Jet Physics with ALICE at the LHC

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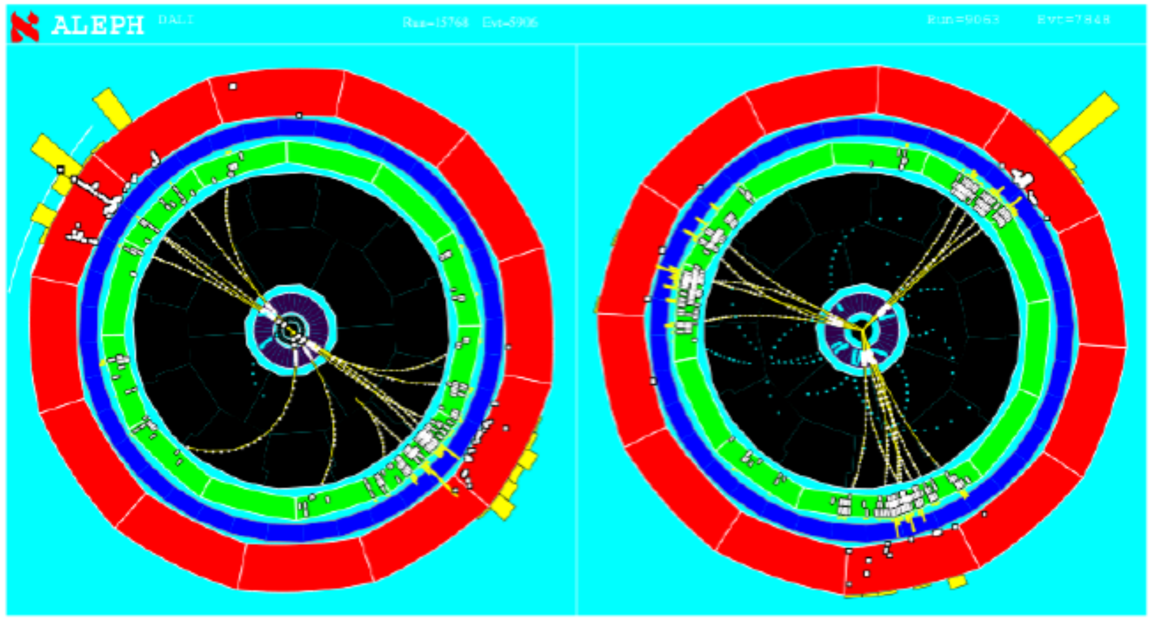
for the ALICE collaboration

Outline

- introduction
- jet nuclear modification factor
- jet shapes
- subjet measurements at STAR, CMS and ALICE

Introduction

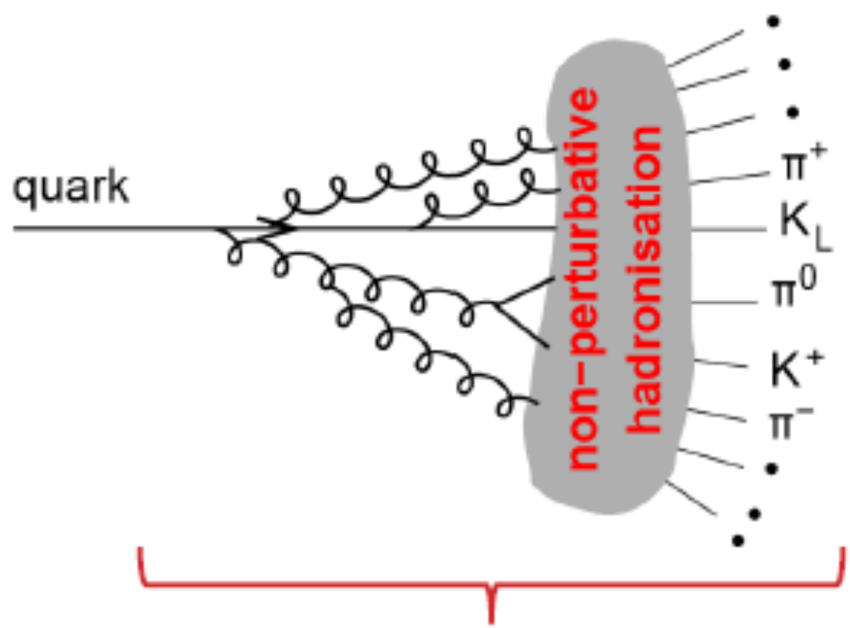
Jets: seeing quarks and gluons



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

Jet fragmentation

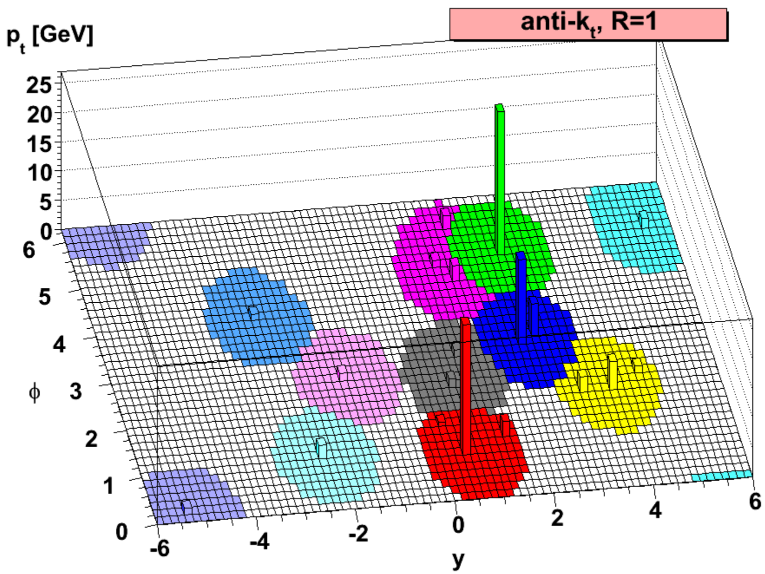
- initial hard scattering: high-p_T partons
- cascade of (anti-)quarks and gluons: parton shower
- at soft scale ($O(\Lambda_{QCD})$): hadronization

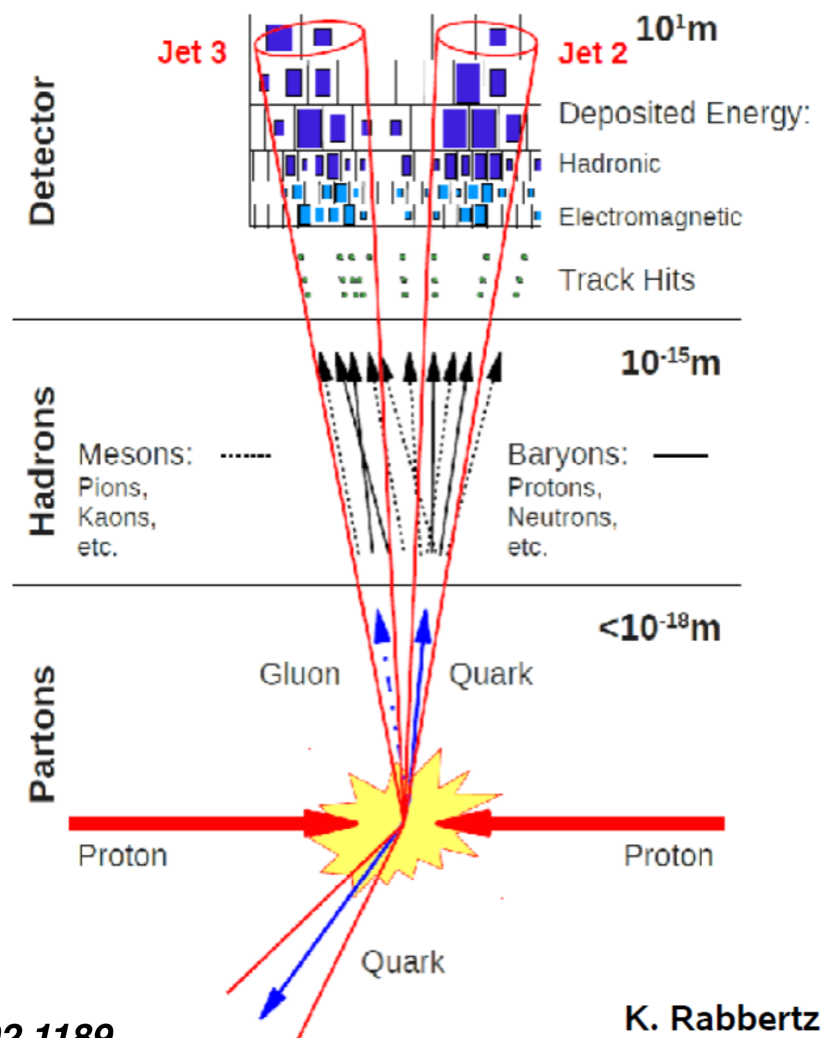


Fragmentation = Parton shower + hadronization

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

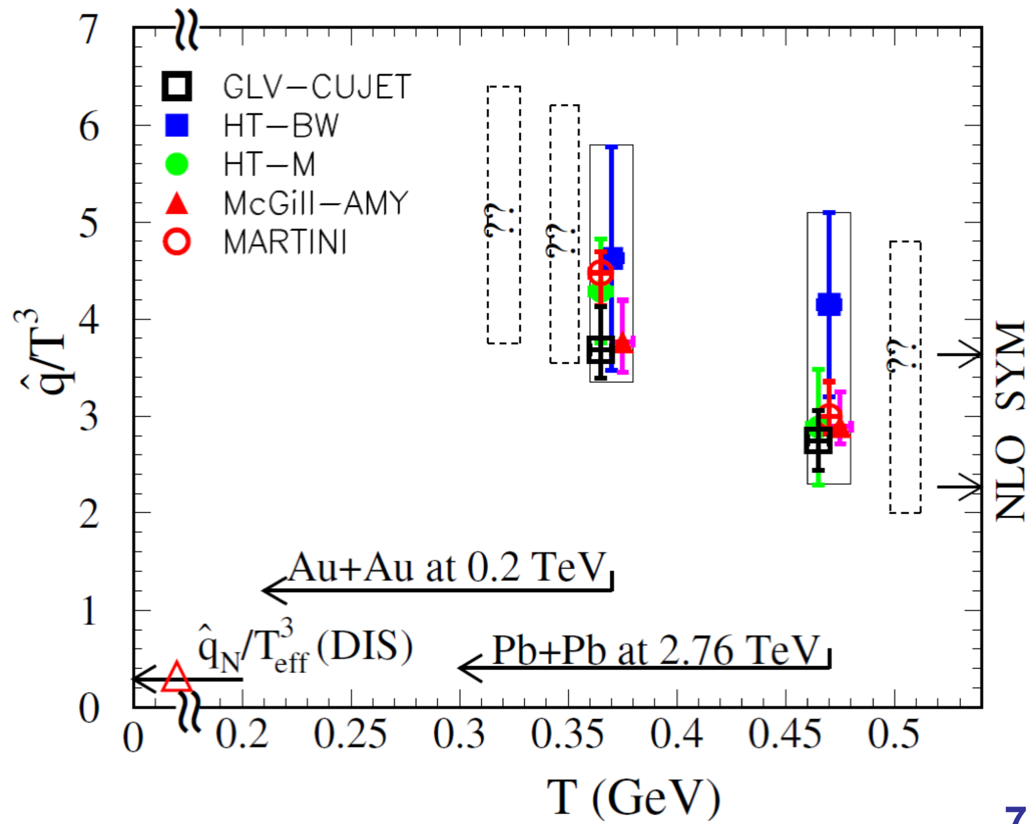




hep-ph/0802.1189

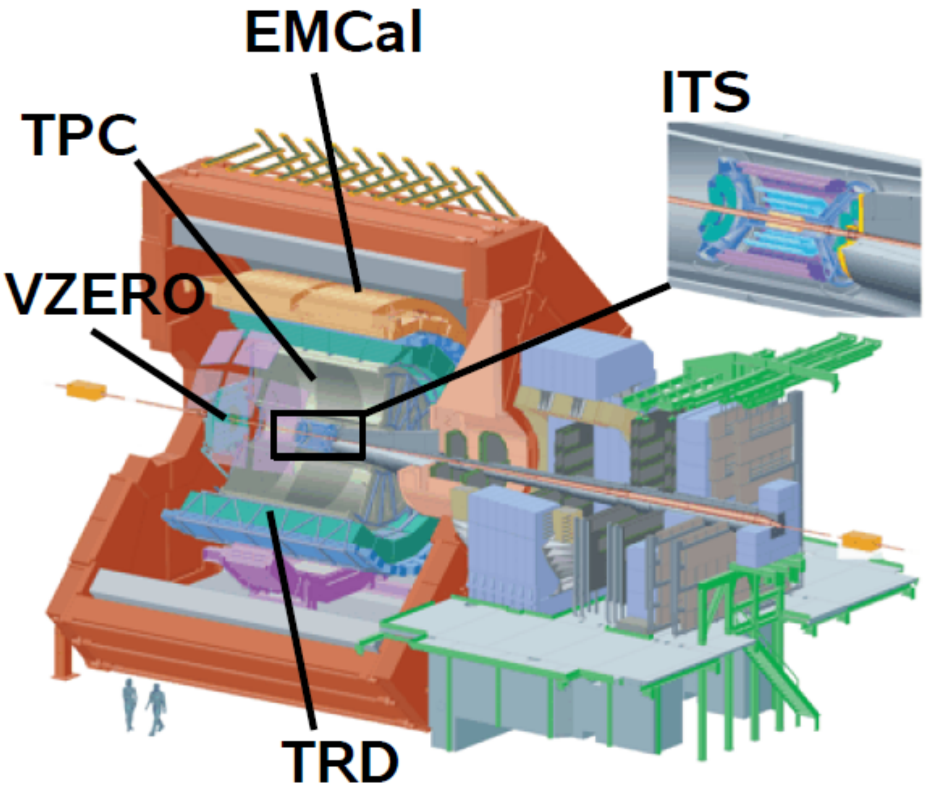
Partons in heavy-ion collisions

- 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,
Phys. Rev. C 90 (2014) 014909

Jets at ALICE (LHC run 1)



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

- EMCal :
  - neutral particles
  - Δφ = 107°, |η|<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

Jet nuclear modification factor

- $$R_{AA}(p_{\rm T}) = \frac{1}{T_{AA}} \frac{{\rm d}^2{\rm N}_{\rm ch}/{\rm d}\eta\,{\rm dp_T}}{d^2\sigma^{\rm pp}_{\rm ch}/d\eta\,{\rm dp_T}}$$

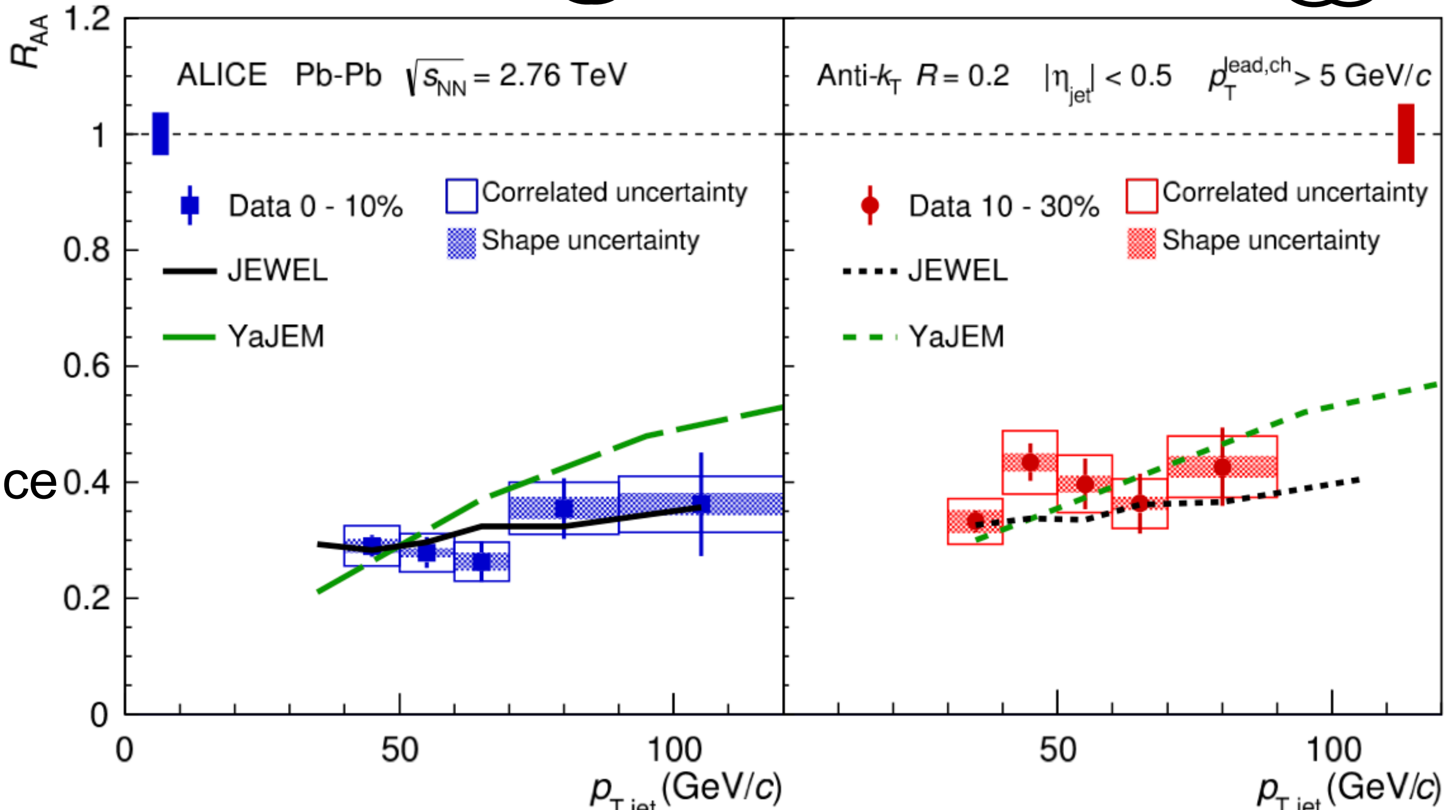
Phys.Lett. B746 (2015) 1

JEWEL: PLB 735 (2014)

YaJEM:PRC 88 (2013) 014905

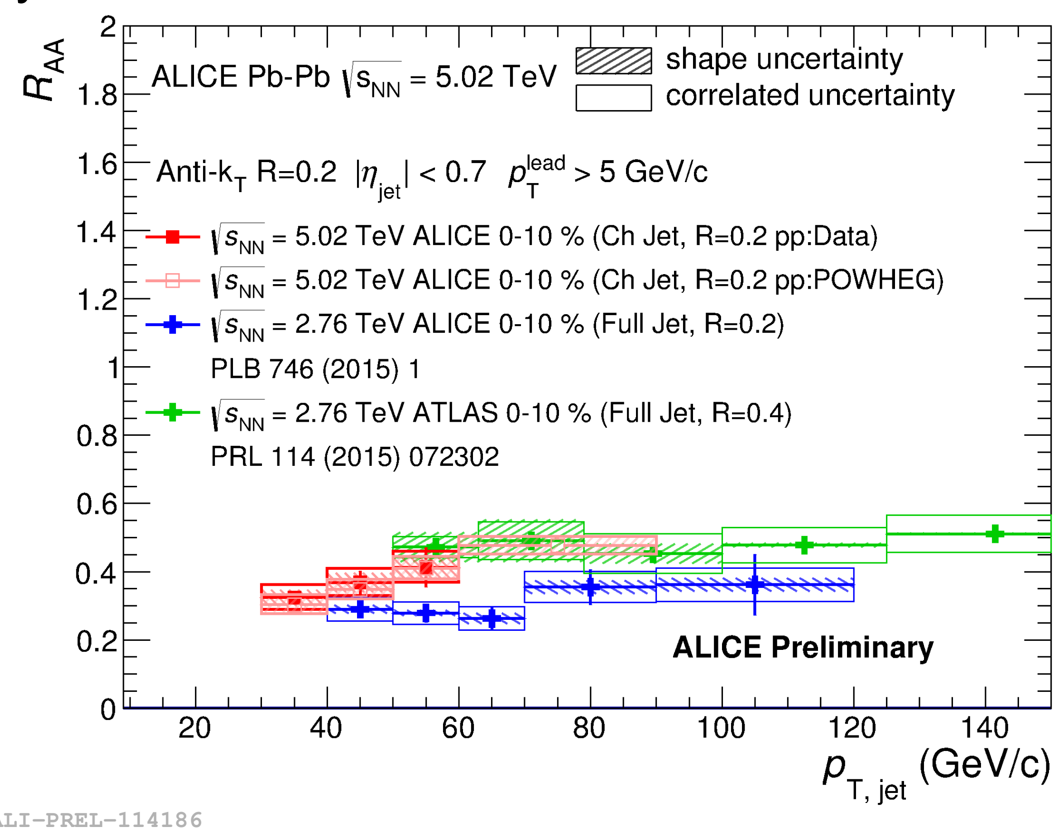
- strong suppression observed, similar to hadron RAA
  → parton energy not recovered inside jet cone
- increase of suppression with centrality
- JEWEL and YaJEM jet quenching models reproduce suppression

central **semi-central**



Jet R_{AA} at 5 TeV

- motivation: compare to previous results at 2.76 TeV to study $\sqrt{s_{NN}}$ dependence of R_{AA}
  - with increasing $\sqrt{s_{NN}}$ higher initial energy density
  - stronger jet quenching ?



- comparable R_{AA}:
  - with increasing $\sqrt{s_{NN}}$ flatter parton spectra
  - effect of flattening compensated by stronger suppression

Jet Shapes

Jet shapes

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

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

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

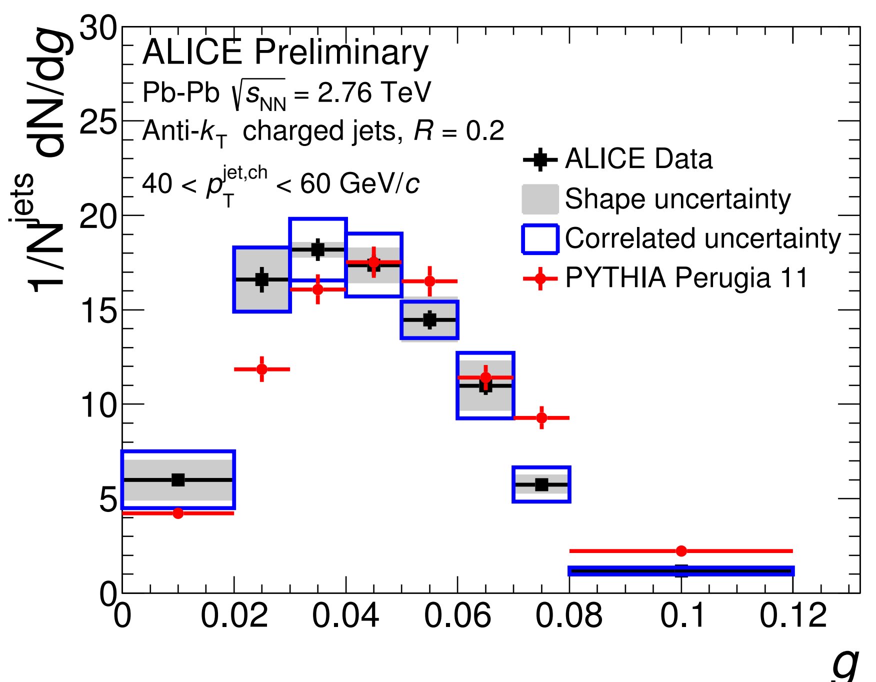
$$\mathrm{LeSub} = p_T^{lead,track} - p_T^{sublead,track}$$

- 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

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

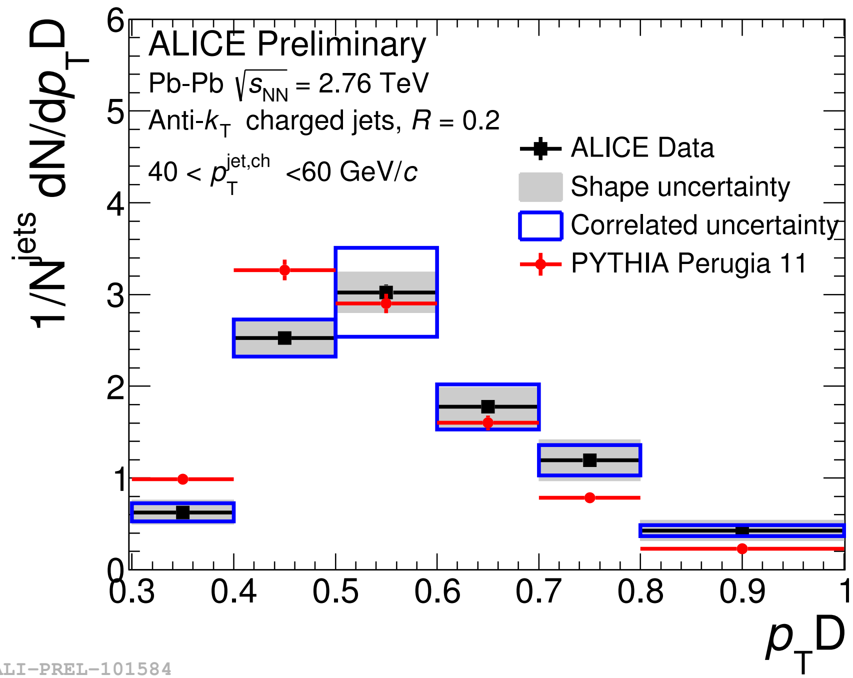


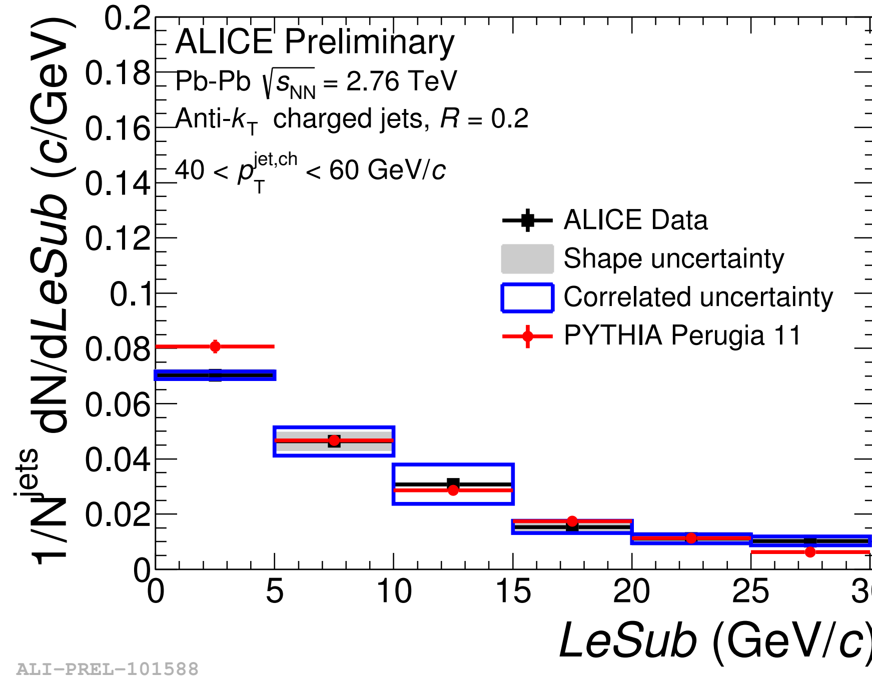
ALI-PREL-101580

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

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

- collimation through emission of soft particles at large angles

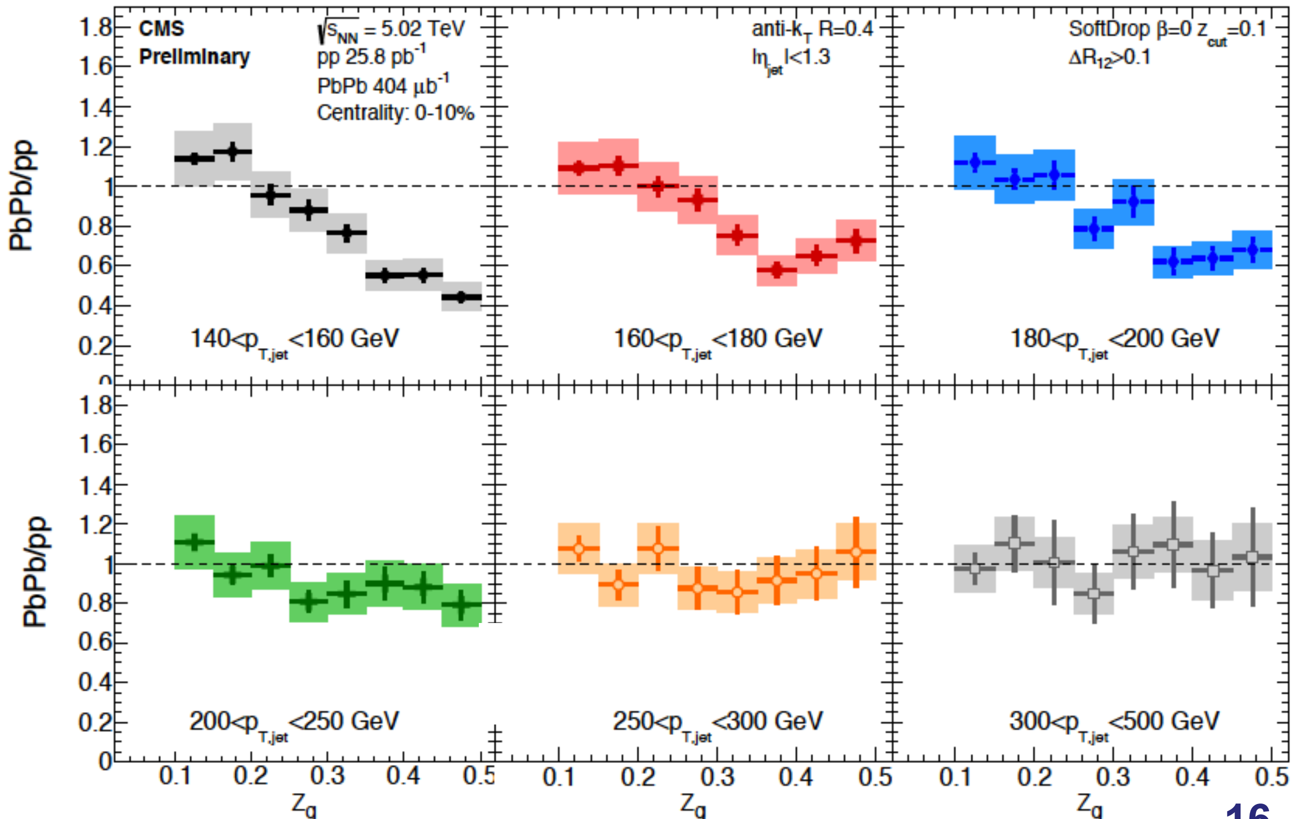




Subjets

Subjets at LHC

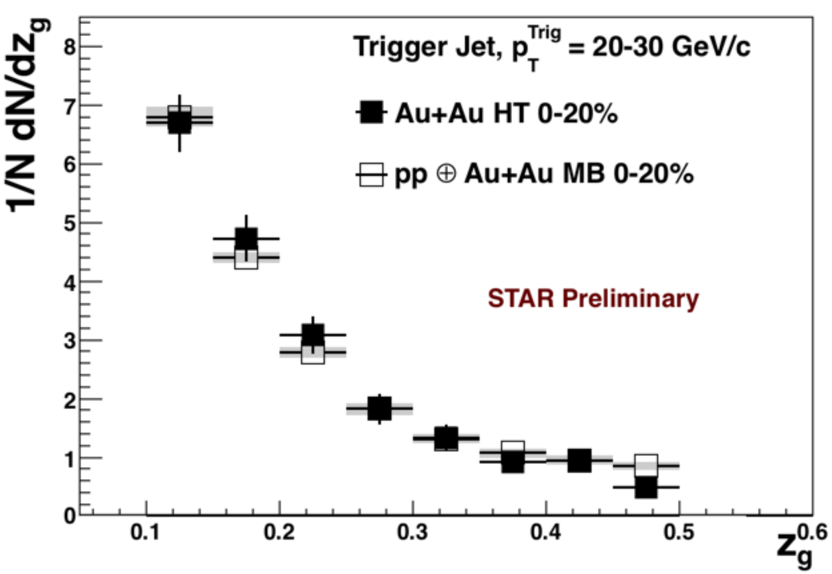
- declustering and soft drop grooming to identify hard jet substructure
- subjet momentum balance $z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$ > 0.1
- in vacuum, $d\sigma/dz_g$ ~ splitting function
- CMS: strongest suppression for lower p_T^{jet} at high z_g

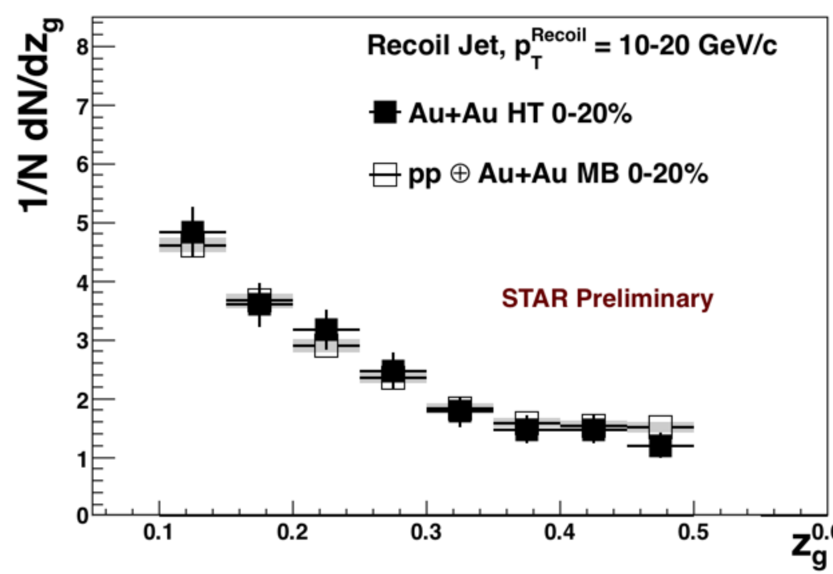


CMS PAS HIN 16-006

Subjets in STAR

- STAR: RHIC accelerator (USA), $\sqrt{s_{NN}} = 200$ GeV
- select dijet pairs matching to ‘hard core’ jets reconstructed with high constituent cut $p_T^{const} > 2$ GeV/c
- no suppression observed
- role of different kinematics, STAR selection bias, subjet ΔR cut ?



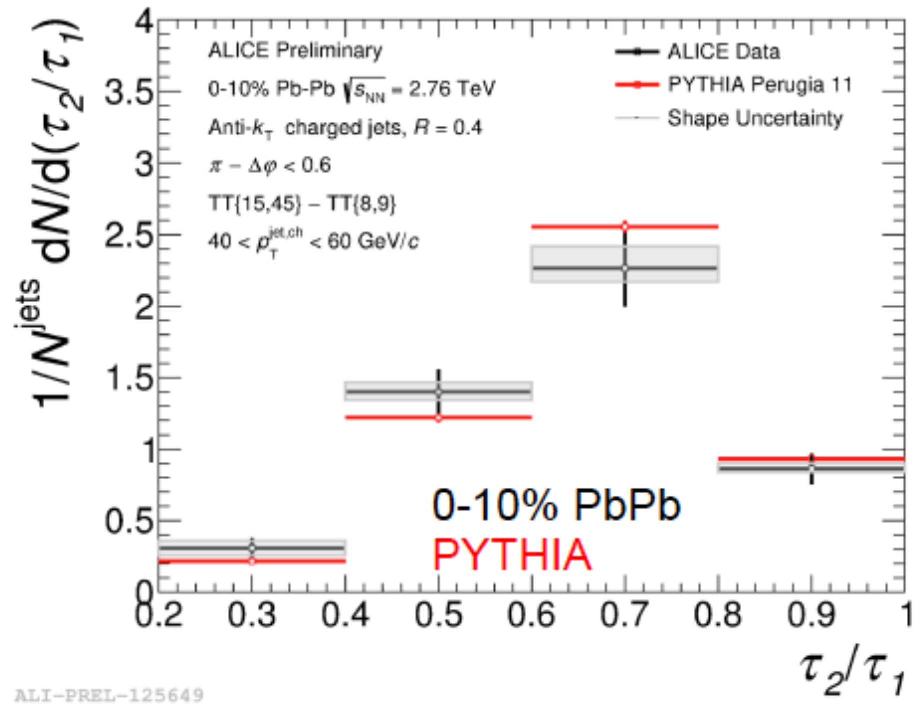


STAR, HP 2016

ALICE subjets

- charged jets, kt declustering
- subjettiness τ_N: how consistent is a jet with having N subjets
- τ_2/τ_1 : no significant modification

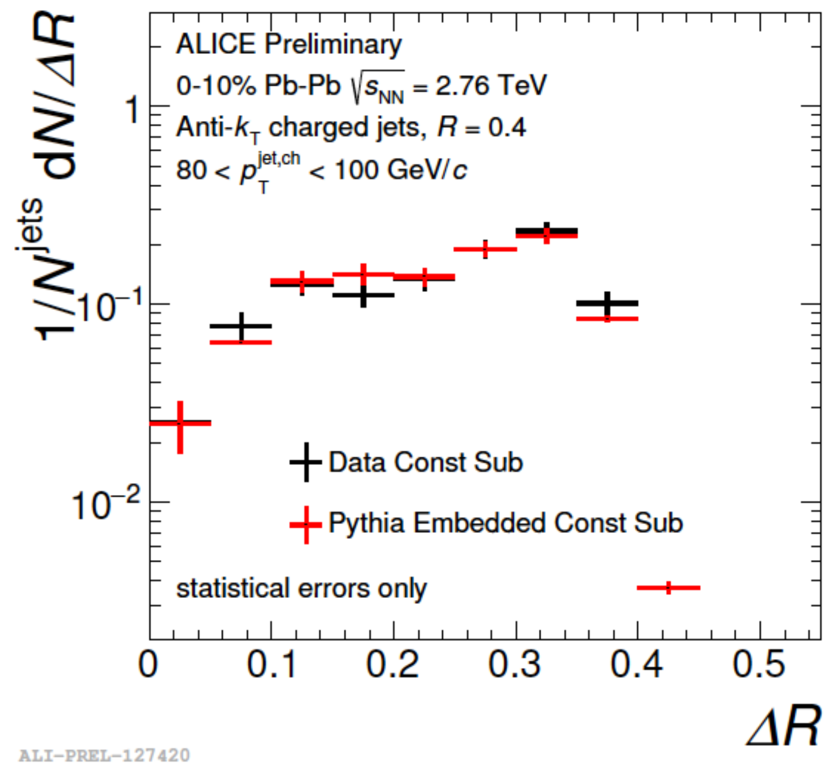
$$\tau_N = \frac{\sum_{i=1} p_{T,i} Min(\Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N})}{R_0 \sum_{i=1} p_{T,i}}$$



2-prong jet 1-prong jet

ALICE subjet ΔR

- subjet distance ΔR - observable potentially sensitive to medium response *(J. G. Milhano, U. A. Wiedemann, K. C. Zapp, arXiv: 1707.04142)*
- data uncorrected for detector effects and background fluctuations compared to PYTHIA embedded reference
- no significant modification observed relative to reference, full correction to particle level in progress



Summary

- hard probes allow to probe properties of the QGP

- first insights on dynamics parton of energy loss from jet nuclear modification factor and jet shape measurements
  - collimation through emission of soft particles at large angles

- exploring potential of subjet observables

  - intriguing jet p_T dependence
  - dN/dz_g from ALICE under preparation

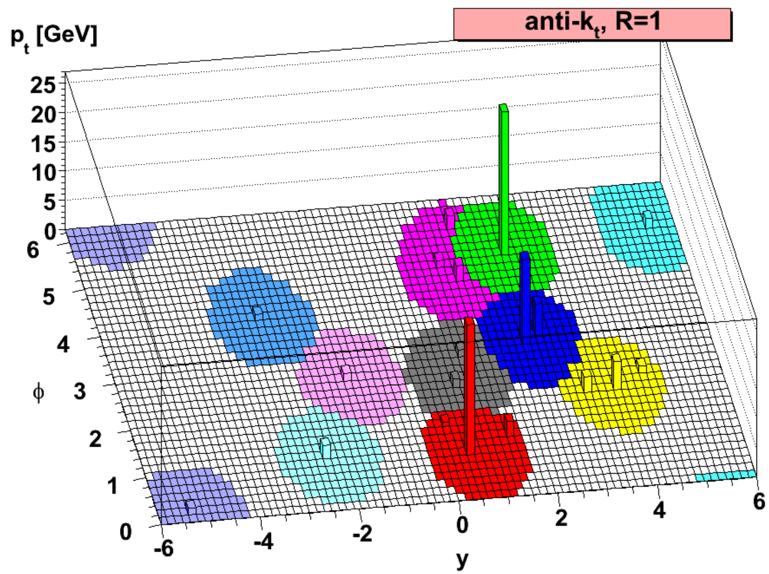
- Backup -

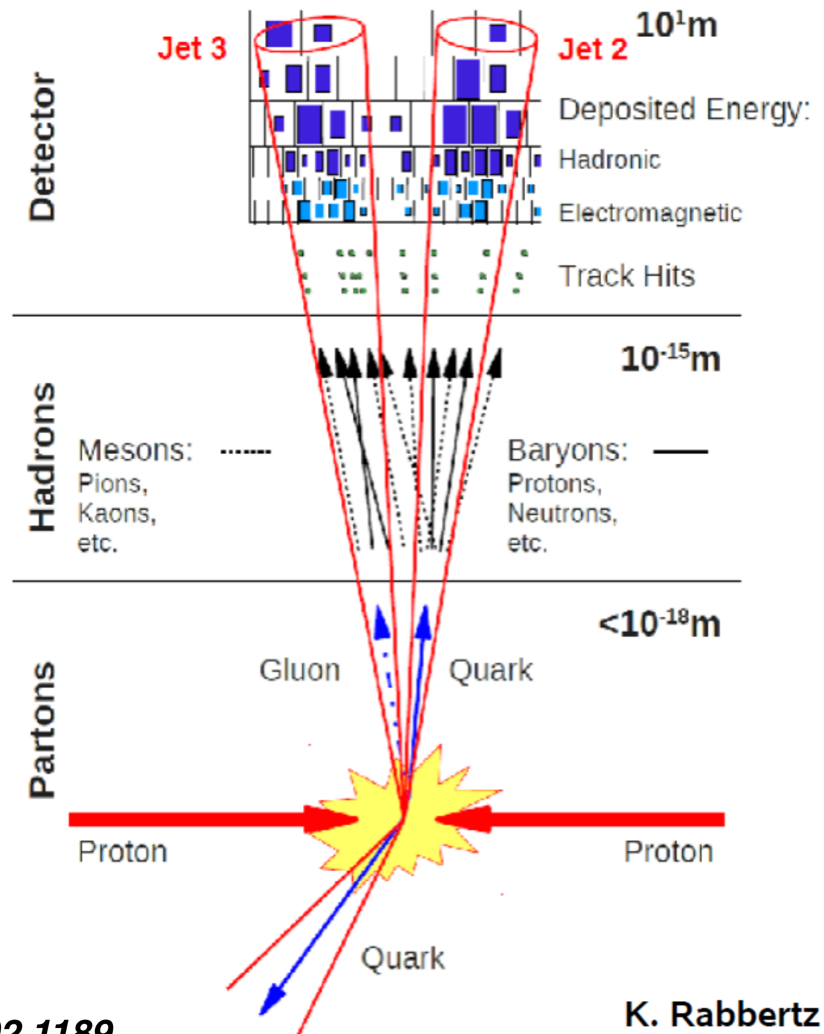
Jet reconstruction

- 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





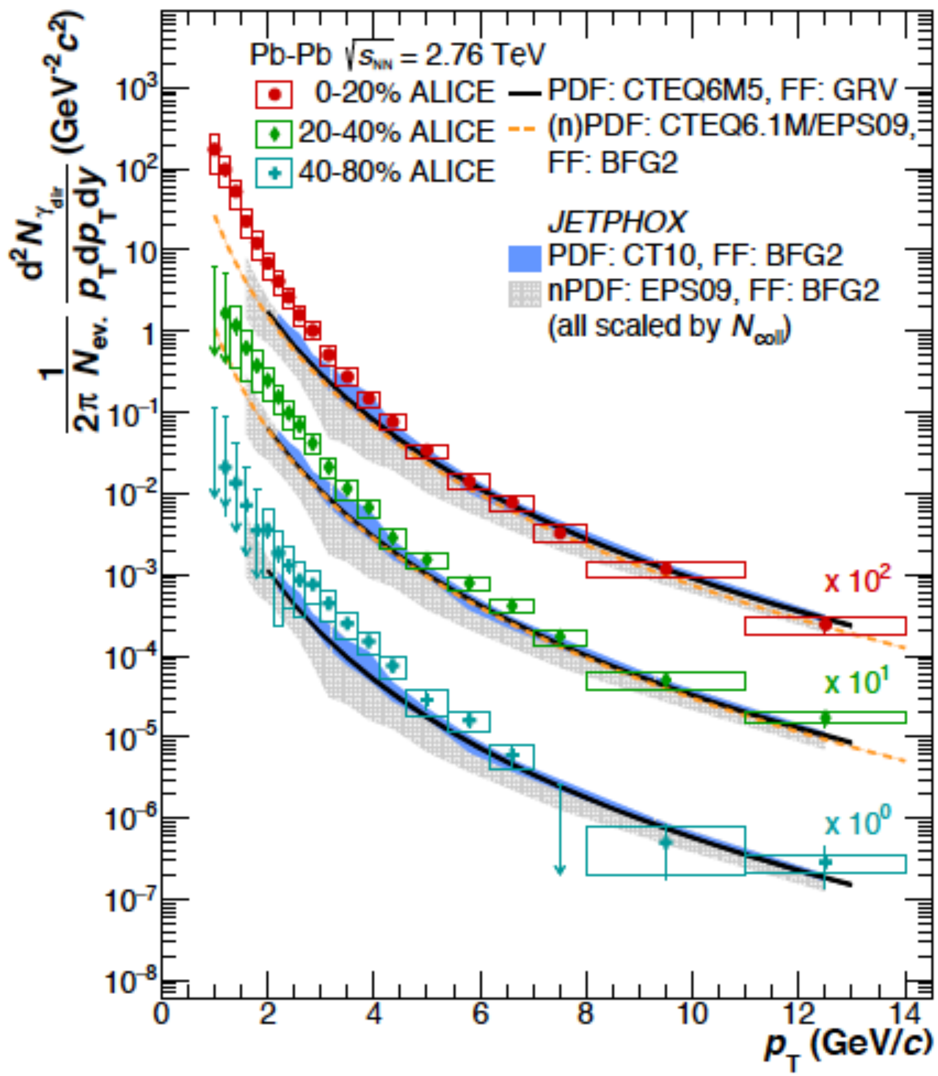
hep-ph/0802.1189

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]

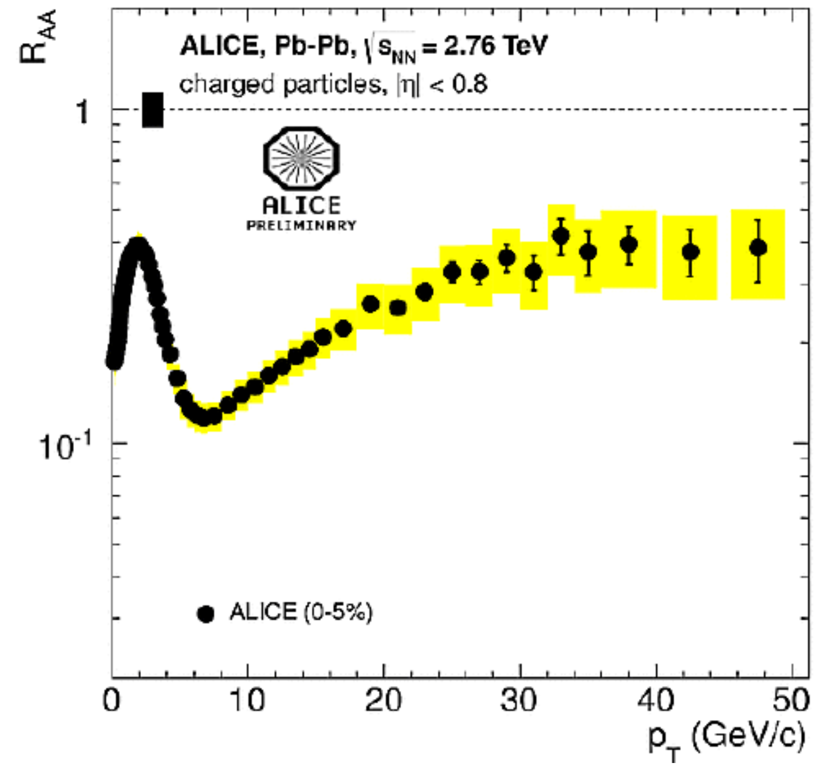
Hadrons in heavy-ion collisions

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

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

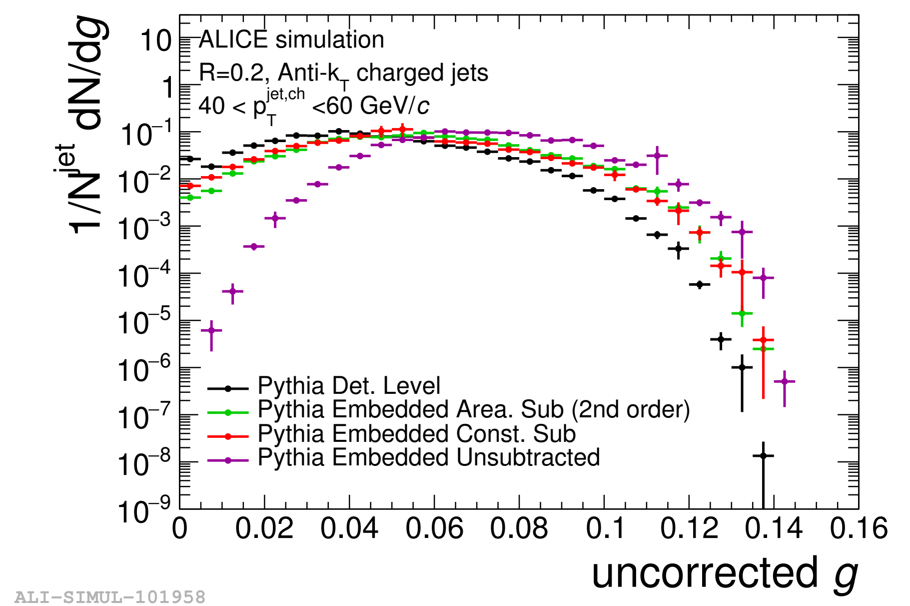
- hadron observables biased towards leading fragment



→ study the effect for fully reconstructed jets

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

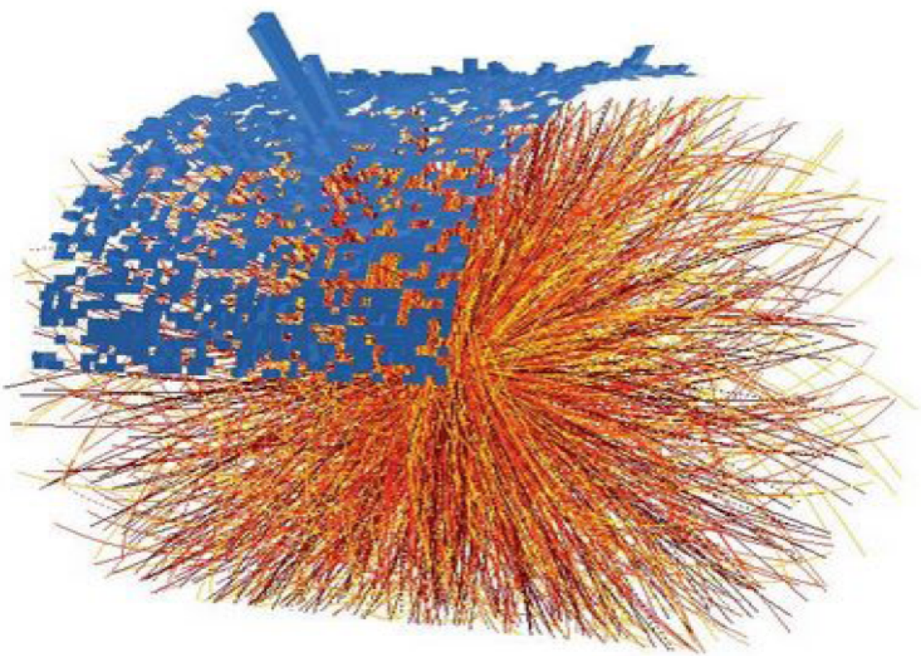


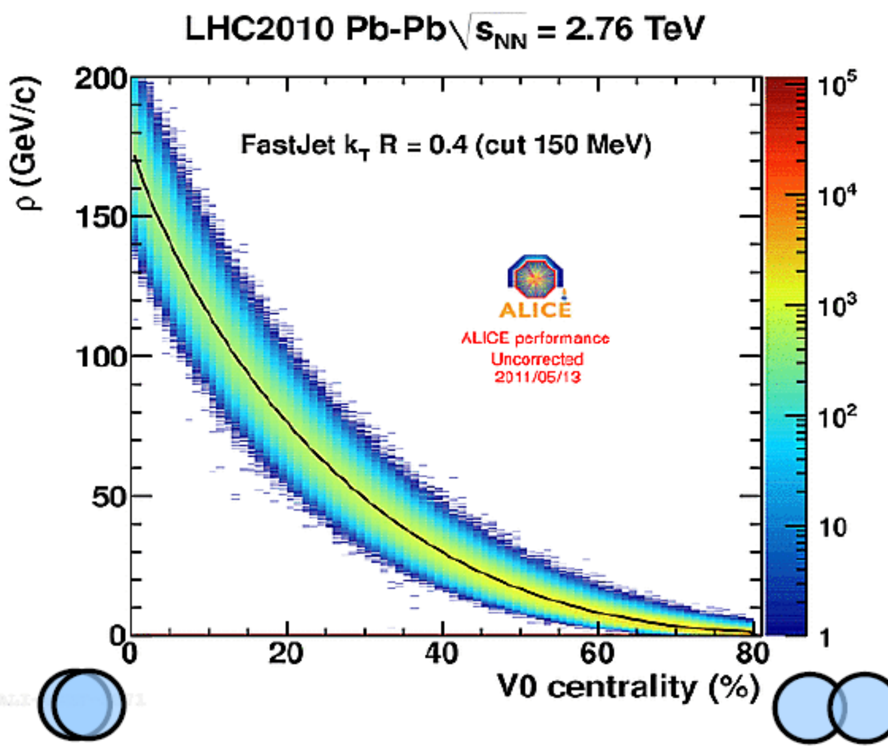
Underlying event in heavy-ion collision

- 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



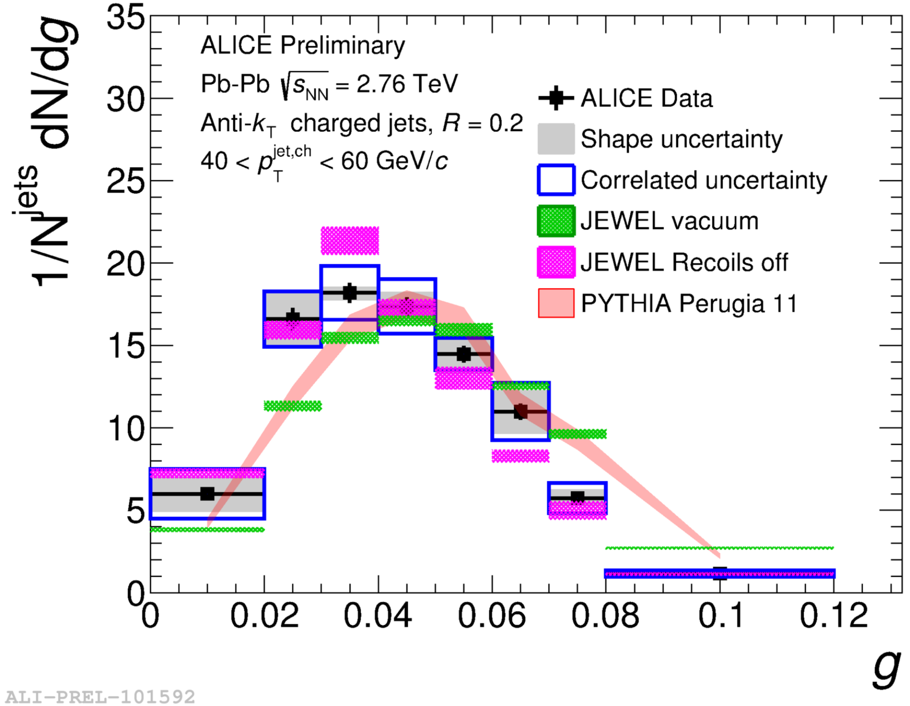


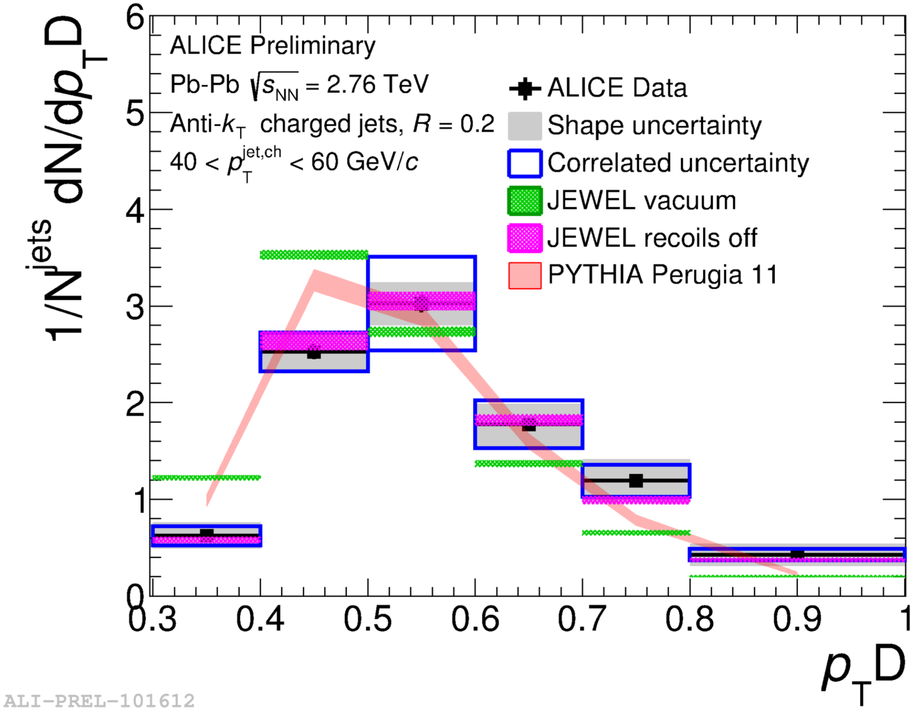
jet area ~ 0.5 (R = 0.4)

central *peripheral*

Jet 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