Jet Physics with ALICE

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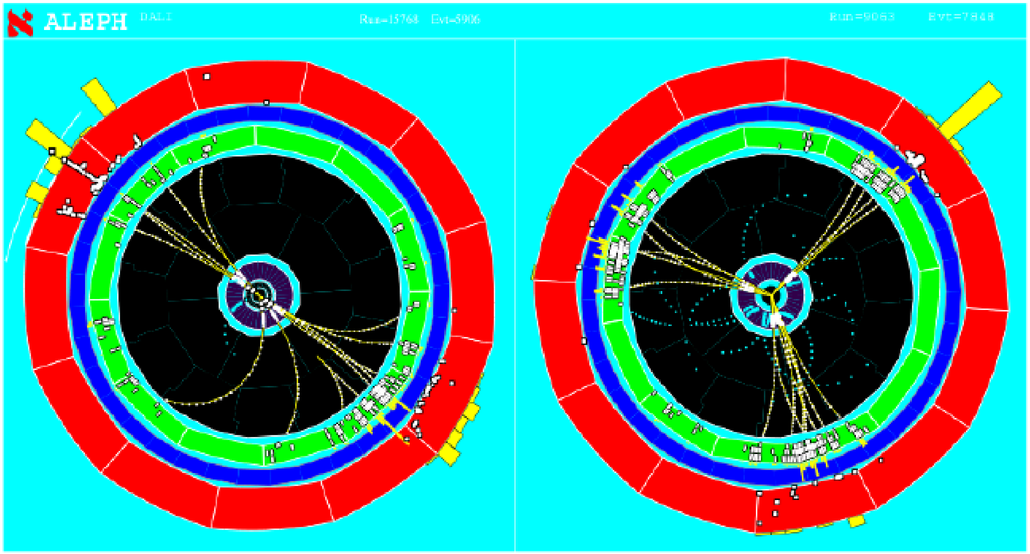
for the ALICE collaboration

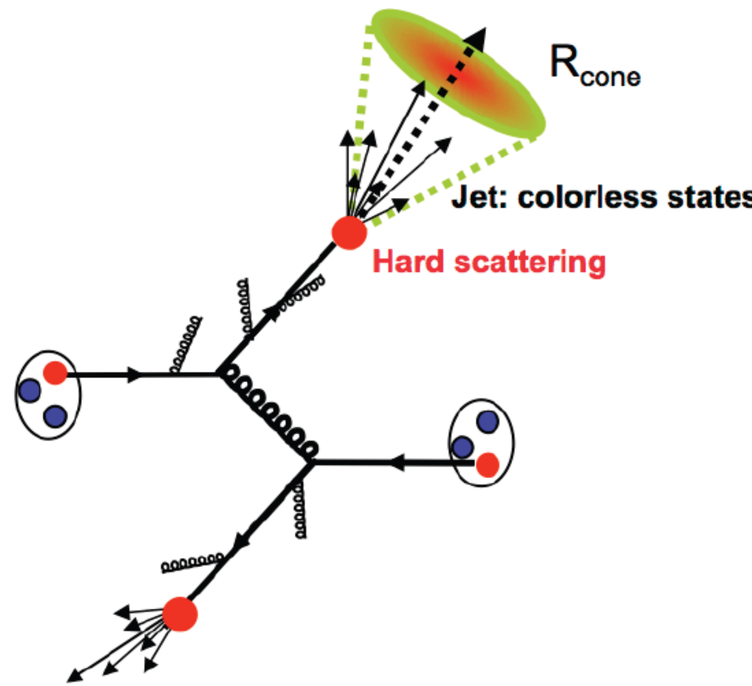
Outline

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

Introduction

Jets: seeing quarks and gluons

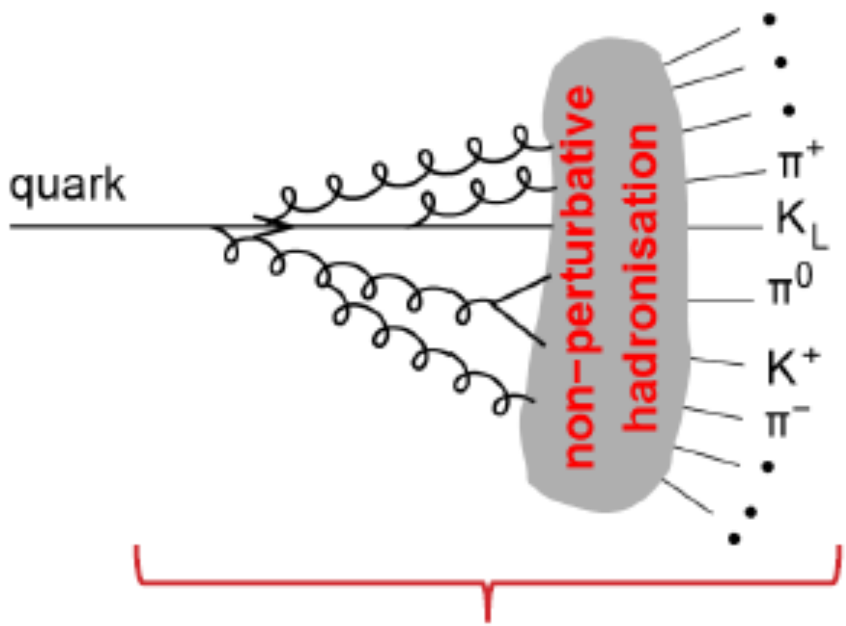




- jet: collimated spray of hadrons
- quasi-free parton scattering at high Q^2:
  the best available experimental equivalent to quarks and gluons

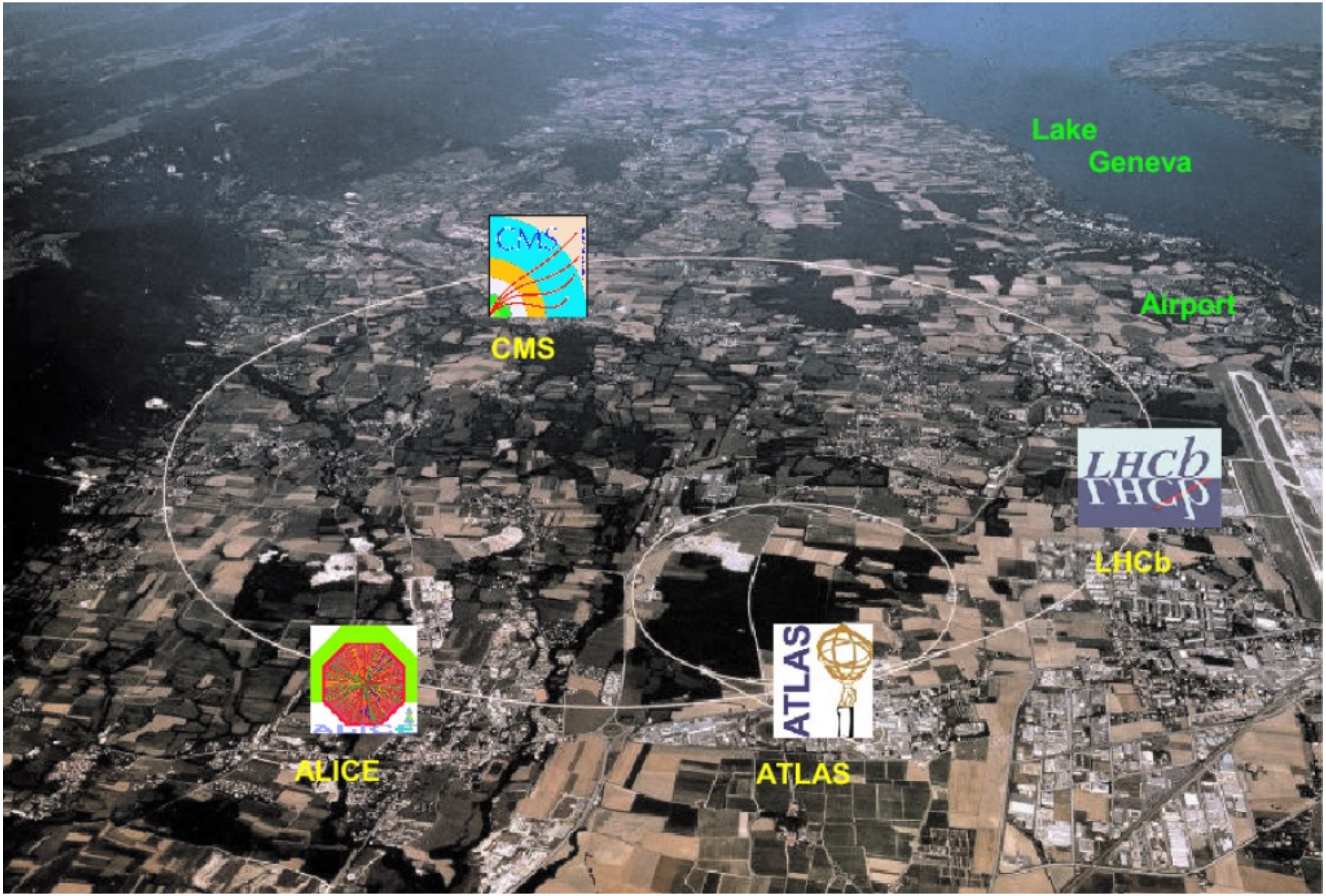
Jet fragmentation

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

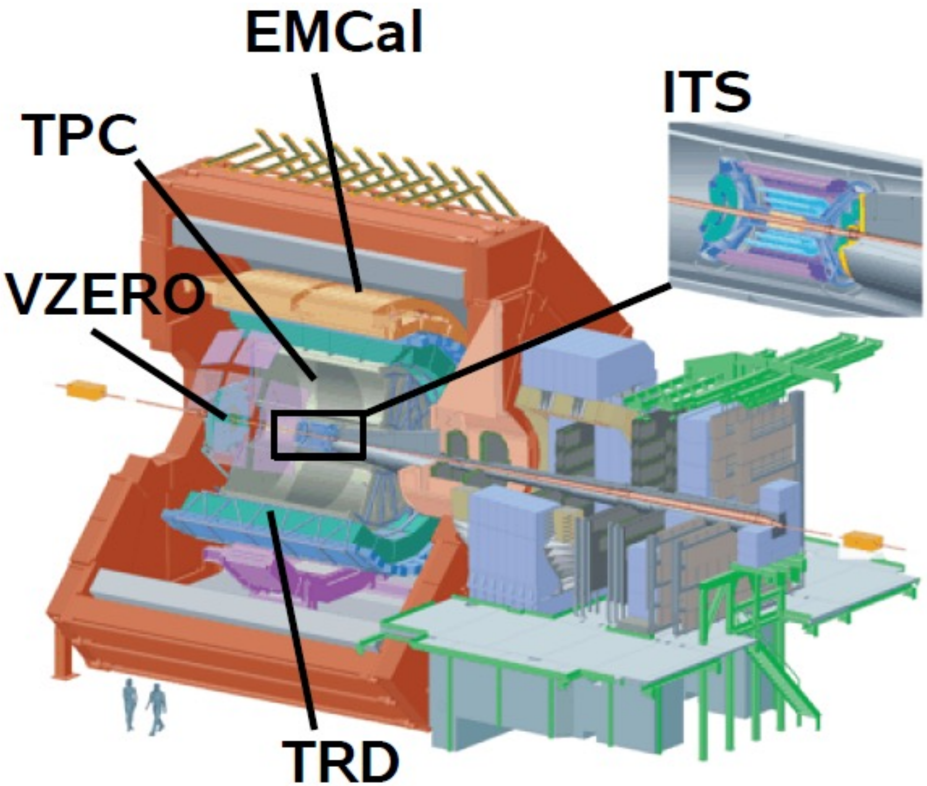


Fragmentation = Parton shower + hadronization

LHC aerial view



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

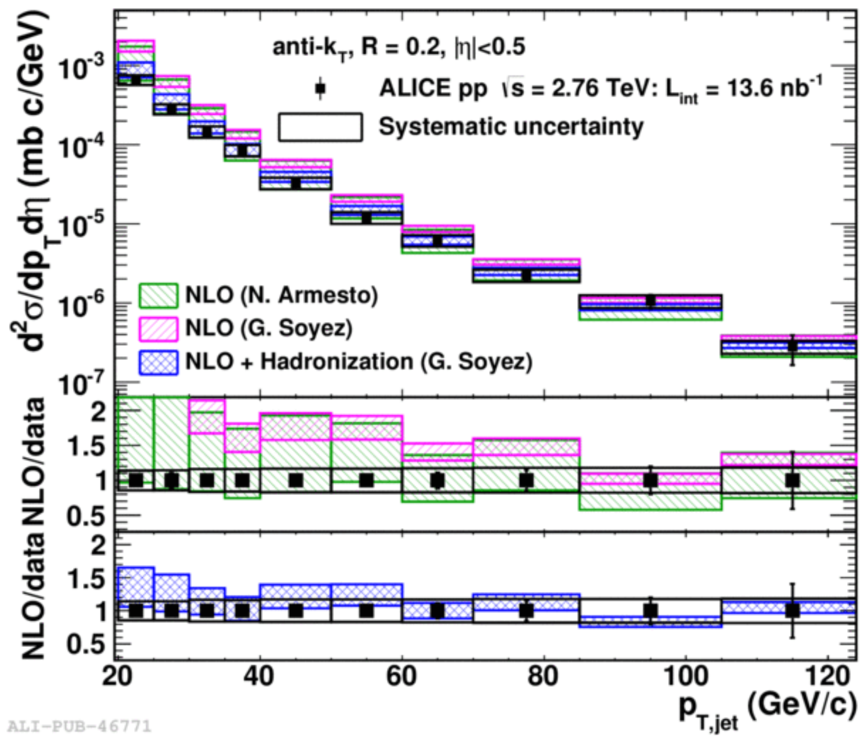
- jet trigger with EMCal and TRD
- `charged’ (tracking) jets and `full’ jets
- full jets from charged particle tracking and EM energy: conceptually different and complementary to traditional approach

Results from pp collisions

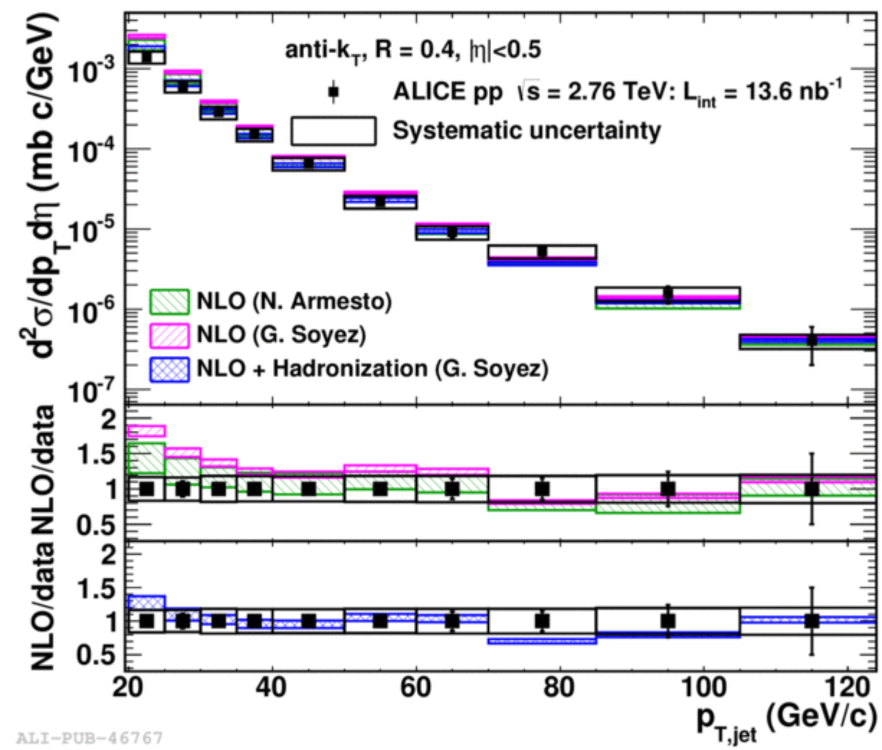
Full jets in pp at $\sqrt{s}$ = 2.76 TeV

- 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



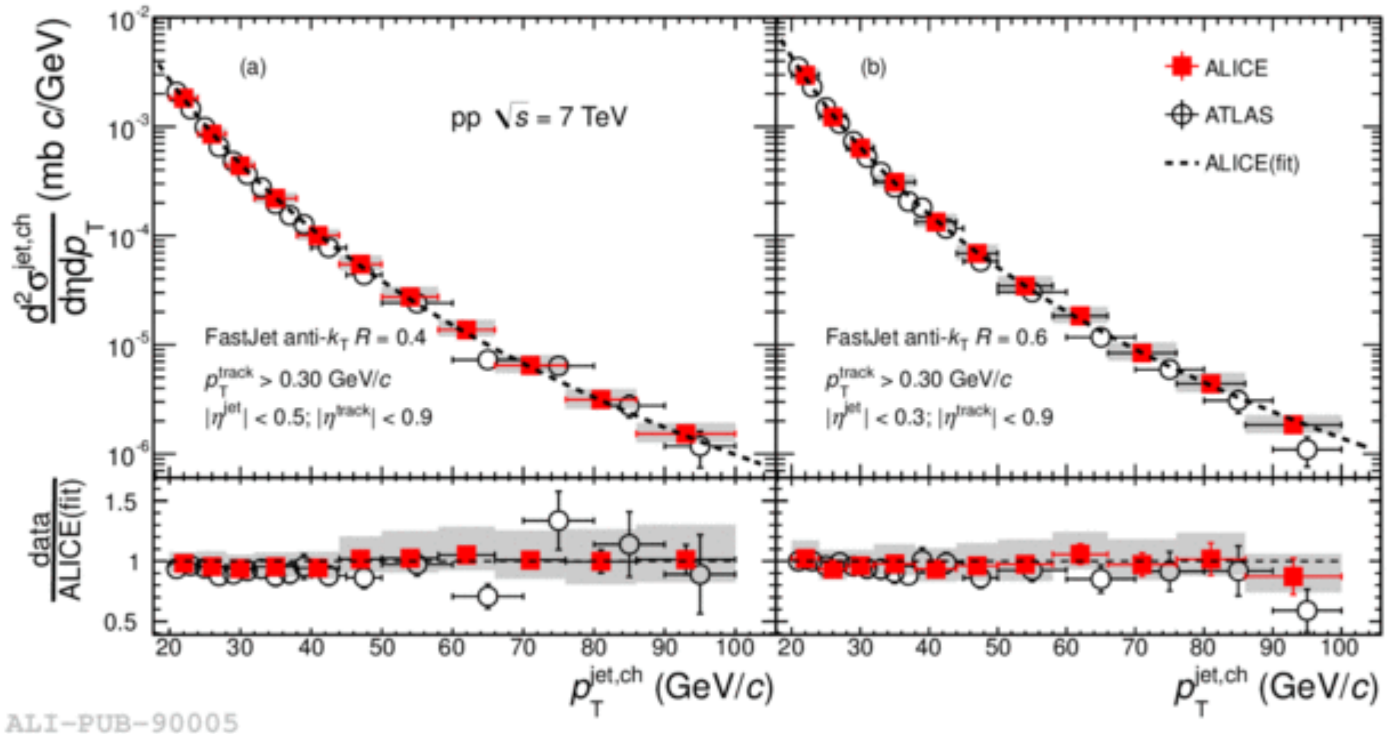
Phys. Lett. B 722 (2013) 262

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)

nucl-ex/1411.4969

R = 0.4



R = 0.6

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

- $z^{ch} = p_T^{\mathrm{particle}} / p_T^{\mathrm{jet,ch}}$ distributions of charged particles in charged jets
- scaling for z > 0.2
- bulk production at low z: ~ 5-10 charged particles per jet

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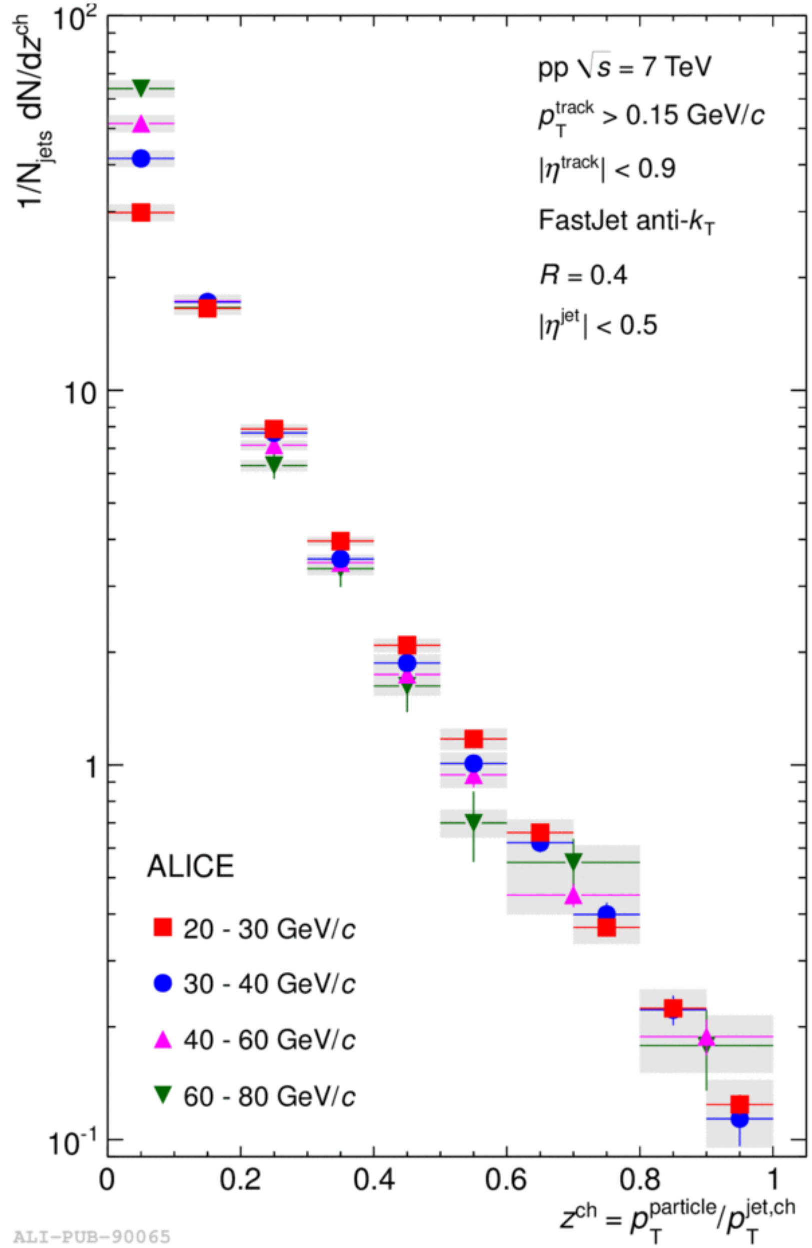
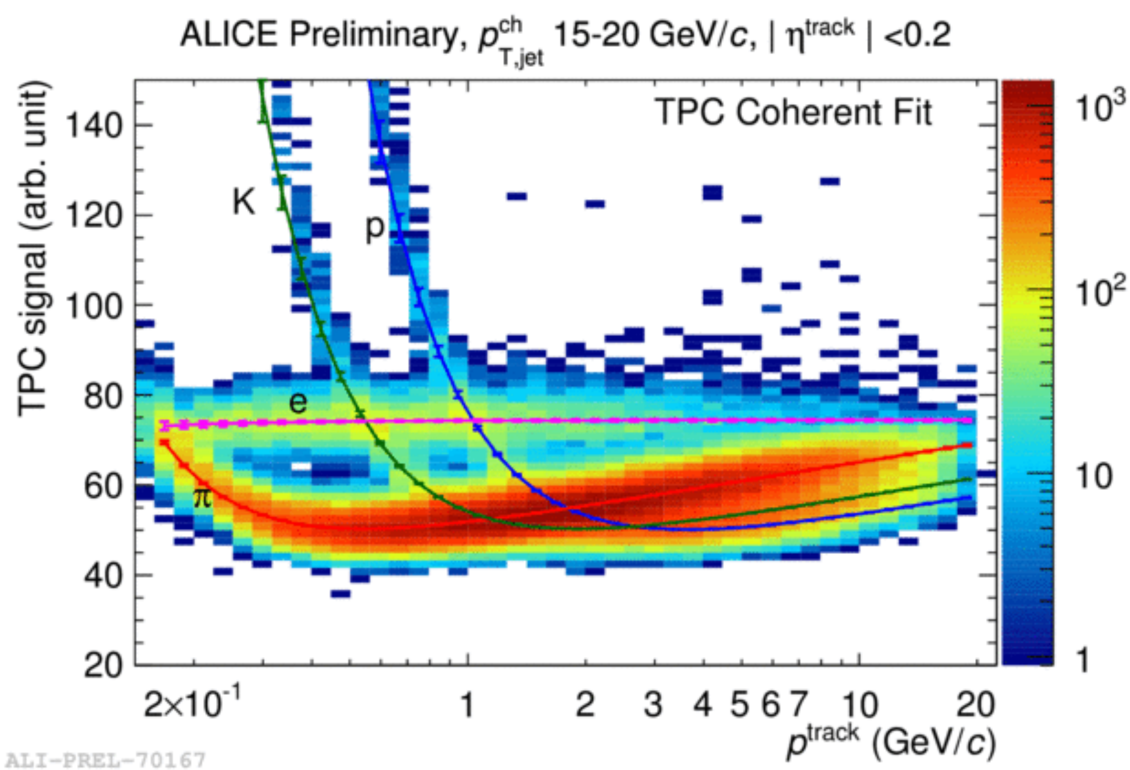


PID in jets : `TPC coherent fit'

- 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

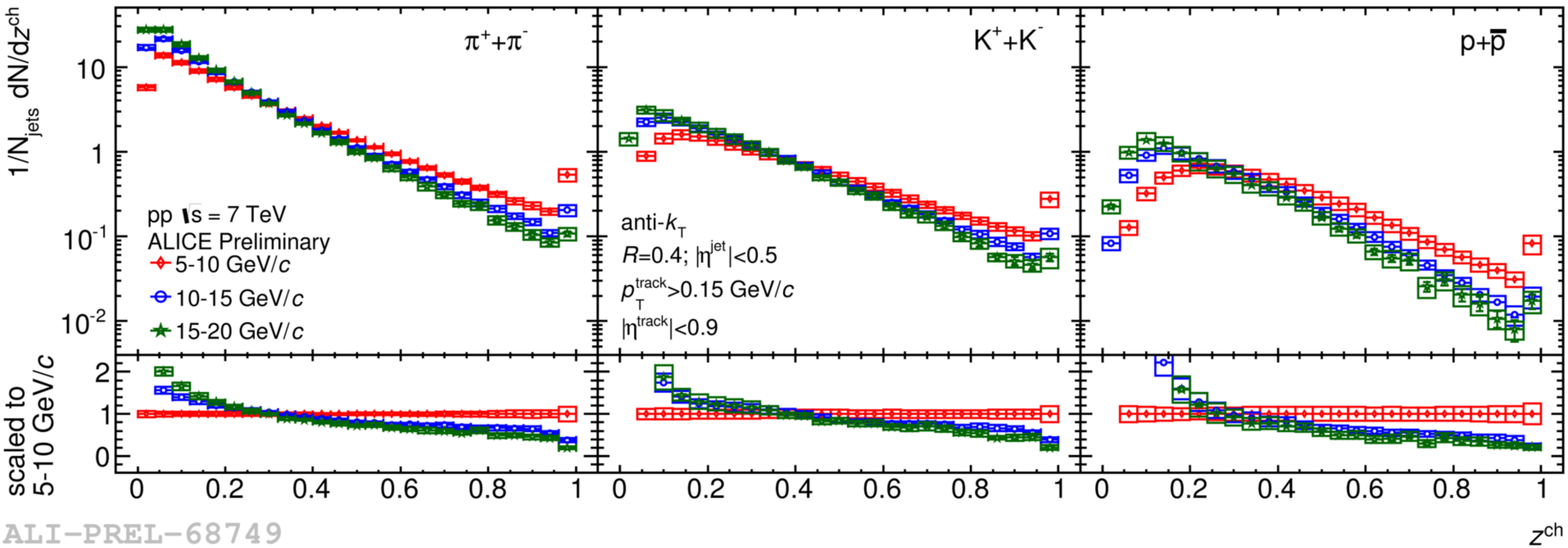


- regularization requiring continuity of particle fractions

- complementary and consistent: multi-template fit

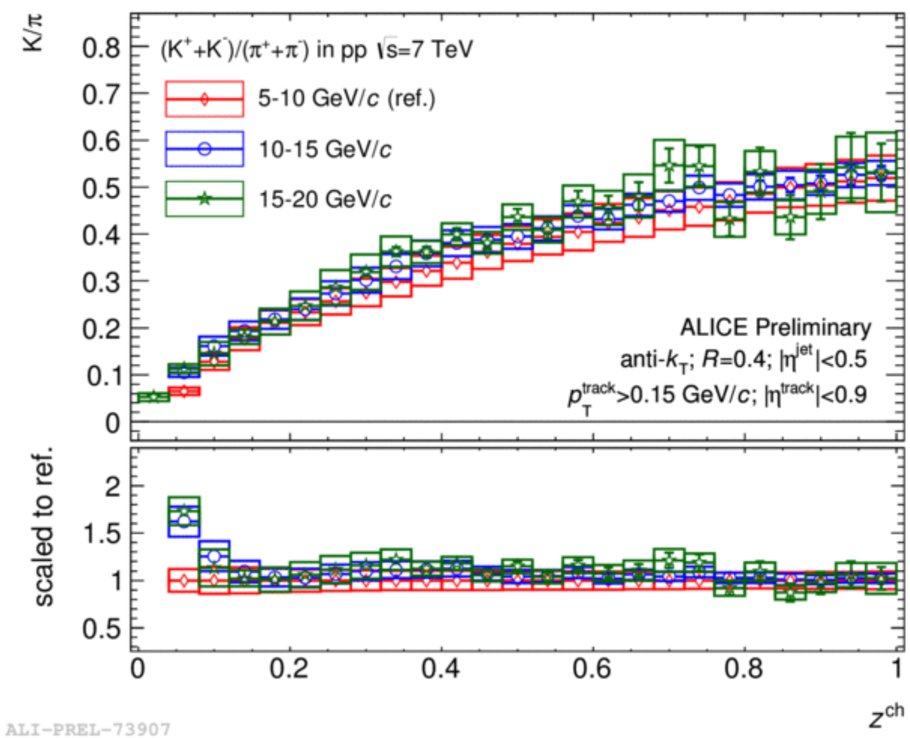
Particle identified fragmentation

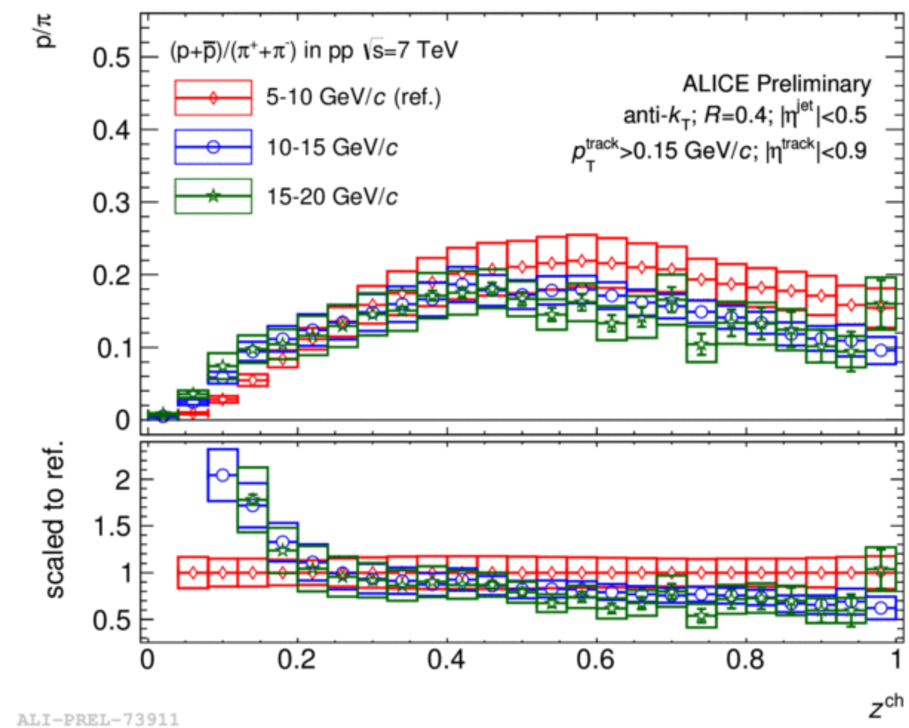
- identified charged hadrons in charged jets at $\sqrt{s}$ = 7 TeV
- π, K, p, 5 < $p_T^{ch\ jet}$ < 20 GeV/c
- scaling for z^{ch} > 0.2 for higher jet p_T bins



Particle ratios in jets

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

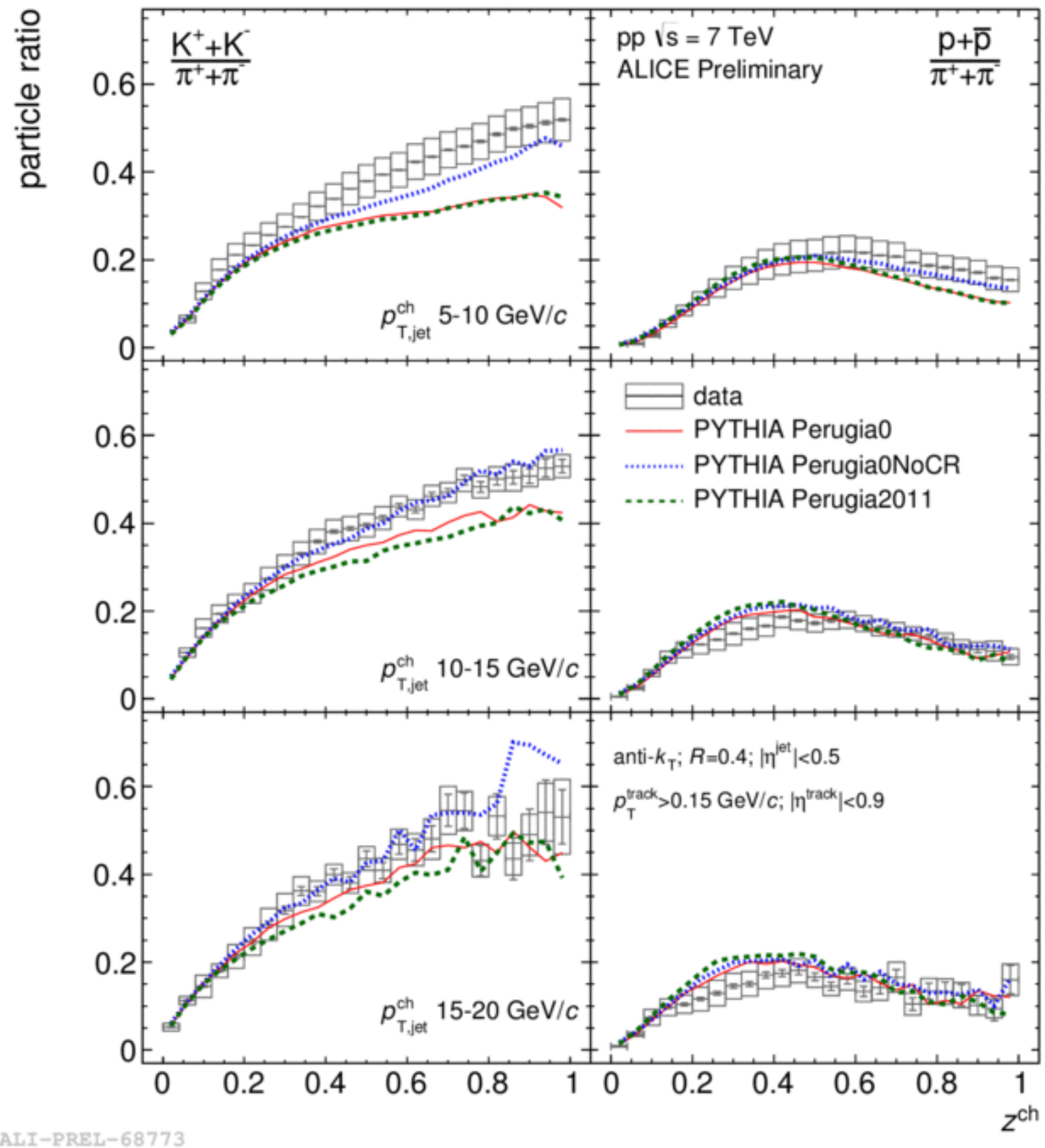




Event generator comparison

筑波大学 University of Tsukuba

- 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

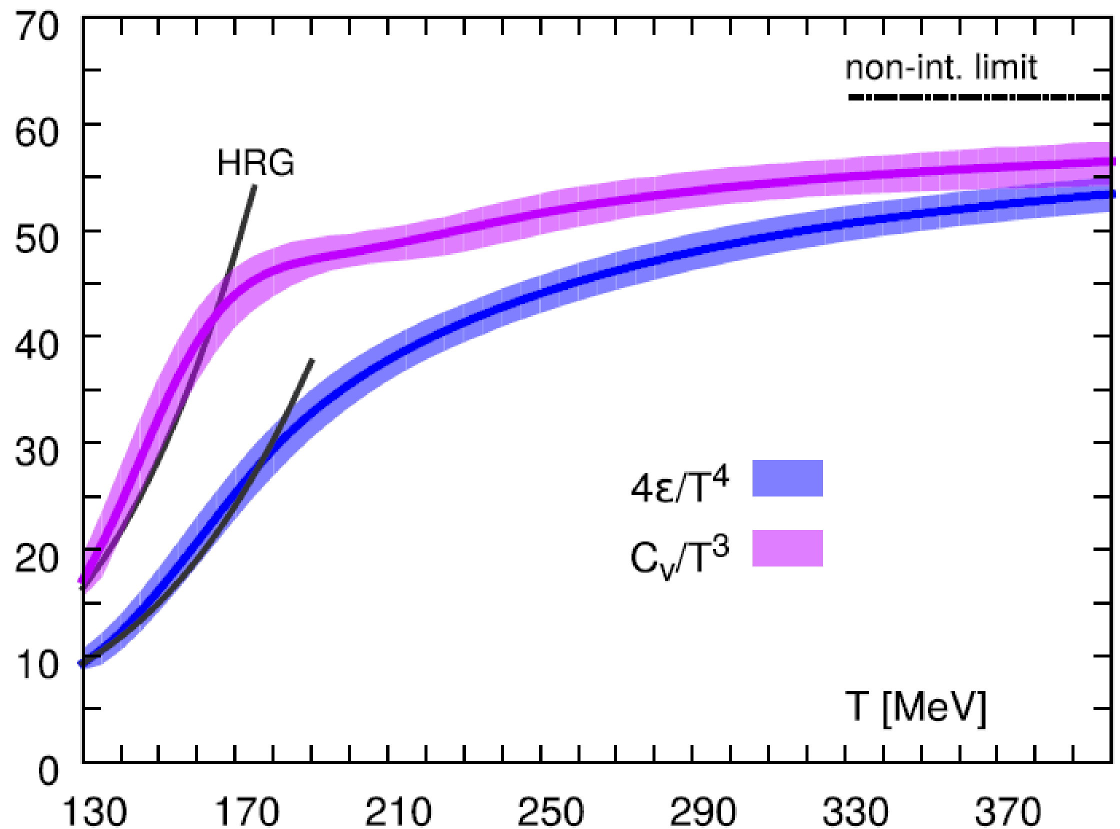
- in heavy-ion collisions at ultra-relativistic energies, a quasi macroscopic fireball of hot, strongly interacting matter in local thermal equilibrium is created

- 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

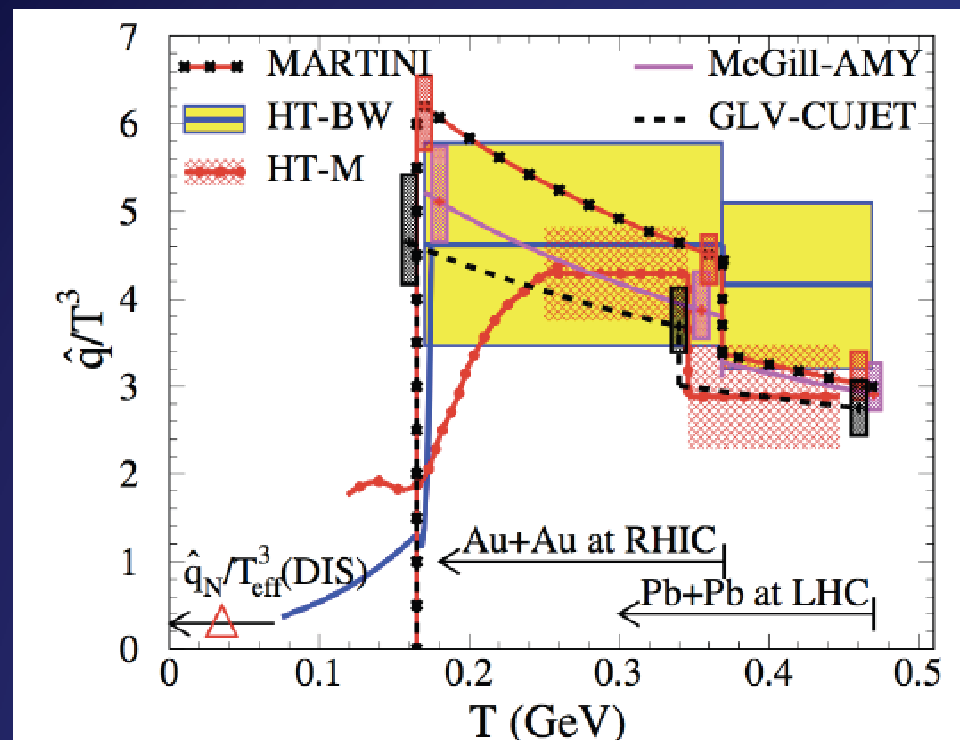
HotQCD, PRD 90, 094503



Partons in heavy-ion collisions

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

JET Collaboration: arXiv:1312.5003



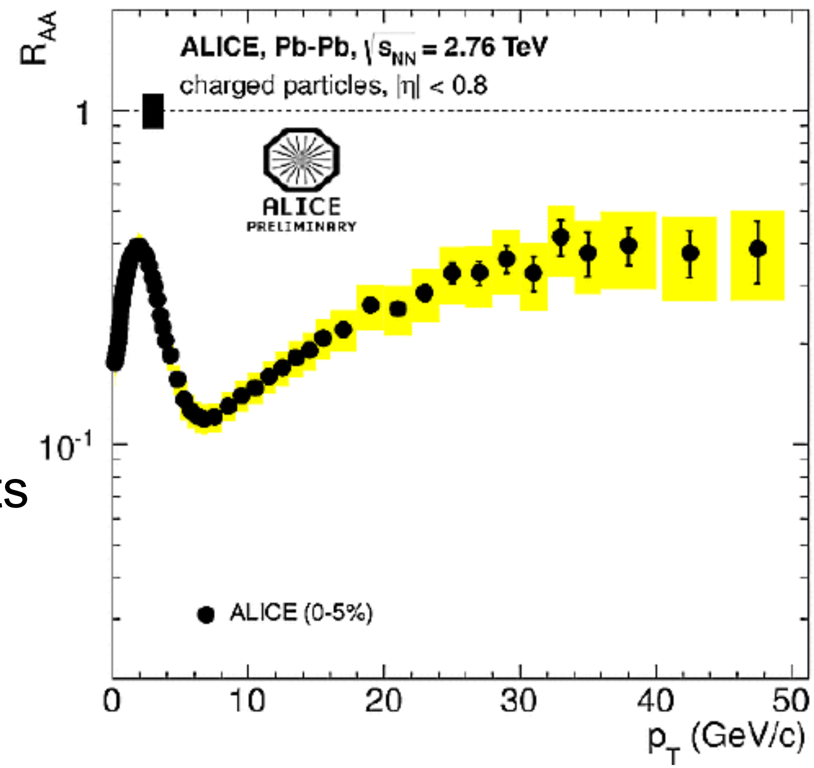
Hadrons in heavy-ion collisions

- hard partons `proxy' for jet

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

PLB 720 (2013) 250

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



- hadron observables biased towards leading fragment

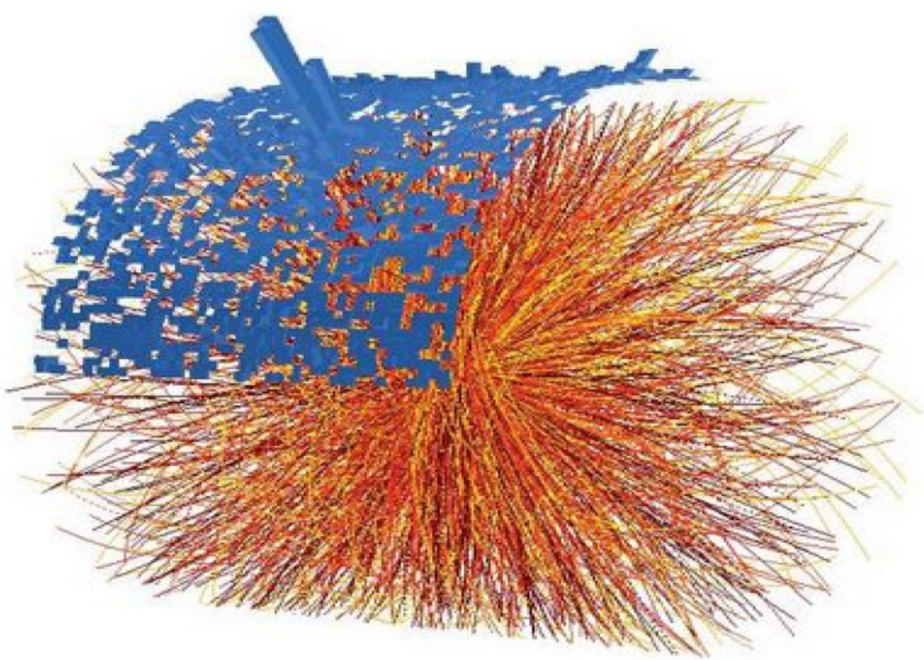
→ study the effect for fully reconstructed jets

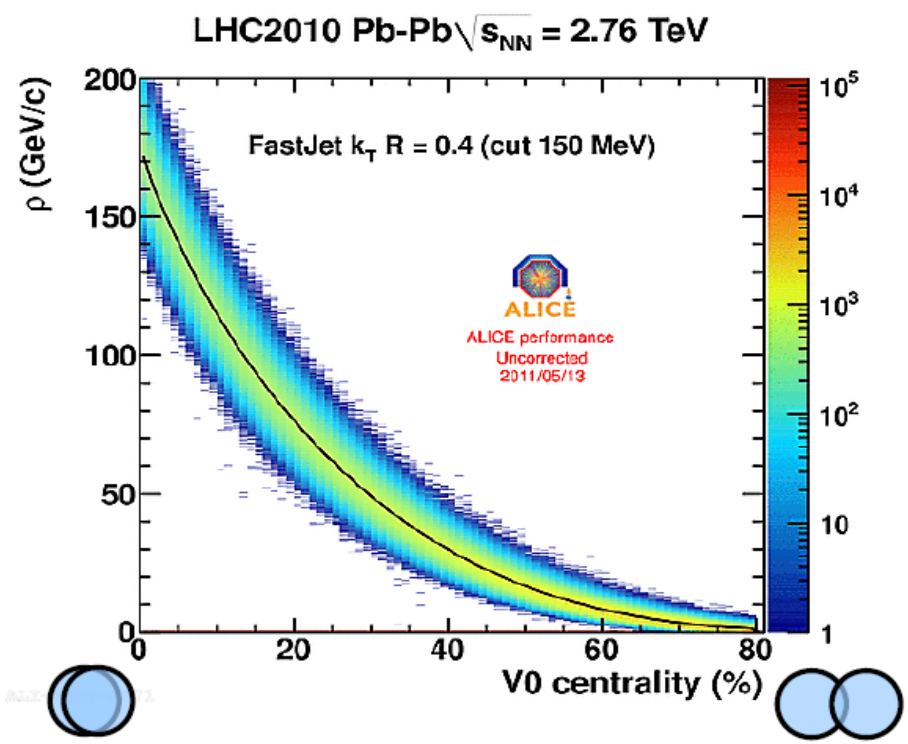
Underlying event in heavy-ion collision

- 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 0 p_T





jet area ~ 0.5 (R = 0.4)

central *peripheral*

Jet nuclear modification factor

- strong suppression observed, similar to hadron R_{AA}
  -> parton energy not recovered inside jet cone

nucl-ex/1502.01689

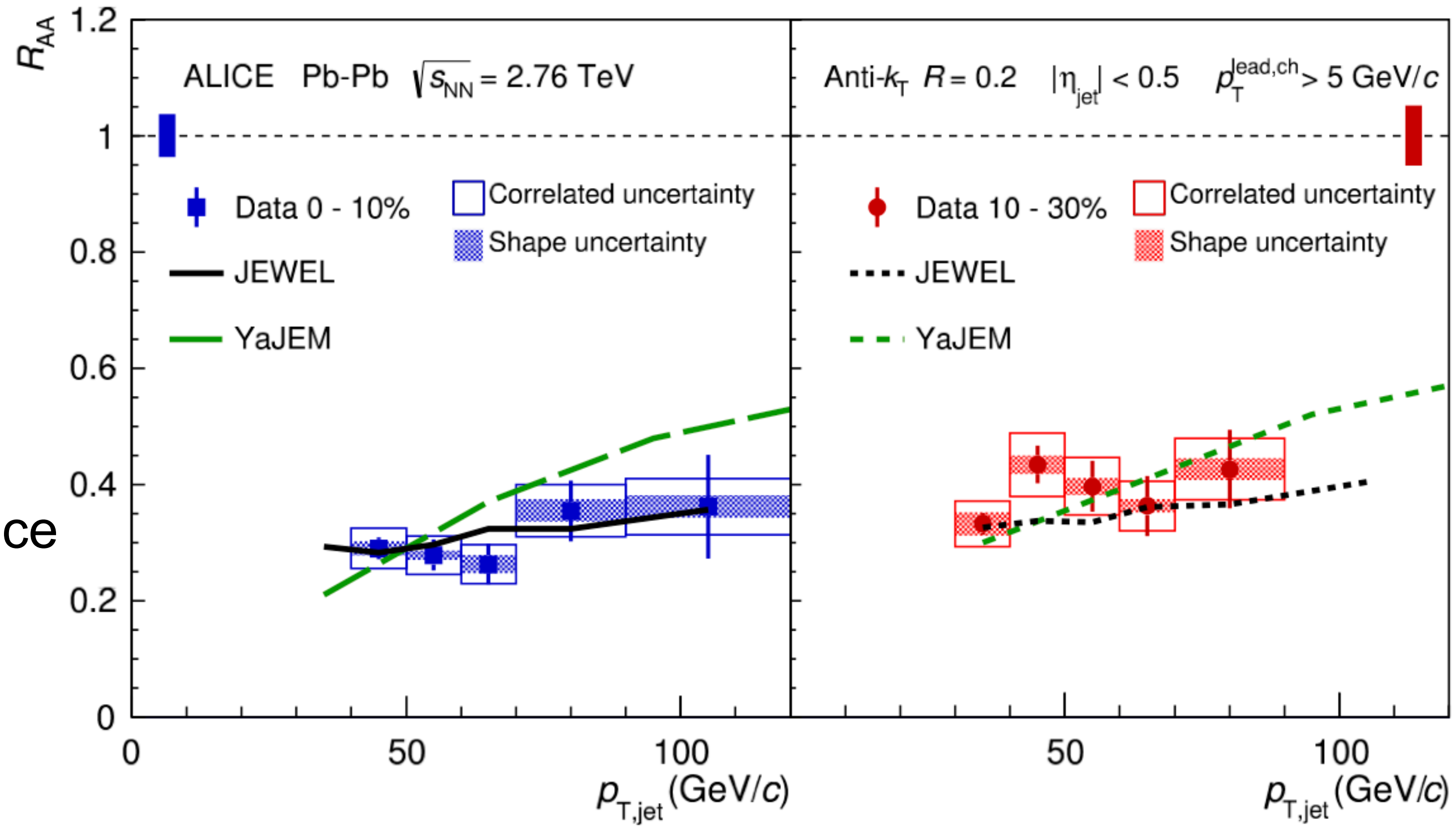
- increase of suppression with centrality

JEWEL: PLB 735 (2014)

YaJEM:PRC 88 (2013) 014905

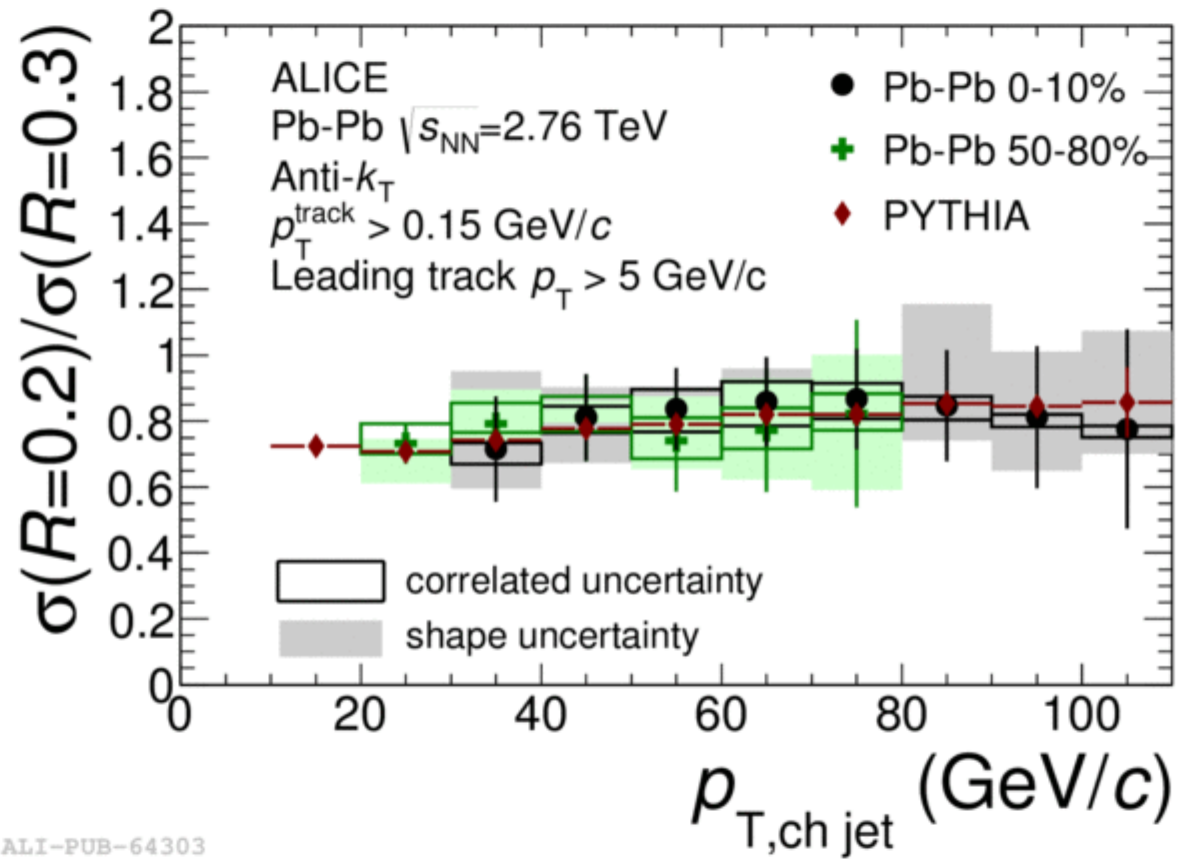
- mild p_T dependence

- JEWEL and YaJEM jet quenching models reproduce suppression



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)



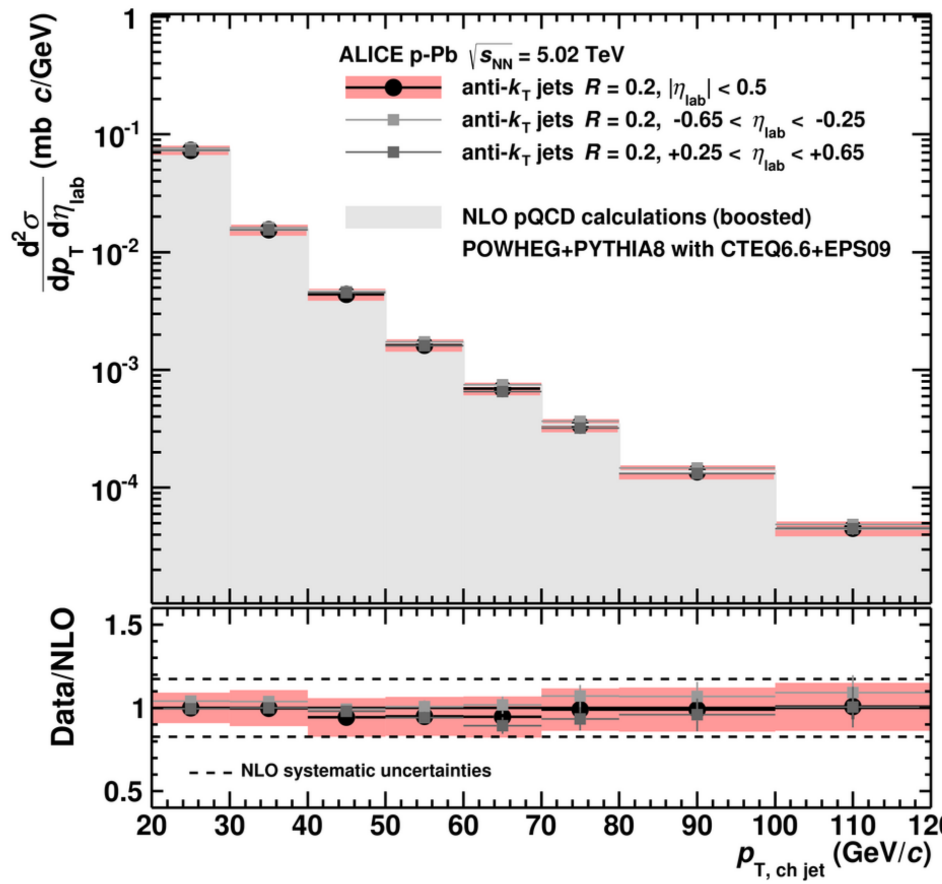
JHEP 03 (2014) 013

Results from p-Pb collisions

Charged jets in p-Pb collisions

- p + Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- check potential initial state effects (nuclear modification of PDF) and effects of cold nuclear matter
- measured spectrum consistent with POWHEG NLO calculations (= NLO + PYTHIA fragmentation)

nucl-ex/1503.00681

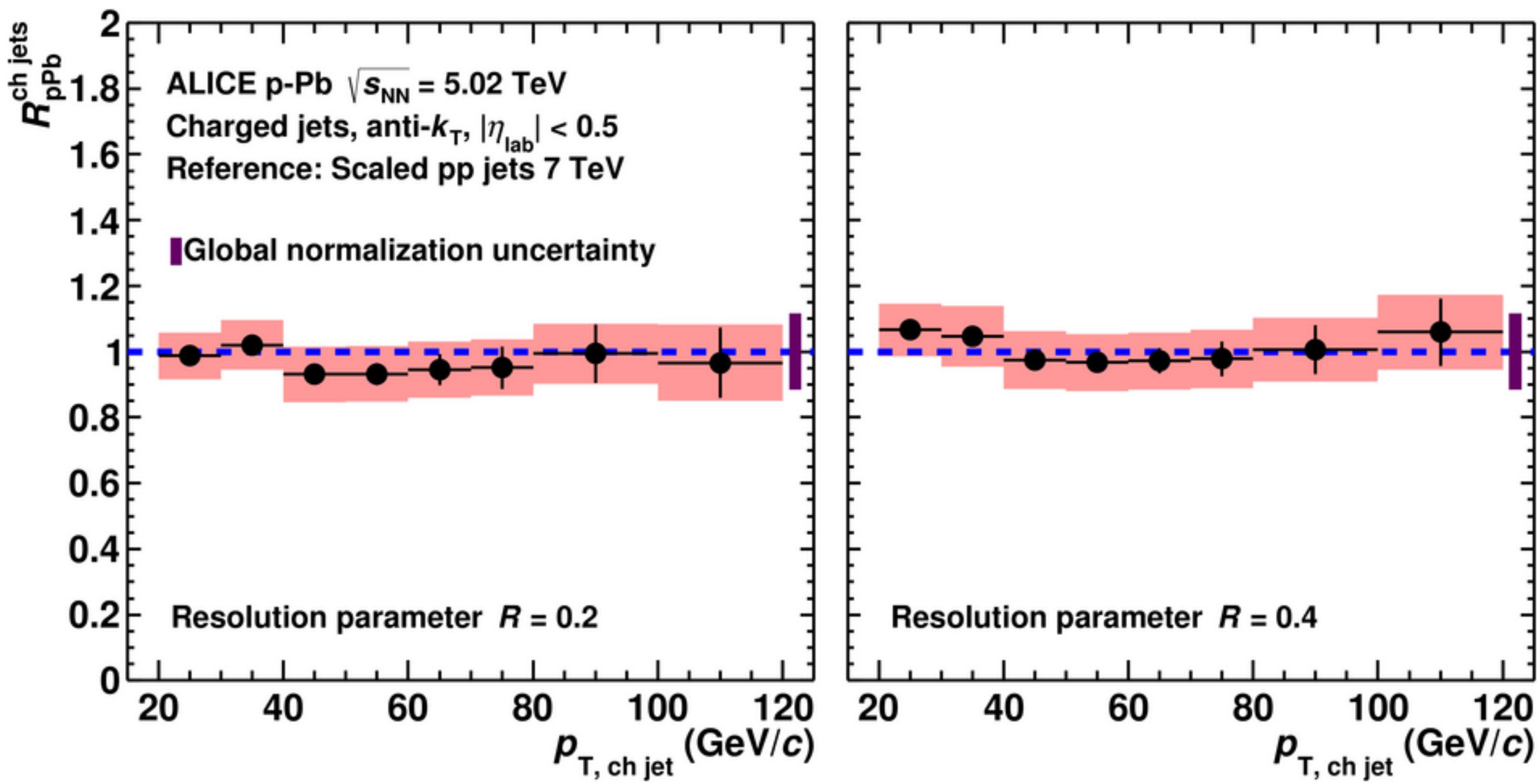


Charged jet $R_{p\text{-}Pb}$

- $R_{p\text{-}Pb}$ using scaled charged jet spectrum measured at 7 TeV as reference

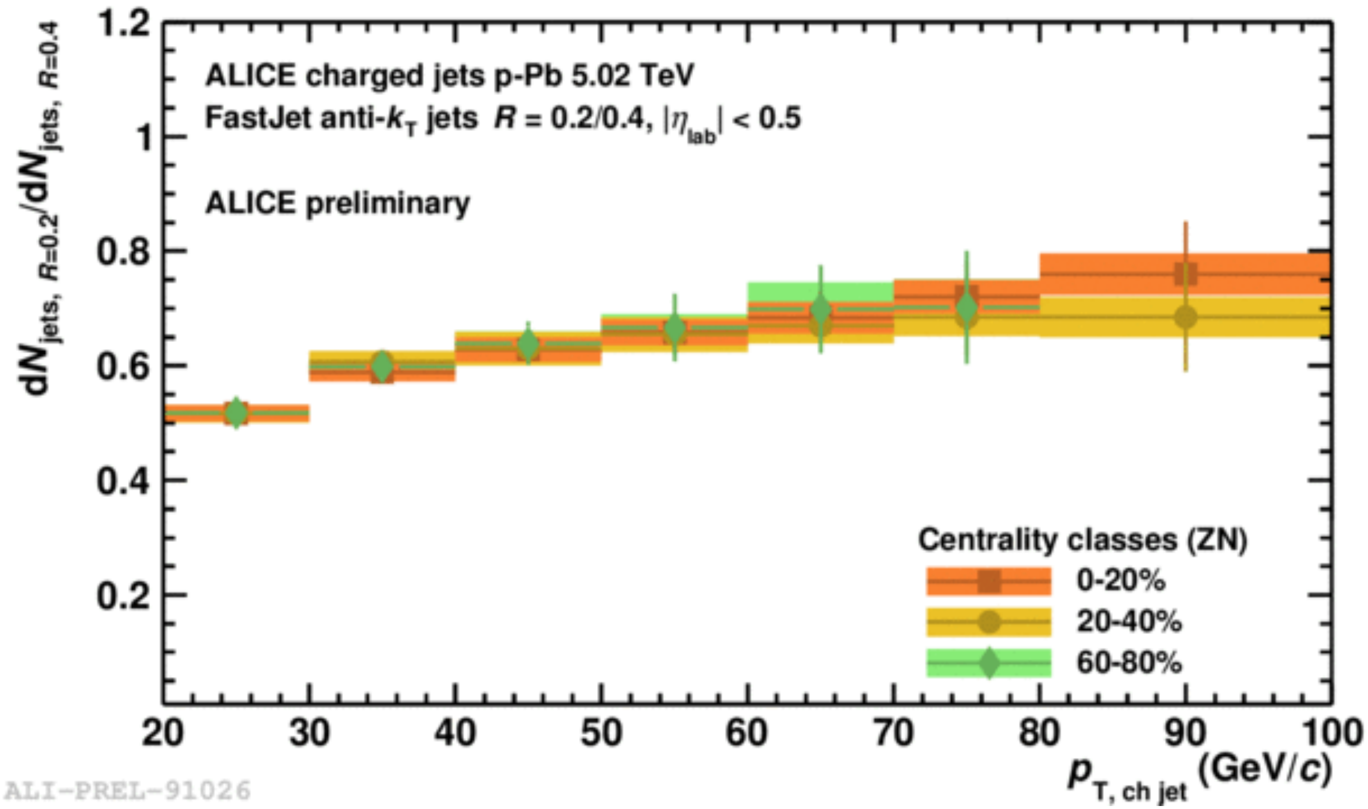
- no jet suppression observed in p-Pb
  -> suppression in Pb-Pb is final state effect

nucl-ex/1503.00681



Jet structure in p-Pb

- `jet structure ratio' R=0.2 / R=0.4 for different centrality classes
- no modification, even for most central p-Pb

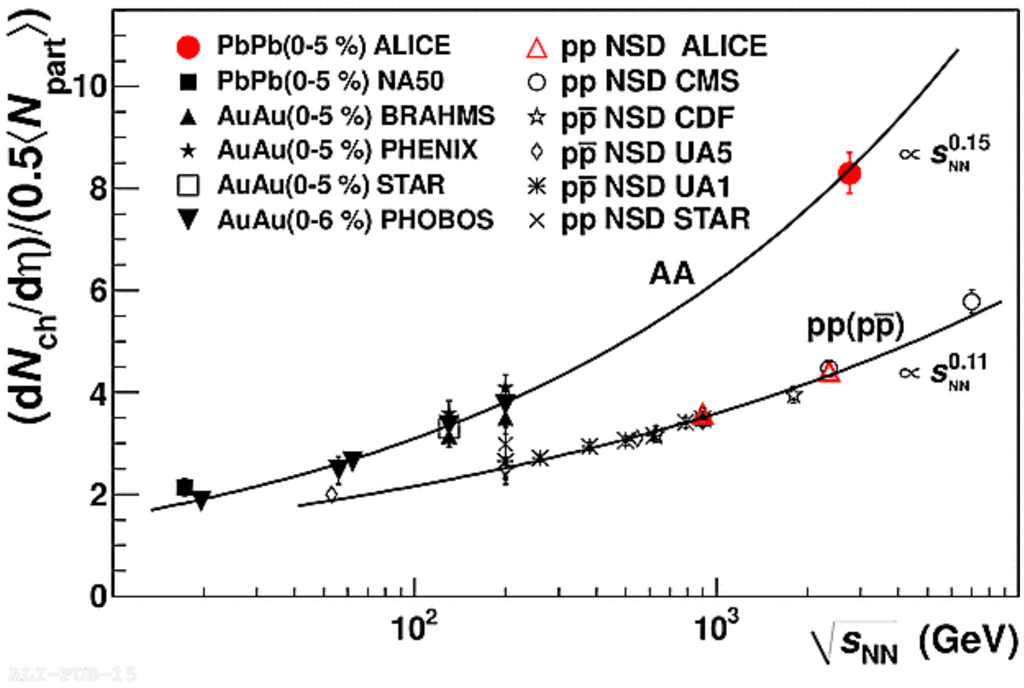


Perspectives for LHC run 2

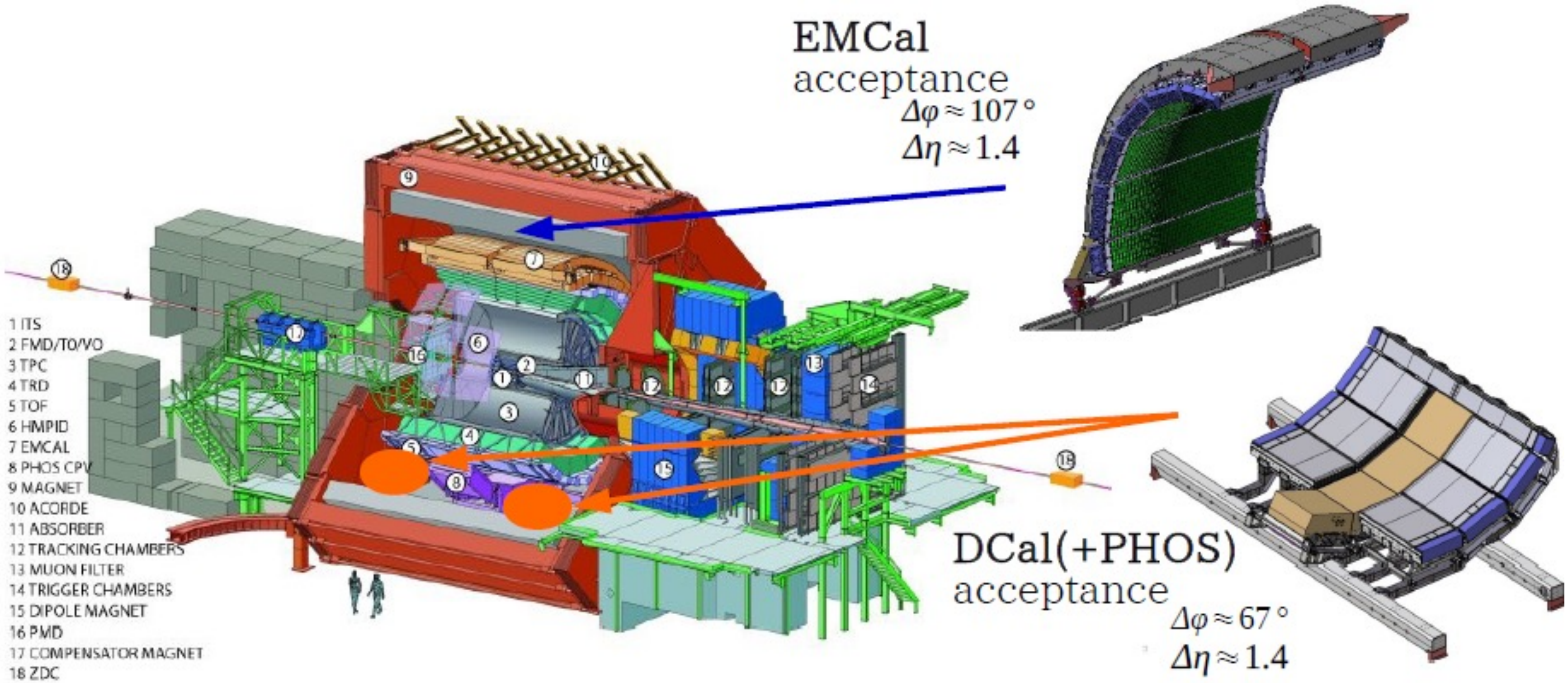
LHC run 2

- LHC run 2: 2015 - 2017
- 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



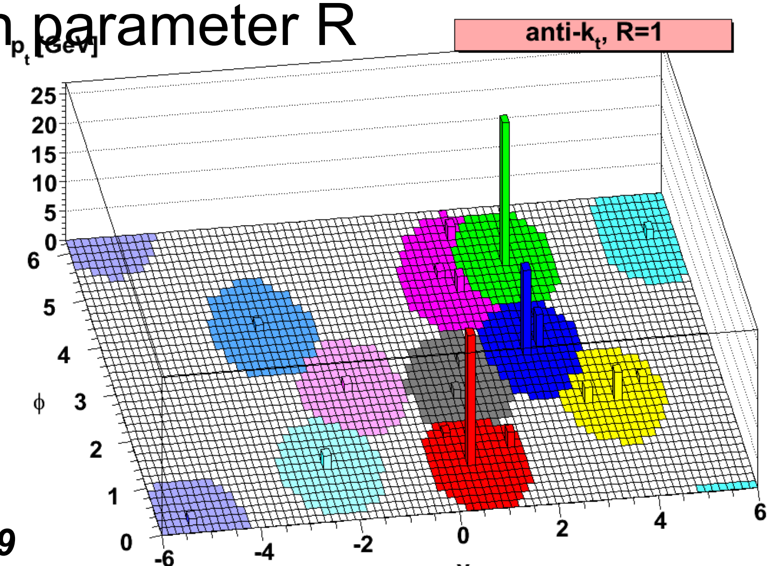
- run 2: DCal upgrade
  - significantly extended jet acceptance
  - back-to-back in azimuth (di-jet topology)

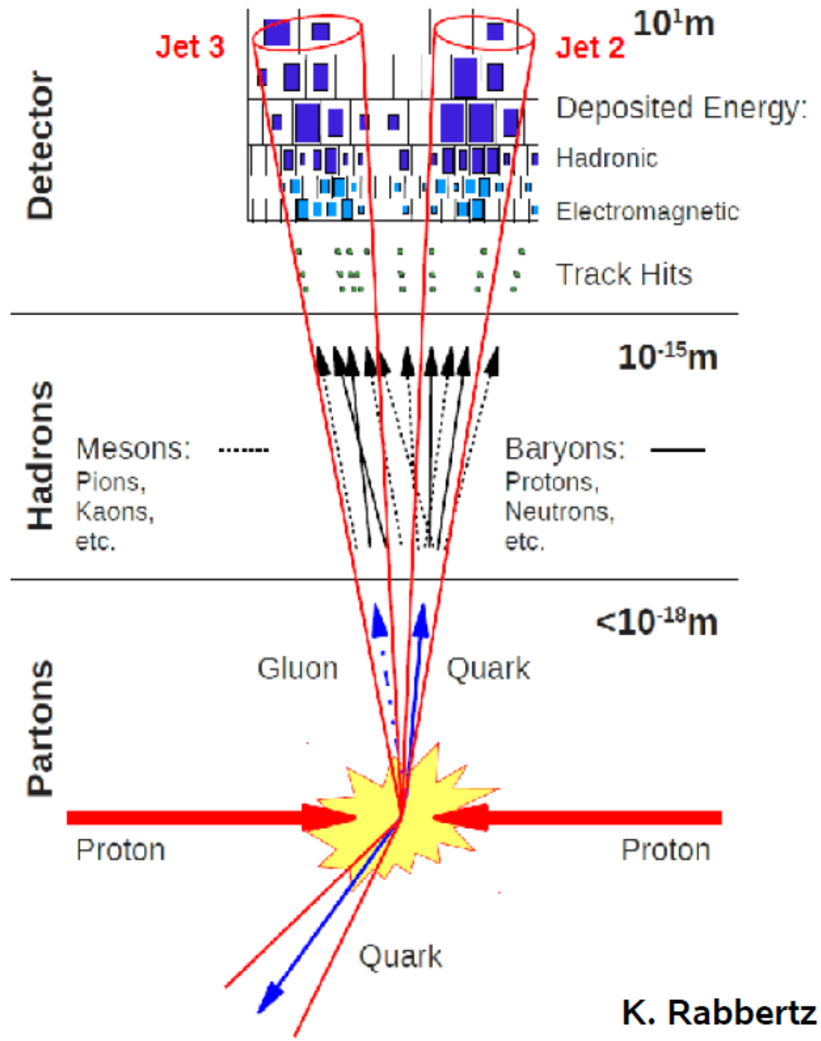
Summary

- jet cross sections and properties in pp
- identified jet fragmentation in pp
- strong jet suppression observed in Pb-Pb collisions
- p-Pb results: initial-state and cold-nuclear-matter effects negligible
- looking forward to LHC run 2 !

Jet reconstruction

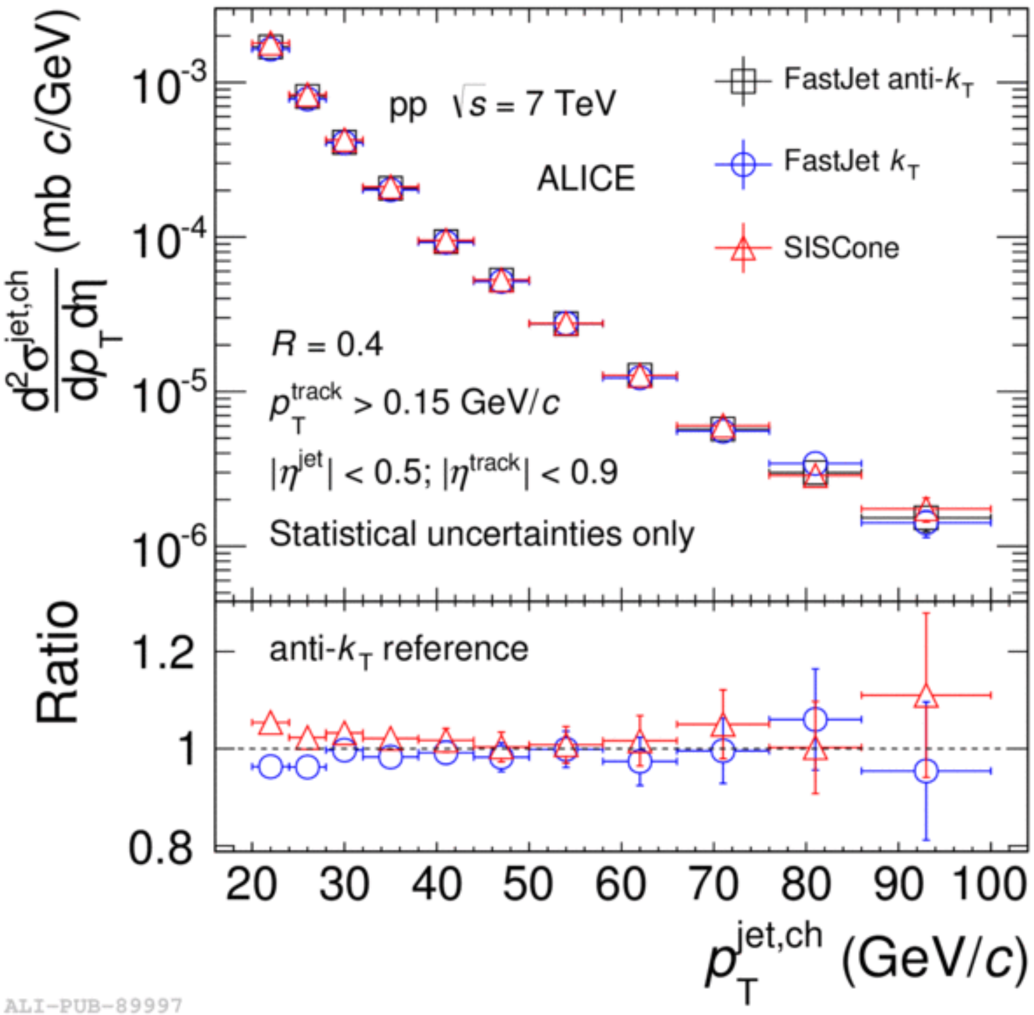
- Establish correspondence between detector measurements / final state particles / partons
- two types of jet finder:
  - iterative cone
  - sequential recombination (e.g. anti-k_T)
- resolution parameter R





hep-ph/0802.1189

Jet finder comparison



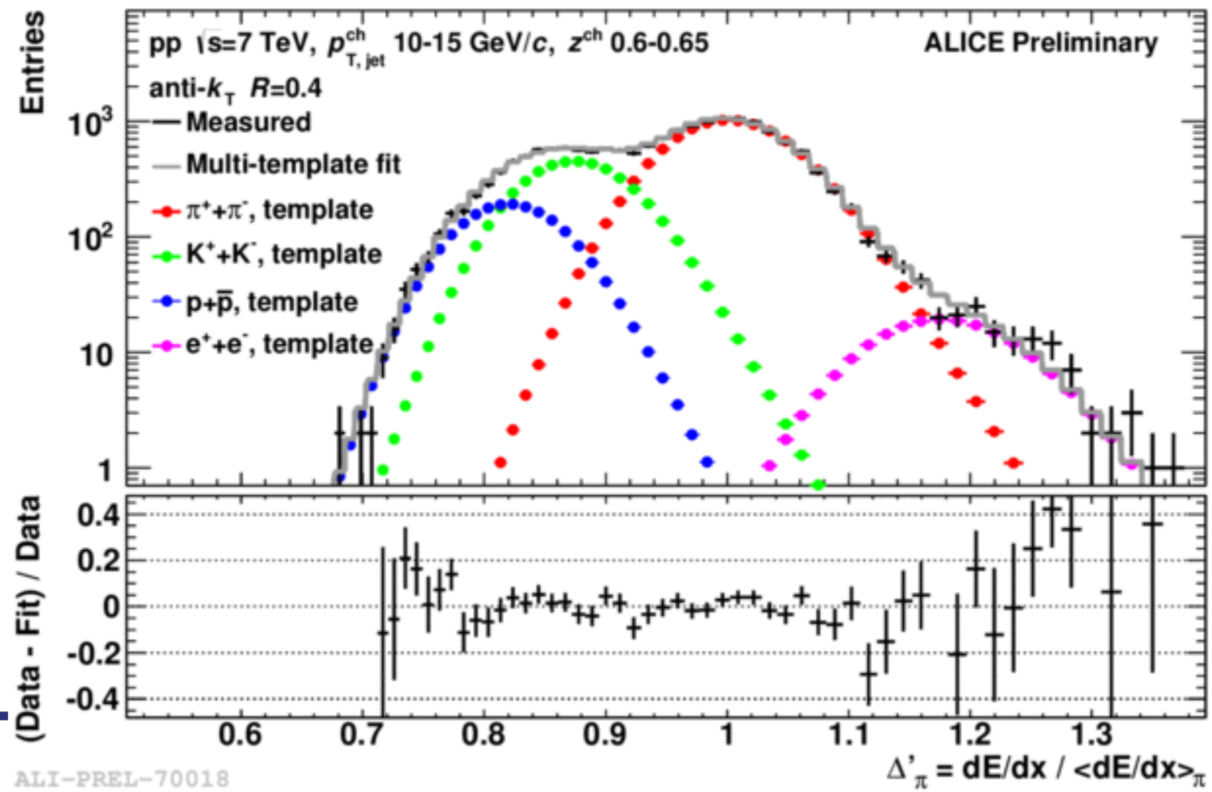
- k_T: sequential recombination
- SISCone: cone algorithm

nucl-ex/1411.4969

Multi Template Fit

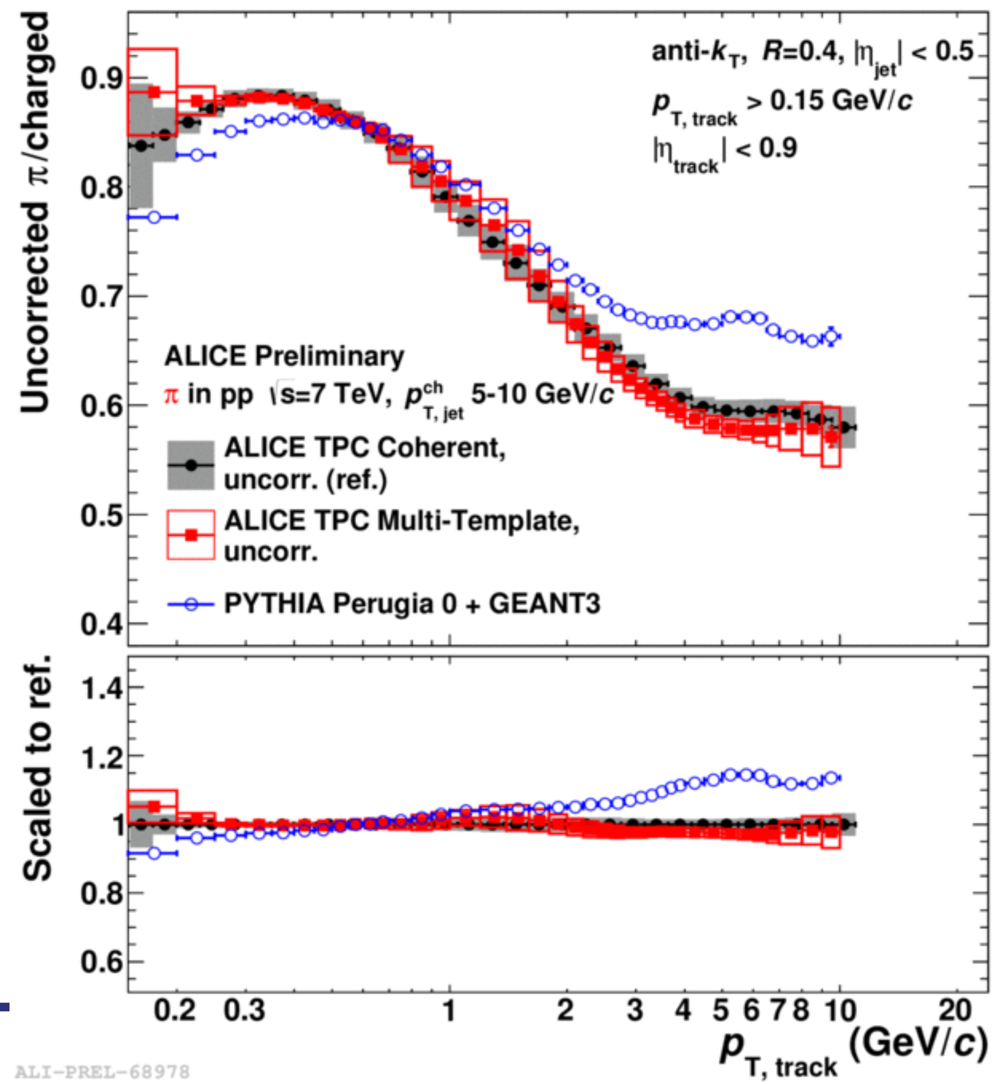
- TPC multi-template fit
  - best possible description of dE/dx from external reference
  - parametrize dependences on η, TPC nClusters
  - templates in transverse momentum (z, xi) slices

- 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



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

- transverse structure: p_T sum in radial slices
- increasing collimation for higher p_T jets
- fragmentation and jet structure reasonably described by event generators

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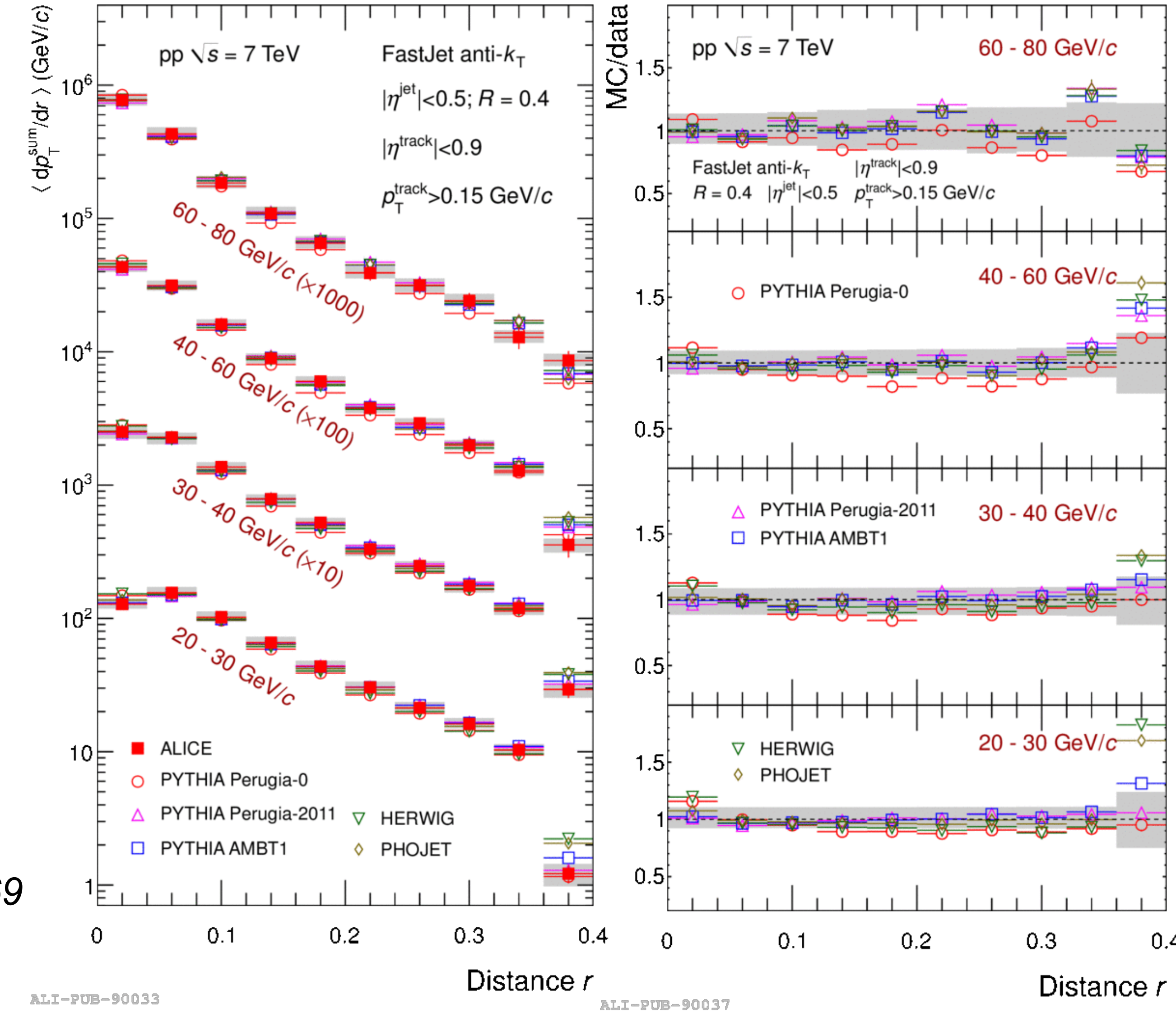
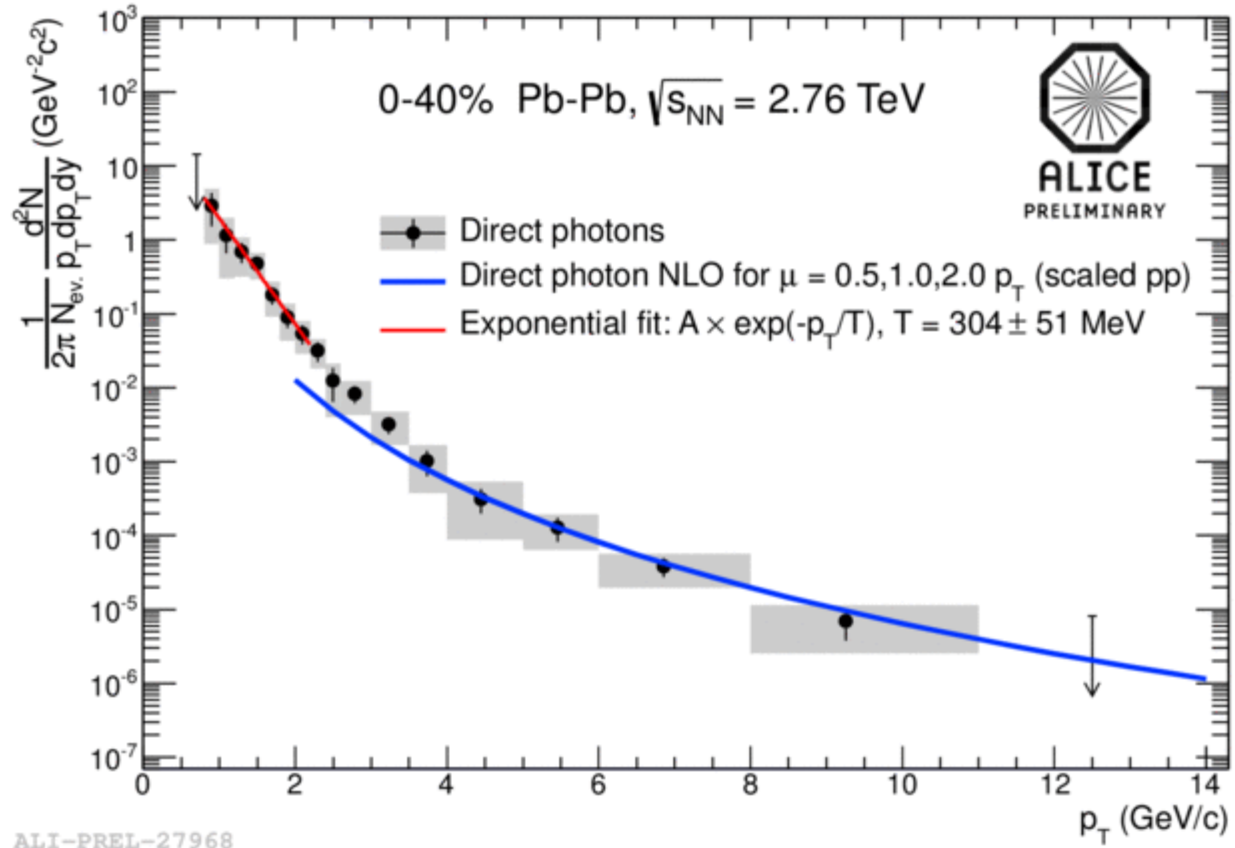


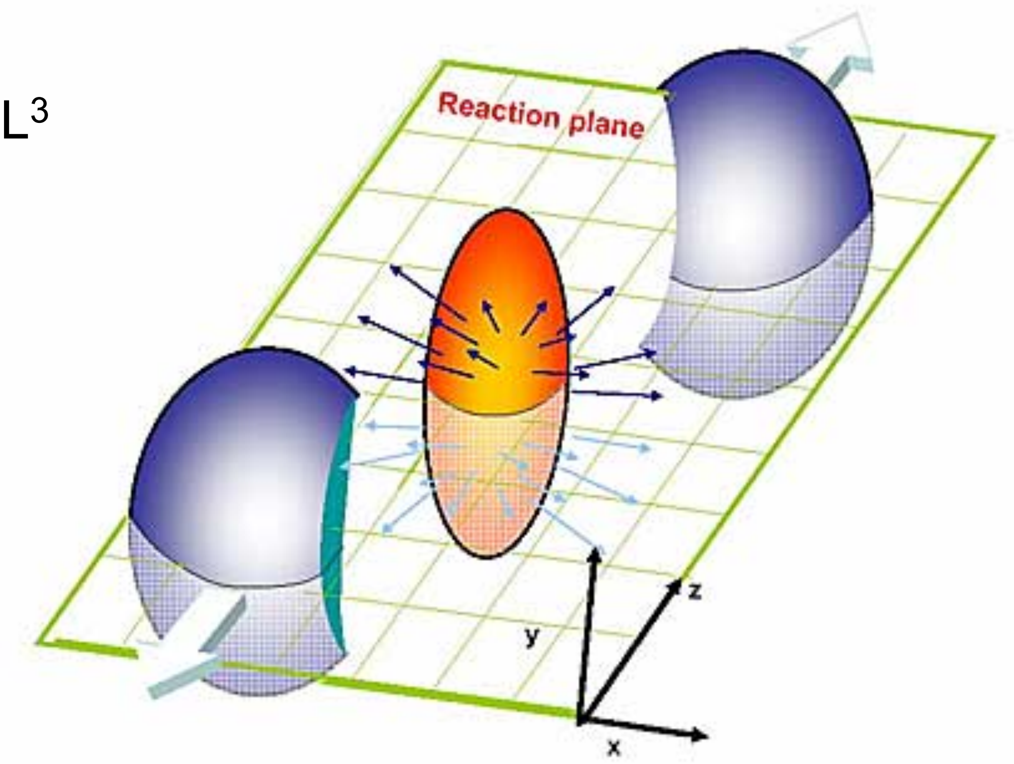
QCD matter at LHC

- direct photons: thermal radiation from the early stage of the fireball
- indicates initial temperature way above T_C



Reaction plane dependence

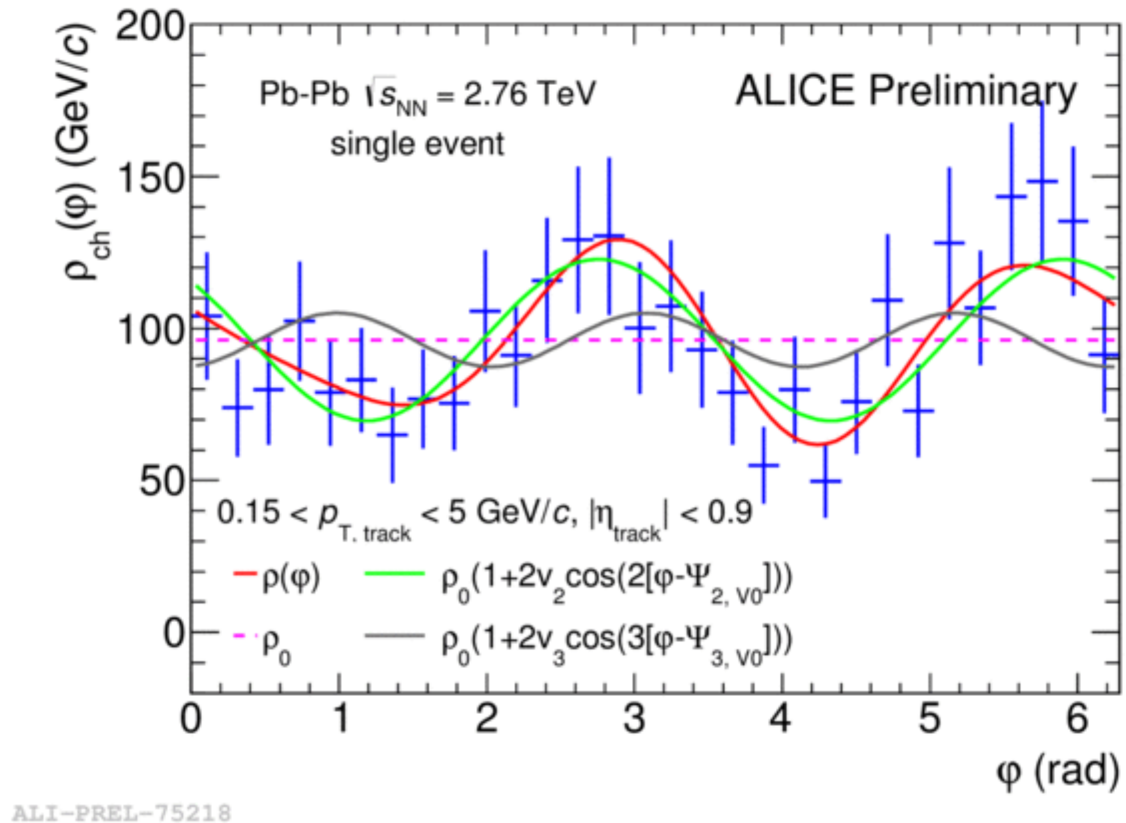
- different medium thickness in- and out-of plane
- sensitive to path length dependence of jet quenching
  pQCD radiative E-loss : ~L^2
  collisional E-loss : ~L
  strong coupling (ADS/CFT) : ~L^3



Local background subtraction

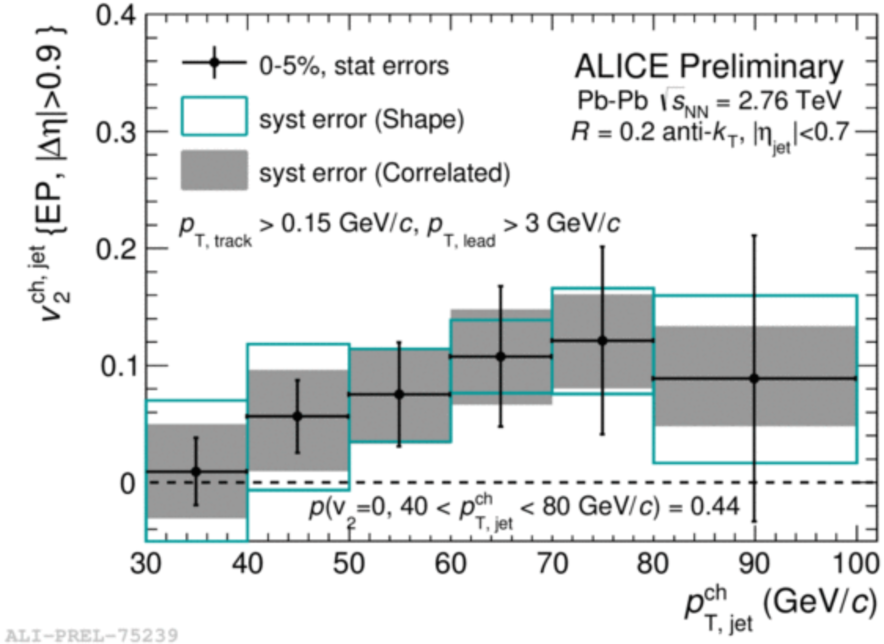
- prerequisite: take event plane dependence of background density into account

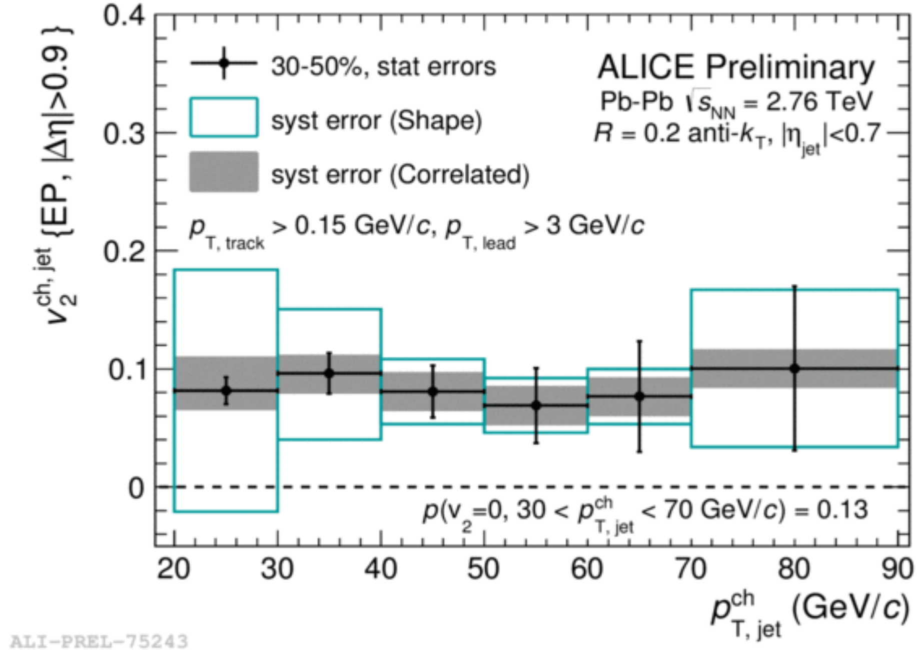
- event-by-event local ρ fit



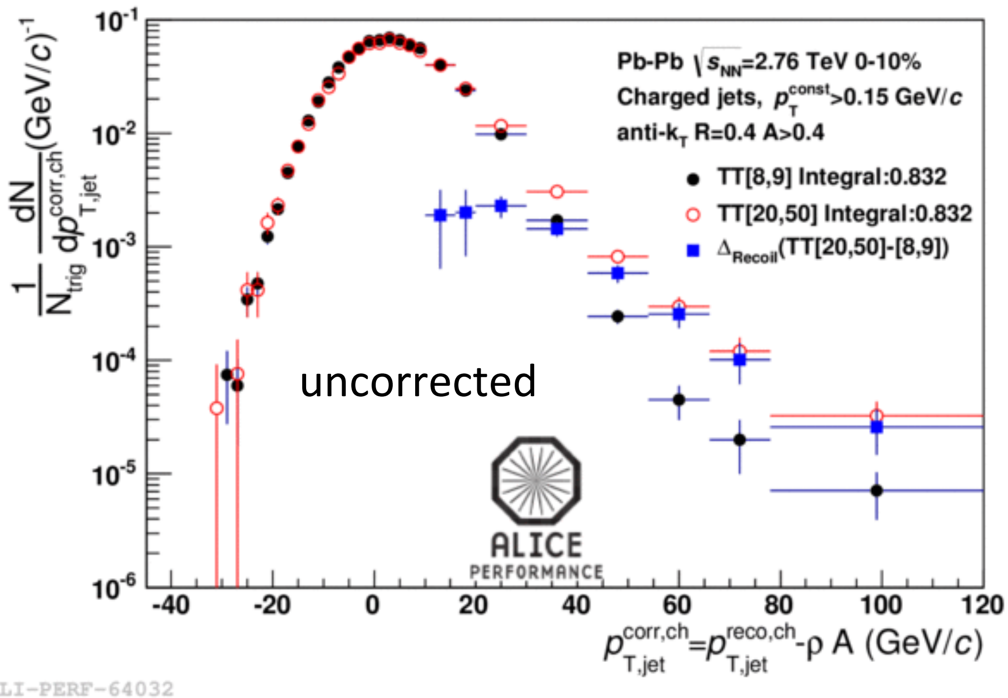
Jet v2 : results

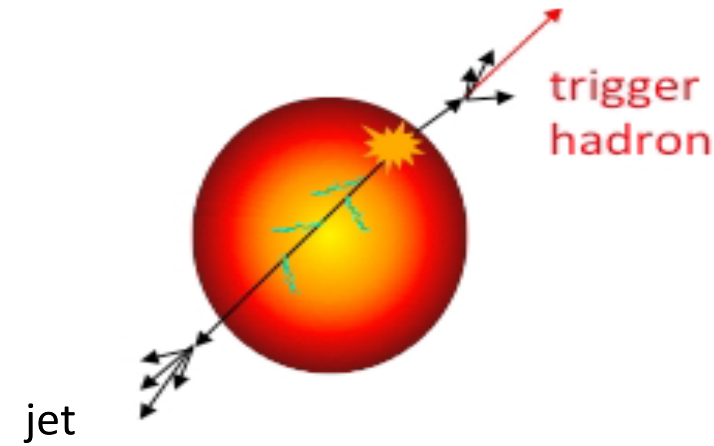
- charged jets, R = 0.2
- quantify azimuthal asymmetry via 2nd Fourier harmonic v2
- strongly hints to non-zero jet v2





Recoil jets





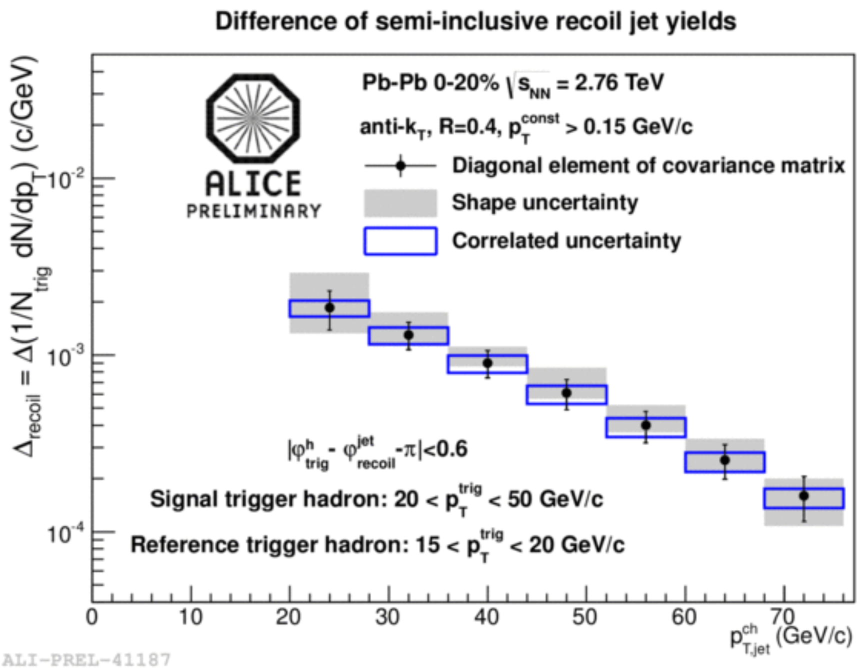
- semi – inclusive recoil jet spectra :
  - reduce fake jet background through 'dijet' topology
  - residual combinatorics subtracted in Δ_{recoil} observable

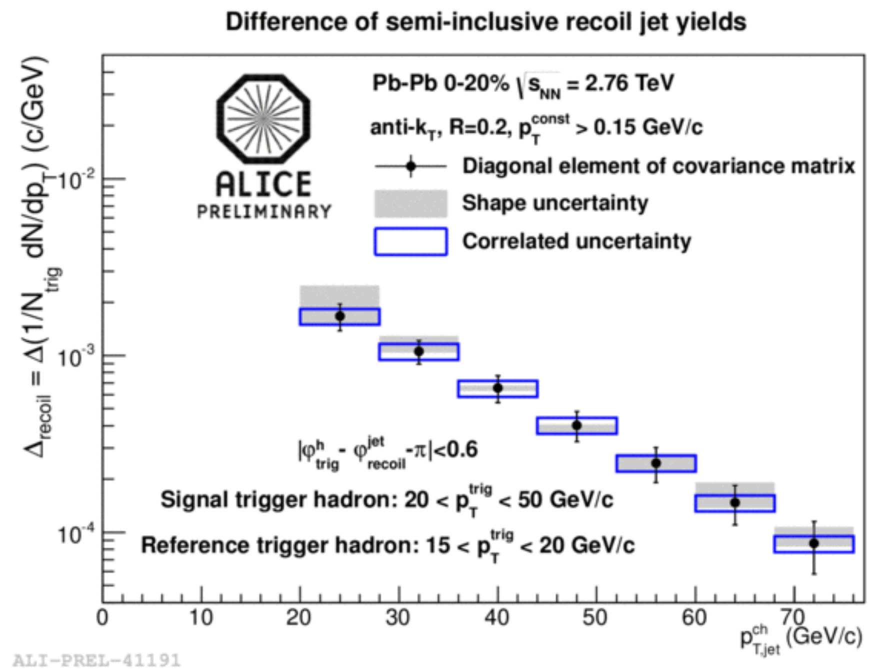
$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{dN_{jet}}{dp_T}\bigg|_{p_{T,trig} \in TT_{Sig}} - \frac{1}{N_{trig}} \frac{dN_{jet}}{dp_T}\bigg|_{p_{T,trig} \in TT_{Ref}}$$

- trigger hadron surface biased → maximize path length for jet

Δ_{recoil}

- fully corrected Δ_{recoil} : R=0.2 and R=0.4



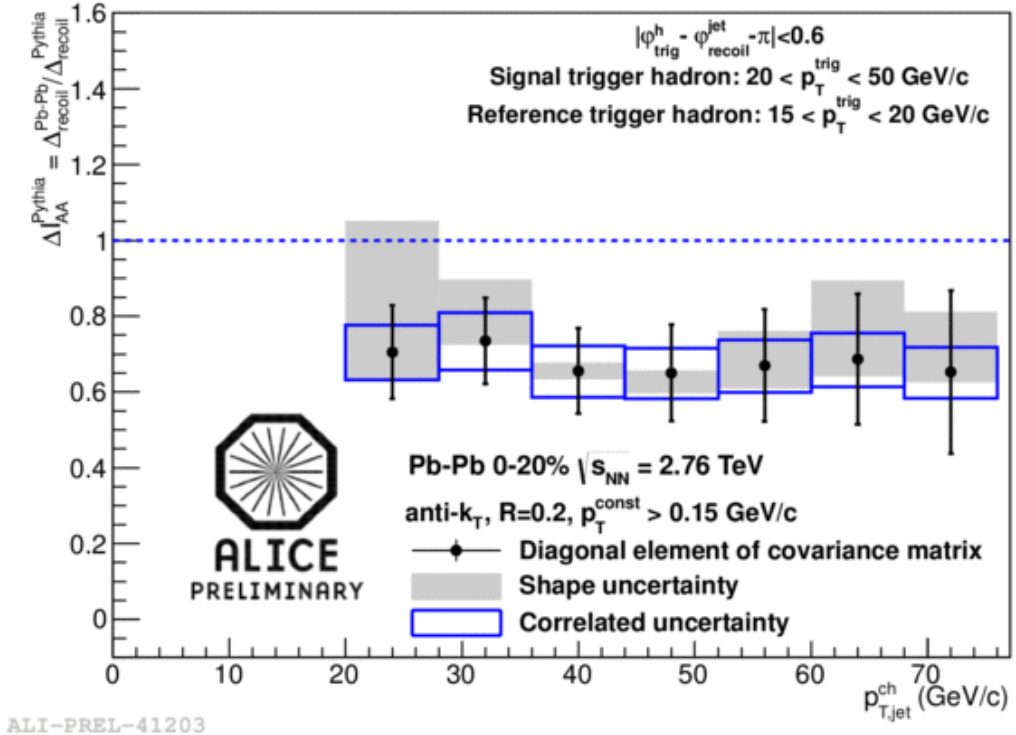


- measurement down to constituent p_T of 150 MeV/c, for large radii (up to R = 0.5) and low jet p_T, without biasing leading constituent

ΔI_{AA}

- ΔI_{AA} : compare to PYTHIA pp reference

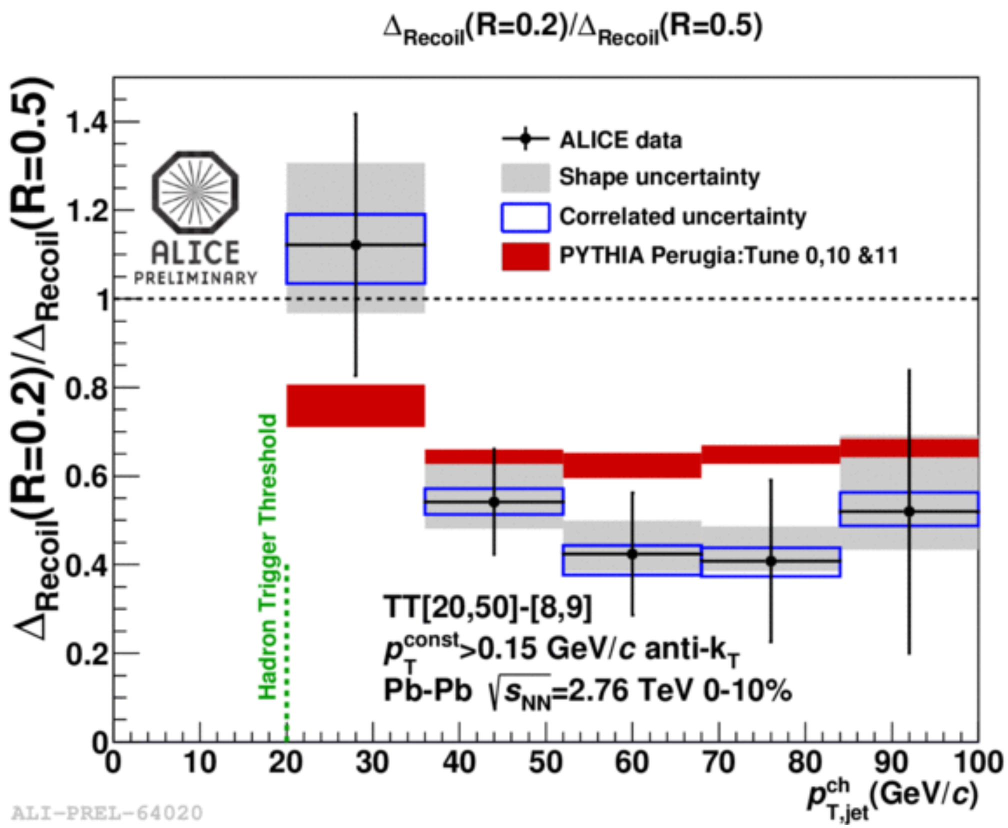
$$\Delta I_{AA} = \Delta^{\text{Pb-Pb}}_{\text{recoil}} / \Delta^{\text{pp}}_{\text{recoil}}$$



- suppression observed

Jet structure ratio

- Δ_{recoil} Ratio R=0.2 / R=0.5 :
  sensitive to potential broadening of jet structure



- consistent with PYTHIA within large experimental uncertainties