JET MEASUREMENTS IN HIC AT LHC

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Bose Institute, Kolkata

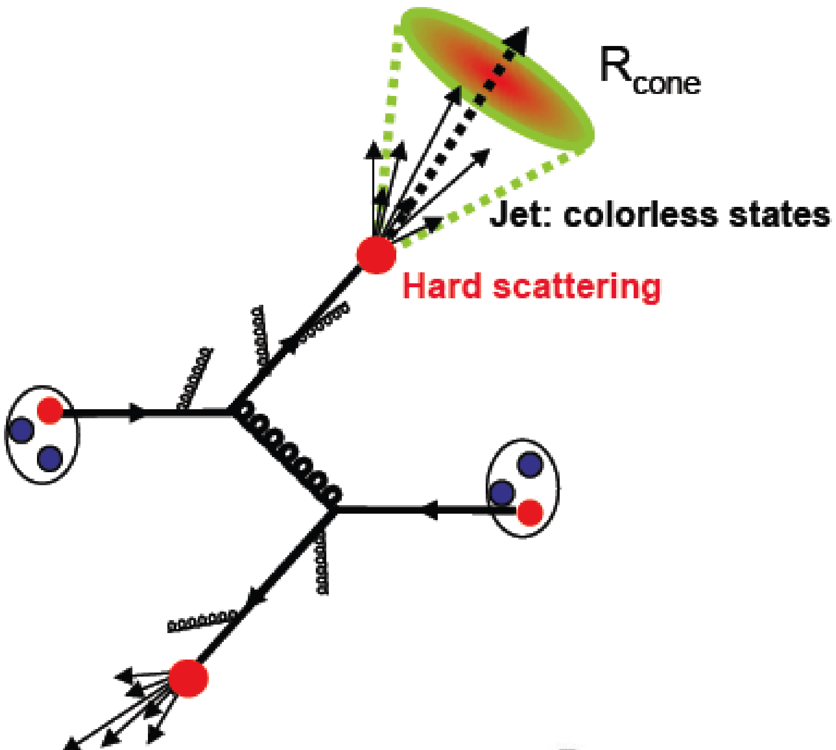
Discussion meeting on Jets@LHC

21 – 28, January 2017, ICTS, Bengaluru

HAPPY REPUBLIC DAY 2017

Jet production

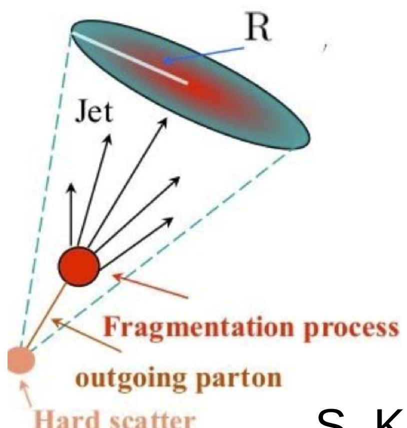
$\sum p_{T\ \text{particles}} = p_{T\ \text{jet}}$



Cascades of consecutive emissions of partons from initial hard scattering

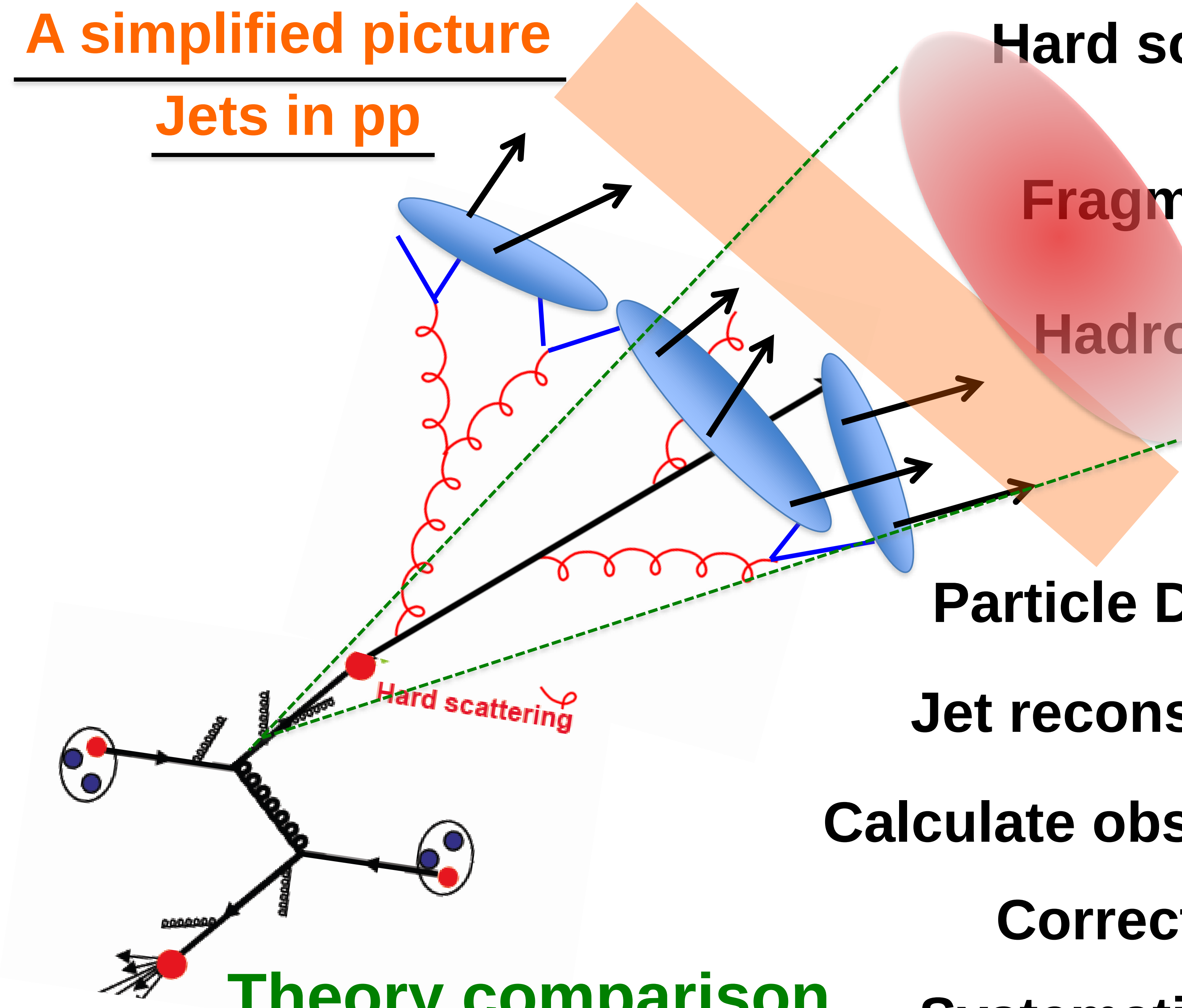
(partons produce observed hadrons)

Collimated spray of particles originating from the fragmentation of hard scattered partons



A simplified picture

Jets in pp



Hard scattering

Fragmentation

Hadronization

Particle Detection

Jet reconstruction

Calculate observables

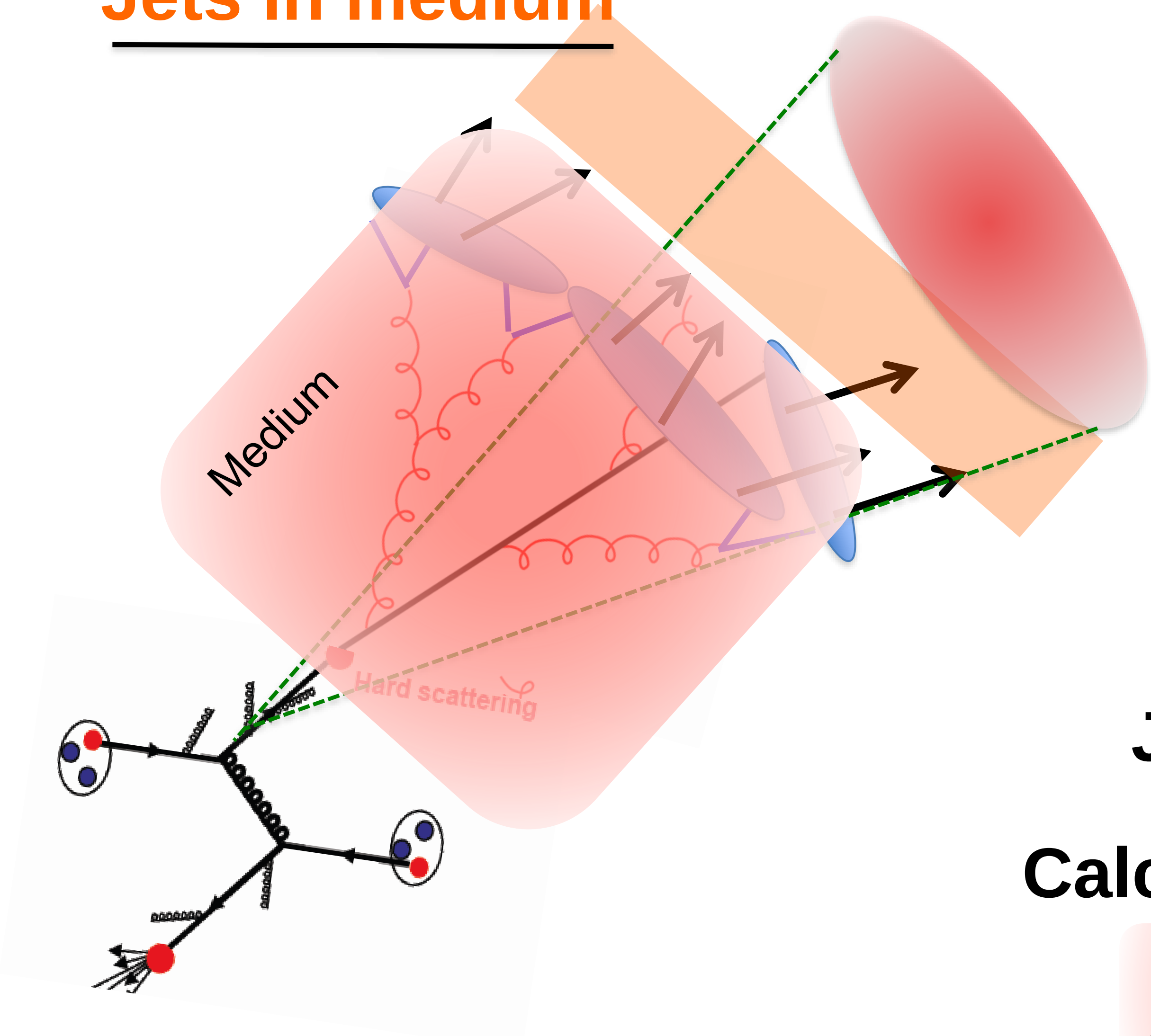
Correction

Systematic unc.

Theory comparison

A simplified picture

Jets in medium



Hard scattering

Fragmentation

Hadronization

Particle Detection

Jet reconstruction

Calculate observables

Background Correction

Systematic unc.

Theory comparison

Jets: connection between theory and experiment

pQCD: partonic level

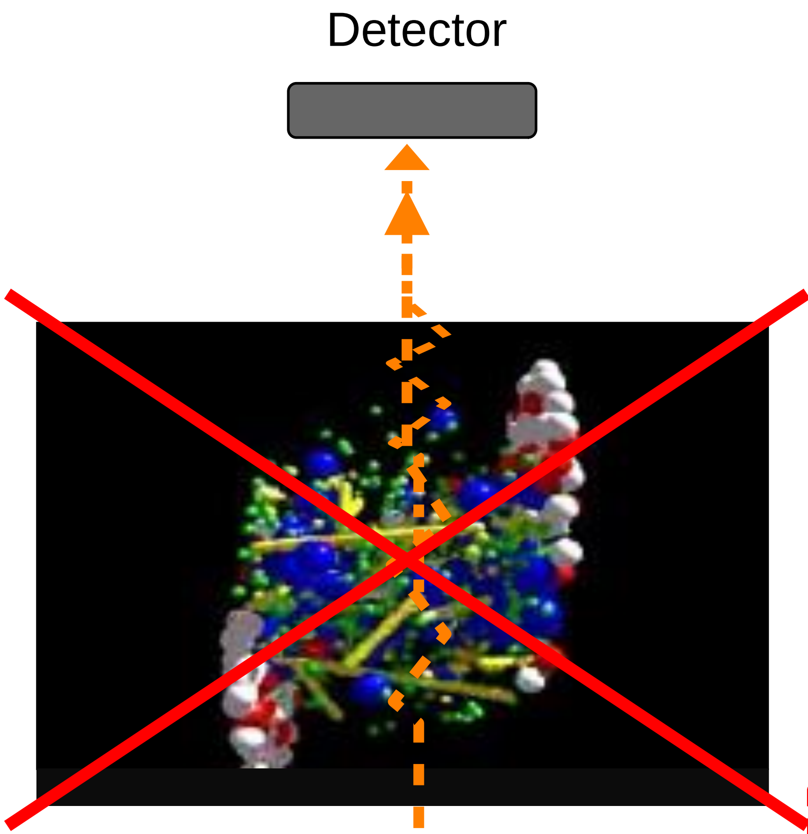
Experiments measure hadrons

Re-associate measurable hadrons to accurately reconstruct parton kinematics

Tools: jet finding algorithms
Apply same algorithm to data and theoretical calculations

- Proxy for high p_T partons produced in collisions
- Testing ground for pQCD
- References for jets in AA

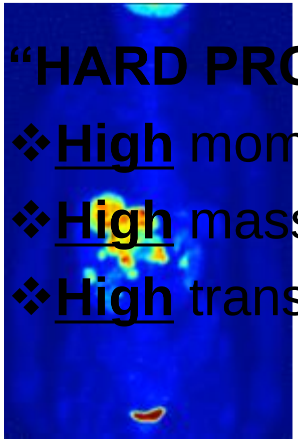
Tomography of the QGP



Self generated HARD PROBES in the early stage of the collision

Calibrated LASER/XRAY

Unfortunately not possible! Lifetime of QGP too short



Human body

"HARD PROBES" calculable in pQCD:

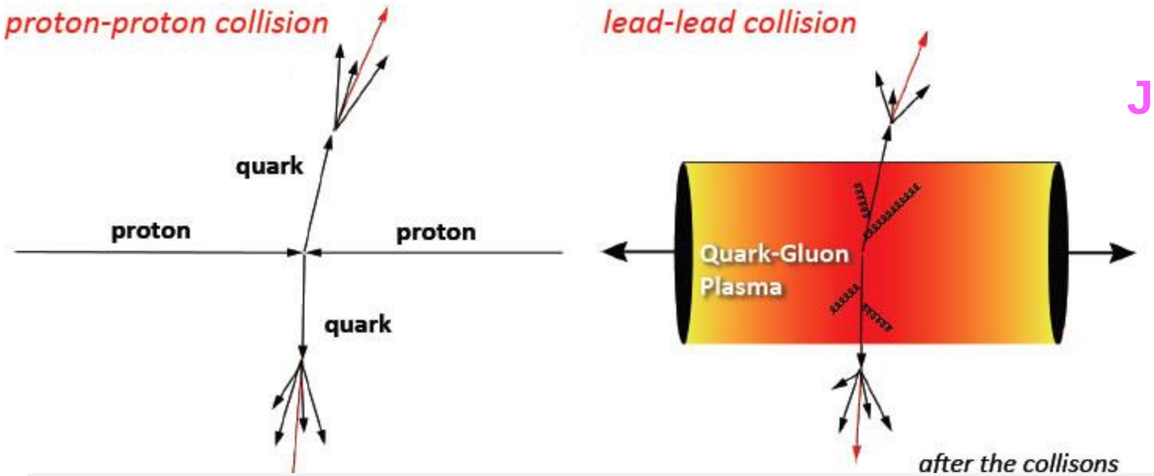
- ❖ **High** momentum transfer, Q^2
- ❖ **High** mass
- ❖ **High** transverse momentum p_T

Variety of "HARD PROBES"…

- ❖ **Hadron production**
- ❖ **Heavy flavours**
- ❖ **JET PRODUCTION**
- ❖ **Direct photon production**

Jets in medium: Jet quenching

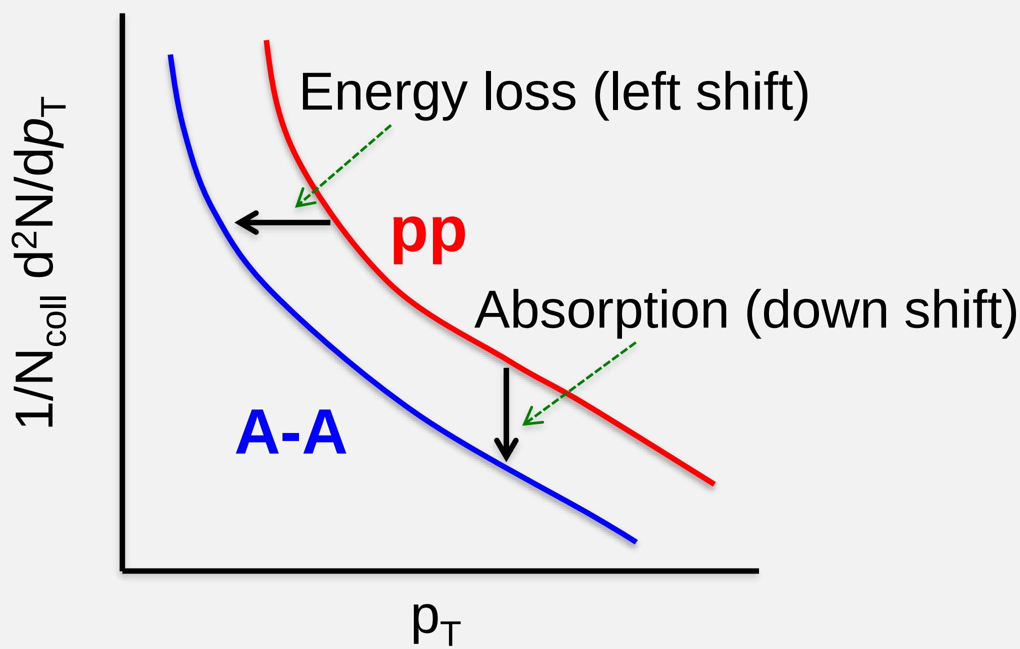
Comparing jet yields in pp and AA at same energy

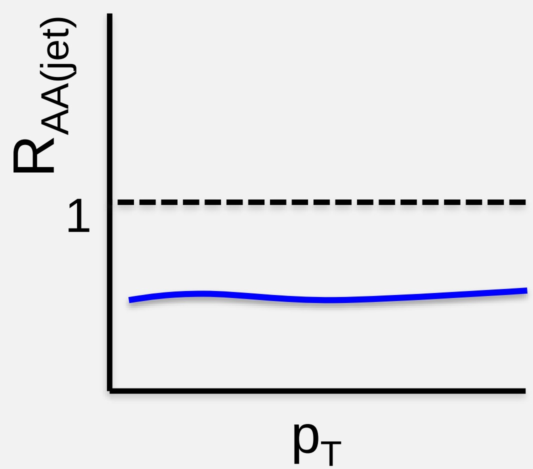


Jet nuclear modification factor

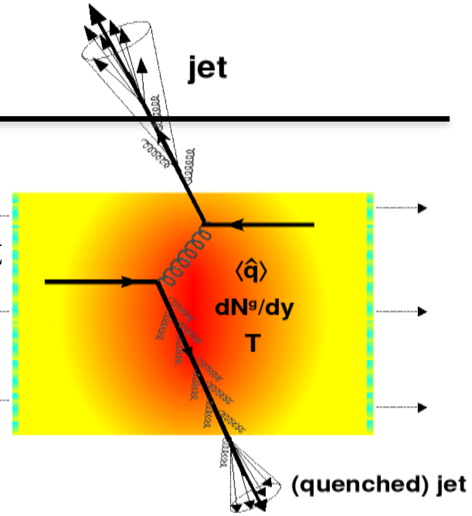
$$R_{AA}^{jet} = \frac{dN/dp_T|_{PbPb}}{N_{coll}\, dN/dp_T|_{pp}}$$

Average number of pp collisions in AA

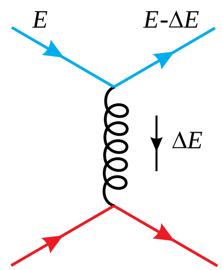


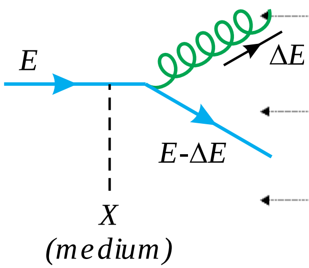


Jet quenching



Hard parton in presence of dense coloured medium lose energy via elastic scattering and multiple gluon radiation





Mean parton energy loss ⇔ medium properties

$\Delta E \sim \rho_{gluon}$ (gluon density)

$\Delta E \sim \Delta L$ (medium length)

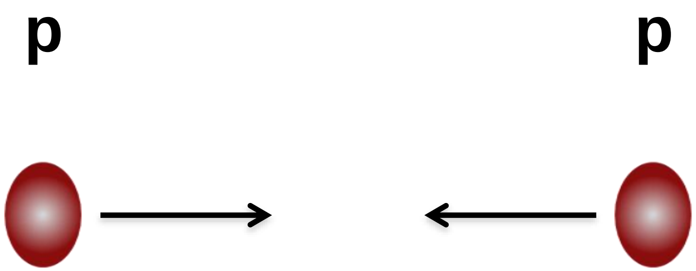
Characterization of the medium via jet transport coefficient q-hat:

(mean transverse momentum squared transferred to the traversing parton per unit path length)

Many theories/models: q-hat ~ 2 to 10 GeV^2/fm (RHIC data)

JET collaboration: q-hat ~ 1.2 GeV^2/fm (RHIC), 1.9 GeV^2/fm (LHC)

Phys. Rev. C 90, 014909, 2014

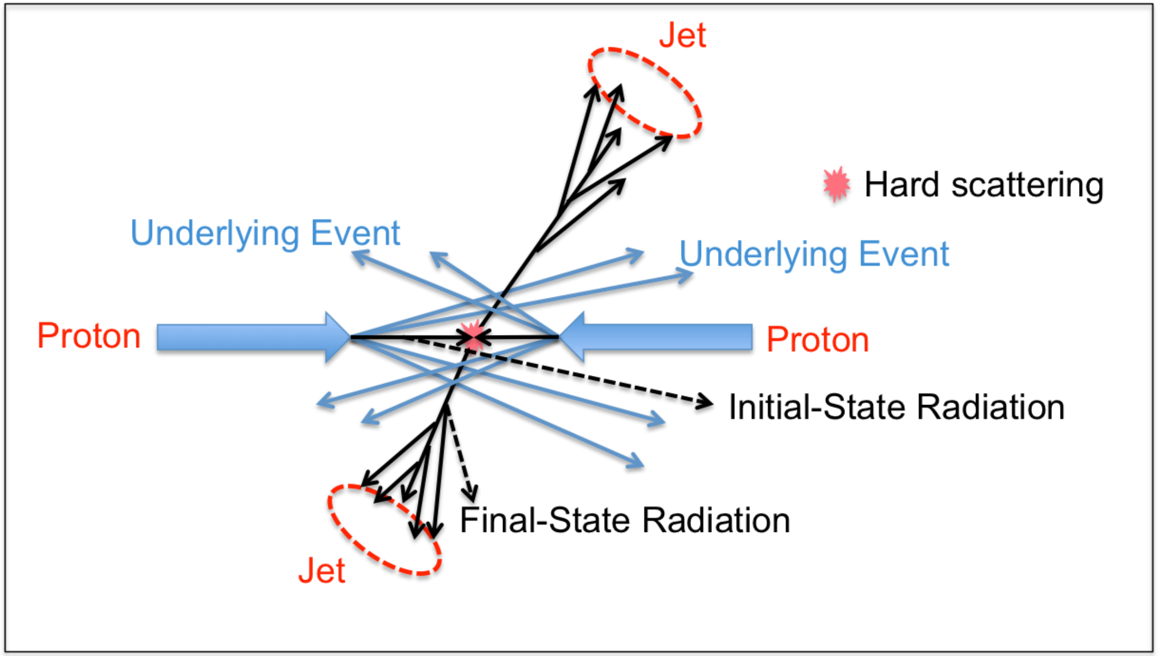


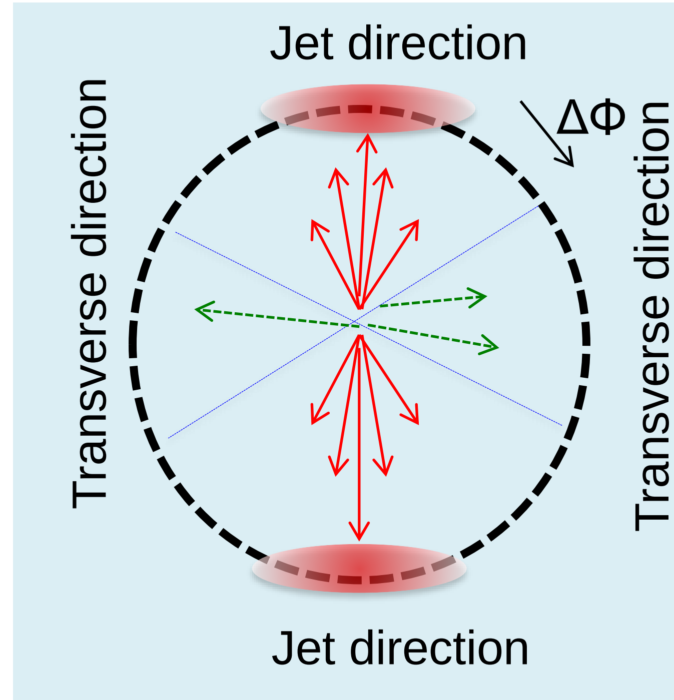
Jets in pp

Calibrate the probe !

Testing ground for pQCD

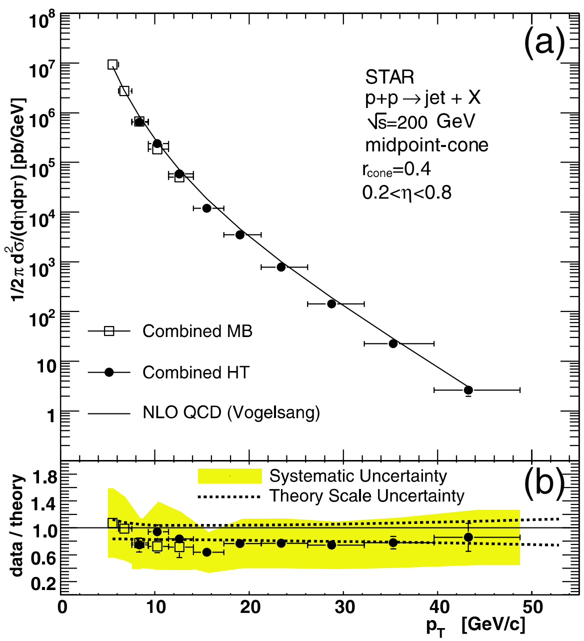
Underlying event (UE) in pp

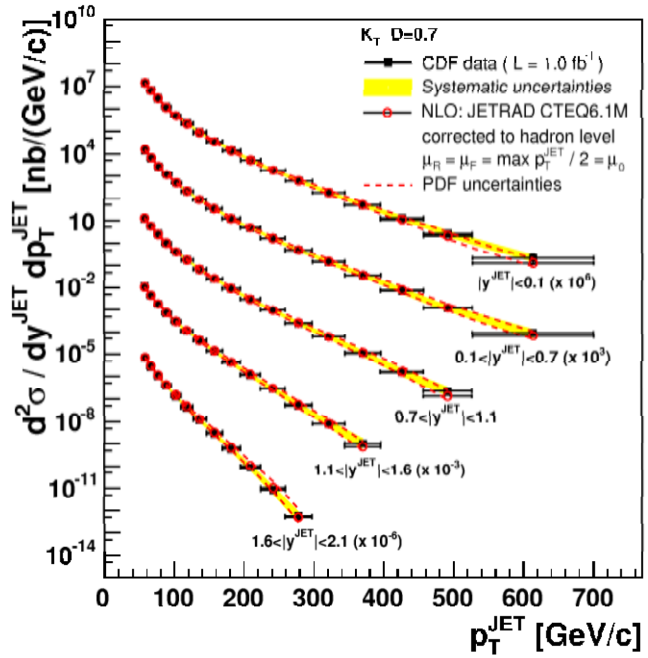


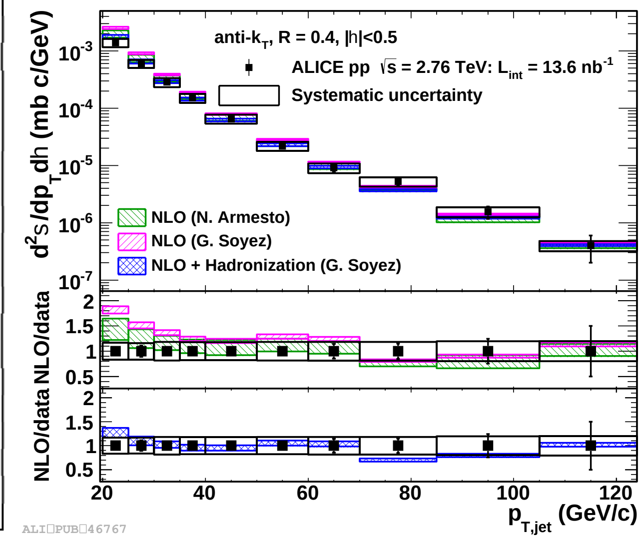


- **<u>UE:</u>** contributions from ISR, beam remnants, MPI
- **<u>UE estimation:</u>** collect all particles in transverse direction to the jet axis
- Subtract from the jet energy
- For differential quantities subtract on an statistical basis

Jet cross sections





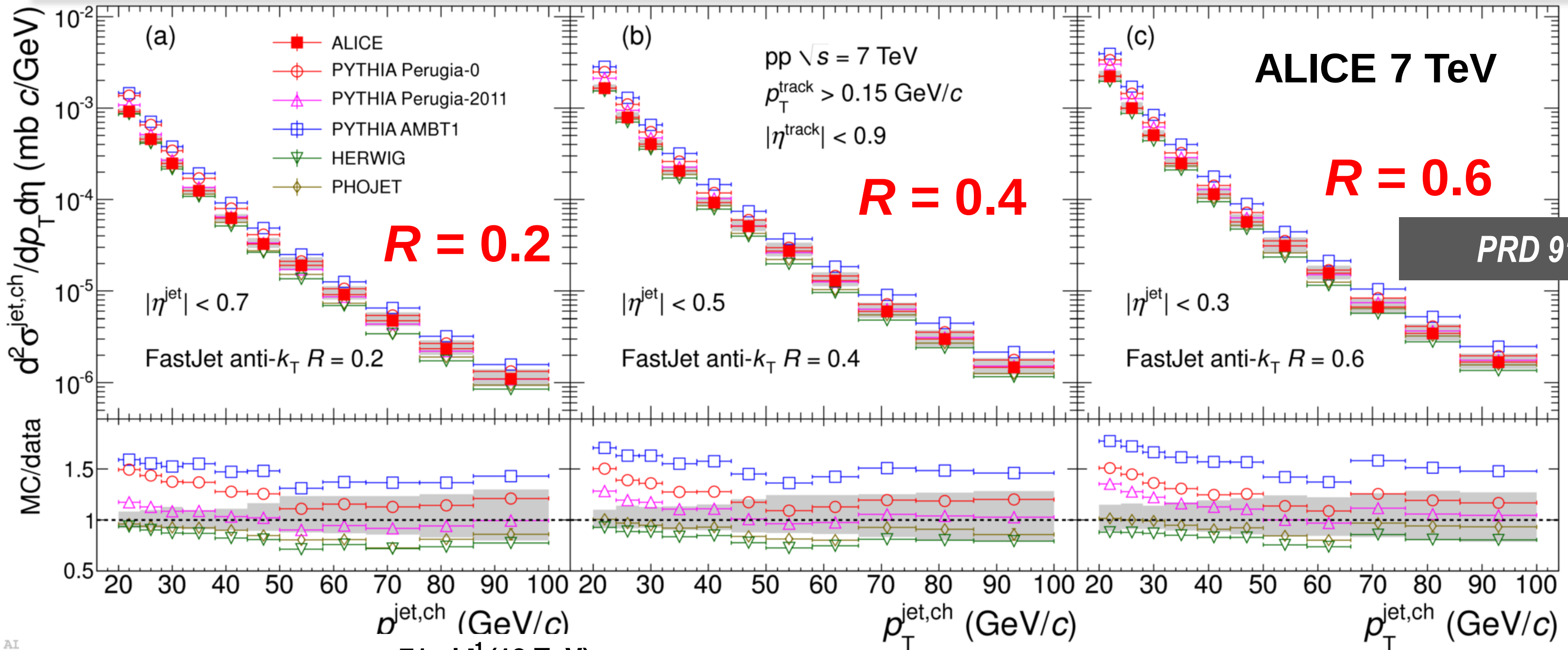


RHIC 0.2 TeV **Tevatron 1.8 TeV** **LHC 2.76 TeV**

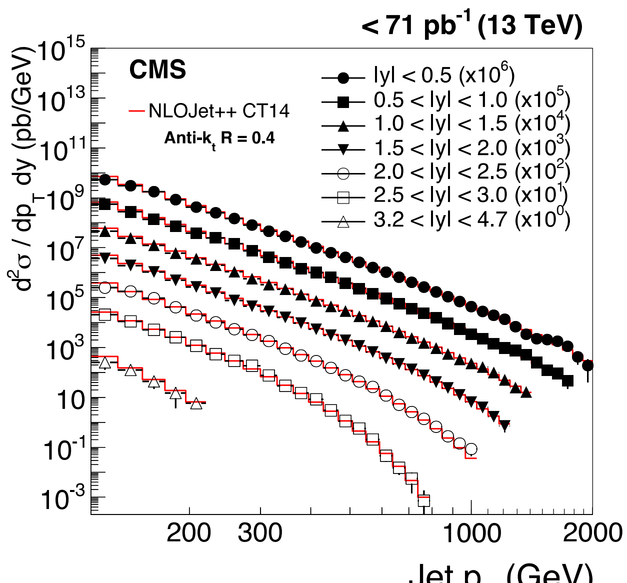
Phys. Rev. Lett. **97** (2006) 252001 PRD **75,** 092006 (2007) Phys. Lett. B 722 (2013) 262-272

Good agreement between data and theory over many orders of magnitude

Jet cross sections



PRD 91, 112012 (2015)



CMS 13 TeV

Eur. Phys. J. C 76 (2016) 451

ALICE data compared to PYTHIA6, PHOJET, HERWIG at 7 TeV

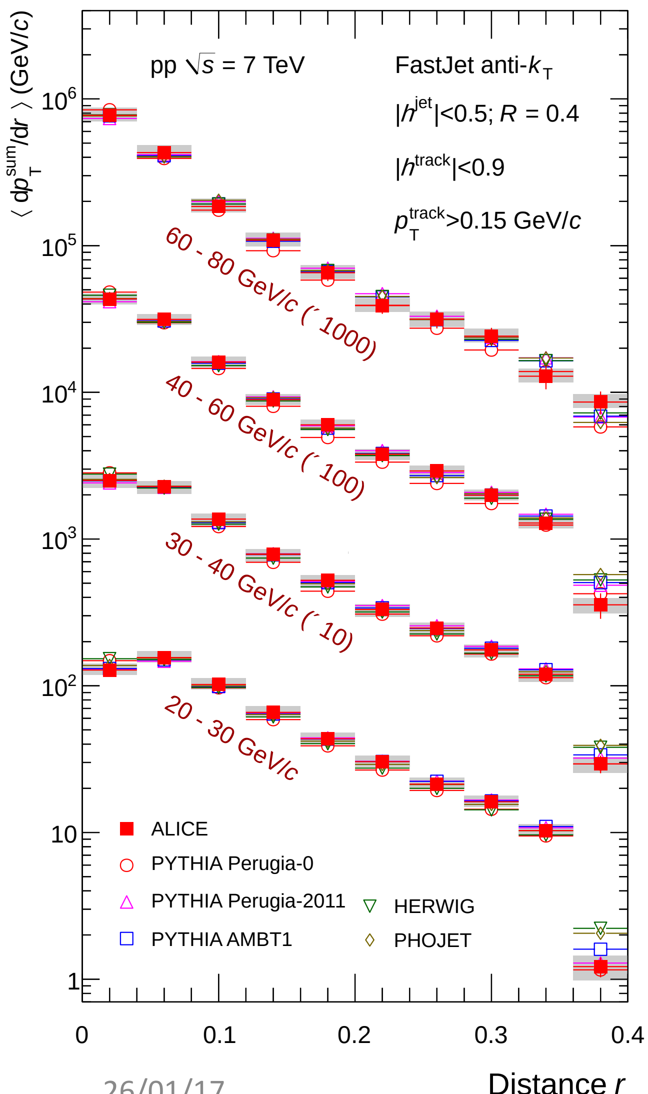
CMS results: Good agreement between CMS data and NLOJet++ prediction at 13 TeV in wide range of p_T and rapidity

Good agreement between data and theory

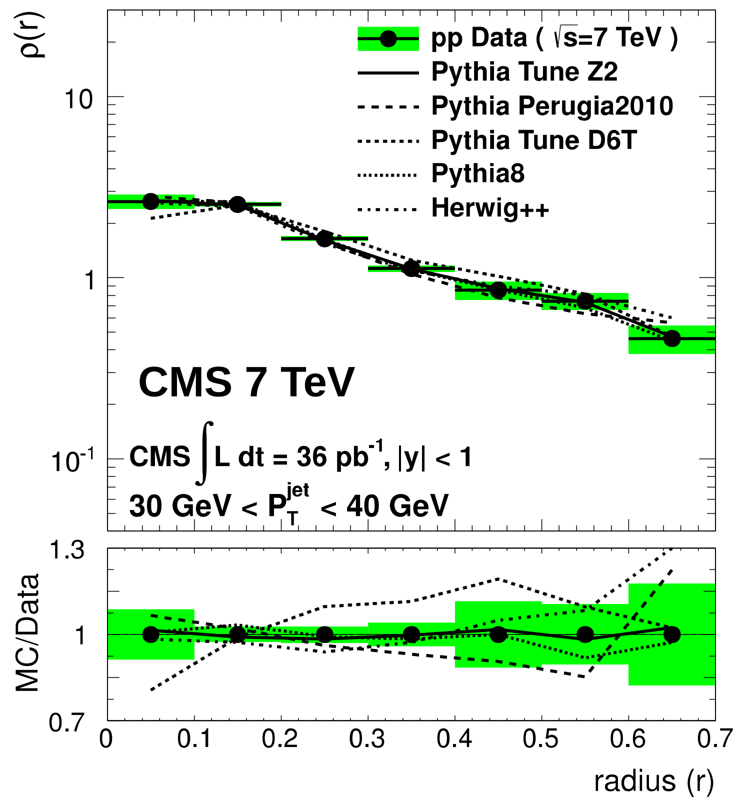
Jet shape (transverse)

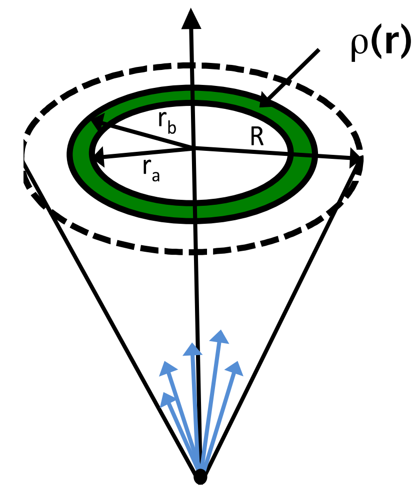
PRD 91, 112012 (2015) (ALICE)

$$\left\langle \frac{dp_T^{sum}}{dr} \right\rangle (r) = \frac{1}{\Delta r}\frac{1}{N_{jets}}\sum_{i=1}^{N_{jets}} p_T(r-\Delta r/2, r+\Delta r/2)$$



ALICE 7 TeV

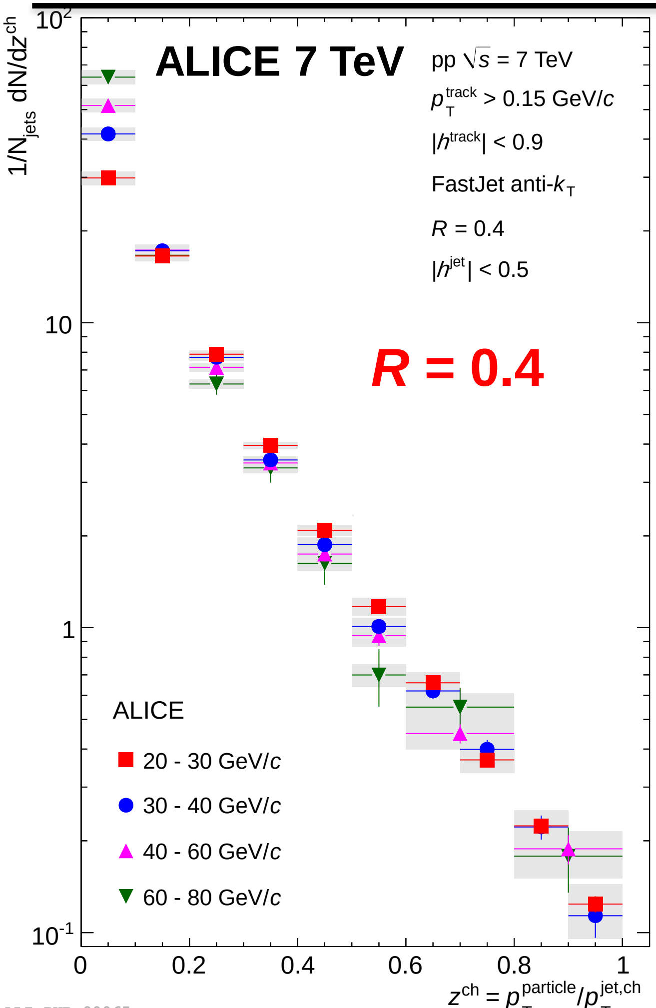




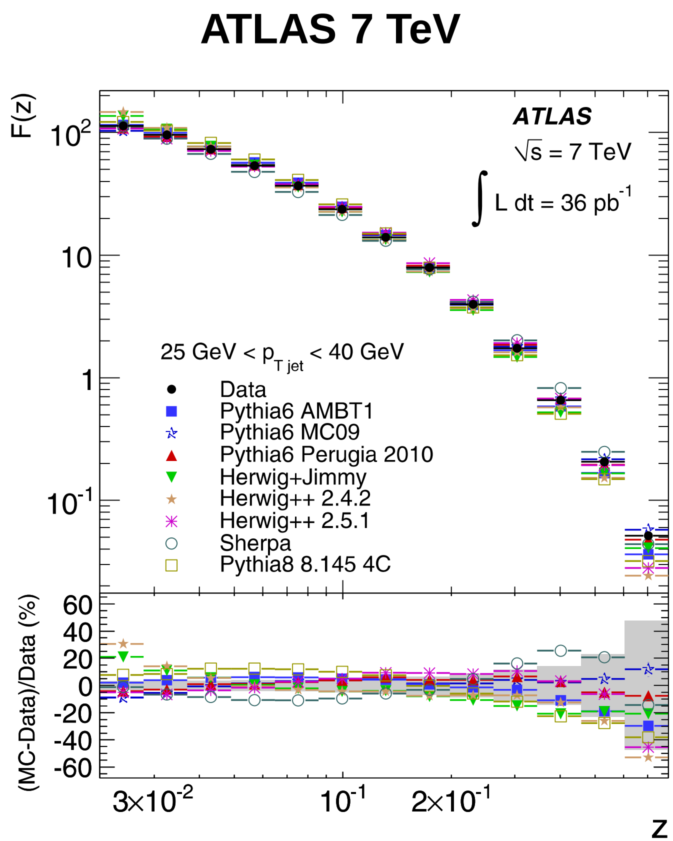
JHEP 06 (2012) 160

- p_T density largest near the jet axis
- High p_T jets more collimated
- Well reproduced by event generators

Jet shape (longitudinal)



PRD 91, 112012 (2015) (ALICE)



Eur. Phys. J. C (2011) 71:1795

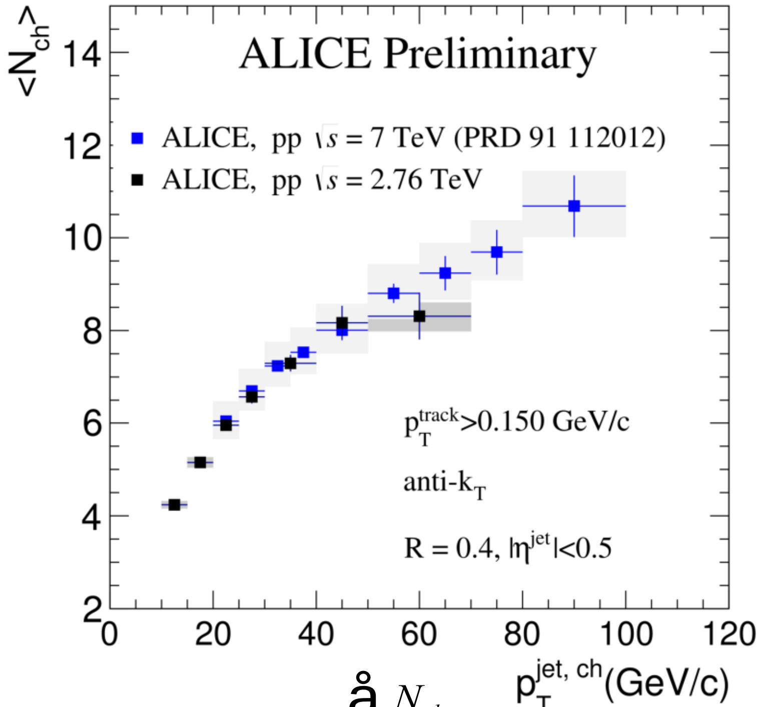
Scaled momentum

$$z^{ch} = p_T^{particle} / p_T^{jet,ch}$$

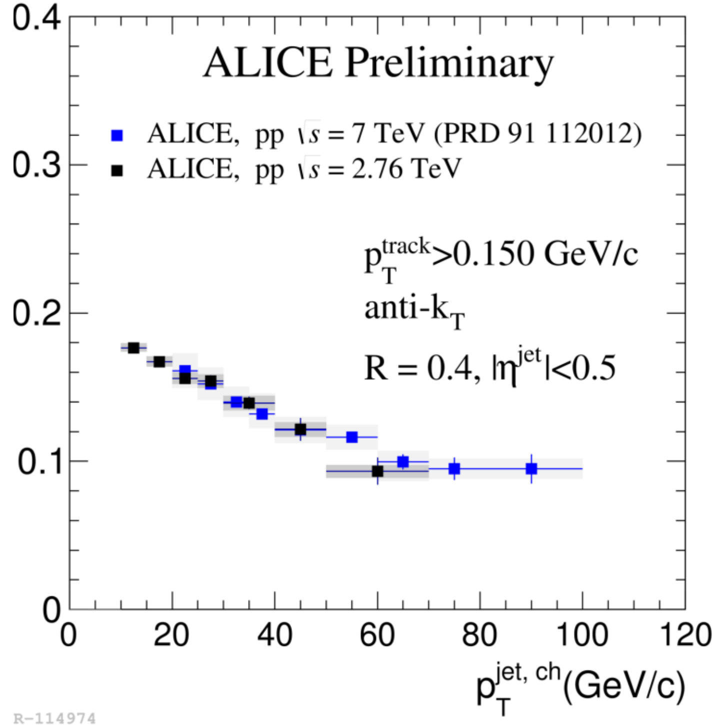
Scaling of charged jet fragmentation with jet p_T for $z^{ch} > 0.1$

Good agreement between data and MC predictions

Jet shape (Transverse): √s dependence



$$\langle N_{ch} \rangle (p_t) = \frac{\sum_{jets} N_{ch}}{N_{jets}}$$



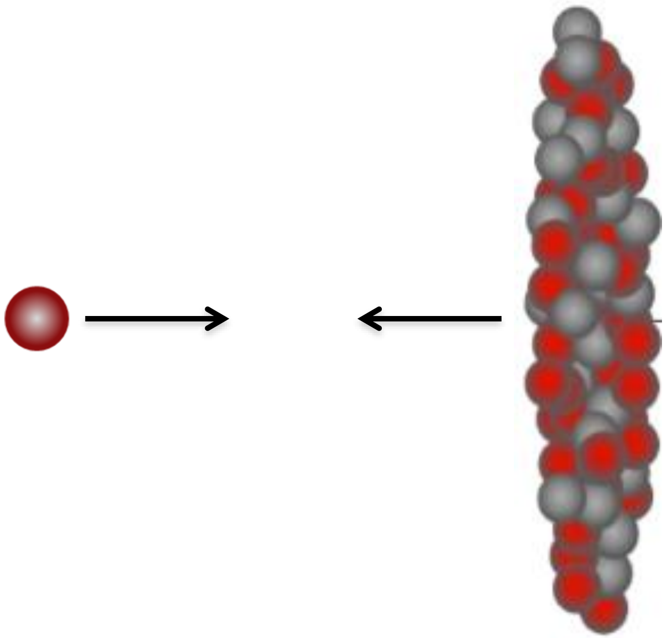
$$\langle R_{80} \rangle (p_t) = \frac{\sum_{jets} R_{80}}{N_{jets}}$$

Talk by Rathijit DAE-BRNS High Energy Physics Symposium, Delhi, 2016

q/g contribution to jets should be √s dependent

Change in observables expected depending upon it's sensitivity to q/g

<N_{ch}> and <R_{80}> found independent of √s

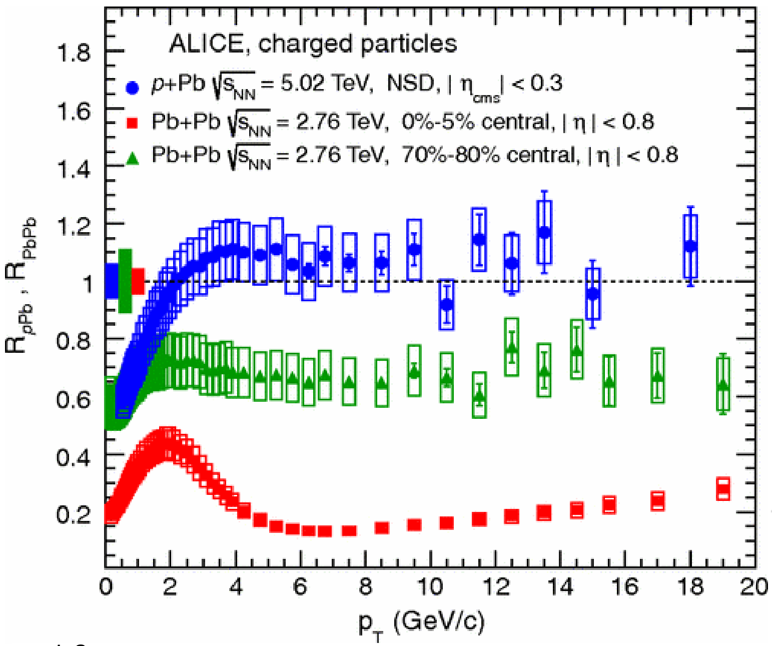


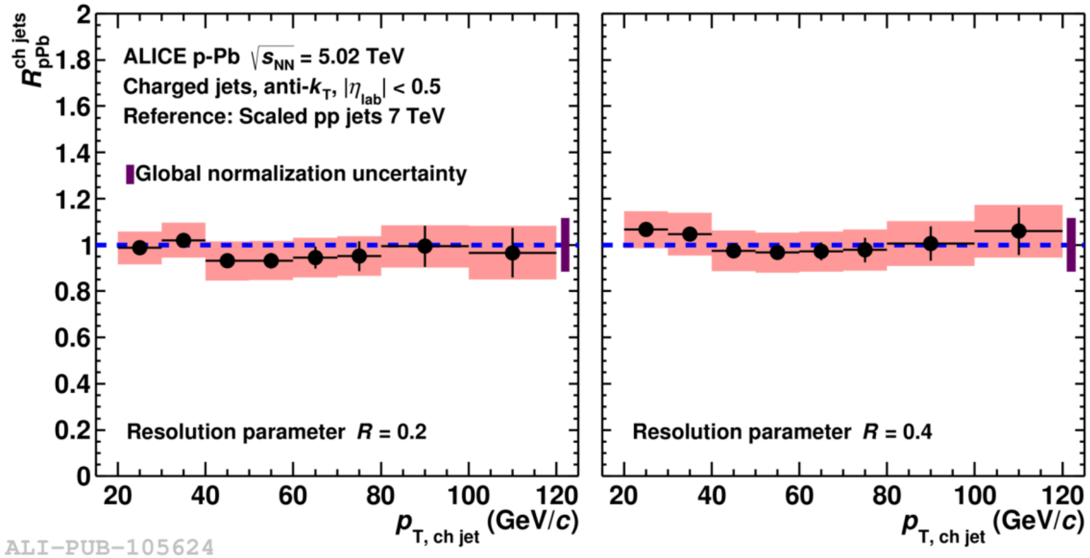
Jets in p-Pb

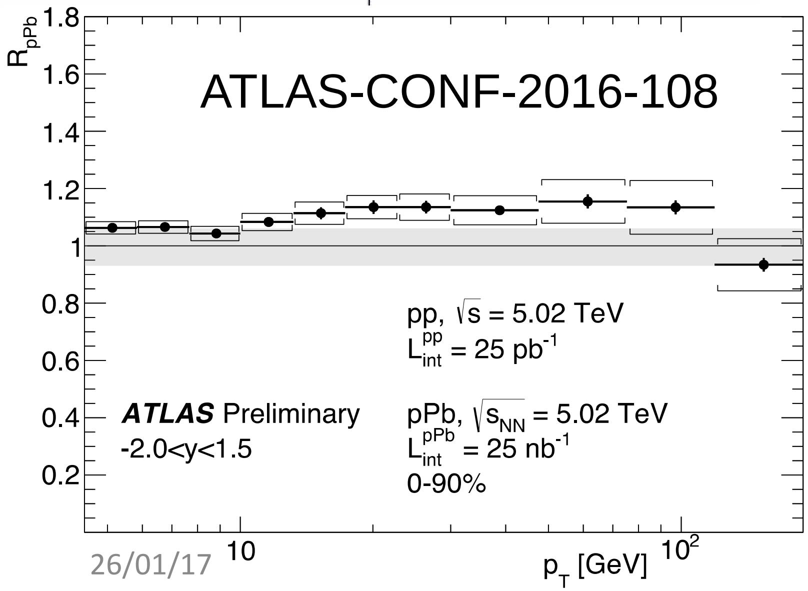
Cold Nuclear Matter Effects

Nuclear Modification Factor

Phys. Rev. Lett. 110, 082302



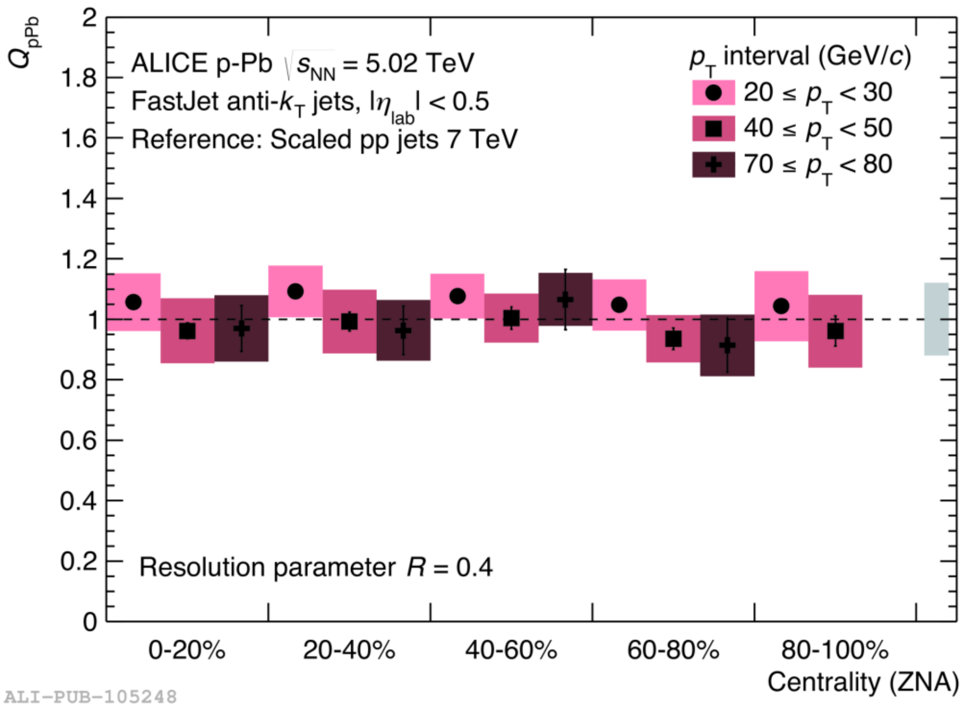


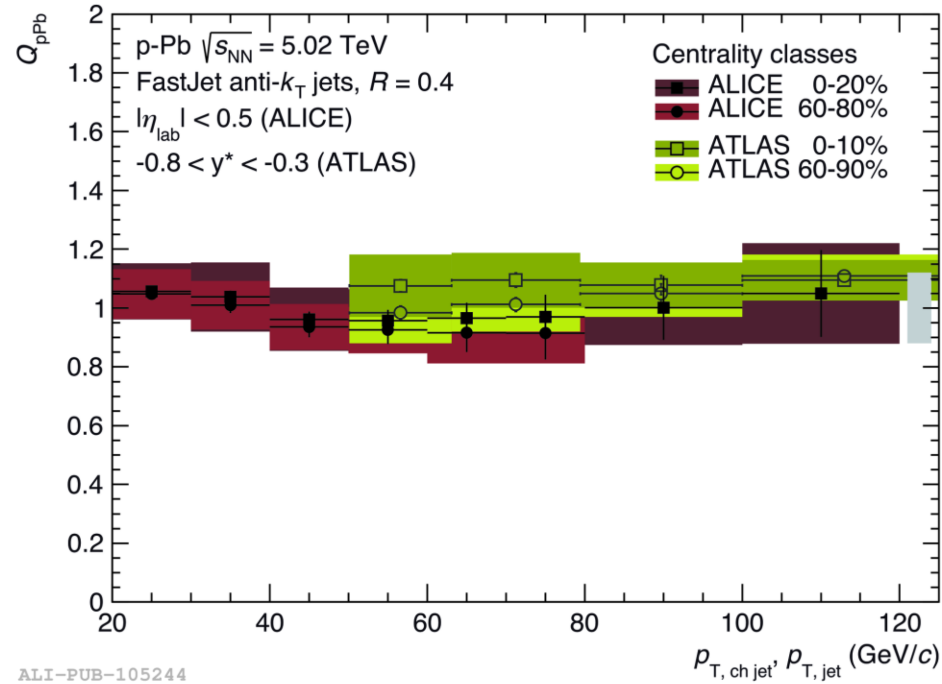


R_{ppb}: consistent with unity for hadrons and jets over wide kinematic range

Good agreement between ALICE and ATLAS

Nuclear Modification Factor





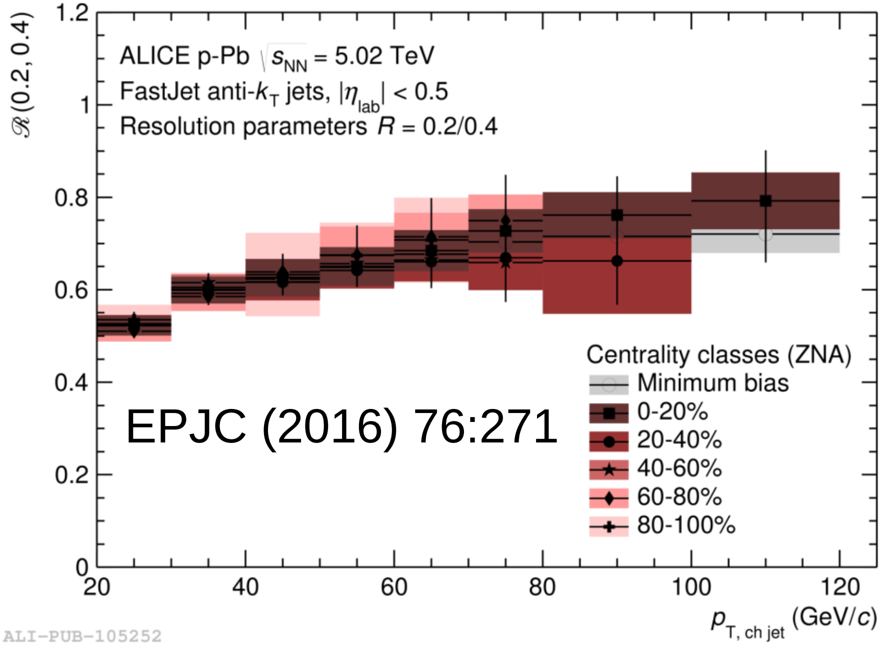
EPJC (2016) 76:271

$Q_{\rm pPb}$ as a function of centrality
Consistent with unity
No centrality dependent
Consistent with ATLAS full jet measurements

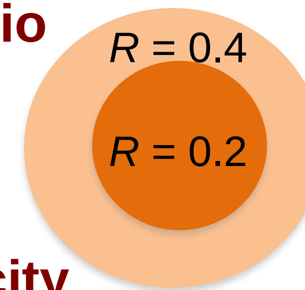
$$Q_{\rm pPb} = \frac{{\rm d}^2 N^c_{\rm pPb}/{\rm d}\eta {\rm d}p_{\rm T}}{\langle N^c_{\rm coll}\rangle \cdot {\rm d}^2 N_{\rm pp}/{\rm d}\eta {\rm d}p_{\rm T}}$$

Indication of absence of any significant final state effects

Jet shape modifications



ALICE: Cross section ratio (R=0.2/R=0.4) show no centrality dependence

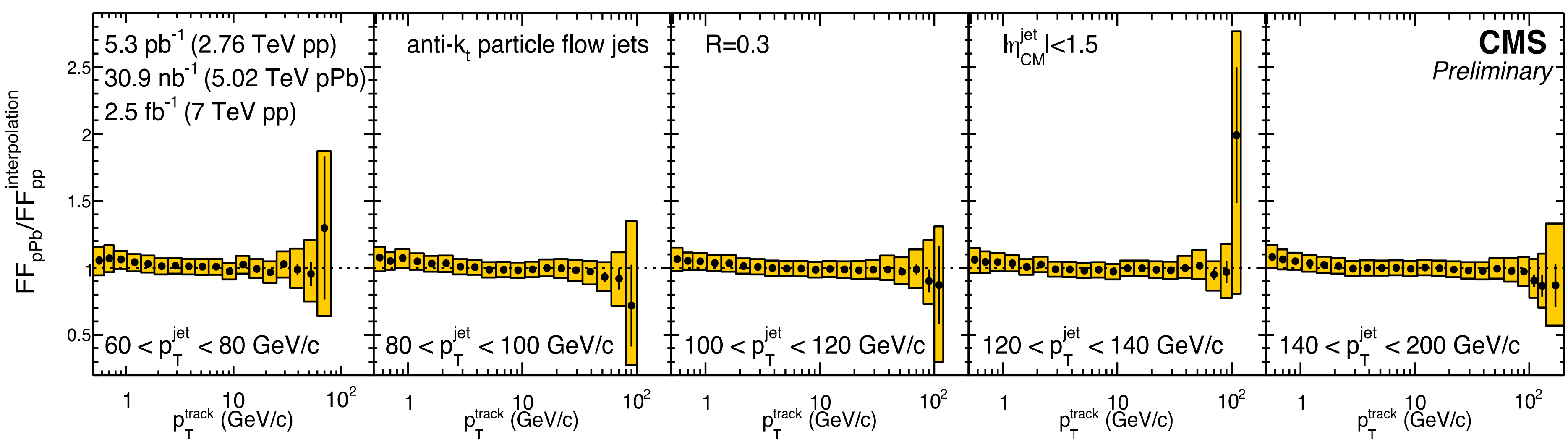


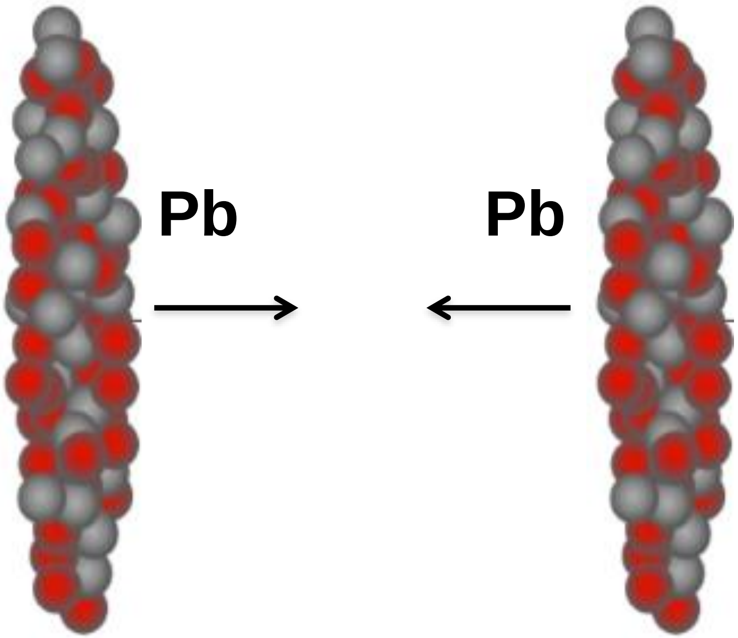
No modification of jet collimation with multiplicity classes in pPb

CMS: Jet FF in pPb found to be consistent with pp

No jet modification in pPb compared to pp

CMS PAS HIN-15-004

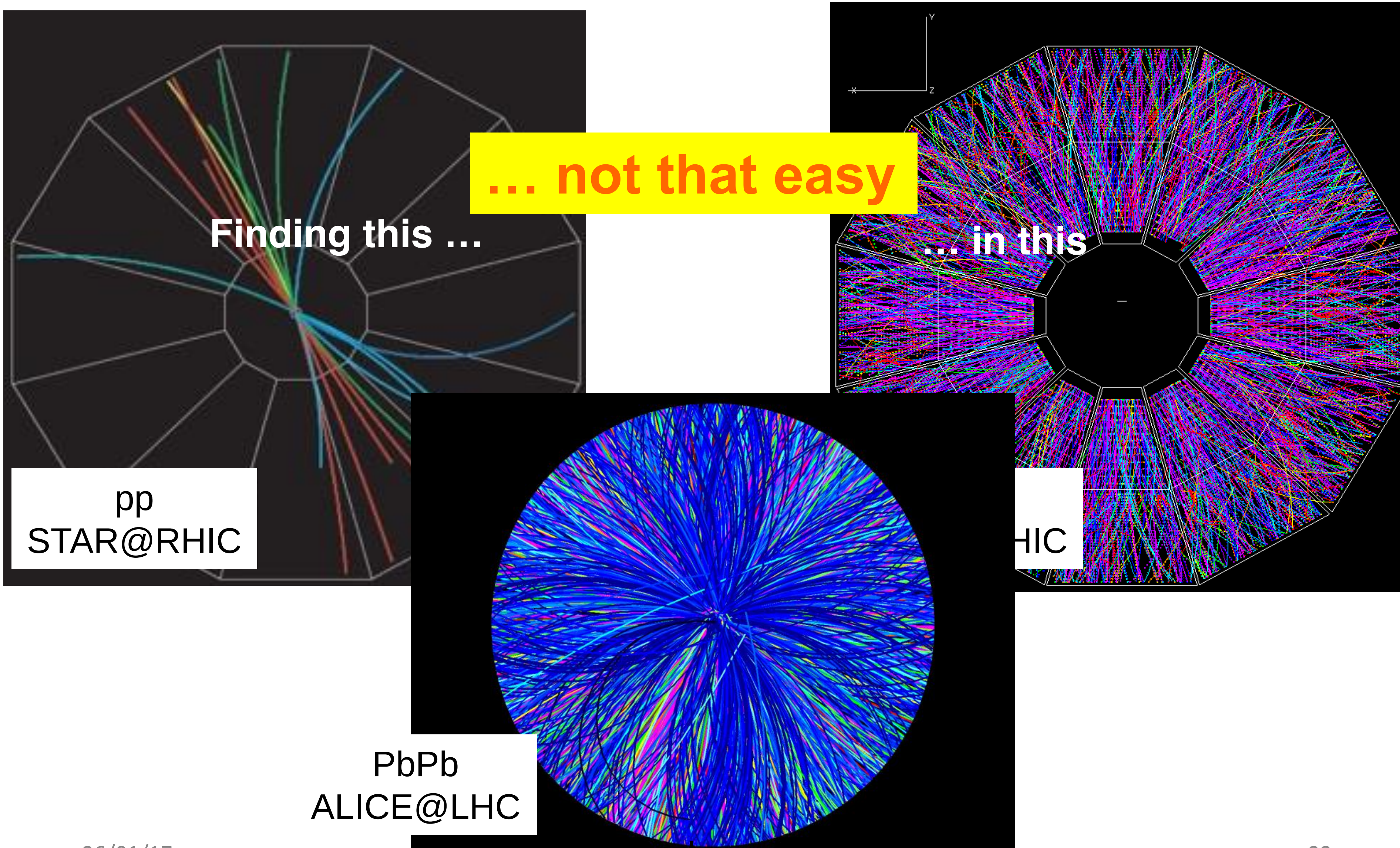




Jets in Pb-Pb

Medium Effects

Experimental challenge in measuring jet in heavy ion collision

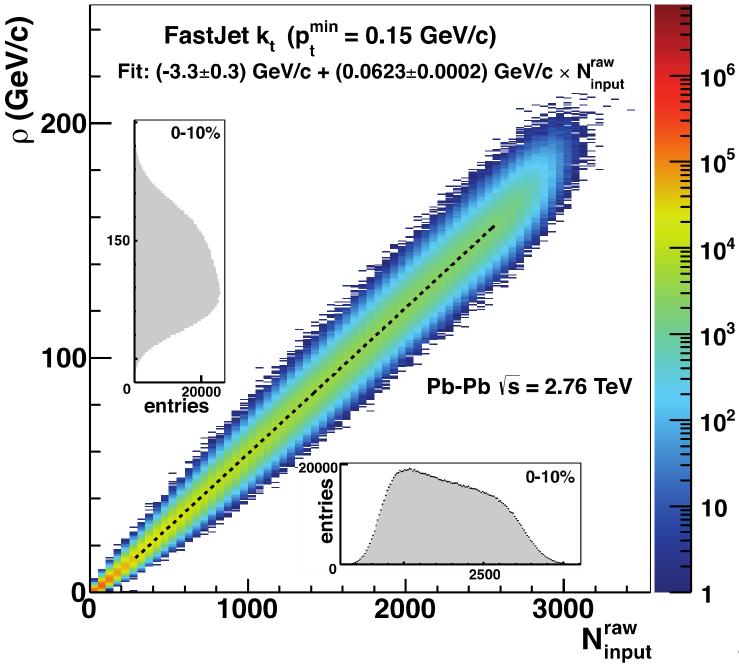


The problem: Underlying event and background

Large background: consisting of particles from soft scattering processes and fragments from other jets

JHEP 1203 (2012) 053 (ALICE)
JHEP 1403 (2014) 013 (ALICE)

Background estimation: determine average background density ρ: median of $\rho_i = p_T^{cluster,i}/A_i$; except the two leading clusters to limit the hard jet signal from the background estimate (corrected ρ = **~155.8 +/- 3.7 GeV/*c***)



p_t^{min} (GeV/c)	$\langle\rho\rangle$ (GeV/c)	$\sigma(\rho)$ (GeV/c)
0-10%		
0.15	138.32 ± 0.02	18.51 ± 0.01
1.00	59.30 ± 0.01	9.27 ± 0.01
2.00	12.28 ± 0.01	3.29 ± 0.01
50-60%		
0.15	12.05 ± 0.01	3.41 ± 0.01
1.00	4.82 ± 0.01	1.77 ± 0.01
2.00	4.41 ± 0.05	0.92 ± 0.04

Background correction:

$$p_{T,jet} = p_{T,jet}^{raw} - r A$$

Jet area

(Background subtracted)

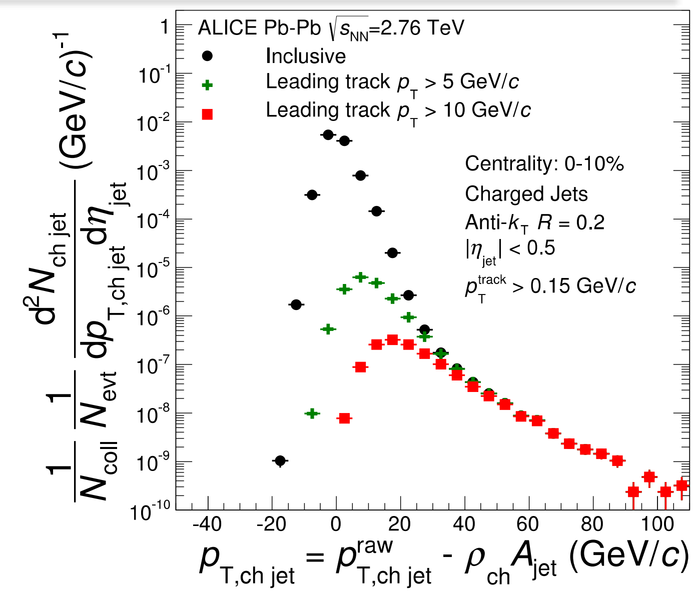
Avg. background density

The problem: Background fluctuations

Background fluctuations: due to statistical fluctuations of the particle number and momentum, elliptic flow, etc.

Background subtraction removes background on an average.

Due to fluctuations low p_T jet might appear as high p_T jet (Combinatorial jets)

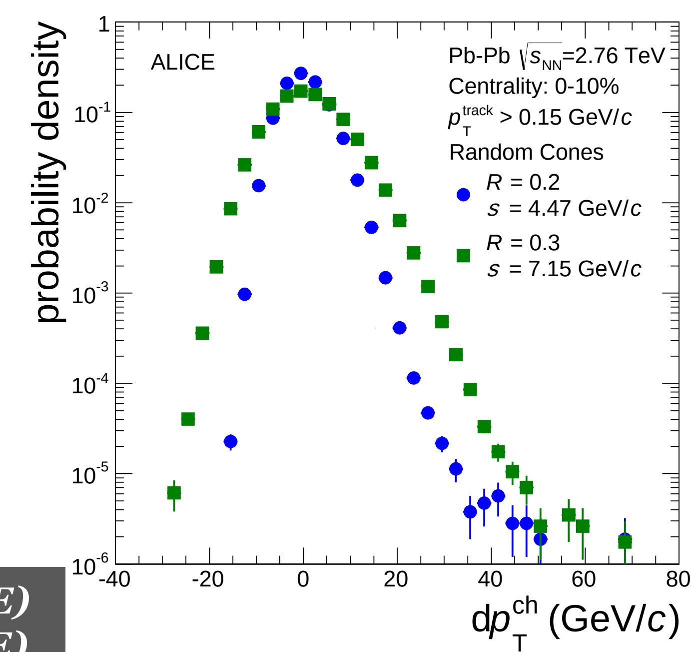


Background fluctuation correction: using unfolding

Quantifying Background fluctuation:

$$dp_T^{ch} = p_{T,ch,jet}^{raw} - \rho_{ch}A - p_T^{probe}$$ Embedding

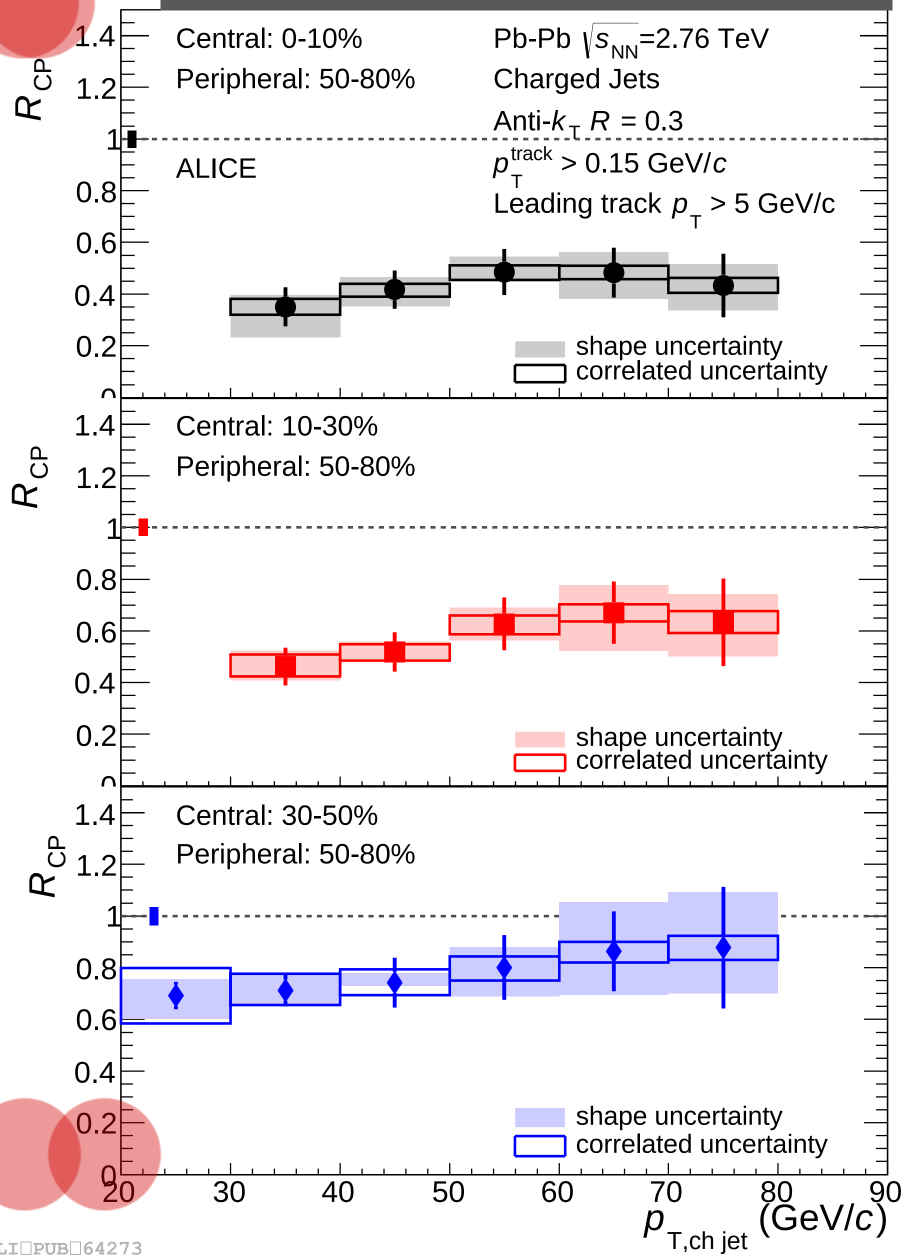
$$dp_T^{ch} = \sum_i^{RC} p_{T,i} - \rho_{ch}A$$ Using random cones

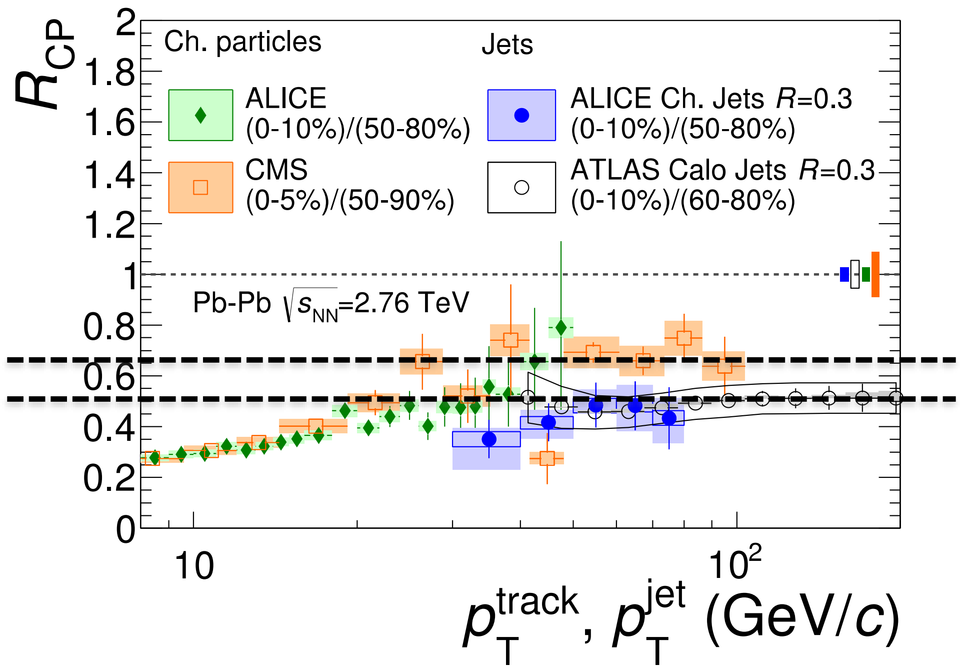


JHEP 1203 (2012) 053 (ALICE)
JHEP 1403 (2014) 013 (ALICE)

Nuclear Modification Factor (PbPb 2.76 TeV)

JHEP 1403 (2014) 013 (ALICE)





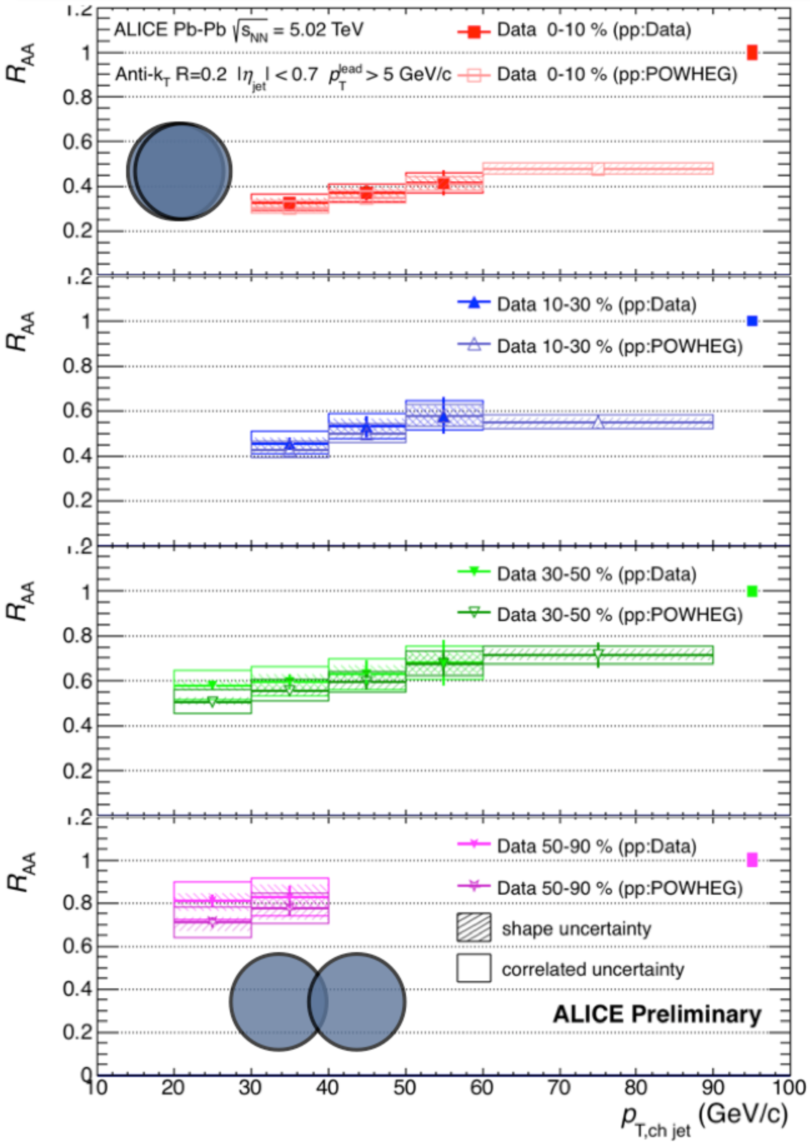
Large jet suppression

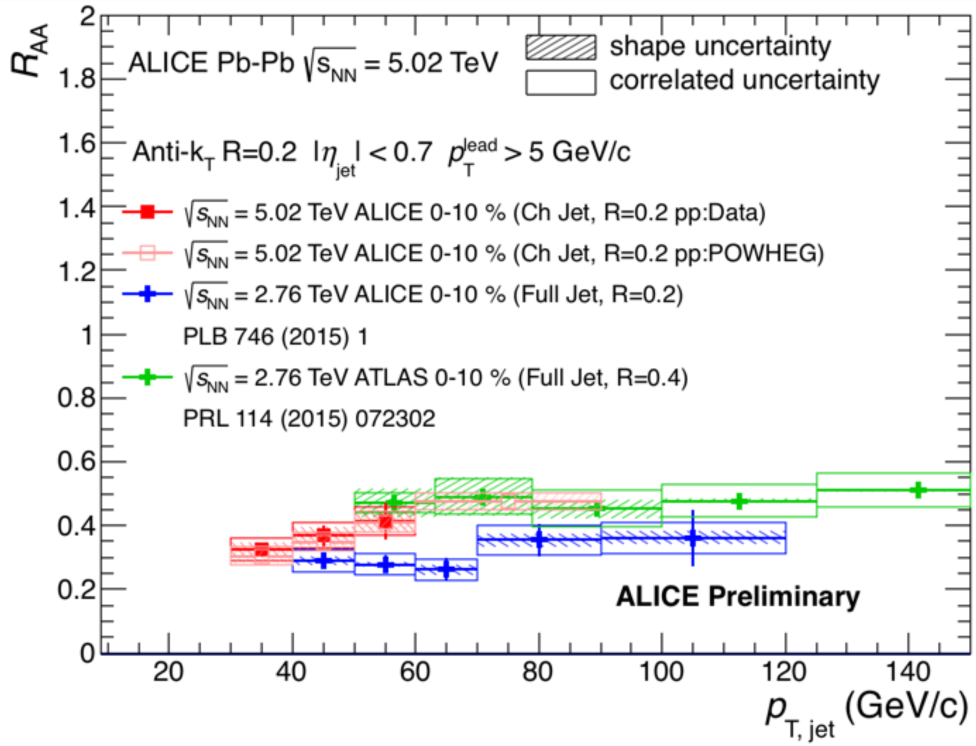
Centrality and mild p_T dependence

R_{cp} for Hadrons and Jets are in agreement

ATLAS and ALICE in agreement

Nuclear Modification Factor (PbPb 5.02 TeV)





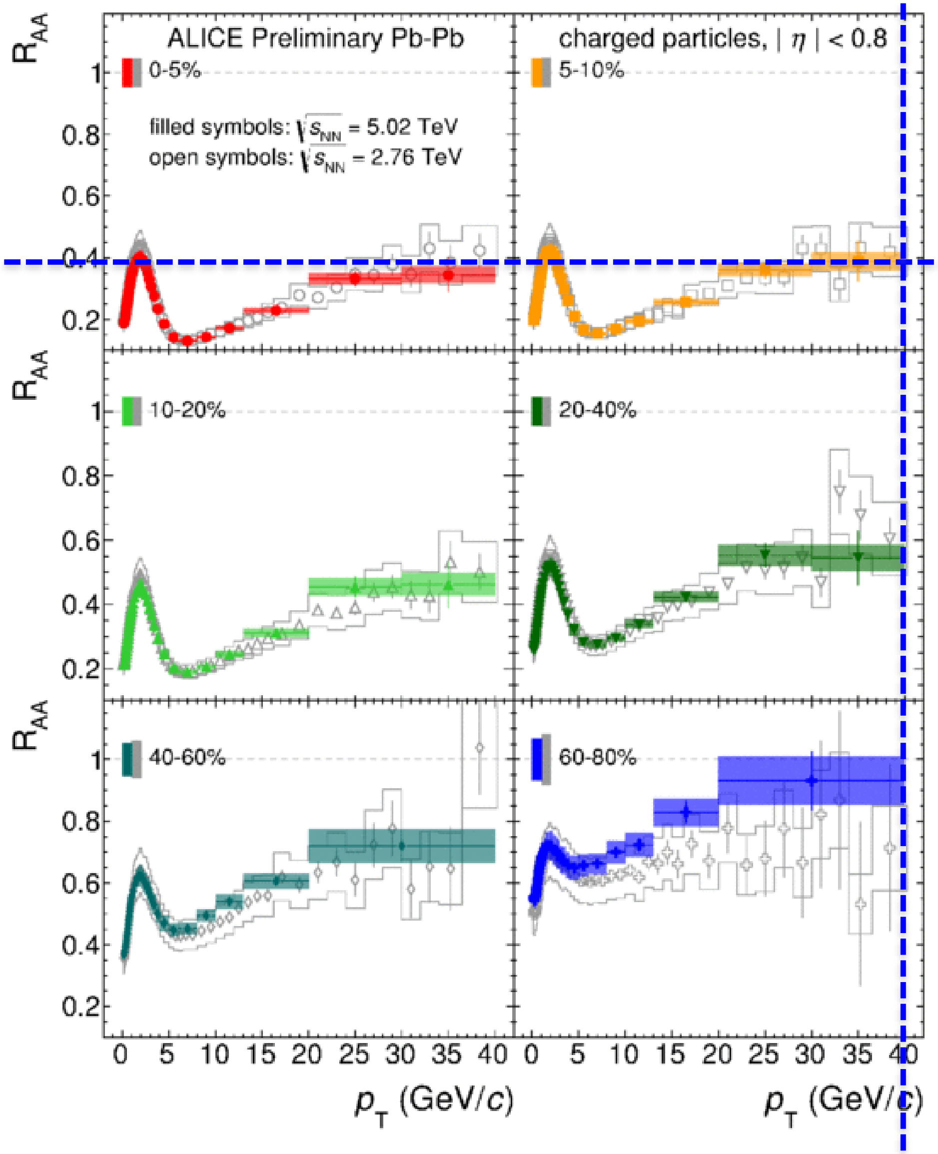
First results on jet R_{AA} at 5.02 TeV

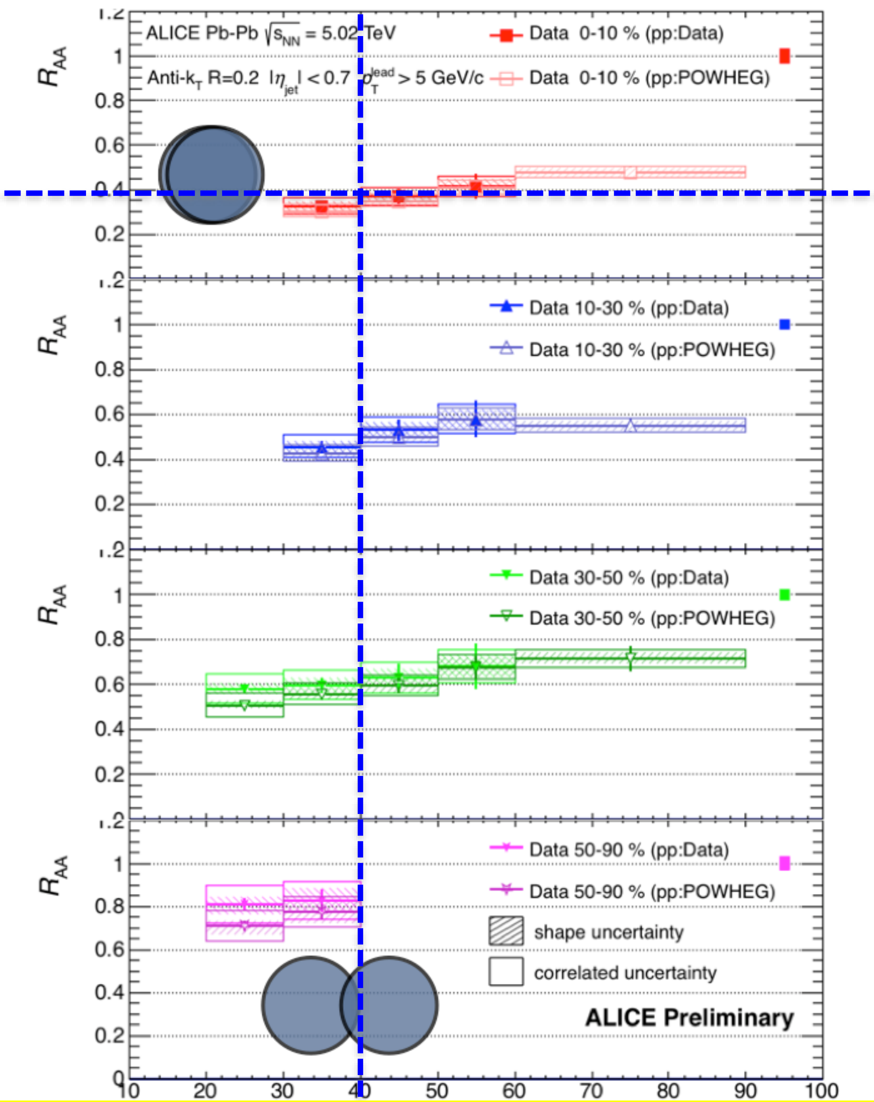
Large jet suppression

Similar jet R_{AA} at 2.76 and 5.02 TeV

ALICE Talk by H. Yokoyama (HP 2016)

Nuclear Modification Factor: Hadron vs Jets





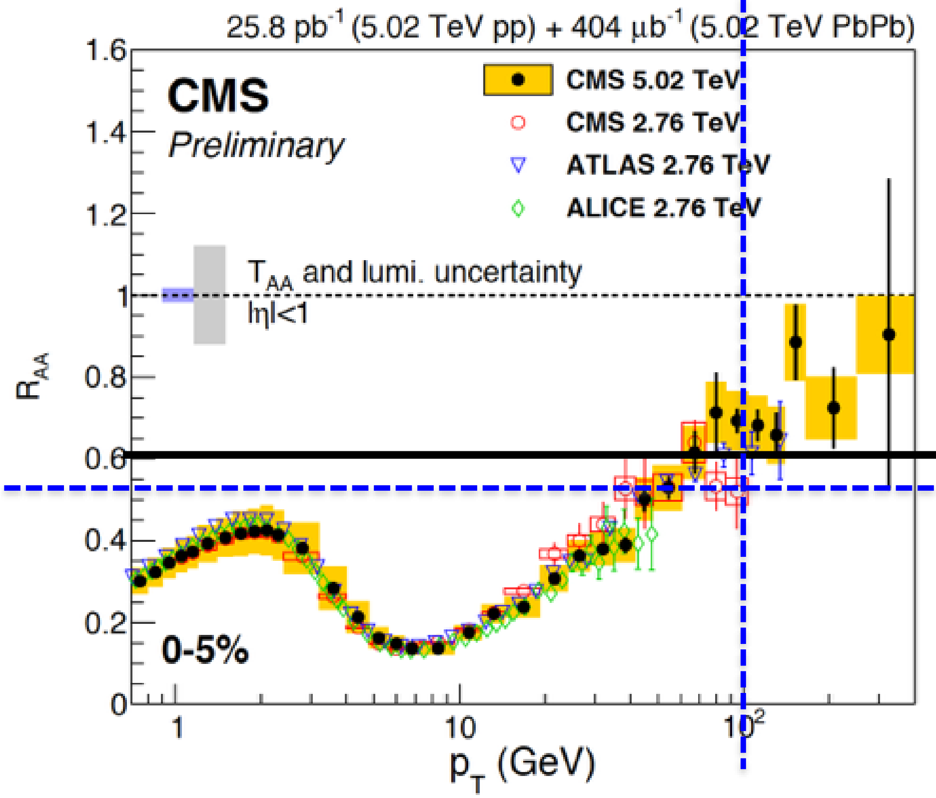
ALICE Talk by M. L. Knic

Indication of similar hadron and jet R_{AA} at 5.02 TeV

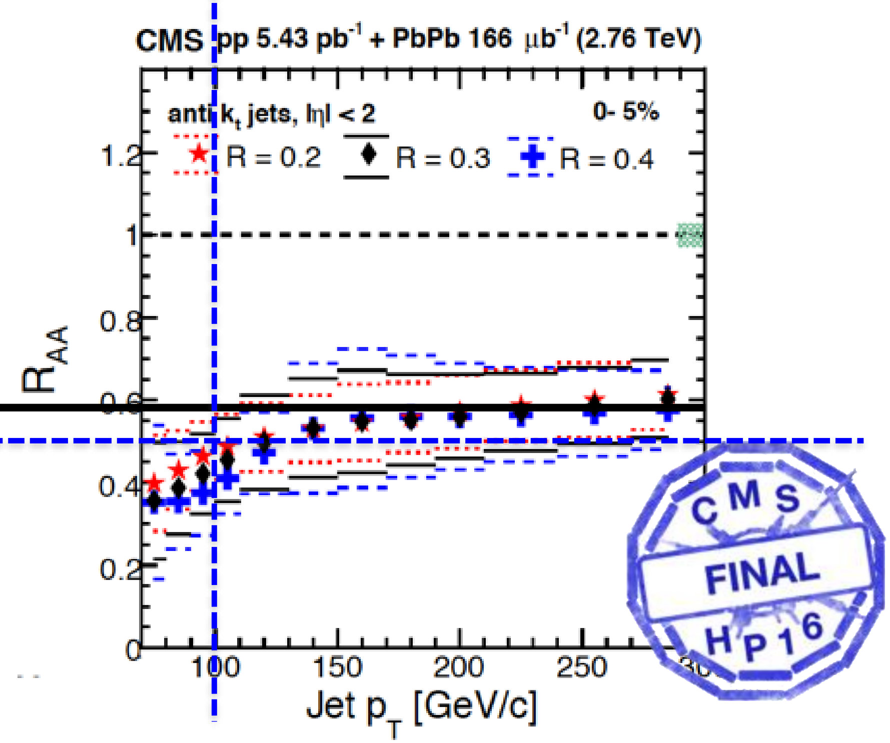
Nuclear Modification Factor: Hadron vs Jets

arXiv:1609.05383

2.76 and 5 TeV charged hadrons



2.76 TeV jets



- Charged hadrons at high p_T →hard fragmenting high p_T jets

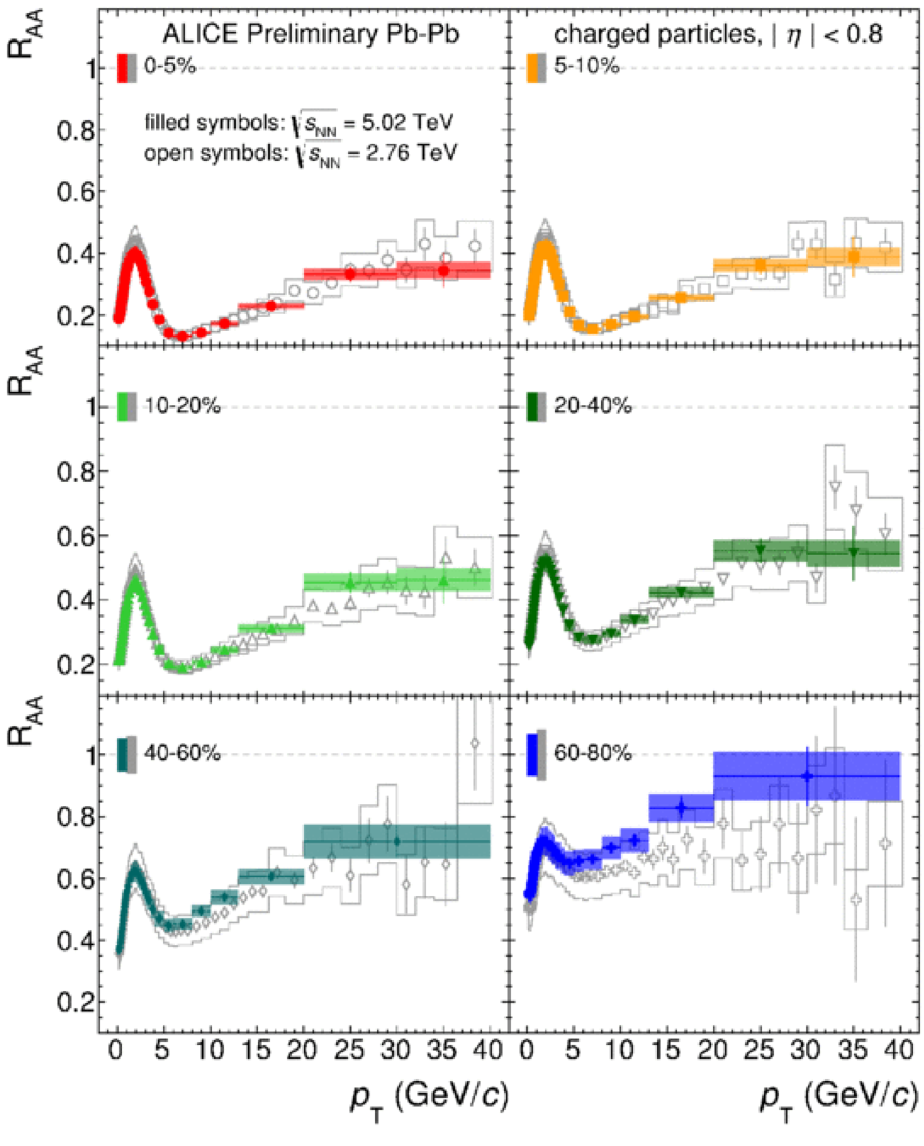
Center of mass energy is different but change is expected to be small

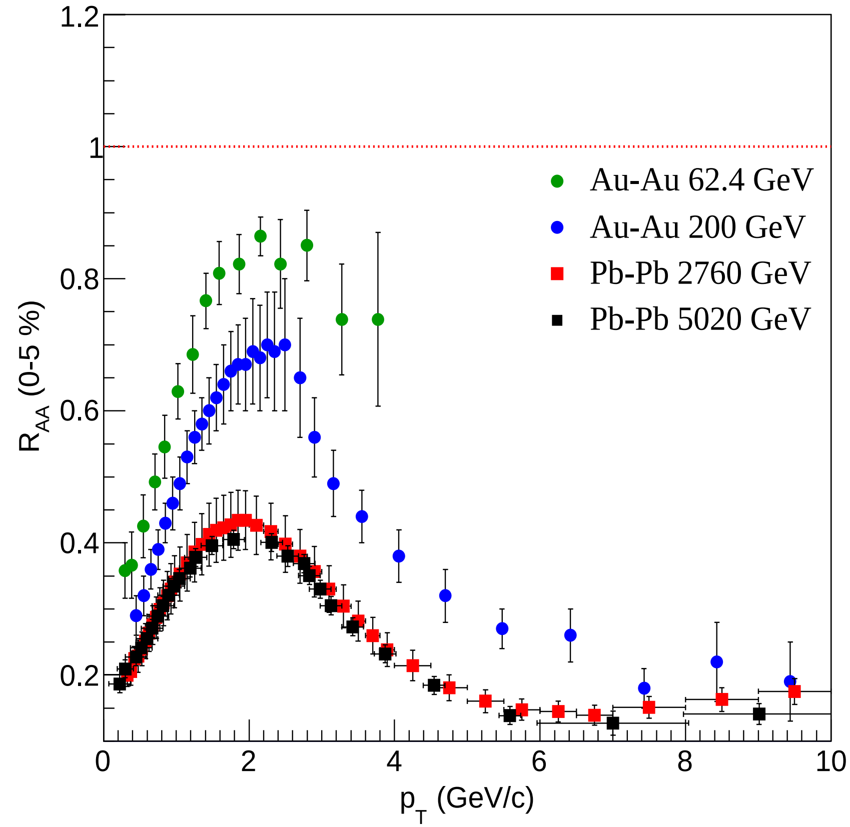
High p_T tracks are less suppressed than jets

Slide from CMS Talk by Doga Gulhan (HP 2016)

Indication of similar hadron and jet R_{AA} at 2.76 TeV

Nuclear Modification Factor: √s dependence

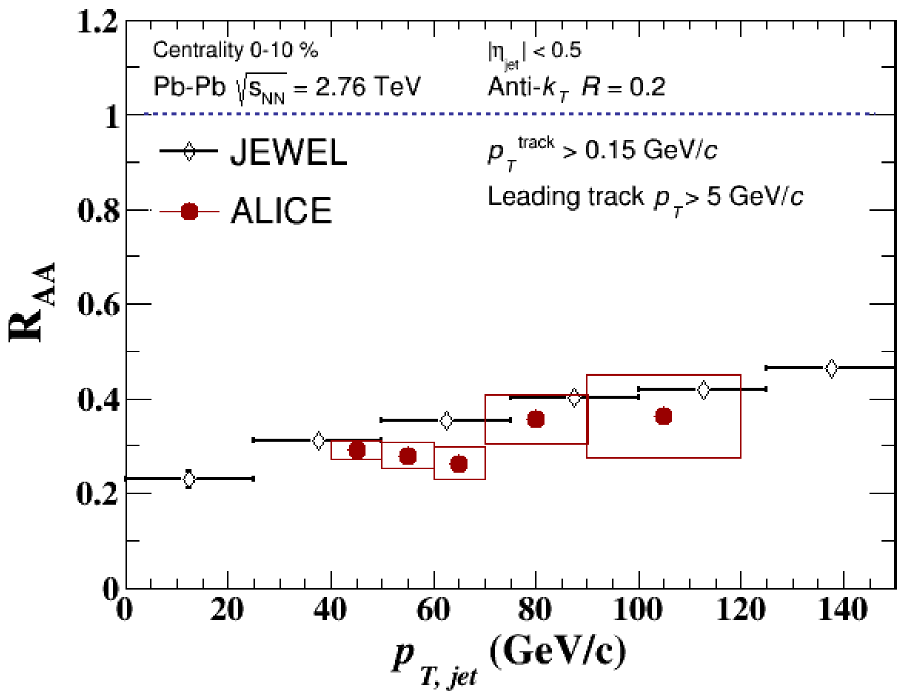


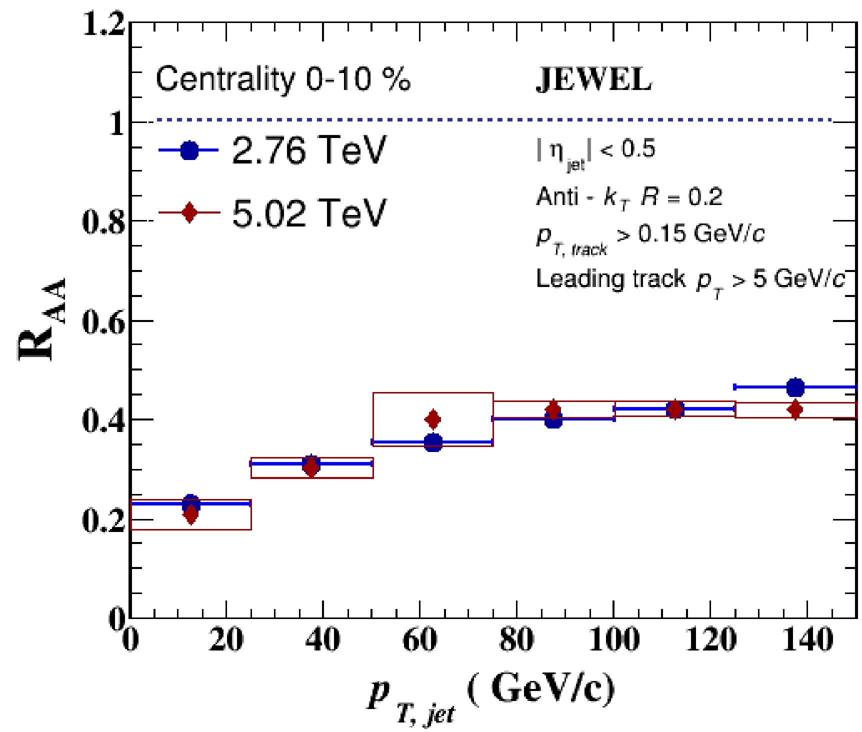


Similar hadron R_{AA} at 2.76 and 5.02 TeV Pb—Pb collisions !!

Nuclear Modification Factor: √s dependence

Subikash, Rathijit DAE-BRNS High Energy Physics Symposium, Delhi, 2016

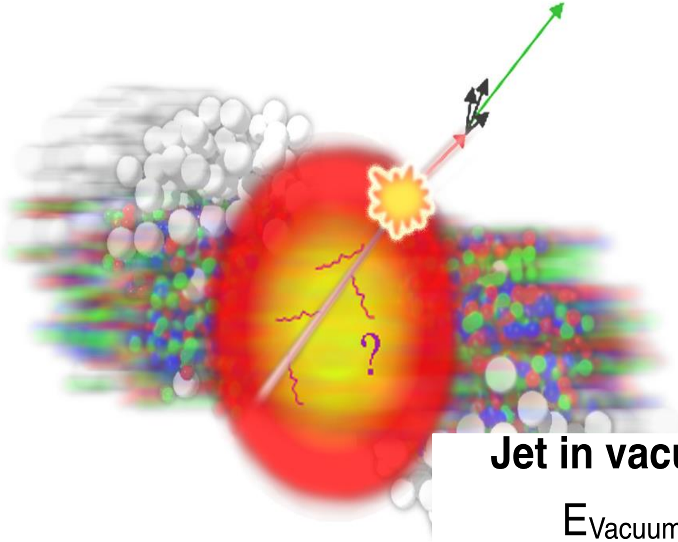




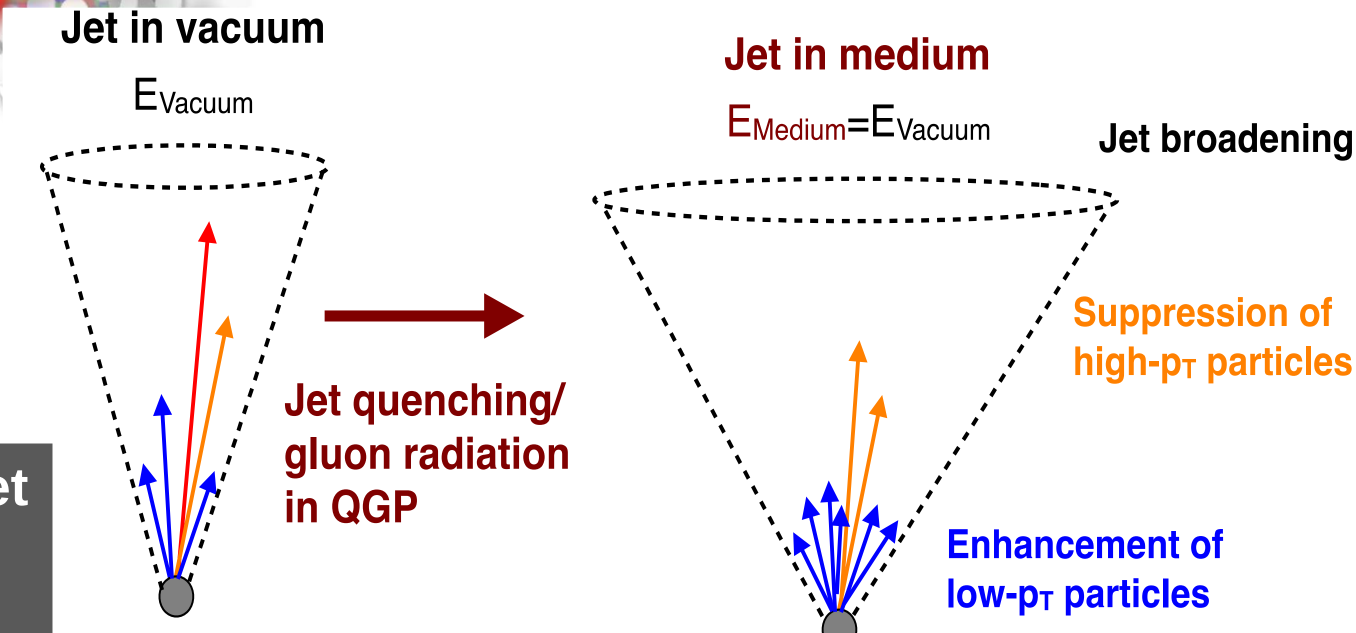
JEWEL can qualitatively reproduce the pattern

Jet Evolution With Energy Loss (JEWEL):
K. C. Zapp, J. Stachel, F. Krauss and U. A. Wiedemann

Jet: Probing the medium



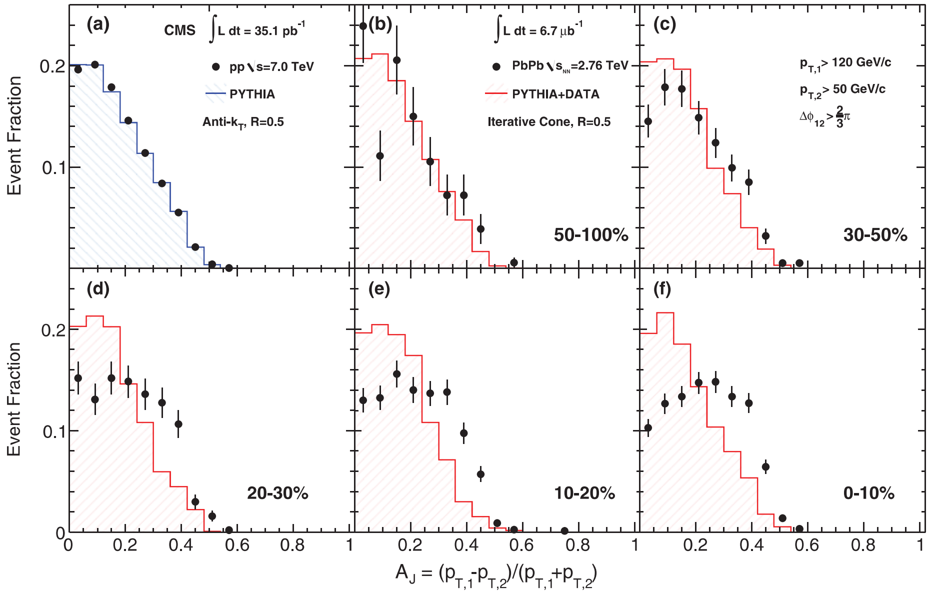
How is the energy redistributed around the jet ?



Modification in jet fragmentation and jet structure

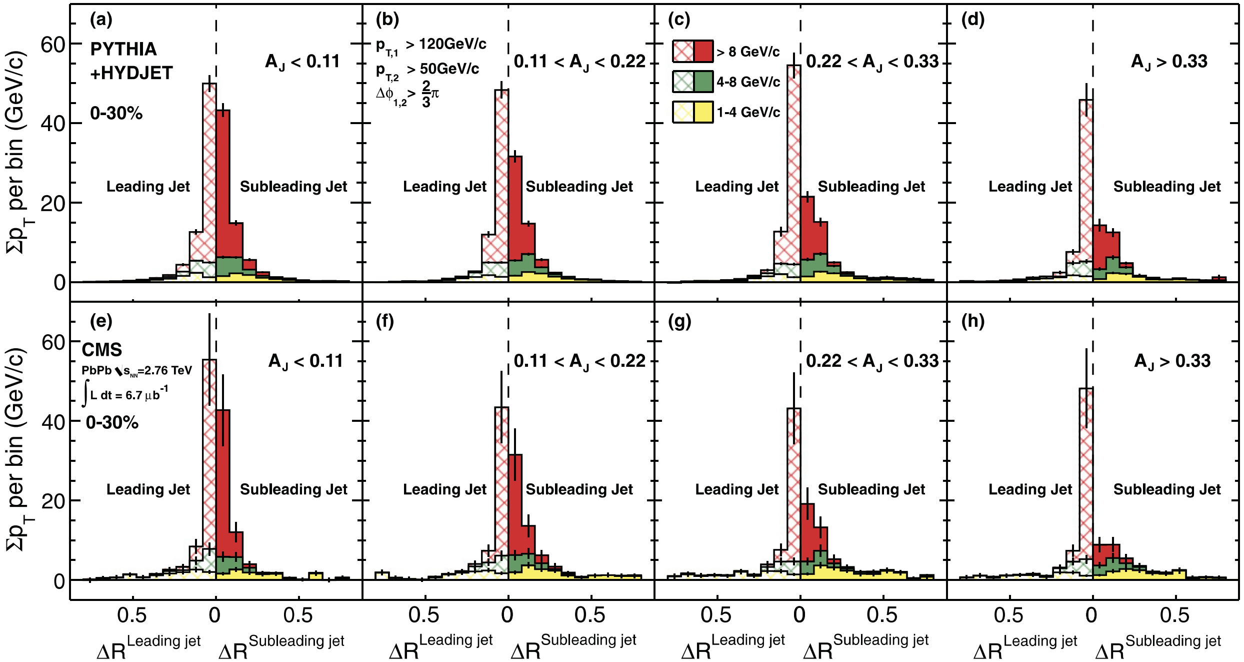
Jet in medium: Multiple gluon radiation in presence of dense medium

Dijet Asymmetry (Momentum Imbalance)



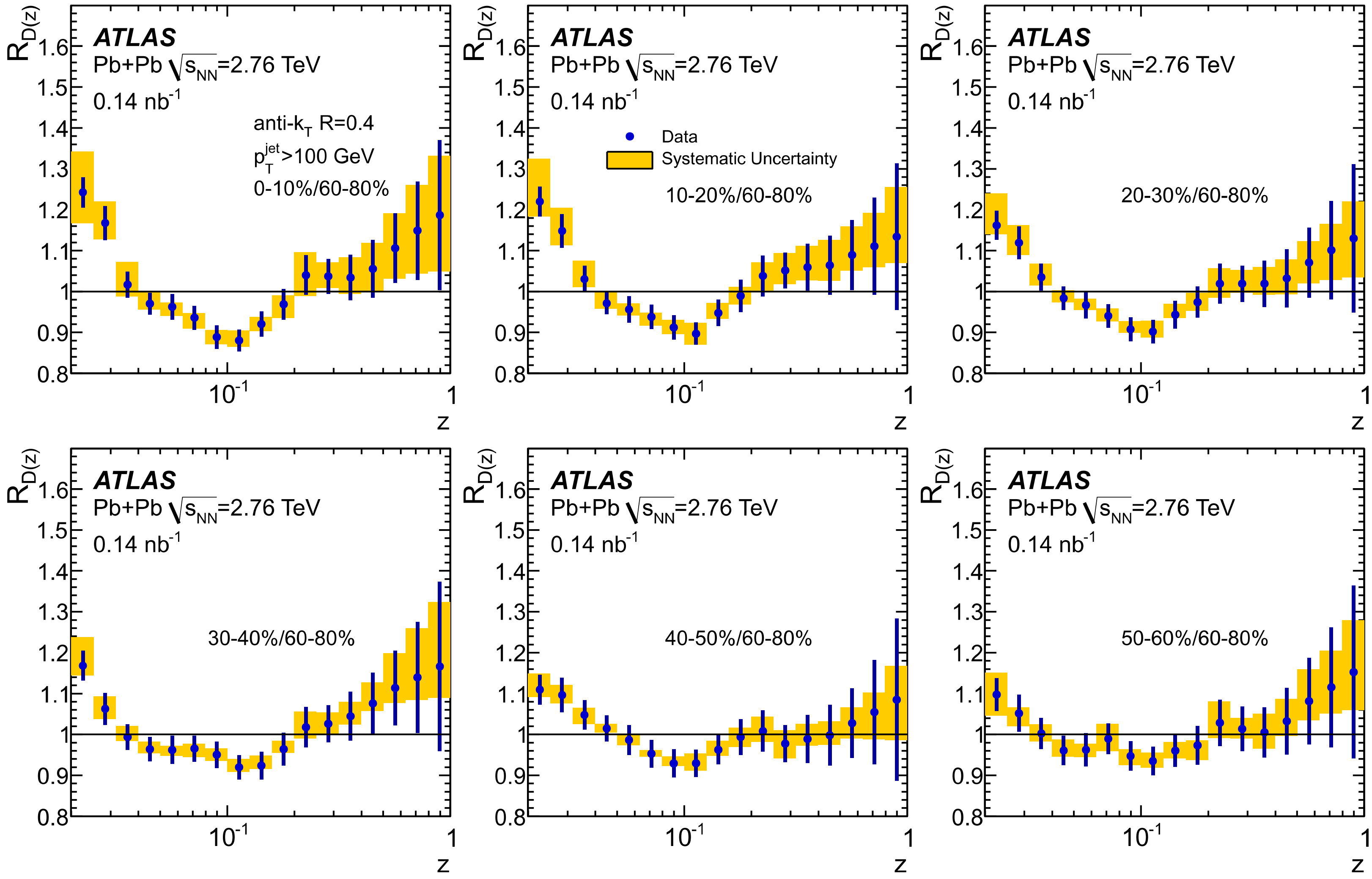
CMS PRC 84 024906

A_j increases with centrality



The quenched energy manifest itself in terms of low and intermediate p_T particles appearing at larger jet cone.

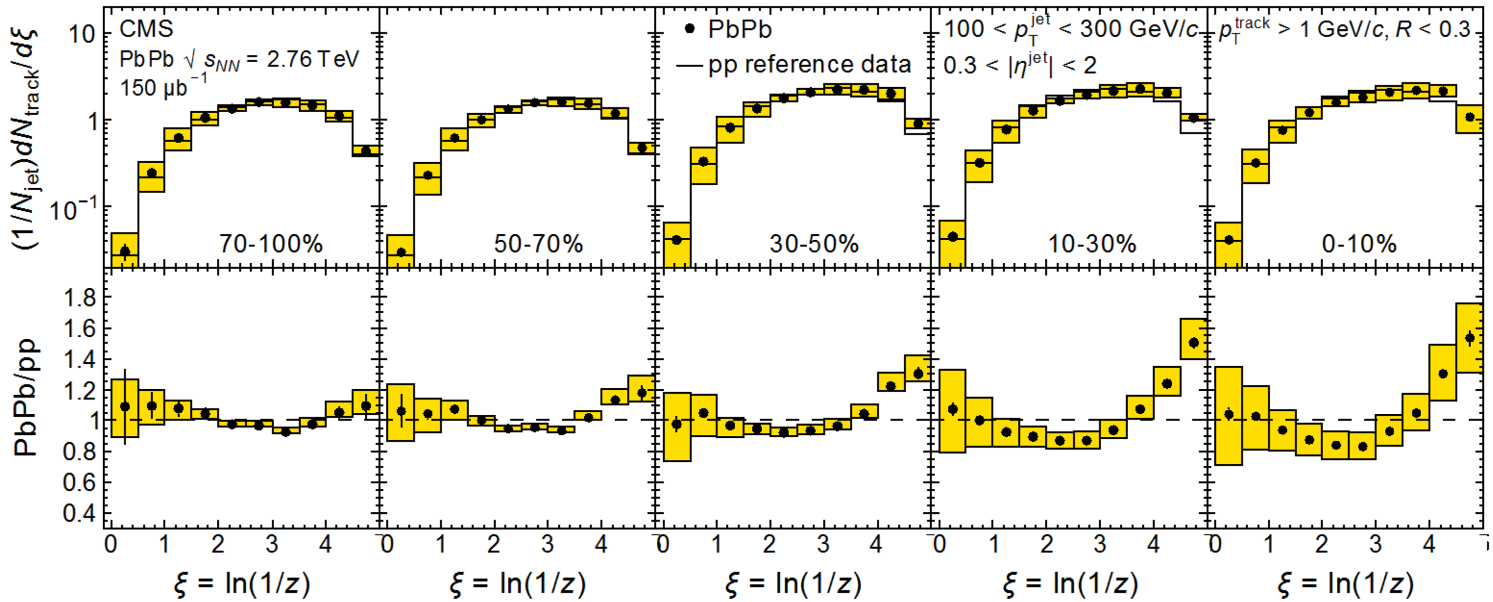
Jet Fragmentation: pp vs PbPb (ATLAS)

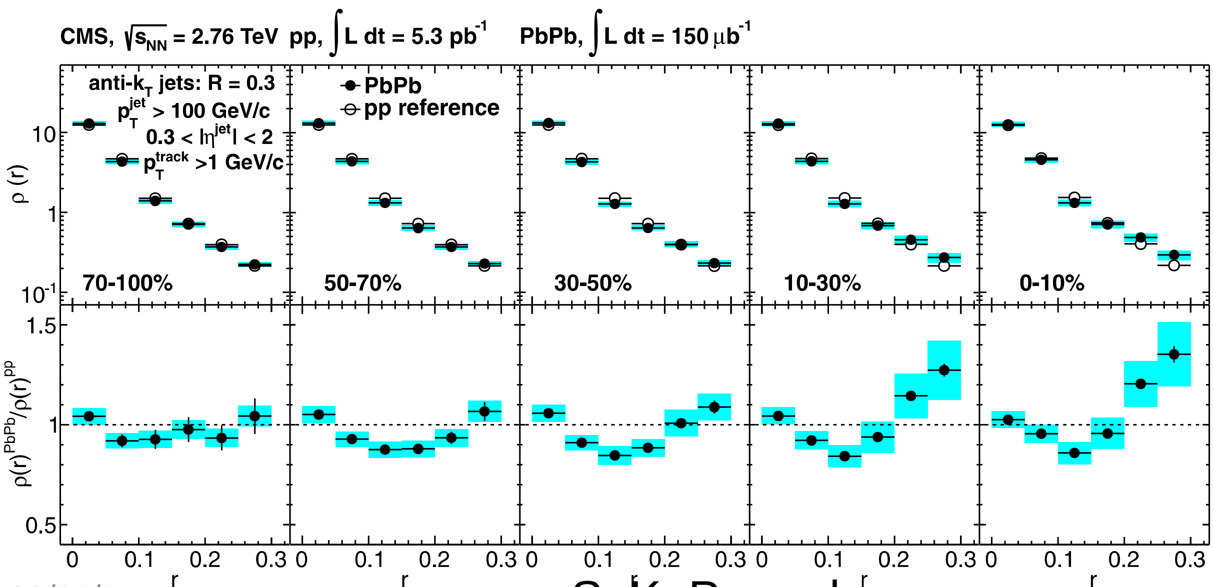


The quenched energy manifest itself in terms of low and intermediate p_T particles appearing at larger jet cone – enhancement observed at low p_T region.

ATLAS PLB 739 (2014) 320-342

Jet Fragmentation: pp vs PbPb (CMS)





CMS PRC 90 024908

CMS PLB 730 243-263 (2014)

Similar observations from CMS

Jet Shape: pp vs PbPb (ALICE)

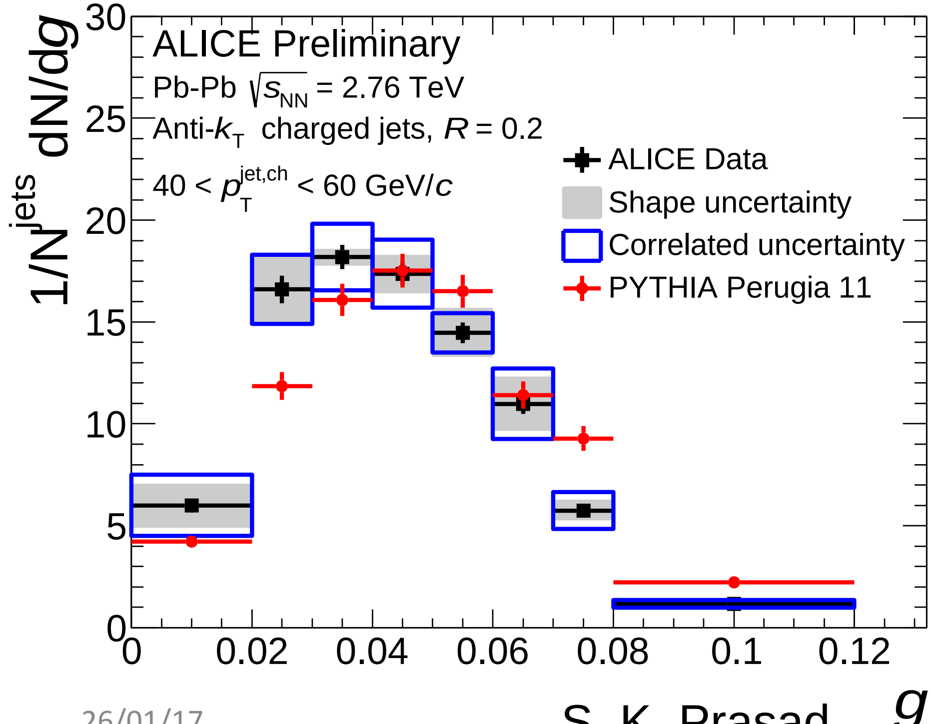
$$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{jet}} |r_i|$$

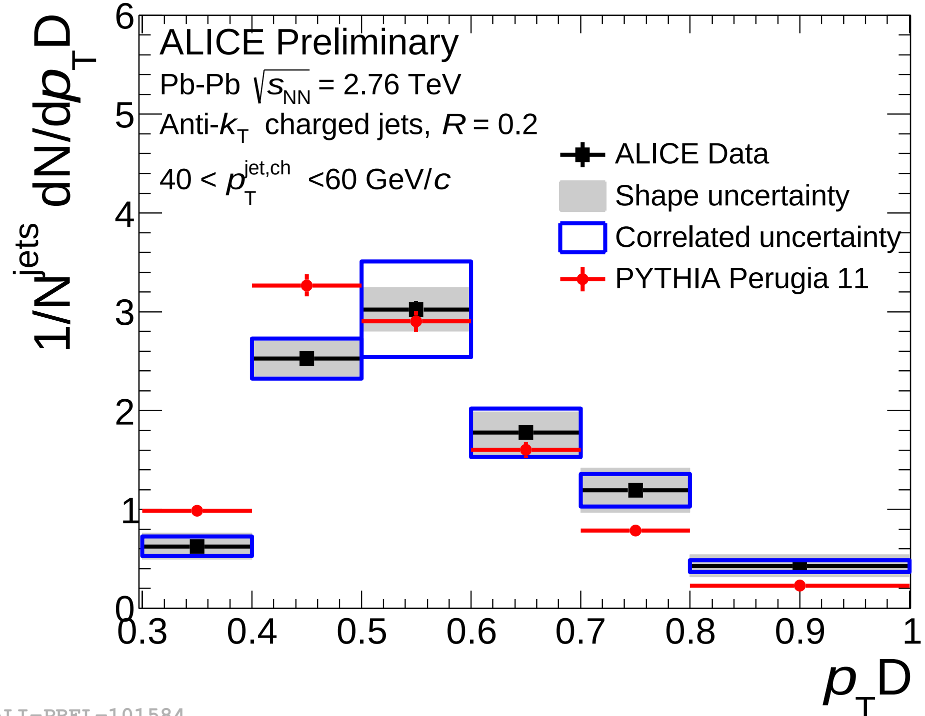
r_i is distance beween Consituent and jet axis

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

g – Radial moment (p_T-weighted width of the jet)
- small/large for collimated/broader jets

$p_T D$ – dispersion of the constituents of the jet
- small/large for more/less constituents





ALICE Nucl. Phys. A 956 (2016) 593-596

Jet Shape: pp vs PbPb (ALICE)

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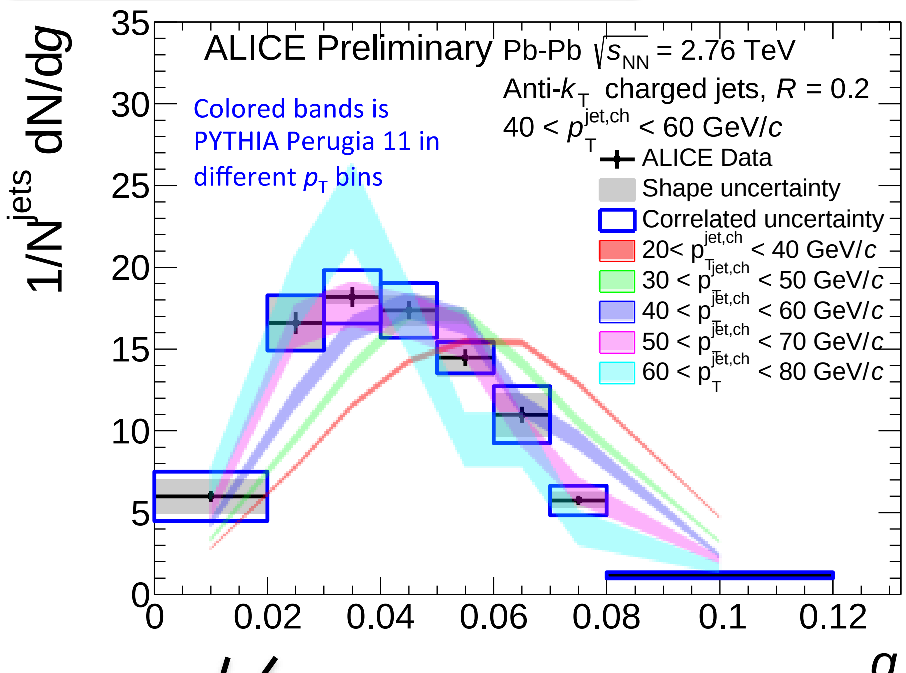

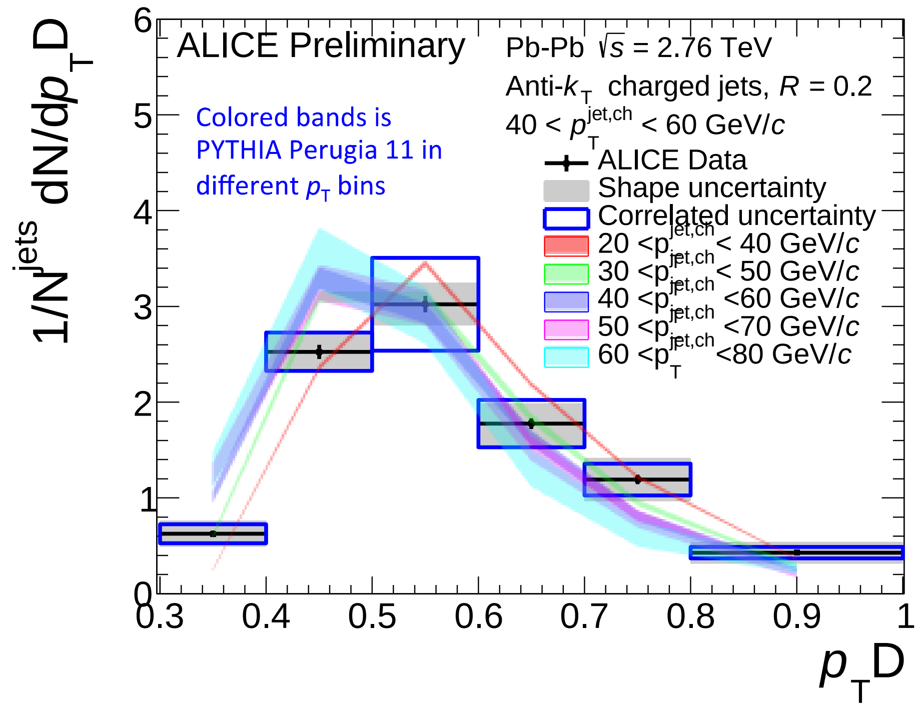

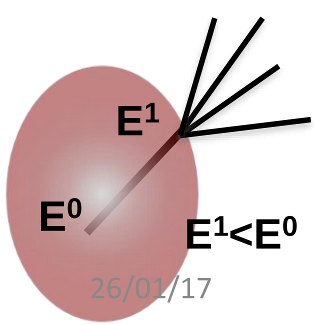

If jet loose energy as a whole followed by vacuum fragmentation
⇒ PbPb shape to be in agreement with pp/vacuum shape at higher p_T

g qualitatively agrees with this but in case of p_TD it is not.

ALICE Nucl. Phys. A 956 (2016) 593-596

Summary and Outlook

- pp collisions:
  - Jet production and shapes in pp are well understood
  - Several new observables (jet-mass, subjetiness, radial moment, dispersion, etc.) available at LHC
- pA collisions:
  - Several inclusive and differential measurements available
  - No significant change observed compared to pp
- AA collisions:
  - Large jet suppression, similar to hadron R_{AA}
  - Modification in jet shapes relative to pp

- New differential observables should be followed up in PbPb

THANK YOU