Jet Quenching at RHIC and LHC

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- Nuclear modification factor
- Event plane dependence
- Semi-inclusive jet-hadron yields
- Jet shapes, subjets, jet mass
- Identified jet fragmentation

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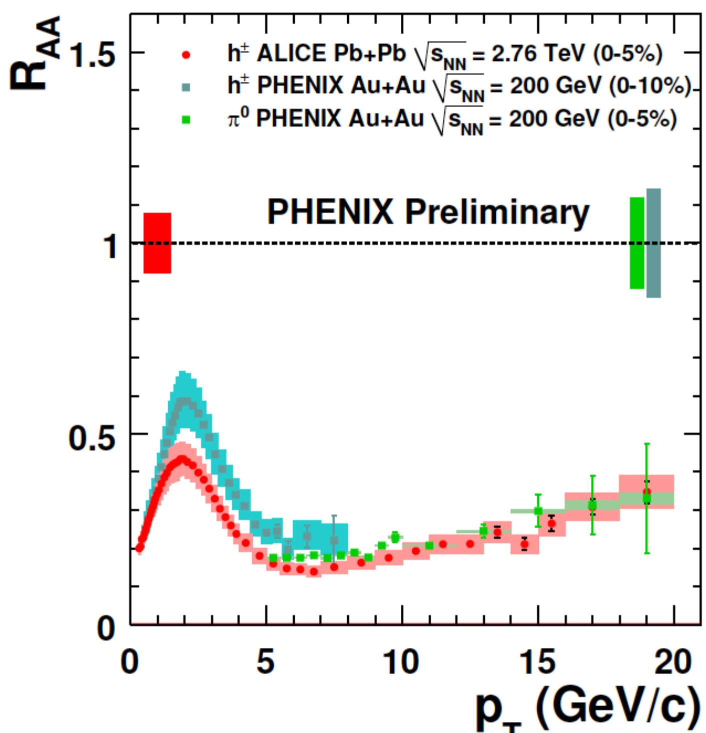
selection strongly biased towards:

- light flavour jet results
- LHC
- ALICE

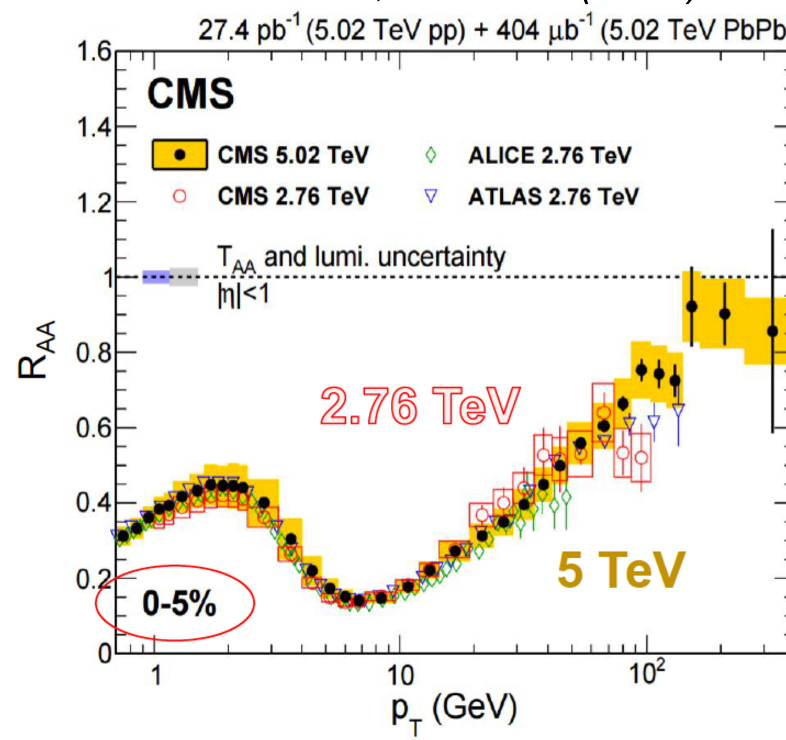
Hadron nuclear modification factor

- high-p_T hadron suppression both at RHIC and LHC
- hadron observable biased towards leading fragment
  → study the effect for fully reconstructed jets
- theory: energy loss ⊗ leading hadron fragmentation
  → parton shower ⊗ energy loss ⊗ hadronisation

PHENIX, Nucl Part. Phys 38 (2011) 124016



CMS, JHEP 04 (2017) 039



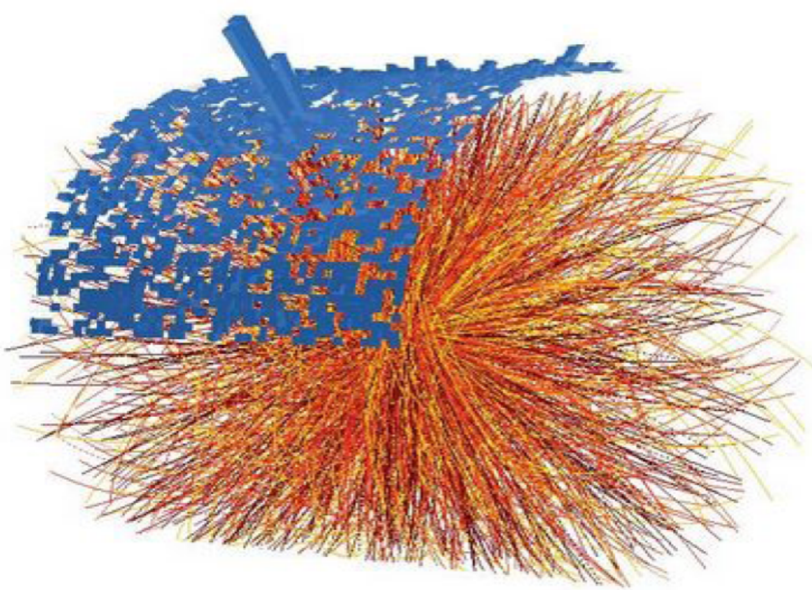
Underlying event

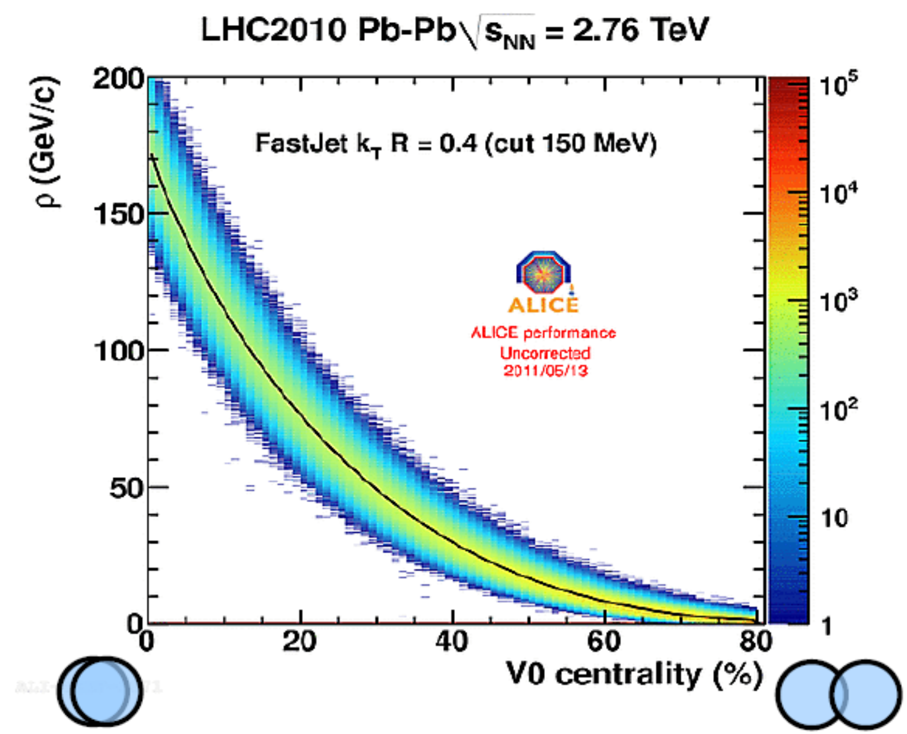
- jet reconstruction in heavy-ion collisions :
  difficult due to the high underlying event background
  not related to hard scattering

- correct spectra for background fluctuations and detector effects

- not possible down to lowest jet p_T

- fake jets





jet area ~ 0.5 (R = 0.4)

central *peripheral*

Experimental aspects / differences

- jet reconstruction:
    - EM + hadron calorimeter based (ATLAS)
    - charged track + EMCal based (STAR + ALICE)
    - particle flow (CMS)

- fake jet rejection:
    - constituent p_T cuts
    - leading constituent bias / track jet matching
    - di-jet (hadron-jet) coincidence
    - subtraction
    - ….
    - consistently applied to the reference, but may introduce physics bias

- background subtraction:
    - median density from clusters (ALICE, STAR)
    - iterative geometrical (ATLAS, CMS)

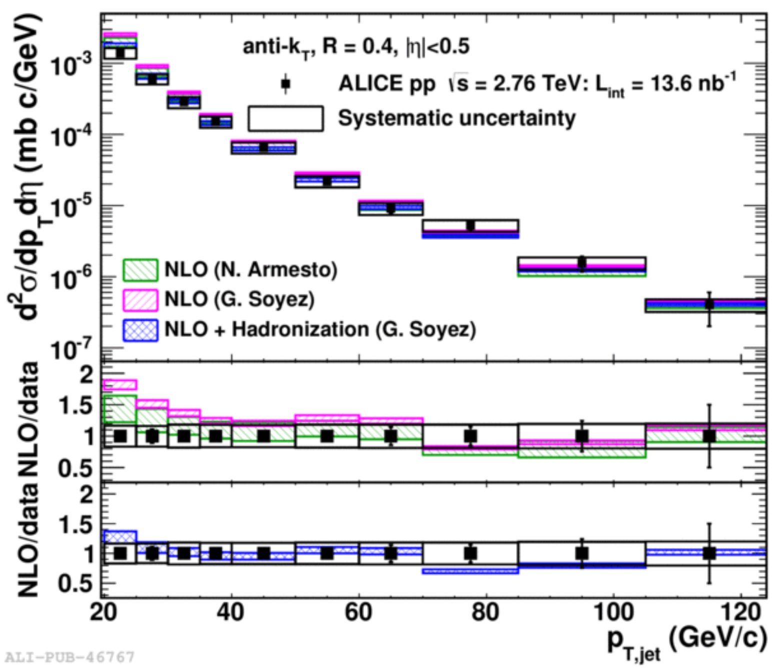
- corrections: for detector effects (efficiency, resolution) and background fluctuations (resolution-like)
    - typical: full corrections to particle level
    - sometimes: detector and/or background effects applied to a reference

complementarity of LHC experiments

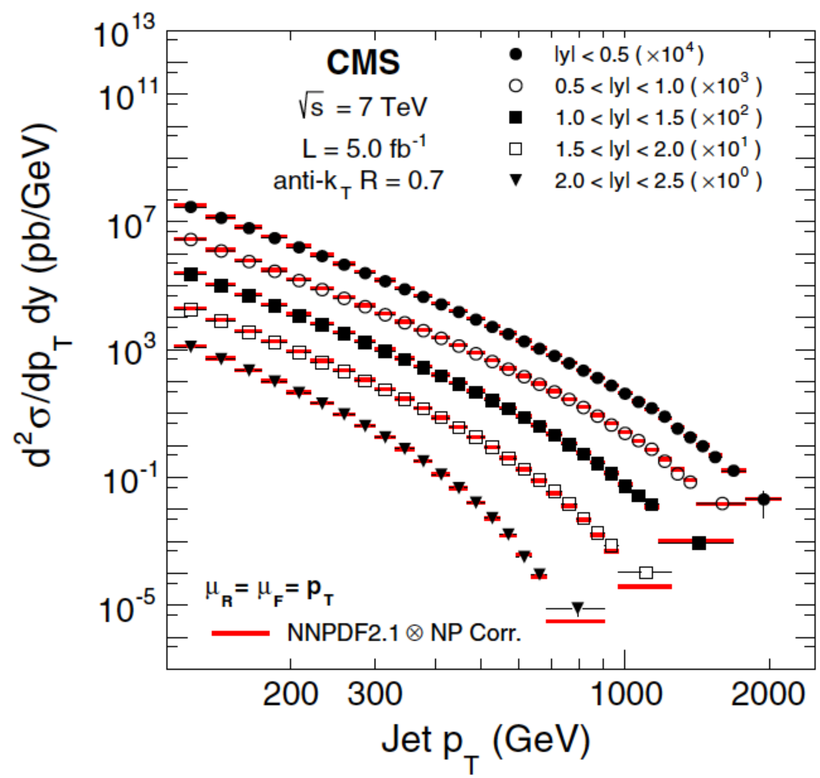
- ALICE: ‘charged’ jets from charged particle tracking

  + ‘full’ jets from tracking + em. Calorimeter
- ATLAS/CMS: em. + hadronic calorimetry (+tracking)
- complementary jet p_T reach, ALICE typically lower constituent p_T cutoff

ALICE, Phys. Lett. B 722 (2013) 262



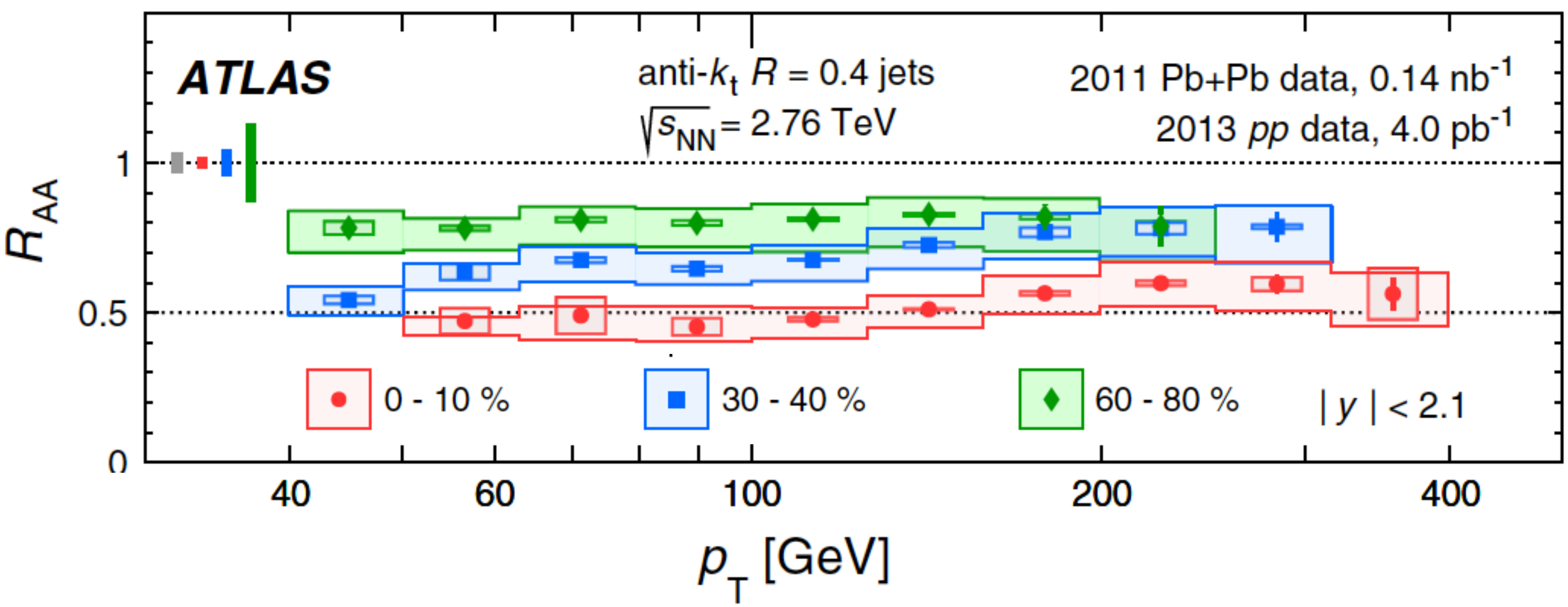
CMS, PRD 87 (2012) 112002



Jet nuclear modification factor: ATLAS

- ATLAS jet R_{AA} at $\sqrt{s_{NN}}$ = 2.76 TeV, R = 0.4
- strong suppression observed, similar to hadron R_{AA}
  → parton energy not recovered inside jet cone
- stronger suppression for more central events
- weak p_T dependence

ATLAS, PRL 114, 072302



Jet nuclear modification factor: ALICE

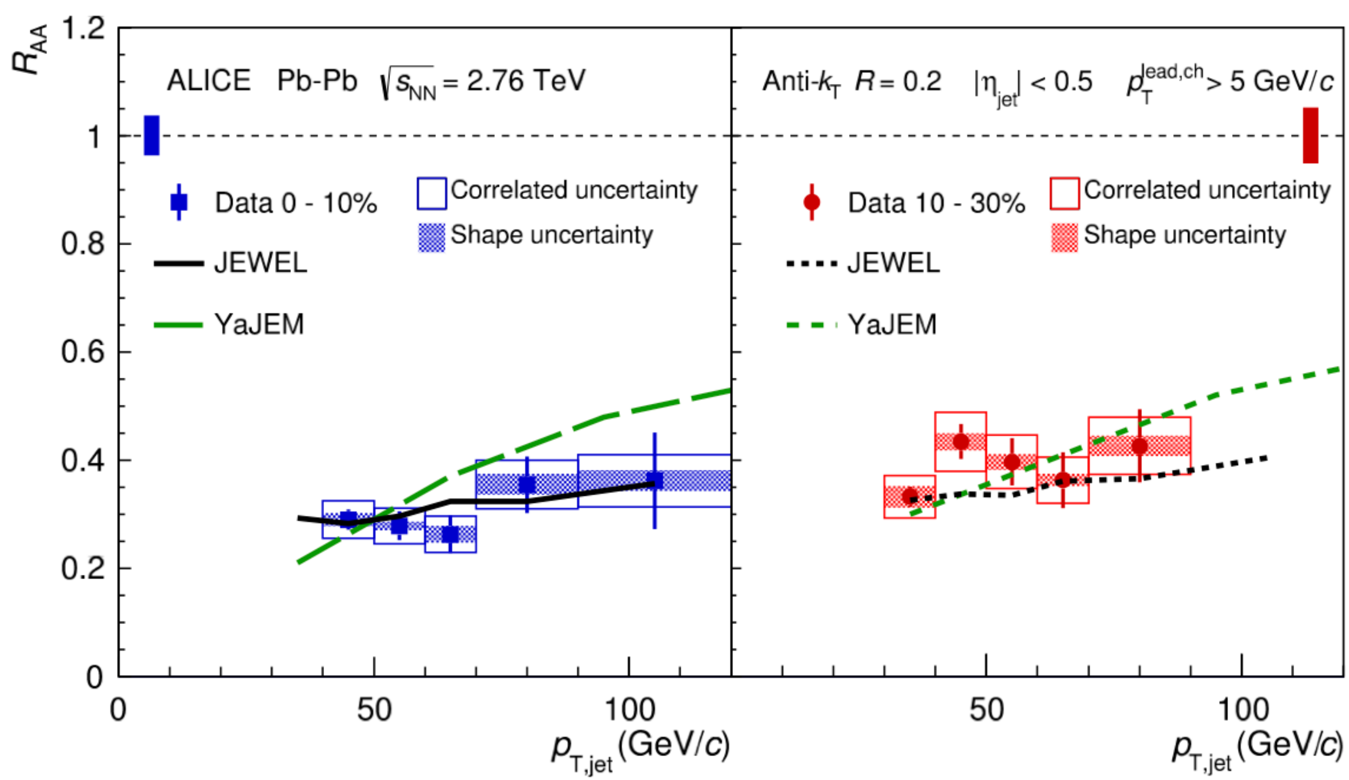
- ALICE full jet R_{AA} at $\sqrt{s_{NN}}$ = 2.76 TeV, R = 0.2
- $p_T^{const,ch}$ > 150 MeV, $E^{Cluster}$ > 300 MeV, $p_T^{lead,\,ch}$ > 5 GeV/c
- maybe hint for weak p_T dependence

Phys.Lett. B746 (2015) 1

JEWEL: PLB 735 (2014)

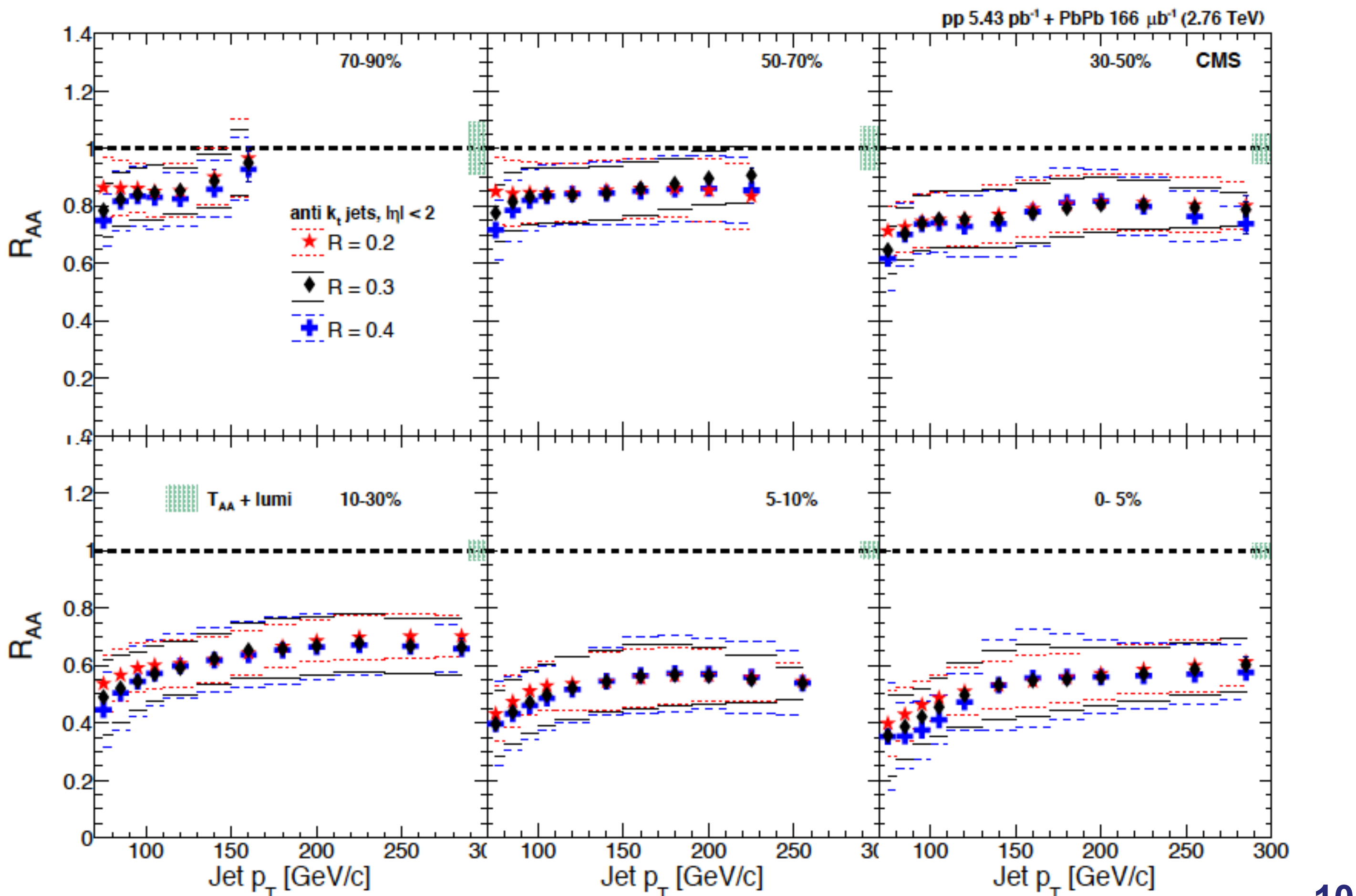
YaJEM:PRC 88 (2013) 014905

- JEWEL and YaJEM jet quenching models reproduce suppression



Jet nuclear modification factor: CMS

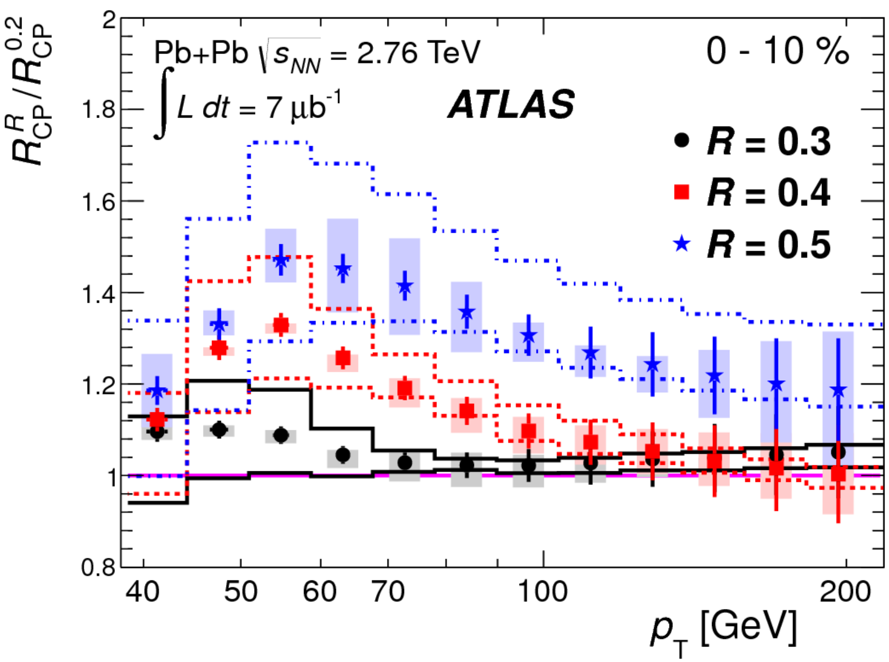
- CMS jet R_{AA} at $\sqrt{s_{NN}}$ = 2.76 TeV, R = 0.2, 0.3, 0.4
- constituent p_T > 150 MeV/c, fake jet spectrum from 'background events' subtracted
- no significant R dependence for p_T > 70 GeV/c



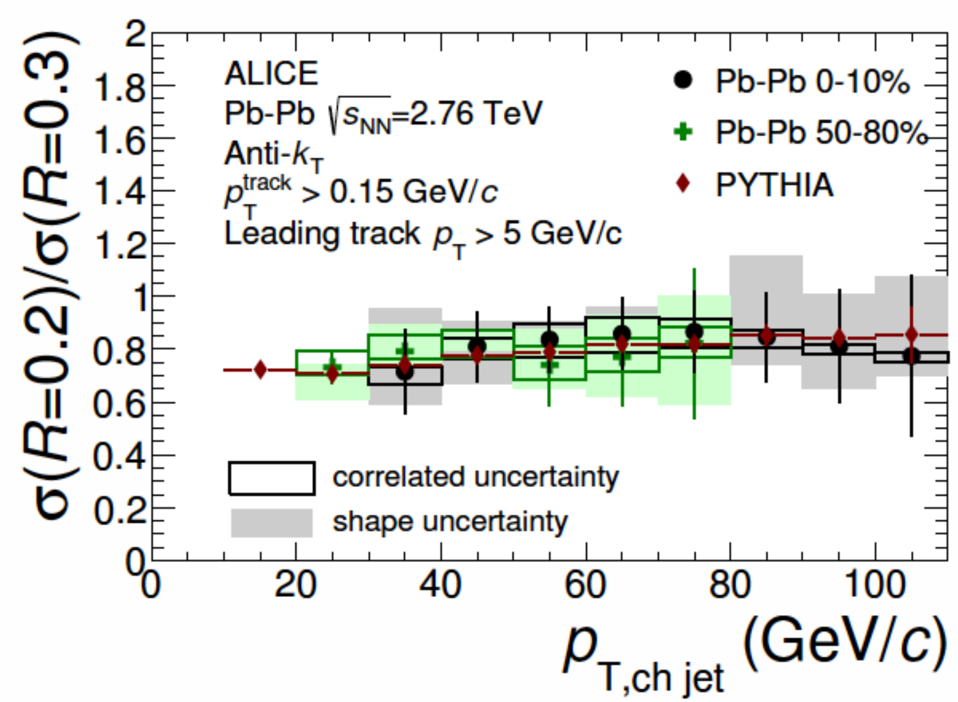
CMS, nucl-ex/1609.05383

Angular dependence

- R dependence sensitive to broadening of transverse jet profile
- ATLAS RCP double ratio: R dependence seen, in particular for low p_T and high R
- not observed in ALICE (but small R difference)



ATLAS, PLB 719 (2013) 220

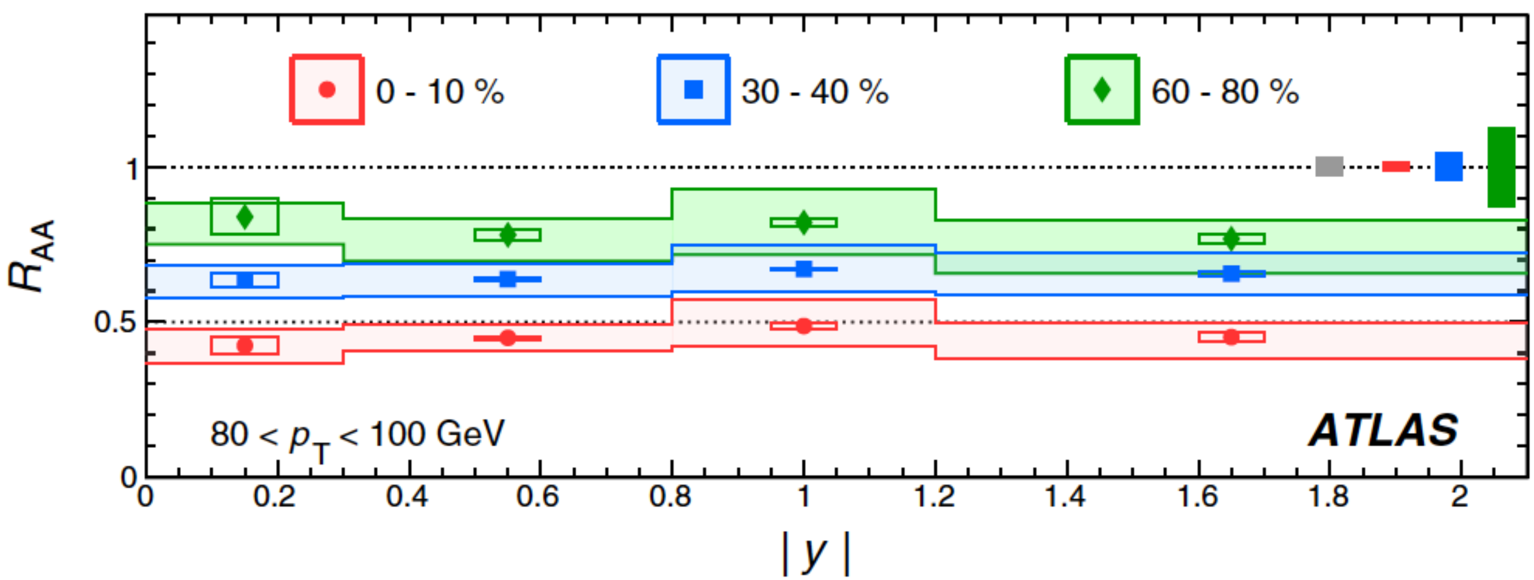


ALICE, JHEP 03 (2014) 013

Rapidity dependence

- expect stronger energy loss for gluons than for quarks
- ATLAS: no significant rapidity dependence of R_{AA}, despite change in q/g
  - balanced by parton spectral slope, y-dependence of energy density ?
  - role of fluctuations / biases ?

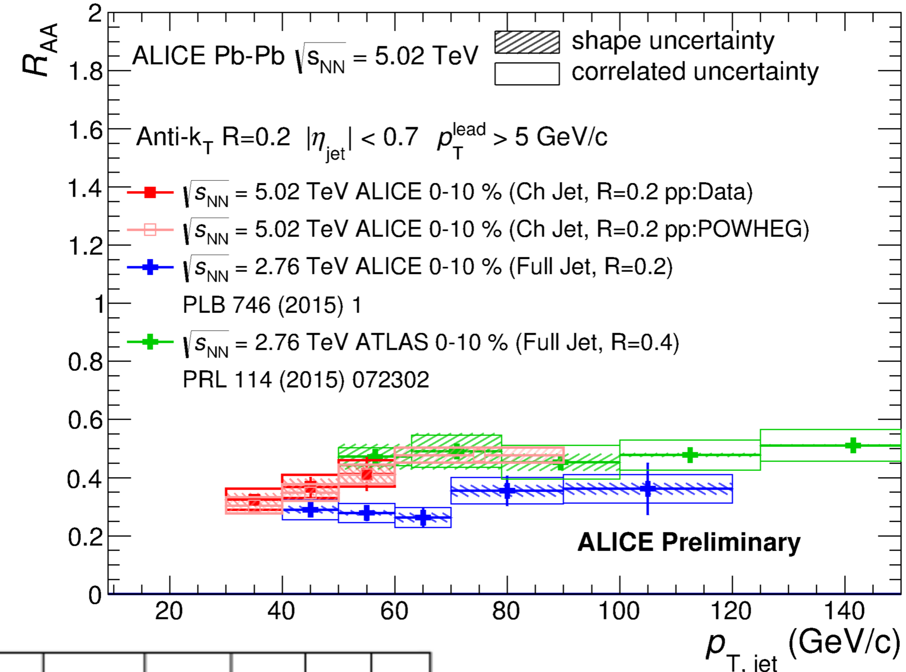
ATLAS, PRL 114, 072302



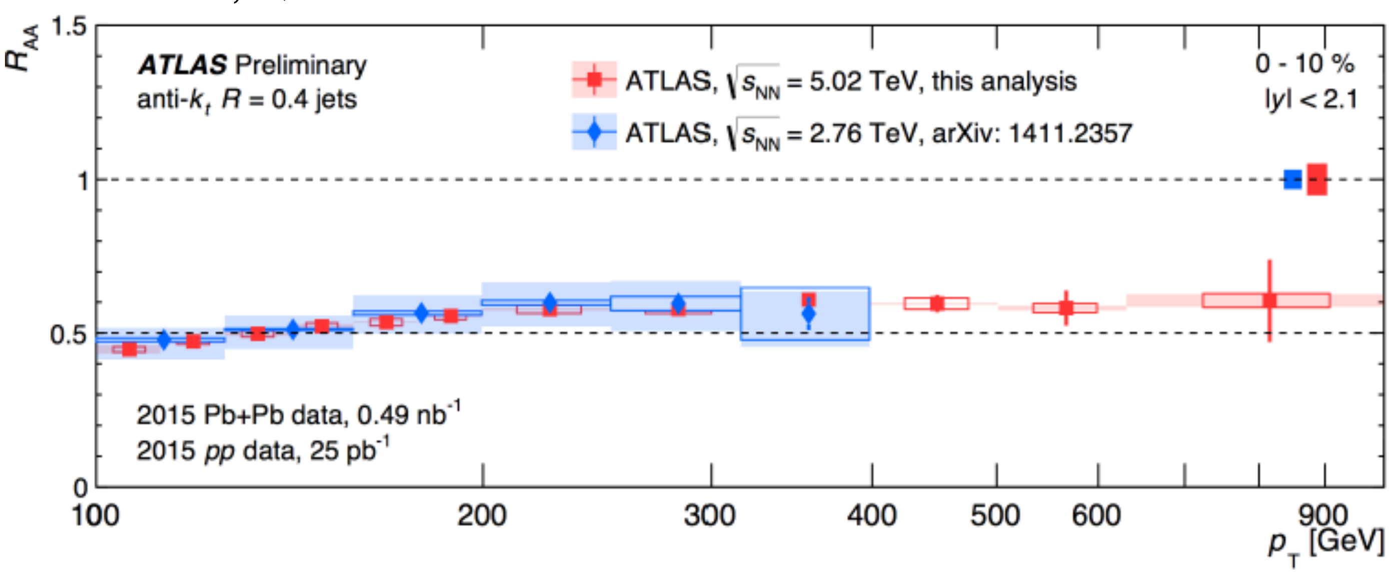
√s depencence

- comparison of different √s constrains energy density dependence
  - no significant difference
  - increased energy loss compensated by flatter parton spectrum ?

ALICE, HP 2016



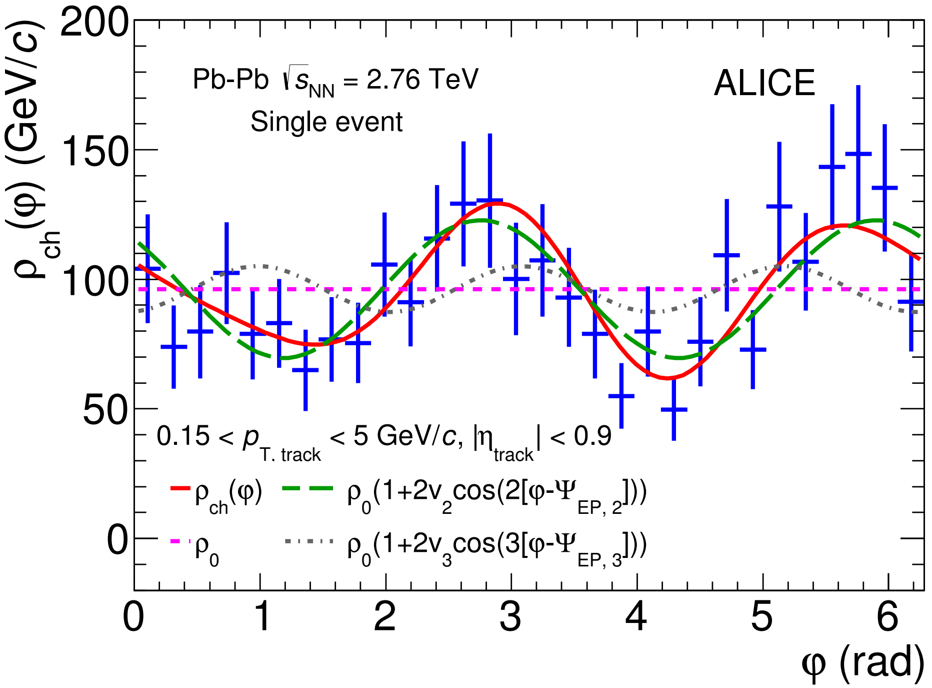
ATLAS, QM 2017



Jet Azimuthal Anisotropy

Local background subtraction

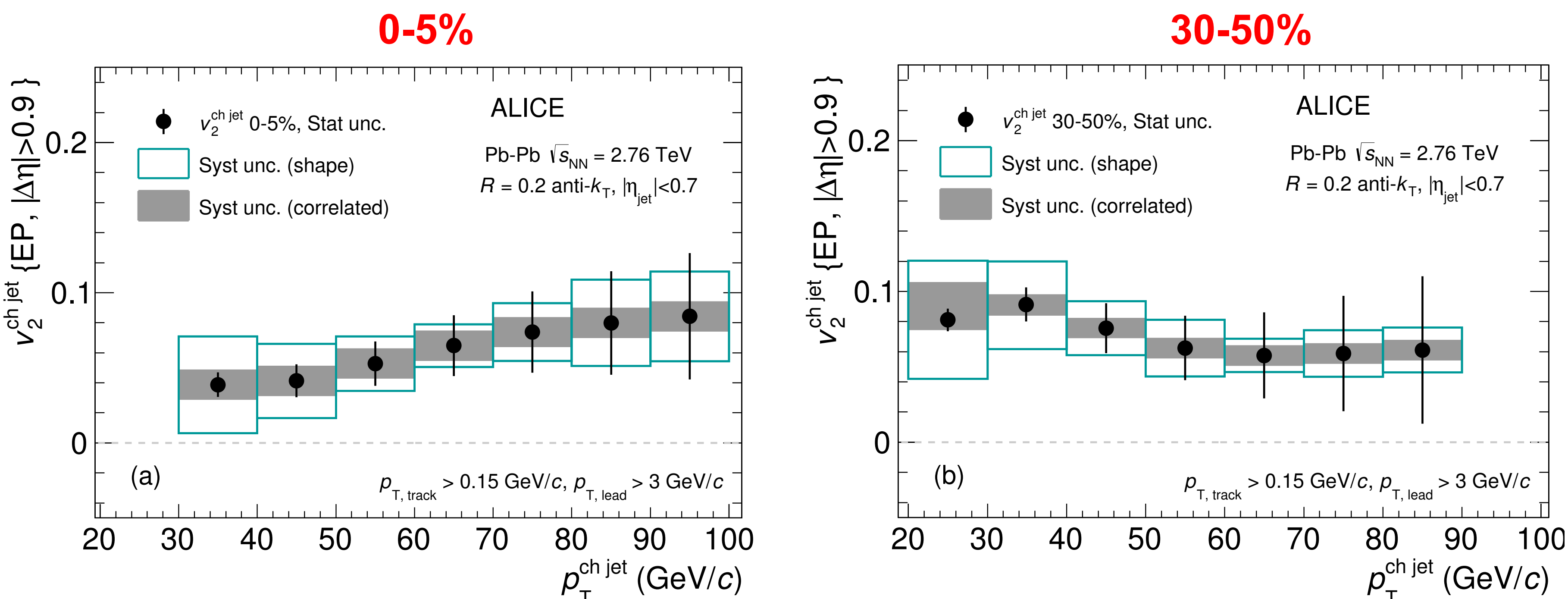
- ALICE jet v2: event plane from forward/backward V0 scintillators
- account for flow-modulation of background via event-by-event fit and subtraction of local background density
- unfolding to account for background fluctuations : separately for spectra in- and out-of-plane



Phys. Lett. B753 (2016) 511

Charged 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

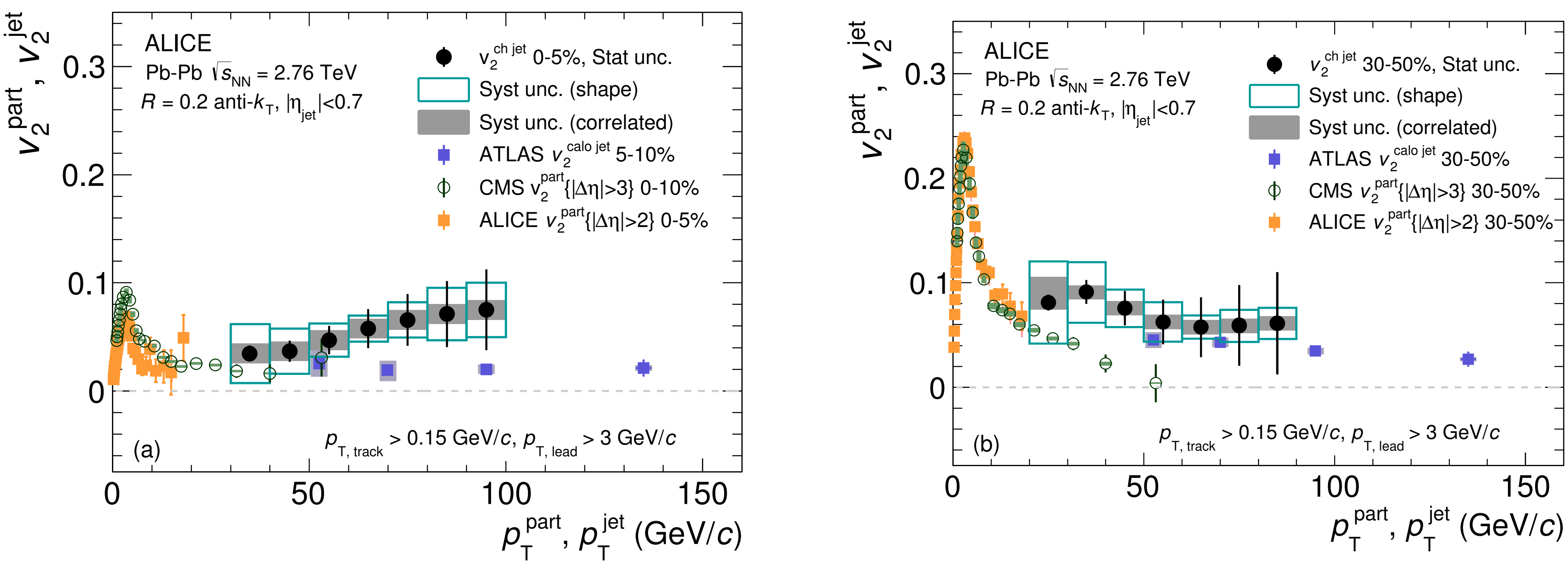


Phys. Lett. B753 (2016) 511

Comparison to previous results

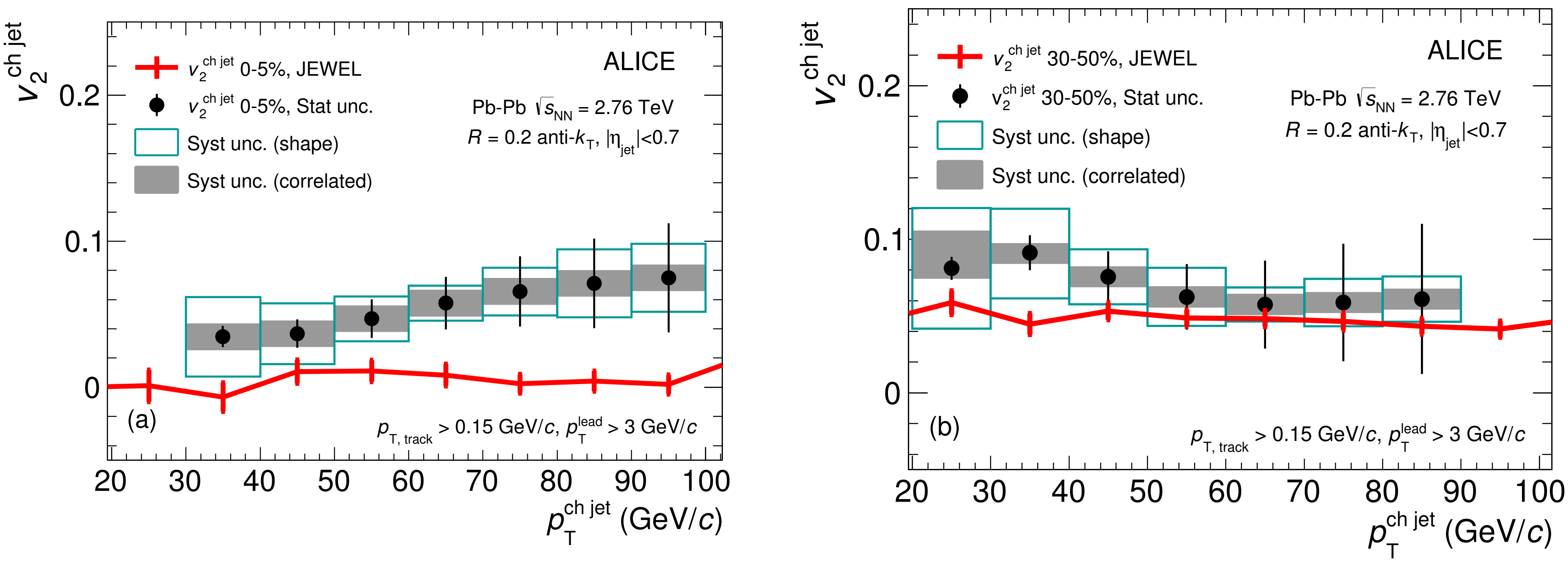
- ALICE + CMS single particles, ATLAS full jets : different energy scales !
- non-zero v2 up to high p_T

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

- good agreement with JEWEL in semi-central collisions
- clear indication of path-length dependence of energy loss
- caveat: no transverse expansion in JEWEL

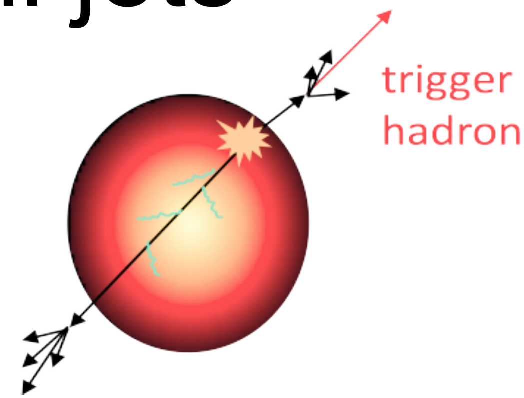


Phys. Lett. B753 (2016) 511

Semi-Inclusive Hadron-Jet Distributions

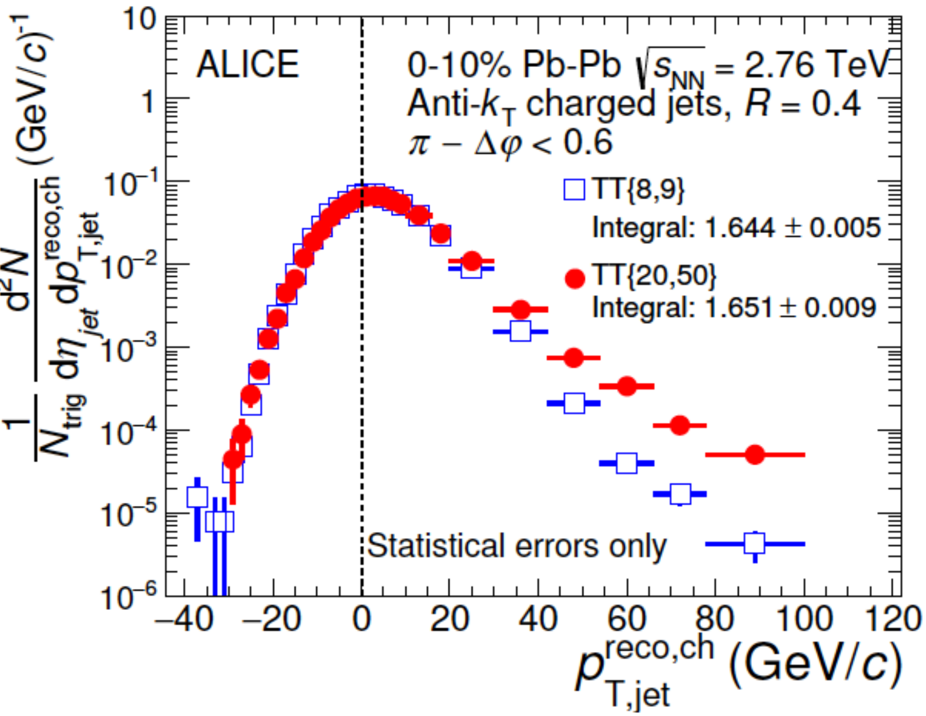
Hadron triggered recoil jets

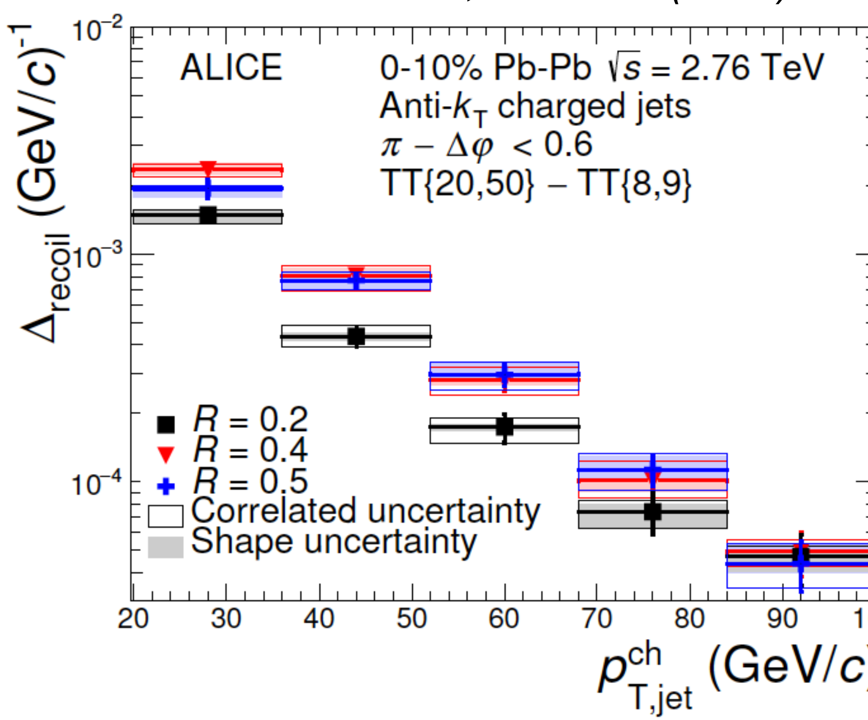
- charged jets recoiling from charged hadron
  - hadron biased towards surface
- Δ_{recoil}: difference between hadron trigger p_T classes
  - further fake jet removal



$$\Delta_{\mathrm{recoil}} = \frac{1}{\mathrm{N}^{\mathrm{AA}}_{\mathrm{trig}}} \frac{\mathrm{d}^2\mathrm{N}^{\mathrm{AA}}_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\mathrm{d}\eta_{\mathrm{jet}}}\bigg|_{p_{\mathrm{T,trig}}\in \mathrm{TT_{Sig}}} - c_{\mathrm{Ref}} \cdot \frac{1}{\mathrm{N}^{\mathrm{AA}}_{\mathrm{trig}}} \frac{\mathrm{d}^2\mathrm{N}^{\mathrm{AA}}_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\mathrm{d}\eta_{\mathrm{jet}}}\bigg|_{p_{\mathrm{T,trig}}\in \mathrm{TT_{Ref}}}$$

ALICE, JHEP 09 (2015) 170



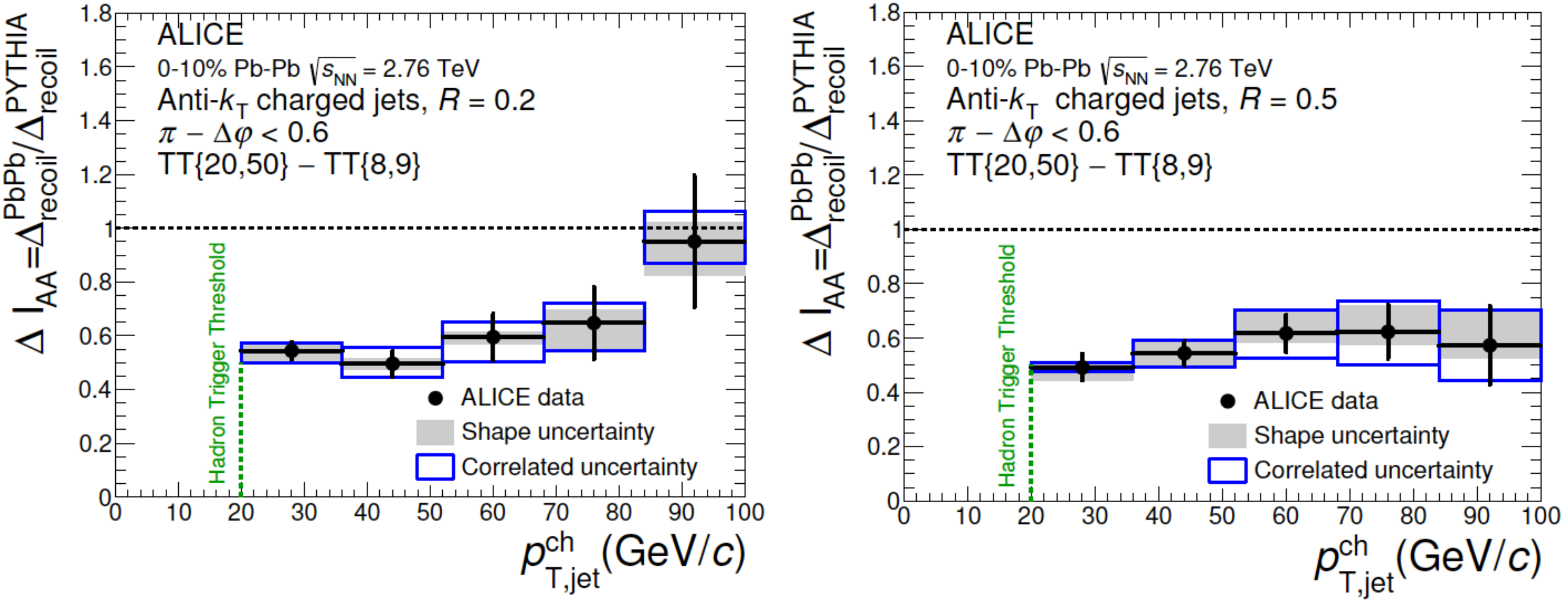


Δ_{IAA}

- Δ_{recoil} divided by PYTHIA reference: significant suppression observed

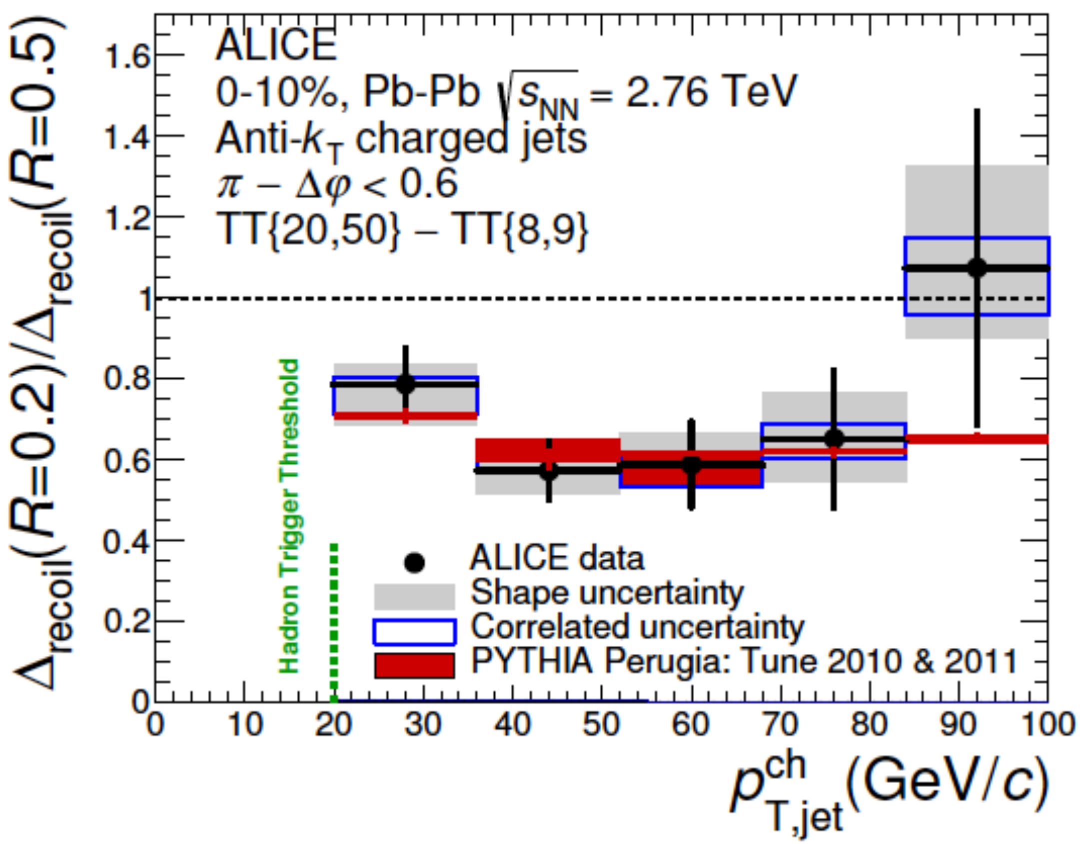
- subtraction technique allows for large R up to 0.5
  with constituent p_T > 0.150 GeV/c, no leading constituent bias

ALICE, JHEP 09 (2015) 170



Δ_{IAA}: R dependence

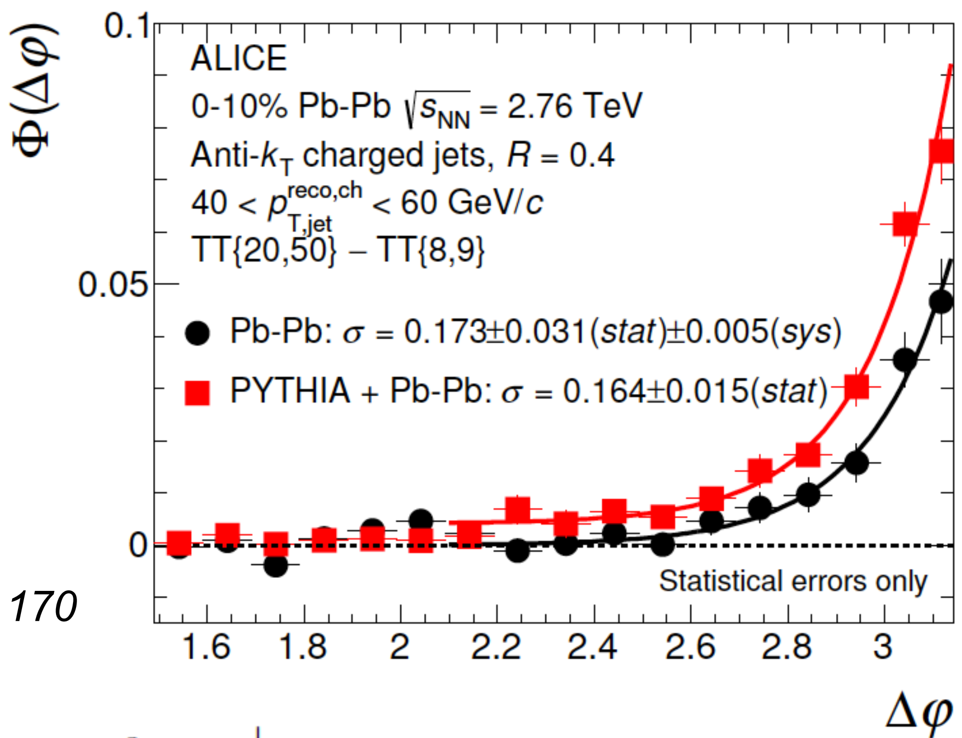
- R dependence as expected for vacuum fragmentation (PYTHIA)
- no medium-induced broadening observed for recoil jets



ALICE,
JHEP 09 (2015) 170

Medium-induced acoplanarity ?

- Δφ hadron-jet: potentially sensitive to large-angle scattering
- data compared to embedded PYTHIA reference
- no significant effect within present uncertainties

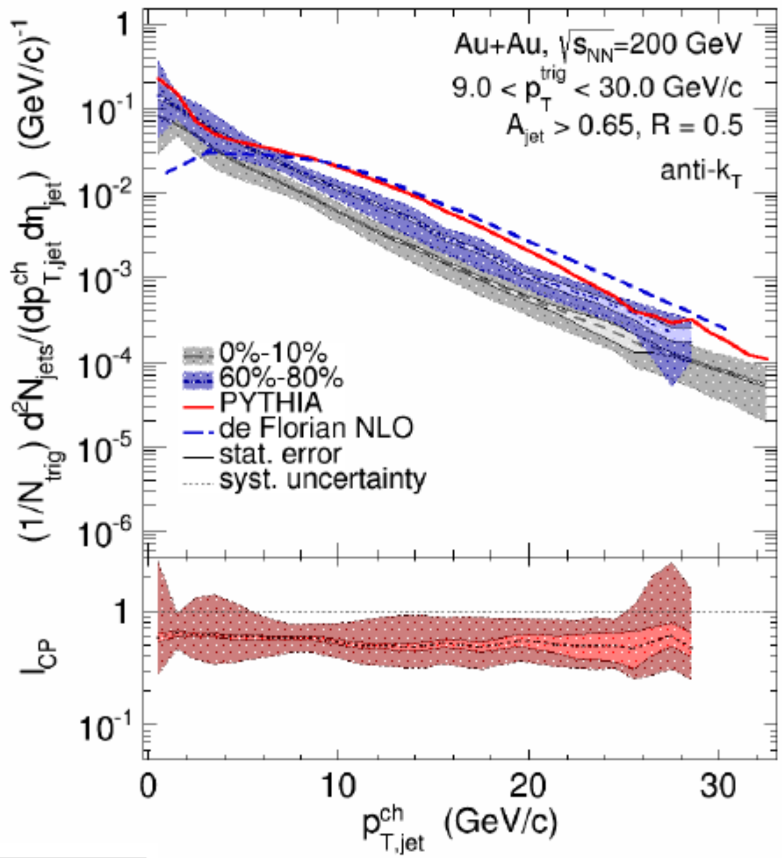


ALICE, JHEP 09 (2015) 170

$$\Phi(\Delta\varphi) = \frac{1}{N_{trig}^{AA}} \frac{d^2N_{jet}}{dp_{T,jet}^{ch} d\Delta\varphi}\bigg|_{p_{T,trig}\in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}^{AA}} \frac{d^2N_{jet}}{dp_{T,jet}^{ch} d\Delta\varphi}\bigg|_{p_{T,trig}\in TT_{Ref}}$$

Recoil jets at RHIC

- STAR charged jets, mixed event background subtraction
- I_{CP}(central-peripheral): jet suppression observed
- estimate E-loss through spectral 'shift'
  ΔE : energy transported out-of-cone
  smaller at RHIC than LHC



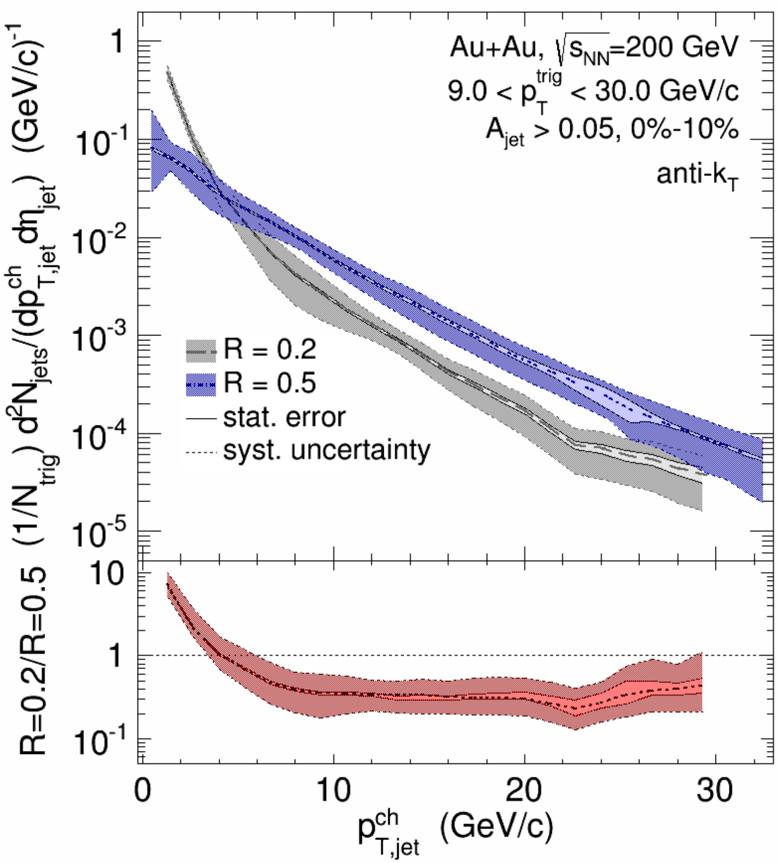
System	Au+Au $\sqrt{s_{NN}} = 200$ GeV	Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV
$p^{ch}_{T,jet}$ range (GeV/c)	[10,20]	[60,100]

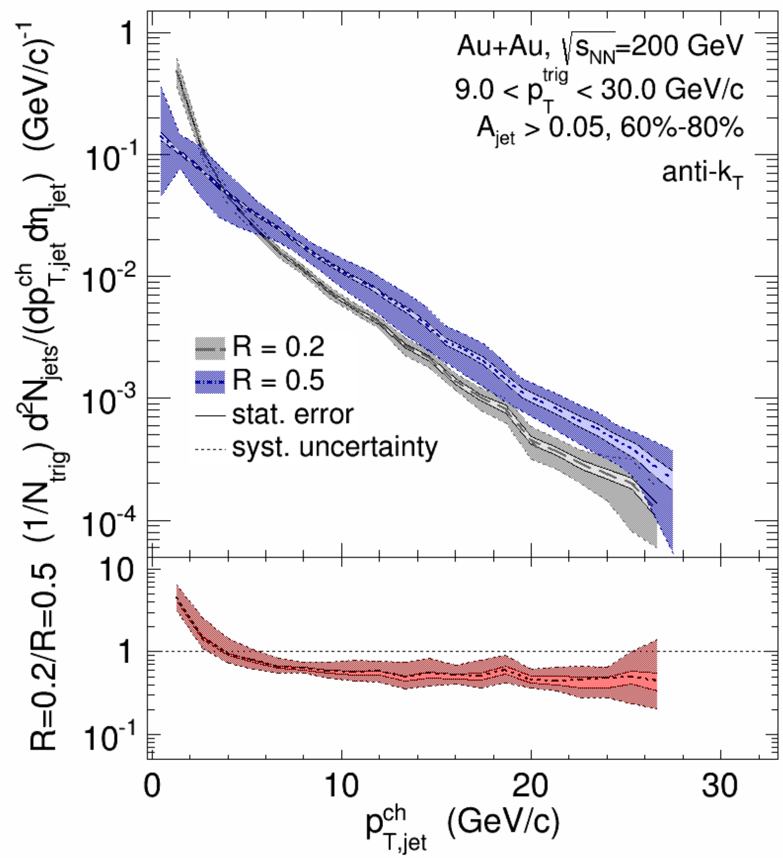
		p_T-shift of $Y\left(p^{ch}_{T,jet}\right)$ (GeV/c)	
		peripheral→central	p+p→central
R	0.2	$-4.4 \pm 0.2 \pm 1.2$	
	0.3	$-5.0 \pm 0.5 \pm 1.2$	
	0.4	$-5.1 \pm 0.5 \pm 1.2$	
	0.5	$-2.8 \pm 0.2 \pm 1.5$	-8 ± 2

STAR, nucl-ex/1702.01108

Recoil jets at RHIC: R dependence

- no evidence of broadening





STAR, nucl-ex/1702.01108

Intrajet Observables and Subjets

Jet shapes

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

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

- shapes in pp collisions at 7 TeV:
  - constrain QCD calculations of small-R jets
    ('microjets': M. Dasgupta, F. Dreyer, G. Salam, G. Soyez hep-ph/1602.01110)

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

  - validate MC simulations

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

- shapes in Pb-Pb probe of quenching of low-p_T jets: characterise fragment distributions and are sensitive to medium induced changes of intra-jet momentum flow

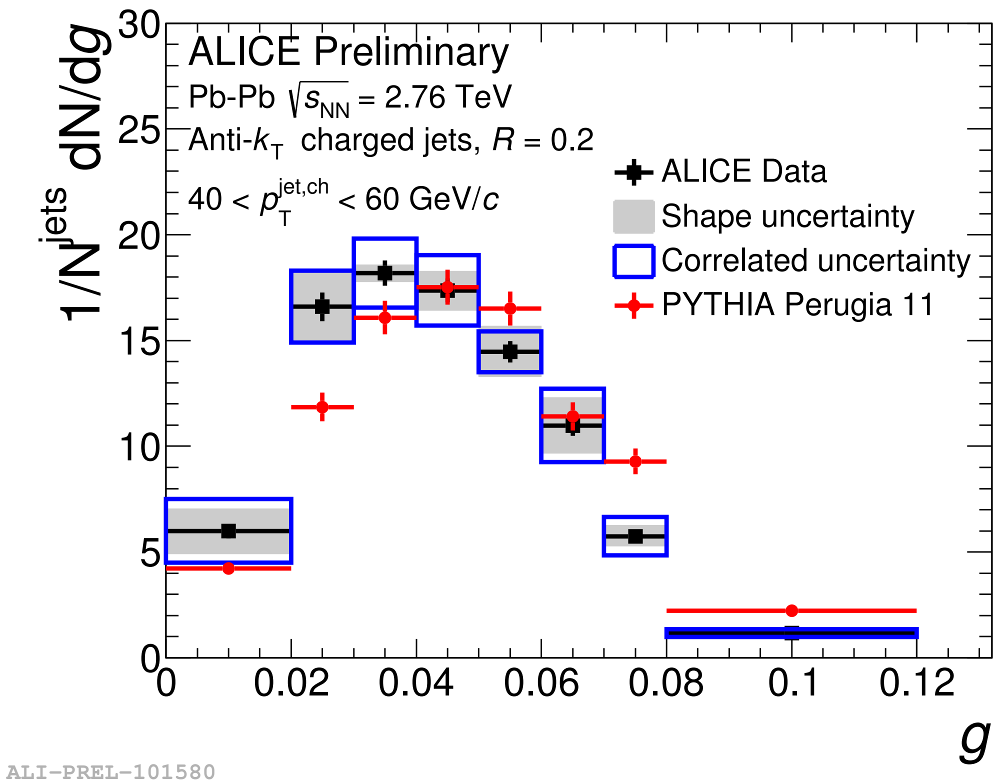
- 'event-by-event' measure, sensitive to fluctuations

- infrared (& collinear) safe

Jet shapes in Pb-Pb

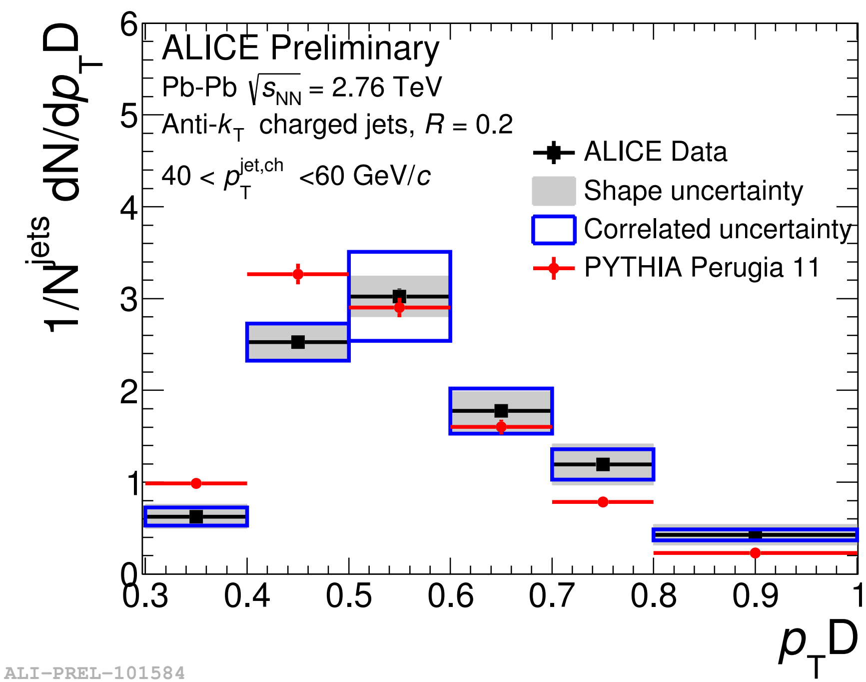
- R=0.2, 40 < p_T^{jet} < 60 GeV/c, no leading constituent cut, fully corrected to charged particle level

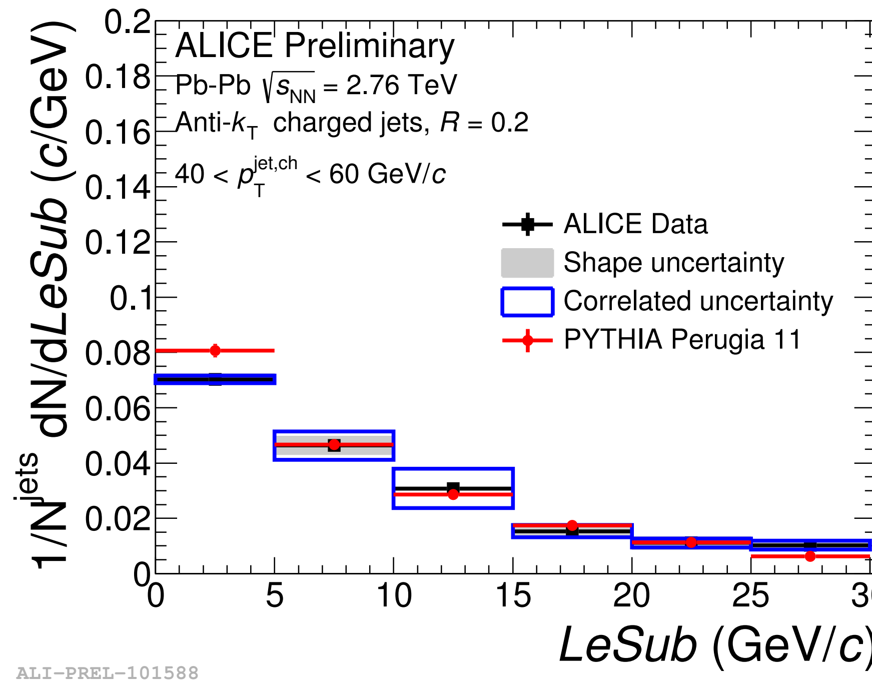
- g shifted to smaller values compared to PYTHIA reference
  → indicates more collimated jet core



- larger $p_T D$ in Pb-Pb compared to PYTHIA
  → indicates fewer constituents in quenched jets (or 'less democratic' splitting)

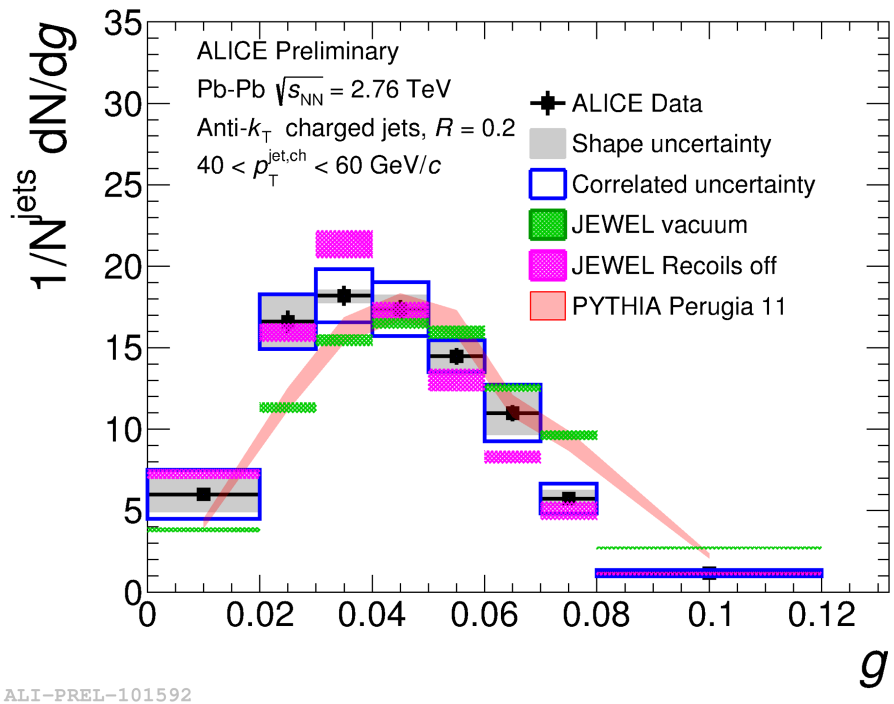
- LeSub in Pb-Pb in good agreement with Pb-Pb:
  → hardest splittings likely unaffected

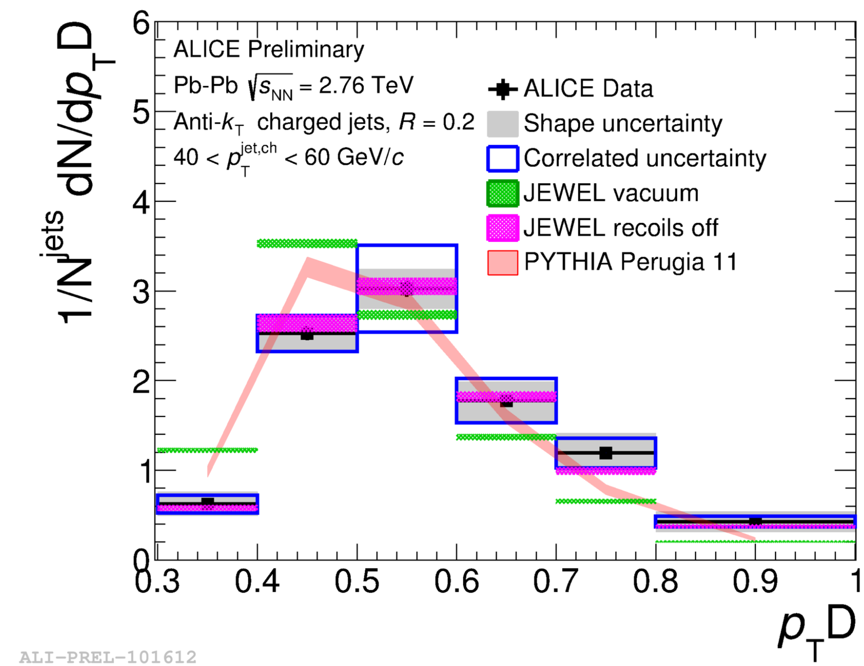




Model comparison

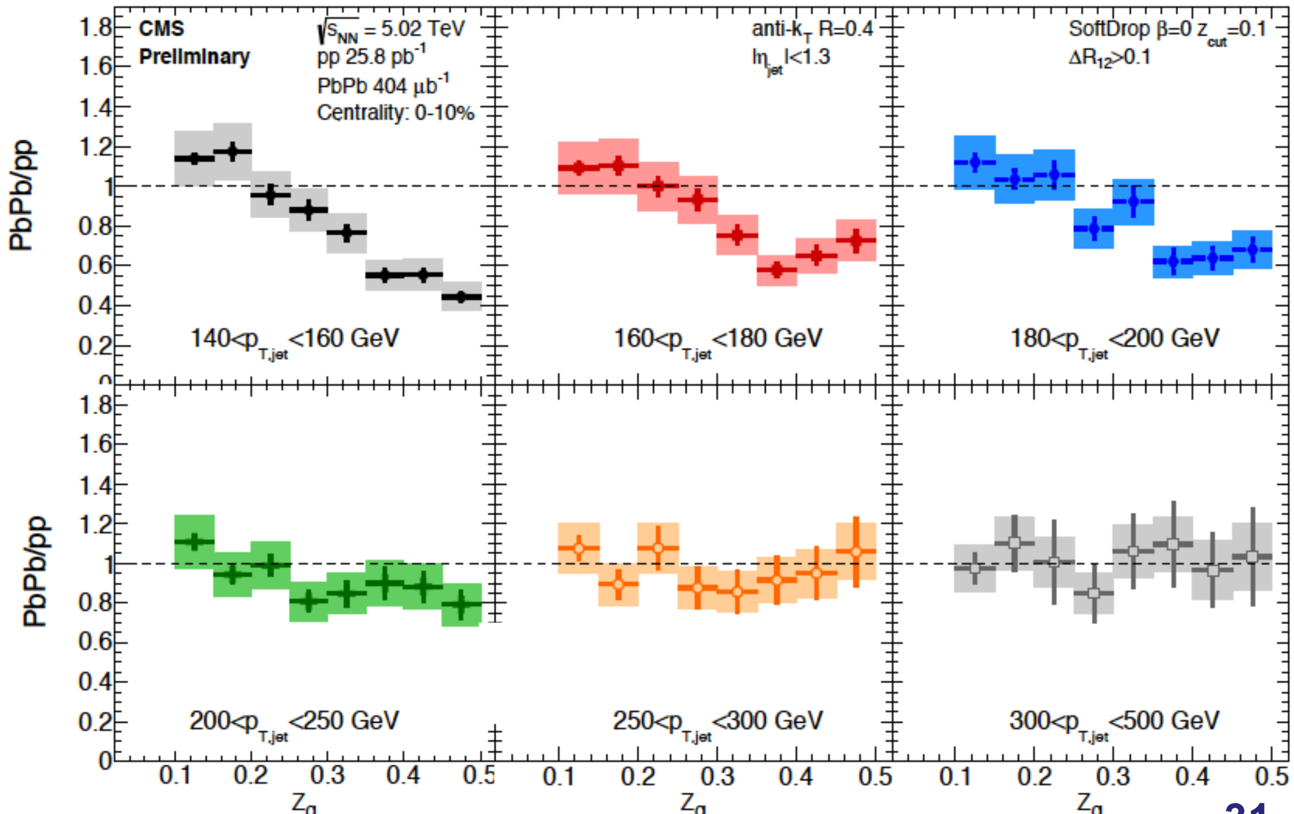
- trends reproduced by JEWEL
  → indicates collimation through emission to large angles
- ‘recoils off’: no medium recoils partons in final state (note R=0.2)





Subjets at LHC

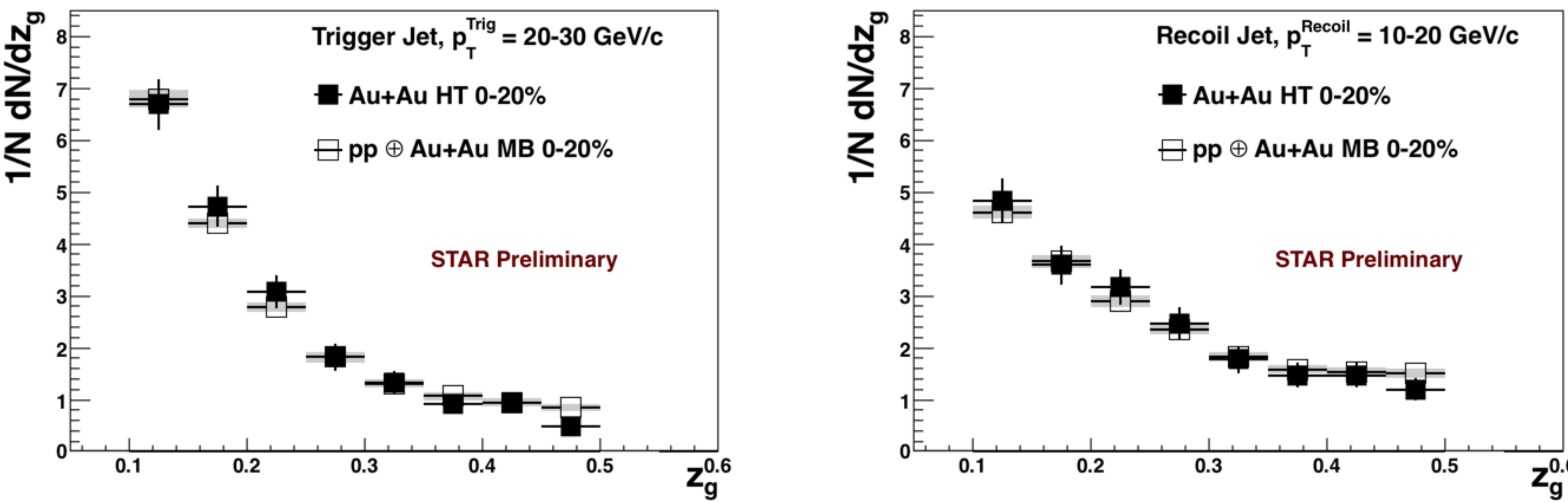
- declustering and soft drop grooming to identify hard jet substructure
- subjet momentum balance $$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$
- in vacuum, $d\sigma/dz_g$ ~ splitting function
- CMS: strongest suppression for lower p_{Tj}^{jet} at high z_g



CMS PAS HIN 16-006

Subjets in STAR

- 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 ?

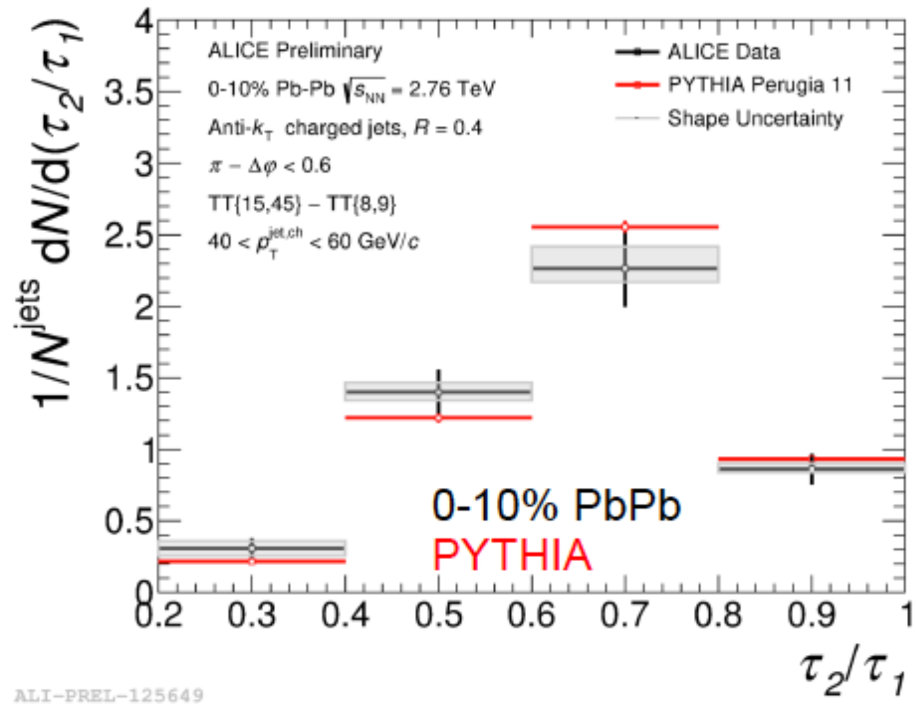


STAR, HP 2016

ALICE subjets

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

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



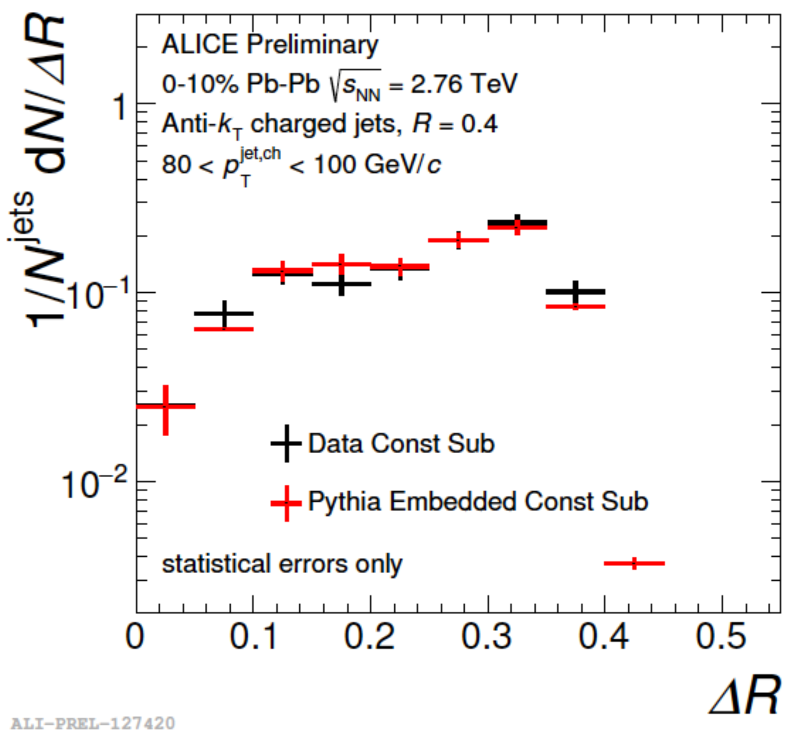
2-prong jet

1-prong jet

ALICE, QM 2017

ALICE subjet ΔR

- subjet distance ΔR
- data uncorrected for det. effects and background fluctuations compared to PYTHIA embedded reference
- no significant modification observed relative to reference, full correction to particle level in progress



ALICE, QM 2017

Jet Mass

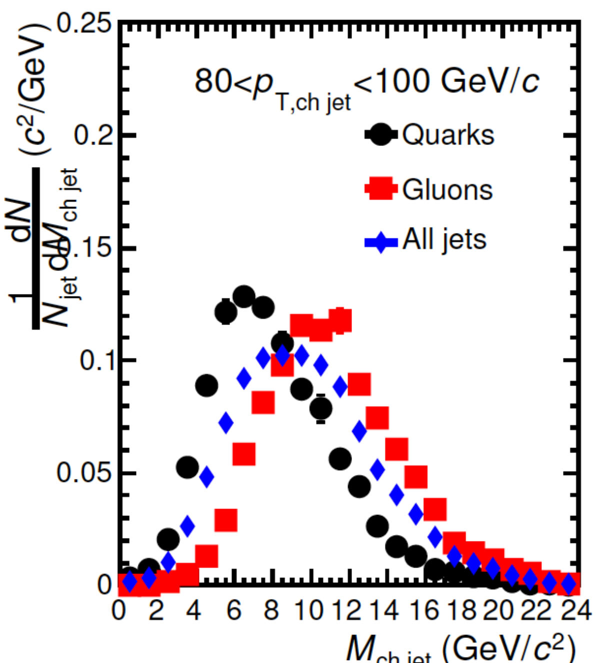

EXPLOSIVE MUSCLE GAINS FASTER!
GROUNDBREAKING, PRECISION-ENGINEERED ANABOLIC MATRIX
Stimulant Free
GAT
NEW
MOST POTENT
POST-WORKOUT
FORMULA!
PREMIUM CREATINES, HIGHEST ORAC CAPROS 1700 AND GROWTH INDUCERS
JETMASS
FASTEST-ACTING
MUSCLE VOLUMIZER
GERMAN CREATINE SYSTEM
ULTRAPURE CREATINE FROM Essen, Germany
»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

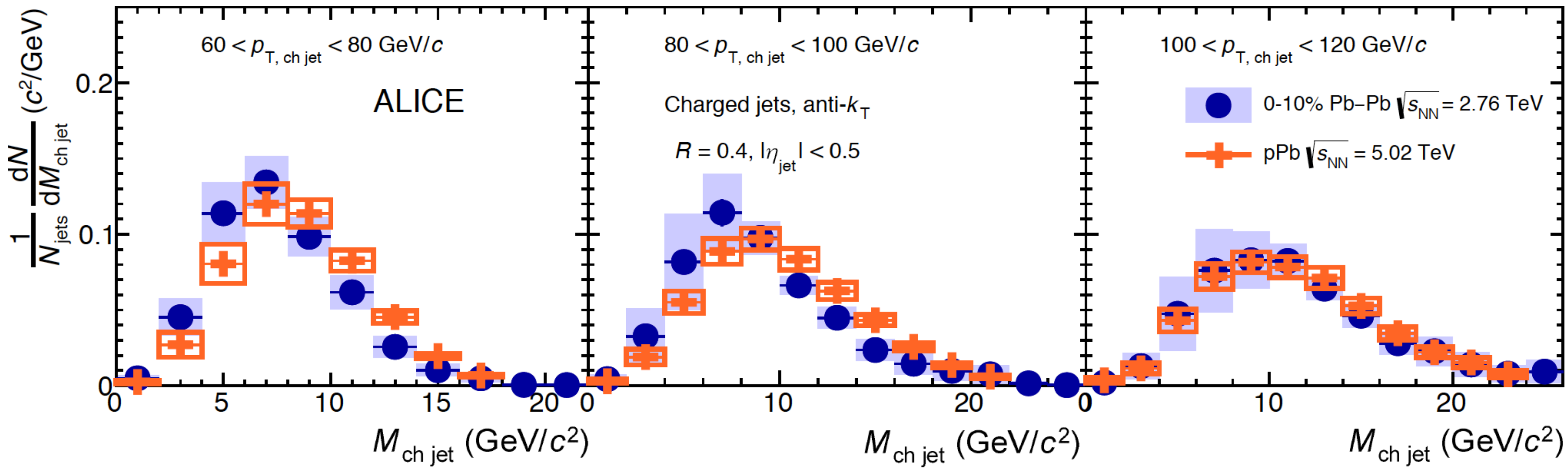
(*A. Majumder, J. Putschke, nucl-th 1408.3404)*



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

Results: 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



- small √s dependence is expected (quark / gluon composition)

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

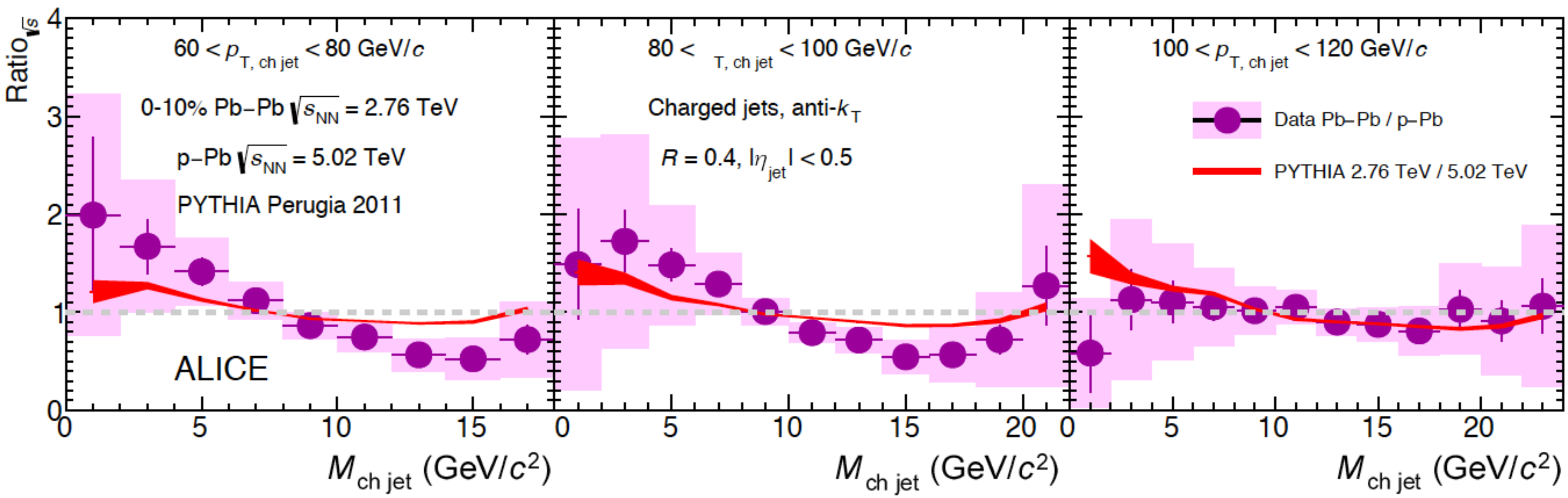
$$\Re_{\sqrt{s}} = \frac{\frac{1}{N_{jets}} \frac{dN}{dM_{chjet}} \Big|_{\sqrt{s_{NN}}=2.76\text{ TeV}}}{\frac{1}{N_{jets}} \frac{dN}{dM_{chjet}} \Big|_{\sqrt{s_{NN}}=5.02\text{ TeV}}}$$

ALICE, nucl-ex / 1702.00804

Ratio Pb-Pb / p-Pb

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

- overall small modification - cancellations ?

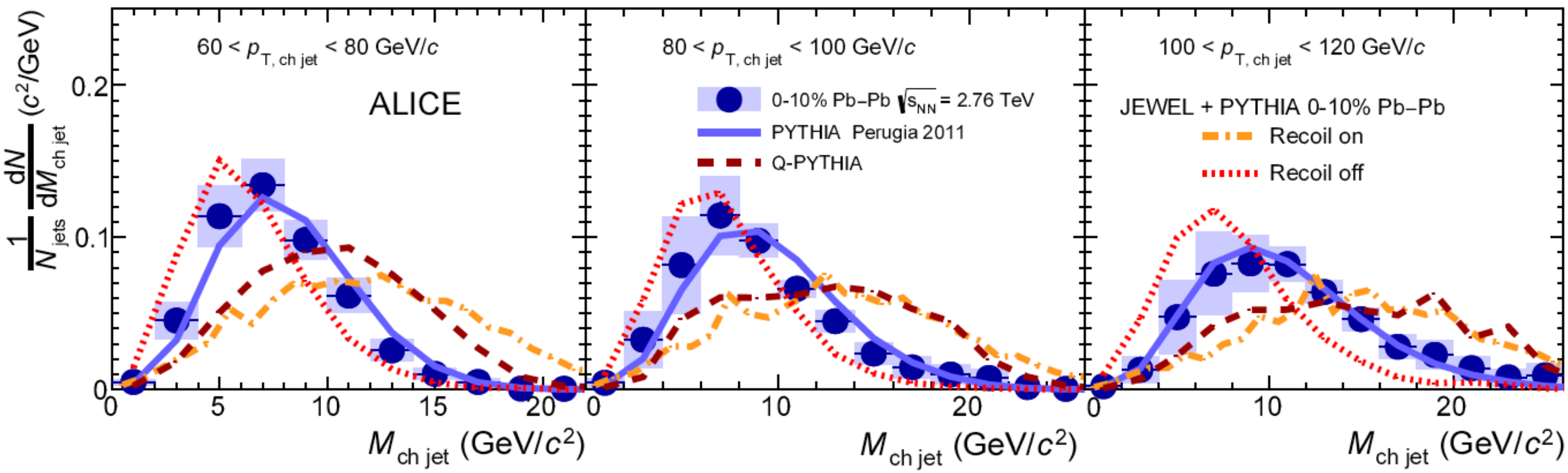


ALICE,
nucl-ex / 1702.00804

Model comparison

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

ALICE, nucl-ex / 1702.00804



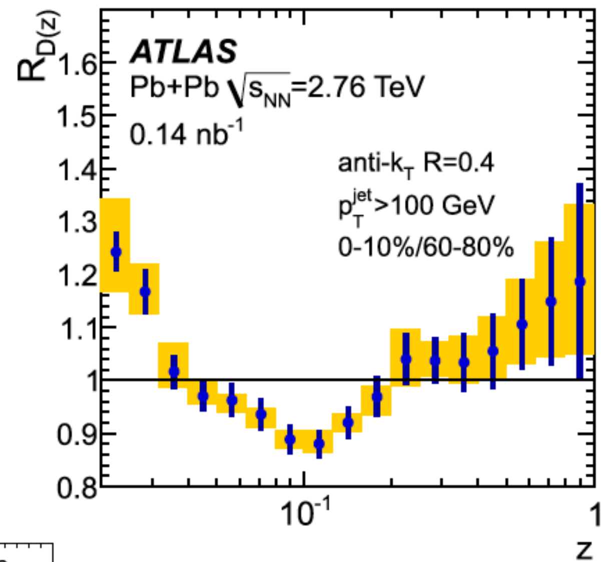
- Q-PYTHIA: radiative energy loss modelled by enhanced splitting functions

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

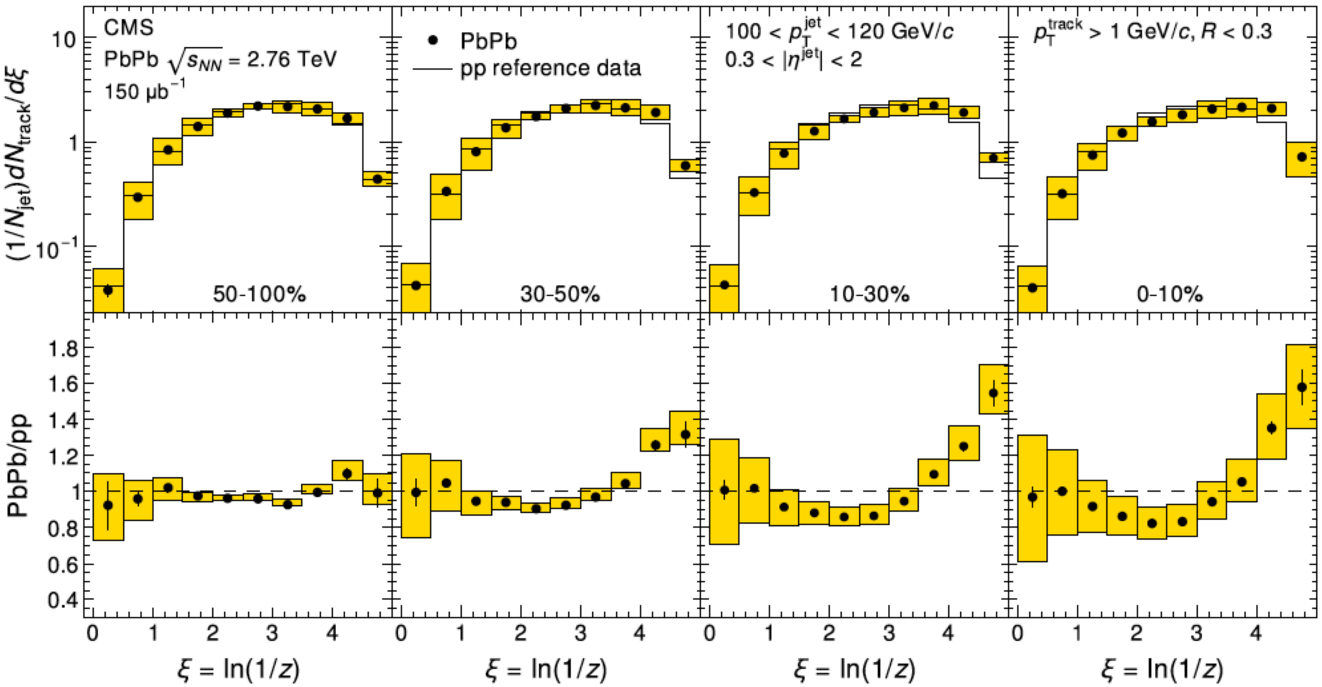
Strangeness Production in Jets

Charged particle fragmentation

- ATLAS, CMS: enhancement at low z observed for unidentified charged particles in high-p_T jets
- p_T^{ch} > 2 GeV/c (ATLAS), 1 GeV/c (CMS)



ATLAS, *PLB 739 (2014) 320*



Strangeness production in nuclear collisions

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

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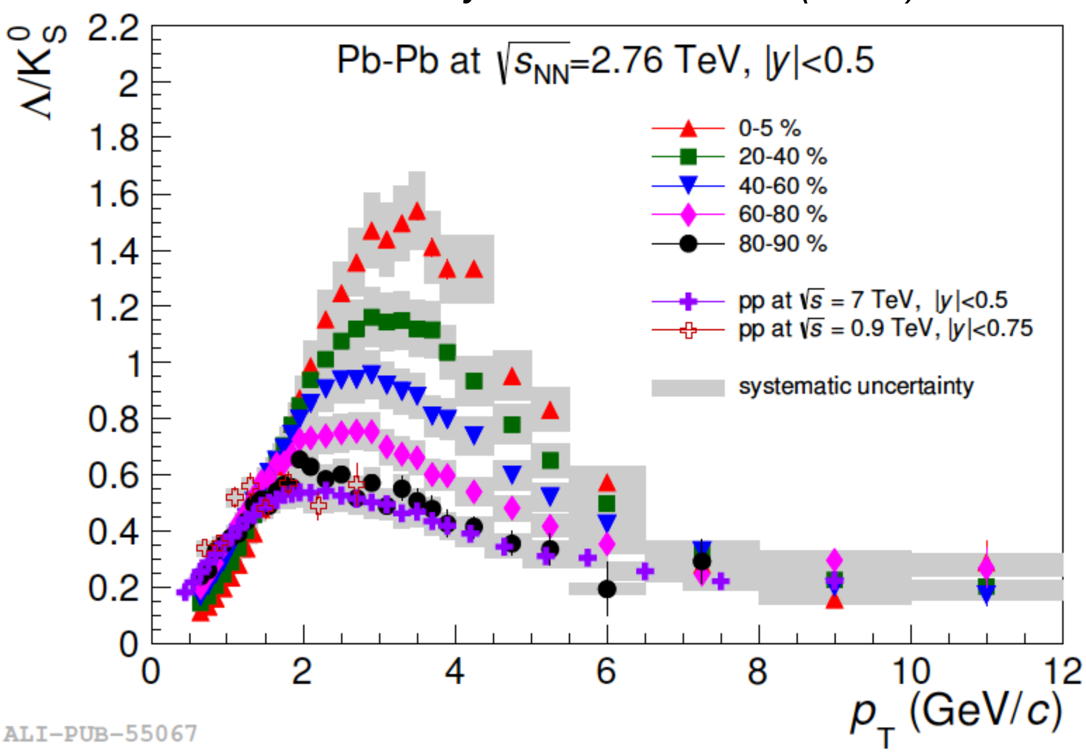


- measurement of identified particles in jets helps to constrain hadronisation and energy loss scenarios

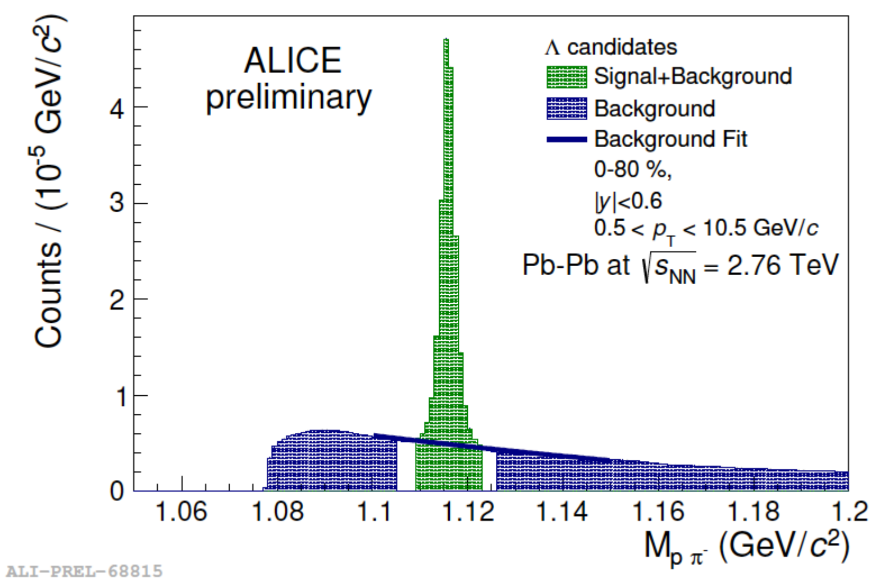
Strangeness in jets

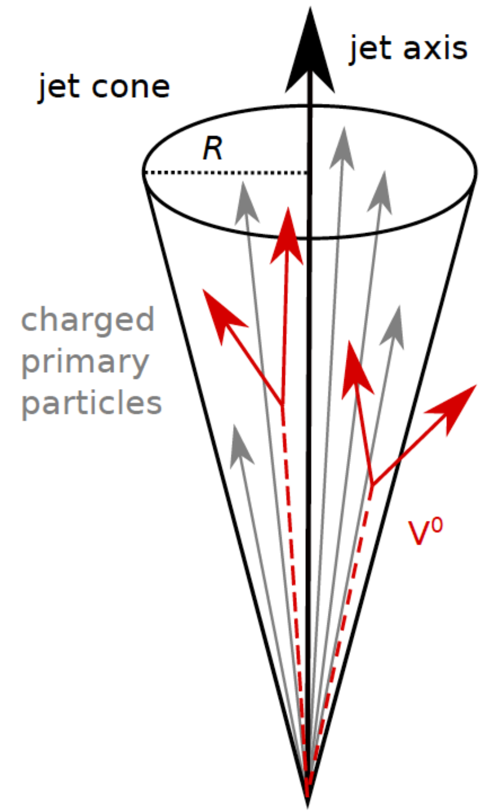
- neutral strange particles reconstructed via decay topology (‘V^0’):

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

- V^0 - jet matching

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



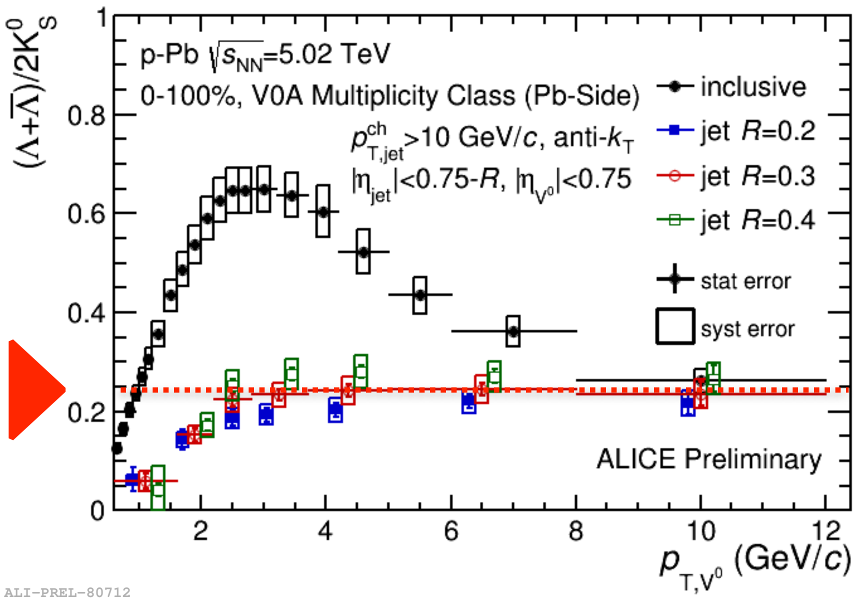


- signal extraction via invariant mass
- corrections for efficiency, feed-down, UE background + fluctuations

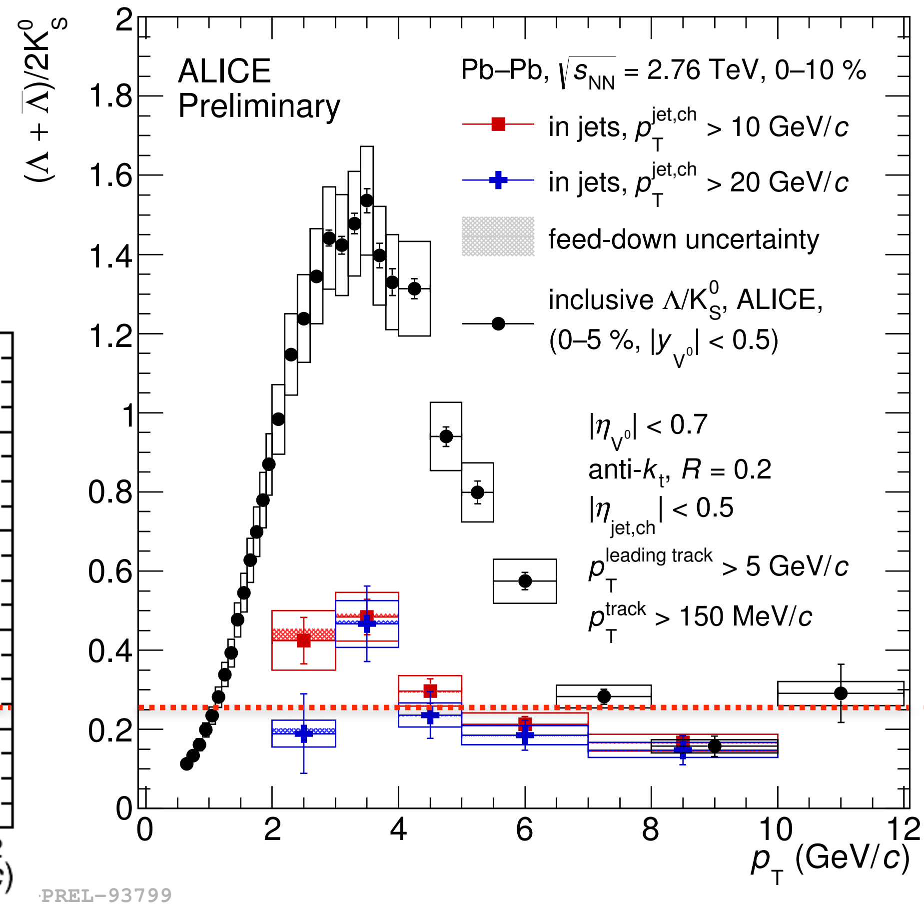
$(\Lambda+\Lambda)/2K^0_s$ ratio in jets

- ratio in jets significantly lower than for inclusive hadrons
- compare Pb-Pb results to reference from p-Pb collisions at 5.02 TeV: agreement within uncertainties

p-Pb

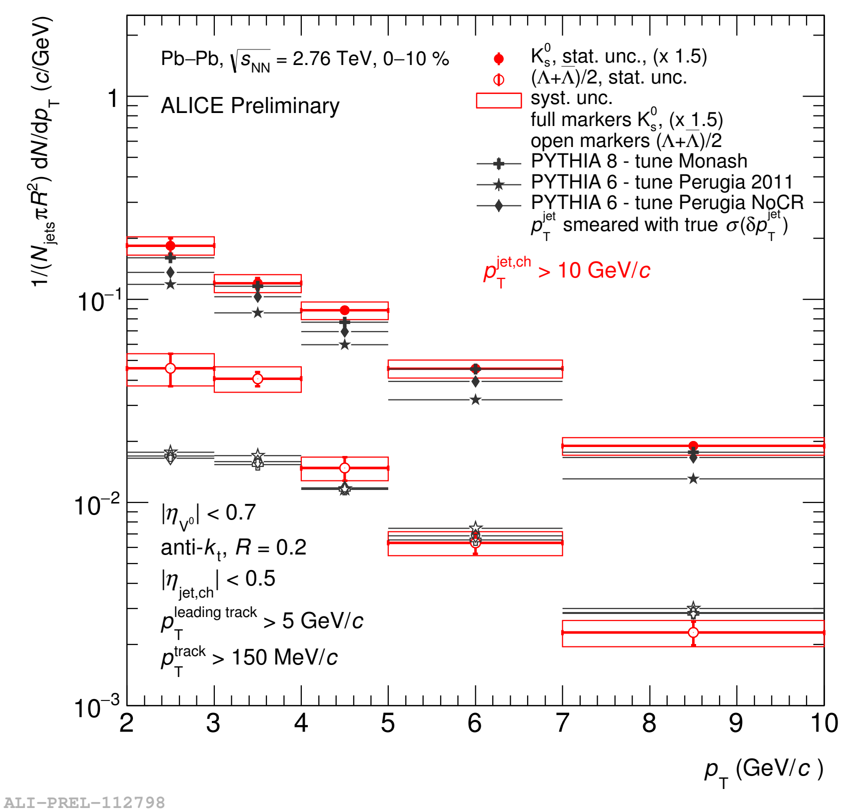


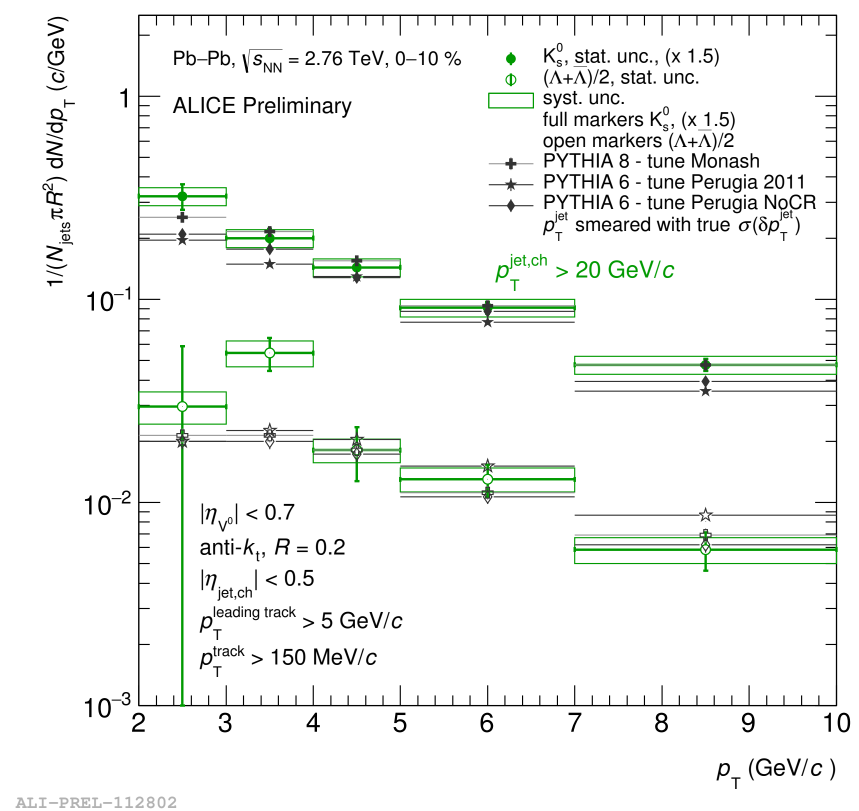
Pb-Pb



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





Summary

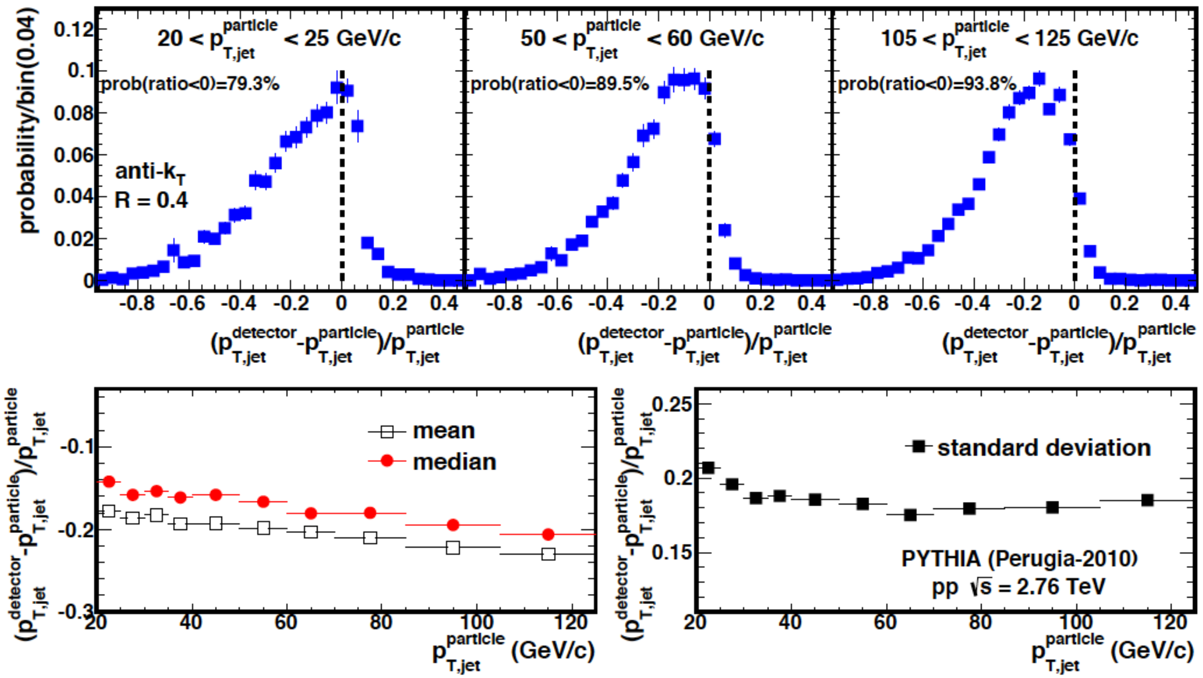
- LHC inclusive jet R_{AA} and recoil jet measurements at RHIC and LHC
- subjet momentum balance at LHC and RHIC
- jet shapes
- jet mass
- strange particles in jets

- Backup -

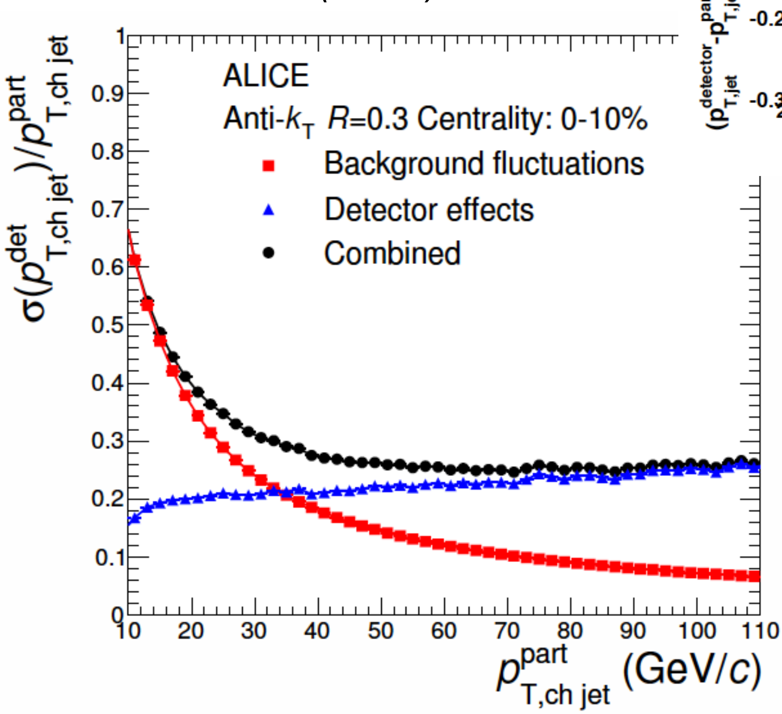
ALICE jet response

Phys. Lett. B 722 (2013) 262

- full jets, pp at 2.76 TeV
- JES uncertainty ~ 3.6% at p_T^{jet} = 100 GeV/c



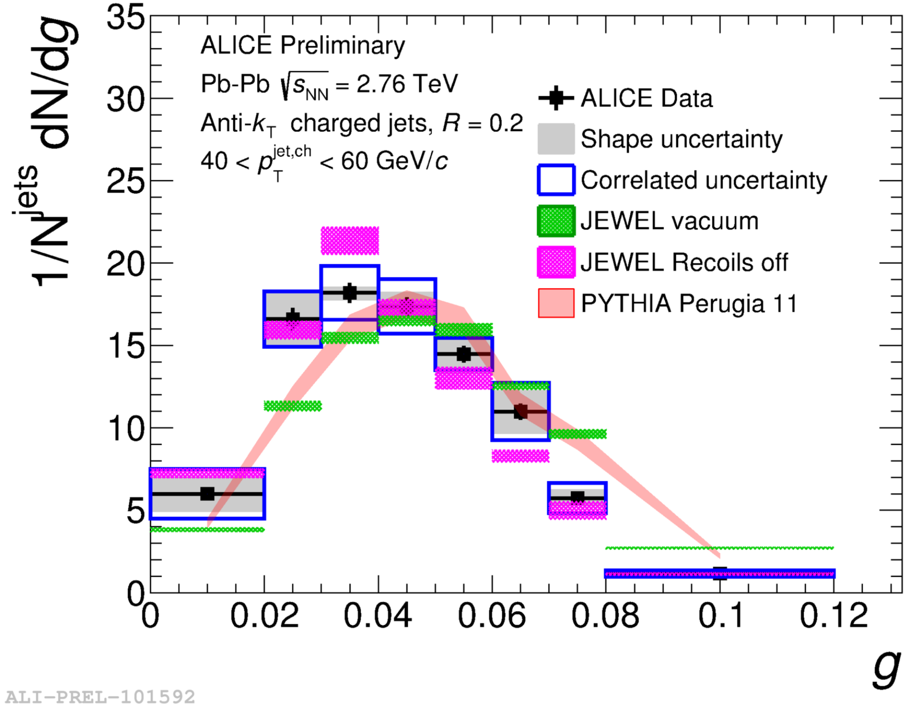
JHEP 03 (2014) 013

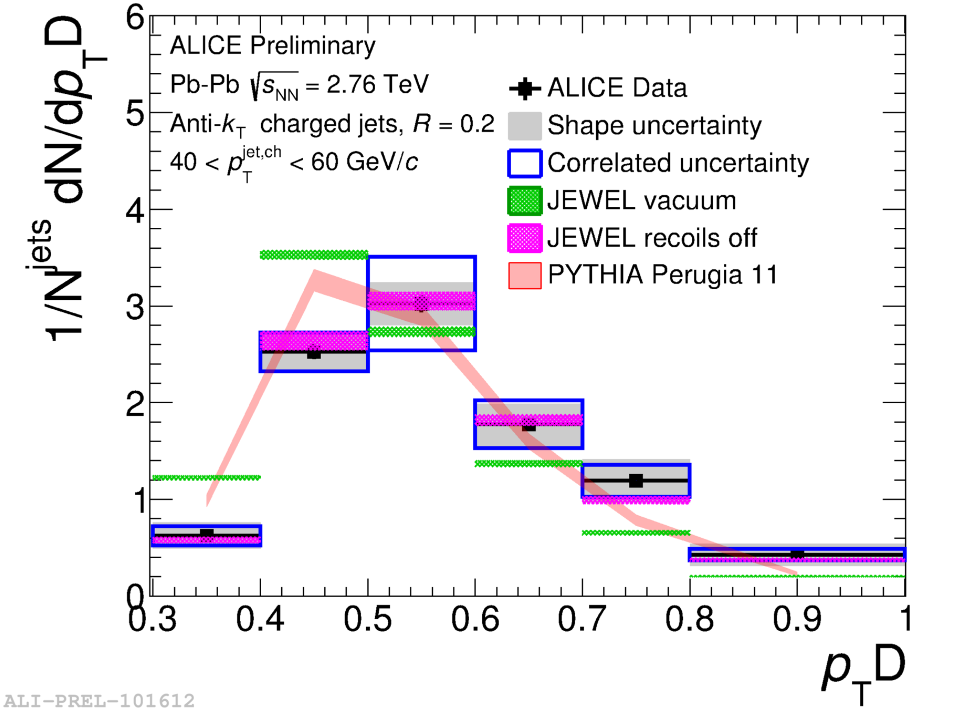


- charged jets: Pb-Pb
- JE resolution at low p_T dominated by background, at high p_T by detector effects

Jet Structure : Model Comparison

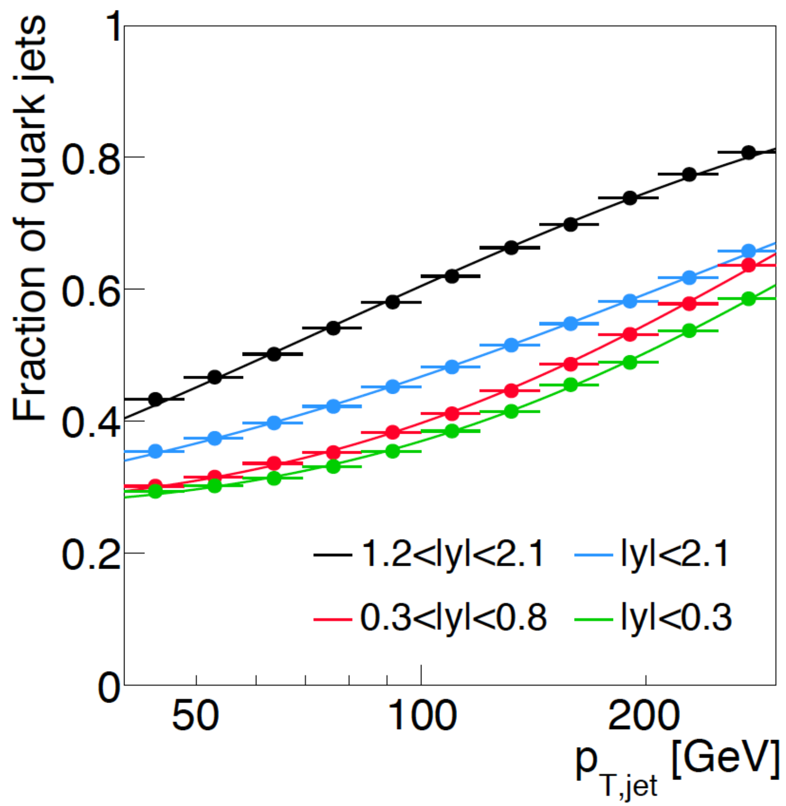
- trends reproduced by JEWEL jet quenching model





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

q/g fraction



Spousta, Cole, hep-ph/1504.06169

jet mass: pPb

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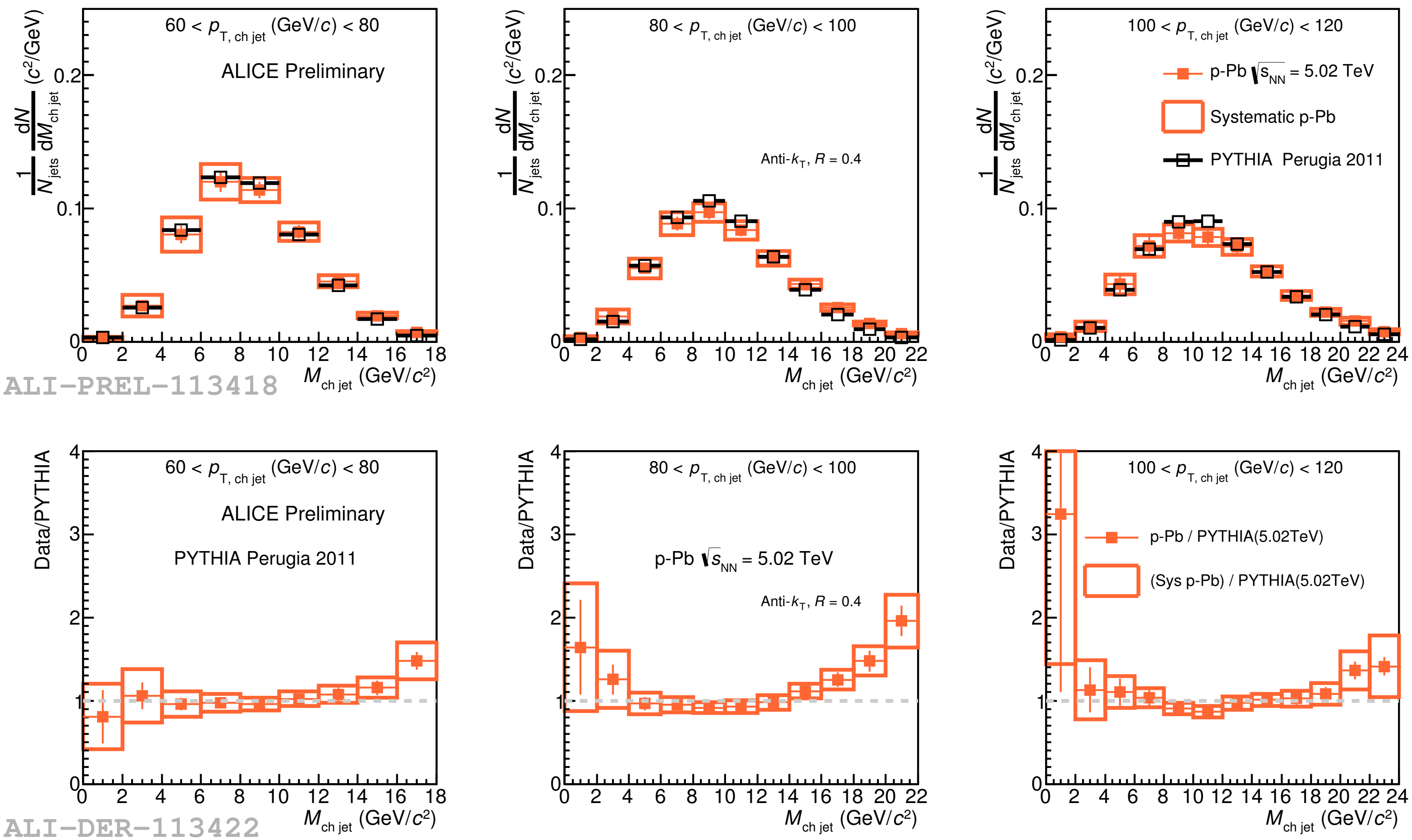
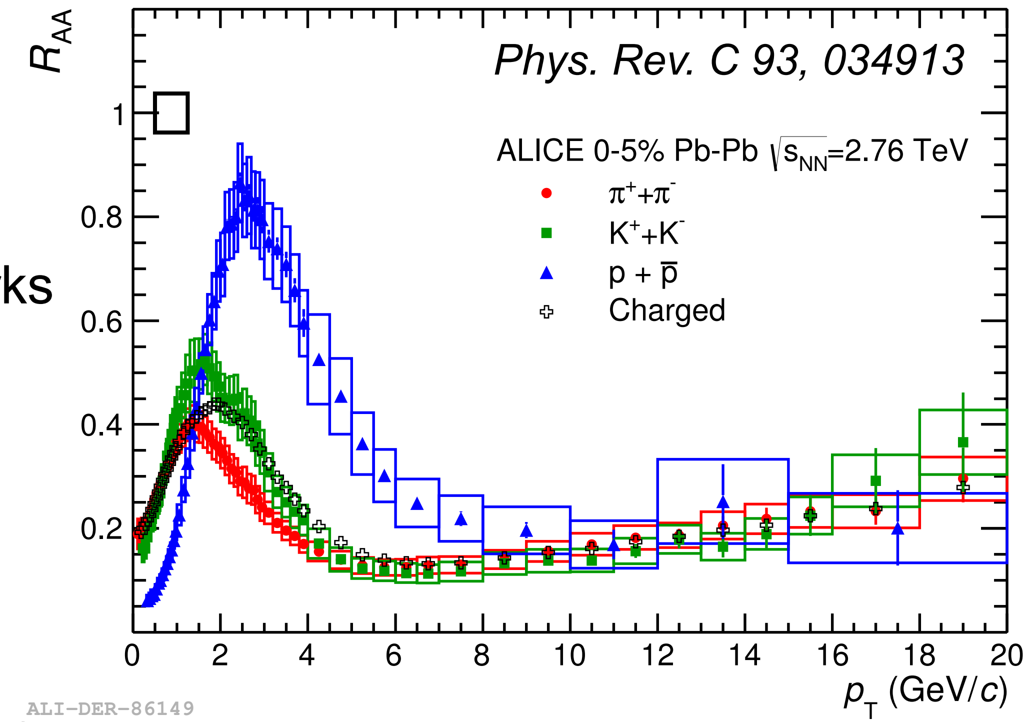
- jet mass in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, charged jets with R=0.4
- overall well described by PYTHIA with some tension in the tails



Identified hadrons in heavy-ion collisions

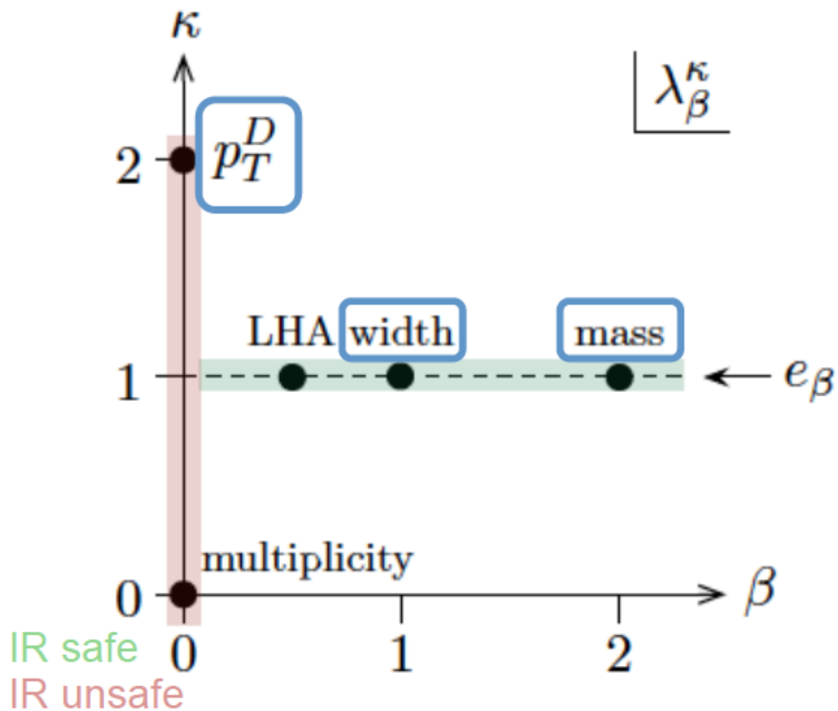
- baryons / meson R_{AA} a probe of gluon / quark energy loss?
- would expect stronger radiative energy loss for gluons than for quarks
  - subtle cancellations?
  - hadron observable biased towards hard fragmentation?



- 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

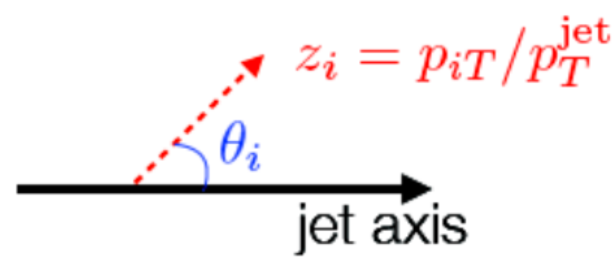
  (*J.G. Milhano, K. C. Zapp, hep-ph/1512.0819, T. Renk, Phys. Rev. C 81, 014906, B. Mueller, hep-ph/1010.4258*)

generalized angularities



Larkoski, Thaler, Waalewijn JHEP 1411 (2014) 129

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\theta_i}{R} \right)^\beta$$



Underlying event subtraction

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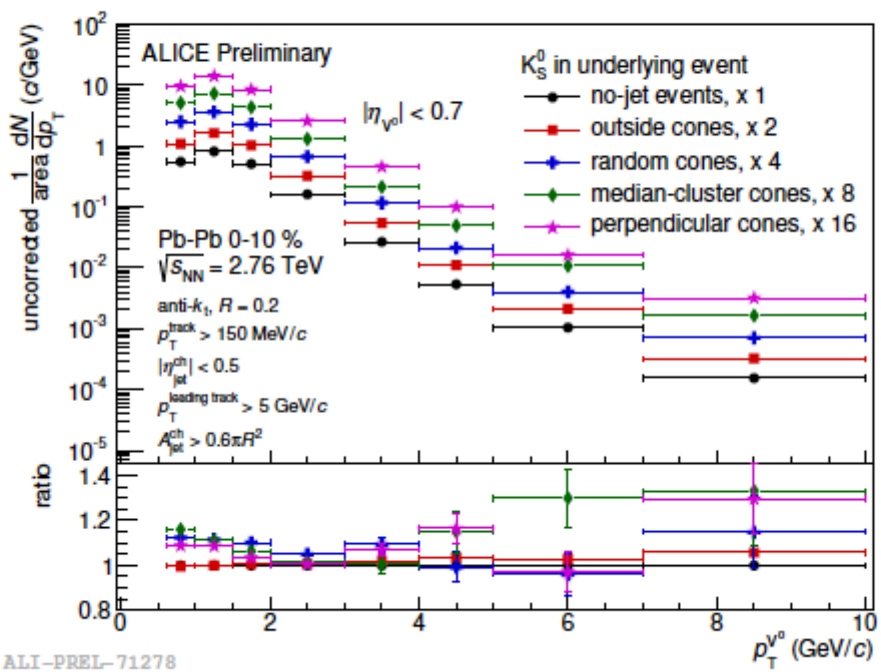
- subtract underlying event contribution to K^0_S, Λ spectra in jets
- various methods with different sensitivity to acceptance, event plane correlations, presence of additional jets, …
- apply a correction to account for background density fluctuations

K^0_S



Λ