Neutron analysis in LHCf Arm2

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Outline

- Introduction
  - The LHCf Arm2 detector
  - Event reconstruction
  - Event selection
- Analysis strategy
  - Correction factors
  - Spectra unfolding
  - Systematic uncertainties
- Results

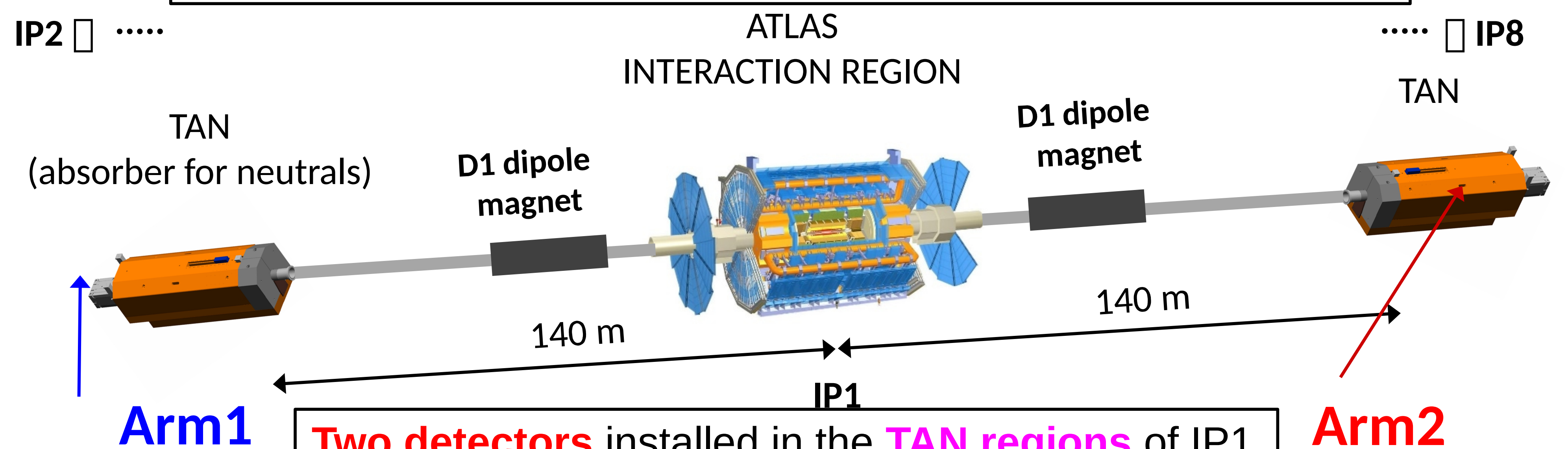
This analysis is relative to **Arm2** detector (LHCf), not **Arm1** detector (LHCf and RHICf)

Measurements of the energy spectra relative to neutrons produced in $\sqrt{s}$ = 13 TeV p-p collisions using the LHCf Arm2 detector

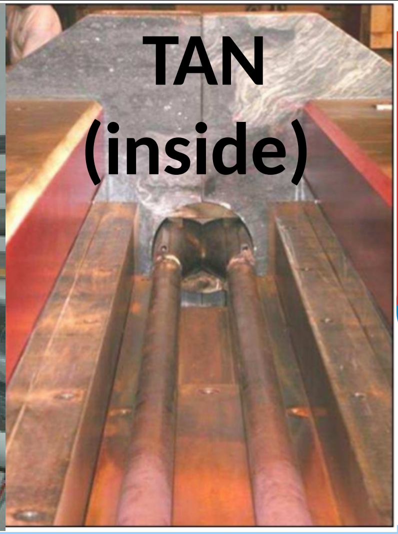
Even it the analysis is well established, it is still preliminary

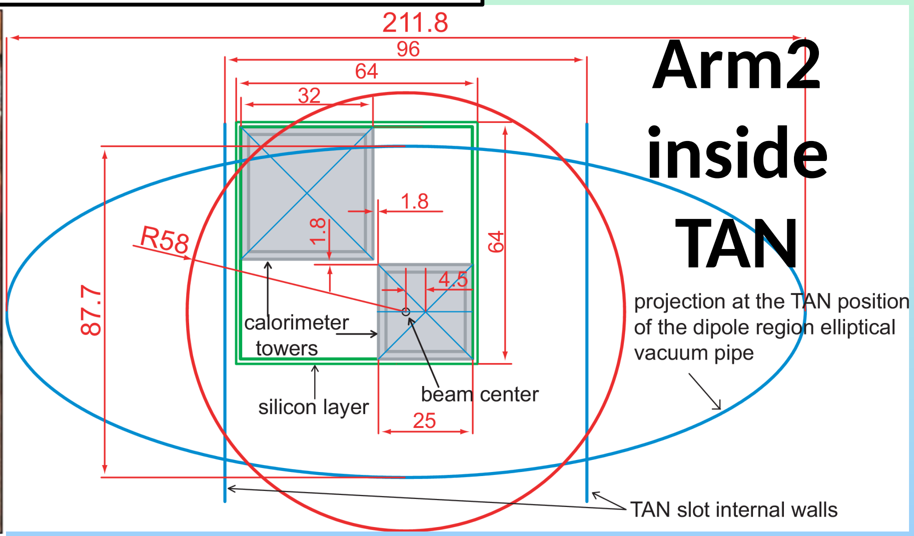
The LHCf Experiment

Detection of **neutral particles** having **pseudorapidity η > 8.4**



Two detectors installed in the **TAN regions** of IP1





LHCf detectors

Arm1

Towers Size:

20 x 20 and 40 x 40 mm^2

Imaging layers:

4 x-y GSO bars

Position resolution:

< 200 μm (photons)

< 1 mm (hadrons)

Two sampling calorimeters

Two towers:

22 W and 16 GSO layers

Depth: 21 cm, 44 X_0, 1.6 λ_I

Energy resolution:

< 2% (photons above 100 GeV)

~ 40% (neutrons above 1 TeV)

Arm2

Towers Size:

25 x 25 and 32 x 32 mm^2

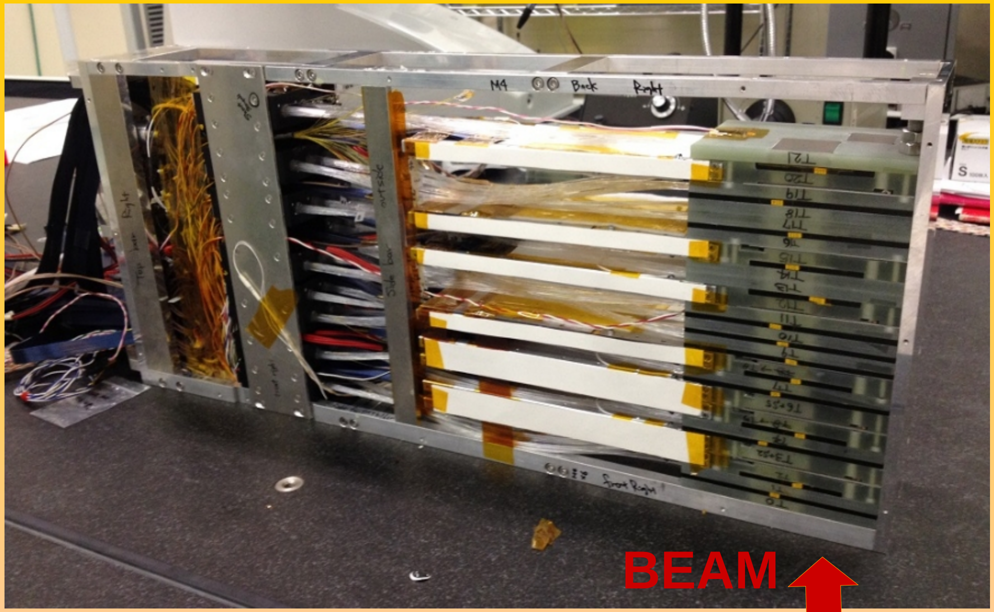
Imaging layers:

4 x-y silicon microstrip

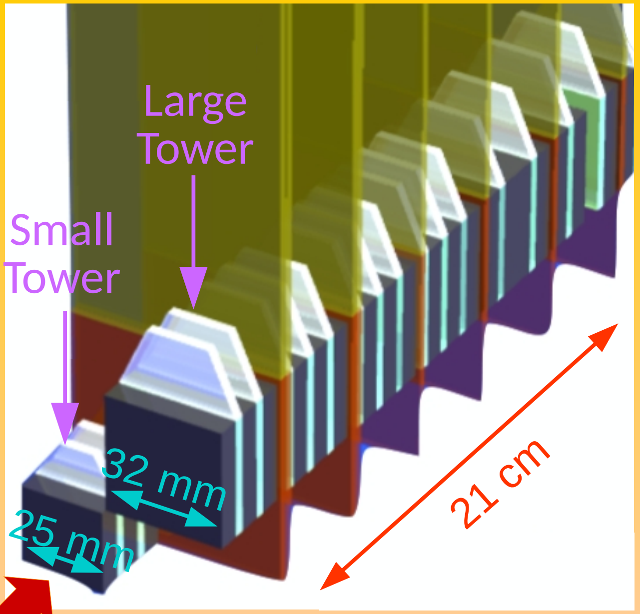
Position resolution:

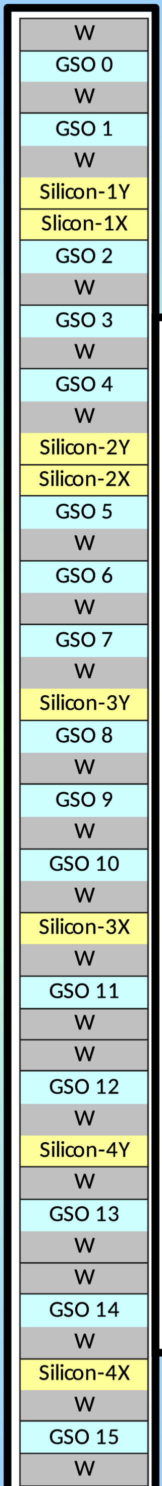
< 40 μm (photons)

< 400 μm (hadrons)



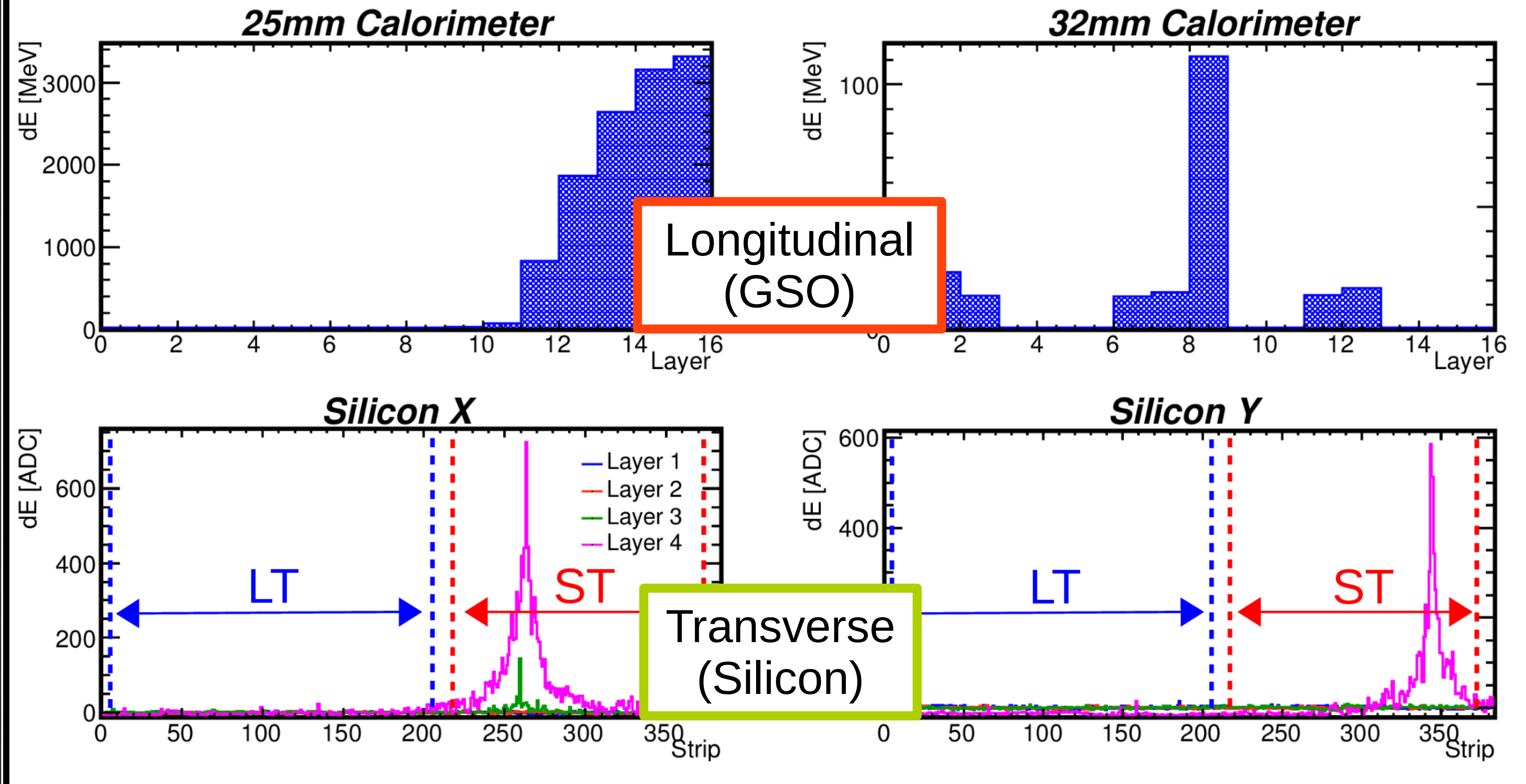
Arm2 detector





Detector information

Interaction of a hadron with Small Tower



Event reconstruction

Note:
All events are reconstructed as singlehit

Silicon detectors: Lorentzian fit on layers having the maximum energy deposit

determination of transverse position
(x, y)

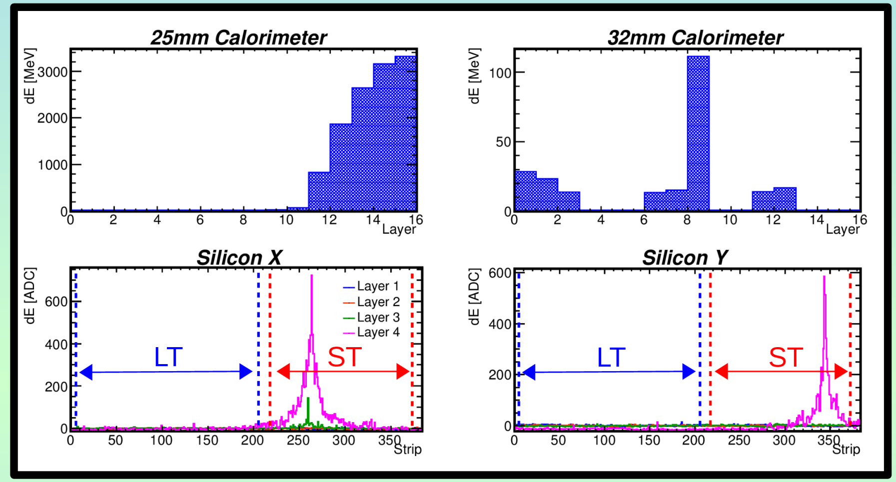
Determination of position dependent correction factors:
$Eff_i(x,y)$,
$Leak(x,y)$

Scintillator detectors: determination of the energy deposit in each layer dE_i

Application of position dependent correction factors
$dE_i / [Eff_i(x,y) * Leak(x,y)]$

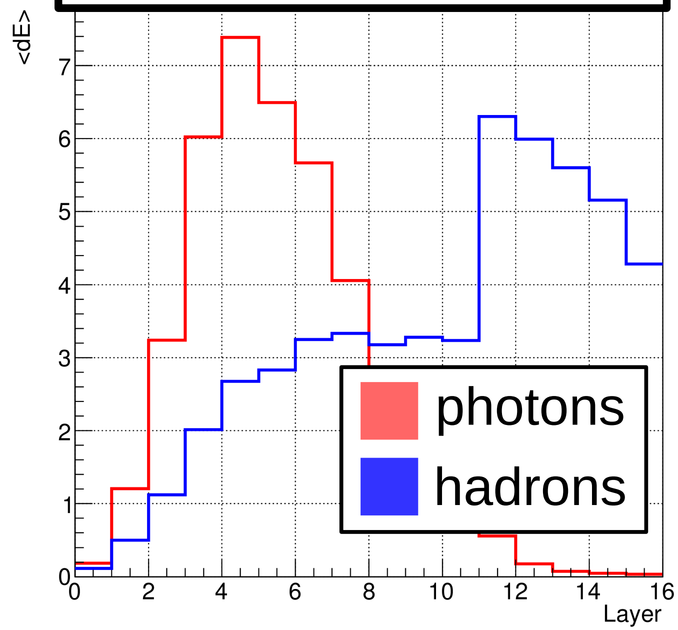
$L_{20\%}$, $L_{90\%}$, L_{2D} → *PID*

sumdE → *E*

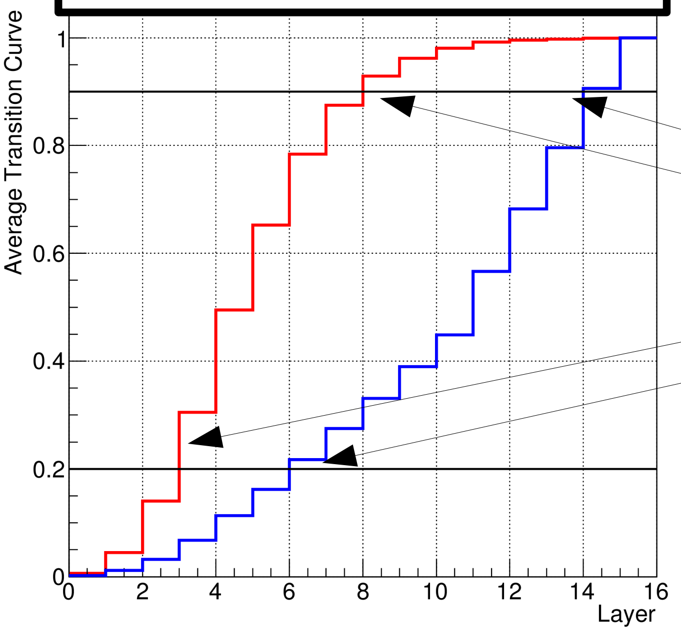


Particle Identification

Average energy deposit



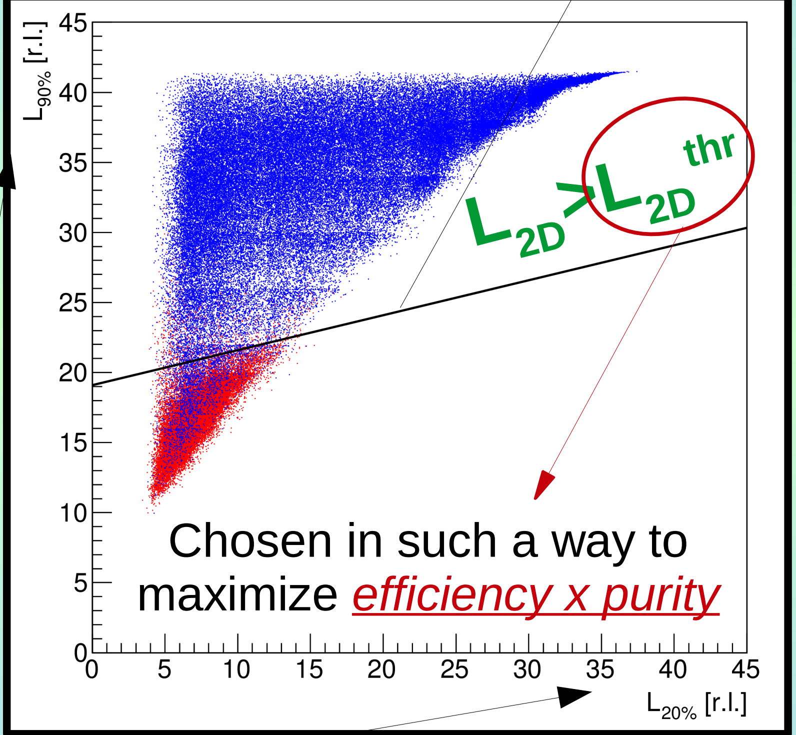
Average integrated energy deposit normalized to the total energy deposit



$L_{90\%}$

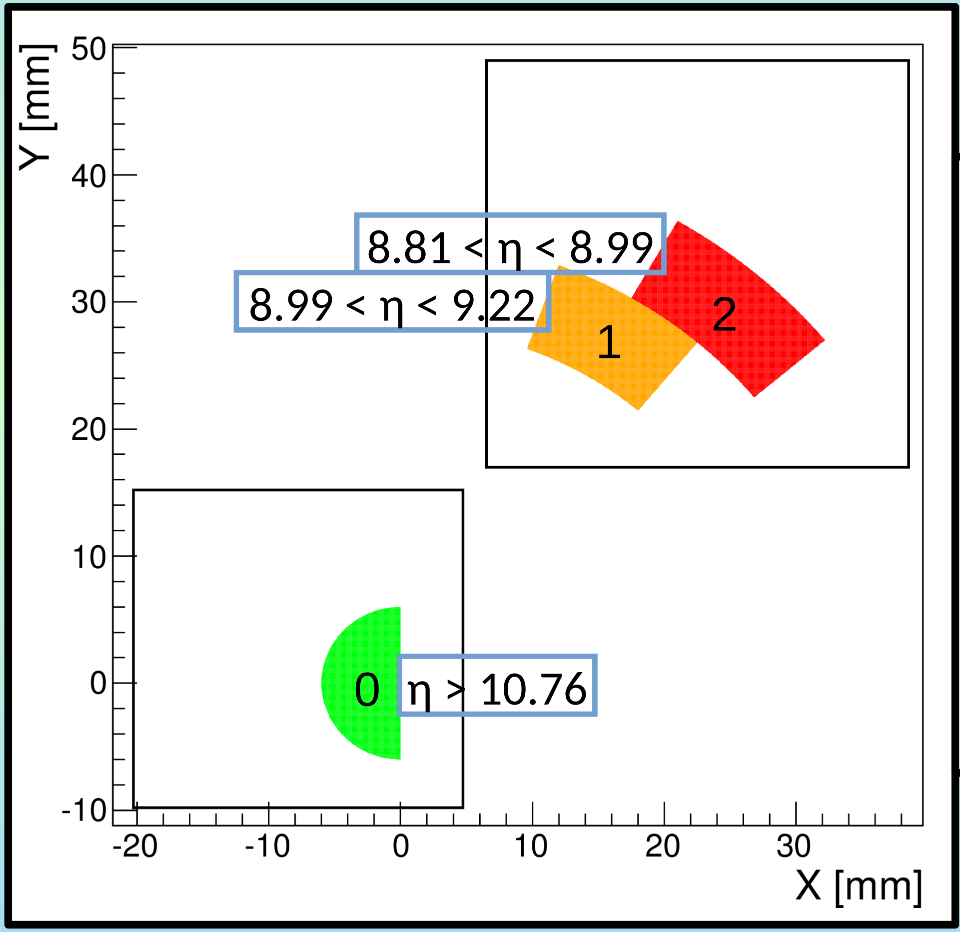
$L_{20\%}$

$$L_{2D} = L_{90\%} - 0.25 \times L_{20\%}$$



Note:
It is not possible to separate neutrons from neutral hadrons (Λ^0, K^0_L, ...) that represent a fraction of 15-35% of the entries in the final energy spectra

Event selection



Event selection criteria:

- **software trigger**
  at least 3 consecutive layers with deposit above threshold $dE>dE^{thr}$
- **PID selection**
  $L_{2D}>L_{2D}^{thr}$ where L_{2D} is a variable related to shower longitudinal profile
- **pseudorapidity acceptance**
  - 3 different pseudorapidity regions

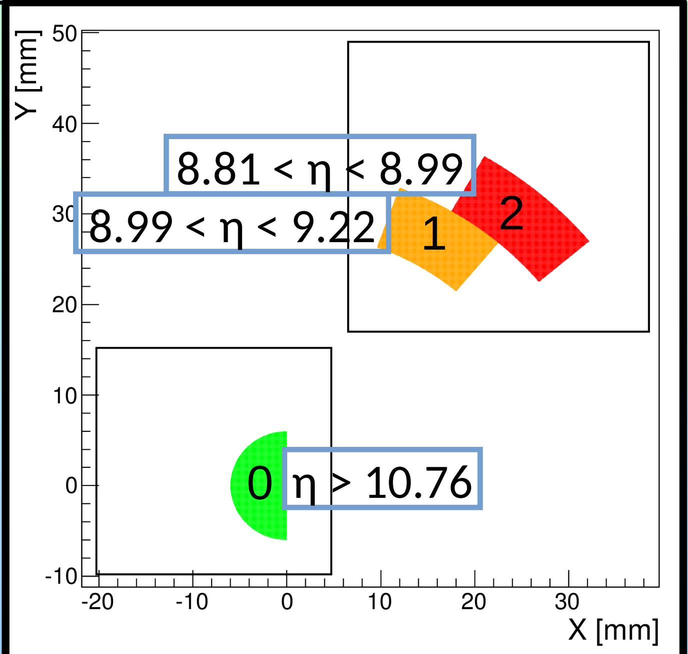
Analysis data set

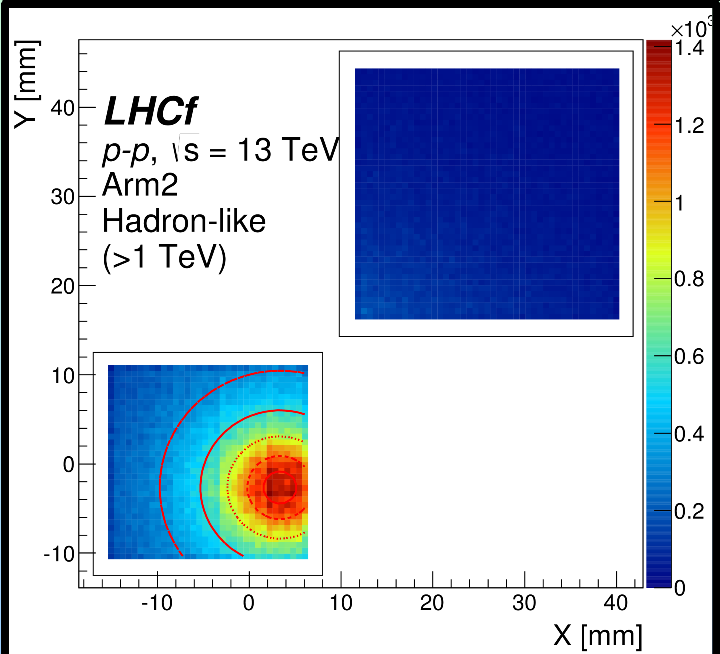
Data set

- 12 July 2015, 22:32-1:30 (3 hours)
- Fill # 3855
- $\mu = 0.01$
- $\int L dt = 0.19\ nb^{-1}$
- $\sigma_{ine} = 78.53$ mb

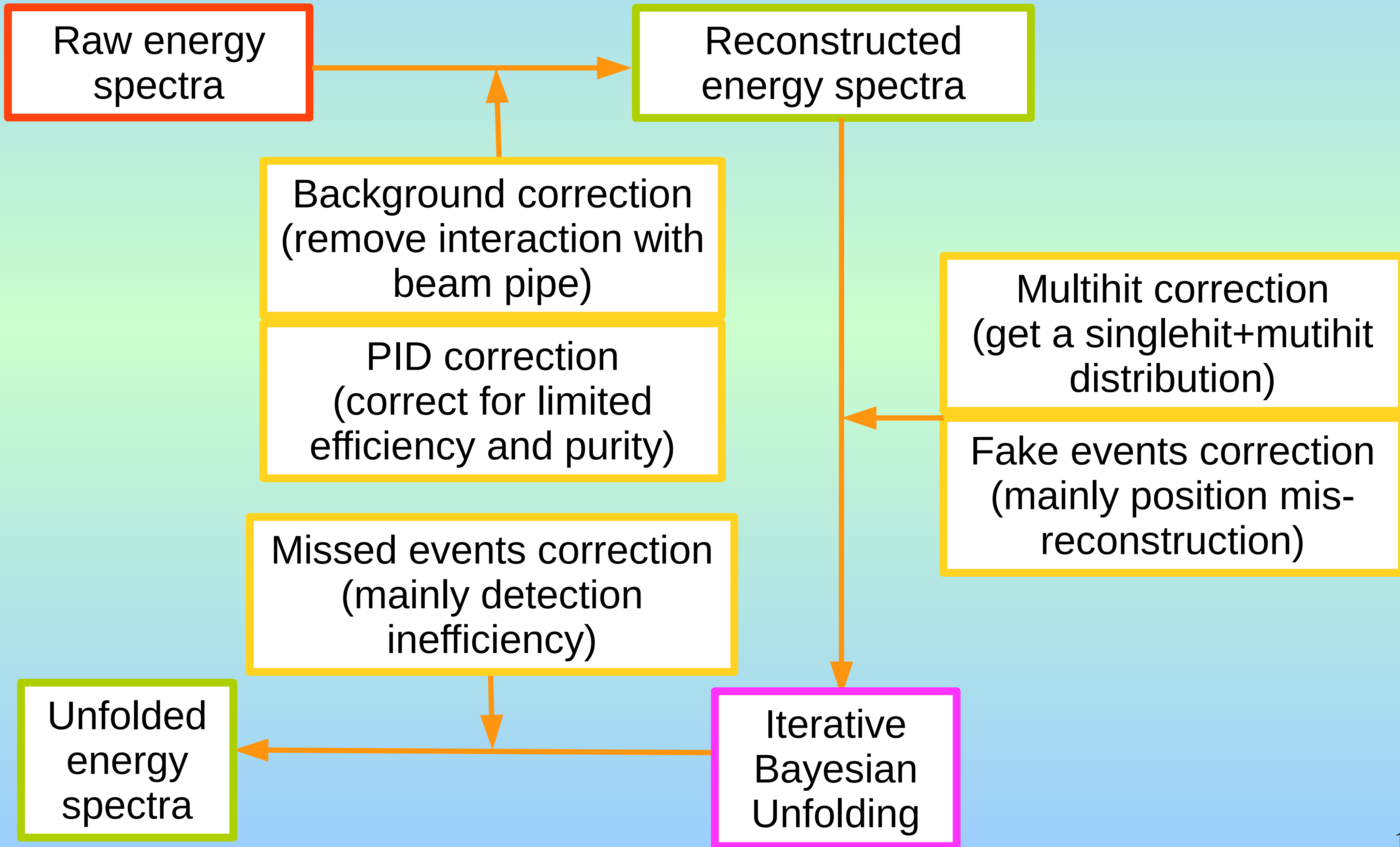
Determination of beam center

- Neutrons peaked along beam direction
- Perform a fit on 2D distribution
- Beam center is (+3.3, -2.7) mm
- Uncertainty is 0.3 mm for both x and y

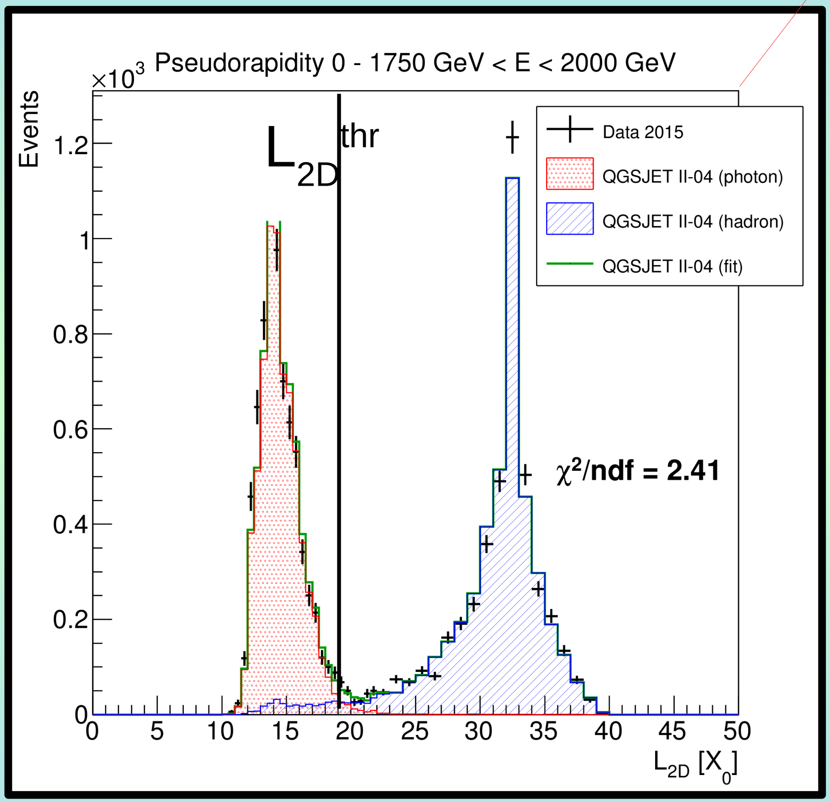


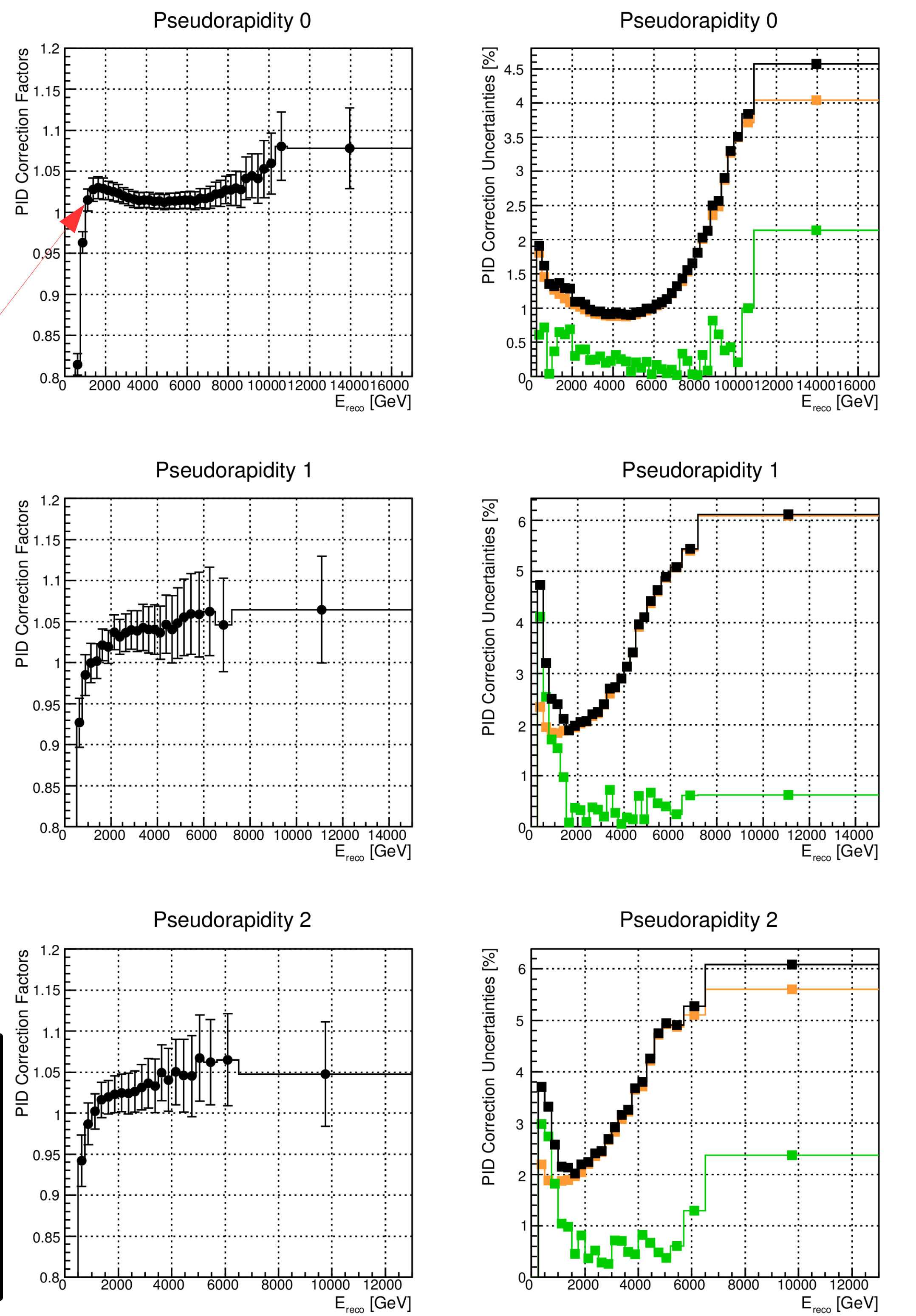


Analysis strategy

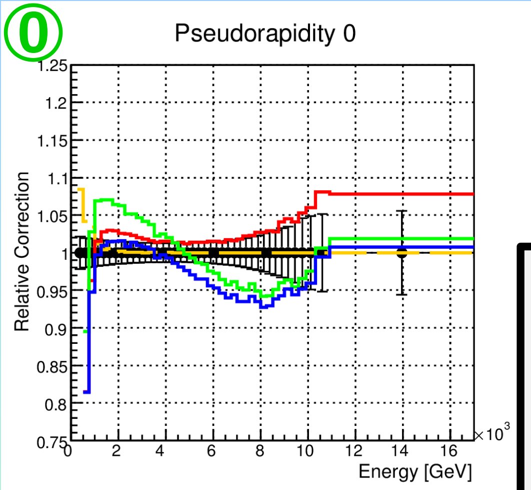


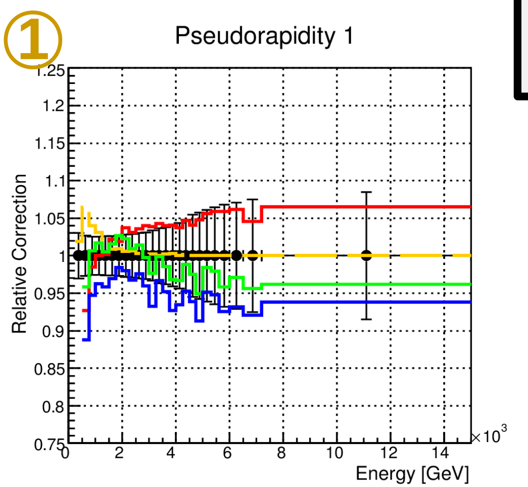
PID Correction

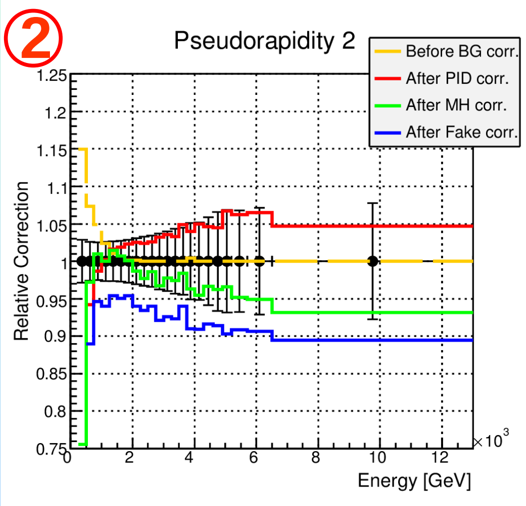




Template fit between L_{2D} distributions in data and in MC.
Estimation of purity and efficiency.
Correction factors are given by
c = purity/efficiency







Correction Factors

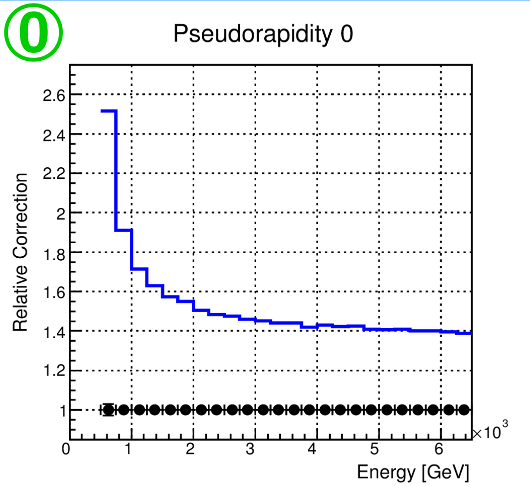
- Before BG corr.
- After PID corr.
- After MH corr.
- After Fake corr.

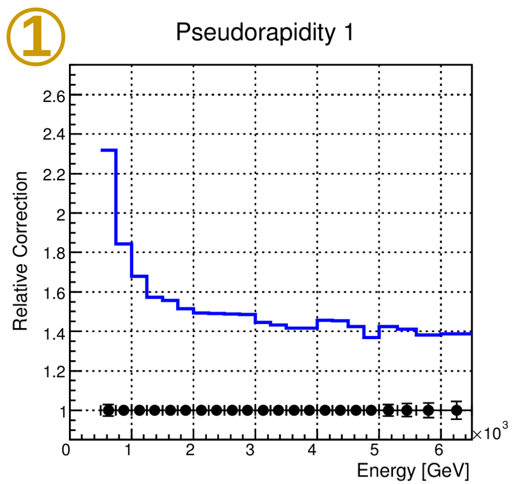
All correction factors have been determined using **QGSJet II-04** and **EPOS-LHC** generators and **full detector simulation**.

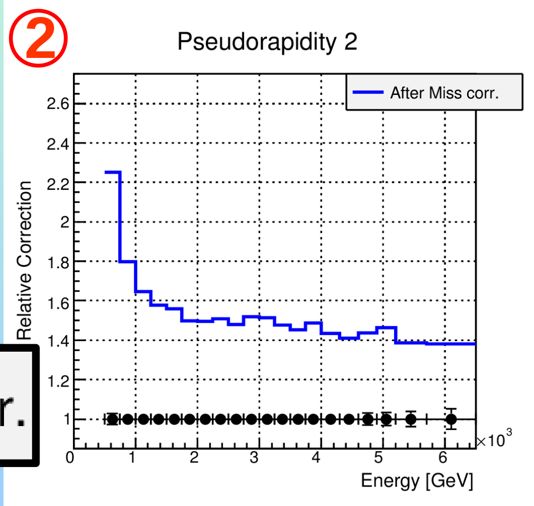
Multihit correction is the only generator-dependent correction

All corrections are mostly below 10% apart from **Missed events correction**, due to small detection efficiency (<75% at high energy)

- After Miss corr.

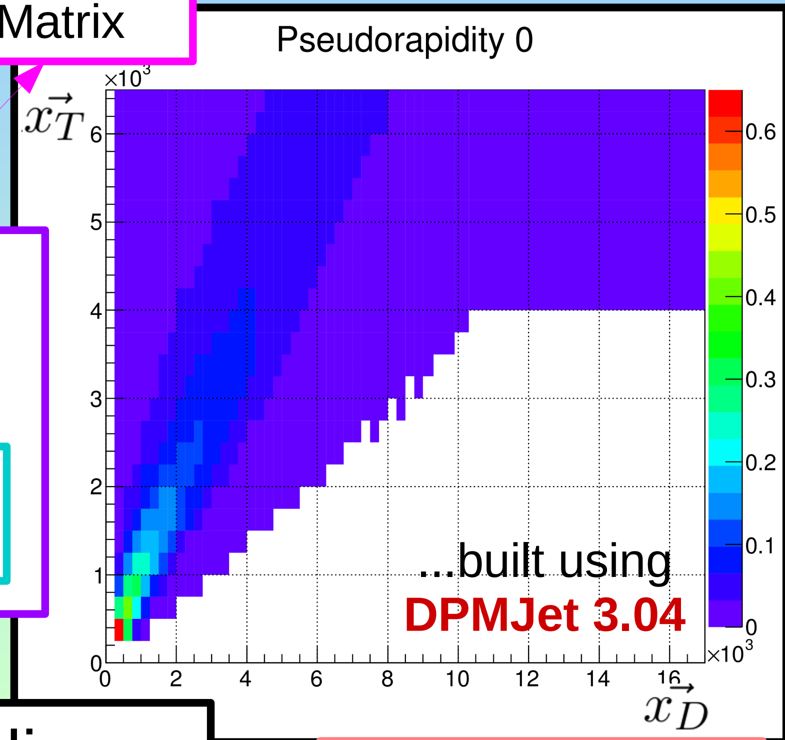






Spectra unfolding

Response Matrix



The limited energy resolution strongly affect the measured spectra.
It is necessary to unfold the reconstructed spectra using detector response.

In our case $\vec{x}$ is energy

$$\vec{x_D} = \Lambda \vec{x_T}$$

Reconstructed spectra

True spectra

Iterative Bayesian Unfolding

Posterior
$$\theta_{ij} \equiv P(T_i|D_j)$$

Input prior → Prior $P(T_i)$ →

Bayes theorem

$$\theta_{ij} = \frac{\lambda_{ji} P(T_i)}{\sum_{i=1}^{N_T} \lambda_{ji} P(T_i)}$$

with

$$\lambda_{ji} \equiv P(D_j|T_i)$$

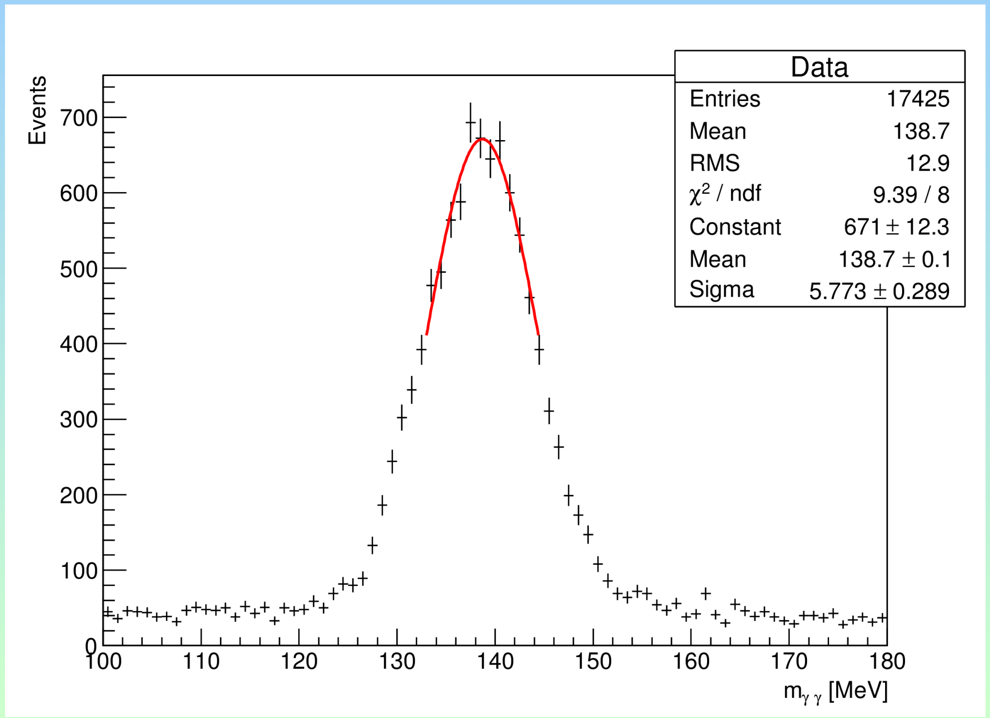
from MC

→ Unfolded spectra

$$x_{T_i} = \frac{1}{\epsilon_i} \sum_{j=1}^{N_D} \theta_{ij} x_{D_j}$$

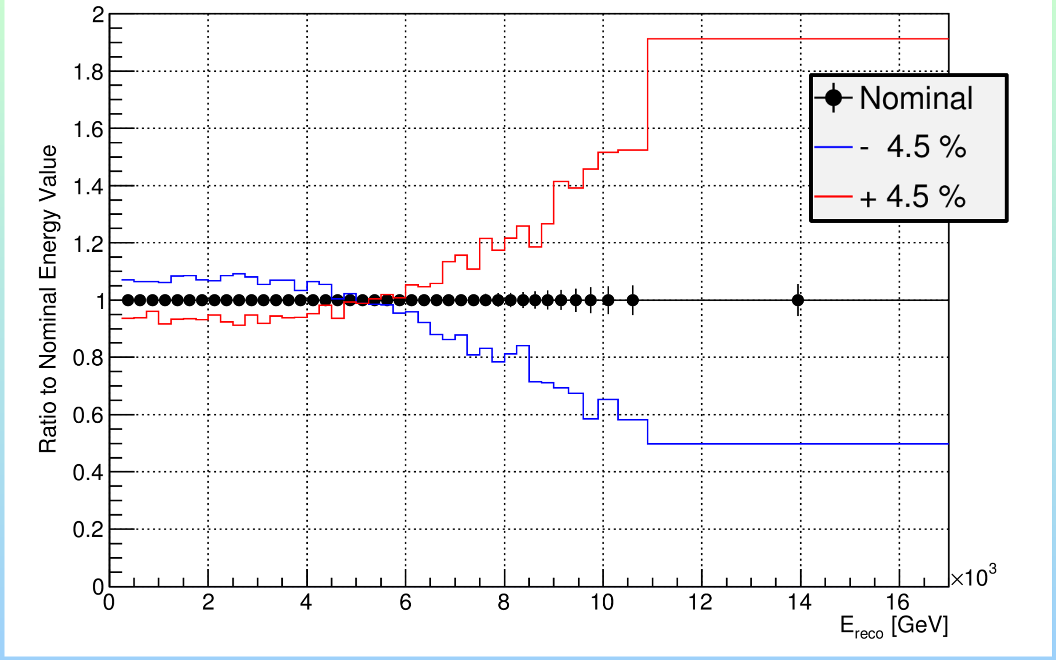
The iterative procedure converges when $\Delta\chi^2$ < threshold

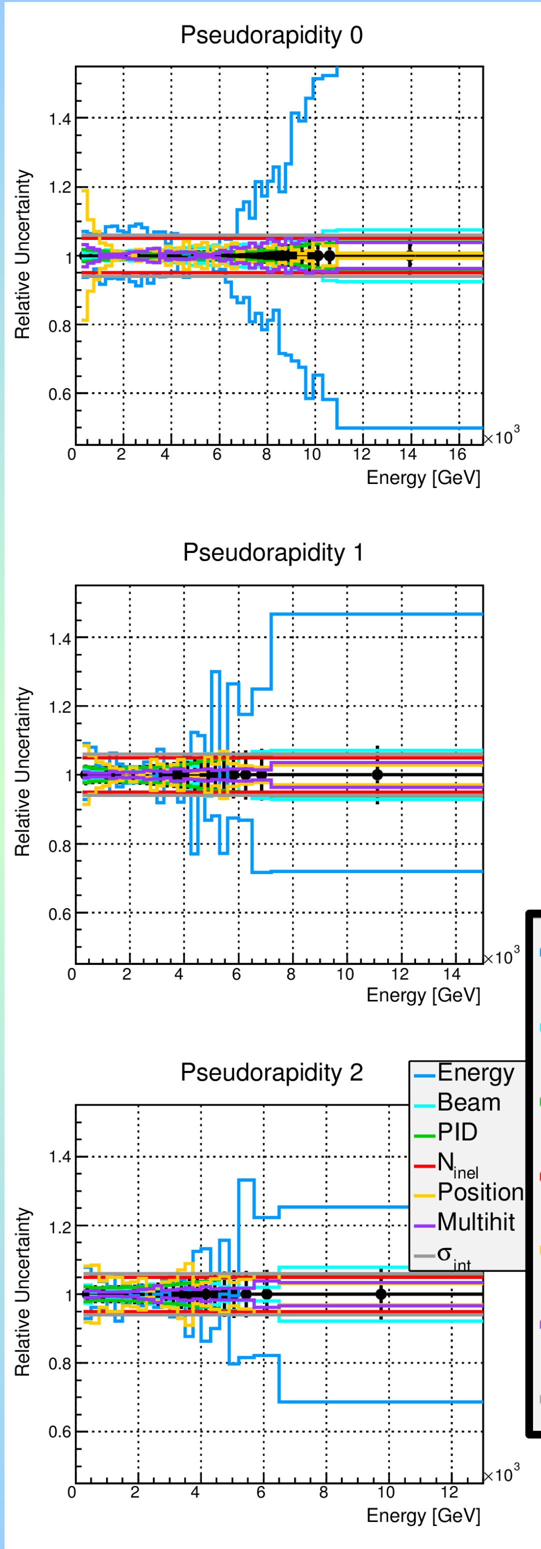
Uncertainty on the energy scale



calibration effect = 3.5%
hardware effect = 2%
π^0 mass shift = 2.15%
$\sigma_{energy} = \sqrt{\sigma_{cal}^2 + \sigma_{hw}^2 + \sigma_{\pi^\circ}^2} = 4.5\%$

Artificially shift energy by $\pm\sigma_{energy}$
Take the ratio to nominal value
Estimate error bands

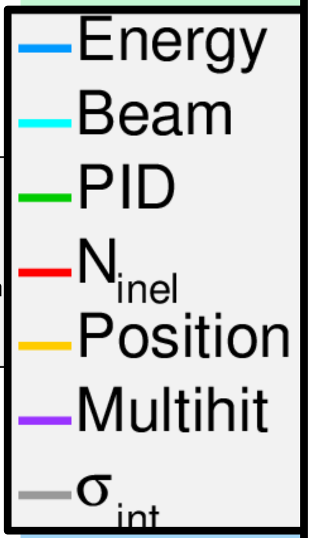




How uncertainties are propagated through unfolding

Iterative Bayesian Unfolding can **NOT** handle systematic uncertainties

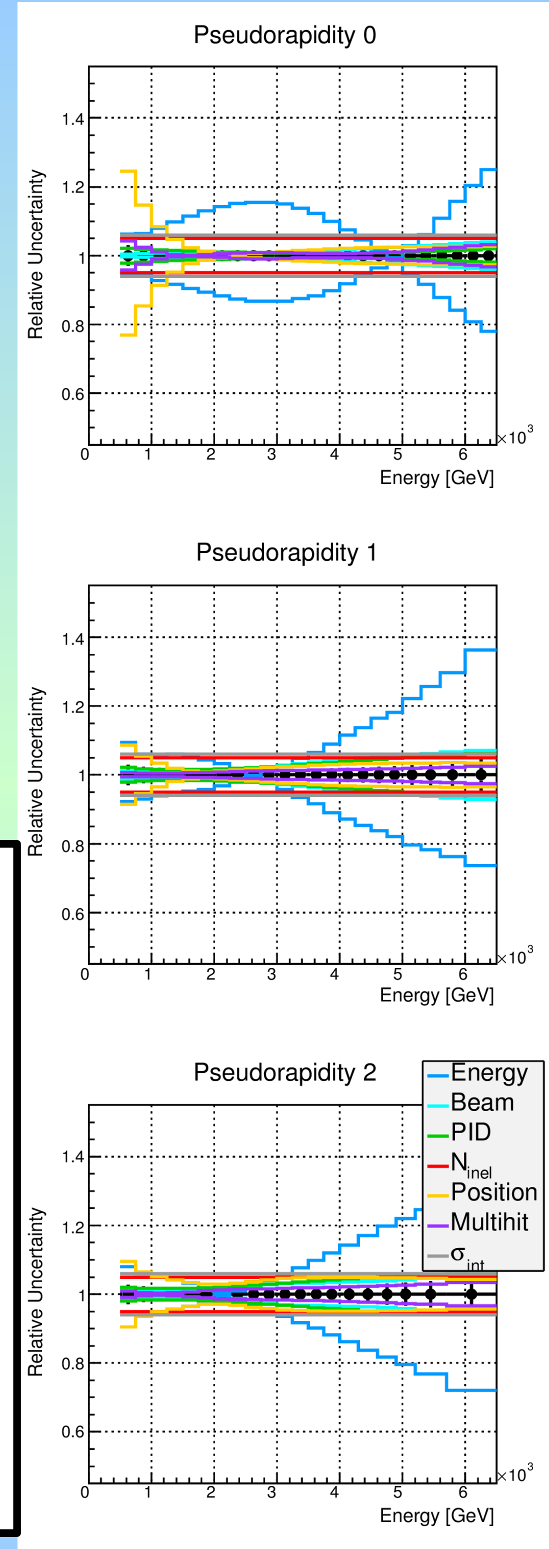
We **manually** propagated uncertainties through the unfolding



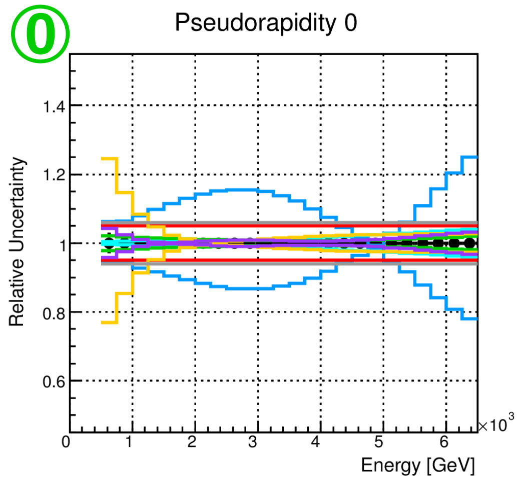
For each systematic:

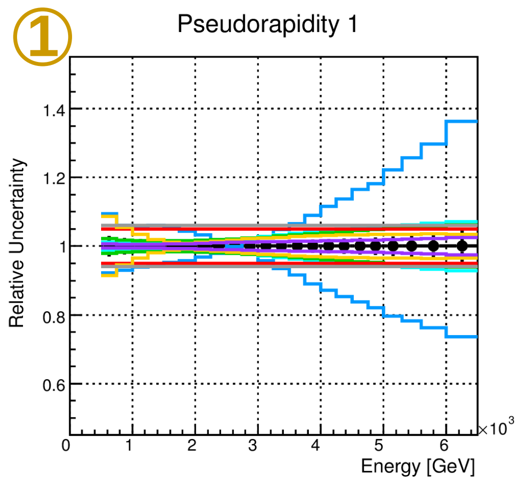
- we shift *reconstructed spectra* for the high (low) edge of the estimated uncertainty
- we unfold shifted-spectra
- the high (low) edge of uncertainty on *unfolded spectra* is given by the ratio

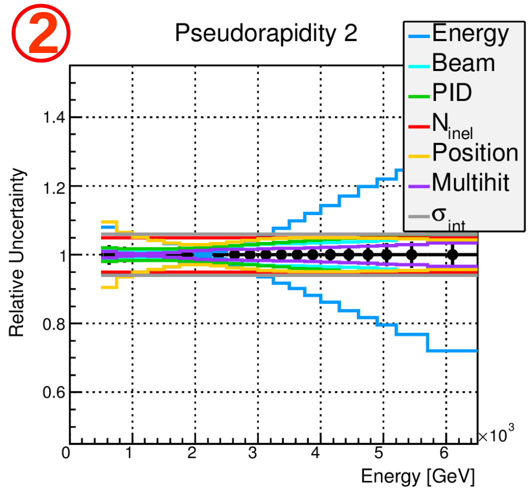
$$\frac{unfolded_{shifted}}{unfolded_{nominal}}$$



Systematic uncertainties





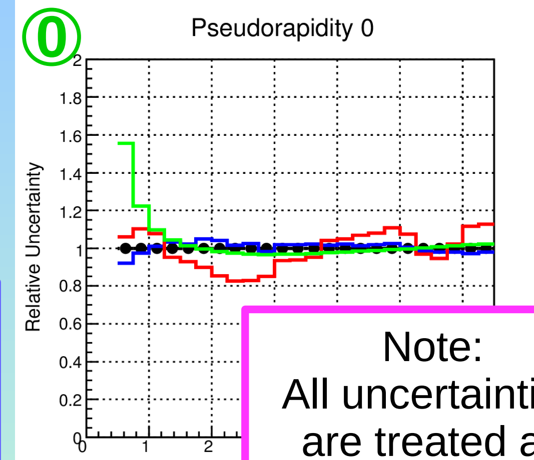


- Energy
- Beam
- PID
- N_{inel}
- Position
- Multihit
- σ_{int}

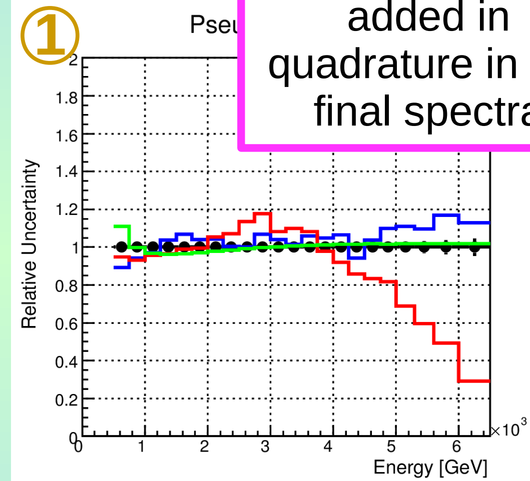
The dominant contribution related to the reconstruction process is the **Energy systematic**, whereas other terms, due to correction factors (PID, Multihit), beam parameters (Beam center, N_{inel}) or detector performances (Position Resolution), are mostly below 5%

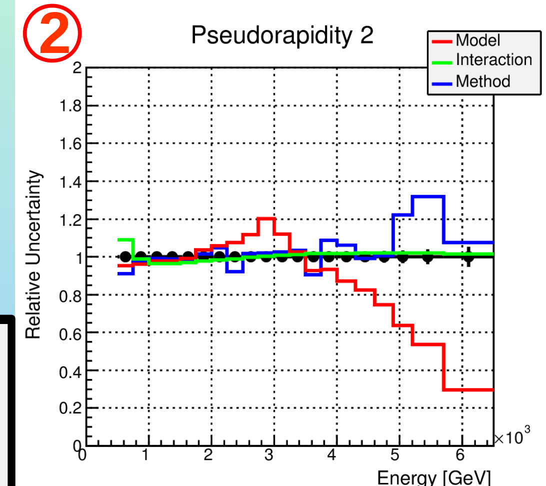
The dominant contribution related to the unfolding process is **Model systematic**, due to the large dependence on the generator used for training of unfolding algorithm

- Model
- Interaction
- Method



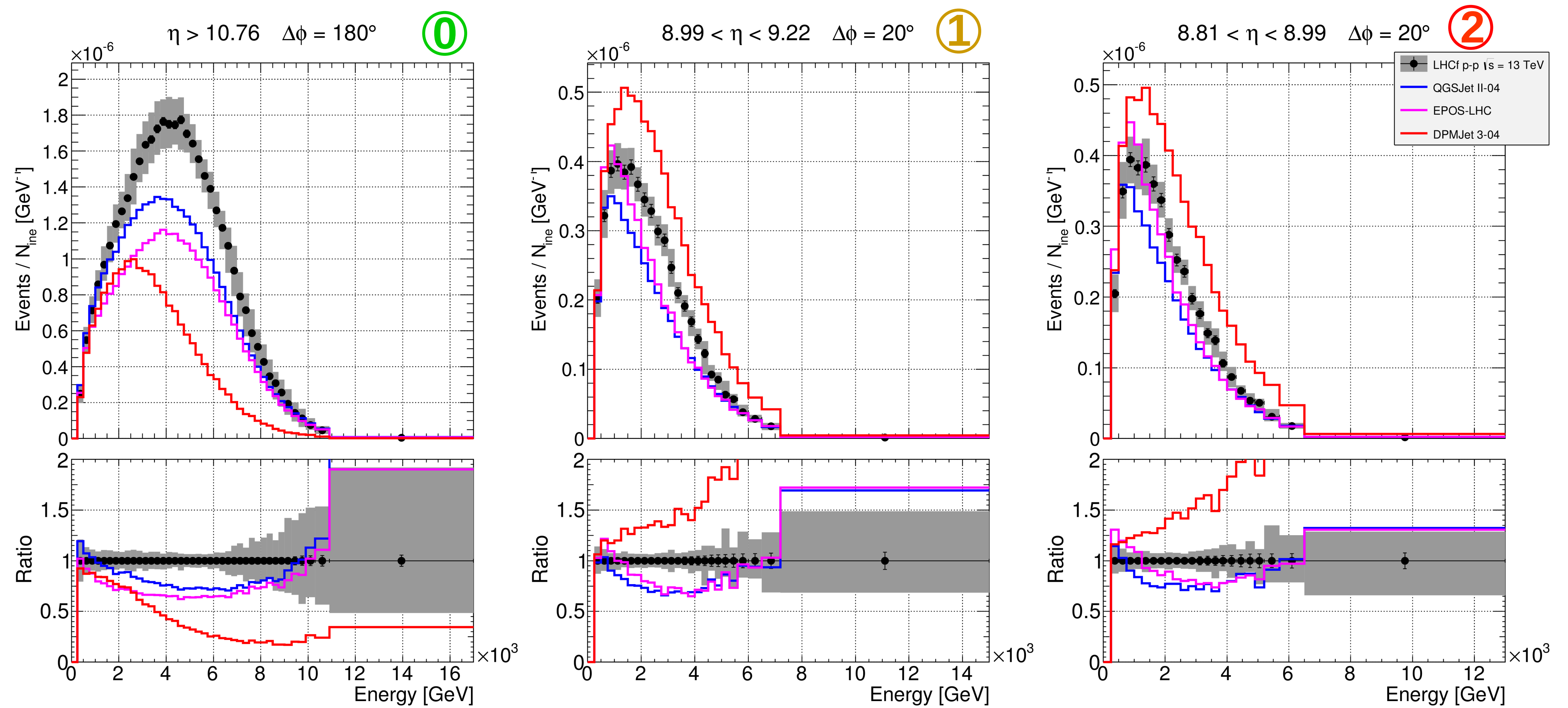
Note:
All uncertainties are treated as independent and added in quadrature in the final spectra





Reconstructed energy spectra

Events / N_{ine} / dE

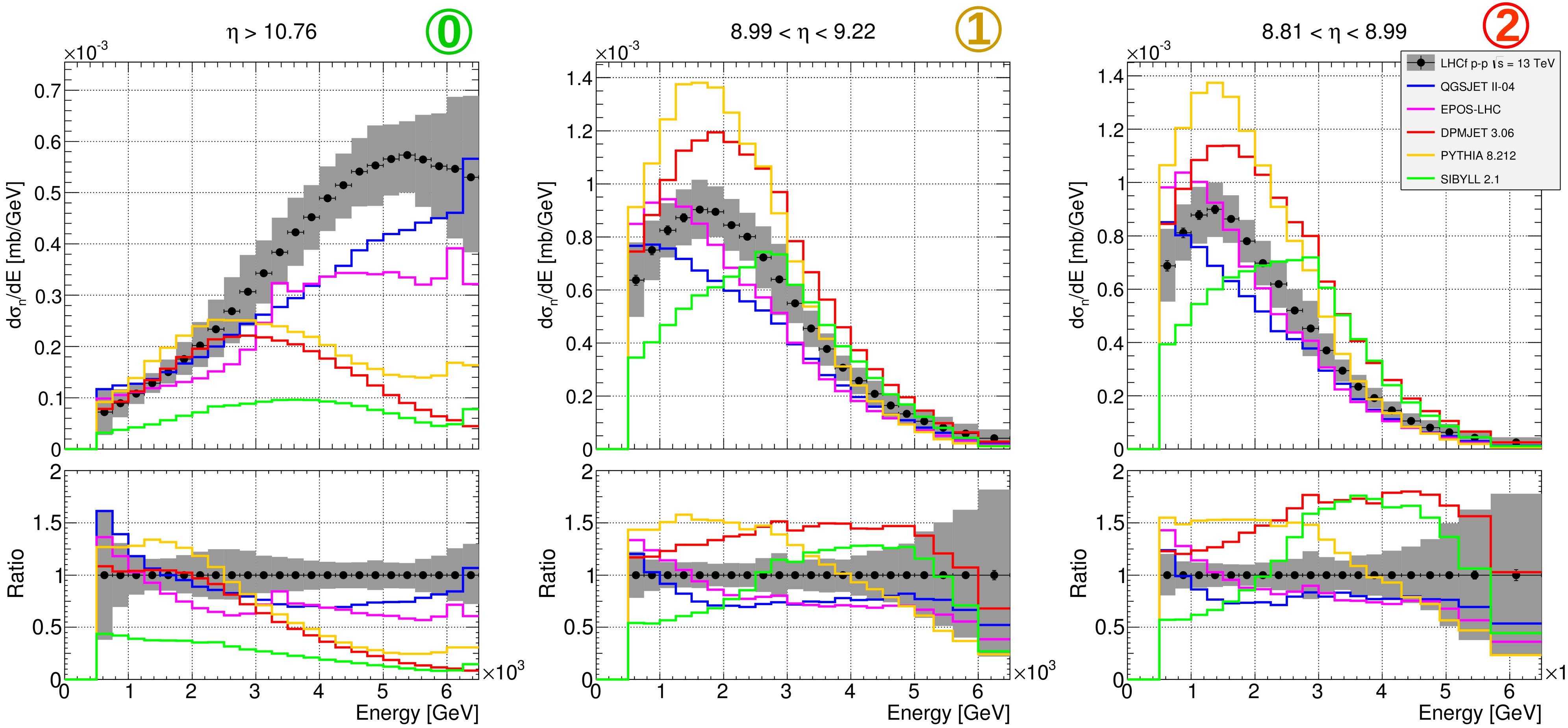


QGSJET II-04 and **EPOS-LHC** have similar shape but lower yield
DPMJET 3.04 have very different shape and yield

Unfolded energy spectra

Differential production cross section

$$d\sigma_n/dE = \frac{dN(\Delta\eta,\Delta E)}{E}\frac{1}{L}\times\frac{2\pi}{d\varphi}$$



Only **QGSJET II-04** qualitatively reproduces behavior of data in η > 10.76
EPOS-LHC has similar shape in 8.81 < η < 9.22, but lower yield

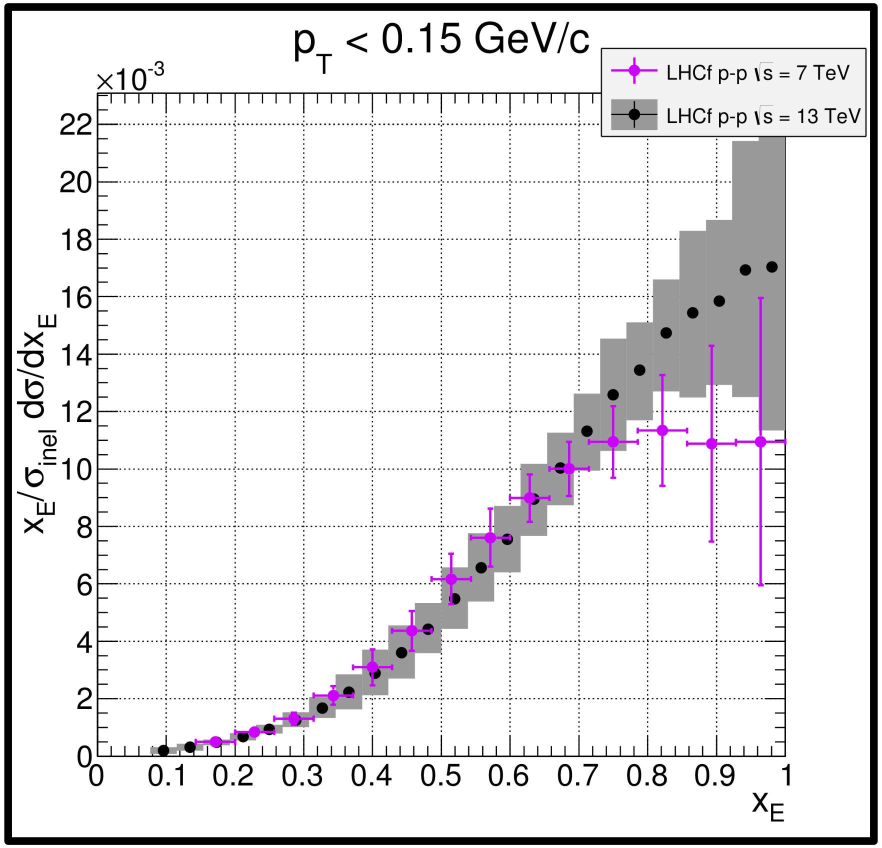
Test of Feynman scaling

Approximations:
- $p_Z \sim E$
- $p_T \sim \theta \times \sqrt{s}/2$

Feynman scaling hypothesis
In the very forward region, secondary particles production cross sections, expressed as a function of the $x_F = 2p_Z/\sqrt{s}$ variable, should be independent on $\sqrt{s}$ if we consider the same p_T interval

Idea
Use neutron production cross section measured in case of p-p collisions at $\sqrt{s}$=7 and 13 TeV to test Feynman scaling hypothesis

How to Proceed
In case of $\sqrt{s}$=7 TeV, the region $\eta > 10.76$ corresponds to $p_T < 0.15$ GeV/c
The analysis at $\sqrt{s}$=13 TeV was repeated for the region $\eta > 11.38$ to have same p_T coverage



Feynman scaling hypothesis holds within the error bars
Consistency is good especially in the region $0.2 < x_E < 0.75$

Summary

We presented the **analysis procedure** for the reconstruction of the energy spectra relative neutral hadrons with the LHCf Arm2 detector

- Estimation of ***correction factors*** using generators with detector simulation :
  main contribution (> 30 %) from detection efficiency
- Estimation of ***systematic uncertainties*** :
  main contribution (< 35 %) from the energy scale
- Use of ***iterative bayesian unfolding*** to cope with 40% energy resolution :
  uncertainties due to unfolding procedure itself are also take into account

Making use of these analysis procedure we measured the **energy spectra** relative to neutrons produced in $\sqrt{s}$=13 TeV p-p collisions

- A large amount of high energy neutrons was found in the region ***$\eta > 10.76$***, qualitatively reproduced only by **QGSJet II-04**
- **EPOS-LHC** and **QGSJet II-04** reproduce enough well the differential production cross section in the region ***$8.81 < \eta < 9.22$***
- A ***test of Feynman scaling*** using data relative to $\sqrt{s}$=7 and 13 TeV showed that the hypothesis holds within the uncertainties