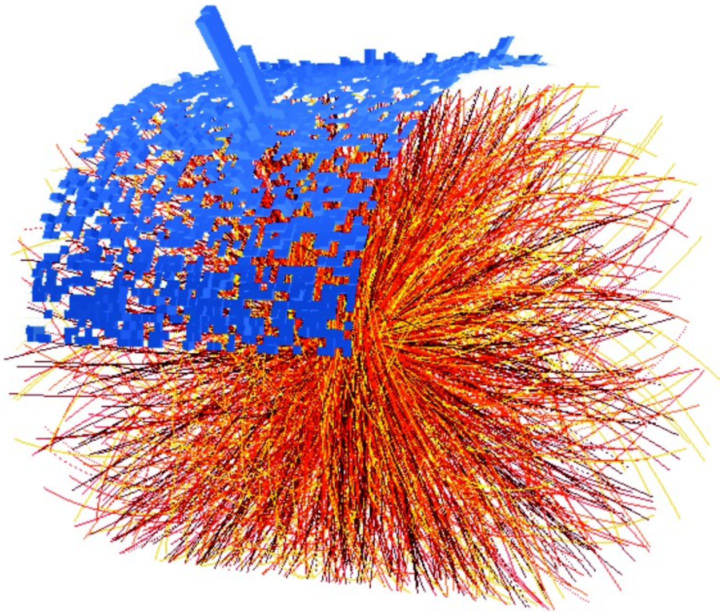


Results on Jet Spectra and Structure from ALICE

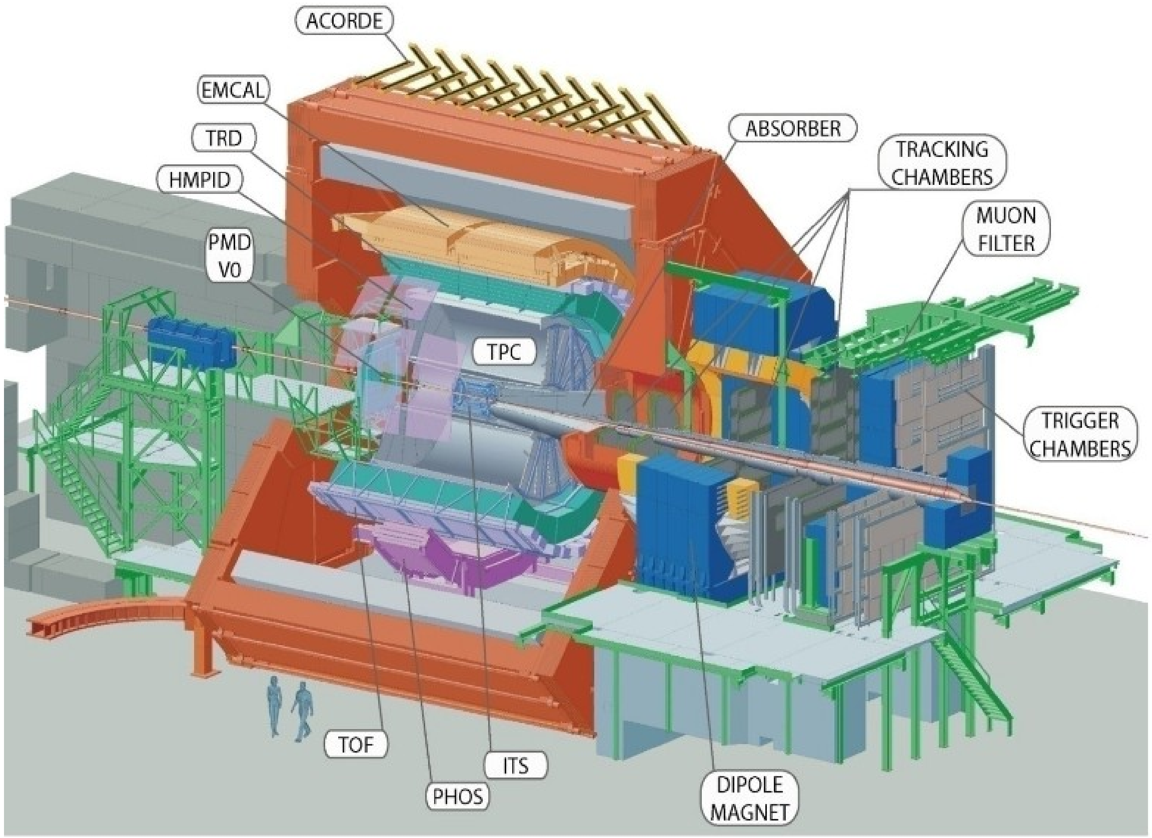
Andreas Morsch
CERN
for the ALICE Collaboration

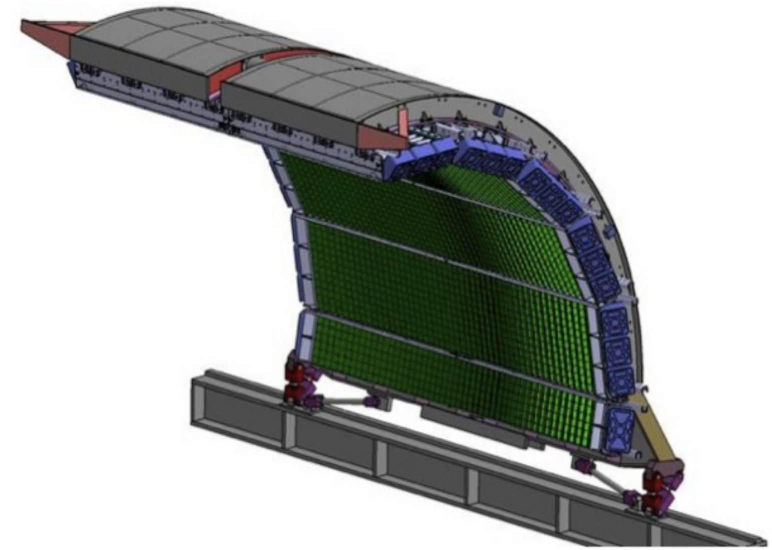
Quark Matter 2012
Washington DC, 08/14/2012

Outline

- Jet reconstruction in ALICE
- Jet spectra pp at $\sqrt{s}$ = 2.76 TeV
  - Reference for Pb-Pb
- Charged jet yield suppression in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
  - $R_{AA}(p_T^{Jet})$ using Pythia reference
  - Resolution parameters R dependence
- Hadron-Jet correlations
  - Modification of conditional yields and their R dependence
- Isolated γ-hadron correlations
- Conclusions

Jet Reconstruction in ALICE





Energy and direction of neutral particles

EMCal: Pb-scintillator sampling calorimeter which covers:

$|\eta| < 0.7$, $80° < \varphi < 180°$

- 11520 towers with each covers

$\Delta\eta \times \Delta\varphi \sim 0.014 \times 0.014$

4-momenta of charged particles

Tracking: $|\eta| < 0.9$, $0 < \varphi < 360°$

TPC: gas detector

ITS: silicon detector

Charged constituents

Neutral constituents

JET

Jet Finder and Inputs

- Anti-k_T Algorithm from FastJet* package
  - Resolution parameter R = 0.2, 0.3, 0.4
  - Area cut A > 0.1-0.4 avoids extremes
  - Jet vector from boost invariant p_T recombination scheme
- Charged Jets
  - Input: tracks with p_T > 150 MeV/c
  - Advantage: full azimuth (φ) coverage
- Fully reconstructed jets
  - Input
    - Tracks with p_T > 150 MeV/c
    - EMCAL clusters E_T^{clus} > 150 MeV after correction for energy from charged particles
    - Jet required to be fully contained in EMCAL acceptance
  - Advantages: trigger capability, higher $p_{T,Jet}$ reach, unbiased fragmentation

* M. Cacciari, G.P. Salam and G. Soyez, Eur.Phys.J. C72 (2012) 1896 [arXiv:1111.6097]

Distance Definition

$$D_{ij} = \min\left(p_{Ti}^{2p}, p_{Tj}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2}; D_i = p_{Ti}^{2p}$$

$$k_T(\text{anti}\,k_T): p = 1(-1)$$

Compute all D_{ij}, D_i, $d = \min(D_{ij}, D_i)$

if $d = D_{ij}$: combine i with j

if $d = D_i$: i is final state jet

Jet Reconstruction
Corrections

- Jet-by-Jet
  - Charged particle energy correction for EMCAL clusters

$$E_{\rm clus}^{\rm corr} = E_{\rm clus}^{\rm raw} - \sum p^{\rm matched}, \quad E_{\rm clus}^{\rm corr} > 0$$

  - Pb-Pb: Underlying event (UE) energy correction

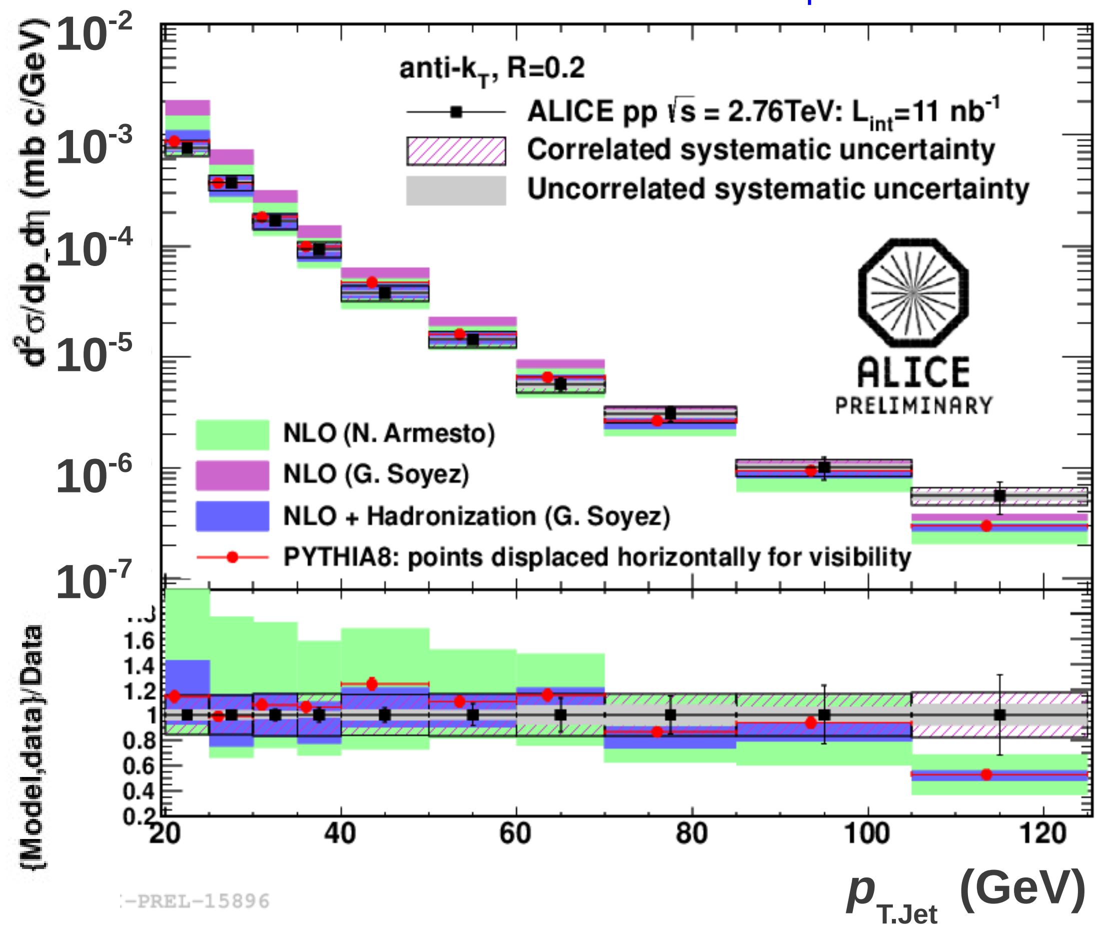
$$p_{\rm T\,,Jet} = p_{\rm T}^{\rm rec} - p_{\rm T}^{\rm UE}$$

- Jet spectrum corrections: bin-by bin or unfolding
  - Corrections for unmeasured neutral energy (n, K^0_L) and related fluctuations of the jet energy scale (JES)
  - Tracking inefficiency and corresponding fluctuations
  - Pb-Pb: Smearing due to UE energy fluctuations

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

- JES uncertainty: 4%
  - Missing neutral energy
  - Tracking efficiency
  - Energy double counting (charged particle correction)
- Jet p_T resolution 20%
  - Event-by-event fluctuations of JES
  - Track $\Delta p_T / p_T$ = 40 GeV/c: 4%
  - EMCAL resolution at E = 40 GeV: 3%
- Effects of efficiency and resolution on jet spectrum are corrected bin by bin.

anti k_T : R = 0.2



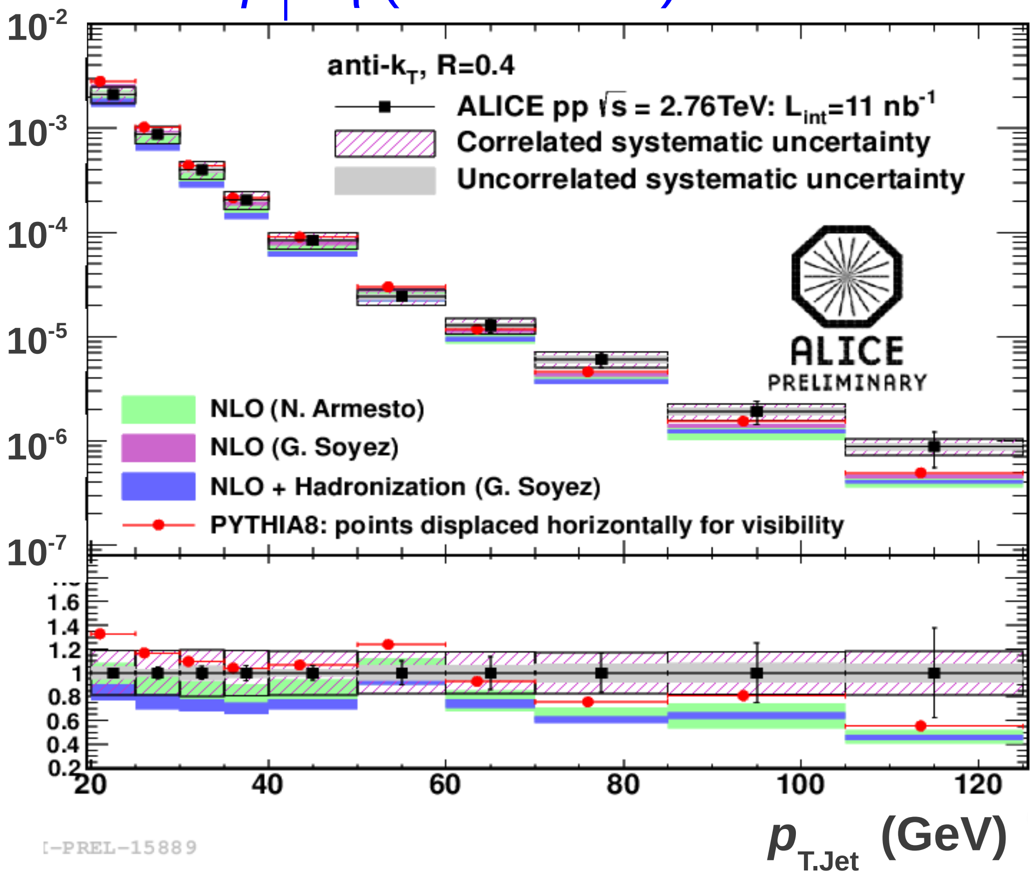
- Good agreement with NLO pQCD + hadronization and Pythia8

- Important reference for Pb-Pb analysis

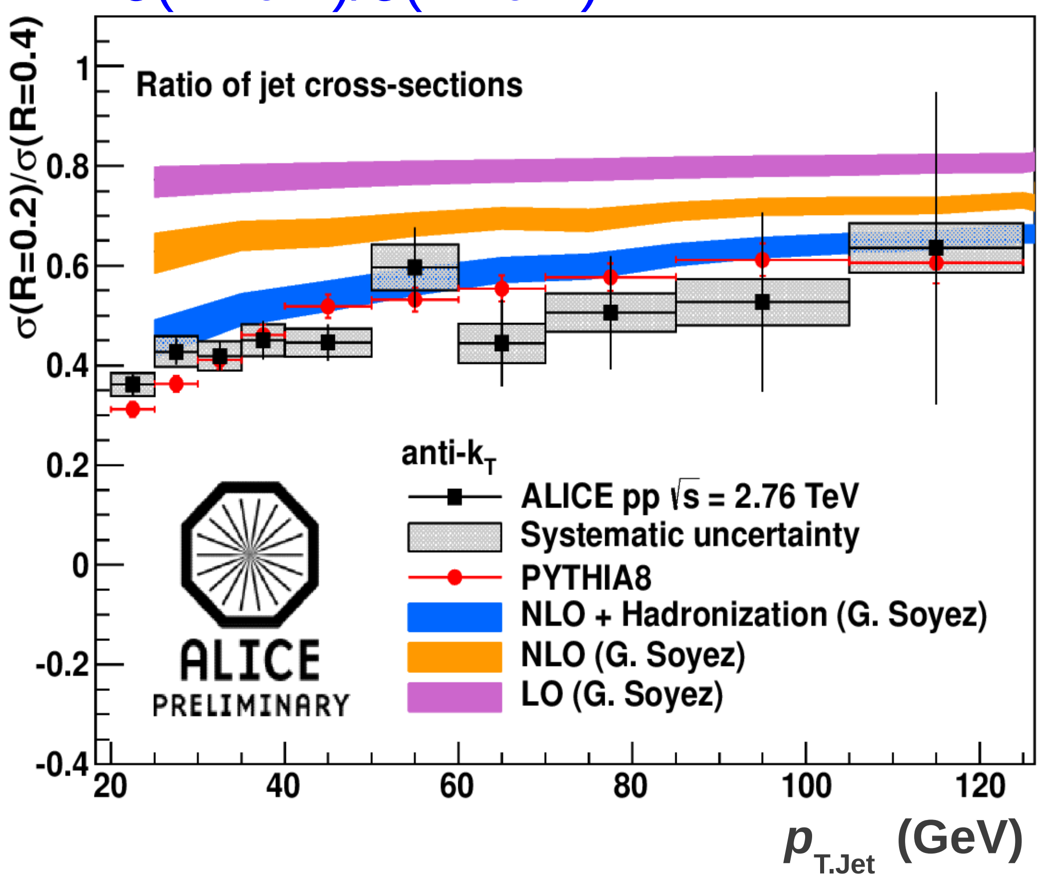
Jets in pp at $\sqrt{s}$ = 2.76 TeV :
Jet shape information by varying R

anti k_T : R = 0.4

$d^2\sigma/dp_T d\eta$ (mb c/GeV)



$\sigma(R=0.2)/\sigma(R=0.4)$

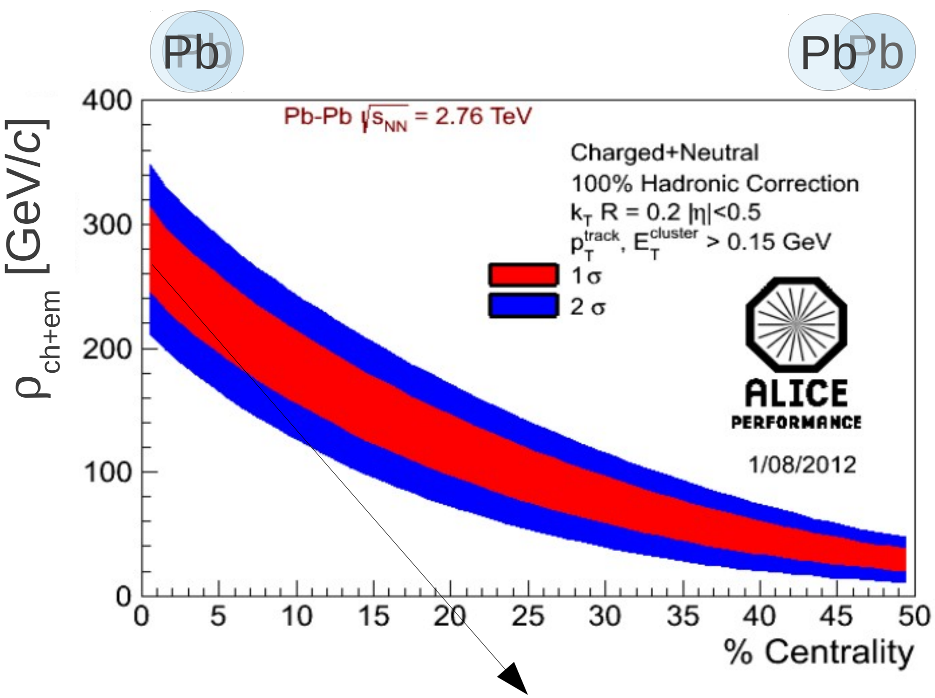


Good agreement with NLO pQCD and Pythia8

Increase of $\sigma(R=0.2)/\sigma(R=0.4)$: Higher p_T jets are more collimated

Jets in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

Background from UE



In jet with R=0.4: ρA = 130 GeV

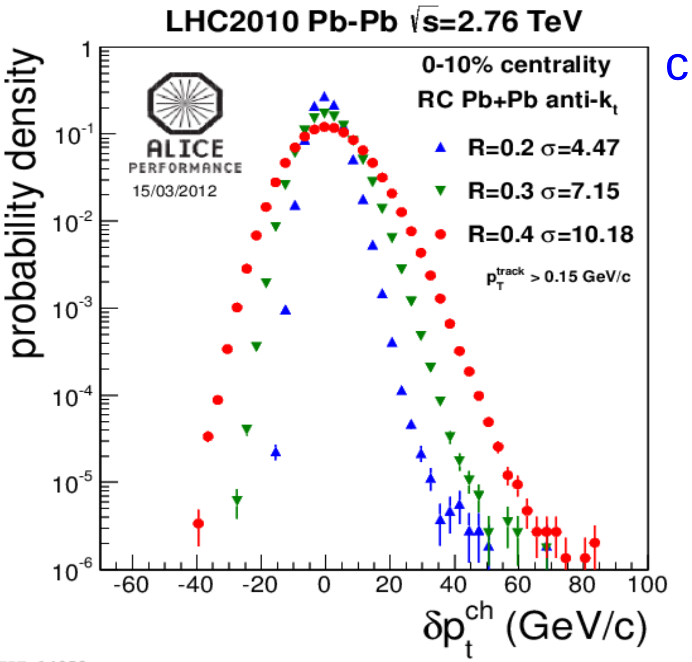
- Corrections required due to UE Energy
  - Event-by-event subtraction of the background energy: $A^{Jet}\,\rho$

$$\rho = \text{median}\left(\frac{p_T^{Jet}}{A^{Jet}}\right)_{k_T-\text{Algorithm}}$$

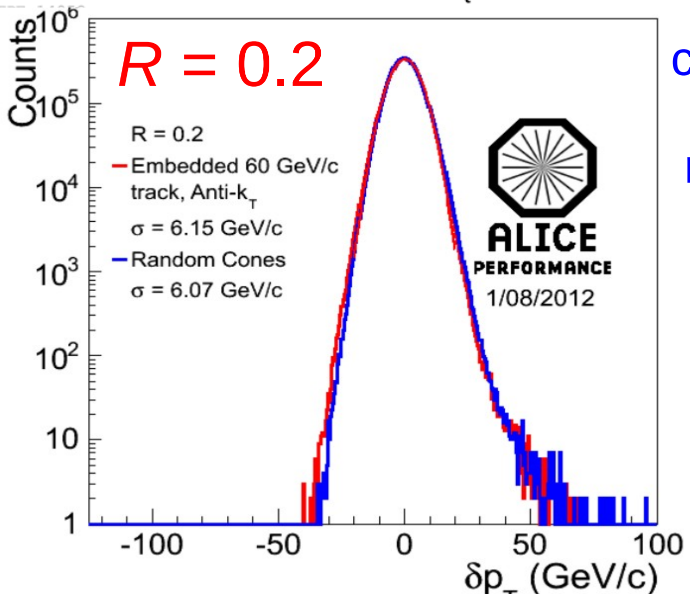
  - Raw spectrum smeared by background energy fluctuations
    - Need to unfold using resolution matrix
  - Jets from background combinatorics (fake jets) at low p_T^{Jet}:
    - Efficiently removed by requiring a p_T > 5 GeV/c leading hadron inside jet

Background Fluctuations

Pb-Pb 0-10%



charged



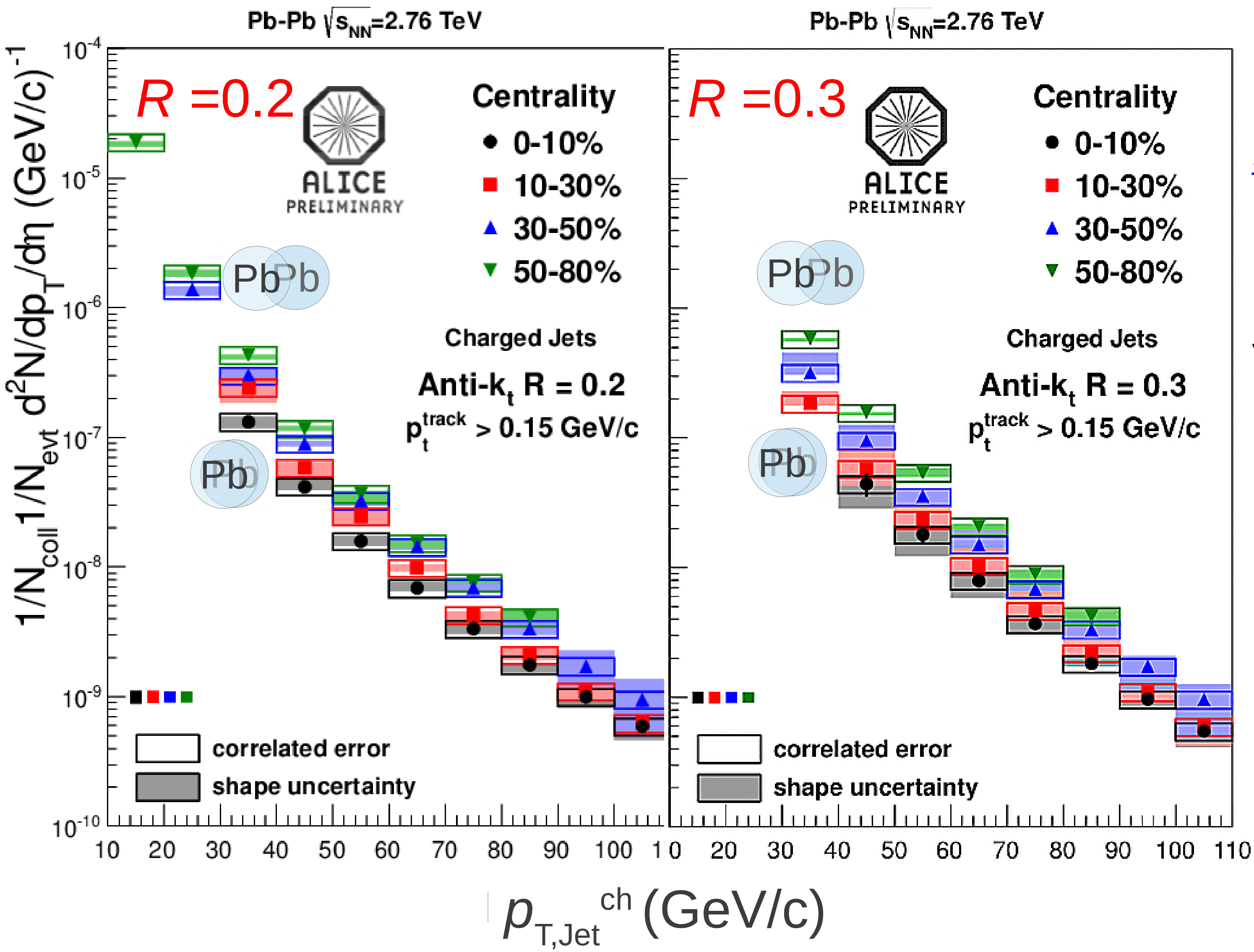
charged + neutral

- In Pb-Pb jet energy resolution limited by background fluctuation within jet area.
- Fluctuations characterized by distribution of

$$\delta p_T = (p_T^{rec} - \rho A^{Jet}) - p_T^{true}$$

- Distribution obtained by embedding particles into min. bias event or by placing random cones with areas close to the ones of reconstructed jets.
  - For anti-k_T: $A \approx \pi R^2$

Charged Jet Spectra in Pb-Pb



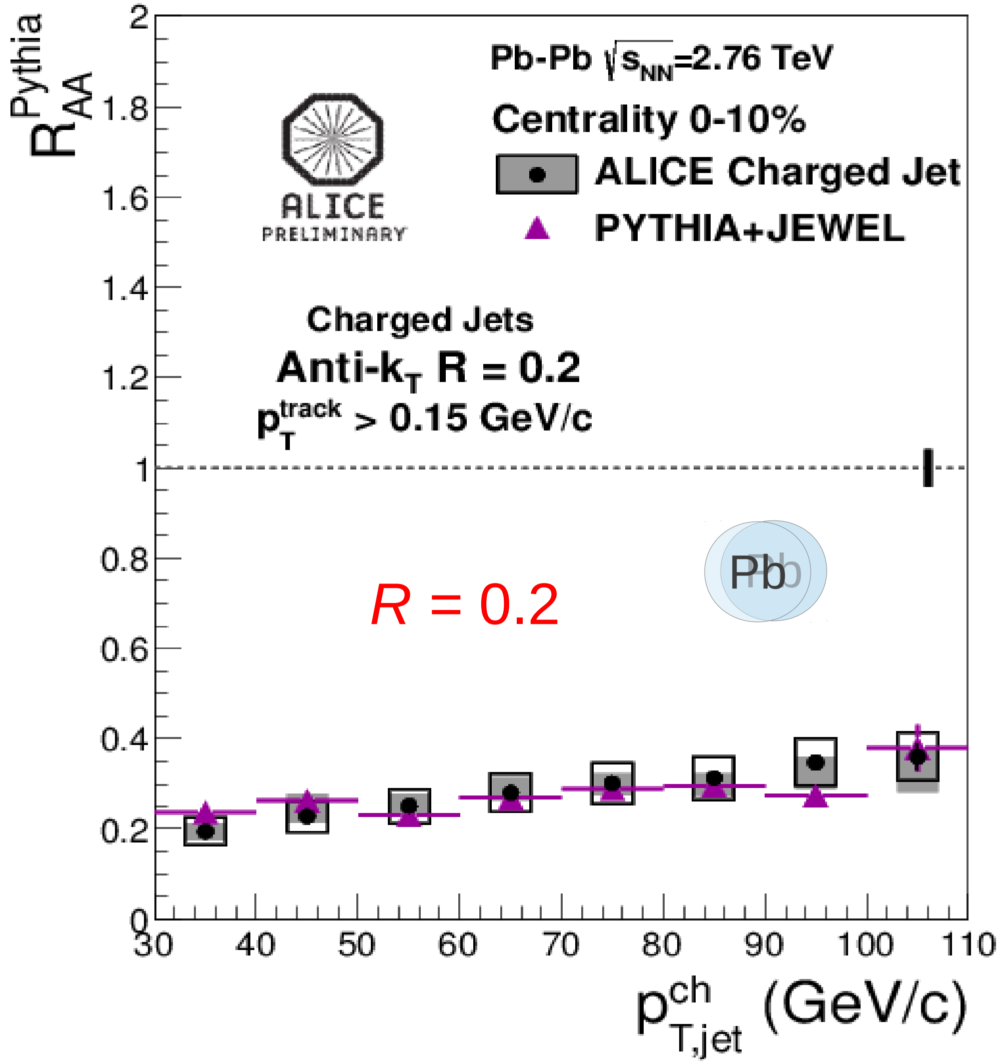
[Systematic uncertainties:]

Regularization: 4%

JES correction: 4-10%

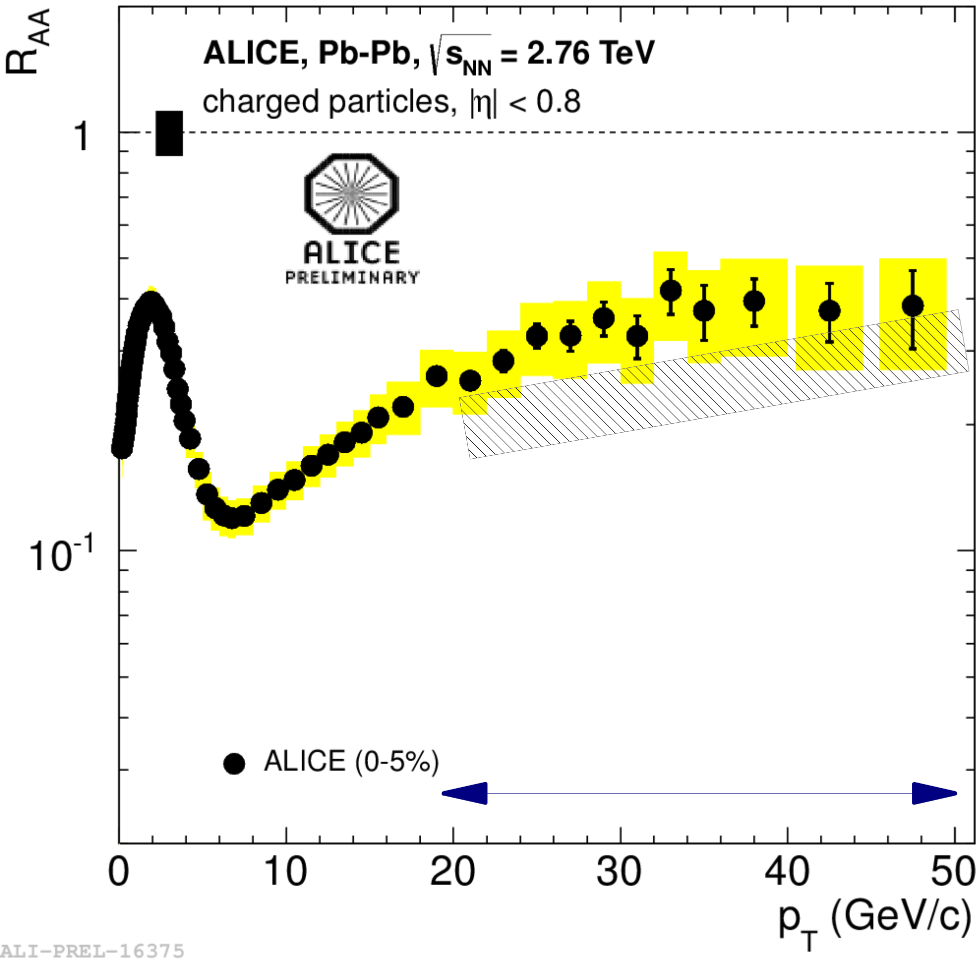
Normalized yield shows suppression increasing with centrality.

Charged Jet R_{AA} wrt Pythia Reference



- Strong jet suppression: R_{AA}^{Jet} = 0.2-0.35 rising with p_T^{Jet}
- Low R_{AA}^{Jet} reproduced by JEWEL MC K. Zapp et al, Eur.Phys.J. **C69** (2009) 617

Comparison with inclusive hadron R_{AA}



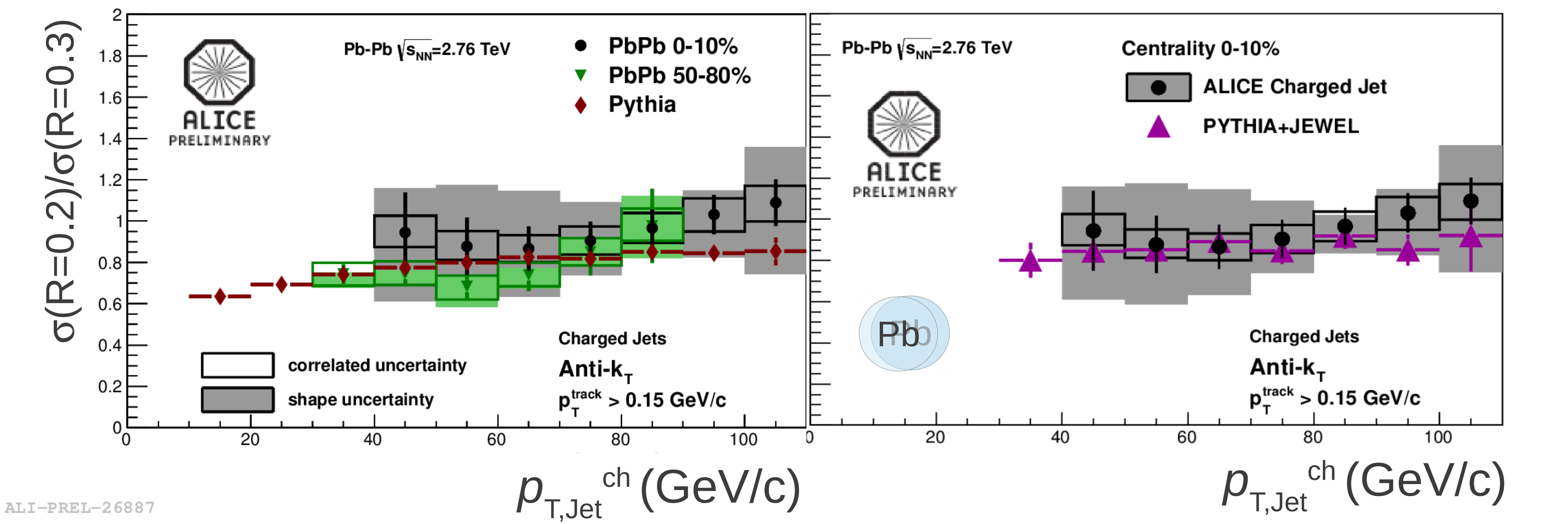
Jet suppression similar to inclusive hadron suppression at comparable parton p_T

Possible scenario:

- Radiated energy mainly outside jet cone
- Leading particle p_T shifted in proportion to its contribution to the jet energy

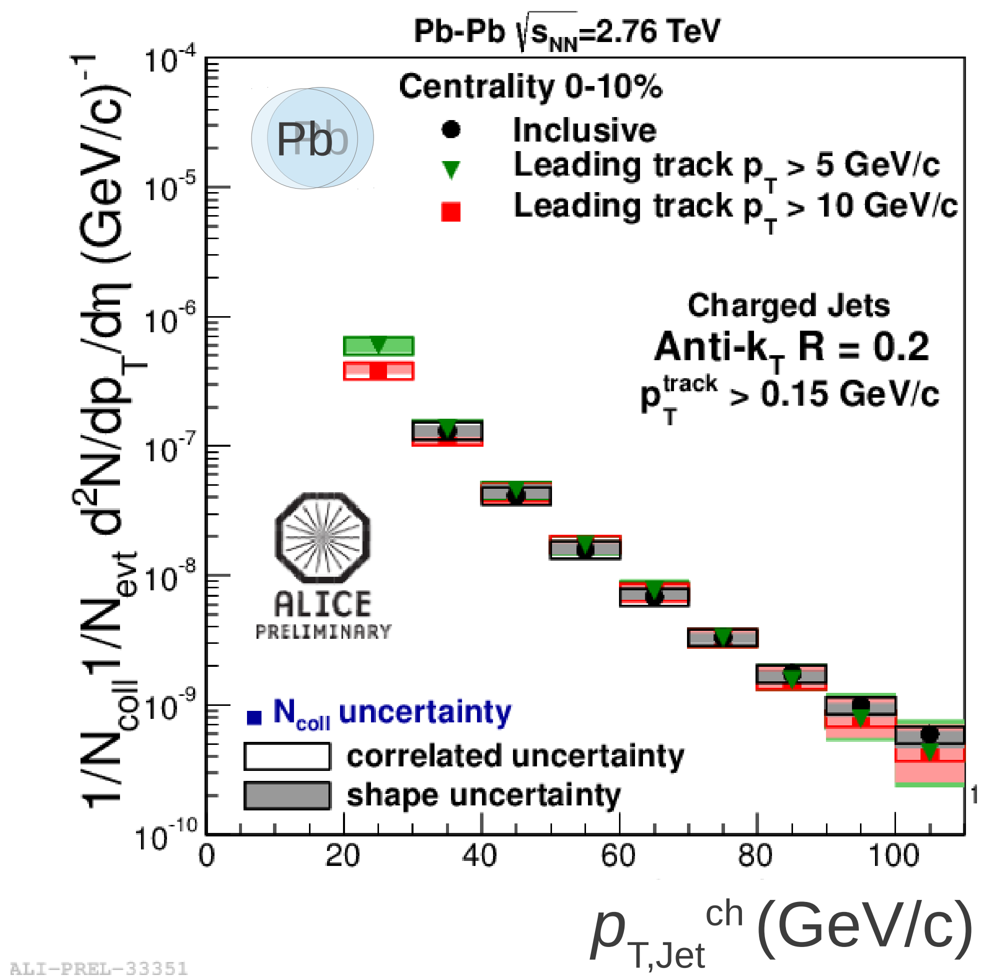
$$\Delta E_{leading} = z_L \, \Delta E_{part}$$

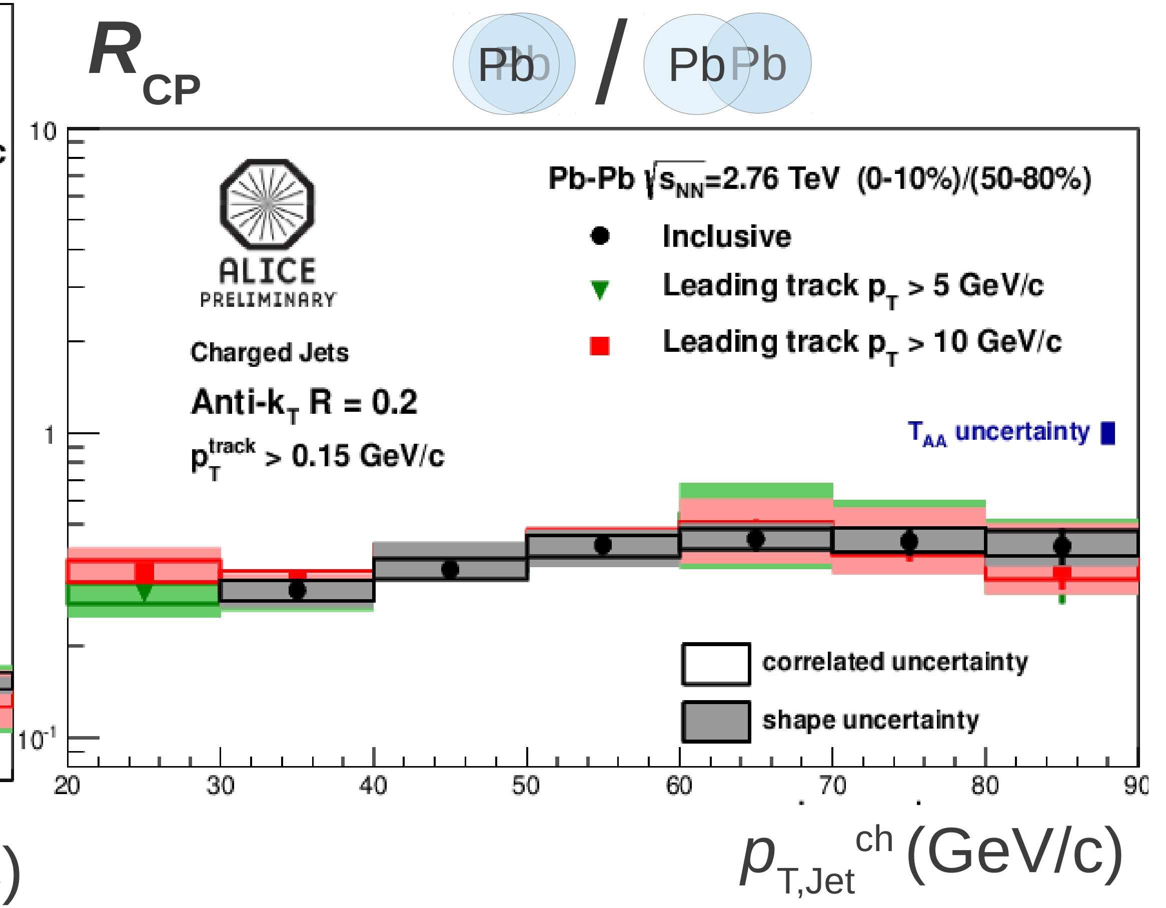
Possible Redistribution of Energy Between *R*= 0.2 and 0.3



- No redistribution of energy within experimental uncertainties
- Ratios consistent with
  - Results from more peripheral collisions
  - Pythia (vacuum fragmentation) and
  - JEWEL MC model calculations

Jets Tagged by High-p_T Hadron





Requirement of high p_T hadron reduces contribution from combinatorial (fake jets)

Improved stability of unfolding allows to assess lower $p_{T,Jet}^{ch}$

No change of fragmentation within uncertainties except for lowest $p_{T,Jet}^{ch}$ bin.

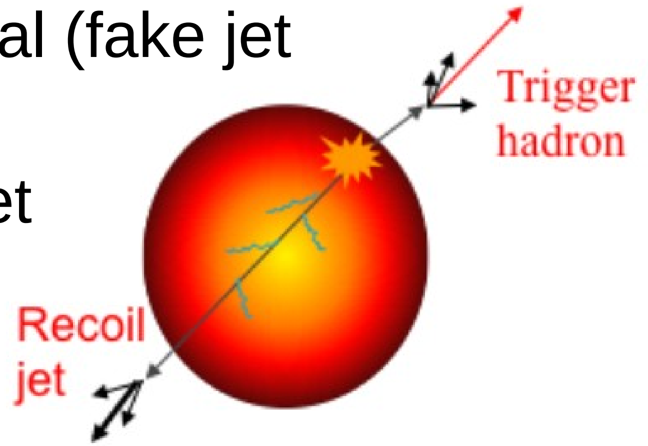
ALICE

More details ...

Rosi Reed, Parallel Session 2B
Poster by Marta Verweij
Poster by RongRong Ma

Hadron-Jet Correlations

- Can surface bias of leading hadrons be used to increase jet suppressions and structure modification ?
  - Idea: Study conditional jet yield requiring a trigger hadron back-to-back with respect to jets
  - If surface bias present the parton producing the jet is biased towards higher in-medium path length
  - Additional advantages:
    - Requiring correlated high-p_T hadron tags hard scatterings suppressing the combinatorial (fake jet background)
    - No fragmentation bias on the recoiling jet



See Talk Leticia Cunqueiro, Parallel Session 3B

Hadron-Charged Jet Correlation Analysis

Uncorrected yield per trigger particle

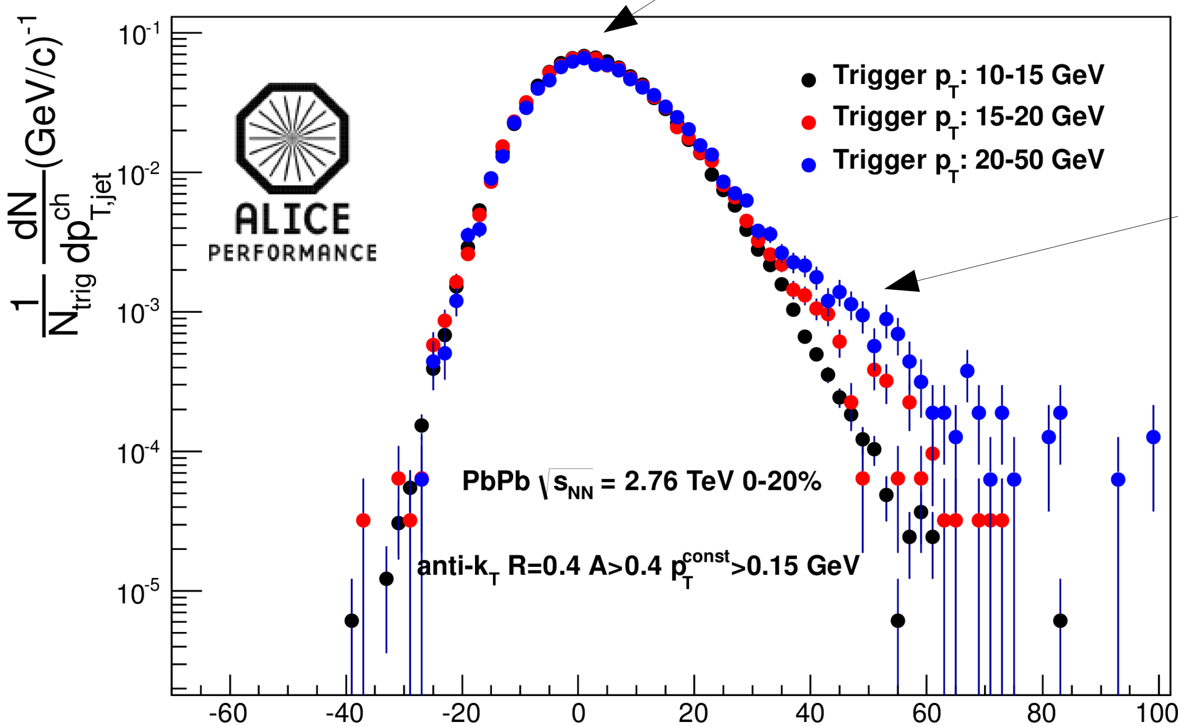
$\Delta\varphi$(hadron, jet) > π-0.6

Low $p_{T,Jet}$ dominated by fake jets and uncorrelated BG

High $p_{T,Jet}$

Clear correlation with trigger p_T

Dominated by high Q^2 events



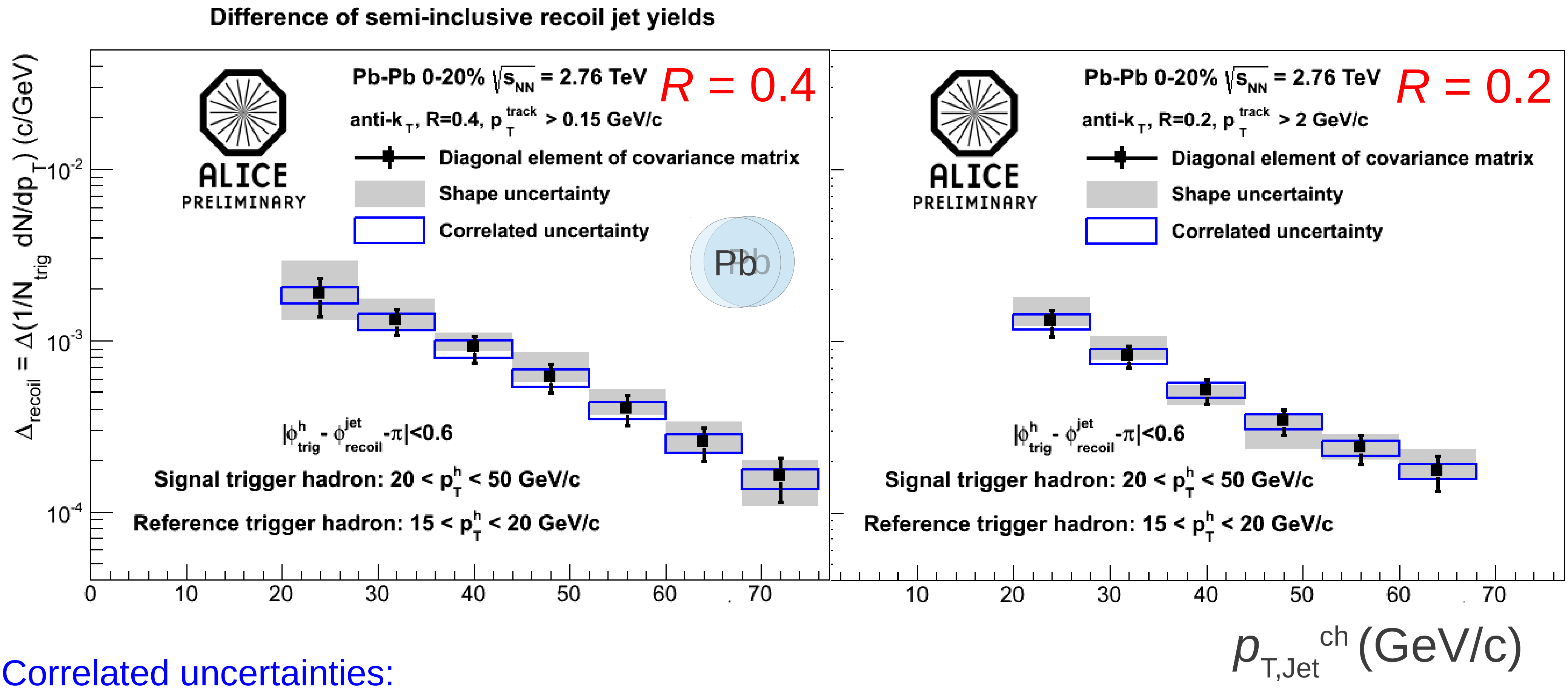
$$p^{ch}_{T,Jet} = p^{rec}_{T} - \rho A^{Jet} \quad [GeV/c]$$

$$\Delta_{recoil}(p^{ch}_{T,Jet}) = \frac{1}{N_{trig}} \frac{d N(p^{ch}_{T,Jet}; p^{min}_{T}, p^{max}_{T})}{d p^{ch}_{T,Jet}} - \frac{1}{N_{trig,ref}} \frac{d N(p^{ch}_{T,Jet}; p^{min}_{T,ref}, p^{max}_{T,ref})}{d p^{ch}_{T,Jet}}$$

How to remove uncorrelated component ?

Study difference between signal recoil spectrum and a reference: $\Delta_{recoil}(p_{T,Jet}^{ch})$

Difference Recoil Spectra



Correlated uncertainties:

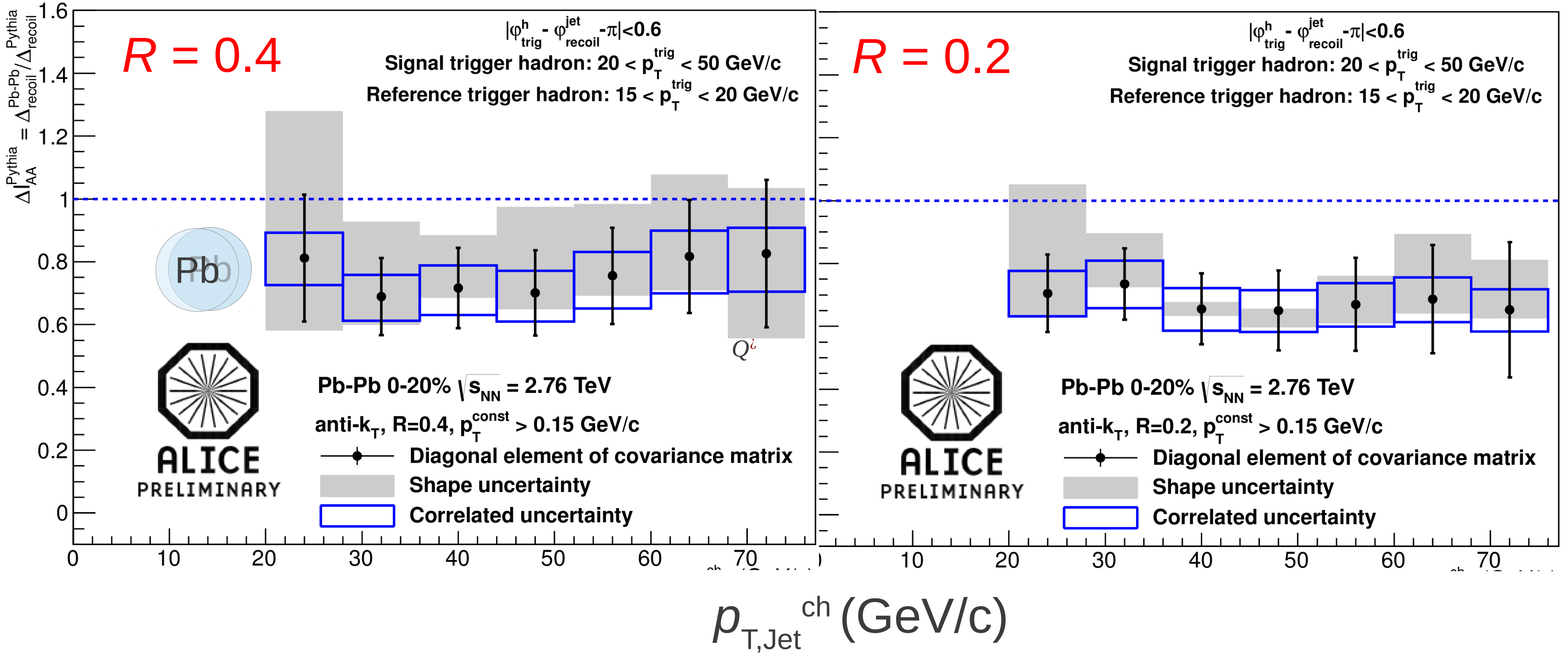
- Flow bias on background induced by hadron trigger
- Tracking efficiency uncertainty
- Reference distribution scaling factor

Shape uncertainty (from unfolding):

- p_T^{min} cut variations, feed in/out
- Regularization: β variations and difference to Bayesian result

$$\Delta I_{AA}\left(p_{T,Jet}^{ch}\right) = \Delta_{recoil}^{Pb-Pb} / \Delta_{recoil}^{pp}$$

ΔI_{AA} using Pythia Reference



Ratio of conditional yield close to unity: $\Delta I_{AA} = 0.75$

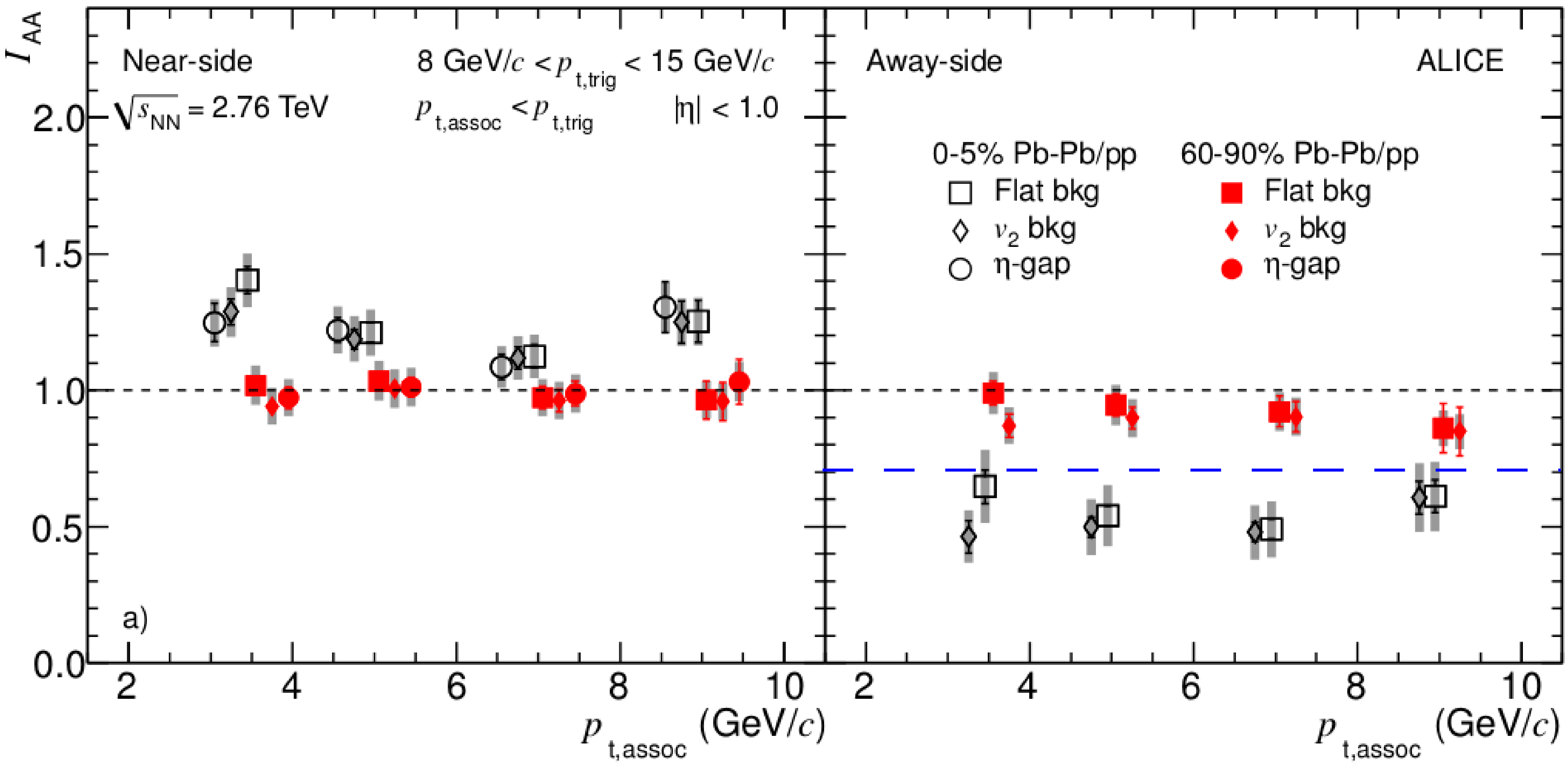
Strong h-Jet pair suppression $R_{AA}^{h}\ \Delta I_{AA} \approx 0.25 \times 0.75 = 0.2$

However, two competing effects are possible:

Recoil jet suppression: ΔI_{AA} decreases

Trigger parton energy loss: ΔI_{AA} increases since at the same p_T^{trig} : $Q^2_{Pb-Pb} > Q^2_{pp}$

Comparison to Di-Hadron Correlations



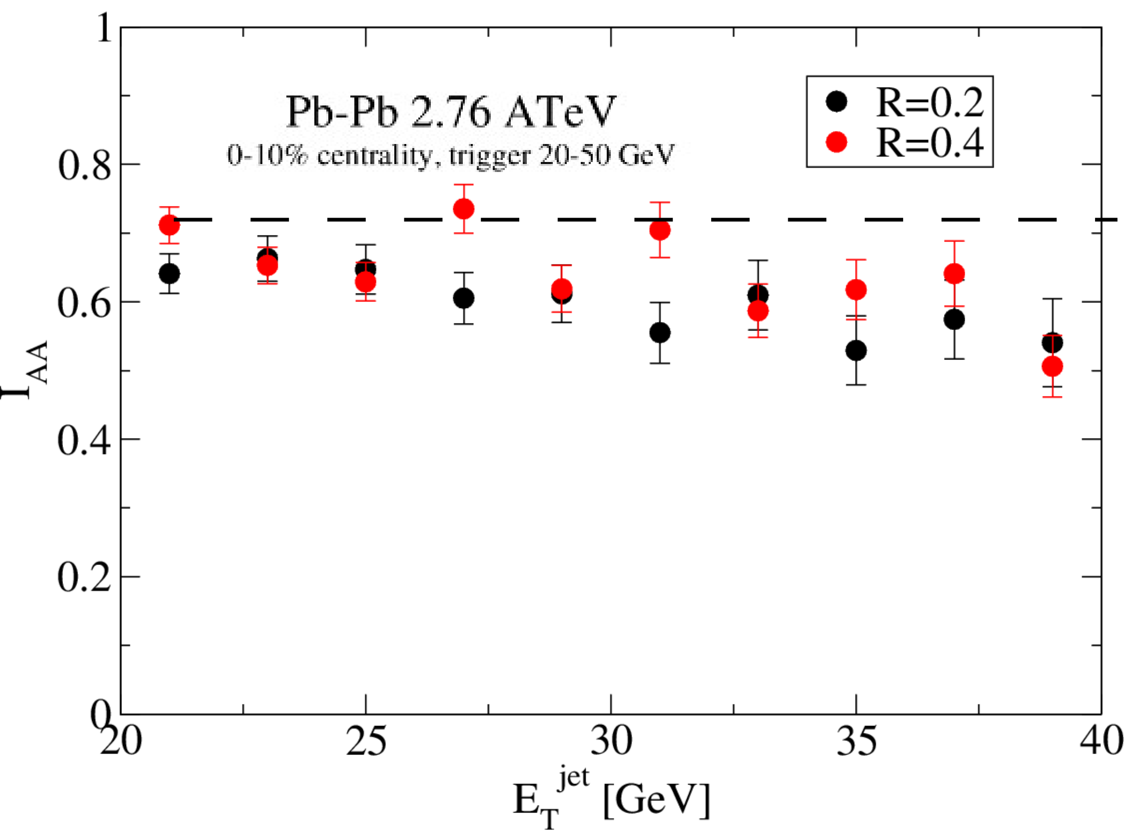
PhysRevLett.108.092301

arXiv:1110.0121v2 [nucl-ex]

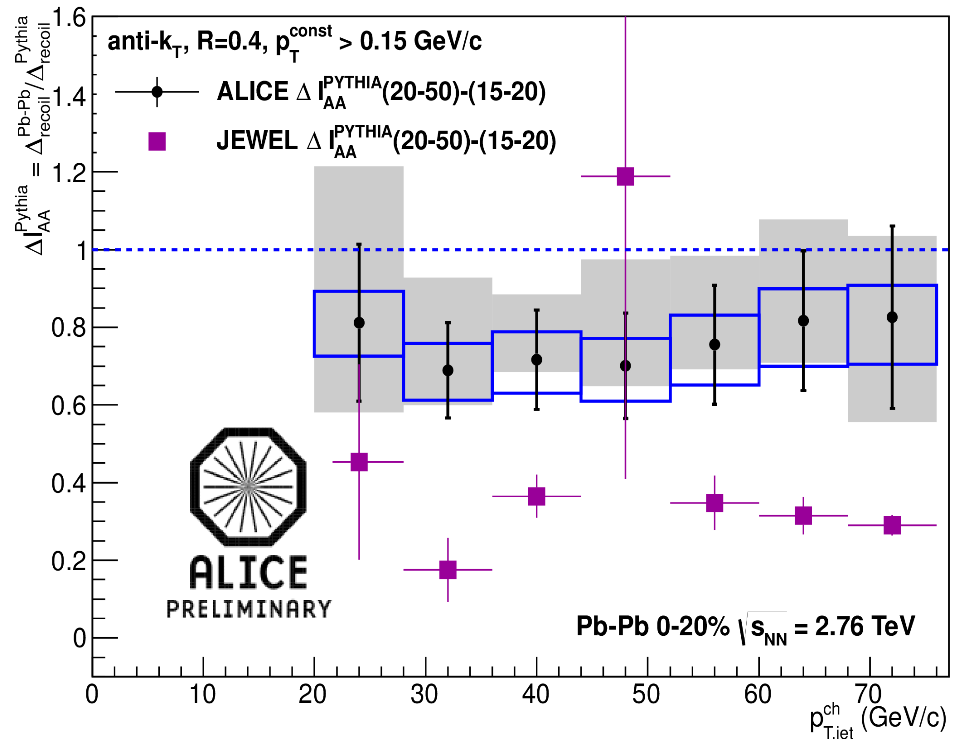
Qualitatively and quantitatively similar behavior in di-hadron correlations at lower Q^2.

Model Comparisons

YaJEM [T. Renk, Phys. Rev. C 80 (2009) 044904]



JEWEL [K. Zapp et al Eur.Phys.J.C69 (2009) 617]

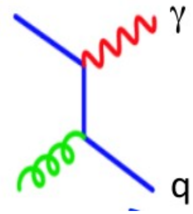


$p_{T,Jet}^{ch}$ (GeV/c)

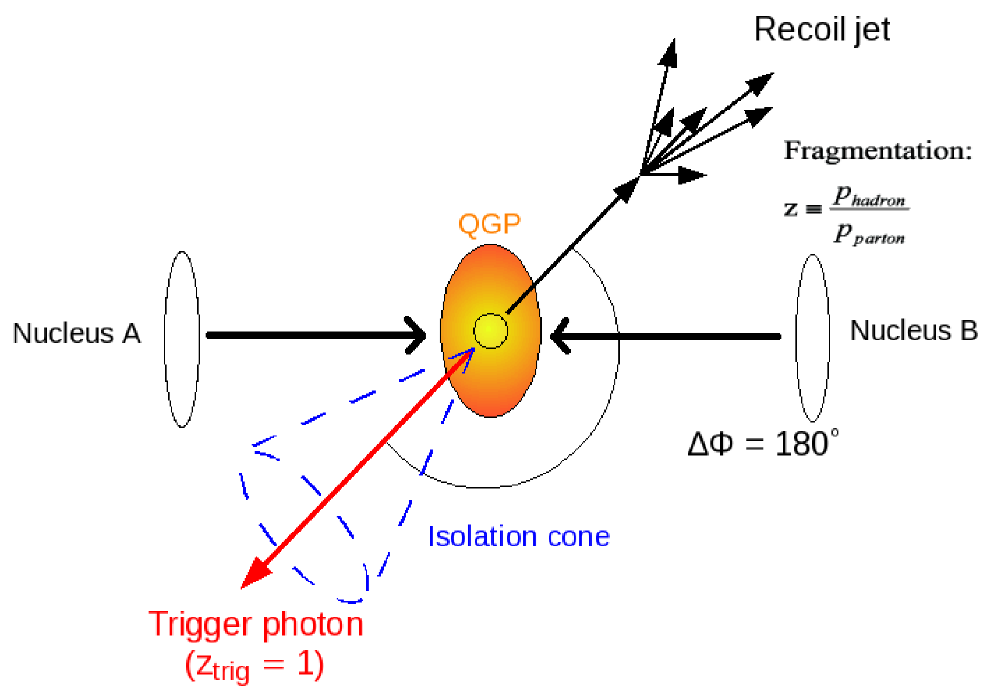
preliminary:unexplored systematics

Isolated Photon Hadron Correlations in pp at √s = 7 TeV

$$x_E = -\frac{p_T^h}{p_T^\gamma}\cos\Delta\Phi \xrightarrow[p_T^\gamma \approx p_T^{parton}]{\text{Isolated photon}} x_E \approx z = \frac{p^h}{p^{parton}}$$



Quark Fragmentation



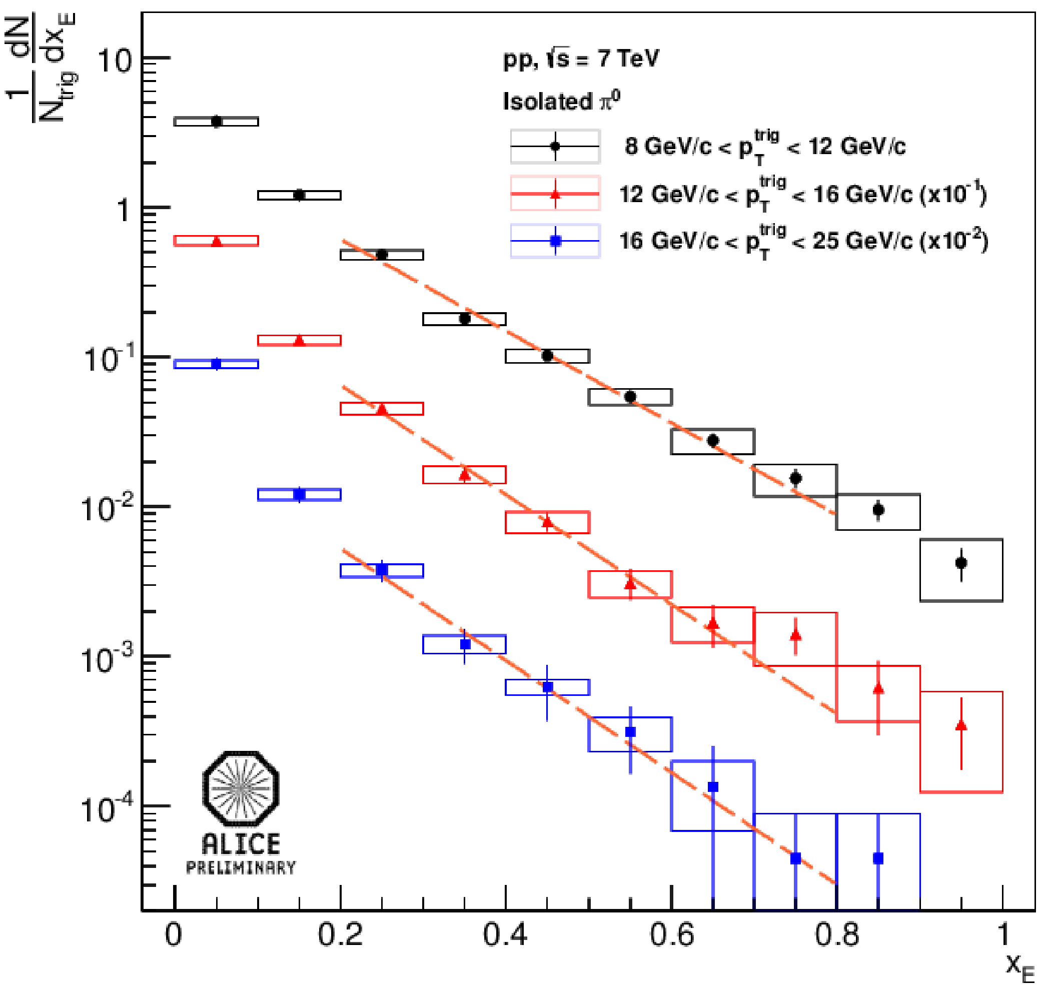
Isolation criterion:
No particle with p_T > 0.5 GeV in cone R=0.4

See Talk Nicolas Arbor, Parallel Session 1B

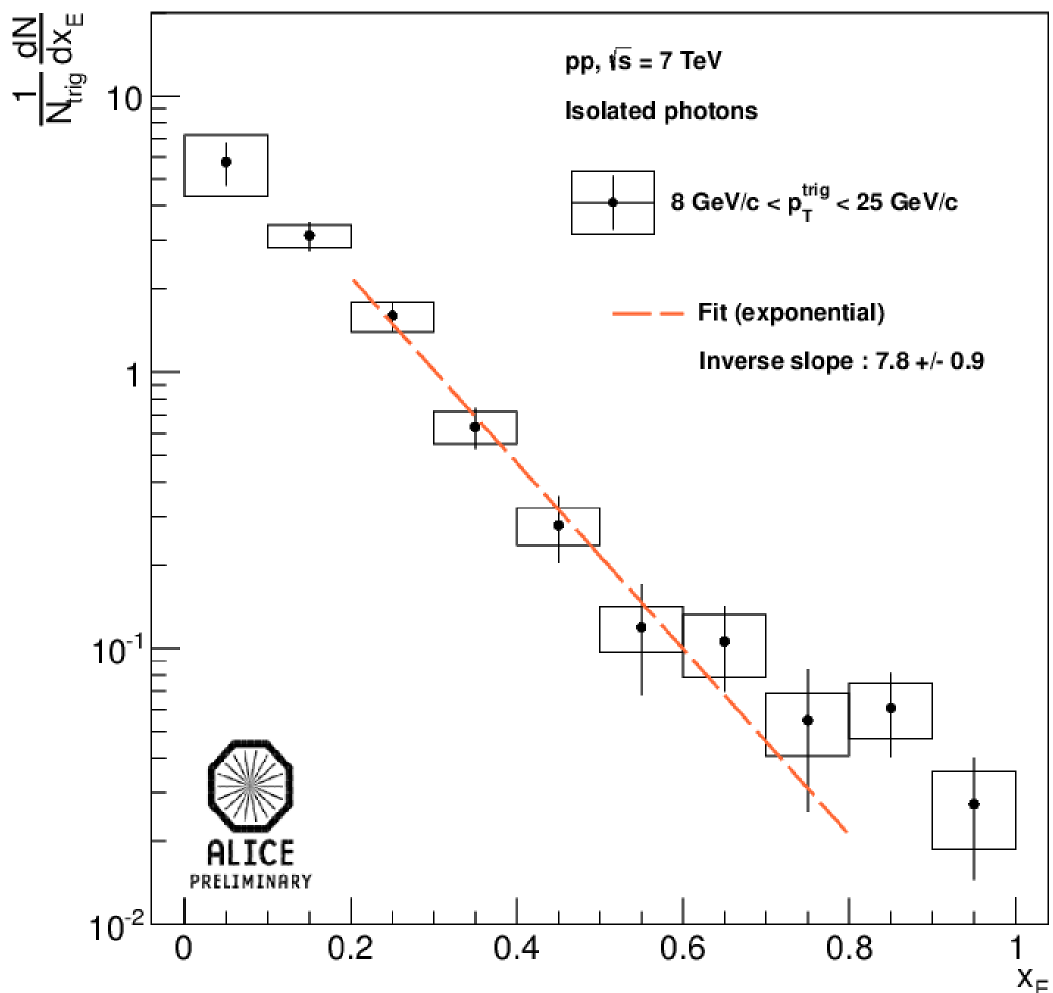
x_E Distributions

$$x_E = -\frac{p_T^h}{p_T^\gamma}\cos\Delta\Phi$$

Isolated π^0



Isolated γ



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Conclusions

- We observe a strong suppression of the inclusive charged jet yield in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  - $R_{AA}^{\text{charged Jet}}$ = 0.2-0.35 in the 30 < $p_{T,\text{ Jet}}^{ch}$ < 100 GeV/c
  - Lower than inclusive hadron R_{AA} at similar parton p_T
- No indication of energy redistribution observed from ratios of jet yields $\sigma(R=0.2)/\sigma(R=0.3)$ within exp. uncertainties.
- Conditional hadron-jet yield suppressed by factor of 0.75 with respect to Pythia reference.
  - Similar to conditional away-side hadron-hadron yields at lower Q^2.
- Yield and conditional yield suppression patterns qualitatively and to some extent quantitatively similar for single hadrons and jets.
  - Consistent with interpretation as consequence of energy loss through radiation outside jet cone.
- γ-hadron measurements (x_E) in pp at at $\sqrt{s_{NN}}$ = 7 TeV
  - Important step towards Pb-Pb measurement.

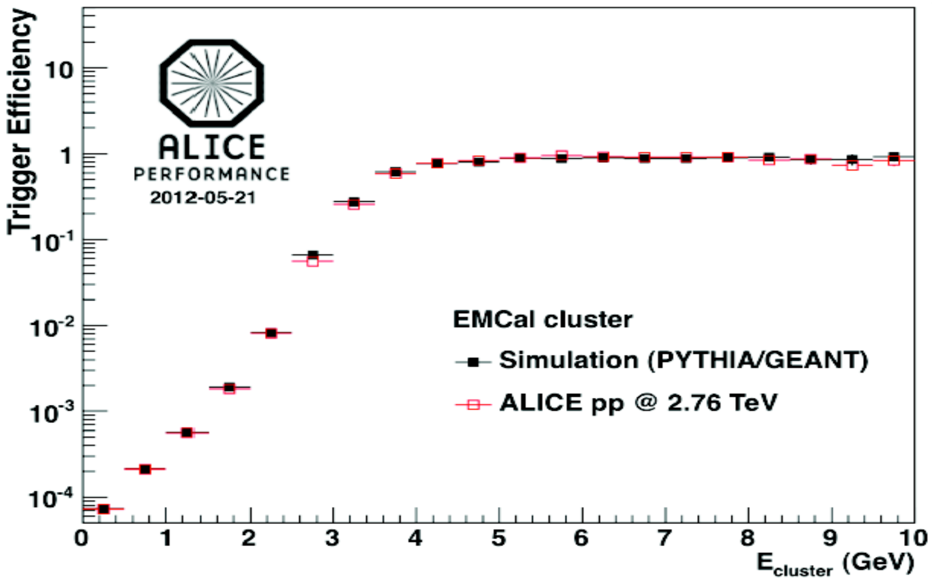
ALICE

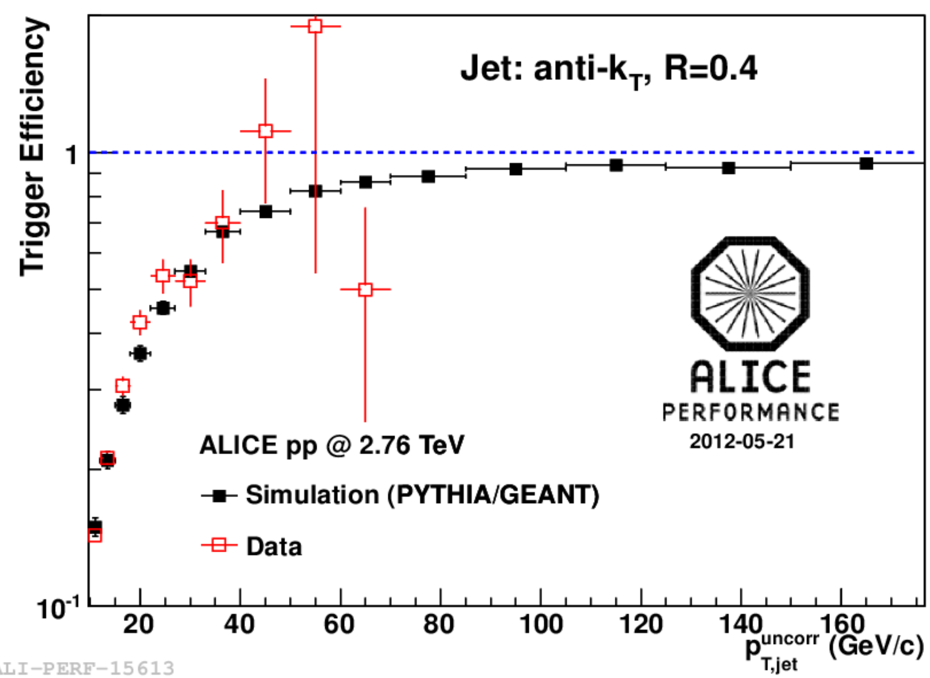
Additional Posters

- Measurements of charged particle jet properties in pp collisions at $\sqrt{s}$ = 7 TeV (Sidharth Kumar Prasad)
- Jet measurements in proton-proton collisions (Michal Vajzer)
- Jet-Hadron Azimuthal Correlation Measurements in p+p Collisions at $\sqrt{s}$ = 2.76TeV and 7TeV (Dosatsu Sakata)

Backup

Jets in pp
Trigger Efficiency



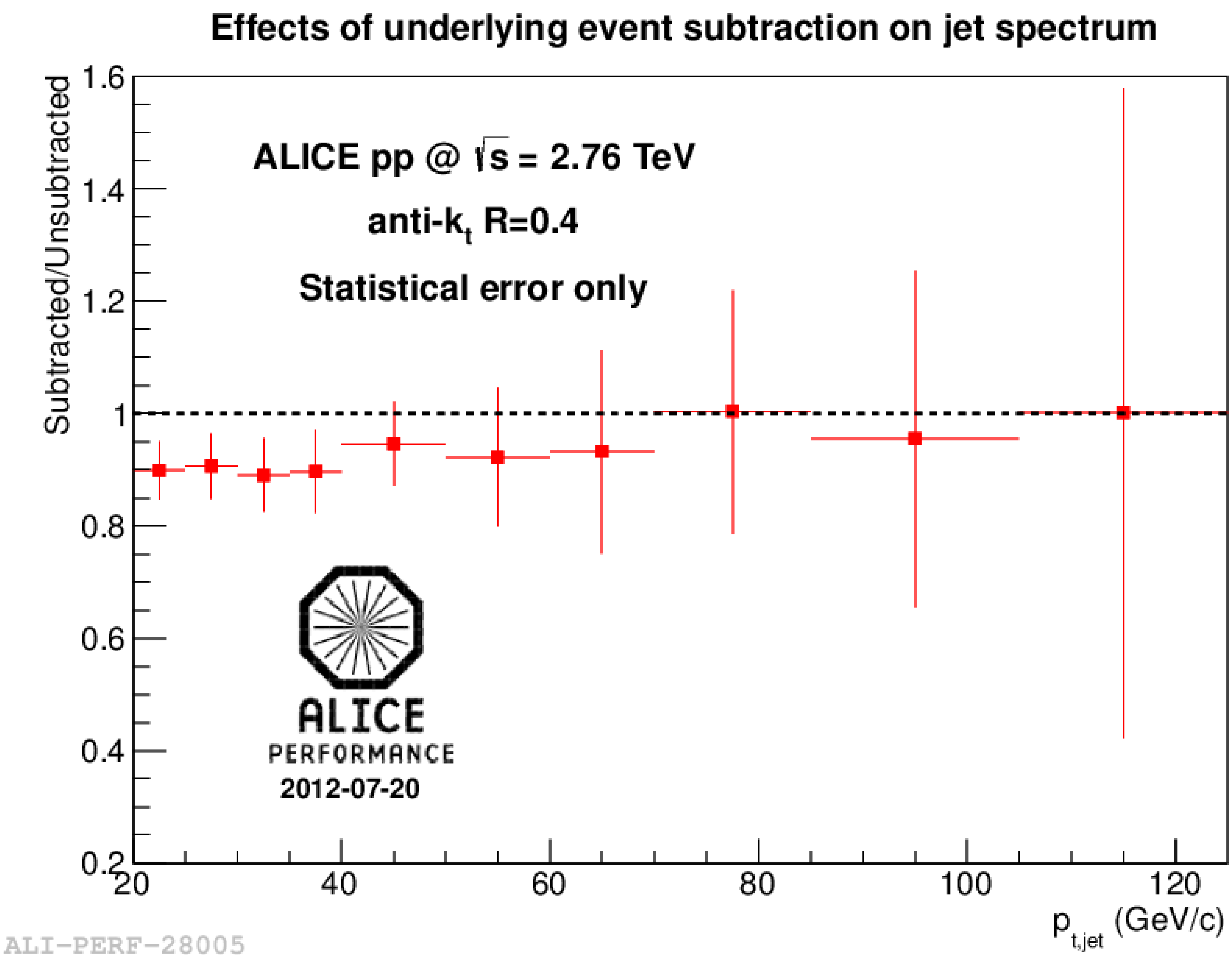


- EMCal Level-0 trigger
  - Used in data-taking to extend the kinematic reach of jet spectrum.
- Bias on the jet population
  - Estimated in simulation via incorporating the EMCal cluster turn-on curves and local inefficiency of the trigger system extracted from data.

Jets in pp
Bin by Bin Corrections

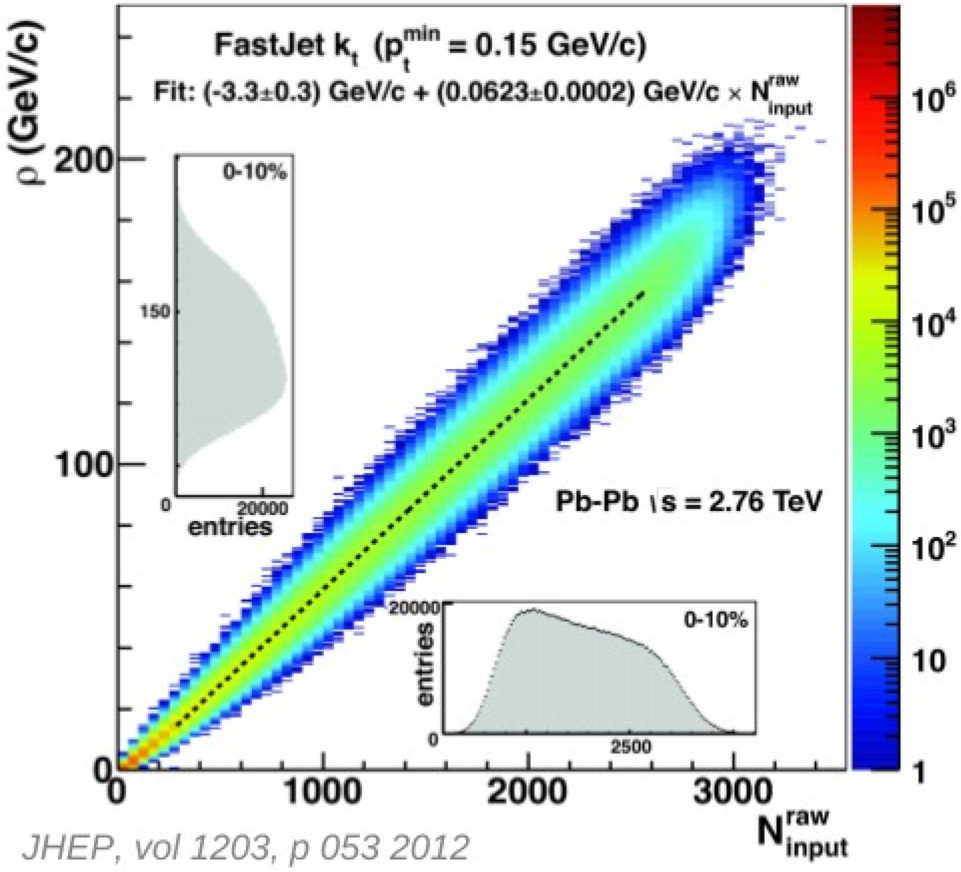
$$C_{\mathrm{MC}}\left(p_{\mathrm{T}}^{\mathrm{low}}, p_{\mathrm{T}}^{\mathrm{high}}\right)=\frac{\int_{p_{\mathrm{T}}^{\mathrm{low}}}^{p_{\mathrm{T}}^{\mathrm{high}}} \mathrm{d}\, p_{\mathrm{T}} \frac{\mathrm{d}\, F_{\mathrm{measure}}^{\mathrm{unorr}}}{\mathrm{d}\, p_{\mathrm{T}}} \frac{\mathrm{d}\,\sigma_{\mathrm{MC}}^{\mathrm{Particle}}/\mathrm{d}\, p_{\mathrm{T}}}{\mathrm{d}\,\sigma_{\mathrm{MC}}^{\mathrm{Detector}}/\mathrm{d}\, p_{\mathrm{T}}}}{\int_{p_{\mathrm{T}}^{\mathrm{low}}}^{p_{\mathrm{T}}^{\mathrm{high}}} \mathrm{d}\, p_{\mathrm{T}} \frac{\mathrm{d}\, F_{\mathrm{measure}}^{\mathrm{unorr}}}{\mathrm{d}\, p_{\mathrm{T}}}}$$

Jets in pp
Underlying Event



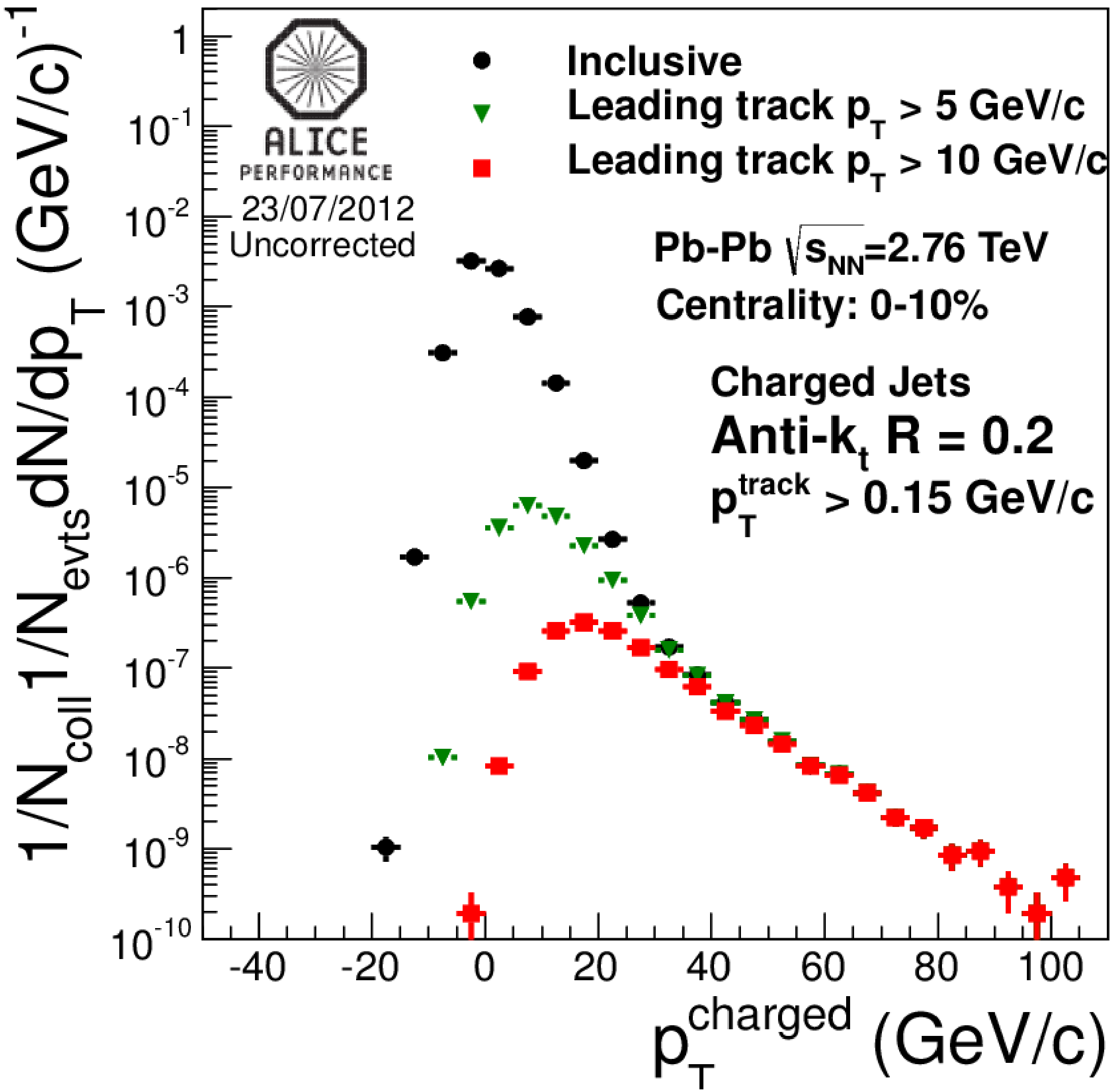
Event-by-Event Background Subtraction

$$\rho = \mathrm{median}\left(\frac{p_{\mathrm{T}}^{\mathrm{jet},i}}{A_i^{\mathrm{jet}}}\right)$$



JHEP, vol 1203, p 053 2012

Charged Jets in PbPb Raw Spectra



Jets in Pb-Pb
Unfolding

Truth ⟶ **D** ⟶ **Measured**

$\mathbf{RM_{det}}$ $\mathbf{RM_{\delta pT}}$

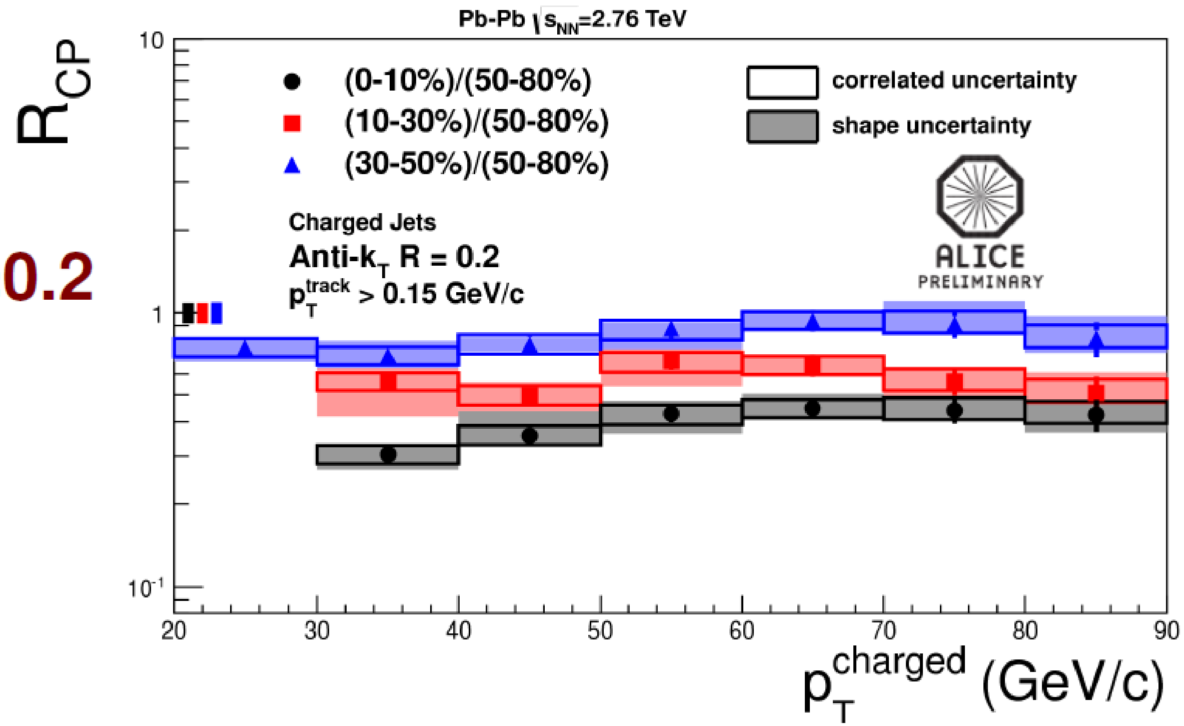
$$\chi^2 = \sum_{\text{refolded}} \left(\frac{y_{\text{refolded}} - y_{\text{measured}}}{\sigma_{\text{measured}}} \right)^2 + \beta \sum_{\text{unfolded}} \left(\frac{d^2 log\ y_{\text{unfolded}}}{d\ log\ p_T^2} \right)^2$$

χ^2-term *Regularization/penalty*

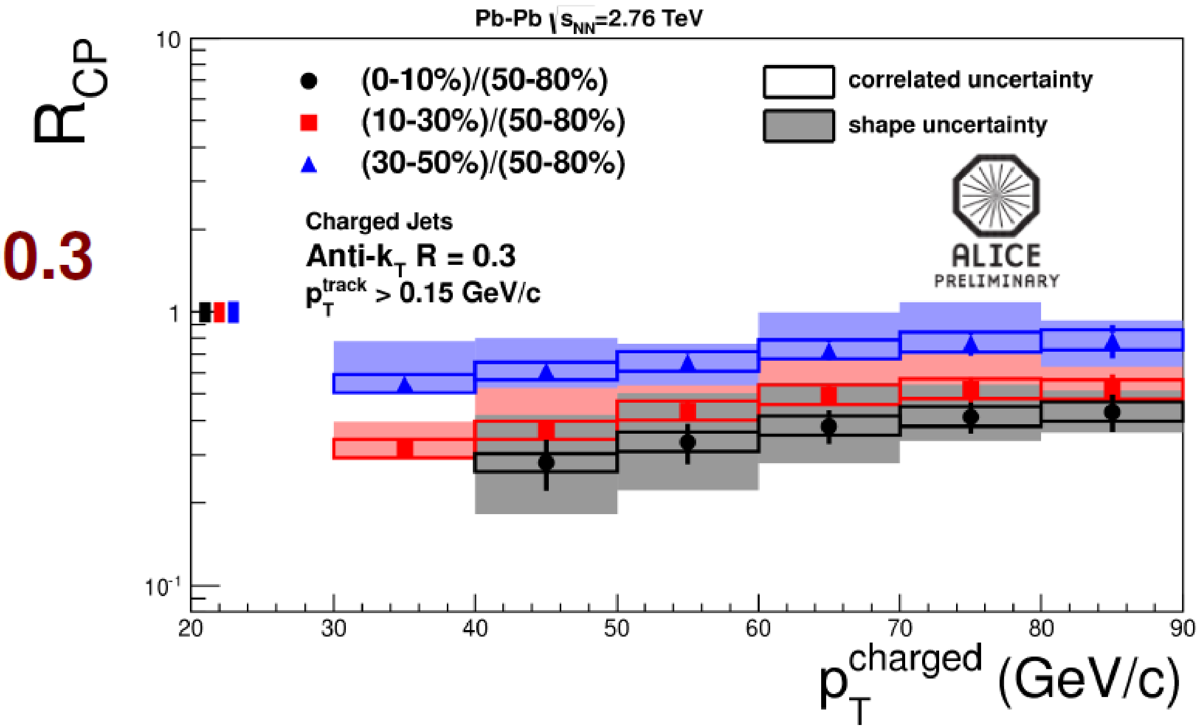
Pb-Pb: Unfolding

- Choice of p_T ranges in unfolding and systematic uncertainties
  - Measured spectrum: Suppression of background jets by $p_{T,meas}$ > $5\sigma(\delta p_T)$.
  - Feed in from low p_T. Unfolded spectrum starts at p_T=0 GeV/c
  - Regularization strength: systematic uncertainty on extracted jet yield 10% for central events and 4% for peripheral events
  - Jet energy scale correction from detector effects: ~10%

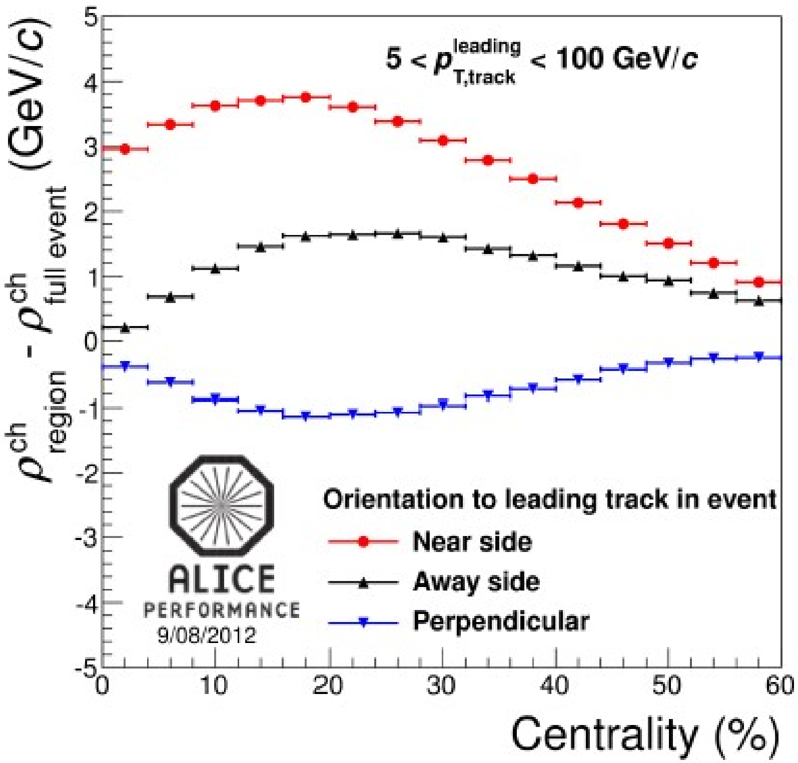
R=0.2

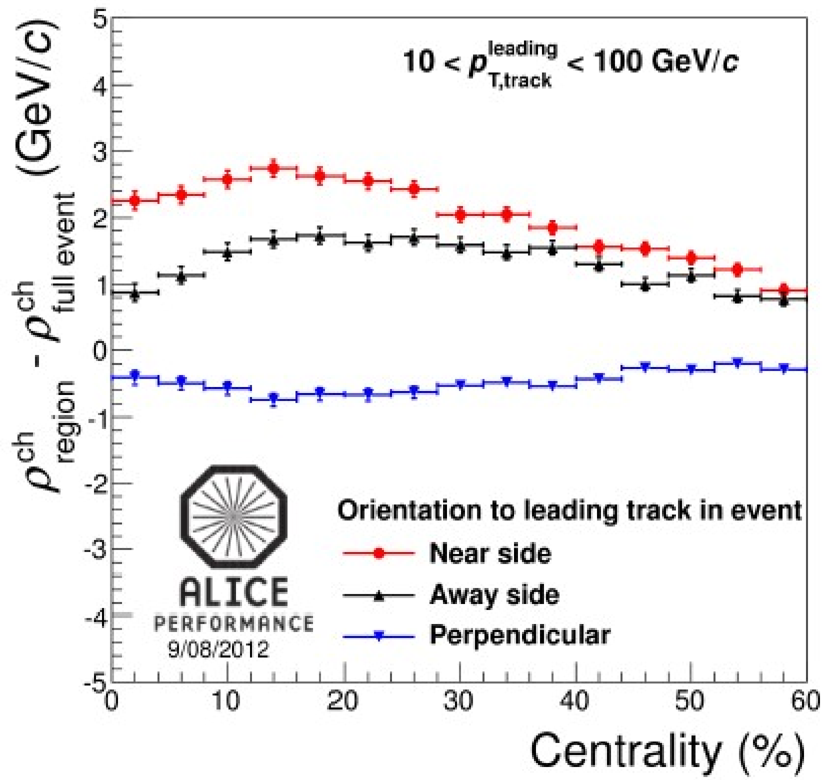

Pb-Pb √sNN=2.76 TeV
RCP
(0-10%)/(50-80%)
(10-30%)/(50-80%)
(30-50%)/(50-80%)
correlated uncertainty
shape uncertainty
Charged Jets
Anti-kT R = 0.2
pTtrack > 0.15 GeV/c
ALICE PRELIMINARY
pTcharged (GeV/c)

R=0.3


Pb-Pb √sNN=2.76 TeV
RCP
(0-10%)/(50-80%)
(10-30%)/(50-80%)
(30-50%)/(50-80%)
correlated uncertainty
shape uncertainty
Charged Jets
Anti-kT R = 0.3
pTtrack > 0.15 GeV/c
ALICE PRELIMINARY
pTcharged (GeV/c)

Leading Particle Tag: Flow Bias





- Flow bias: high p_T hadron correlated to event and participant plane.
  - Background density per unit area below jet is larger.
- Magnitude of bias on inclusive jet spectra depends on p_T of trigger.
  - Hadron triggered jet spectra are corrected for the flow bias.

Jet and leading particle energy loss

$$E_{\text{jet}} \rightarrow E_{\text{jet}} - \Delta E$$

$$p_{\text{T, leading}} \rightarrow p_{\text{T, leading}} - z_{\text{leading}} \Delta E$$

$$\frac{p_{\text{T, leading}} - z_{\text{leading}} \Delta E}{E_{\text{jet}} - \Delta E} = \frac{z_{\text{leading}} E_{\text{jet}} - z_{\text{leading}} \Delta E}{E_{\text{jet}} - \Delta E} = z_{\text{leading}}$$