Measurement of jet spectra in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV with ALICE

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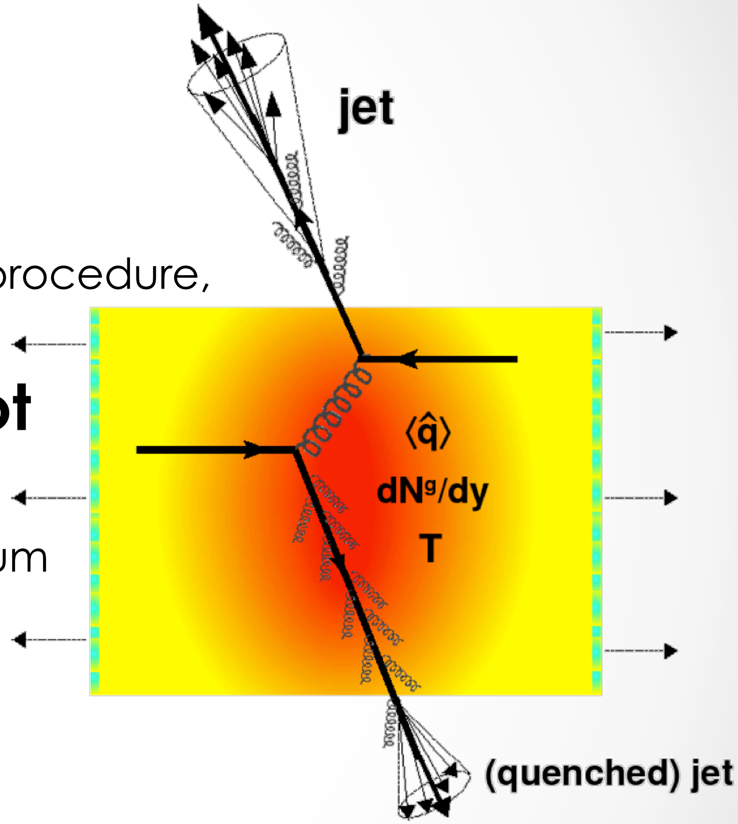
on behalf of the ALICE collaboration
INFN Catania and LBNL

Outline

- Introduction
- Analysis overview
- Jet reconstruction
- Background estimation
- Unfolding
- Jet spectra
- Conclusions & Outlook

Jets in heavy-ion collisions

- Jet: **collimated spray of hadrons**
  - QCD branching of a high p_T parton
  - Subsequent hadronization of fragments
  - Experimentally grouped according to given procedure, *jet algorithm*
- Jets can be used to **probe the hot QCD medium**
  - Observable properties modified by the medium
    - p_T distribution
    - …and many more



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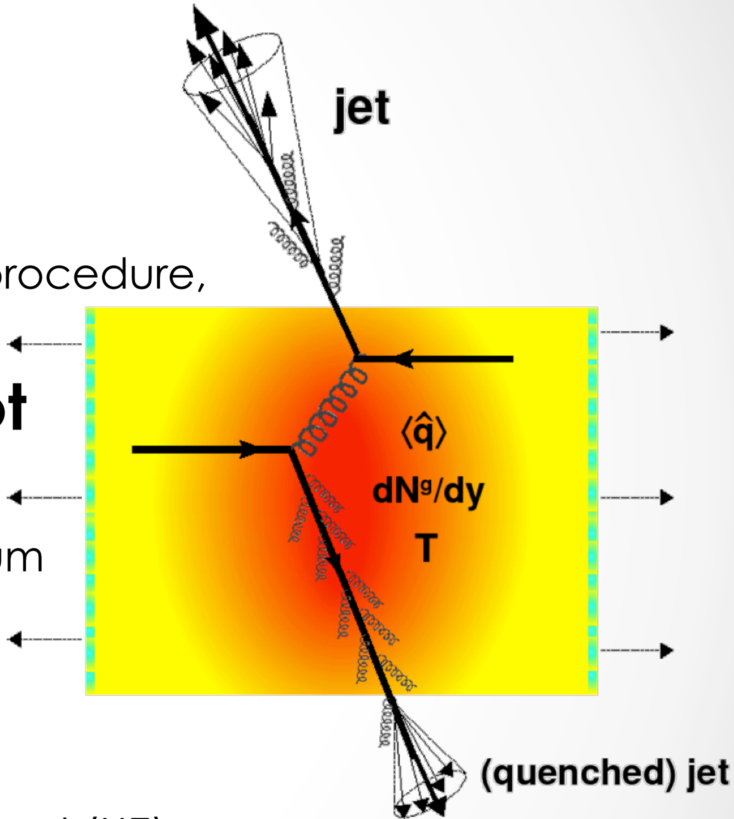
  - Huge background given by the underlying event (UE)
    1. **Average background**
    2. **Combinatorial jets**
    3. ***p_T* smearing due to background fluctuations**



Jet-by-jet and event-by-event correction

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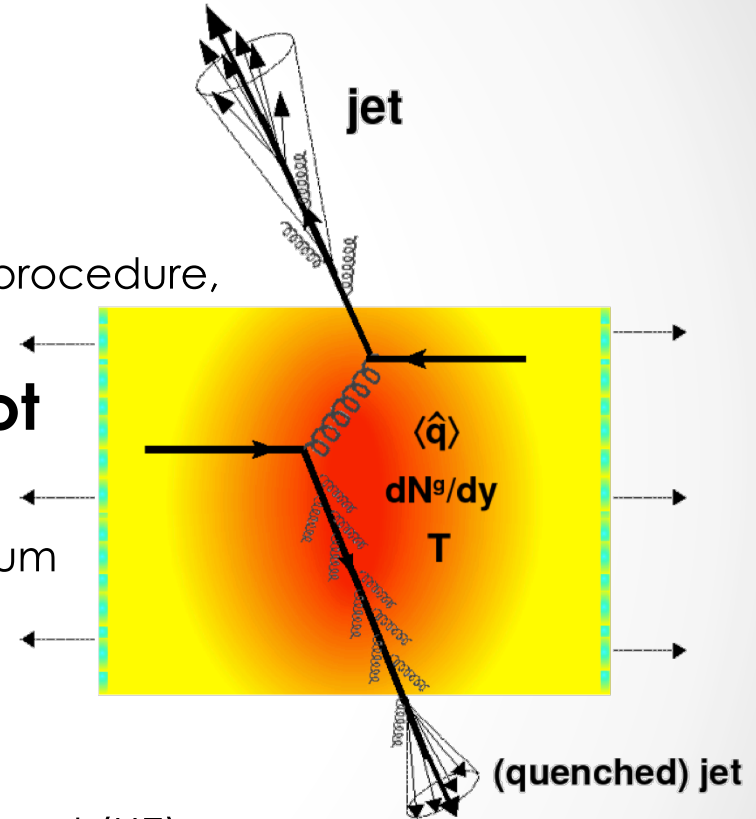

Efficiently removed by a leading hadron p_T requirement

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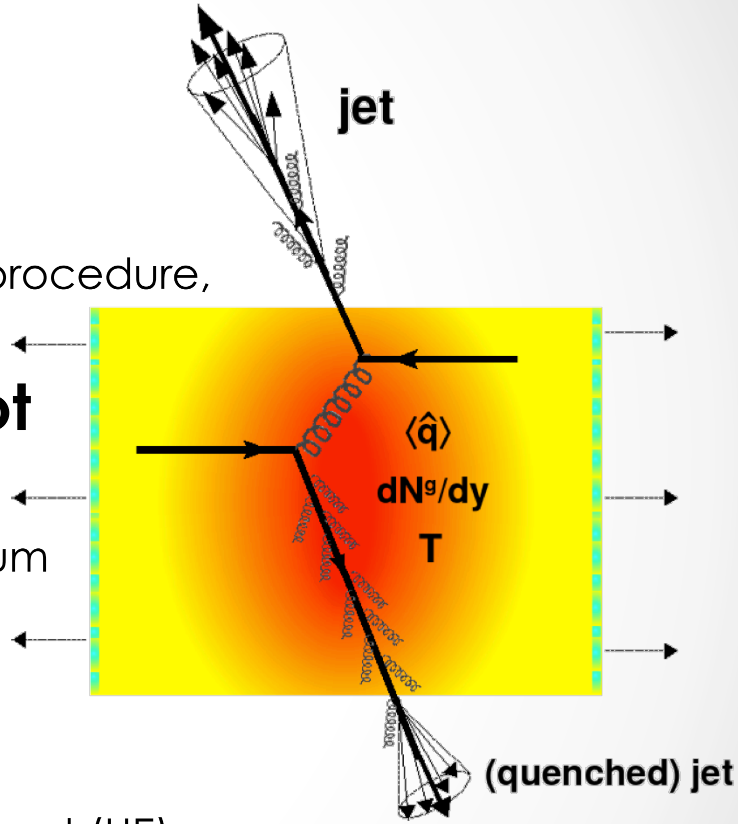
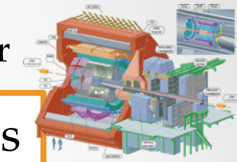


Statistical correction based on δp_T distributions

Analysis overview

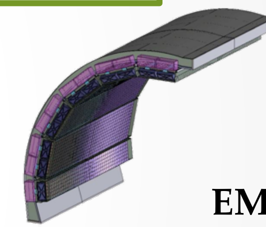
Tracking: $|\eta| < 0.9$, $0° < \varphi < 360°$
TPC: gas detector
ITS: silicon detector



Charged tracks

Hadronic correction

EMCal clusters



EMCal
Pb-scintillator sampling calorimeter
$|\eta| < 0.7$, $80° < \varphi < 180°$

Charged tracks | Corrected EMCal clusters

Jet finder
Anti-k_T

Average background subtraction

Raw jet spectrum

Final jet spectrum

Unfolding
Inverse matrix calculation through numerical methods

$$f^{raw}(p_T) = RM_{bkg} \times RM_{det} \times f^{true}(p_T)$$

Jet reconstruction

- Inputs to the jet finder
  - Assumed to be massless
  - **Charged tracks** with $p_T > 150$ MeV/c
  - **EMCal clusters** with $E_T > 300$ MeV/c after charged particle correction

- Jet reconstructed using FastJet* package
  - **Infrared-** and **Collinear-Safe** algorithms
    - Good for comparison with theory
  - **Radii** $R = 0.2, 0.3$
  - **Area cut** $A > 0.6 * \pi R^2$ removes extremes
  - Fiducial cut selects jets **fully contained in the EMCal** acceptance

Sequential recombination

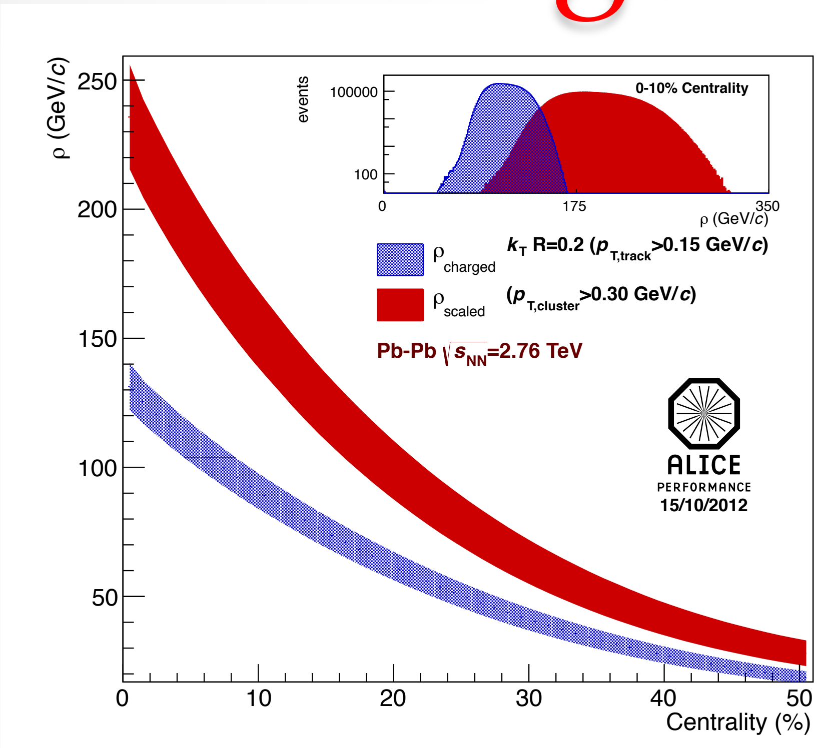
$$d_{ij} = \min(k_{Ti}^{2p}, k_{Tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \qquad d_{iB} = k_{Ti}^{2p}$$

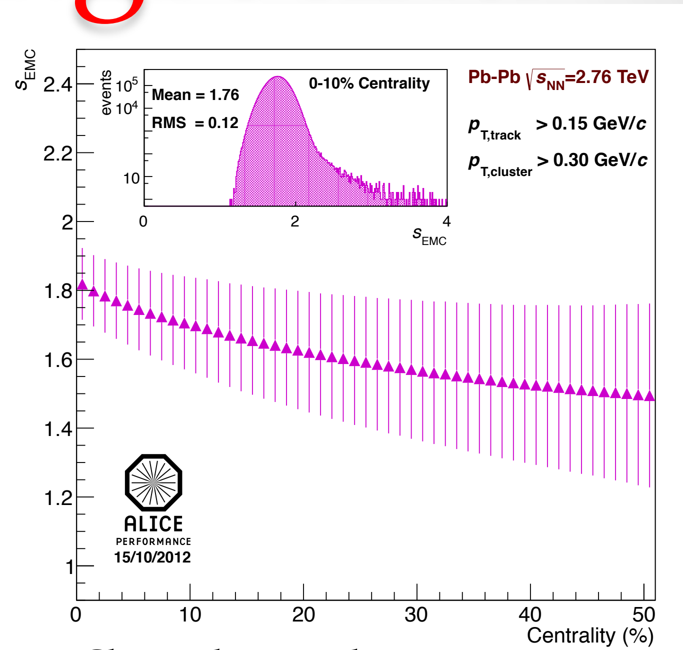
$p = 1$ **k_T algorithm**
Clustering starts from the low p_T particles
Used for ϱ calculation

$p = -1$ **Anti-k_T algorithm**
Clustering starts from the highest p_T particle, regular cone-like jet shapes
Used for signal jets

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

1. Average background

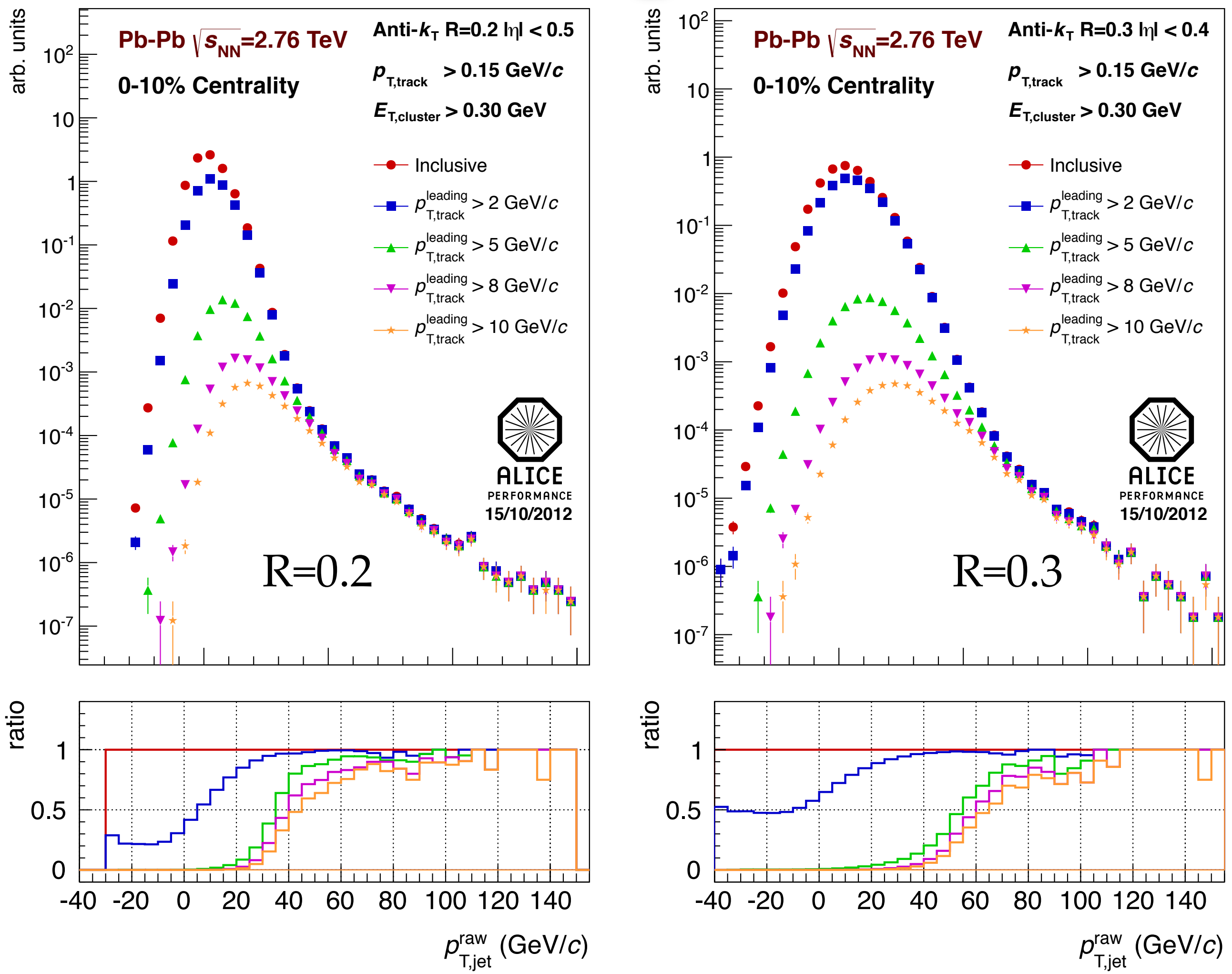




Charged+neutral momentum density / charged only momentum density

- Calculated on an **event-by-event basis**
- The median of the density of k_T charged jets gives $\rho_{ch} = median\left[\left\{\frac{p_{Tj}^{k_T}}{A_j^{k_T}}\right\}\right]$
- A parametrization of the scale s_{EMC} factor as a function of centrality is used to obtain $\rho_{ch+ne} = \rho_{ch} \times s_{EMC}$

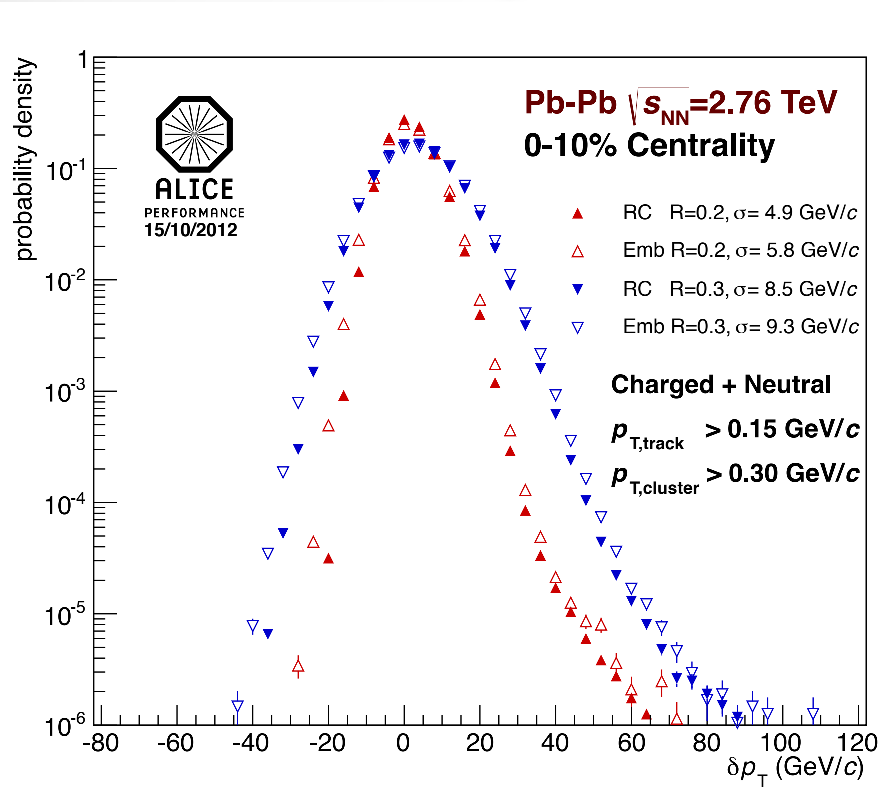
2. Leading hadron trigger



- **Combinatorial jets**: jet finder clusters together also soft particles from the UE
- Efficiently remove the fake jets by **requiring a high p_T constituent**
- Bigger effect when changing the p_T threshold from 0 ➔ 5 GeV/c than 5➔10 GeV/c
- Bias still effective up to 100 GeV/c

5 GeV/c is our default choice for R=0.2 jet spectra

3. Background fluctuations



- Region-by-region background fluctuations are estimated through **random cones** (solid symbols) and **single particle embedding** (open symbols)
- Fluctuations limit **jet energy resolution**
  - **Smearing** of the p_T raw jet spectrum

Random cones

1. Throw a random direction in the (η,ϕ) plane
2. Sum up the momenta of all particles in the cone of radius R
3. Calculate

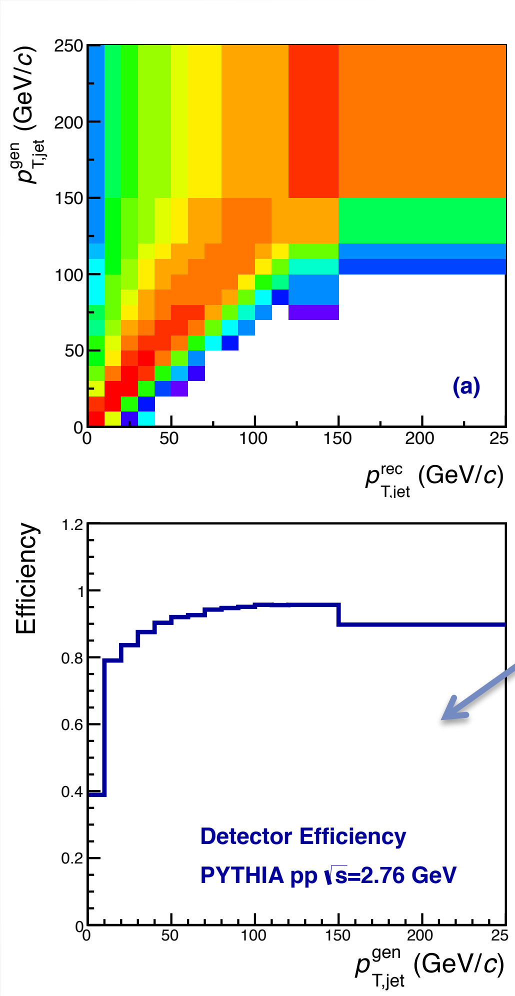
$$\delta p_T^{RC} = p_T^{RC} - \pi R^2 \rho$$

Single particle embedding

1. Embed a high p_T particle
2. Run the Anti-k_T jet finder
3. Pick up the jet which contain the embedded particle and calculate

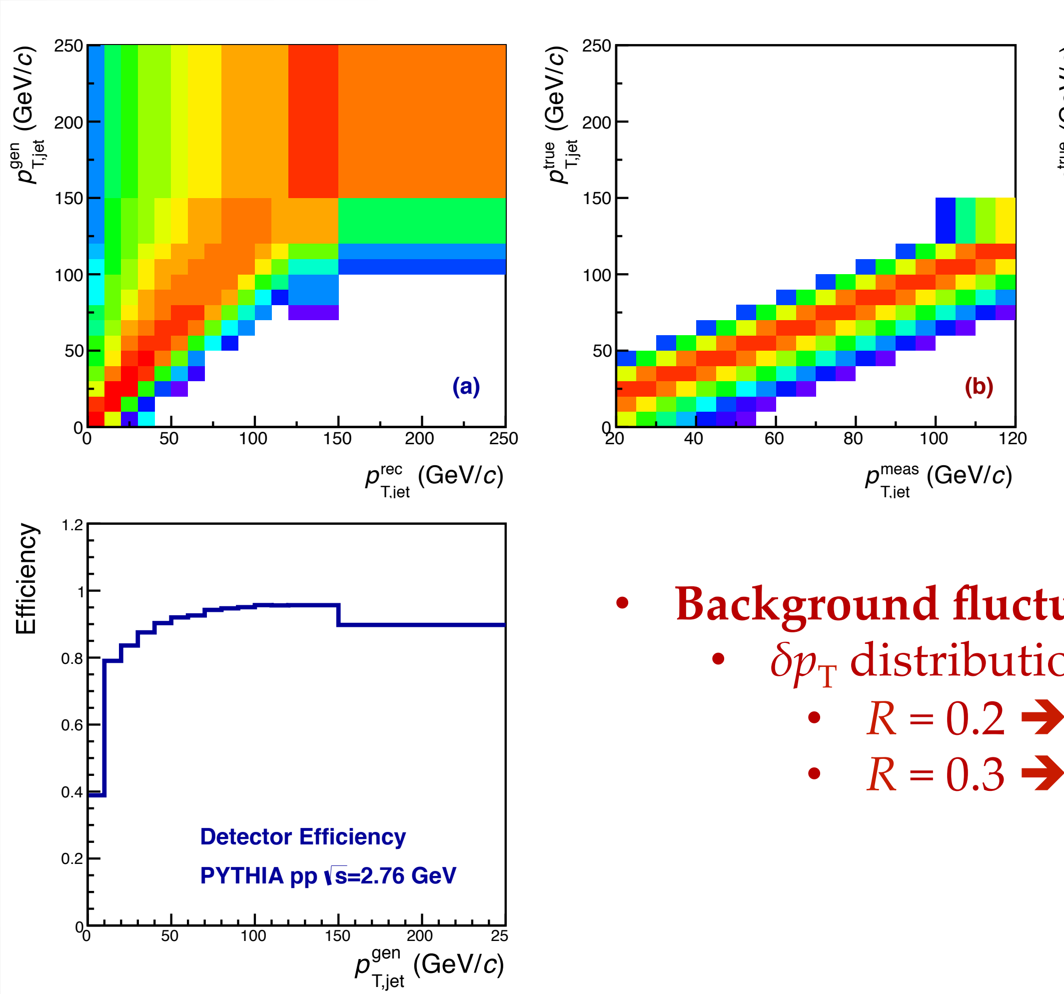
$$\delta p_T^{emb} = p_T^{jet} - p_T^{probe} - A^{jet} \rho$$

Response matrices



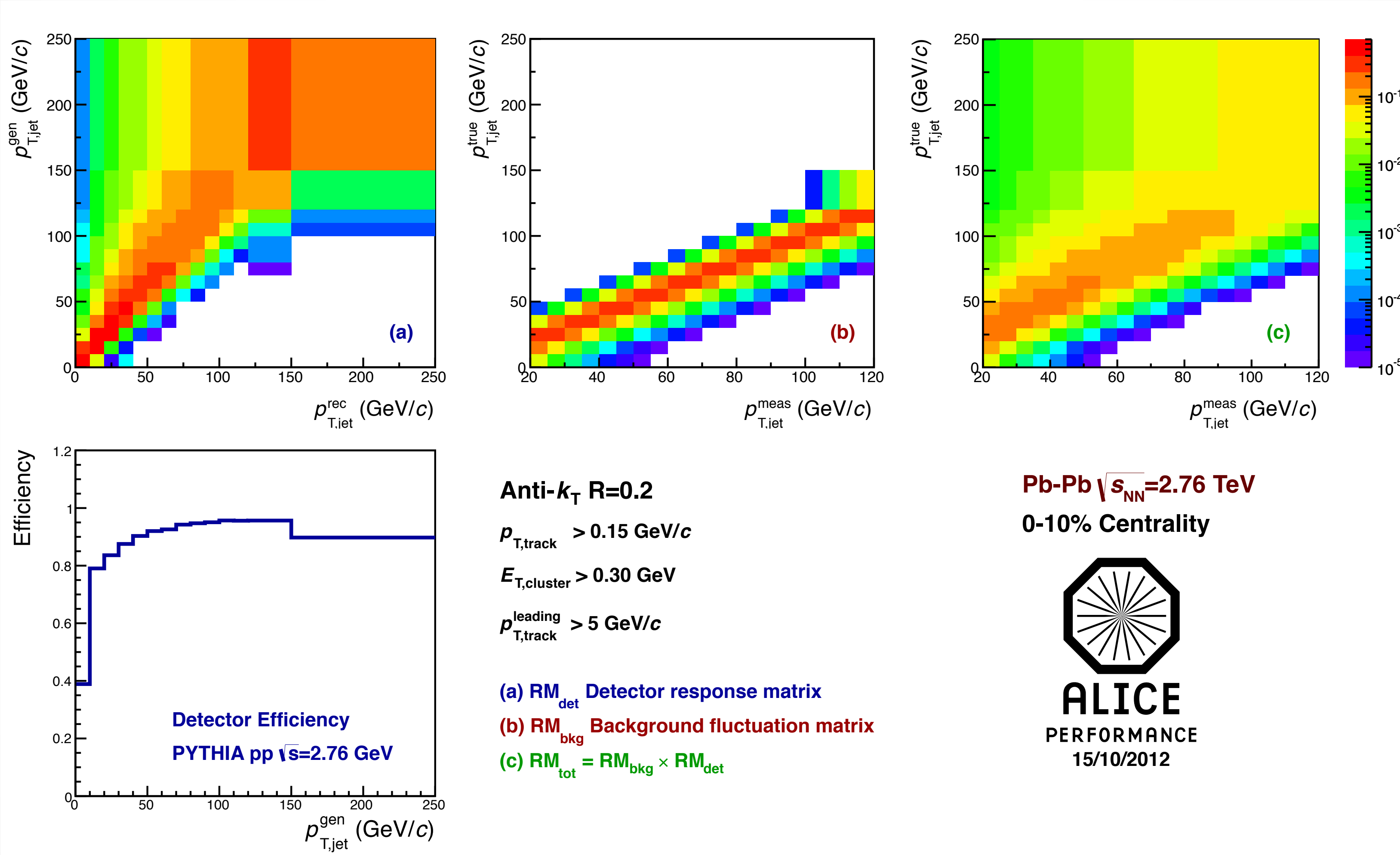
- **Detector effects**
  - PYTHIA+GEANT3 simulation
    - Assumes jet detector response is the same as in **vacuum fragmentation**
  - Shift **jet energy scale** ~ 20-25%
    - Unreconstructed neutrons and K^0_L
    - Tracking inefficiency
  - **Jet energy resolution** ~ 18%
  - **Jet reconstruction efficiency** ~ 95% at 80 GeV/*c*

Response matrices



- **Background fluctuations**
  - δp_{T} distribution (RC)
    - $R = 0.2$ ➔ $\sigma = 4.9$ GeV/c
    - $R = 0.3$ ➔ $\sigma = 8.5$ GeV/c

Response matrices



Why unfolding

- **Remove detector and analysis specific features** from the observables to be compared with theory
- Another **simpler but less elegant approach**: use the response matrix to include these distortions in the theoretical predictions
- **Advantages of unfolding**
  - Comparison between experiments is possible
  - Final results are more "fundamental" and easier to read

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  - **X^2 minimization**

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Bayes' theorem

$$P(C_i \mid E) = \frac{P(E \mid C_i) P(C_i)}{\sum_{l=1}^{n_c} P(E \mid C_l) P(C_l)}$$

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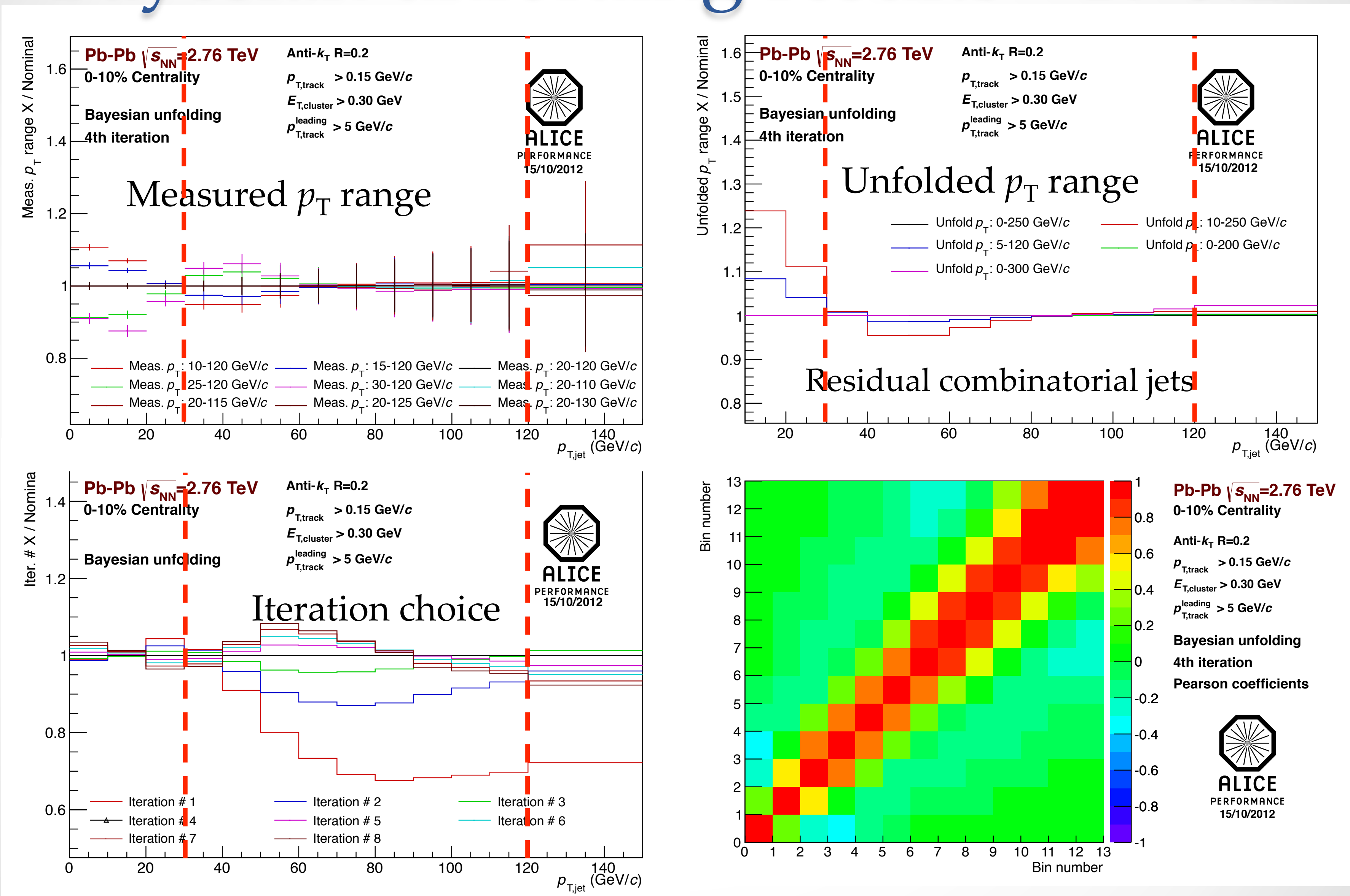
$$\chi^2 = \sum_{refolded} \left(\frac{y_{refoled} - y_{measured}}{\sigma_{measured}} \right)^2 + \beta \sum_{unfolded} \left(\frac{d^2 \log y_{unfolded}}{d \log p_T^2} \right)$$

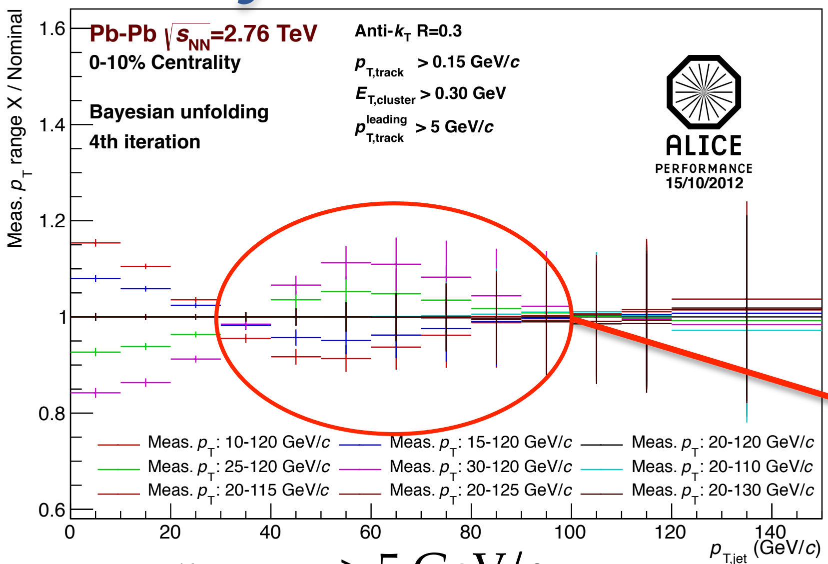
  - **Bayesian**
    - Uses the Bayes' theorem to iteratively update the estimators' probabilities, starting from a "prior" guess (**finite # of iterations**)
    - Infinite iterations would give the best mathematical solution, but highly fluctuating, not useful for physics
- **Regularization parameter**: *a priori* knowledge about spectrum shape
  - Avoids wildly fluctuating results
  - Introduce a bias in the result

G. D'Agostini, Nuclear Instr. Meth., 362 (1995) 487-498
G. Cowan, A Survey of Unfolding Methods in Part. Phys., Proc. Adv. Stat. Tech. in Part. Phys., Durham (2002) (link)

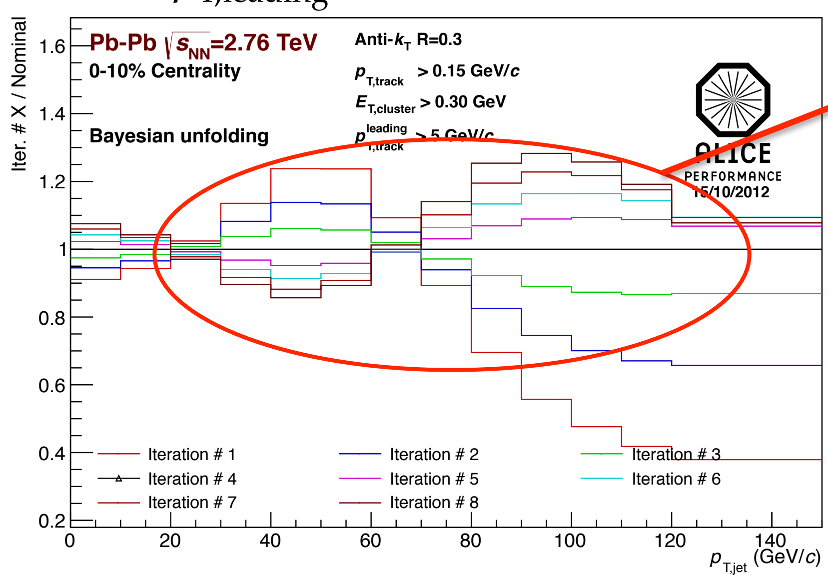
Bayesian unfolding results – R=0.2



Bayesian unfolding results – R=0.3

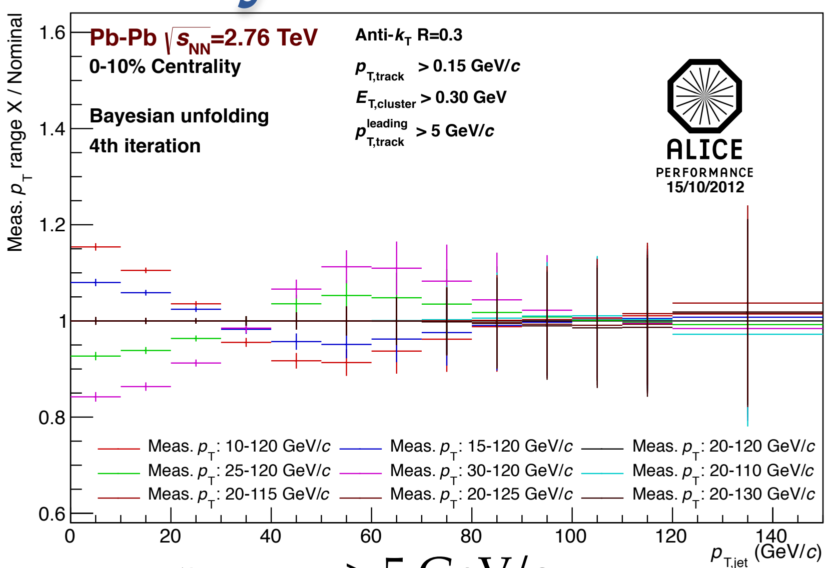


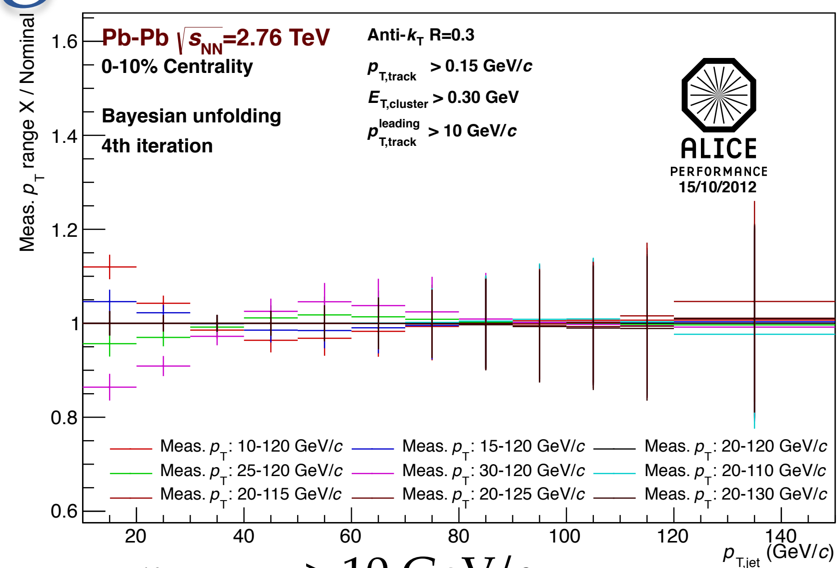
$p_{T,leading} > 5$ GeV/c



Unfolding instabilities…

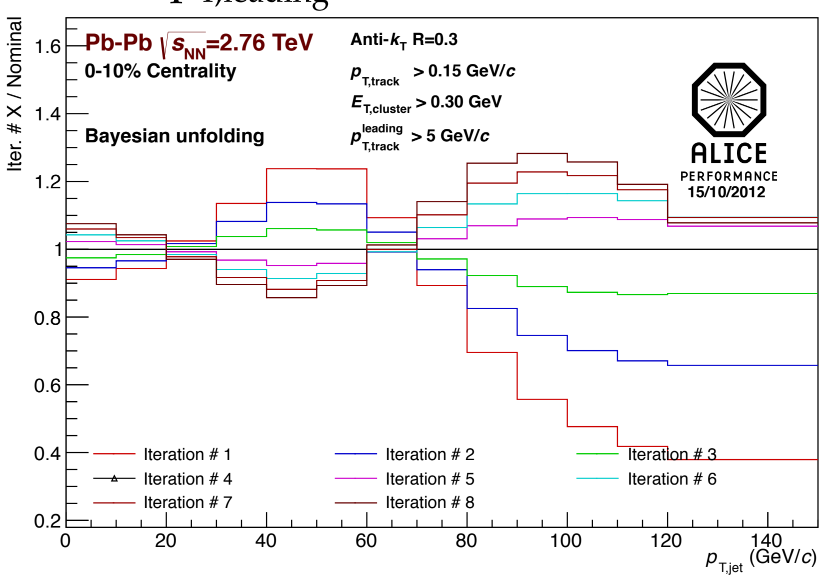
Bayesian unfolding results – R=0.3

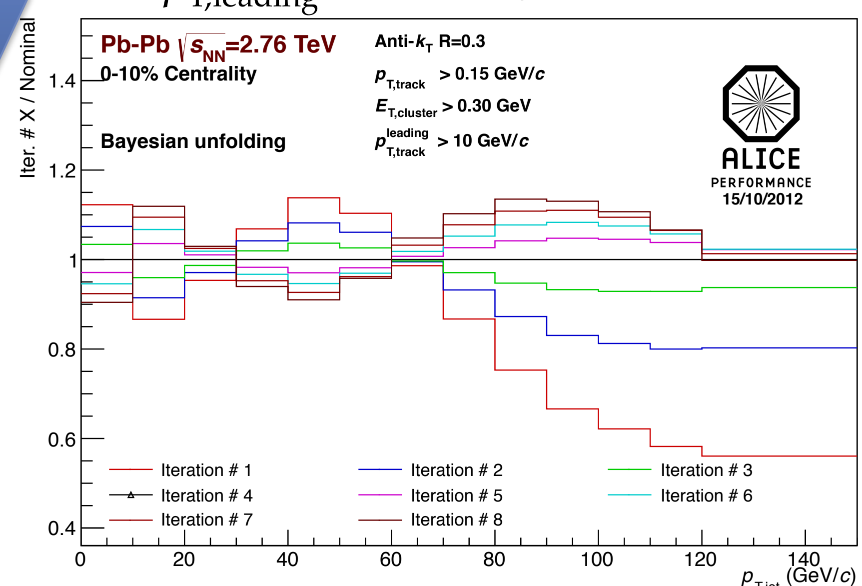




$p_{T,leading} > 5$ GeV/c

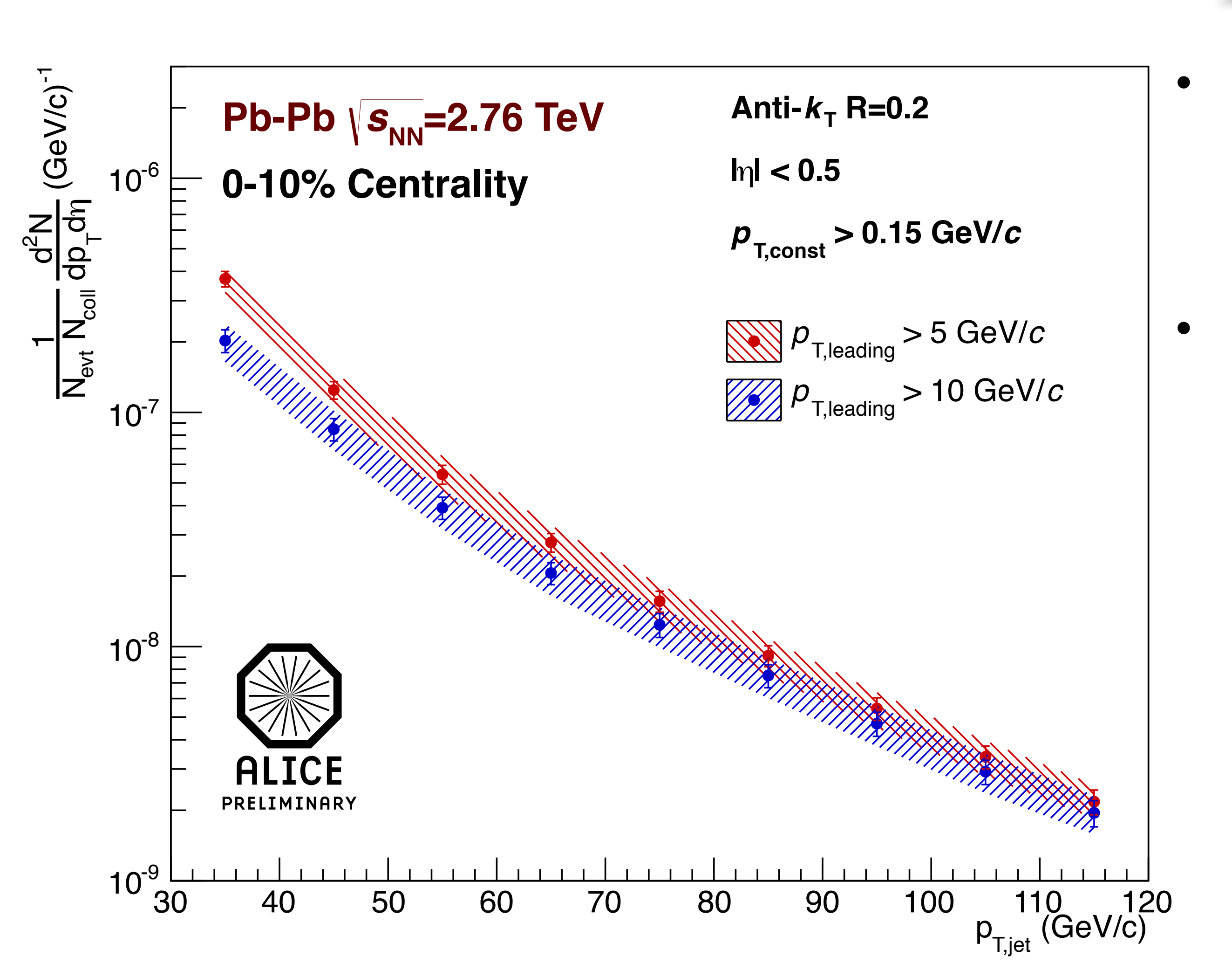
$p_{T,leading} > 10$ GeV/c





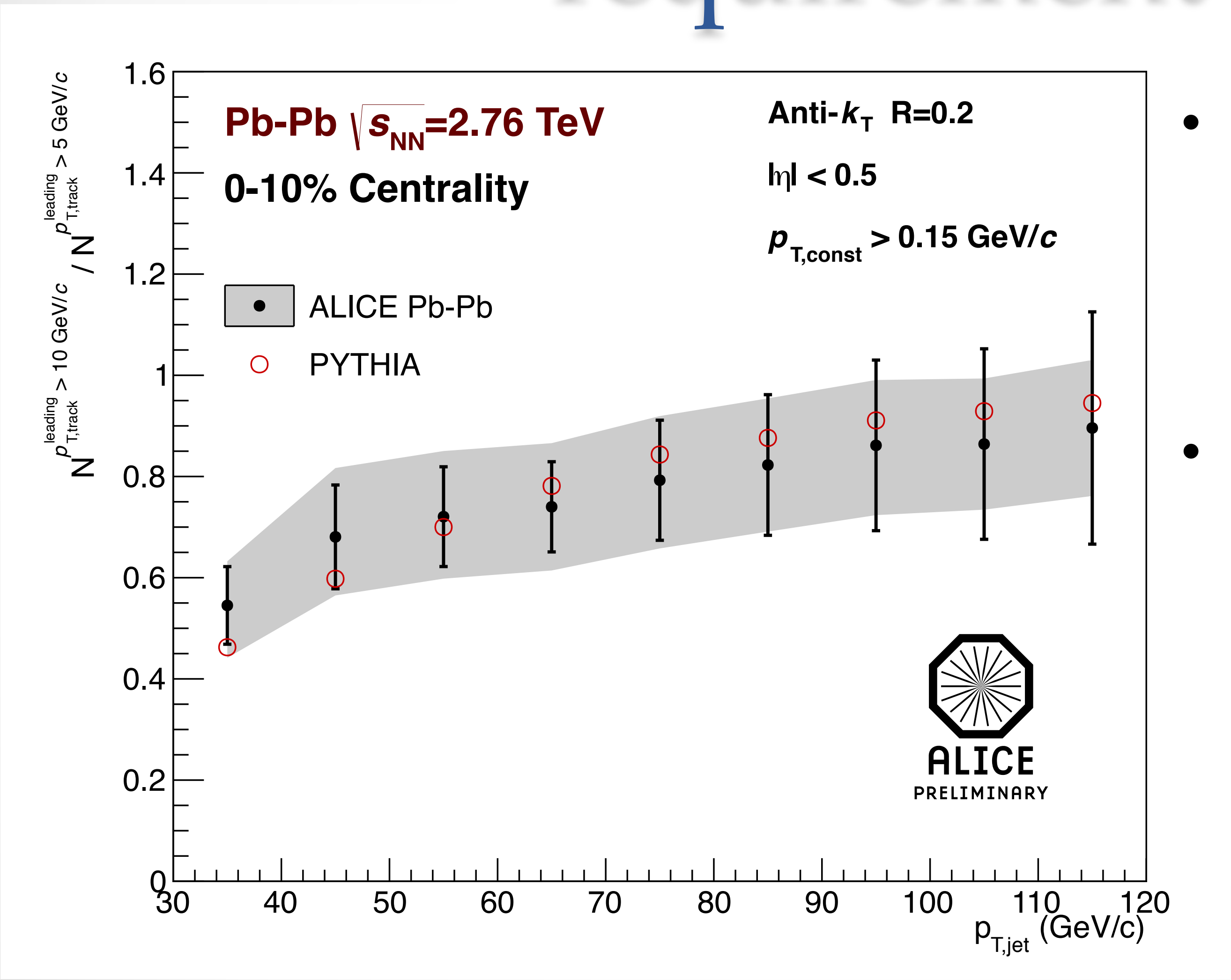
In progress…

Unfolded biased spectra



- Fully corrected p_T jet spectra
  - R=0.2
  - $p_{T,const}$ > 0.15 GeV/c
- Two different leading hadron triggers
  - trigger only on charged tracks to avoid difficulties in the theoretical predictions
  - $p_{T,track}$ > 5 GeV/c
  - $p_{T,track}$ > 10 GeV/c

Effect of the leading hadron requirement



- Statistics and systematics
  - Take into account correlated uncertainties
- Agreement with PYTHIA is consistent with vacuum-like fragmentation of the jet core

Conclusions & Outlook

- **Background** in Pb-Pb central collisions has been studied in order to be able to extract a "clean" signal
- **Bayesian unfolding** used to correct spectra for **background fluctuations** and **detector-induced effects**
  - Studies are ongoing to unfold the **R=0.3 spectra**
- Effect of the **leading hadron requirement** studied for two different thresholds, 5 GeV/c and 10 GeV/c
  - Agreement with PYTHIA is **consistent with vacuum-like fragmentation** of the jet core

Backup

Systematic uncertainties

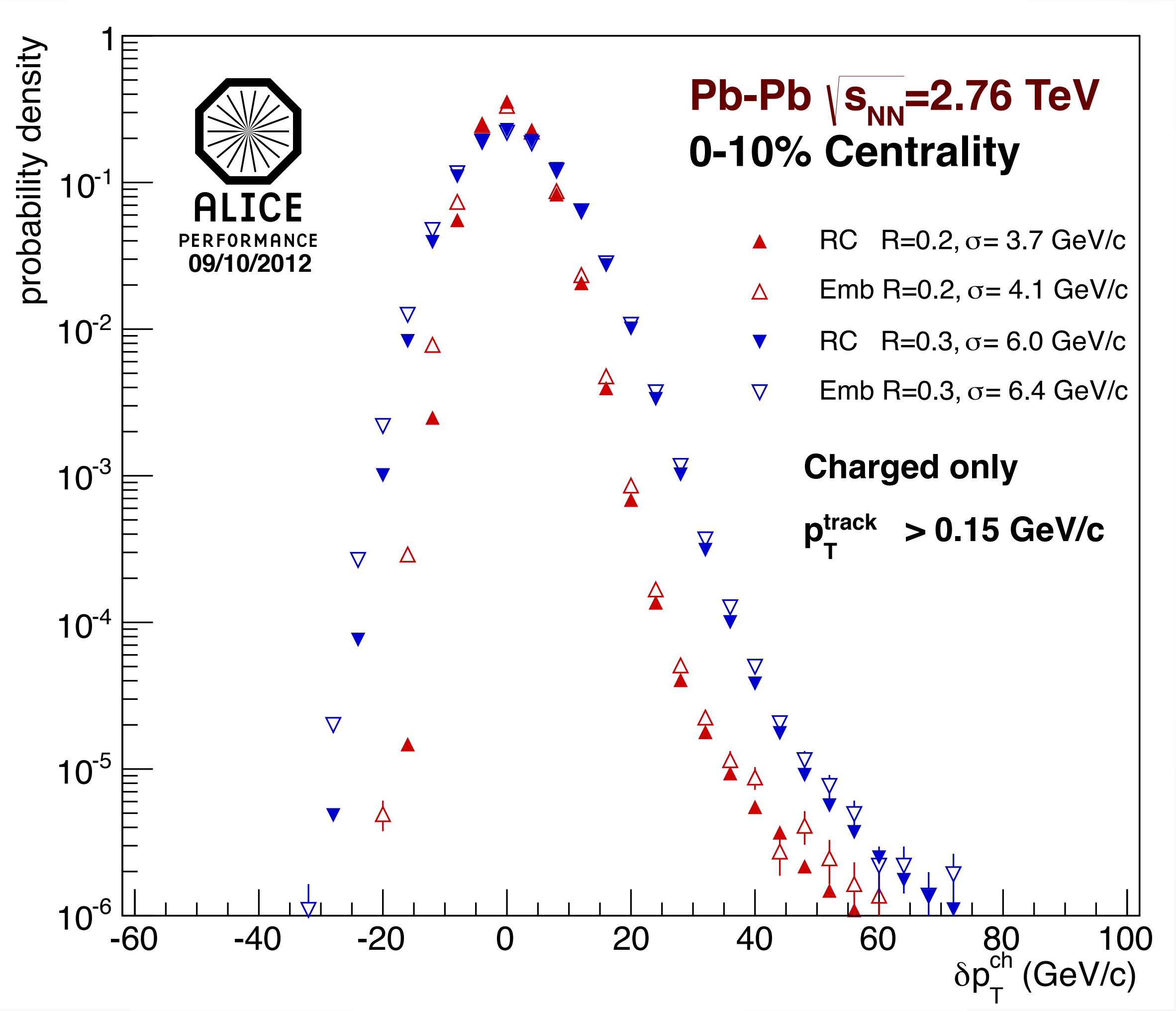
Uncertainty	% on jet spectrum
EMCal (resolution, energy scale, clusterizer, non-linearity)	5.3
Tracking Efficiency	10
Hadronic Correction	10
Scale Factor	2
δp_T RC vs. Embedding	5
Unfolding	14
Flow bias	< 1%
Total	**19**

Unfolding uncertainty	% on jet spectrum
Iteration	5
Measured p_T range	9
Unfolded p_T range	5
Prior choice	10
Total unfolding	**14**

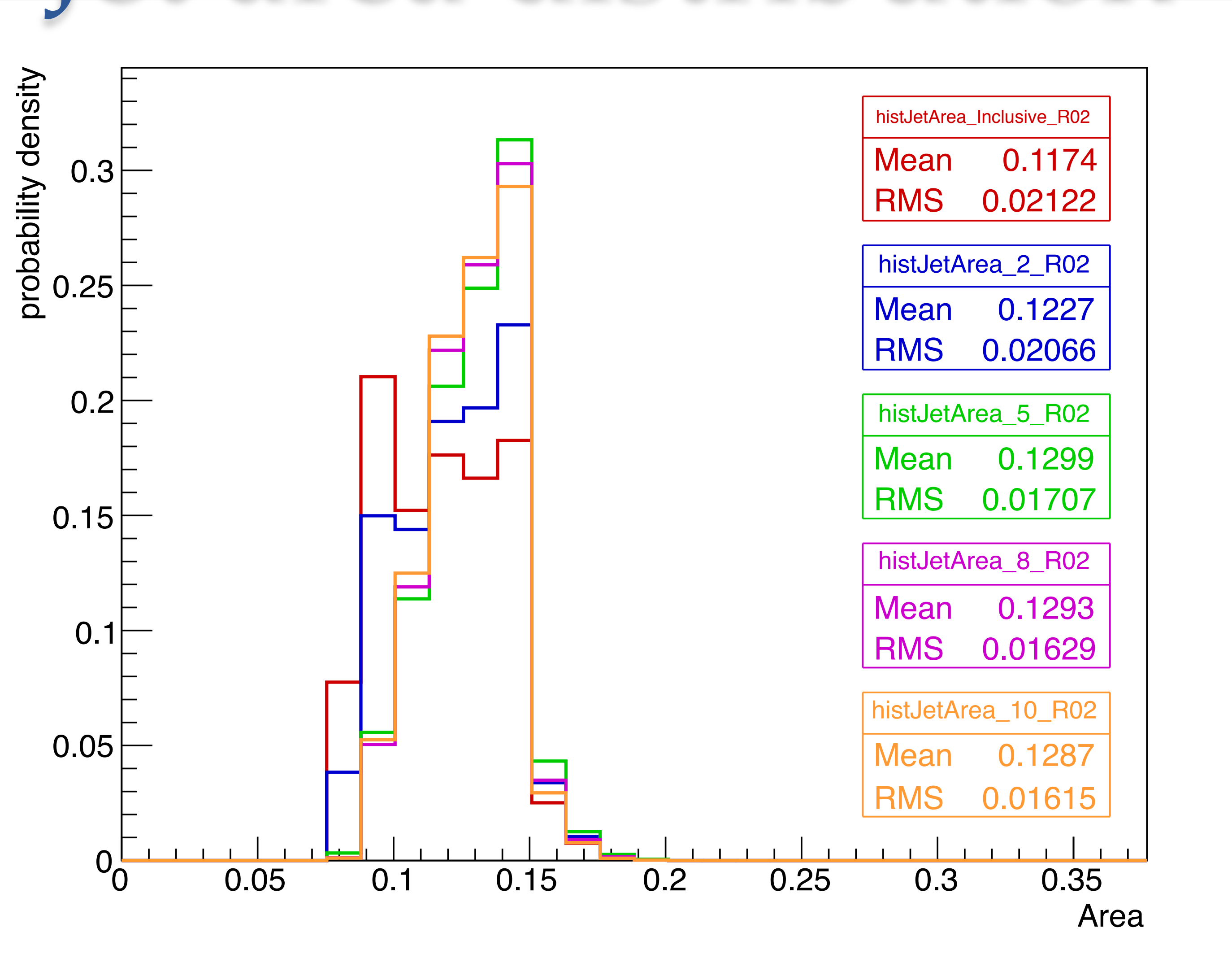
Some of the uncertainties are asymmetric and p_T dependent.
Here only the maximum value is shown.

Systematic uncertainties for 10 GeV/c bias are very similar

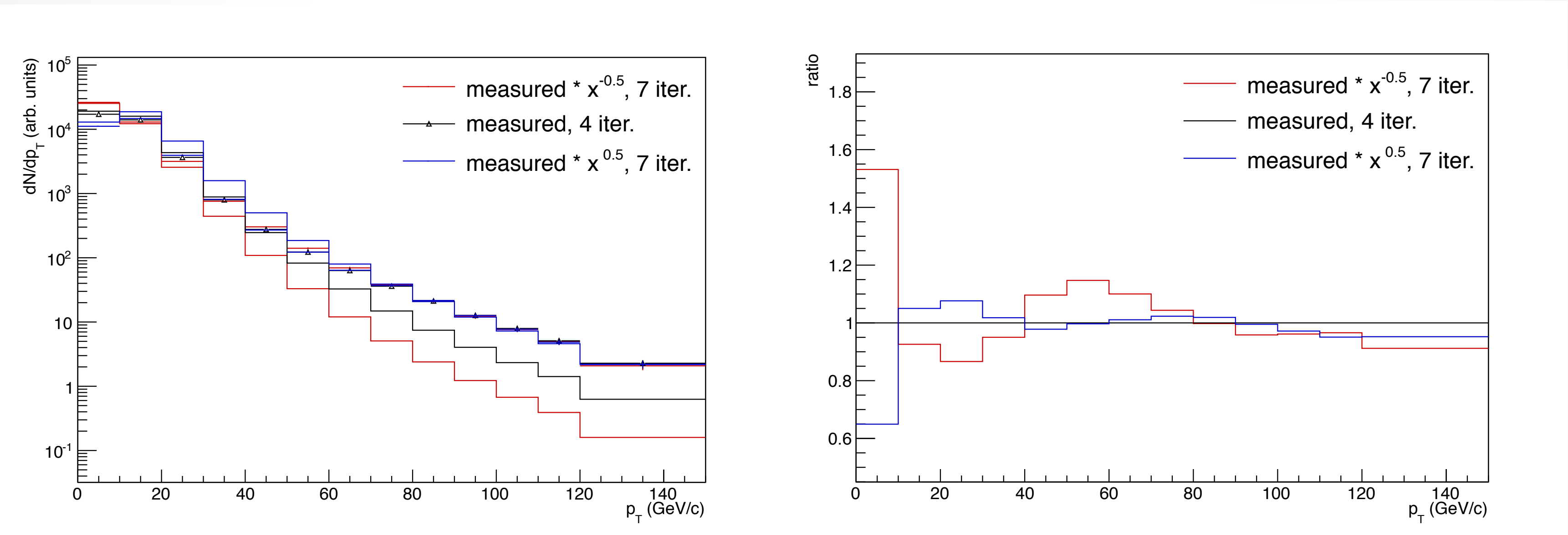
Charged δp_T



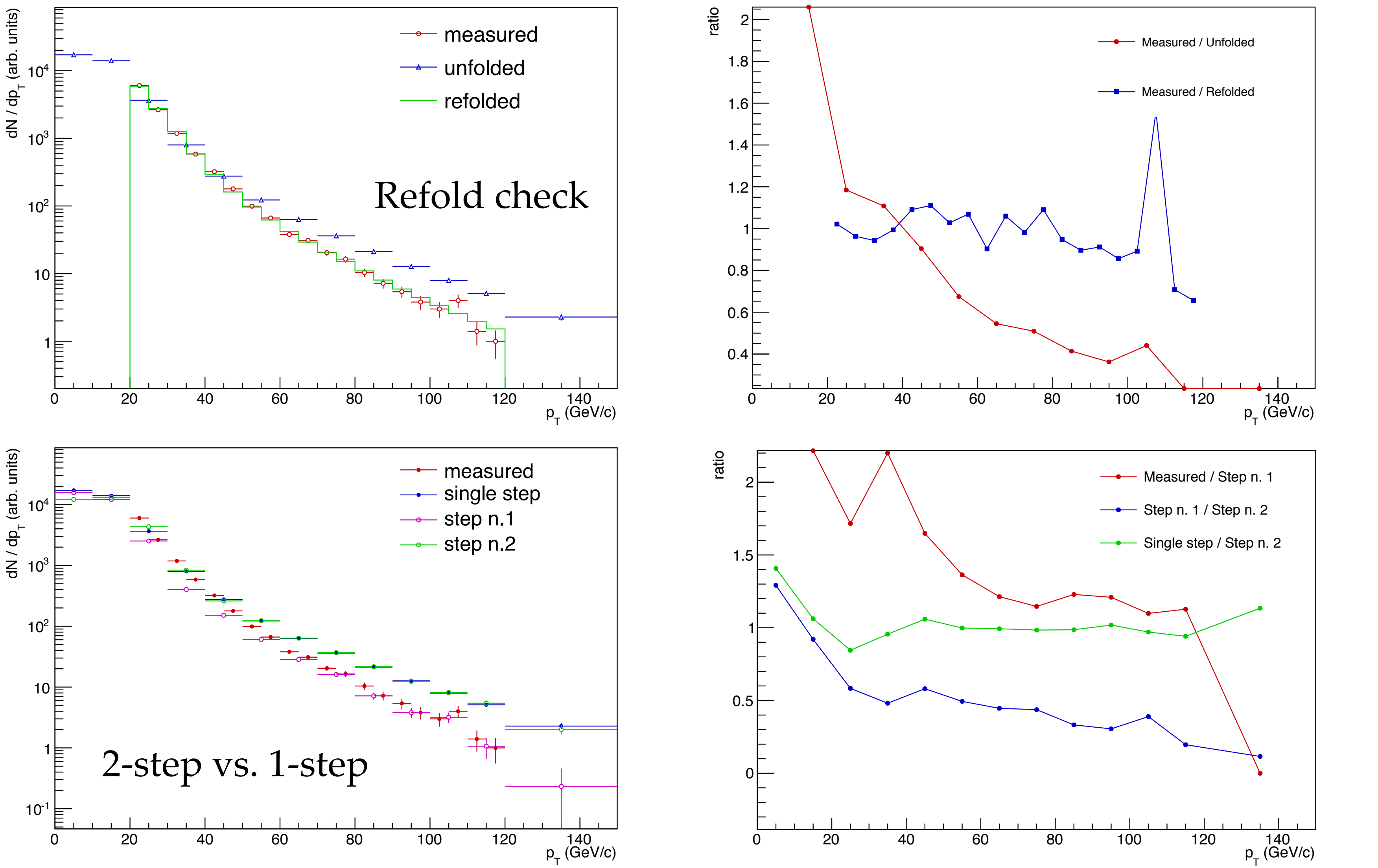
Jet area distribution



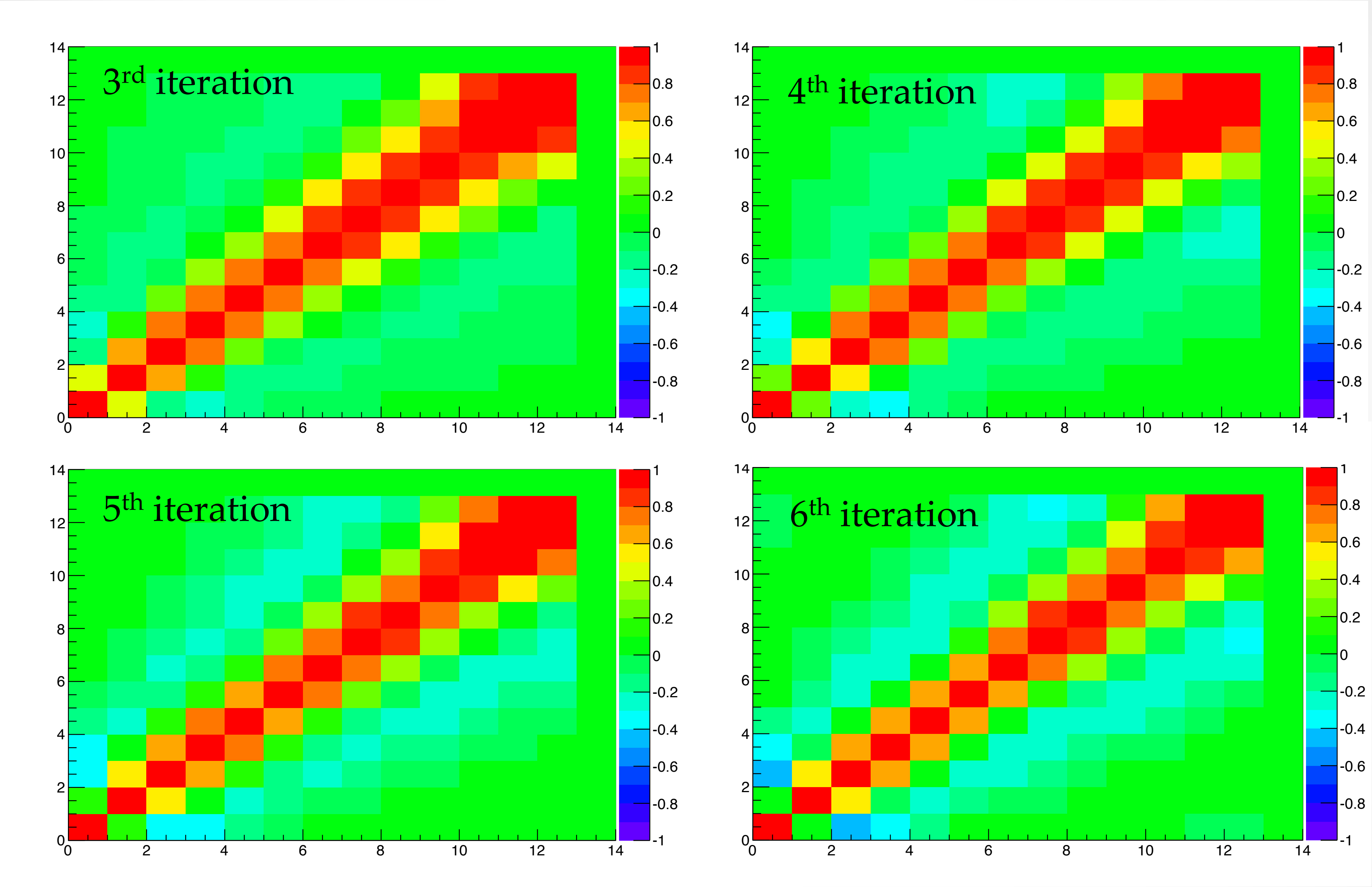
Unfolding prior choice



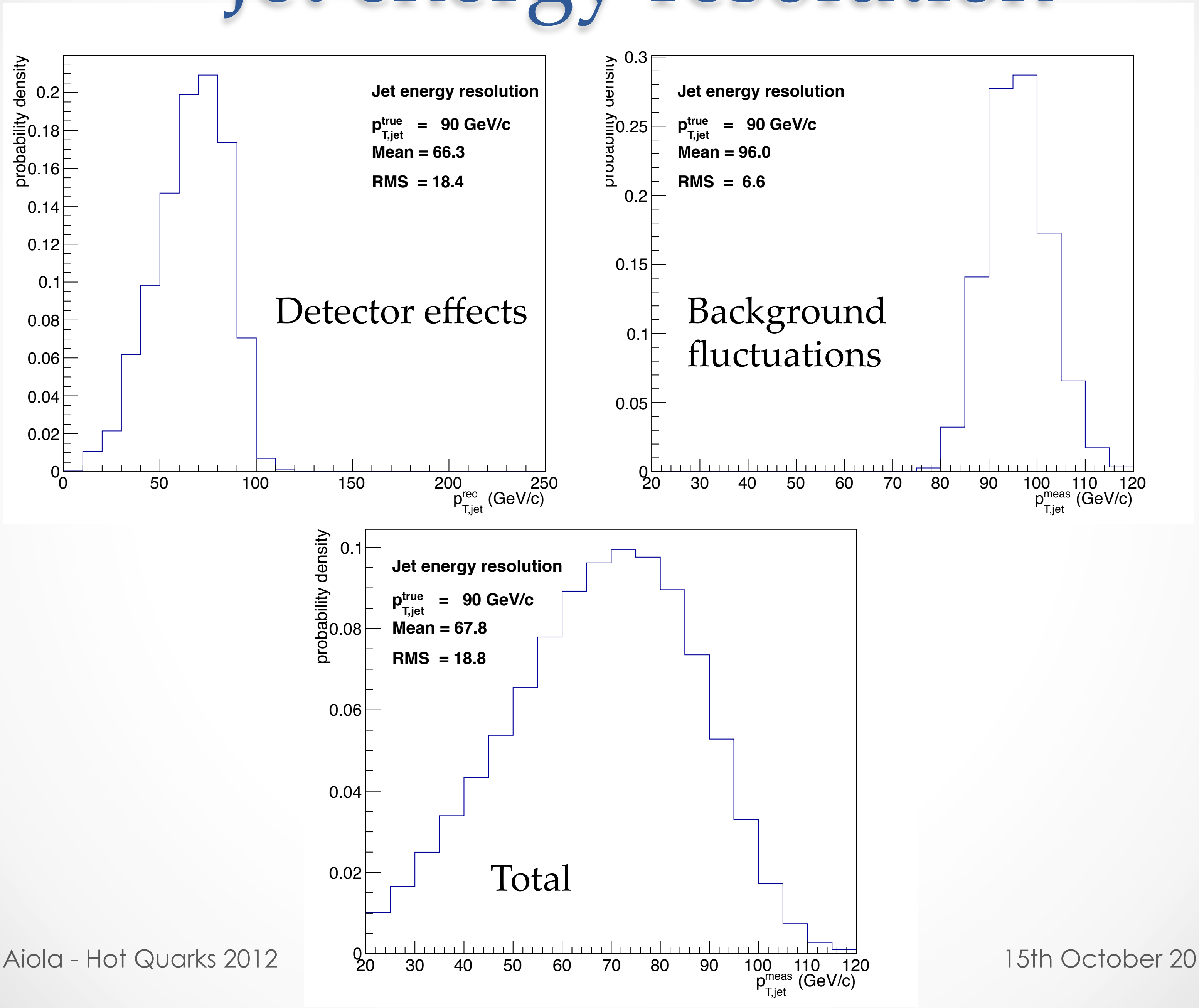
Refold, 2-step



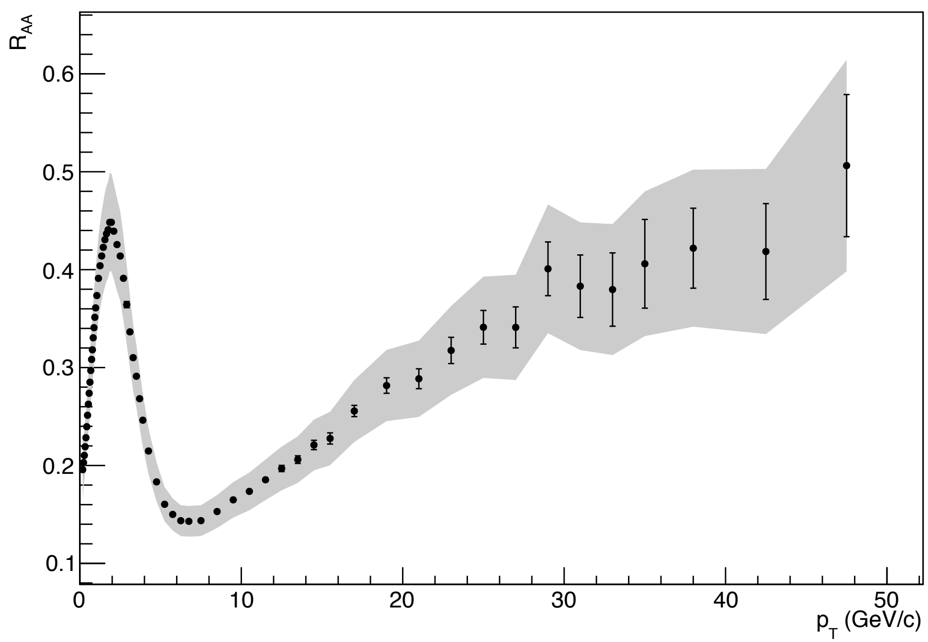
Pearson coefficients

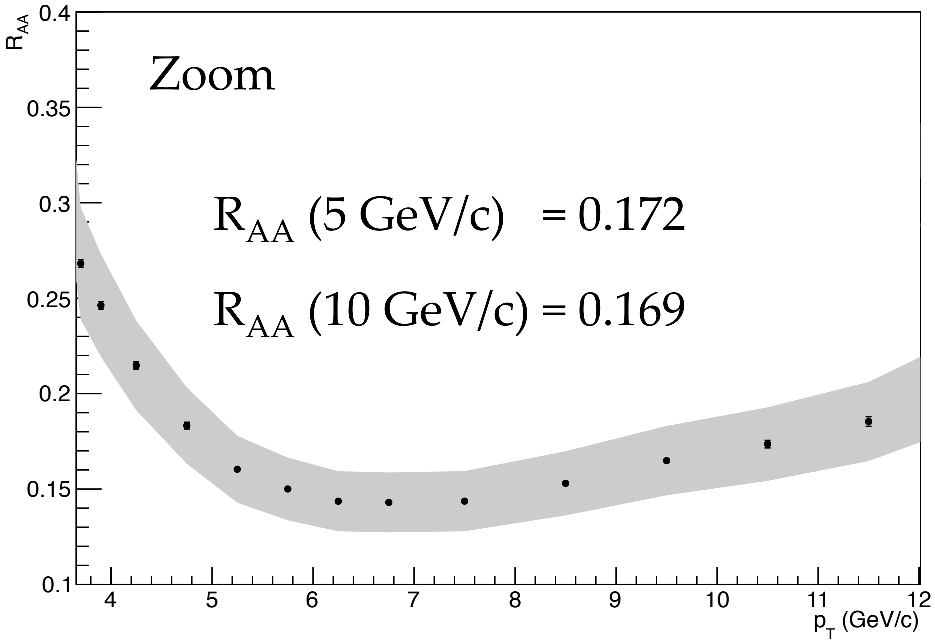


Jet energy resolution

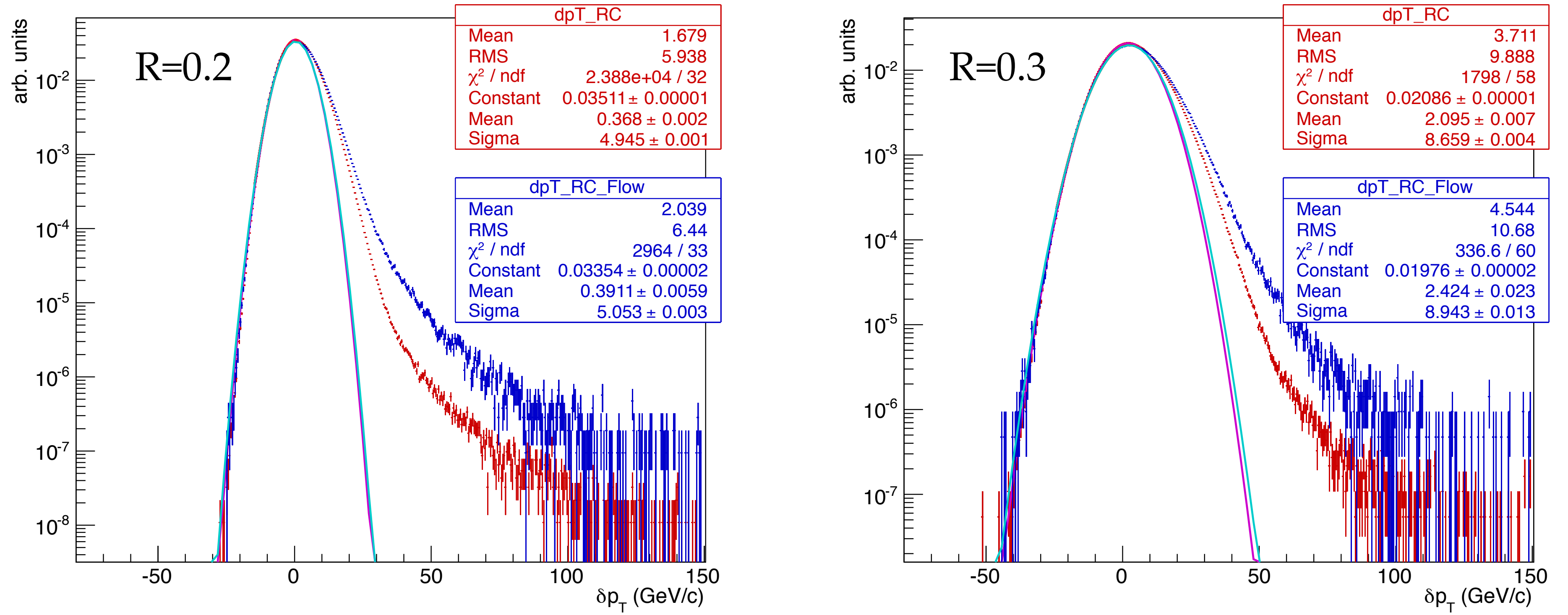


Charged particles R_{AA}





Flow bias



Blue = random cones δp_T distributions obtained requiring a 5 GeV/c charged track in the calorimeter

Red = regular random cones δp_T distributions

The shift measured with the mean of the Gaussian fit on the LHS is **< 100 MeV/c for R=0.2** and **300 MeV/c for R=0.3**