Jet Properties in Pb-Pb collisions at ALICE

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Outline

- Introduction
- Jets in heavy-ion collisions
- Strangeness production in jets
- Jet shapes
- Summary

Introduction

QCD phase transition

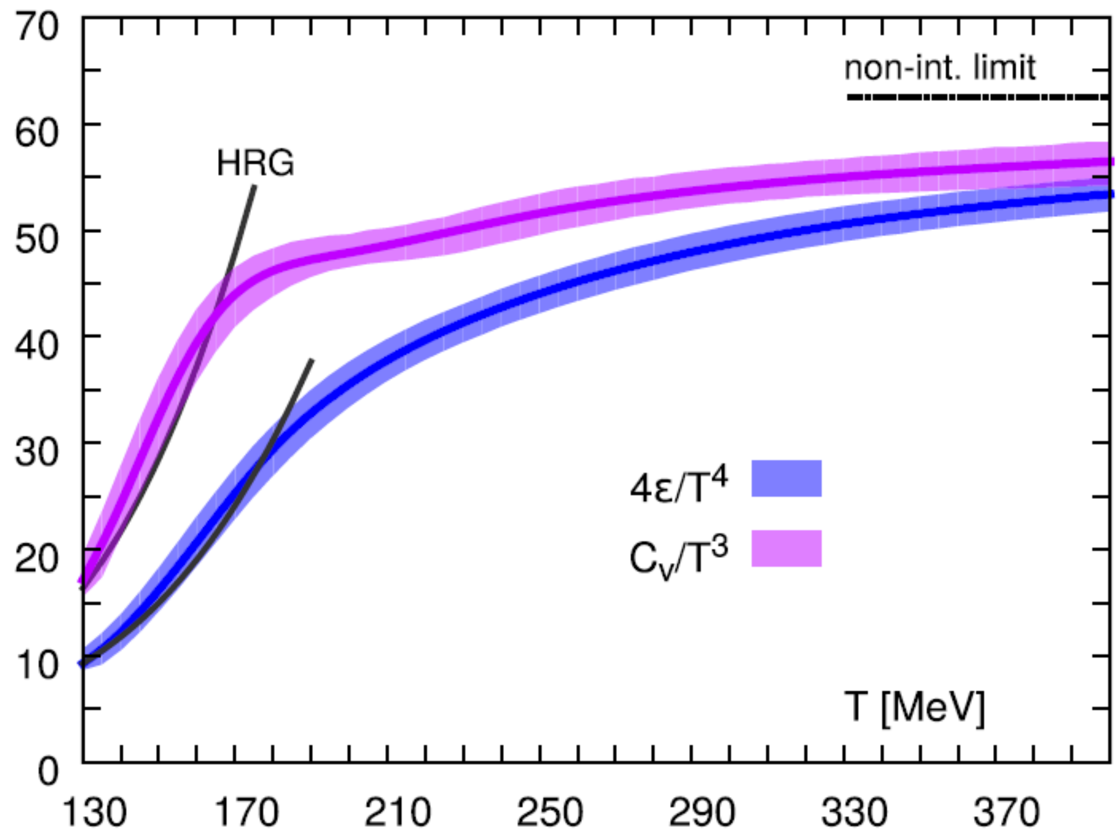
- in heavy-ion collisions at ultra-relativistic energies, a quasi macroscopic fireball of hot, strongly interacting matter in local thermal equilibrium is created

- lattice QCD predicts phase transition to deconfined, chirally symmetric matter

- energy density from the lattice: rapid increase around T_C, indicating increase of degrees of freedom (pion gas → quarks and gluons)

- T_C = 154 ± 9 MeV
  E_C = 340 ± 45 MeV/fm^3

HotQCD, PRD 90, 094503

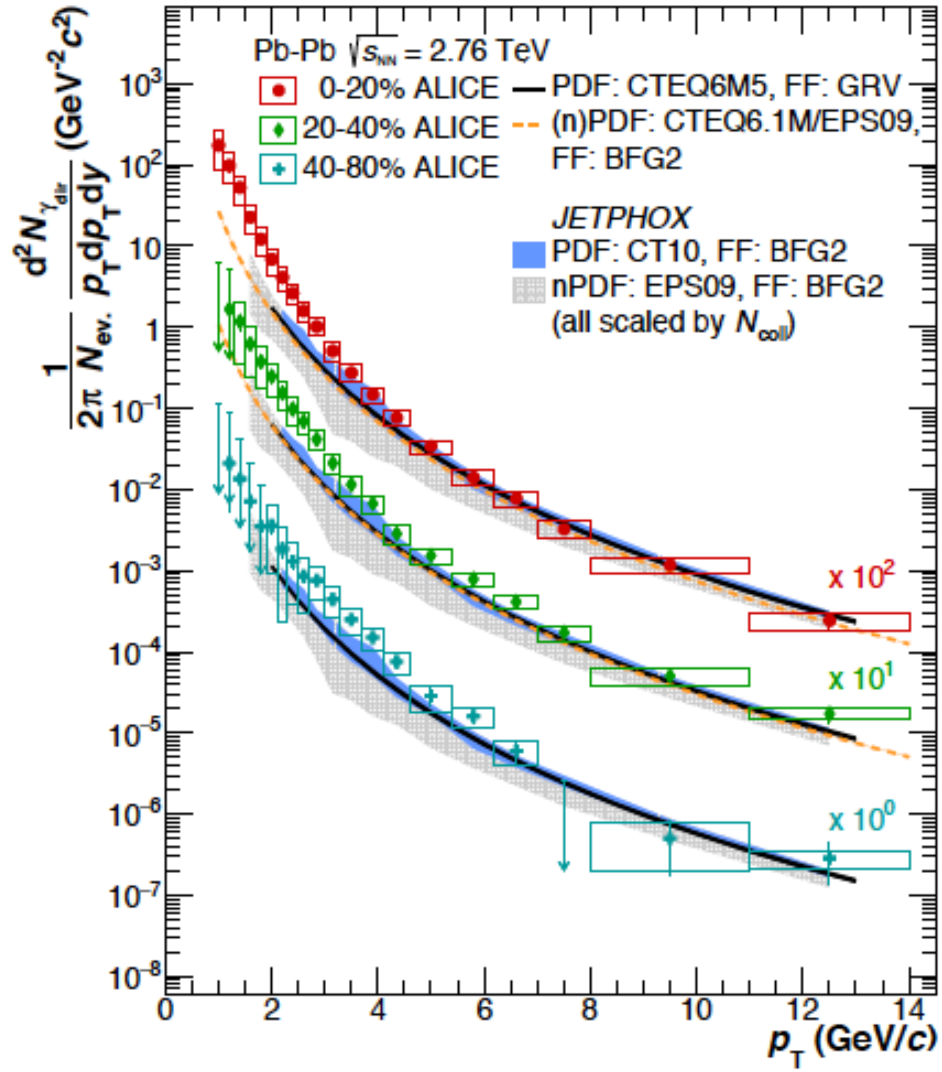


QCD matter at LHC

- direct photons:
  prompt photons from hard scattering
  + thermal radiation from QCD matter

- low-p_T inverse slope parameter:
  $T_{eff} = 297 \pm 12^{stat.} \pm 42^{syst.}$ MeV/c

- indicates initial temperature way above T_C



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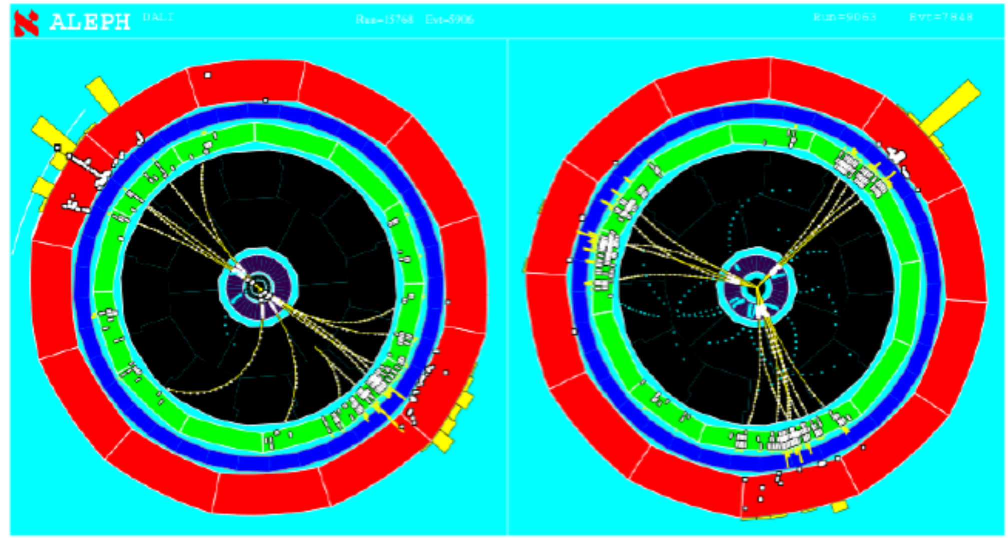
Partons in heavy-ion collisions

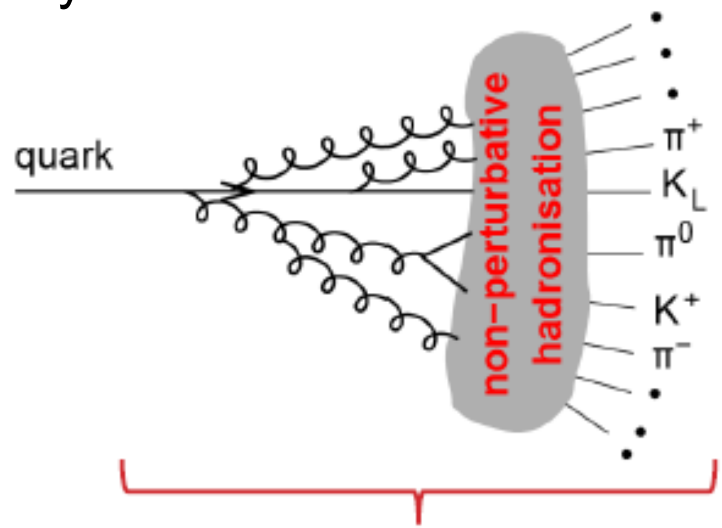
- hard partons are produced early and traverse the hot and dense QGP
- expect enhanced parton energy loss, (mostly) due to medium-induced gluon radiation: ‘jet quenching’



- 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 ...)



Hadrons in heavy-ion collisions

- high- p_T hadrons 'proxy' for jet
- jet quenching for charged hadrons, Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

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

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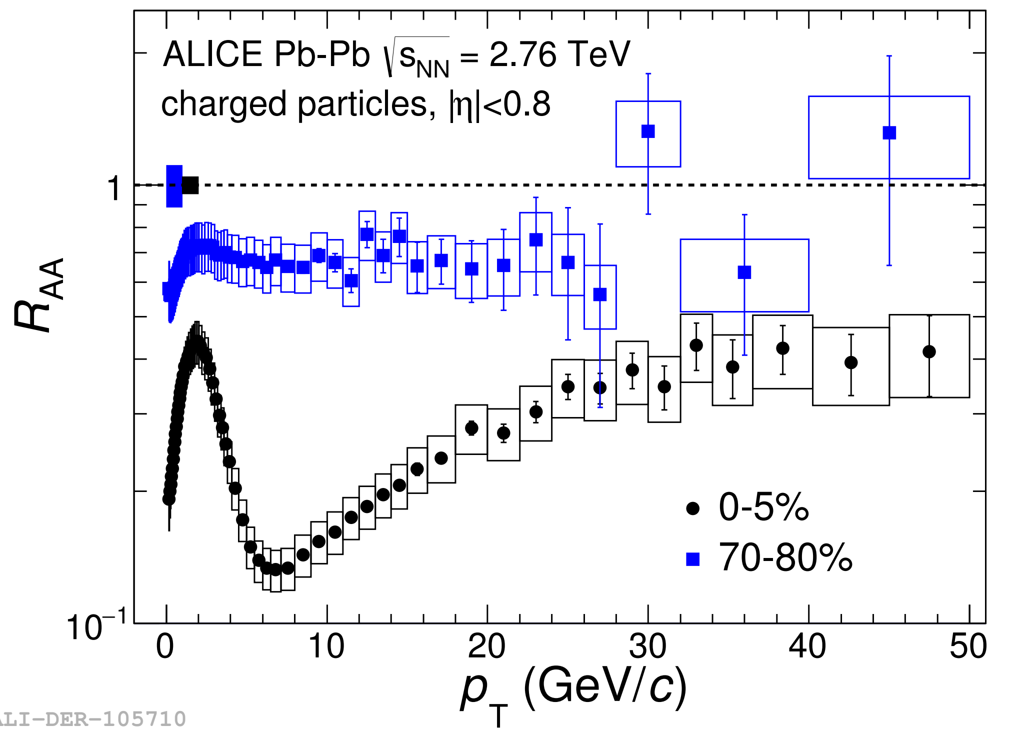
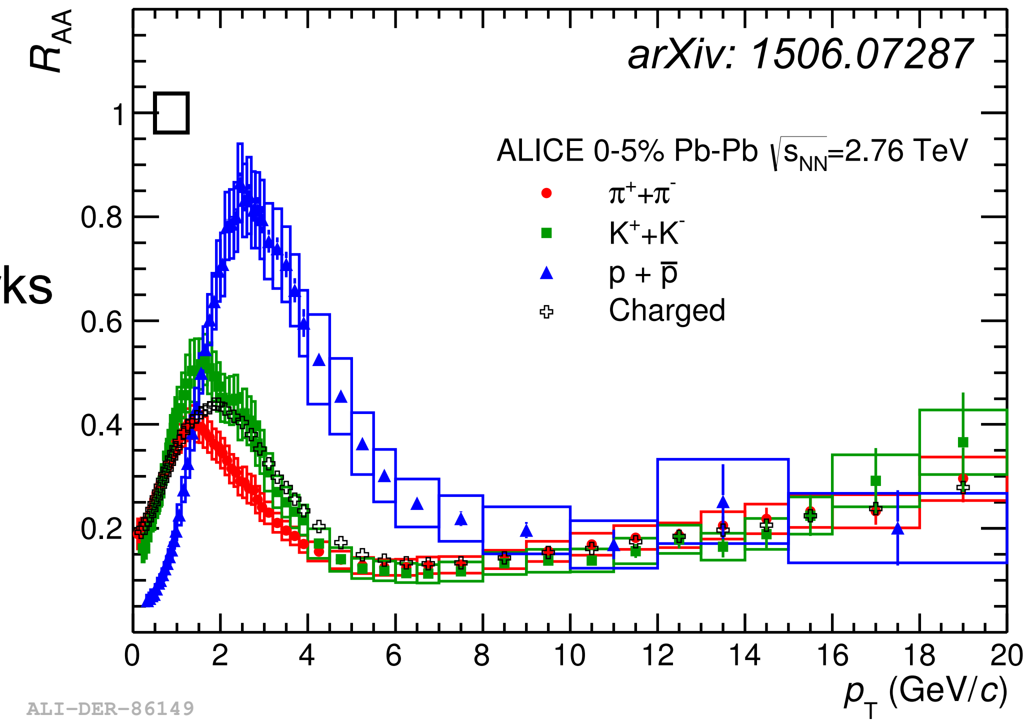


ALI-DER-105710

Identified hadrons in heavy-ion collisions

- baryons / meson R_{AA} a probe of gluon / quark energy loss?

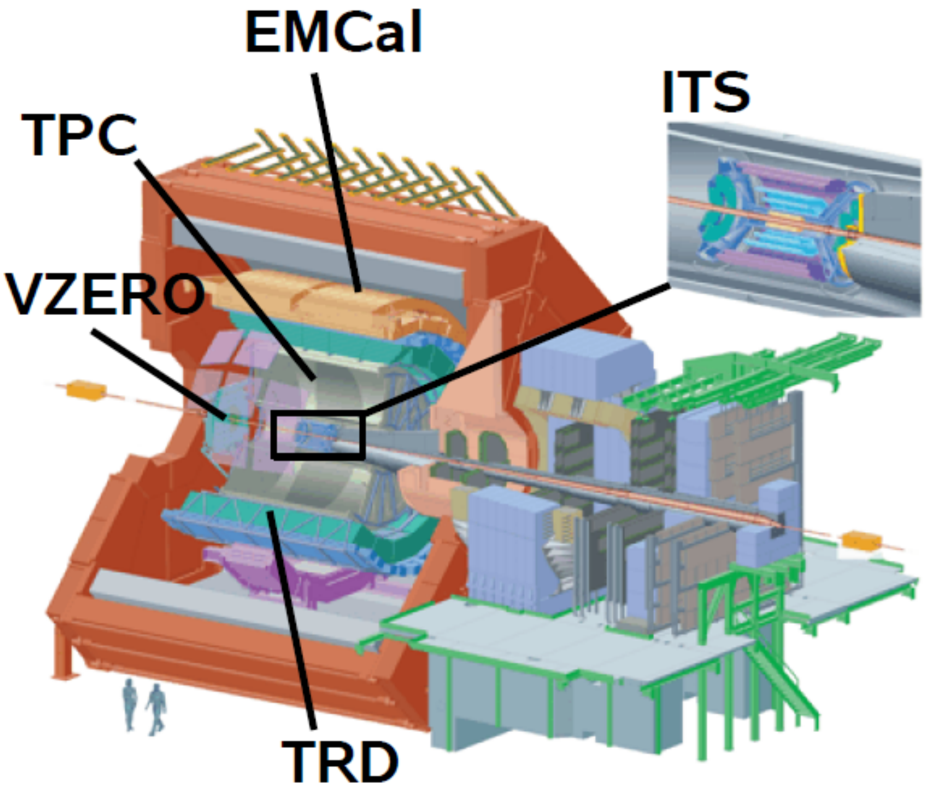
- would expect stronger radiative energy loss for gluons than for quarks
  - subtle cancellations?
  - hadron observable biased towards hard fragmentation?



- study jets to improve our understanding of parton energy loss:
  - PID in reconstructed jets mitigates fragmentation biases
  - enhanced sensitivity to medium effects measuring soft particles in jets

- note: medium effects likely strongest at scales of ~ medium Temperature
  (*J.G. Milhano, K. C. Zapp, hep-ph/1512.0819, T. Renk, Phys. Rev. C 81, 014906, B. Mueller, hep-ph/1010.4258*)

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

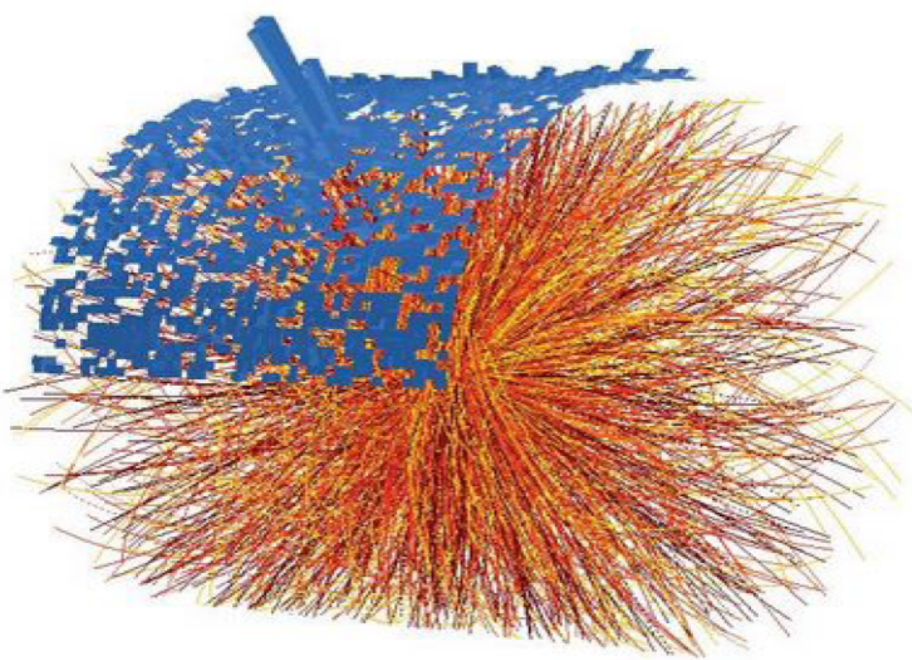
- charged (tracking) jets:
  - full azimuthal coverage
  - measures parton energy deposited into charged fragments
  - good definition of jet axis: well suited for fragmentation, jet structure, PID …

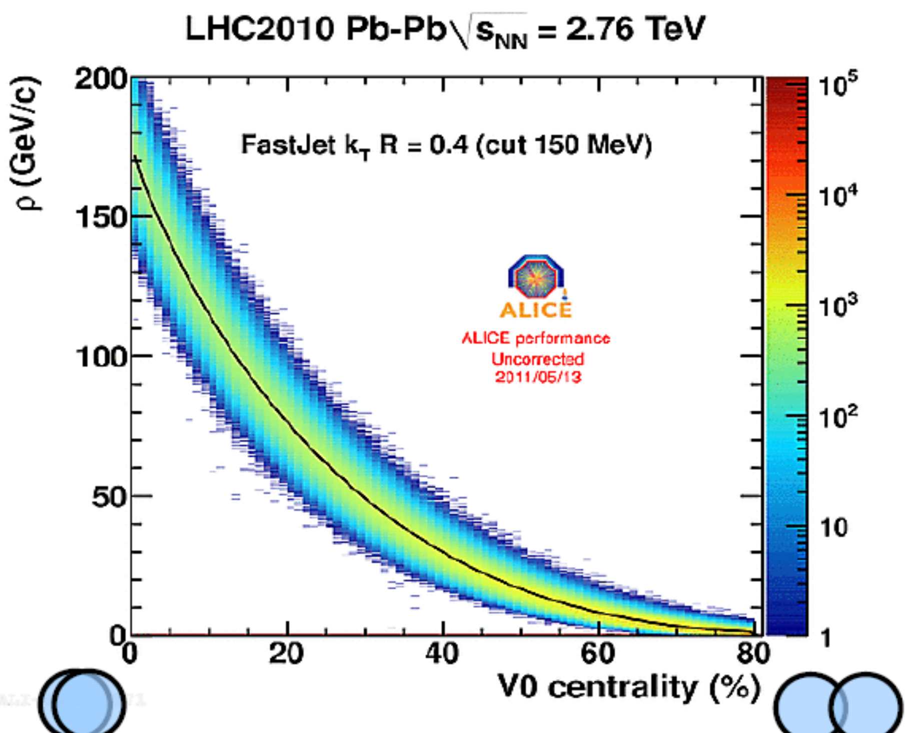
Underlying event in heavy-ion collisions

- 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*

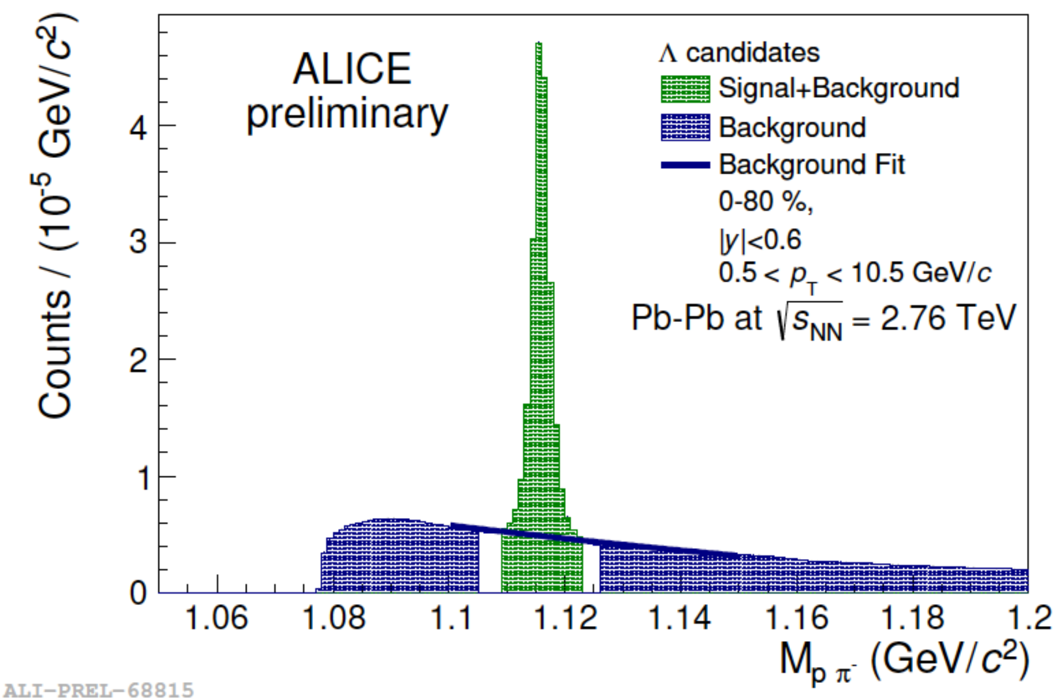
Strangeness Production in Jets

Strange hadron reconstruction

- neutral strange particles reconstructed via decay topology ('V^0'):

$$K^0_S \rightarrow \pi^+ + \pi^- \quad (69.2\%)$$
$$\Lambda \rightarrow p + \pi^- \quad (63.9\%)$$

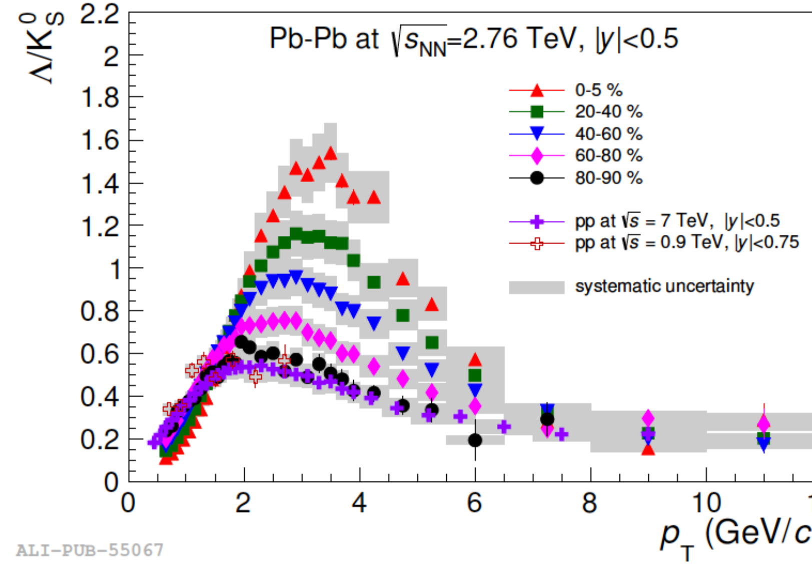
- signal extraction from invariant mass distributions



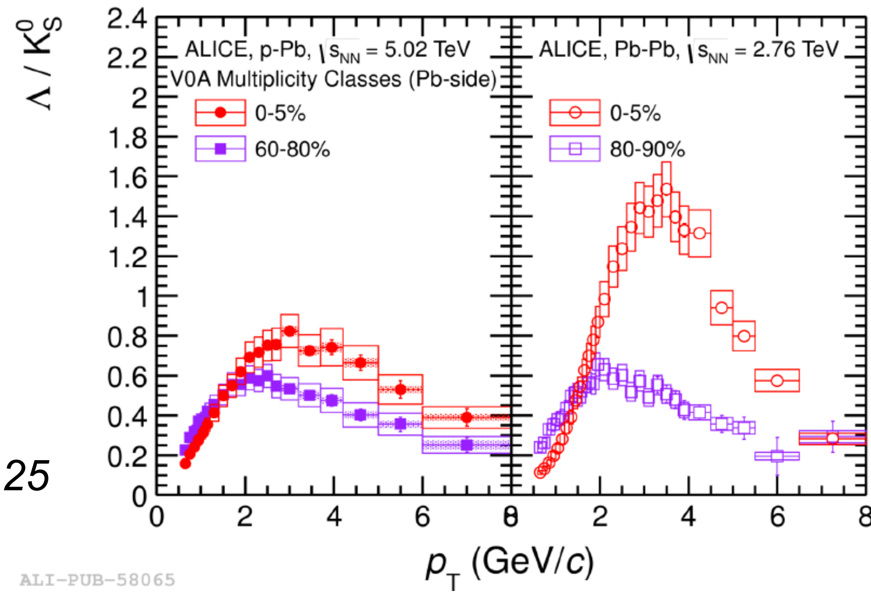
Strangeness production in nuclear collisions

- Baryon / Meson ratio enhanced in Pb-Pb and p-Pb collisions
  - collective effects ?
  - parton recombination ?
  - jet fragmentation ?

- measurement of identified particles in jets helps to constrain hadronisation and energy loss scenarios



Phys. Rev. Lett. 111 (2013) 223001



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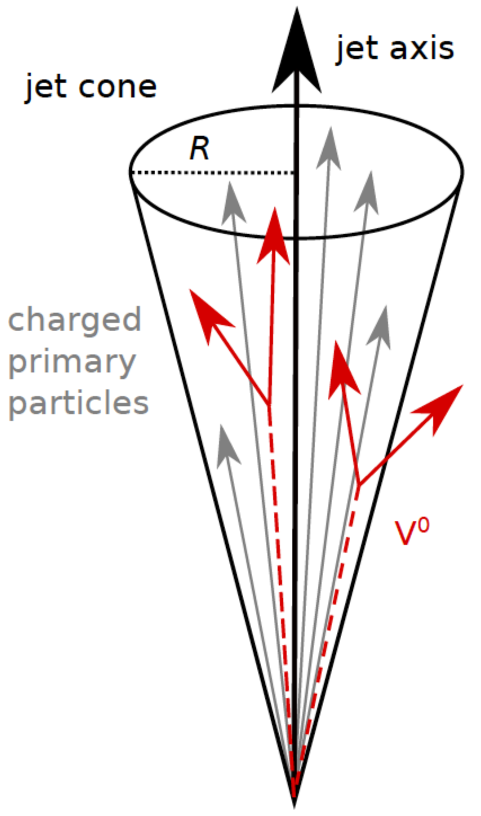
Strangeness in jets

- candidate - jet matching (V^0 in jet cone)

$$\sqrt{(\phi_{V^0} - \phi_{\text{jet,ch}})^2 + (\eta_{V^0} - \eta_{\text{jet,ch}})^2} < R$$

$$|\eta_{\text{jet,ch}}|^{\text{max}} < |\eta_{V^0}|^{\text{max}} - R$$

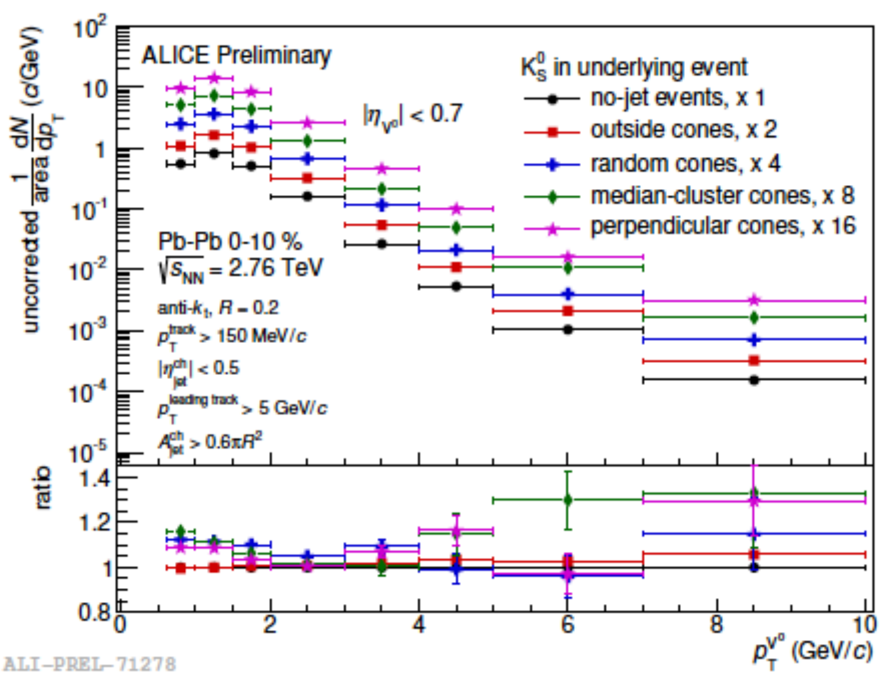
- jet R = 0.2, acceptance $|\eta^{V0}| < 0.7$
- candidate - bulk matching: underlying event V^0
- signal extraction from invariant mass distributions
- correct for efficiency and feed-down
- subtract underlying event from spectra



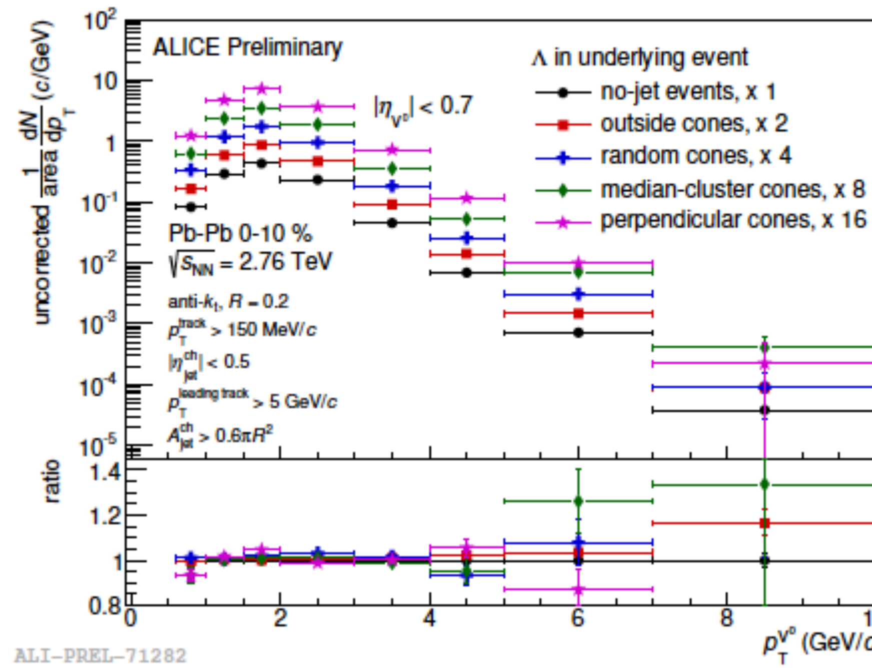
Underlying event subtraction

- subtract underlying event contribution to K^0_S, Λ spectra in jets
- various methods with different sensitivity to acceptance, event plane correlations, presence of additional jets, …
- differences used to estimate systematic uncertainty

K^0_S

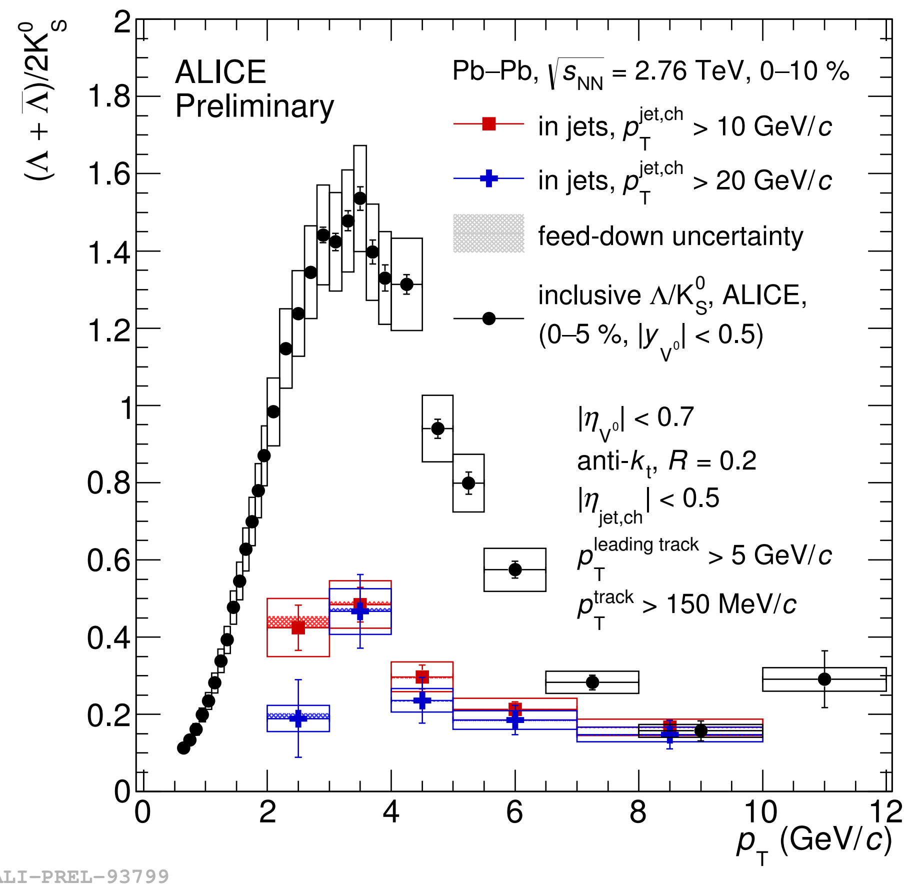


Λ



$(\Lambda+\bar{\Lambda})/2K^0_s$ ratio in jets

- Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
- jet R = 0.2
- p_T^{jet} > 10 GeV/c (20 GeV/c)
- leading constituent bias
  $p_T^{leading}$ > 5 GeV/c
  to reject 'fake' jets
- no significant jet p_T^{jet} dependence
- ratio in jets significantly lower
  than for inclusive case

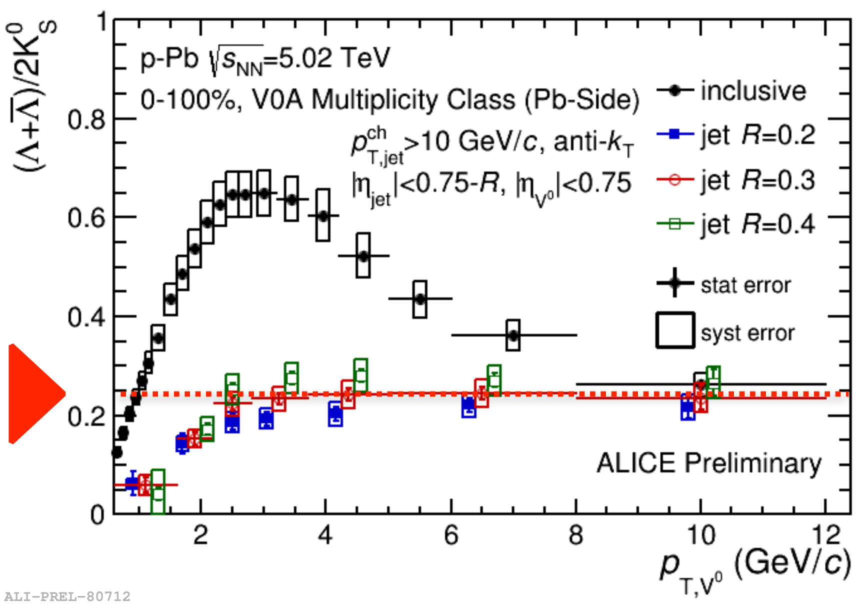


Comparison to p-Pb

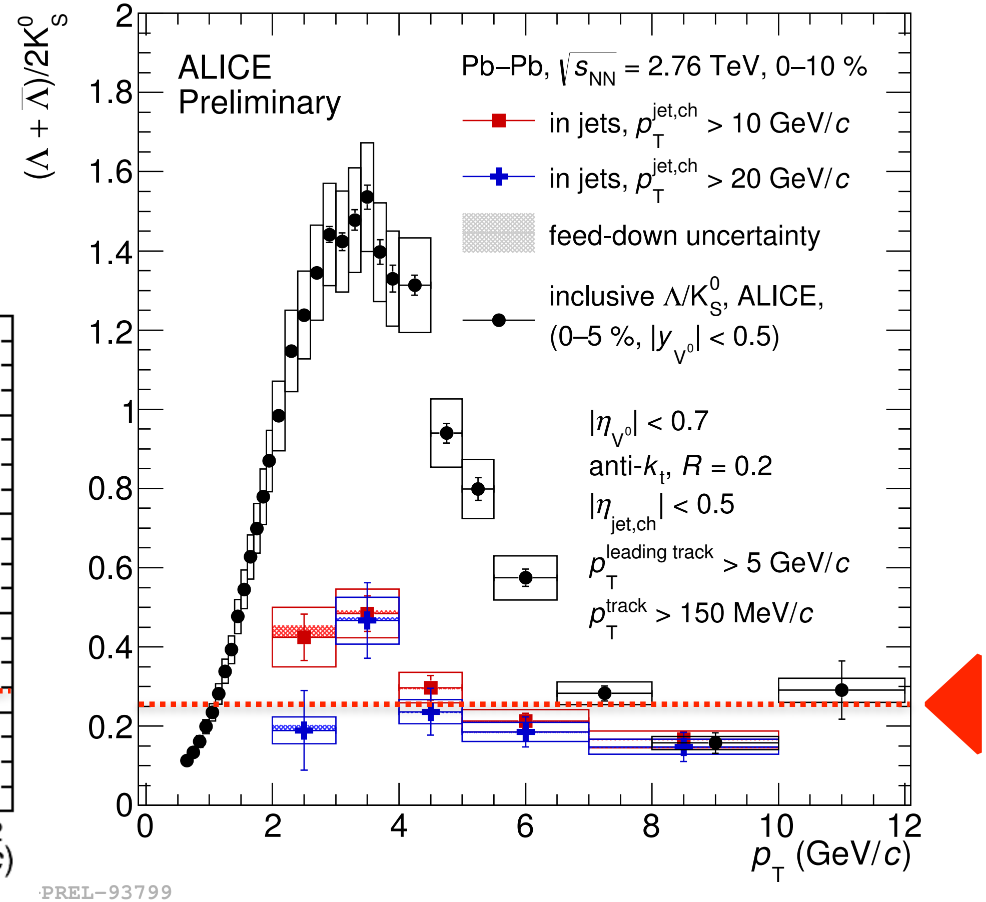
- compare Pb-Pb results to reference from p-Pb collisions at 5.02 TeV: agreement within uncertainties

- ongoing efforts to improve systematics for lowest K^0_S, Λ p_T

p-Pb



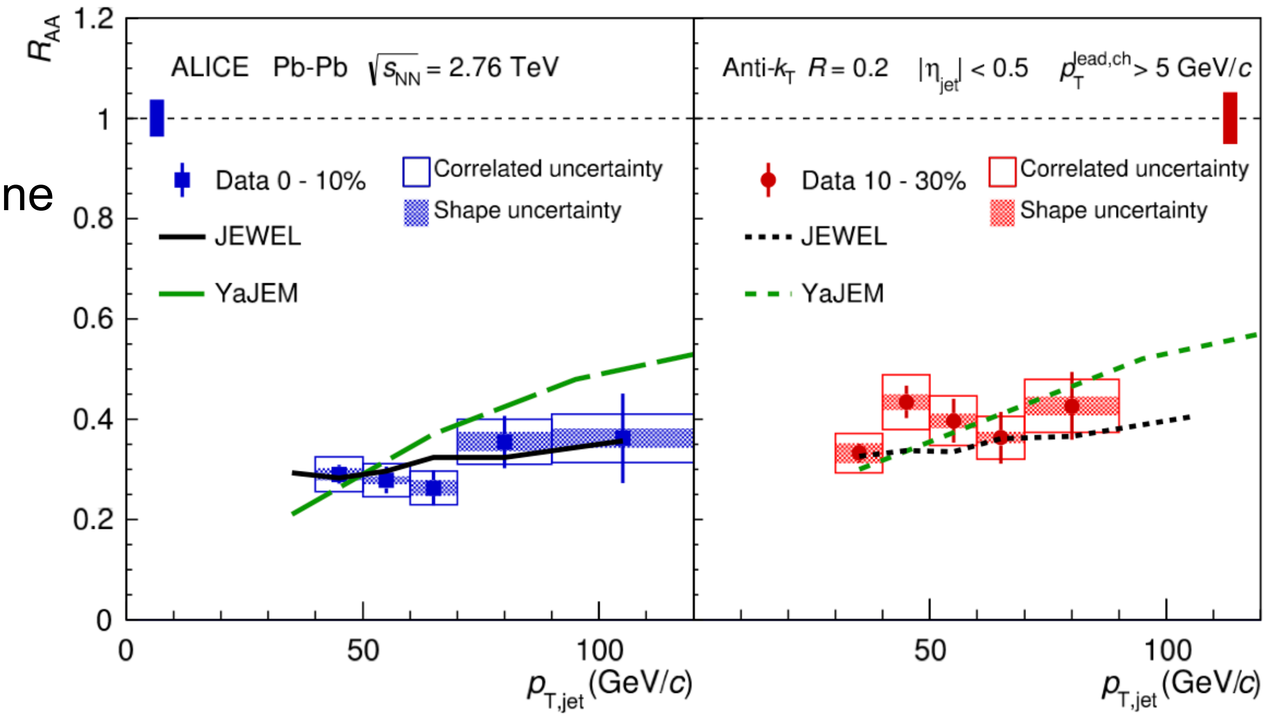
Pb-Pb



Jet Shapes

Jet nuclear modification factor

- 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



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JEWEL: PLB 735 (2014)

YaJEM:PRC 88 (2013) 014905

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

Jet shapes

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

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

- shapes in pp collisions at 7 TeV:
  - constrain QCD calculations of small-R jets
    ('microjets': M. Dasgupta, F. Dreyer, G. Salam, G. Soyez)

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

  - validate MC simulations

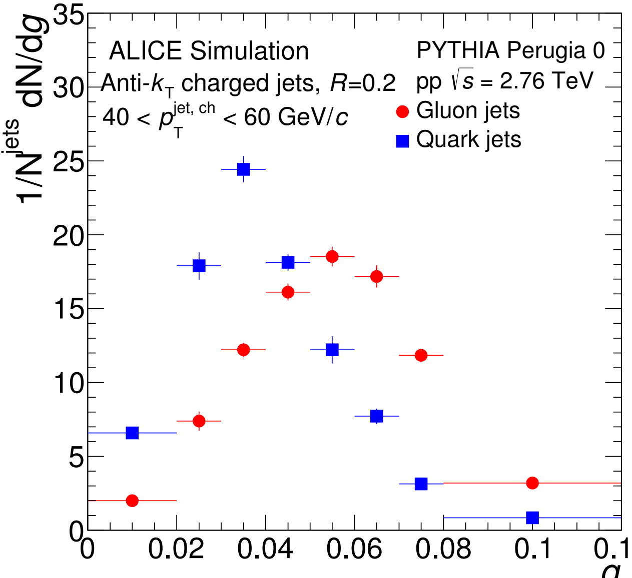
$$\mathrm{LeSub} = p_T^{lead,track} - p_T^{sublead,track}$$

- shapes in Pb-Pb as IRC safe 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

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



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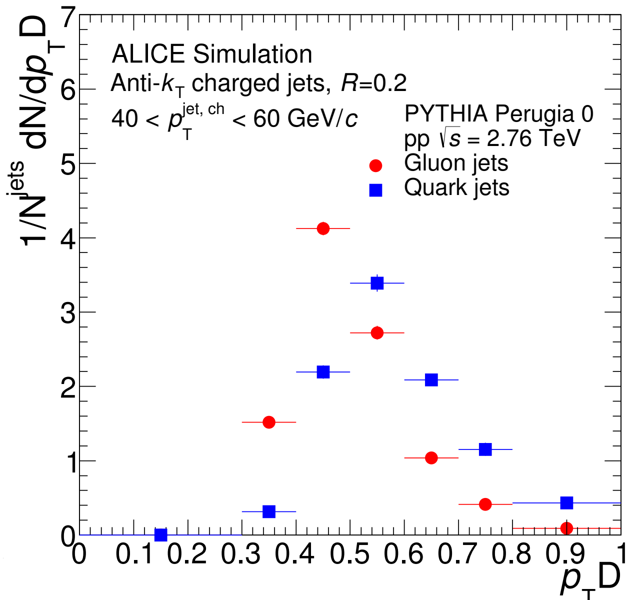

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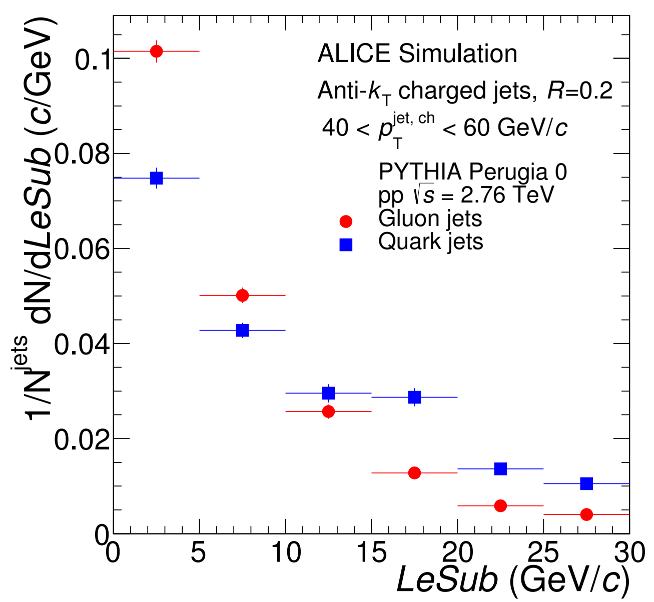


ALI-SIMUL-101551

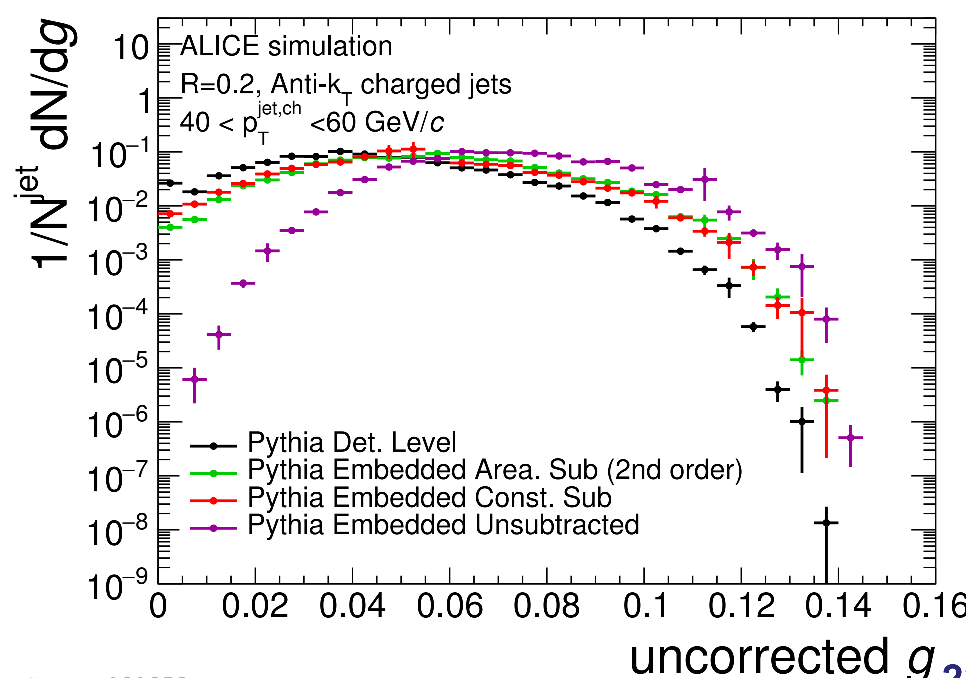
Analysis details

- 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*)

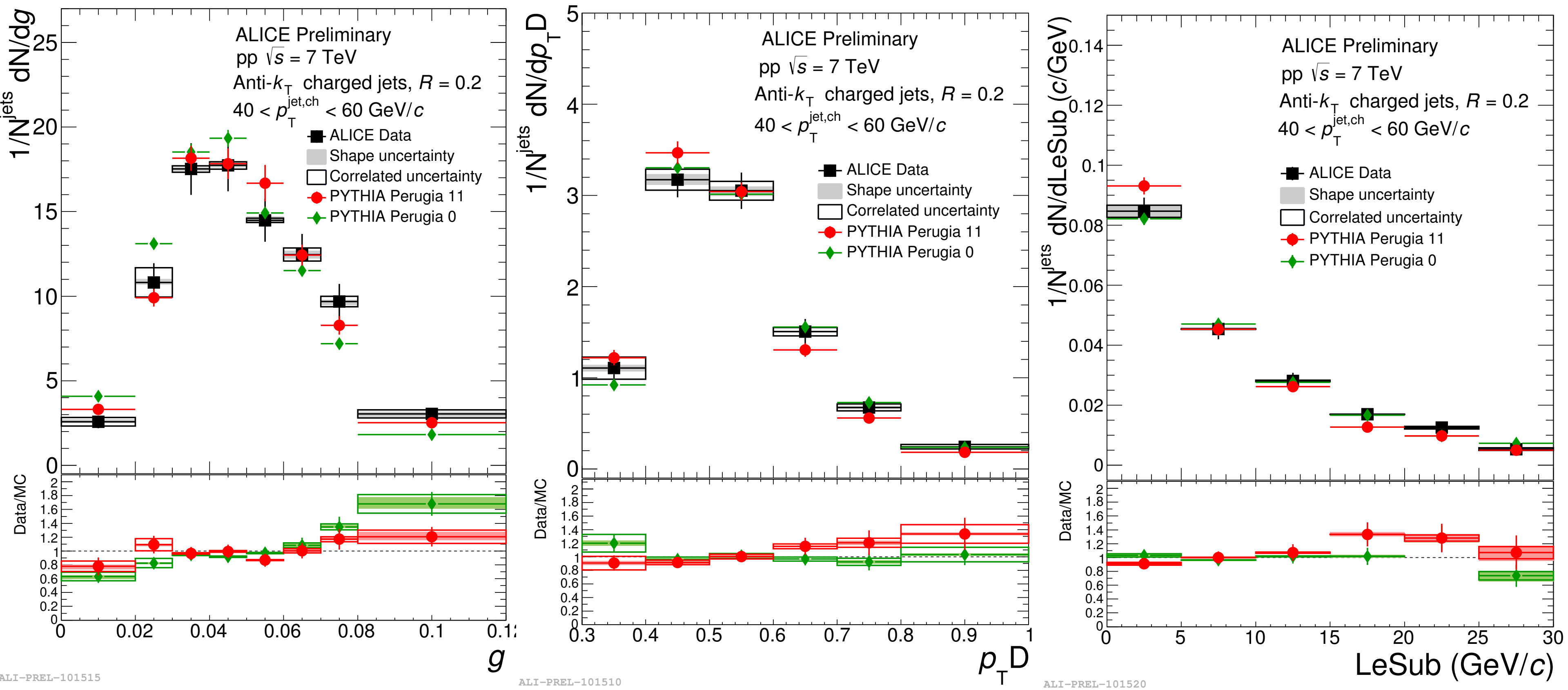
- 2D unfolding to correct for background fluctuations and detector effects



ALI-SIMUL-101958

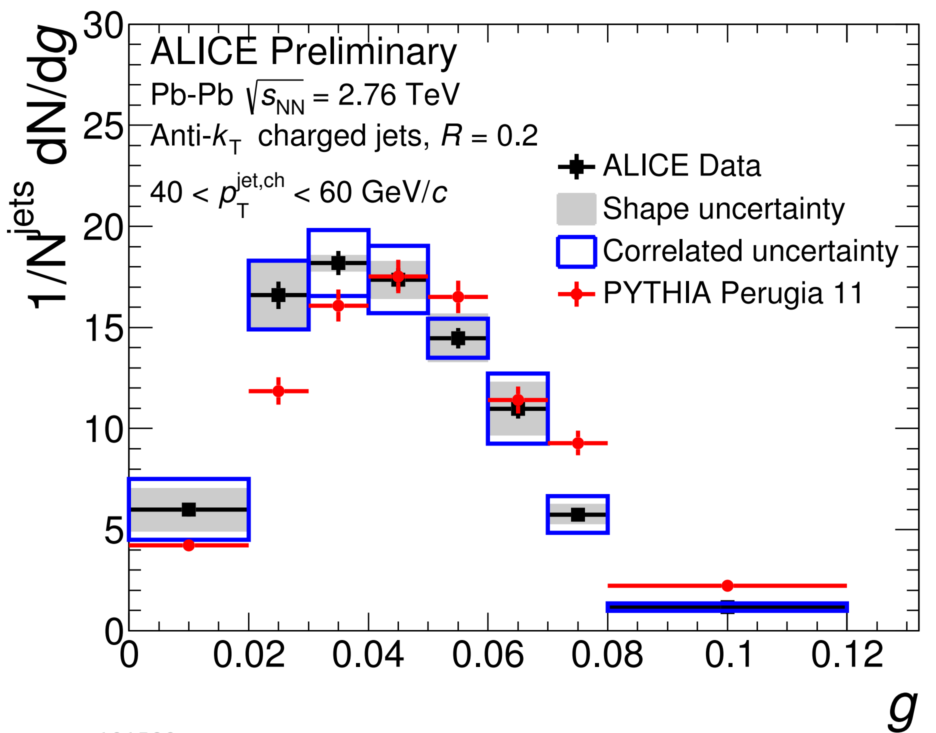
Jet shapes in pp

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



Jet shapes in Pb-Pb

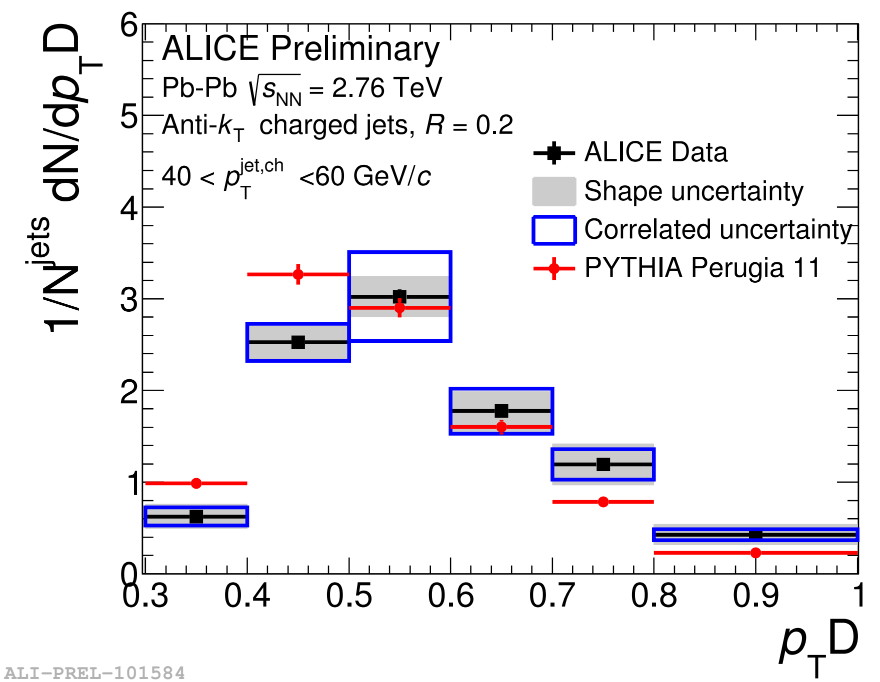
- fully corrected to charged particle level
- g shifted to smaller values compared to PYTHIA reference
  → indicates more collimated jet core

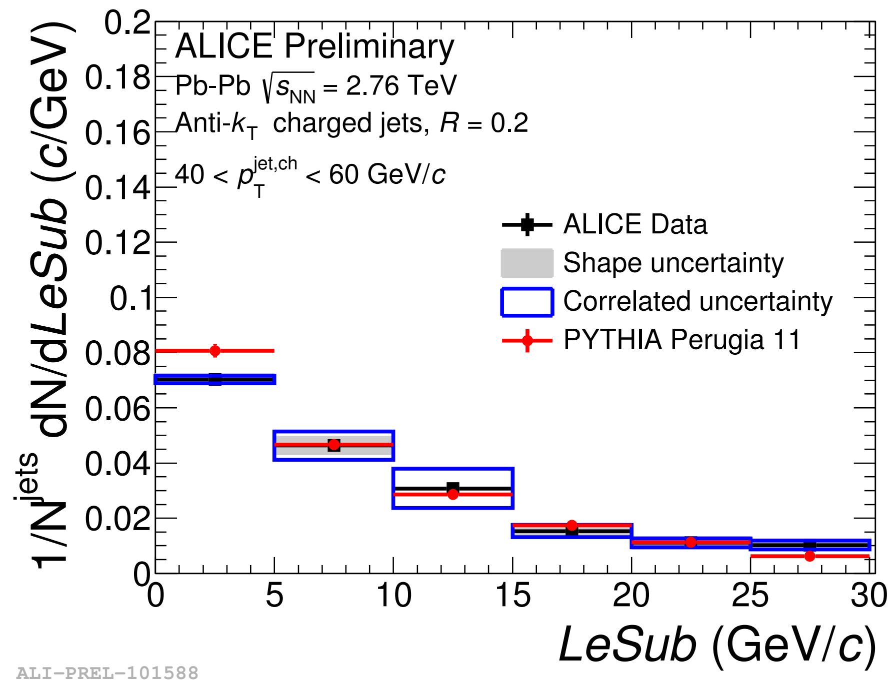


ALI-PREL-101580

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

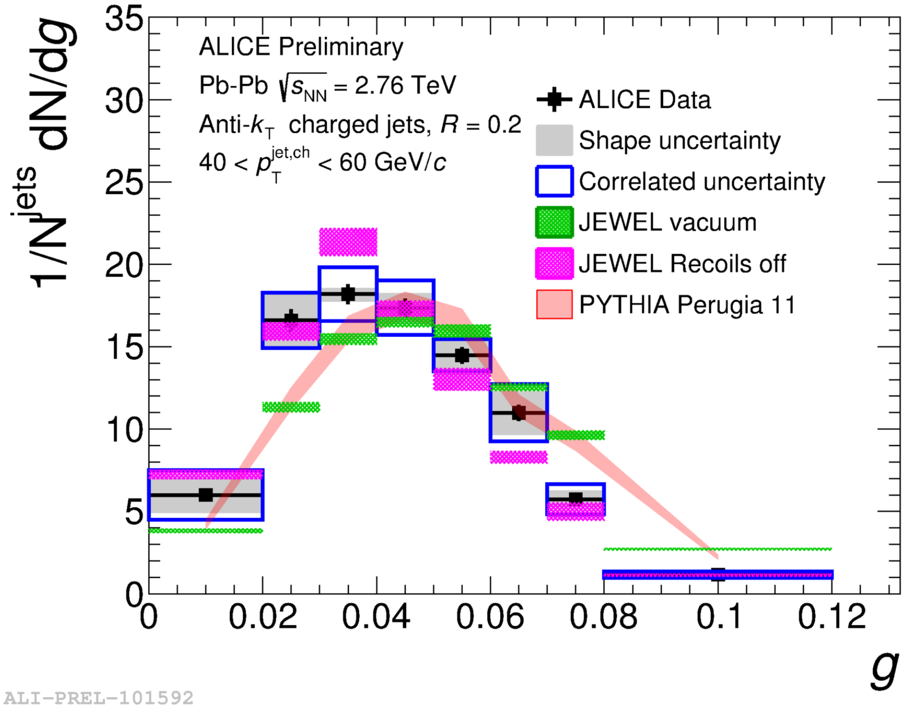
- LeSub in Pb-Pb in good agreement with Pb-Pb:
  → hardest splittings likely unaffected

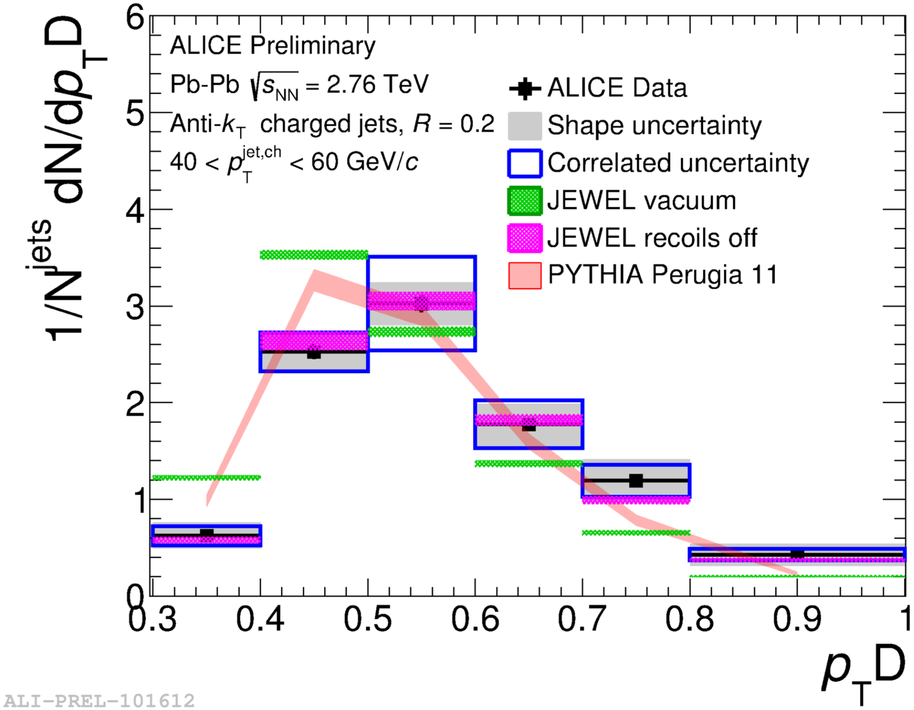




Jet structure: model comparison

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

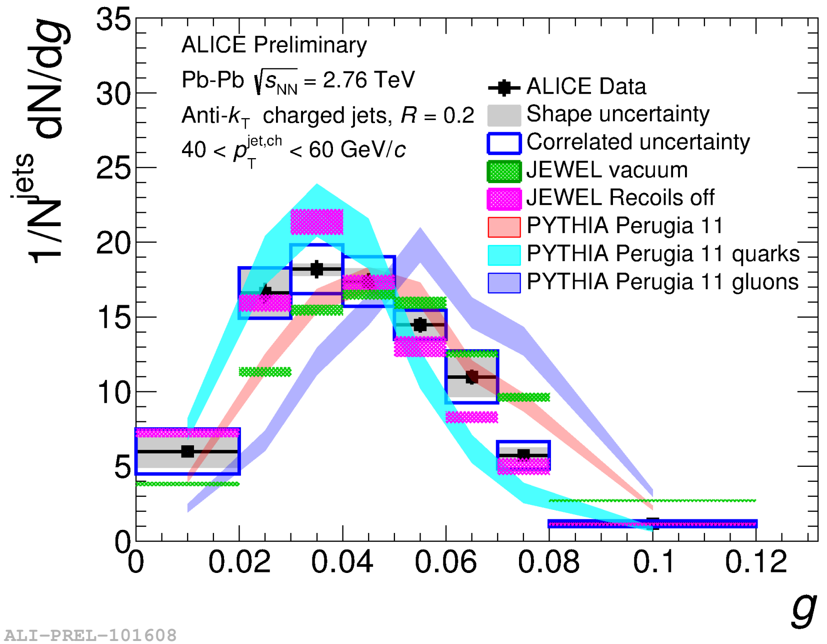


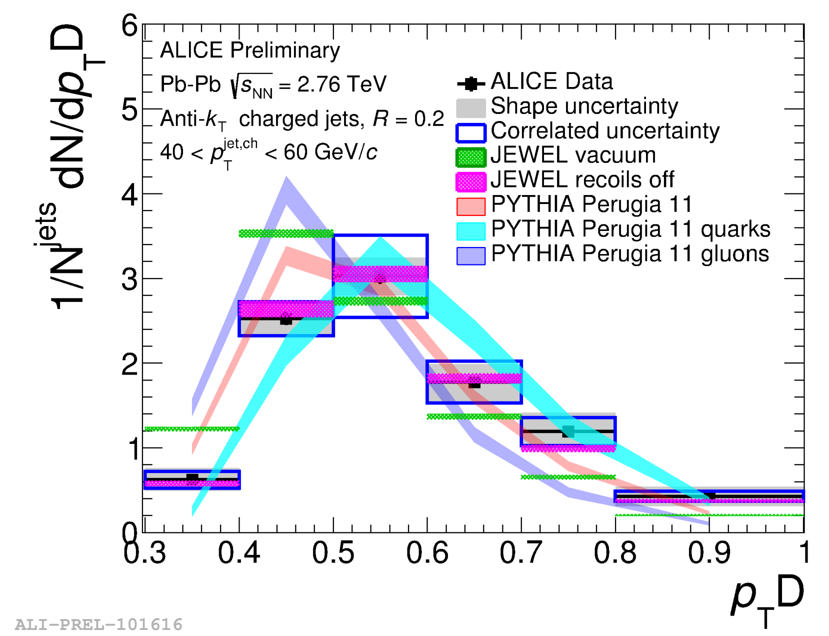


JEWEL: K.C. Zapp, F. Kraus, U.A. Wiedemann, JHEP 1303 (2013) 080

Qualitiative discussion

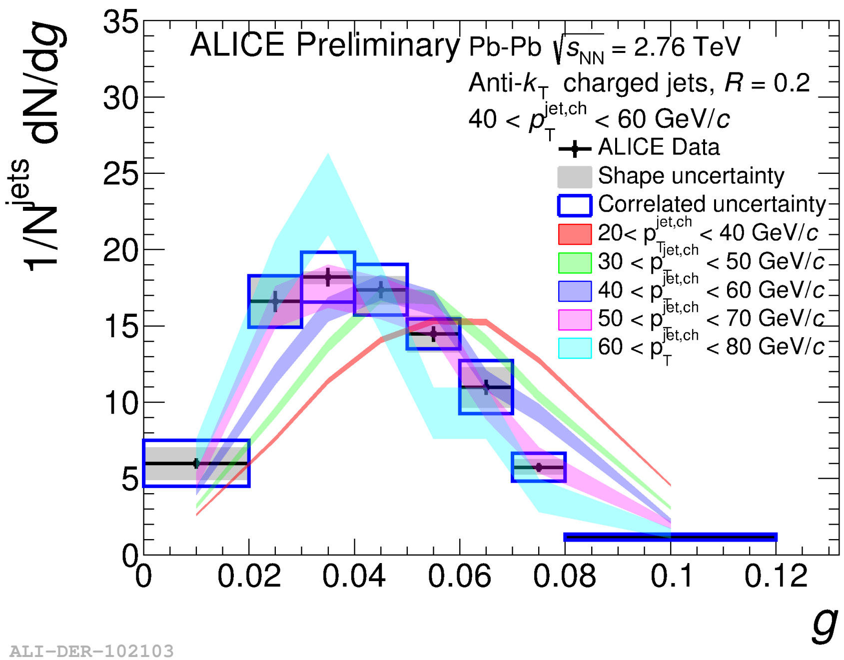
- characterise degree of dispersion and broadening in terms of ‘quark-like’ and ‘gluon-like’
- observed effects favour ‘quark-like’ scenario
- quenching mechanism or change of quark/gluon composition caveat: jet p_T not equal parton p_T

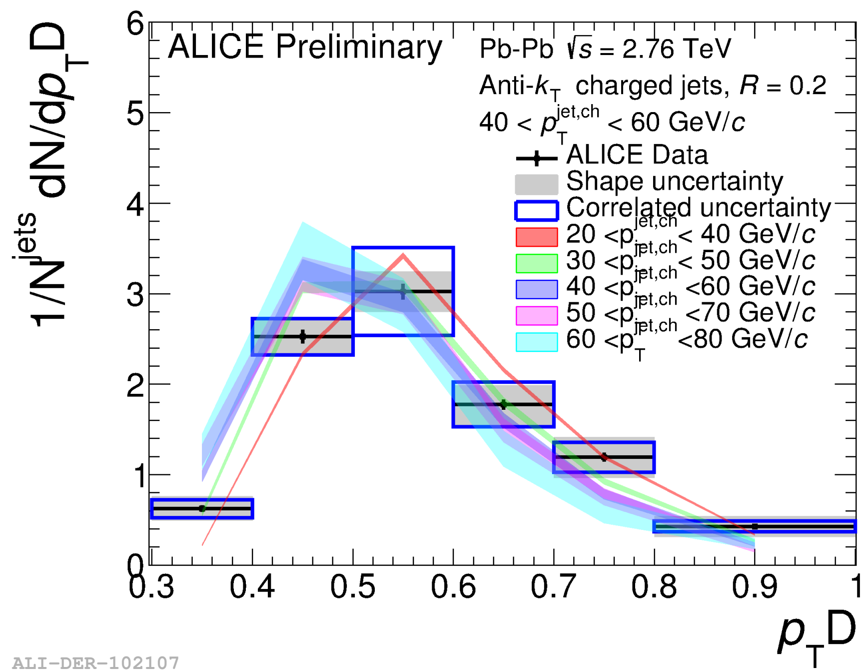




Qualitiative discussion II

- 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





Summary

- strangeness production in jets in Pb-Pb collisions

  - significant difference between the Λ/K^0_S ratio of inclusive particles and the ratio in charged jets

- 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

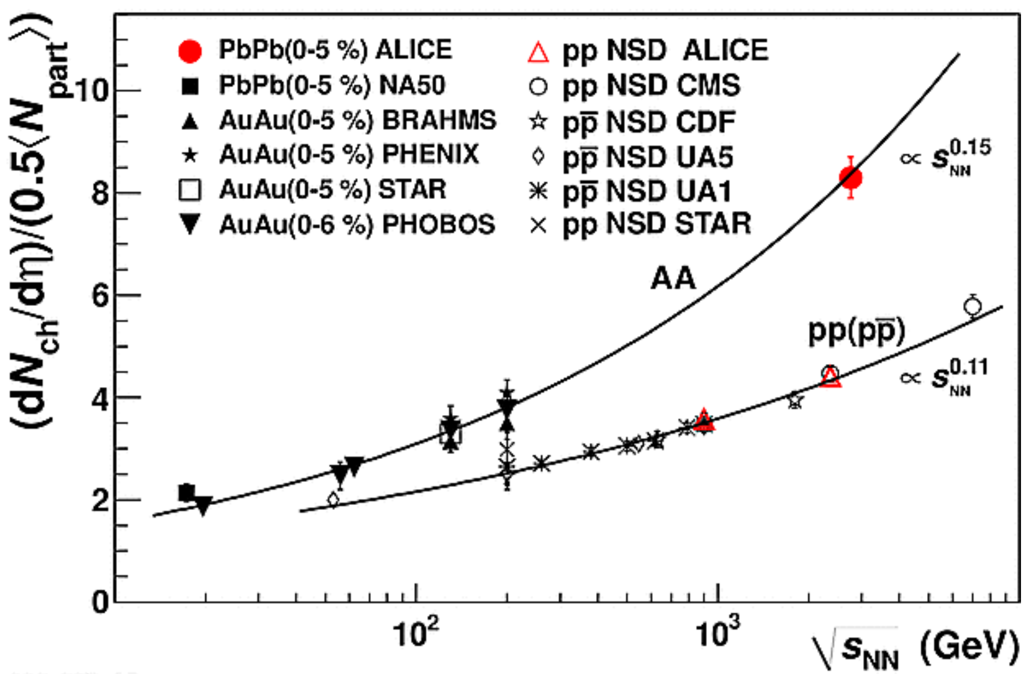
  - results in qualitative agreement with quark-like fragmentation and described by quenching models like JEWEL

- Backup -

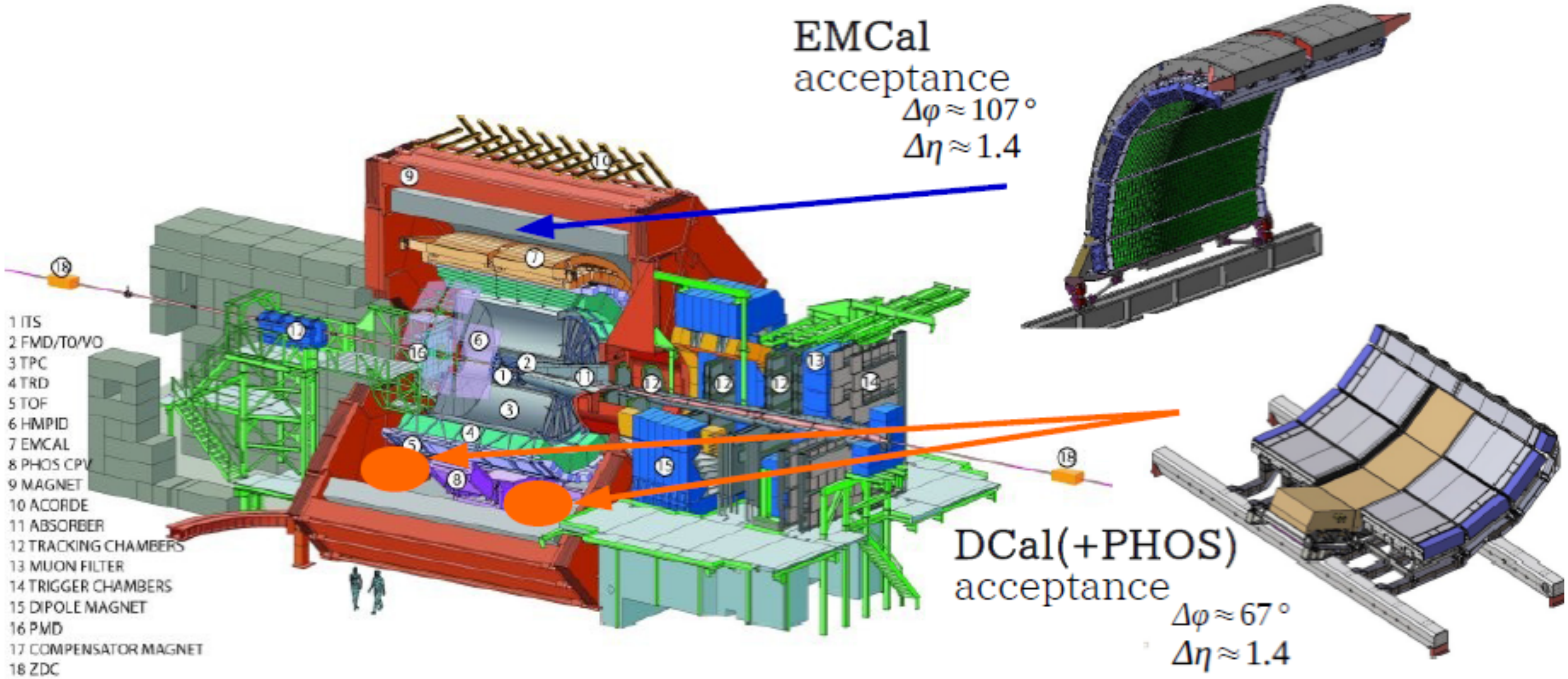
LHC run 2

- LHC run 2: 2015 - 2017, heavy-ion run November 2015
- increased CMS energy for Pb-Pb collisions from 2.76 → 5.1 TeV
- quenching strength $\hat{q} \sim s \sim \varepsilon^{3/4}$
- expect (modest) increase in ε, T
  → measure energy density
  dependence of jet quenching
- note: also a dependence on
  parton 'input spectrum'
  (increased R_{AA} ???)

ALICE, PRL 105, 252301



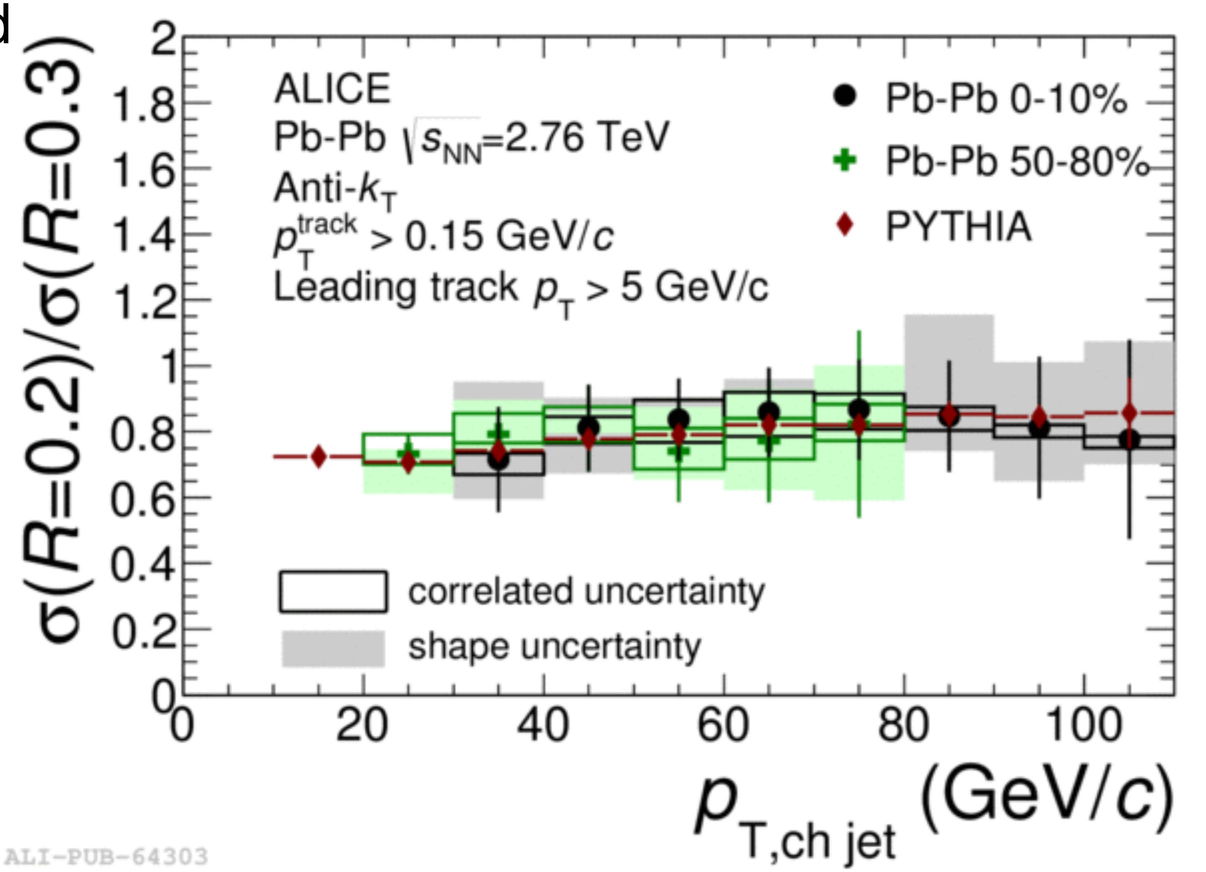
ALICE in run 2: DCal



- run 2: DCal upgrade
  - significantly extended jet acceptance
  - back-to-back in azimuth (di-jet topology)

Jet structure

- 'jet structure ratio' R=0.2 / R=0.3 for charged jets
- sensitive to potential broadening of jet shape
- consistent with PYTHIA pp:
  no modification observed
  within small radii
  (jet core)



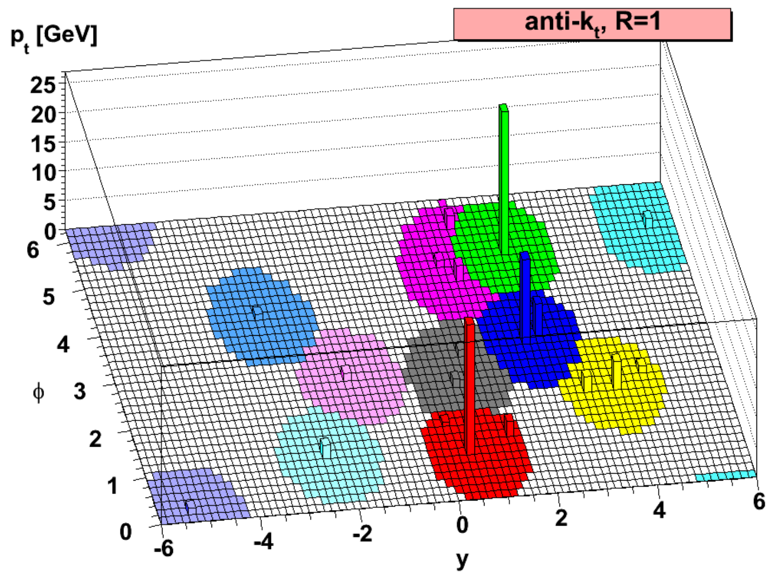
JHEP 03 (2014) 013

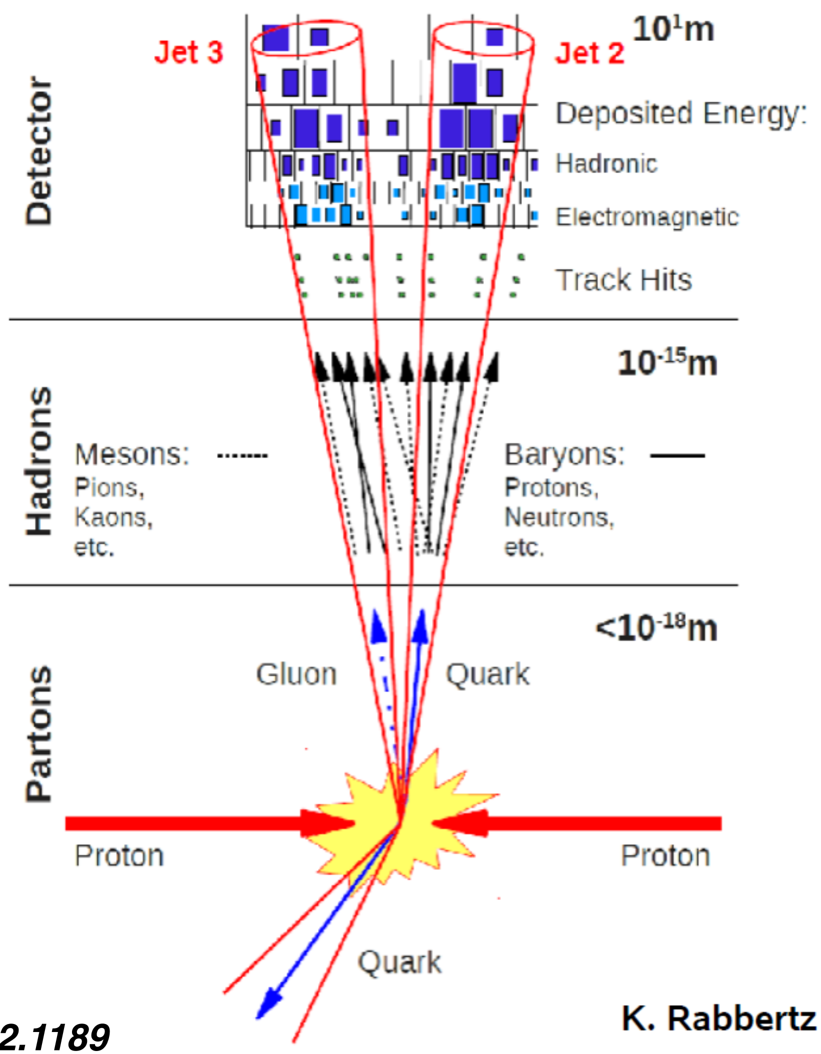
Jet reconstruction

- Establish correspondence between detector measurements / final state particles / partons

- two types of jet finder:
  - iterative cone
  - sequential recombination (e.g. anti-k_T)

- resolution parameter R



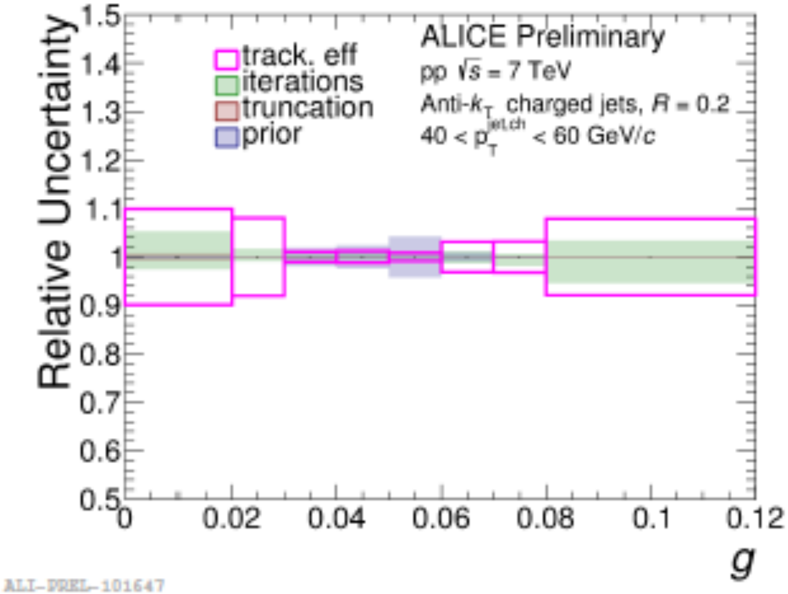


hep-ph/0802.1189

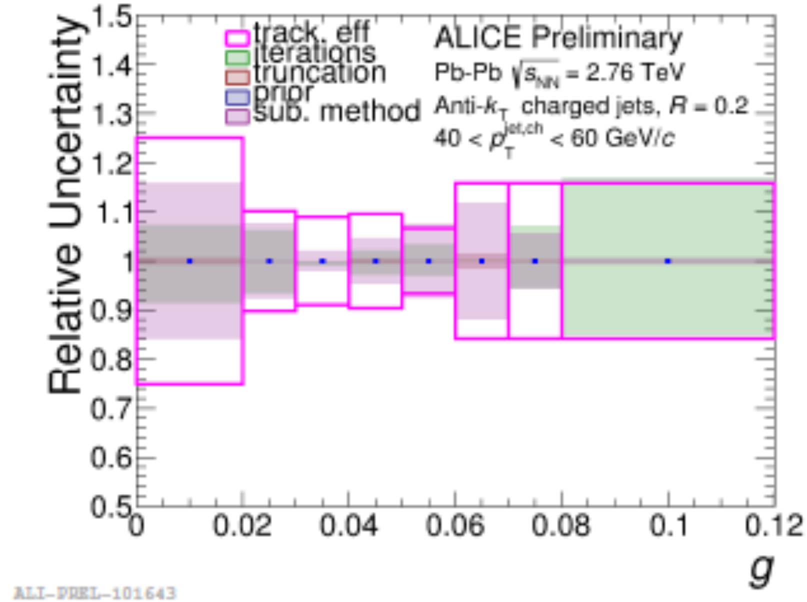
K. Rabbertz

Uncertainties in the measurement

pp



Pb-Pb



Uncertainties:

-Tracking efficiency uncertainty of ±4% dominates the Jet Energy Scale uncertainty

-Unfolding:

Regularization variations of ±3 iterations

Truncation of the measured yield at a 10 GeV lower value (10 and 20 GeV/c in pp and Pb-Pb resp.)

Prior: intrinsic correlation between $p_T^{jet,part}$ and shape^{part} with which response is built.

Default is PYTHIA Perugia 0, variation is a smearing of such correlation by 20%

-Additional ingredient in Pb-Pb: background subtraction method variation