Strangeness production and nuclear modification at LHC energies

Oliver Busch

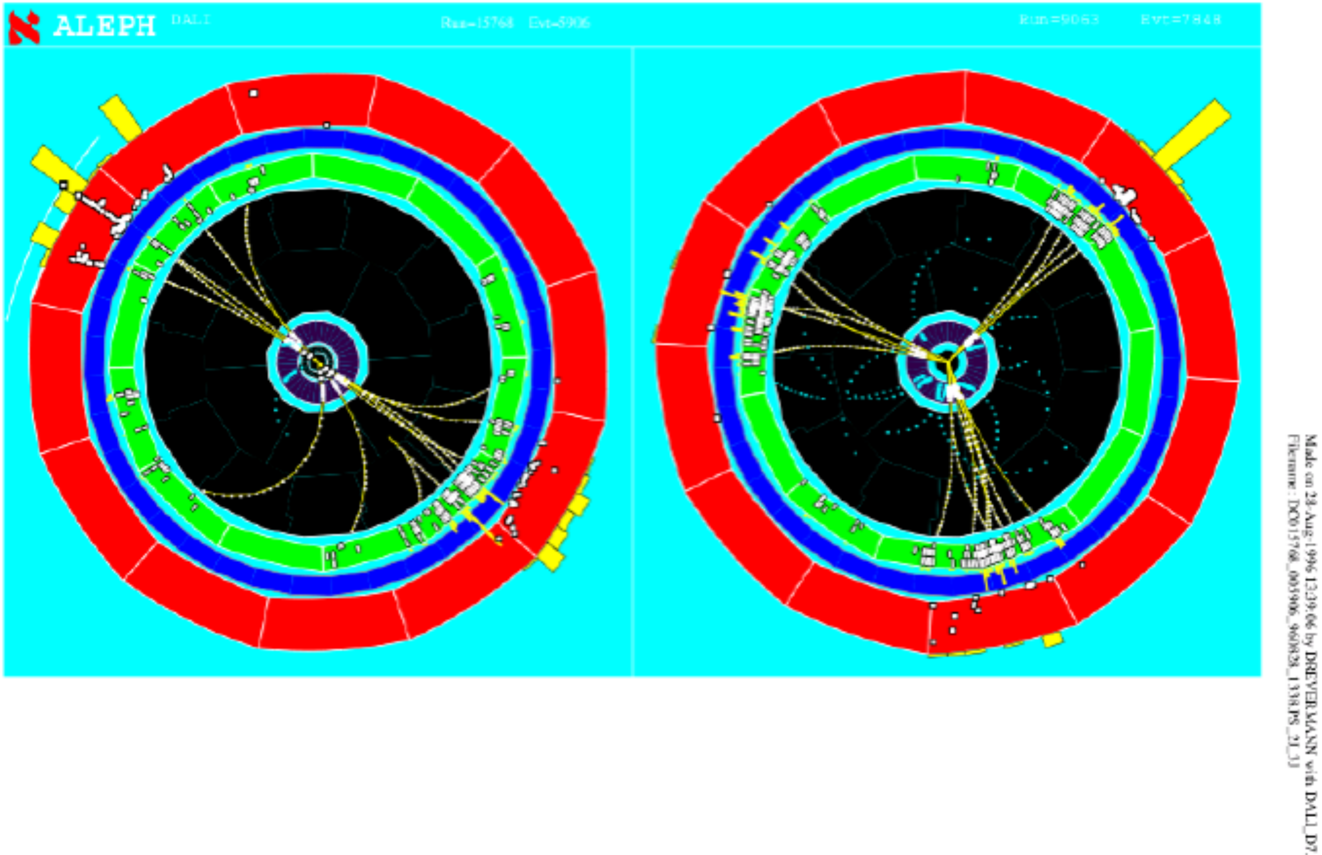
for the ALICE collaboration

Outline

- introduction
- jet azimuthal anisotropy
- jet shapes

Introduction

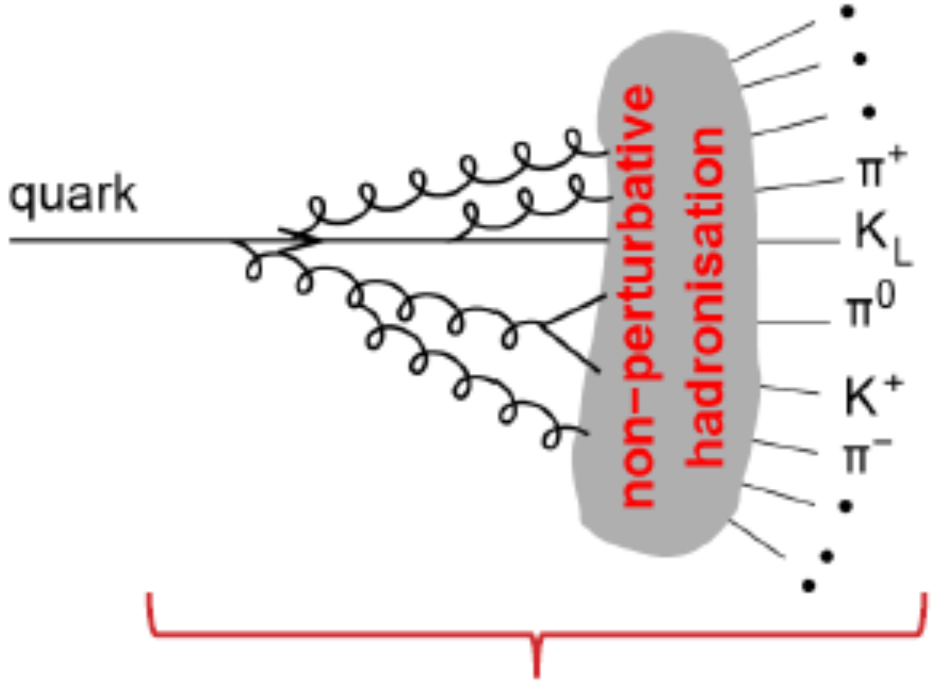
Jets: seeing quarks and gluons



- 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 (anti-)quarks and gluons: parton shower
- at soft scale ($O(\Lambda_{QCD})$): hadronization



QCD phase transition

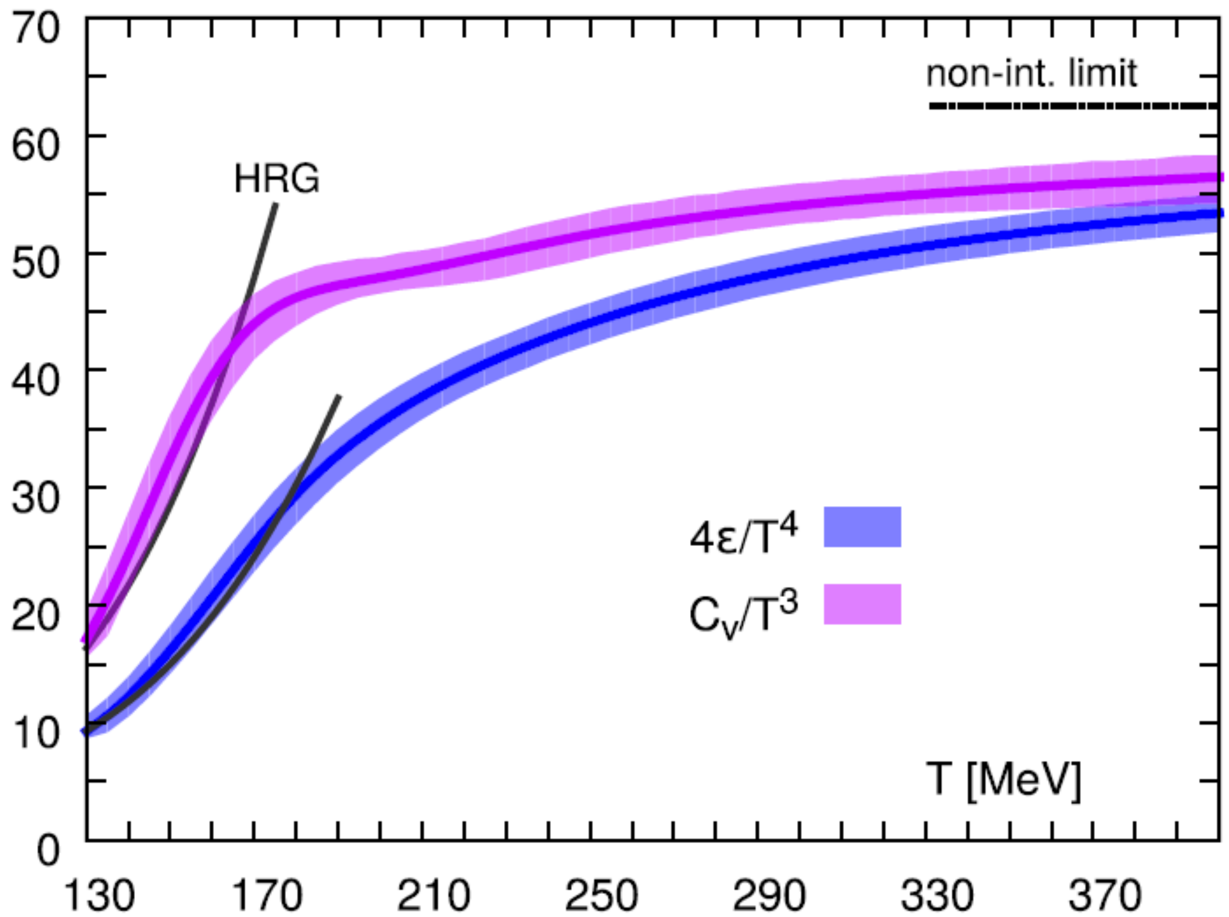
- in heavy-ion collisions at ultra-relativistic energies, a quasi macroscopic fireball of hot, strongly interacting matter in local thermal equilibrium is created

- 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)

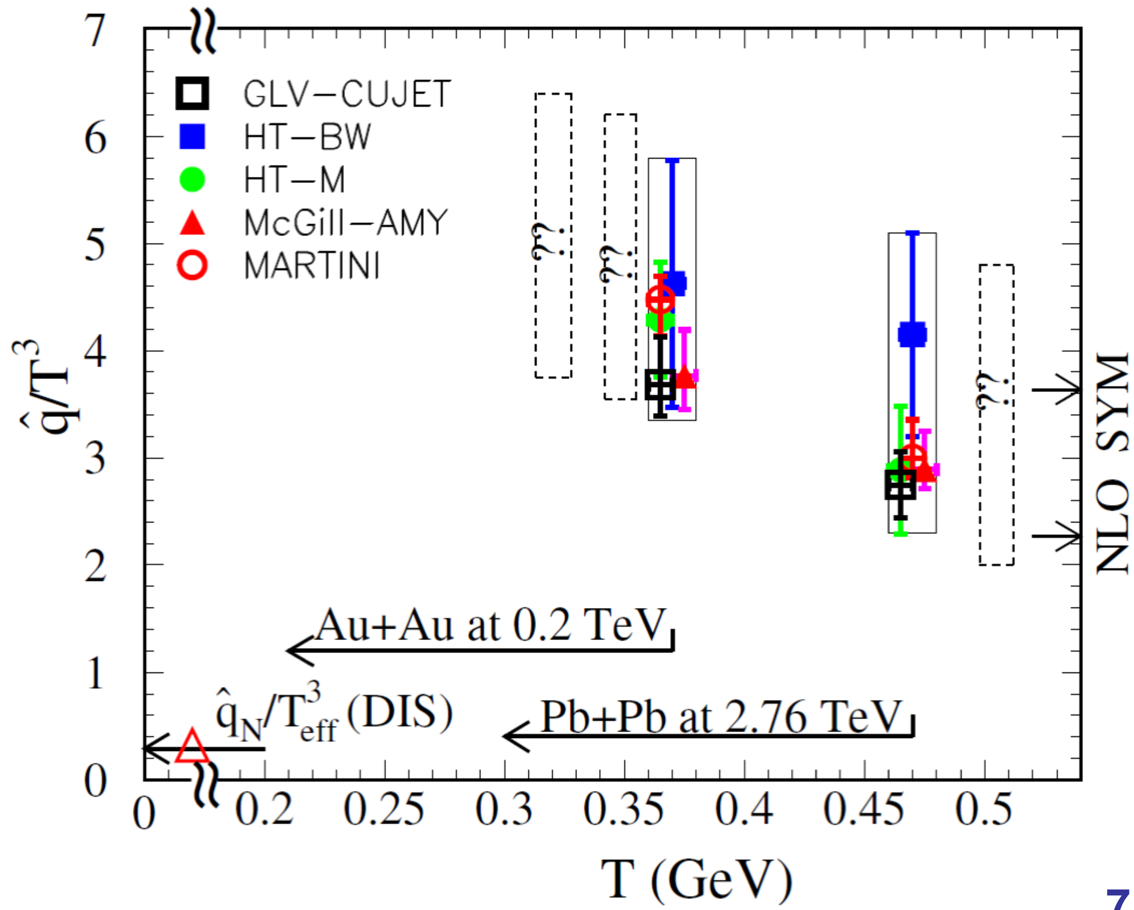
- T_C = 154 +/- 9 MeV
  ε_C = 340 +/- 45 MeV/fm^3

HotQCD, PRD 90, 094503



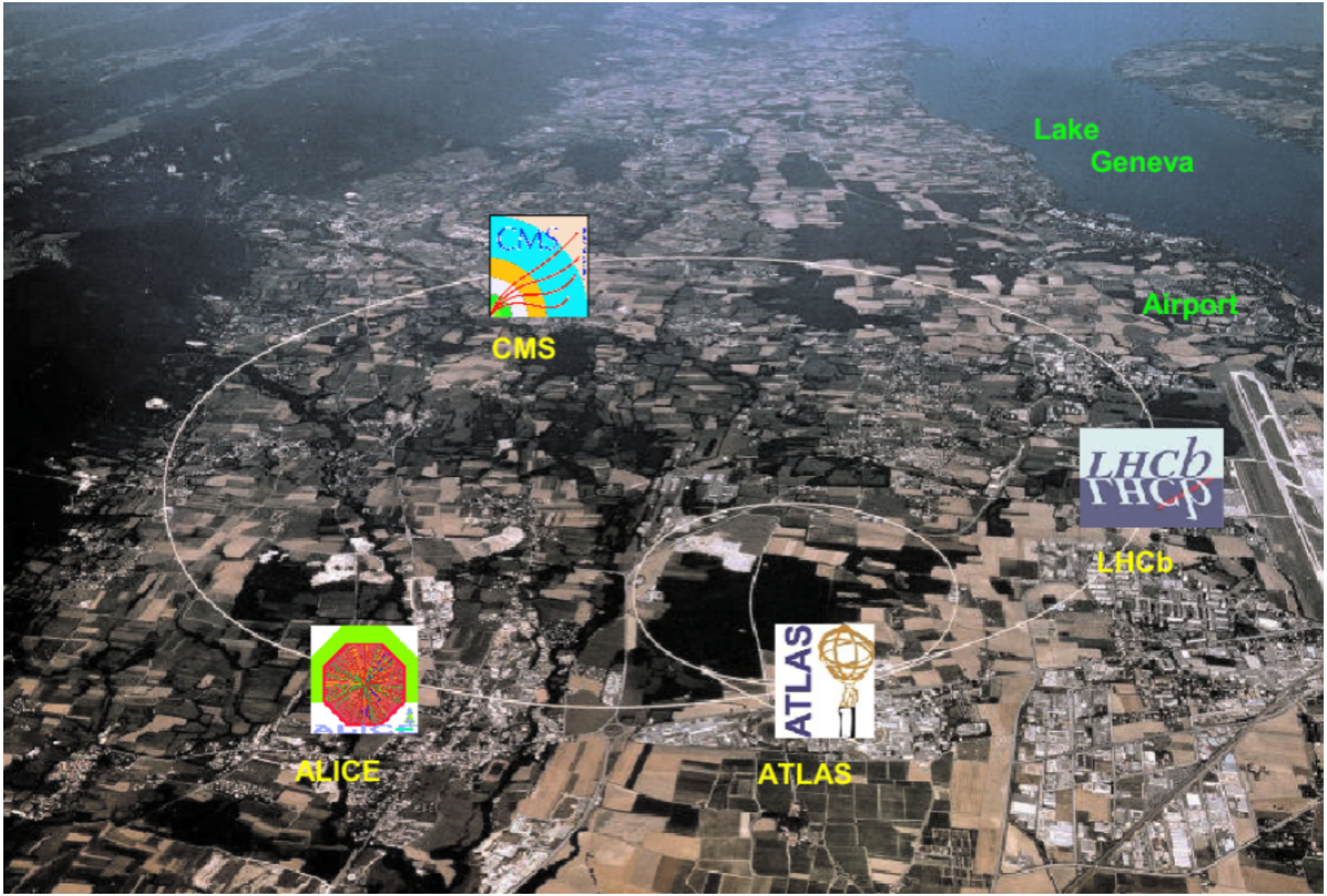
Partons in heavy-ion collisions

- hard partons are produced early and traverse the hot and dense QGP
- 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 ...)

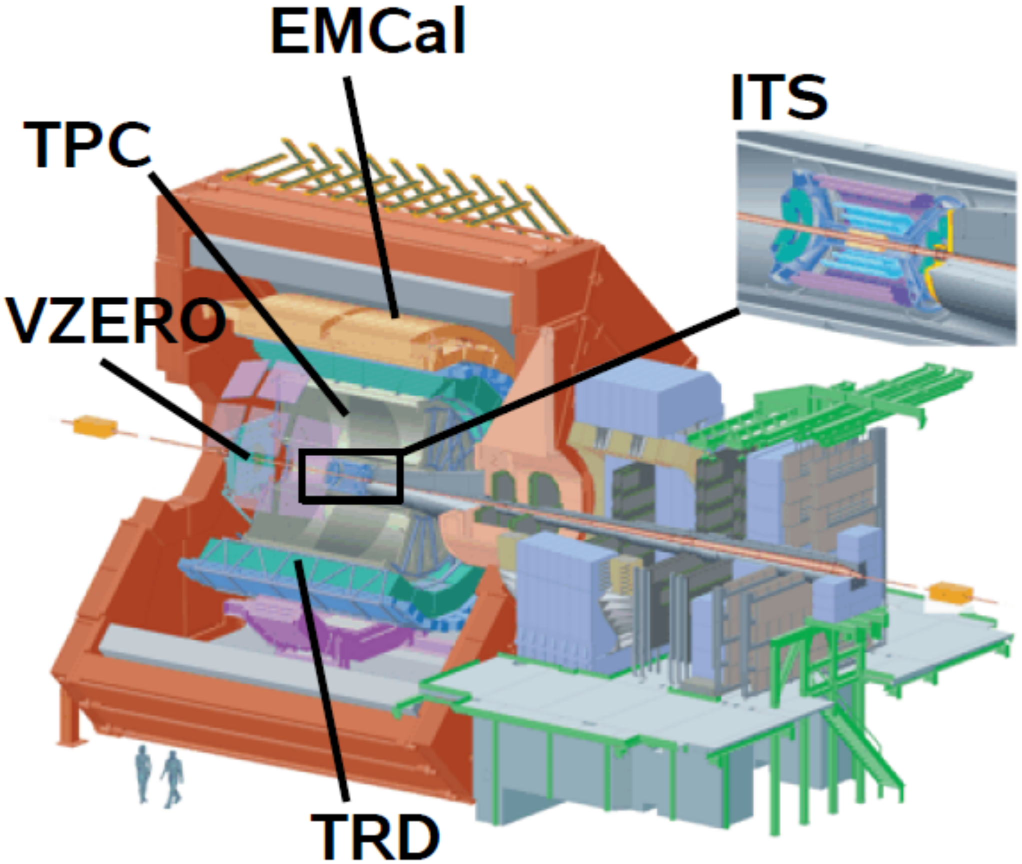


JET collaboration, arXiv: 1312.5003

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

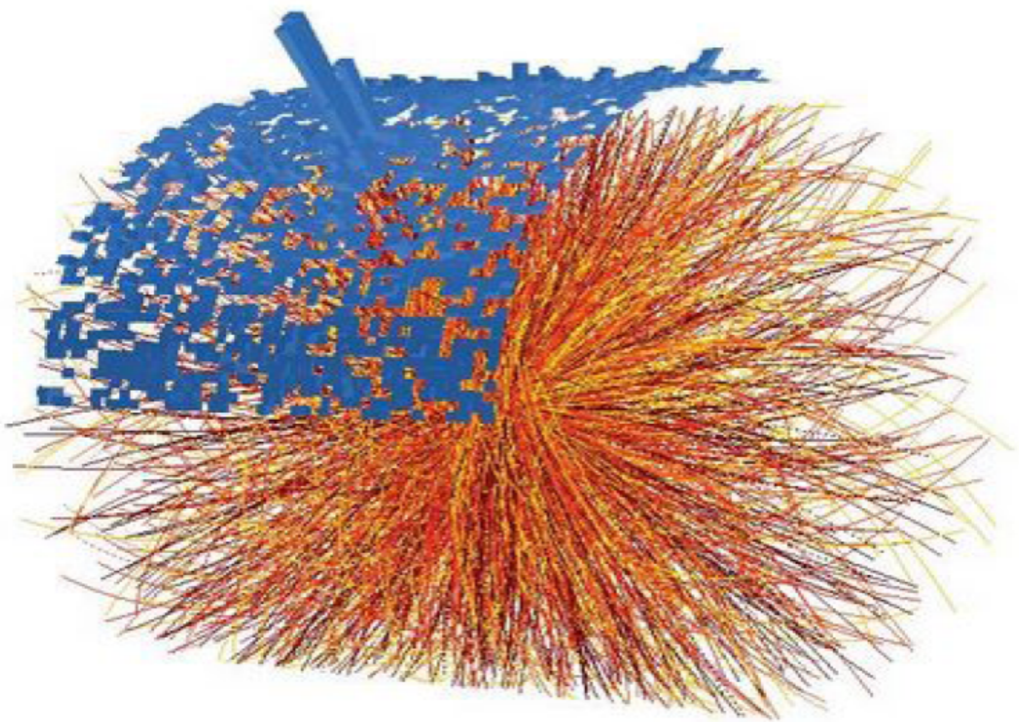
- full jets from charged particle tracking and EM energy:
  conceptually different and complementary to traditional approach

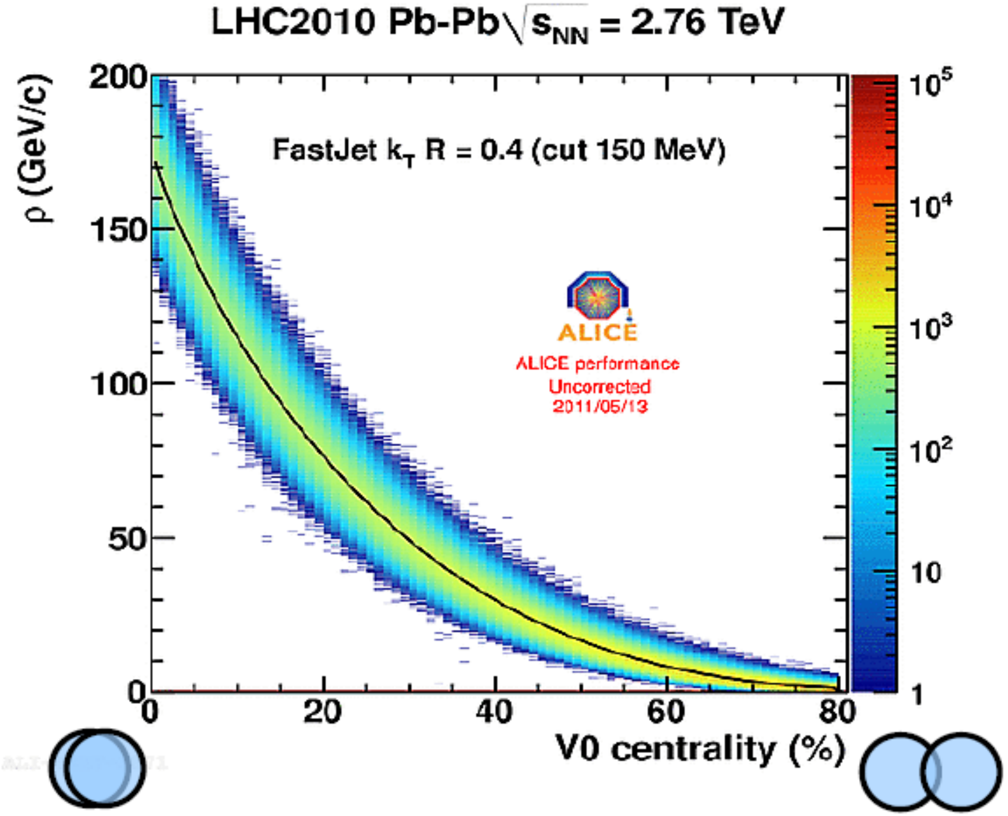
Underlying event in heavy-ion collision

- 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

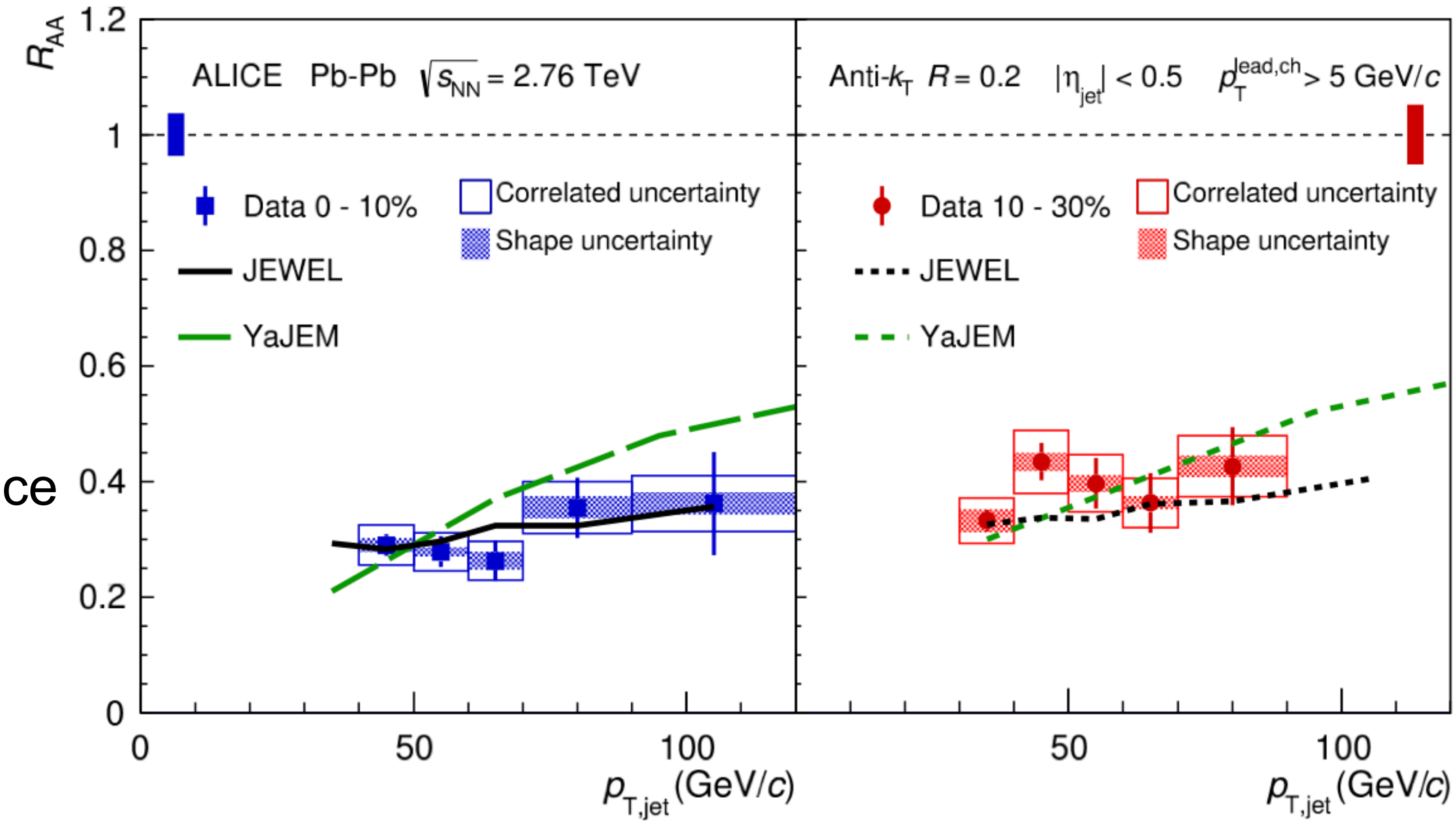
- strong suppression observed, similar to hadron RAA
  → parton energy not recovered inside jet cone

Phys.Lett. B746 (2015) 1

- 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

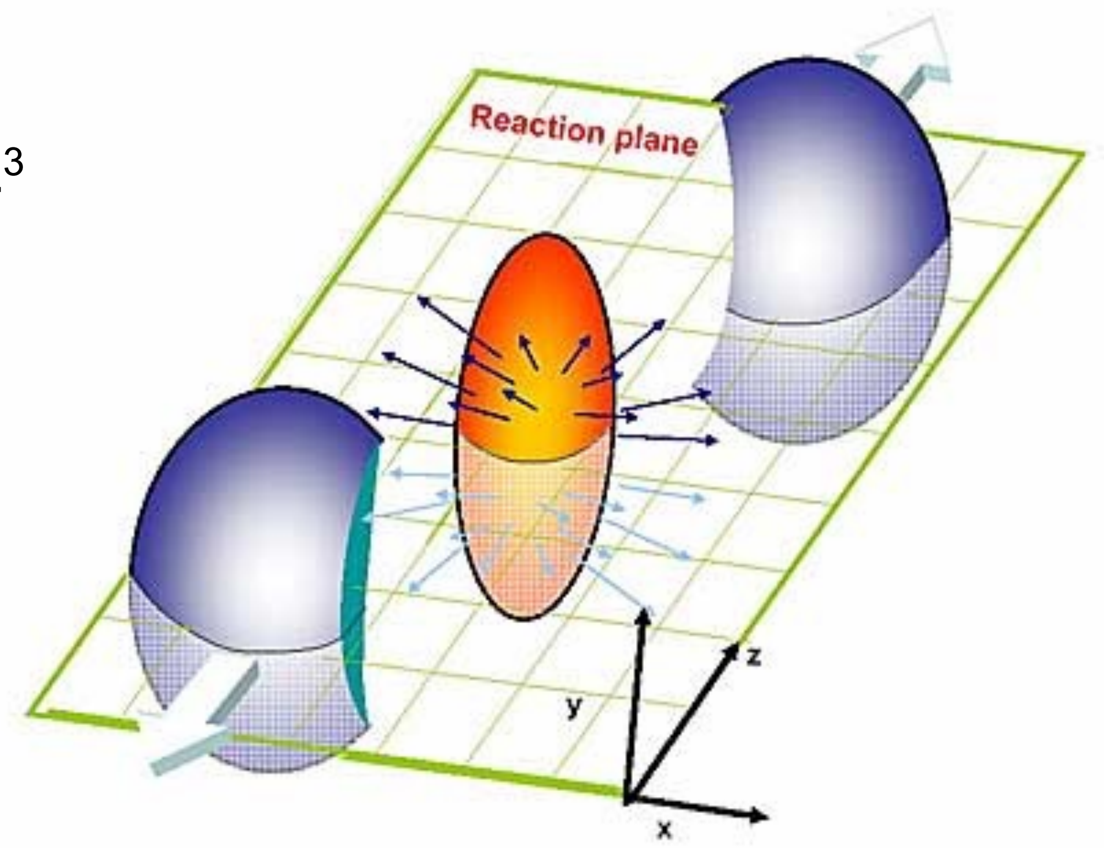


Jet azimuthal anisotropy

Reaction plane dependence

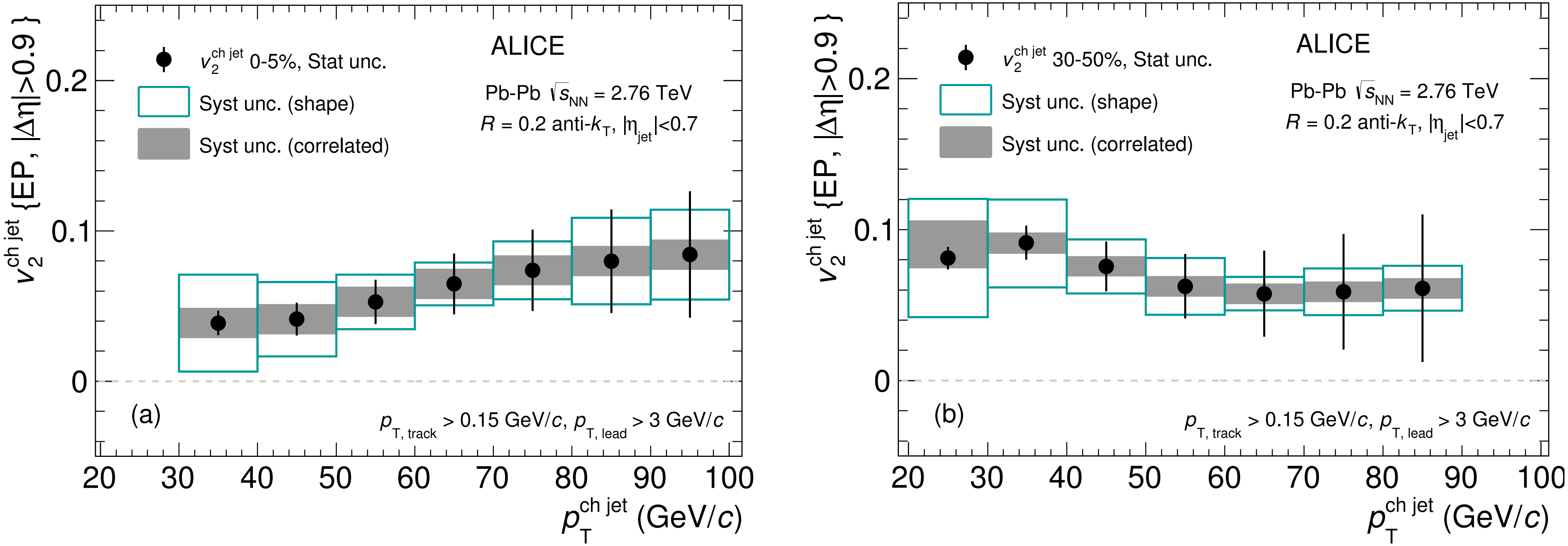
- different medium thickness in- and out-of plane

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



Jet v_2 : results

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

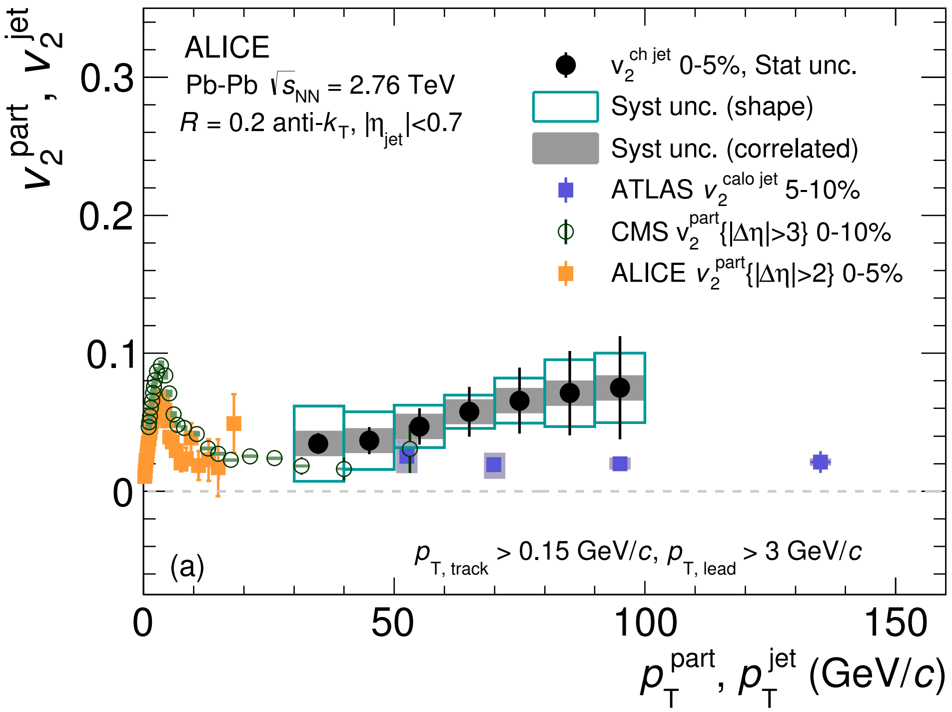


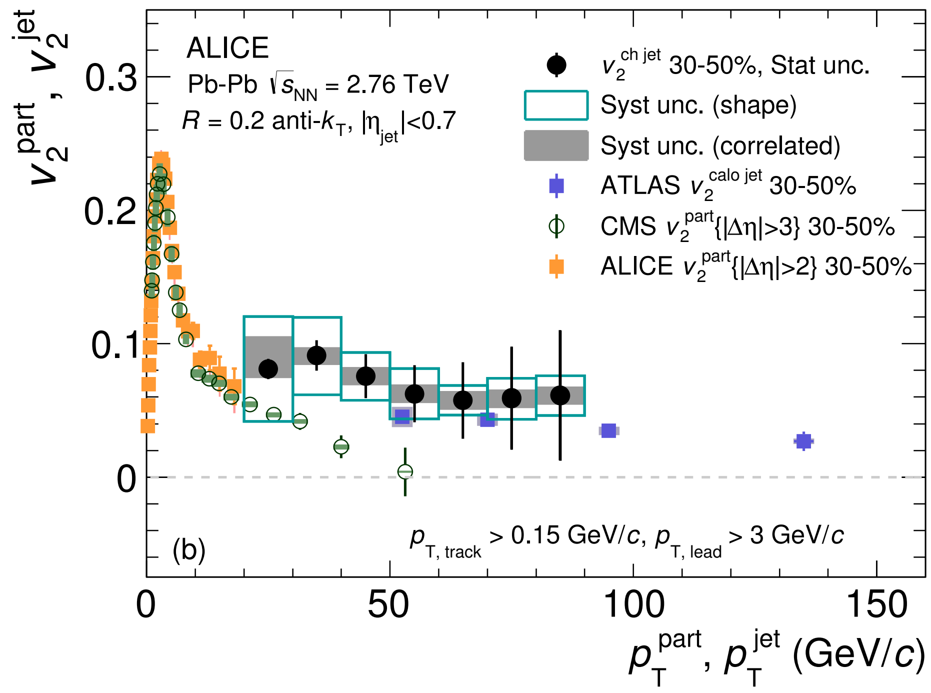
Phys. Lett. B753 (2016) 511

Comparison to previous results

- ALICE + CMS single particles, ATLAS full jets : different energy scales !
- non-zero v2 up to high p_T

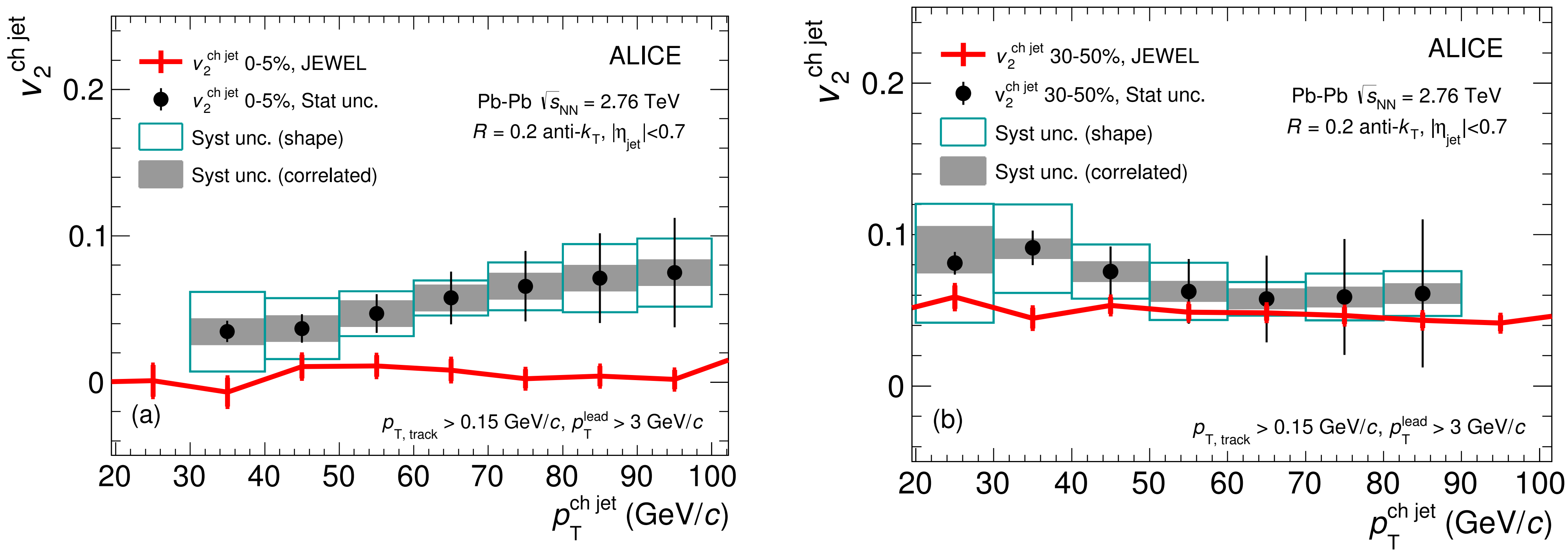
CMS, PRL 109 (2012) 022
ATLAS, PRL 111 (2013) 152
ALICE, Phys. Lett. B753 (2016) 511
ALICE, Phys. Lett. B719 (2013) 18





Comparison to JEWEL

- in semi-central collisions, good agreement with JEWEL (collisional + 'pQCD' radiative energy loss)
- clear indication of path-length dependence of energy loss



Phys. Lett. B753 (2016) 511

Jet Shapes

Jet shapes

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

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

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

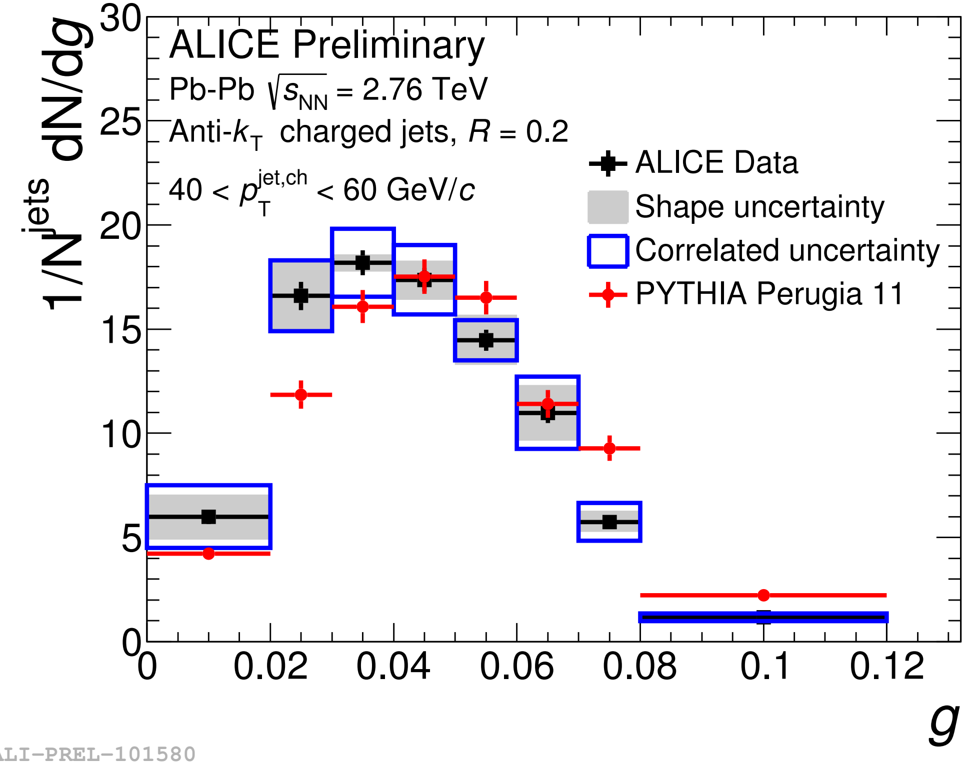
$$LeSub = p_T^{lead,track} - p_T^{sublead,track}$$

- 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

Jet shapes in Pb-Pb

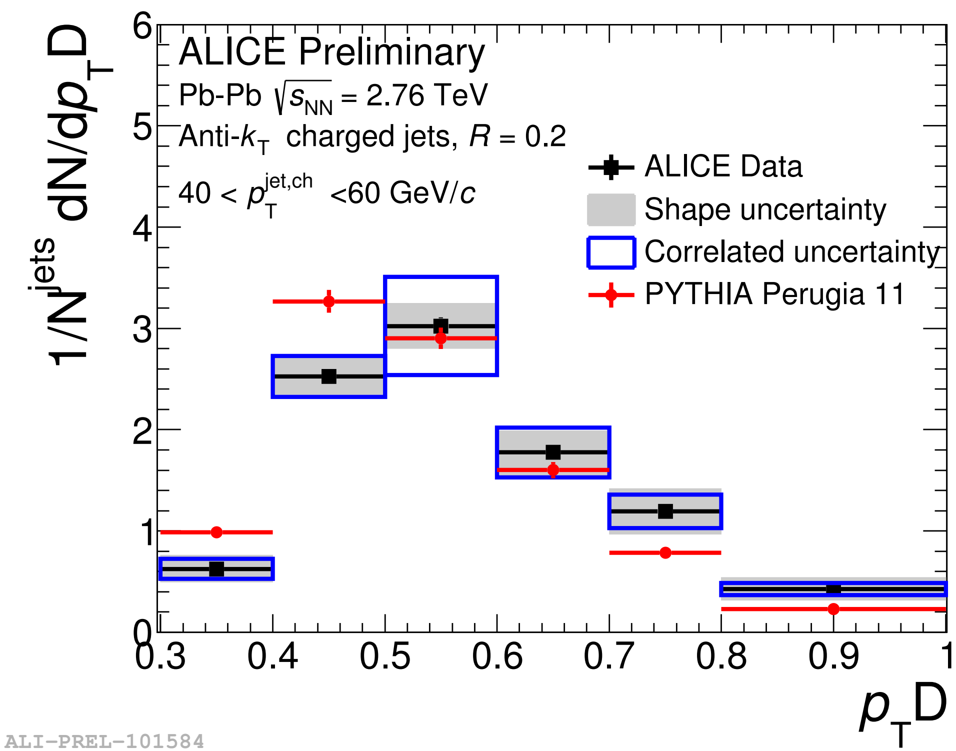
- fully corrected to charged particle level
- compare to PYTHIA reference, validated with results from pp collisions at 7 TeV
- g shifted to smaller values → indicates more collimated jet core

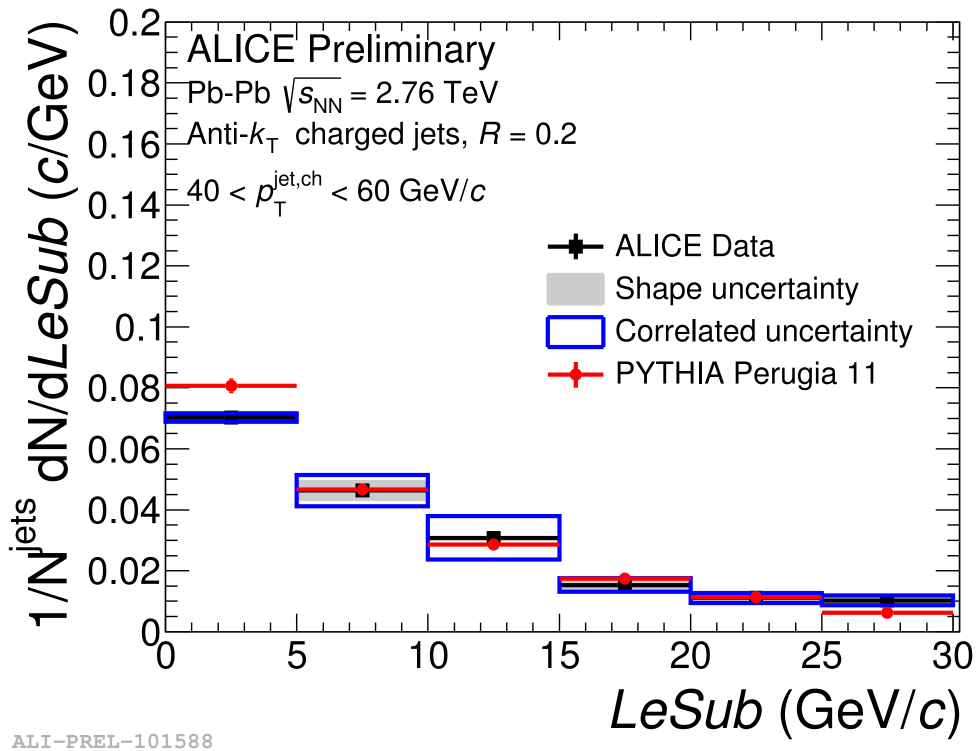


ALI-PREL-101580

- larger p_TD in Pb-Pb compared to PYTHIA
  → indicates fewer constituents in quenched jets

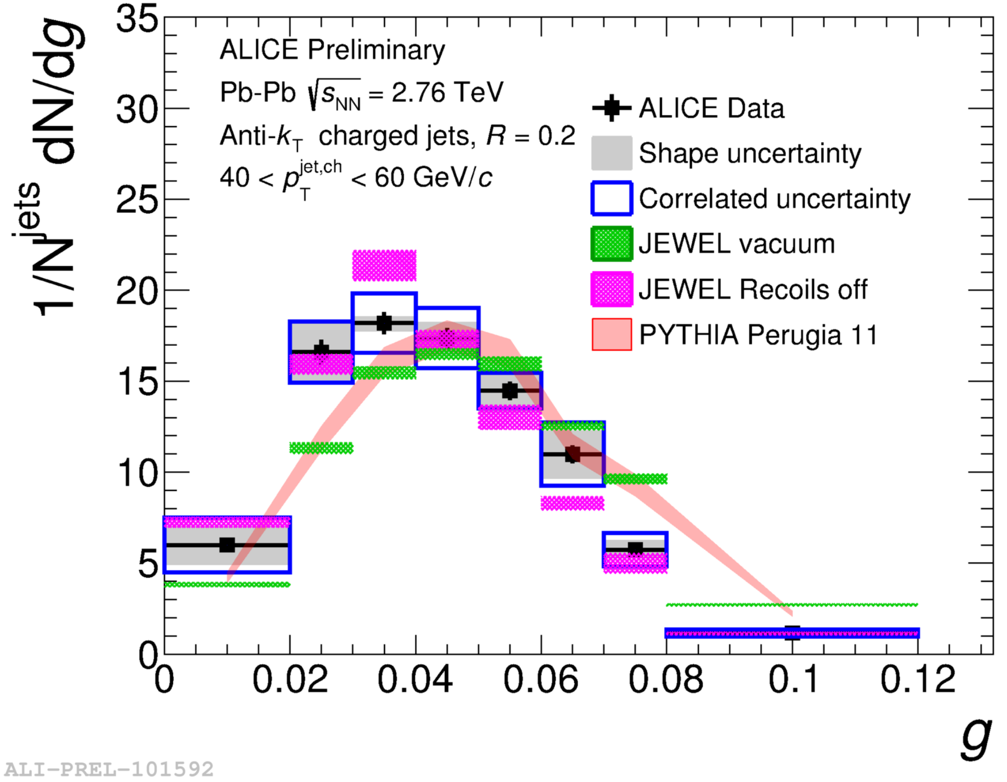
- LeSub in Pb-Pb in good agreement with Pb-Pb:
  → hardest splittings likely unaffected

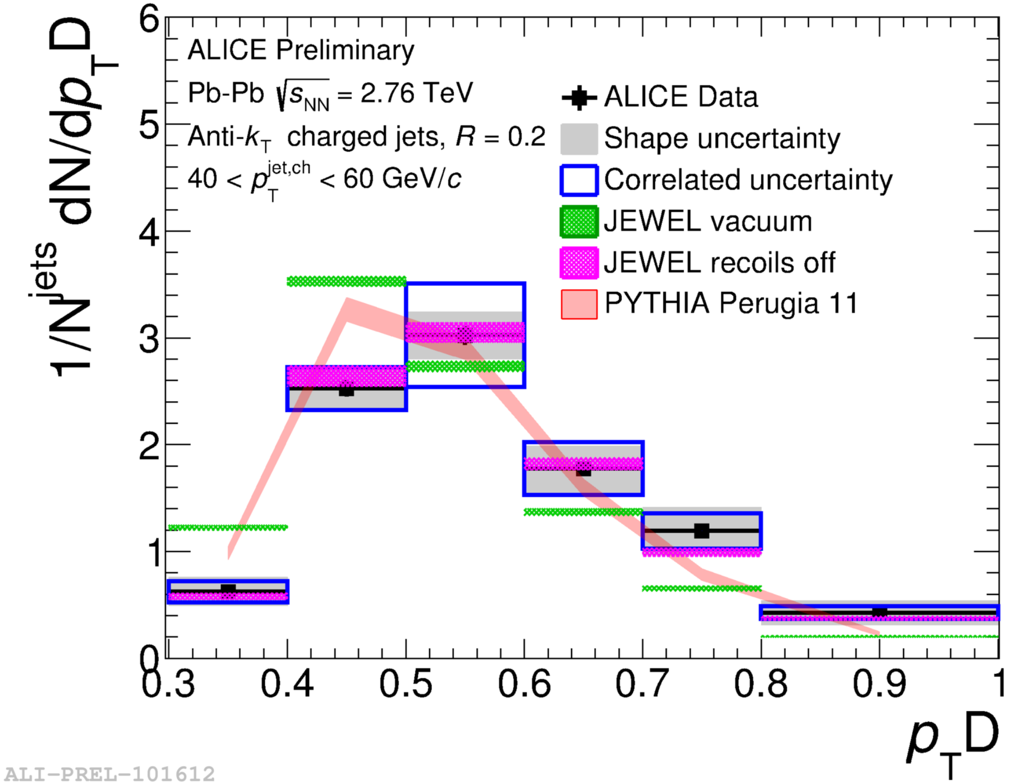




Jet shapes: model comparison

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

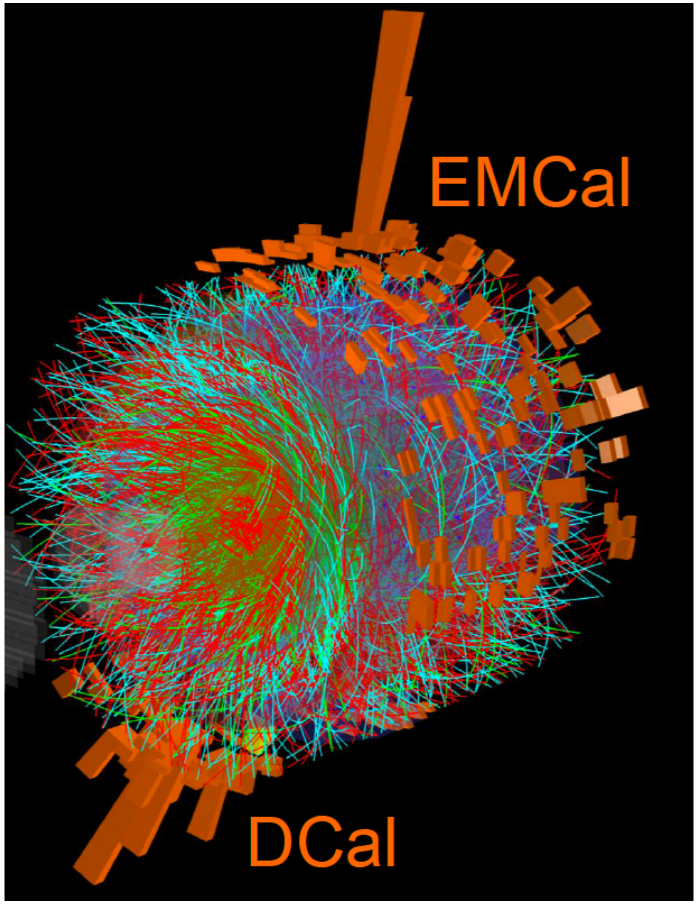




JEWEL: K.C. Zapp, F. Kraus, U.A. Wiedemann, JHEP 1303 (2013) 080

Summary

- hard probes allow to probe properties of the QGP
- first insights on dynamics parton of energy loss from jet nuclear suppression factor and jet shape measurements
- non-zero jet v_2 indicates path-length dependence of jet quenching
- run2: extended calorimetry
  allows to assess new observables



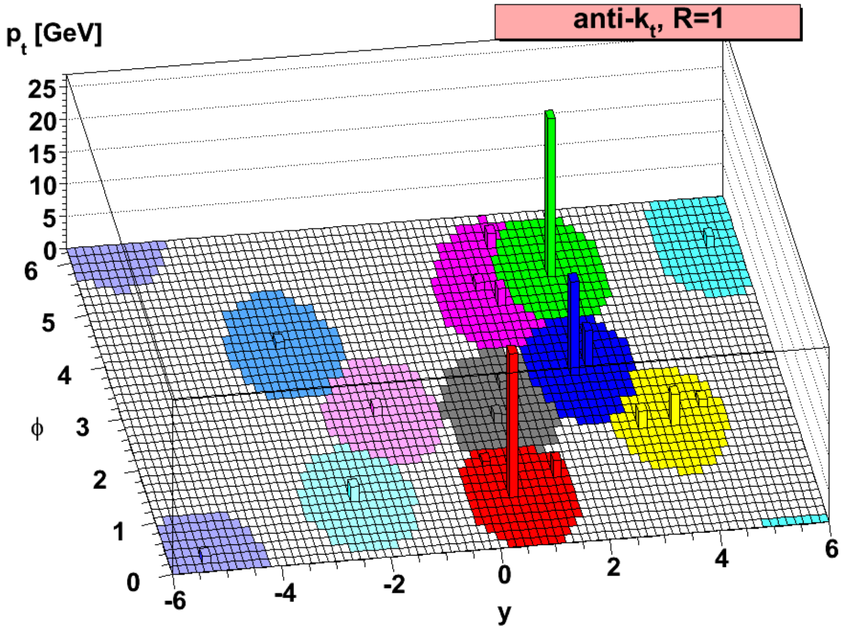
- Backup -

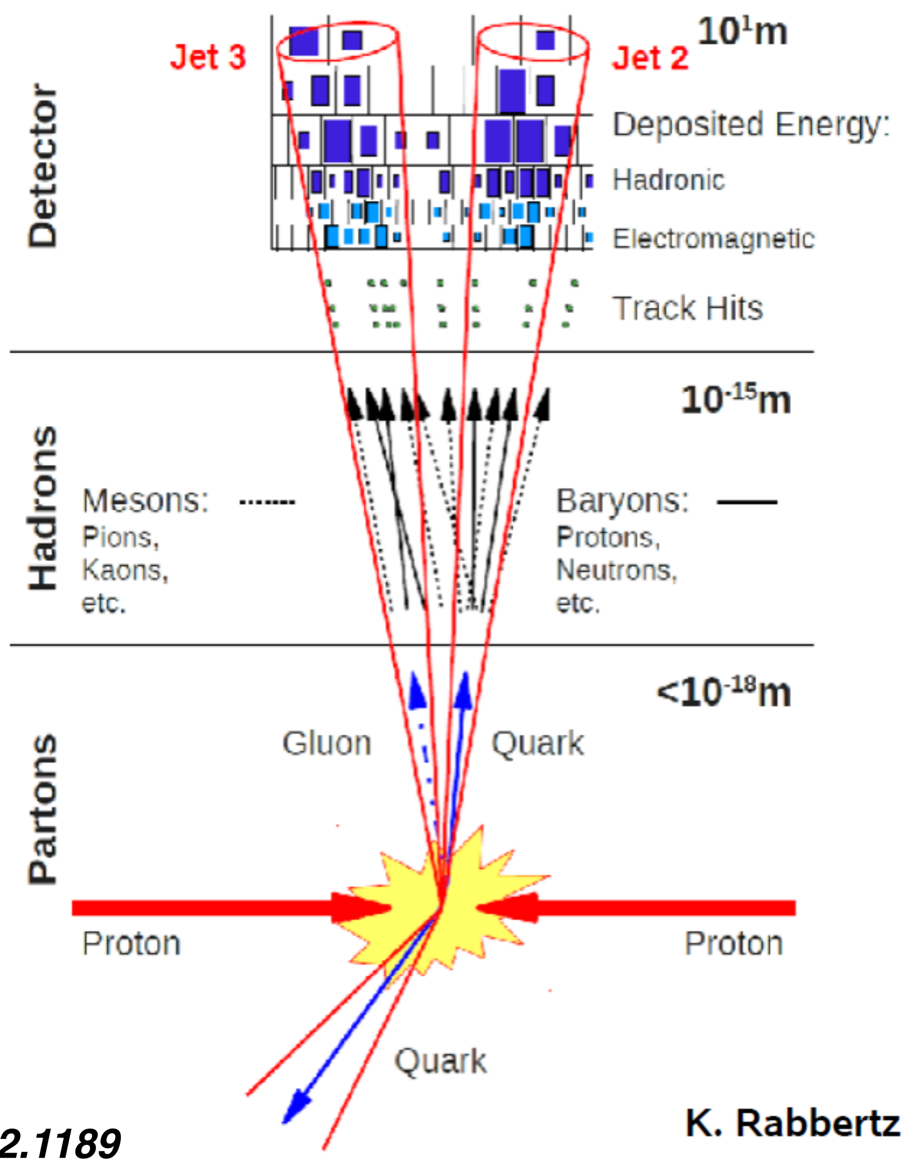
Jet reconstruction

- 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





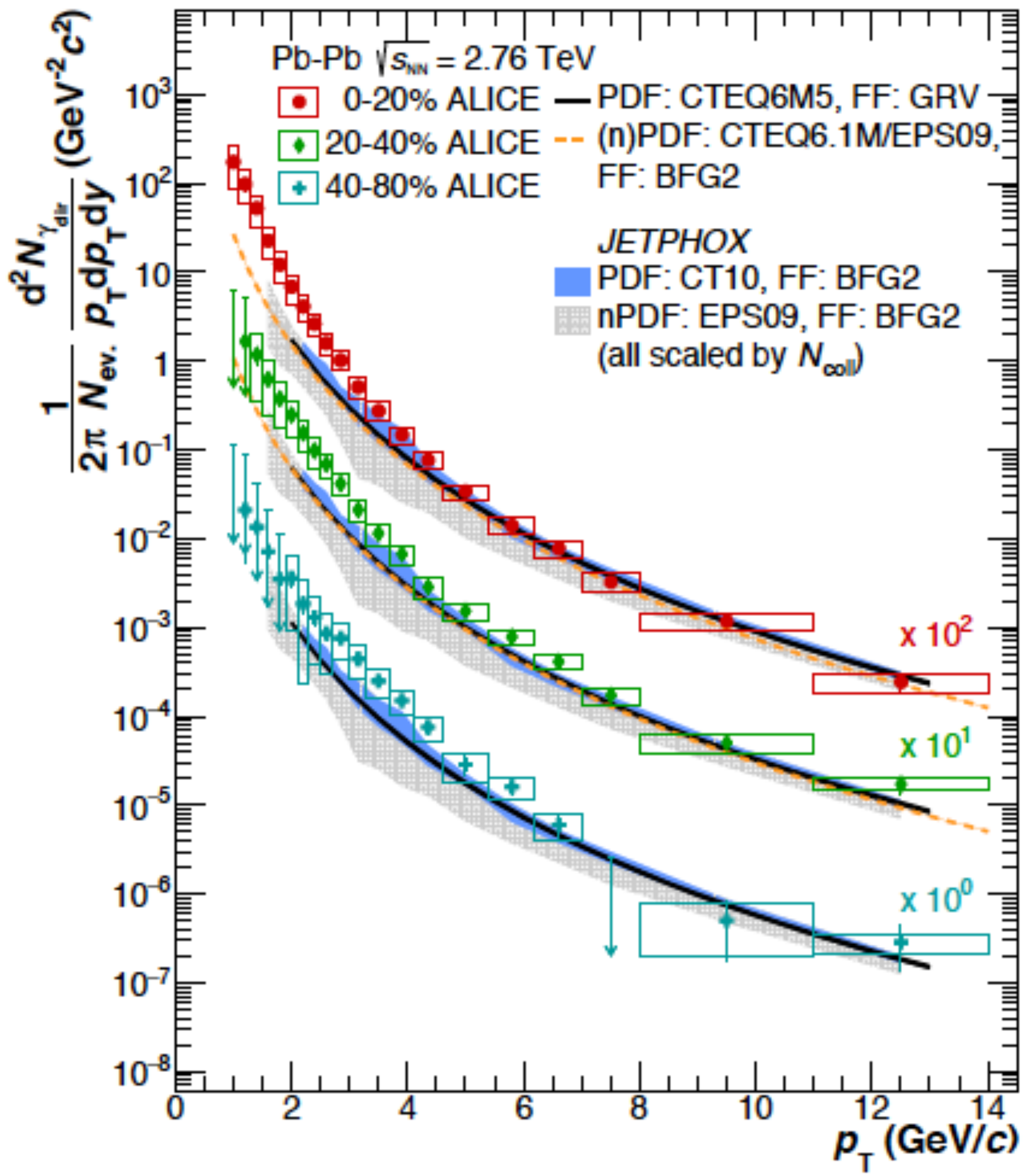
hep-ph/0802.1189

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 T_C



arXiv 1509.07324 [nucl-ex]

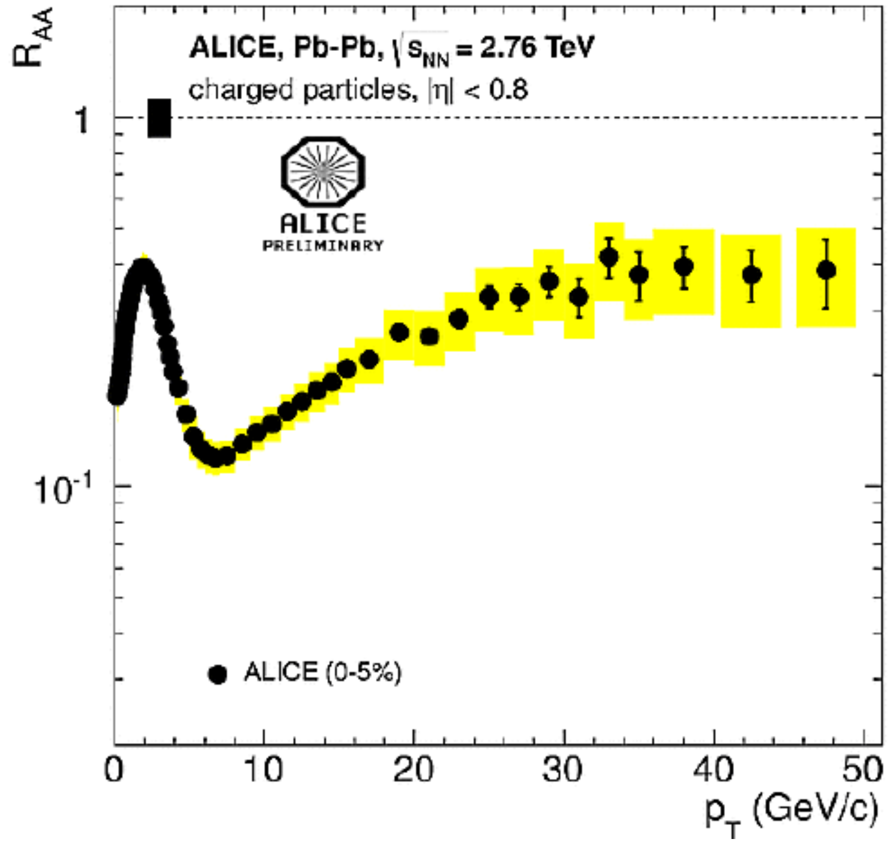
Hadrons in heavy-ion collisions

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

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

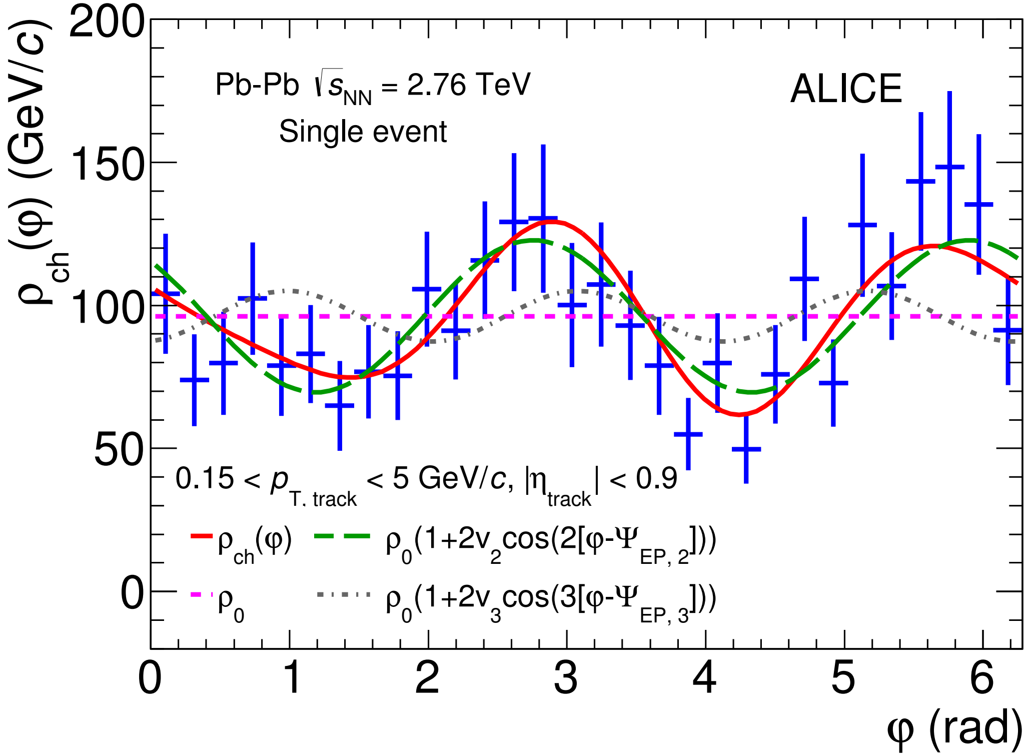
- hadron observables biased towards leading fragment



→ study the effect for fully reconstructed jets

Analysis details

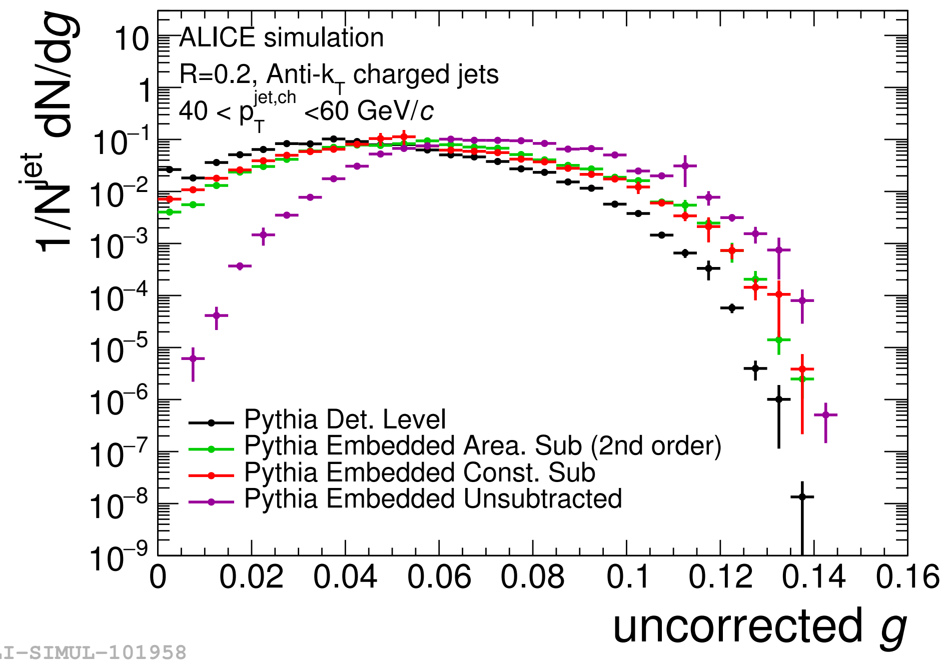
- charged jets, R = 0.2
- account for flow-modulation of background via event-by-event fit and subtraction of local background density
- unfolding to account for background fluctuations : separately for spectra in- and out-of-plane



Phys. Lett. B753 (2016) 511

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