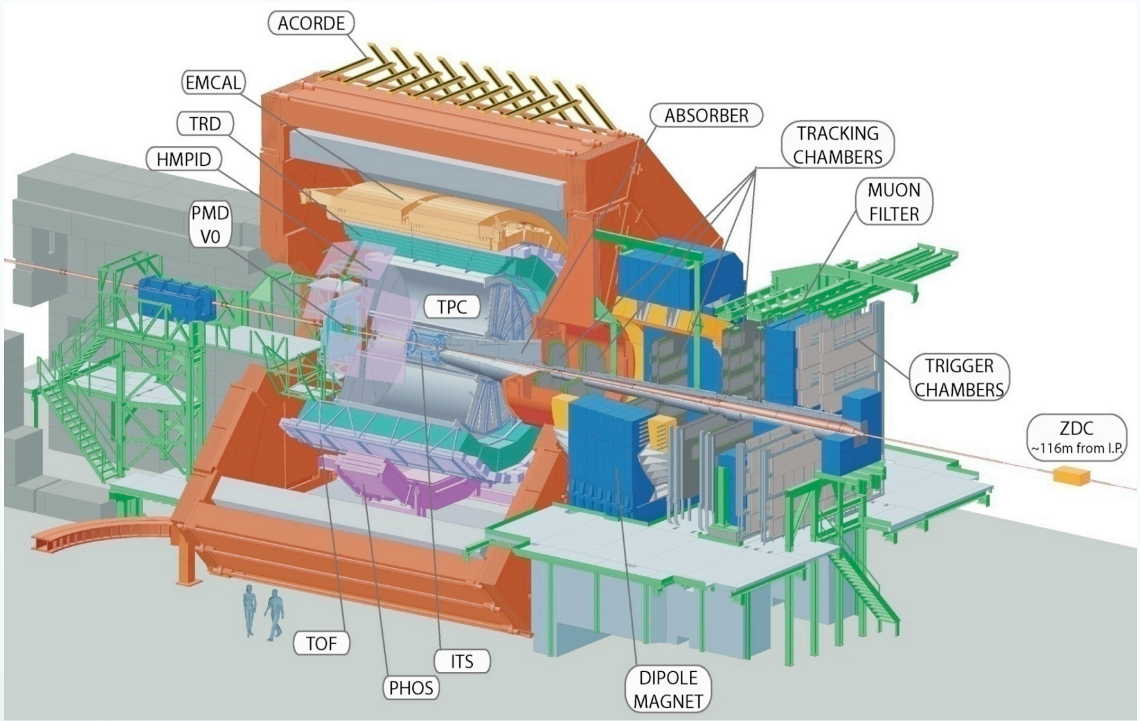
Jet production and structure in pp, p-Pb and Pb-Pb collisions measured by ALICE

Rosi Reed
on behalf of the ALICE Collaboration
Yale University

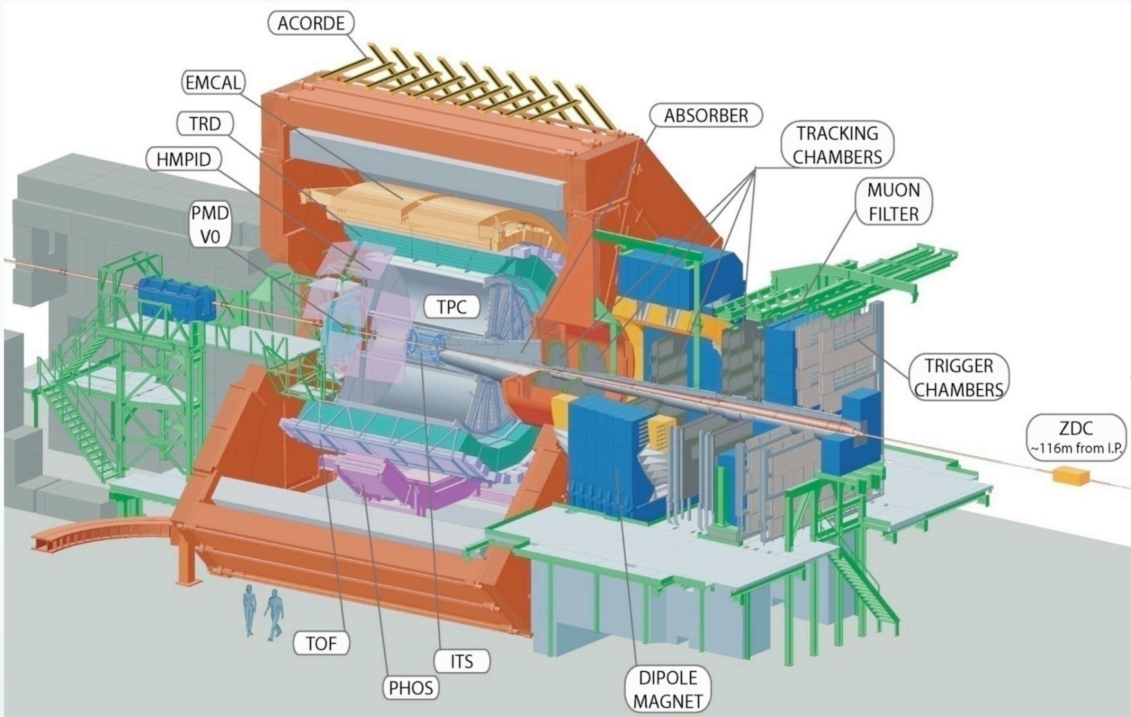
Charged jets at ALICE

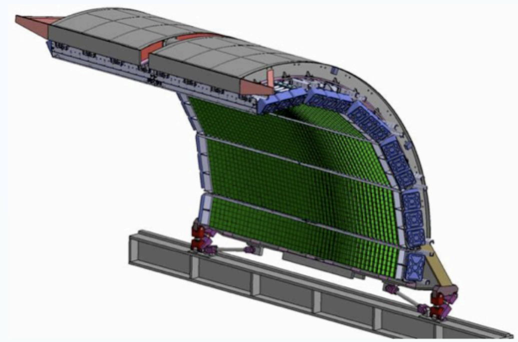


Tracking: $|\eta| < 0.9$, $0<\varphi<2\pi$
TPC: gas drift detector
ITS: silicon detector

→ *charged constituents* → **Charged JET**

Full jets at ALICE





- EMCal is a Pb-scintillator sampling calorimeter which covers:
  - $|\eta| < 0.7$, $1.4 < \varphi < \pi$
  - tower $\Delta\eta \sim 0.014, \Delta\varphi \sim 0.014$

Corrected for energy due to charged particles

Tracking: $|\eta| < 0.9$, $0 < \varphi < 2\pi$
TPC: gas drift detector
ITS: silicon detector

Charged constituents → **JET** ← *Neutral constituents*

Jet Reconstruction at ALICE

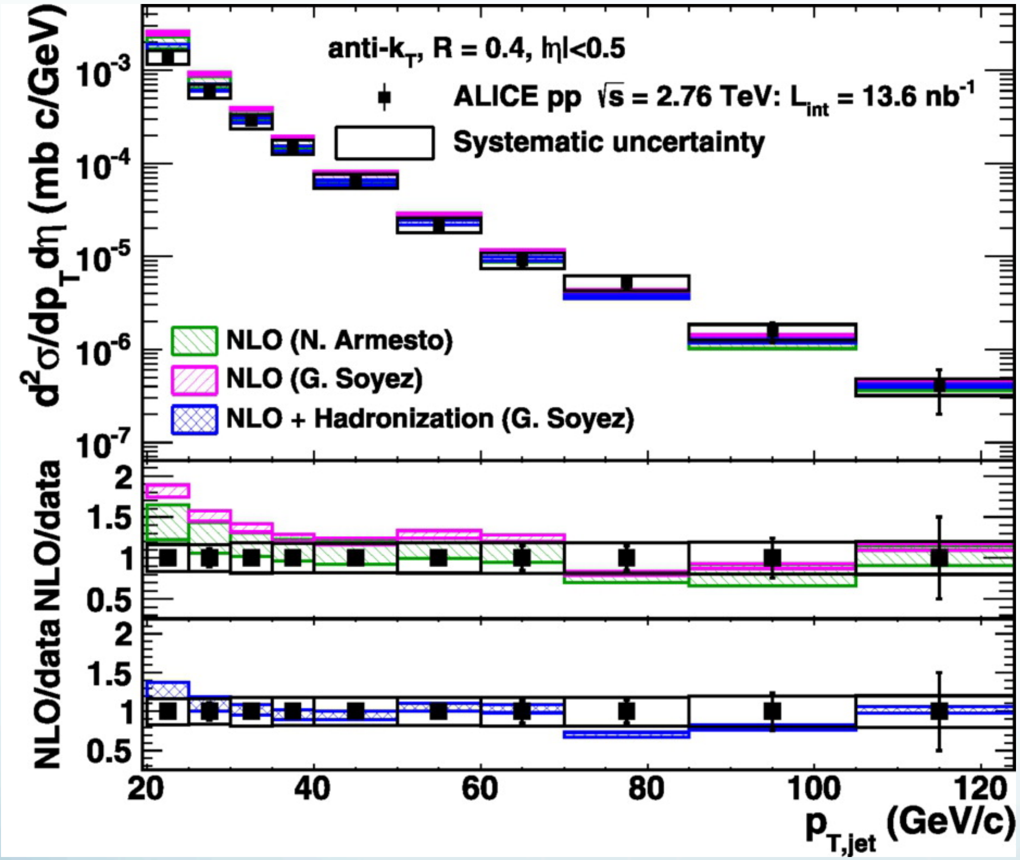
- **There is no unambiguous jet definition!**
  - Algorithms must be **IR and collinear safe**
- **Fluctuating background** and **combinatorial jets** require care in HI analyses
- Input to the jet finder
  - Charged tracks (ITS+TPC) with p_{T} > 150 MeV/c
  - EMCal clusters corrected for charged particle contamination with $E_{T,cluster}^{cor} \geq 300$ MeV
    - $E_{cluster}^{cor} = E_{cluster}^{orig} - f\sum p^{matched}$, $E_{cluster}^{cor} \geq 0$, f = 100%
- FastJet package: Anti-k_{T} (k_{T} used for background)
  - R = 0.2 – 0.6
  - Boosted p_{T} recombination scheme

Jets in pp
QCD baseline studies

Jet Cross-Section (pp)

√s = 2.76 TeV, R = 0.4 Inclusive

PLB 722, 262 2013

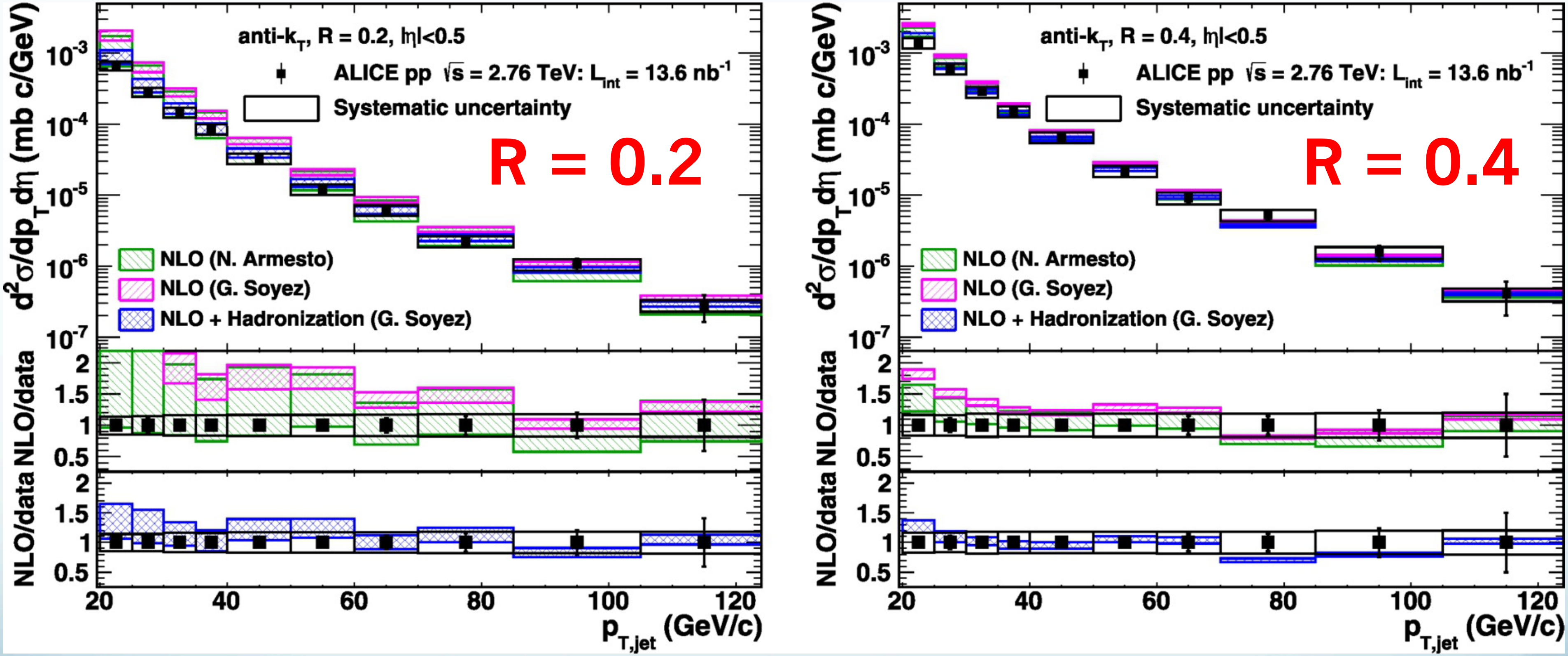


- **Important reference** for Pb-Pb collisions
- Good agreement between data and NLO calculations
  - Many orders of magnitude
  - Jets are a well **calibrated probe** for the QGP

Hadronization needed for theory-data agreement!

Jet Cross-Section (pp)

PLB 722, 262 2013

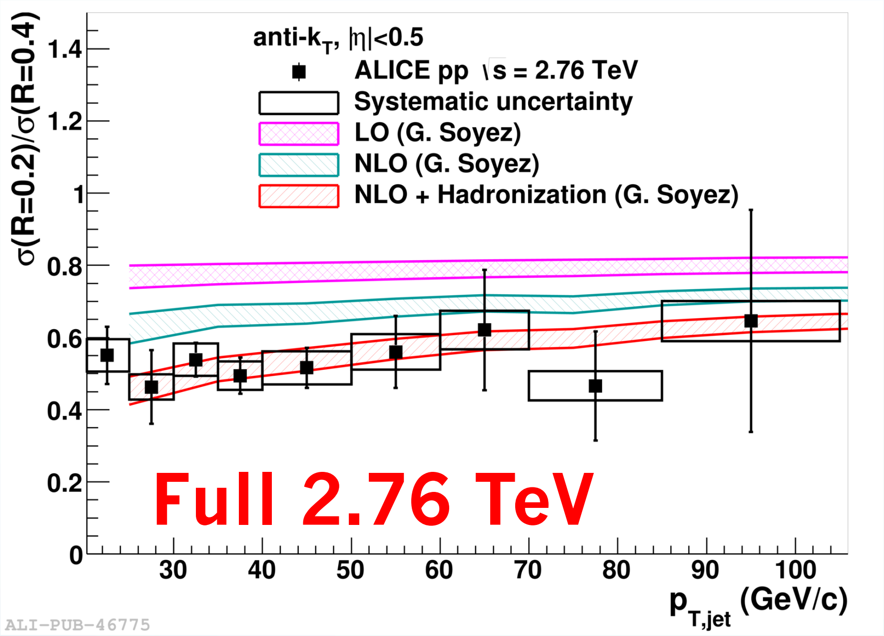


Agreement between data and NLO calculations is good for both R = 0.2 and 0.4

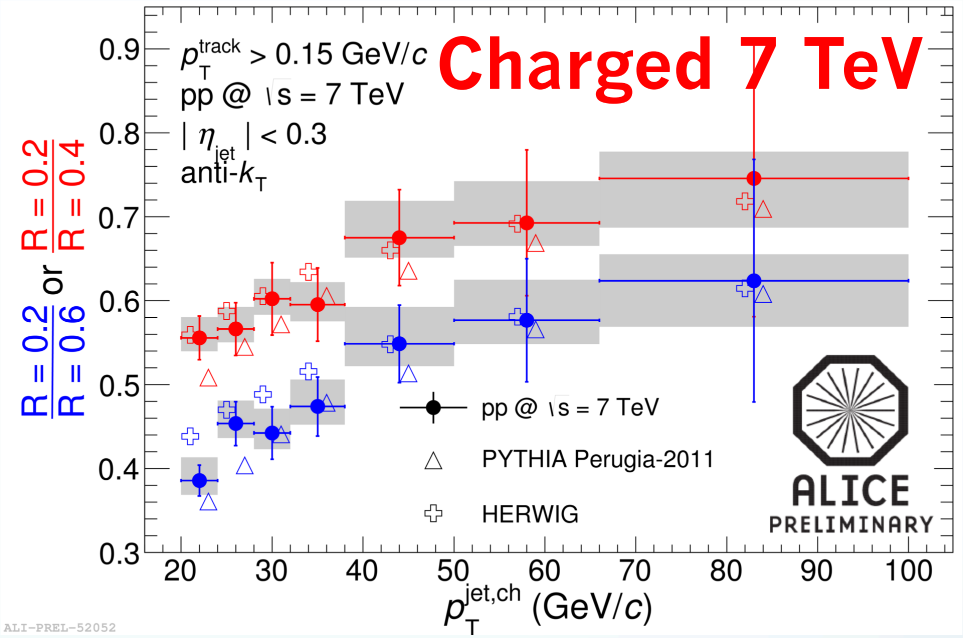
Jet Cross-Section Ratios

√s = 2.76, 7 TeV, R = 0.2-0.6 Inclusive

PLB 722, 262 2013



J Phys Conf 446, 012004 2013



Hadronization necessary for theory-data agreement

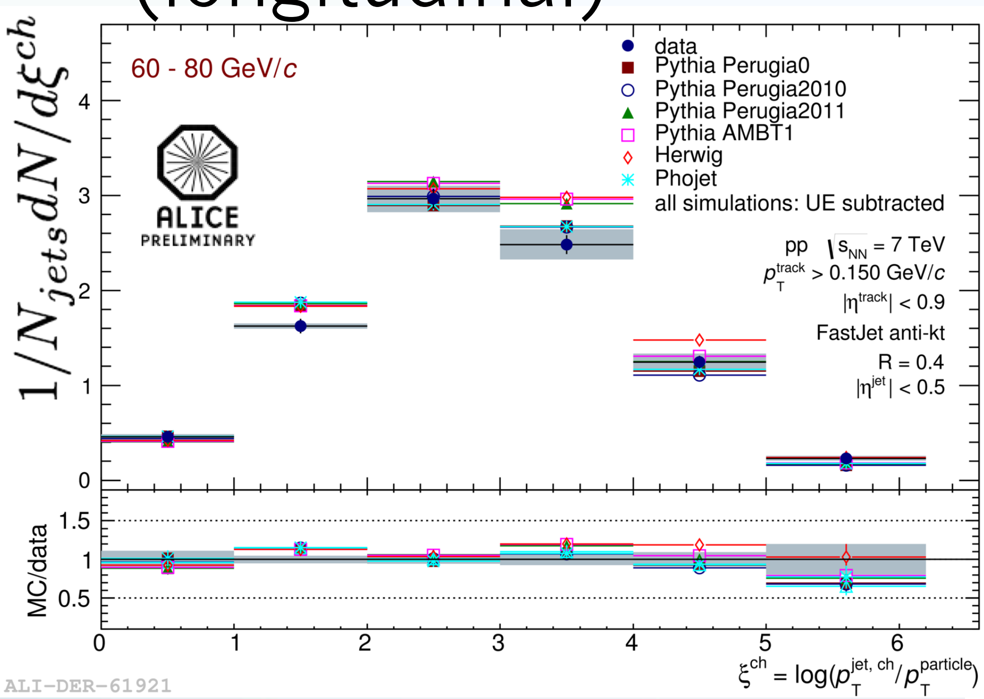
Sensitive to jet structure

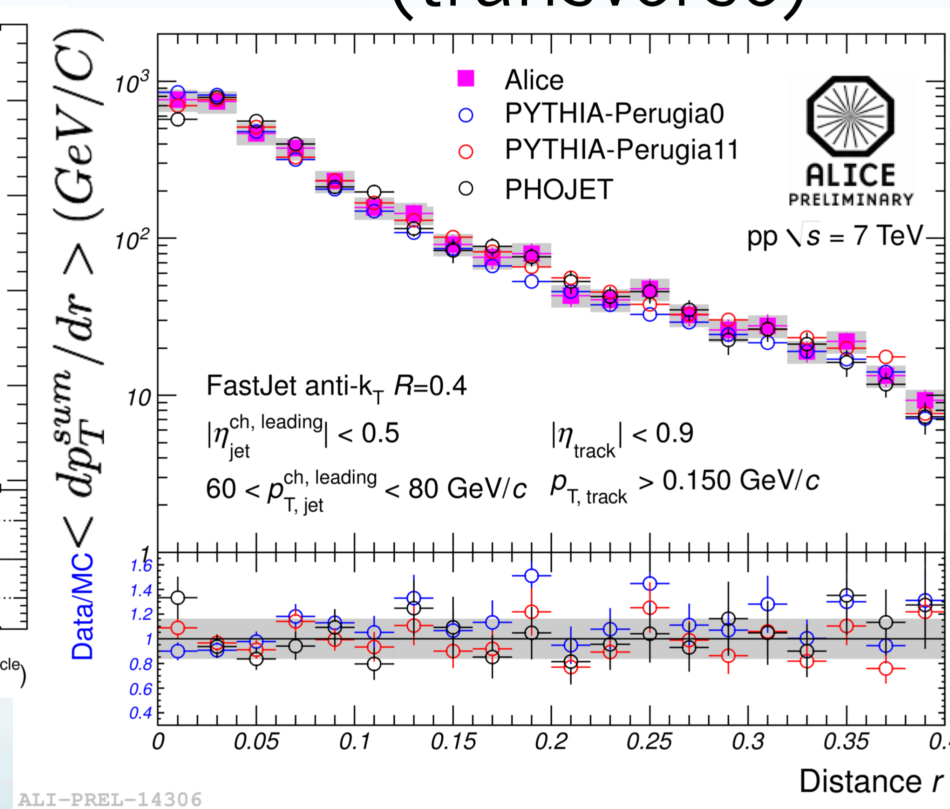
Jet broadening due to medium effects could change this ratio

√s = 7 TeV, R = 0.4 leading charged jet

See Poster

Fragmentation Spectrum (longitudinal) $60 < p_{T,jet}^{ch} < 80\ GeV/c$ Momentum density (transverse)





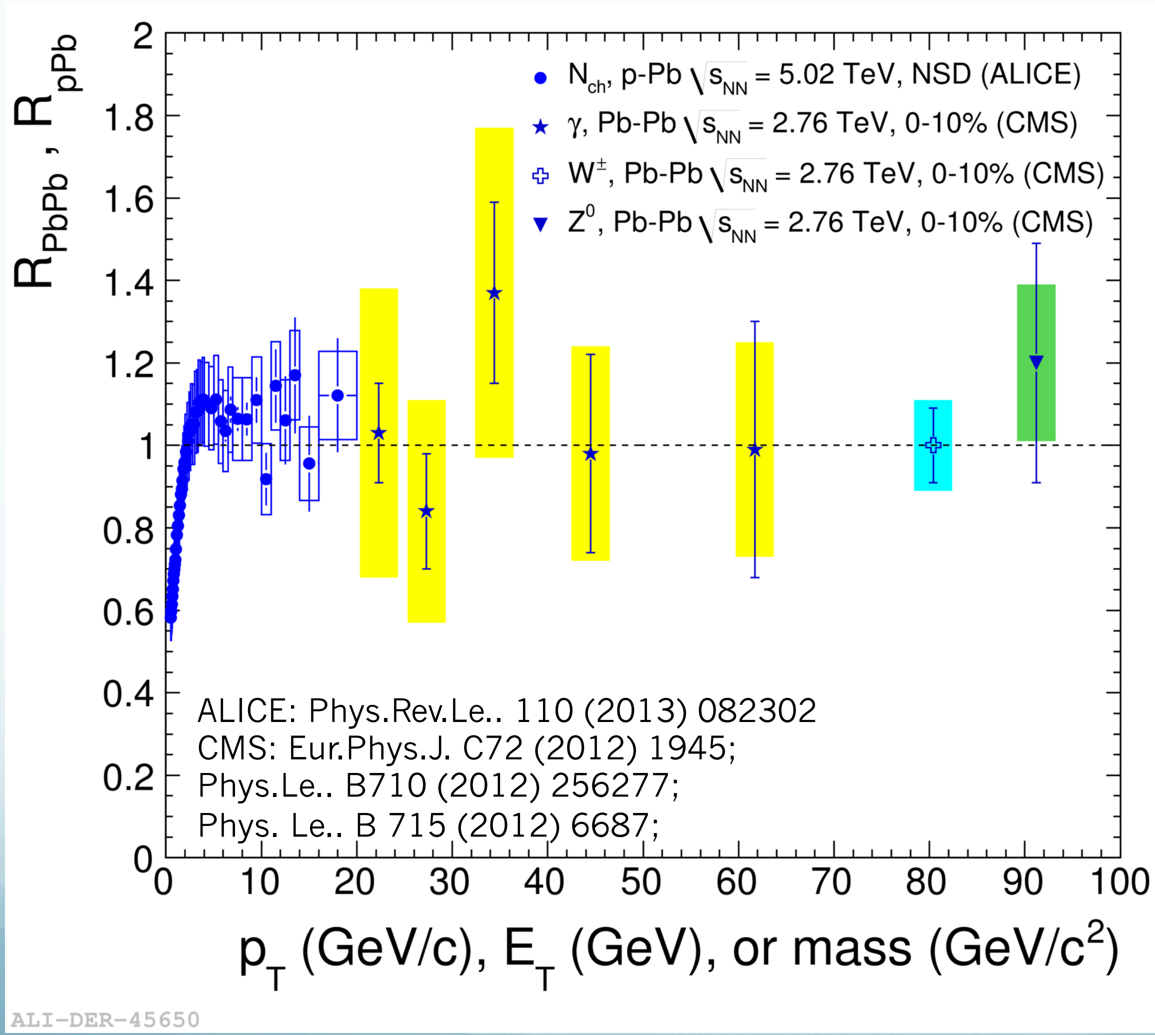
$$\xi^{ch} = \log\left(\frac{p_T^{jet,ch}}{p_T^{particle}}\right)$$

J.Phys.Conf.Ser. 389 (2012) 012005

Jet constituent analyses are **more differential** structure measurements than cross-section ratio

Jets in p-Pb
Cold Nuclear Matter (CNM) baseline studies

pp → p-Pb
Vacuum → CNM

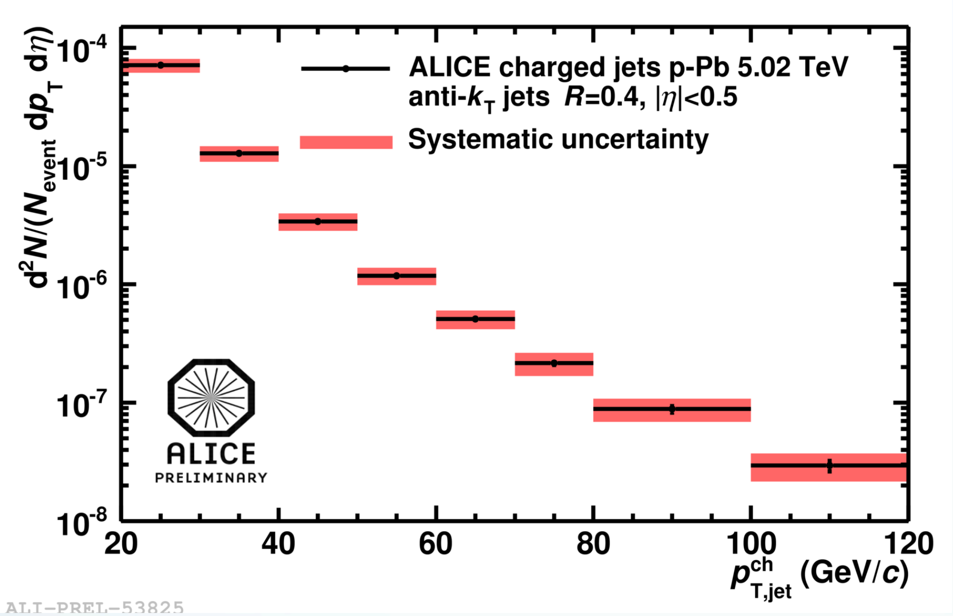


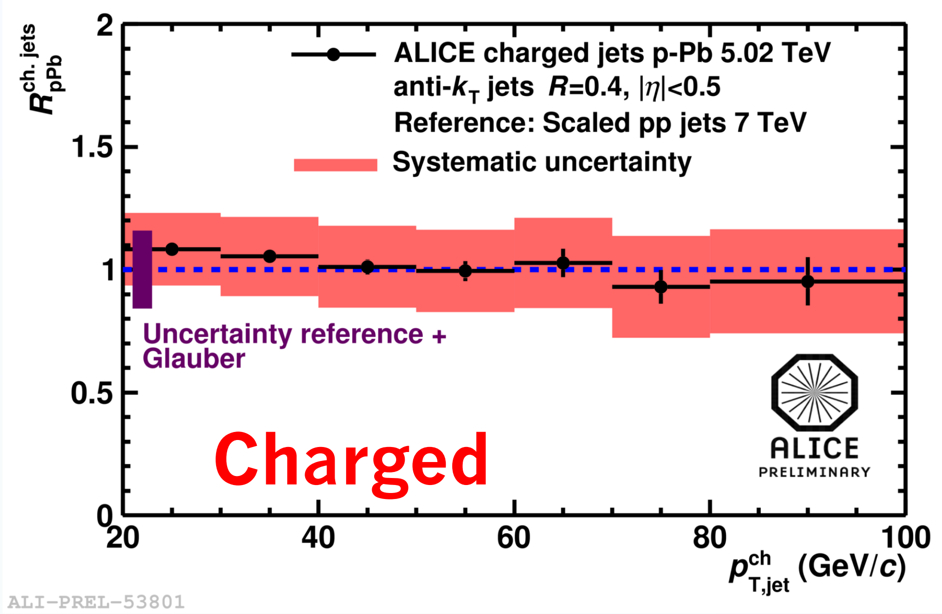
- p-Pb collisions allow us to study CNM
- Important to understand QGP effects
- **Initial state effects vs final state effects**
  - **Small** for inclusive spectra

Jet cross-section and R_{pPb}

$\sqrt{s_{NN}}$ = 5.02 TeV, R = 0.4 Inclusive

arXiv:1310.3612





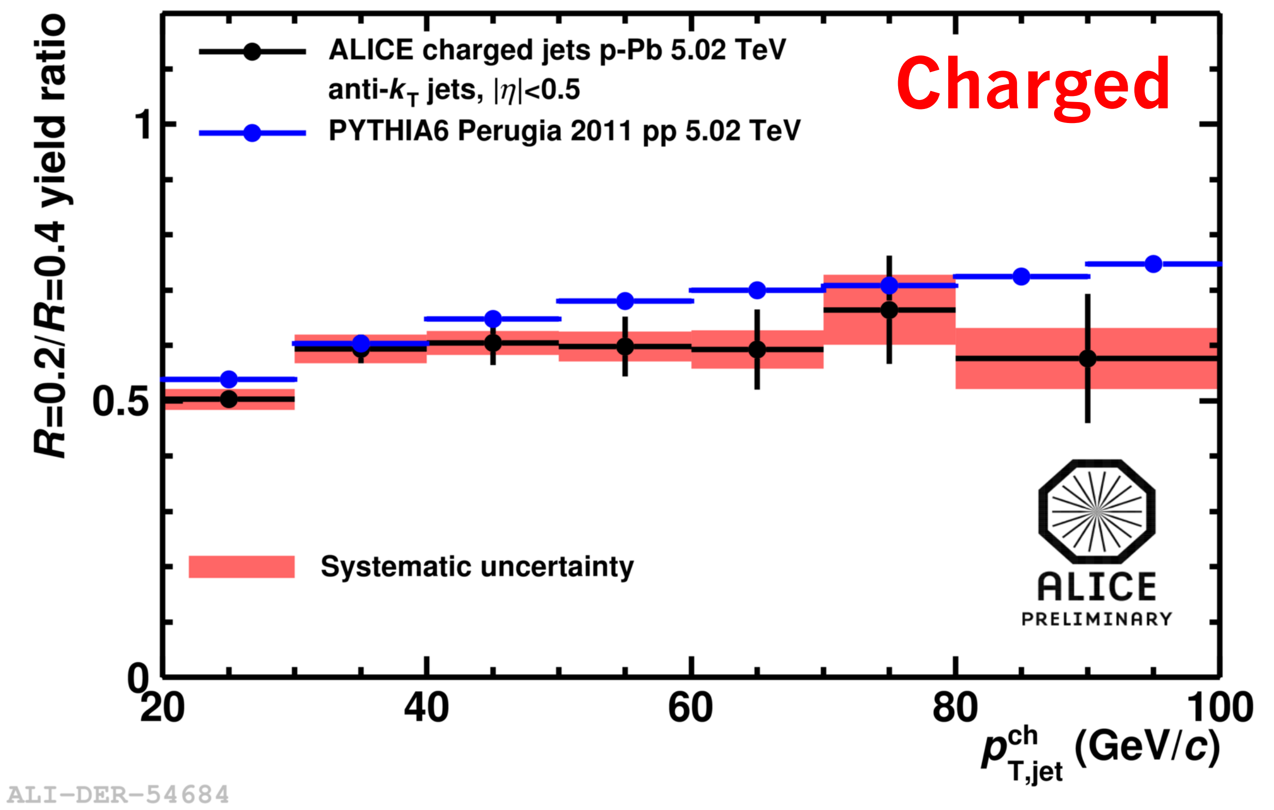
R_{pPb} = 1 for minimum bias charged jets

CNM have a negligible effect on the cross-section

- binary scaling holds

pp reference 7 TeV data scaled using Pythia

Jet cross-section Ratio
$\sqrt{s_{NN}}$ = 5.02 TeV, R = 0.4 Inclusive



arXiv:1310.3612

Cross-section ratio in **p-Pb not significantly different from PYTHIA**

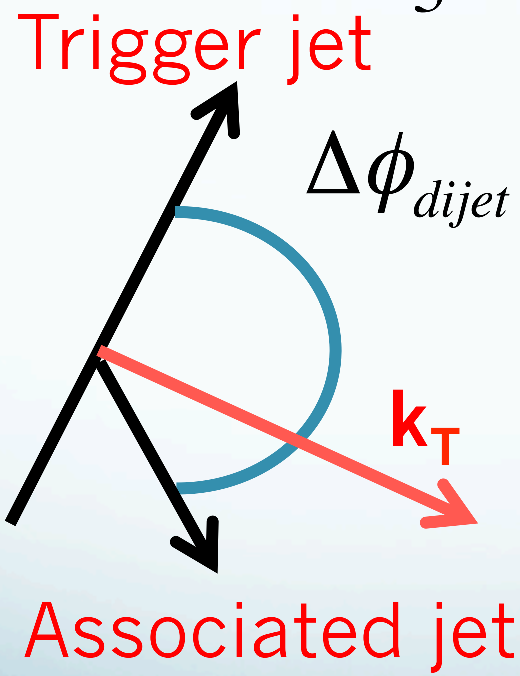
Charged k_T in p-Pb

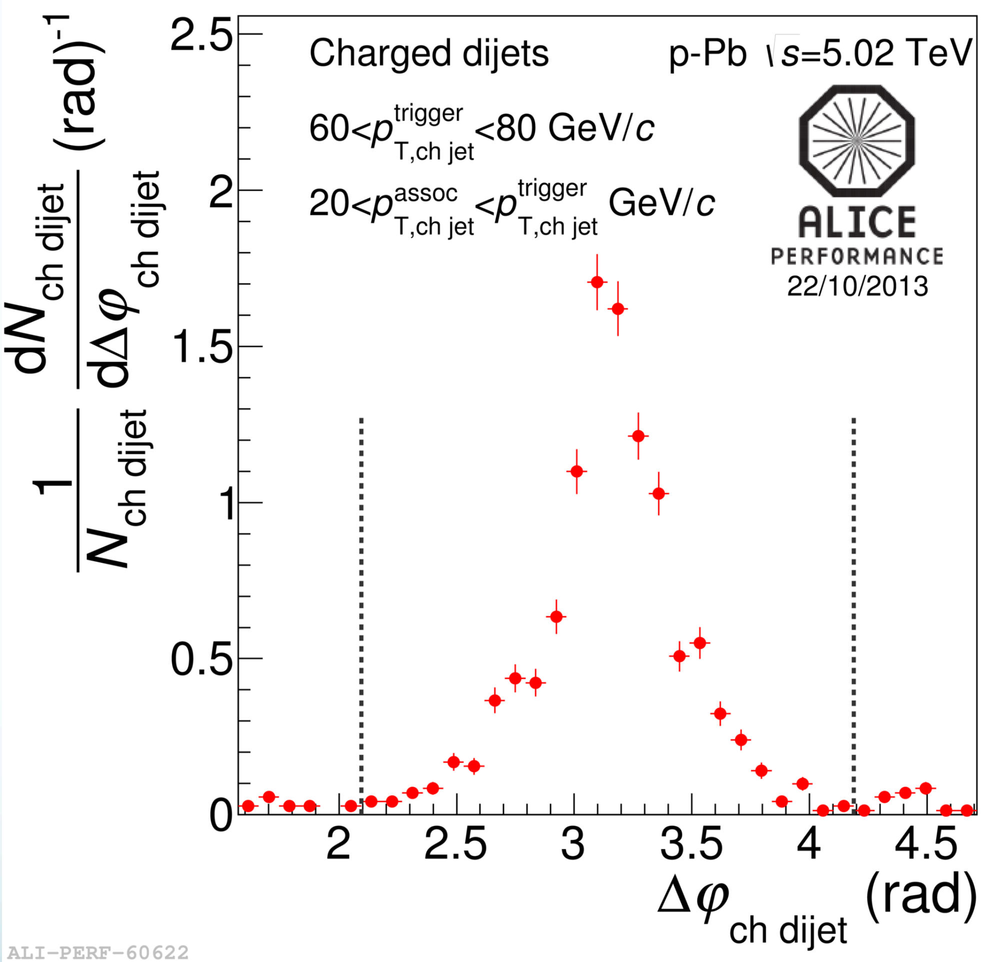
$\sqrt{s_{NN}} = 5.02$ TeV, R = 0.4

M. Verweij
Thurs 14:30

$$k_T = p_{T,jet}^{trigger} \sin(\Delta\phi_{dijet})$$

$$|\Delta\phi_{dijet} - \pi| \leq \frac{\pi}{3}$$



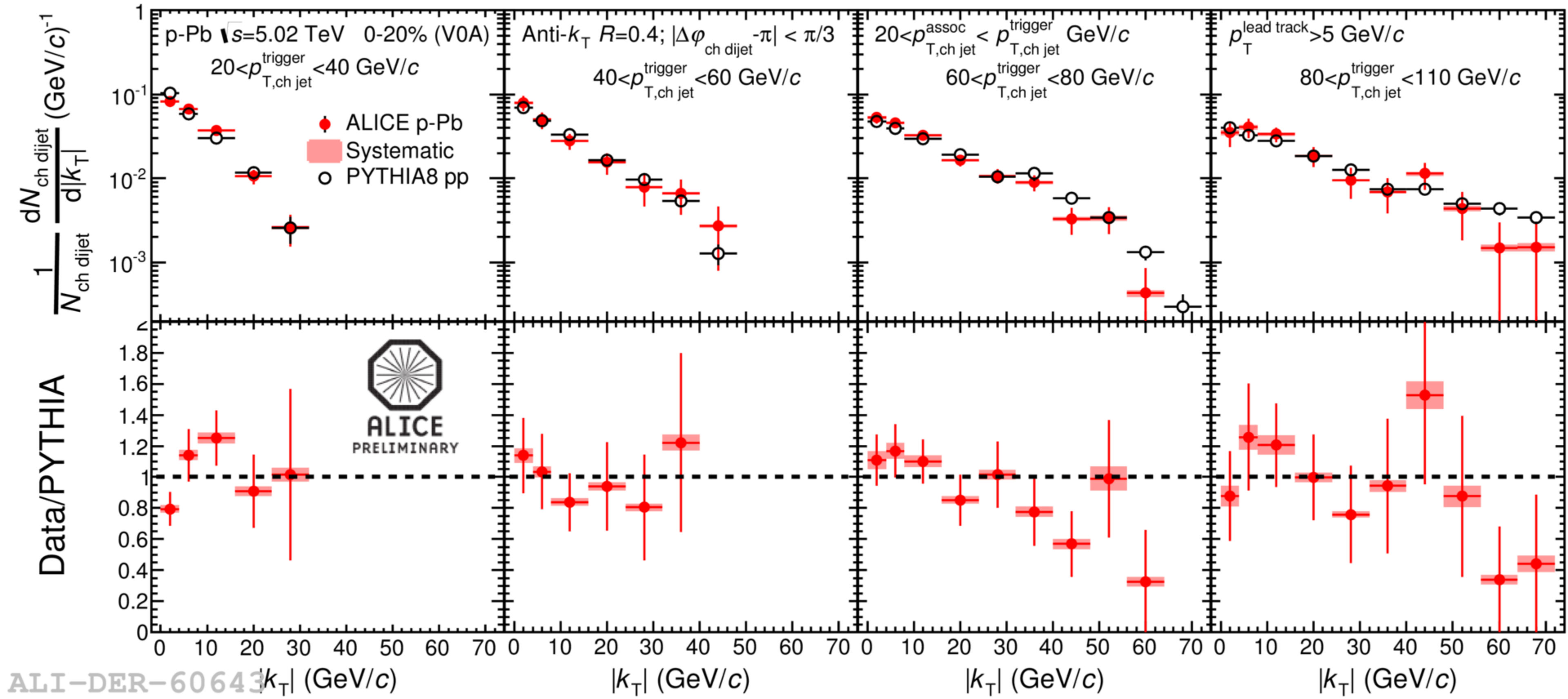


Perpendicular component of k_T

Corrected for p_T + angular jet resolution

Charged k_T vs trigger $p_{T,jet}$ in p-Pb

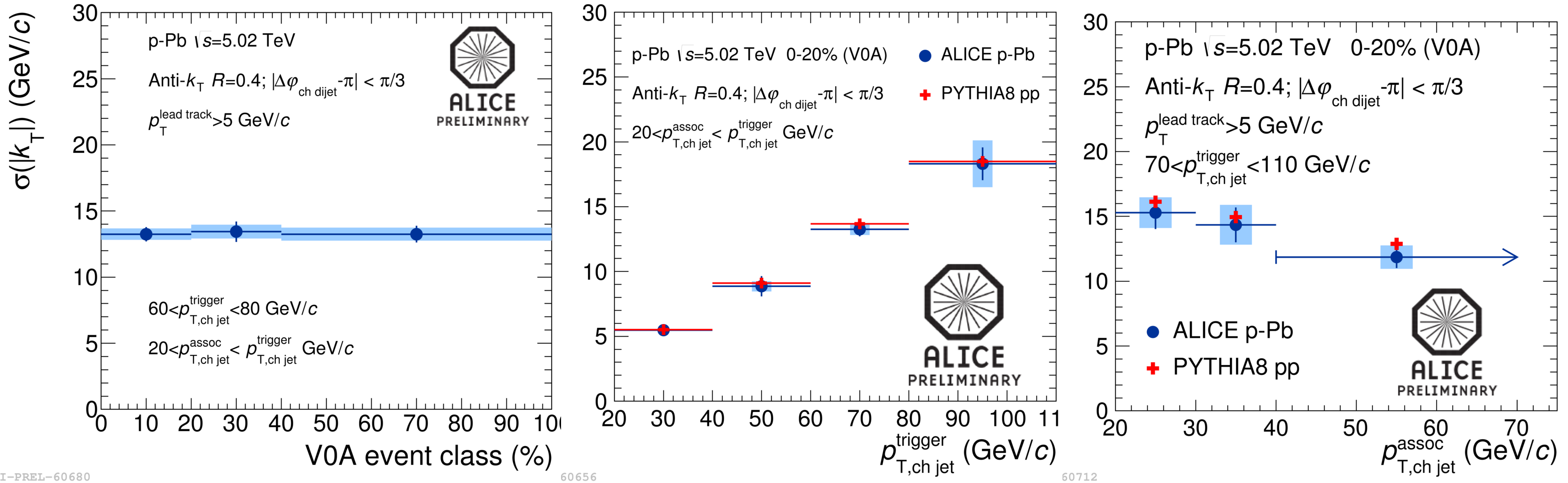
$\sqrt{s_{NN}}$ = 5.02 TeV, R = 0.4, 0-20% VZERO Multiplicity



- Good **agreement between data and PYTHIA** versus $p_{T,jet}$
- No indication of additional k_T in p-Pb collisions

p-Pb charged $\sigma(|k_T|)$

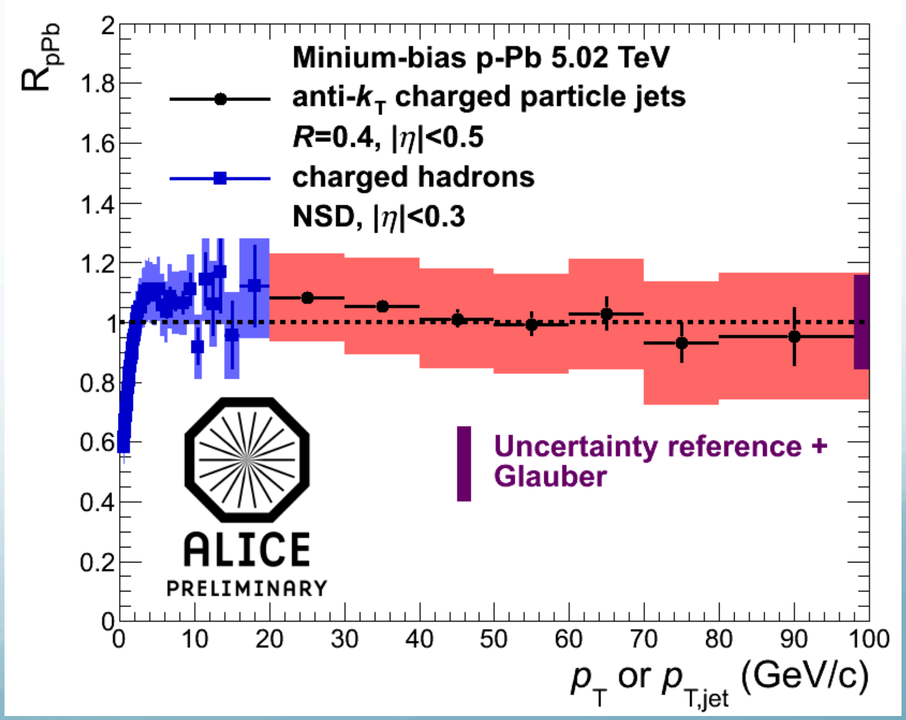
$\sqrt{s_{NN}}$ = 5.02 TeV, R = 0.4



- **No multiplicity dependence**
  - V0A = VZERO A Event multiplicity class
  - Pb-going ($2.8 < \eta_{lab} < 5.1$)
- Good **agreement between data and PYTHIA** for $\sigma(|k_T|)$

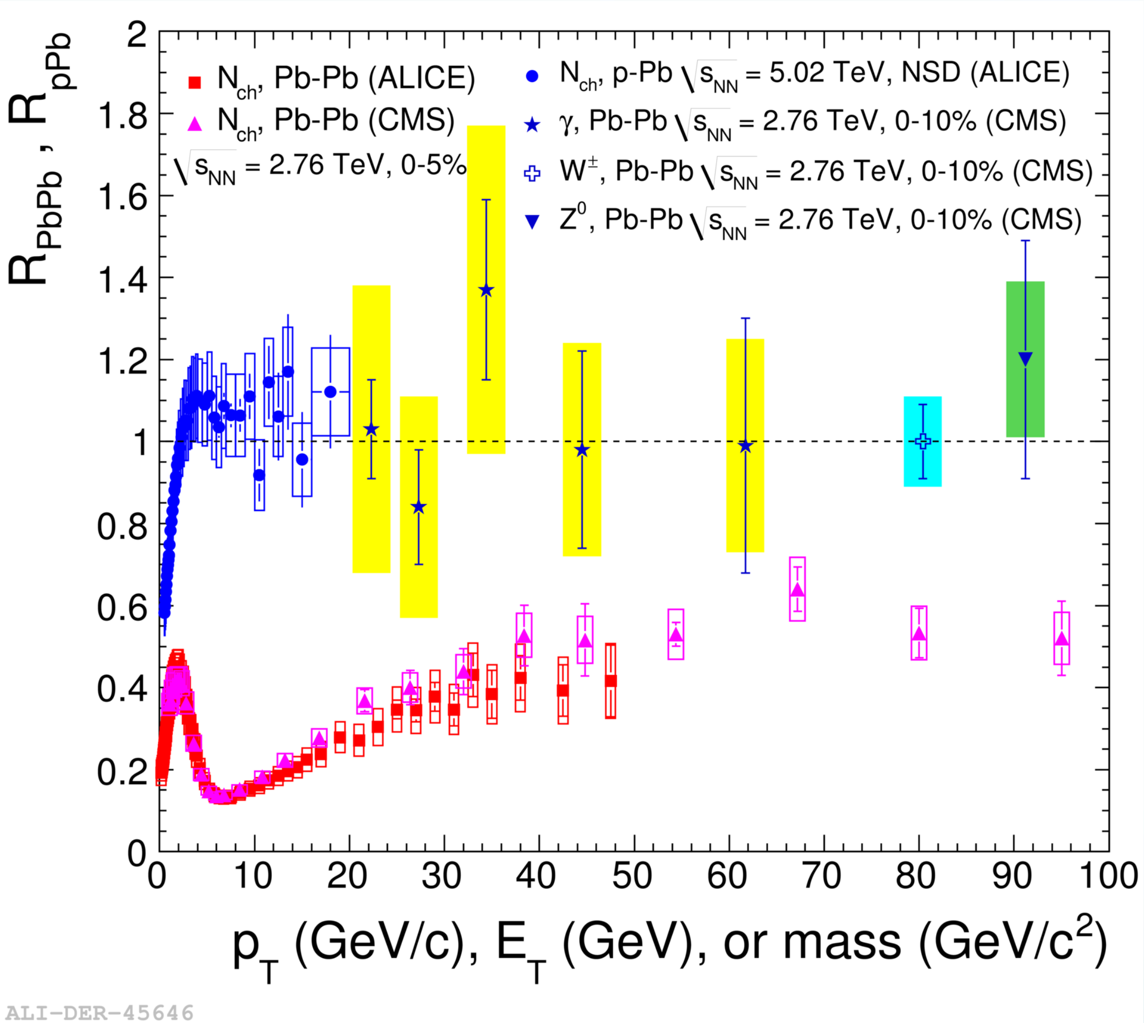
pp and p-Pb jets

- We have established a good baseline for heavy ion jet measurements by quantifying observables in both pp and p-Pb
  - pp jet observables agree well with models
- Jets do not appear to be modified in p-Pb compared to pp
  - However more differential analyses are on-going!



Jets in Pb-Pb
QGP

Pb-Pb



Charged hadrons are suppressed in heavy ion collisions

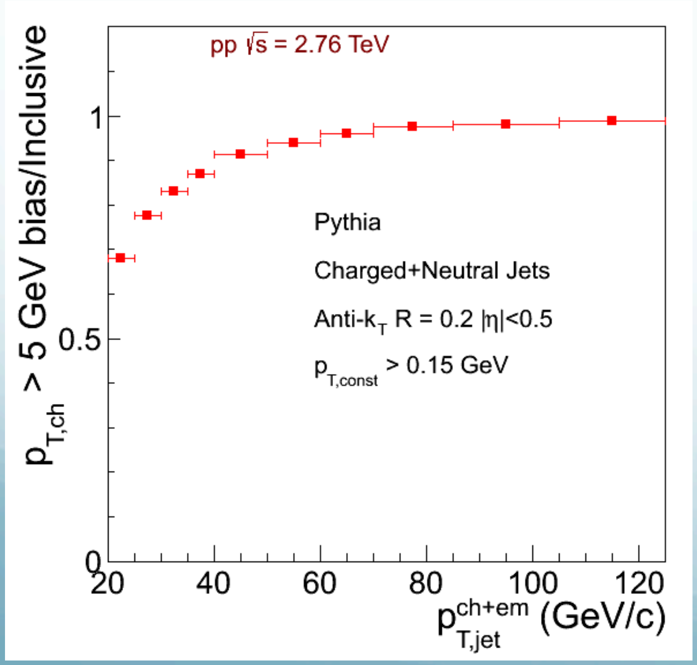
Time to quantify suppression mechanisms

Jet spectra and structure

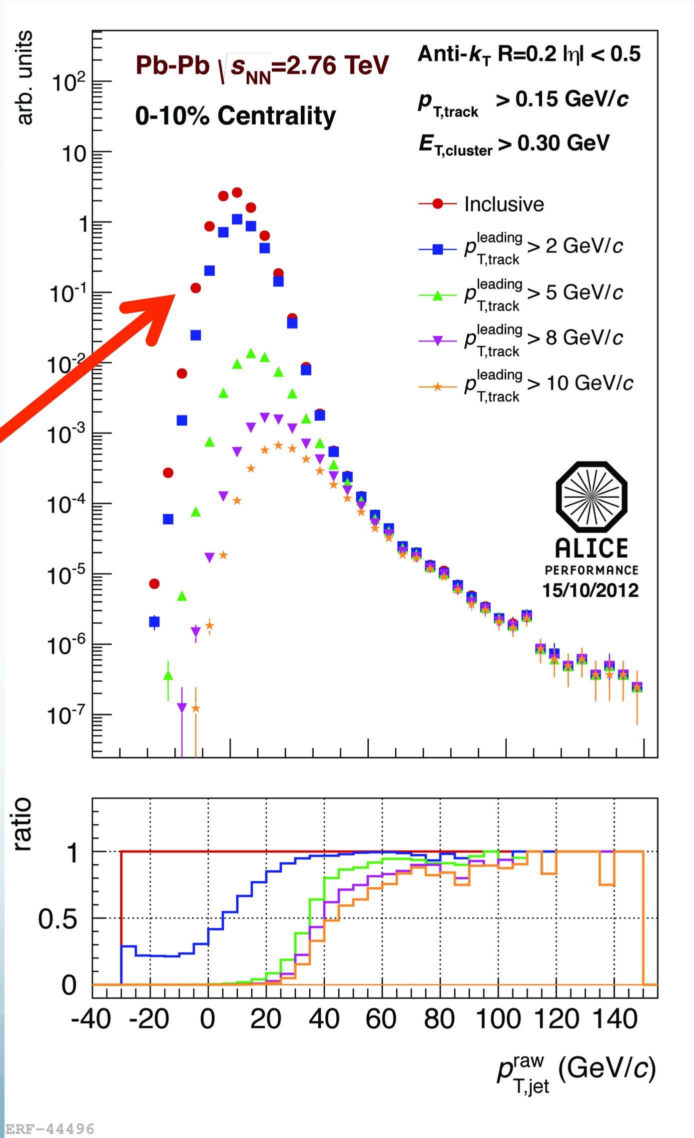
ALICE: PLB 720 (2013) 5262
PRL. 110 (2013) 082302
CMS: Eur.Phys.J. C72 (2012) 1945
PLB 710 (2012) 256277
PLB 715 (2012) 6687

Heavy-Ion challenges

- Jet finding algorithms will cluster "jets" from soft background
  - Combinatorial jets (fake)
  - Depend on R and jet constituent p_T
- 2 methods to remove fake jets
  - Leading track bias, h-jet correlations



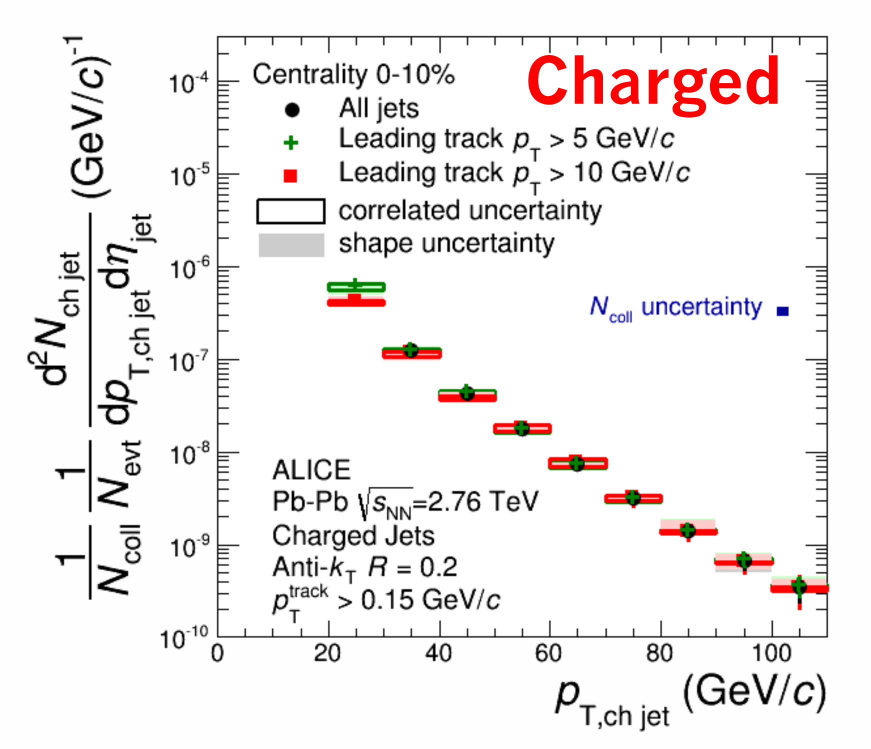
fake jets

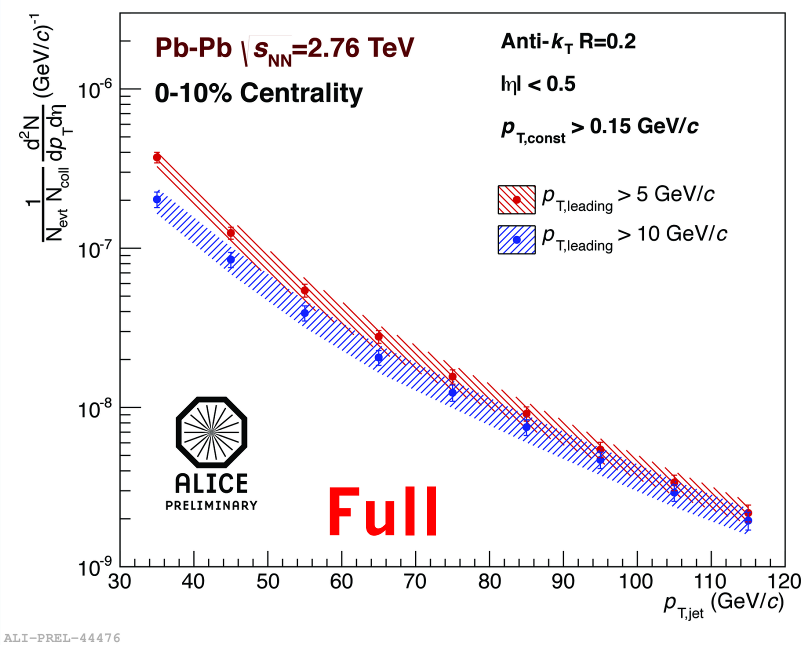


Jet Spectra

$\sqrt{s_{NN}}$ = 2.76 TeV, R = 0.4 Inclusive

arXiv:1311.0633





arXiv:1304.6668

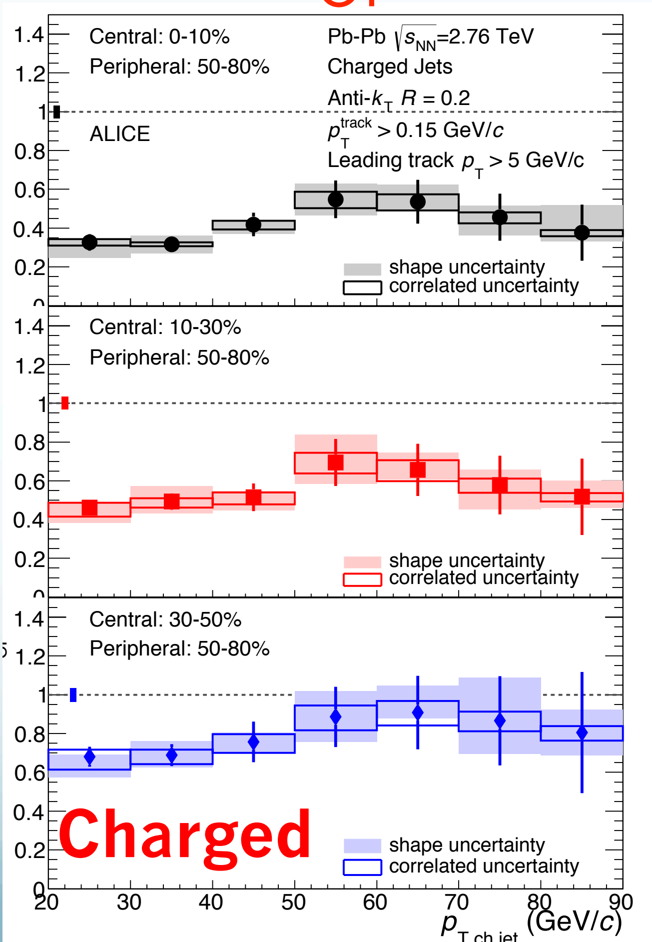
Leading track bias removes combinatorial jets but biases the fragmentation

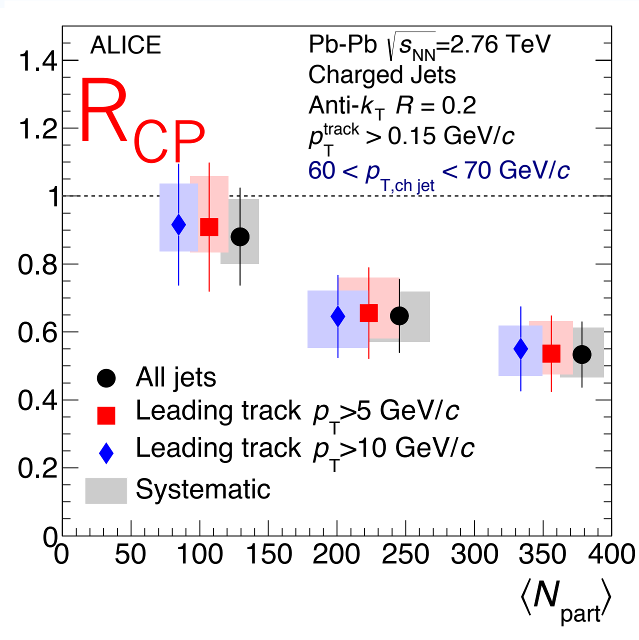
ALICE uses a leading track bias of $p_{T,track}$ > 5 GeV/c

Jet R_{AA} and R_{CP}

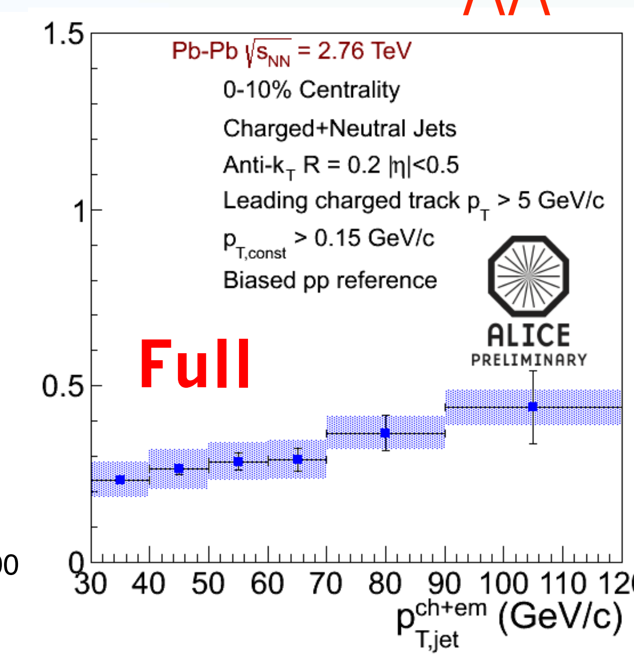
$\sqrt{s_{NN}}$ = 2.76 TeV, R=0.2

R_{CP}





R_{AA}

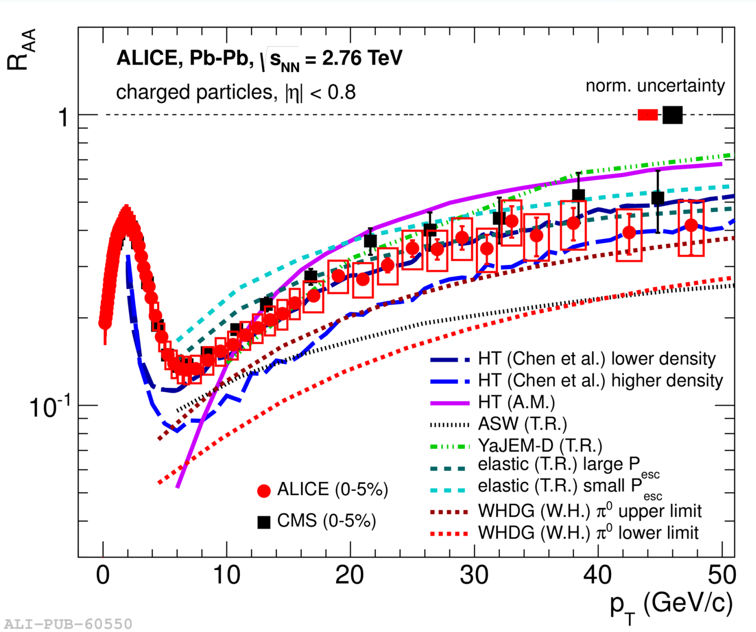


arXiv:1304.5945

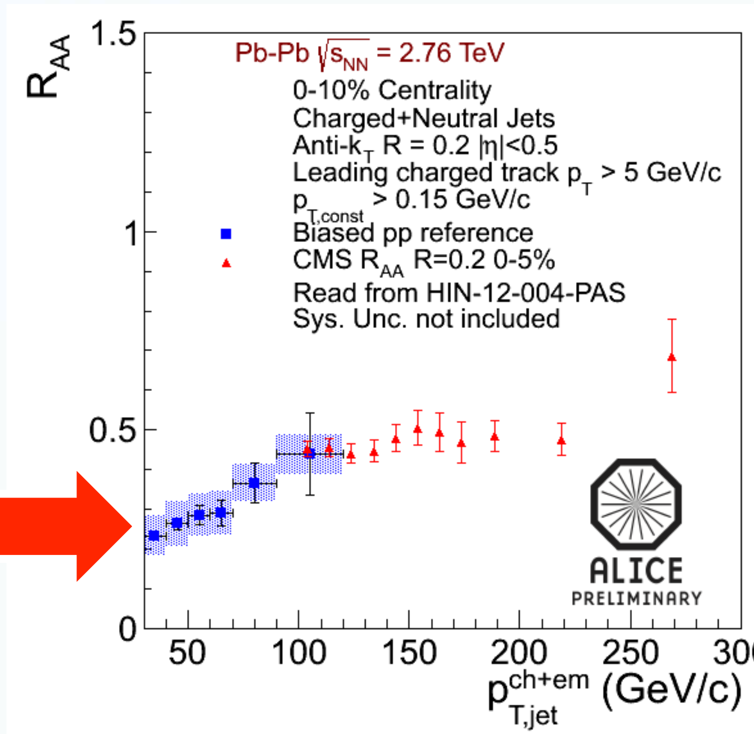
Jets are suppressed in a centrality and p_T dependent manner

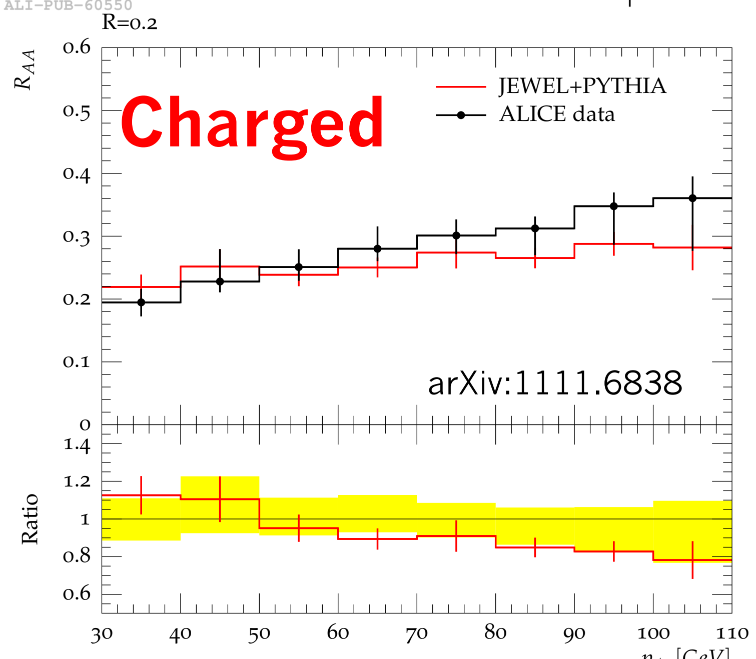
arXiv:1311.0633

R_{AA} Models and comparisons



Your model here!

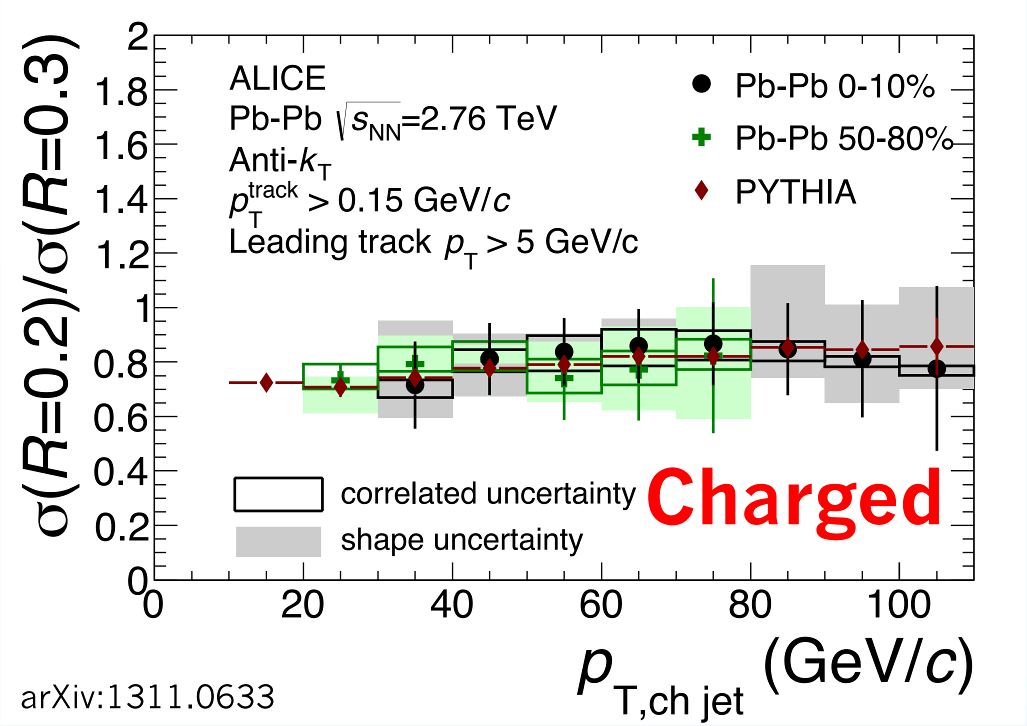




- Direct connection between charged hadron and jet R_{AA} requires theory interpretation
- Understanding jet quenching requires well developed models

Ratio of Jet Spectra

$\sqrt{s_{NN}}$ = 2.76 TeV, R=0.2,0.3



- No evidence of jet structure modification in core
- Charged jet ratio σ(R=0.2)/σ(R=0.3)
  - **consistent with vacuum jets** (PYTHIA)
  - no centrality dependence

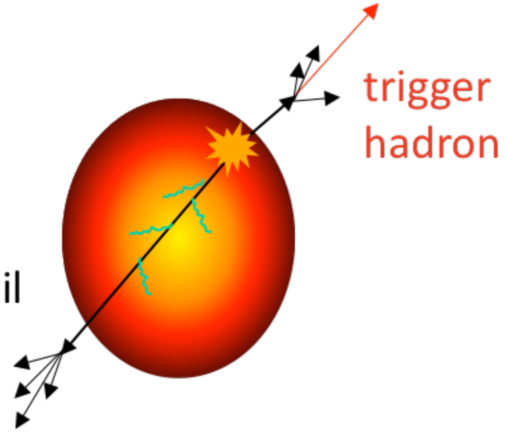
Hadron-jet

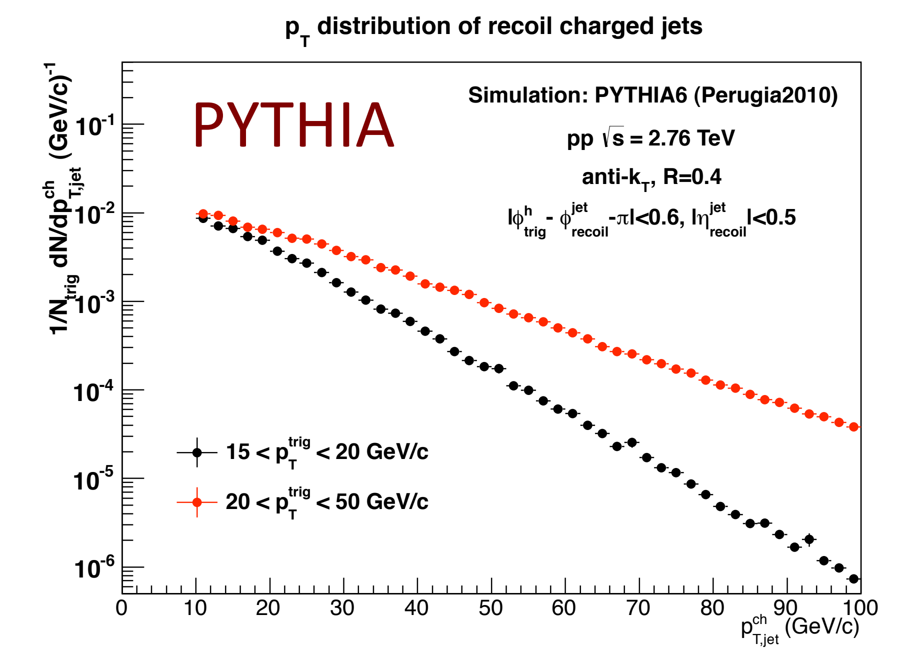
$\sqrt{s_{NN}}$ = 2.76 TeV, R=0.4

L. Cunqueiro Mendez Thurs 13:50

Assumes combinatorial jets are not correlated with the trigger hadron

$$|\varphi_{trig}^{h} - \varphi_{recoil}^{jet} - \pi| < 0.6$$



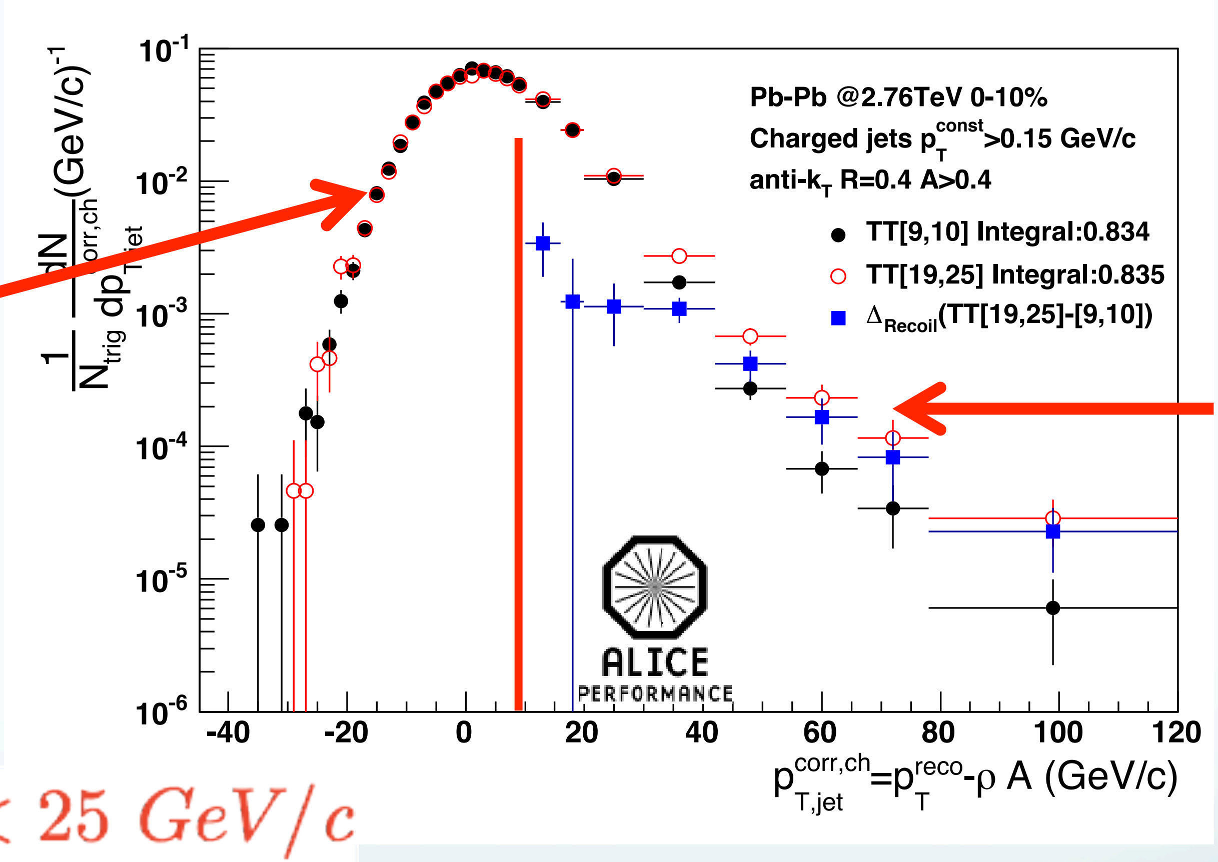


Hadron triggered recoil jet spectrum has a **minimal fragmentation bias** down to low p_T and large R

Hadron-jet

Another way to remove combinatorial background

Dominated by uncorrelated combinatorial jets



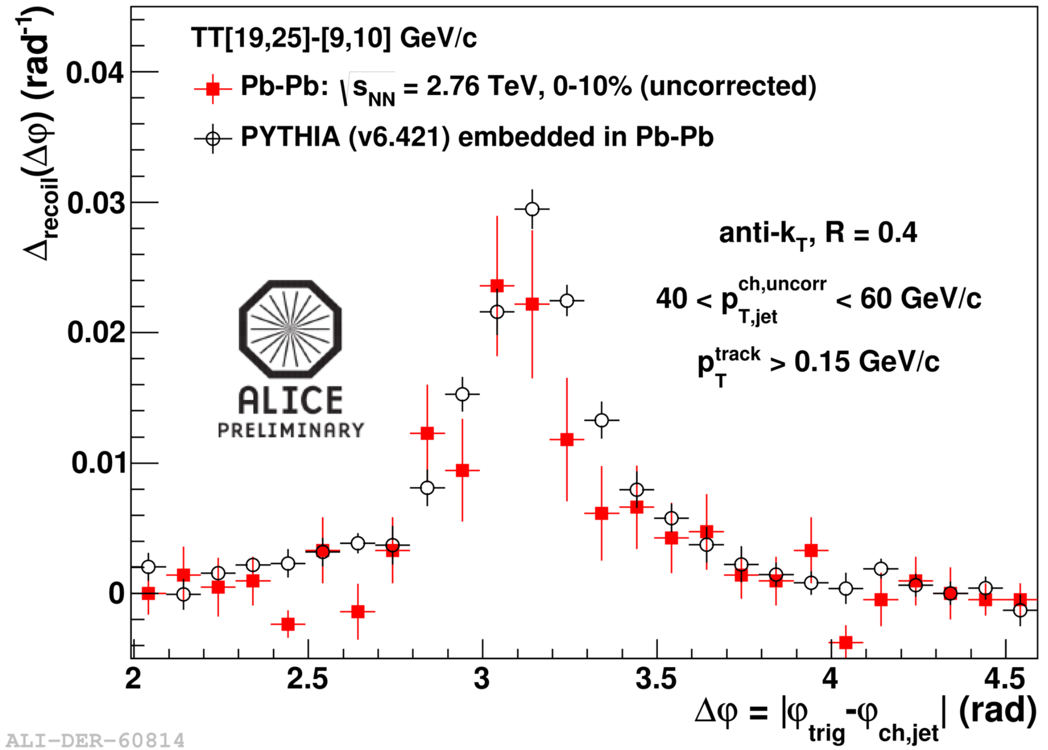
QCD jets

$$19 < p_T^{trigger} < 25\ GeV/c$$

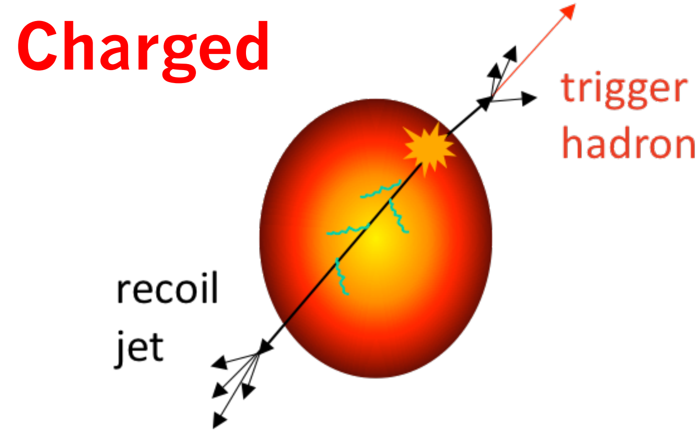
$$9 < p_T^{trigger} < 10\ GeV/c$$

Δ_{recoil} = **Difference** of per trigger yield of recoil jet spectra

Hadron-jet azimuthal correlation



Charged



Pb-Pb σ_{2Gaus}=0.215±0.023±0.031

PYTHIA: σ_{2Gaus}=0.256±0.009

$$\Delta_{recoil}(\Delta\varphi) = \left(\frac{1}{N_{trig}}\frac{dN}{d\Delta\varphi}\right)_{19-25} - \left(\frac{1}{N_{trig}}\frac{dN}{d\Delta\varphi}\right)_{9-10}$$

Folded PYTHIA reference consistent with data

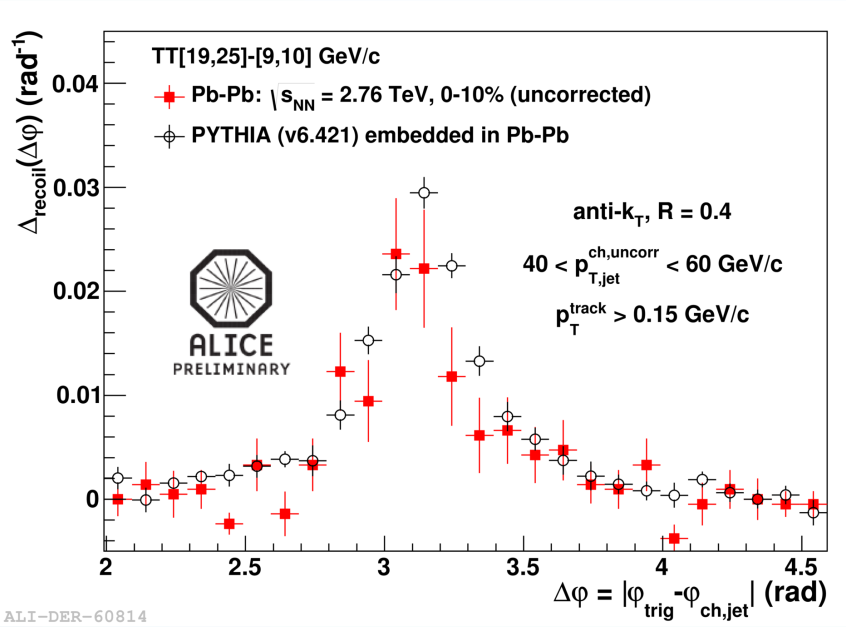
Consistent with **no medium-induced jet deflection**

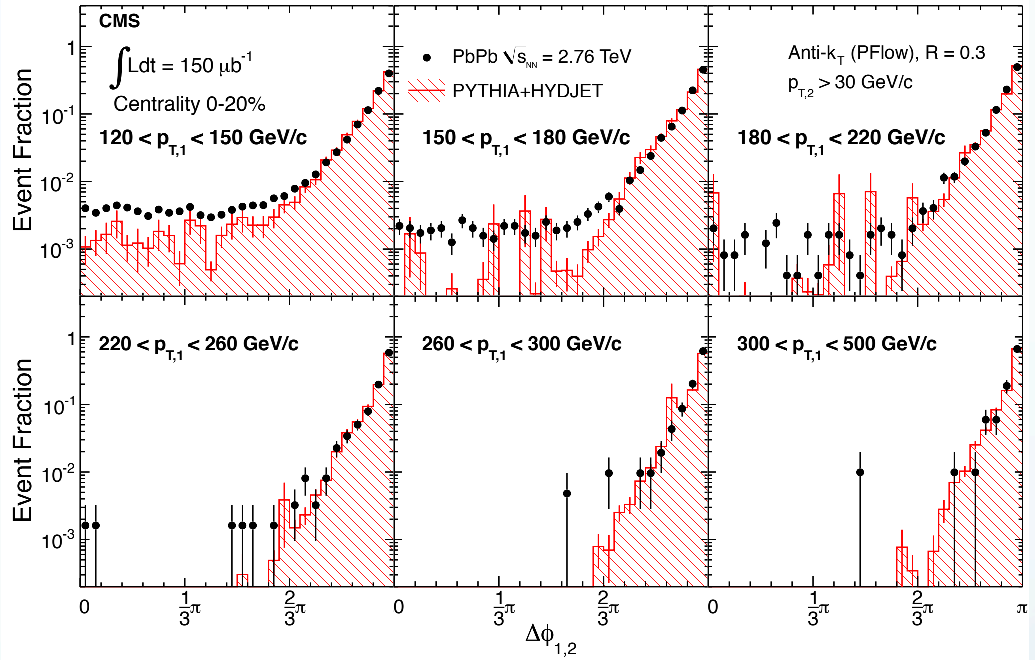
Hadron-jet azimuthal correlation

Comparison to CMS dijet

Charged

PRC 84 (2011) 024906

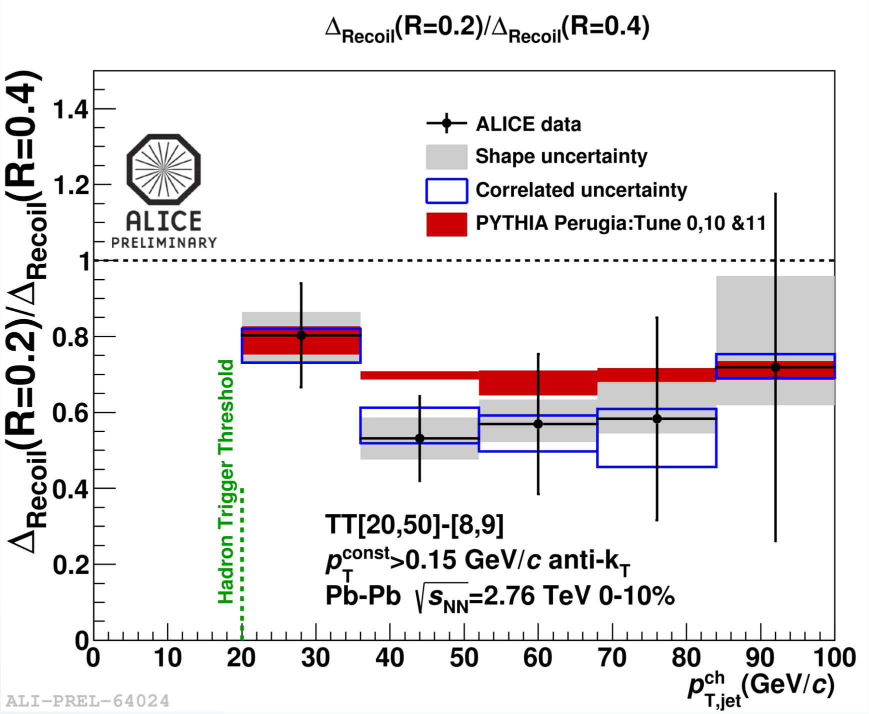


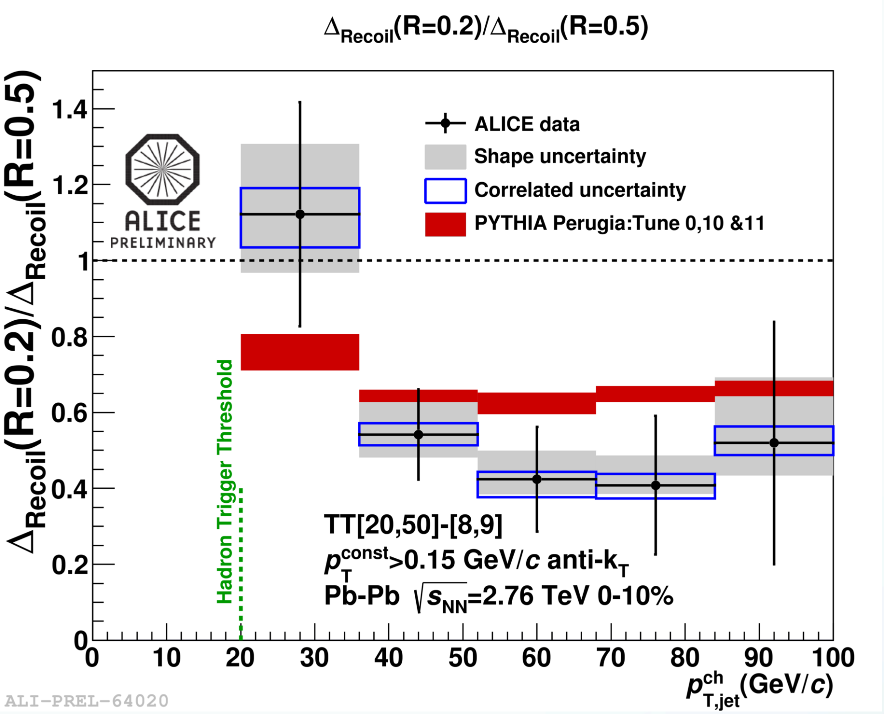


- Hadron-jet results in agreement with dijet results
- Over a broad momentum range, jets are not deflected by the medium
  - Deflection is similar to vacuum jets

Charged Jet Recoil Spectra

$\sqrt{s_{NN}}$ = 2.76 TeV, R=0.2, 0.4, 0.5





$$\Delta_{recoil} = \left(\frac{1}{N_{trig}}\frac{dN}{dp_{T,jet}}\right)_{20-50} - \left(\frac{1}{N_{trig}}\frac{dN}{dp_{T,jet}}\right)_{8-9}$$

Corrected for background fluctuations and detector effects

Δ_{recoil} ratio **compatible with no energy** redistribution within **R=0.5**

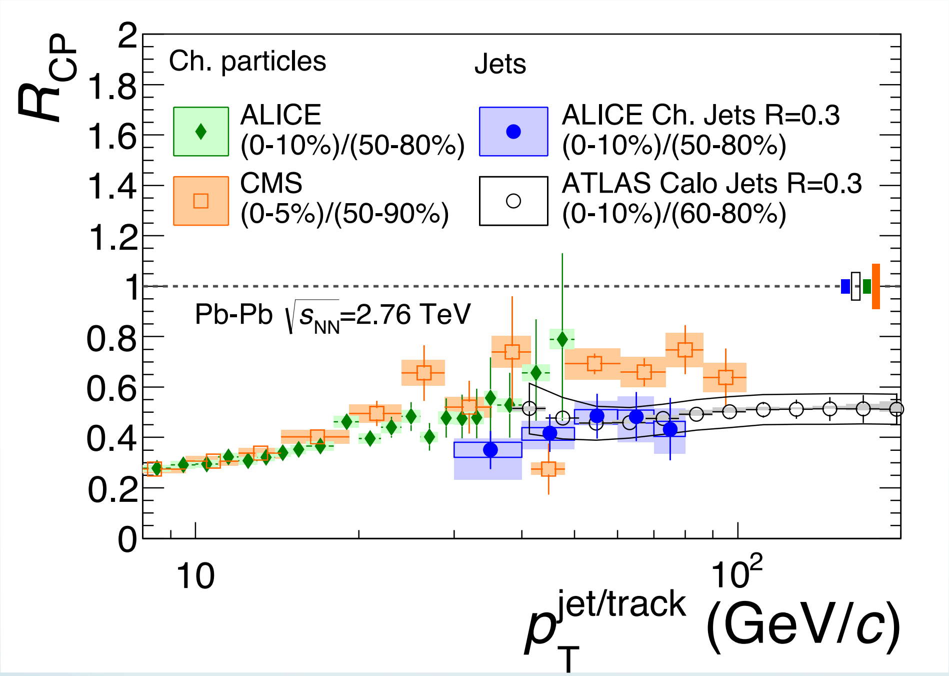
Hint of some effect in $p_{T,jet}$ region of ~60 GeV/c?

Conclusions

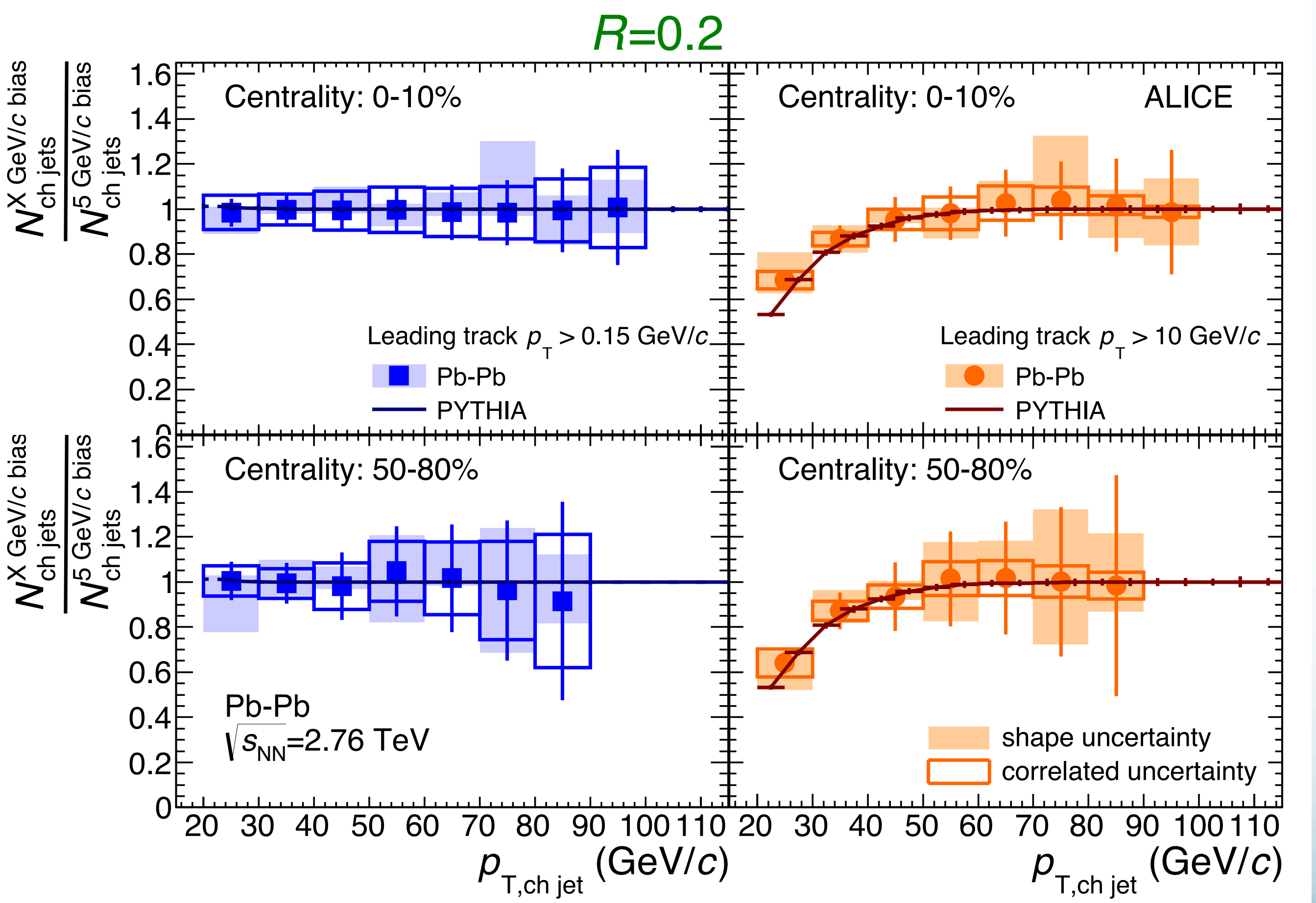
- In Pb-Pb collisions ALICE has shown that
  - **Jets are suppressed $R_{AA,}$ R_{CP} < 1**
  - **Ratio of jet cross-sections** in HI collisions consistent with vacuum case
  - Hadron-jet analysis allows for a larger R
    - **Compatible with no energy** redistribution within **R=0.5**
- **No indication of CNM effects** for these jet observables
  - $R_{pPb} = 1$
  - k_T is in agreement with the vacuum case
  - Good baseline for future 5.5 TeV Pb-Pb collisions!
- Coming soon: more differential jet structure analyses, PID jets and modification versus reaction plane

Poster on future
b-tagging capabilies

Back-up



R_{CP}
Ch. particles
Jets
ALICE
(0-10%)/(50-80%)
CMS
(0-5%)/(50-90%)
ALICE Ch. Jets R=0.3
(0-10%)/(50-80%)
ATLAS Calo Jets R=0.3
(0-10%)/(60-80%)
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10
10^2
$p_T^{jet/track}$ (GeV/c)

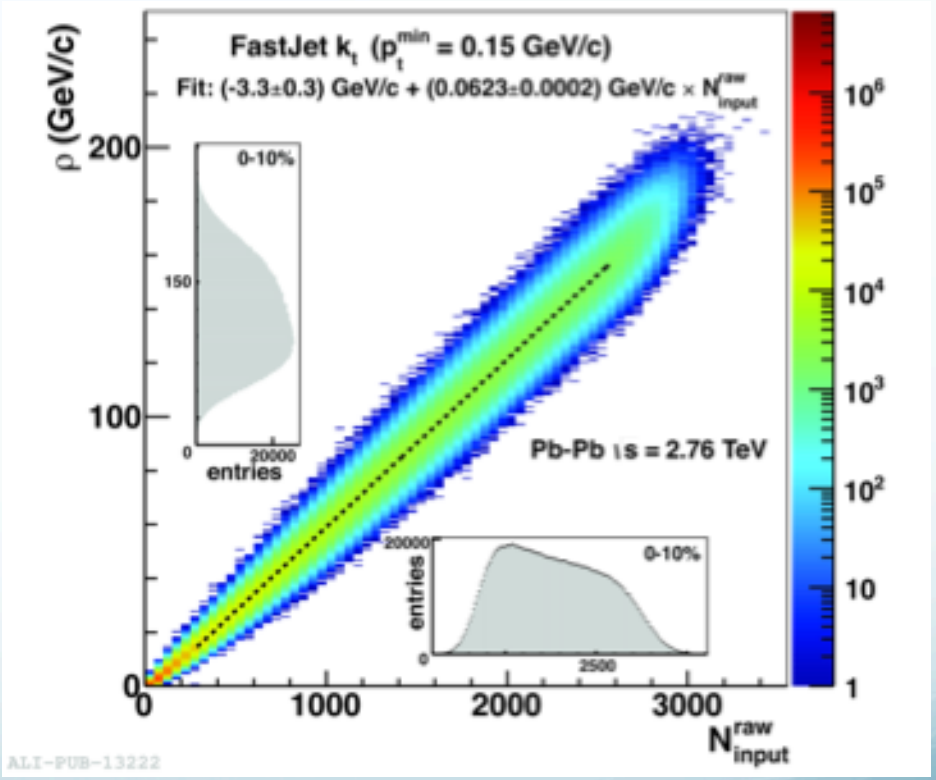

R=0.2
Centrality: 0-10%
Centrality: 0-10%
ALICE
Leading track p_T > 0.15 GeV/c
Pb-Pb
PYTHIA
Leading track p_T > 10 GeV/c
Pb-Pb
PYTHIA
Centrality: 50-80%
Centrality: 50-80%
Pb-Pb
$\sqrt{s_{NN}}$=2.76 TeV
shape uncertainty
correlated uncertainty
$N^{X\ GeV/c\ bias}_{ch\ jets} / N^{5\ GeV/c\ bias}_{ch\ jets}$
$p_{T,ch\ jet}$ (GeV/c)

HI Background Determination

Charged Jets $\sqrt{s_{NN}}$ = 2.76 TeV

- Underlying event density (ρ_{ch}), depends on
  - Constituent cut
  - Centrality
  - Event plane
- ρ_{ch} : **median** of $p^{ch}_{T,kTjet} / A_{kTjet}$
  - 2 leading jets removed
    - May be sensitive to jet fragments outside k_T jet cone
  - Determined event-by-event
- ρ_{ch} is not corrected for detector effects or missing energy
- Subtracted from signal jets on a jet-by-jet basis

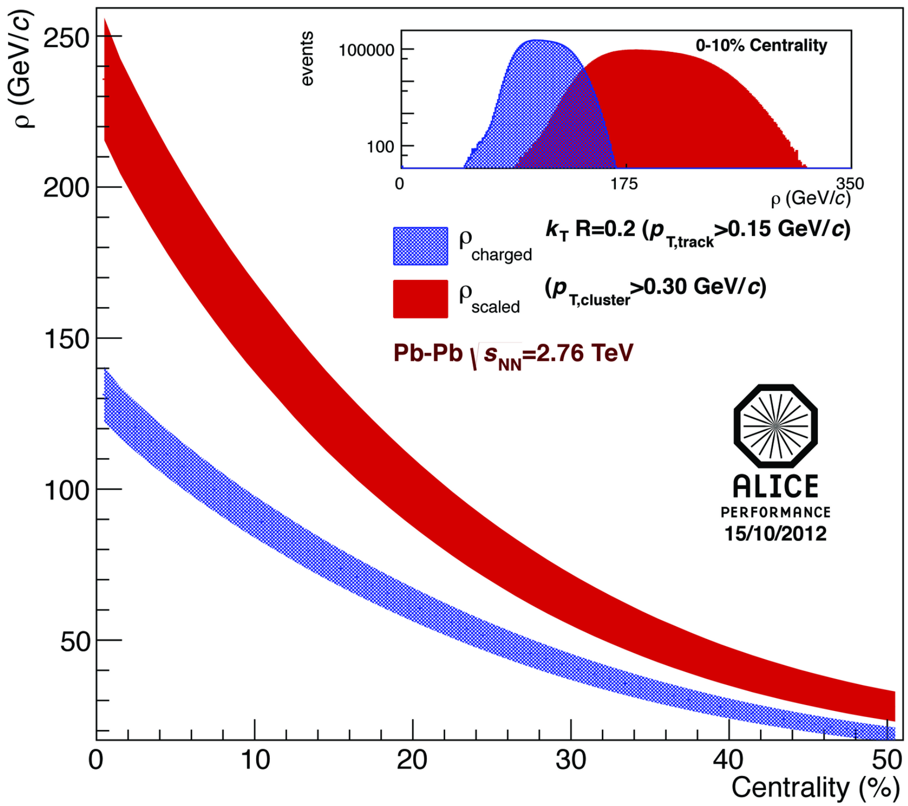
JHEP 1203:053, 2012
(arxiv:1201.2423)



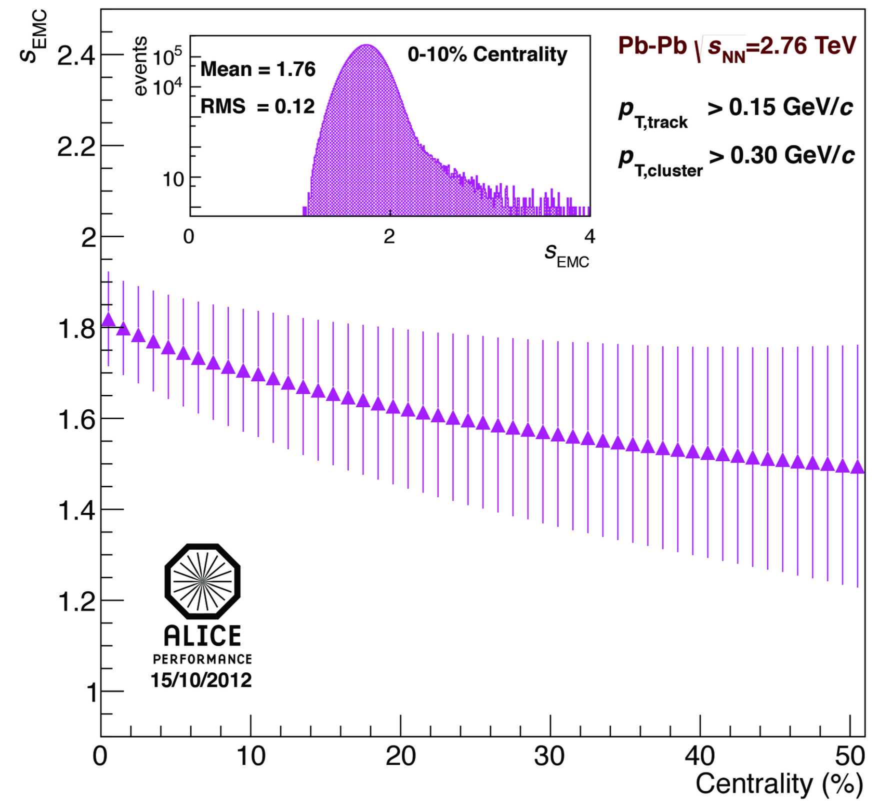
$$p^{ch,unc}_{T,jet} = p^{rec}_{T,jet} - \rho_{ch} A$$

HI Background Determination Full Jets

$\sqrt{s_{NN}}$ = 2.76 TeV



ALI-PERF-44505



ALI-PERF-44509

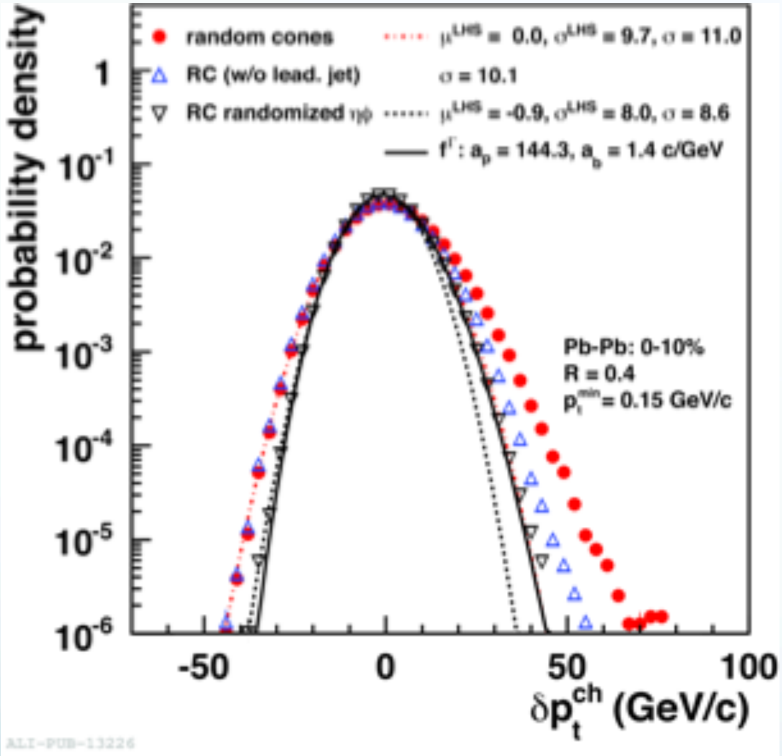
Centrality dependent scale factor accounts for neutral energy

$$\rho_{scaled} = \rho_{ch} \times s_{EMC}$$

Background Fluctuations

JHEP 1203:053, 2012 (arxiv:1201.2423)

Jets $\sqrt{s_{NN}}$ = 2.76 TeV



- Fluctuations in the background determined via δp_T
  - Random cones (RC)
  - Depend on
    - Constituent cut
    - R
    - Centrality
    - Event plane
    - Detector

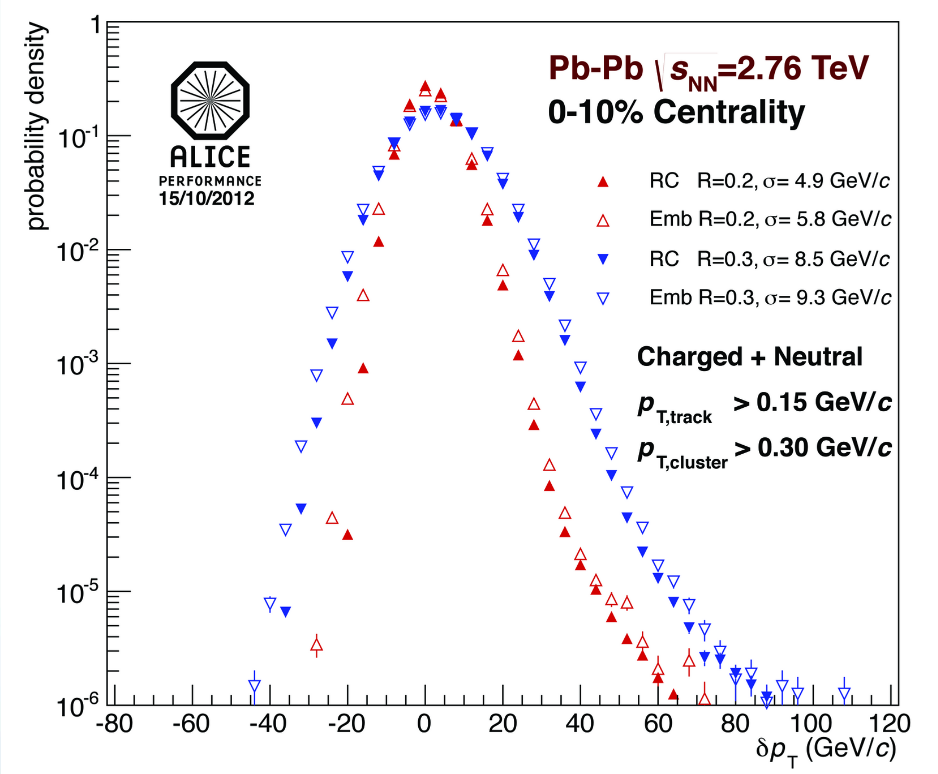
δp_T is not corrected for detector effects – Experiment specific

$$\delta p_T^{ch} = p_{T,RC}^{rec} - \rho_{ch} \pi R^2$$

- δp_T is used to construct unfolding response matrix

Background fluctuations

Full Jets $\sqrt{s_{NN}}$ = 2.76 TeV



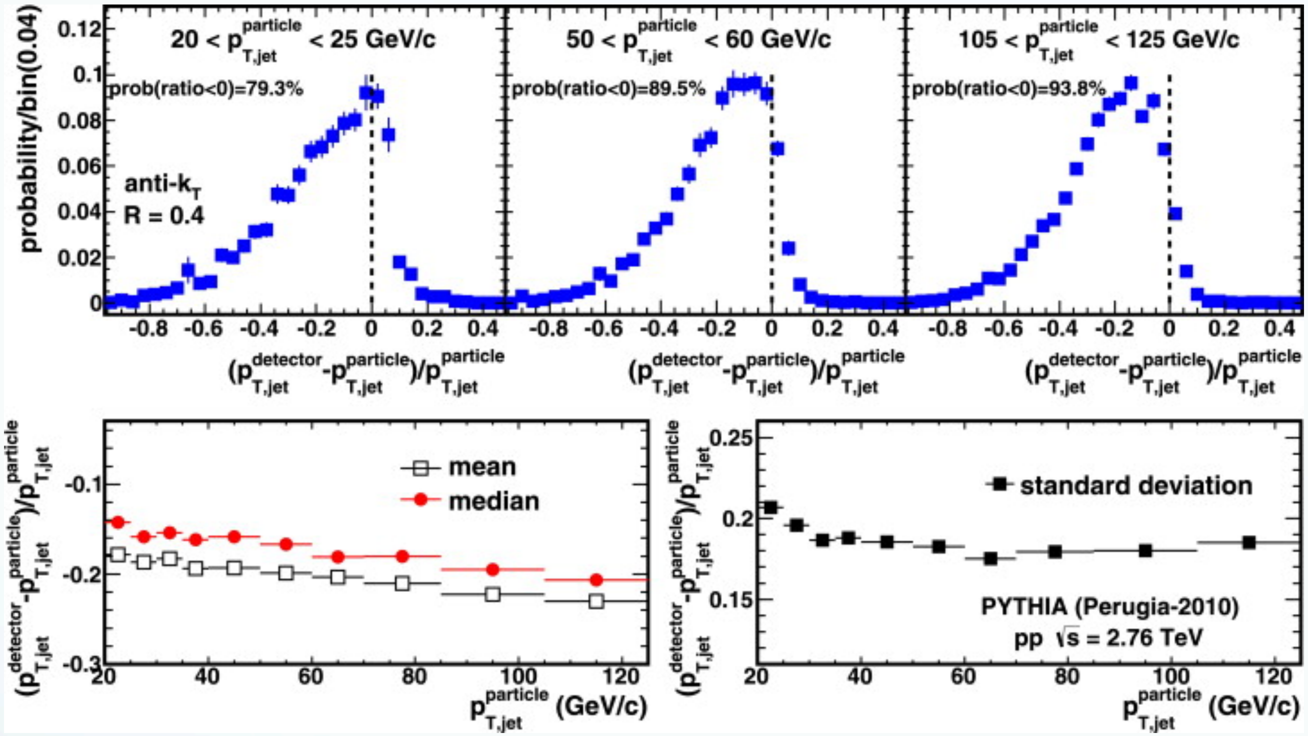
- Different method can be used to determine δp_T
  - Random cones
  - Embedded track
  - Embedded Pythia jet

$$\delta p_T = p_{T,RC}^{rec} - \rho\pi R^2$$

$$\delta p_T = p_{T,RC}^{rec} - \rho A - p_{T,probe}$$

- As R increases, width of δp_T increases which complicates unfolding
- δp_T is used to construct unfolding response matrix

Full Jet Detector Effects pp



Probability vs

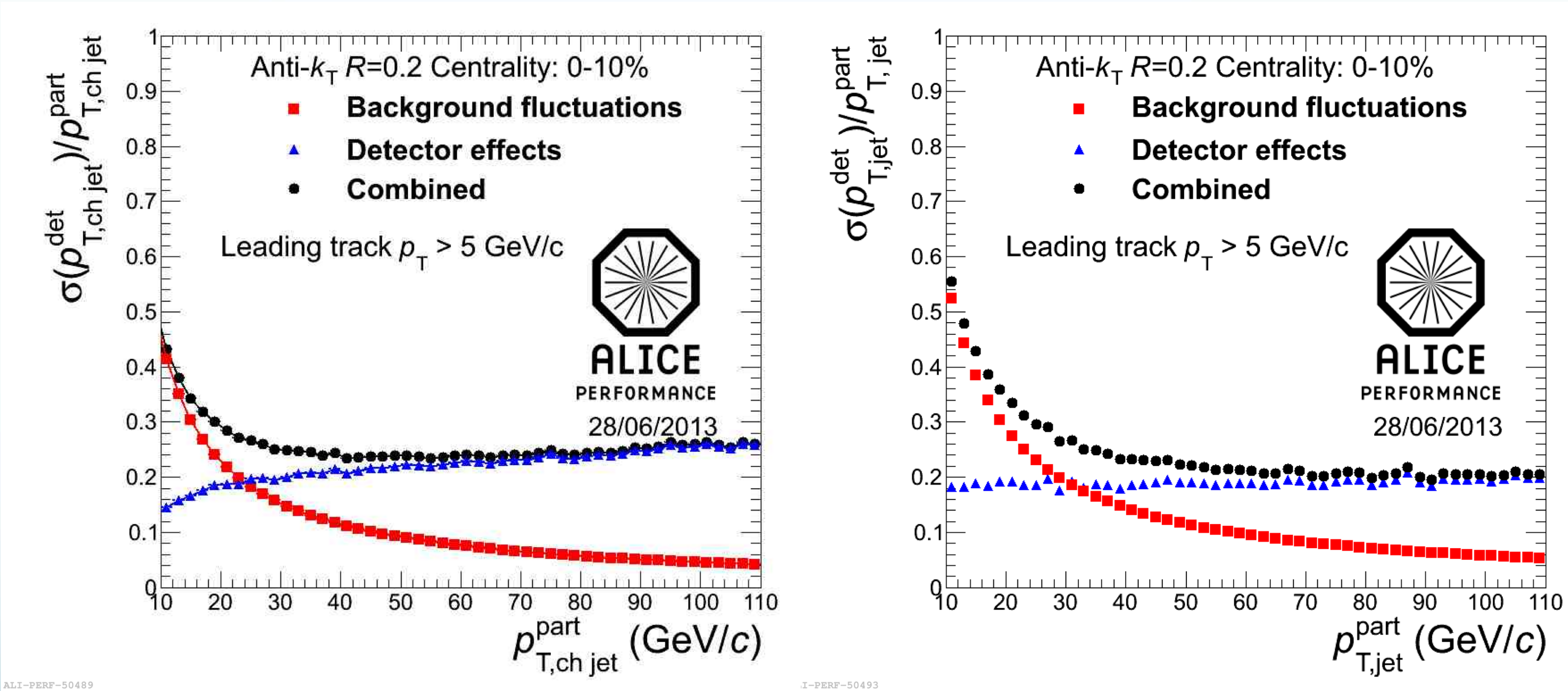
$$\frac{(p_{T,jet}^{detector} - p_{T,jet}^{particle})}{p_{T,jet}^{particle}}$$

$$\frac{(p_{T,jet}^{detector} - p_{T,jet}^{particle})}{p_{T,jet}^{particle}} \text{ vs } p_{T,jet}^{particle}$$

- *Shift of jet energy scale ~ 20%, JES uncertainty < 3.6%*
  - *Depends on fragmentation model*
    - *PYTHIA vs HERWIG, quark vs gluon jets*
- *Jet energy resolution ~ 18%*
  - Dominated by tracking efficiency (similar in Pb-Pb)

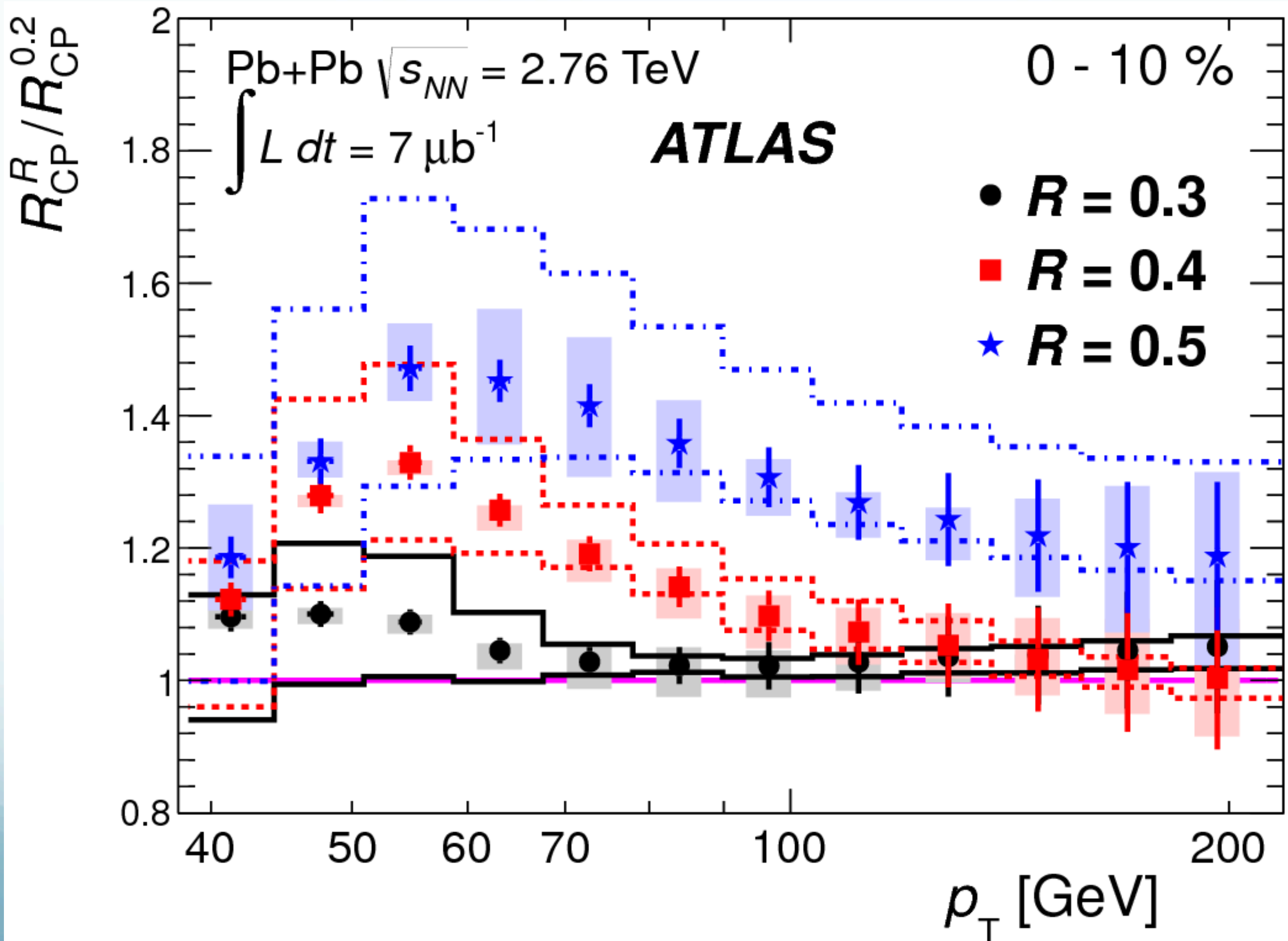
Bin-by-bin unfolding technique used to correct detector effects

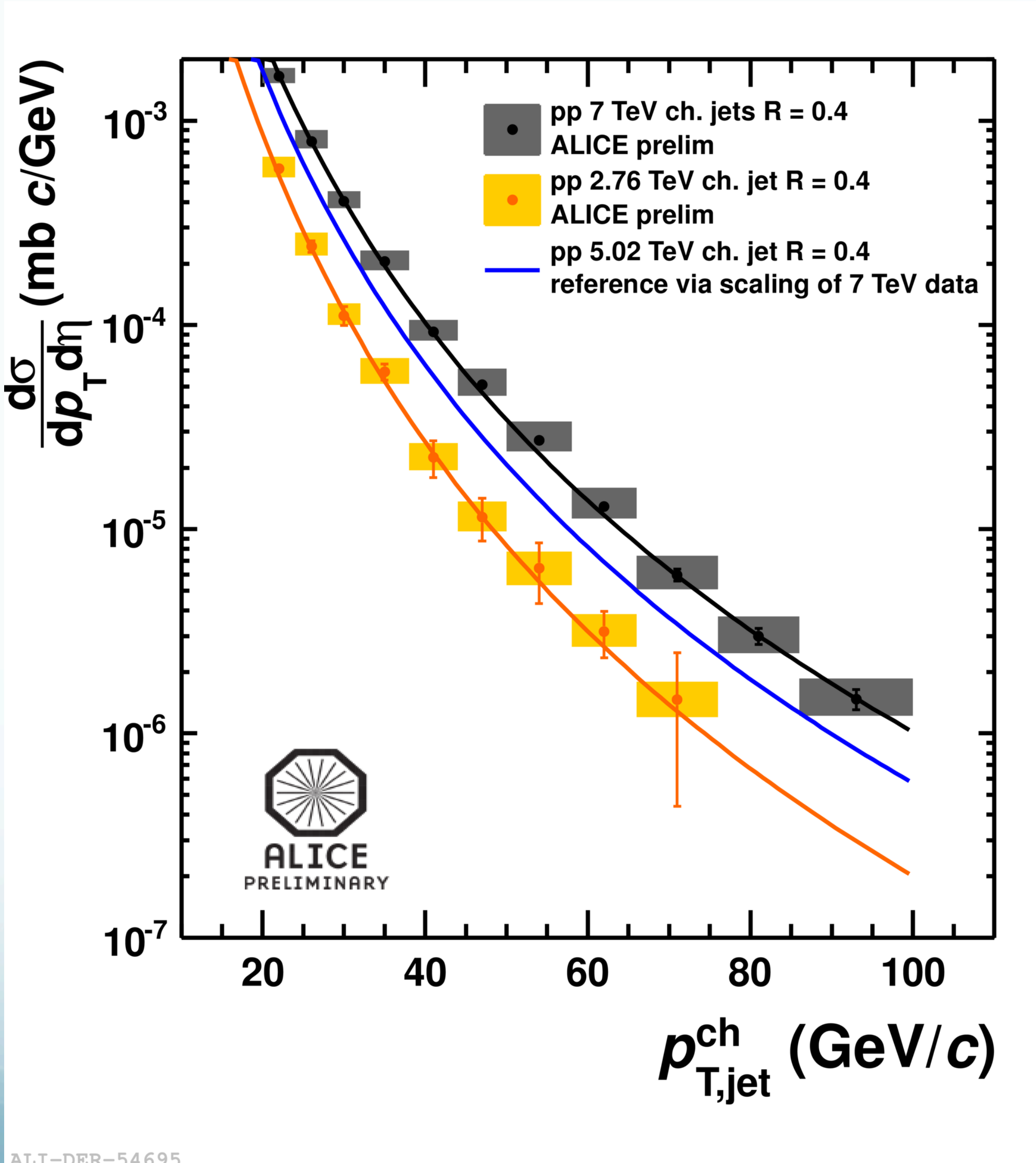
arXiv:1301.3475
PLB: 10.1016/j.physletb.2013.04.026



Charged jet 5% JES uncertainty is at 50 GeV and 3% is at 100 GeV

Phys. Lett. B 719 (2013) 220-241





reference is created from pp jets at 7 TeV scalign done via reproducing the same scaling obtained from MC described by:

$$N_{5TeV} = N_{7TeV} \frac{N_{5TeV\_MC}}{N_{7TeV\_MC}}$$

Where N is one bin of the jet spectrum. Several Monte Carlo generators used give an uncertainty of roughly 2%

2.76 TeV data has larger uncertainty