Exploring the QGP with Jets at ALICE

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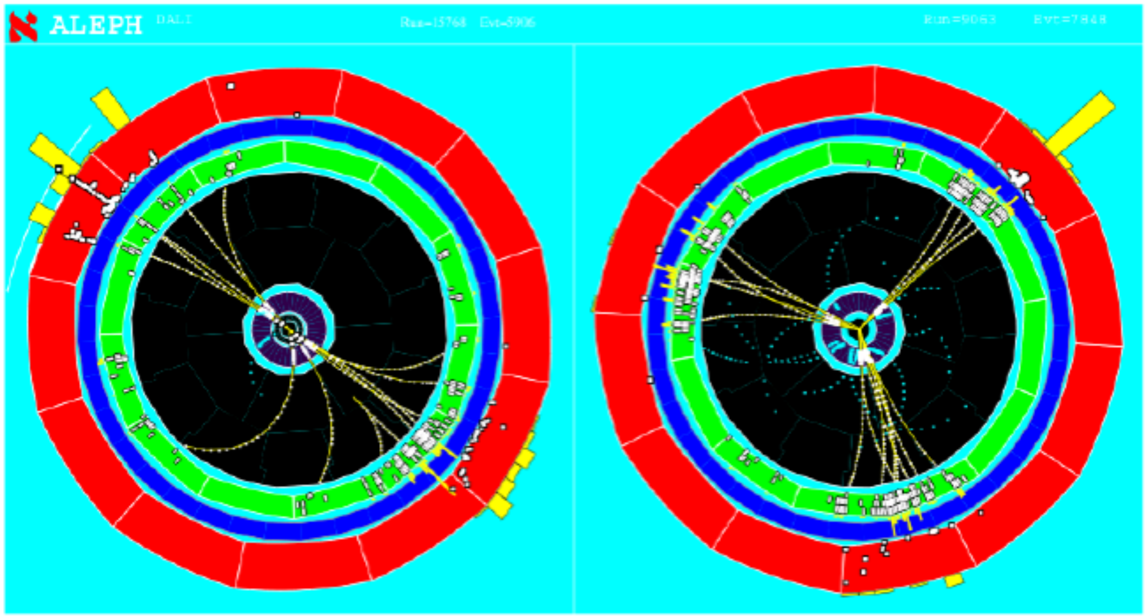
- jets in pp collisions
- jets in heavy-ion collisions
- jet nuclear modification factor
    - event plane dependence
    - collision energy dependence
- strangeness production in jets
- jet mass

Introduction

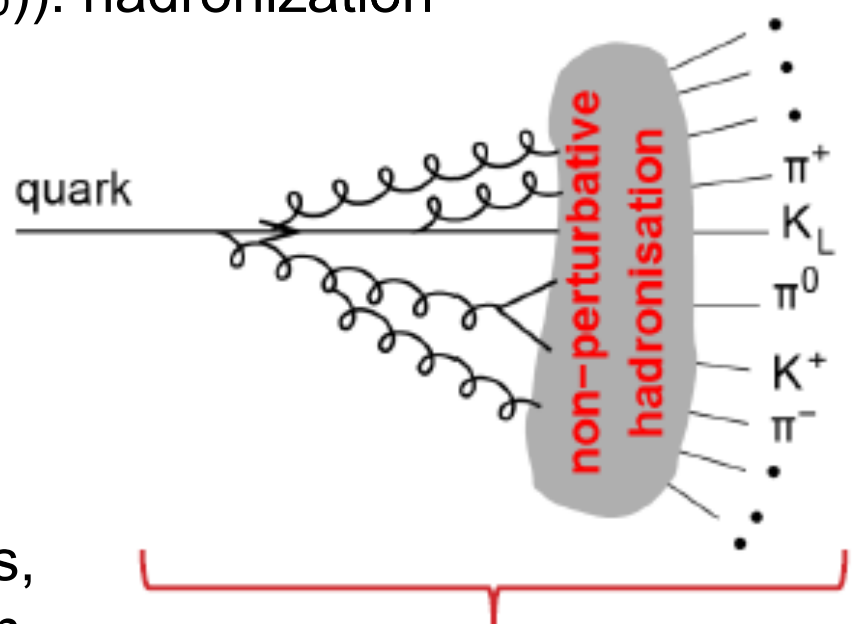
Jets: seeing quarks and gluons



- 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



Fragmentation = Parton shower + hadronization

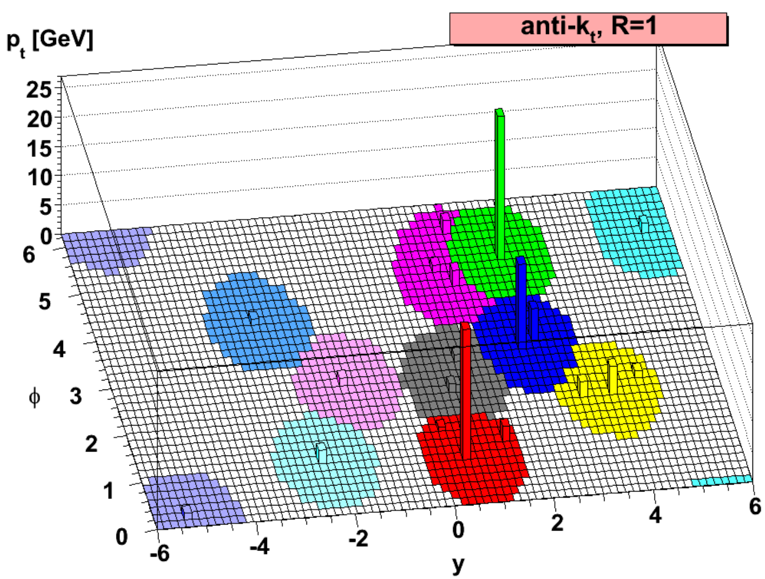
- in heavy-ion collisions, jets probe the medium at a variety of scales

Jet reconstruction

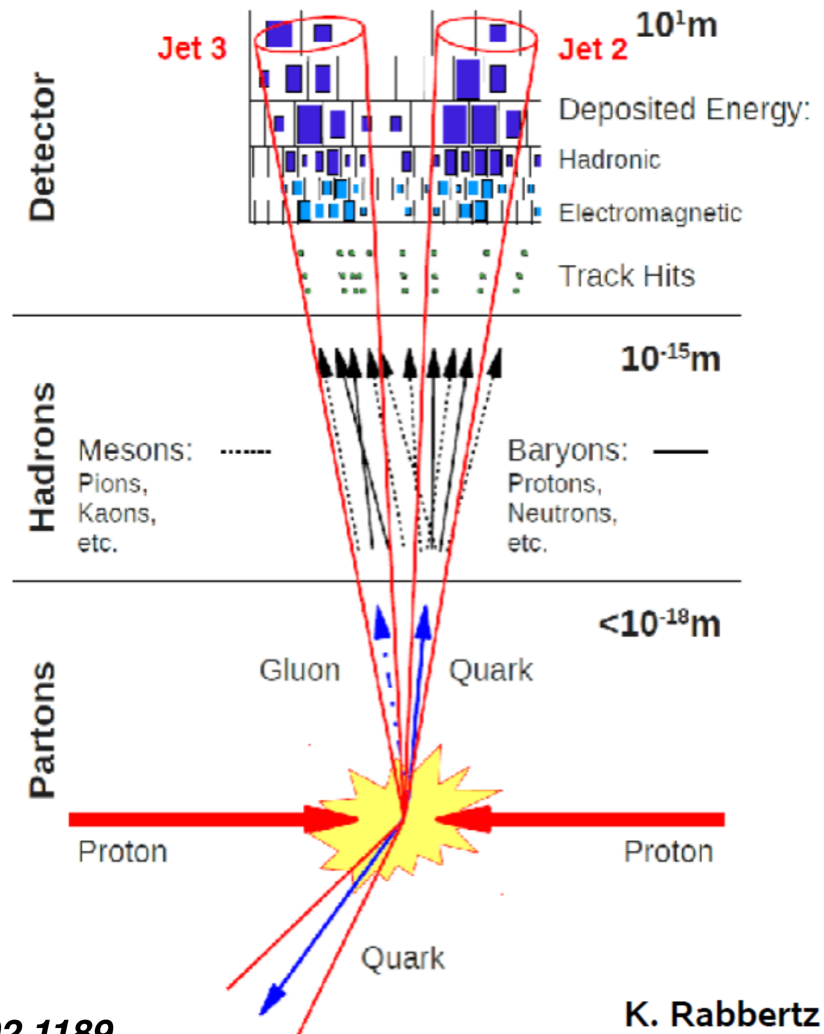
- Establish correspondence between detector measurements / final state particles / partons

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

- resolution parameter R

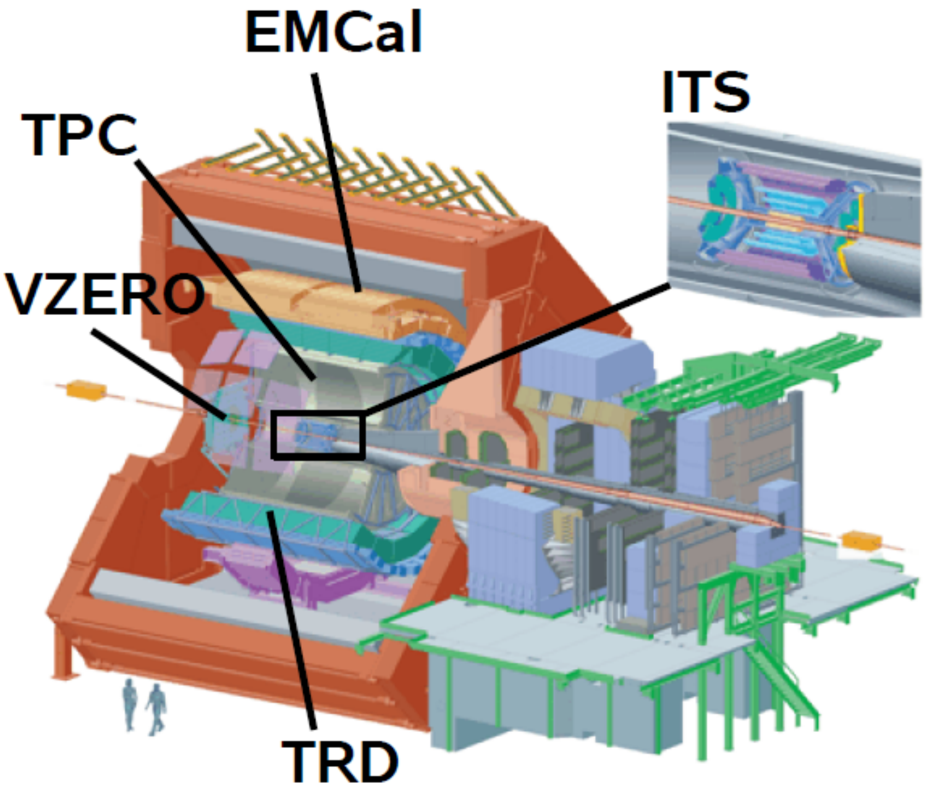


hep-ph/0802.1189



K. Rabbertz

Jets at ALICE (run 1)



- charged particle tracking:
  - Inner Tracking System (ITS)
  - Time Projection Chamber (TPC)
  - full azimuth, $|\eta| < 0.9$
    $p_T > 150$ MeV/c
- Electromagnetic Calorimeter (EMCal) :
  - neutral particles
  - $\Delta\varphi = 107°$, $|\eta|<0.7$
    cluster $E_T > 300$ MeV

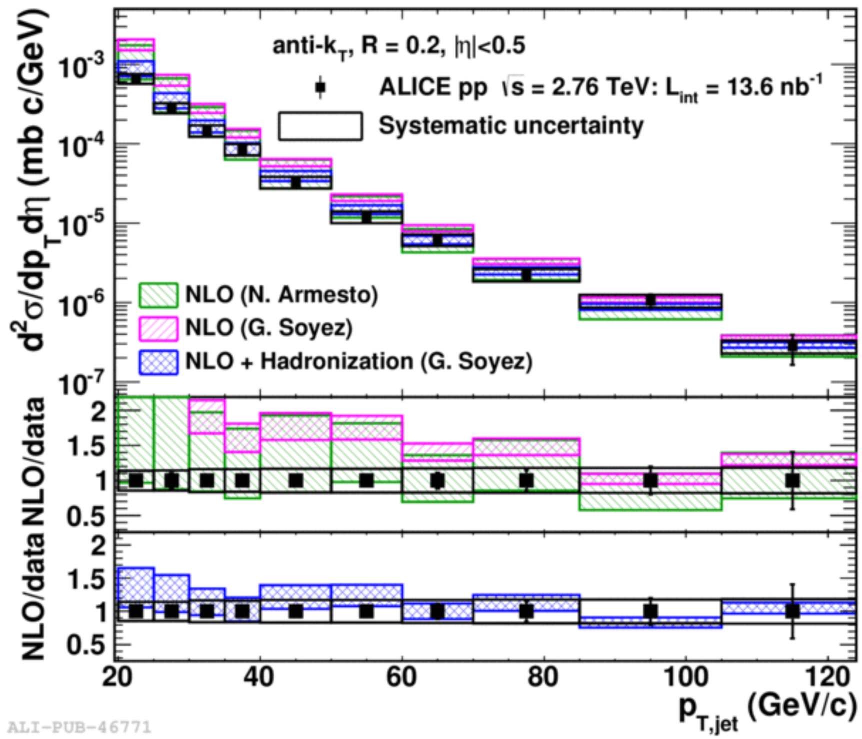
- jet trigger with EMCal and TRD
- \`charged' (tracking) jets and \`full' jets
- full jets from charged particle tracking and EM energy:
  conceptually different and complementary to traditional approach

Jet Cross Section in pp Collisions

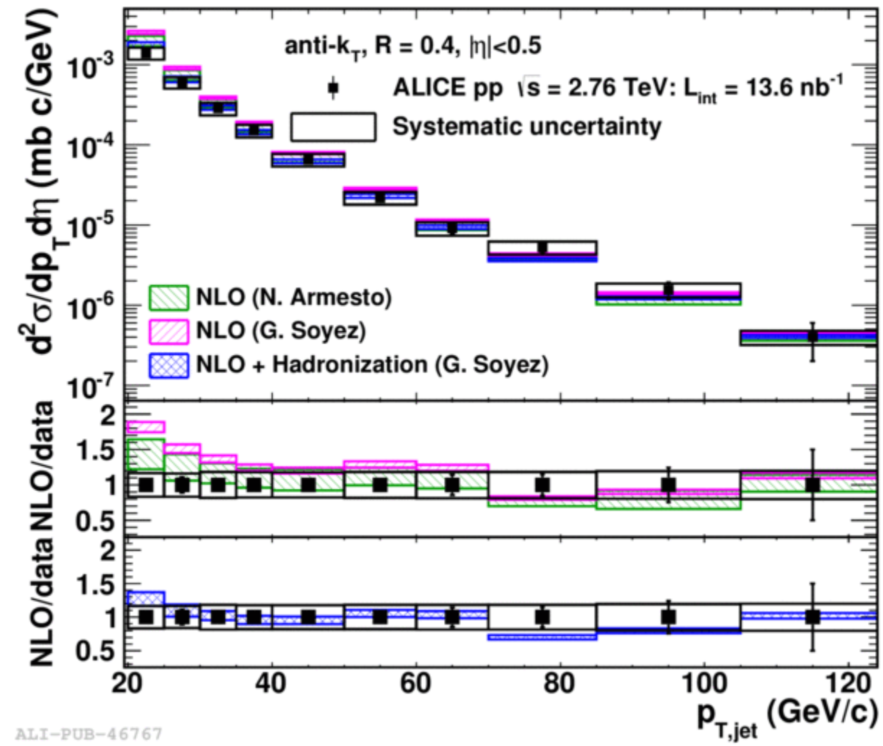
Full jets in pp at $\sqrt{s}$ = 2.76 TeV

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

R = 0.2



R = 0.4



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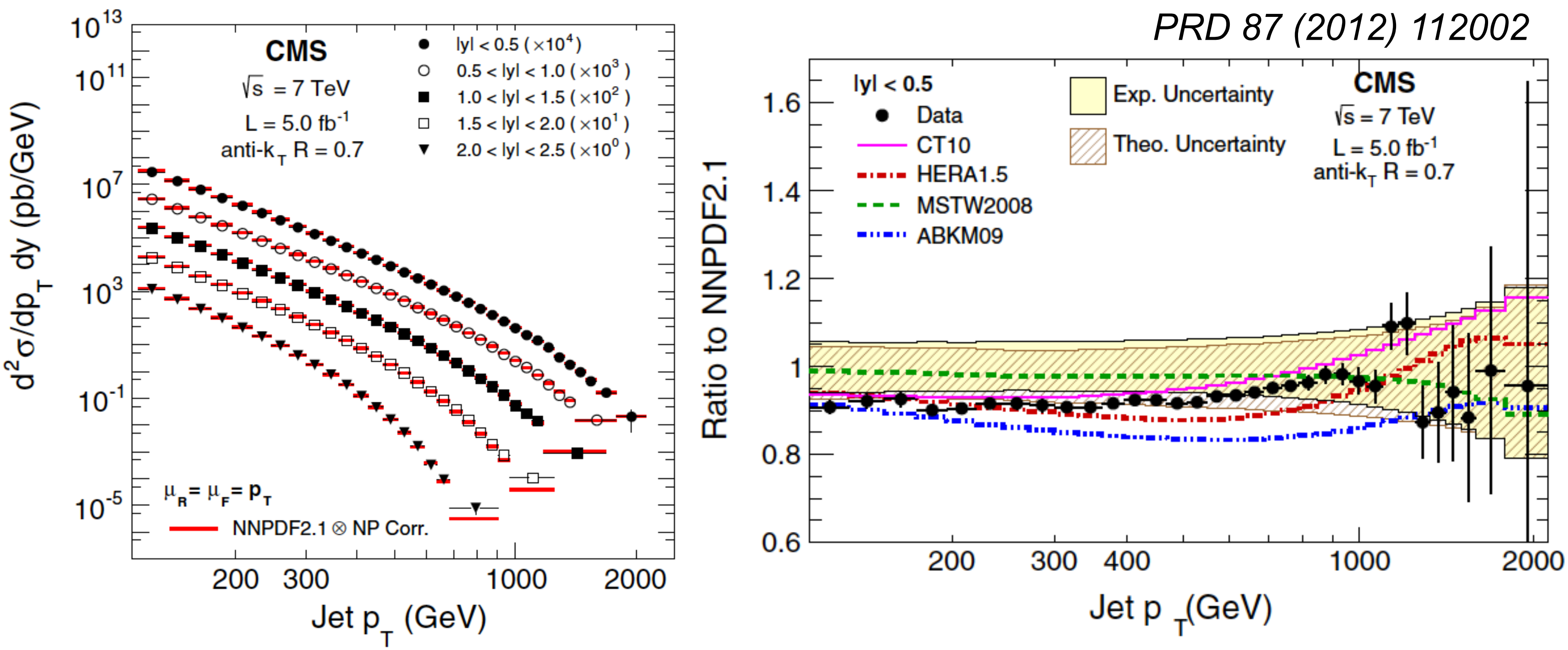
CMS: jets at $\sqrt{s}$ = 7 TeV

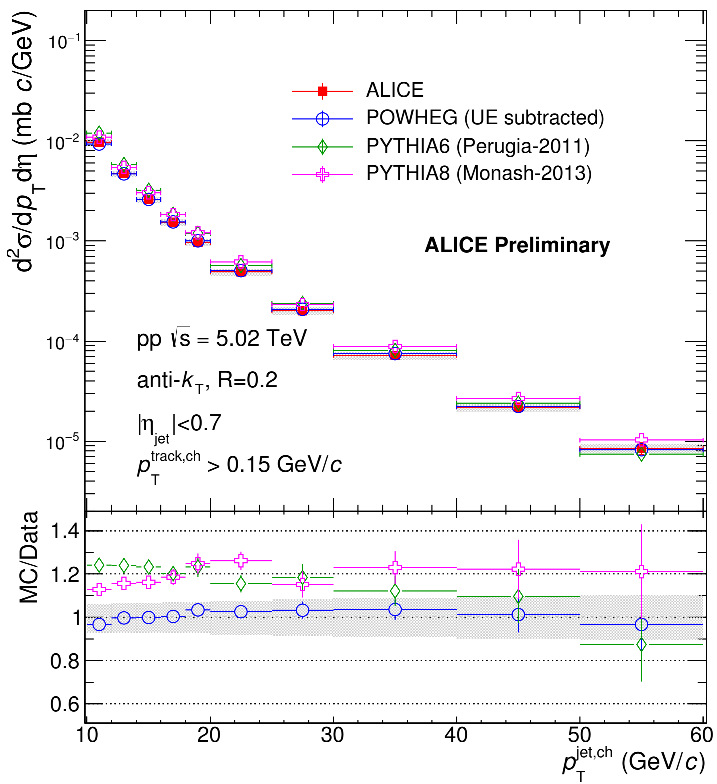
- single inclusive jet cross sections compared to NLO pQCD: agreement over 14 orders of magnitude
- comparable theoretical and experimental uncertainties
- complementary jet p_T reach of the LHC experiments

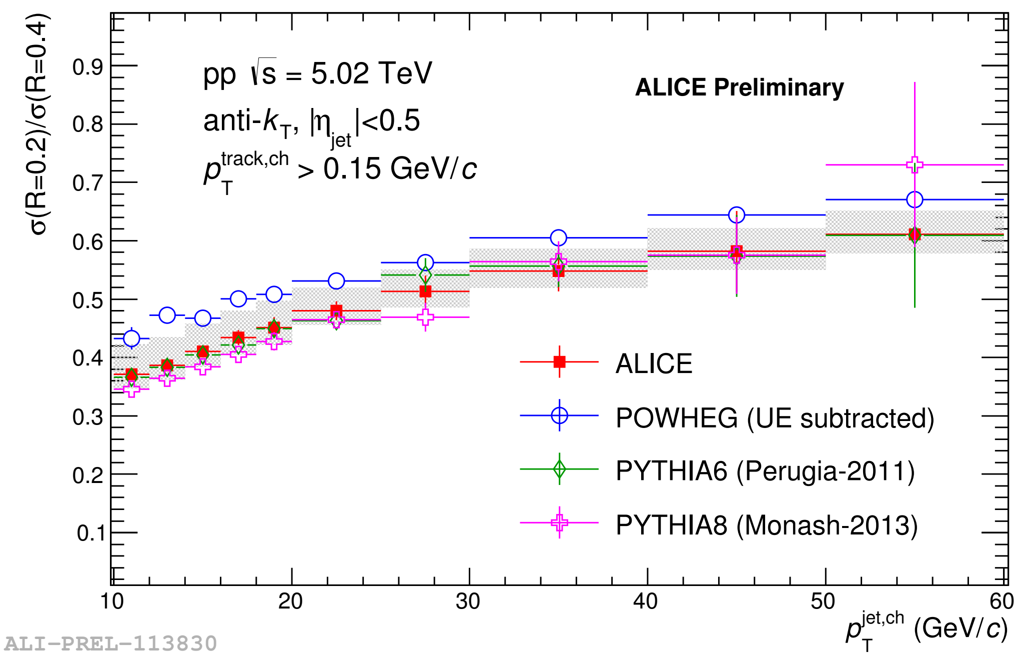
PRD 87 (2012) 112002



pp charged jet cross-sections

- inclusive charged jet cross section in minimum bias collisions at $\sqrt{s}$ = 5.02 TeV: well described by POWHEG NLO calculations
- cross section ratio: well described by PYTHIA and POWHEG
- reference for run 2 Pb-Pb collisions at same $\sqrt{s_{NN}}$





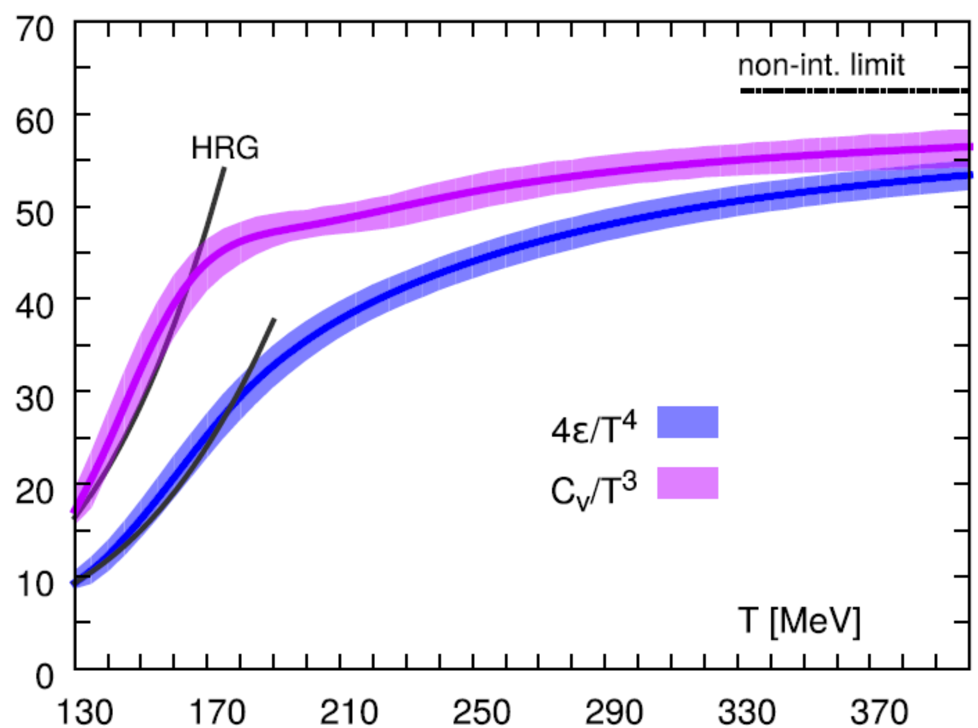
ALI-PREL-113830

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

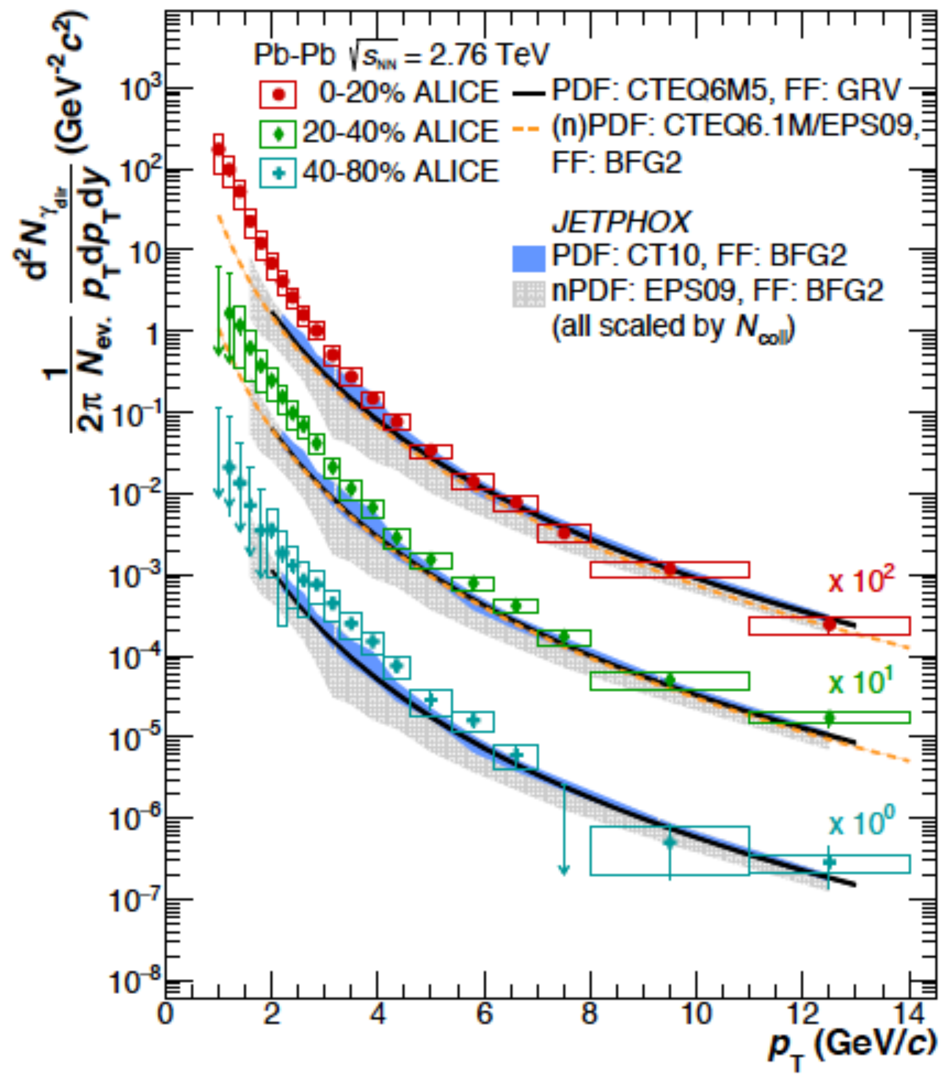


QCD matter at LHC

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

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

- indicates initial temperature way above T_C



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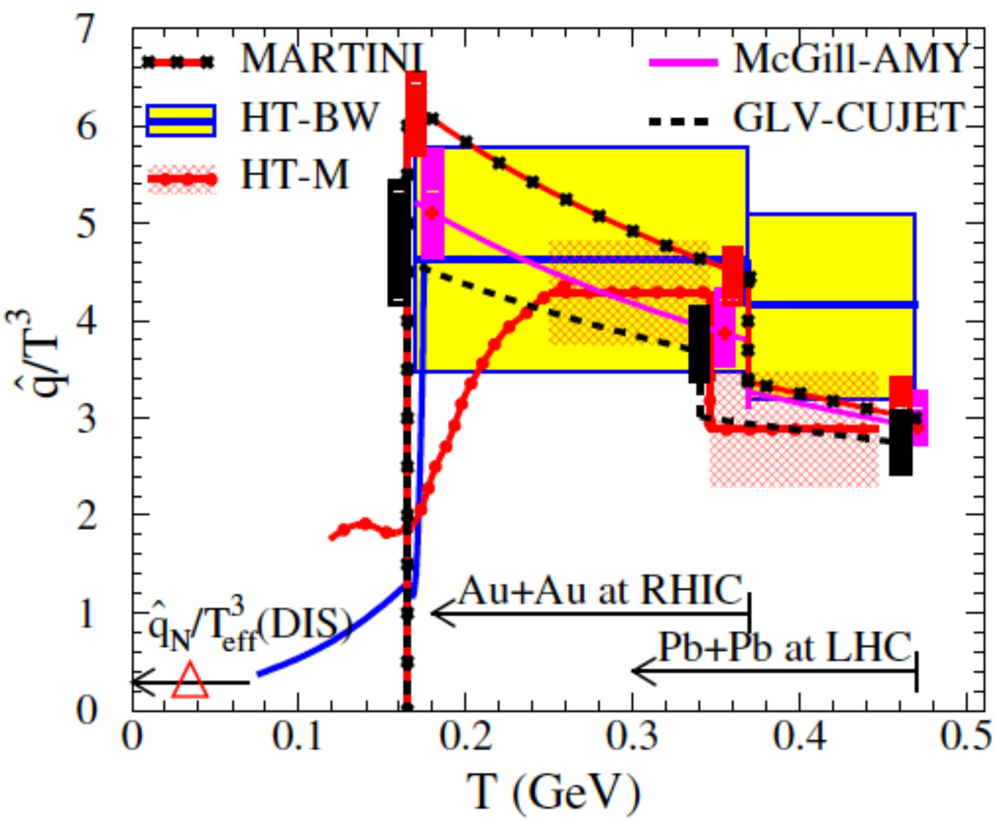
Partons in heavy-ion collisions

- hard partons are produced early and traverse the hot and dense QGP
- expect enhanced parton energy loss : `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 ...)



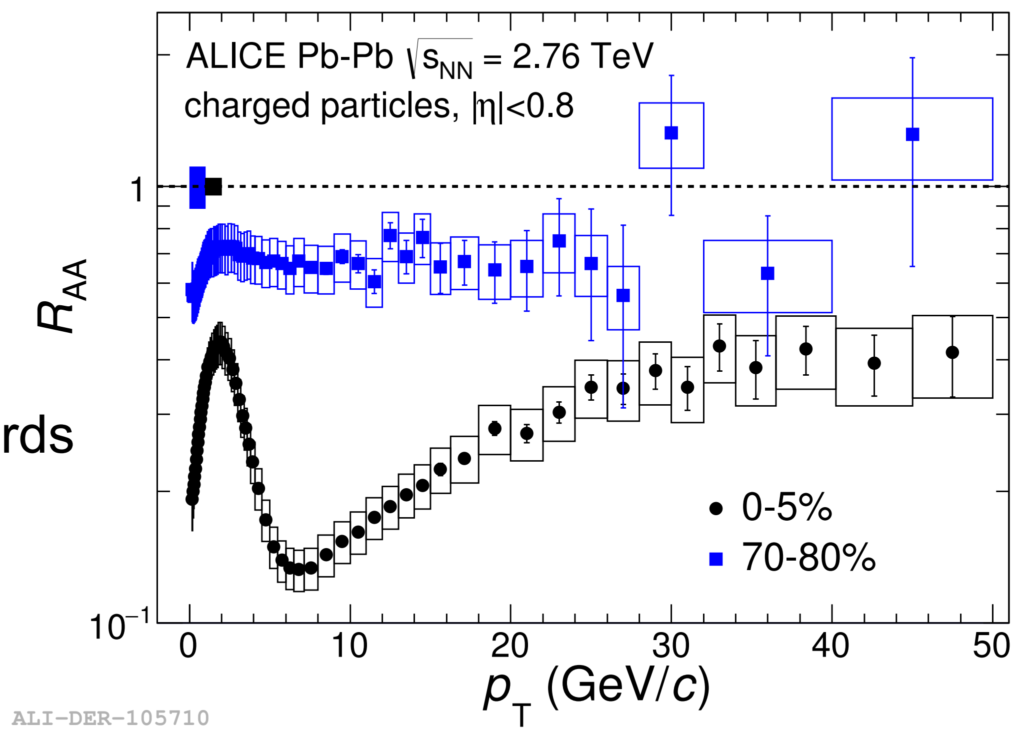
JET collaboration, PRC 90, 014909

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

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

PLB 720 (2013) 250



- hadron observables biased towards leading fragment

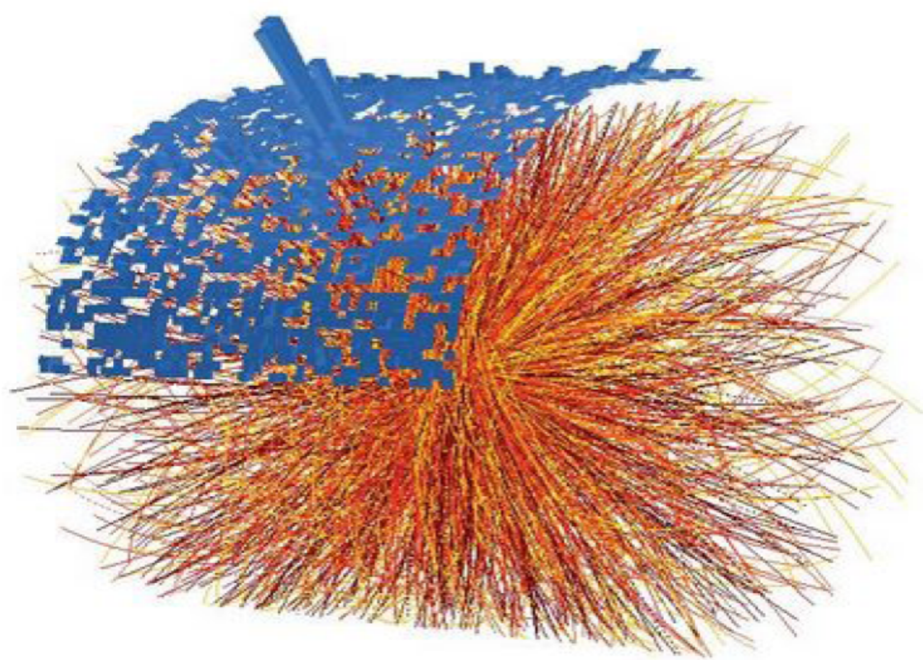
→ study the effect for fully reconstructed jets

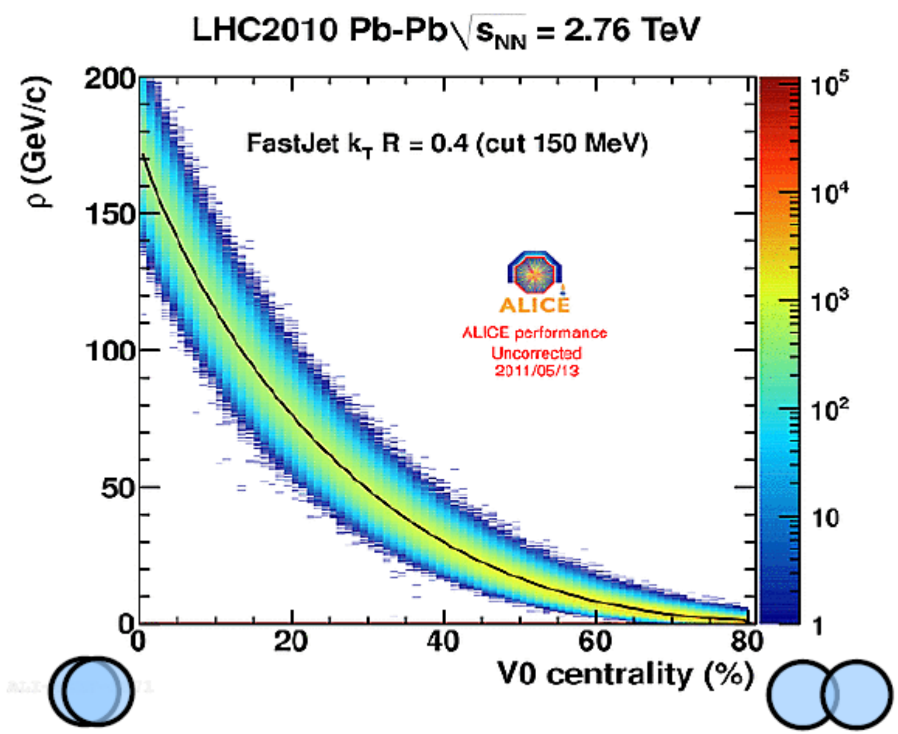
Underlying event

- 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

- full jet R_{AA} at $\sqrt{s_{NN}}$ = 2.76 TeV, R = 0.2

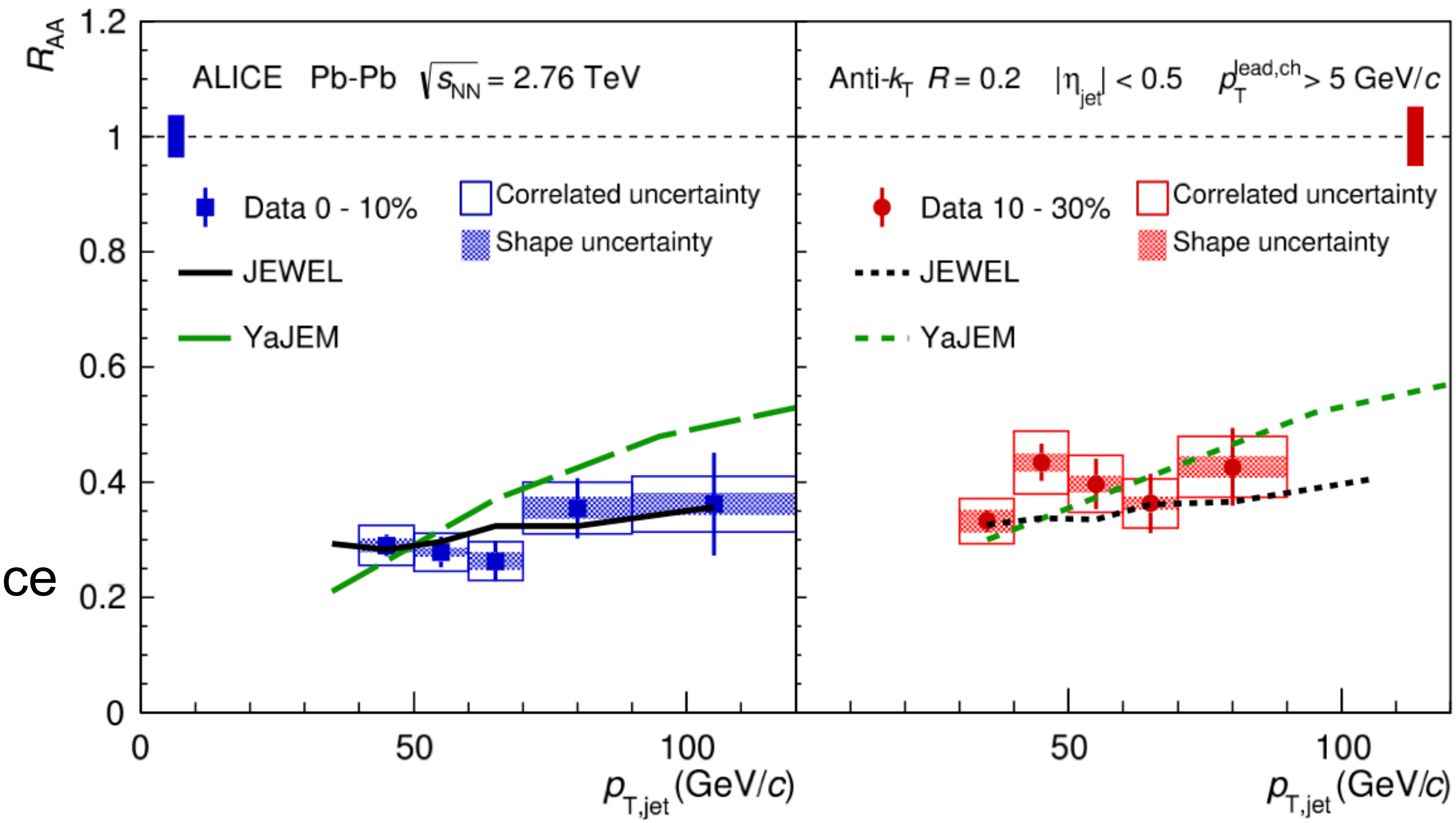
Phys.Lett. B746 (2015) 1

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

JEWEL: PLB 735 (2014)

YaJEM:PRC 88 (2013) 014905

- increase of suppression with centrality
- weak p_T dependence
- JEWEL and YaJEM jet quenching models reproduce suppression

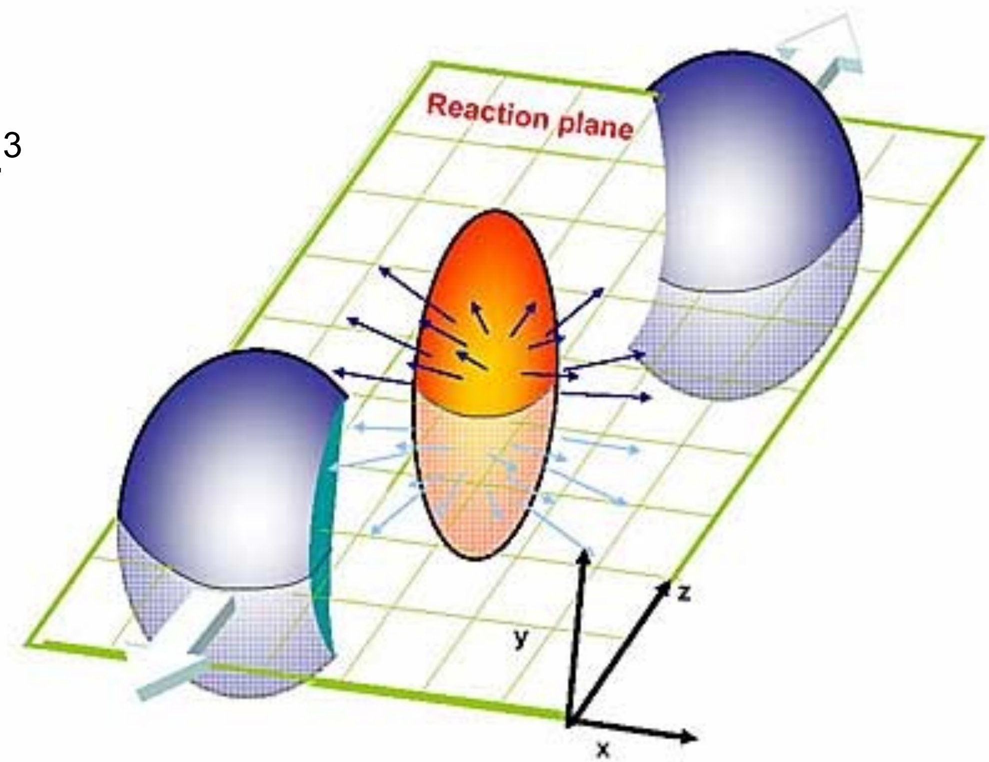


Jet azimuthal anisotropy

Reaction plane dependence

- different medium thickness in- and out-of plane

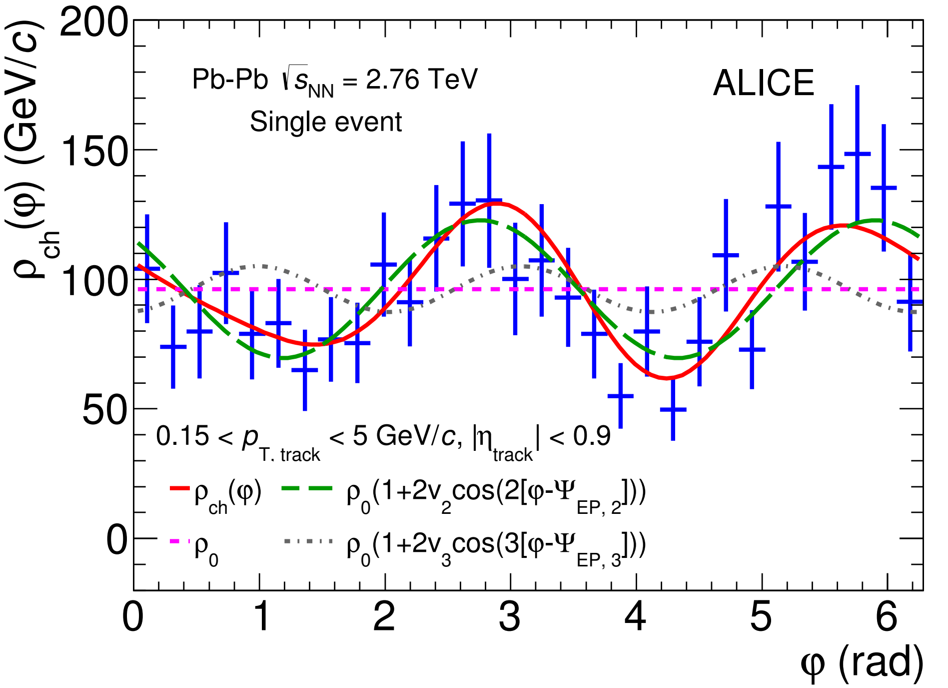
- sensitive to path length dependence of jet quenching:
  pQCD radiative E-loss : $\sim L^2$
  collisional E-loss : $\sim L$
  strong coupling (ADS/CFT) : $\sim L^3$



Local background subtraction

- 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



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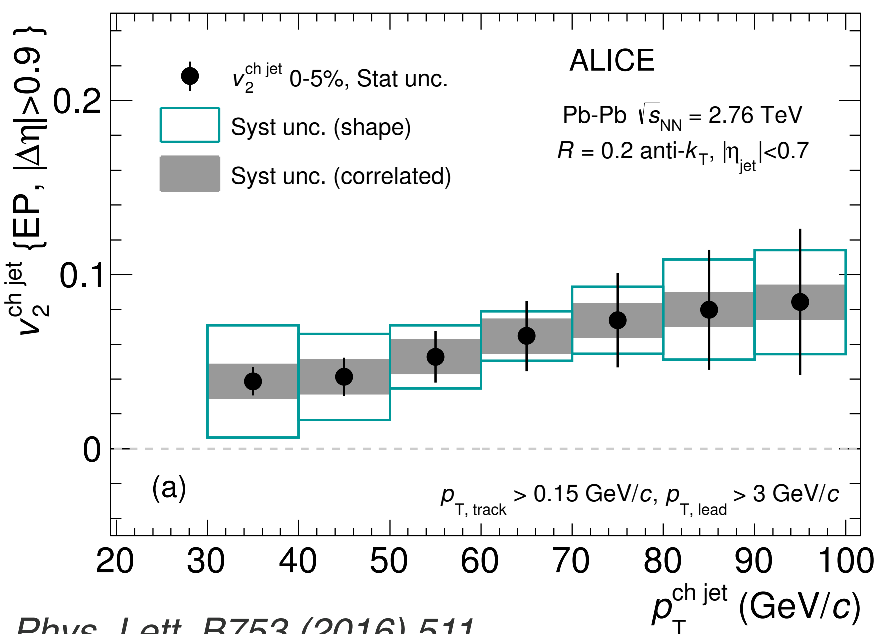
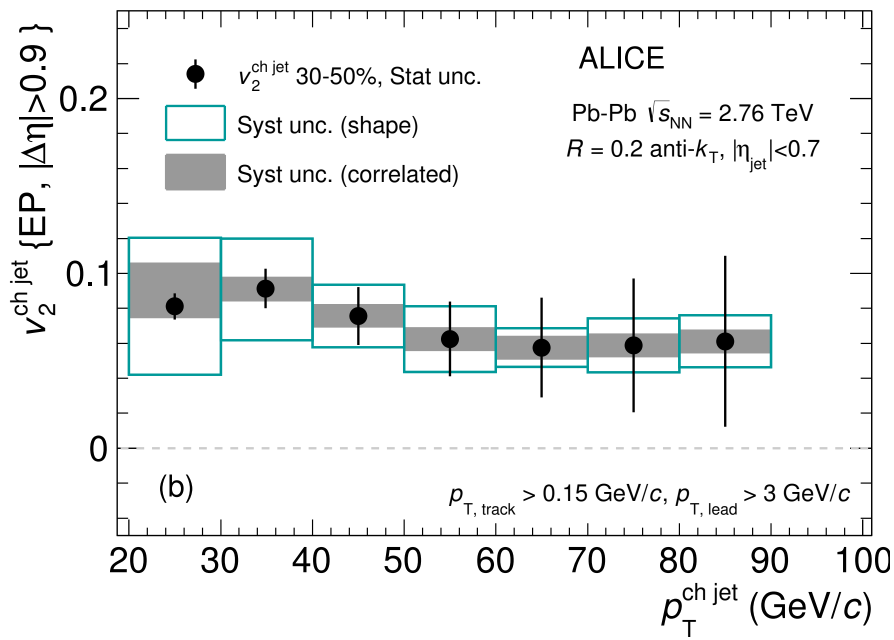
Jet v_2: results

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

0-5%



30-50%



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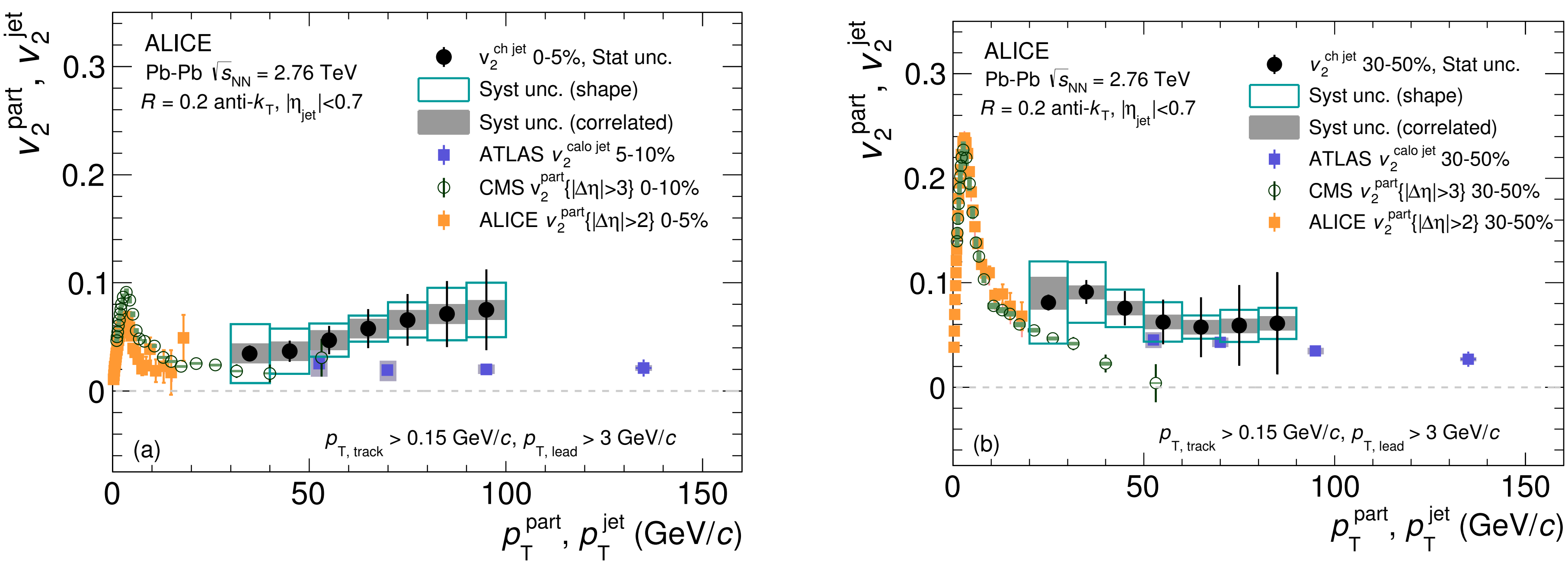
Comparison to previous results

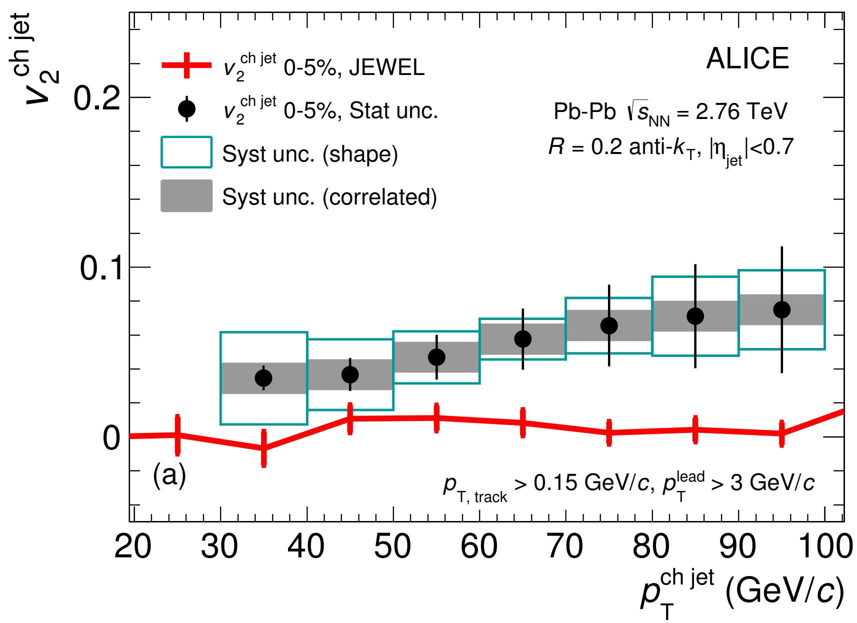
- ALICE + CMS single particles, ATLAS full jets : different energy scales !
- non-zero v2 up to high p_T

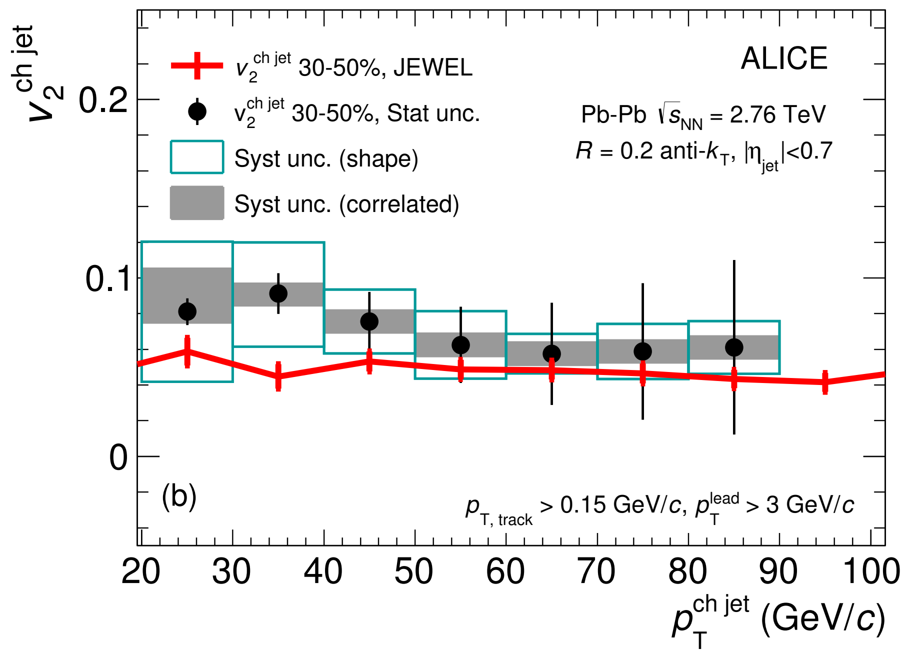
CMS, PRL 109 (2012) 022
ATLAS, PRL 111 (2013) 152
ALICE, Phys. Lett. B753 (2016) 511
ALICE, Phys. Lett. B719 (2013) 18



Comparison to JEWEL

- good agreement with JEWEL in semi-central collisions
- clear indication of path-length dependence of energy loss





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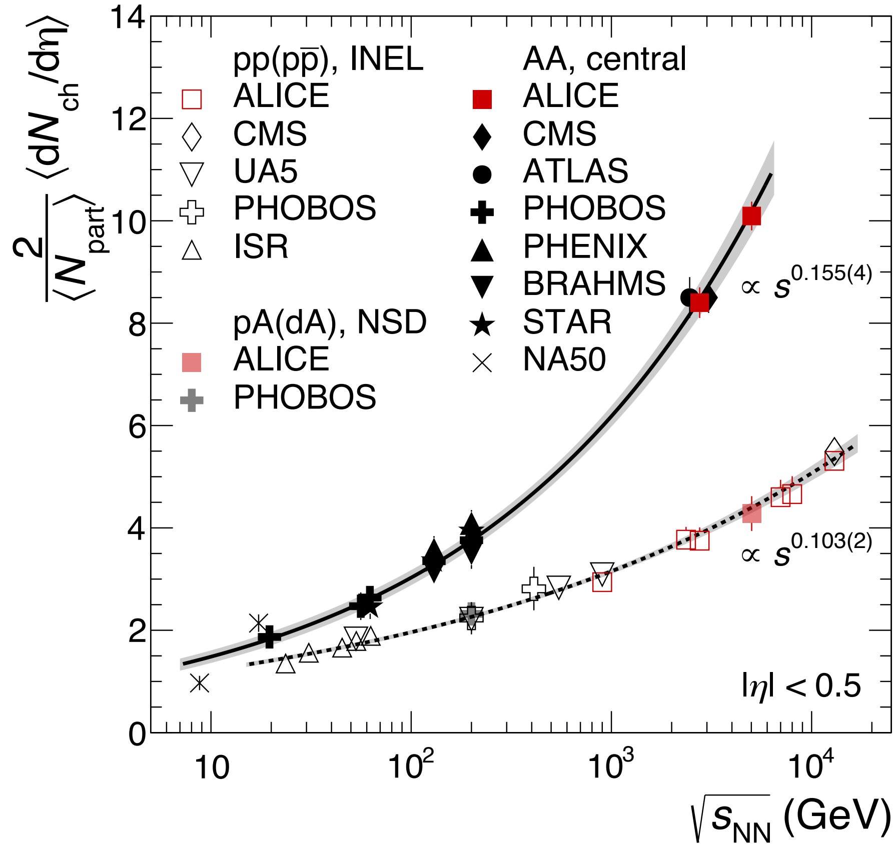
Jet Nuclear Modification Factor at $\sqrt{s_{NN}}$ = 5.02 TeV

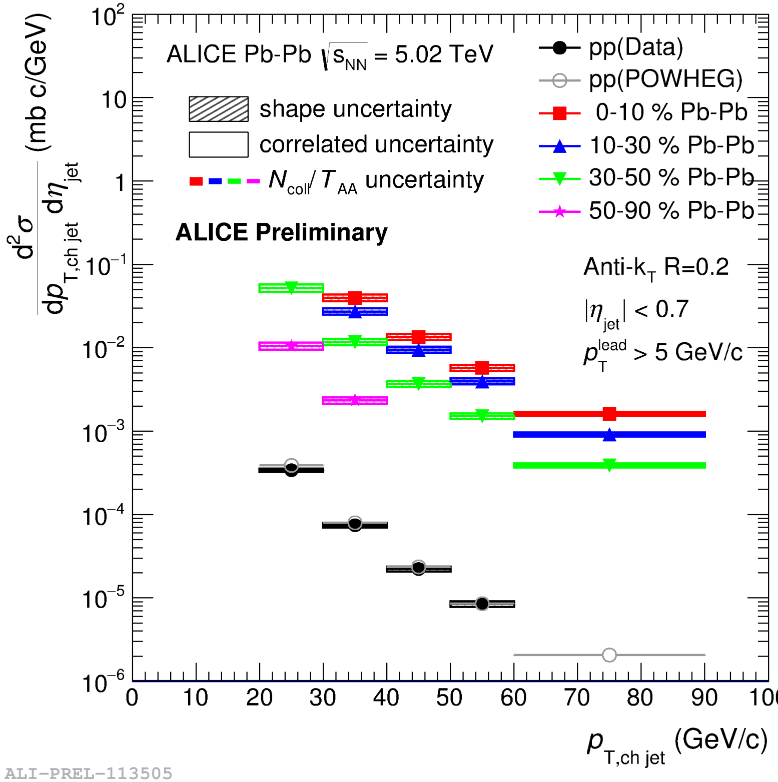
LHC run 2

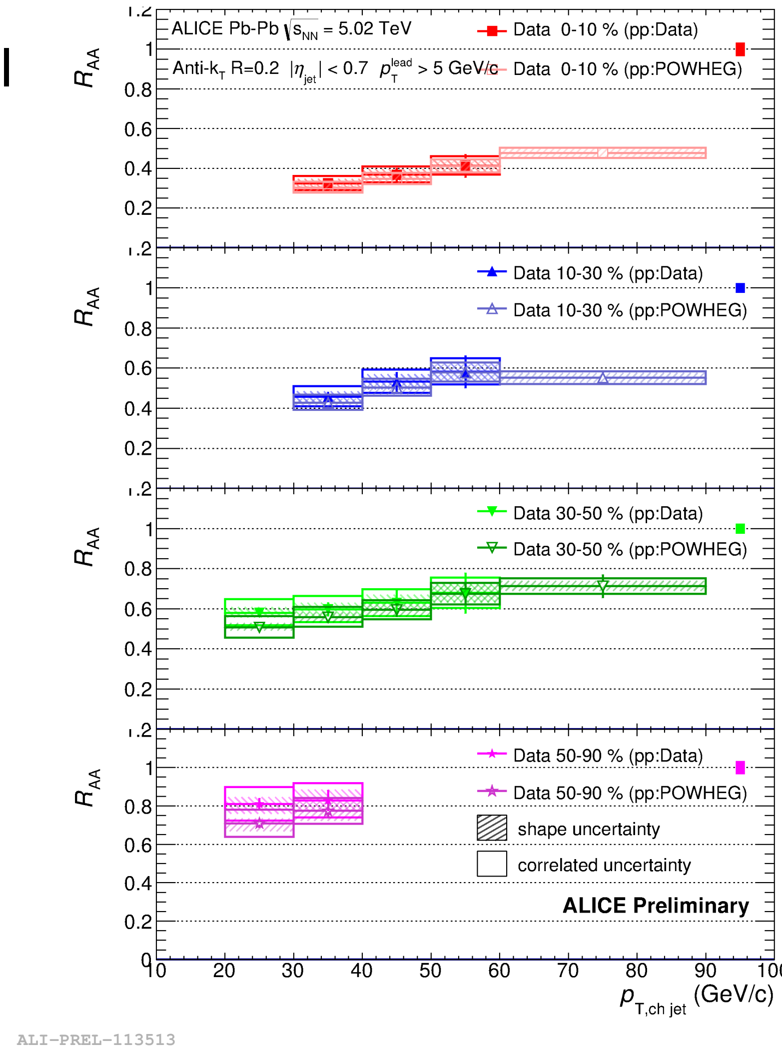
- increased CMS energy for Pb-Pb collisions from 2.76 → 5.02 TeV
- quenching strength $\hat{q}$ ~ s ~ $\varepsilon^{3/4}$
- expect (modest) increase in ε, T
  → measure energy density dependence of jet quenching
- note: R_{AA} also depends on parton 'input spectrum': at higher √s, flatter spectrum → larger R_{AA}



Run 2 jet cross section and RAA

- jet cross section and nuclear modification factor at $\sqrt{s_{NN}}$ = 5.02 TeV
- stronger suppression in more central collisions, slight increase with p_T



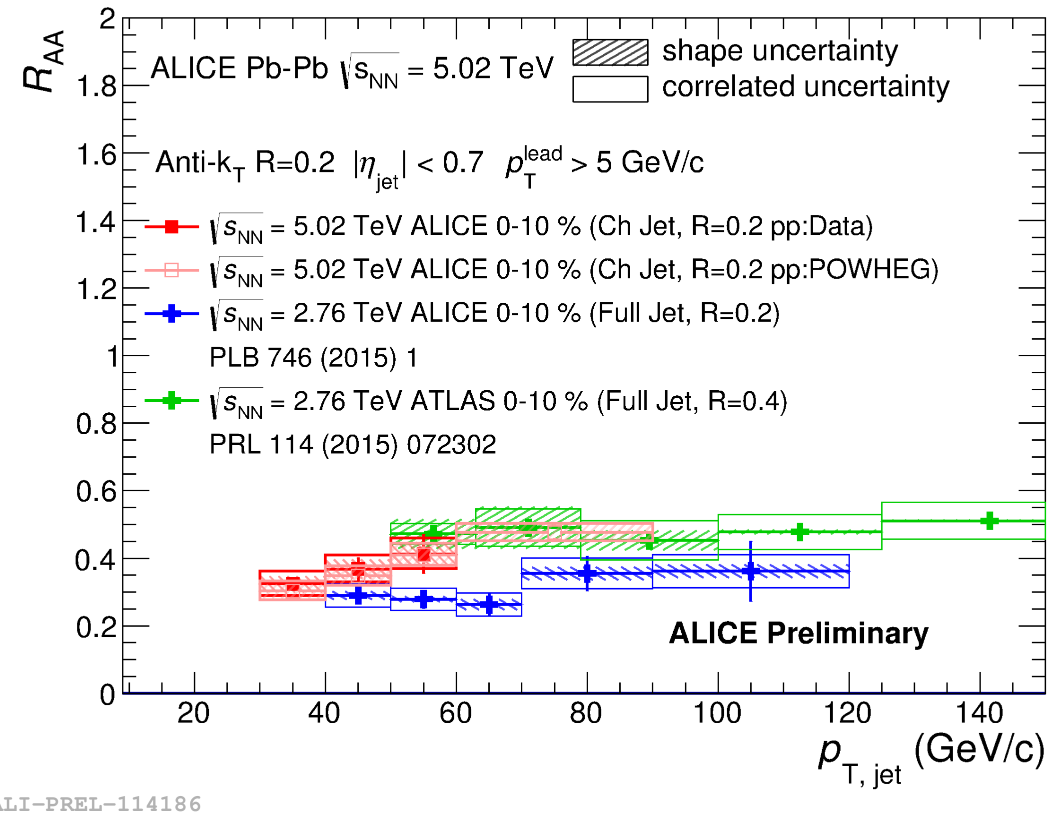


$\sqrt{s_{NN}}$ dependence of R_{AA}

- charged jet R_{AA} at $\sqrt{s_{NN}}$ = 5.02 TeV compared to:
  - ALICE full jet R_{AA} at 2.76 TeV (R = 0.2)
  - ATLAS jet R_{AA} (R = 0.4)

  → different jet energy scales

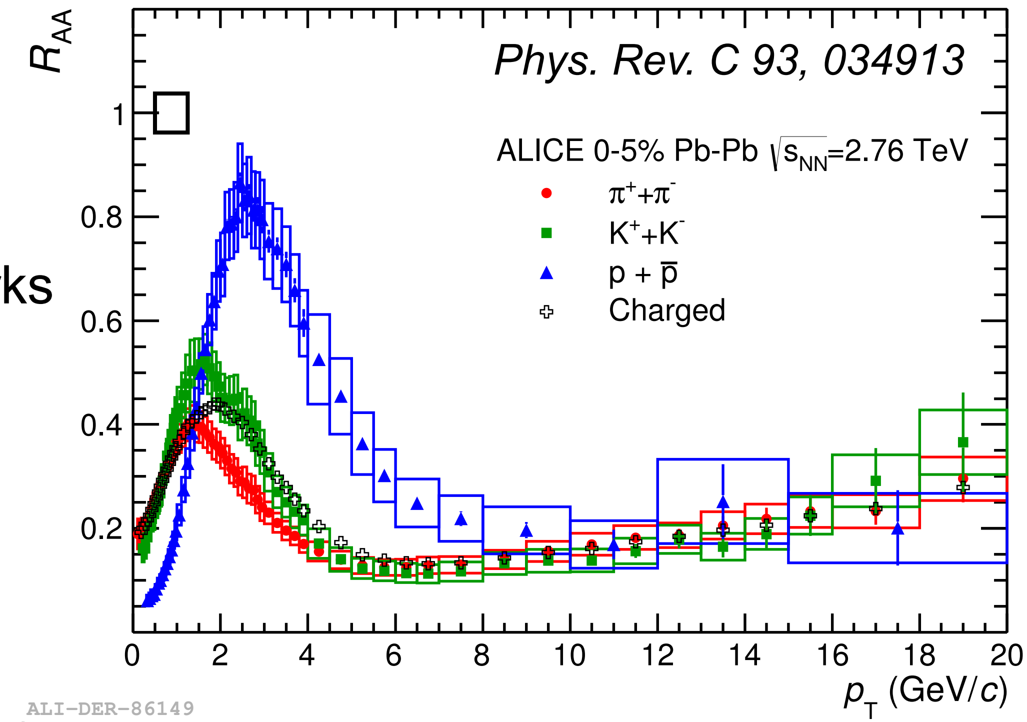
- comparable R_{AA}:
  effect of flattening of the spectrum compensated by stronger suppression



Strangeness Production in Jets

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

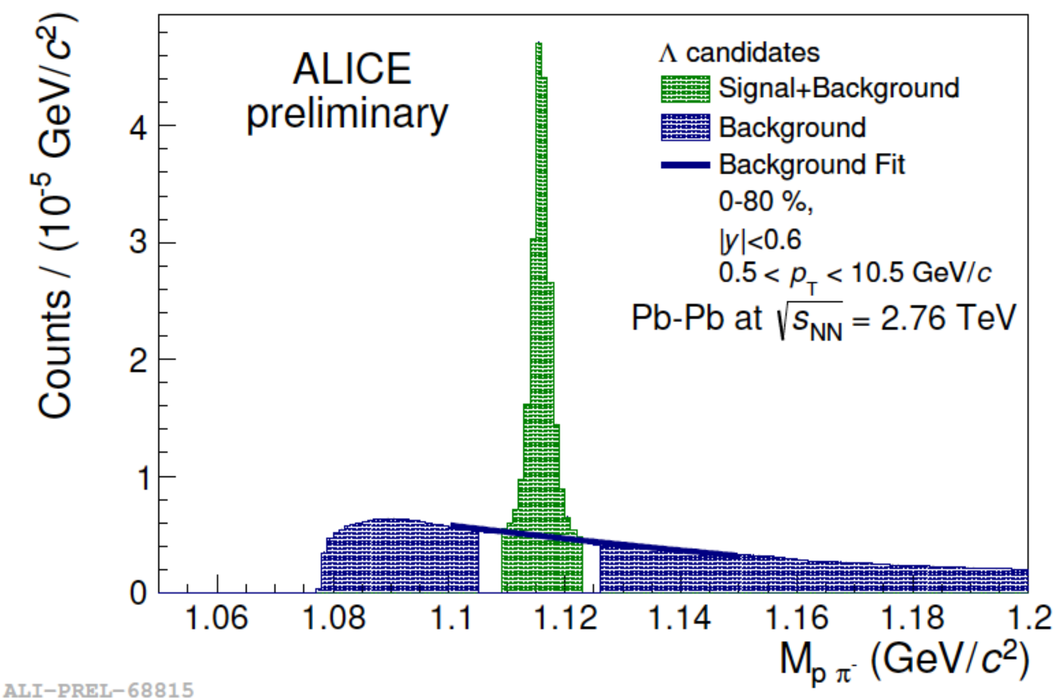
- note: medium effects likely strongest at scales of ~ medium Temperature
  (*J.G. Milhano, K. C. Zapp, hep-ph/1512.0819, T. Renk, Phys. Rev. C 81, 014906, B. Mueller, hep-ph/1010.4258*)

Strange hadron reconstruction

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

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

- signal extraction from invariant mass distributions

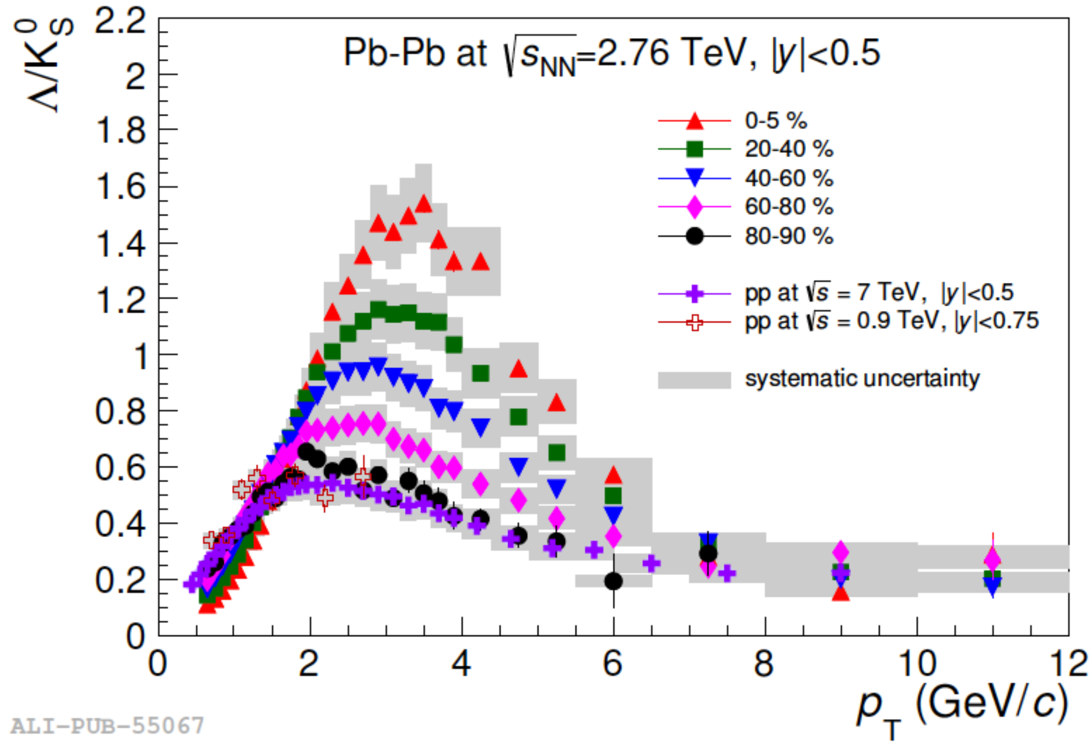


Strangeness production in nuclear collisions

筑波大学
University of Tsukuba

- Inclusive strangeness production in Pb-Pb:
  Baryon / Meson ratio enhanced
  - collective effects ?
  - parton recombination ?
  - jet fragmentation ?

Phys. Rev. Lett. 111 (2013) 223001



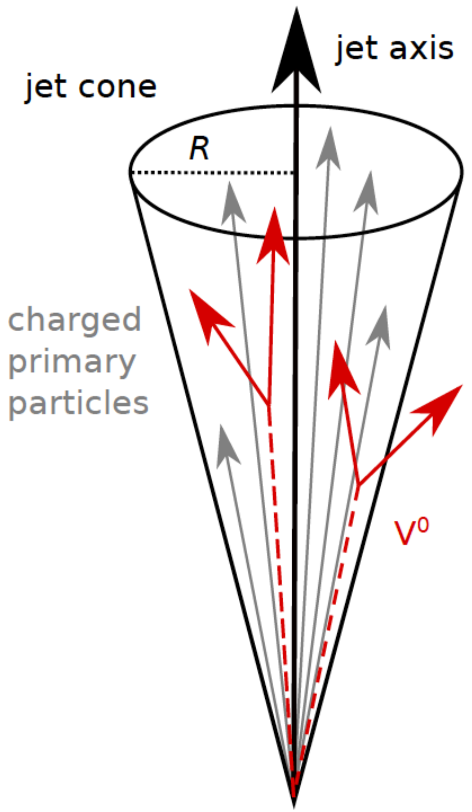
- measurement of identified particles in jets helps to constrain hadronisation and energy loss scenarios

Strangeness in jets

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

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

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

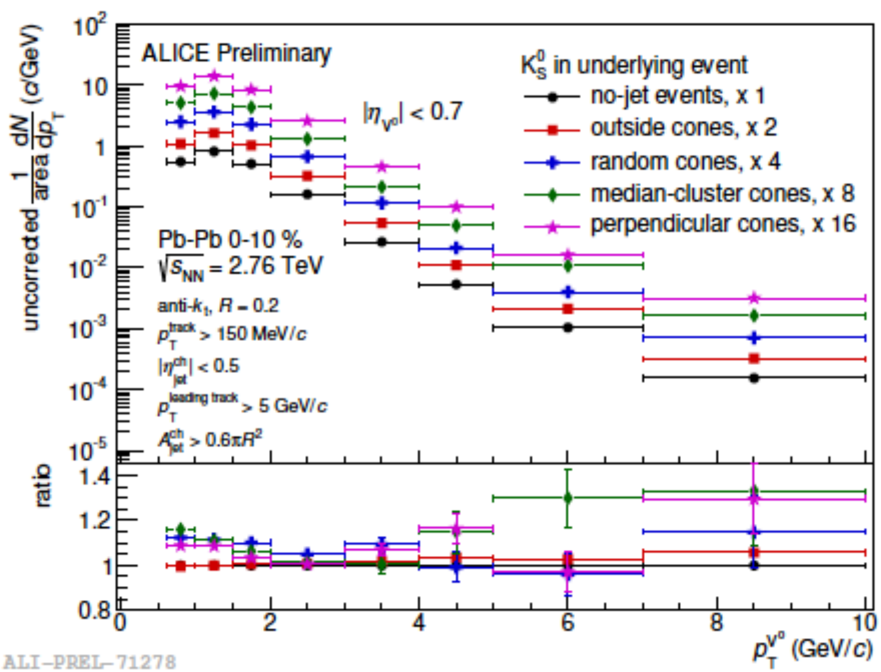


- jet R = 0.2, acceptance $|\eta^{V0}| < 0.7$
- candidate - bulk matching: underlying event V^0
- signal extraction from invariant mass distributions
- correct for efficiency and feed-down
- subtract underlying event from spectra

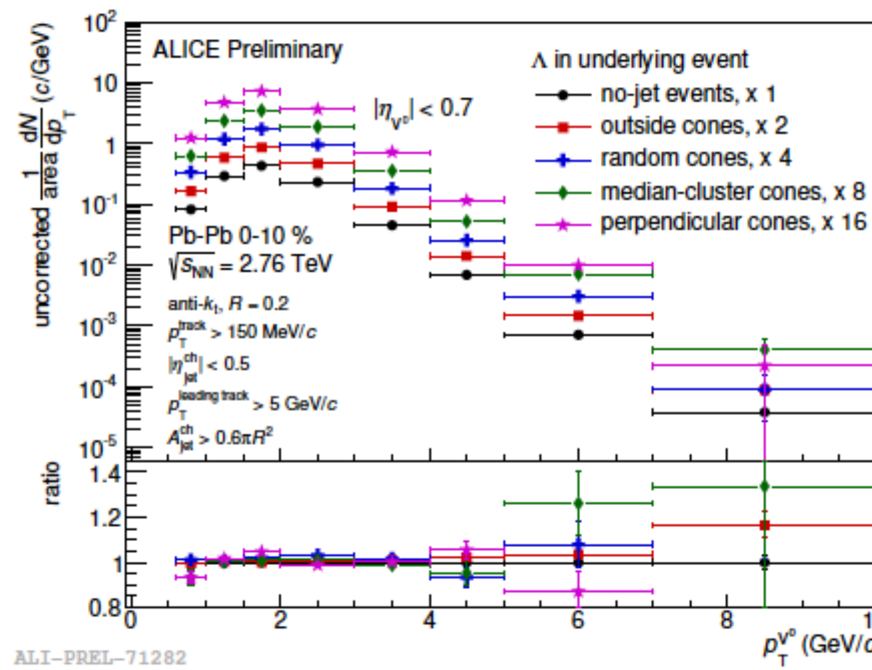
Underlying event subtraction

- 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, …
- apply a correction to account for background density fluctuations

K^0_S

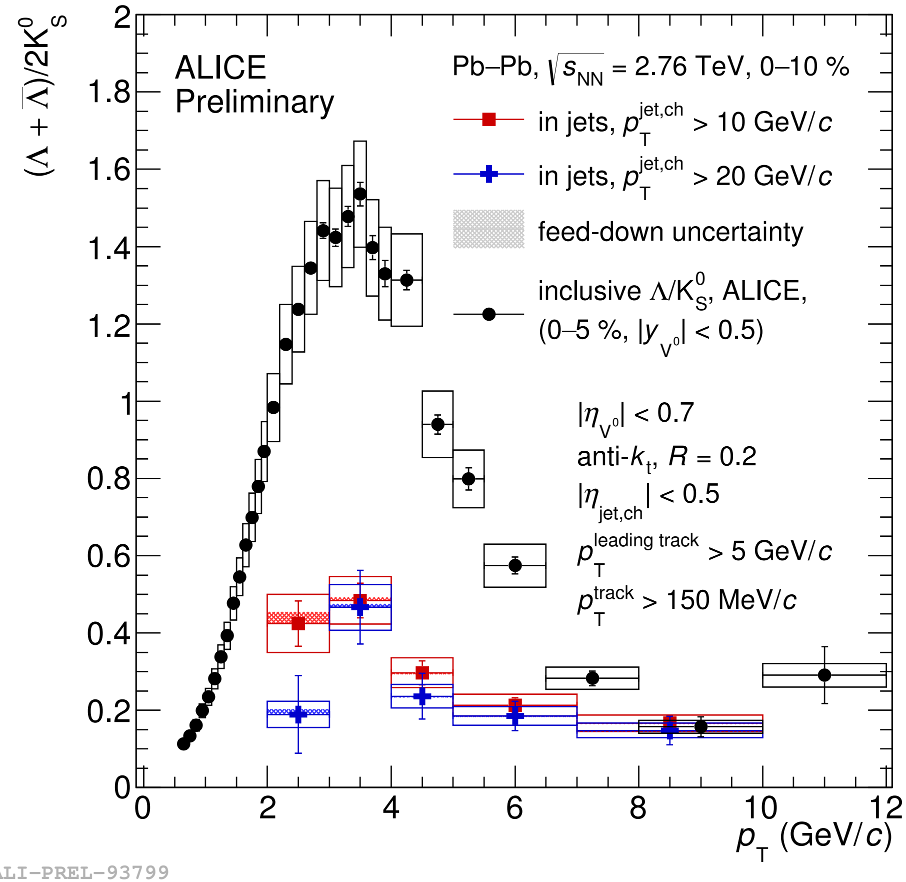


Λ



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

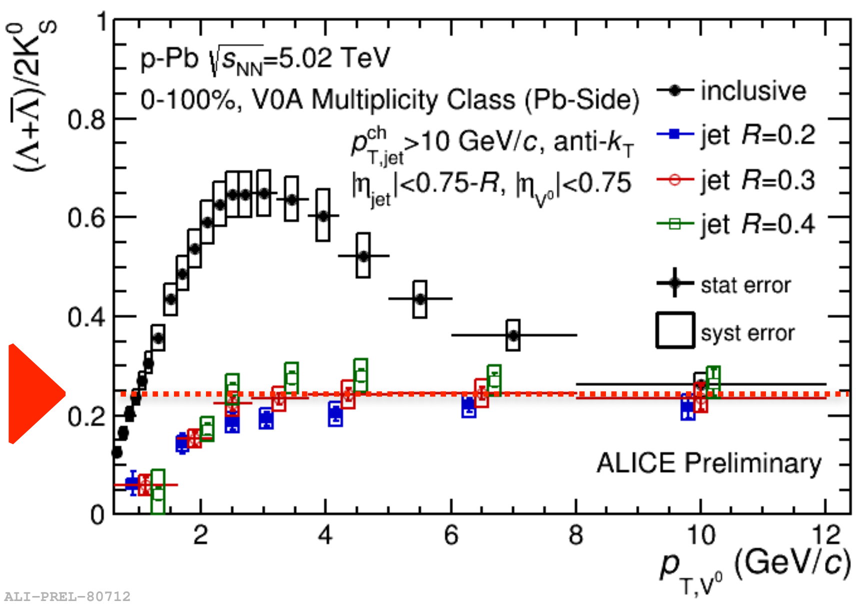


Comparison to p-Pb

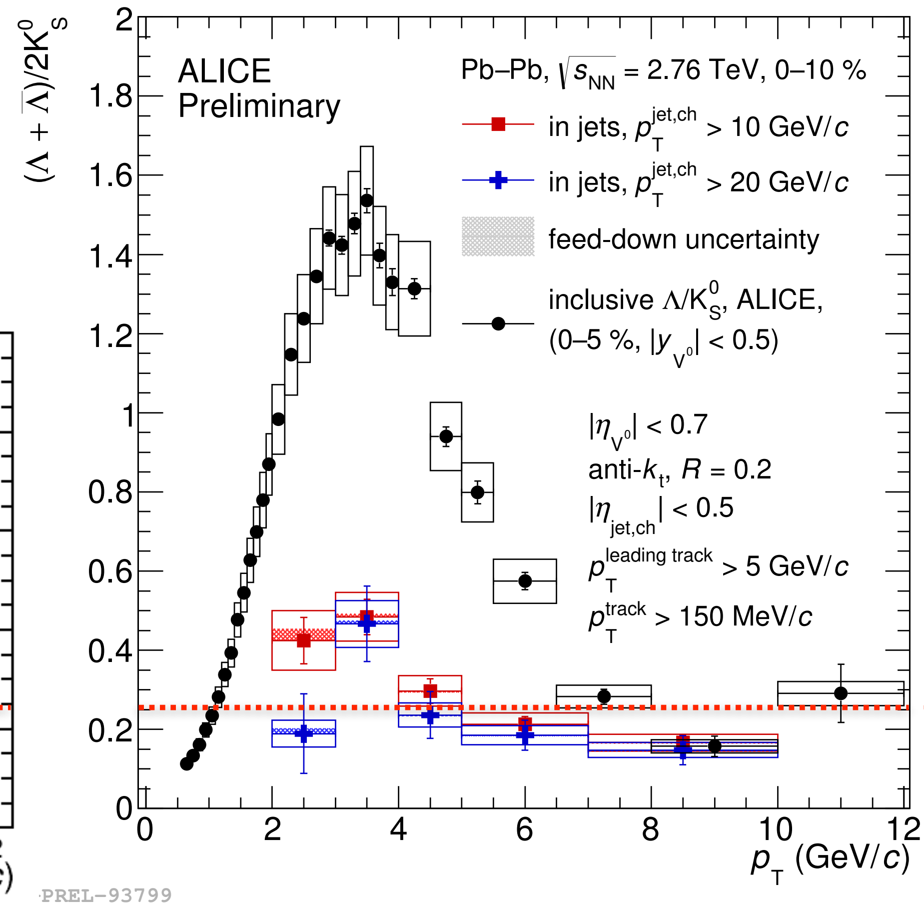
- compare Pb-Pb results to reference from p-Pb collisions at 5.02 TeV: agreement within uncertainties

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

p-Pb

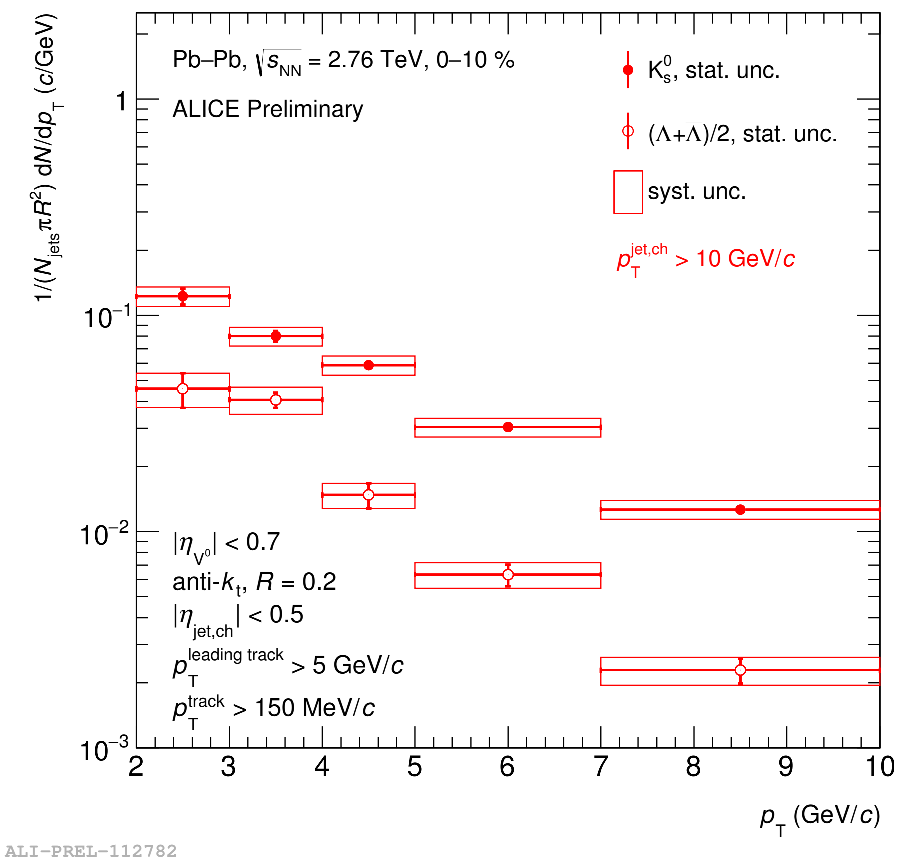


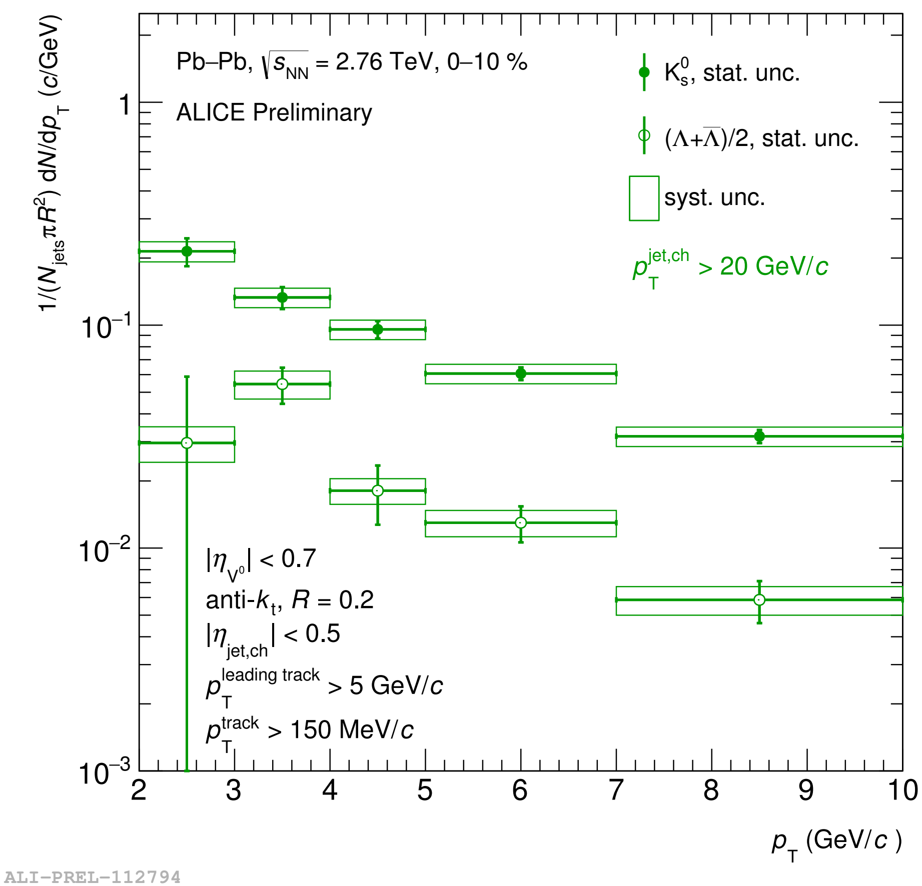
Pb-Pb



Strange particle spectra in jets

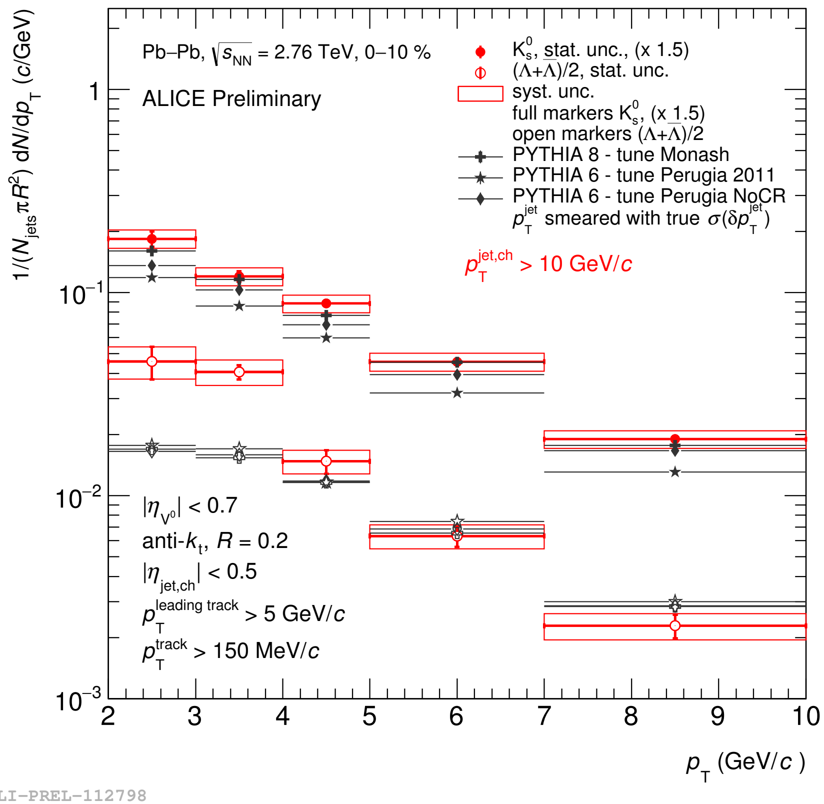
- spectra of K^0_S and Λ particles in jets: more differential observable to increase sensitivity to potentially modified fragmentation

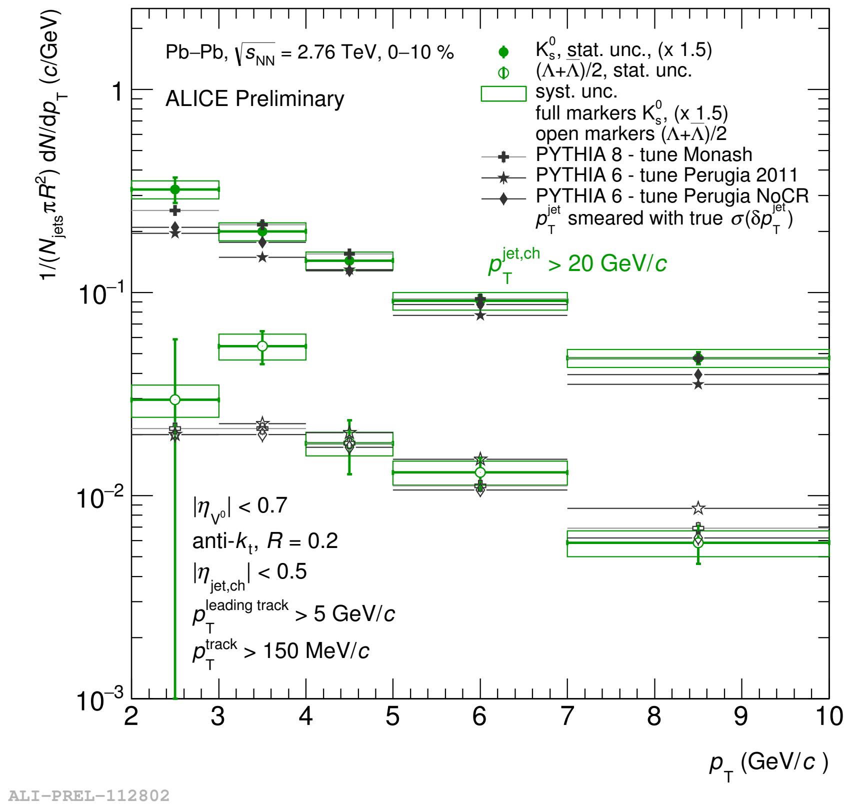




Comparison to PYTHIA

- K^0_S spectra in jets follow similar slope as predicted by PYTHIA simulations
- Λ shape different ? More reliable reference needed !





Jet Mass

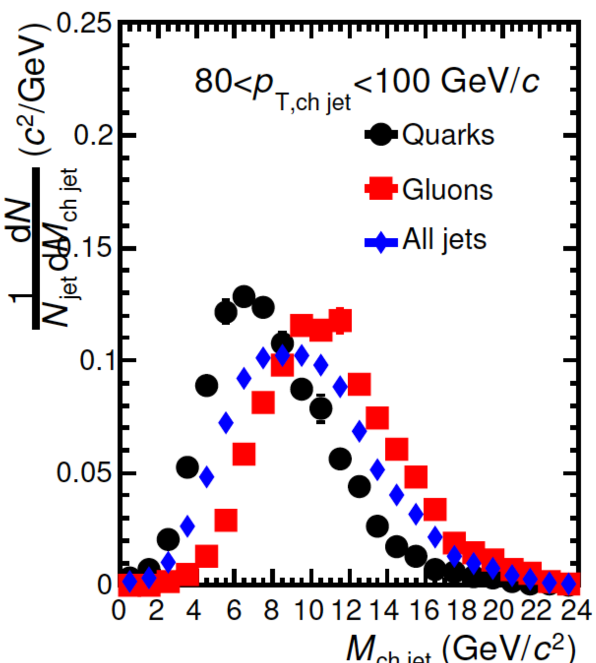

EXPLOSIVE MUSCLE GAINS FASTER!
GROUNDBREAKING, PRECISION-ENGINEERED ANABOLIC MATRIX
Stimulant Free
GAT
NEW
MOST POTENT
POST-WORKOUT
FORMULA!
PREMIUM CREATINES, HIGHEST ORAC CAPROS 1700 AND GROWTH INDUCERS
JET MASS
FASTEST-ACTING
MUSCLE VOLUMIZER
GERMAN CREATINE SYSTEM
ULTRAPURE CREATINE FROM Essen, Germany
»SIZE & STRENGTH
»ANTI-CATABOLIC
»RECOVERY
»MUSCLE TORQUE
»INSULIN MATRIX
»GREAT TASTING
TROPICAL ICE
DIETARY SUPPLEMENT
NET WT. 820 g (1.81 lbs)

Mass and virtuality

- invariant mass of jet constituents, related to virtuality of initial parton
- parton from hard scattering produced off-shell
- in vacuum: virtuality decreases at each emission
- in medium, virtuality can rise due to scatterings

→ quenching observable

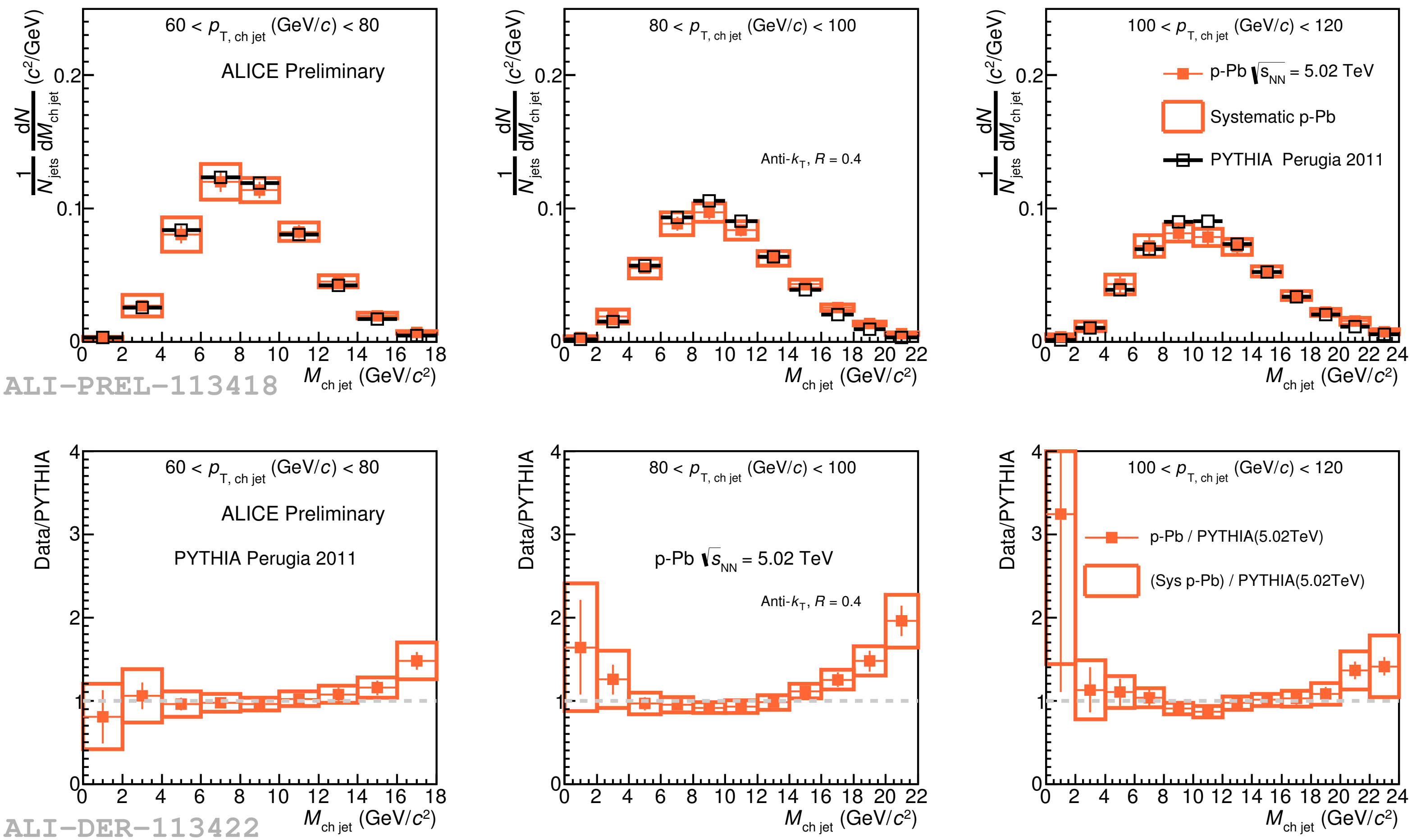
(*A. Majumder, J. Putschke, nucl-th 1408.3404*)



- soft constituents far from jet axis within cone → larger mass
- few hard constituents → smaller mass

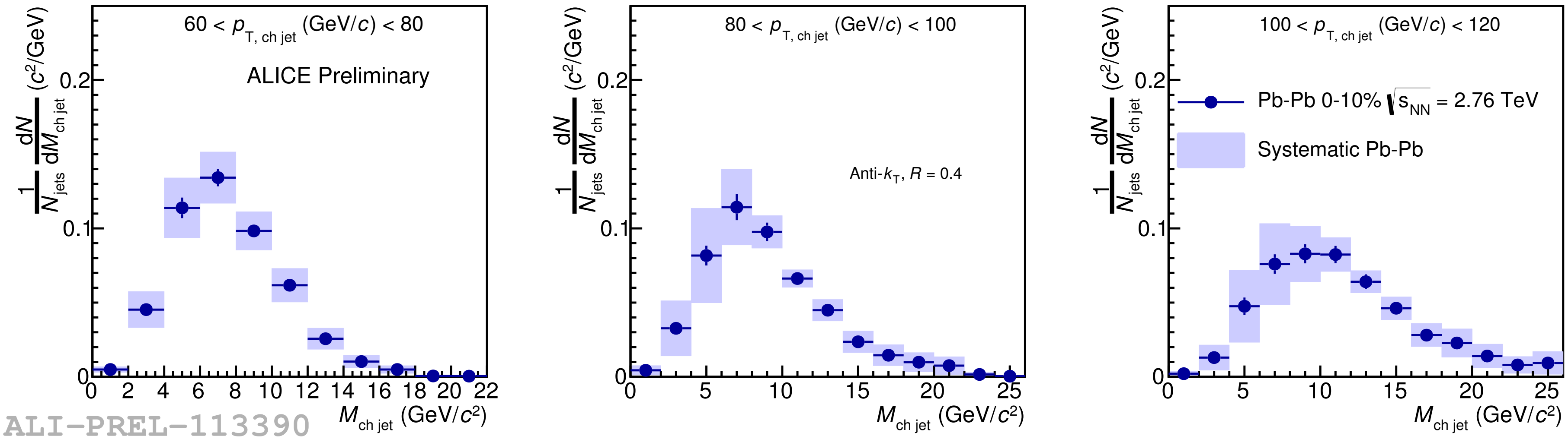
Results: pPb

- jet mass in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, charged jets with R=0.4
- overall well described by PYTHIA with some tension in the tails



Results: Pb-Pb

- jet Mass in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV fully corrected for detector effects and background fluctuations via 2D unfolding



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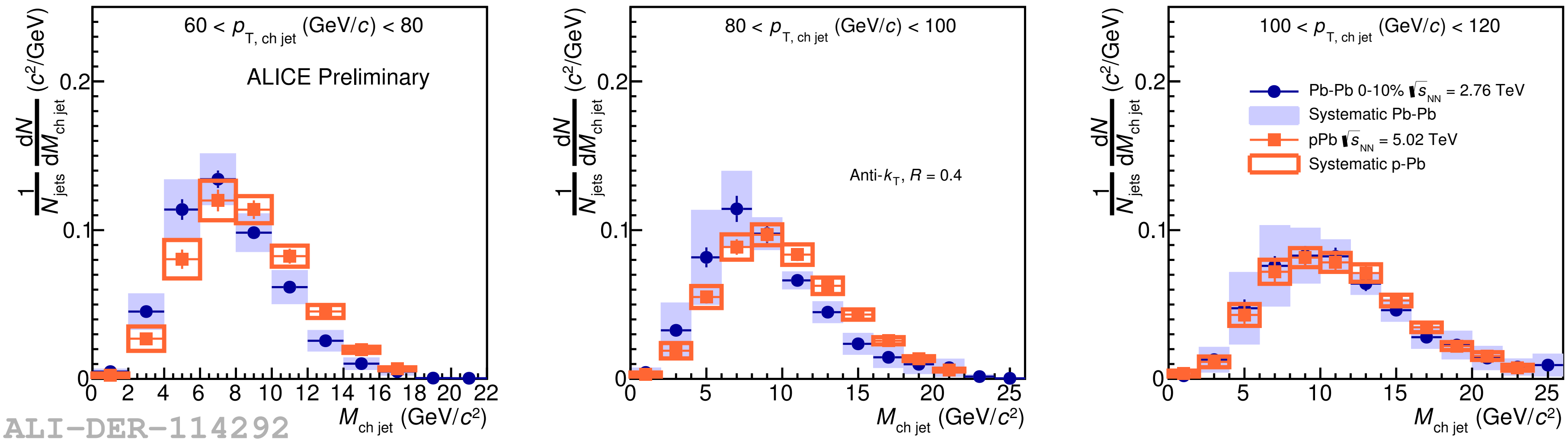


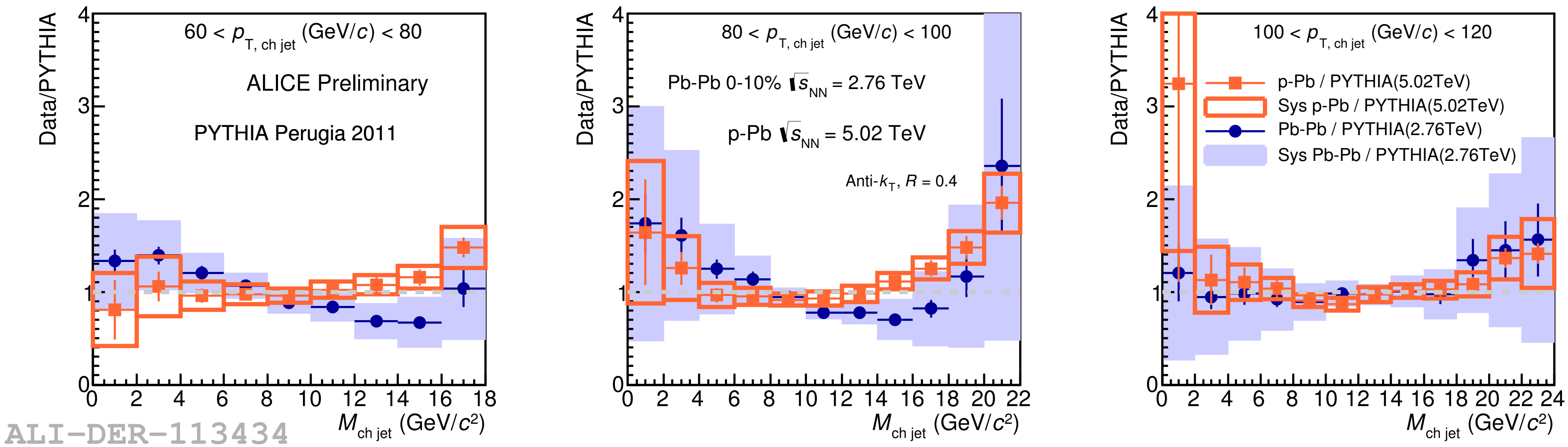
- small $\sqrt{s}$ dependence is expected (quark / gluon composition)

- compare the ratio Pb-Pb / pPb to the ratio in PYTHIA at the 2 energies

$$\Re_{\sqrt{s}} = \frac{\frac{1}{N_{jets}} \frac{dN}{dM_{chjet}} \Big|_{\sqrt{s_{NN}}=2.76\text{ TeV}}}{\frac{1}{N_{jets}} \frac{dN}{dM_{chjet}} \Big|_{\sqrt{s_{NN}}=5.02\text{ TeV}}}$$

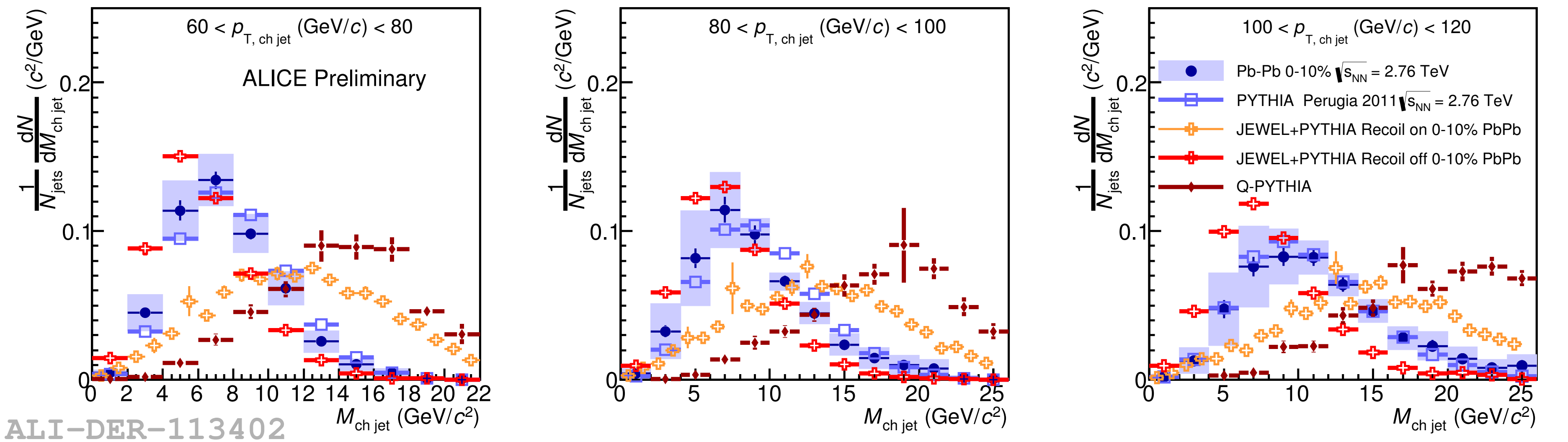
Ratio Pb-Pb / p-Pb

- slope indicates that Pb-Pb distribution is shifted towards smaller masses with respect to pPb



Model comparison

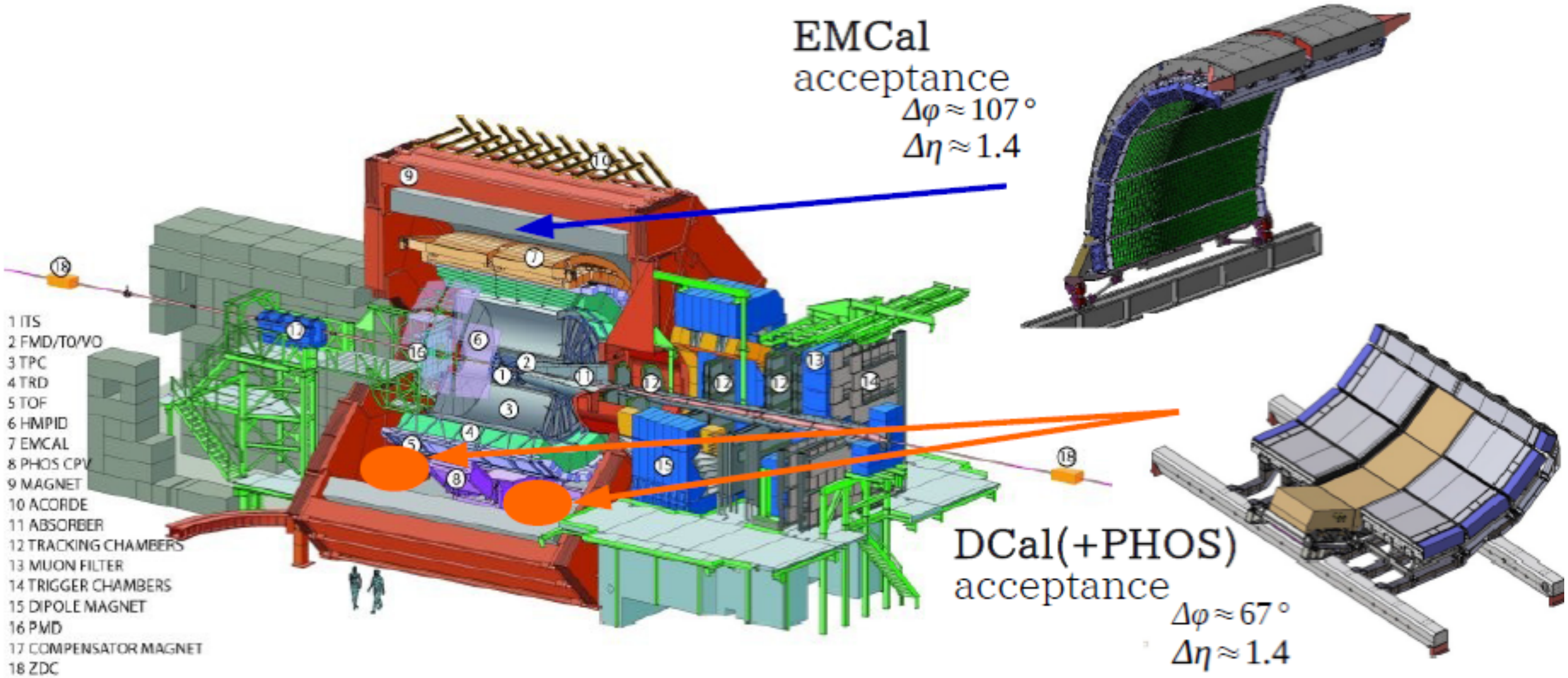
- data lies in between PYTHIA and JEWEL with ‘recoils off’
- Q-PYTHIA and JEWEL with ‘recoils on’ produce too large mass



- Q-PYTHIA: radiative energy loss modelled by enhanced splitting functions

(N. Armesto, L. Cunqueiro, C. A. Salgado, hep-ph/0907.1014)

ALICE in run 2: DCal



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

- new avenues for jet physics in ALICE

Summary

- jet cross sections and properties in pp
- strong jet suppression observed in Pb-Pb collisions
- first jet nuclear modification factor from run 2 indicates stronger suppression at higher energy
- non-zero jet v_2 indicates path-length dependence of jet quenching
- strange particles in jets
- first measurement of jet mass in HI collisions indicate shift to smaller masses
- first results from run 2 - more to come !

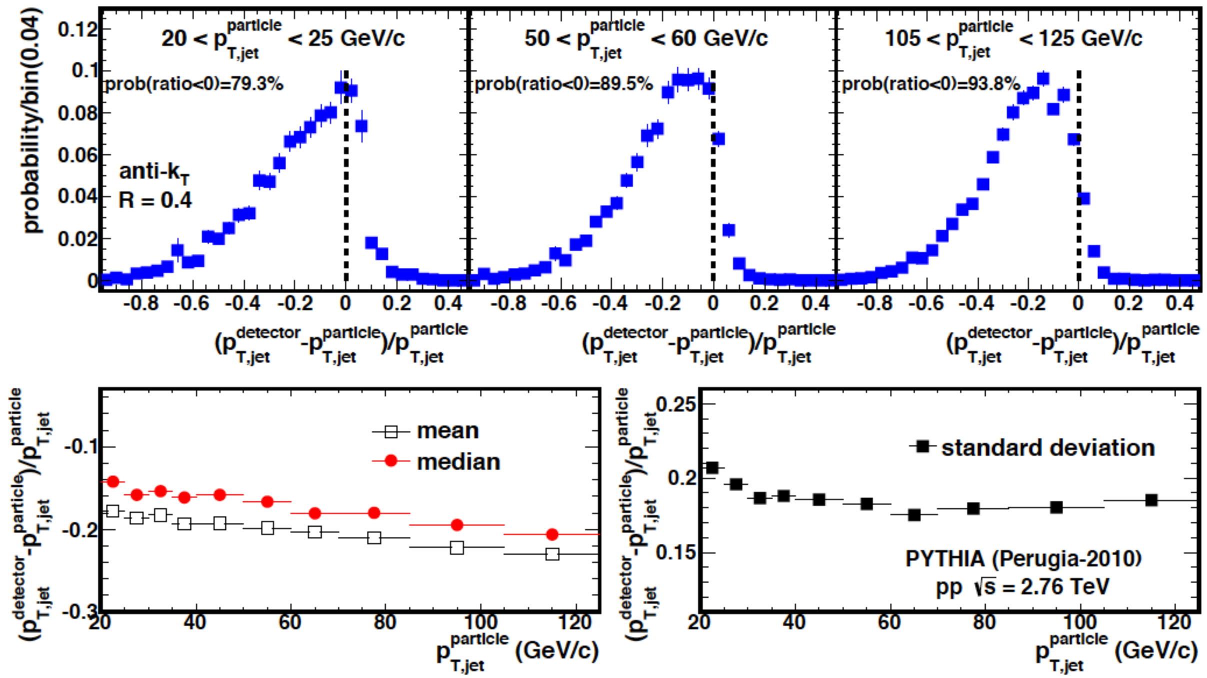
- Backup -

ALICE jet response

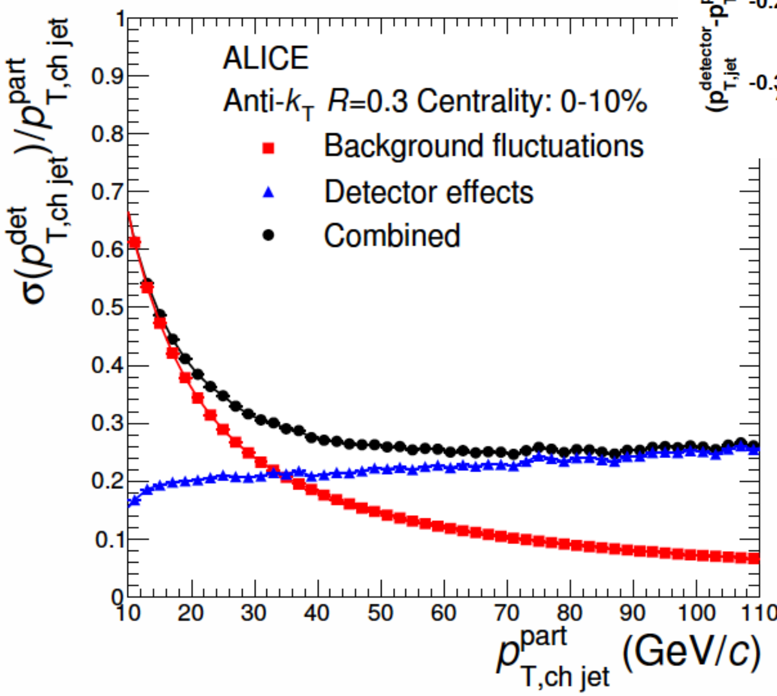
Phys. Lett. B 722 (2013) 262

- full jets, pp at 2.76 TeV
- JES uncertainty ~ 3.6%

  at p_T^{jet} = 100 GeV/c



JHEP 03 (2014) 013



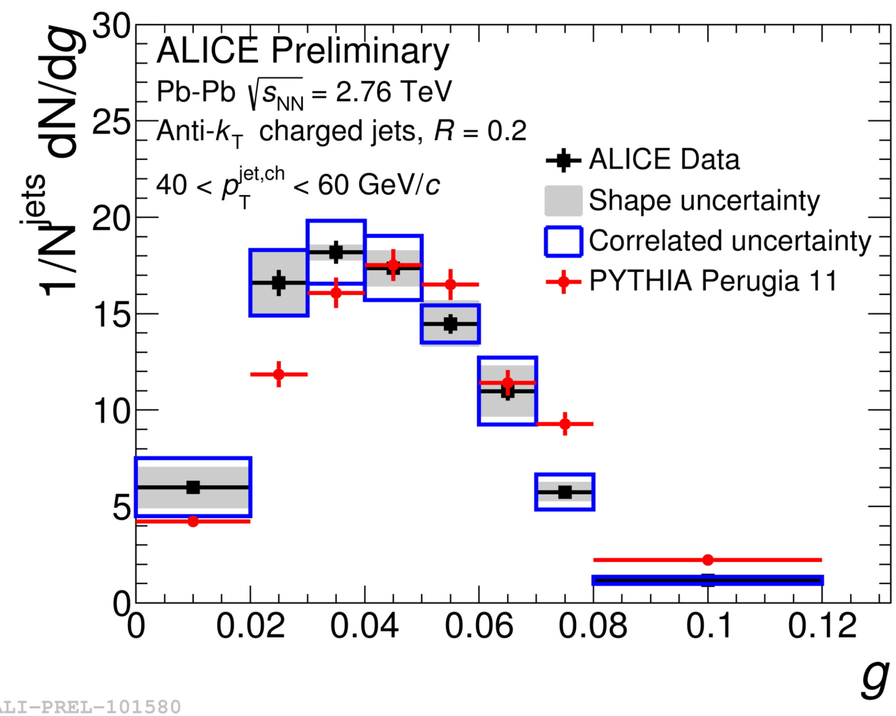
- charged jets: Pb-Pb
- JE resolution at low p_T dominated by background, at high p_T by detector effects

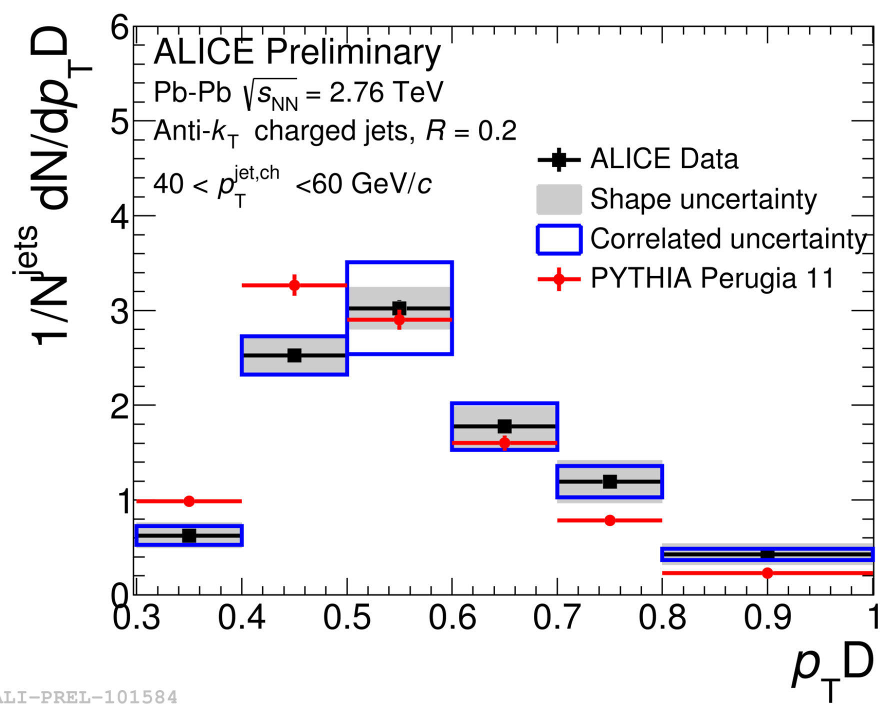
Jet Structure

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

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

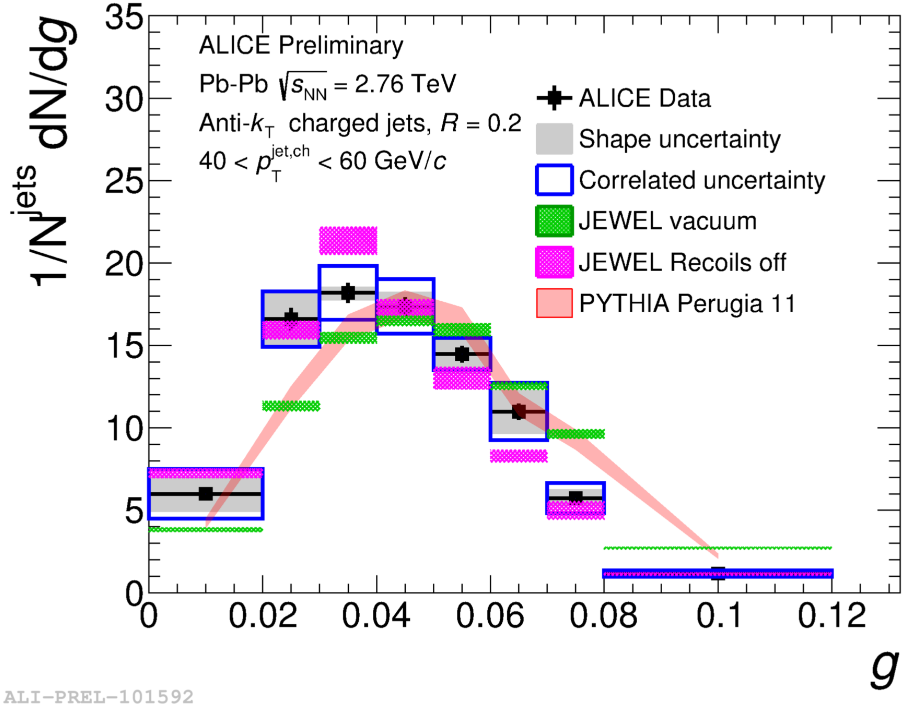
$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

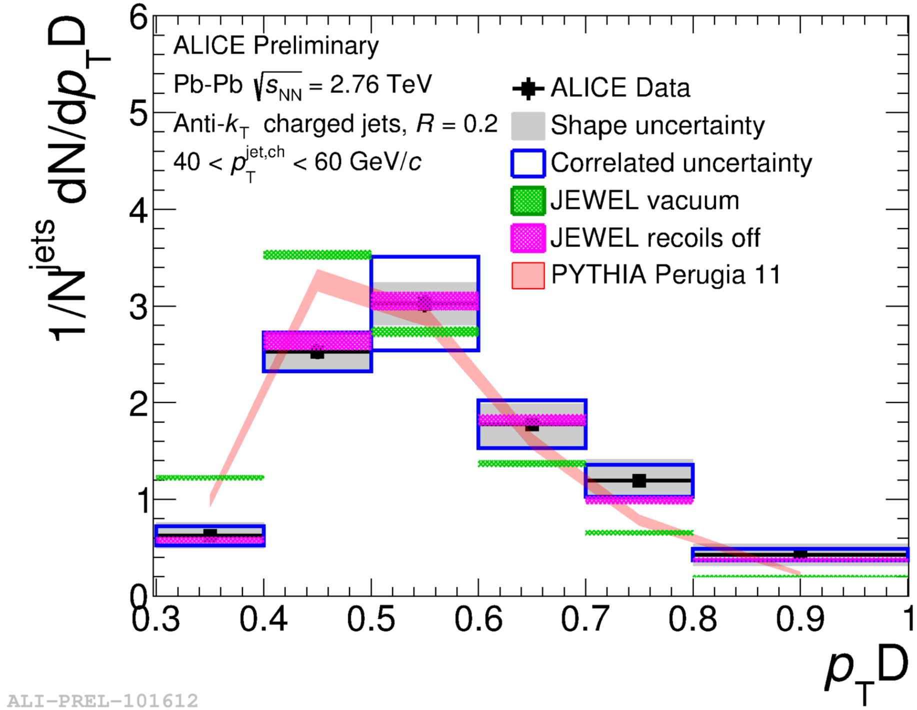




Jet Structure : Model Comparison

- trends reproduced by JEWEL jet quenching model



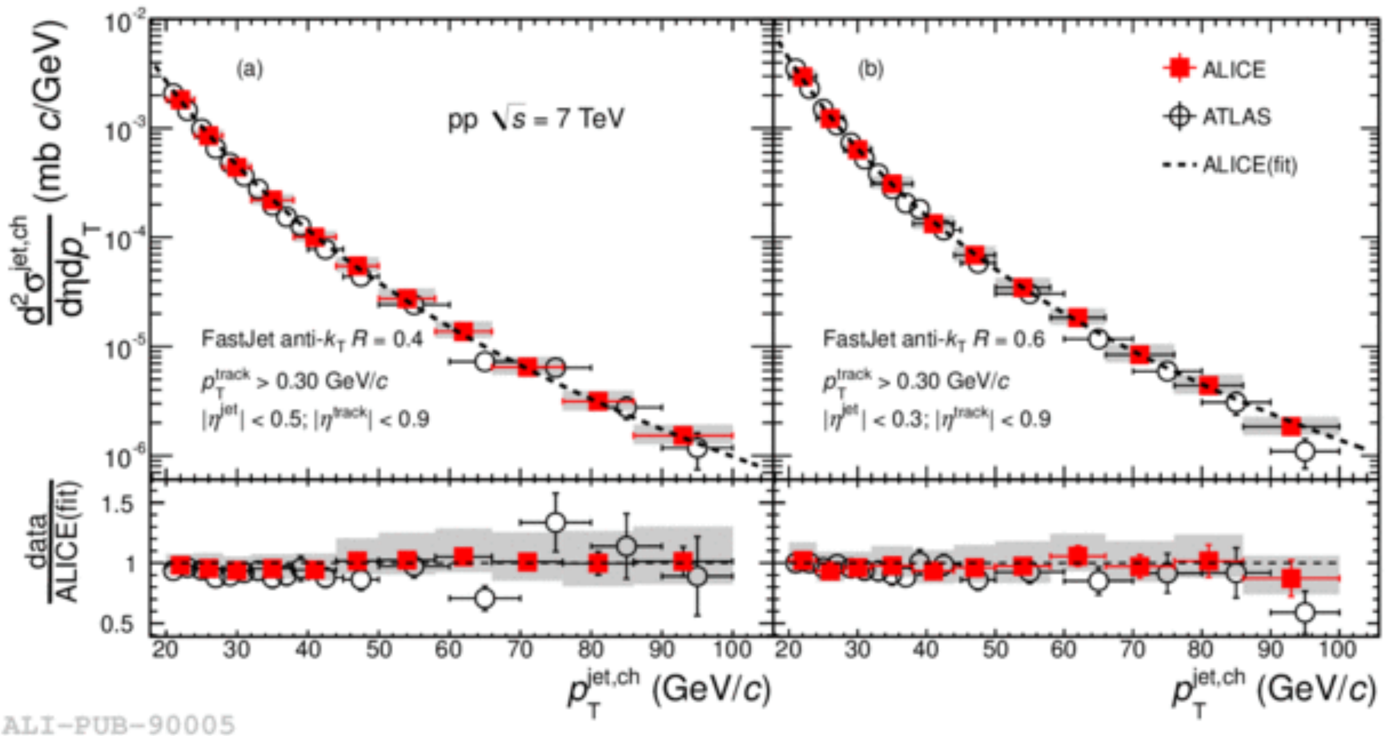


JEWEL: K.C. Zapp, F. Kraus, U.A. Wiedemann, JHEP 1303 (2013) 080

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 (2015) 112012

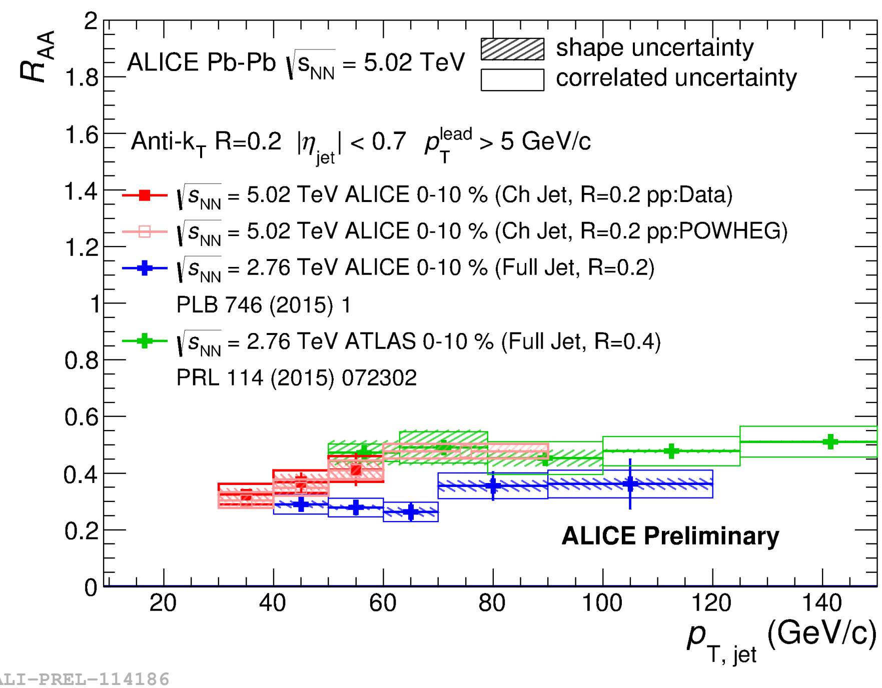
√s_{NN} dependence of R_{AA}

- charged jet R_{AA} at √s_{NN} = 5.02 TeV compared to:
  - ALICE full jet R_{AA} at 2.76 TeV (R = 0.2)
  - ATLAS jet R_{AA} (R = 0.4)

  → different jet energy scales

- comparable R_{AA}: effect of flattening of the spectrum compensated by **stronger suppression**

0-10%



10-30%