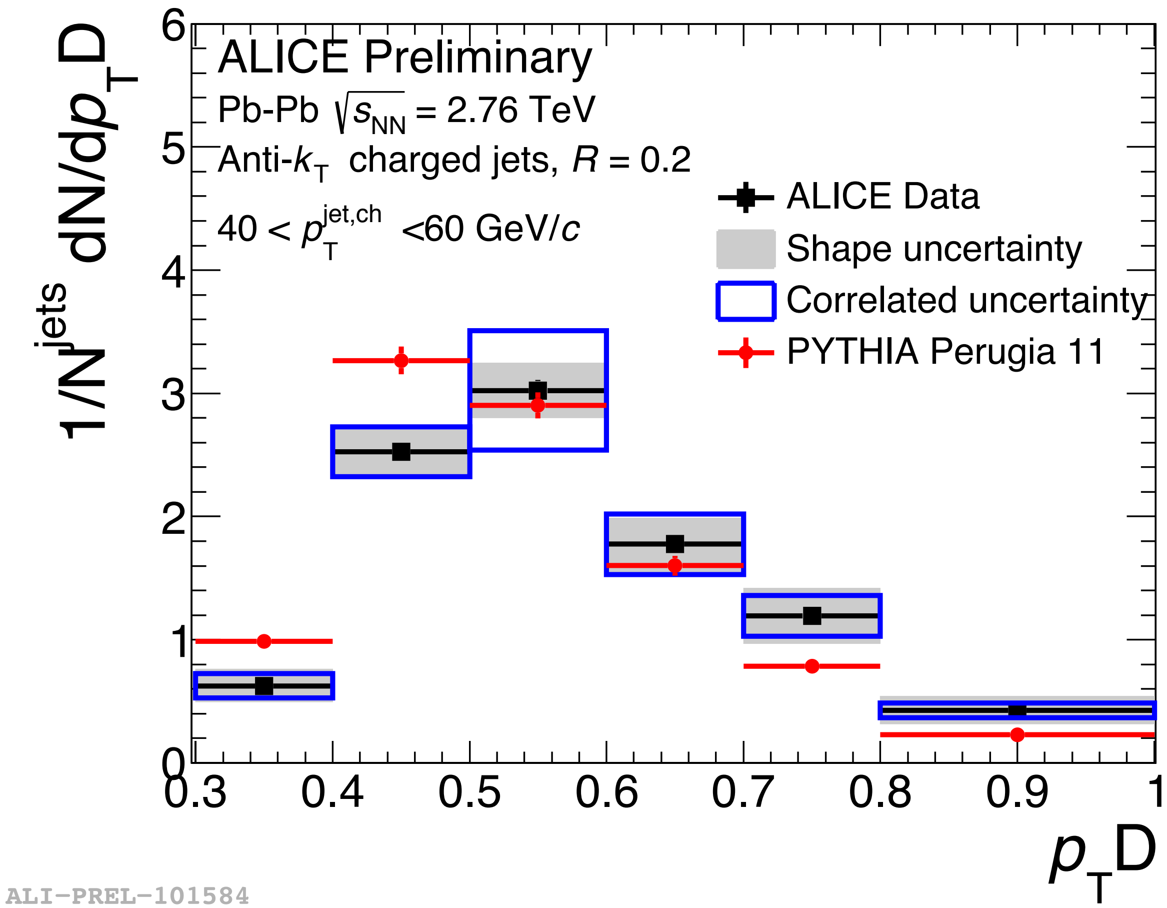




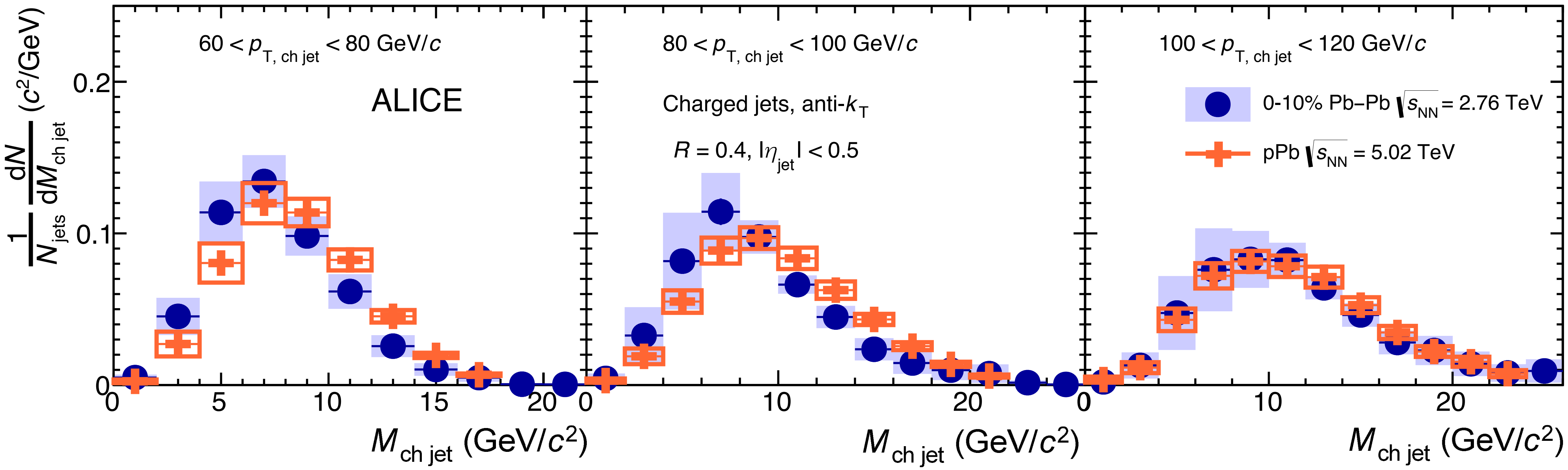
- g shifted to lower values in Pb-Pb collisions relative to PYTHIA Perugia11

These shapes show distributions compatible with a more collimated and harder fragmentation in Pb-Pb than pp collisions.

Charged jet shapes in Pb-Pb collisions

Charged jets, $R = 0.4$, $60 < p_T < 120$ GeV/c

ALICE, Phys. Lett. B 776 (2018) 249

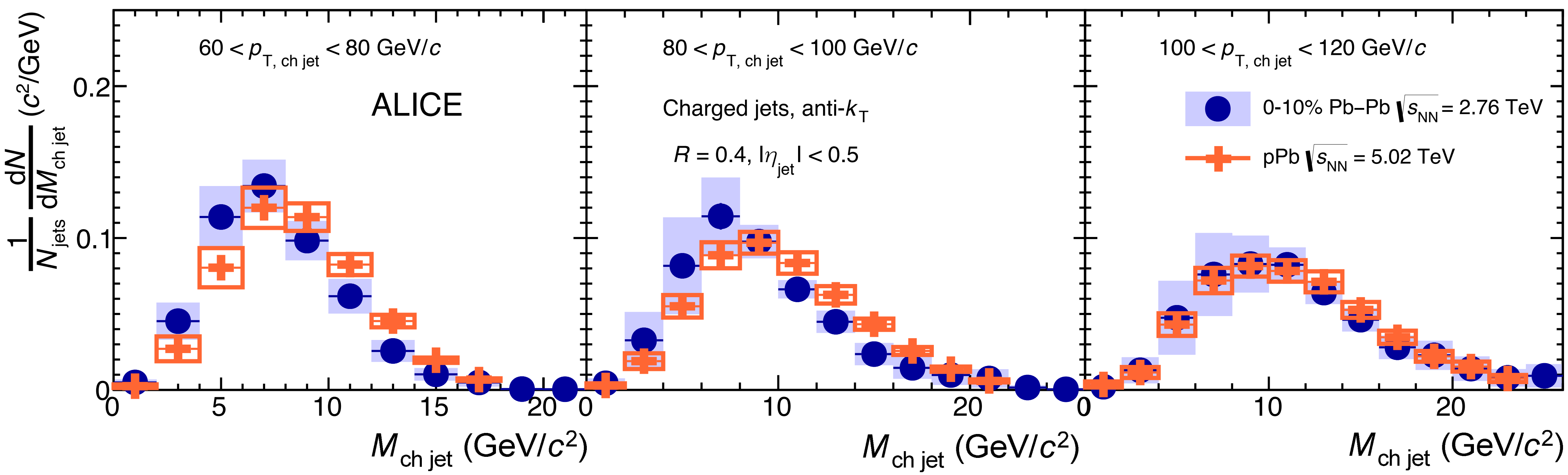


- *M* shows an hint of shift to lower values in **Pb-Pb collisions** with respect to **p-Pb collisions** results for $p_T < 100$ GeV/c

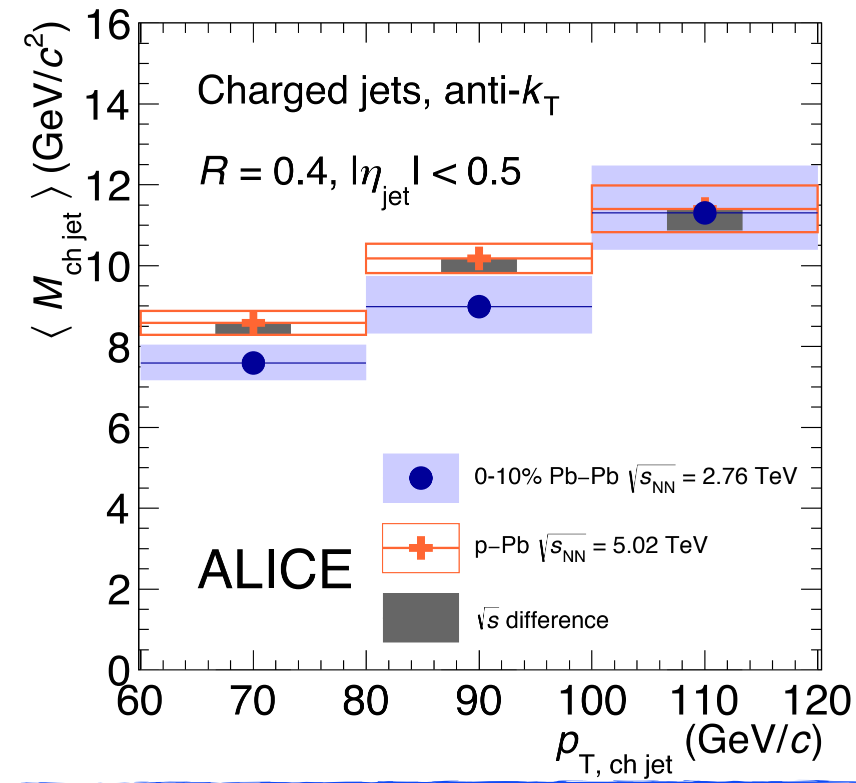
Charged jet shapes in Pb-Pb collisions

ALICE, Phys. Lett. B 776 (2018) 249

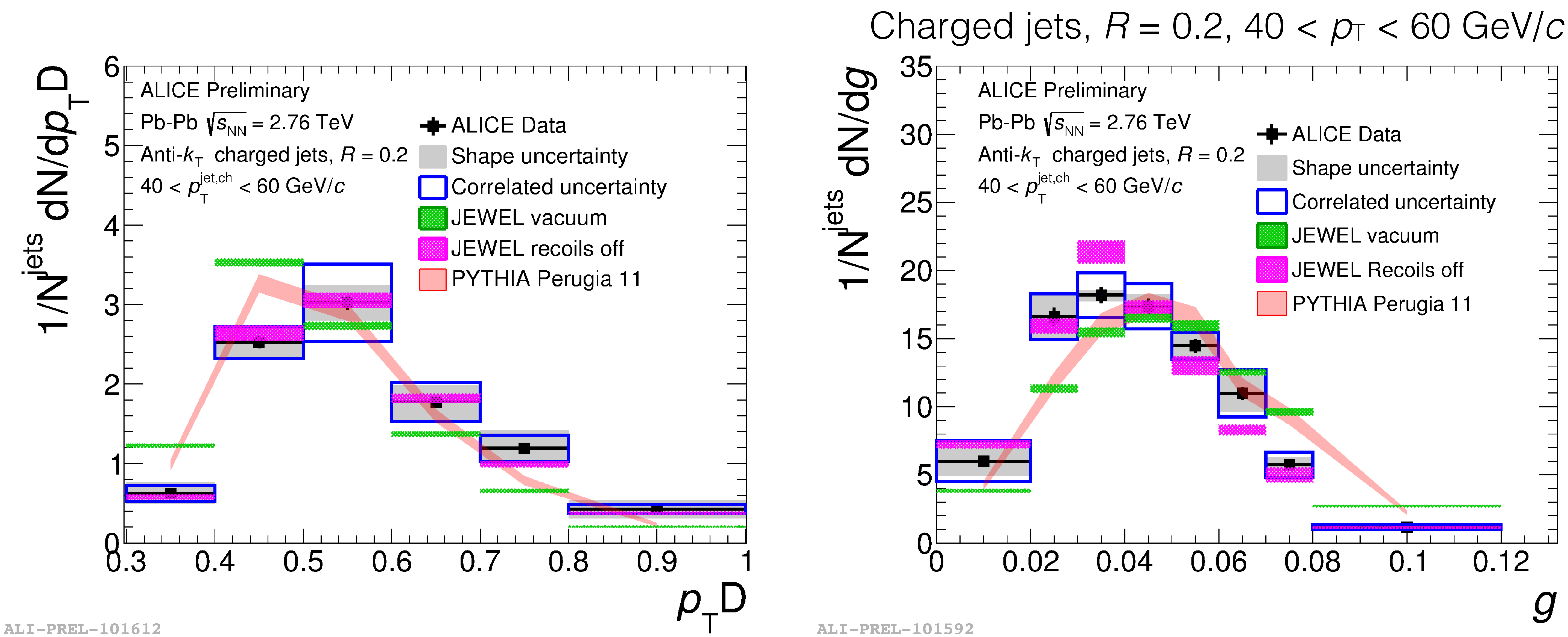
Charged jets, $R = 0.4$, $60 < p_{\mathrm{T}} < 120$ GeV/c



- Difference between **p-Pb** and **Pb-Pb** also observed in the mean jet mass.
  - 1σ difference between $60 < p_{\mathrm{T}} < 80$ GeV/c



Charged jet shapes: comparison with models



- The **different fragmentation observed in Pb-Pb** collisions for R=0.2 jets is **qualitatively described by JEWEL Recoil off model** K. Zapp et al , JHEP 1303 (2013) 080
- Large uncertainties still do not allow to constraint the models

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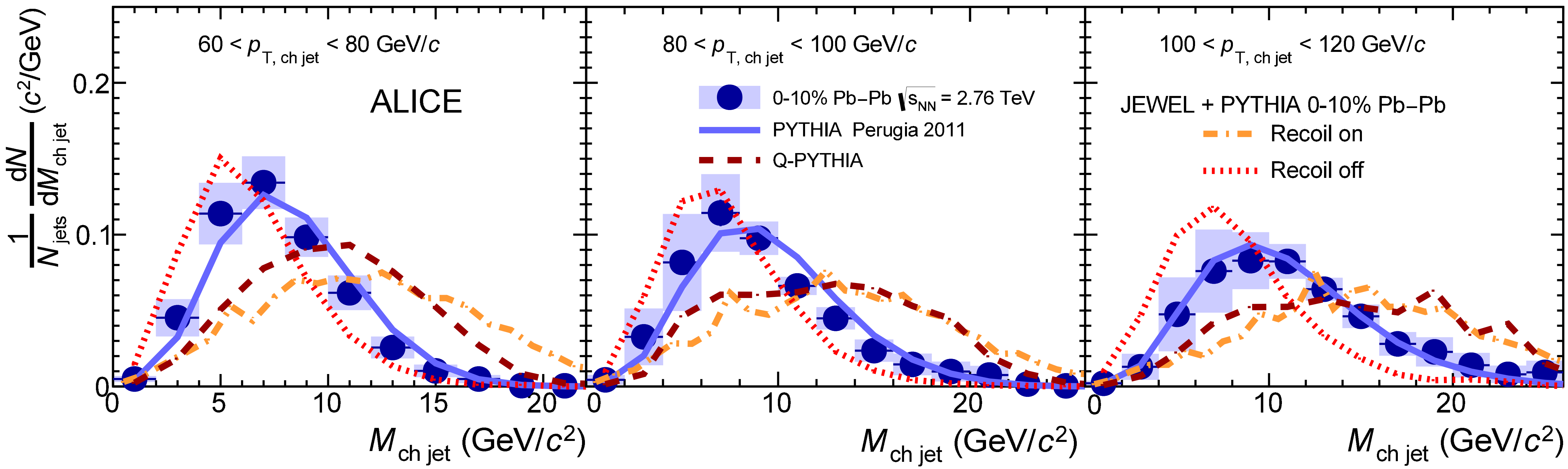
ALICE, Phys. Lett. B 776 (2018) 249



- Data lie between **PYTHIA Perugia 11** and **JEWEL Recoil off**
- **Q-PYTHIA** and **JEWEL Recoil on** seems to produce a large jet mass

- JEWEL collimates the jets since the soft particles are scattered at large angles
- Qualitative picture in agreement for $p_T D$, g and M

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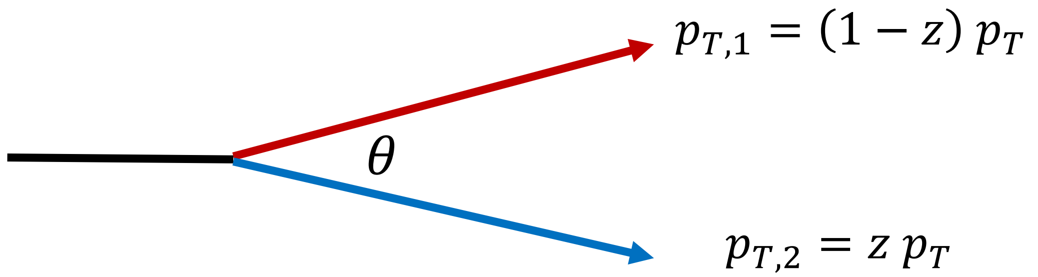
- Jet shapes are observables constructed combining different information coming from the properties of the jet
- They can be classified in three different groups:
  - **Shapes defined considering the clustering history of the jet**
    - **Soft drop subjet momentum balance (z_g)**
      - Momentum balance of the two hard sub-jets after jet grooming procedure
      - Correlated with distance between the two sub-jets (ϑ)

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



A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler JHEP 05 (2014) 146

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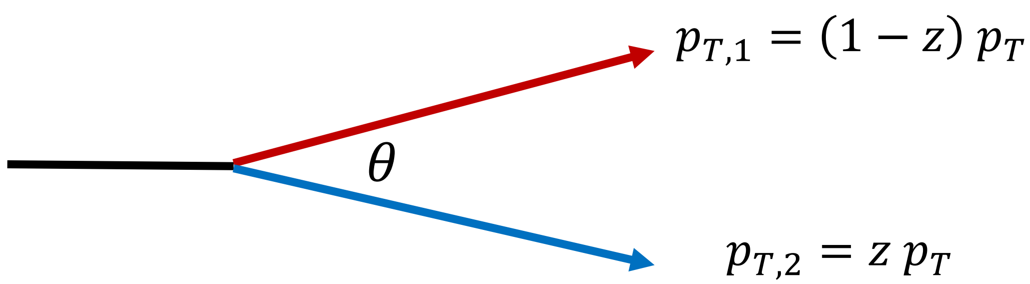
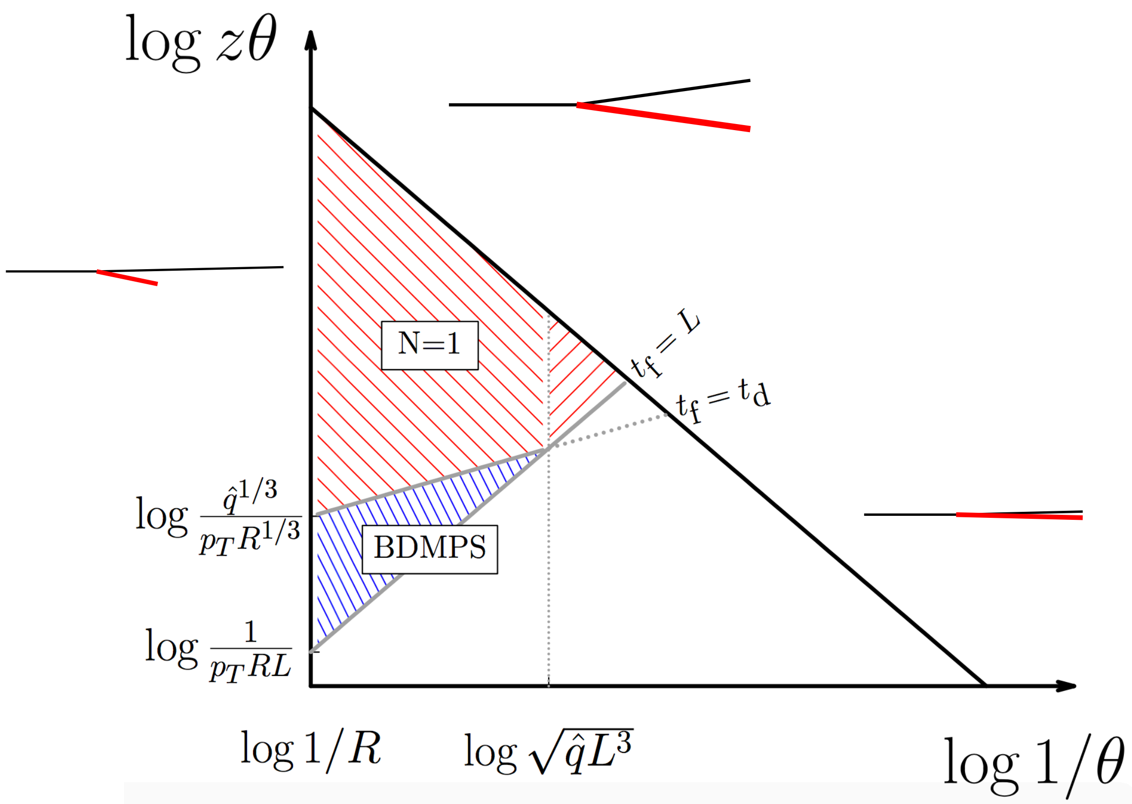


    - **Number of recursive splittings in the jet evolution (n_{SD})**
      - number of branches in the jet clustering history that satisfy the grooming requirement

A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler JHEP 05 (2014) 146

Splitting in the medium

- Map of the splitting in the medium studied via the Lund diagram
- Iterative de-clustering unwinds the jet structure and stores splitting information
- Cambridge/Achen algorithm is used to de-cluster the jets, preserving the angular ordering



Tywoniuk et al. 5th Heavy Ion Jet Workshop/CERN TH institute

A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler JHEP 05 (2014) 146

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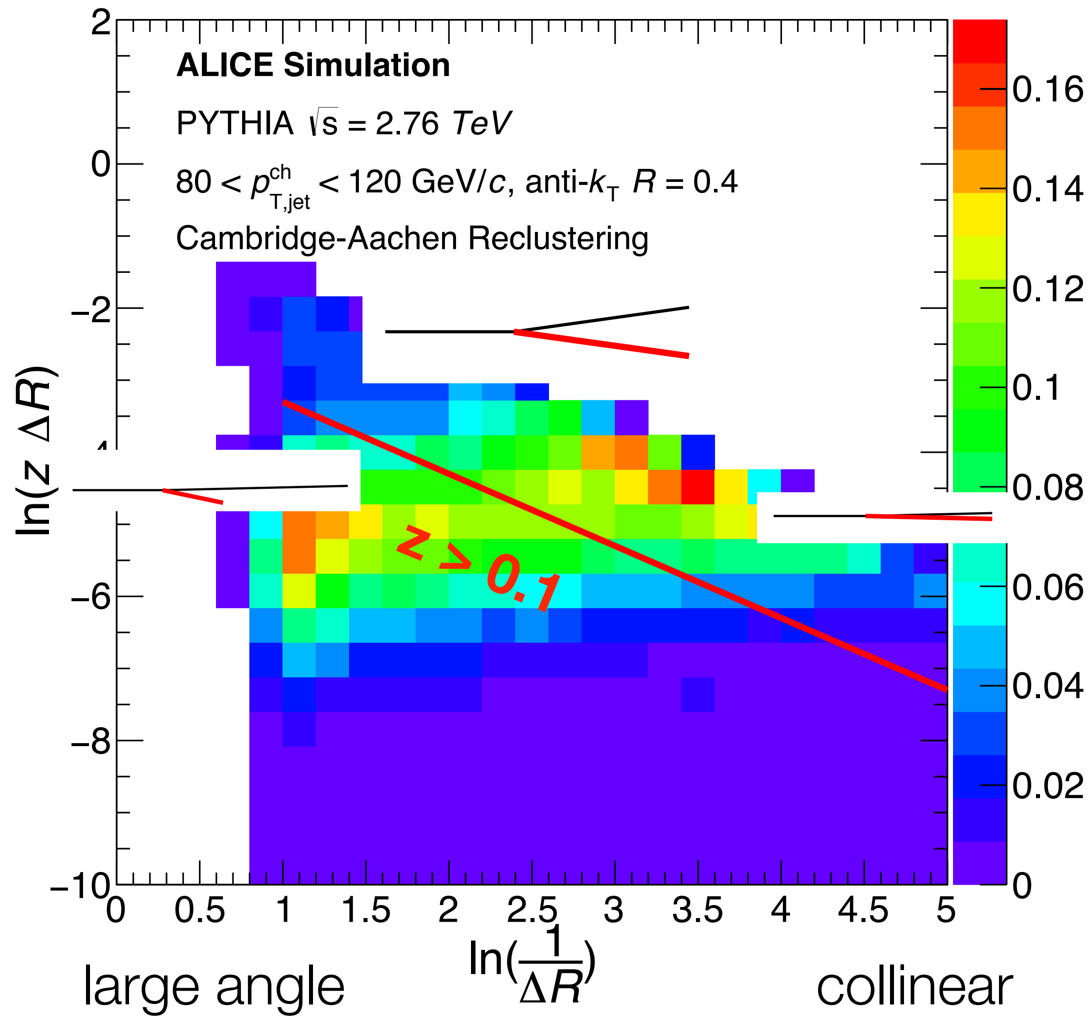
- Cambridge/Achen algorithm is used to de-cluster the jets, preserving the angular ordering
- Focus on different region of the Lund diagram phase-space imposing different grooming conditions

$$z > z_{cut}\theta^{\beta}$$

Soft Drop[2] /mMDT Grooming[3]

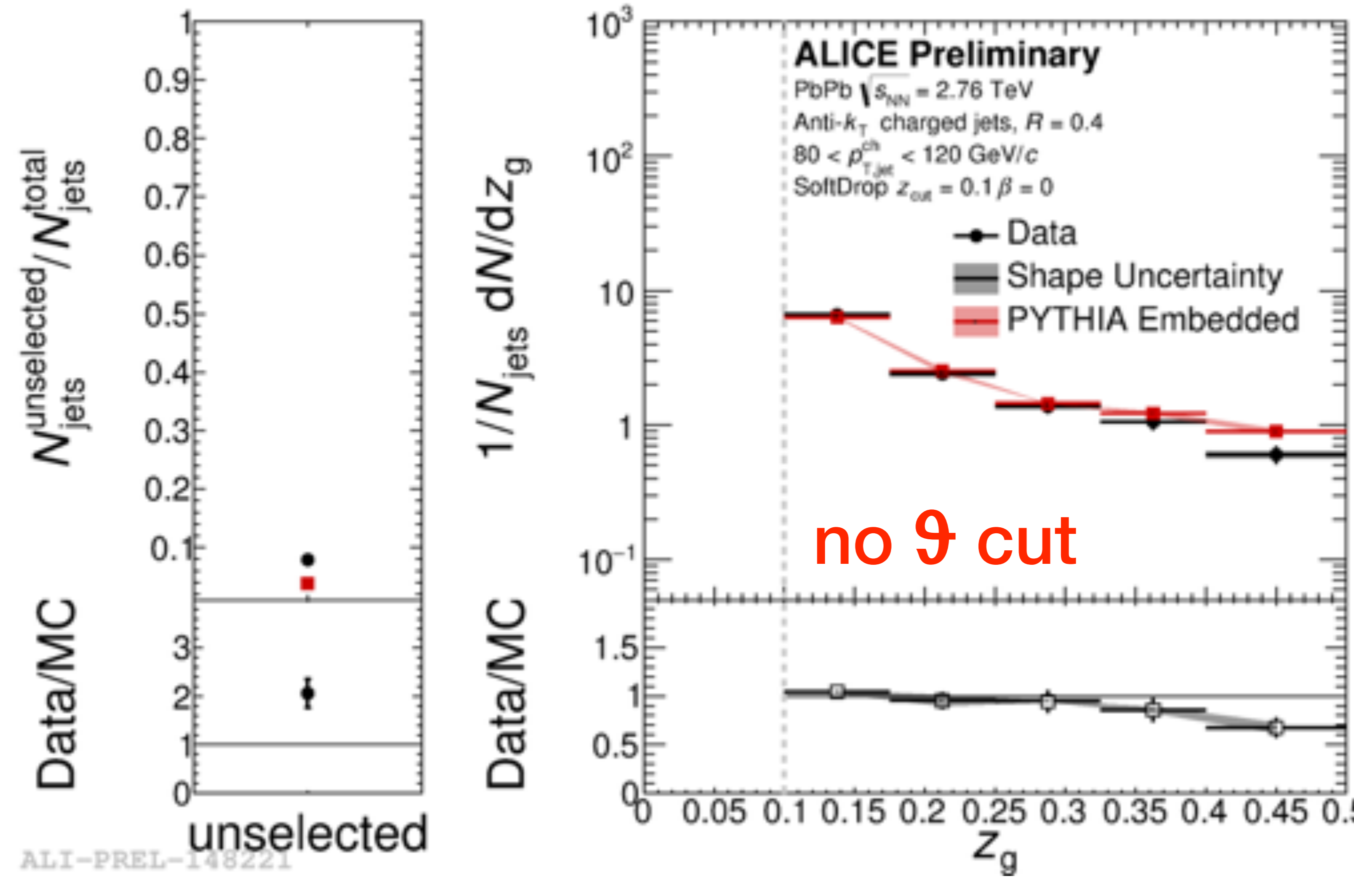
[1] G. Salam gitlab.cern.ch/gsalam/2017-lund-from-MC
[2] M. Dasgupta et al. JHEP 1309 (2013) 029
[3] A. Larkoski et al. JHEP 1405 (2014) 146



z_g, n_{SD} measurements in Pb-Pb collisions

Charged jets, R = 0.4, 80 < p_T < 120 GeV/c

- Difference in the z_g distribution observed when considering less collimated subjets



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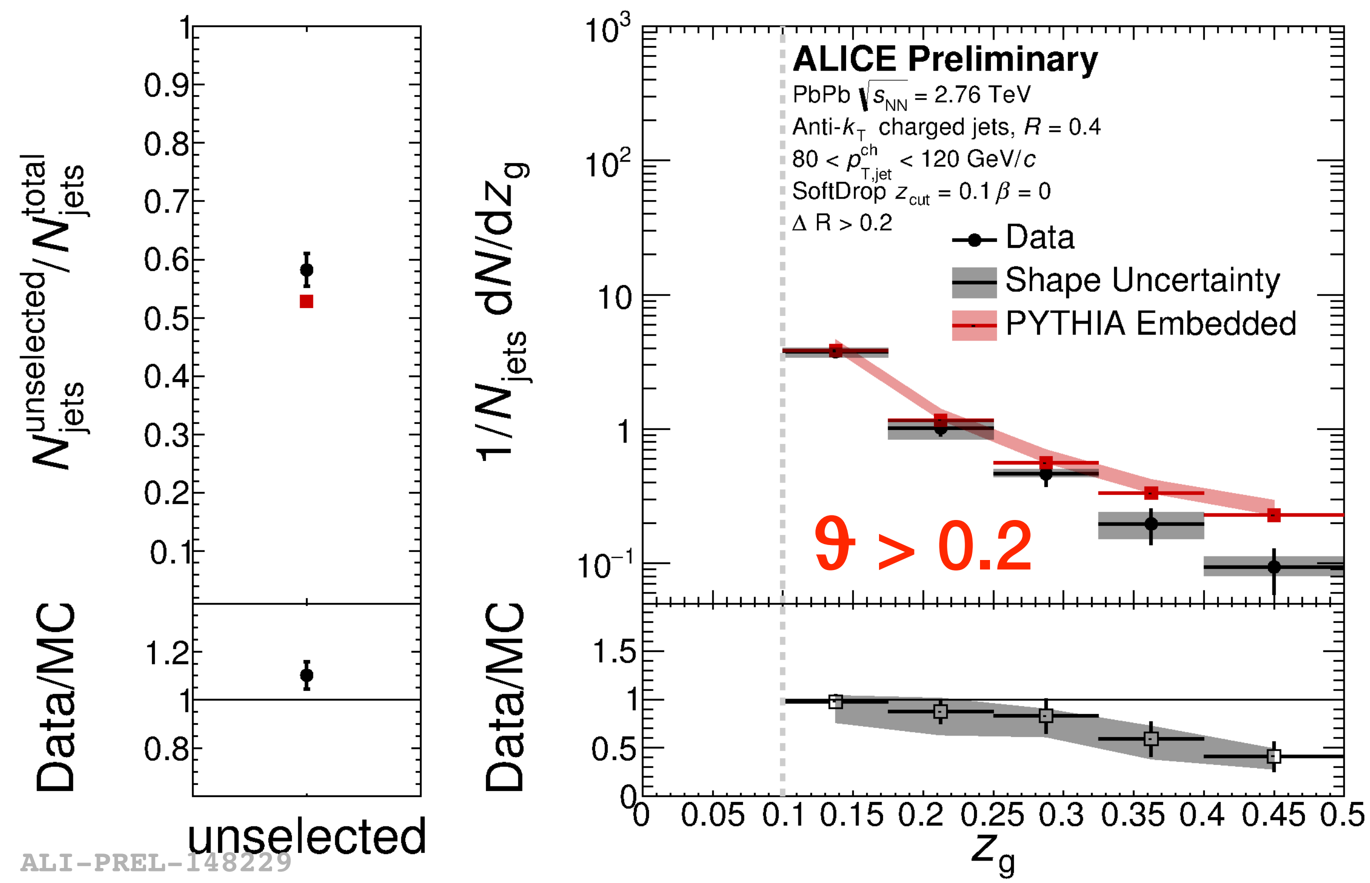

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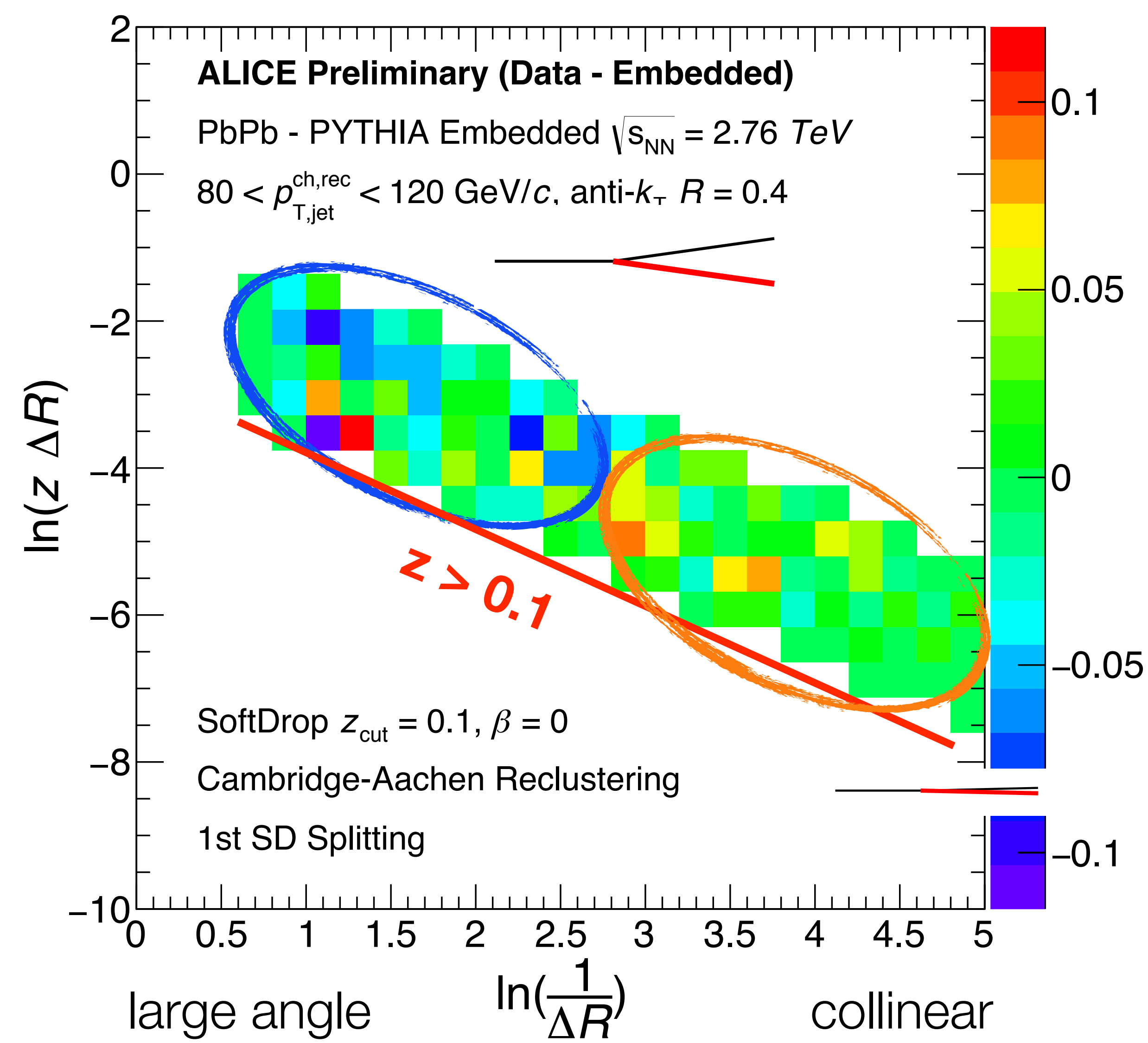

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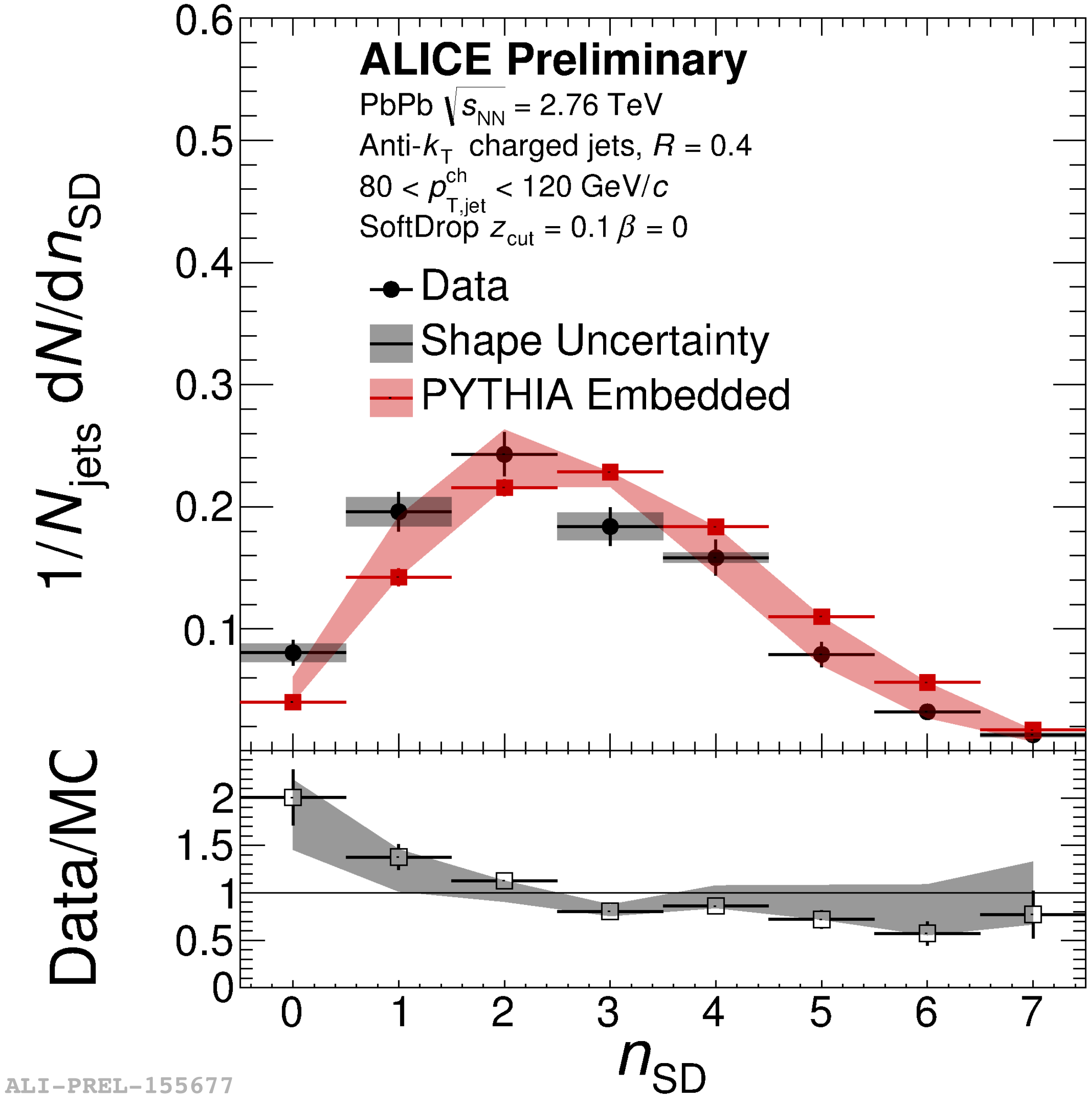
- No enhancement in the n_{SD} is present
  - but larger number of jets that don't satisfy the Soft Drop condition in Pb-Pb



Conclusions

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    - **Jet mass** indicates a **shift toward lower values** for *R*=0.4 jets

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    - **no increase in the number of splitting** observed in Pb-Pb collisions

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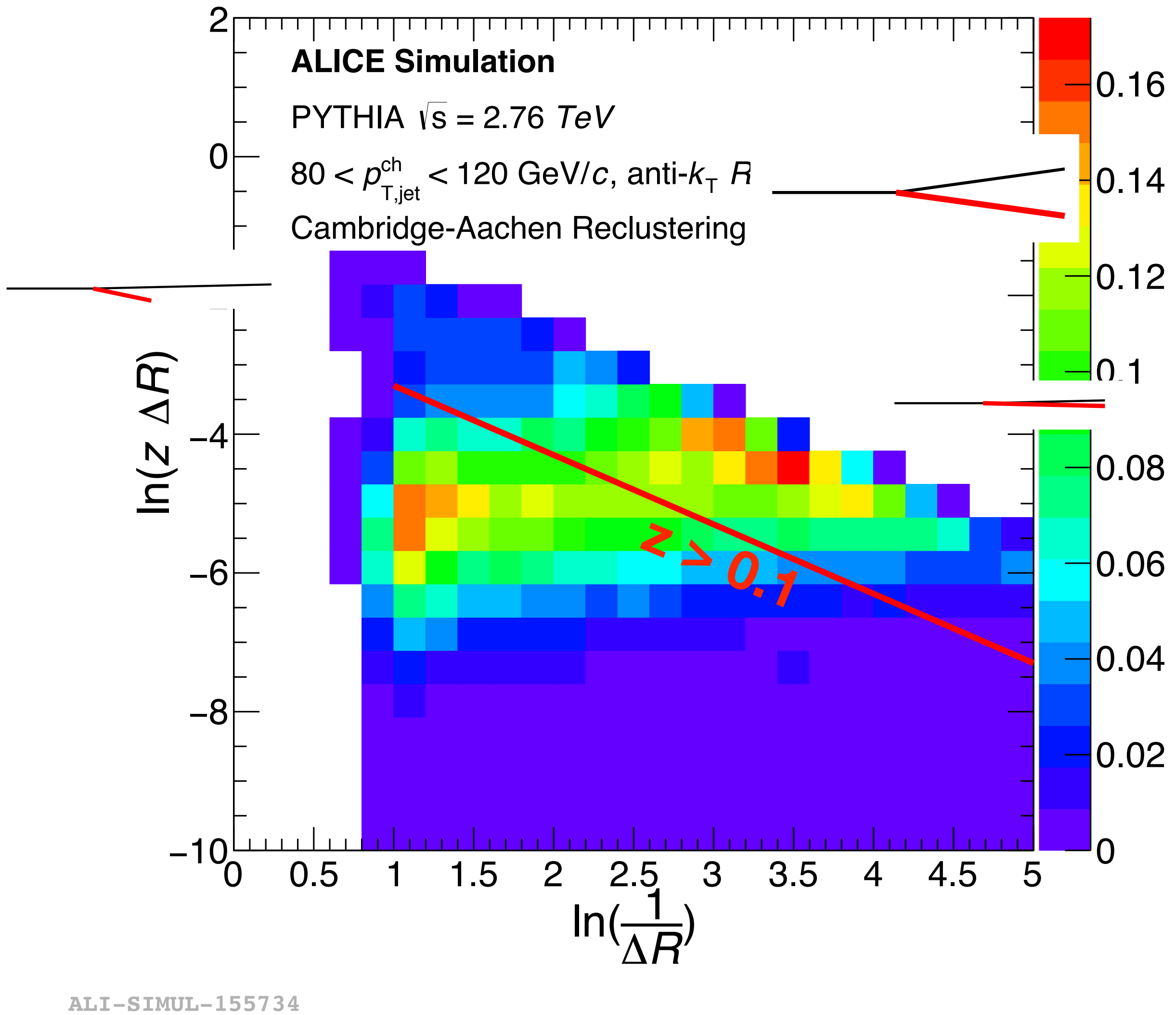
    - Jet mass indicates a shift toward lower values for R=0.4 jets
    - Large angle symmetric splittings seems to be suppressed in Pb-Pb collisions and collinear radiation enhanced
    - no increase in the number of splitting observed in Pb-Pb collisions.
  - New **data at $\sqrt{s}$ = 5.02 TeV** are already allowing more **precise and differential measurements**

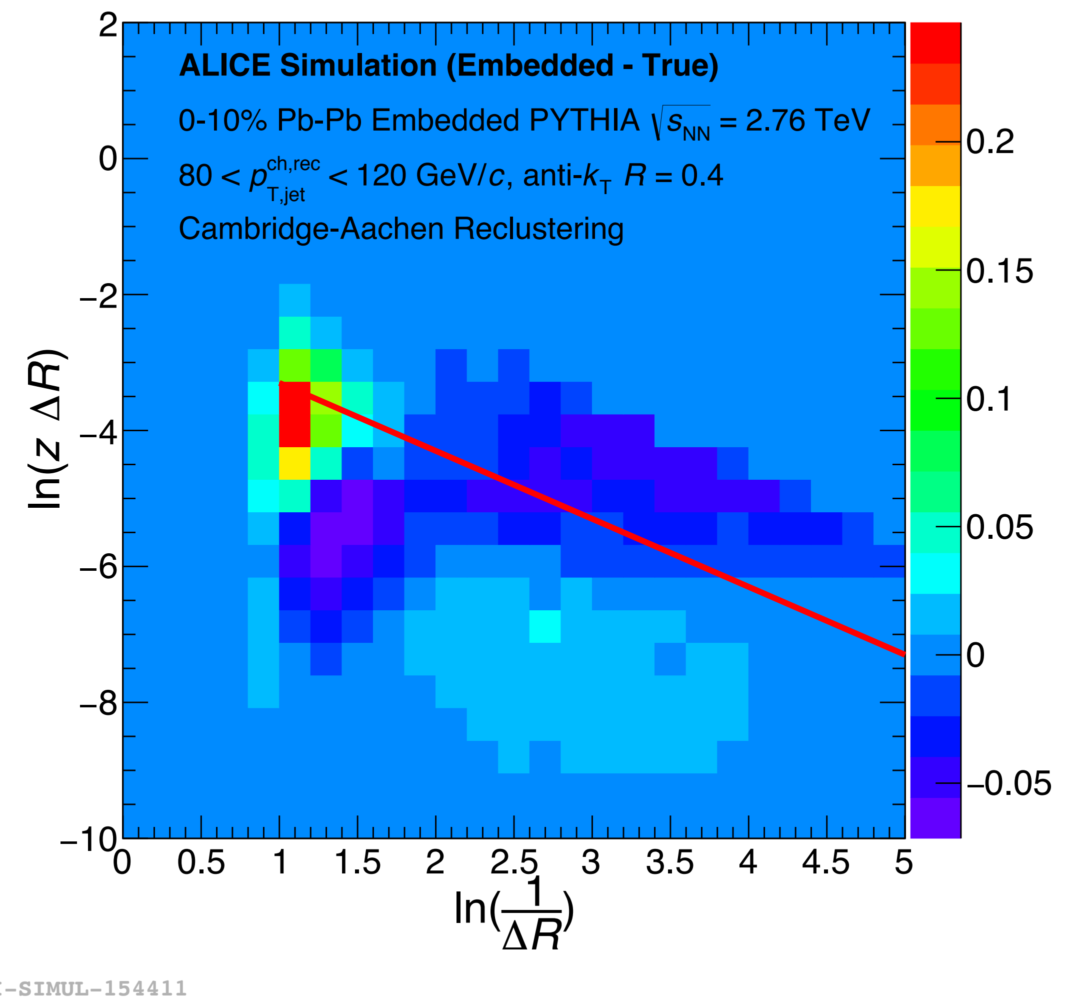
Back up slides

Splitting in the medium

- Map of the splitting in the medium che be studied via the Lund plane



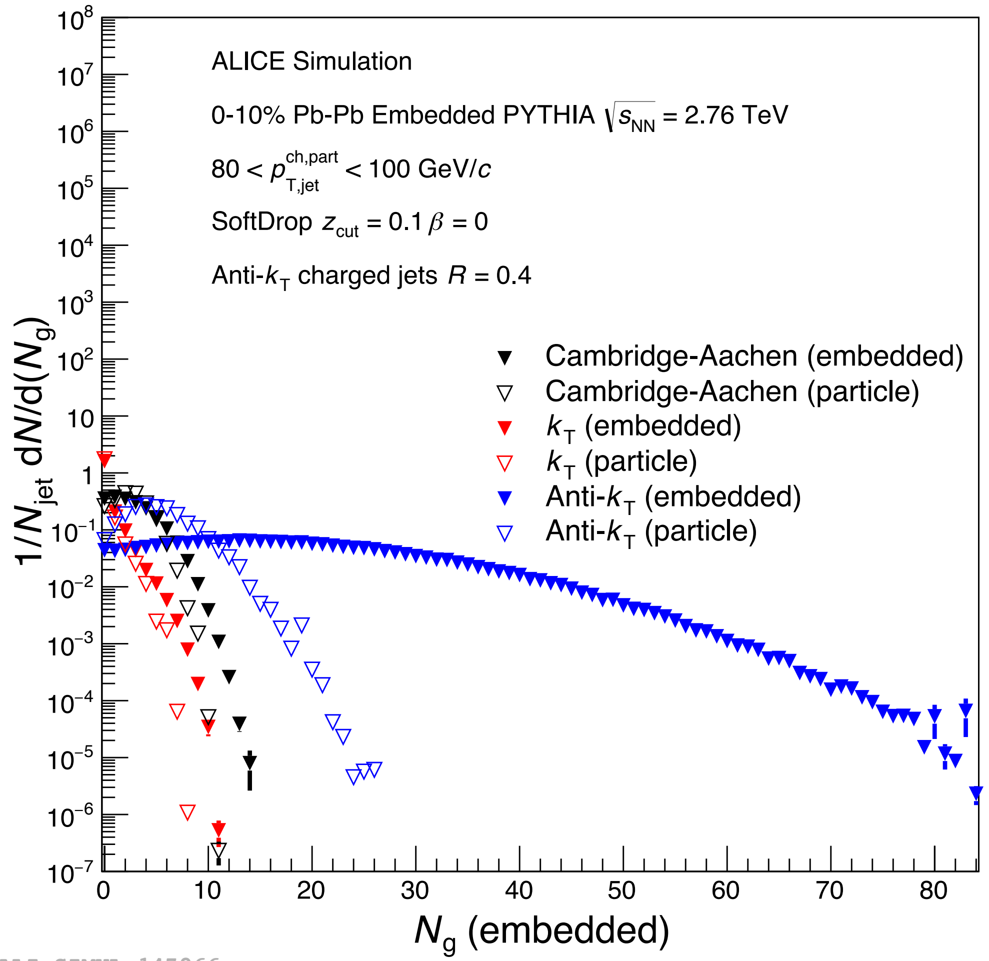
splitting map for difference of embedded and vacuum jets PYTHIA



clear enhancement of splitting at large angular separation: background effect from fake jets

Grooming performance in HI collisions

groomed branches



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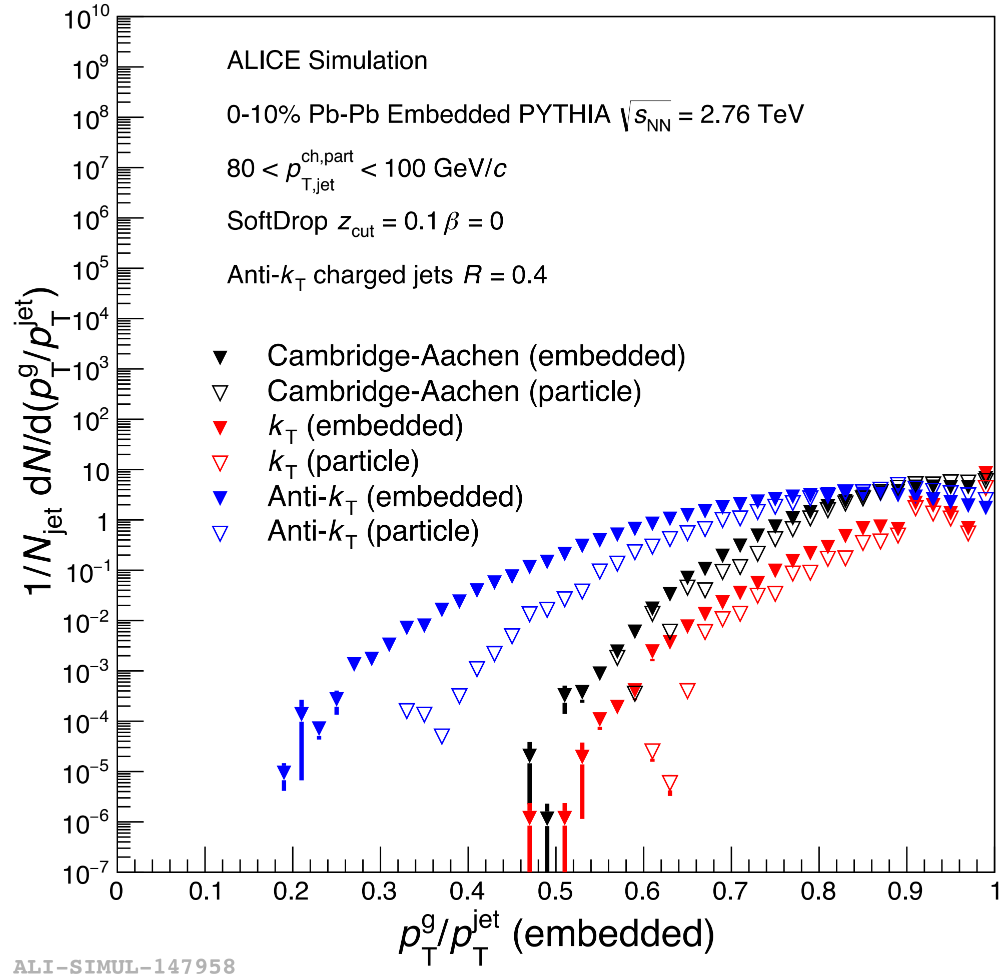
groomed momentum fraction

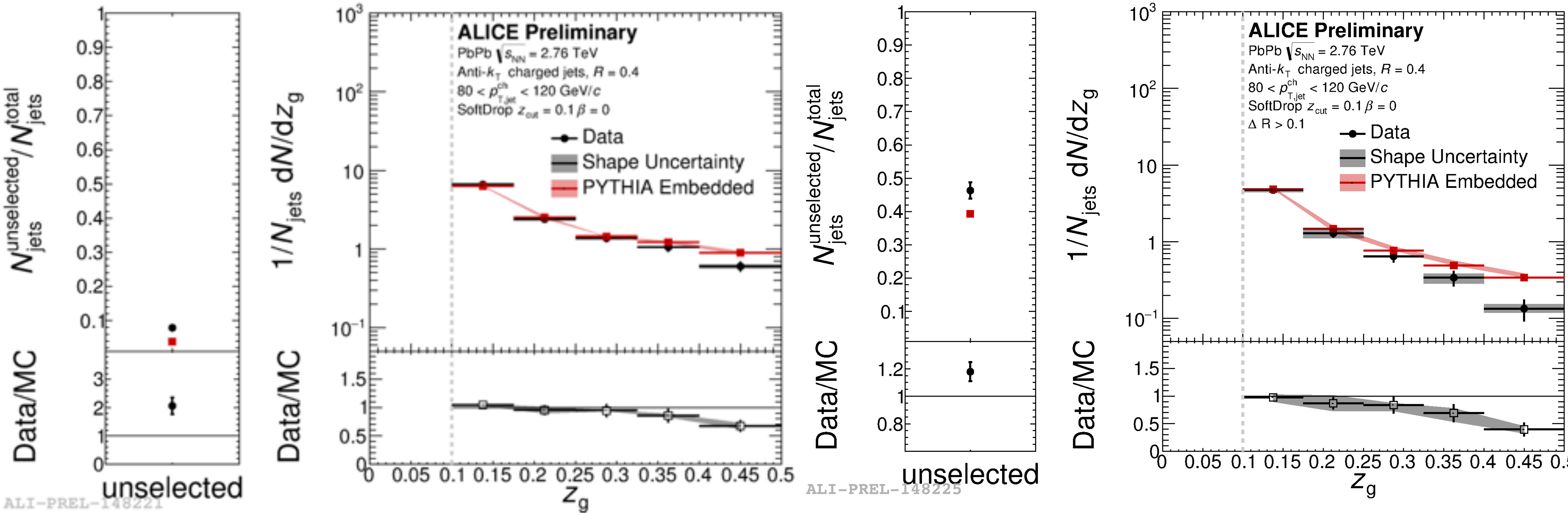


ALI-SIMUL-147958

- Algorithm used for decluttering reflects the ordering of the clustering strategy
- Can be changes to increase sensitivity to a given process
  - k_T for example may be optimal for semi-hard splittings

z_g, n_{SD} measurements in Pb-Pb collisions

Charged jets, R = 0.4, 80 < p_T < 120 GeV/c

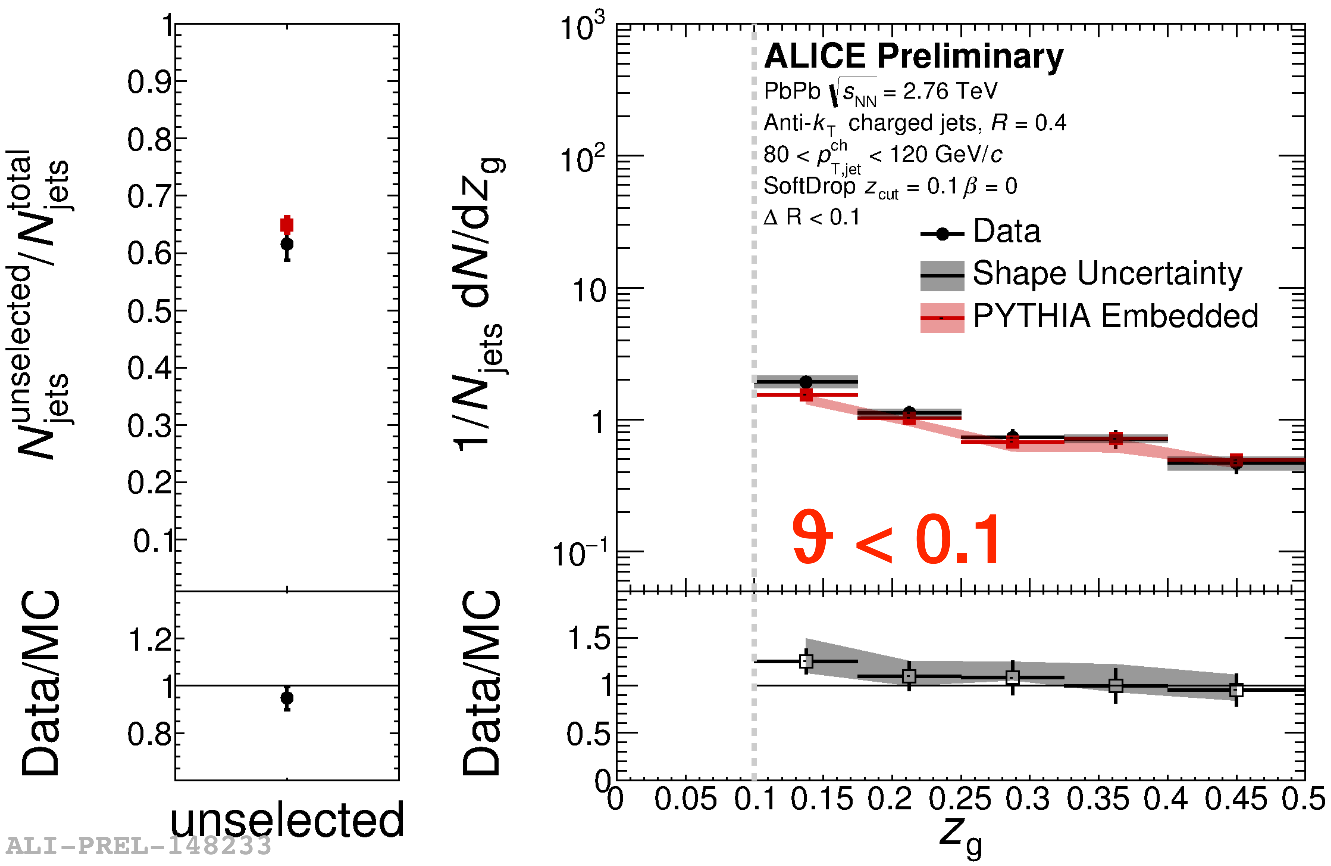


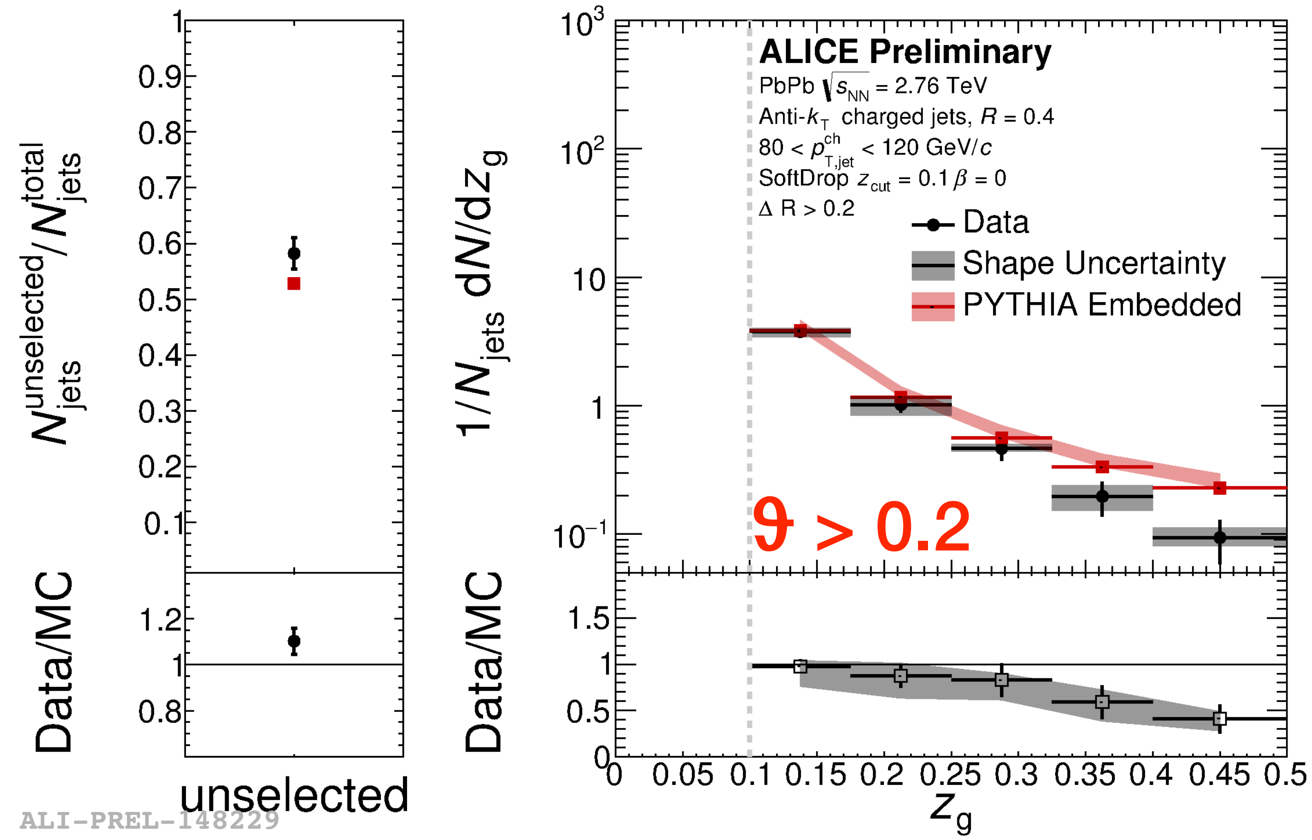
- Without cut on the relative distance (ϑ) between the two sub-jets, difference between PYTHIA embedded jets and Pb-Pb data observed only in the last z_g bin

- Applying a cut ϑ > 0.1, larger fraction of imbalance observed but also a large number of jets who are not selected by the grooming procedure.

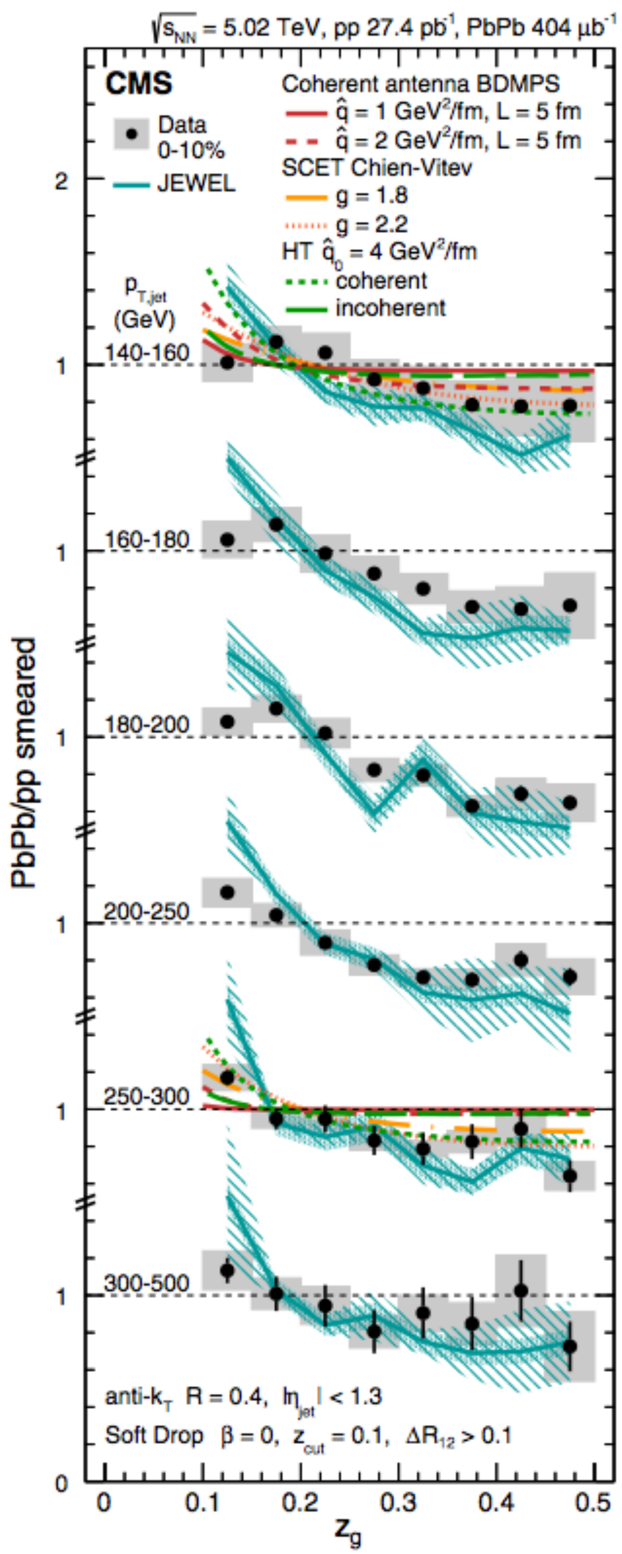
z_g, n_{SD} measurements in Pb-Pb collisions

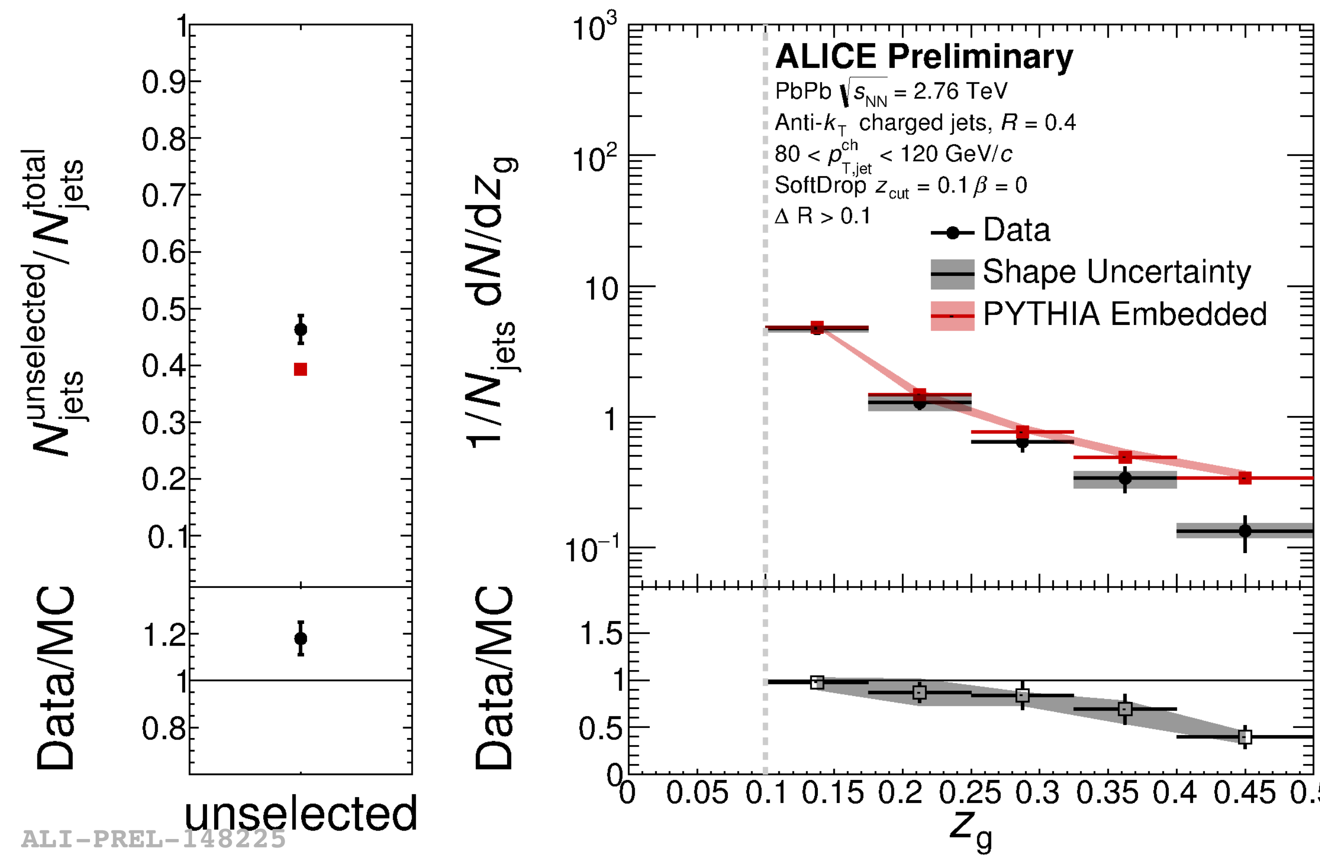
Charged jets, R = 0.4, 80 < p_T < 120 GeV/c





z_g, n_{SD} measurements in Pb-Pb collisions

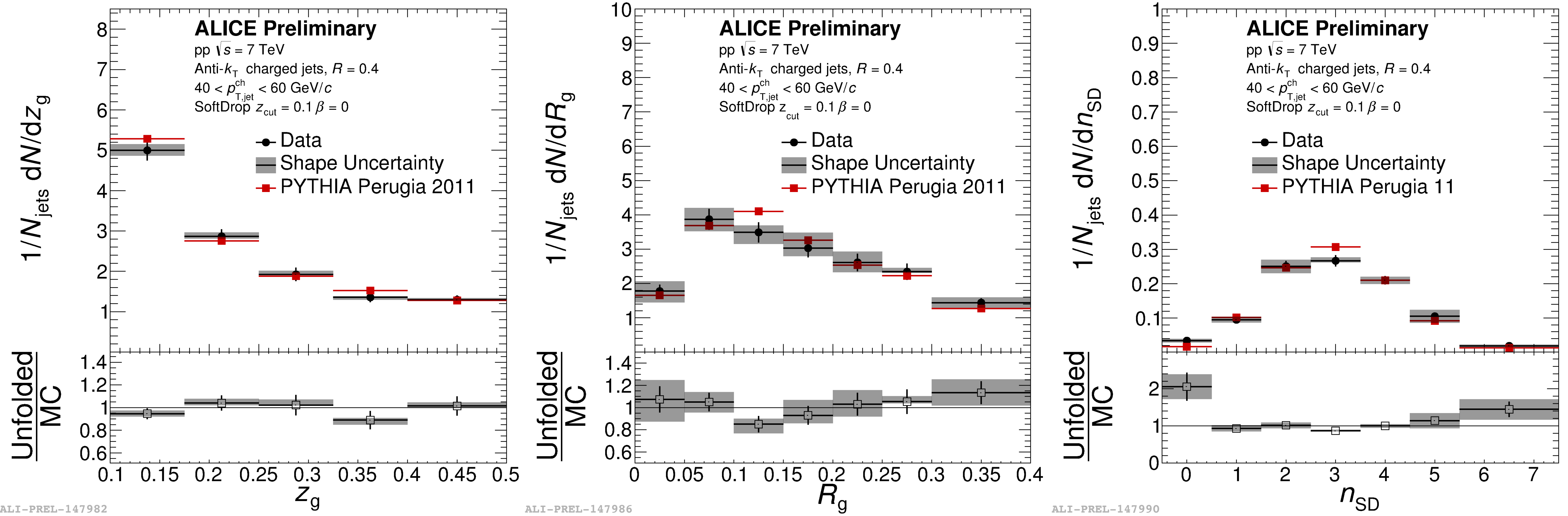




CMS Phys. Rev. Lett. 120, 142302

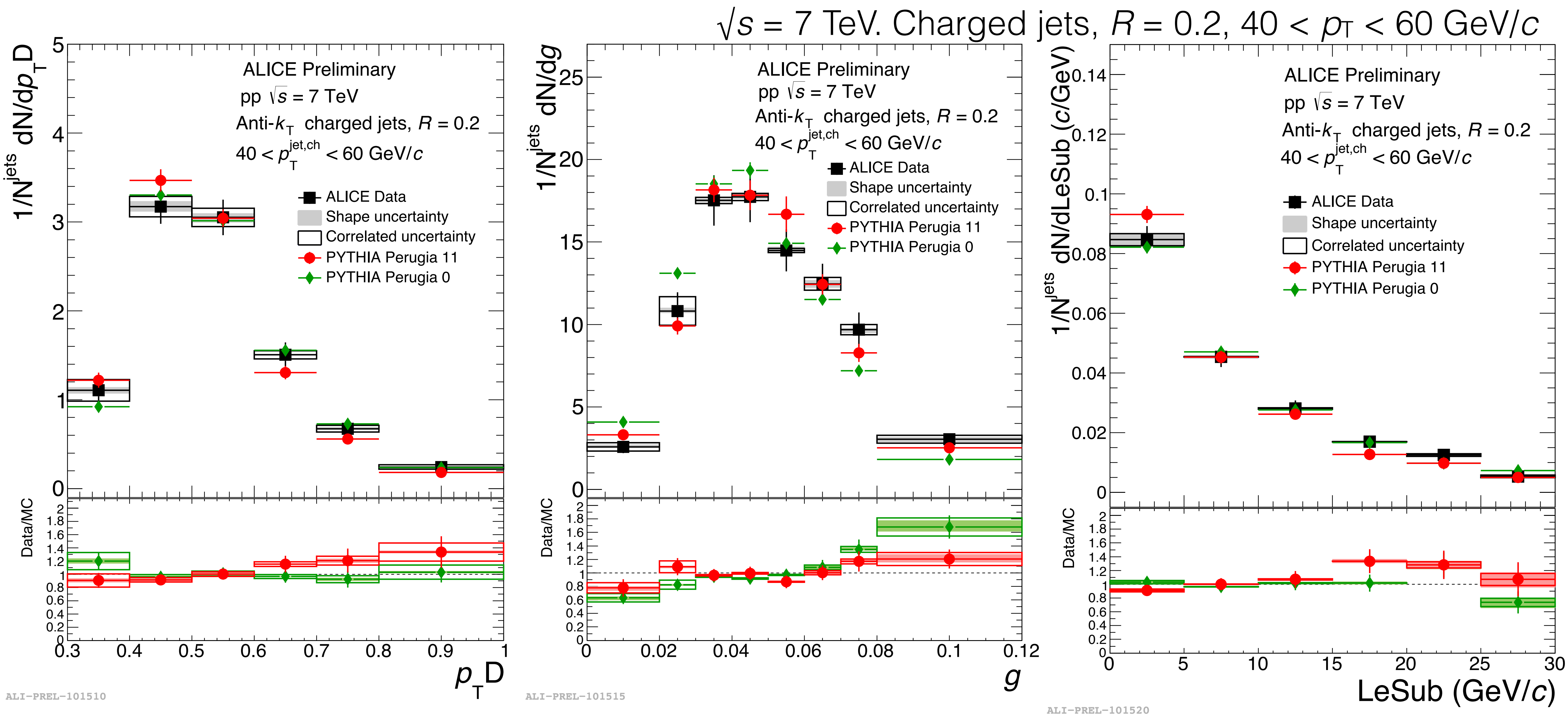
z_g, R_g, n_{SD} measurements in pp collisions

$\sqrt{s}$ = 7 TeV. Charged jets, R = 0.4, 40 < p_T < 60 GeV/c



- Distributions fully corrected to charged particle level.
- Reasonable agreement between data and PYTHIA calculations for all the jet shapes.
  - Use PYTHIA as reference for Pb-Pb
- ~ 97% of jets passing the Soft Drop requirement $z > z_{cut} = 0.1$

$p_T D$, *g*, *LeSub* in pp collisions

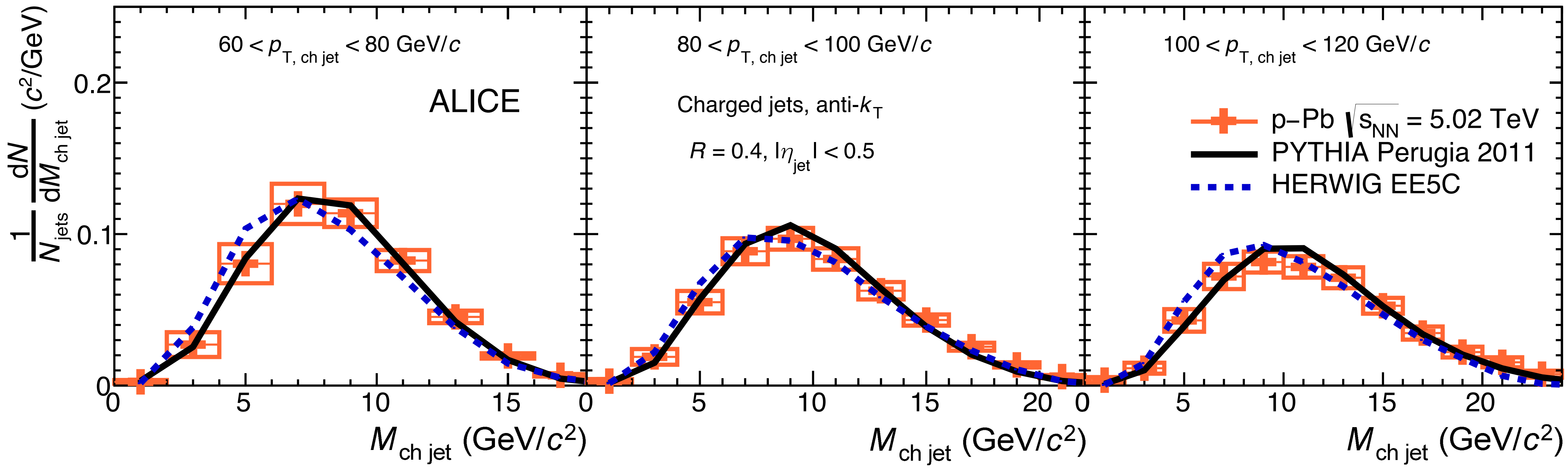


- Jet shapes, fully corrected to charged particle level.
- Reasonable agreement between data and PYTHIA calculations for all the jet shapes.
  - Use PYTHIA as reference for Pb-Pb
- Important for low *R* where hadronisation effects start to play an important role.

Jet Mass in p-Pb collisions

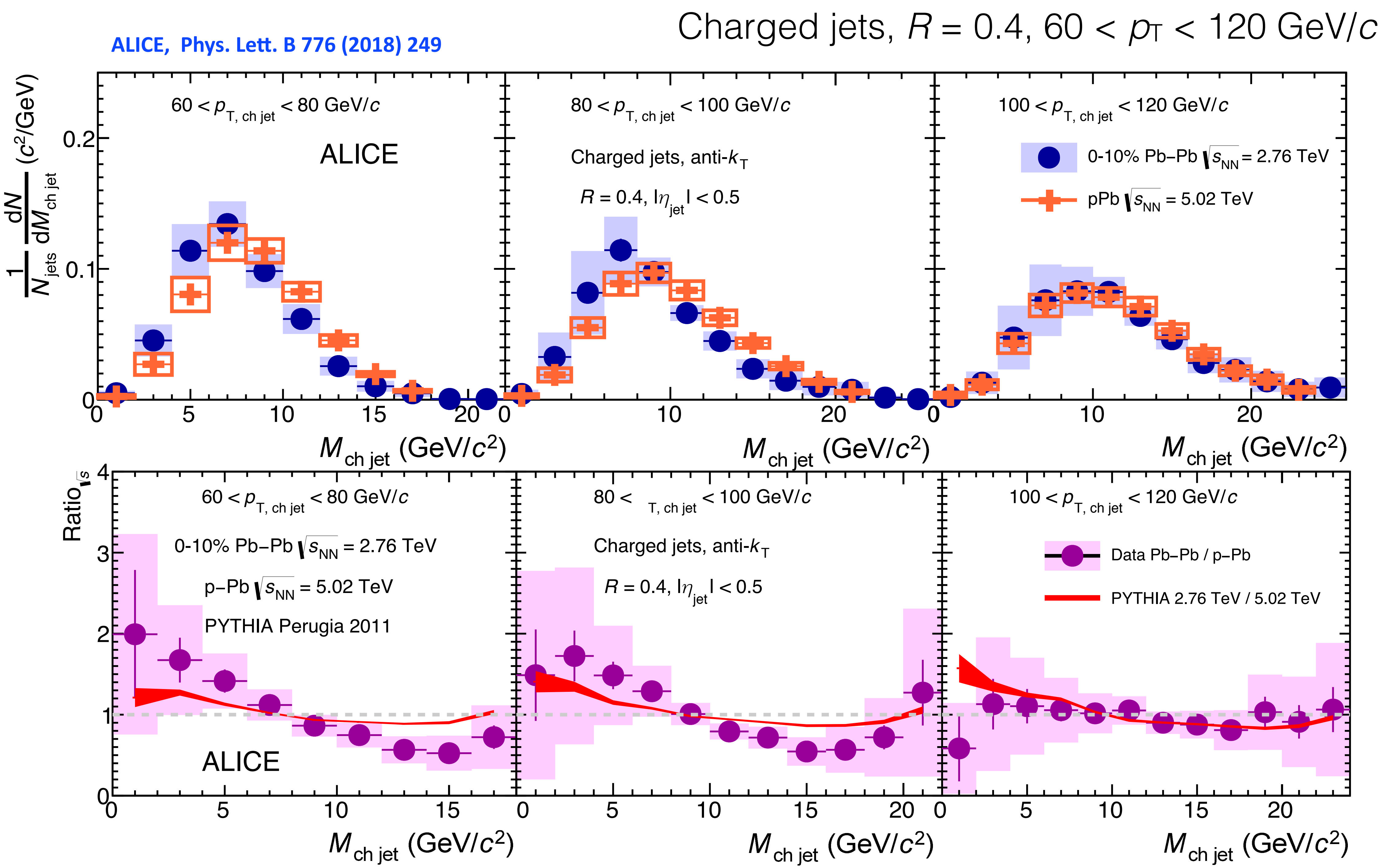
$\sqrt{s}$ = 5.02 TeV. Charged jets, R = 0.4, 60 < p_T < 120 GeV/c

ALICE, arXiv:1702.00804 submitted to PLB



- Reasonable agreement between **data** and **PYTHIA** calculations for jet mass.
  - Within 10-20%, some tensions in the tails.
- Slightly worst agreement with **HERWIG**, in particular in the low mass tail.
- **p-Pb measurement** can be used as **reference** for the comparison with the **Pb-Pb** one.

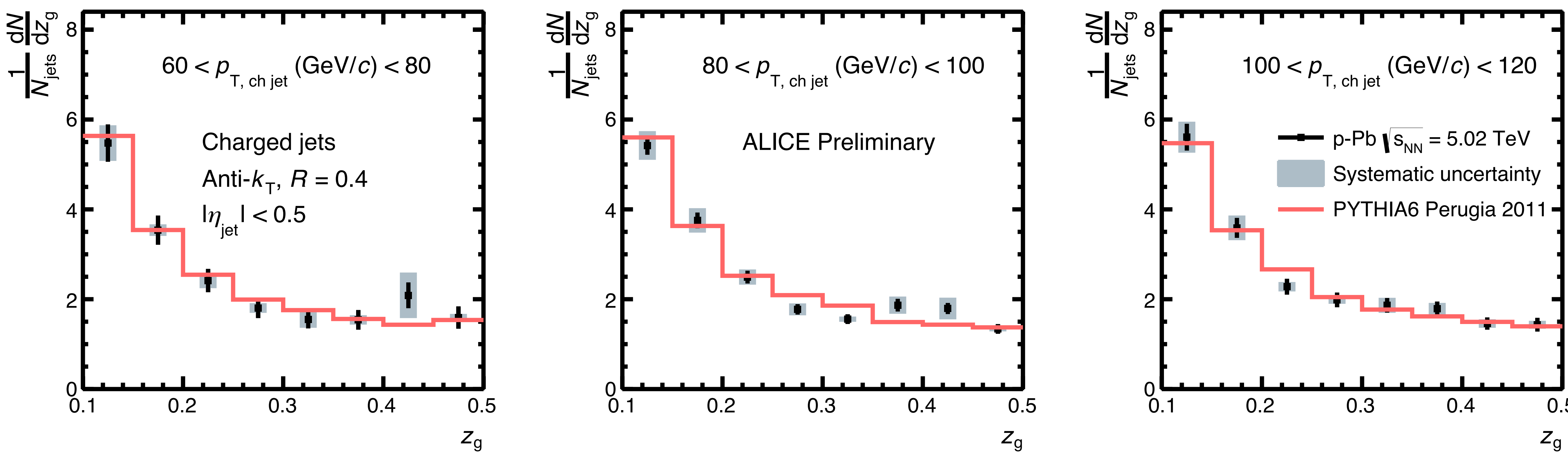
Charged jet shapes in Pb-Pb collisions



- Shift also quantified in terms of the ratio Pb-Pb/p-Pb and PYTHIA at the two energies

z_g measurement in p-Pb collisions

$\sqrt{s}$ = 5.02 TeV. Charged jets, R = 0.4, 60 < p_T < 120 GeV/c



ALI-PREL-120123

- **Jet substructure obtained using SoftDrop method (FastJet)**
- Good agreement between **data** and **PYTHIA Perugia 11**
- Reference measurements for future Pb-Pb results in ALICE

Jet shapes background subtraction

- Average background removal for jet shapes based on recent techniques:
  - Derivatives (area based) subtraction G. Soyez et al, Phys. Rev. Lett 110 (2013) 16
  - Constituent subtraction P. Berta et al, JHEP 1406 (2014) 092

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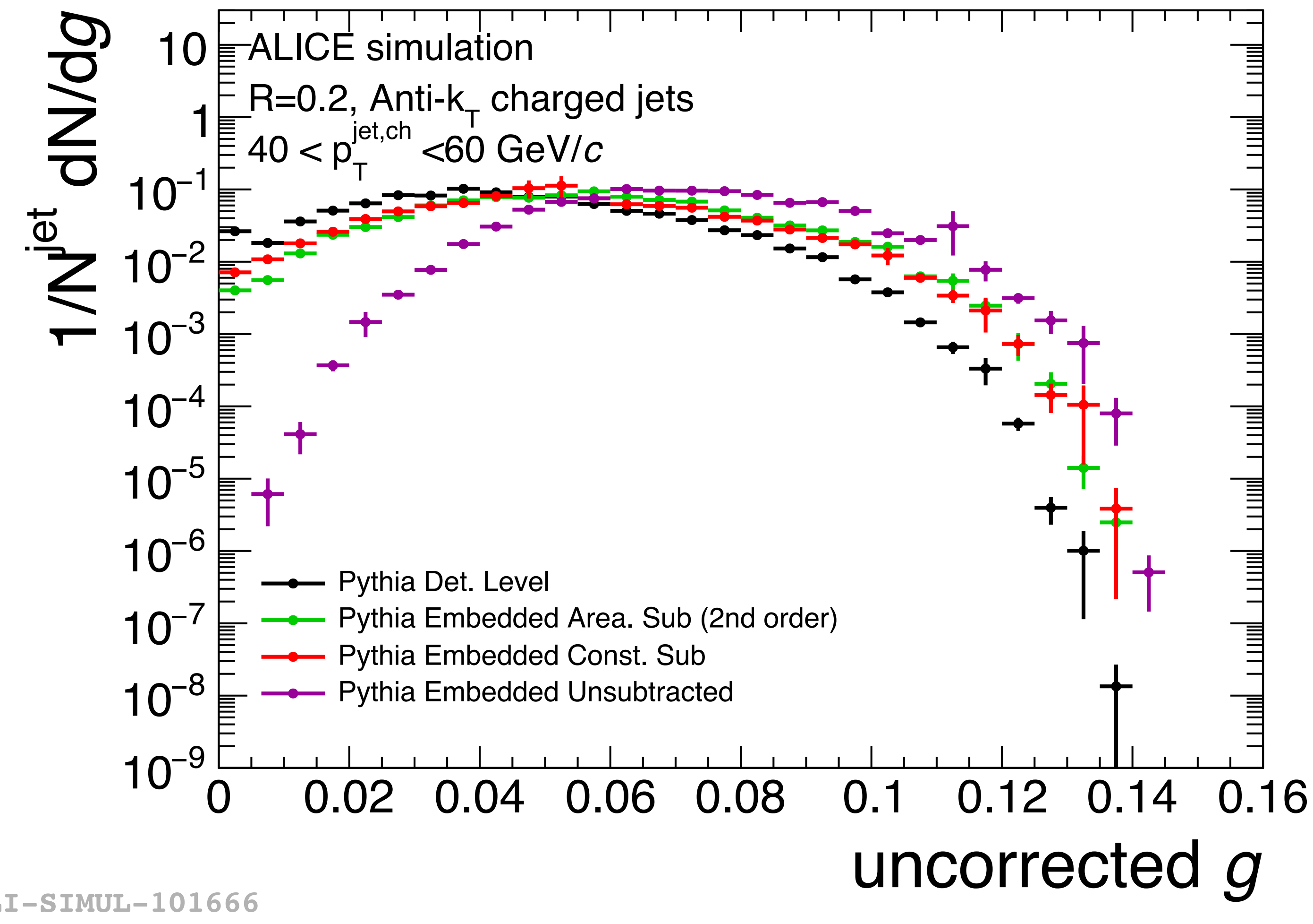
- **PYTHIA detector level** jets **embedded in Pb-Pb events.**



Jet shapes background subtraction

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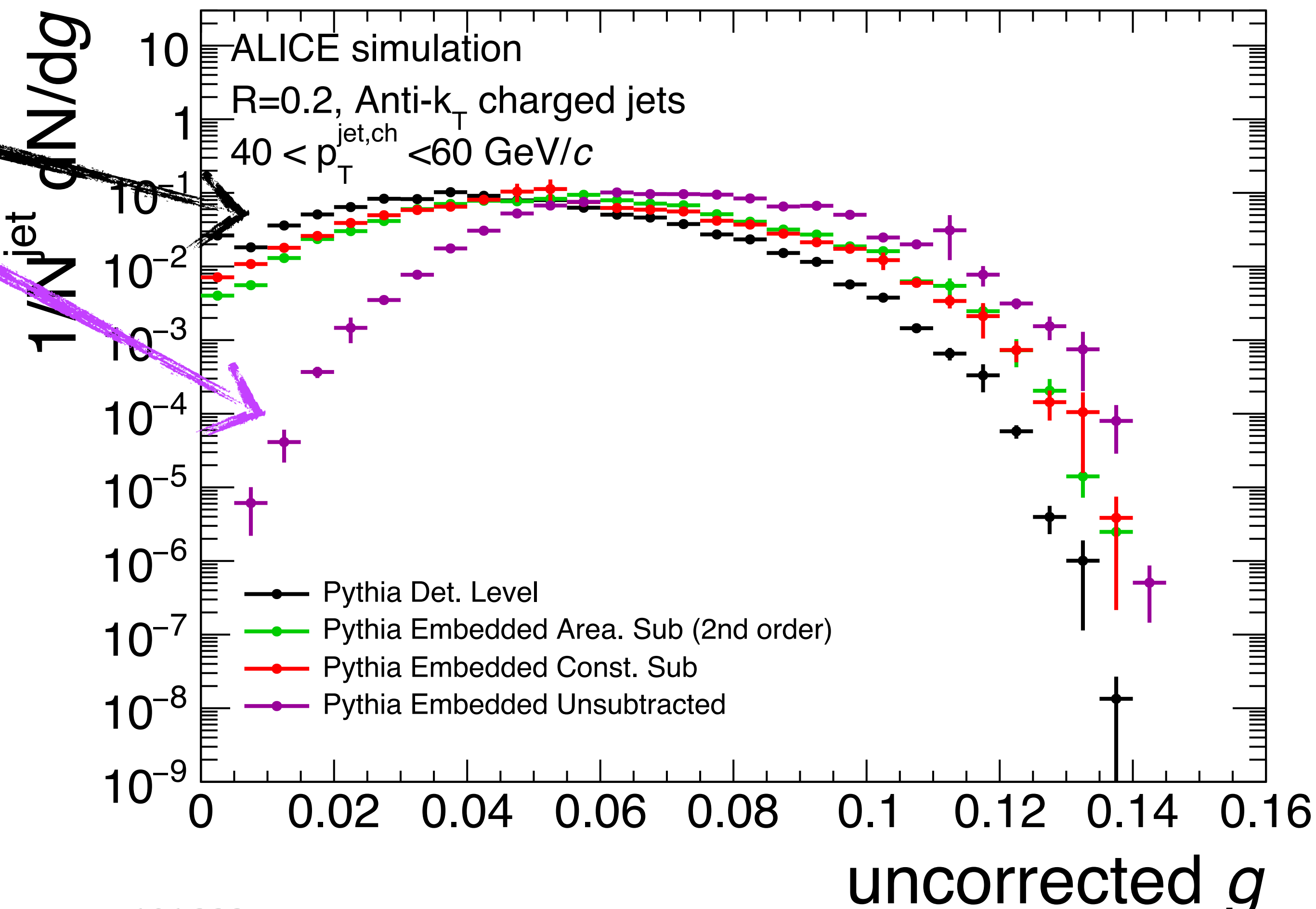
- **PYTHIA detector level** jets **embedded in Pb-Pb events.**
  - Shape distributions are modified by the high background



ALI-SIMUL-101666

Jet shapes background subtraction

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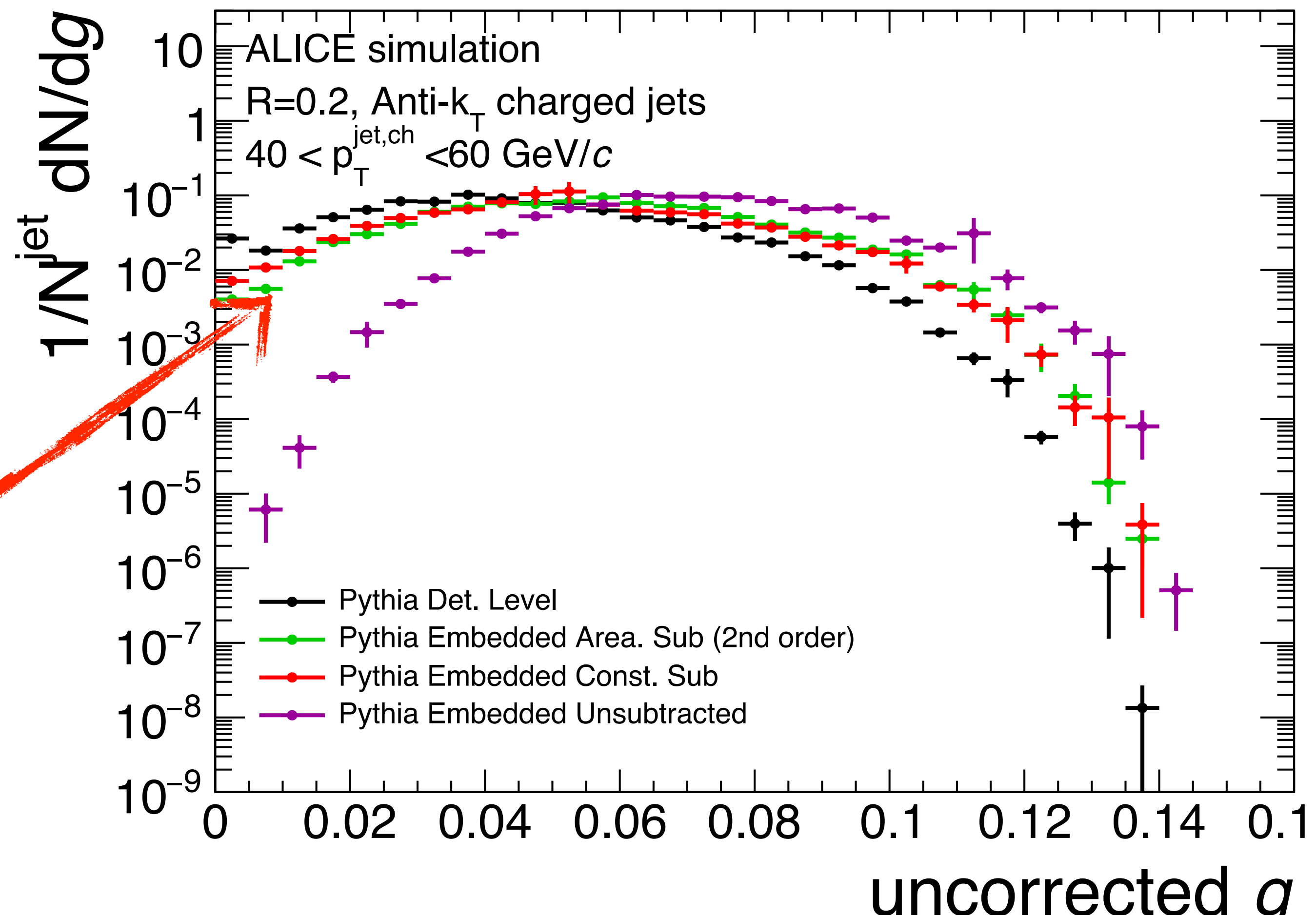
  - Constituent subtraction P. Berta et al, JHEP 1406 (2014) 092

- **PYTHIA detector level** jets **embedded in Pb-Pb events.**
  - Shape distributions are modified by the high background

- Subtraction methods (**area based**, **constituent based**) reduce the influence of the background on the shapes.



ALI-SIMUL-101666

Jet shapes background subtraction

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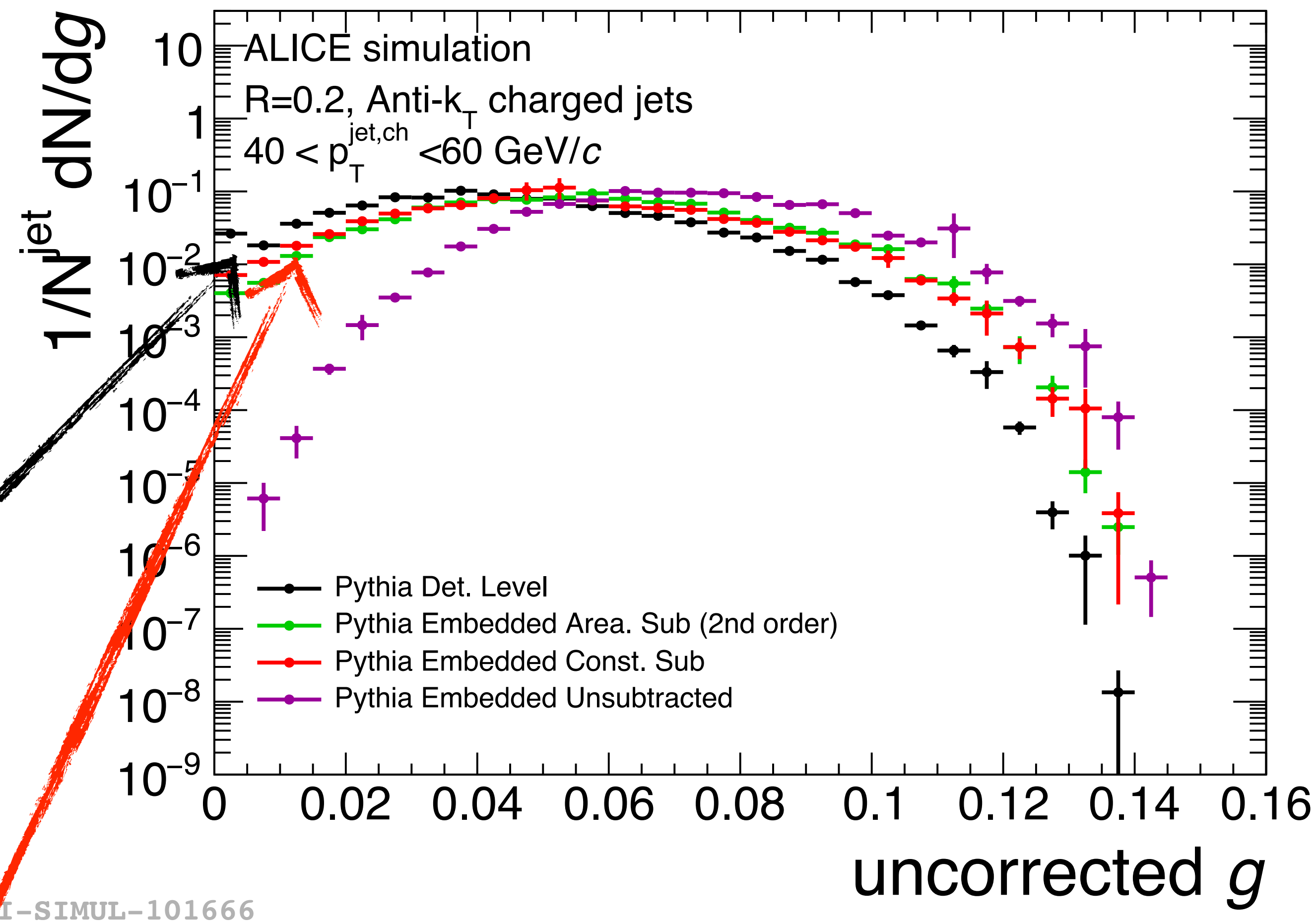
- **PYTHIA detector level** jets **embedded in Pb-Pb events.**
  - Shape distributions are modified by the high background

- Subtraction methods (**area based**, **constituent based**) reduce the influence of the background on the shapes.

- Residual difference between **PYTHIA detector level** jet shapes and **PYTHIA embedded subtracted** ones due to background fluctuations.



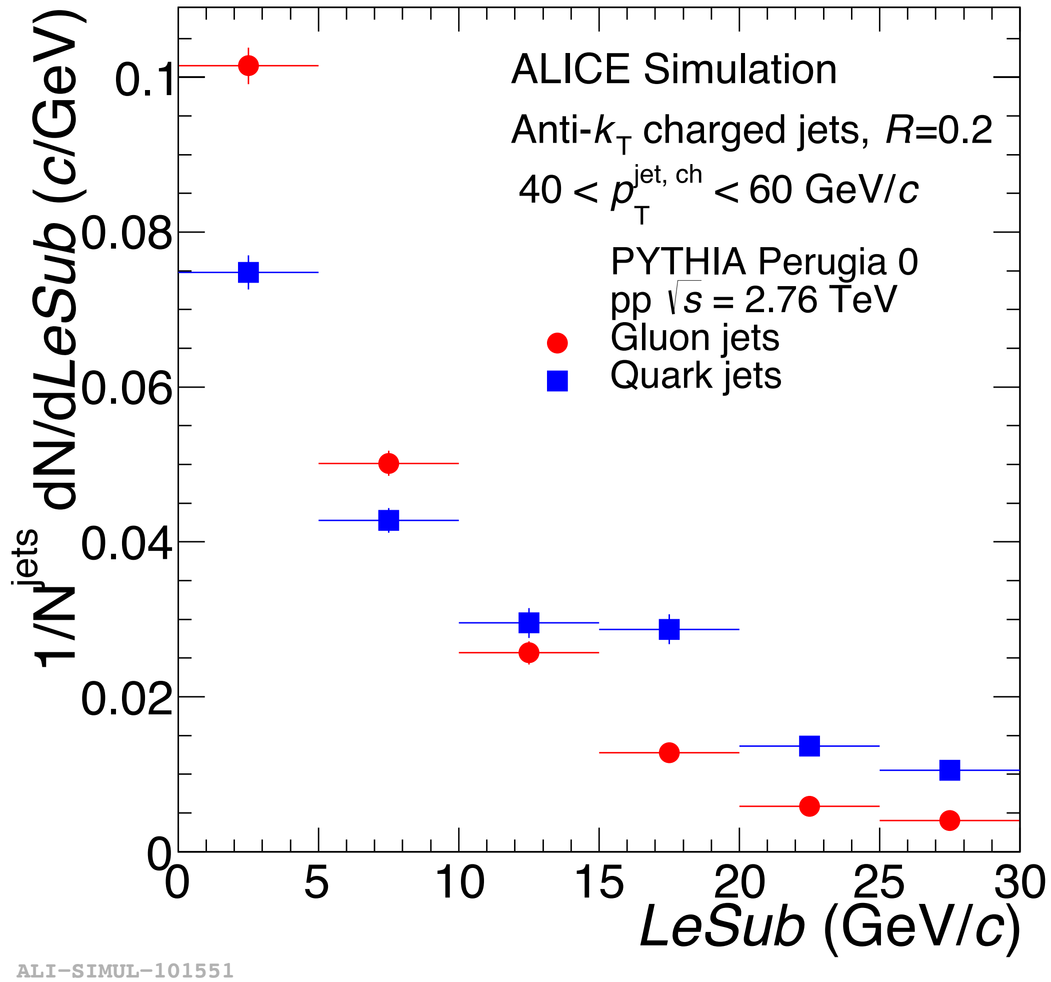
- 2D Bayesian Unfolding applied to remove
  - background fluctuations
  - detector effects.

Jet shapes definitions

- Jet shapes are observables constructed combining information:
  - on how the constituents are distributed in the jet
  - considering the clustering history.

- **Transverse momentum difference of leading and subleading particles (*LeSub*):**
  - Transverse momentum difference of the hardest and second hardest constituents of the jet.
  - Jet shape not IRC safe but essentially background invariant, interesting for Pb-Pb collisions.

$$LeSub = p_{\rm T}^{\rm leading\ track} - p_{\rm T}^{\rm subleading\ track}$$

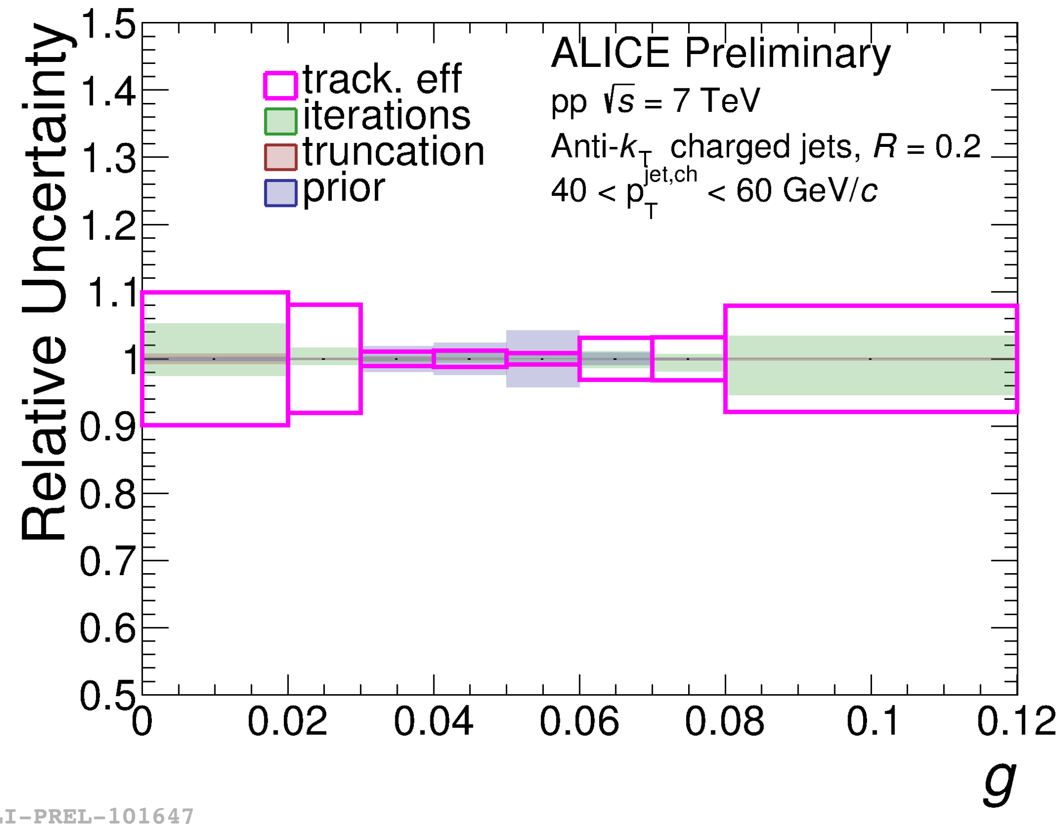


Systematics

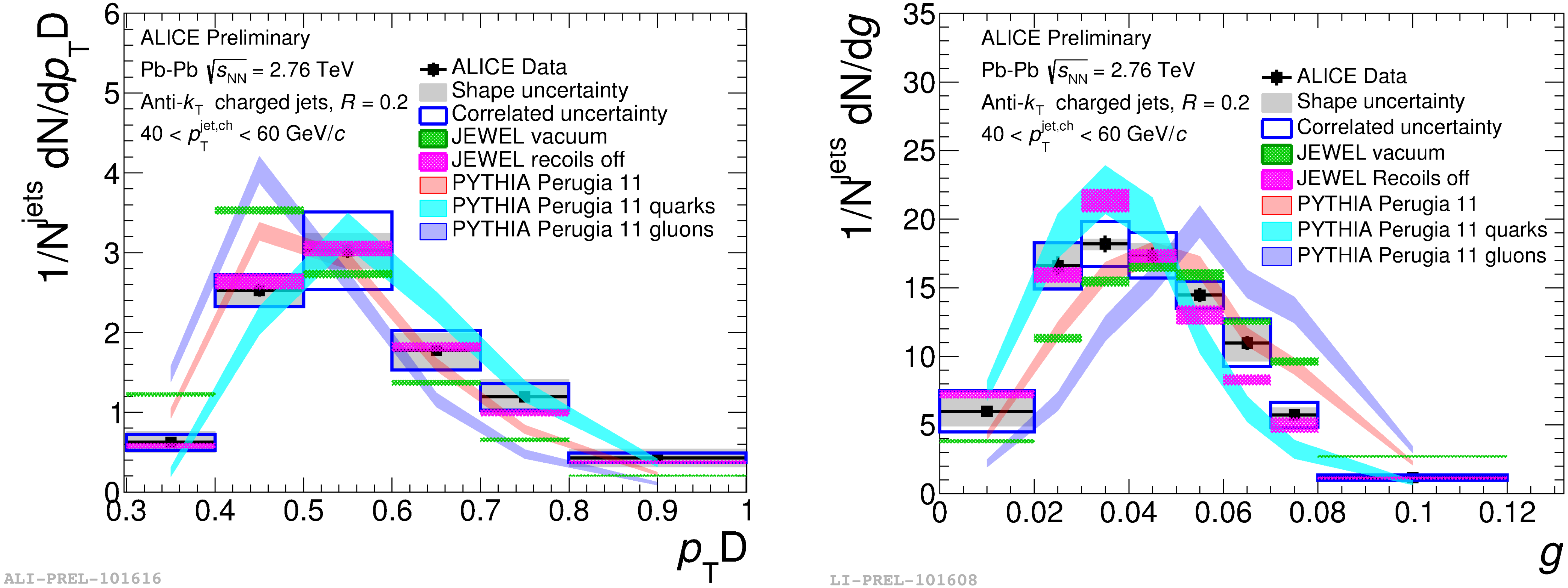
- **Different sources of systematics:**
  - **Tracking efficiency -** Variation of -4% dominate the jet energy scale uncertainty.
  - **Unfolding**
    - Regularization: variations of ±3 iterations in the procedure.
    - Truncation: difference to measured yield at a 10 GeV lower value than default one.
    - Prior: Variation of 20% between p_T^{part} and shape^{part}.
  - **Background subtraction -** two different methods used to estimate the background (only for Pb-Pb)

Mean jet mass

Source	Pb–Pb		
$p_{T,ch\ jet}$ (GeV/c)	60–80	80–100	100–120
Prior	1.0%	3.0%	5.0%
Background	3.0%	3.0%	5.0%
Tracking efficiency	5.0%	5.0%	5.0%
Unfolding (iterations, range)	1.0%	3.0%	4.0%
Total	6.0%	8.0%	9.0%



Charged jet shapes: comparison with models

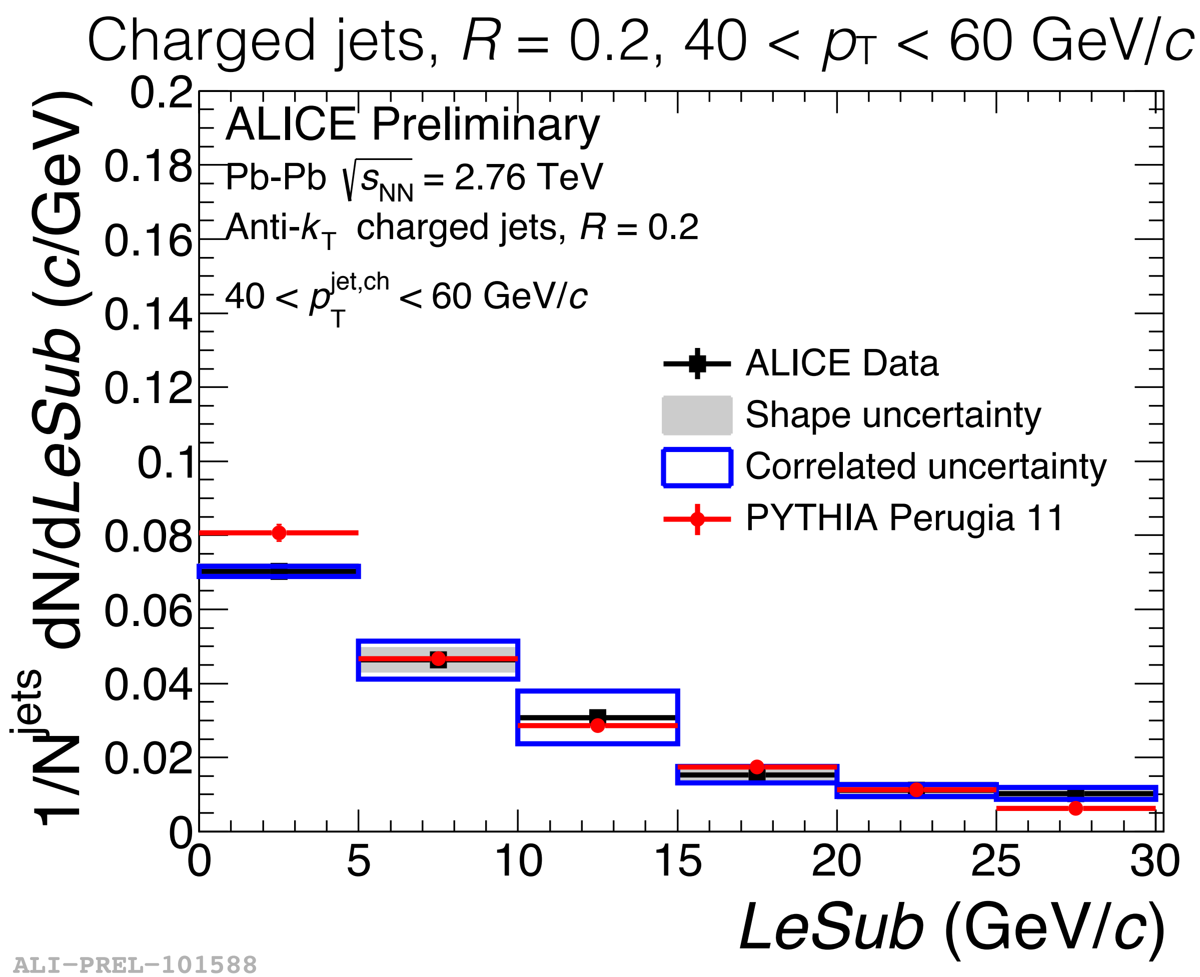


- Qualitative comparison with quark/gluon jets at the same energy:
  - gluon jets: quenched jets with intrajet broadening,
  - quark jets: quenched jets without intrajet broadening.

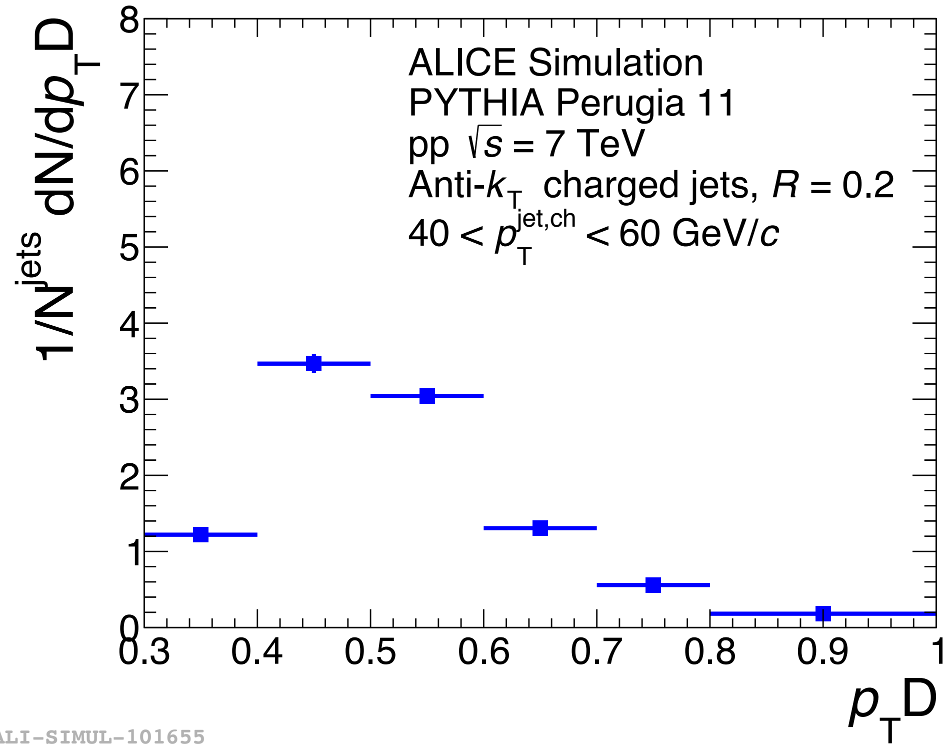
- **Results seem to be closer to quark-like jet fragmentation**.

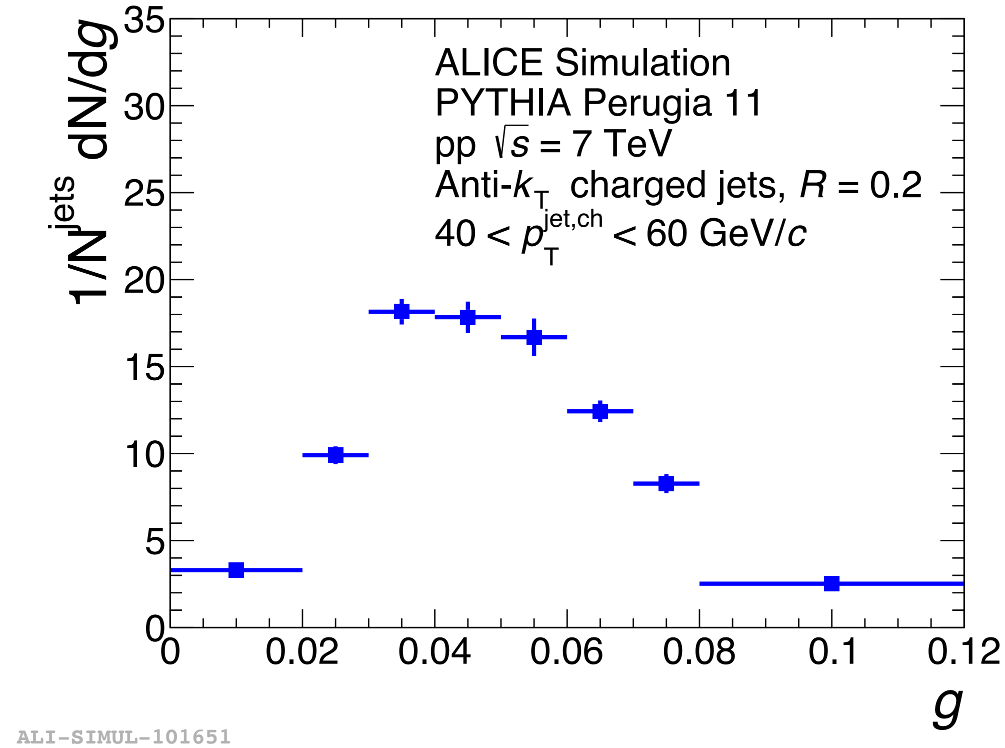
Charged jet shapes in Pb-Pb collisions

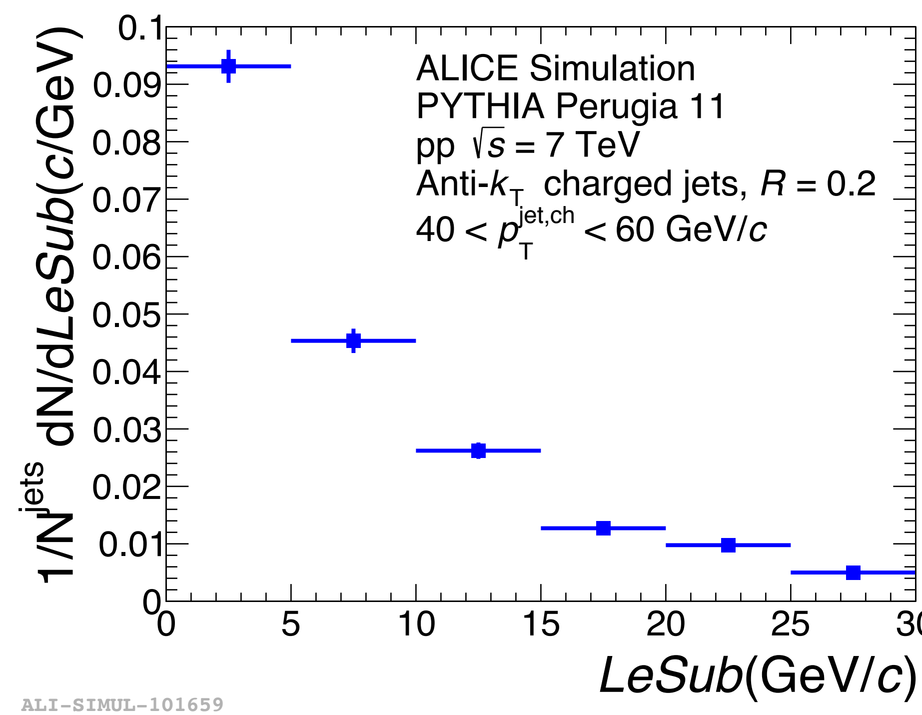
- $p_T D$ shifted to higher values in Pb-Pb collisions relative to PYTHIA Perugia11
- *g* shifted to lower values in Pb-Pb collisions relative to PYTHIA Perugia11
- *M* shows an hint of shift to lower values in Pb-Pb collisions relative to PYTHIA Perugia11
- *LeSub* in fair agreement with PYTHIA Perugia 11



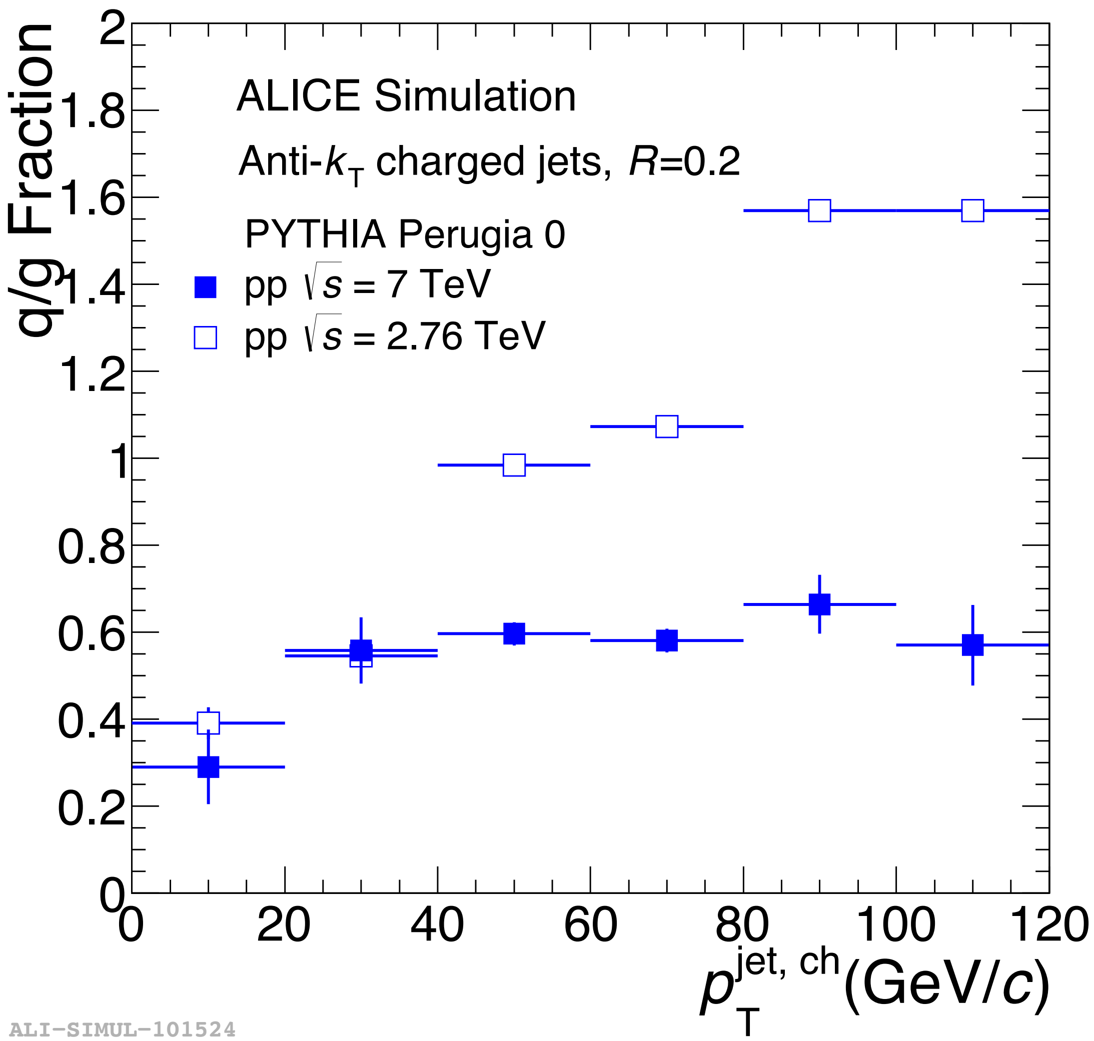
Jet shape distributions PYTHIA Perugia 11

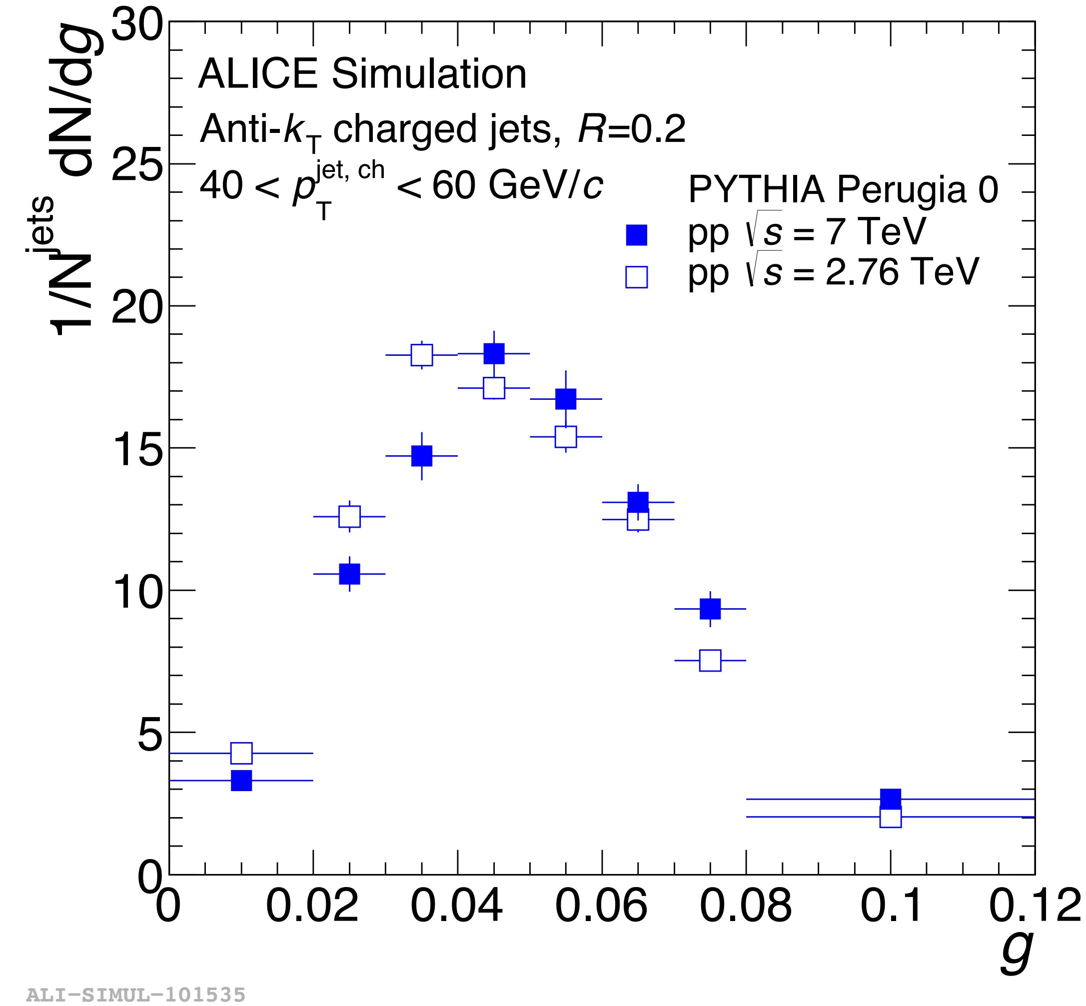






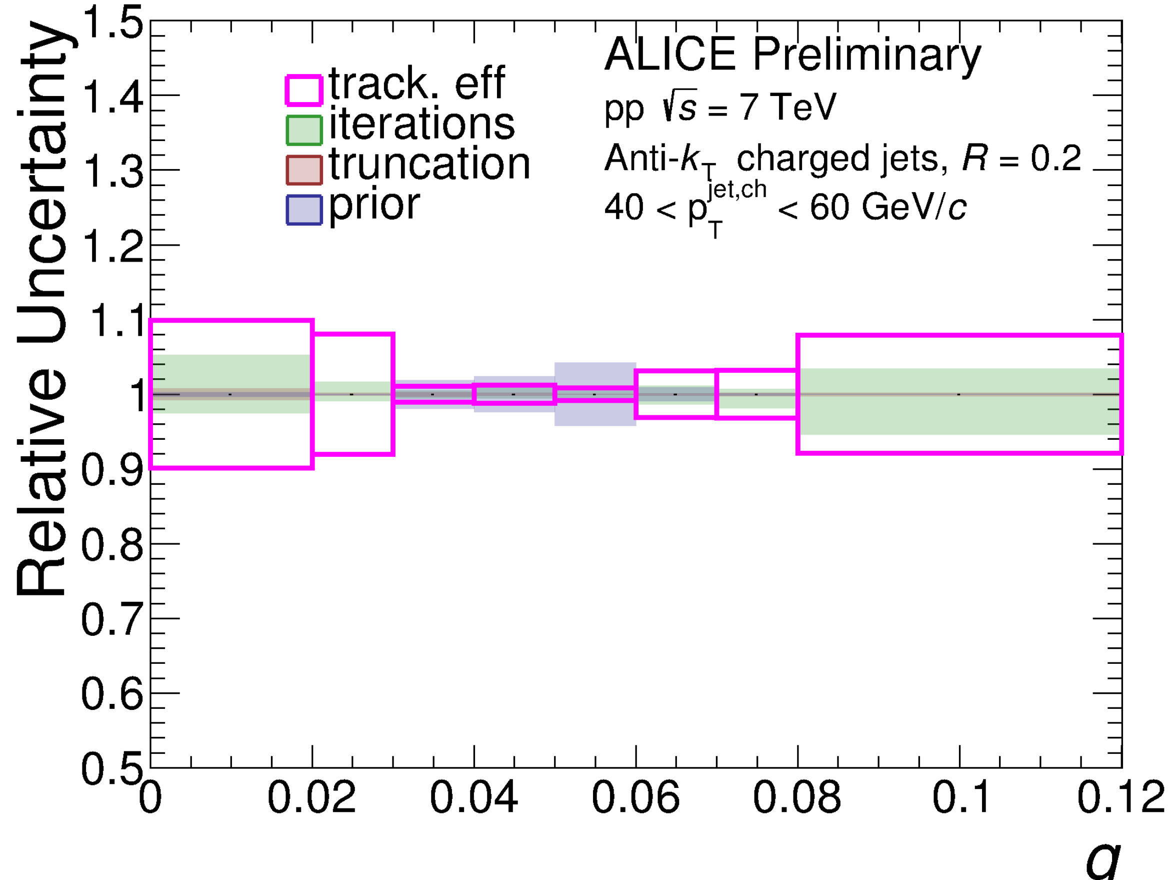
$\sqrt{s}$ dependence of jet shapes PYTHIA

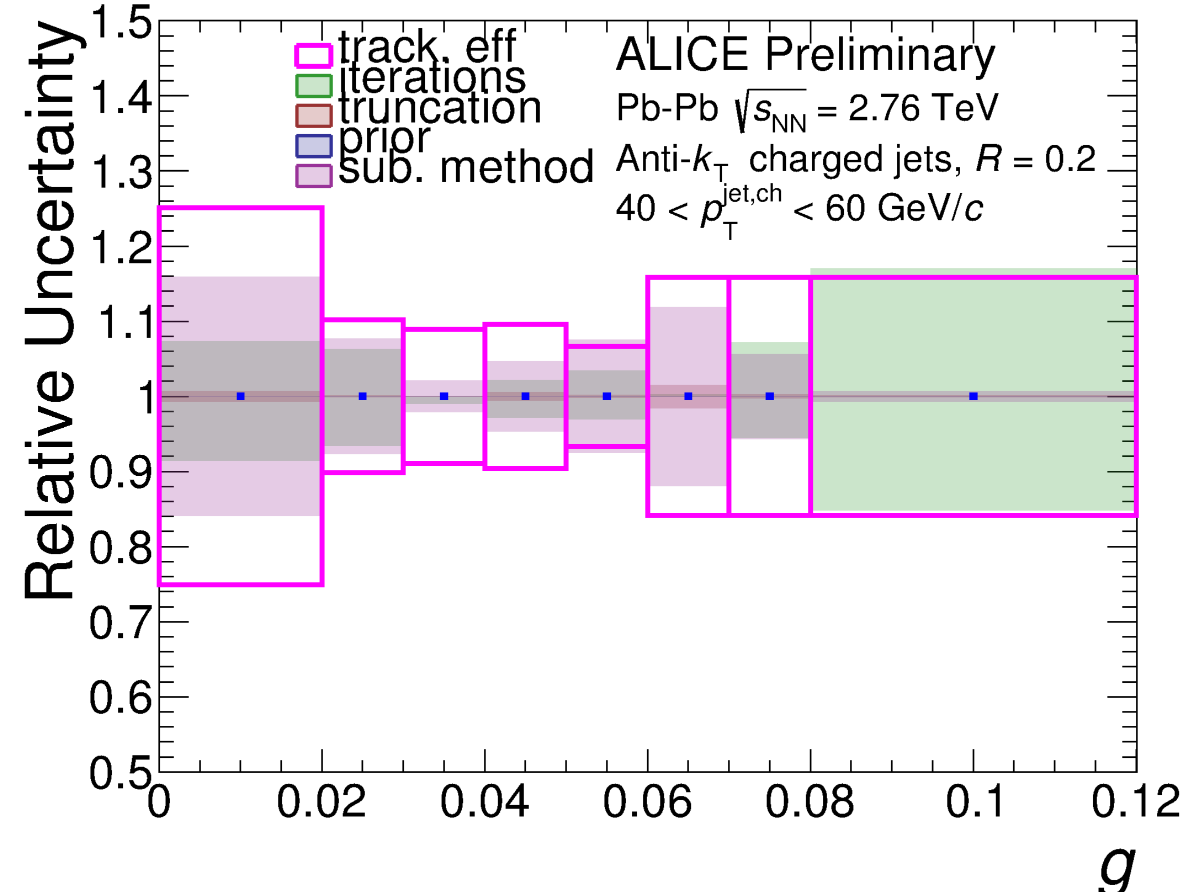




- Not negligible difference in the jet shapes due to due to q/g difference fraction at two collider energies.

Systematics





- Tracking efficiency. Variation of ±4% dominate the jet energy scale uncertainty.
- Unfolding:
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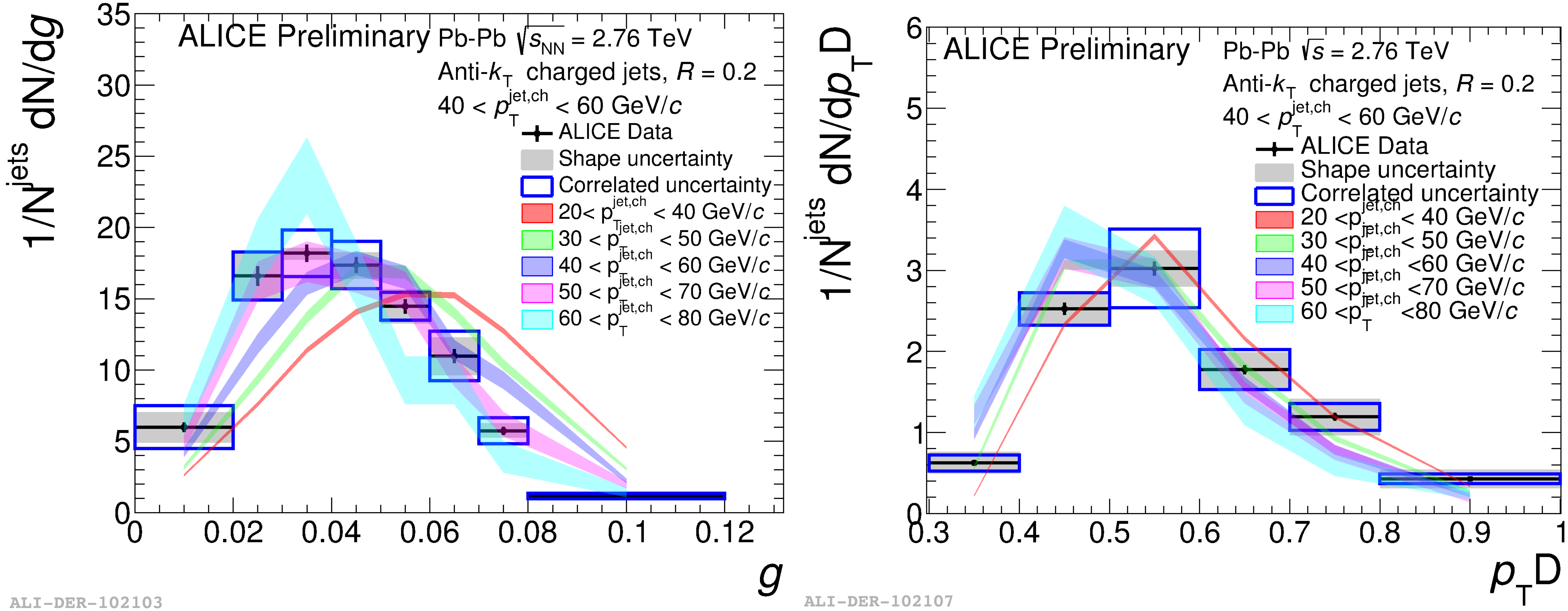
  - Prior: Variation of 20% between p_T^{part} and shape^{part}. Default value PYTHIA Perugia 0.
- Background subtraction: two different methods used to estimate the background.

Charge jet shapes: comparison with models

- If the jet would lose energy as a whole (single emitter) then we would expect Pb-Pb shapes to be in agreement with vacuum shape at higher-p_T



- The radial moment seems to show this behavior.
- p_TD does not, but it has a milder dependence on the transverse momentum.