Jets in in Pb-Pb collisions at ALICE

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for the ALICE collaboration

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- Jet shapes
- Jet azimuthal anisotropy
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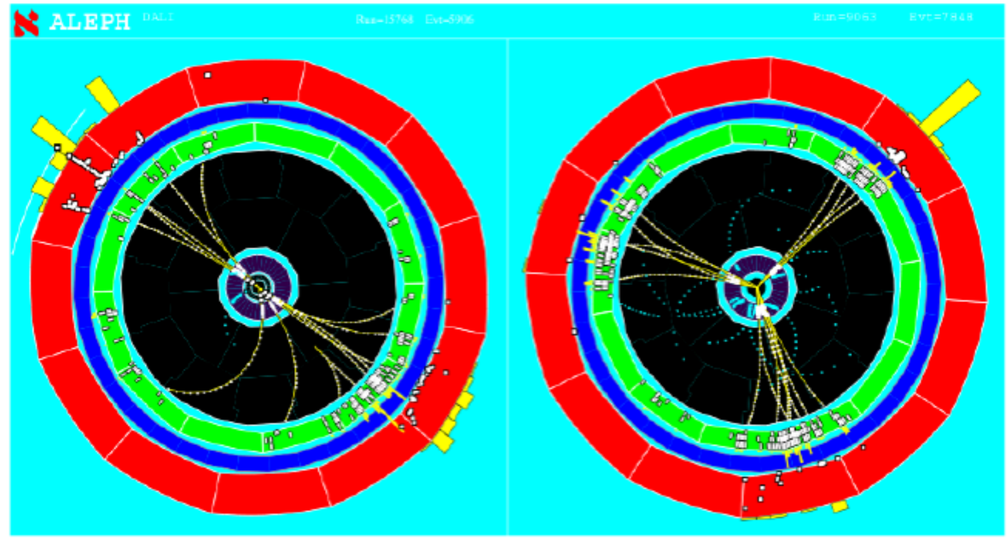
Introduction

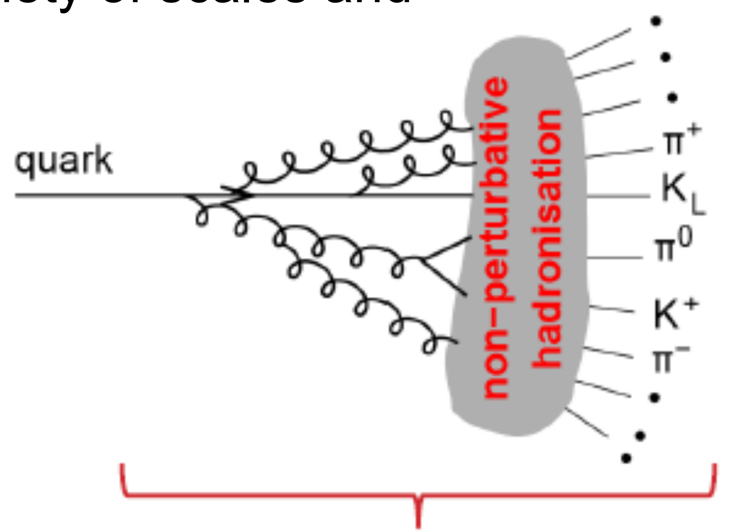
Partons in heavy-ion collisions



- hard partons are produced early and traverse the hot and dense QGP
- expect enhanced parton energy loss, (mostly) due to medium-induced gluon radiation: 'jet quenching'
- jet: 'collimated bunch of hadrons'
- the best available experimental equivalent to quarks and gluons
- 'vacuum' expectation calculable by pQCD: 'calibrated probe of QGP'

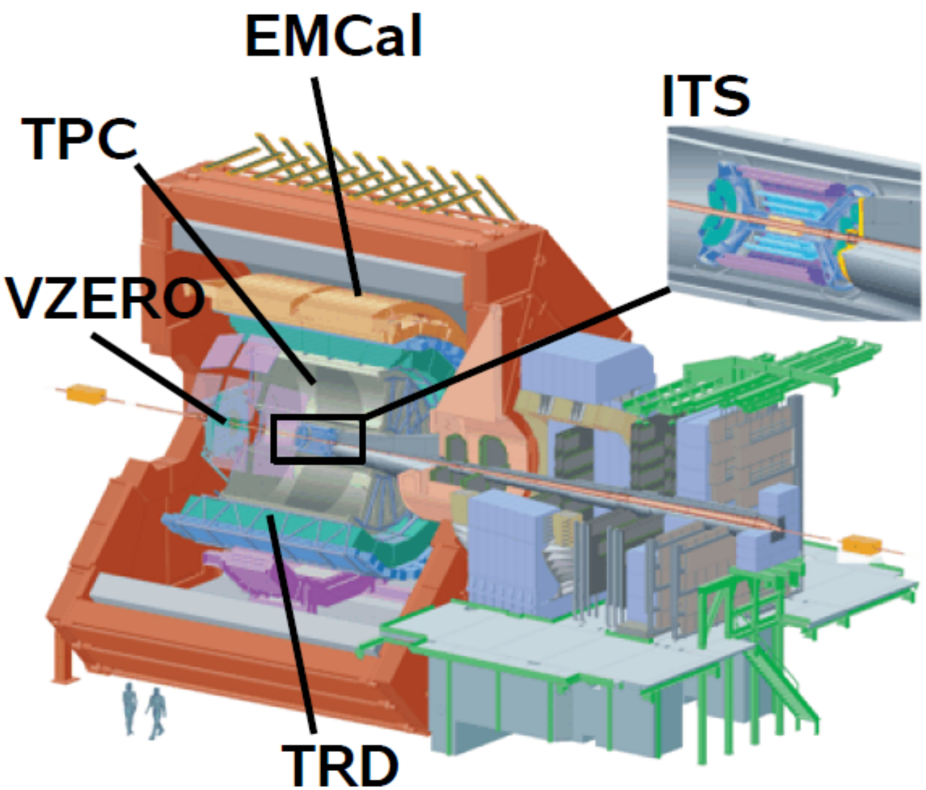
Parton fragmentation

- initial hard scattering: high-p_T partons with high virtuality
- virtuality evolution through parton shower
- hadronisation at a scale ($O(\Lambda_{QCD})$)
- jets probe the medium at a variety of scales and are sensitive to its properties (energy density, $\hat{q}$, mean free path, coupling ...)



Fragmentation = Parton shower + hadronization

Jets at ALICE (LHC run 1)



- charged particle tracking:
  - Inner Tracking System (ITS)
  - Time Projection Chamber
  - full azimuth, $|\eta| < 0.9$
    $p_T > 150$ MeV/c

- EMCal :
  - neutral particles
  - $\Delta\varphi = 107°$, $|\eta|<0.7$
    cluster $E_T > 300$ MeV

- full jets: assess full parton energy

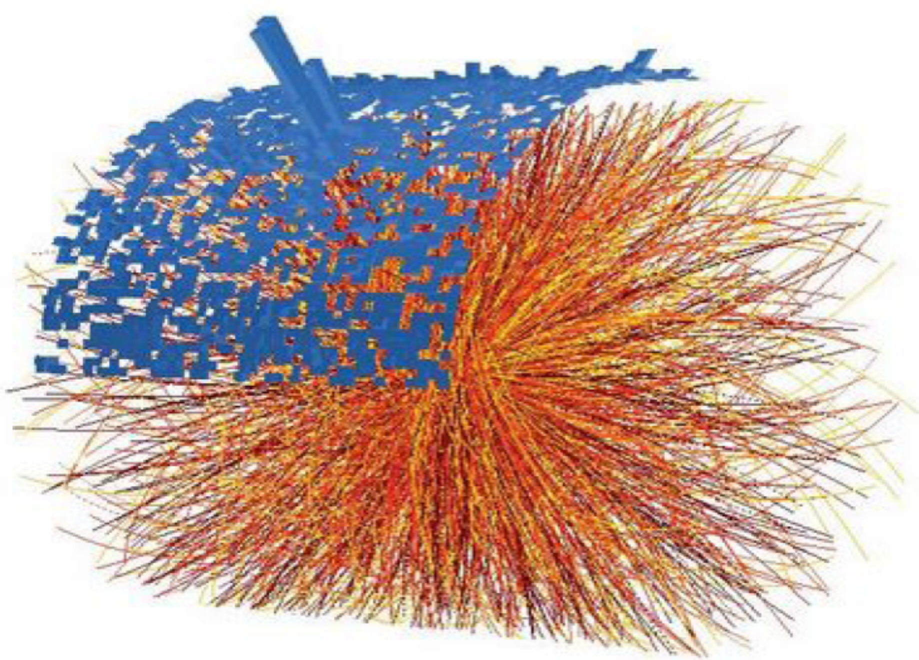
- charged (tracking) jets:
  - full azimuthal coverage
  - measures parton energy deposited into charged fragments
  - good definition of jet axis: well suited for fragmentation, jet structure, PID …

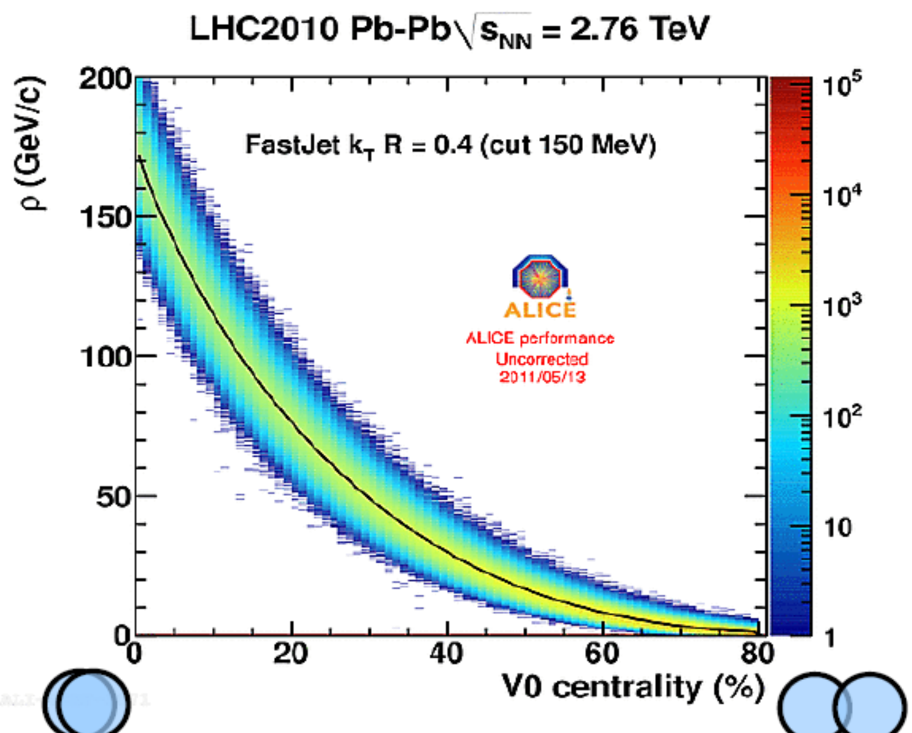
Underlying event in heavy-ion collisions

- jet reconstruction in heavy-ion collisions :
  high underlying event background
  not related to hard scattering

- background is dominant at low jet and constituent p_T

- background fluctuations are important





jet area ~ 0.5 (R = 0.4)

central *peripheral*

Jet nuclear modification factor

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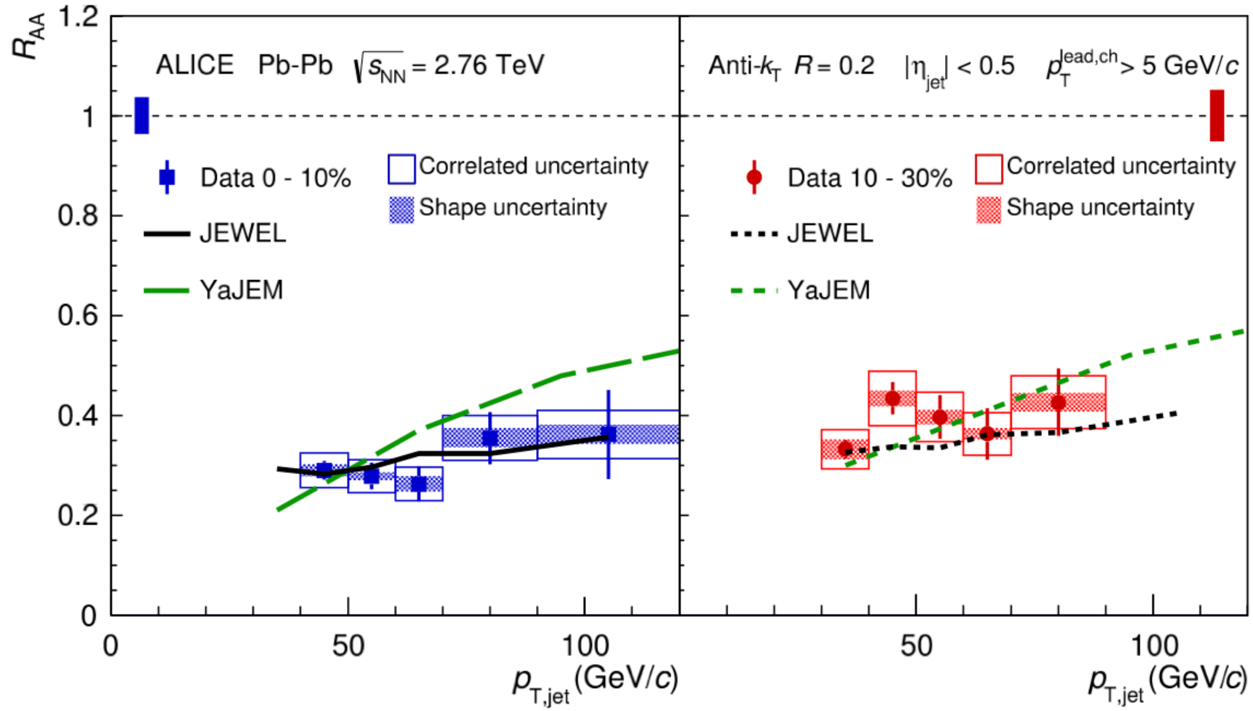
- strong suppression, similar to hadron RAA
  → parton energy not recovered inside jet cone
- increase of suppression with centrality, weak p_T dependence
- JEWEL:
  - microscopic pQCD parton shower + gluon induced emissions
- YaJEM:
  - detailed fireball model
  - parameterisation of radiative and collisional energy loss

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N_{ch}/d\eta\, dp_T}{d^2\sigma_{ch}^{pp}/d\eta\, dp_T}$$



Phys.Lett. B746 (2015) 1
JEWEL: PLB 735 (2014)
YaJEM:PRC 88 (2013) 014905

- different models reproduce observed jet suppression
  → study jet quenching through more differential measurements

Jet Shapes

Jet shapes

- radial moment 'girth' g, longitudinal dispersion $p_T D$, difference leading - subleading p_T LeSub

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

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

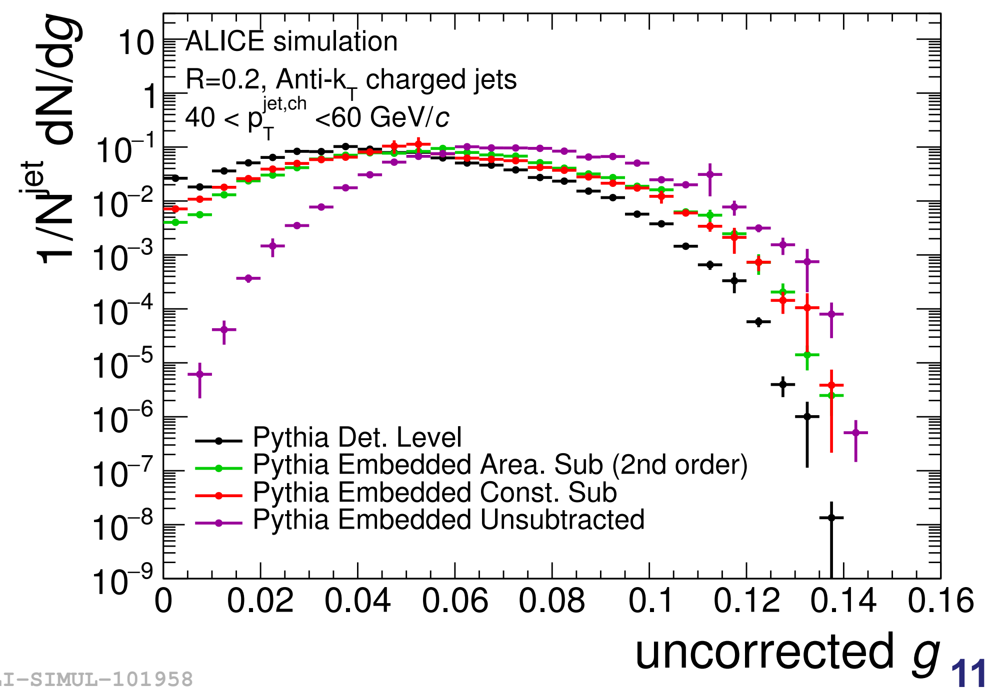
$$\mathrm{LeSub} = p_T^{lead,track} - p_T^{sublead,track}$$

- shapes in Pb-Pb as probe of quenching of low-p_T jets: characterise fragment distributions and are sensitive to medium induced changes of intra-jet momentum flow

- 'event-by-event' measure, sensitive to fluctuations

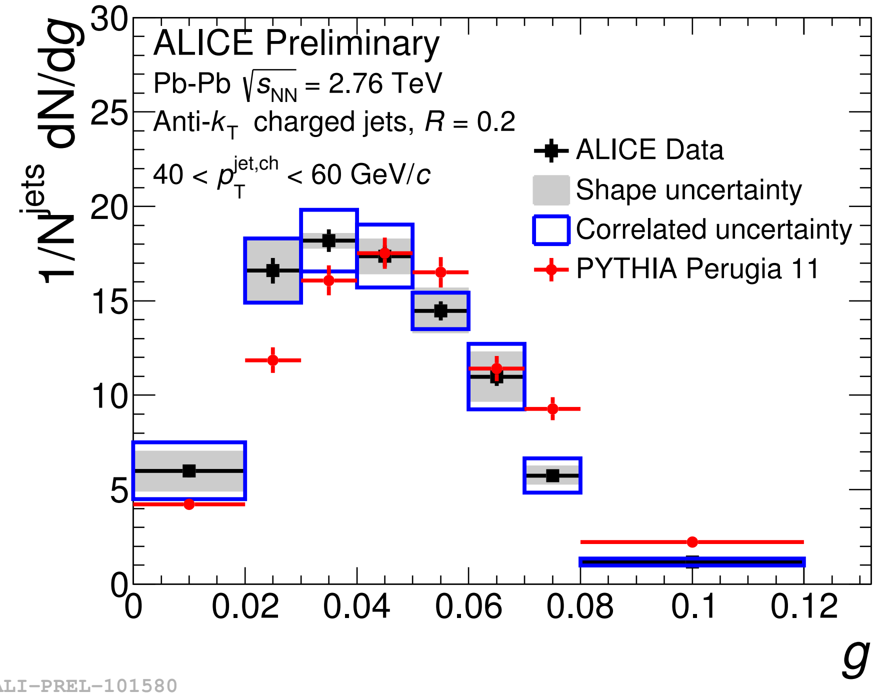
Analysis details

- charged jets from charged particle tracks, $p_T^{const} > 150$ MeV/c in pp MinB at 7 TeV and Pb-Pb 10% central at 2.76 TeV
- R=0.2, $40 < p_T^{jet} < 60$ GeV/c, no leading constituent cut
- novel background subtraction methods (Pb-Pb)
  - area subtraction (*G. Soyez et al, Phys. Rev. Lett 110 (2013) 16*)
  - constituent subtraction (*P. Berta et al, JHEP 1406 (2014) 092*)
- 2D unfolding to correct for background fluctuations and detector effects



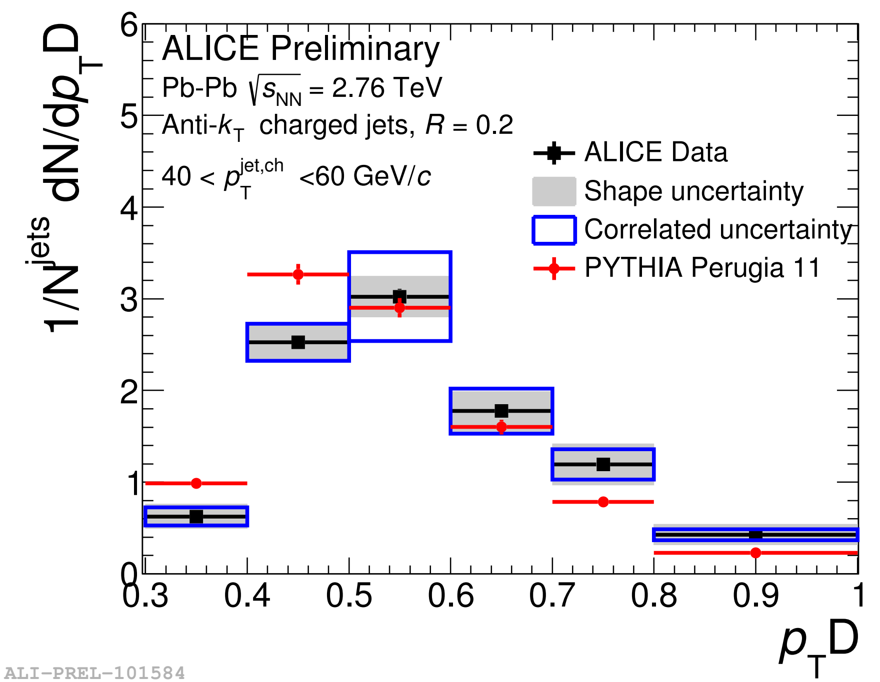
Jet shapes in Pb-Pb

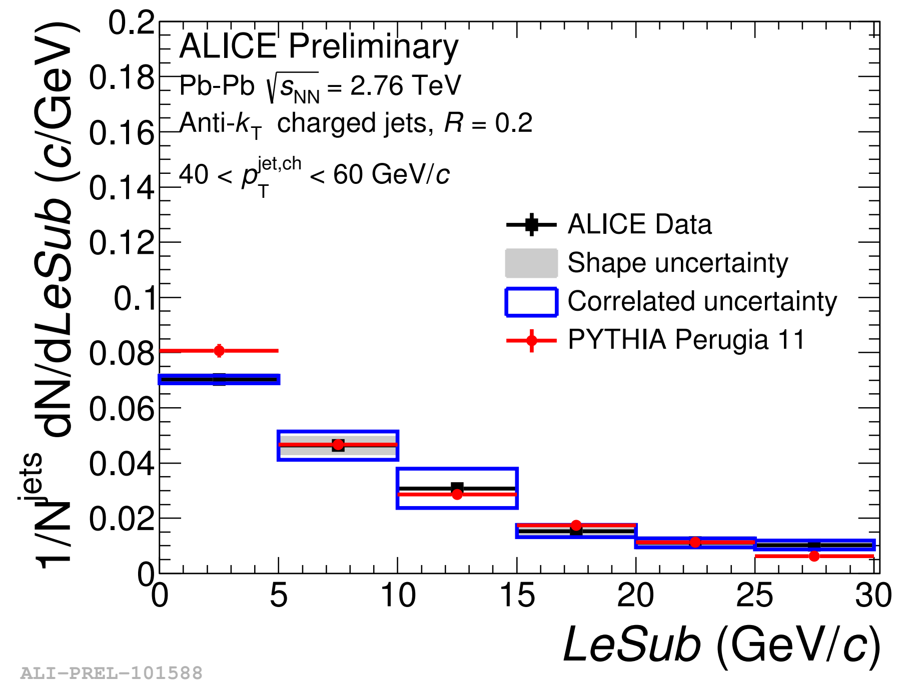
- fully corrected to charged particle level
- compare to PYTHIA reference, validated with results from pp collisions at 7 TeV
- g shifted to smaller values → indicates more collimated jet core



- larger $p_T D$ in Pb-Pb compared to PYTHIA
  → indicates fewer constituents in quenched jets

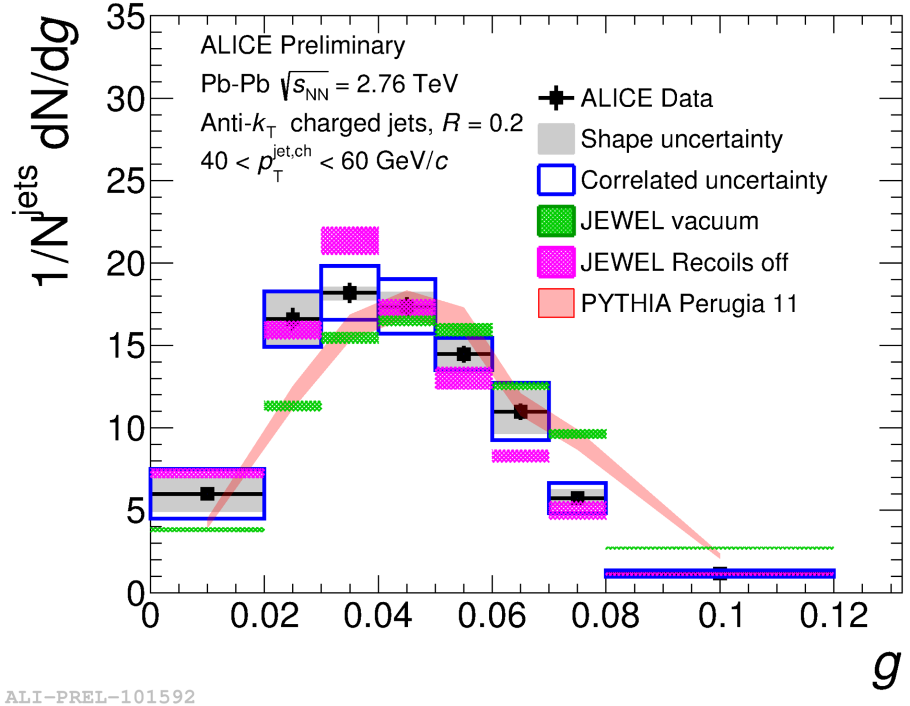
- LeSub in Pb-Pb in good agreement with Pb-Pb:
  → hardest splittings likely unaffected

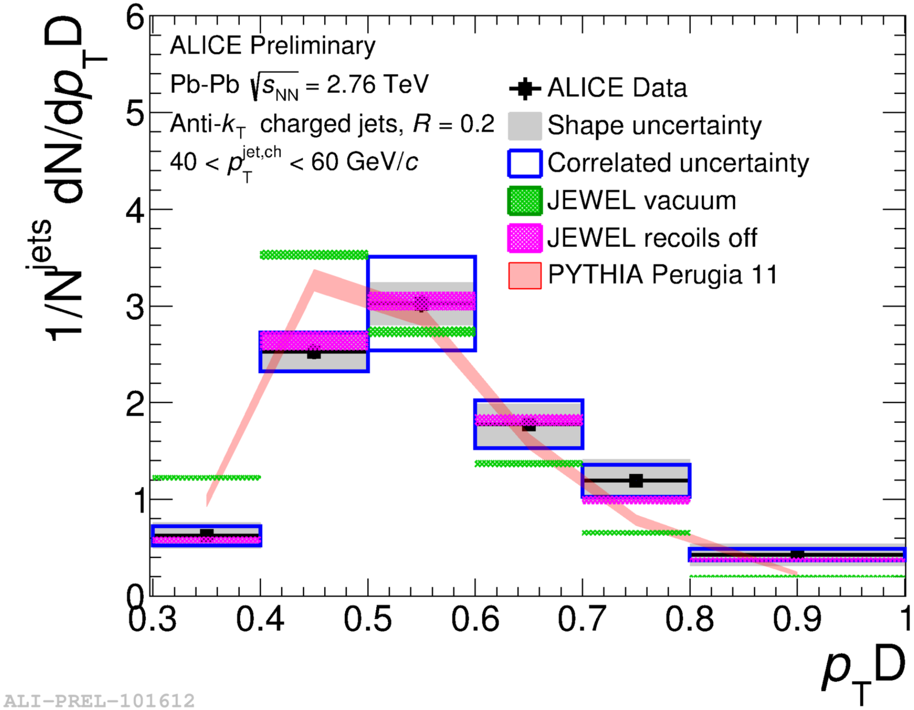




Jet shapes: model comparison

- trends reproduced by JEWEL jet quenching model: collimation through emission of soft particles at large angles





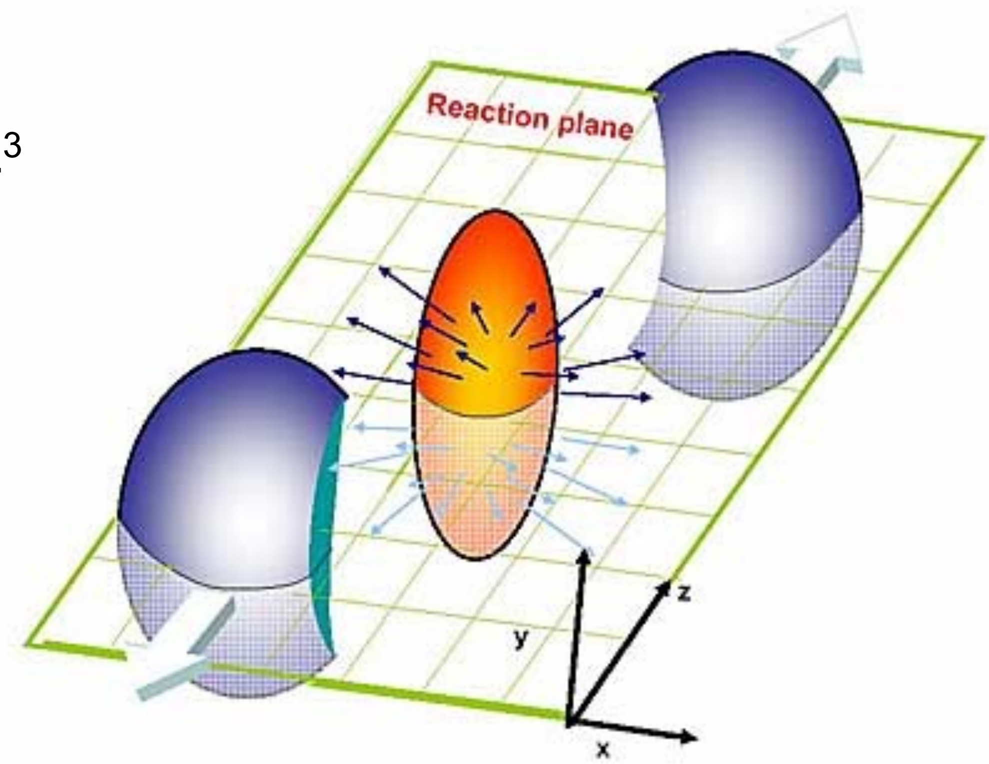
JEWEL: K.C. Zapp, F. Kraus, U.A. Wiedemann, JHEP 1303 (2013) 080

Jet azimuthal anisotropy

Reaction plane dependence

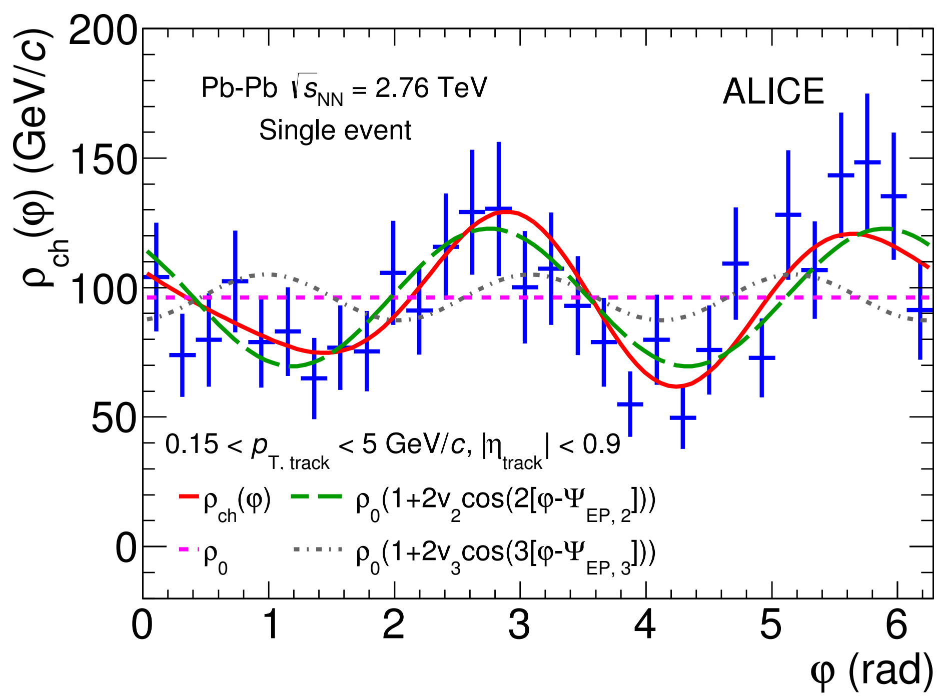
- different medium thickness in- and out-of plane

- sensitive to path length dependence of jet quenching:
  pQCD radiative E-loss : $\sim L^2$
  collisional E-loss : $\sim L$
  strong coupling (ADS/CFT) : $\sim L^3$



Analysis details

- charged jets, R = 0.2
- account for flow-modulation of background via event-by-event fit and subtraction of local background density
- unfolding to account for background fluctuations : separately for spectra in- and out-of-plane



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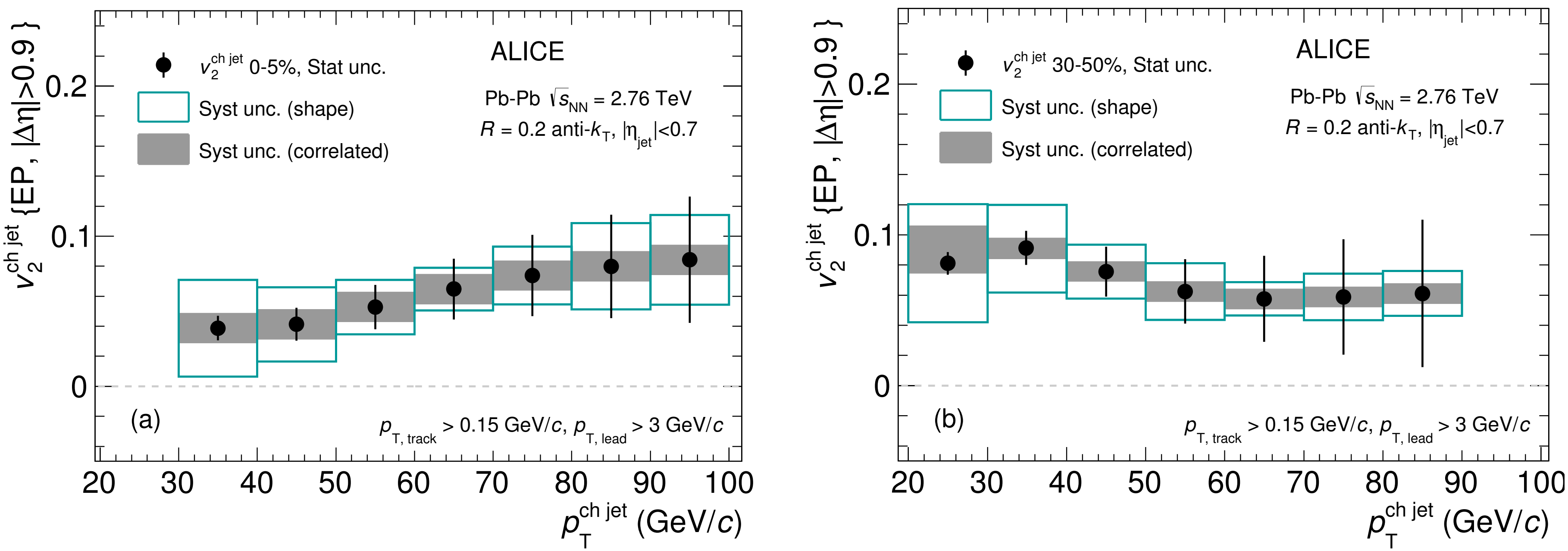
Jet v_2 : results

- quantify azimuthal asymmetry via 2nd Fourier harmonic $v_2^{\text{ch jet}}$
- central collisions: 1.5 - 2 sigma from $v_2^{\text{ch jet}} = 0$
  → consistent with 0, but maybe hint for effect of initial density fluctuations ?
- non-zero $v_2^{\text{ch jet}}$ in semi-central collisions



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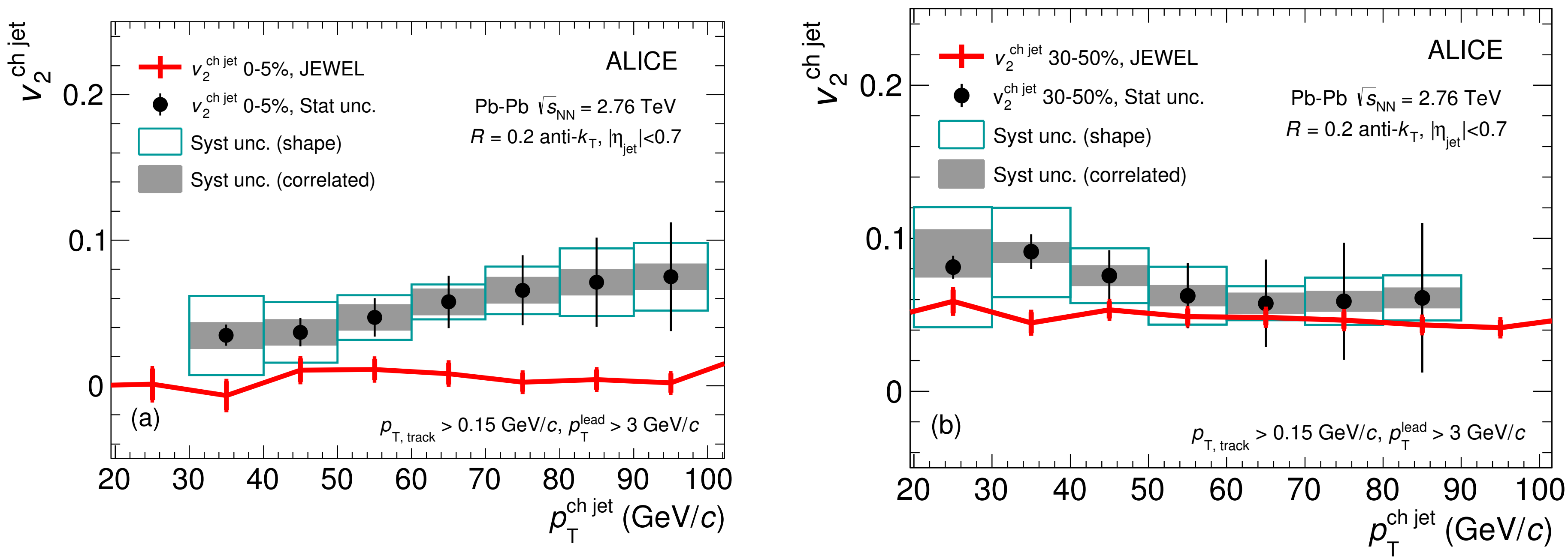
Comparison to JEWEL

- good agreement with JEWEL in semi-central collisions
- clear indication of path-length dependence of energy loss



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Summary

- measurement of jet shapes

  - characterise modifications of intra-jet momentum flow by QGP

  - results indicate that jet cores in Pb-Pb are narrower and harder and have fewer constituents than PYTHIA pp reference

  - results described by quenching models like JEWEL

- jet azimuthal anisotropy

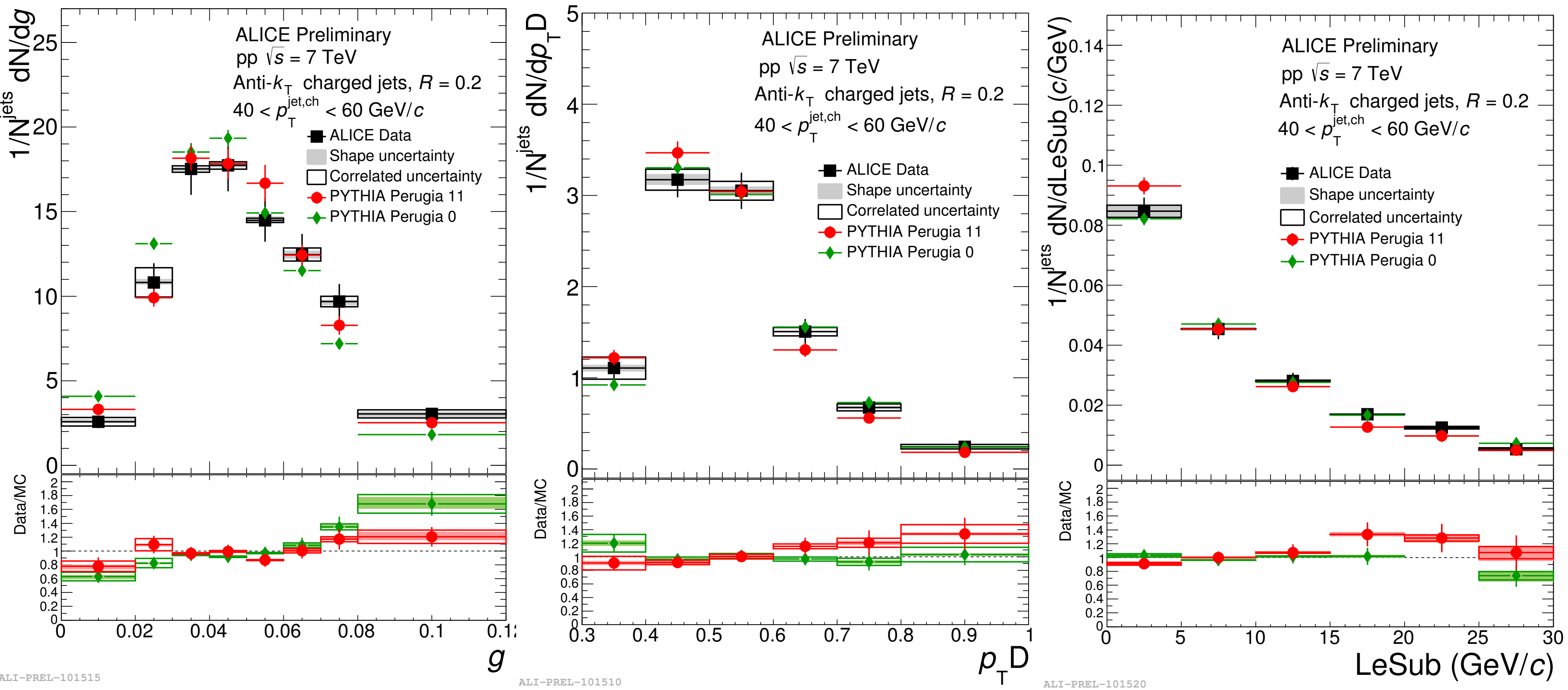
  - significant $v_2^{ch\ jet}$ in semi-central collisions consistent with path-length dependence of energy loss

  - good agreement with JEWEL (semi-central)

- Backup -

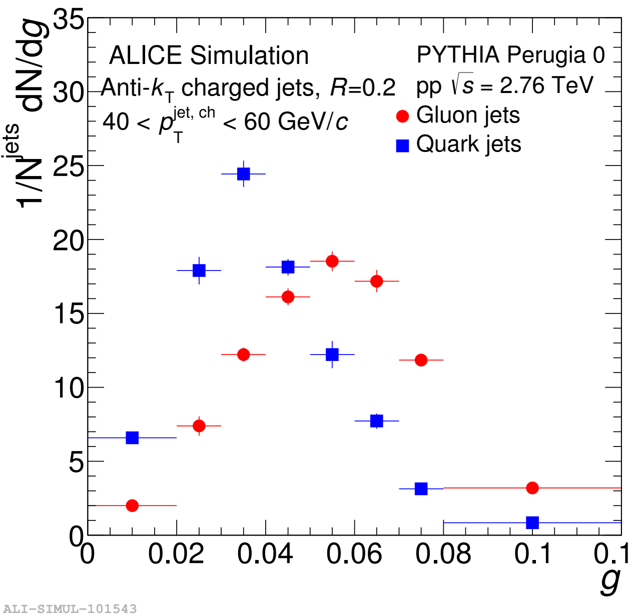
Jet shapes in pp

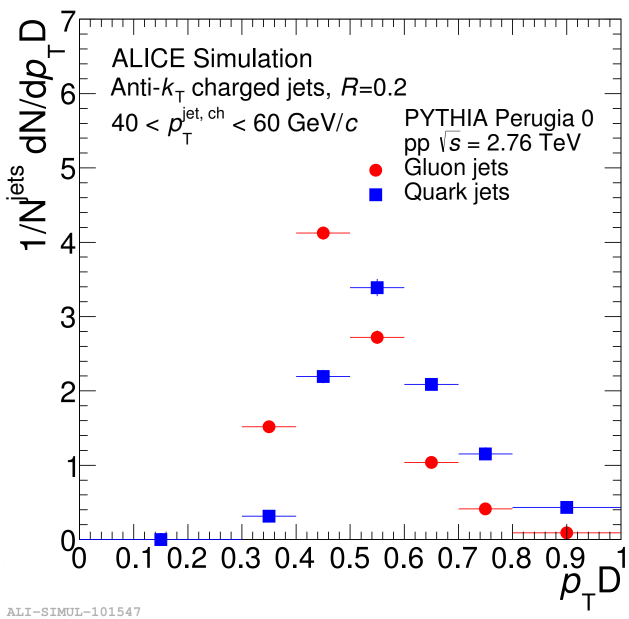
- fully corrected to charged particle level
- fair agreement with PYTHIA simulations: validates PYTHIA as reference for Pb-Pb

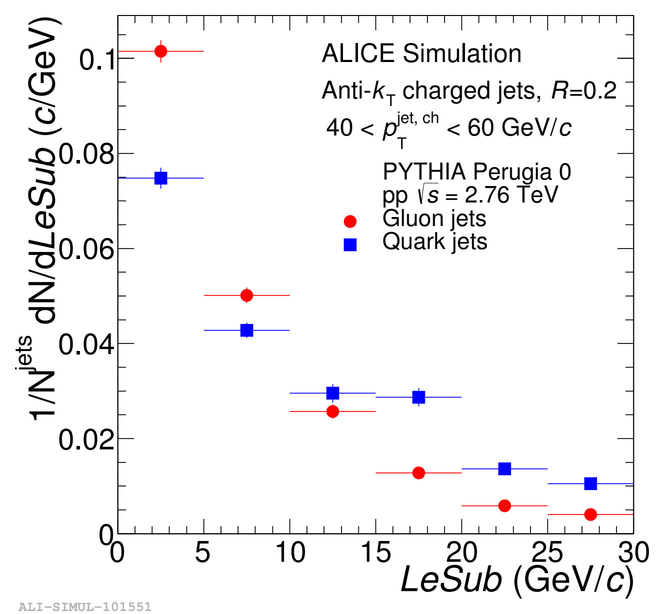


Jet shapes as quenching signatures

- compare quarks and gluons: gluon jets broader and softer
- g is p_T weighted width of the jet:
  - broadening (collimation) →enhanced (reduced) g
- $p_T D$ measures p_T dispersion:
  - less constituents / 'more democratic' splitting → reduced $p_T D$
- LeSub characterises hardest splitting, insensitive against background

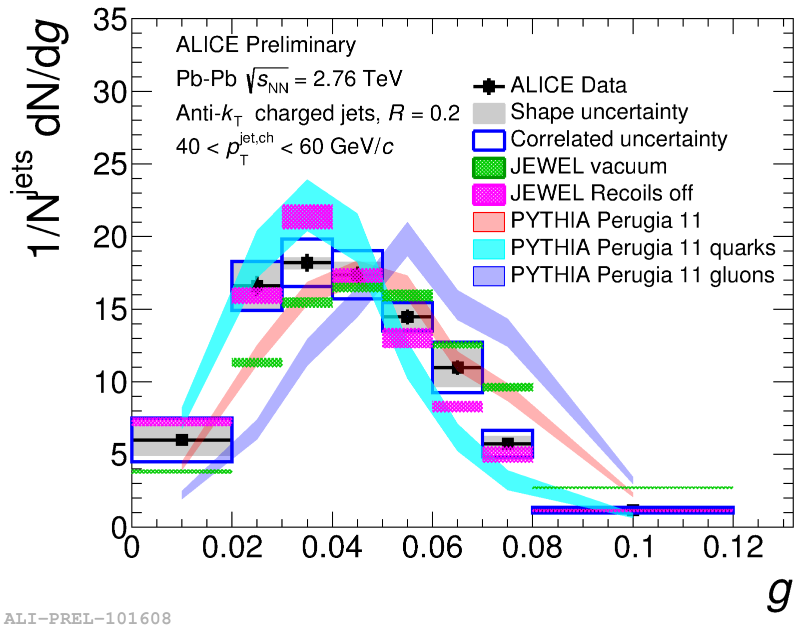


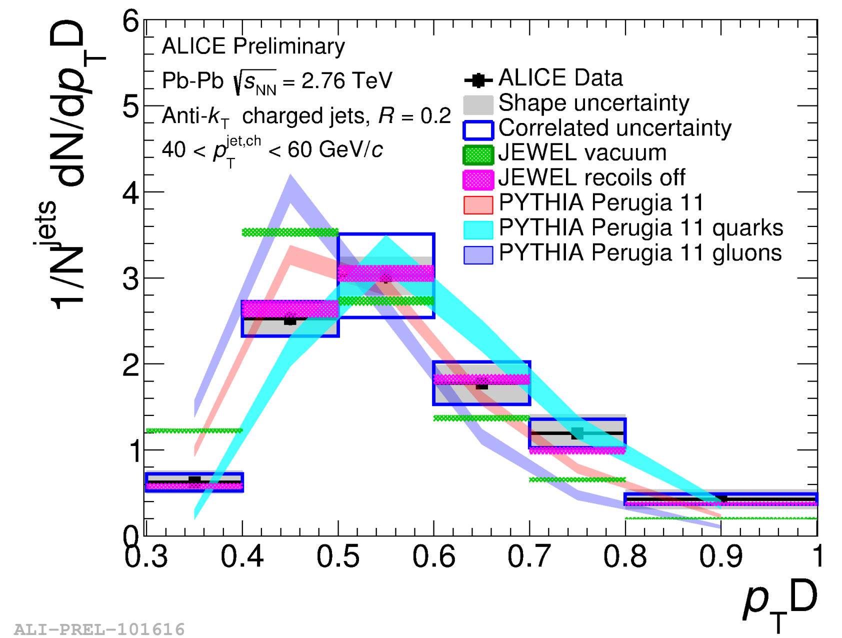




Qualitiative discussion

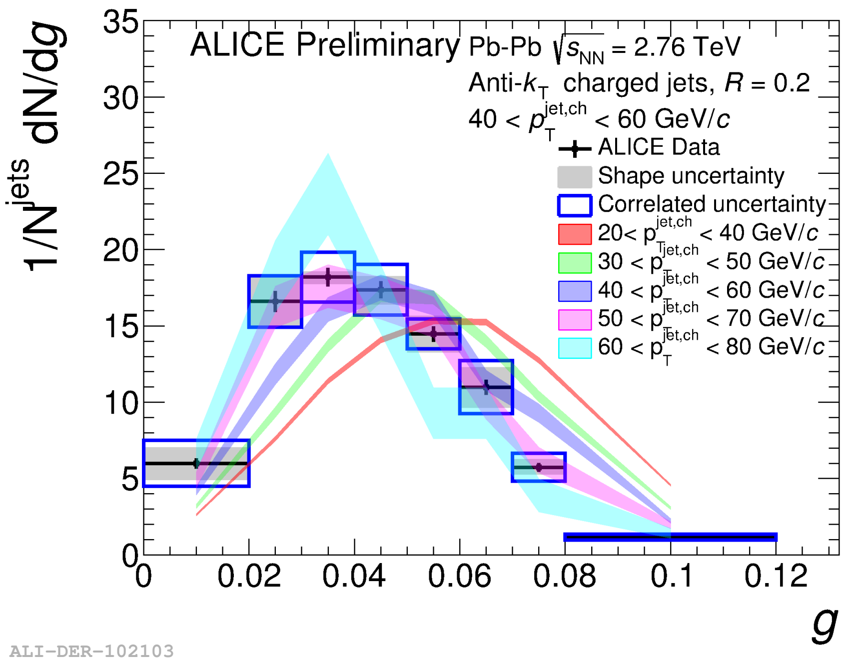
- characterise degree of dispersion and broadening in terms of 'quark-like' and 'gluon-like'
- observed effects favour 'quark-like' scenario
- quenching mechanism or change of quark/gluon composition caveat: jet p_T not equal parton p_T

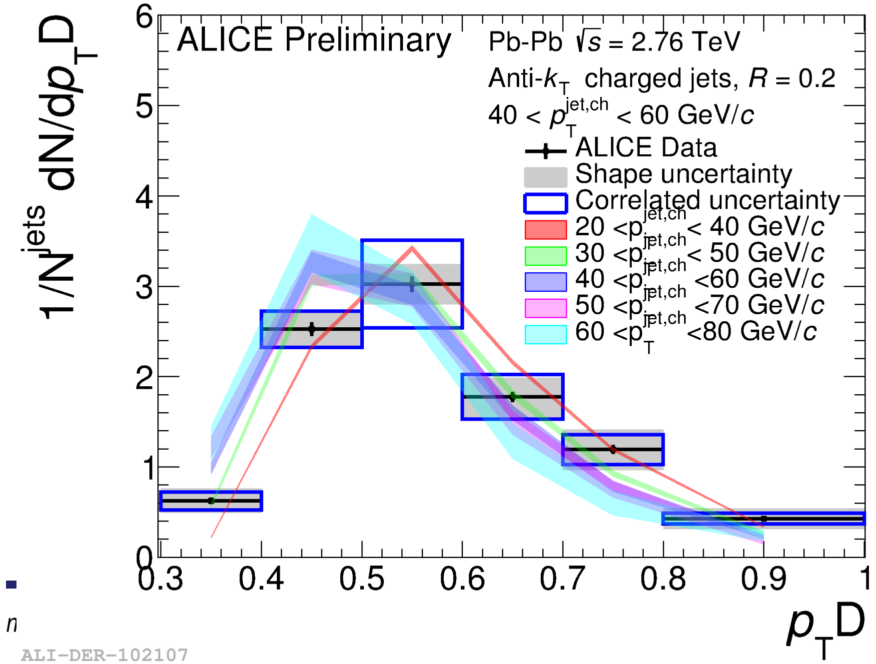




Qualitiative discussion II

- jet quenching = jet p_T shift + vacuum fragmentation?
- if yes, would expect shapes to agree with vacuum shapes from higher p_T jets
- g agrees qualitatively with this picture, however p_TD does not





Comparison to previous results

- ALICE + CMS single particles, ATLAS full jets : different energy scales !

- non-zero v2 up to high p_T

CMS, PRL 109 (2012) 022
ATLAS, PRL 111 (2013) 152

ALICE, Phys. Lett. B753 (2016) 511
ALICE, Phys. Lett. B719 (2013) 18