Jet Measurements in ALICE

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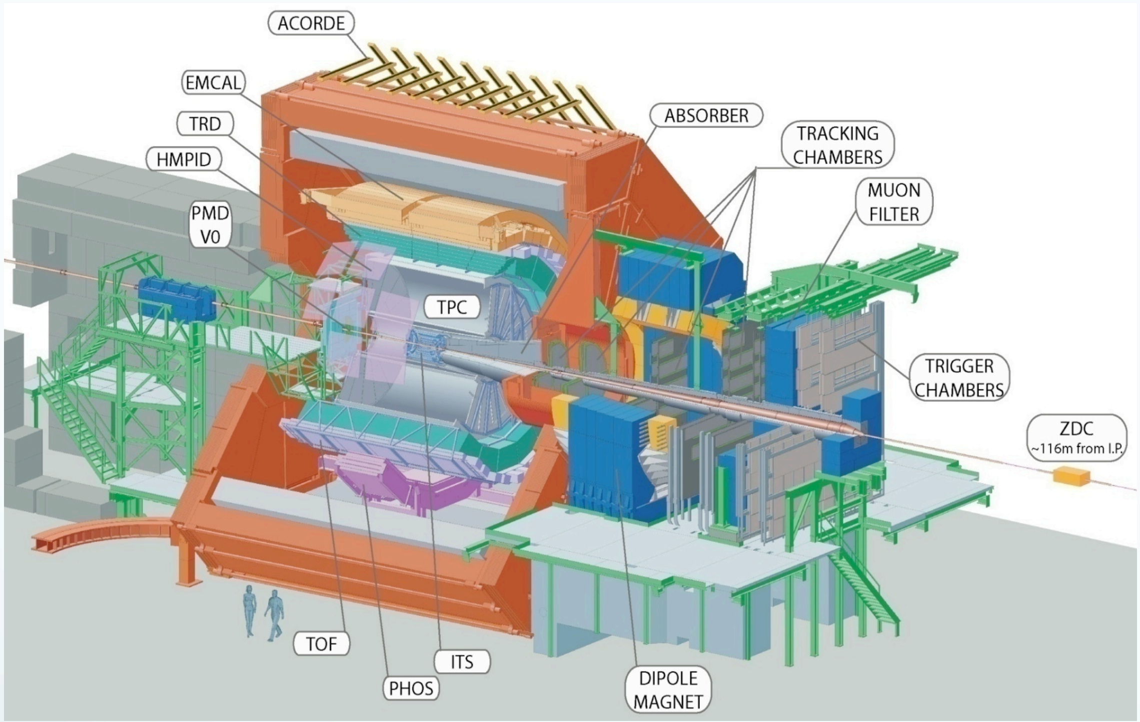
Outline

- Jet reconstruction in ALICE
- Baseline pp results
- Heavy-ion jet reconstruction difficulties
- Unfolding and response matrices
- HI jet results from ALICE

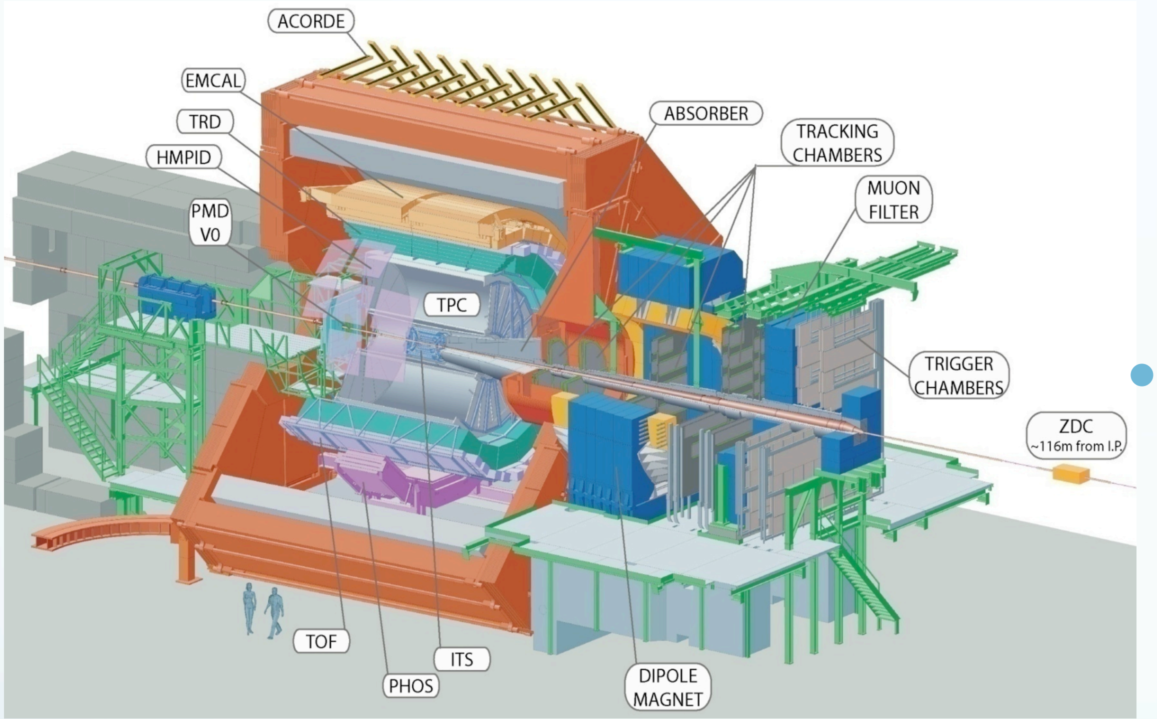
Jets at ALICE

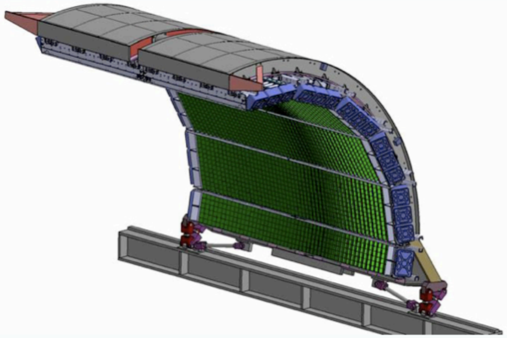


Tracking: $|\,\eta\,| < 0.9$, $0<\varphi<2\pi$
TPC: gas drift detector
ITS: silicon detector

→ *Charged constituents* → **JET**

Jets at ALICE





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

Remove contamination from Charged particles

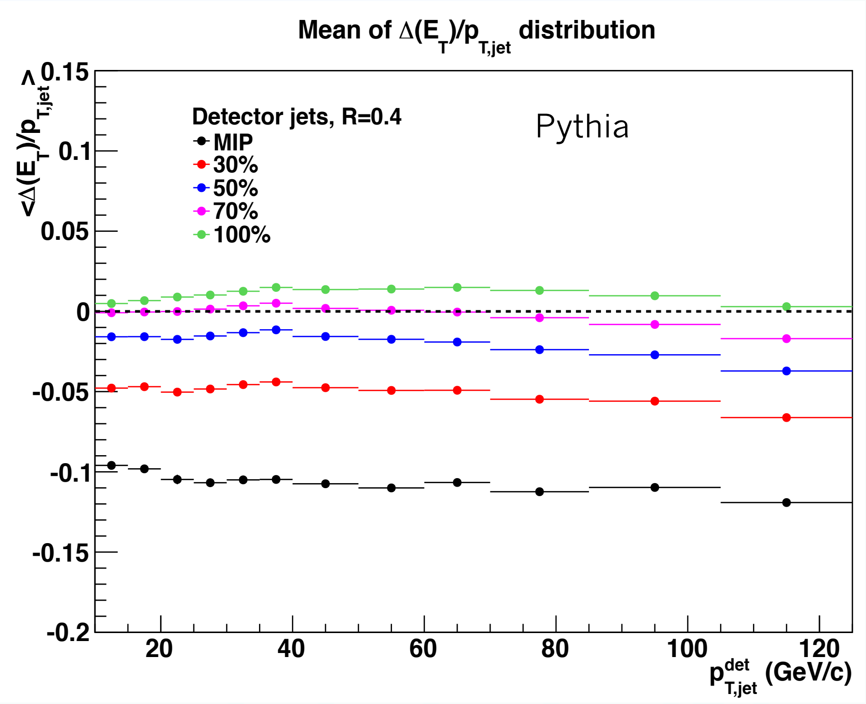
Tracking: $|\eta| < 0.9$, $0 < \varphi < 2\pi$
TPC: gas drift detector
ITS: silicon detector

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

Jet Reconstruction

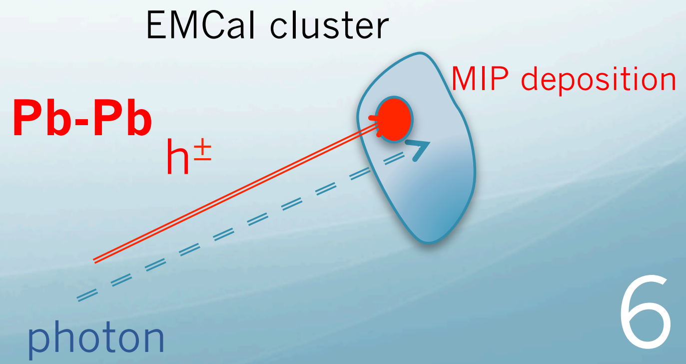
- Input to the jet finder
  - Assumed to be massless
  - Charged tracks (ITS+TPC) with p_T > 150 MeV/c
  - EMCal clusters corrected for charged particle contamination with $E^{cor}_{T,cluster} \geq 300$ MeV
    - $E^{cor}_{cluster} = E^{orig}_{cluster} - f \sum p^{matched}, \quad E^{cor}_{cluster} \geq 0$, f = 100%
- ALICE measures both Full Jets (tracks + clusters) and charged jets (tracks only)
- Jets reconstructed using FastJet package
  - R = 0.2 - 0.4
  - Boosted p_T recombination scheme
    - Anti-k_T – Used for signal determination
    - k_T – Used for background determination

Correction for charged particle EMCal contamination

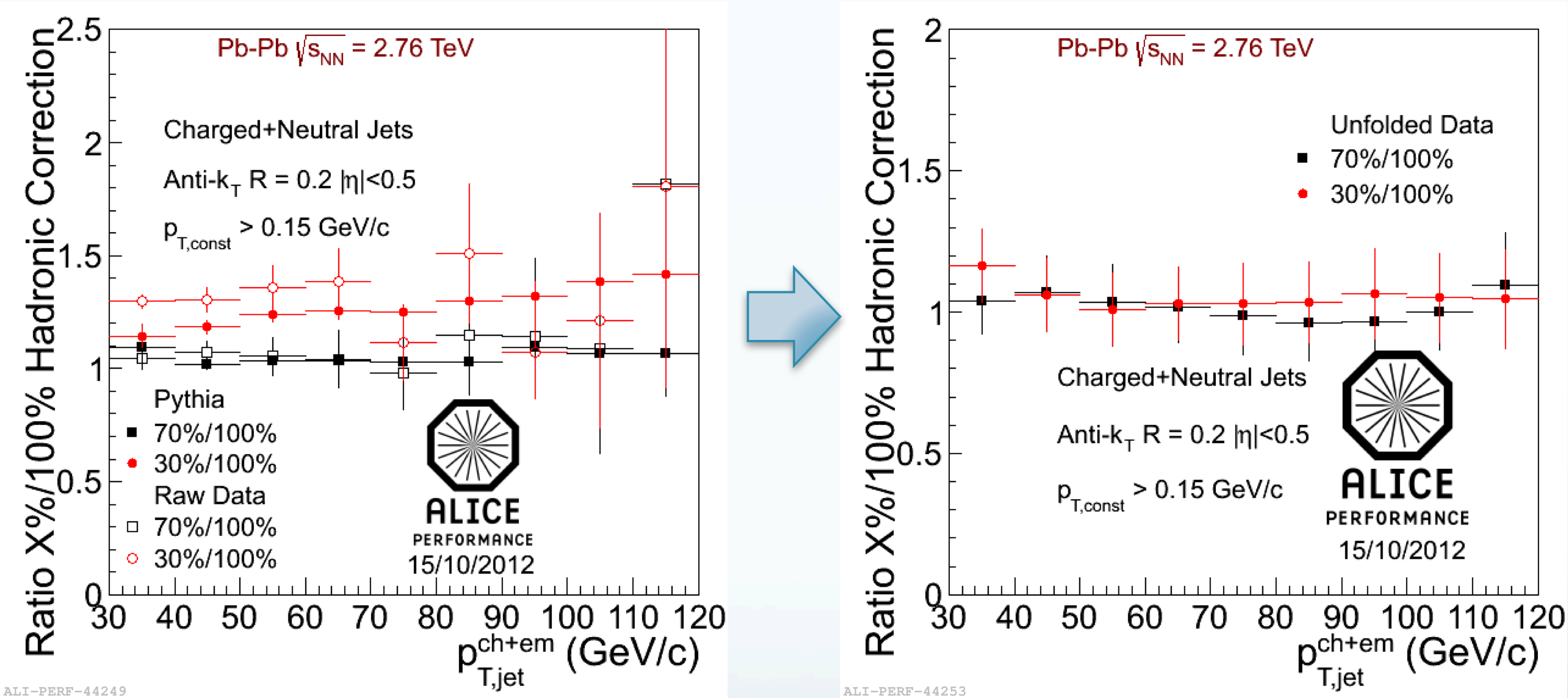


$$E_{\text{cluster}}^{\text{corr}} = E_{\text{cluster}}^{\text{raw}} - f \sum P_{\text{track}}^{\text{matched}}, \quad E_{\text{cluster}}^{\text{corr}} \geq 0$$

- More clusters are matched in Pb-Pb than in pp due to higher multiplicity
  - Most clusters (80%) do not have a matched track



Correction for charged particle EMCal contamination

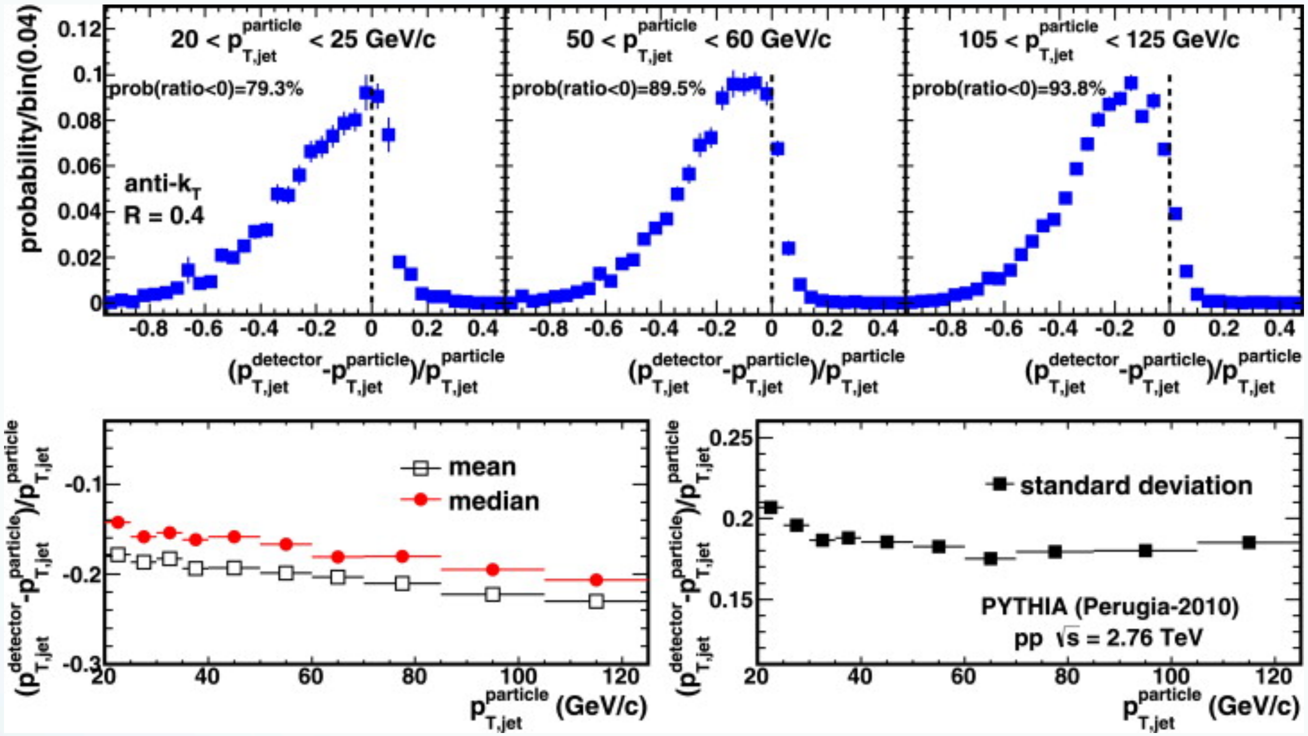


Difference in correction factors can be corrected via simulation, the difference after correction is part of the systematic uncertainty.

Jet Reconstruction
Full Jet Selection Requirements

- EMCal fiducial acceptance cut
  - R away from EMCal boundaries
  - R=0.2:
    - $|\eta_{jet}| < 0.5$
    - $1.60 < \phi_{jet} < 2.94$
- $p_{T,jet}^{rec} > 1$ GeV/c
- Jets with leading track $p_T > 100$ GeV/c are rejected
  - Track quality above 100 GeV uncertain

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

Full Jet Cross-Section (pp)

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

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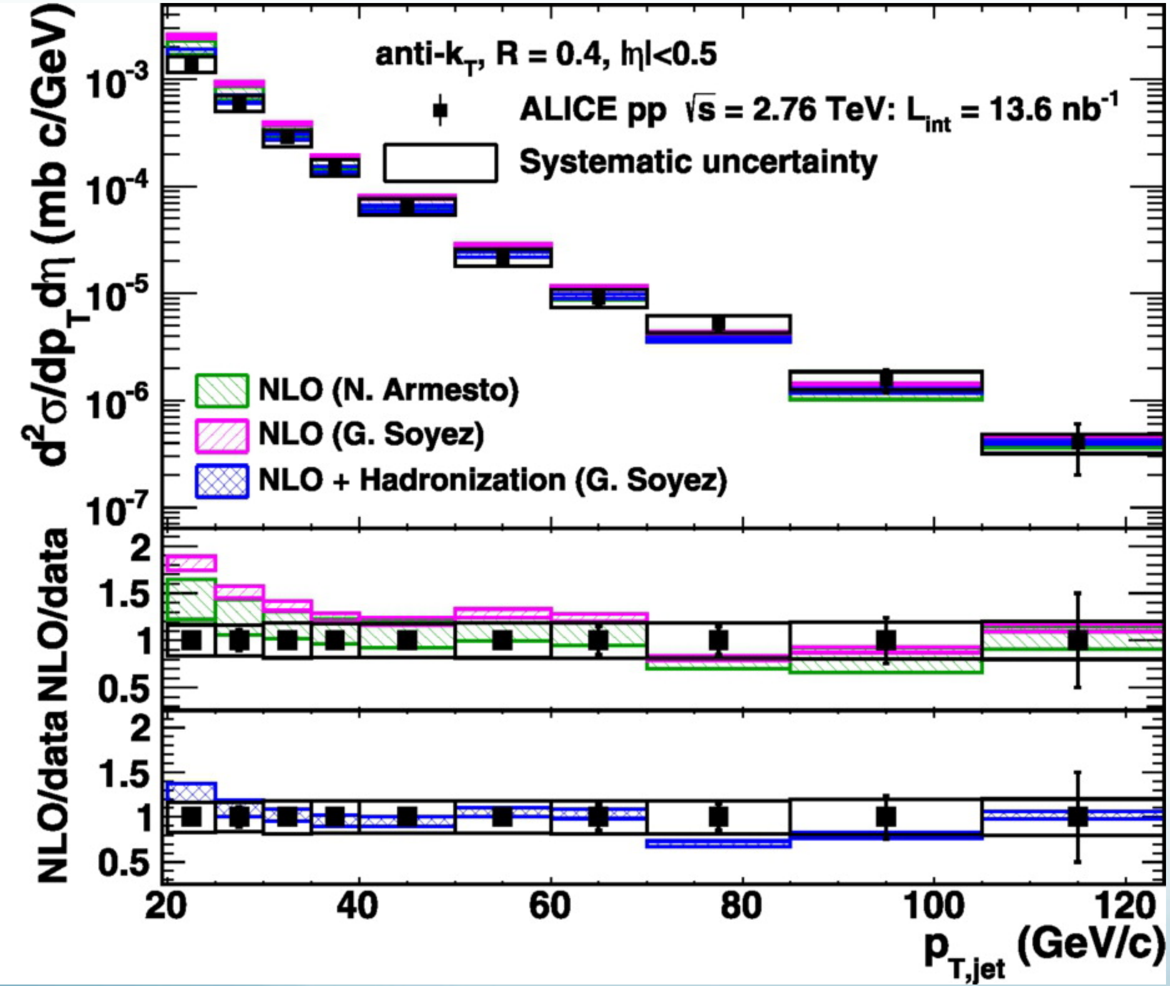

- Green and magenta bands: NLO on Parton level
- Blue band: NLO + hadronization
- Hadronization necessary for better fit to data
- f_{hadcor} = 100%, p_T > 150 MeV/c E_T > 300 MeV

Full Jet Cross-Section (pp)

√s = 2.76 TeV, R = 0.2, 0.4 Inclusive

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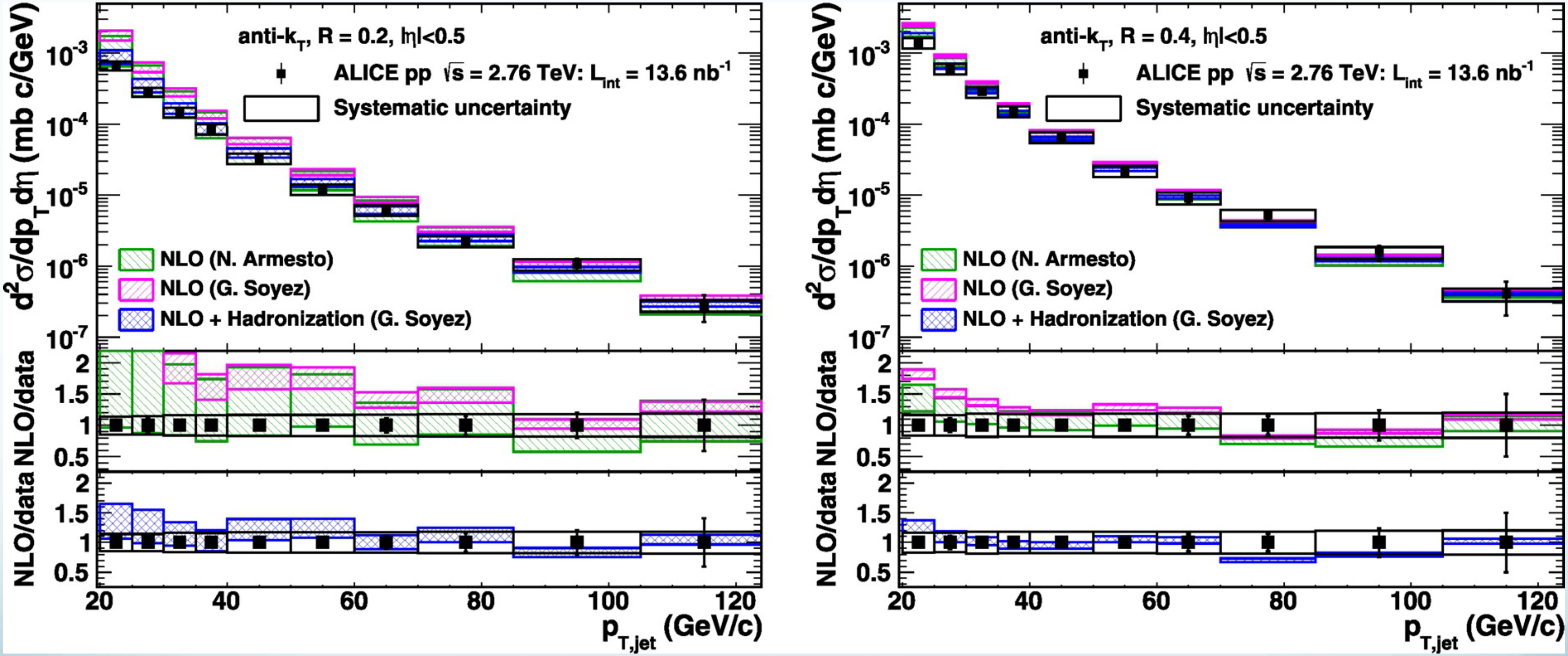


Agreement between data and NLO calculations is good for both R = 0.2 and 0.4

Jets in Heavy Ion Collisions

Experimental Challenges

- Need to remove underlying event (UE) contribution
  - $p_{\mathrm{T,jet}} = p_{\mathrm{T,jet}}^{rec} - \rho A \pm \sigma\sqrt{A}$
    - A = Jet area, ρ = Average UE momentum density
    - $p_{\mathrm{T,jet}}^{rec}$ = Jet p_{T} from jet finder
    - We can only remove the average background contribution
- Combinatorial (fake) jets can be reconstructed from UE
- Detector effect corrections depend on fragmentation
- Both background and detector effects are corrected in unfolding
  - Corrects spectra for the $\sigma\sqrt{A}$ term
  - Quantified in Response Matrix (RM)

Jets in Heavy Ion Collisions

Fake Jets

- Impossible to distinguish if a given jet originates from a hard process or clustering of the UI
- We want to measure jets which come from showers from a parton that has suffered a hard scatter ("Real" jet)
  - There is no precise definition of what is a fake jet and what is a "real" jet
  - In order to resolve this, we define what we consider a real jet in a quantifiable way

Jets in Heavy Ion Collisions

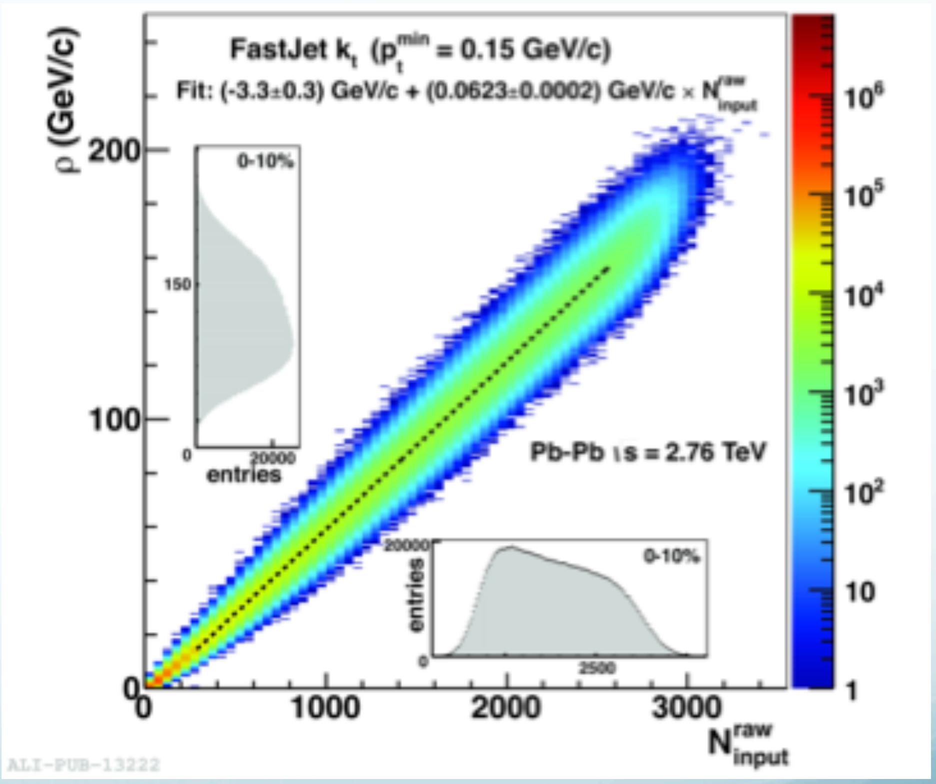
Fake Jets

- "Real" jet definition includes
  - Jet Finding Algorithm
  - Constituent cuts
  - R
  - Any additional track or trigger biases
- "Fake" jets are everything that is not a real jet
- HI jet definition
  - pp definition with additional cuts to remove more combinatorial background
    - Area cut: $A_{jet} > 0.6 * \pi R^2$
    - Requirement on leading track : $p_{T,leading} > 5$ 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

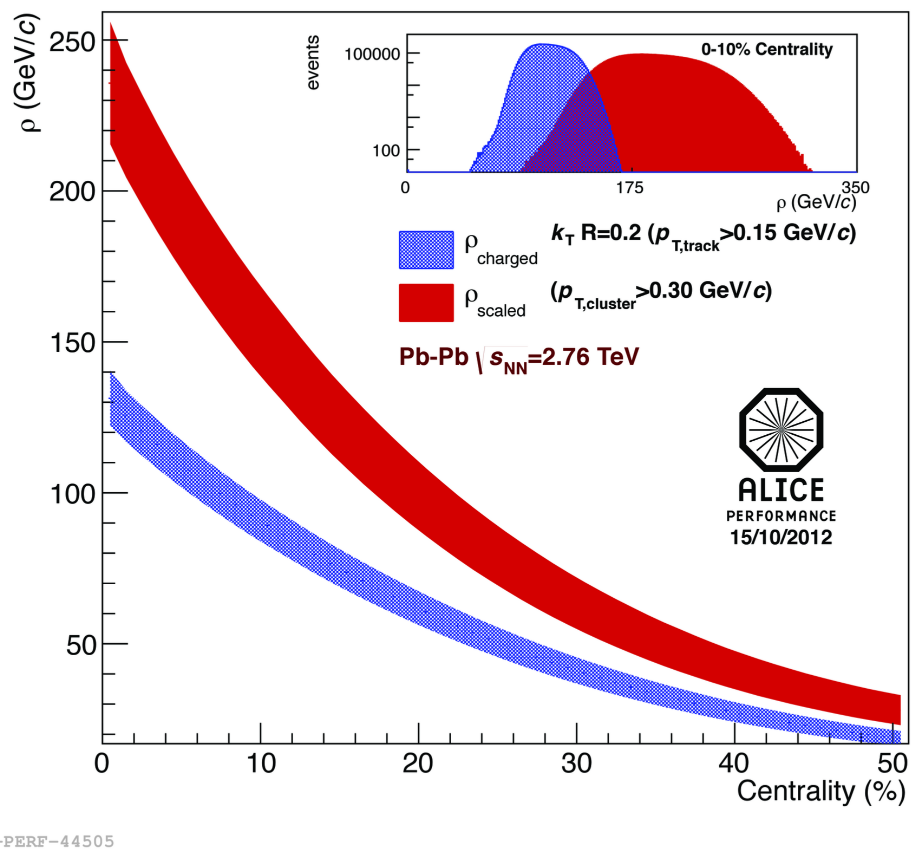
JHEP 1203:053, 2012
(arxiv:1201.2423)

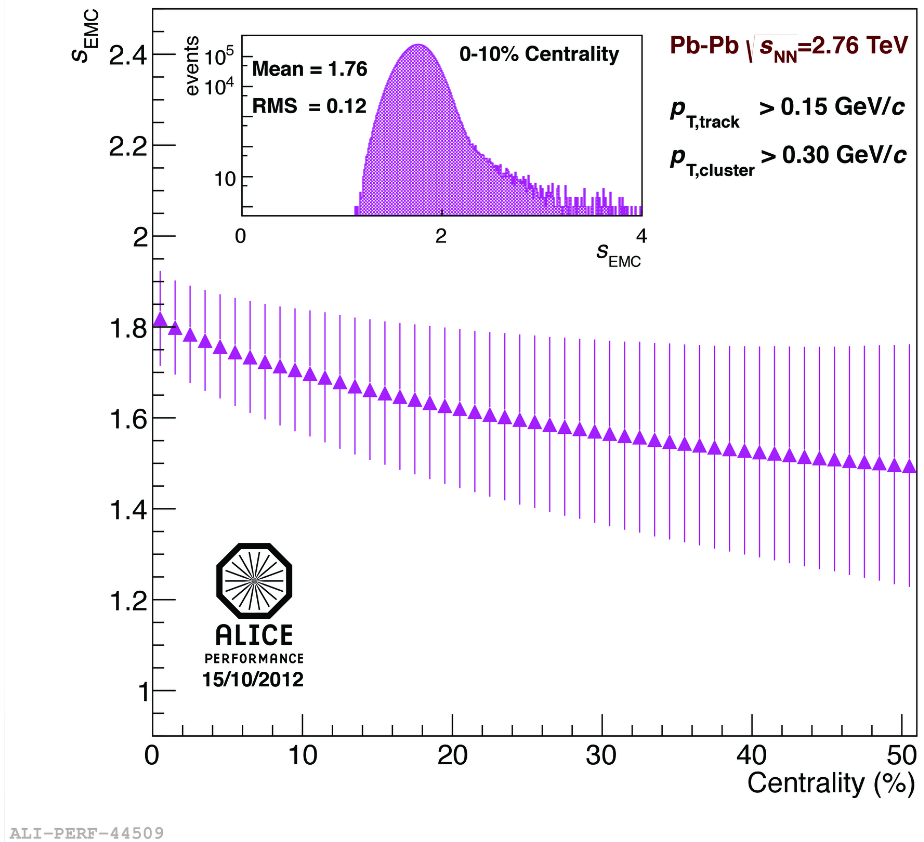


$$p^{ch,unc}_{T,jet} = p^{rec}_{\mathrm{T,jet}} - \rho_{ch} A$$

HI Background Determination

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





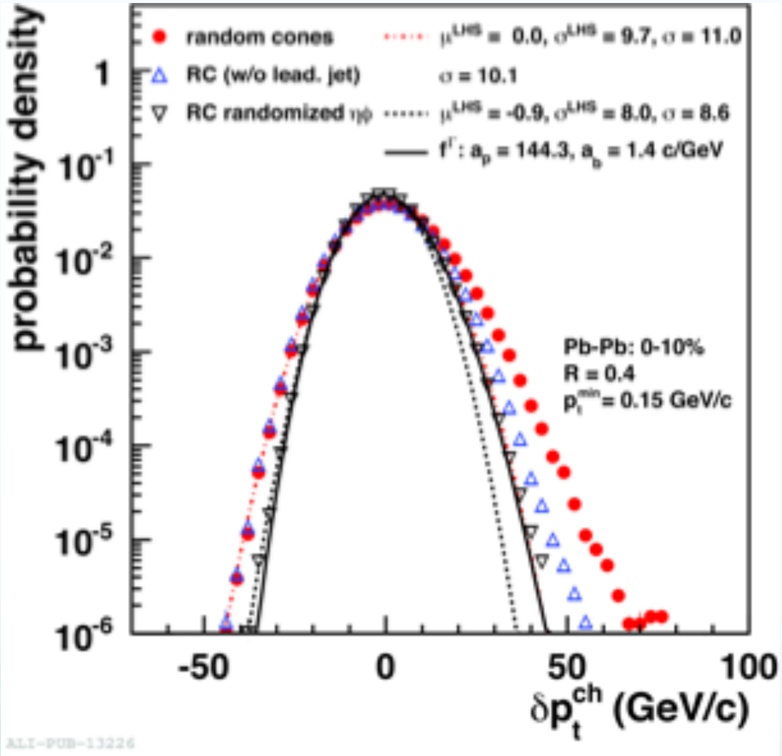
Centrality dependent scale factor accounts for neutral energy

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

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

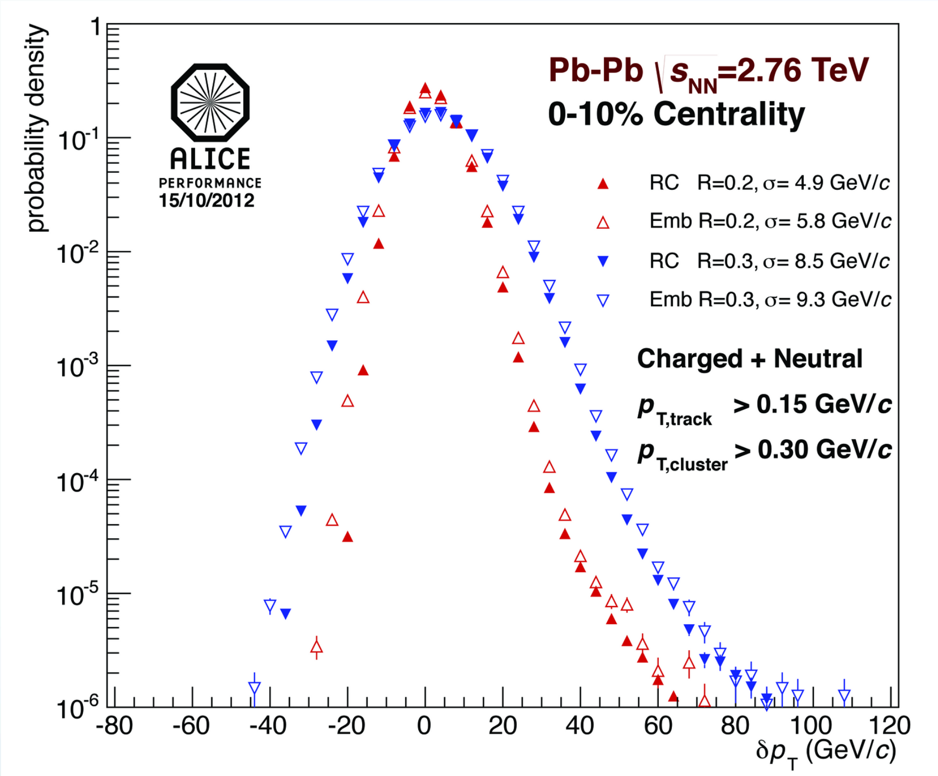
δp_T is not corrected for detector effects – Experiment specific

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

- 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

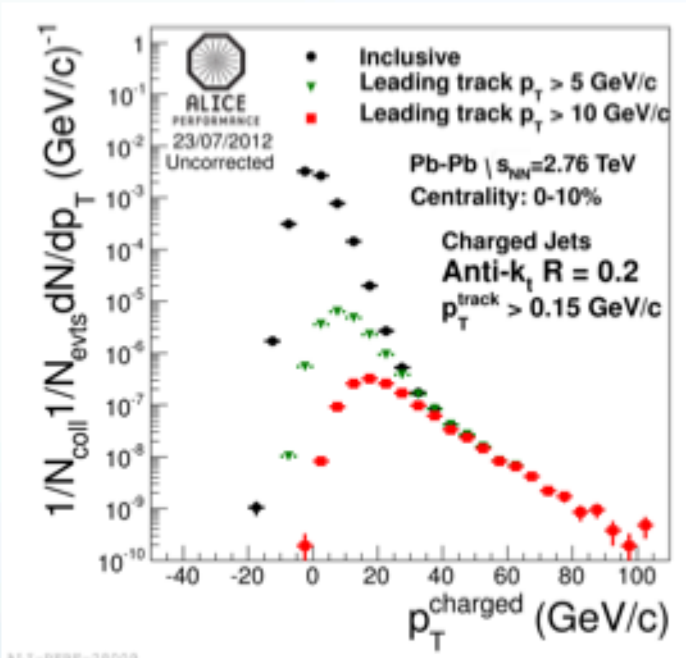
$$\delta p_T = p_{T,RC}^{rec} - \rho \pi R^2$$

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

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

Leading Track Jet Bias

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

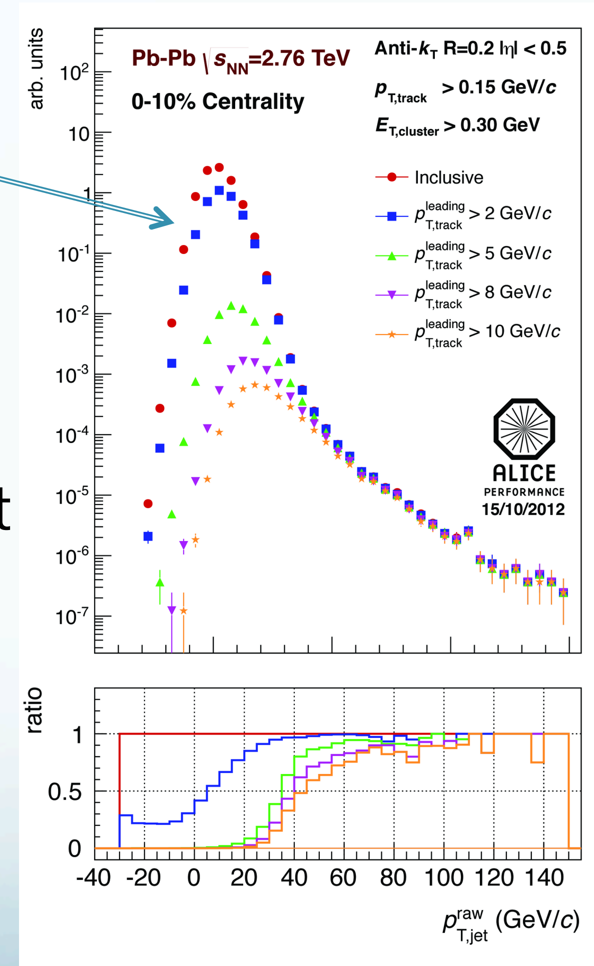


Combinatorial "jets"

Measured spectra:

$$p_{T,jet}^{unc} = p_{\mathrm{T,jet}}^{rec} - \rho\, A$$

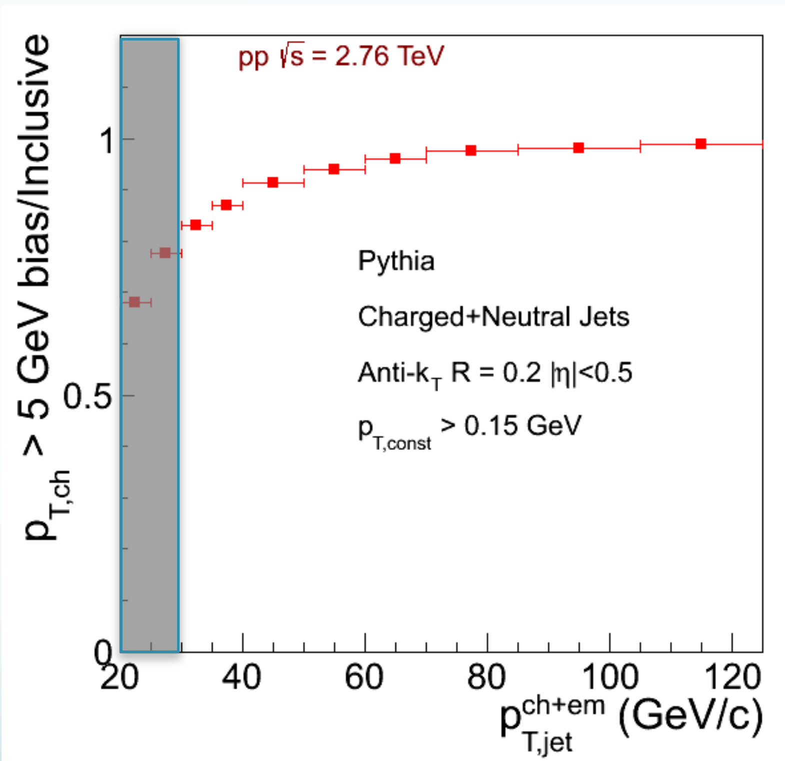
Where $p_{\mathrm{T,jet}}^{rec}, A$ come from FastJet anti-k_T algorithm

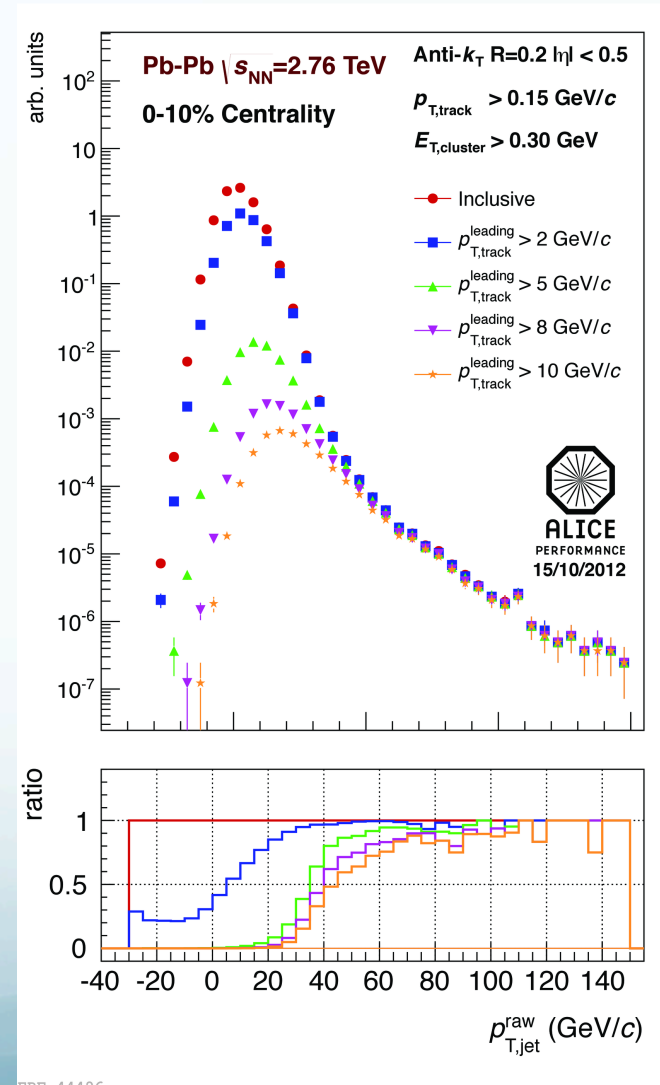


- Combinatorial jets a challenge in HI collisions
  - Require leading track p_T > 5 GeV/c
  - Biases fragmentation

Leading Track Jet Bias

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

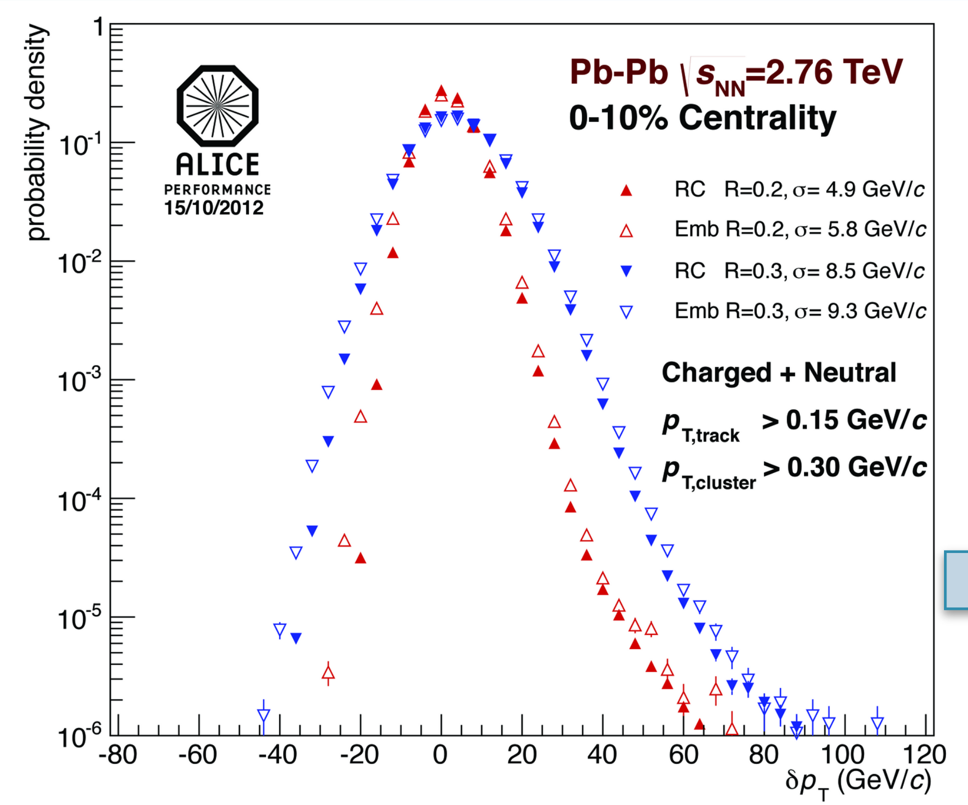


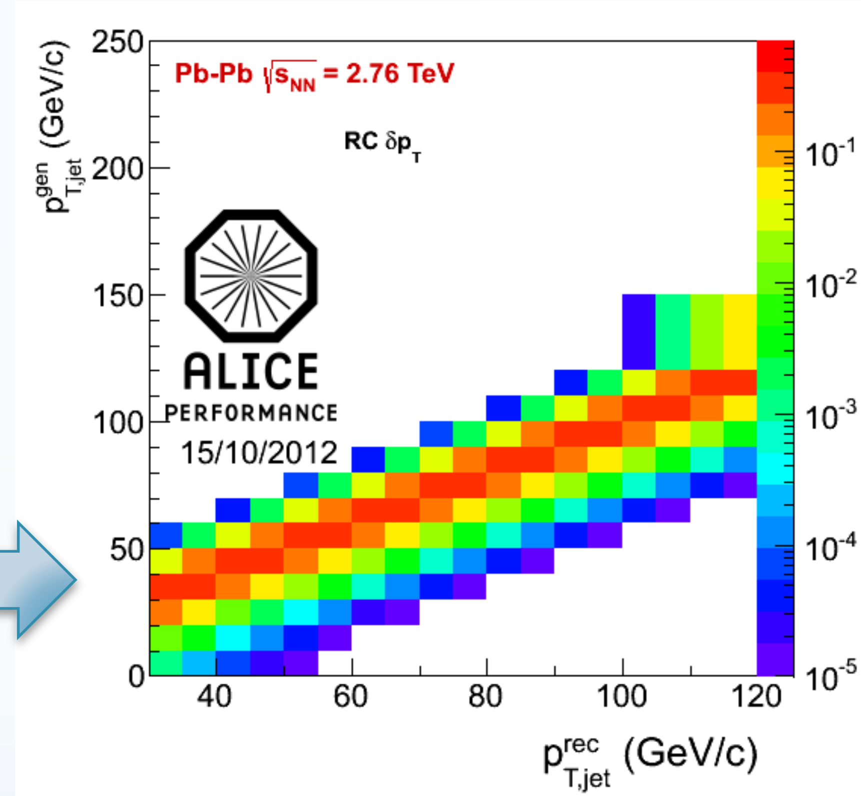


- Above 30 GeV/c the bias has less than a 10% effect in pp/PYTHIA

Response matrix

RM_{bkg}



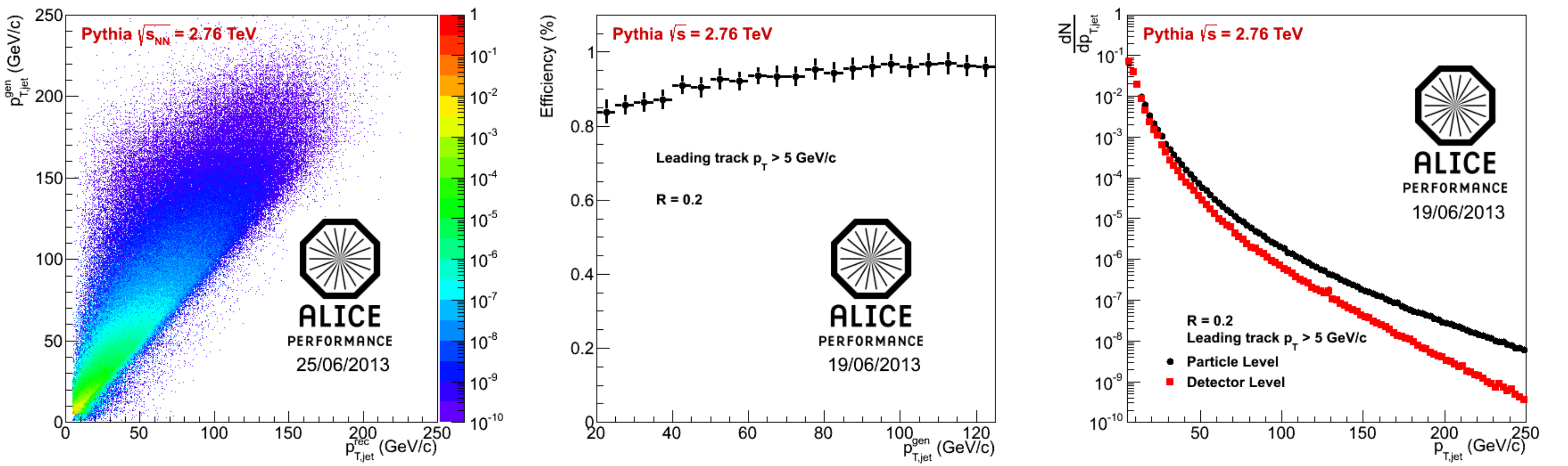


- Data-driven method of determining background fluctuations
  - No p_T dependence ($p_{T,jet}$ > 10 GeV/c) to the effect of background on jets
  - does not account for jet splitting

Response matrix

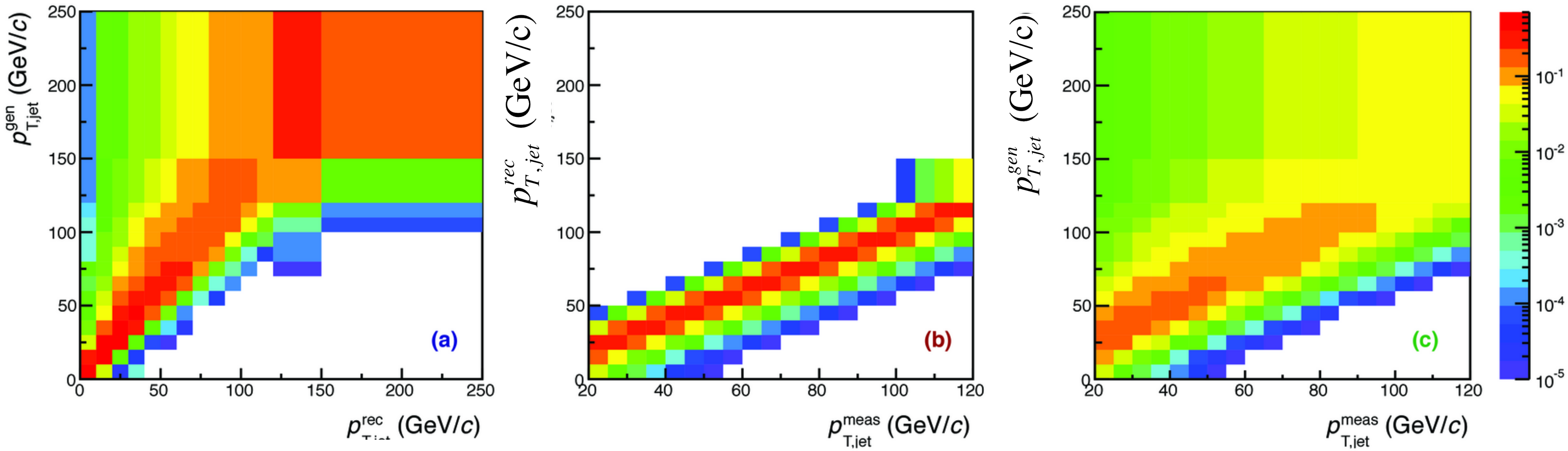
RM_{det}

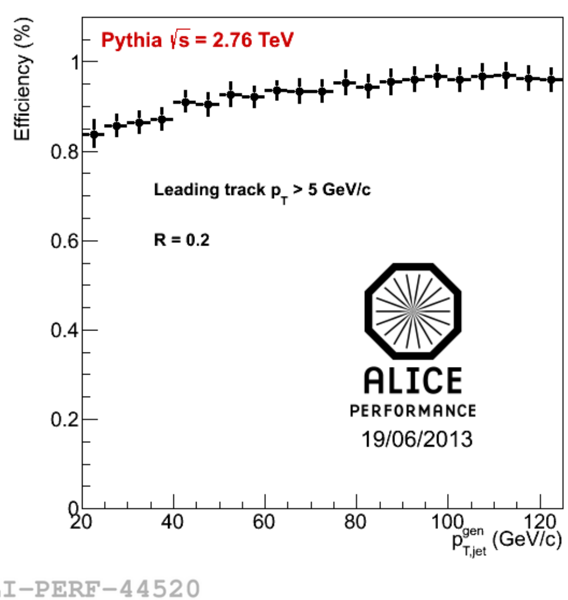
- RM_{det} quantifies detector response to jets
  - "Particle" level jets – defined by jet finder on MC particles
    - Pythia with Pb-Pb tracking efficiency
  - "Detector" level jets – defined by jet finder after event reconstruction through GEANT
  - Particle level jets are geometrically matched to detector level jets
  - Matrix has a dependence on spectral shape and fragmentation
- Jet-finding efficiency is probability of a matched particle level jet



Response Matrix Construction

RM_{det} X RM_{bkg} = RM





Anti-k_T R=0.2

$p_{T,track}$ > 0.15 GeV/c

$E_{T,cluster}$ > 0.30 GeV

$p_{T,track}^{leading}$ > 5 GeV/c

(a) RM_{det} Detector response matrix

(b) RM_{bkg} Background fluctuation matrix

(c) $RM_{tot} = RM_{bkg} \times RM_{det}$

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

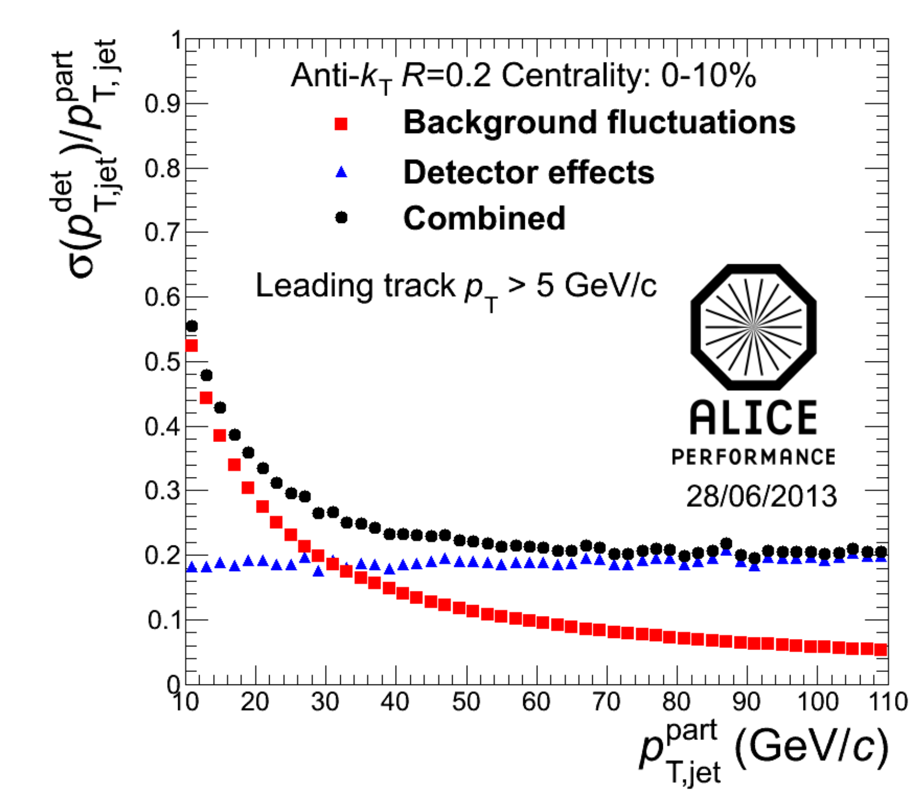
0-10% Centrality

ALICE
PERFORMANCE
15/10/2012

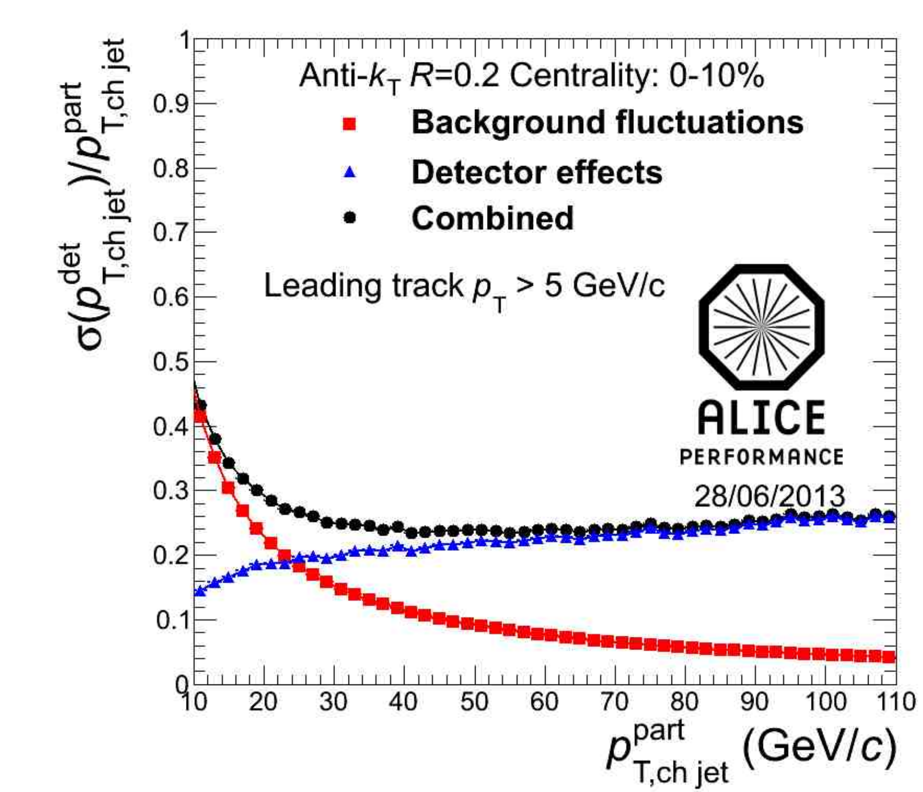
Assumes the RM_{bkg} and RM_{det} are factorizable

Jet Resolution/Corrections

Full



Charged



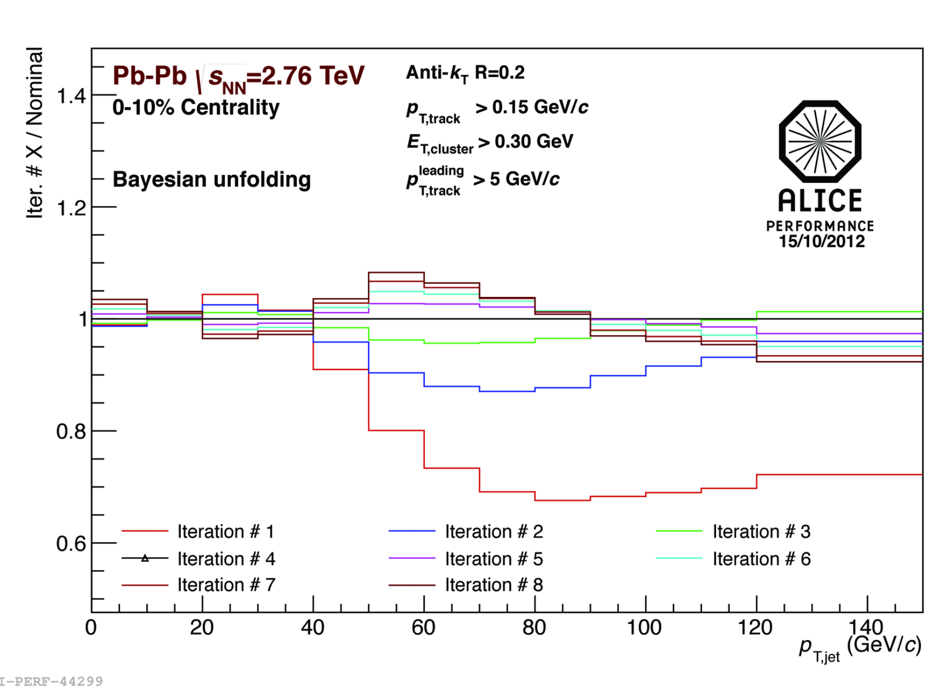
- Jet resolution
  - Dominated by background fluctuations at low momentum
  - Dominated by detector effects at high momentum

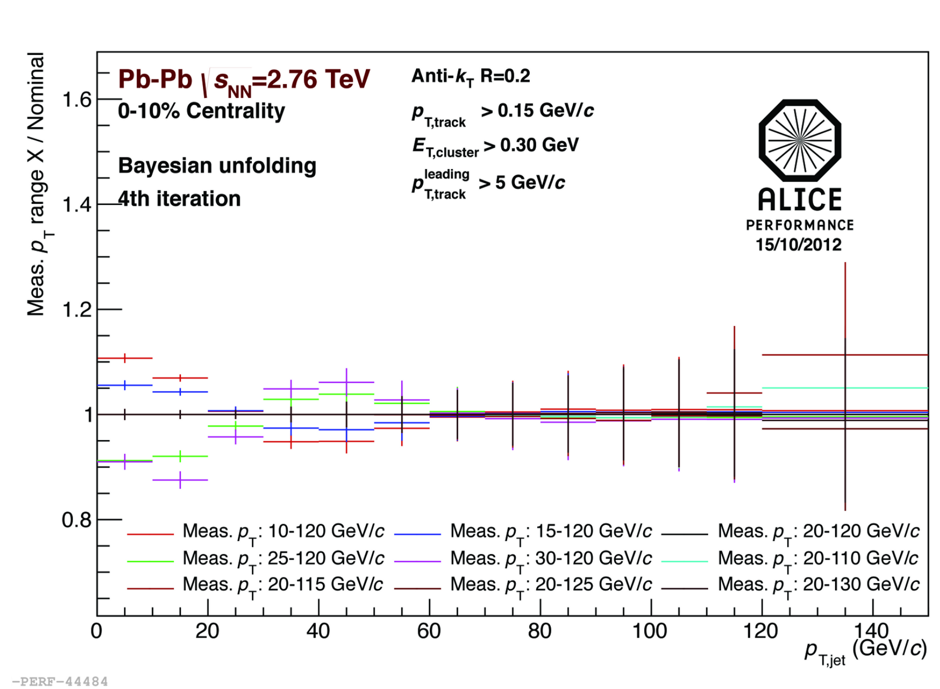
Unfolding Jet Spectra

- Unfolding corrects raw spectra for detector effects and background fluctuations
  - Response Matrix (RM) quantifies effects
  - $f^{raw}(p_T) = RM_{bkg} \times RM_{\det} \times f^{true}(p_T)$
  - Statistical fluctuations yield problematic solutions in the inversion of the RM
    - Regularization is employed as true distribution is assumed to be smooth

- 4 unfolding methods used in ALICE
  - Bayesian
  - χ^2 minimization
  - Singular Value Decomposition (SVD)
  - Bin-by-bin (used in pp)

Unfolding Uncertainties





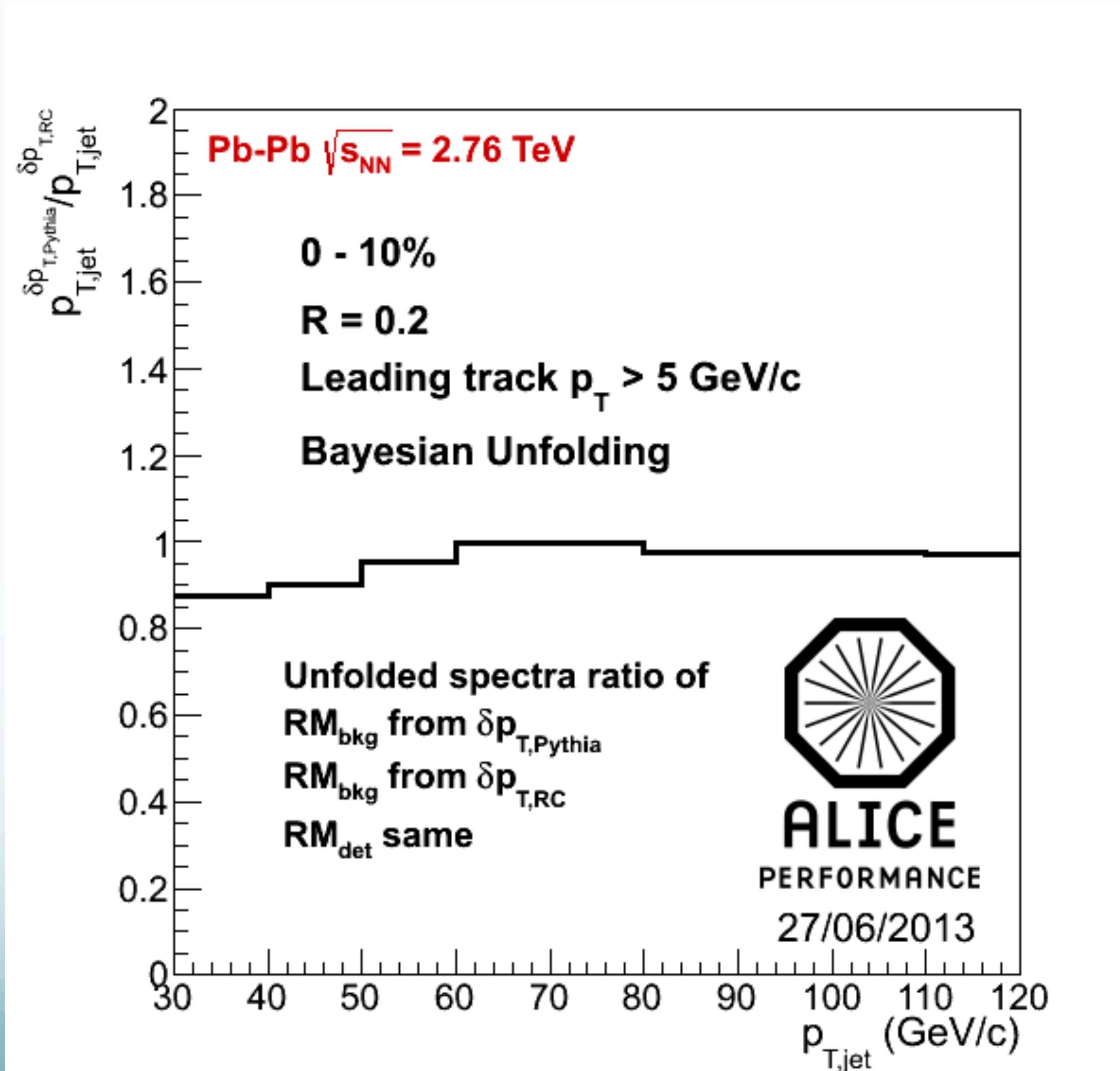
Left plot shows the effect of regularization using Bayesian unfolding

Right plot show unfolding uncertainty due to measured $p_{T,jet}$ range

Embedding

- Combining simulated jets from a MC generator with HI events (HIJING or data) allows cross-checks
  - Closure test
- Closure test is important to validate unfolding framework
  - Unfolding Method
  - RM
- Embedding allows us to check data-driven method for determining δp_T
  - RC vs embedded particle
  - Pythia jets

Using PYTHIA embedding RM



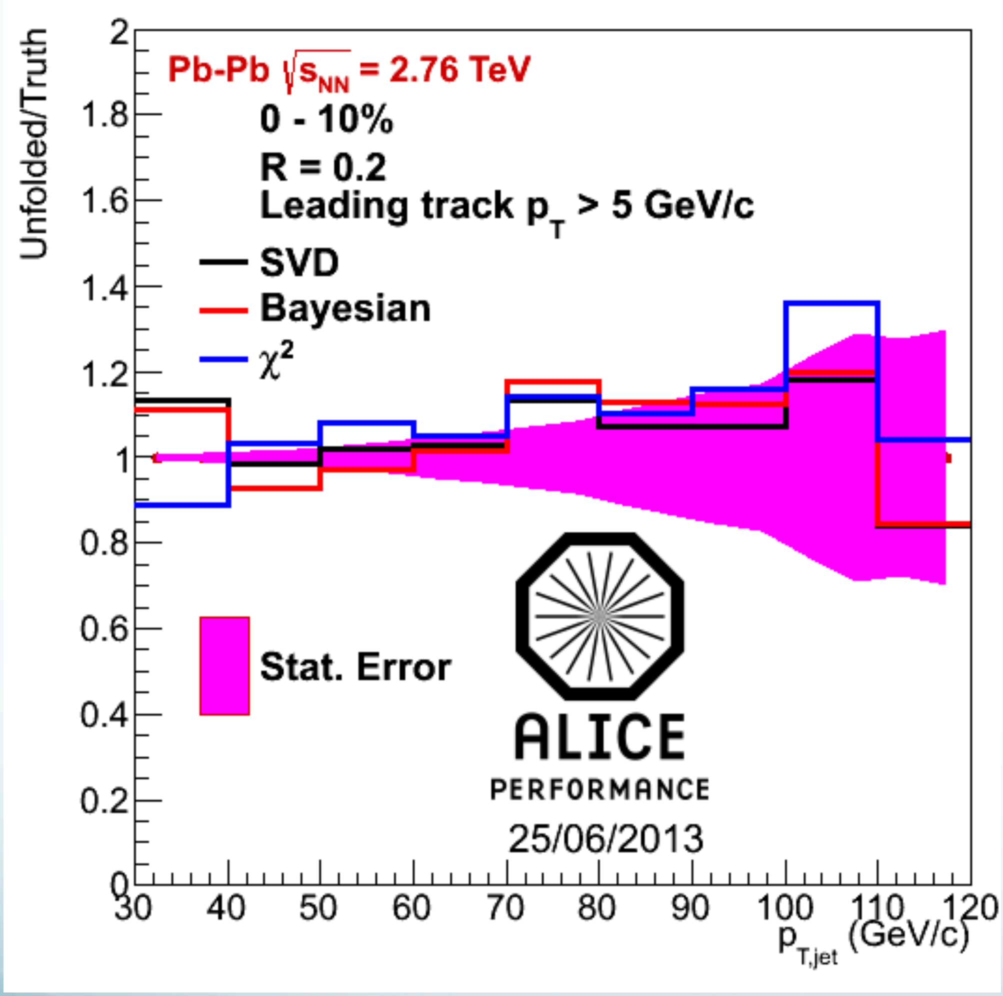
- Choice of RC δp_T for RM_{bkg} determination was simplistic
  - Results are within 10%
  - One of the unfolding uncertainties
- Indicates that the effect of split or merged jets is not large
- Effect of background fluctuations on jet spectra is largely independent of $p_{T,jet}$

Unfolding Evaluation

Closure test

- To benchmark unfolding methods “truth” spectra are embedded into data
  - Do we recover this truth spectrum?
- Embed Pythia jets into Pb-Pb data, at particle level and at detector level
  - Select detector level jets with MC energy “measured jets”
  - Unfold the “measured” jets and compare to embedding particle level jets
    - Tests corrections for both detector effects and background fluctuations
    - Does not test the effect of fake jets

Closure test



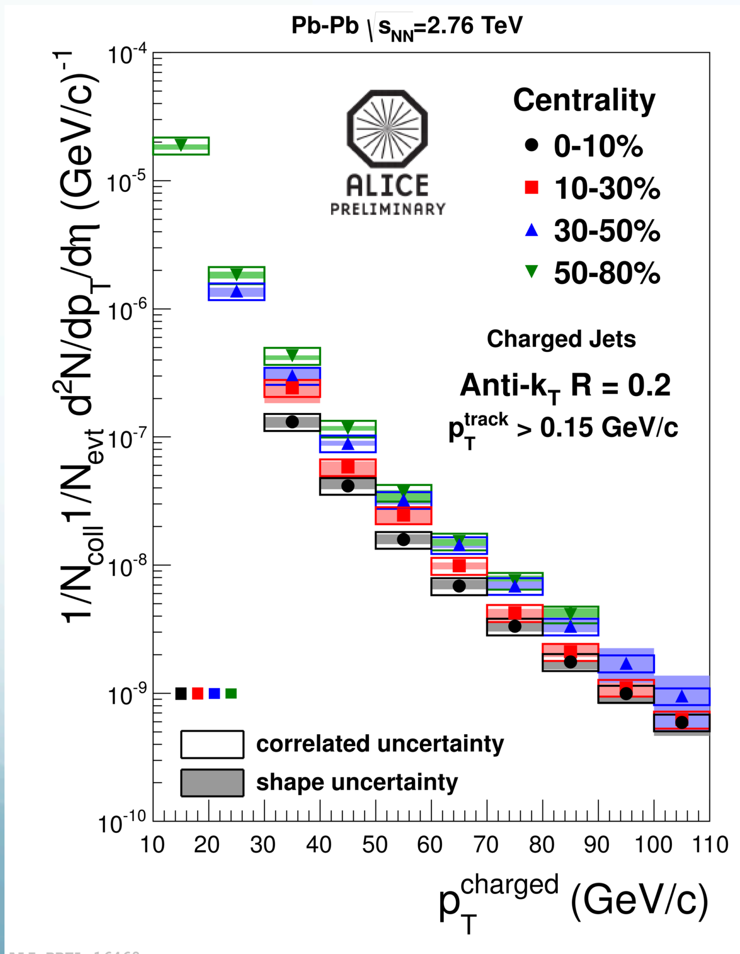
SVD, **Bayesian** and χ^2 **minimization**

- **Measured** jets are all **reconstructed** jets with MC energy > 1 GeV
  - Background subtracted
- **Unfolded** jets are corrected from measured jets
  - RM_{bkg} constructed with RC
  - RM_{det} constructed with PYTHIA
- **Truth** is PYTHIA **particle level** jets

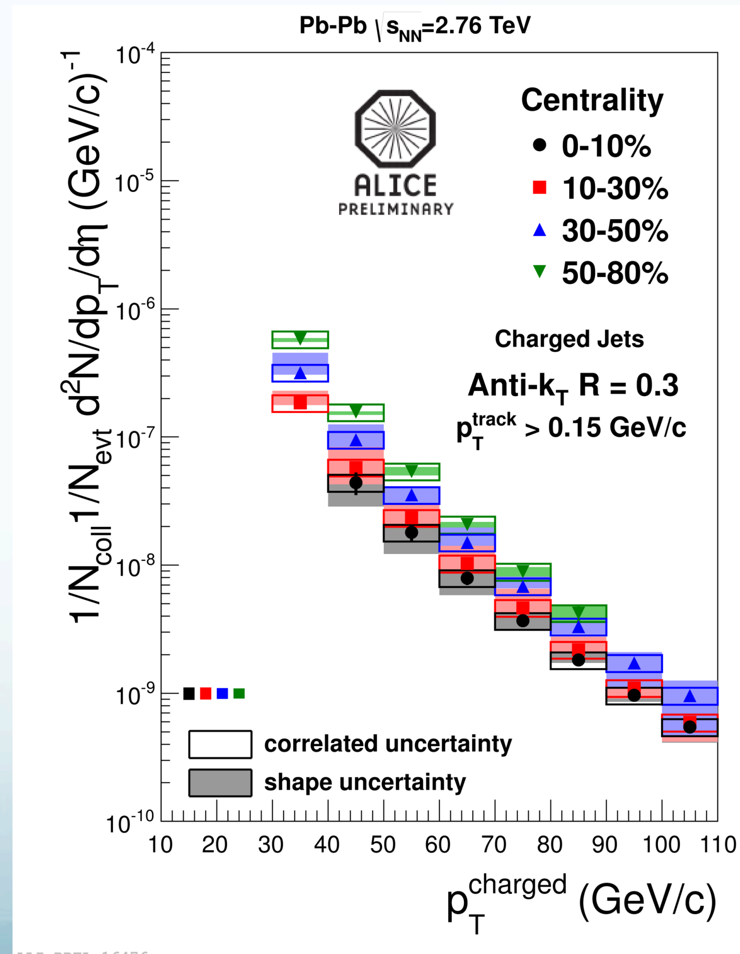
Jet Spectra (unbiased)

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

R = 0.2

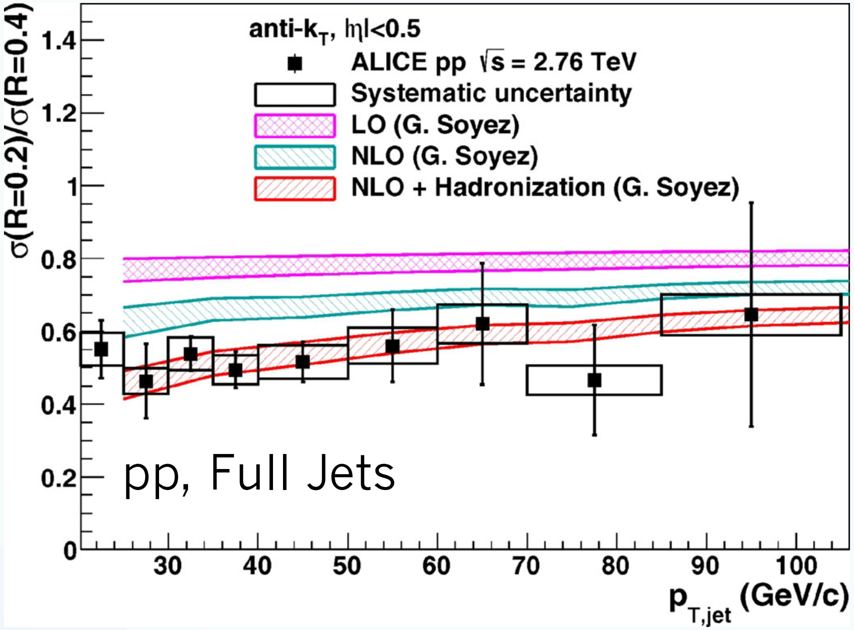


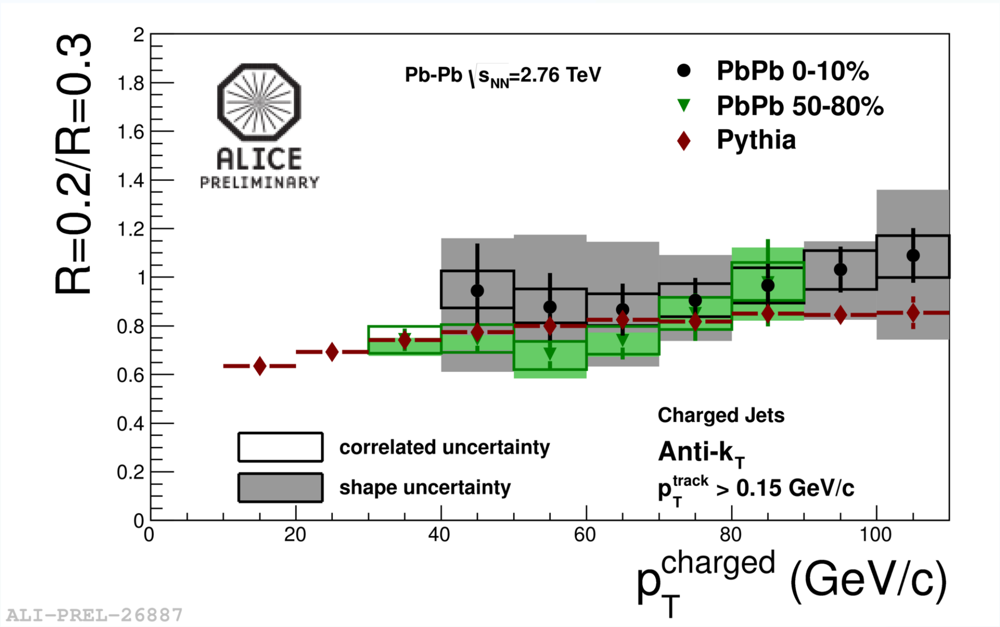
R = 0.3



Ratio of Jet Spectra (unbiased)

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

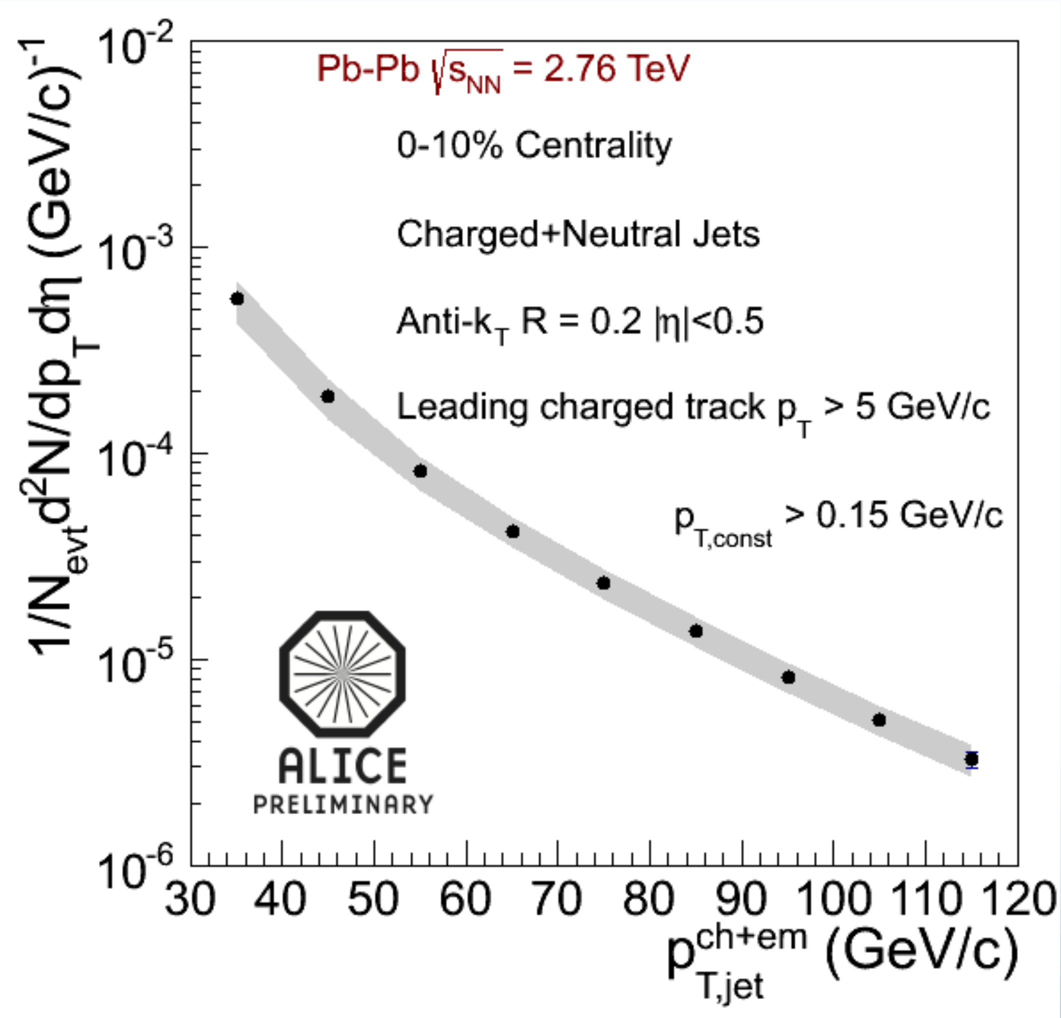




- Charged jet cross-section ratio σ(R=0.2)/ σ (R=0.3)
  - Consistent with vacuum jets
    - PYTHIA
    - Full jet pp

Full Jet Spectrum

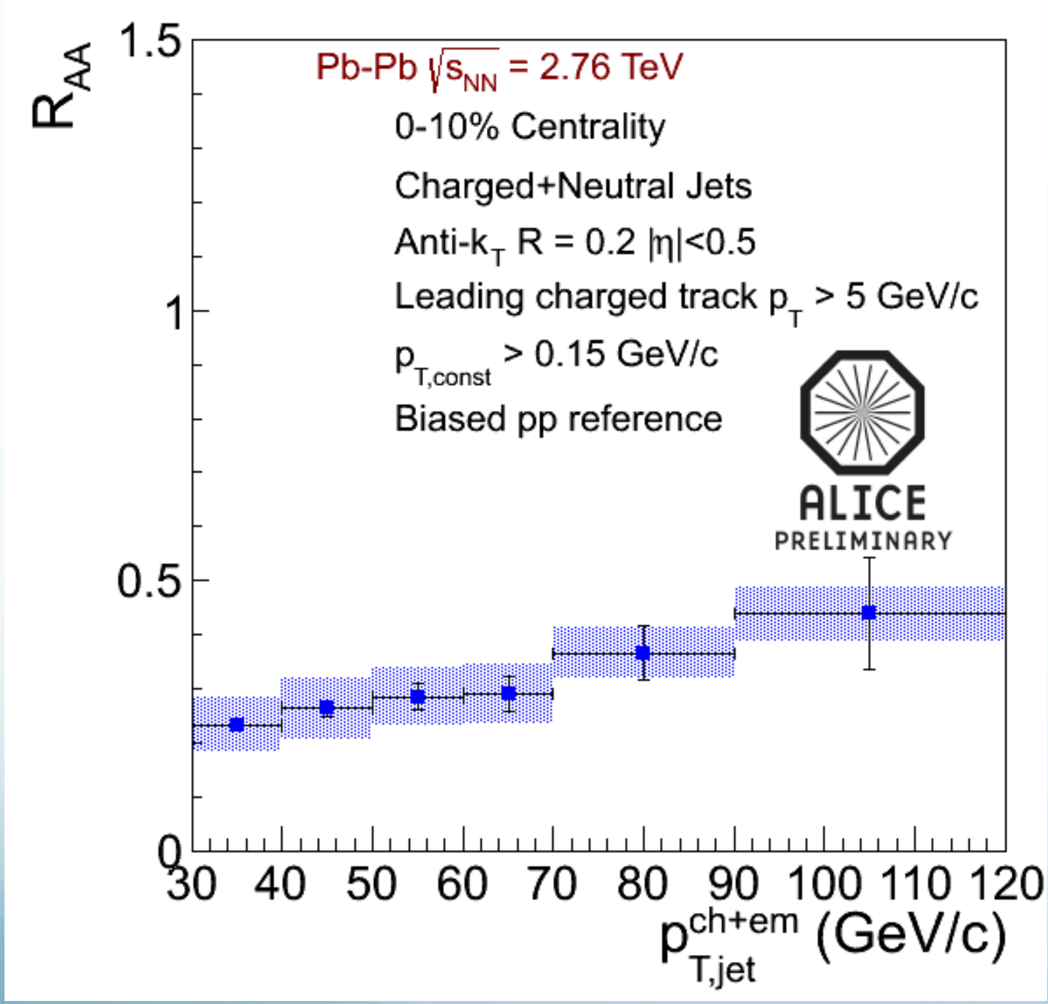
Charged+EMCal Jets $\sqrt{s_{NN}}$ = 2.76 TeV, R=0.2 0-10%



- Jets are corrected for background fluctuations and detector effects in unfolding
  - Bayesian method
- Systematics:
  - ~19% (p_T dependent)
  - EMCal effects (Resolution, scale, clusterizer, non-linearity)
  - Unfolding
  - Tracking efficiency
  - Background

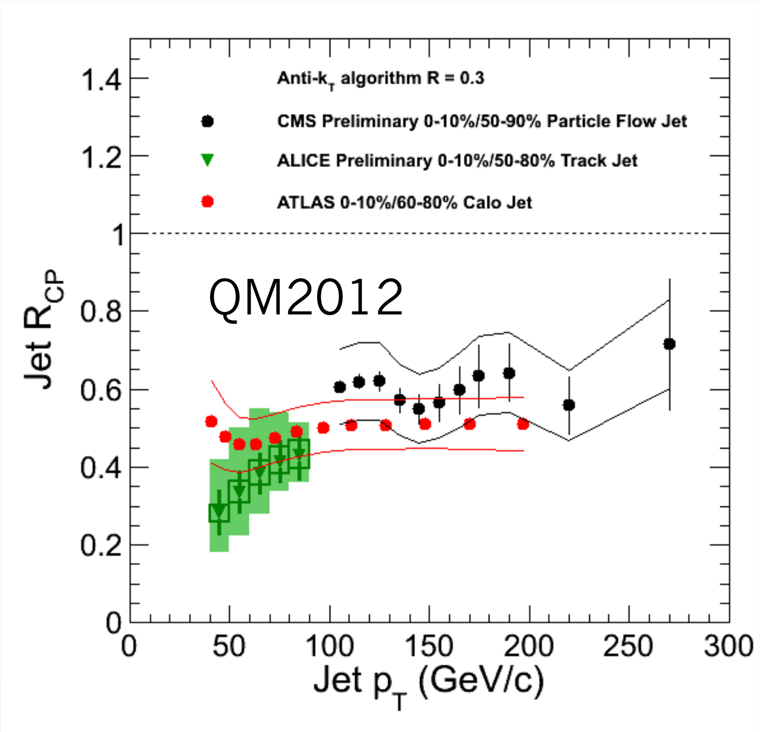
Full Jet R_{AA}

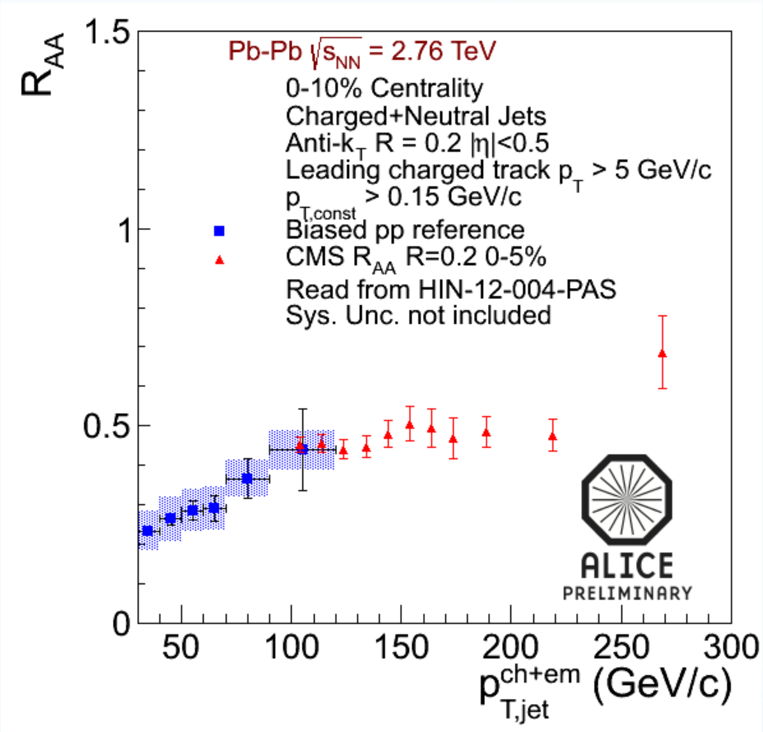
$\sqrt{s_{NN}}$ = 2.76 TeV, R=0.2 0-10%



- Reference pp spectrum and Pb-Pb spectrum both have leading track p_T > 5 GeV/c
- R = 0.2 jets are suppressed in central collisions
- f_{hadcor} = 100%,
  p_T > 150 MeV/c
  E_T > 300 MeV

LHC Jet R_{AA} (R_{CP}) Comparison





- All experiments see jet suppression in central Pb-Pb collisions at 2.76 TeV but comparison is complicated due to different R, η, p_T constituent cuts, background determination
- ALICE and CMS are consistent within overlap region with the same R and different constituent cuts

Conclusions

- Disentangling background effects from jets in heavy ion collisions is complicated
  - But a lot of progress has been made!
    - Background determination
    - Unfolding
  - Each experiment faces unique challenges and uses different strategies to deal with the effect of UE and the detectors on the measured jets
- Effect of large angle radiation and soft physics on jet measurements needs theory guidance
  - Experimental efforts have gained some knowledge
  - See Leticia's talk for more further discussion
    - Experimental observables
    - Theoretical comparisons

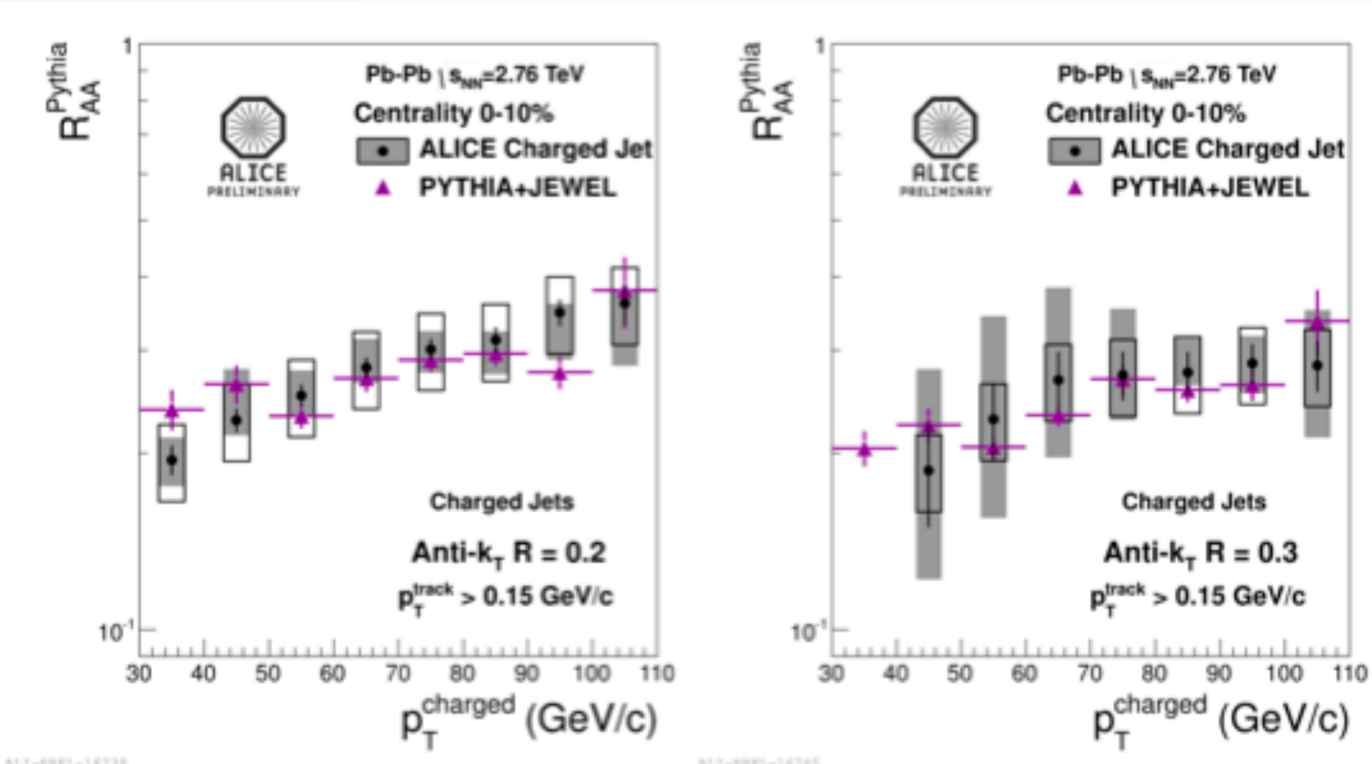
Back-up

Unfolding Methods

- Bayesian
  - Toy model investigation indicates that this method is susceptible to fakes
  - Regularization is number of iterations
  - Requires a reasonable prior
    - Prior is the initial solution for the unfolding method
- SVD
  - Toy model investigation shows this method performs well
  - Tikhonov regularization method suppresses small singular values
  - Requires a reasonable prior
- $\chi 2$
  - Toy model studies show good agreement with SVD
  - Regularization is employed by assuming a local power law (for jet spectra)
  - Does not have a strong dependence on prior

Comparison to Models

$\sqrt{s_{NN}}$ = 2.76 TeV, R=0.2,0.3 0-10%



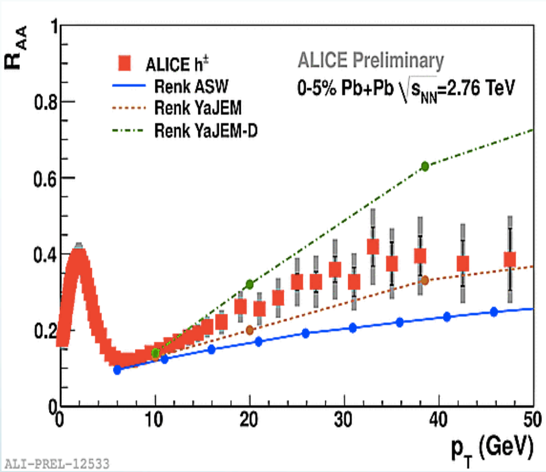
PYTHIA used for charged pp reference spectrum for R_{AA} calculation

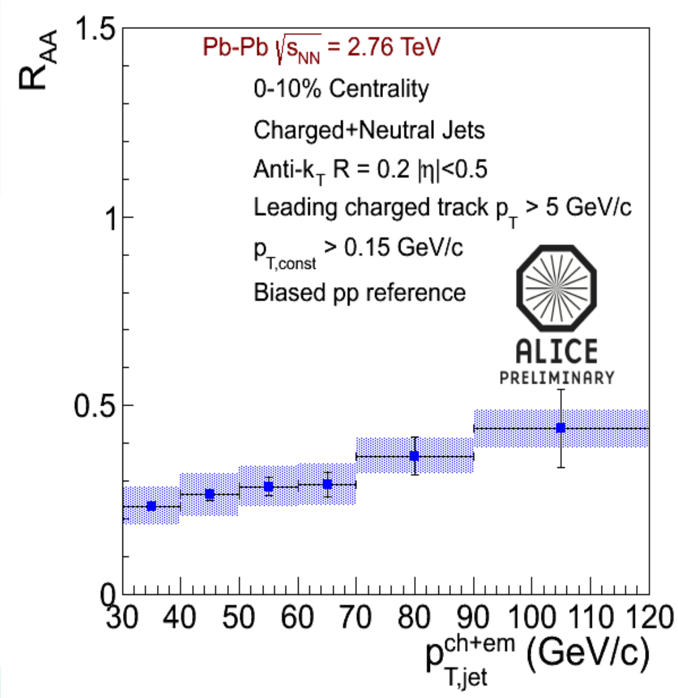
R=0.2,0.3 jets are suppressed in central collisions

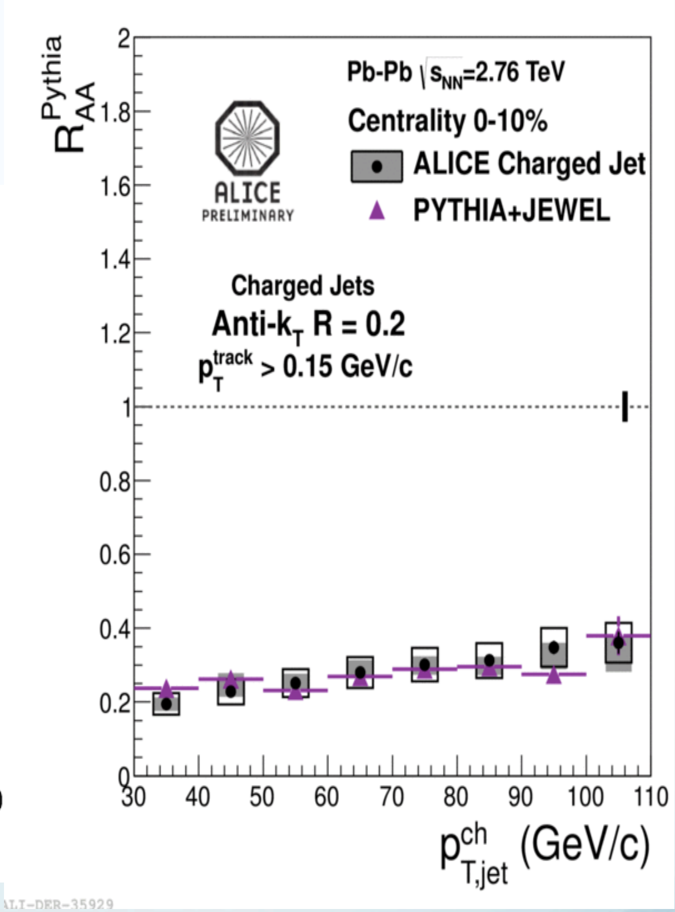
Good agreement between JEWEL and inclusive charged jet R_{AA}

R_{AA} Comparison

Jet R_{AA} ~ Hadron R_{AA}
Charged jet R_{AA} ~ Full Jet R_{AA}







Jet R_{AA} was surprisingly low, though this is reproduced by some models
Where is the missing energy? Large angles? Low p_T?

Unfolded Biased Jet Spectra

- Leading track bias improves unfolding stability
  - Reduces combinatorial jets

    arXiv:1208.1518
  - Bias of 5 GeV/c does not significantly change pp, Pb-Pb spectra