



Exploring jet sub-structure in Pb-Pb and pp collisions with jet shapes in ALICE

Davide Caffarri (CERN), for the ALICE Collaboration



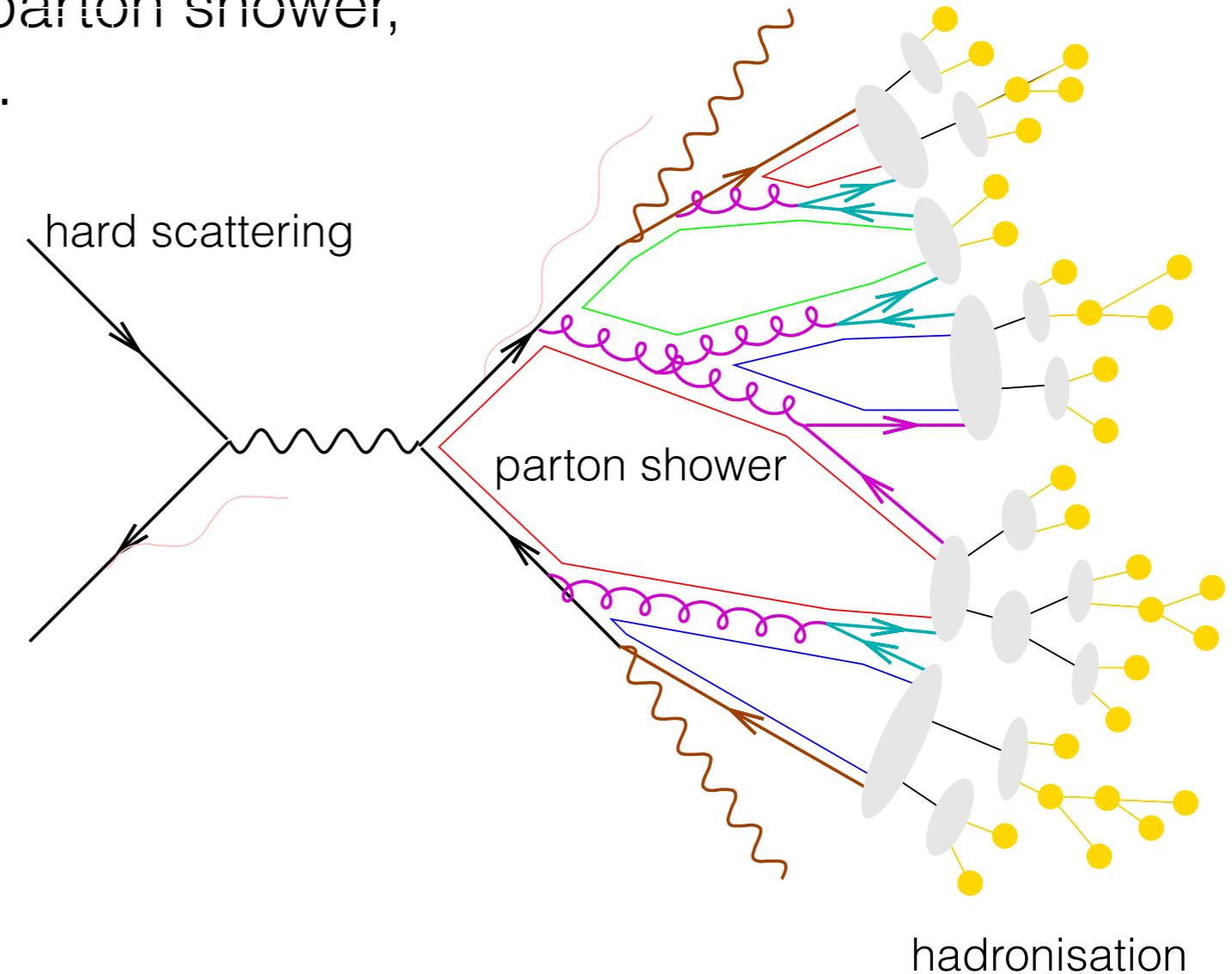
**38th INTERNATIONAL CONFERENCE
ON HIGH ENERGY PHYSICS**

AUGUST 3 - 10, 2016
CHICAGO

Introduction: Jets in hadron collisions



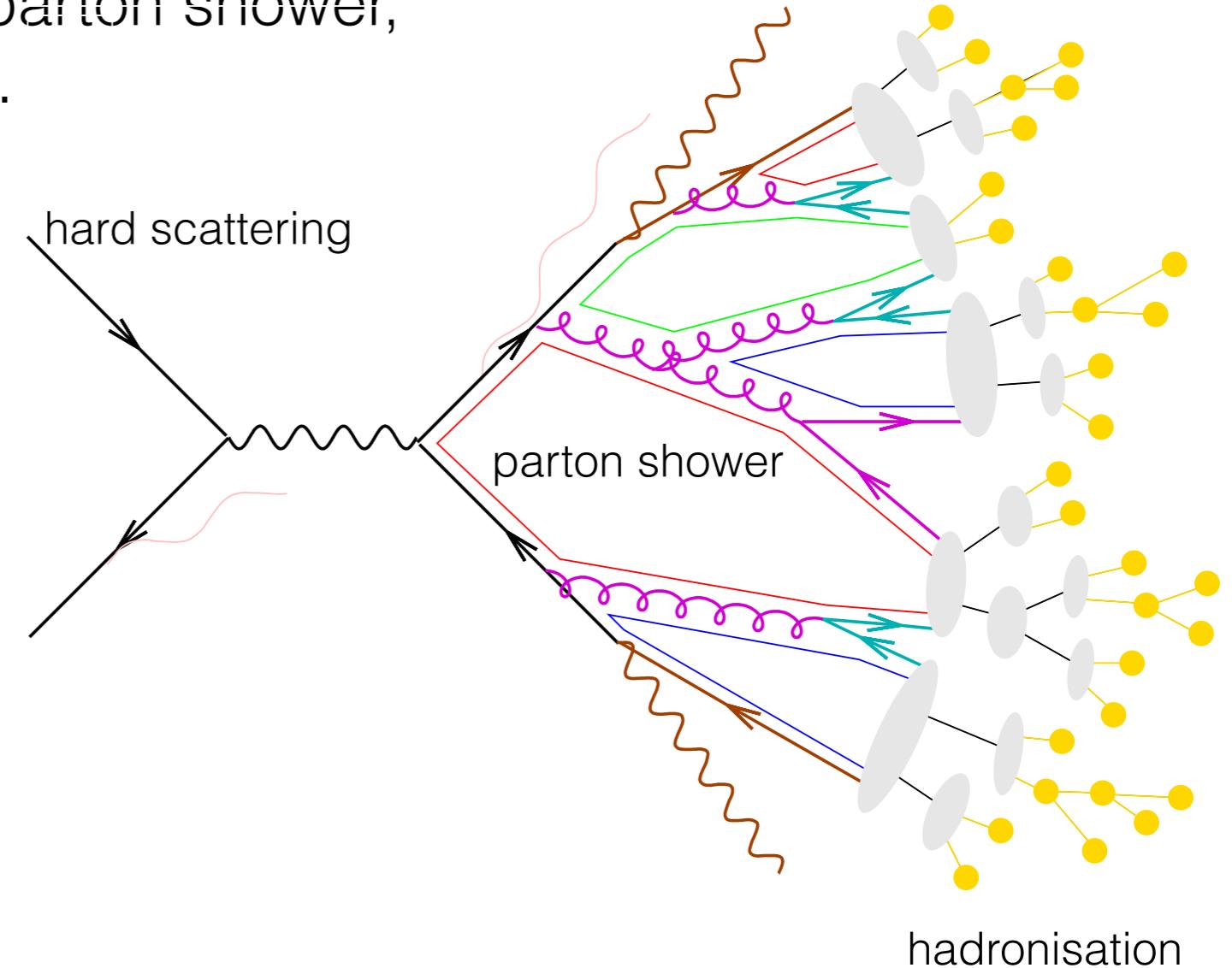
- ▶ High- p_T and virtuality partons are produced in initial hard scatterings:
 - ▶ virtuality evolution through parton shower,
 - ▶ hadronisation at Λ_{QCD} scale.



Introduction: Jets in hadron collisions



- ▶ High- p_T and virtuality partons are produced in initial hard scatterings:
 - ▶ virtuality evolution through parton shower,
 - ▶ hadronisation at Λ_{QCD} scale.
- ▶ No unambiguous definition of a jet:
 - ▶ “collimated bunch of hadrons”
 - ▶ experimental access to quarks and gluons

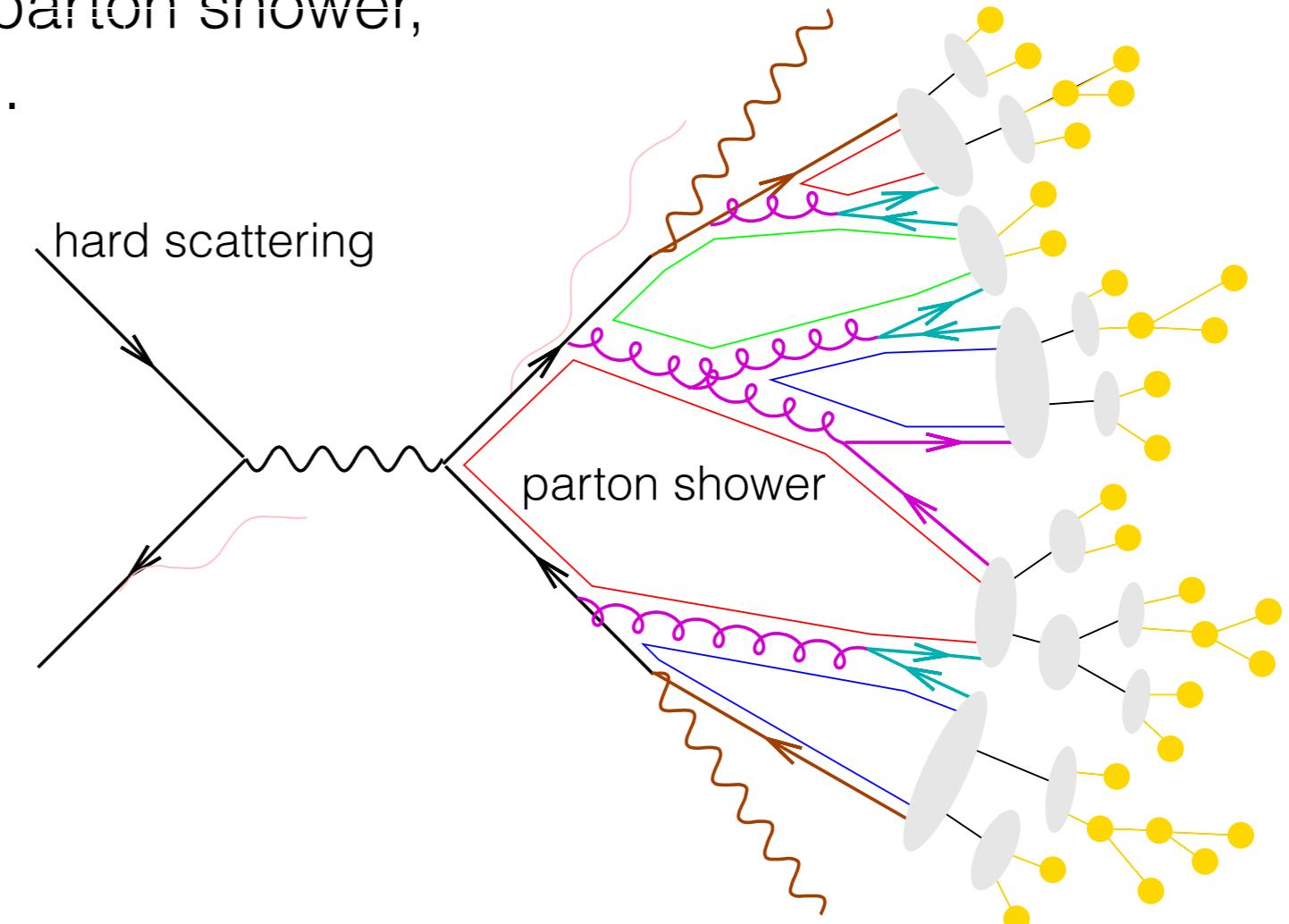


Introduction: Jets in hadron collisions



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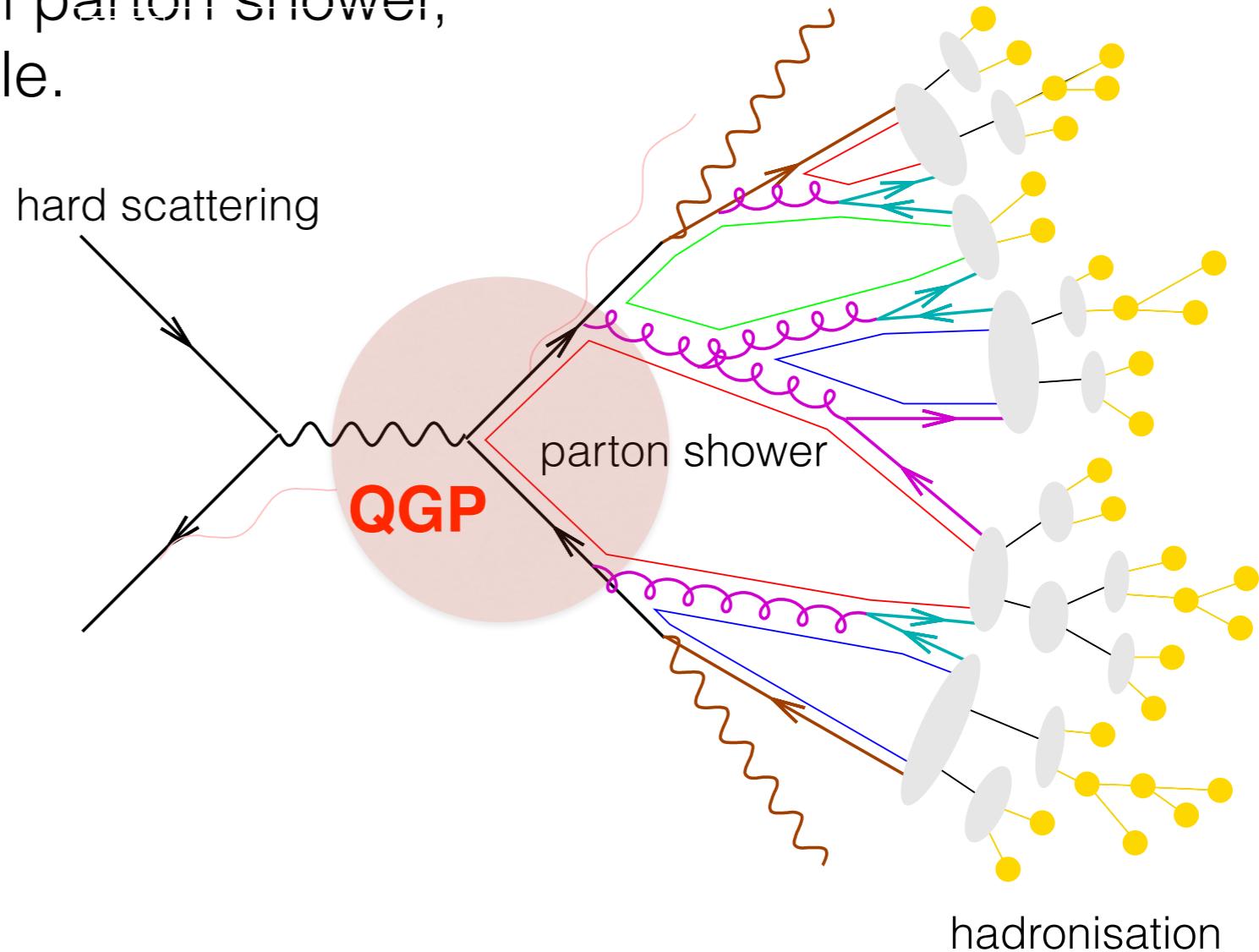


- ▶ In pp collisions:
 - ▶ calculable probes using pQCD,
 - ▶ allow to study hadronisation and underlying event effects.

Introduction: Jets in hadron collisions



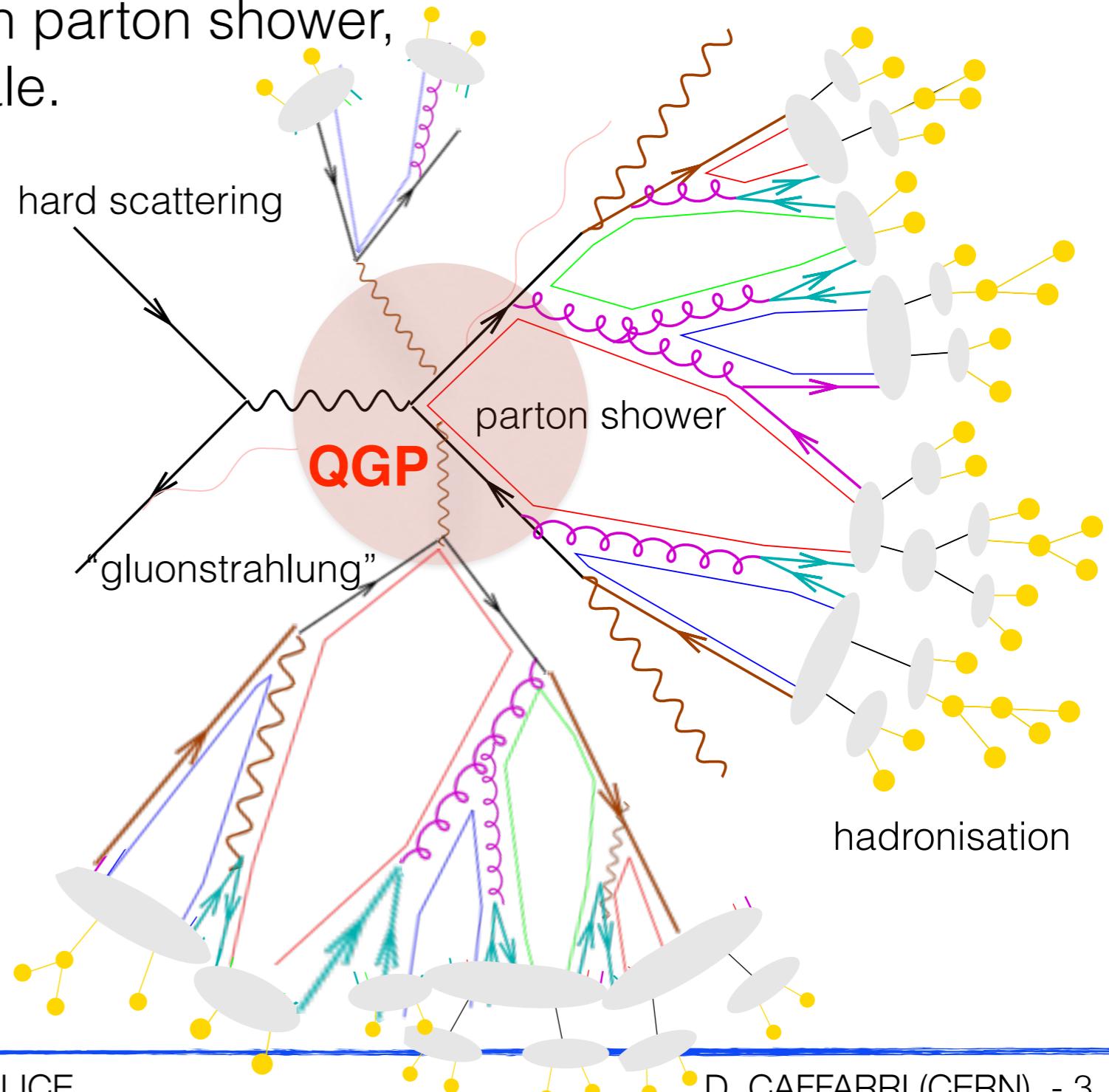
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Introduction: Jets in heavy-ion collisions



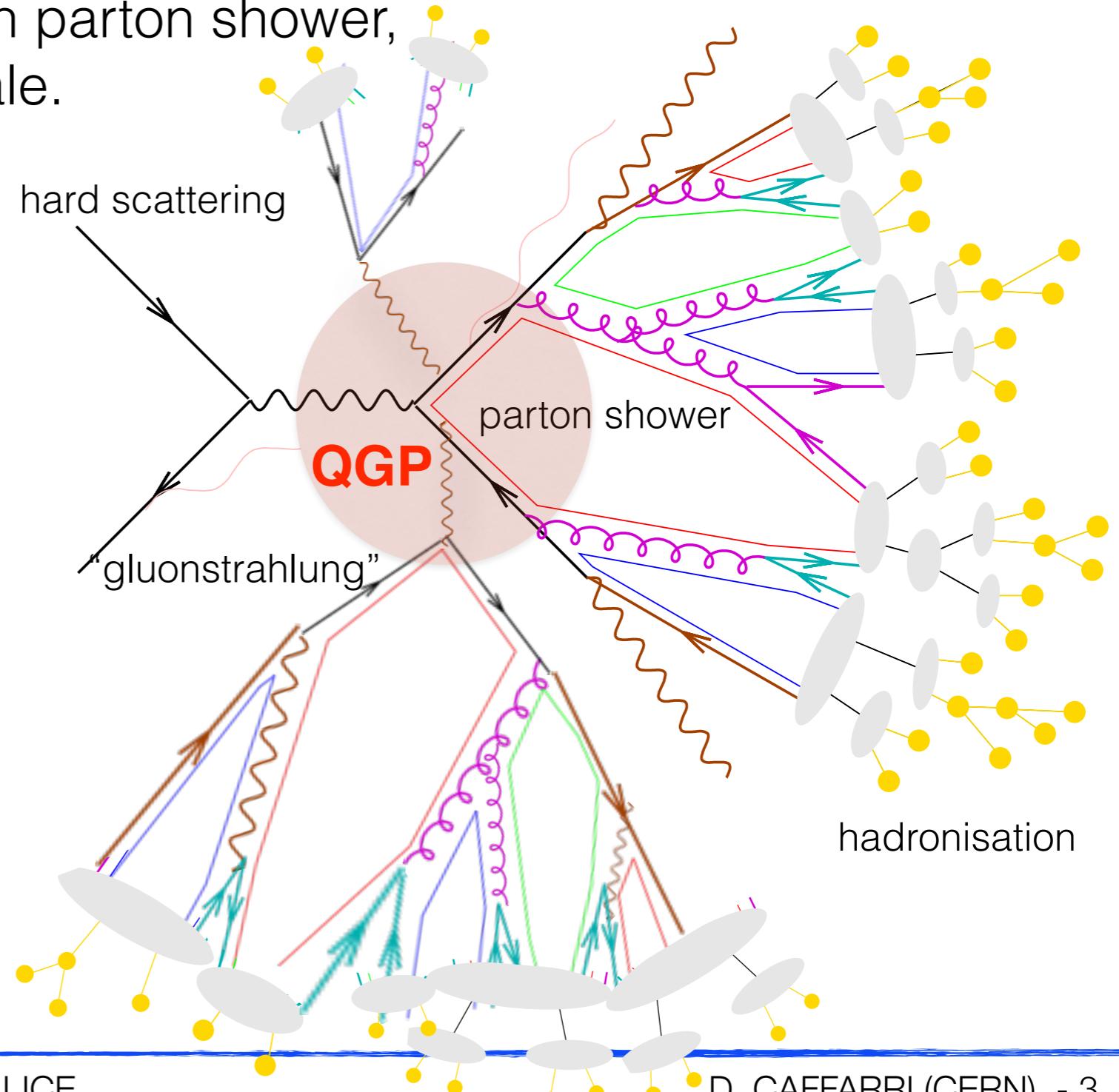
- ▶ High- p_T and virtuality partons are produced in initial hard scatterings:
 - ▶ virtuality evolution through parton shower,
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- ▶ **Hard partons** traverse the QGP and **lose energy** while passing through it: “**Gluon bremsstrahlung effect**”



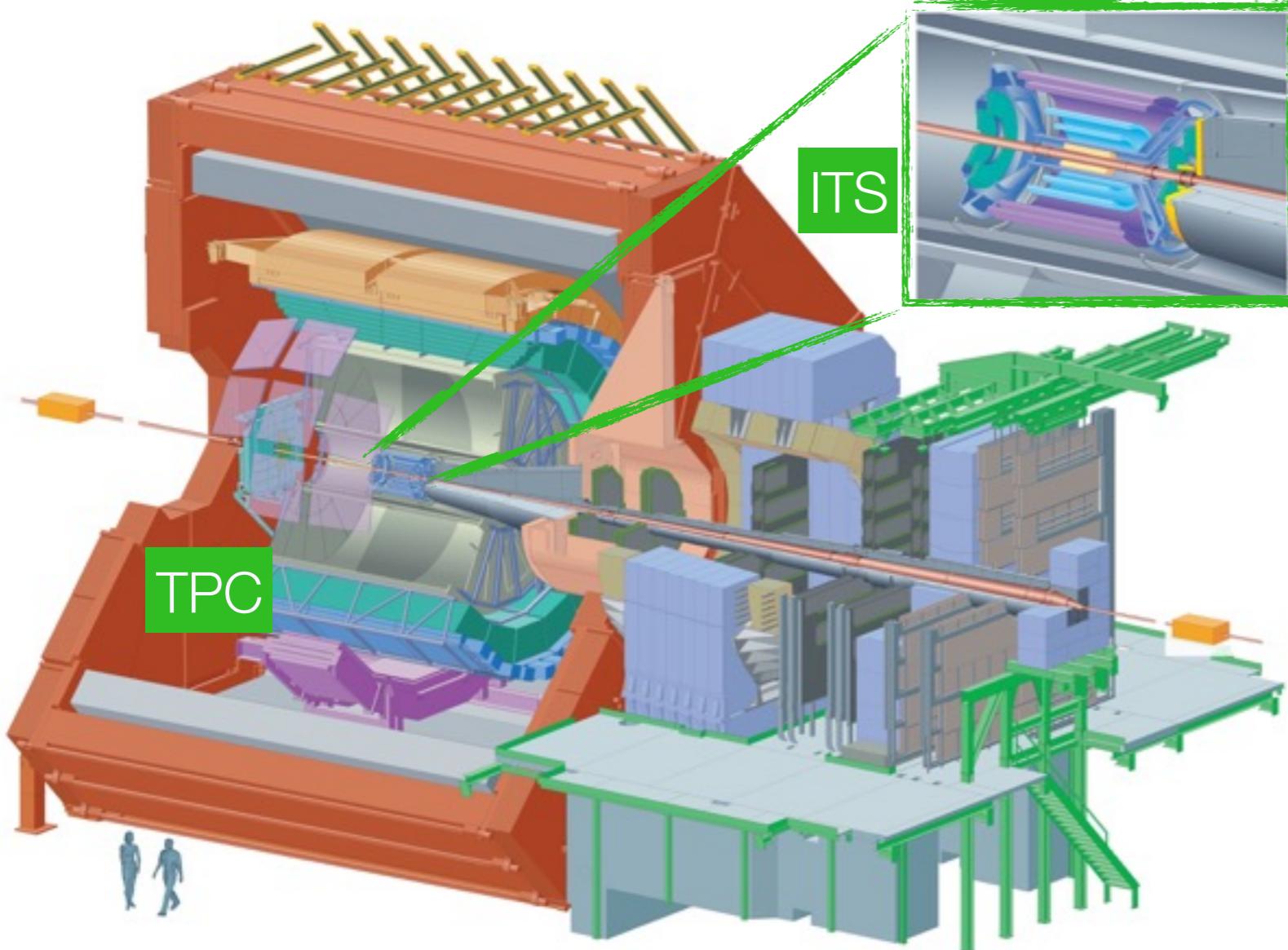
Introduction: Jets in heavy-ion collisions



- ▶ High- p_T and virtuality partons are produced in initial hard scatterings:
 - ▶ virtuality evolution through parton shower,
 - ▶ hadronisation at Λ_{QCD} scale.
- ▶ Hard partons traverse the QGP and lose energy while passing through it: “Gluon-bremsstrahlung effect”
- ▶ Via the **parton interactions with the medium**, jets can be used to:
 - ▶ study possible **modified fragmentation** with respect to the “vacuum” case (pp collisions),
 - ▶ probe jet and medium **properties**.



Jet reconstruction in ALICE



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

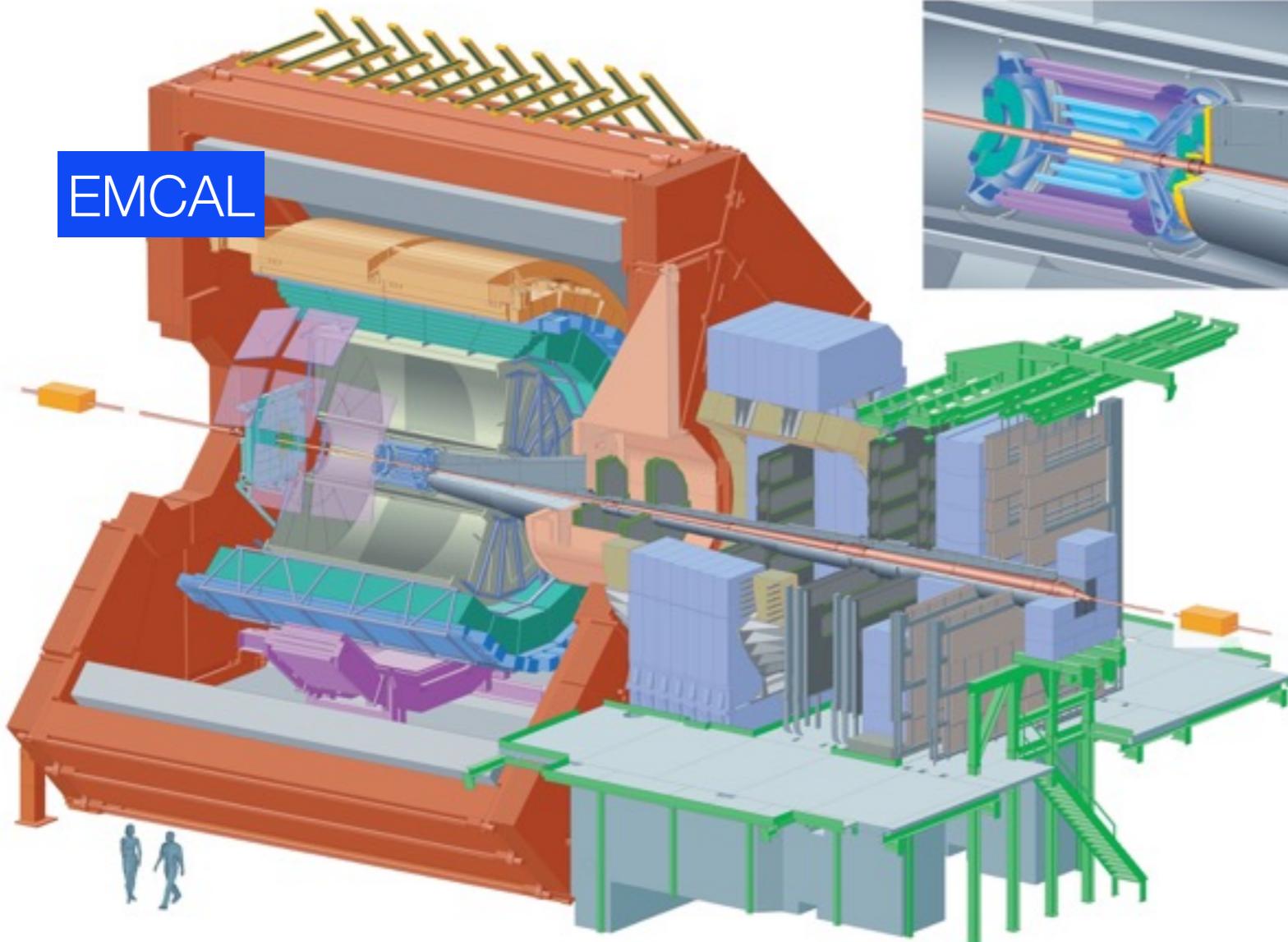
ITS: Inner Tracking System (silicon)

TPC: Time Projection Chamber

Track $p_T > 150$ MeV/c

Charged constituent jets (jet^{ch})

Jet reconstruction in ALICE



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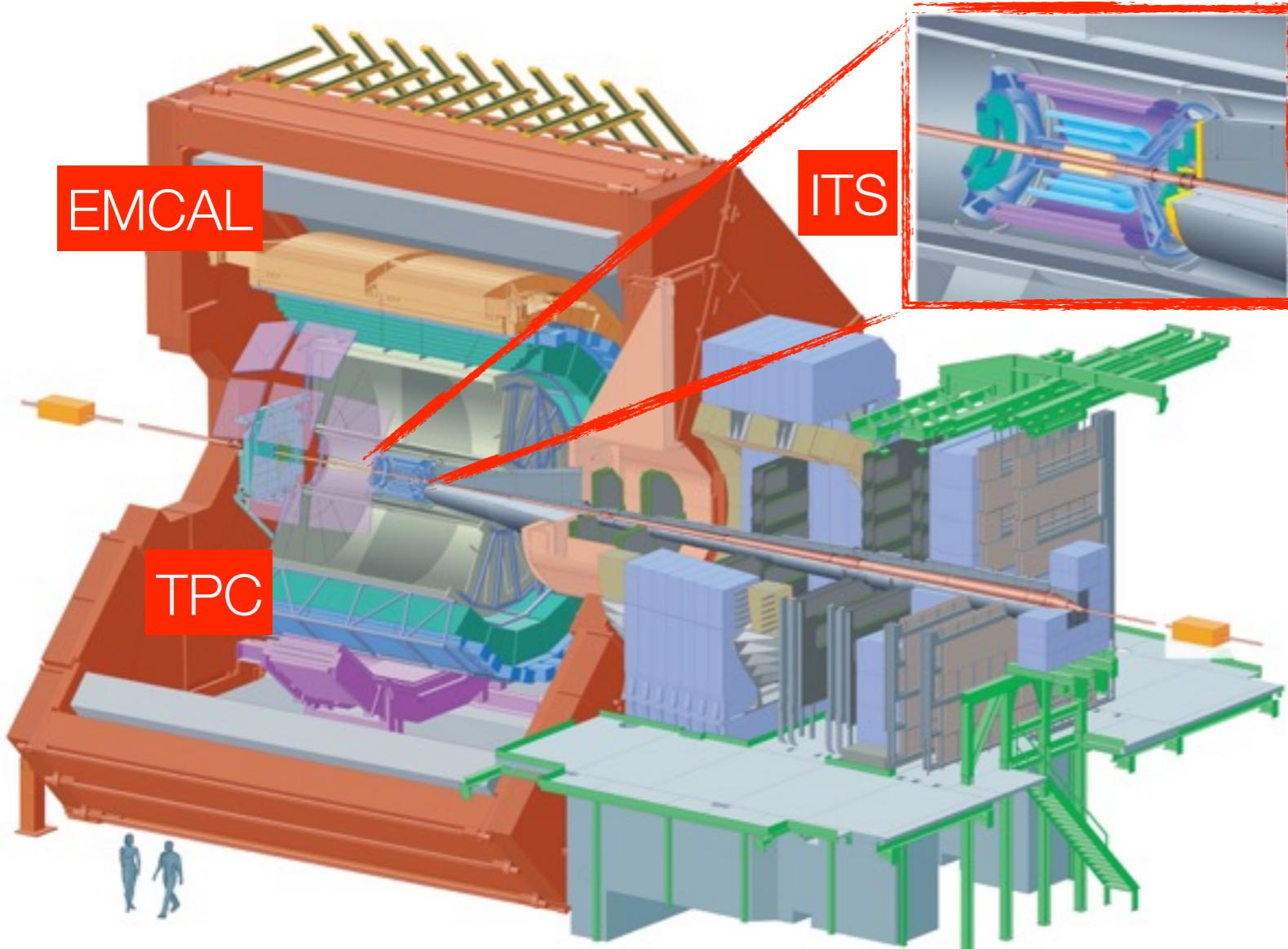
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EMCAL: Pb scintillator sampling calorimeter
 $|\eta| < 0.7, 1.4 < \phi < \pi$
 $\Delta\eta = \Delta\phi \approx 0.014$
Cluster $E_T > 300$ MeV

Neutral constituent jets

Jet reconstruction in ALICE



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Neutral constituent jets



Full jet reconstruction
matching the neutral and charged constituents

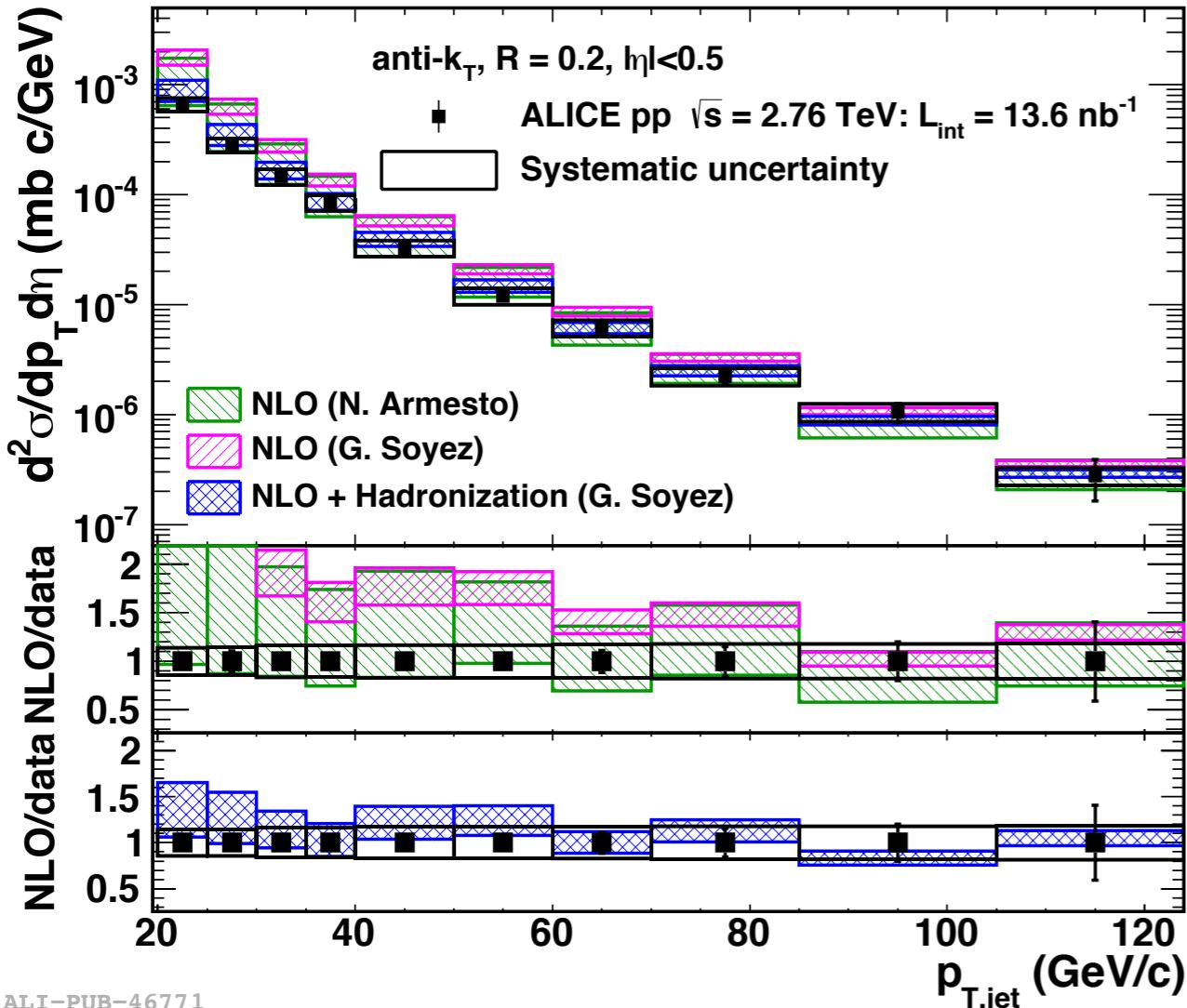


ALICE jet results in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV

Full jet spectra

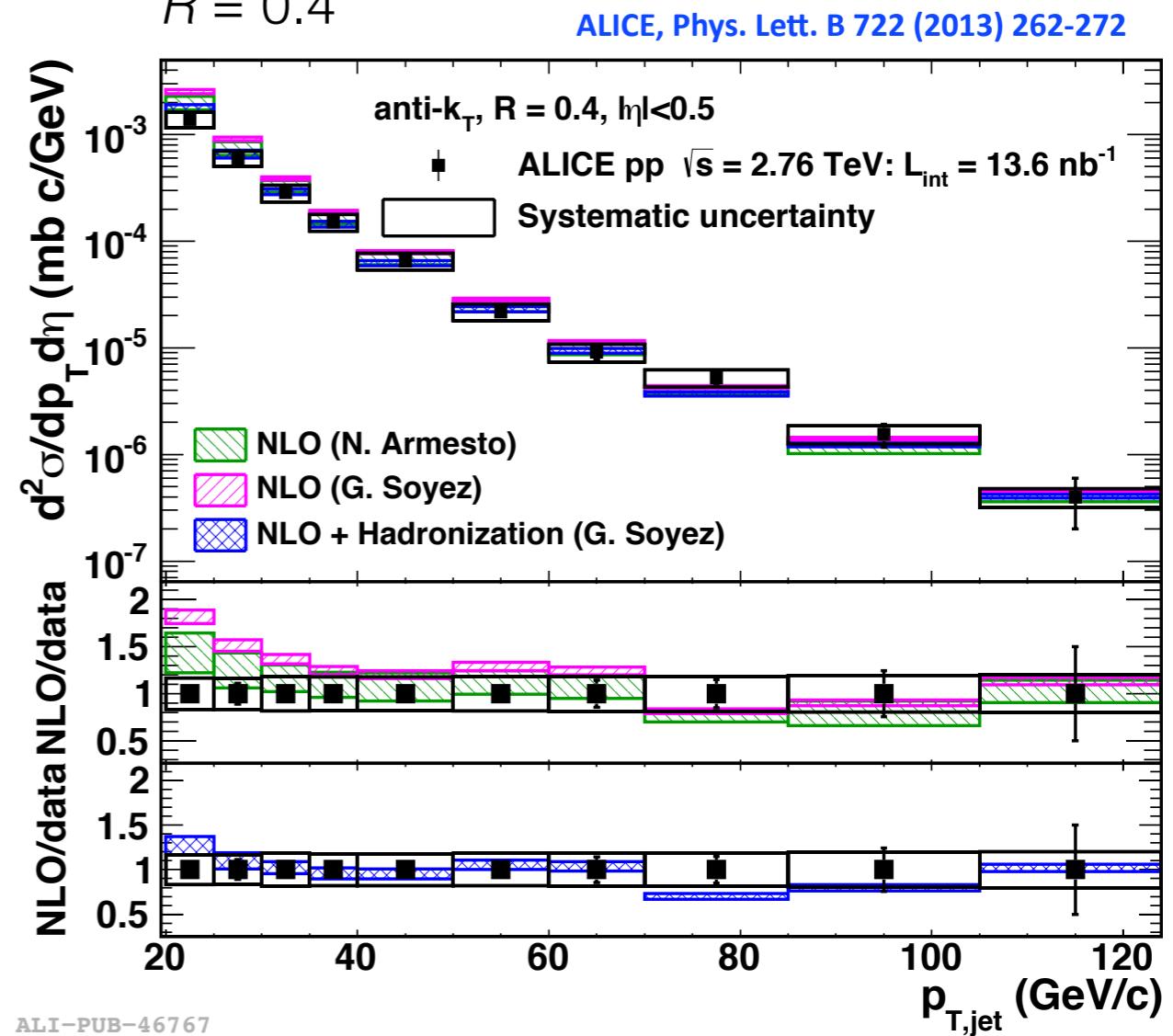


$R = 0.2$



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$R = 0.4$



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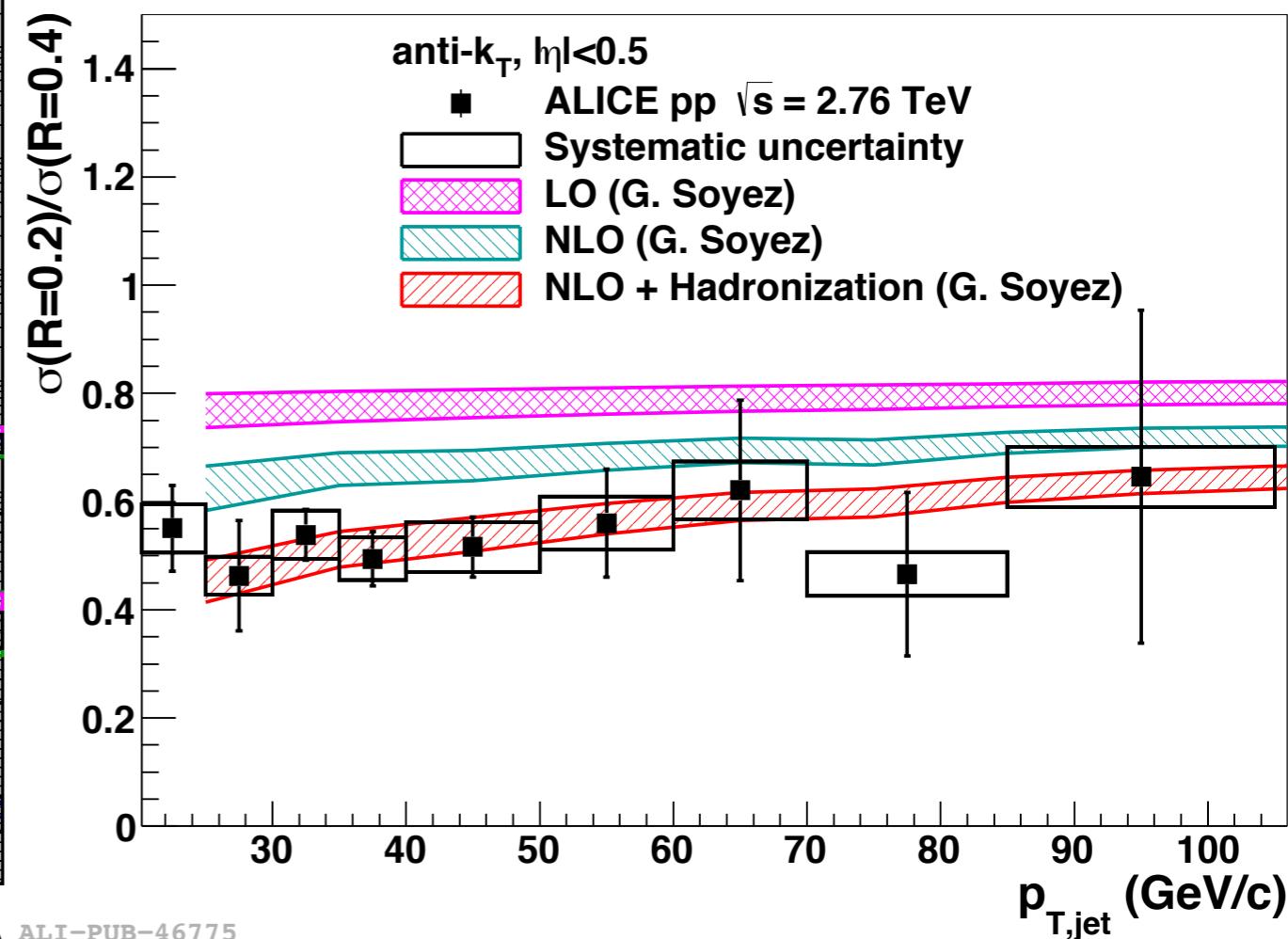
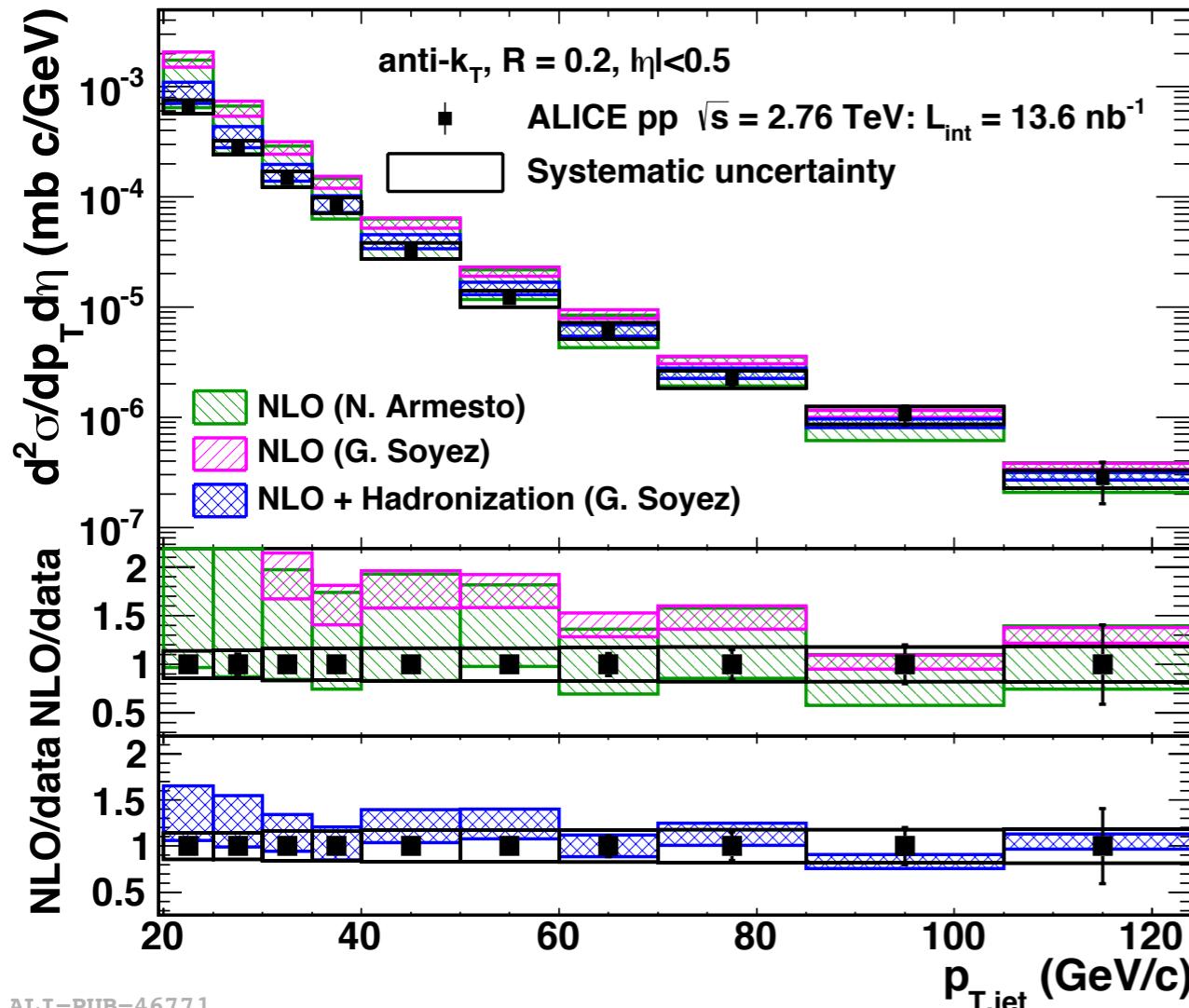
► Good agreement between data and NLO calculations for both $R=0.2$ and $R=0.4$

N. Armesto et al. based on Nucl. Phys. B507 (1997) 295-314
 G. Soyez, Phys Lett B698 (2011) 59-62

Full jet spectra



$R = 0.2$



ALICE, Phys. Lett. B 722 (2013) 262-272

- ▶ Good agreement between data and NLO calculations for both $R=0.2$ and $R=0.4$
- ▶ Better agreement for both the spectra and the jet profile if hadronization effects are taken into account in the calculations.

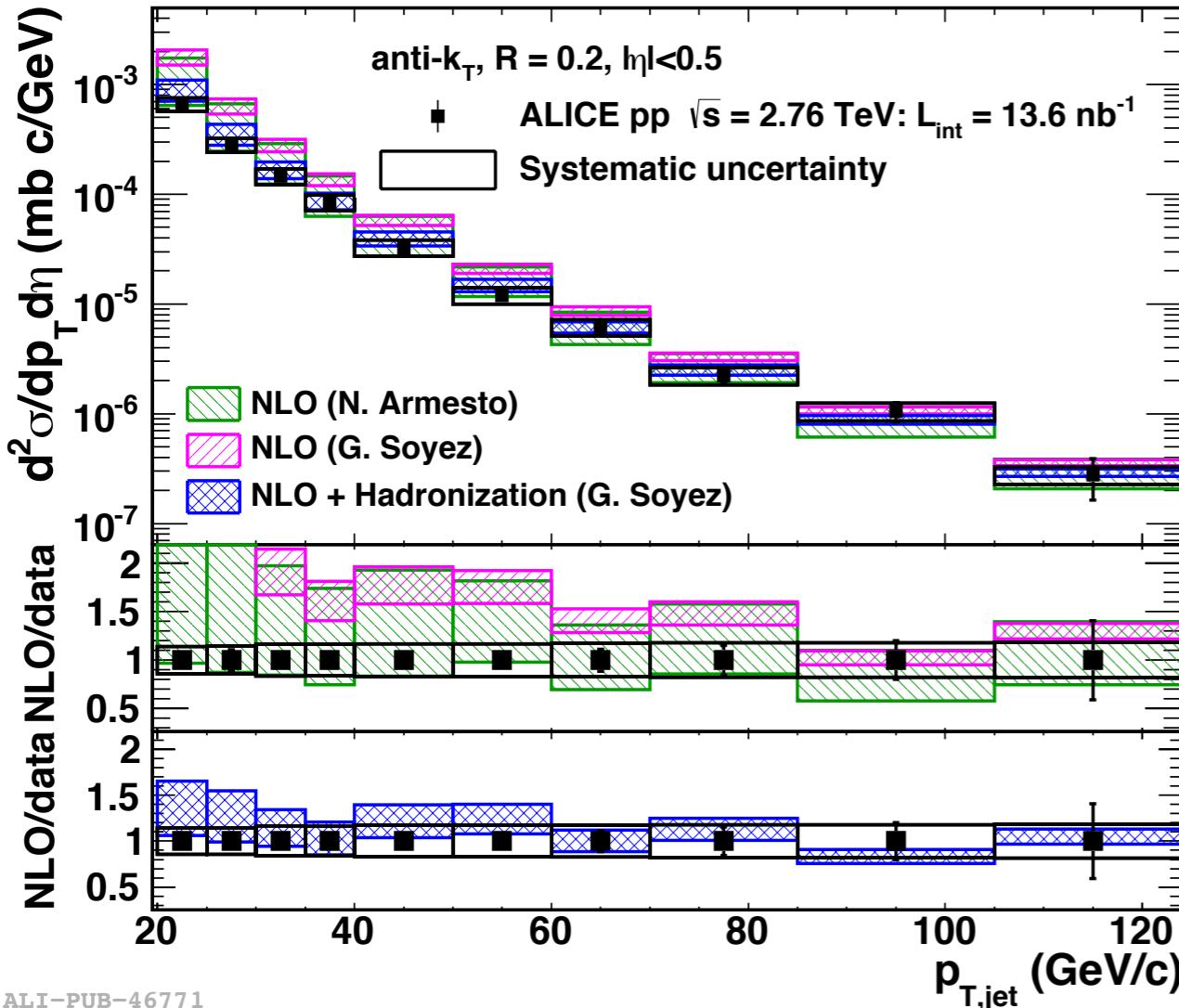
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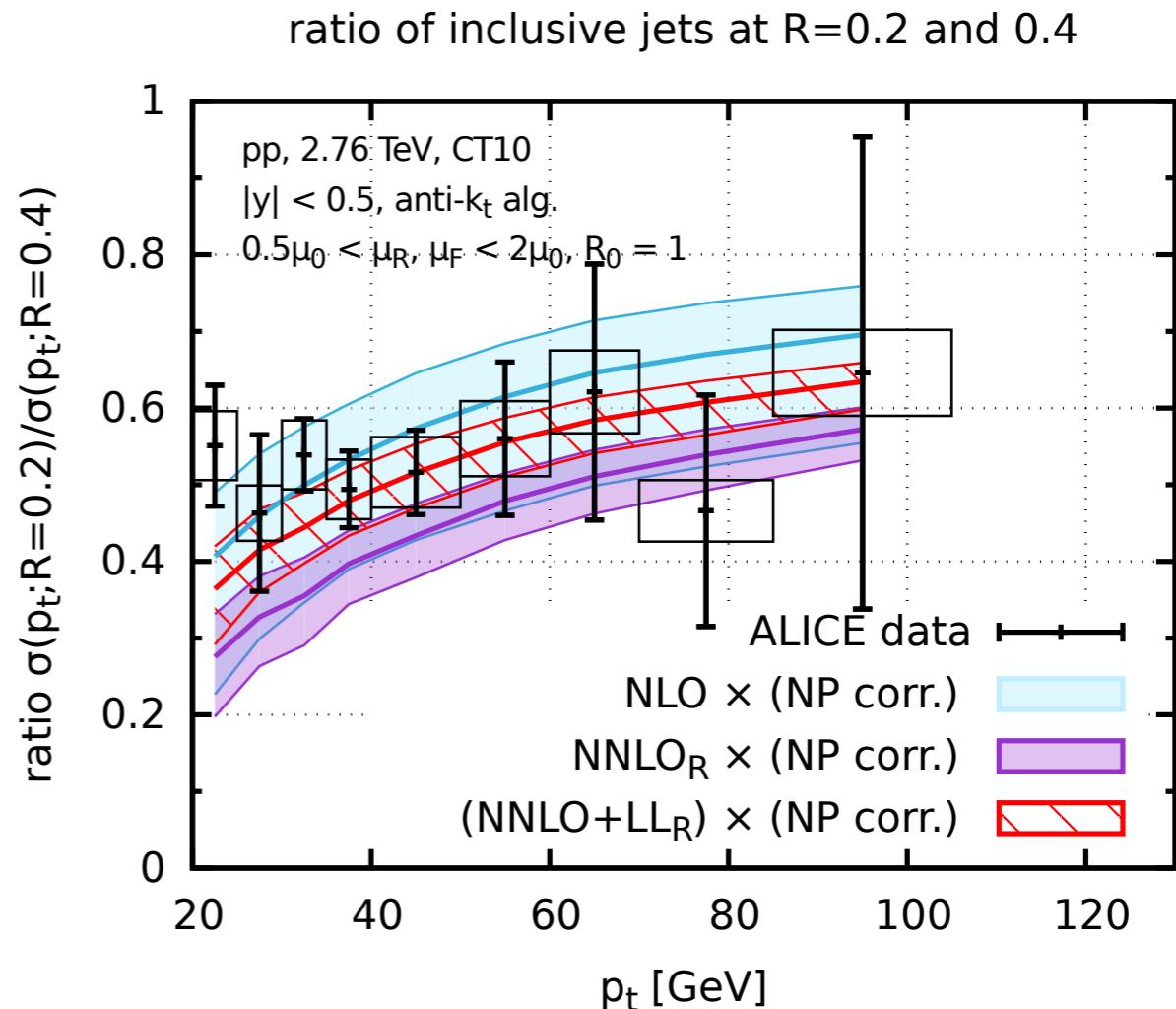


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ALICE, Phys. Lett. B 722 (2013) 262-272



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- ▶ Good agreement between data and NLO calculations for both $R=0.2$ and $R=0.4$
- ▶ Recent calculation based on NNLO+LL_R including UE and hadronization effects seems to be in better agreement than just NNLO calculations.

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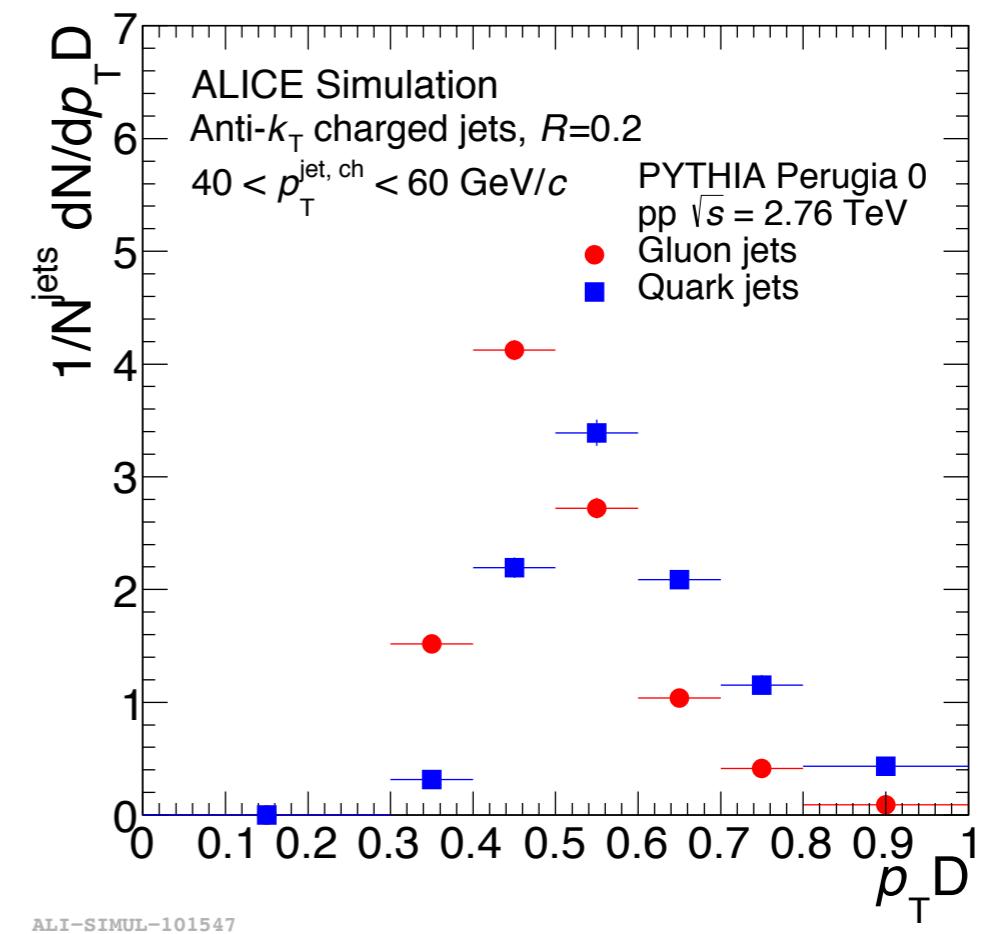
Jet shape definitions

- ▶ **Jet shapes** are observables constructed combining informations on how the variables of the constituents are distributed within the jet.
- ▶ Jet shapes can provide information about:
 - ▶ **parton-to-jet** fragmentation processes
 - ▶ **intra-jet distributions (broadening, collimation)**
 - ▶ possible **quark/gluon jet** differences

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 - ▶ possible **quark/gluon jet** differences
- ▶ **Momentum dispersion ($p_T D$):**
 - ▶ Measures the momentum redistribution of jet constituents.
 - ▶ jets with fewer constituents have higher $p_T D$.
 - ▶ different $p_T D$ expected for **quark/gluon** jets due to the different fragmentation

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



Jet shape definitions

► Momentum dispersion ($p_{\text{T}}\text{D}$):

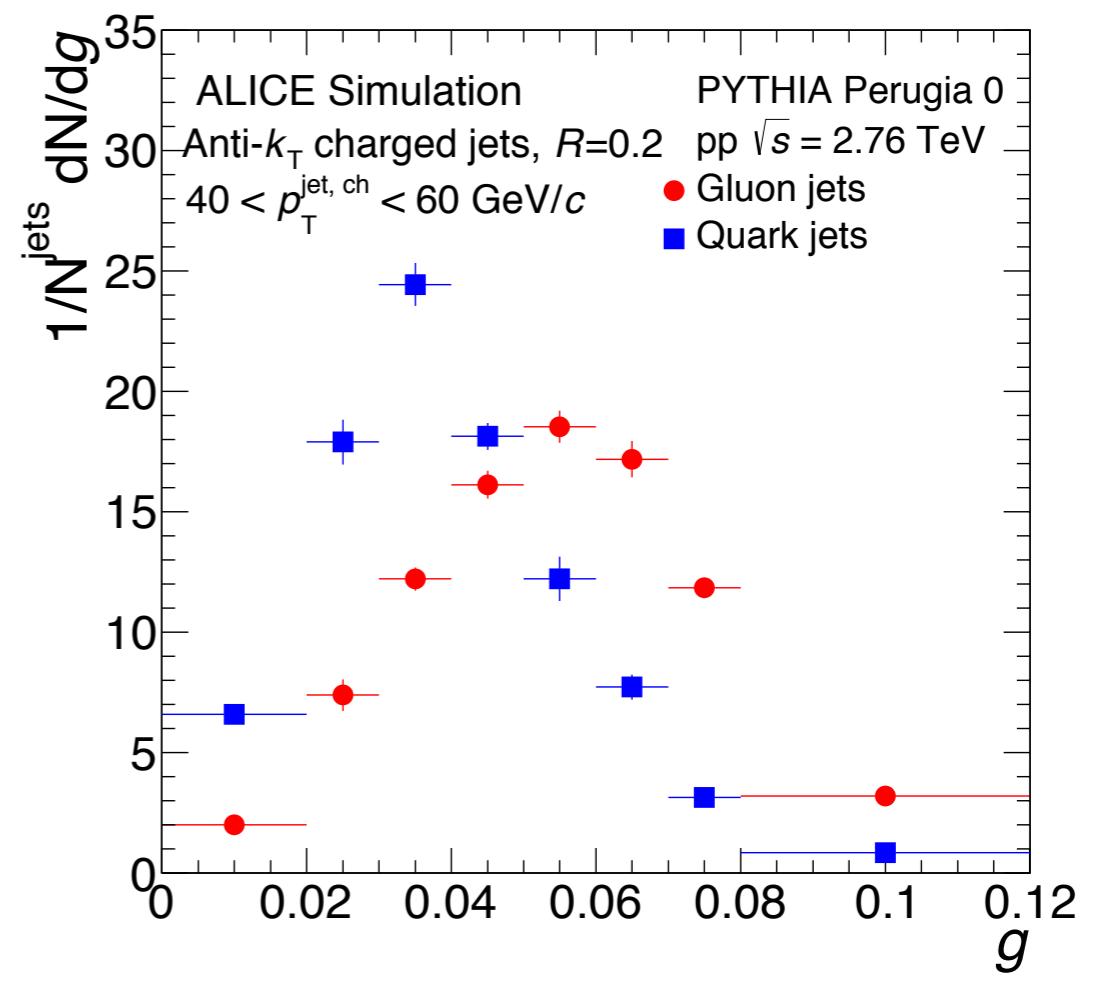
- Measures the momentum re-distribution of jet constituents.

► Radial moment (g):

- Measures the momentum re-distribution of jet constituents weighted by their distance from the jet axis.

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

- large $g \rightarrow$ more broadened jets
- **gluon** jets have more likely large g
- smaller $g \rightarrow$ more collimated jets
- **quark** jets have more likely smaller g



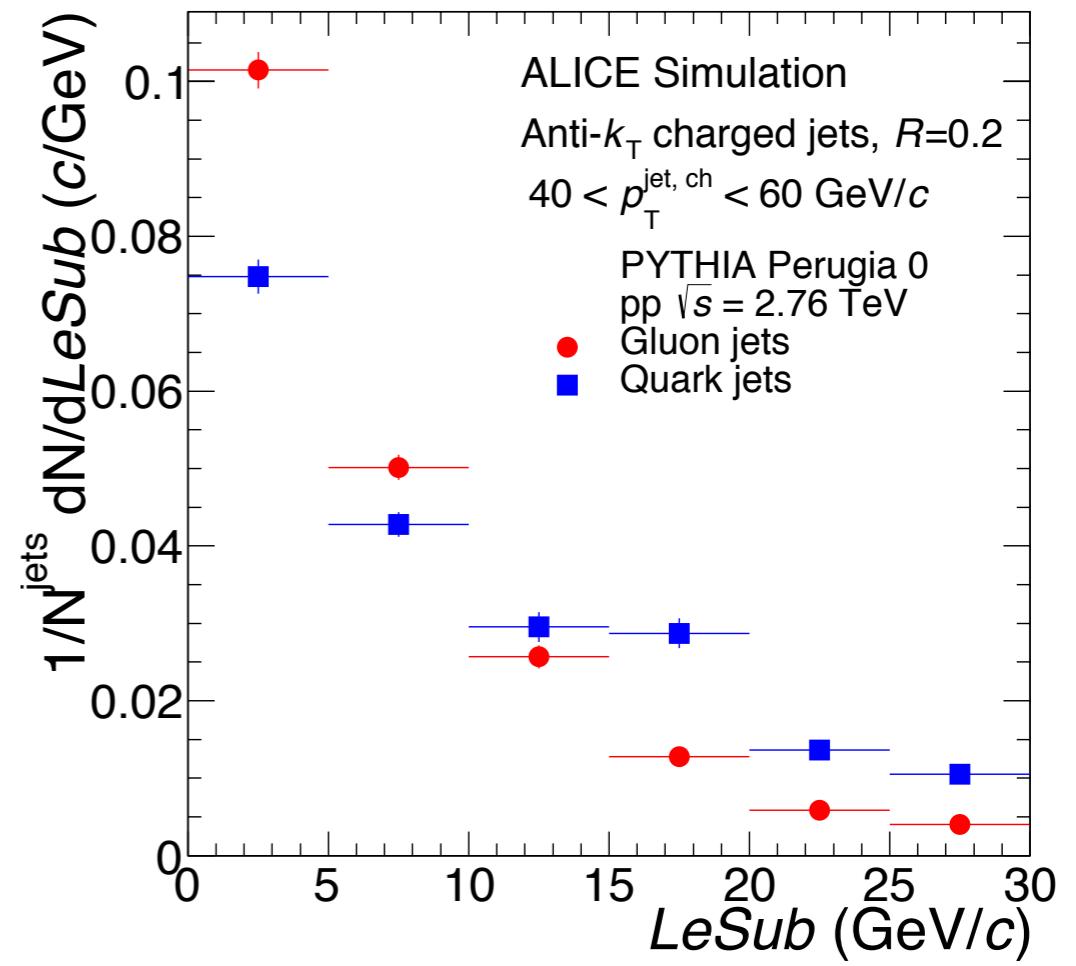
Jet shape definitions

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- ▶ **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.

$$LeSub = p_T^{\text{leading track}} - p_T^{\text{subleading track}}$$

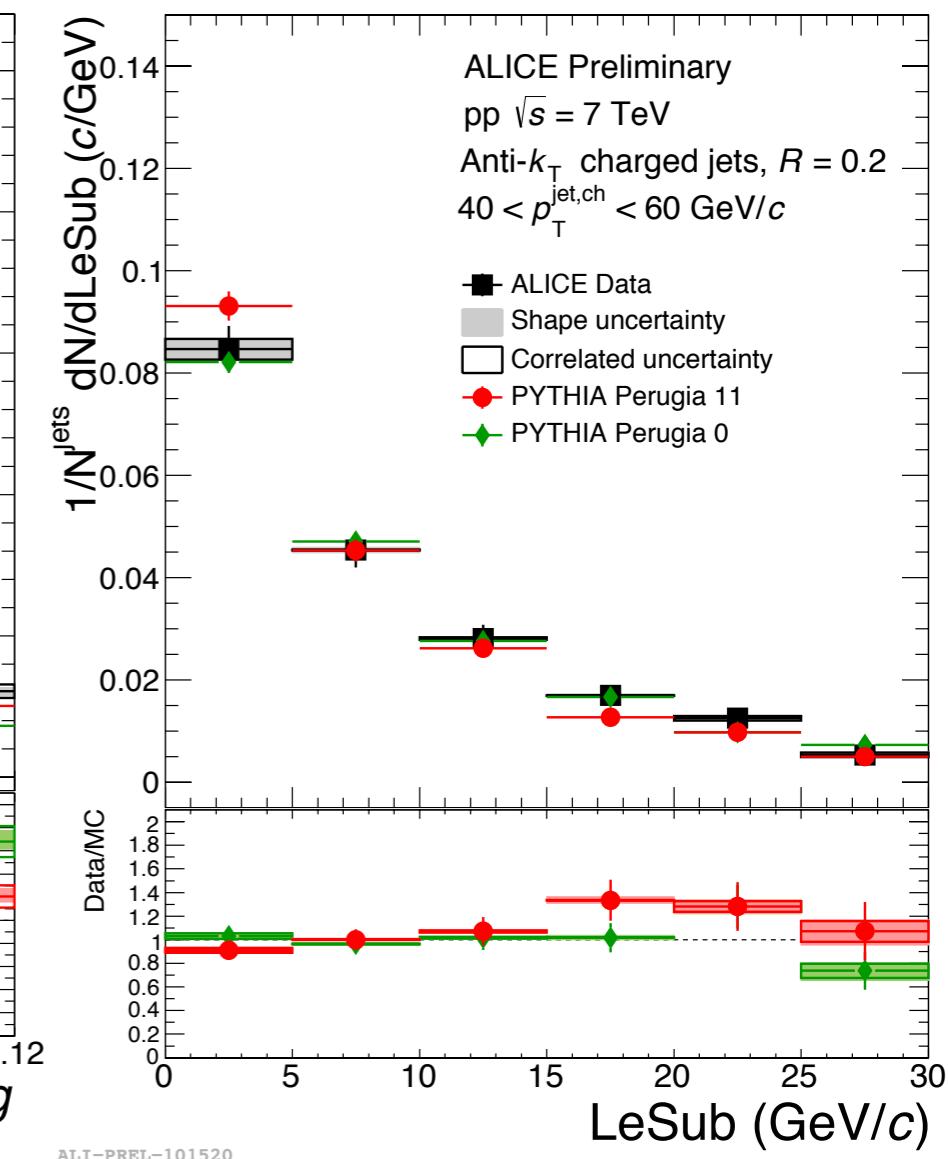
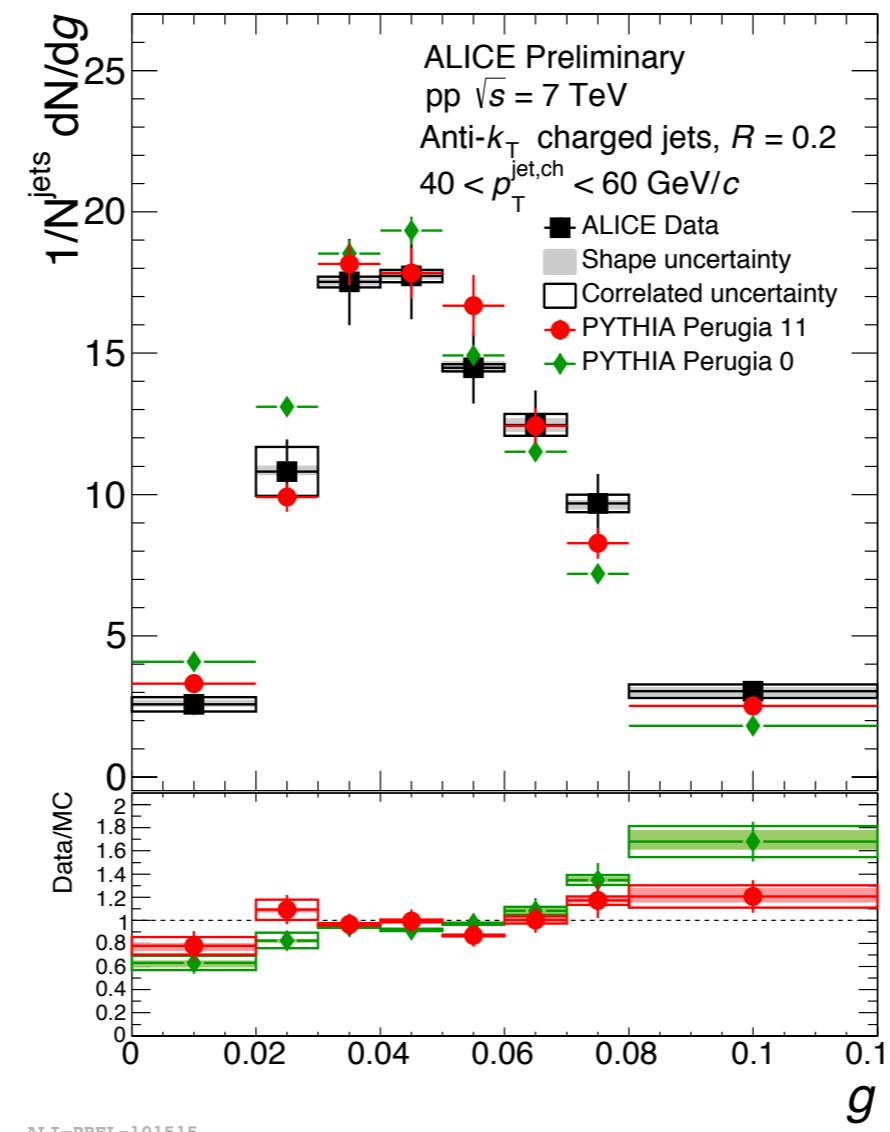
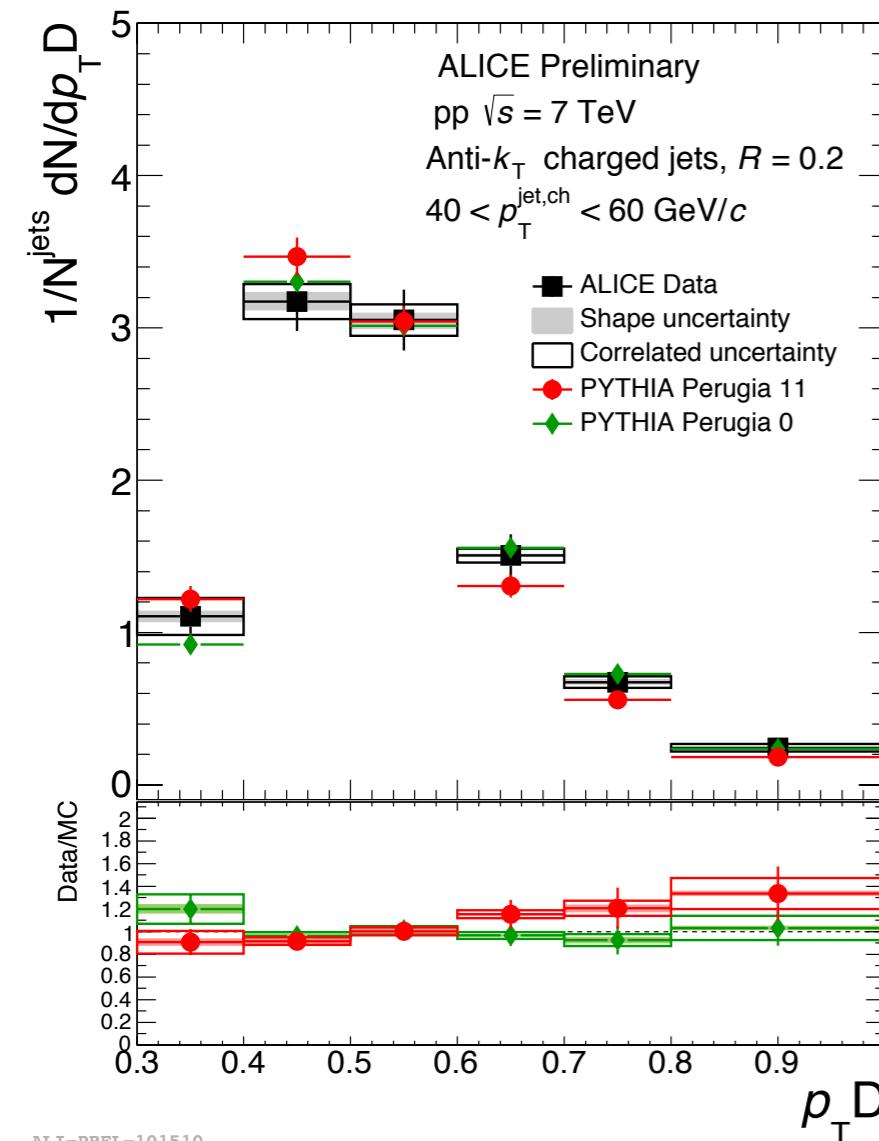


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Charged jet shapes



$R = 0.2$

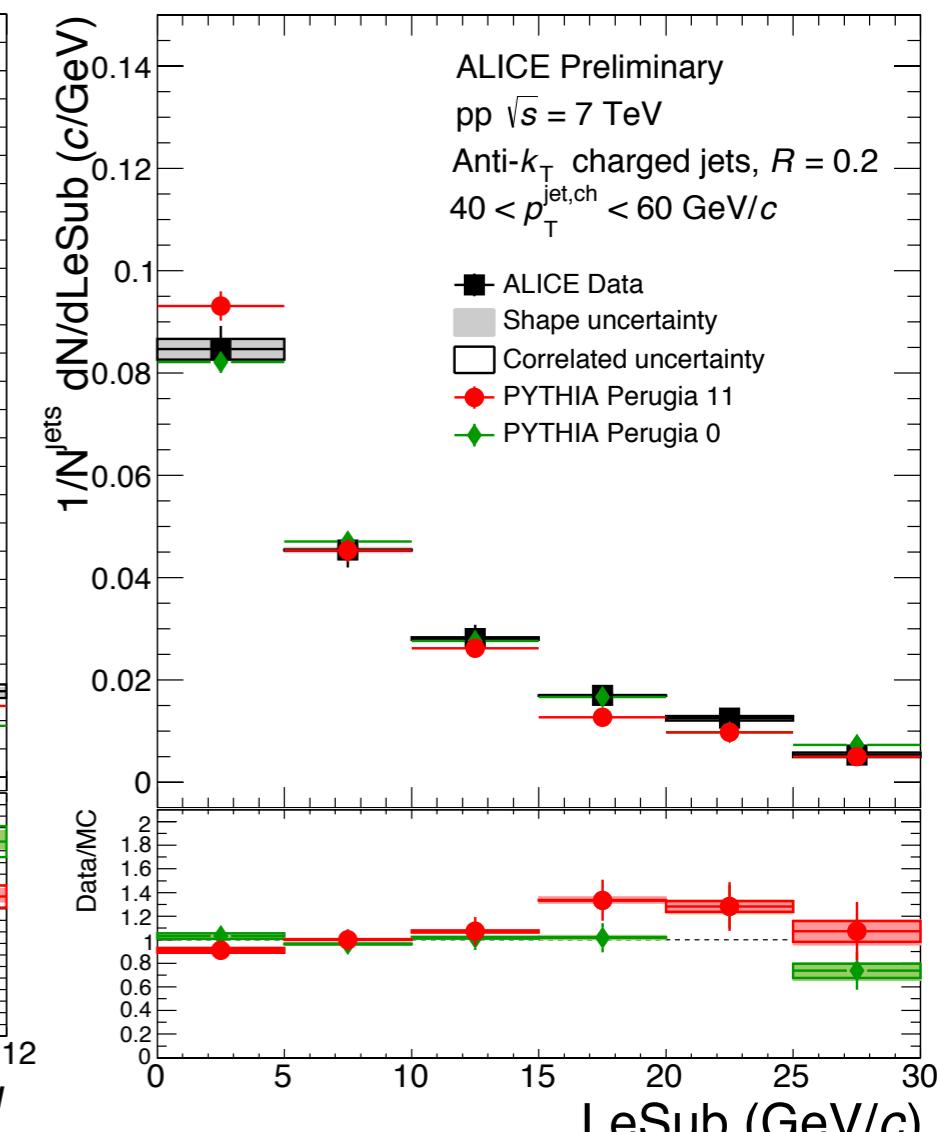
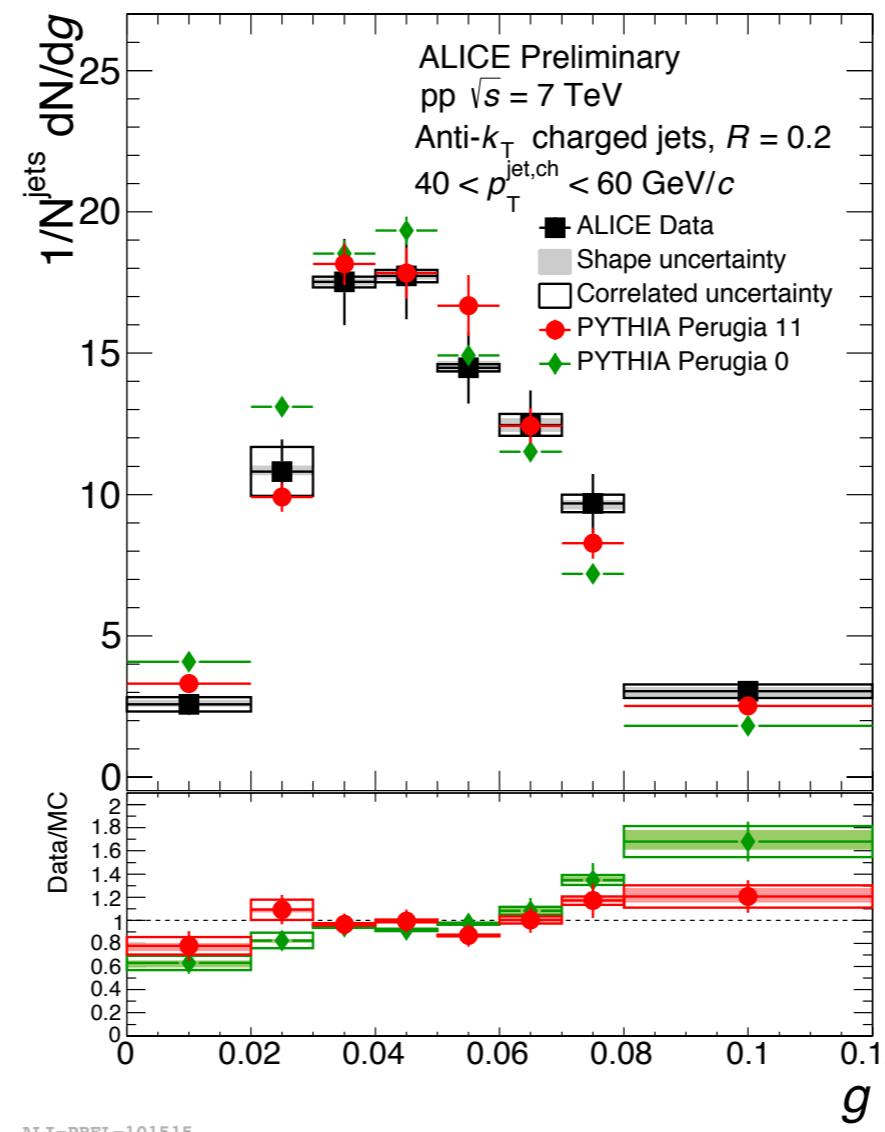
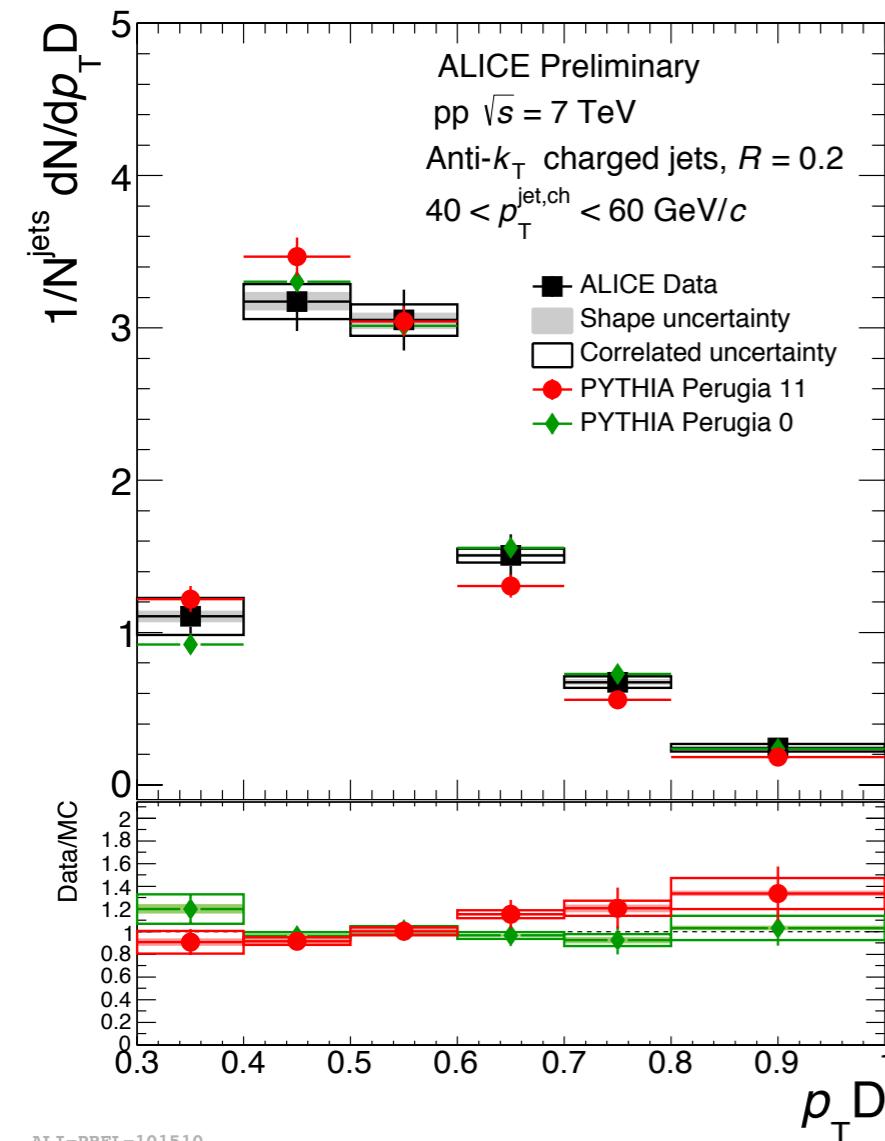


▶ Jet shapes, fully corrected to charged particle level.

Charged jet shapes



$R = 0.2$



- ▶ 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.



ALICE jet results in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$

Jet reconstruction in heavy-ion collisions



- ▶ Heavy-ion collisions characterized by:
 - ▶ high multiplicity of low- p_T particles
 - ▶ not related to hard scattering, coming mainly from soft medium interactions
- ▶ Jet background:
 - ▶ is dominant at low jet and jet constituent p_T
 - ▶ depends on the track multiplicity in the event
 - ▶ increases with R^2

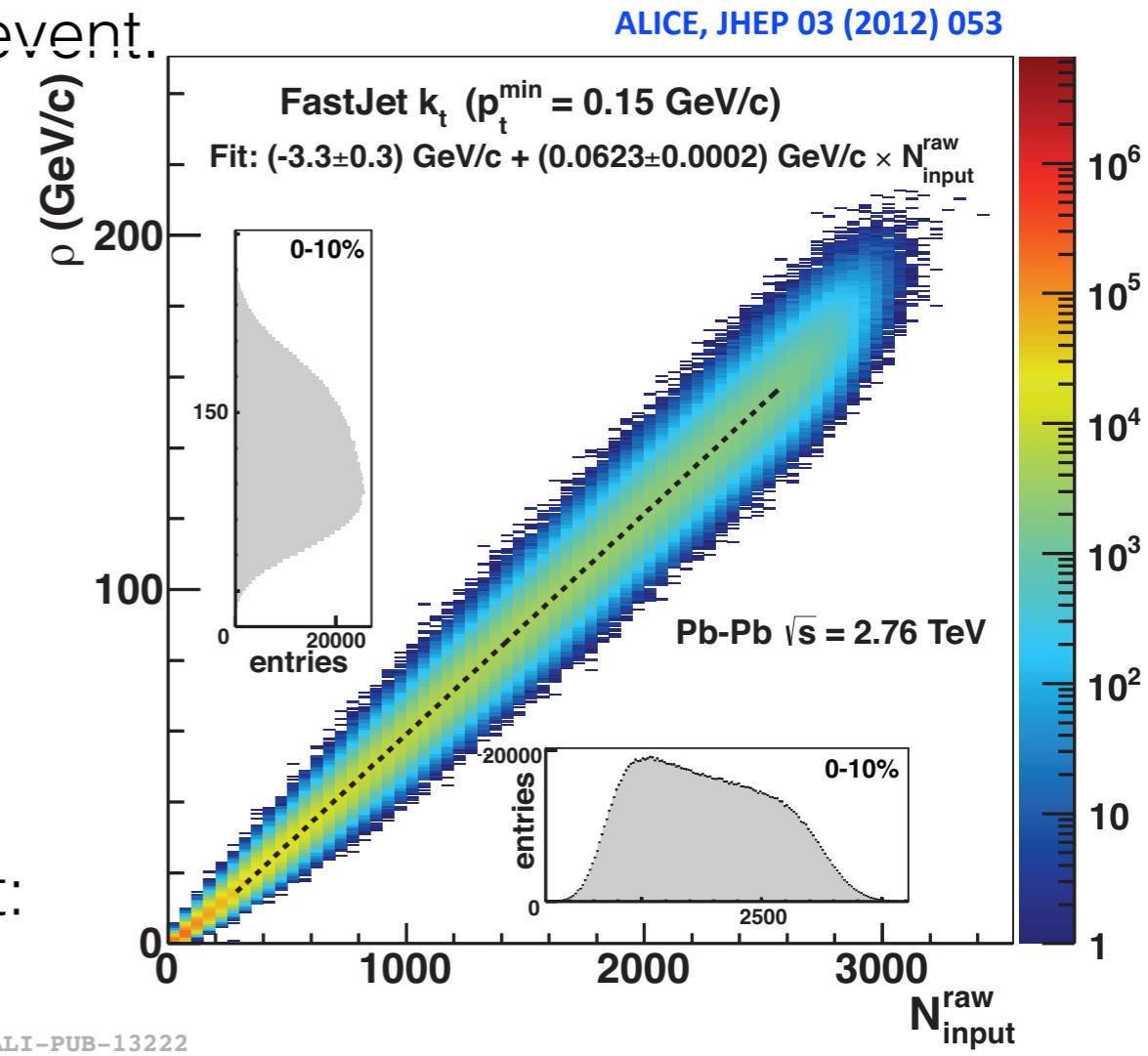
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 - ▶ depends on the track multiplicity in the event.
 - ▶ increases with R^2 .
- ▶ Average background density (ρ_{ch}) estimated as:

$$\rho_{ch} = \text{median} \left\{ \frac{p_{T,k_Tjet}^{ch}}{A_{k_Tjet}} \right\}$$

- ▶ determined event-by-event.
 - ▶ Correction applied to each jet in the event:
- $$p_T^{\text{jet}} = p_T^{\text{jet,rec}} - \rho \times A^{\text{jet,rec}}$$



Jet shapes background subtraction

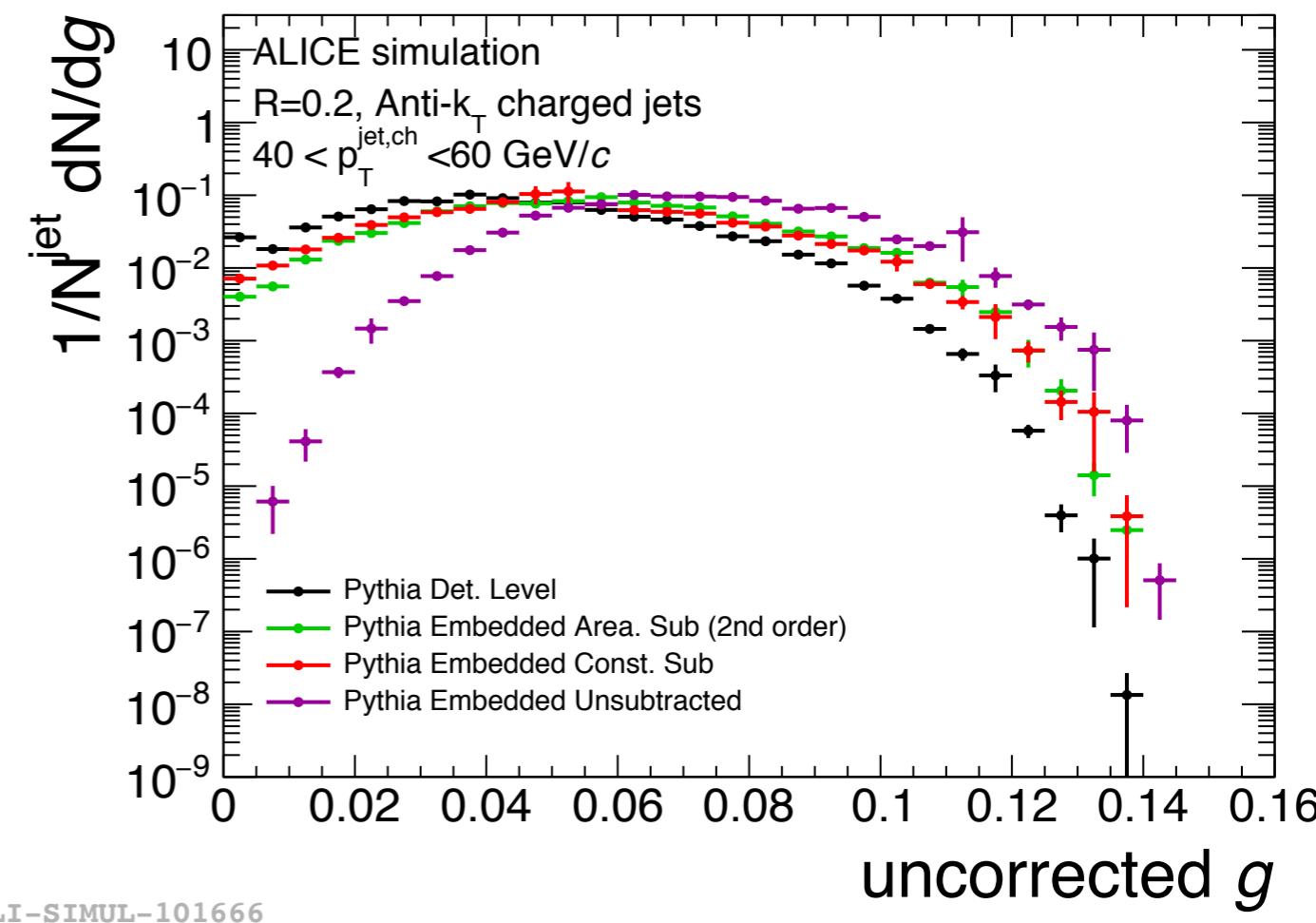


- ▶ Average background removal for jet shapes based on recent techniques:
 - ▶ Derivatives subtraction [G. Soyez et al, Phys. Rev. Lett 110 \(2013\) 16](#)
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Jet shapes background subtraction



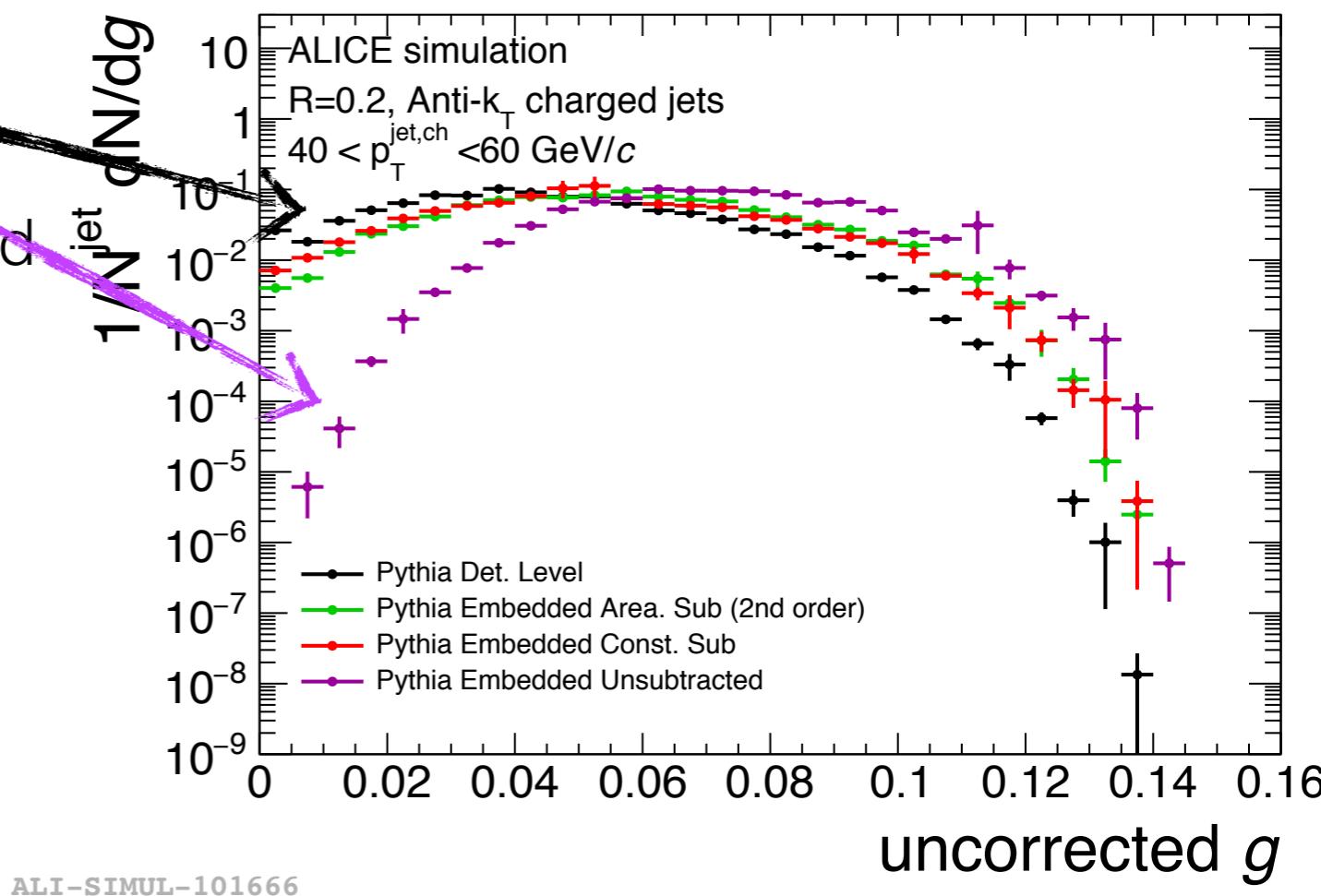
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- ▶ **PYTHIA detector level jets embedded in Pb-Pb events.**



Jet shapes background subtraction



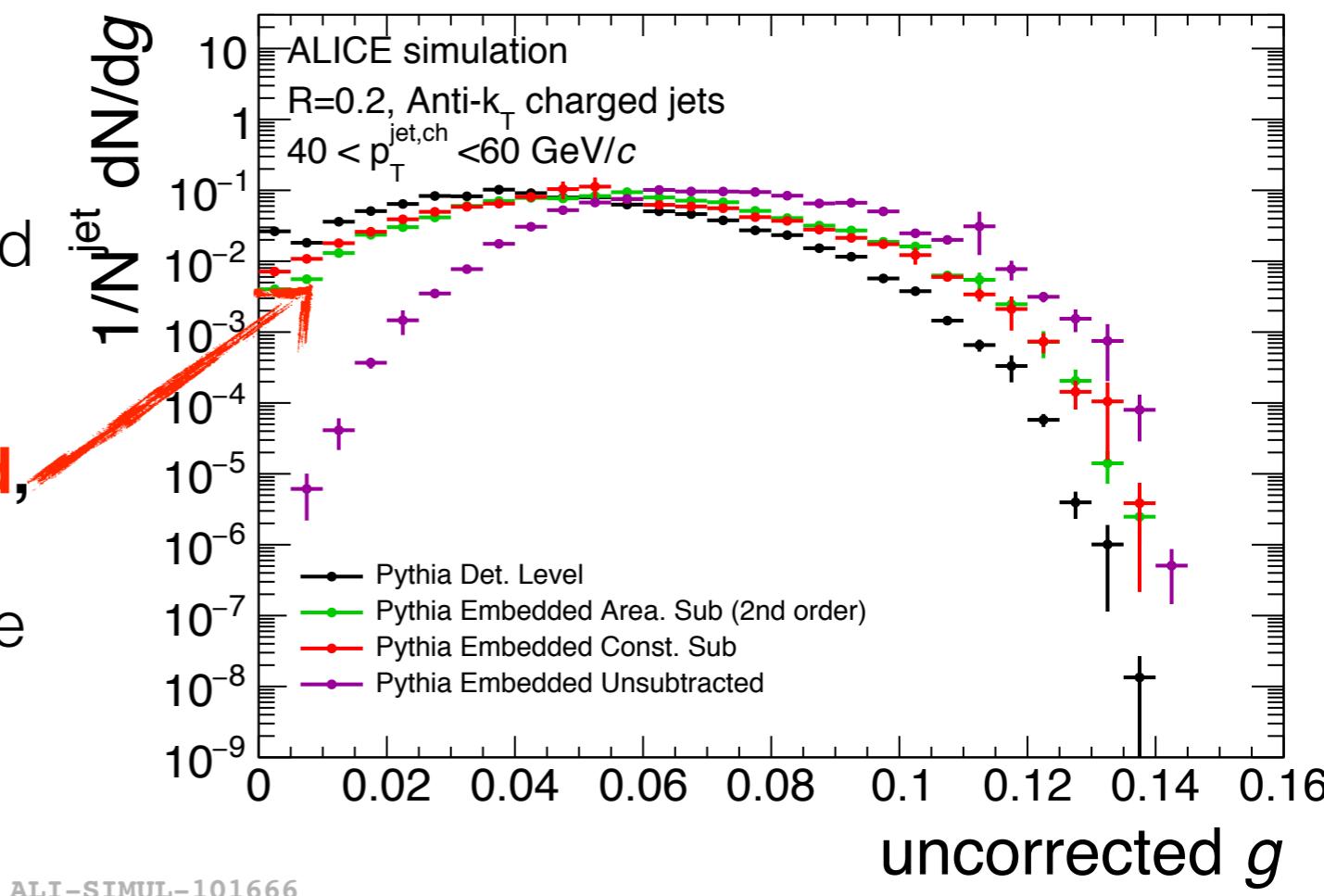
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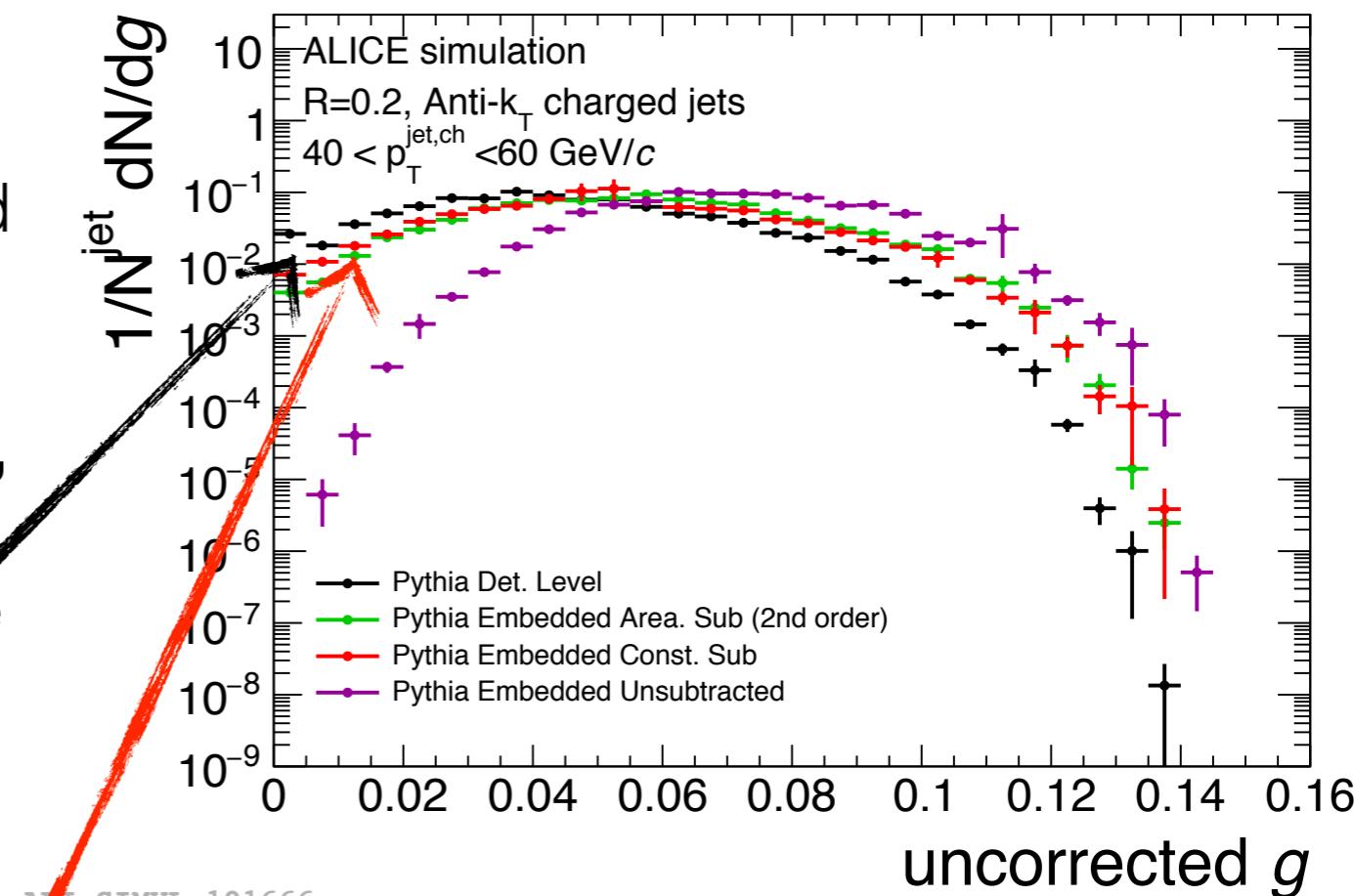
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Jet shapes background subtraction



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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.



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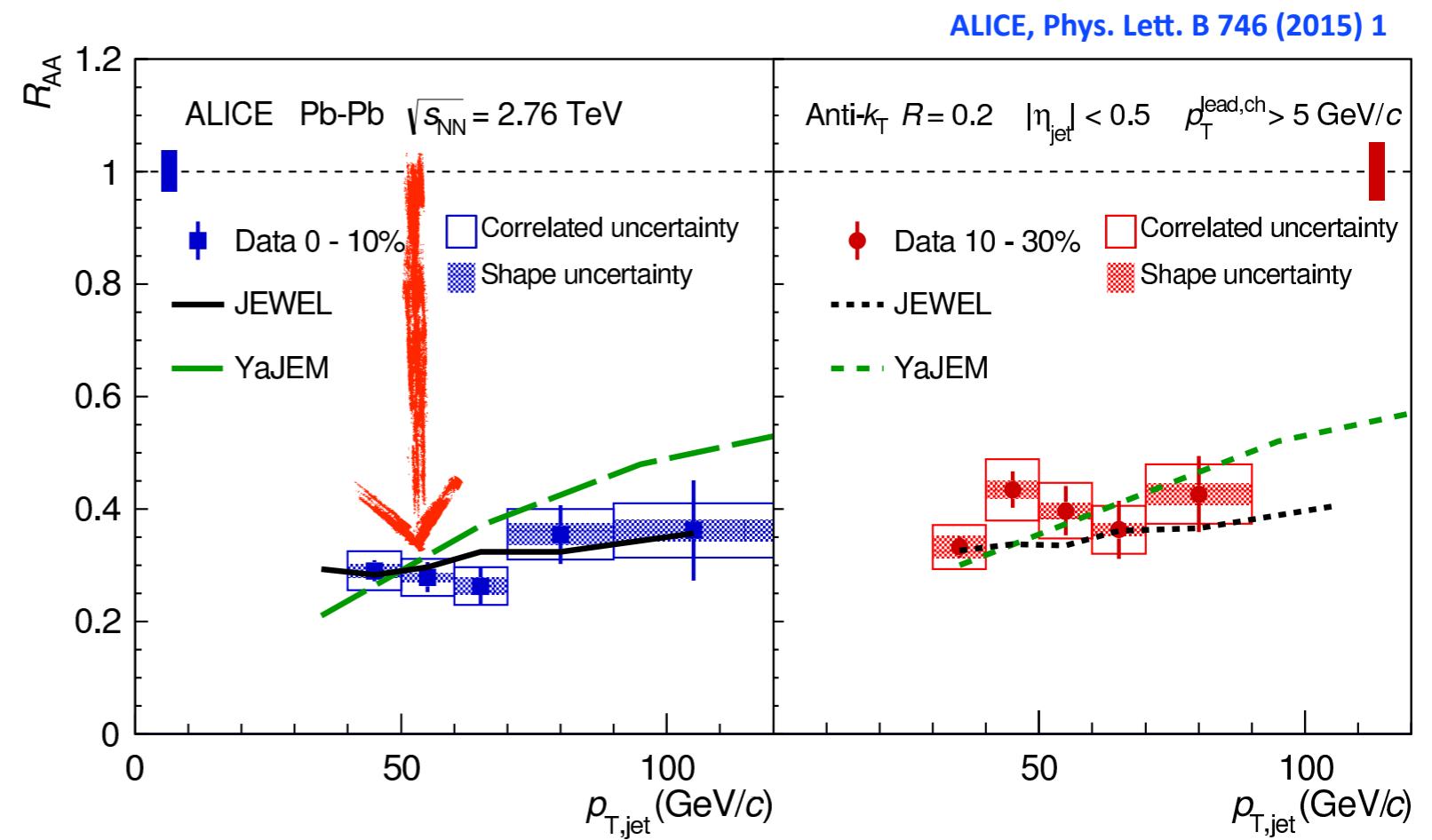
- ▶ 2D Bayesian Unfolding applied to remove
 - ▶ background fluctuations
 - ▶ detector effects.

ALICE Jet results in Pb-Pb collisions



- The **full jet** R_{AA} shows a suppression also at high jet p_T for $R=0.2$.

$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{ch,jet} / dp_T d\eta|_{\text{Pb-Pb}}}{d^2 N_{ch,jet} / dp_T d\eta|_{\text{pp}}}$$



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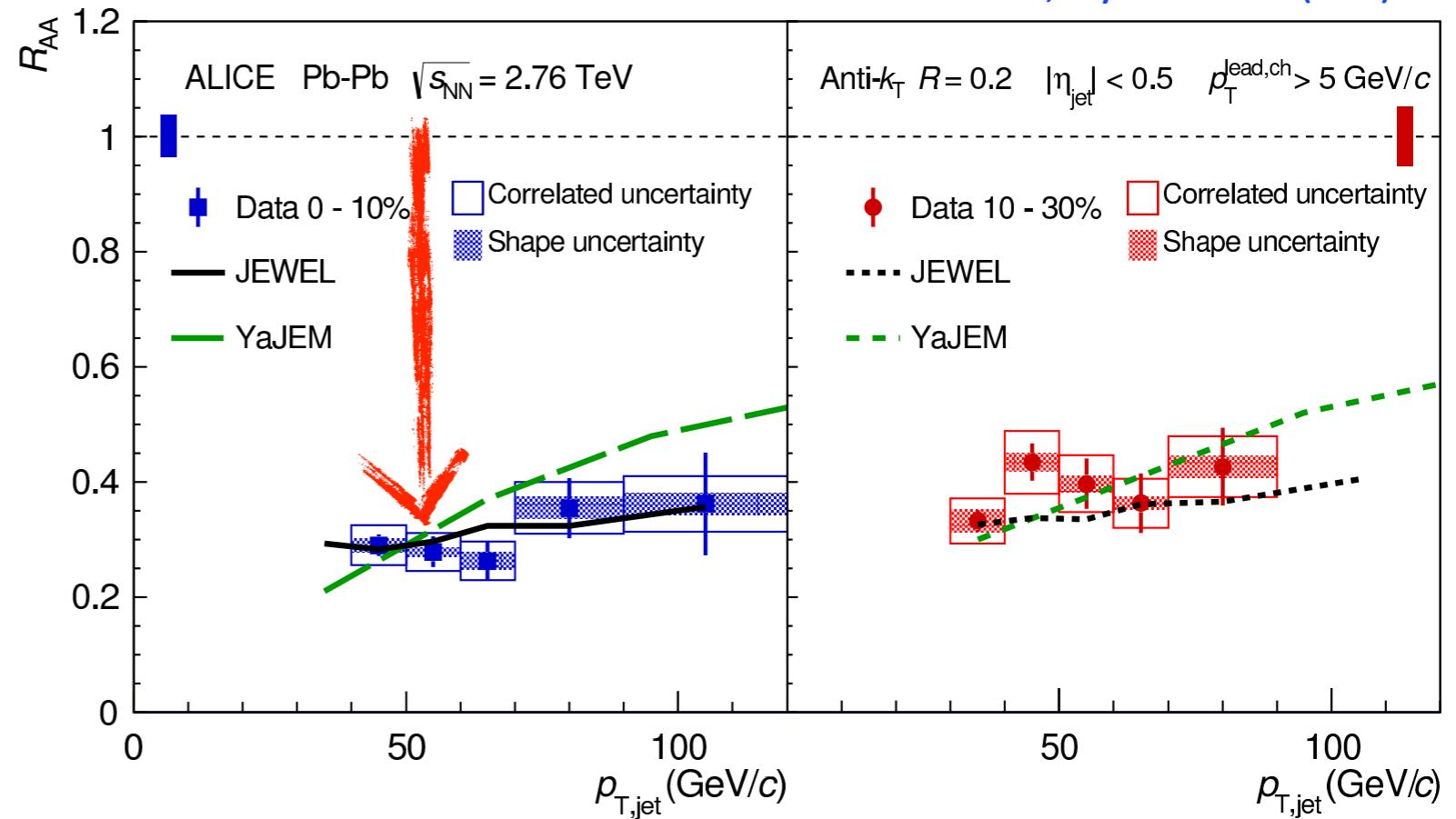
- ▶ **Energy lost from the interaction of the parton within the medium not recovered within $R = 0.3$.**

- ▶ R_{AA} not precise enough to distinguish between the two models

YaJEM: T. Renk , Phys Rev C 88 (2013) 014905

JEWEL: C.Zapp et al. JHEP 1303 (2013) 080

ALICE, Phys. Lett. B 746 (2015) 1



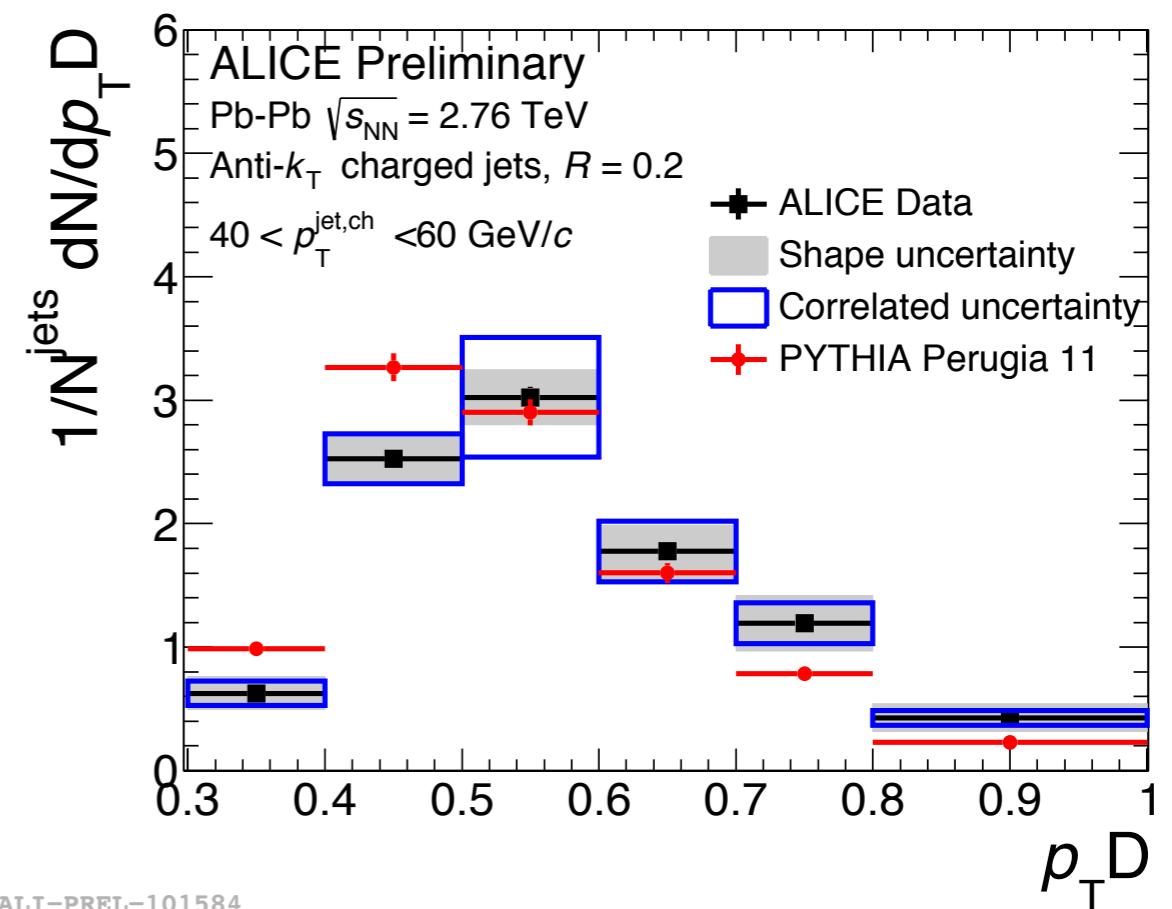


Charged jet shapes

- ▶ Focus on jet shapes to:
 - ▶ to probe quenching at low jet p_T .
 - ▶ using small R jets ($R=0.2$)

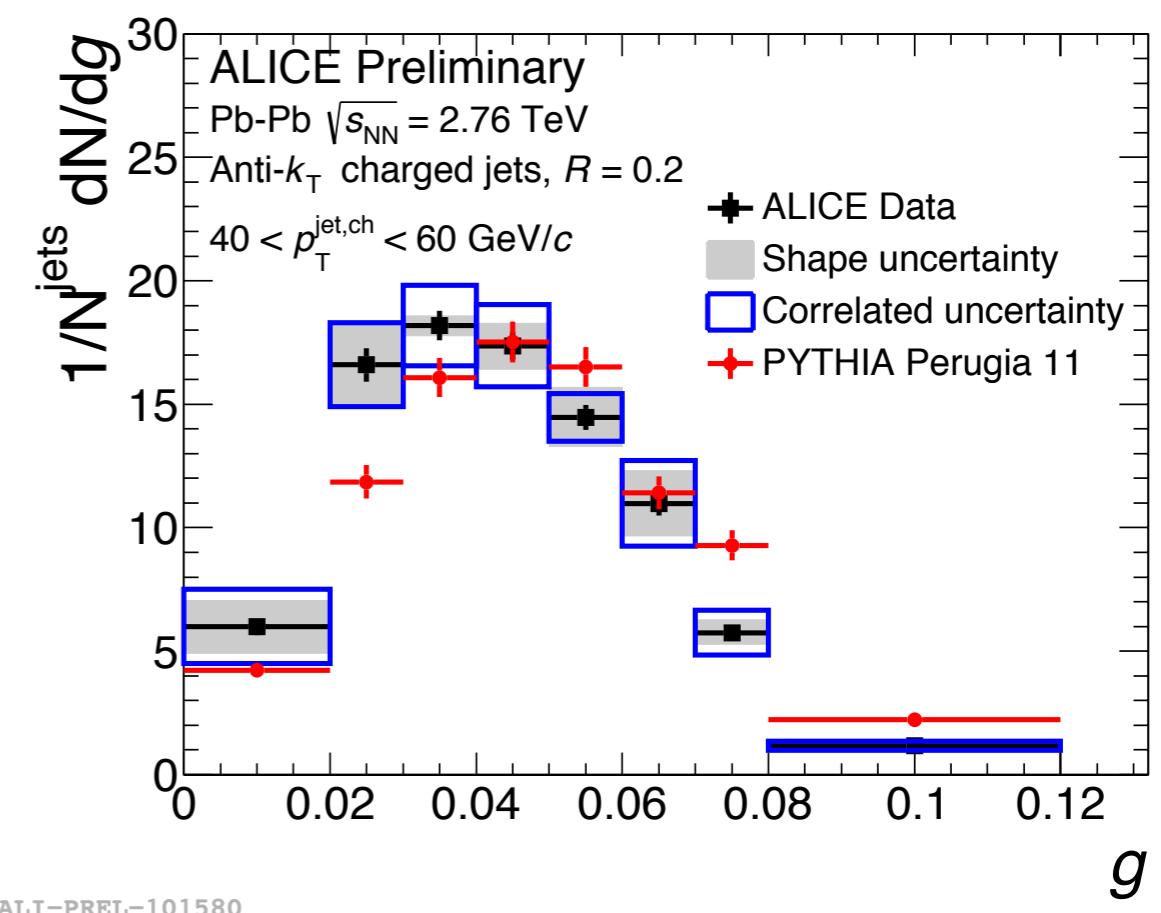
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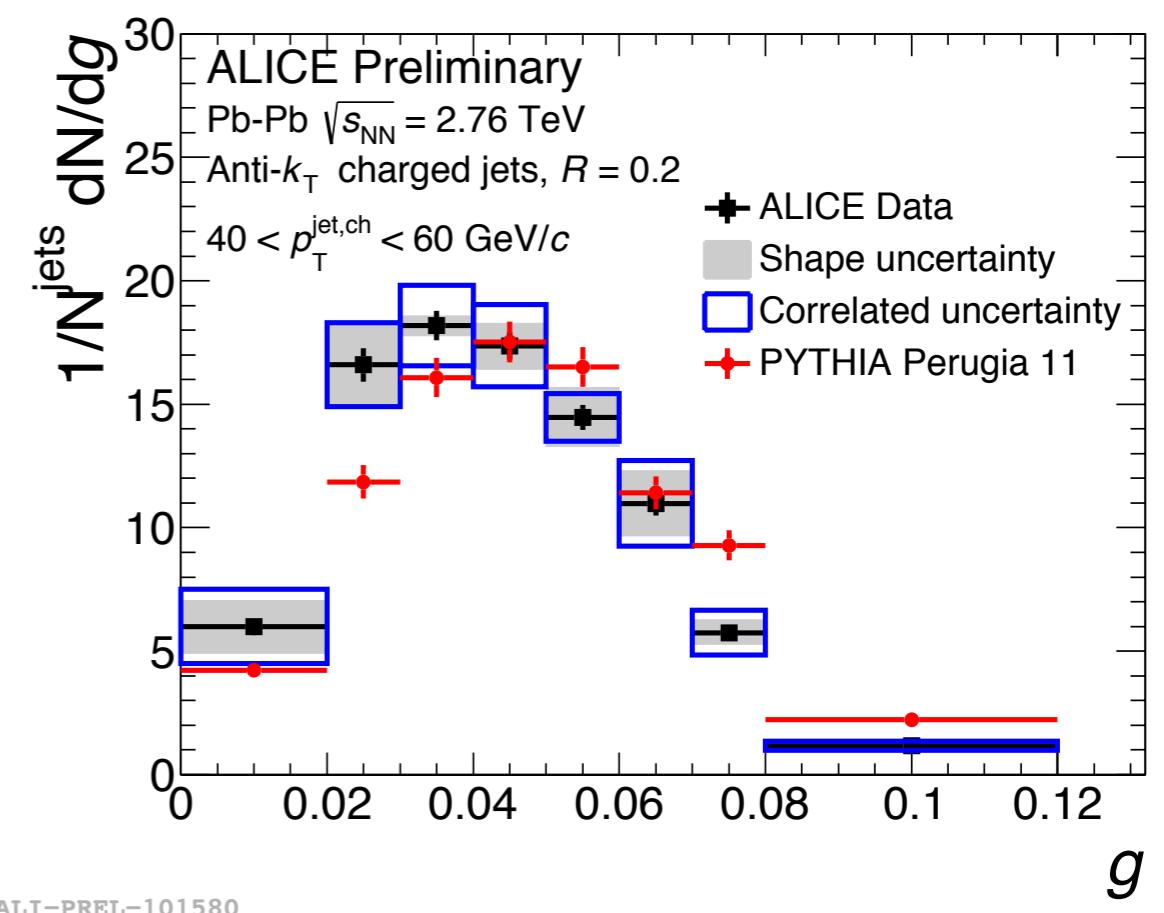
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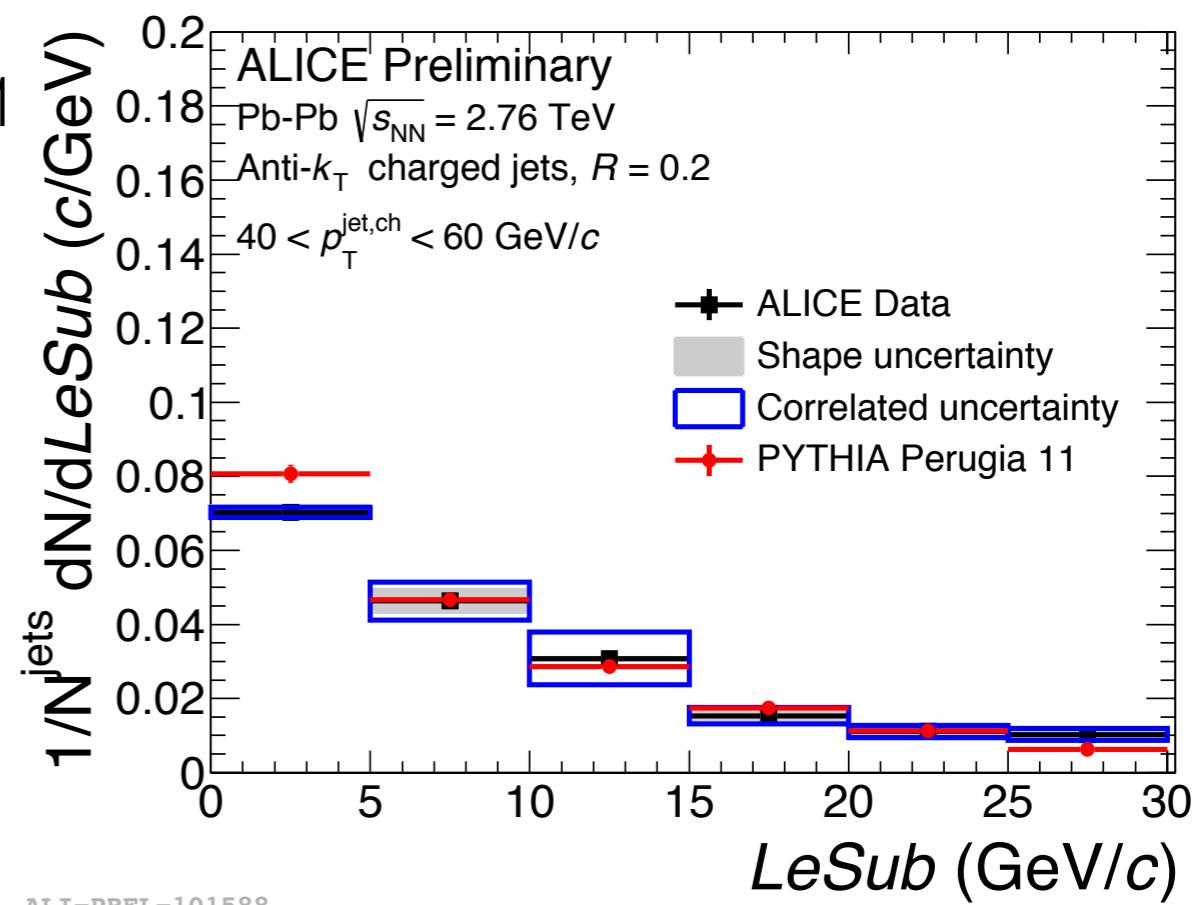


- ▶ $p_T D$ and g distributions for $R=0.2$ jets are compatible with a more collimated and harder fragmentation in Pb-Pb than pp collisions.

Charged jet shapes

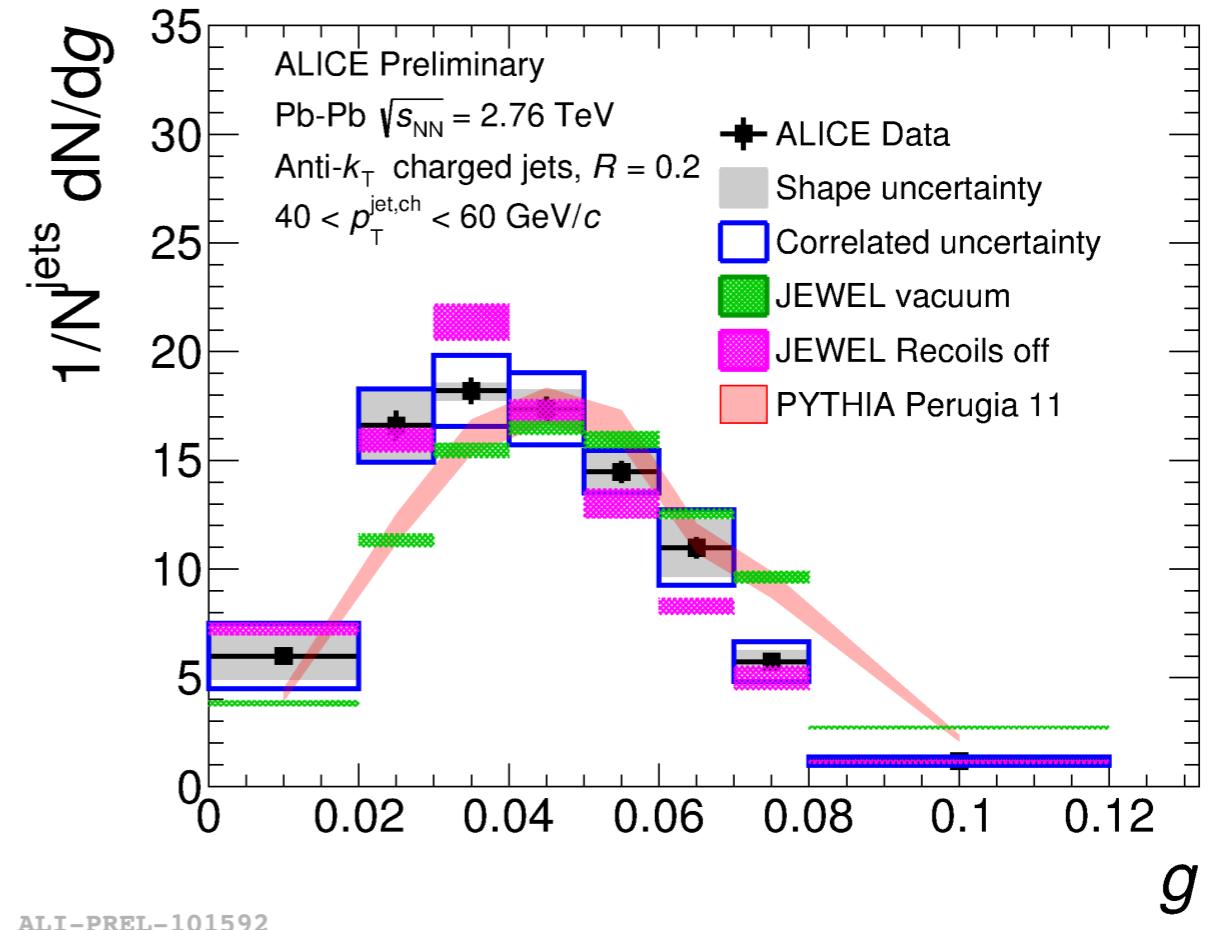
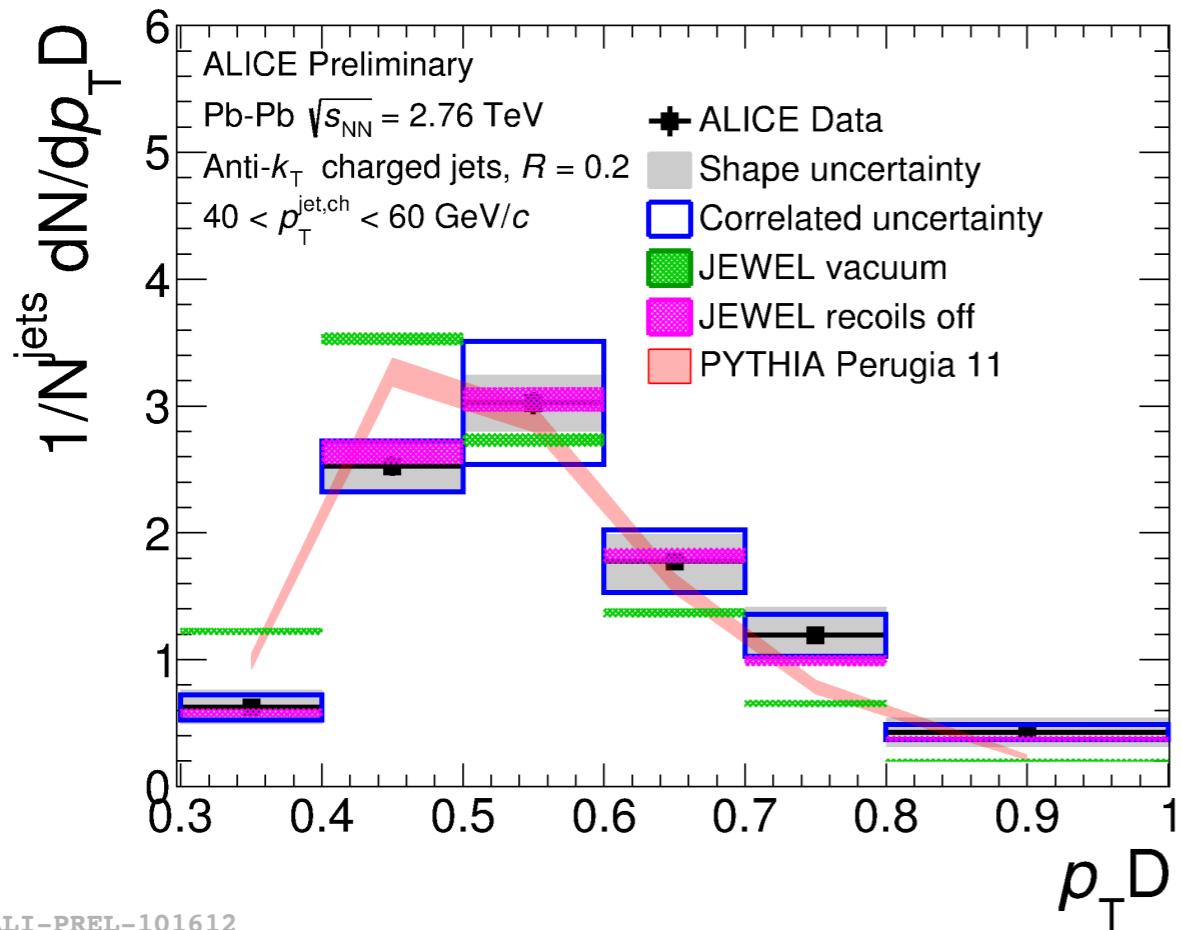
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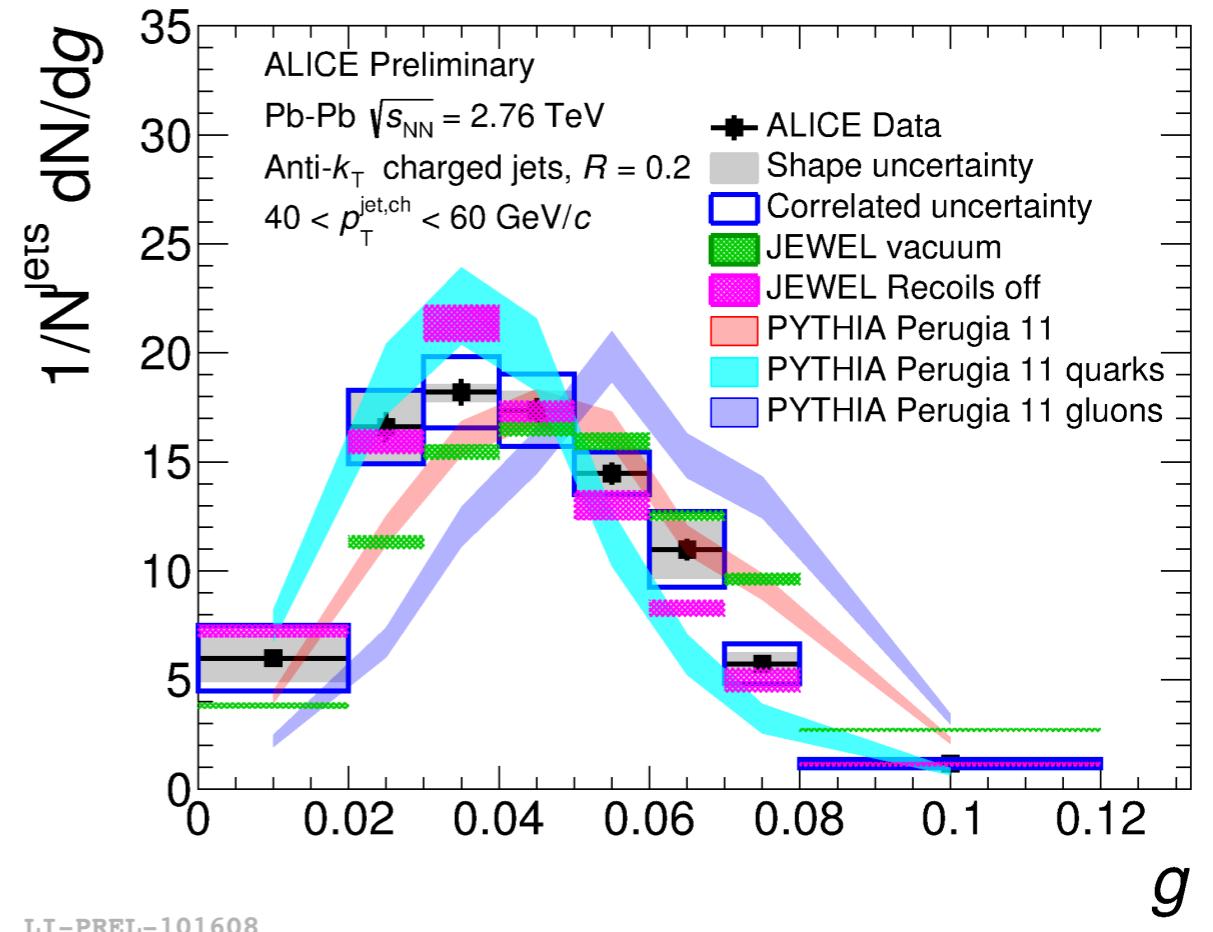
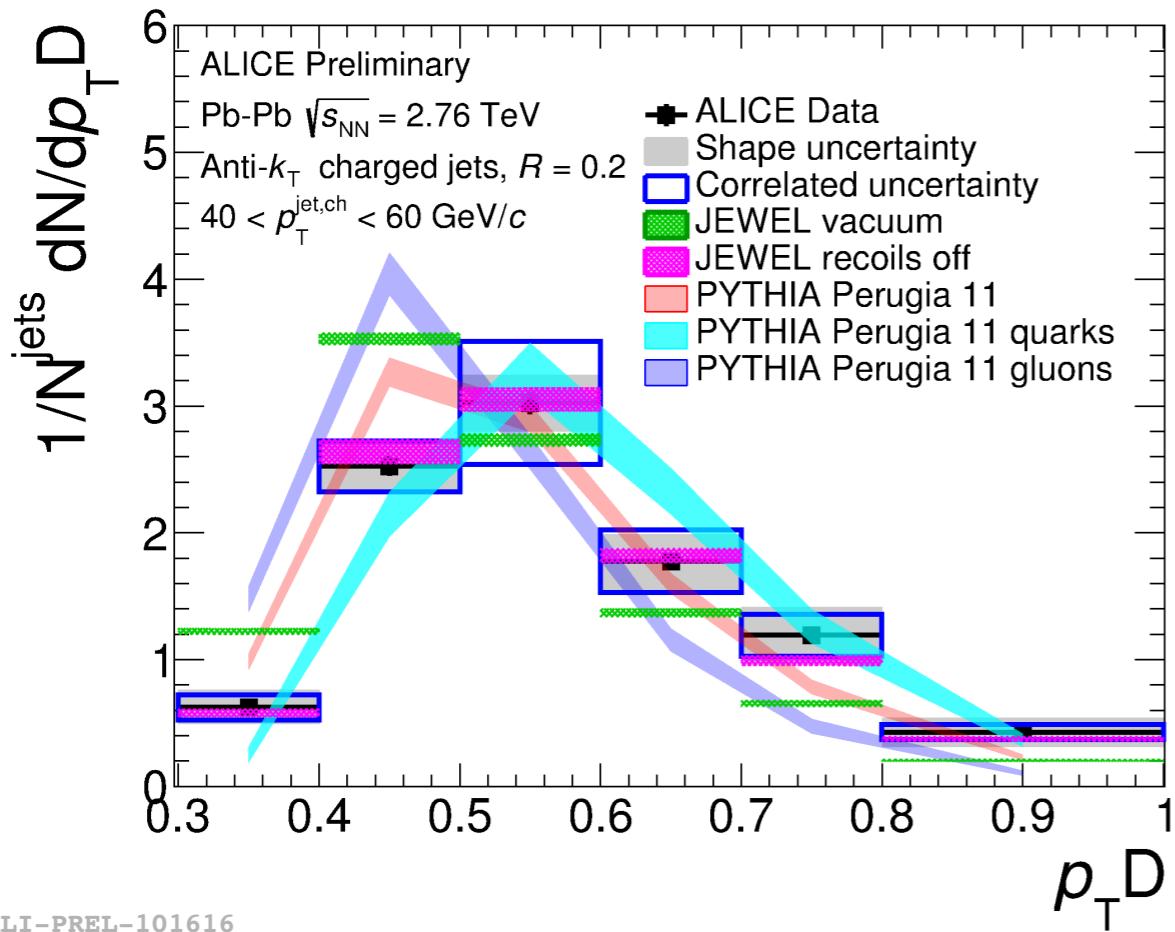
- ▶ $LeSub$ in fair agreement with PYTHIA Perugia 11

Charged jet shapes: comparison with models



- ▶ The **different fragmentation observed in Pb-Pb** collisions for $R=0.2$ jets is **qualitatively described by JEWEL model.** [C. Zapp et al , JHEP 1303 \(2013\) 080](#)
- ▶ JEWEL collimates the jets since the soft particles are emitted at large angles.
- ▶ Results are in qualitative agreement for both $p_T D$ and g

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.**



Conclusions

- ▶ Jet shapes in pp collisions show a **fair agreement with PYTHIA Tune Perugia 11**
- ▶ More differential studies (R , p_T^{jet}) ongoing.
- ▶ Input from theory needed to compare with different MC (including hadronization, UE effects...)

Conclusions

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 - ▶ More differential studies (R , p_T^{jet}) ongoing.
 - ▶ Input from theory needed to compare with different MC (including hadronization, UE effects...)
- ▶ Measurements of jet shapes in Pb-Pb collisions:
 - ▶ allow to **study modification of intra-jet particle distribution** by QGP
 - ▶ indicate that **small R jets ($R = 0.2$) are more collimated and fragment harder than PYTHIA pp reference.**
 - ▶ indicate a **qualitative agreement with quark-like jet fragmentation** and are in agreement with **JEWEL jet quenching model**.

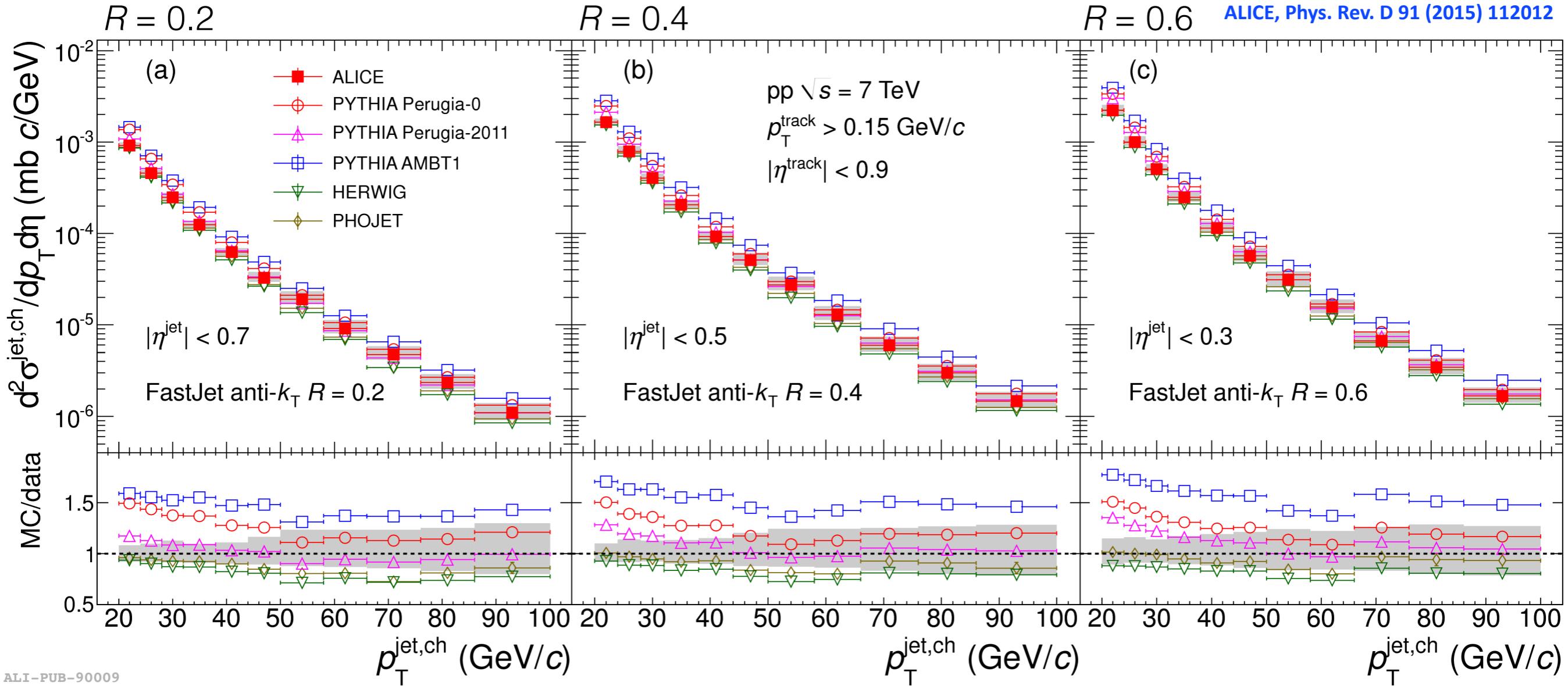


Back up slides

Charged jet spectra



ALICE, Phys. Rev. D 91 (2015) 112012



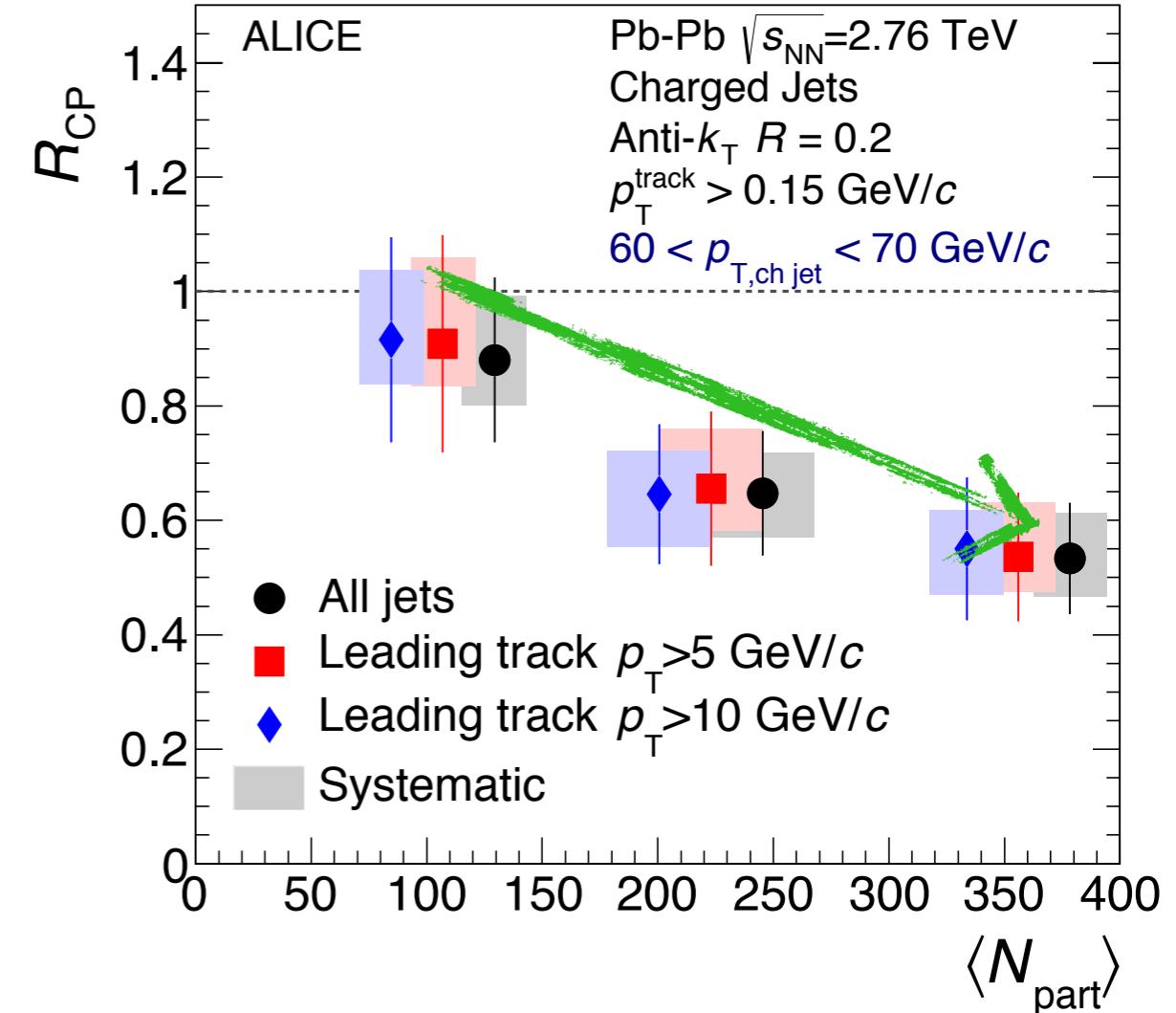
- ▶ Reasonable agreement between data and MC calculations for all resolution parameters.
- ▶ PYTHIA Perugia-2011 tends to better reproduce the results at high- p_T^{jet} .
- ▶ HERWIG seems to be more in agreement in the low jet p_T region.

ALICE jet results in Pb-Pb collisions

ALICE, JHEP 03 (2014) 013

$$R_{\text{CP}} = \frac{\frac{1}{\langle T_{\text{AA}} \rangle} \frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{ch jet}}}{dp_{T,\text{ch jet}} d\eta_{\text{ch jet}}} \Big|_{\text{central}}}{\frac{1}{\langle T_{\text{AA}} \rangle} \frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{ch jet}}}{dp_{T,\text{ch jet}} d\eta_{\text{ch jet}}} \Big|_{\text{peripheral}}},$$

- ▶ The **charged jet** R_{CP} shows a decreasing trend as a function of the collision centrality^(*) for $R=0.3$.

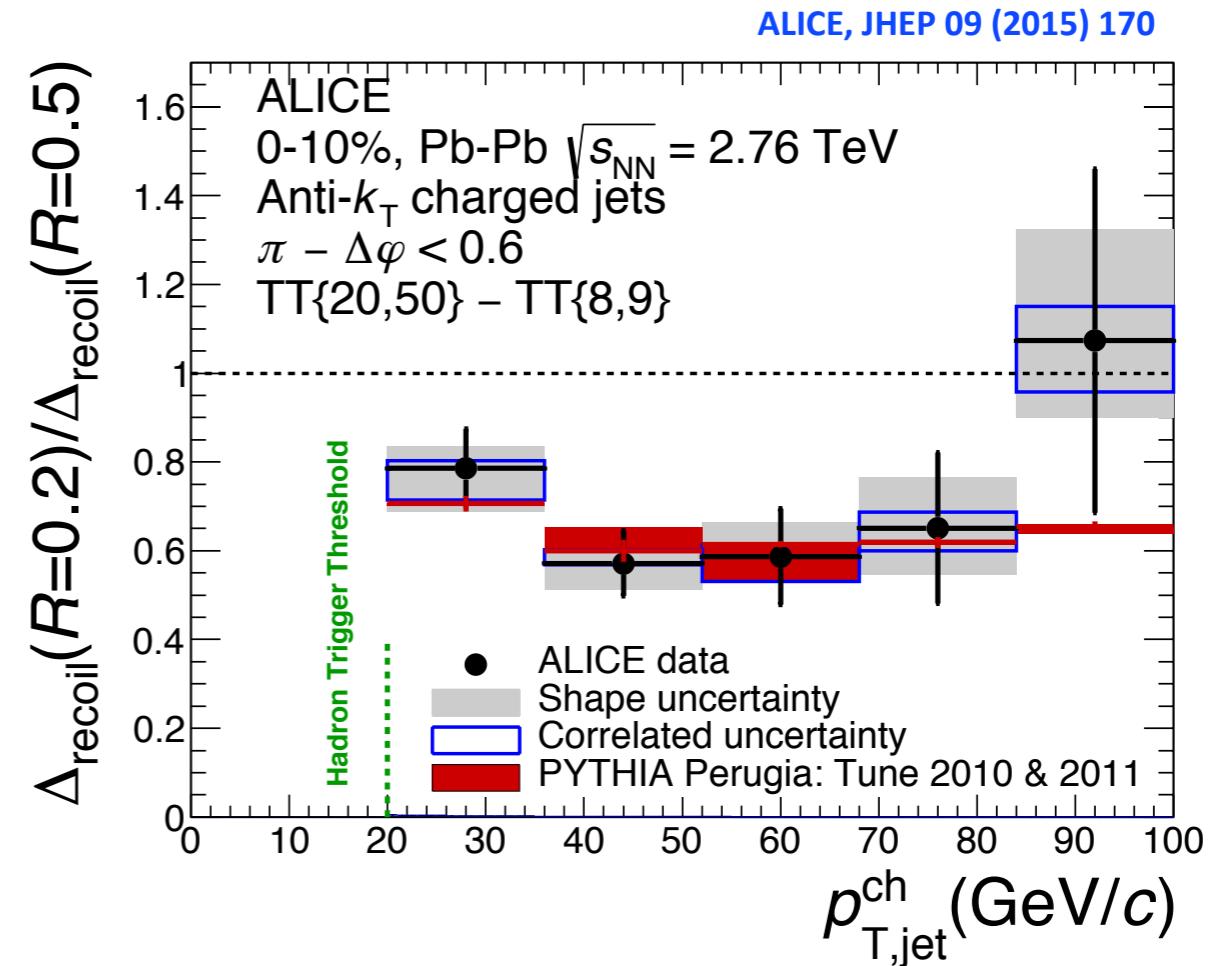


ALI-PUB-64295

^(*)Centrality: quantity used to determine the overlap region of the two colliding nuclei.
Events are classified in centrality classes in terms of the percentiles of the total A-A cross section

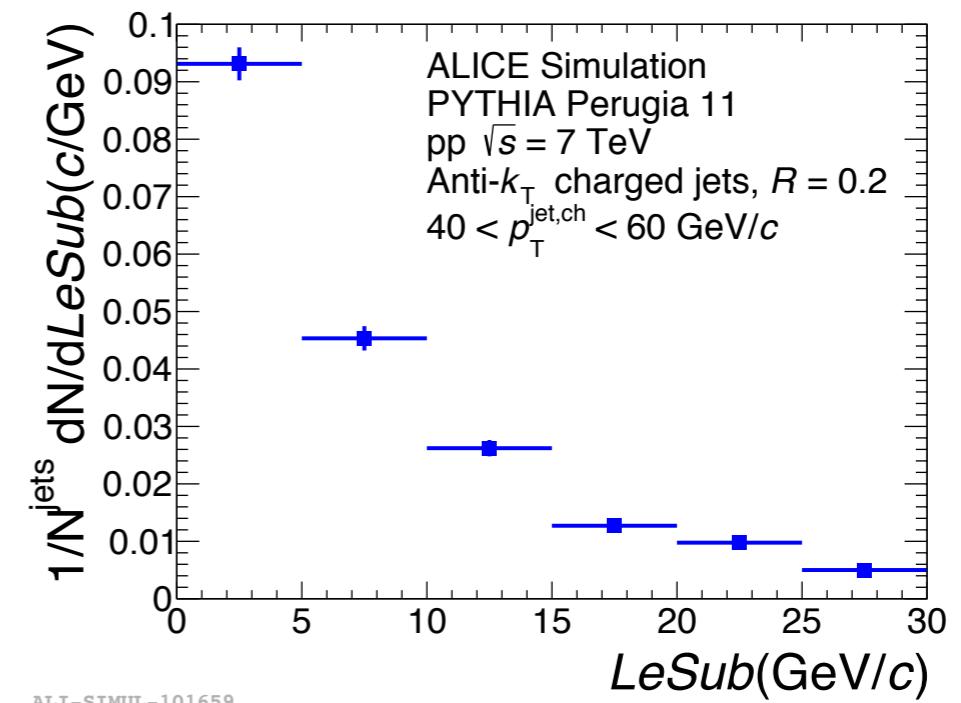
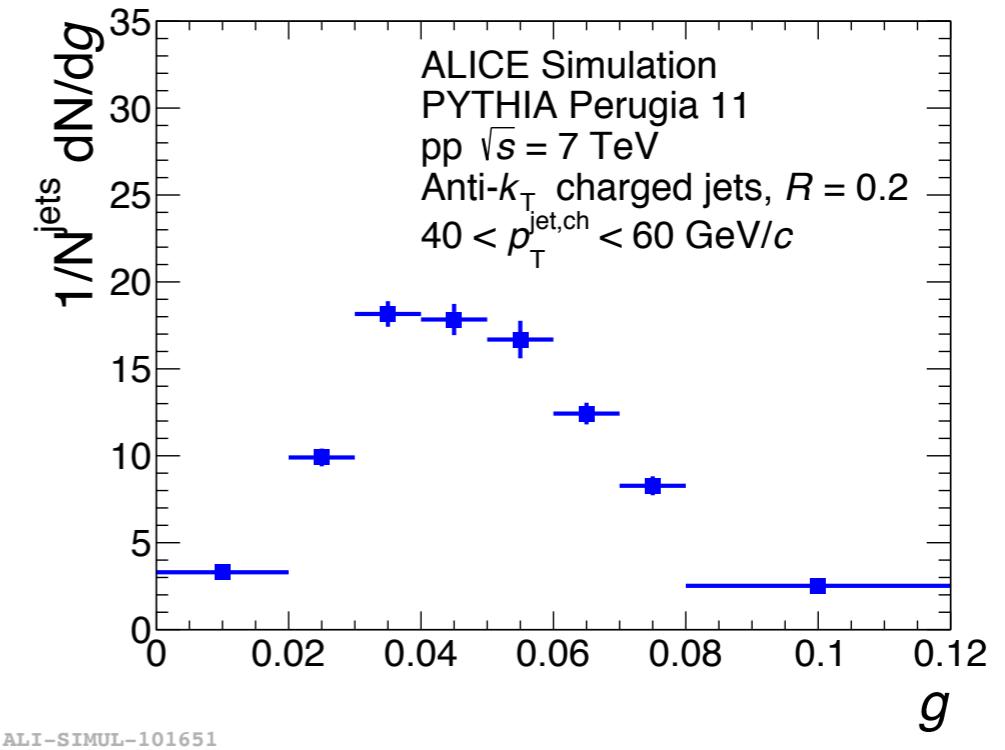
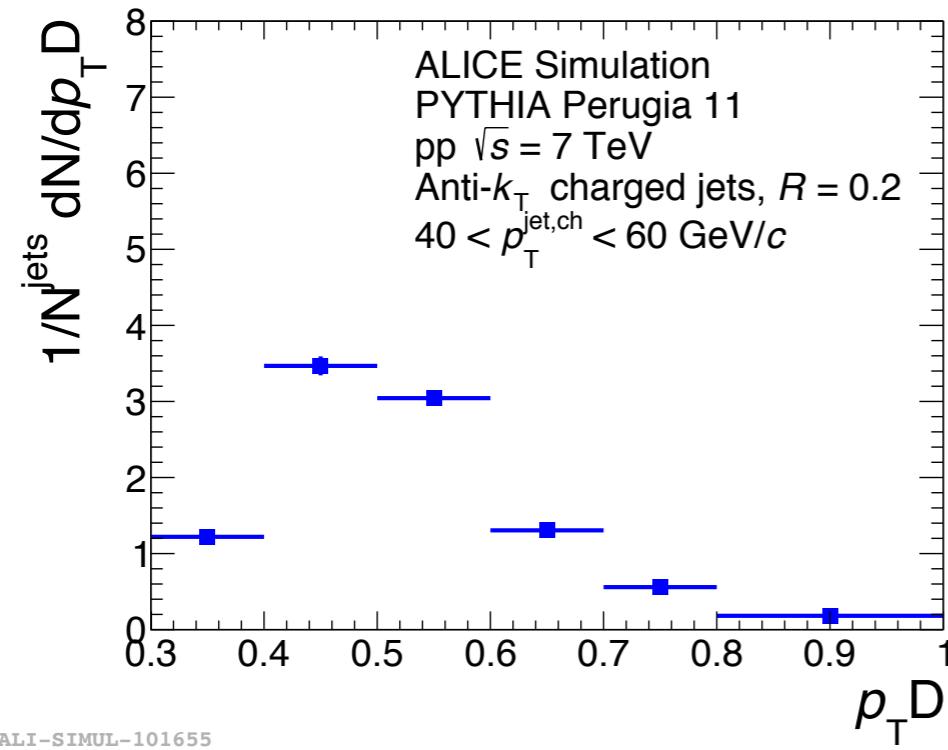
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- ▶ Exploiting the h-jet coincidence measurement it is possible to suppress the combinatorial background effects and explore larger jet radii.

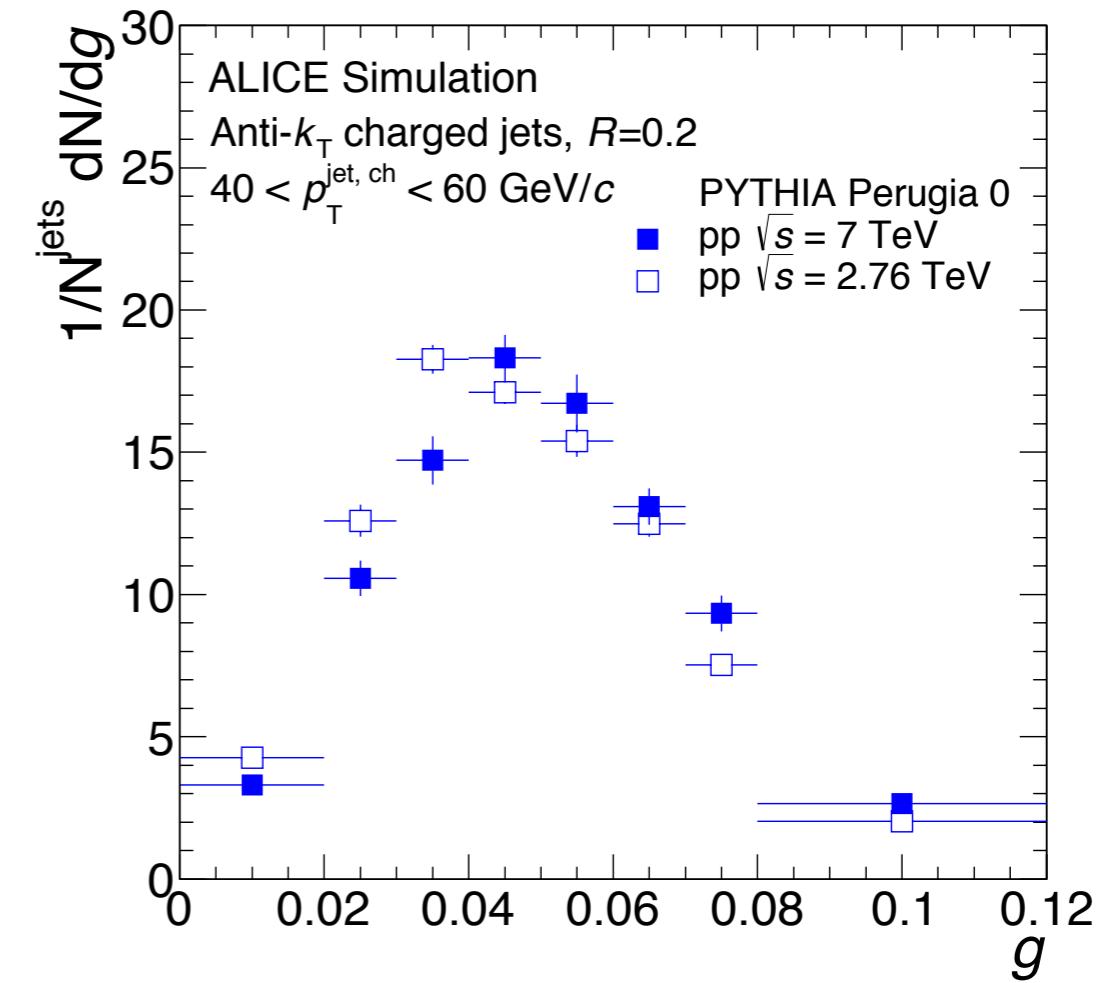
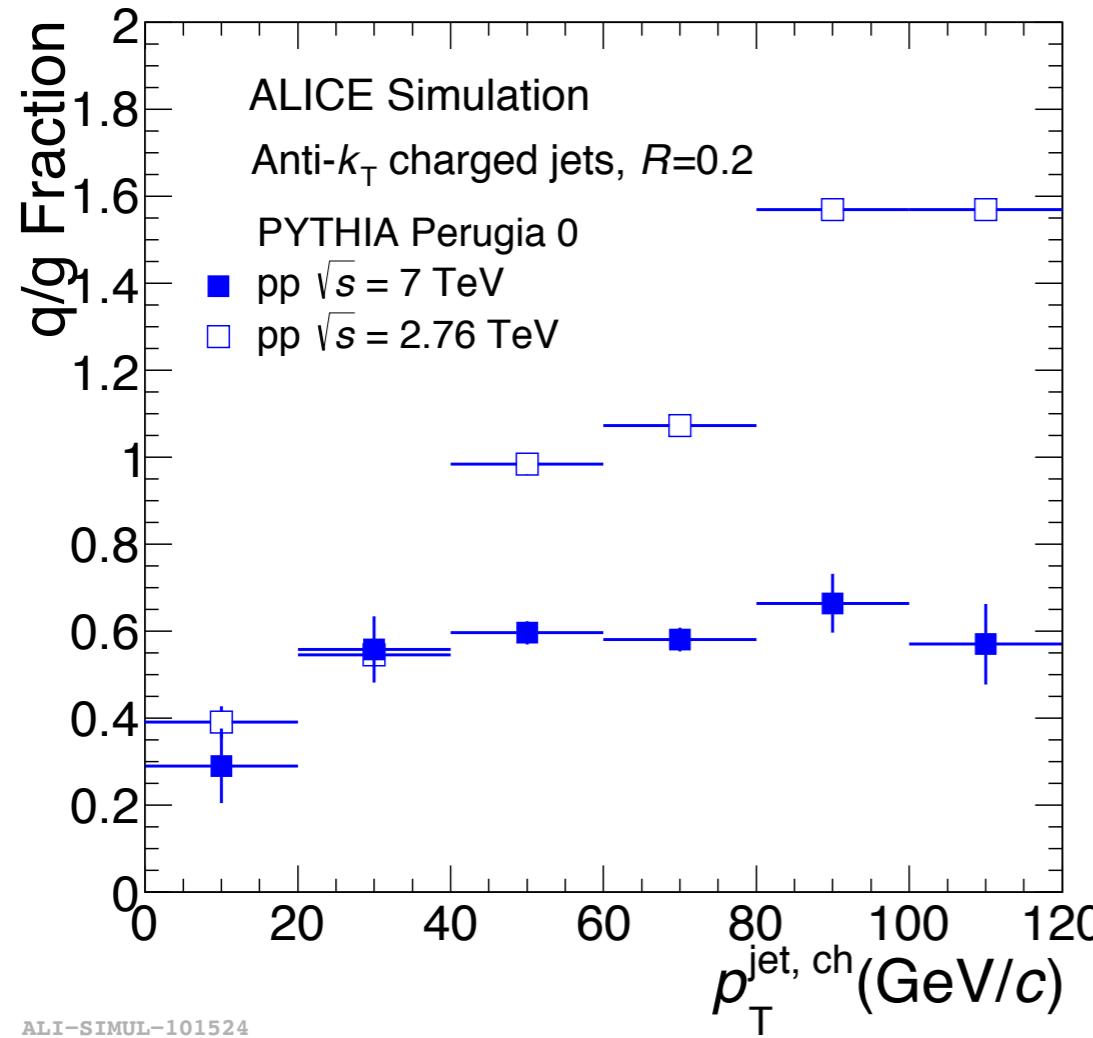


- ▶ **No significant medium-induced modification of intra-jet energy distribution for $R \leq 0.5$ is observed.**

Jet shape distributions PYTHIA Perugia 11

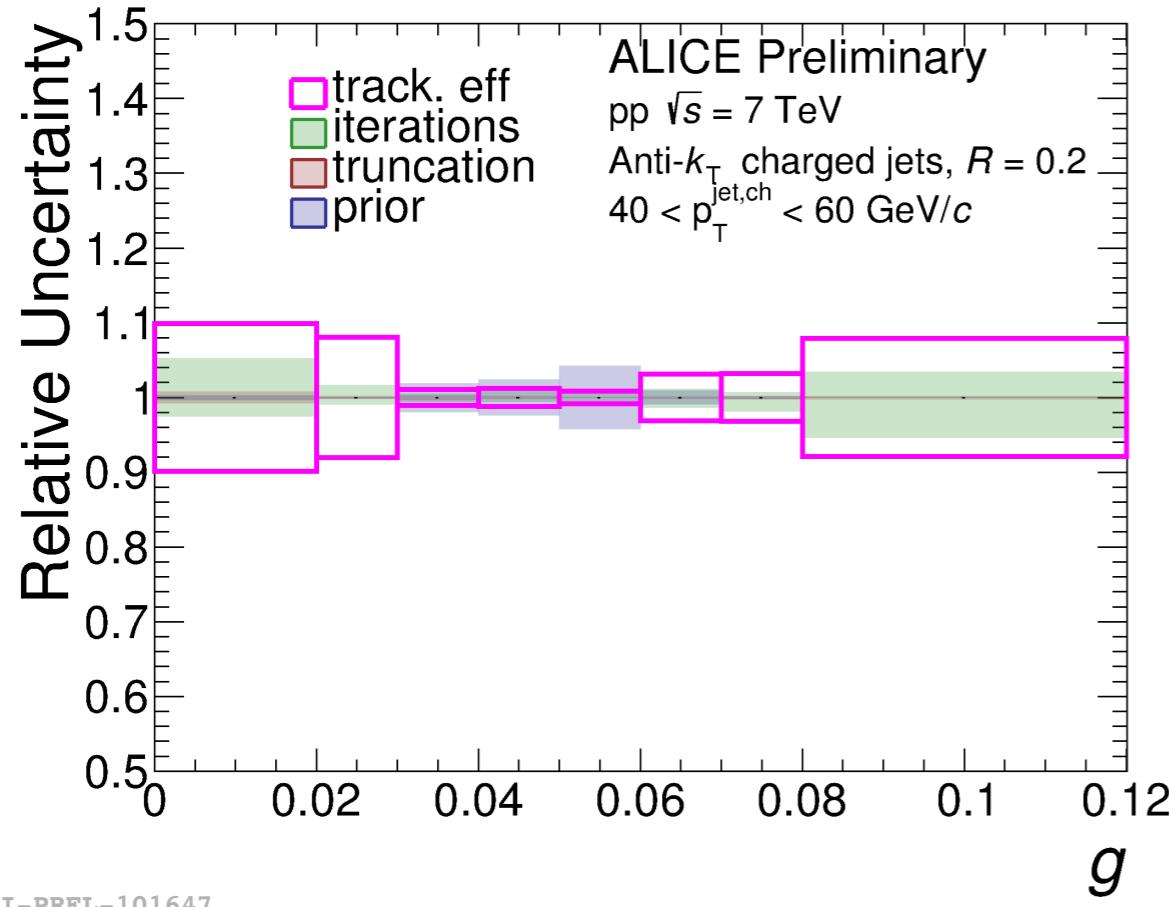


\sqrt{s} dependence of jet shapes PYTHIA Perugia 11

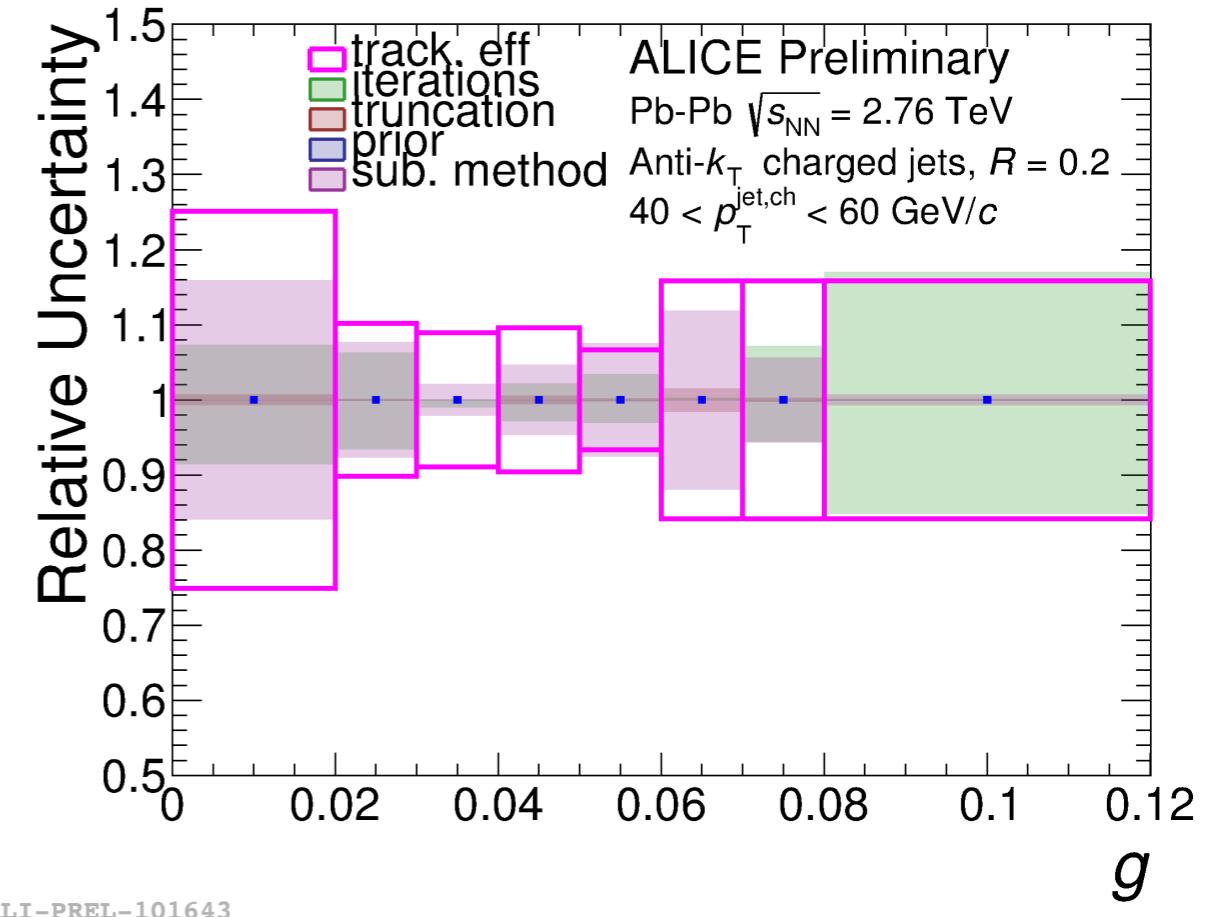


- ▶ Not negligible difference in the jet shapes due to due to q/g difference fraction at two collider energies.

Systematics



ALI-PREL-101647

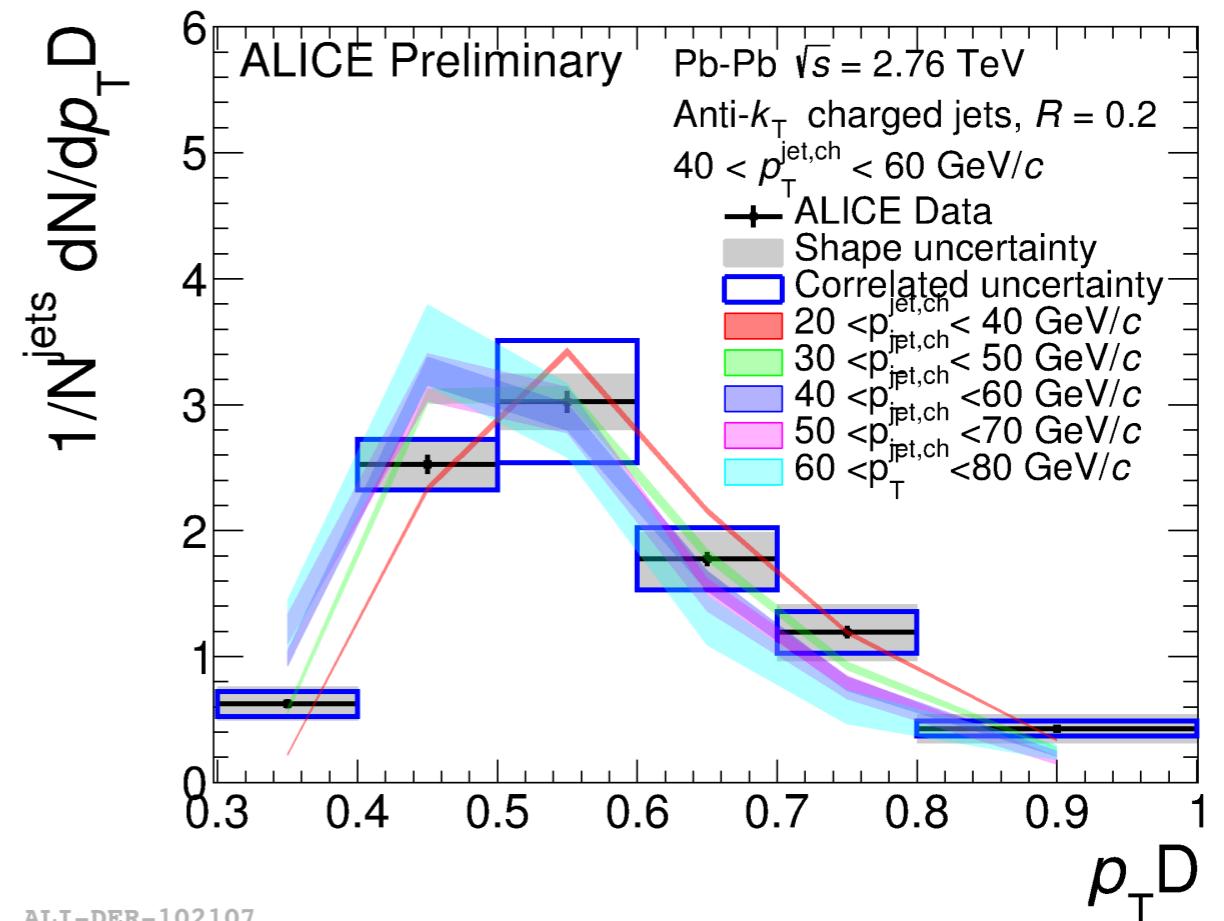
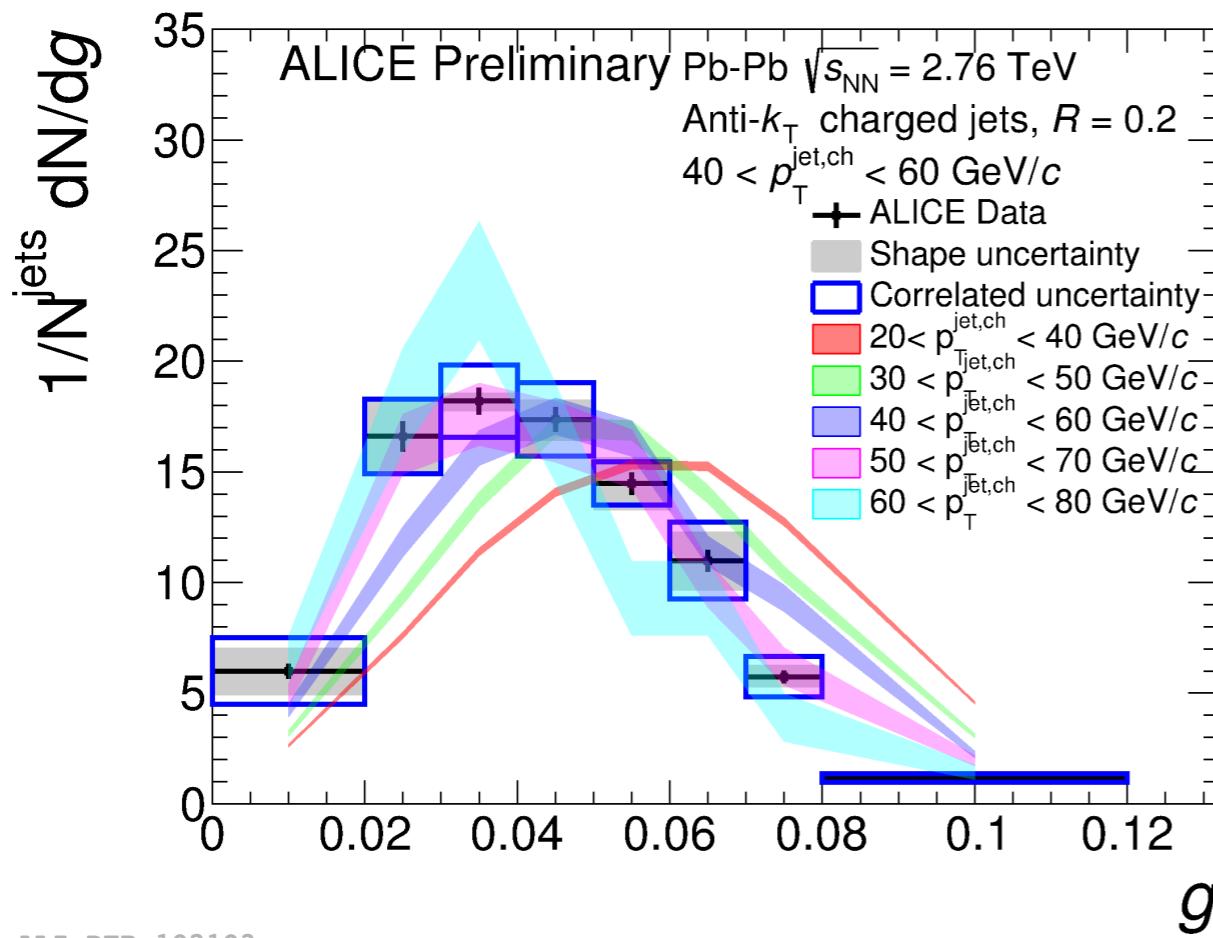


ALI-PREL-101643

- ▶ Tracking efficiency. Variation of $\pm 4\%$ 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 $p_{\text{T}}^{\text{part}}$ and $\text{shape}^{\text{part}}$. 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_T^D does not, but it has a milder dependence on the transverse momentum.