Exploring the QGP with Jets at ALICE

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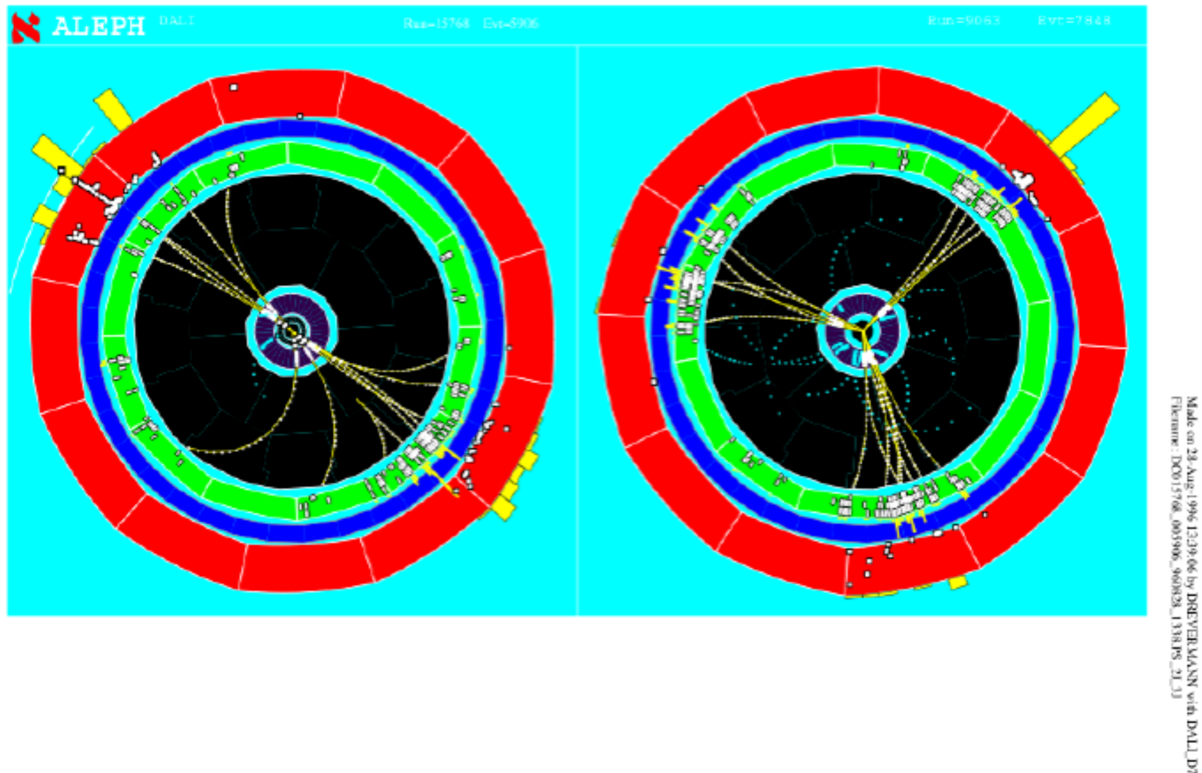
for the ALICE collaboration

Outline

- introduction
- results from pp collisions
- jets in heavy-ion collisions
- results from Pb-Pb collisions
- outlook: LHC run 2

Introduction

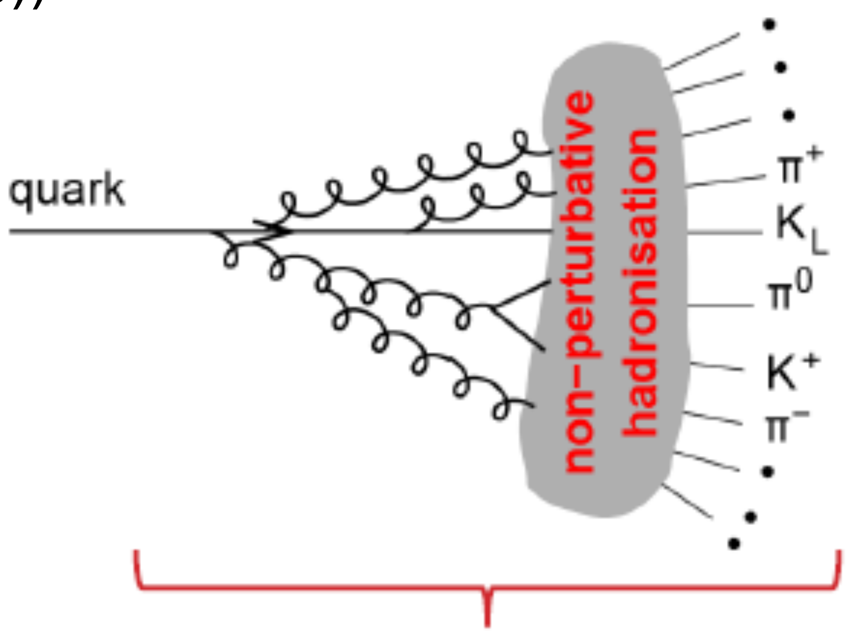
Jets: seeing quarks and gluons



- jet: collimated bunch of hadrons
- quasi-free parton scattering at high Q^2:
  the best available experimental equivalent to quarks and gluons

Jet fragmentation

- initial hard scattering: high-p_T partons
- cascade of gluons: parton shower
- at soft scale ($o(\Lambda_{QCD})$): hadronization

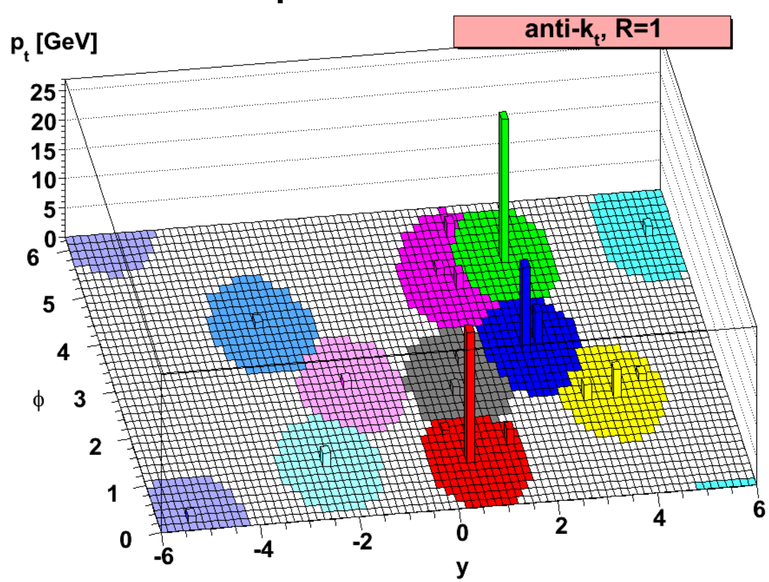


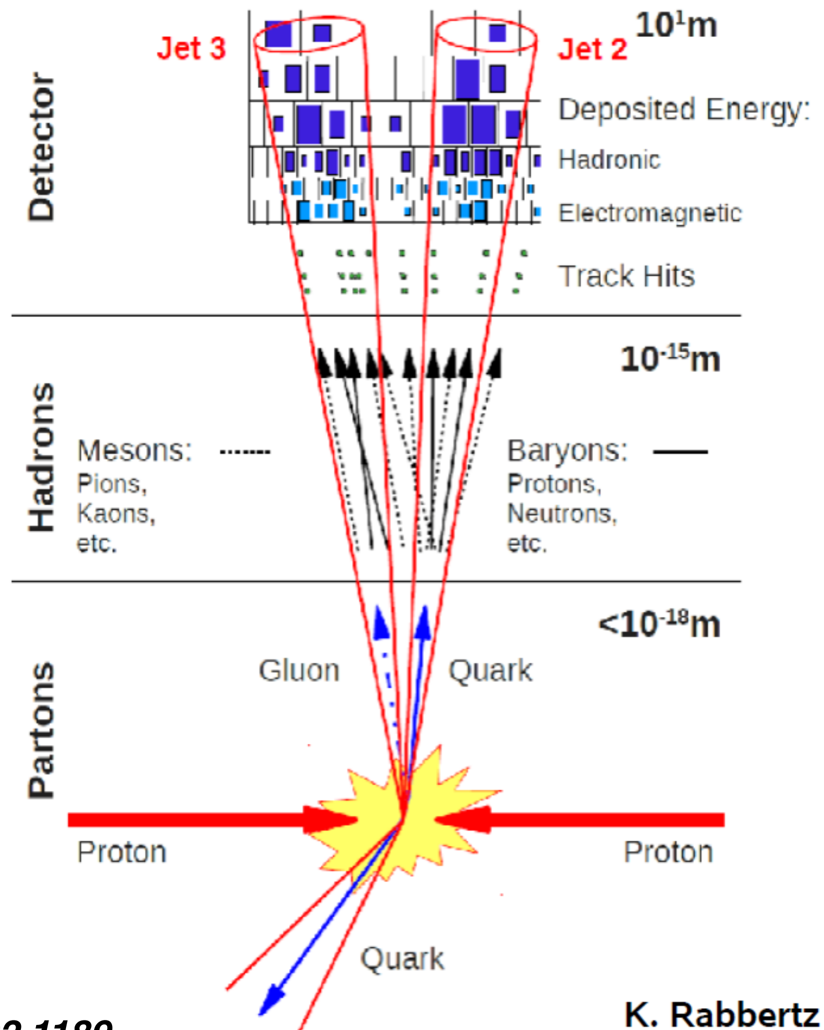
Jet reconstruction

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

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

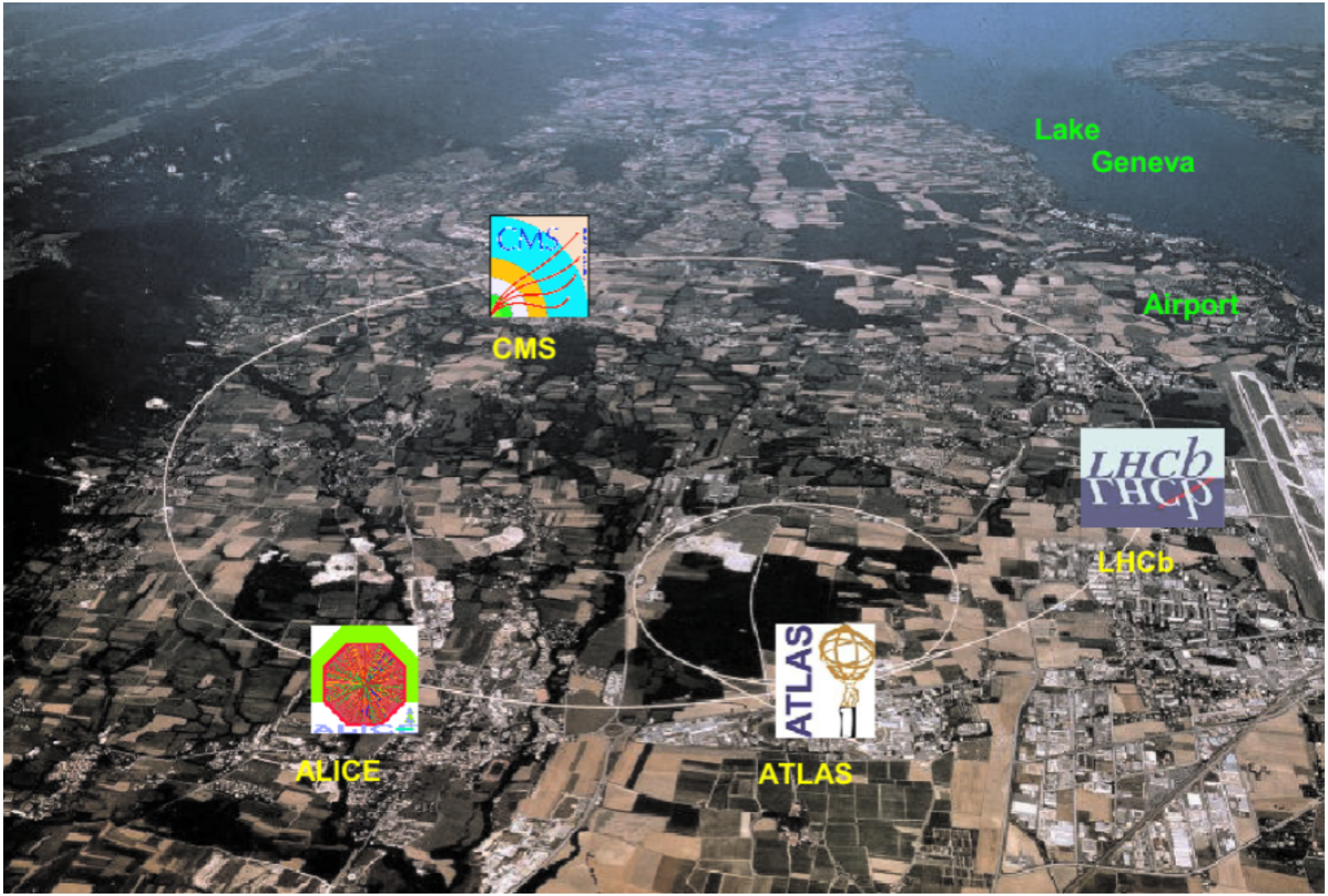
- resolution parameter R



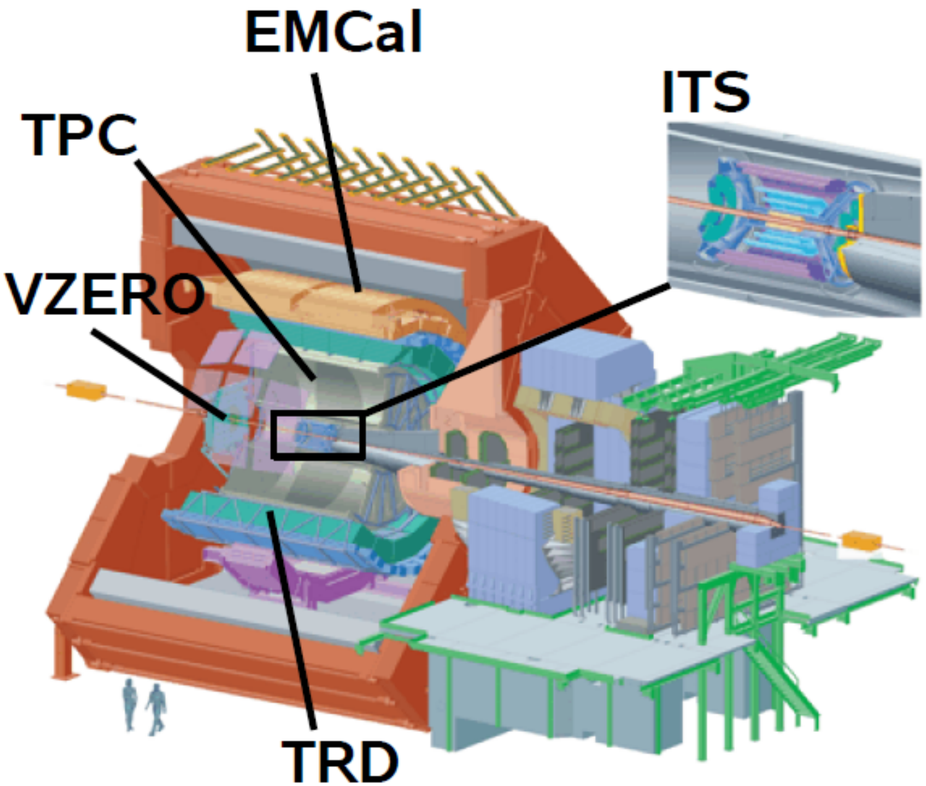


hep-ph/0802.1189

LHC aerial view



Jets at ALICE (LHC run 1)



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

- EMCal :
  - neutral particles
  - Δφ = 107°, |η|<0.7
    cluster ET > 300 MeV

- jet trigger with EMCal and TRD

- \`charged' (tracking) jets and \`full' jets

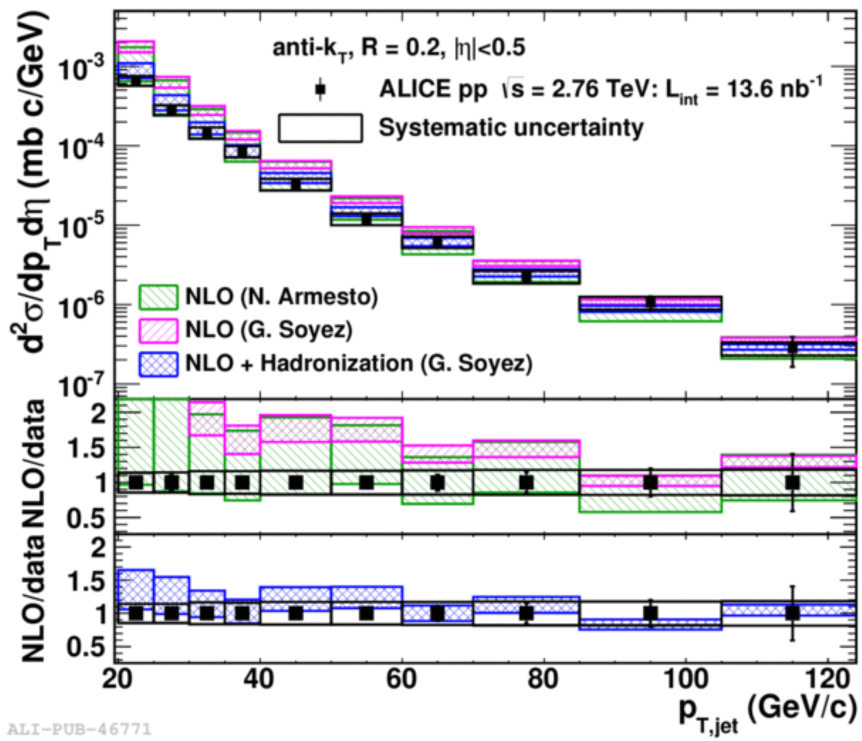
- full jets from charged particle tracking and EM energy:
  conceptually different and complementary to traditional approach

Results from pp collisions

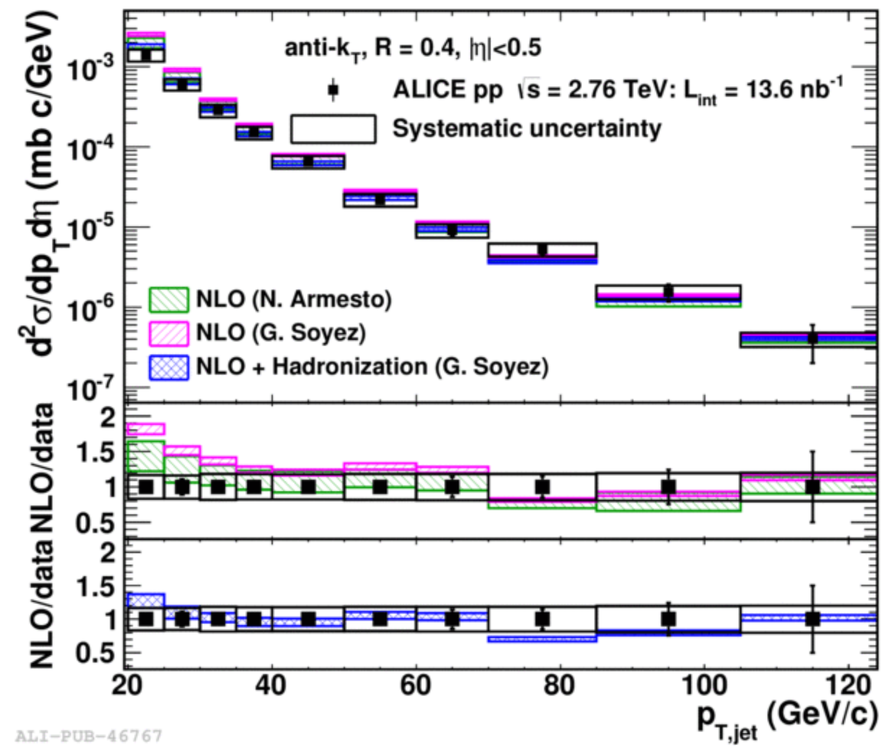
Full jets in pp at $\sqrt{s}$ = 2.76 TeV

- good agreement to NLO calculations for R = 0.2 and R = 0.4
- reference for Pb-Pb at same energy

R = 0.2



R = 0.4

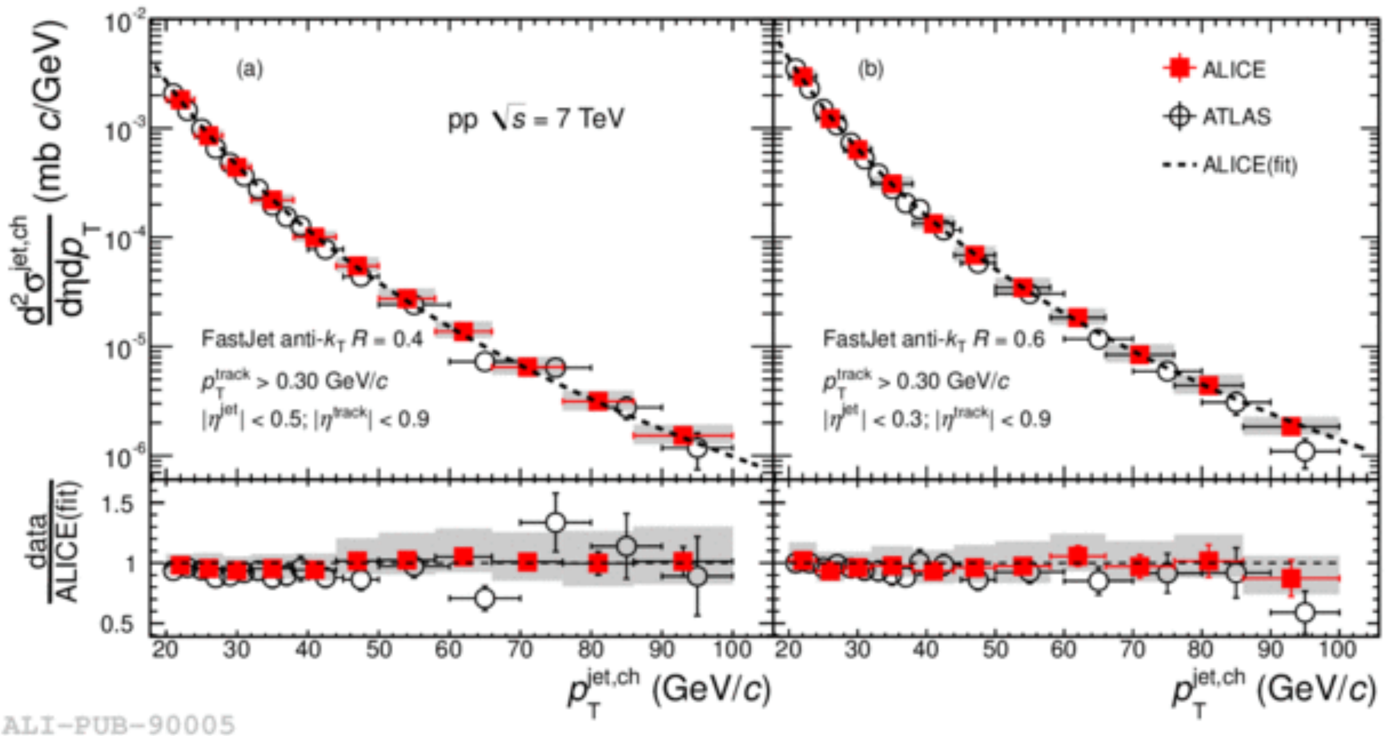


Phys. Lett. B 722 (2013) 262

pp charged jet cross-sections

- measured in minimum bias collisions at $\sqrt{s}$ = 7 TeV
- good agreement with ATLAS charged jet measurements (despite slightly different acceptance and track *p*T range)

R = 0.4 **R = 0.6**

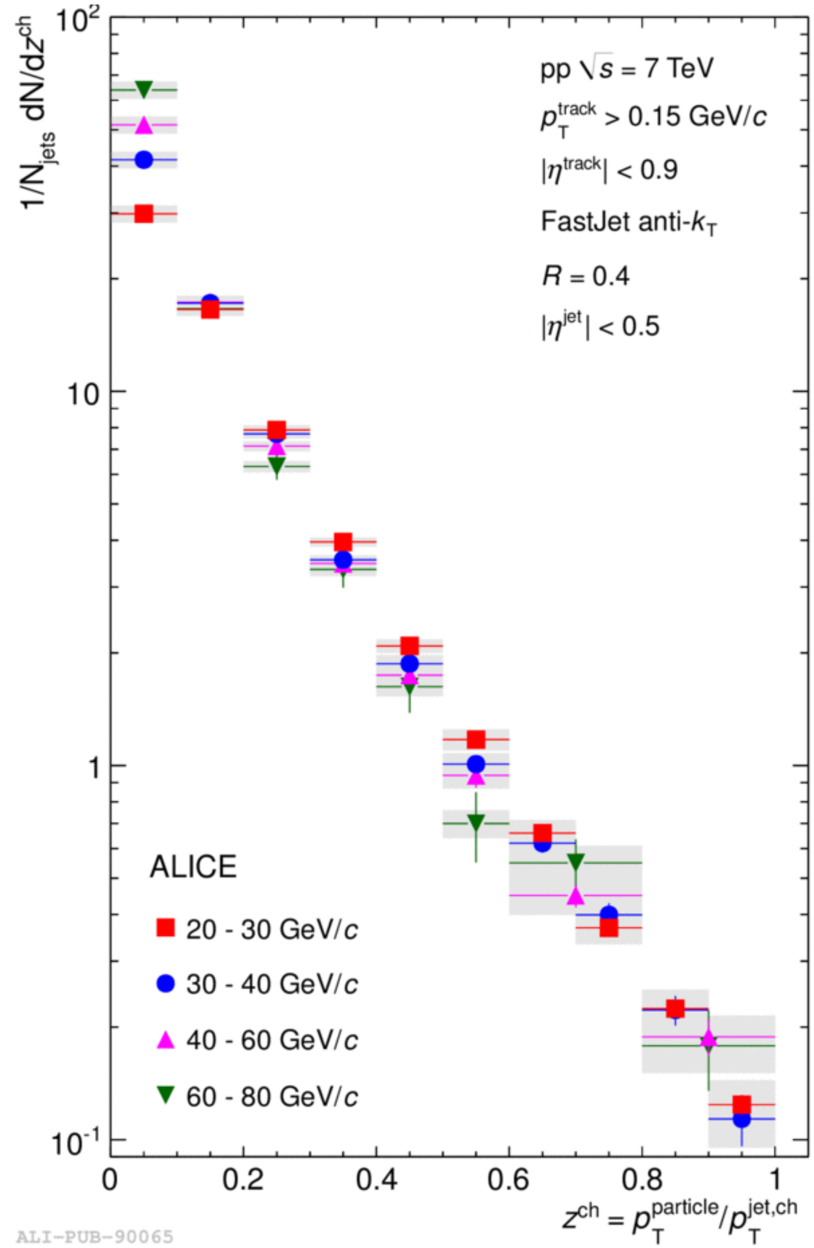


PRD 91, 112012

pp jet fragmentation at $\sqrt{s}$ = 7 TeV

- $z^{ch} = p_{\mathrm{T}}^{\mathrm{particle}} / p_{\mathrm{T}}^{\mathrm{jet,ch}}$ distributions of charged particles in charged jets
- for z > 0.2 distributions consistent for all jet p_T: 'scaling'
- bulk production at low z: ~ 5-10 charged particles per jet

PRD 91, 112012



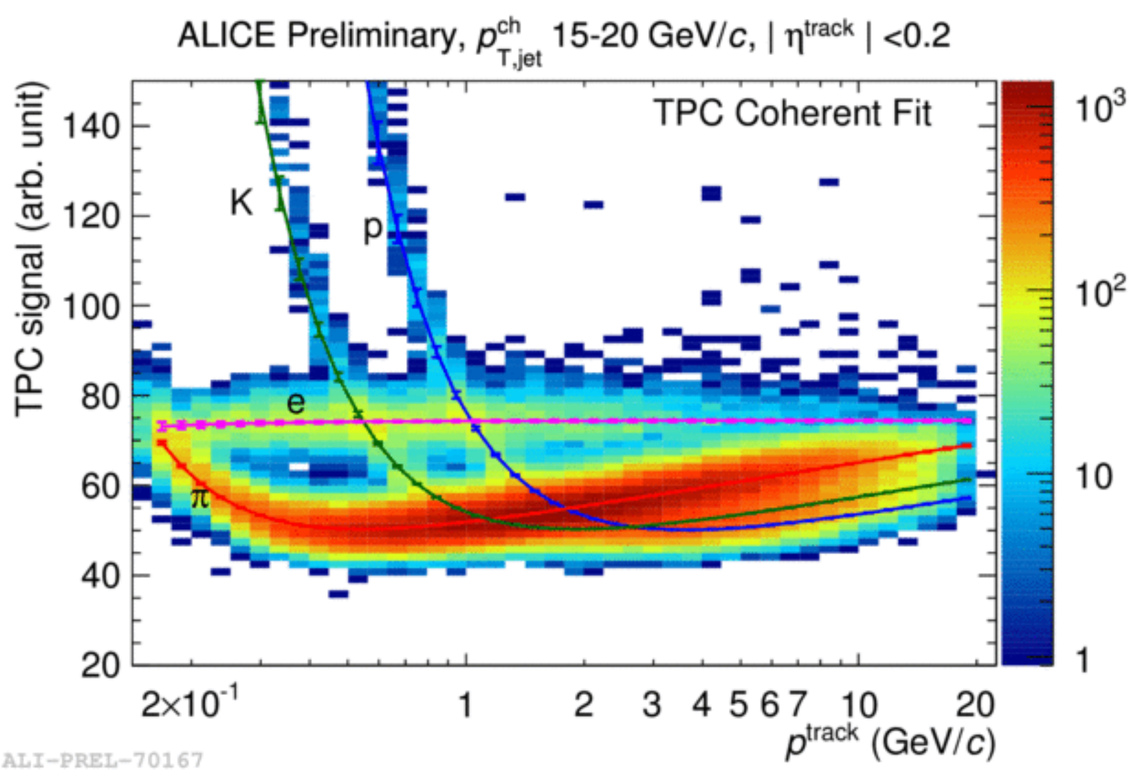
PID in jets : `TPC coherent fit’

- particle identification via specific ionization in TPC ('dE/dx'):

- TPC coherent fit:
  use energy loss model parameterization as input, adjust model parameters and particle fractions `on the fly’ during fit

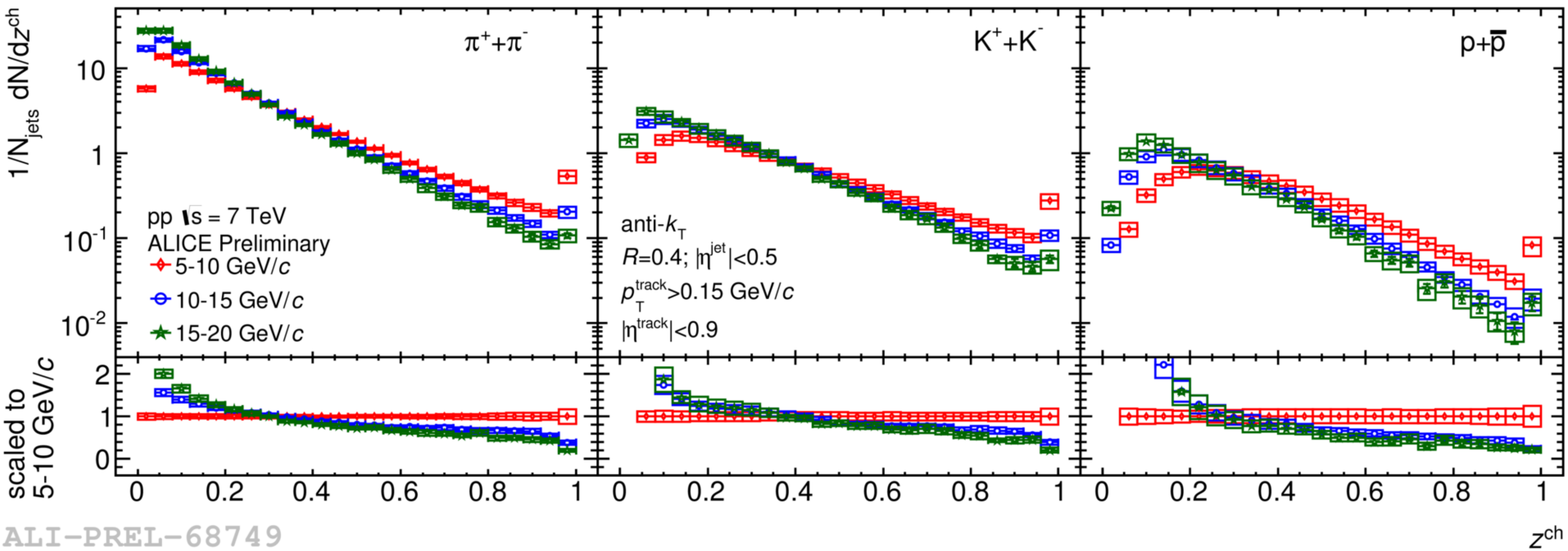
- regularization requiring continuity of particle fractions

- complementary and consistent: multi-template fit



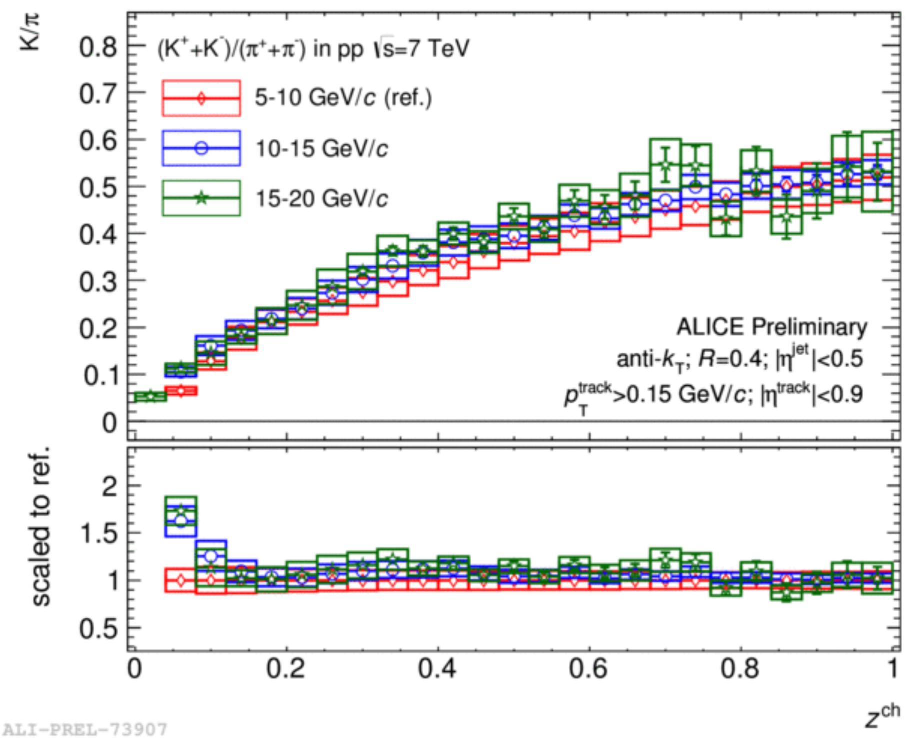
Particle identified fragmentation

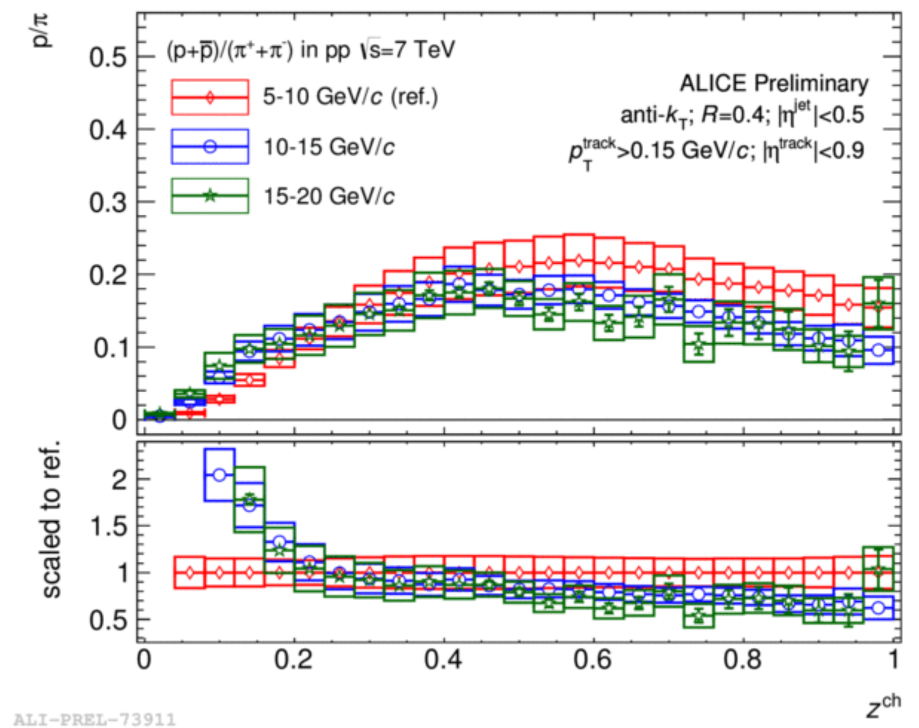
- identified charged hadrons in charged jets at $\sqrt{s}$ = 7 TeV
- π, K, p, 5 < $p_T^{ch\ jet}$ < 20 GeV/c
- scaling for z^{ch} > 0.2 for higher jet pT bins



Particle ratios in jets

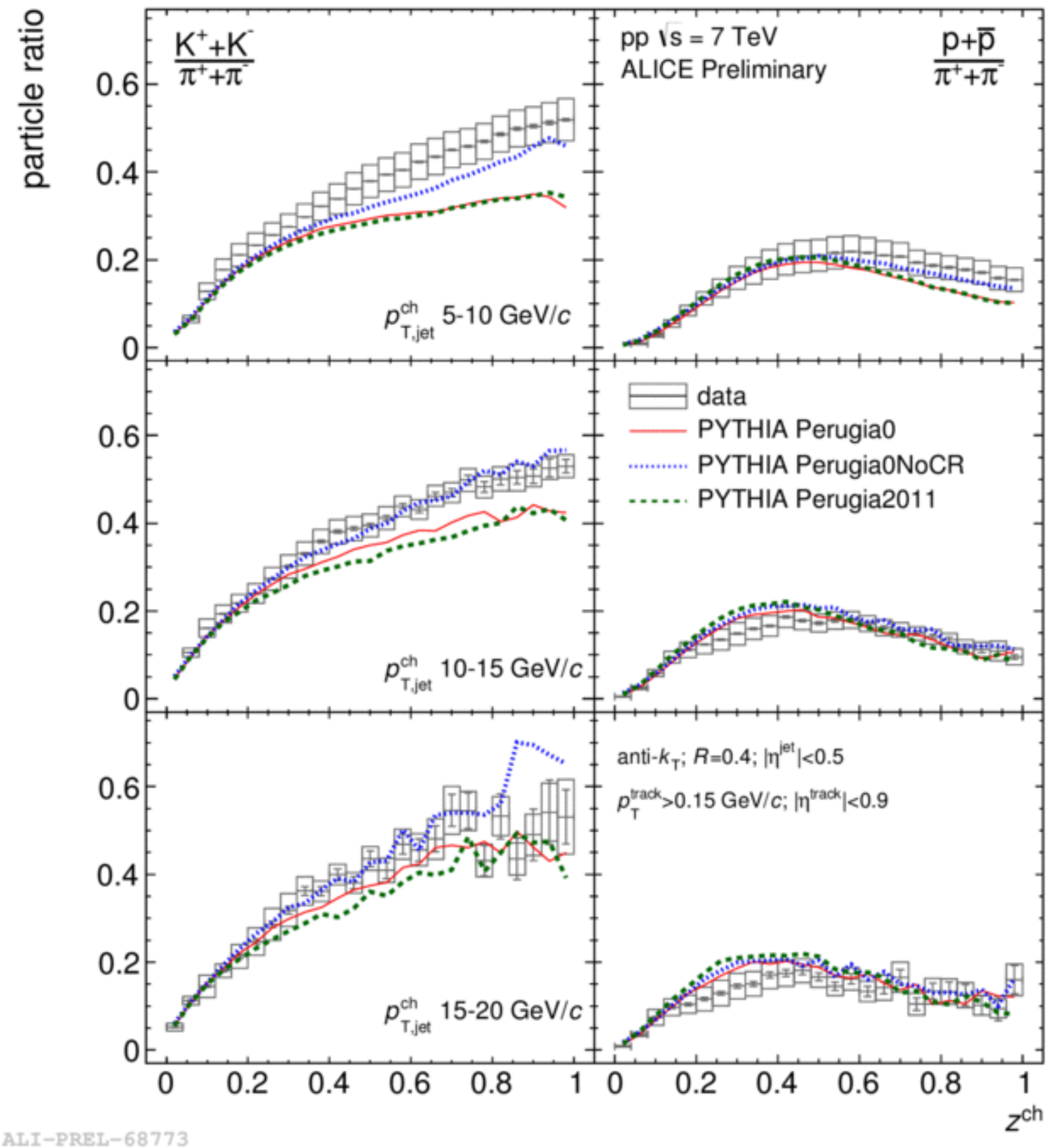
- strangeness content strongly enhanced for $z^{ch} \rightarrow 1$
- leading baryons suppressed





Event generator comparison

- comparison to PYTHIA (p_T ordered parton shower, Lund string fragmentation)
- data reasonably well described
- best reproduced by Perugia tune without color reconnections



Jets and Quark-Gluon Plasma

QCD phase transition

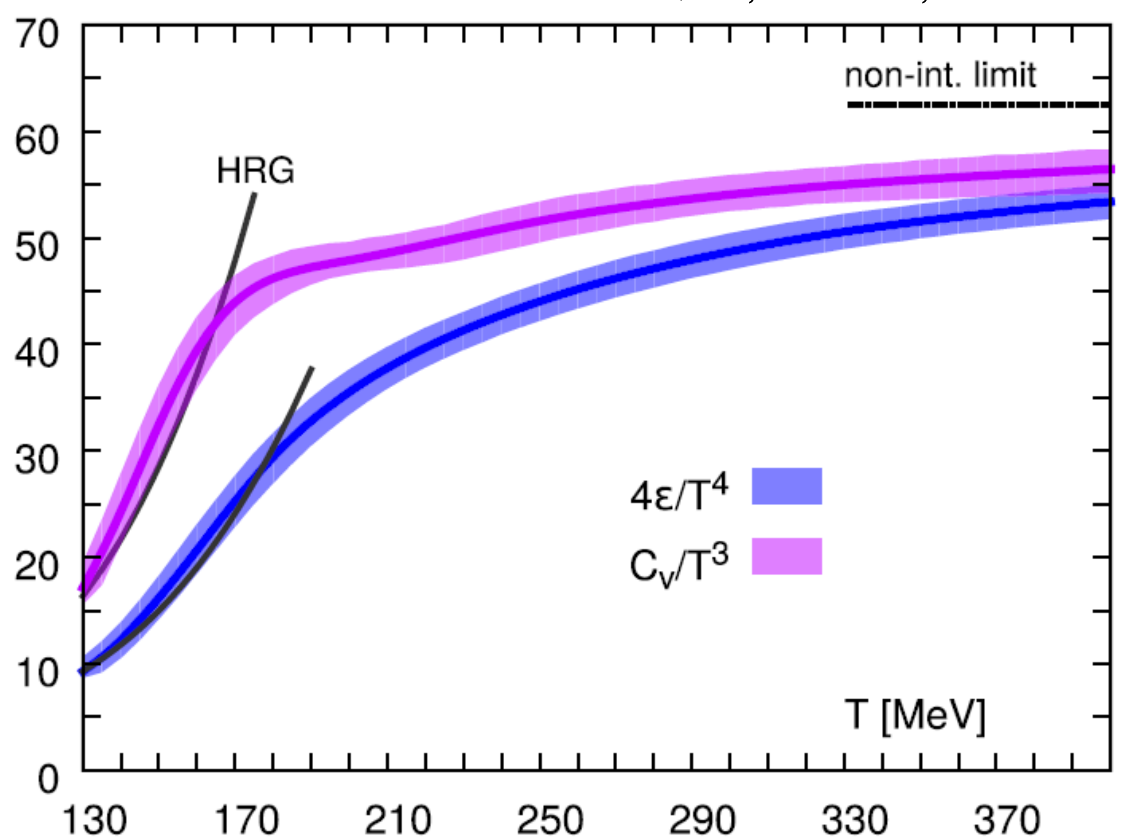
- in heavy-ion collisions at ultra-relativistic energies, a quasi macroscopic fireball of hot, strongly interacting matter in local thermal equilibrium is created

- 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

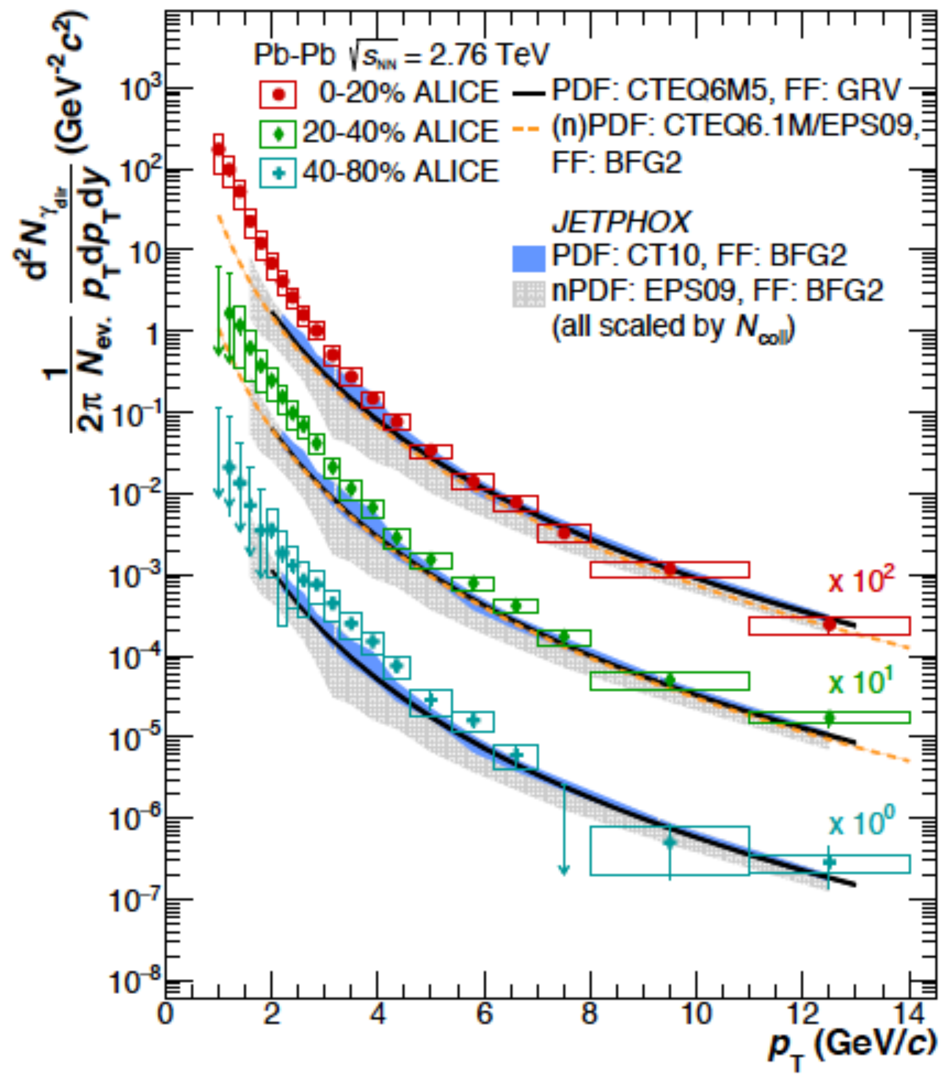


QCD matter at LHC

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

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

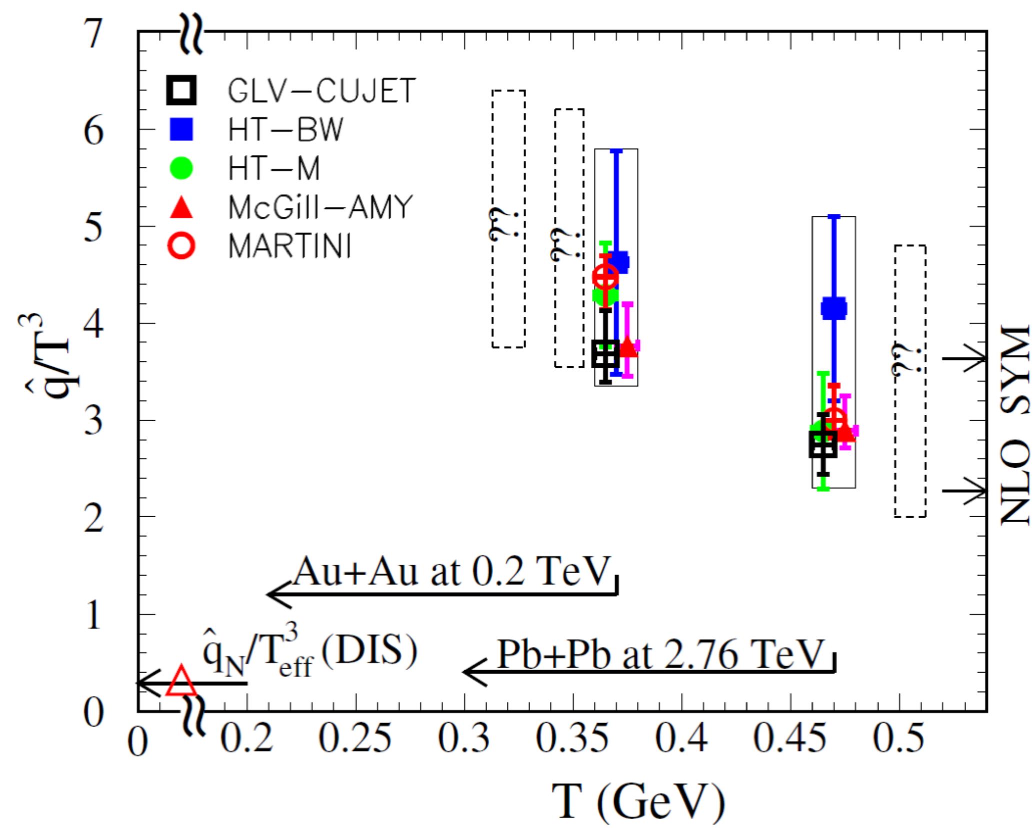
- indicates initial temperature way above TC



arXiv 1509.07324 [nucl-ex]

Partons in heavy-ion collisions

- hard partons are produced early and traverse the hot and dense QGP
- expect enhanced parton energy loss : `jet quenching' (mostly) due to medium-induced gluon radiation
- 'vacuum' expectation calculable by pQCD : 'calibrated probe of QGP'
- jets sensitive to properties of the medium (energy density, $\hat{q}$, mean free path, coupling ...)
- ... but also jet-medium interaction not trivial (strong / weak coupling, parton mass / type, fireball dynamics ...)



JET collaboration, arXiv: 1312.5003

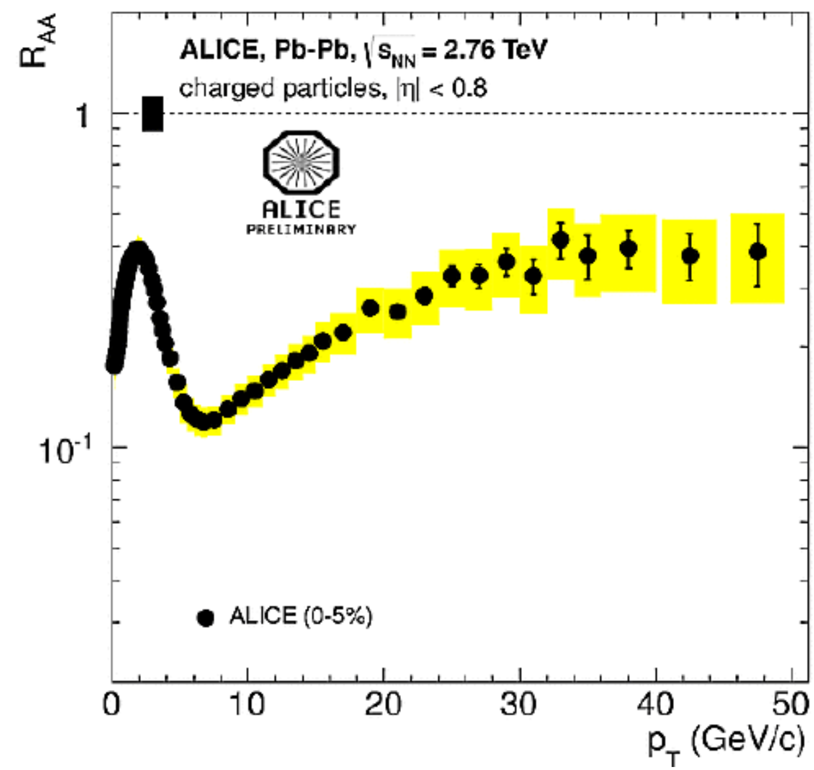
Hadrons in heavy-ion collisions

PLB 720 (2013) 250

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

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

- hadron observables biased towards leading fragment



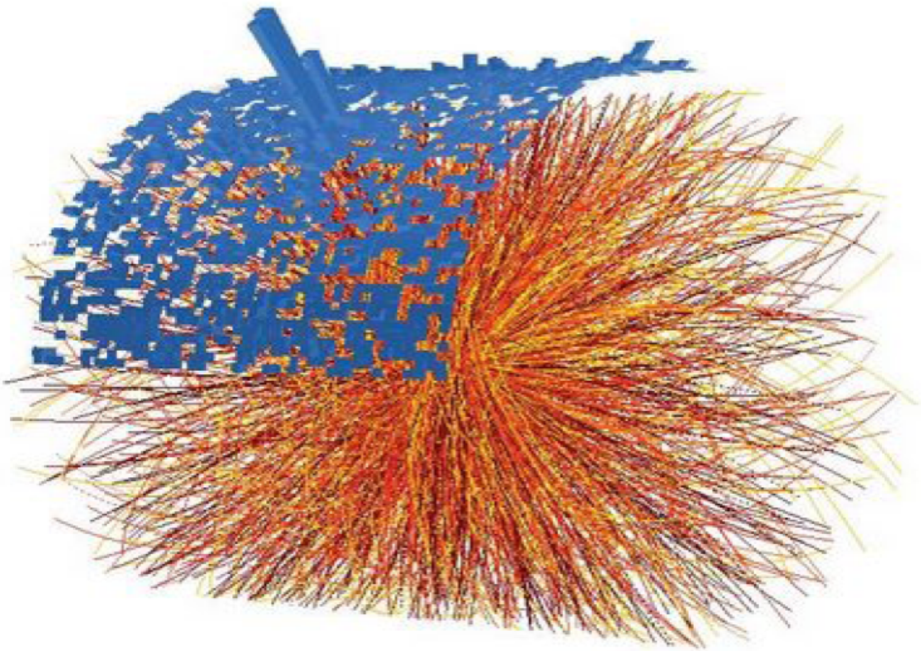
→ study the effect for fully reconstructed jets

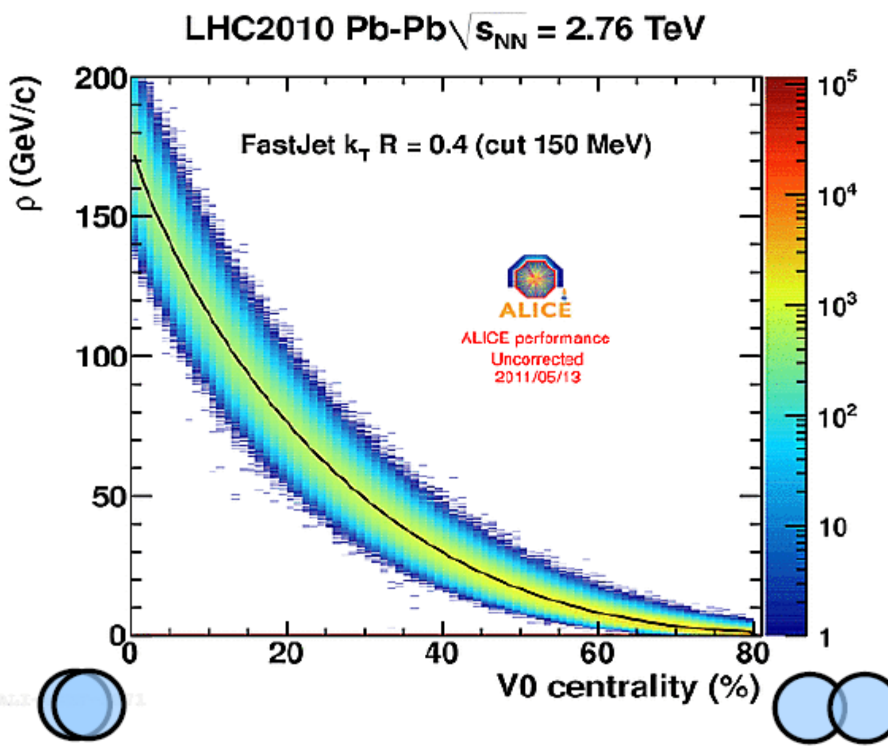
Underlying event in heavy-ion collision

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

- correct spectra for background fluctuations and detector effects via unfolding

- not possible down to lowest jet p_T





jet area ~ 0.5 (R = 0.4)

central *peripheral*

Jet nuclear modification factor

- strong suppression observed, similar to hadron RAA
  -> parton energy not recovered inside jet cone

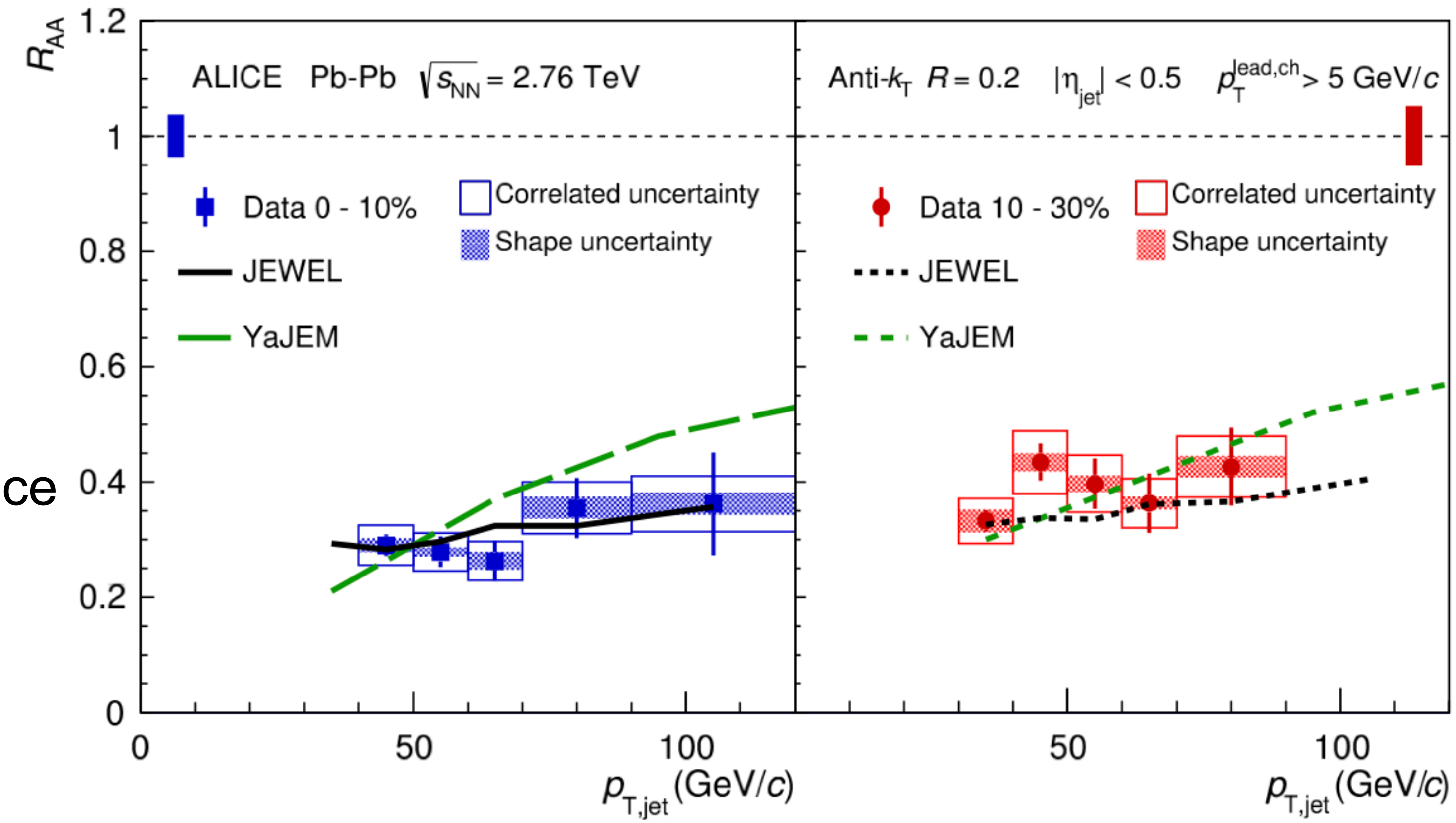
nucl-ex/1502.01689

- increase of suppression with centrality

JEWEL: PLB 735 (2014)

YaJEM:PRC 88 (2013) 014905

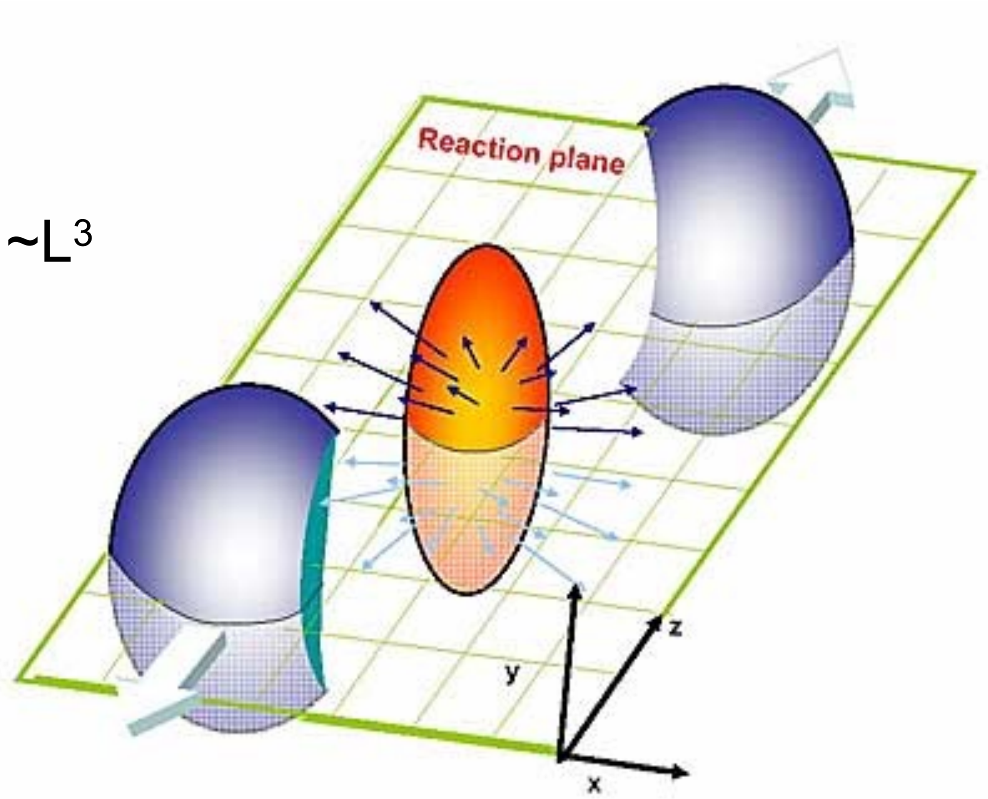
- weak p_T dependence
- JEWEL and YaJEM jet quenching models reproduce suppression



Reaction plane dependence

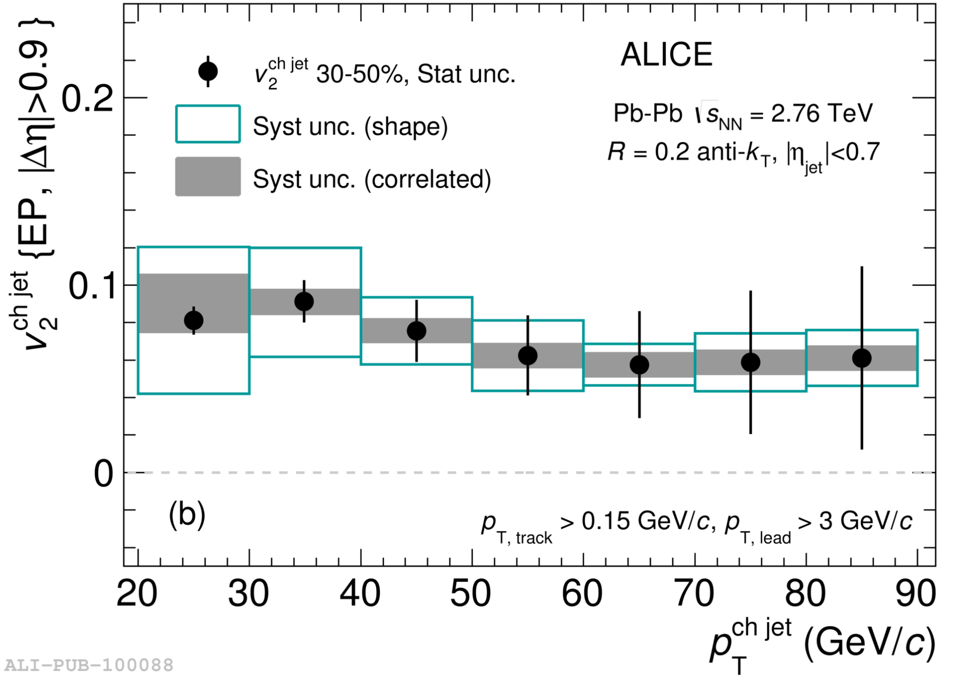
- different medium thickness in- and out-of plane

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



Jet v2 : results

- charged jets, R = 0.2
- quantify azimuthal asymmetry via 2nd Fourier harmonic v2
- non-zero v2 jet in semi-central collisions



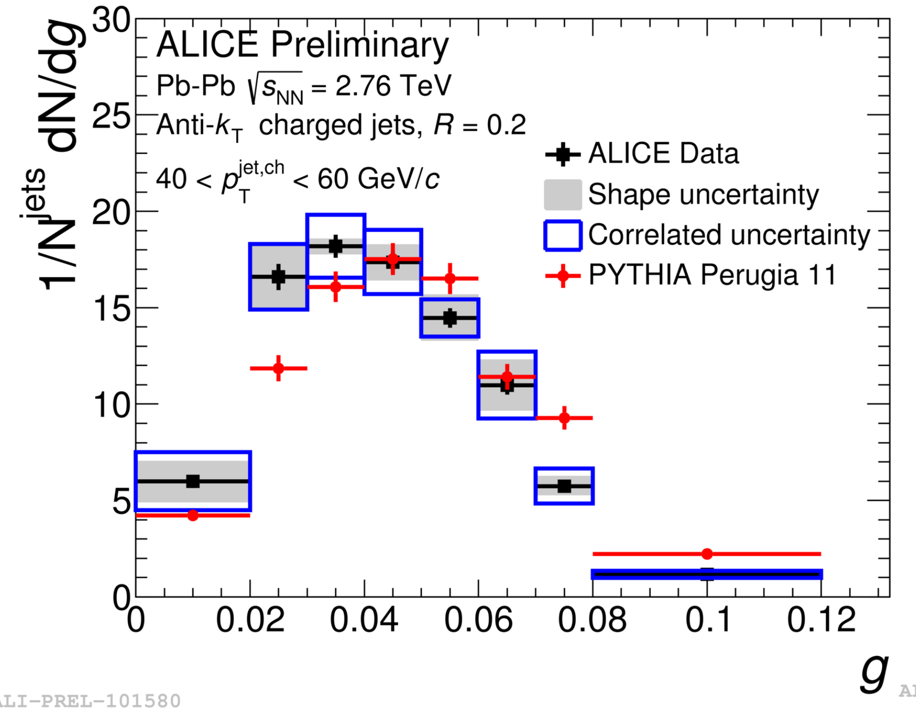
arXiv:1509.07334 [nucl-ex]

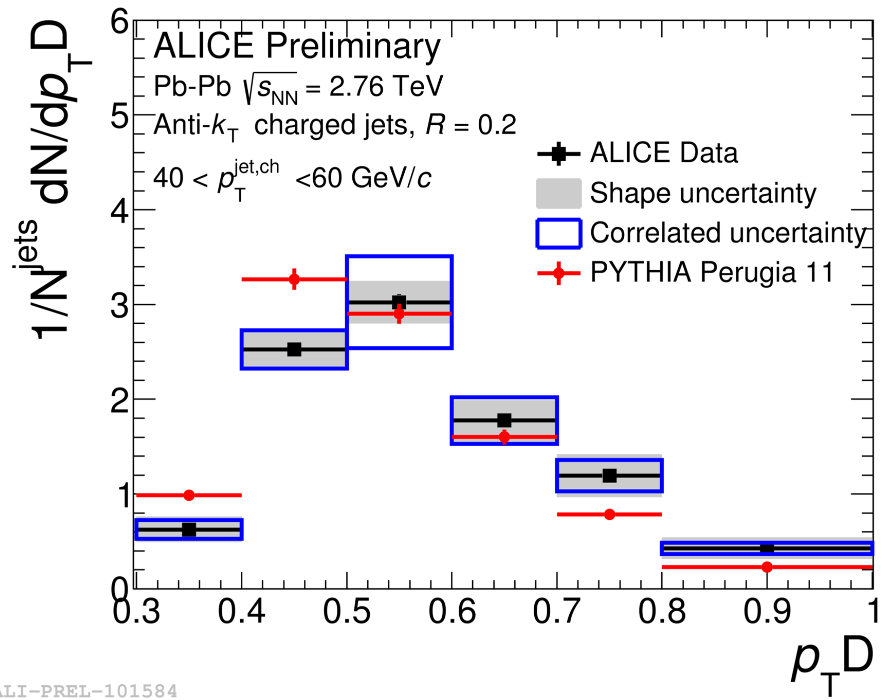
Jet Structure

- different observables, e.g. radial moment g, $p_T D$
- comparison to PYTHIA pp reference shows collimation of jet core (R=0.2)

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

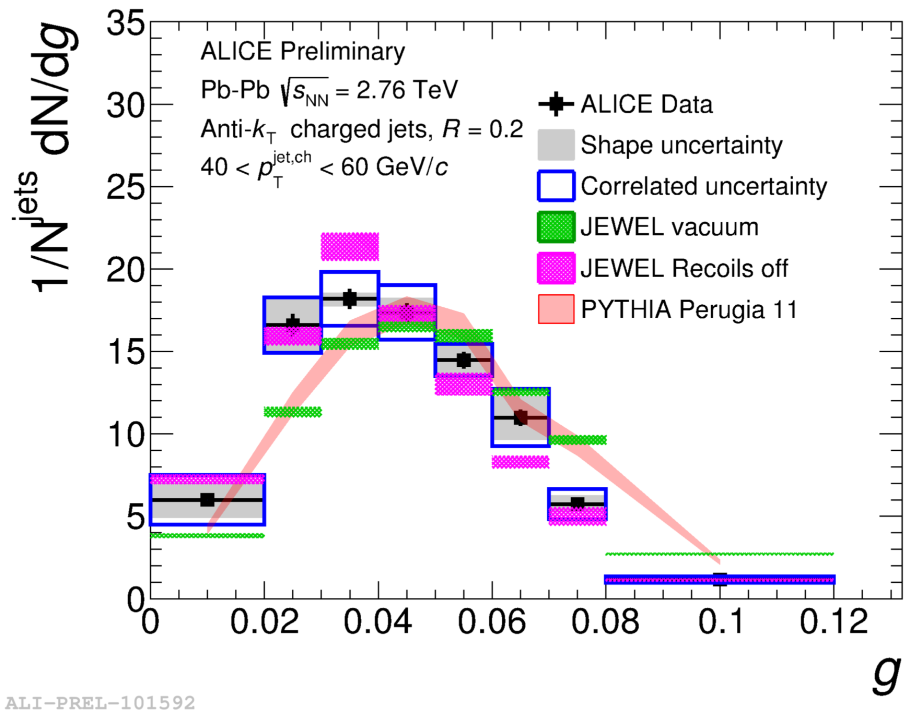
$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

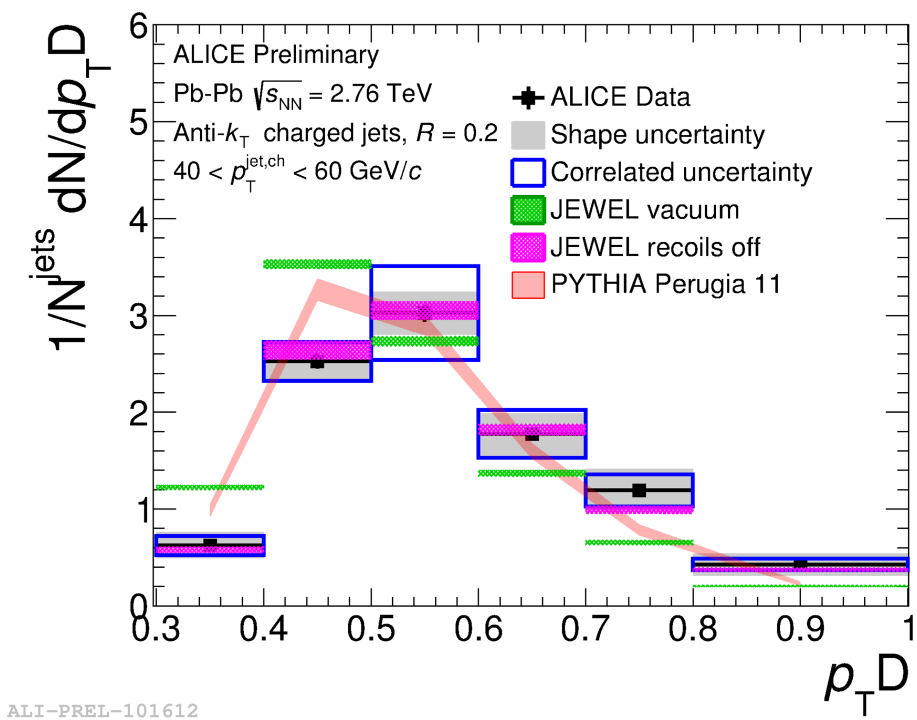




Jet Structure : Model Comparison

- trends reproduced by JEWEL jet quenching model





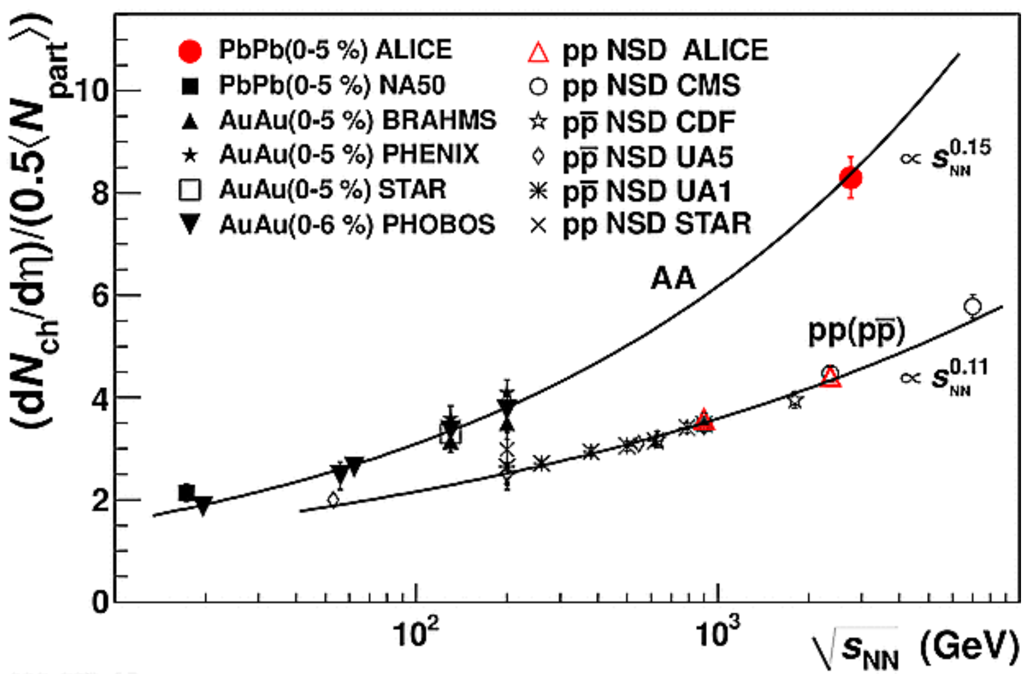
JEWEL: K.C. Zapp, F. Kraus, U.A. Wiedemann, JHEP 1303 (2013) 080

Perspectives for LHC run 2

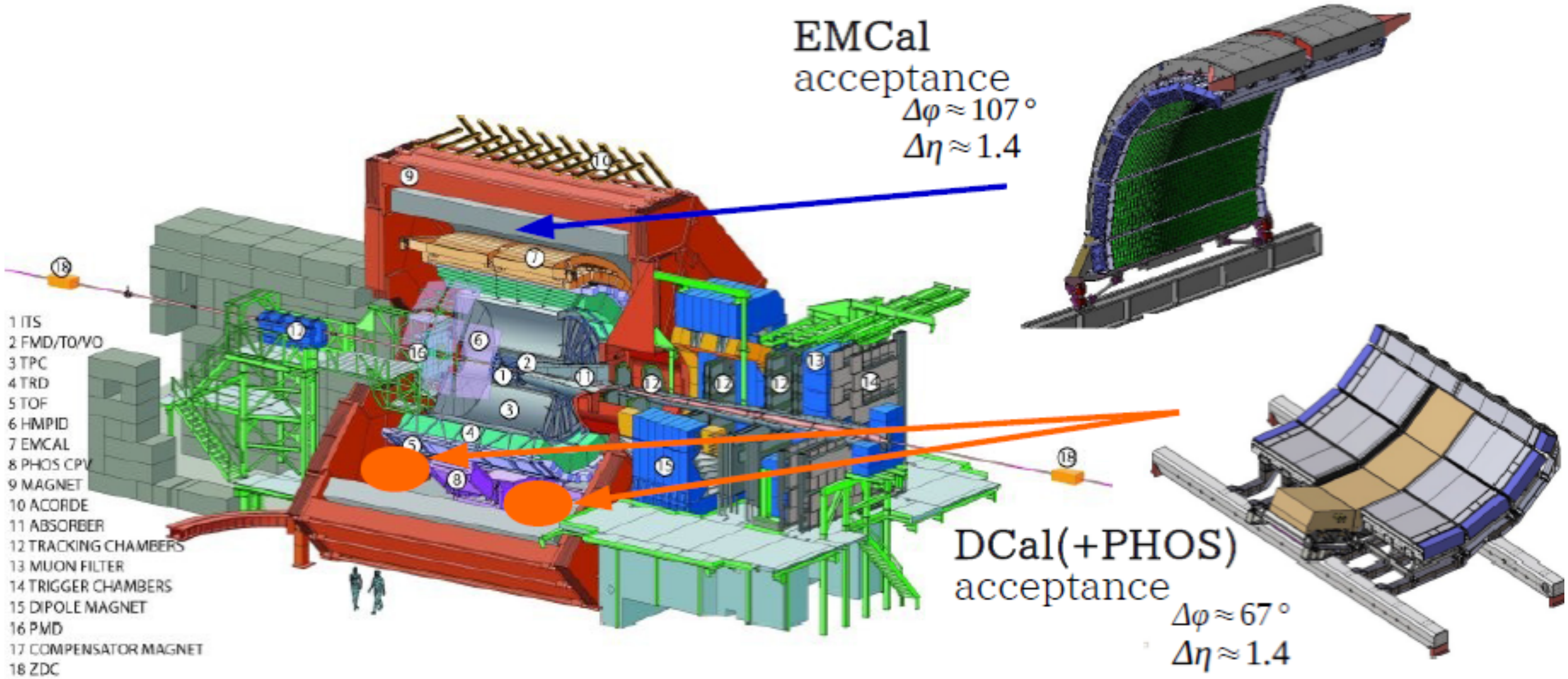
LHC run 2

- 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 RAA ???)

ALICE, PRL 105, 252301



ALICE in run 2: DCal



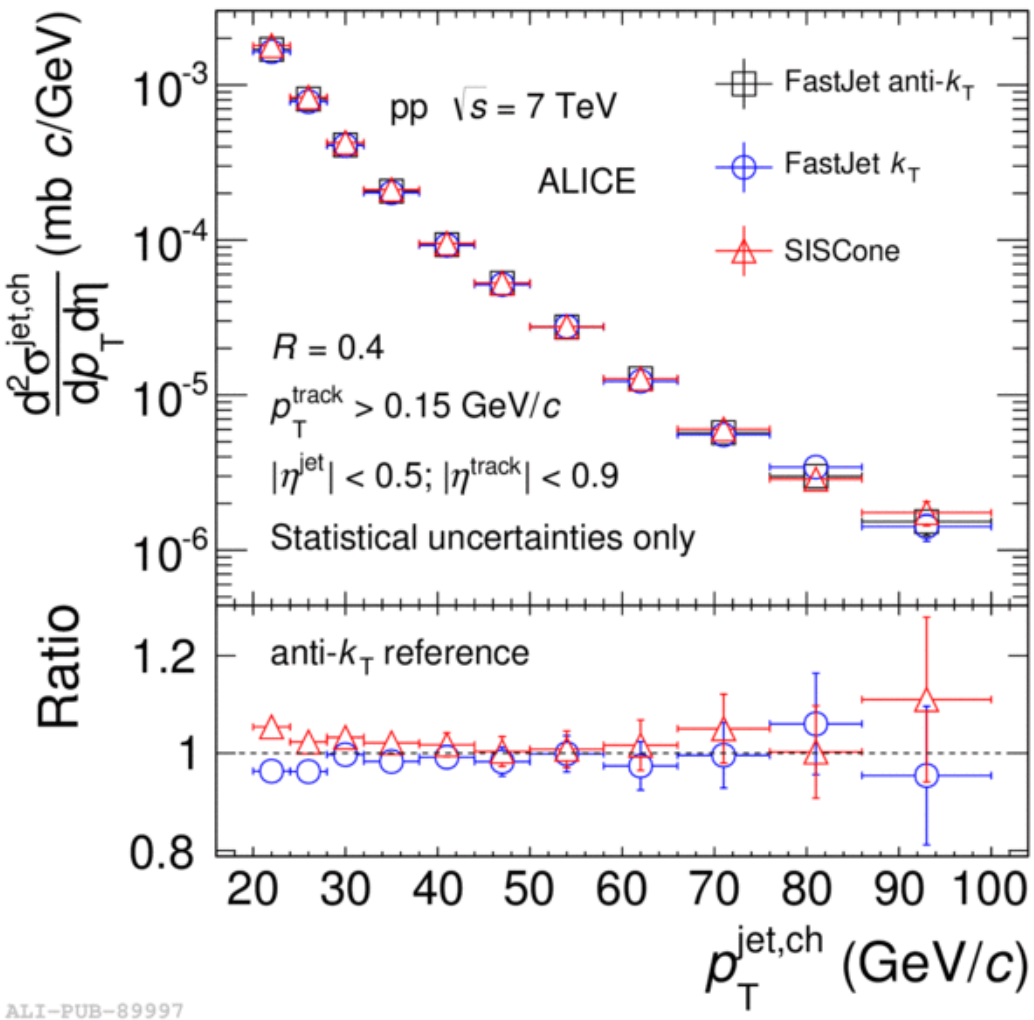
- run 2: DCal upgrade
  - significantly extended jet acceptance
  - back-to-back in azimuth (di-jet topology)

Summary

- jet cross sections and properties in pp
- identified jet fragmentation in pp
- strong jet suppression observed in Pb-Pb collisions
- non-zero jet v2 indicates path-length dependence of jet quenching
- first look at jet shapes
- looking forward to LHC run 2 !

- Backup -

Jet finder comparison



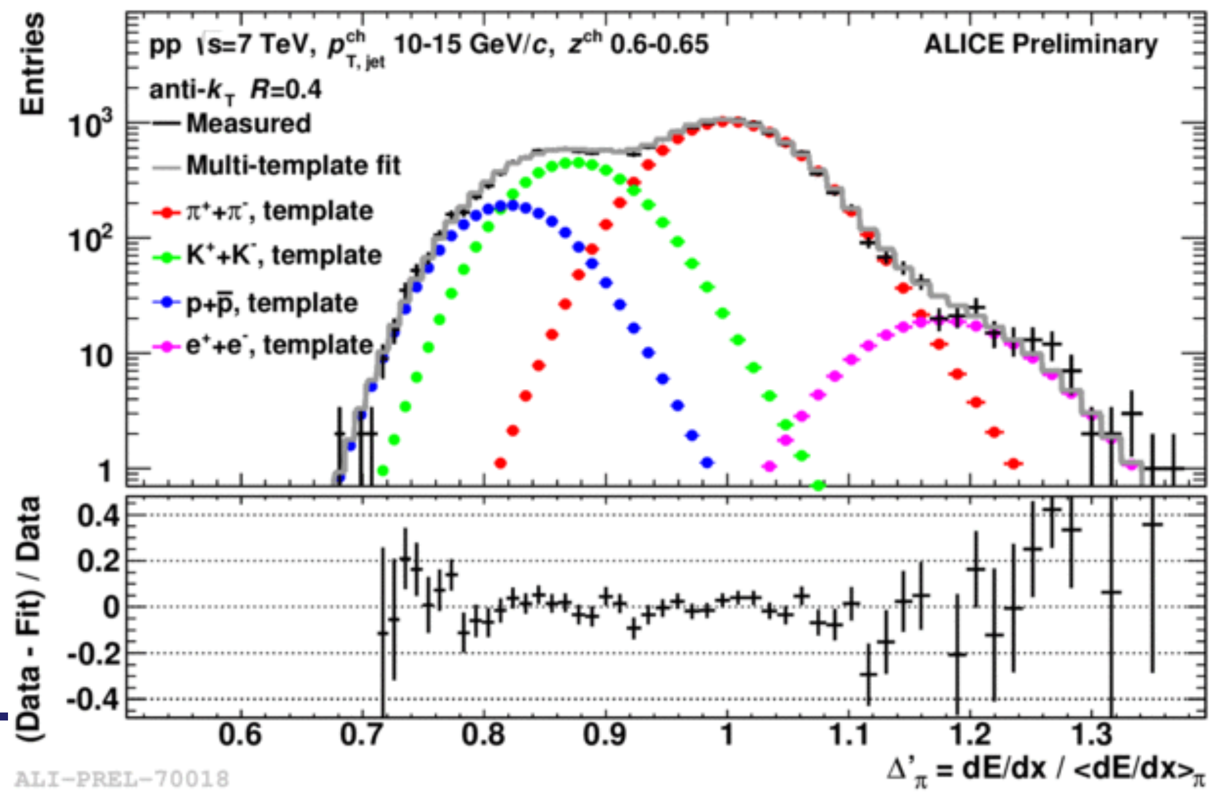
nucl-ex/1411.4969

- kT: sequential recombination
- SISCone: cone algorithm

Multi Template Fit

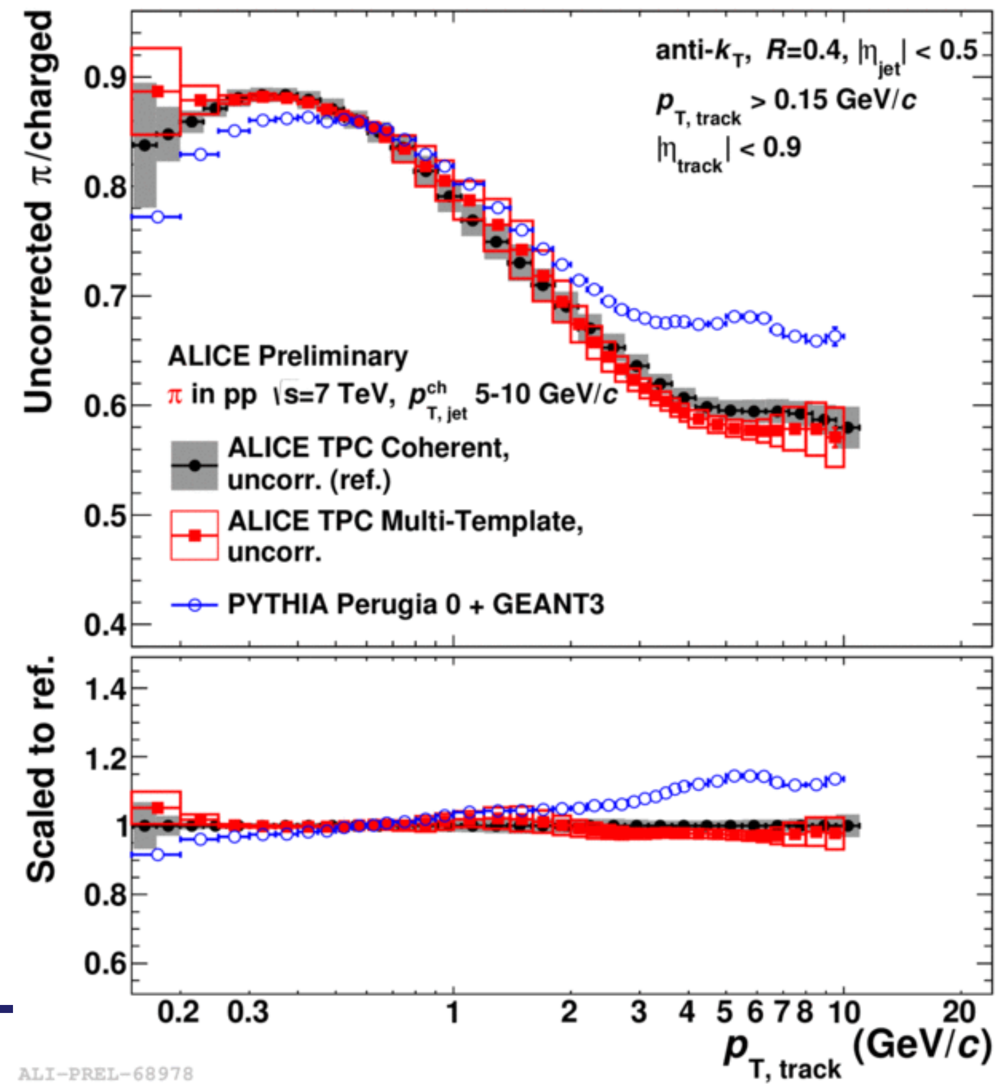
- TPC multi-template fit
  - best possible description of dE/dx from external reference
  - parametrize dependences on η, TPC nClusters
  - templates in transverse momentum (z, xi) slices

- dE/dx in one z slice (0.6 < z < 0.65), 10-15 GeV/c fitted with 4 templates



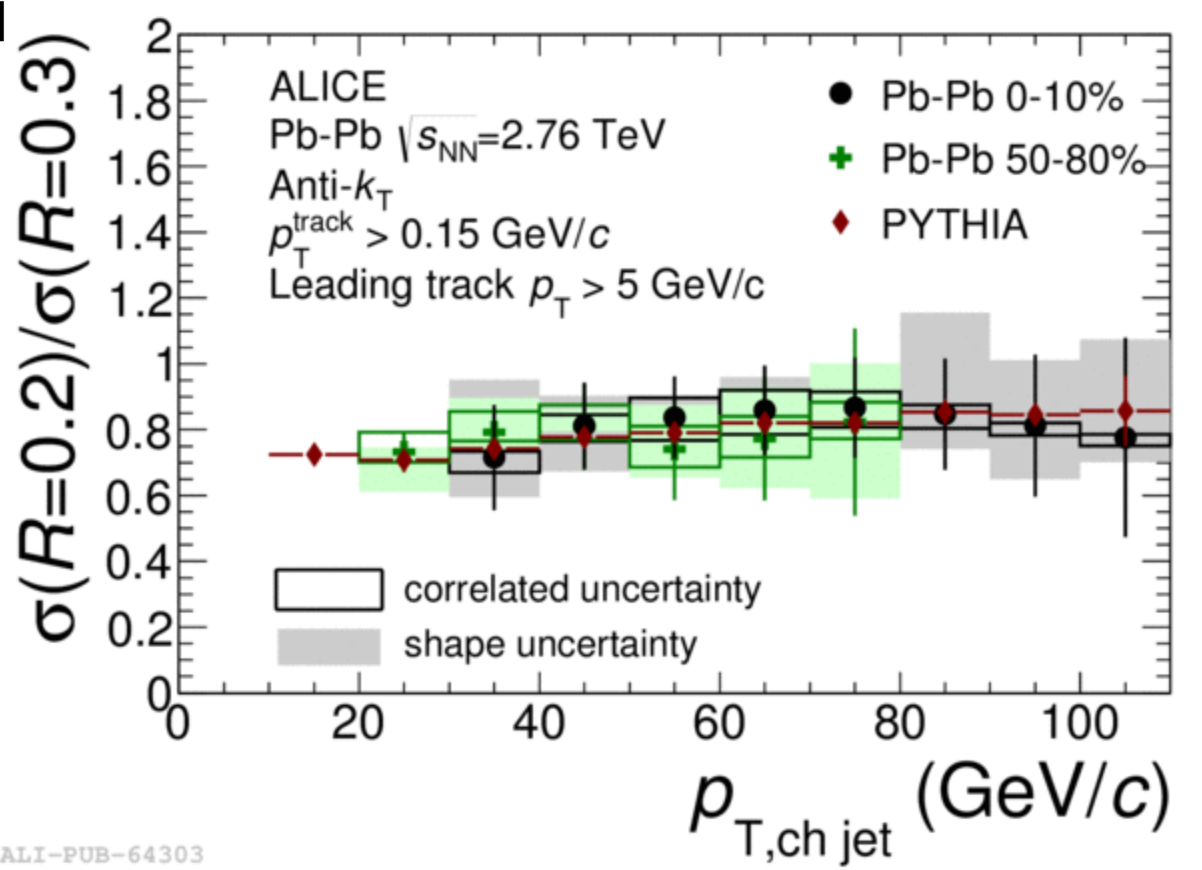
Method comparison

- uncorrected hadron fractions from Multi-Template Fit and TPC Coherent Fit
- 2 complementary methods obtain consistent results



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