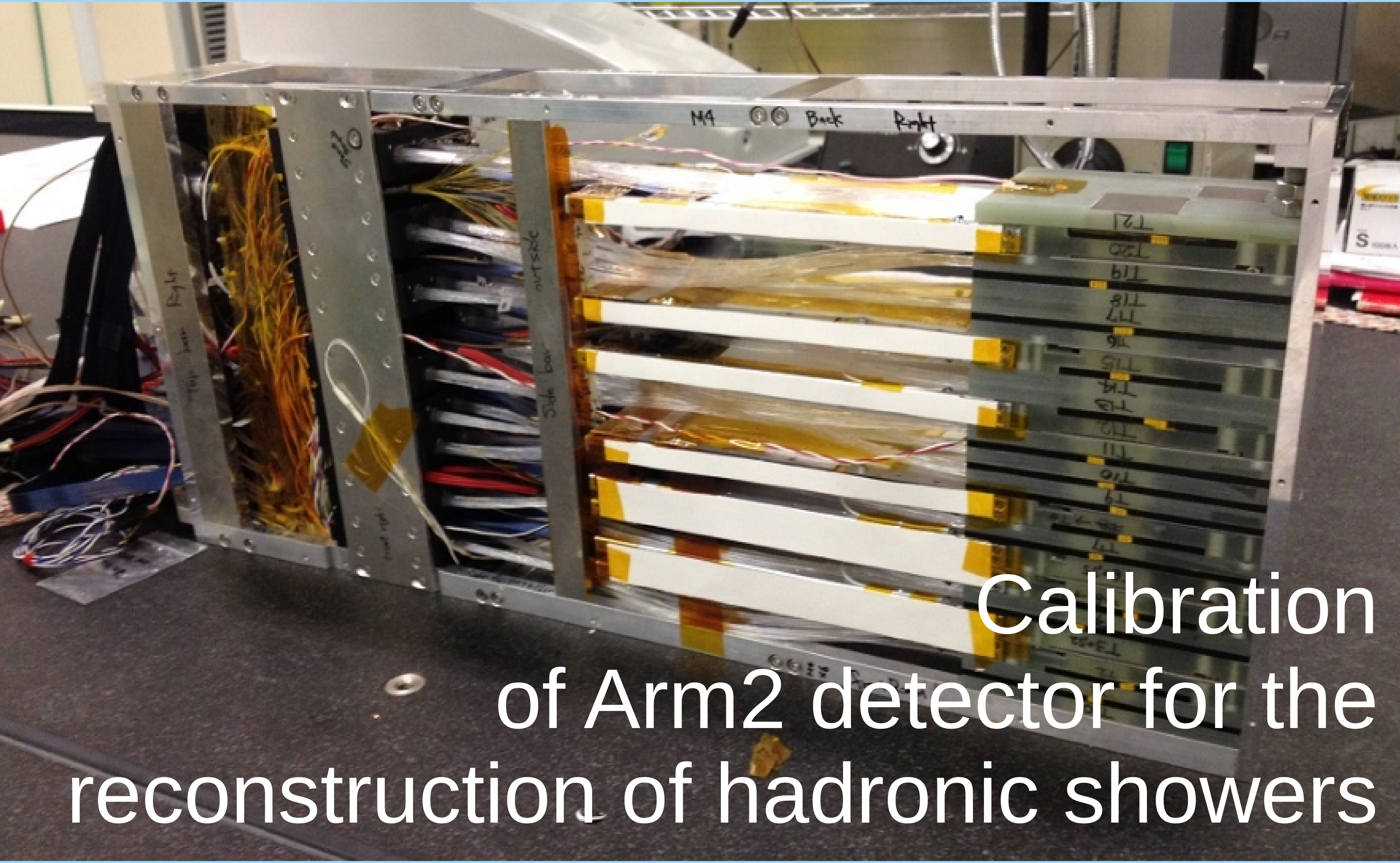
Measurements of the energy spectra relative to neutrons produced in $\sqrt{s}$ = 13 TeV p-p collisions using the LHCf Arm2 detector

Eugenio Berti

LHCf Japan meeting
Nagoya 6th April 2017

Outline

- Calibration of Arm2 detector
  - Calibration of the energy scale
  - Data-Model comparison
  - Detector performances
- Analysis strategy
  - Correction factors
  - Spectra unfolding
  - Systematic uncertainties
- Results

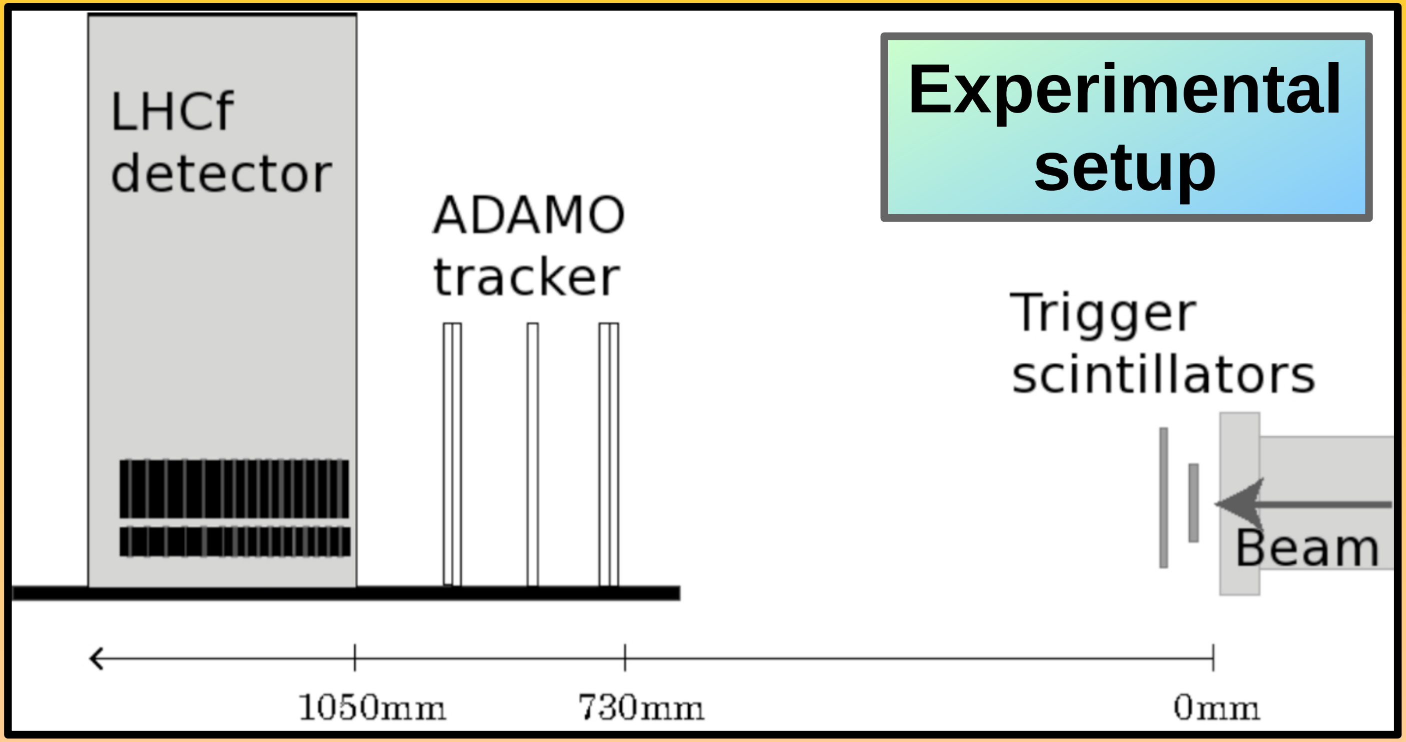


Calibration of Arm2 detector for the reconstruction of hadronic showers

Beam Test in 2015 at the CERN Super Proton Synchrotron (SPS)

Beams

- protons : 300, 350 GeV
- electrons : from 50 to 250 GeV
- muons : 150 GeV



Experimental setup

ADAMO tracker, made by 5 xy Si-µstrip layers, is used as an auxiliary system for independent measurement of trajectory

Simulation data sets

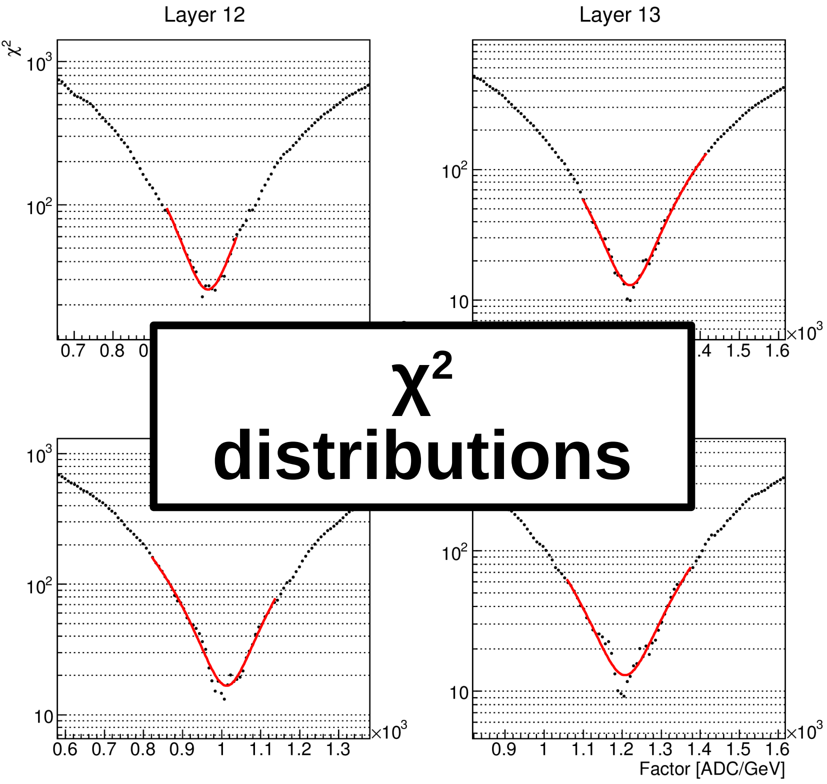
Models use

- **DPM**: DPMJET 3.0-4
- **QGS**: QGSJET II-04 (DPMJET 3.0-4 per E < 90 GeV)

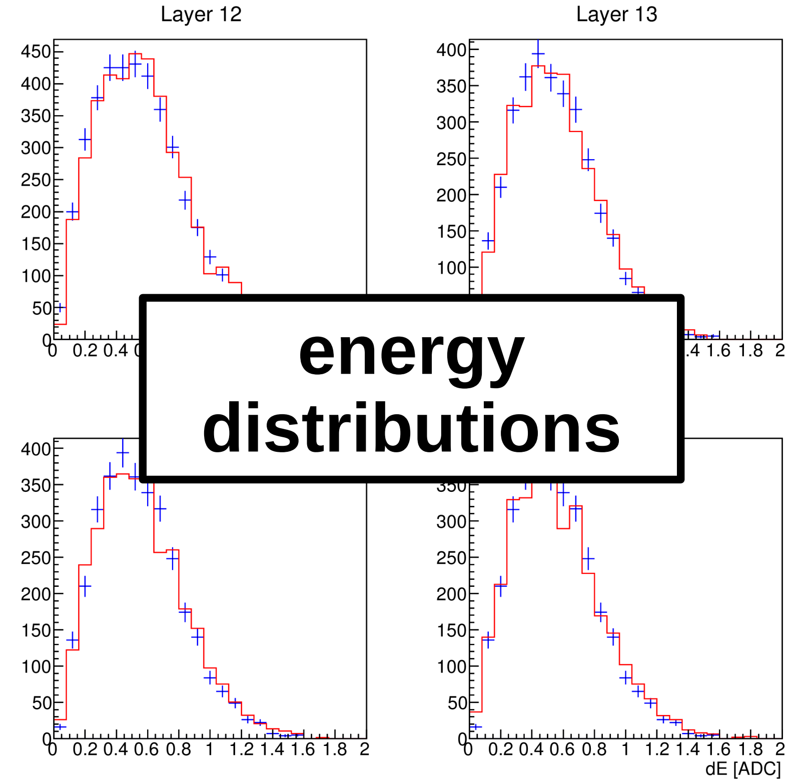
MC samples

- **SPS geometry** - for test (DPM and QGS)
  - monoenergetic **protons** over the whole tower area
    300 and 350 GeV
- **LHC geometry** - for calibration (DPM)
  - monoenergetic **neutrons** at tower center
    from 100 GeV to 6 TeV
  - monoenergetic **neutrons** over the whole tower area
    0.5, 1 and 4 TeV

Gain Calibration Small Tower



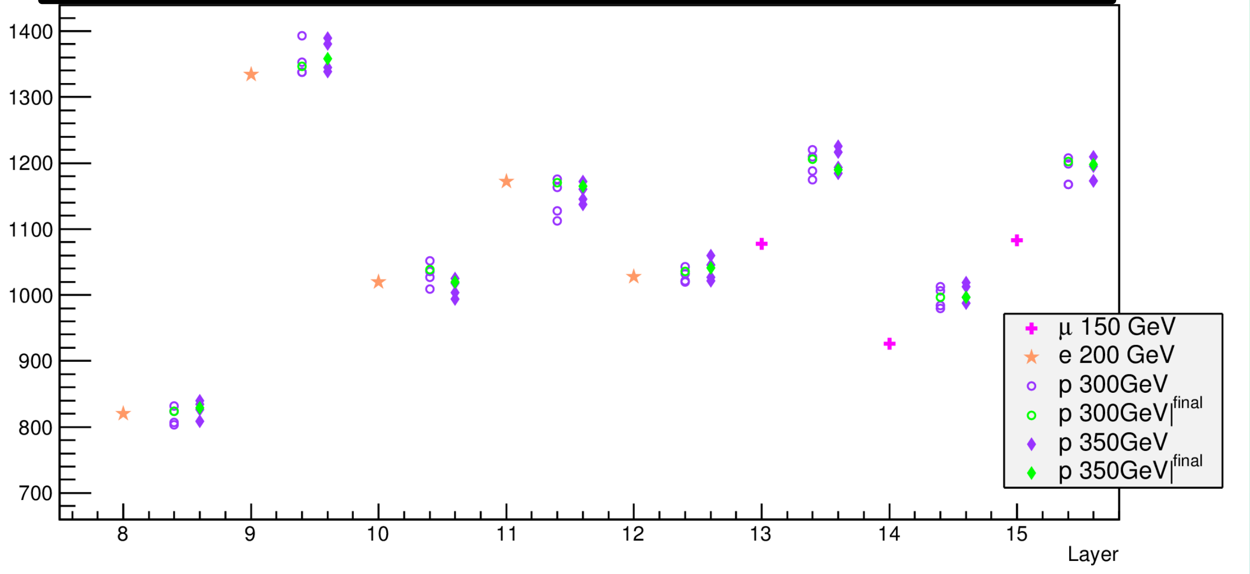
χ^2 distributions



energy distributions

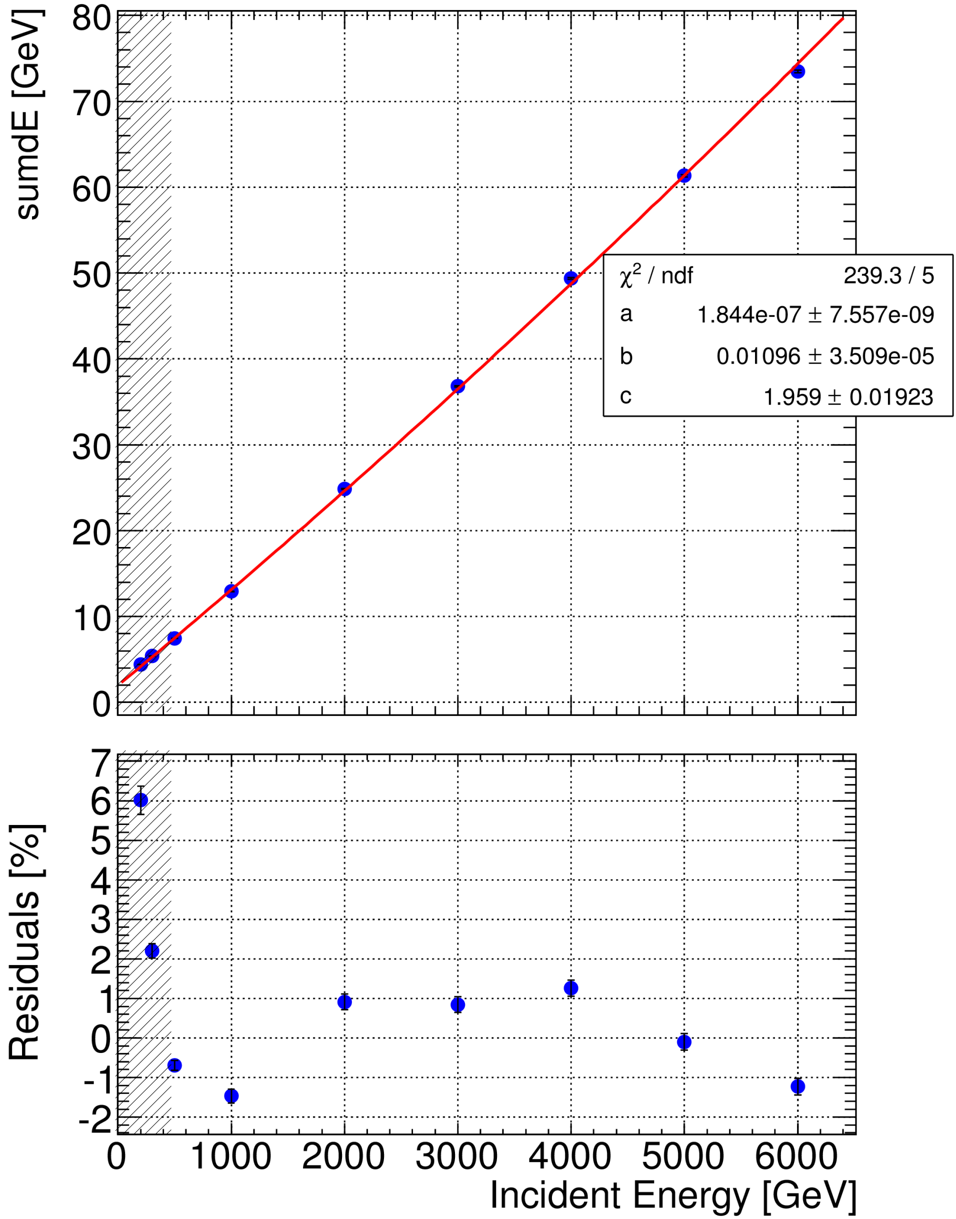
ADC/GeV conversion factors

(For electrons and muons results see presentation by A.Tiberio)



Good agreement between protons and electrons results where both are possible. The gain of each scintillator channel, obtained using electrons and protons beam, was determined with an **average uncertainty $\sigma_{gain} = 2\%$**

Energy conversion coefficients
Small Tower



The sampling-step-weighted energy deposit in the calorimeter is given by

$$sumdE = \sum_{i=2}^{i<11} dE_i + \sum_{i=11}^{i<16} 2\,dE_i$$

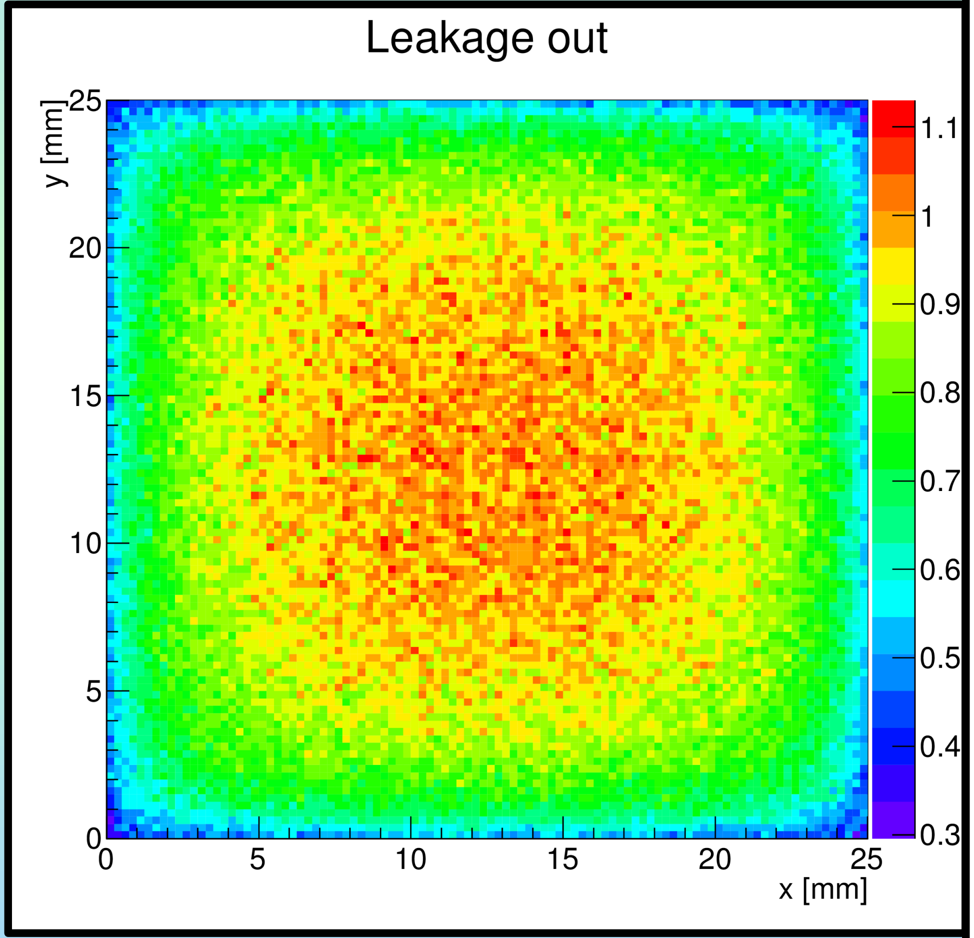
Given the deposited energy ***sumdE*** the primary energy ***E*** is reconstructed using

$$sumdE = a\,E^2 + b\,E + c$$

Parameters ***a***, ***b***, ***c*** are determined from a fit on monoenergetic neutrons

The maximum deviation of the function above 500 GeV has been taken into account as systematic on the energy reconstruction leading to $\boldsymbol{\sigma_{ene\_conv}}$ **= 1.5%**

Lateral leakage
Small Tower



Because of large transverse size of hadronic showers, **a fraction of the energy leaks out from the tower**

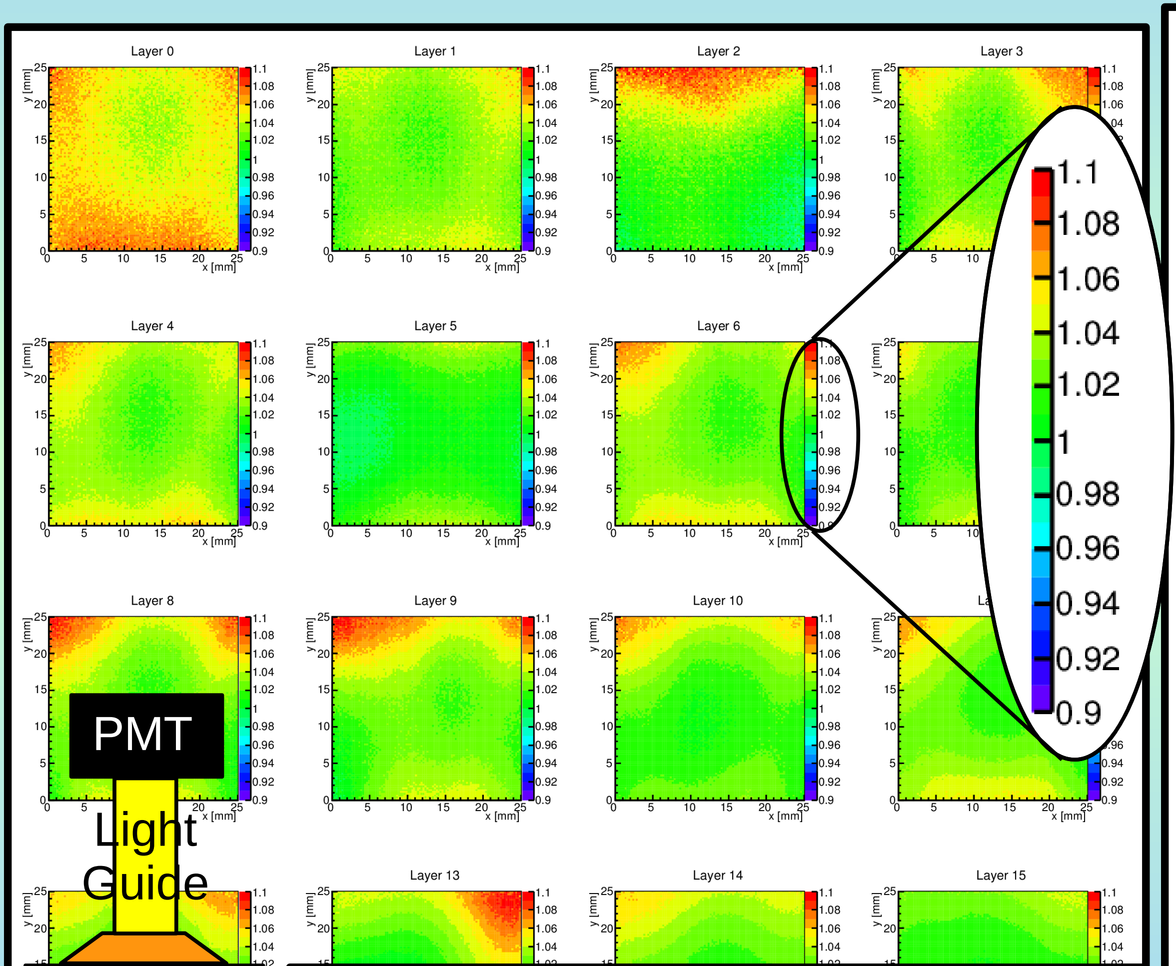
Having reconstructed the impact position making use of imaging layers, it is possible to correct for this effect

In order to do that, we need to compute **leak-out correction factors**, given by the map *Leak(x,y)*

$$\boxed{Leak(x,y) = \left< \frac{sumdE(x,y)}{sumdE_{center}} \right>}$$

The maps are estimated using 1 TeV neutrons, but **no significant energy dependence** was found

Light collection efficiency
Small Tower



$$Eff_i(x,y) = \left< \frac{dE_i^{real}(x,y)}{dE_i^{ideal}(x,y)} \right>$$

Due to **optical coupling between GSO and PMT** the amount of light collected depends on impact position

This effect have been measured with ions beam at the **HIMAC** accelerator and implemented in simulations

Having reconstructed the impact position using imaging layers, it is possible to correct for this effect

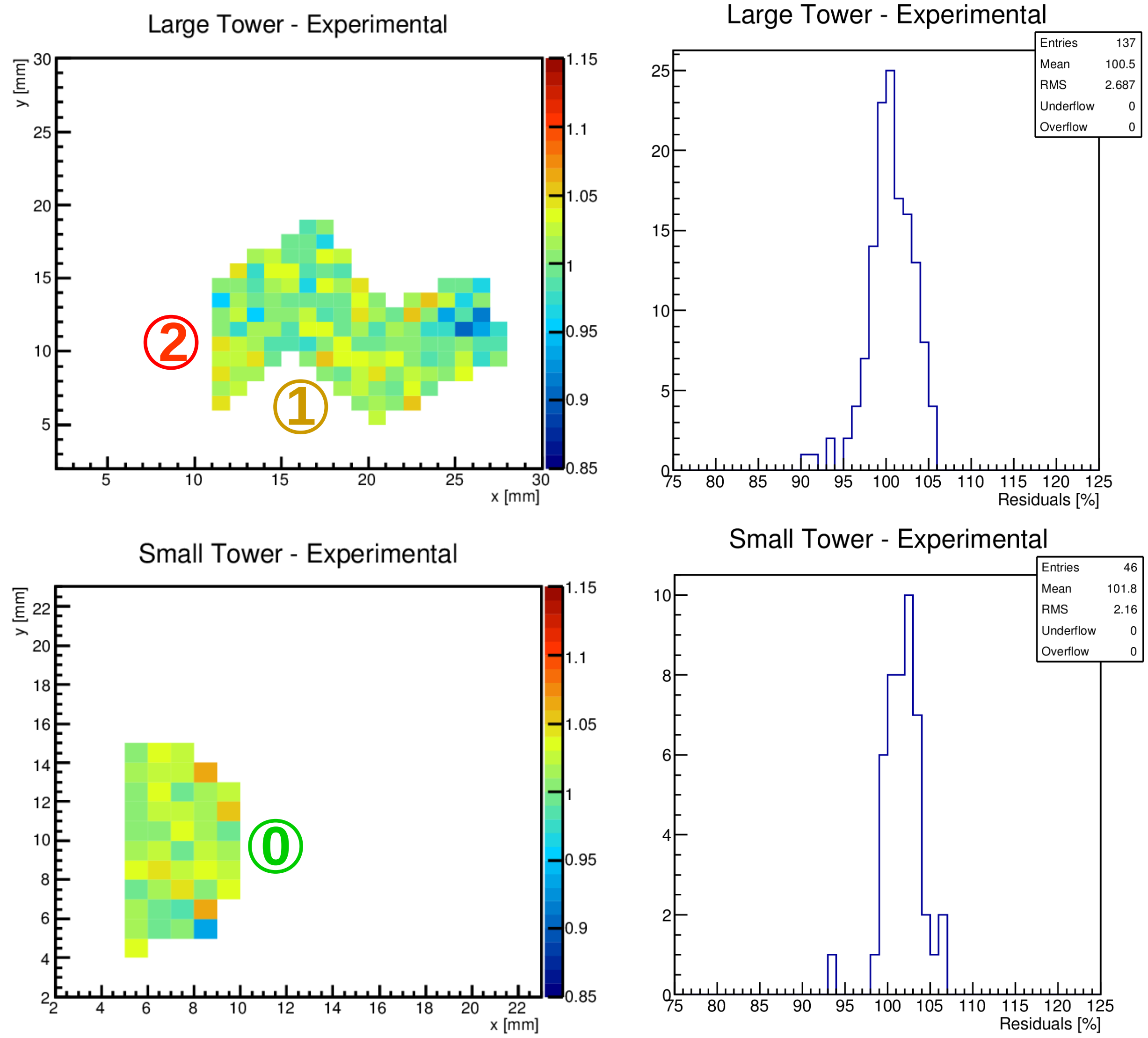
In order to do that, we need to compute **efficiency correction factors**, given by the map $Eff_i(x,y)$

The maps are estimated using 1 TeV neutrons, but **no significant energy dependence** was found

Residuals of position dependent correction factors

$$\langle sumdE \rangle / \langle sumdE_{center} \rangle$$

350 GeV proton beam

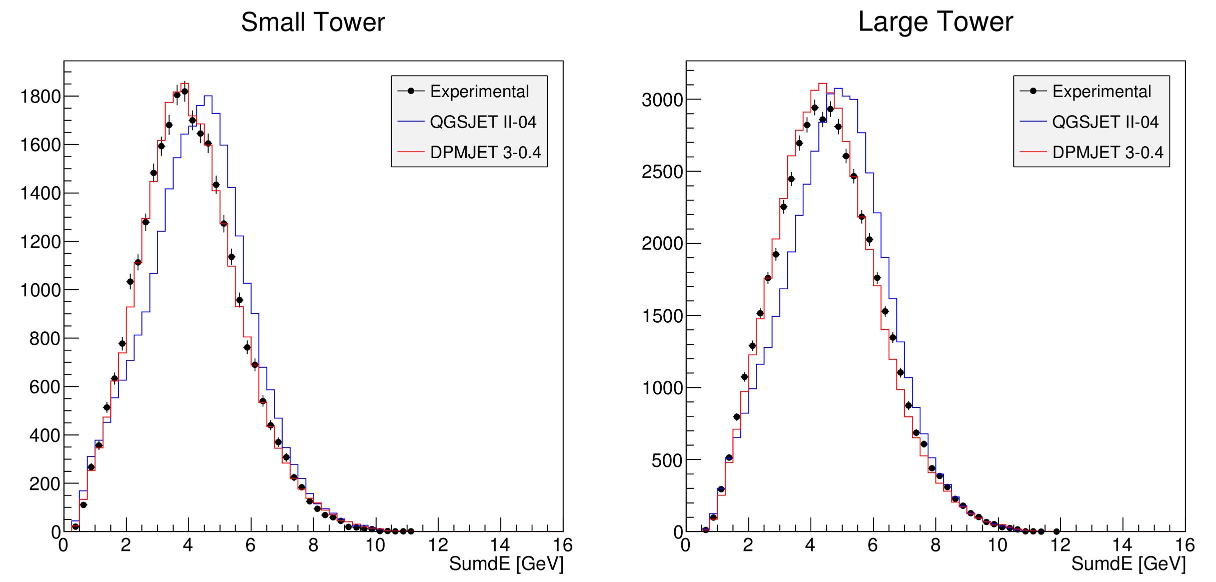


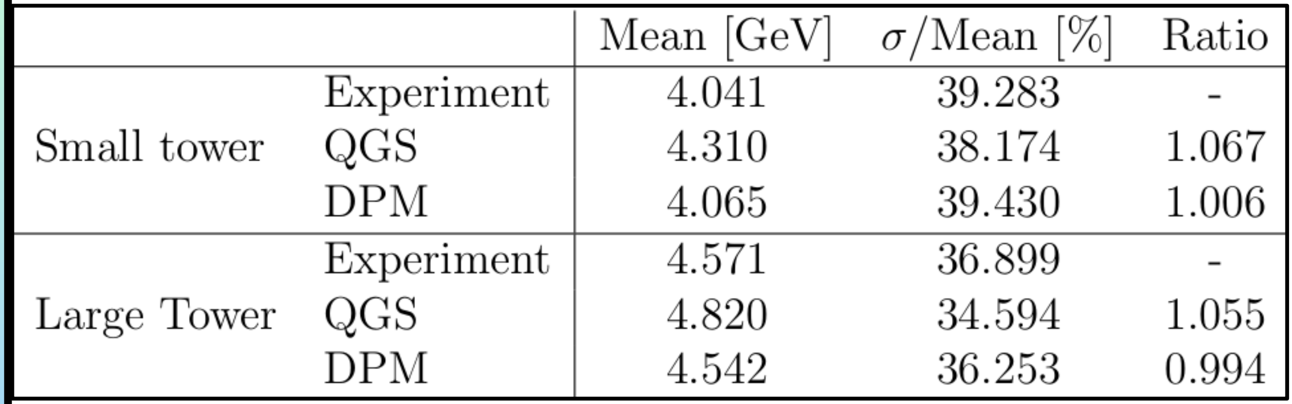
After applying position dependent correction factors, the **non-uniformity is still not negligible**

It can be visualized as the distribution of residuals obtained with 1mmx1mm bins

Using its RMS, the systematic due to non-uniformity of correction factors is **σ_{pos_dep}= 2.4%**

sumdE : comparison between data and MC





		Mean [GeV]	σ/Mean [%]	Ratio
Small tower	Experiment	4.041	39.283	-
	QGS	4.310	38.174	1.067
	DPM	4.065	39.430	1.006
Large Tower	Experiment	4.571	36.899	-
	QGS	4.820	34.594	1.055
	DPM	4.542	36.253	0.994

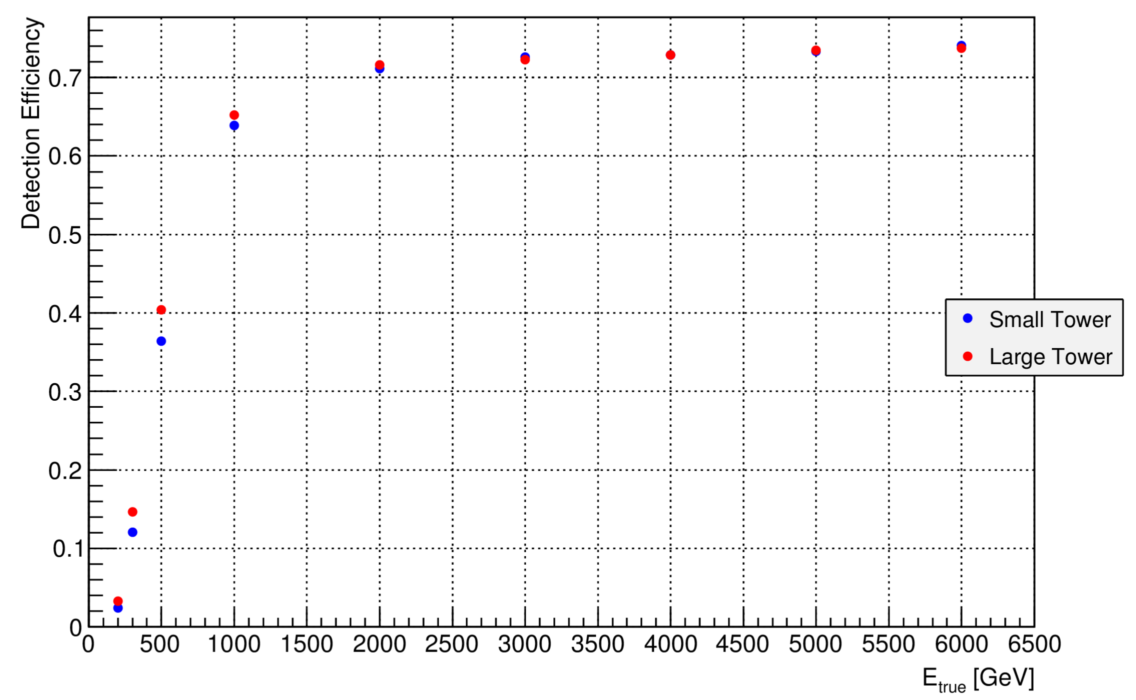
350 GeV proton beam

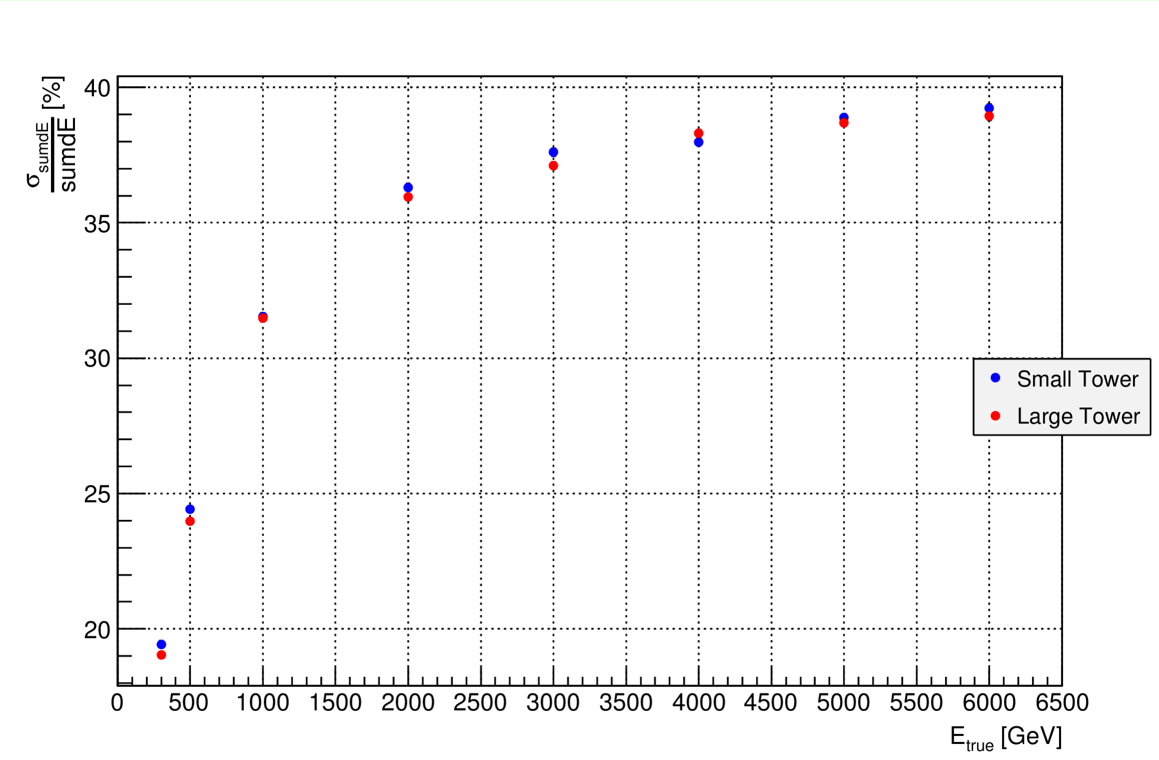
DPM model reproduces very well experimental results, therefore there is no need to add a term to the uncertainty related to model reliability

The **final uncertainty on the energy scale** due to calibration is given by the quadrature sum of $\boldsymbol{\sigma}_{\mathbf{gain}}$, $\boldsymbol{\sigma}_{\mathbf{ene\_conv}}$ and $\boldsymbol{\sigma}_{\mathbf{pos\_dep}}$, resulting in $\boldsymbol{\sigma}_{\mathbf{cal}}$ **= 3.5%**

Detector resolution depends on the choice of dE^{thr} ranging between 35% and 40% making use of a threshold between 50 and 100 MeV

Performances





Detection efficiency

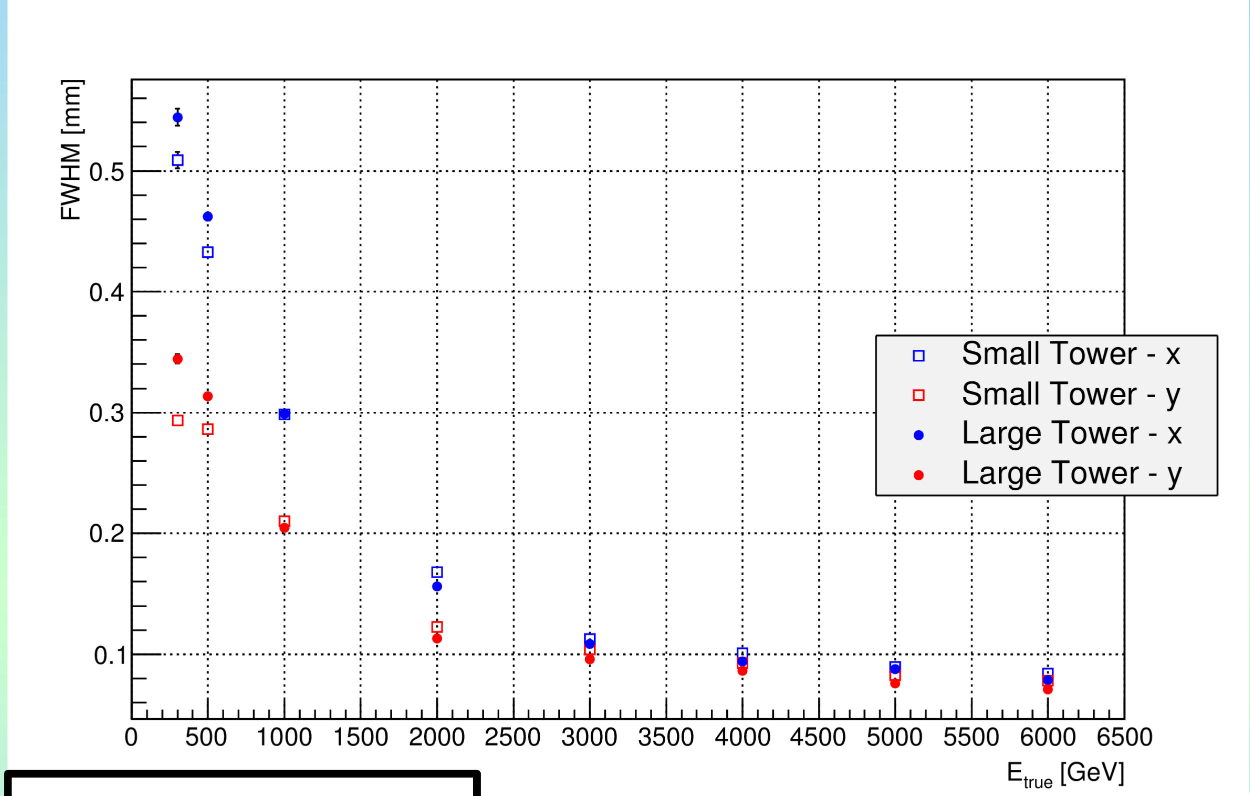
Making use of dE^{thr} = 600 MeV detection efficiency is very small below 500 GeV and reaches an almost constant value of ~70% above 2 TeV

Energy resolution

Energy resolution depends strongly on software trigger below 500 GeV and reaches an almost constant value of ~40% above 2 TeV

using **DPMJet 3.04** to simulate monoenergetic neutrons at tower center

Performances



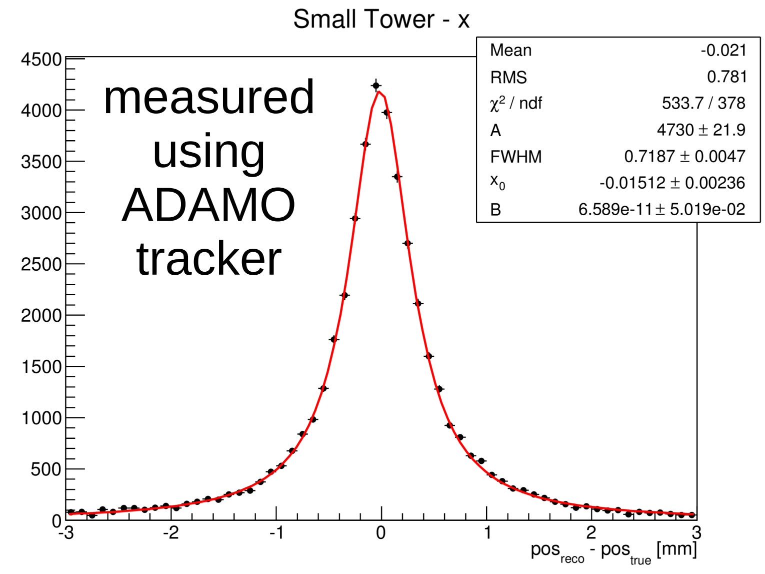
Position resolution

Position resolution, slightly different at low energy between x and y view, is better than 300 and 200 μm respectively above 1 TeV

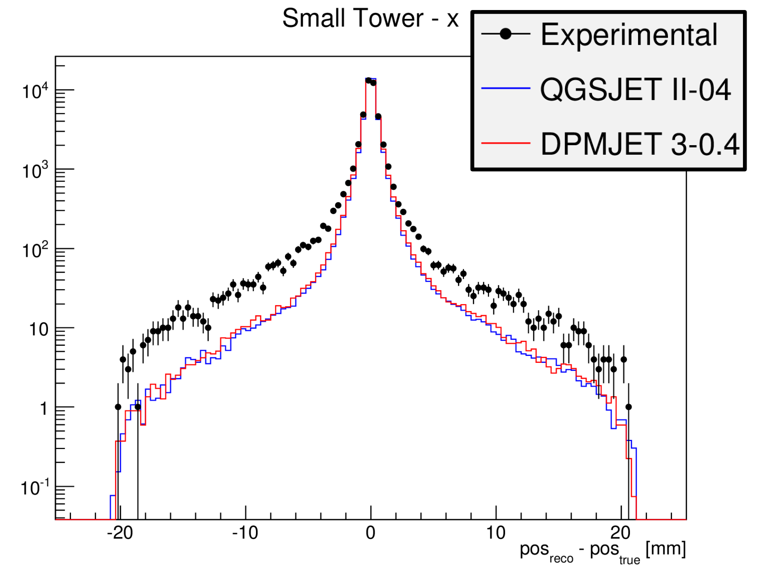
using **DPMJet 3.04** to simulate monoenergetic neutrons at tower center

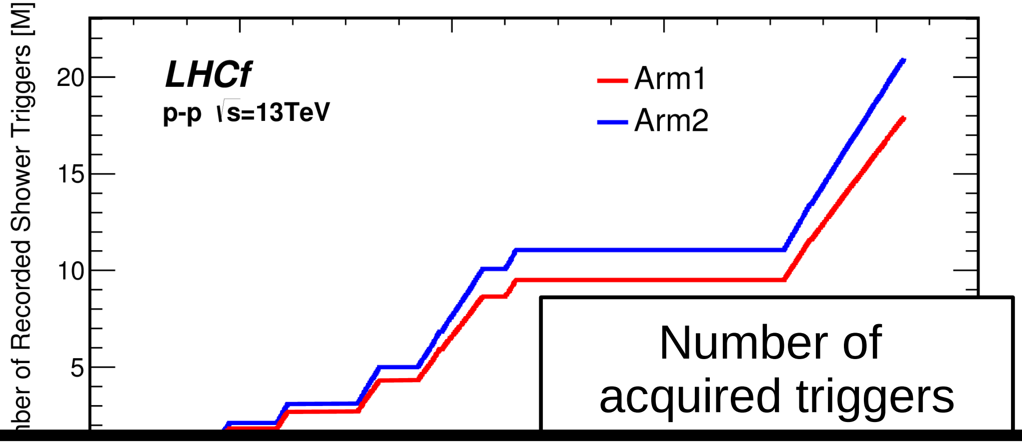
Resolution between 600 and 800 μm but long tails absent in MC

using 350 GeV proton beams beam test data

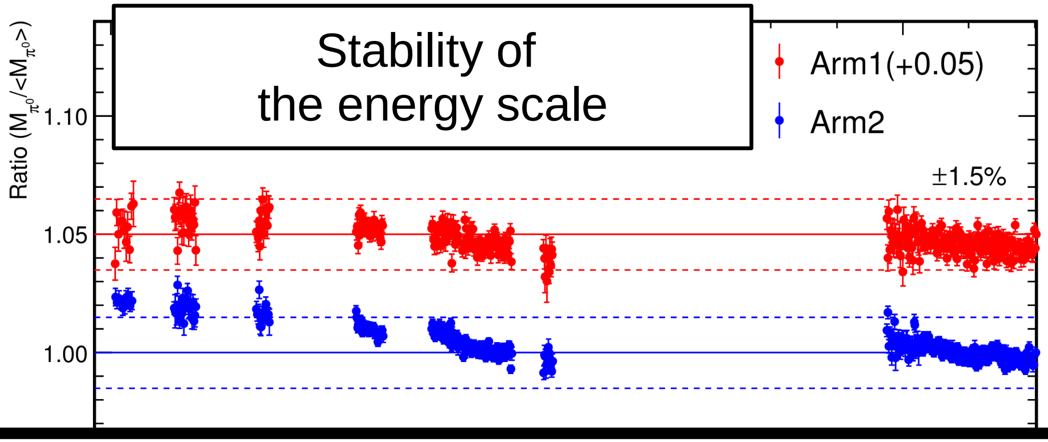


measured using ADAMO tracker



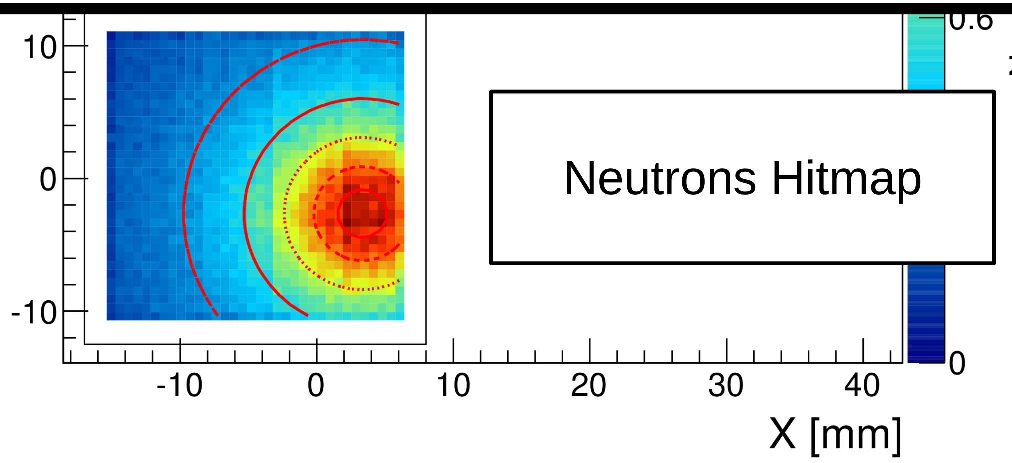


Number of acquired triggers

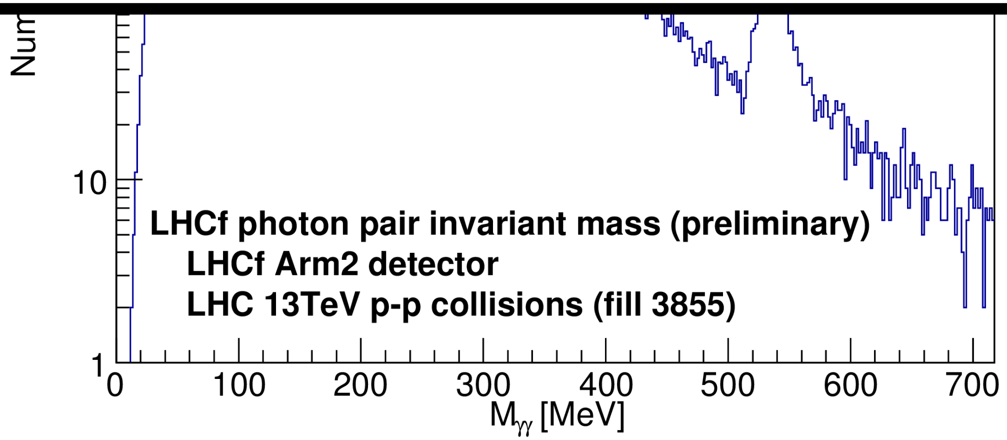


Stability of the energy scale

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



Neutrons Hitmap



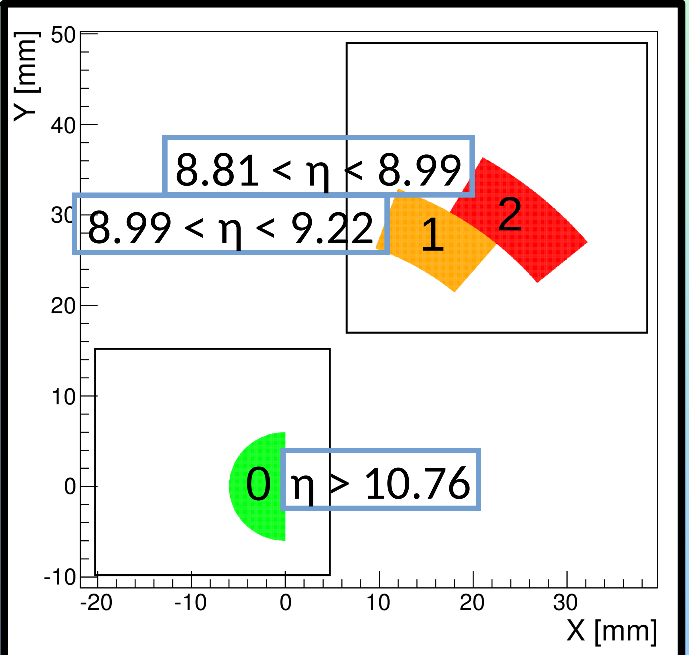
Analysis data set

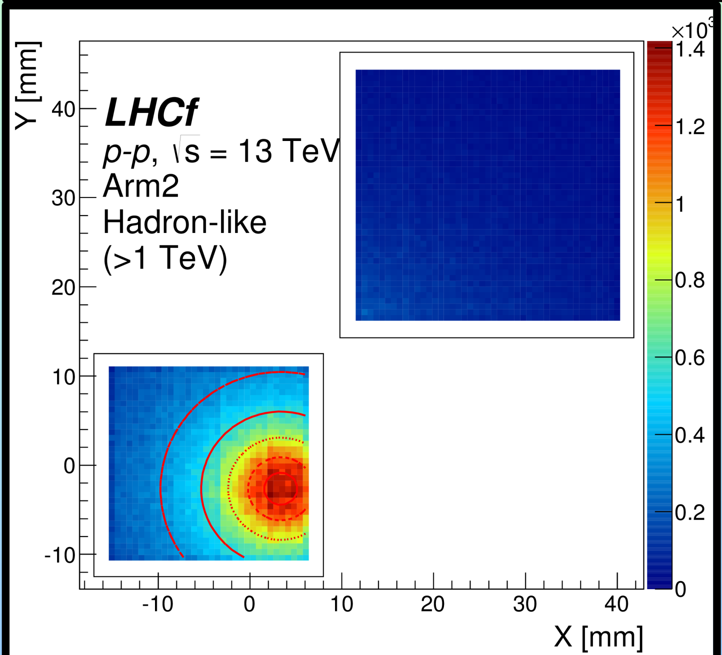
Data set

- 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

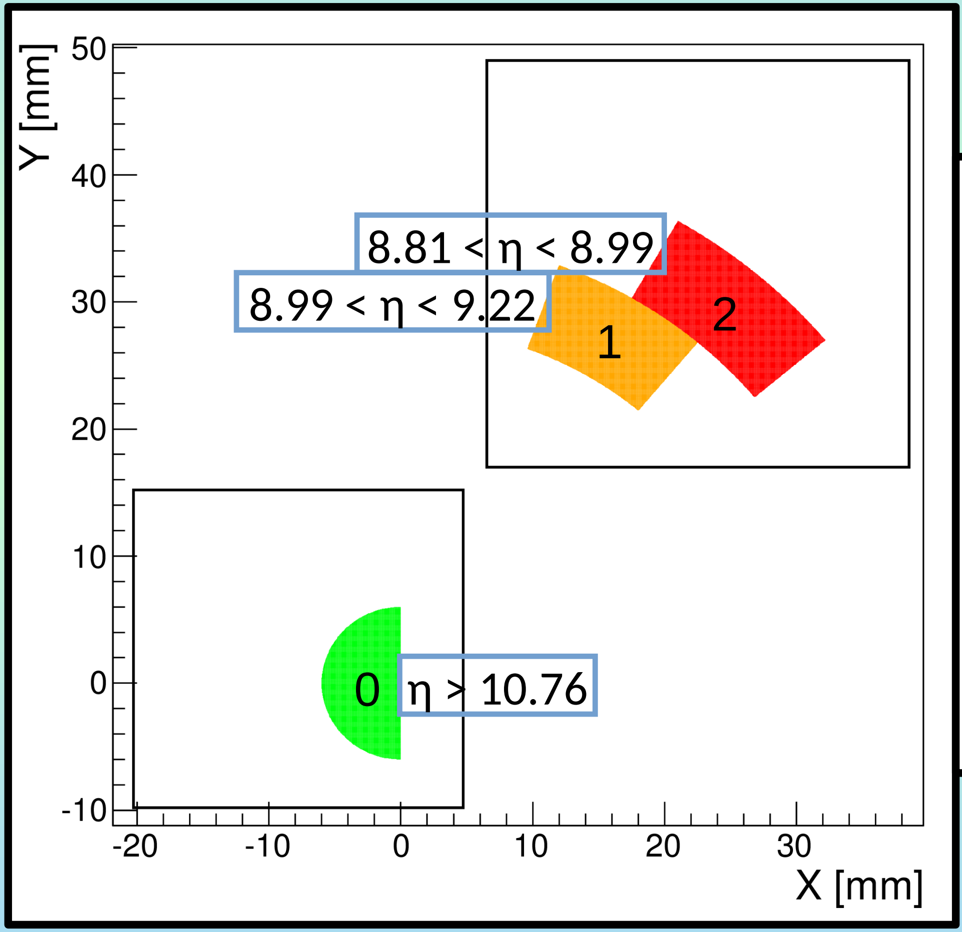
Determination of beam center

- 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





Event selection



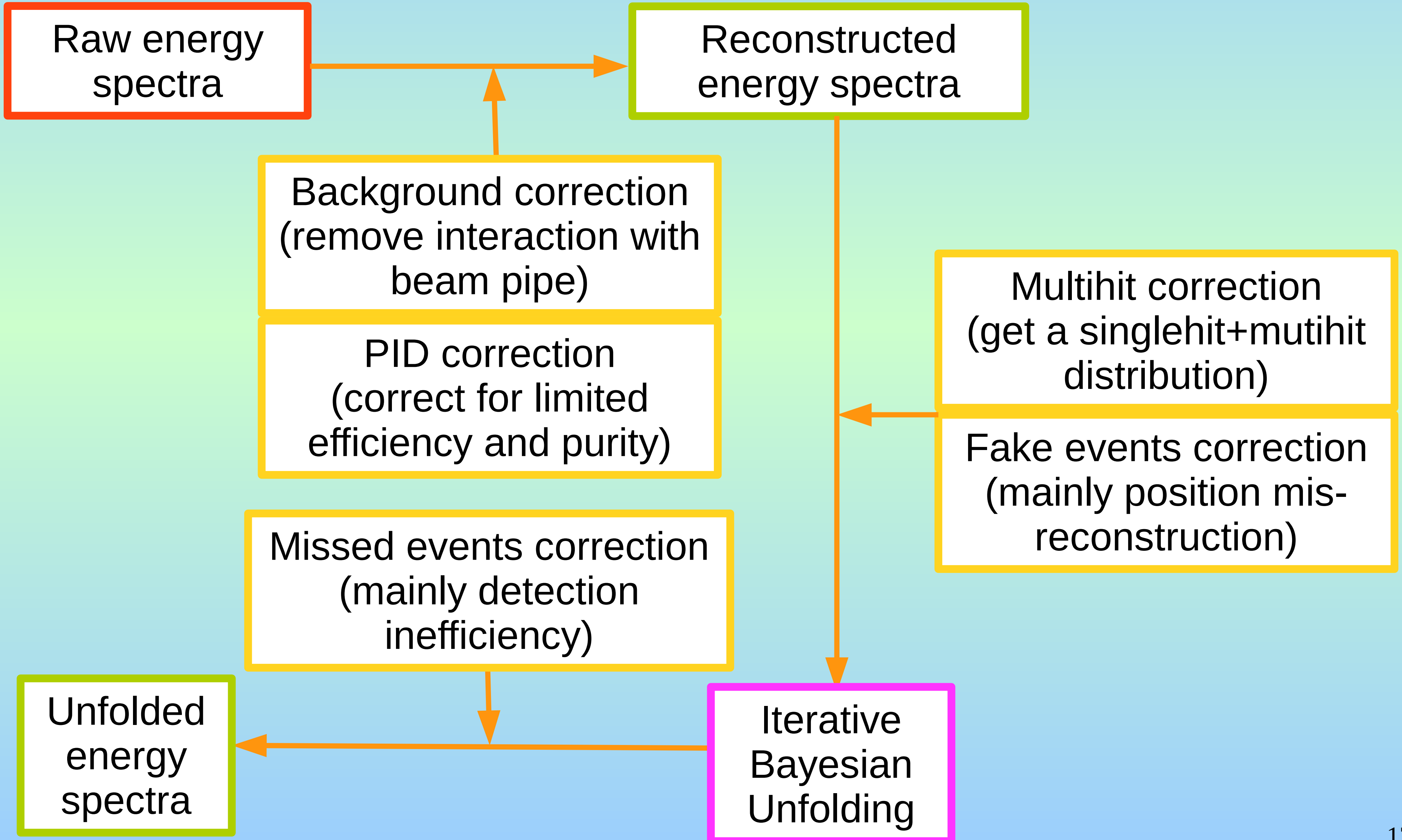
Event selection criteria:

- **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 strategy



Raw energy spectra

Reconstructed energy spectra

Background correction (remove interaction with beam pipe)

PID correction (correct for limited efficiency and purity)

Multihit correction (get a singlehit+mutihit distribution)

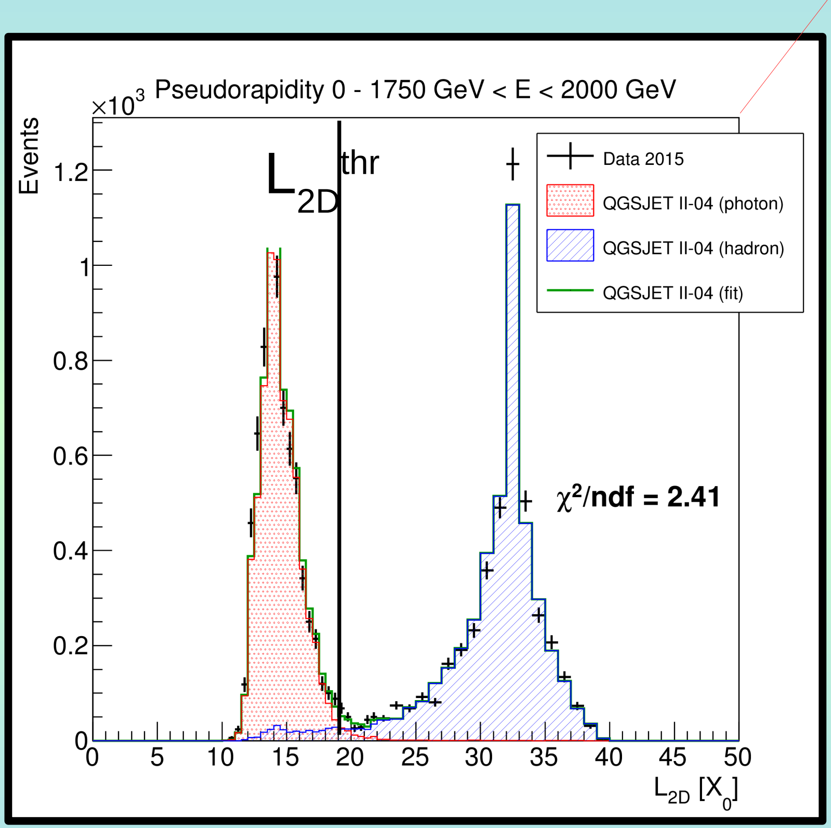
Fake events correction (mainly position mis-reconstruction)

Missed events correction (mainly detection inefficiency)

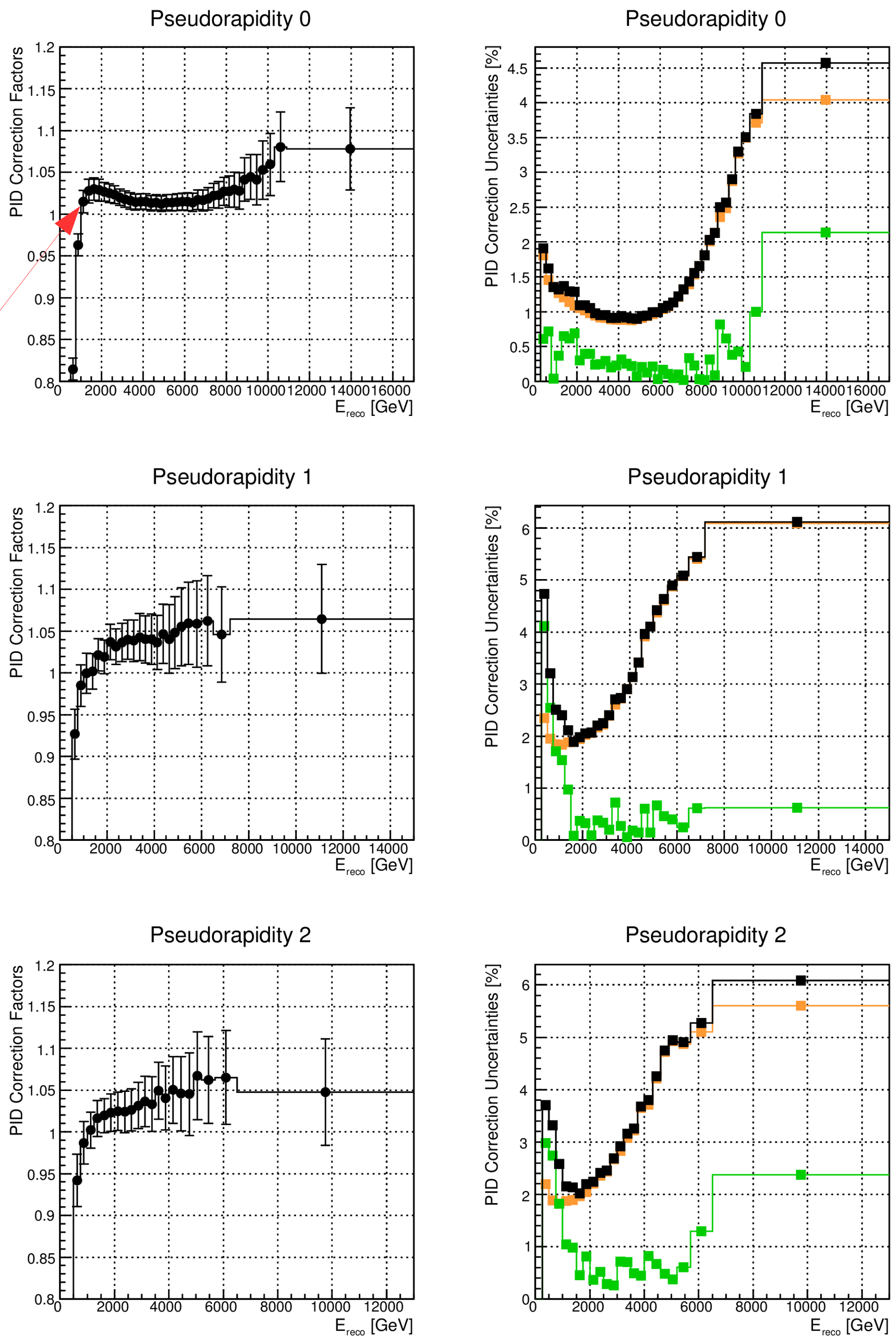
Unfolded energy spectra

Iterative Bayesian Unfolding

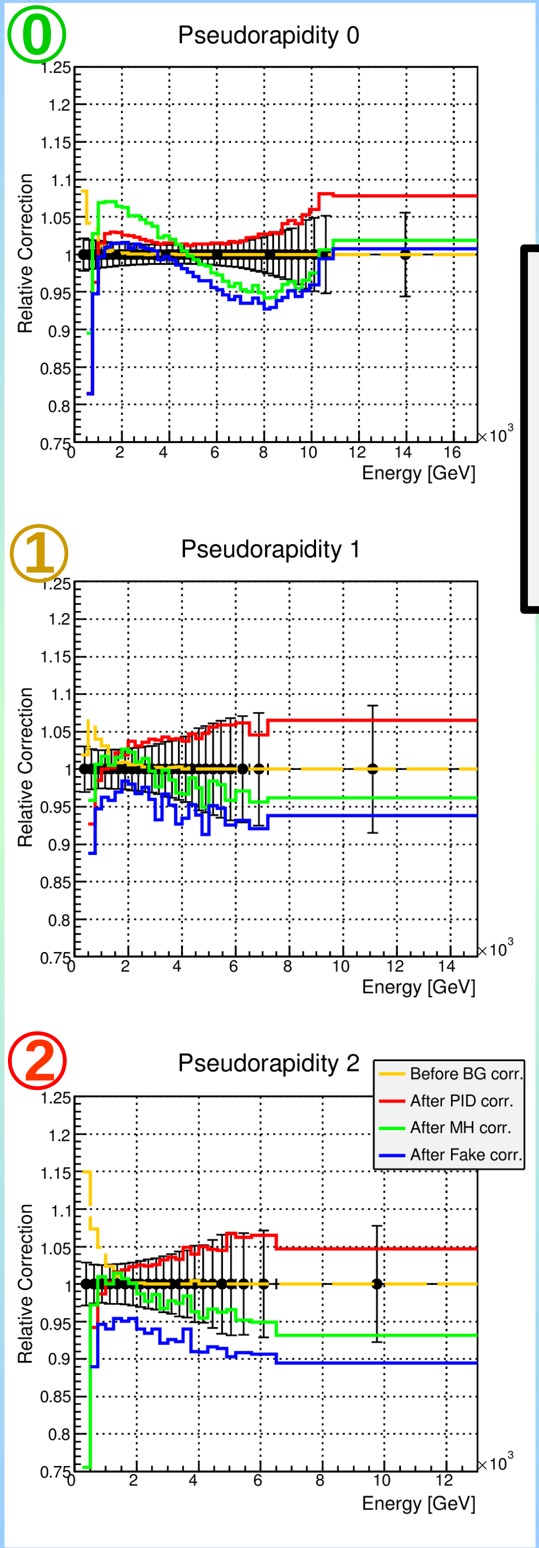
PID Correction



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



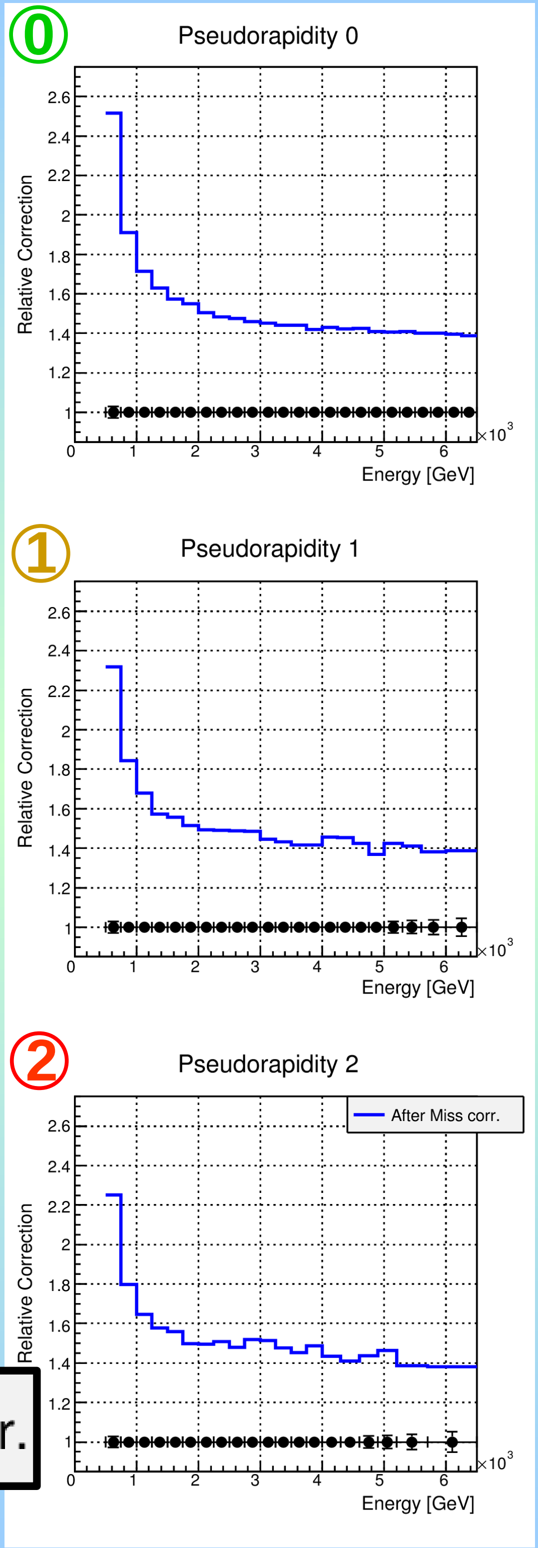
🟨 Before BG corr.
🟥 After PID corr.
🟩 After MH corr.
🟦 After Fake corr.

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

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

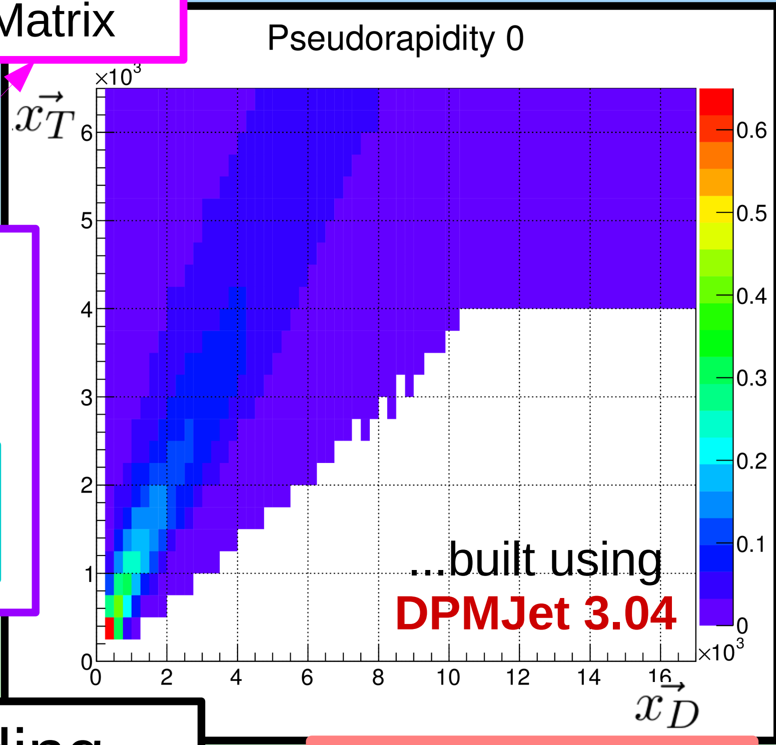
In our case $\vec{x}$ is energy

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

Response Matrix

Reconstructed spectra

True spectra



...built using **DPMJet 3.04**

Iterative Bayesian Unfolding

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

Input prior

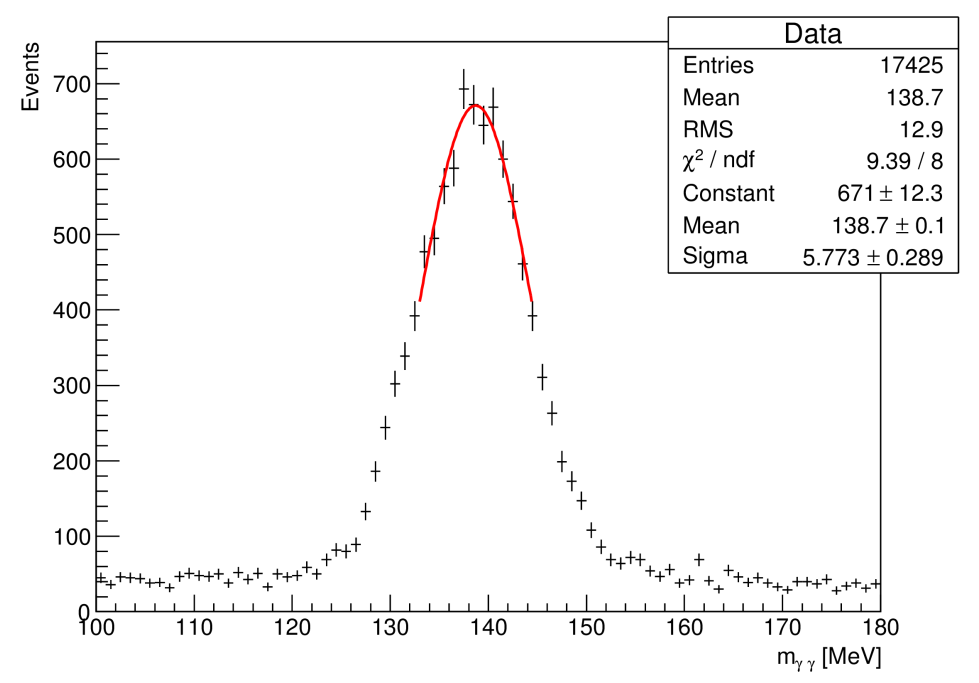
Prior
$P(T_i)$

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

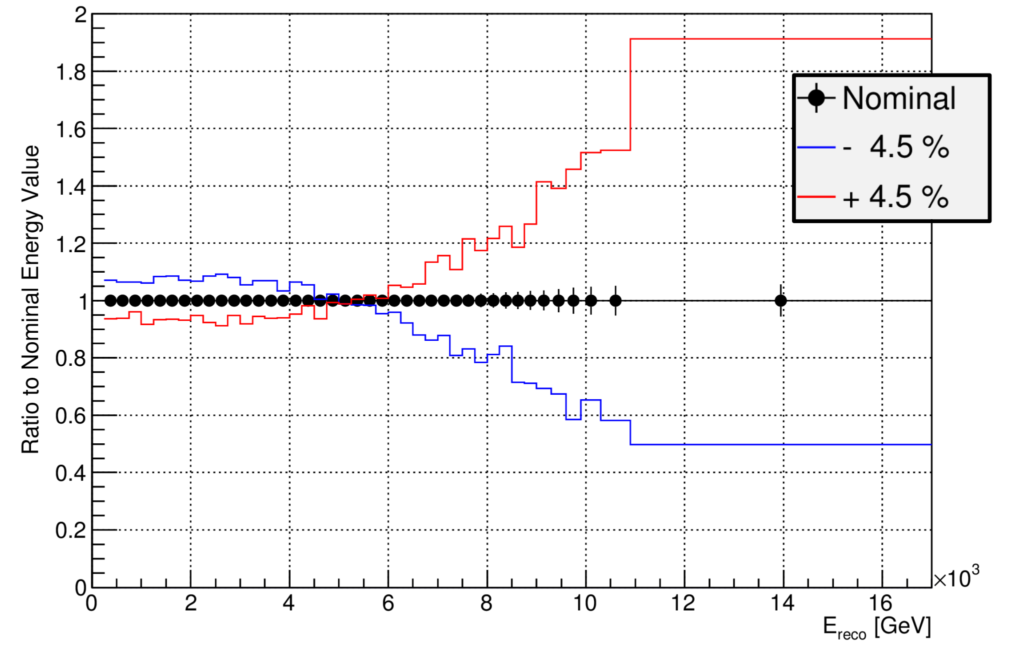
The iterative procedure converges when $\Delta\chi^2 <$ threshold

Uncertainty on the energy scale

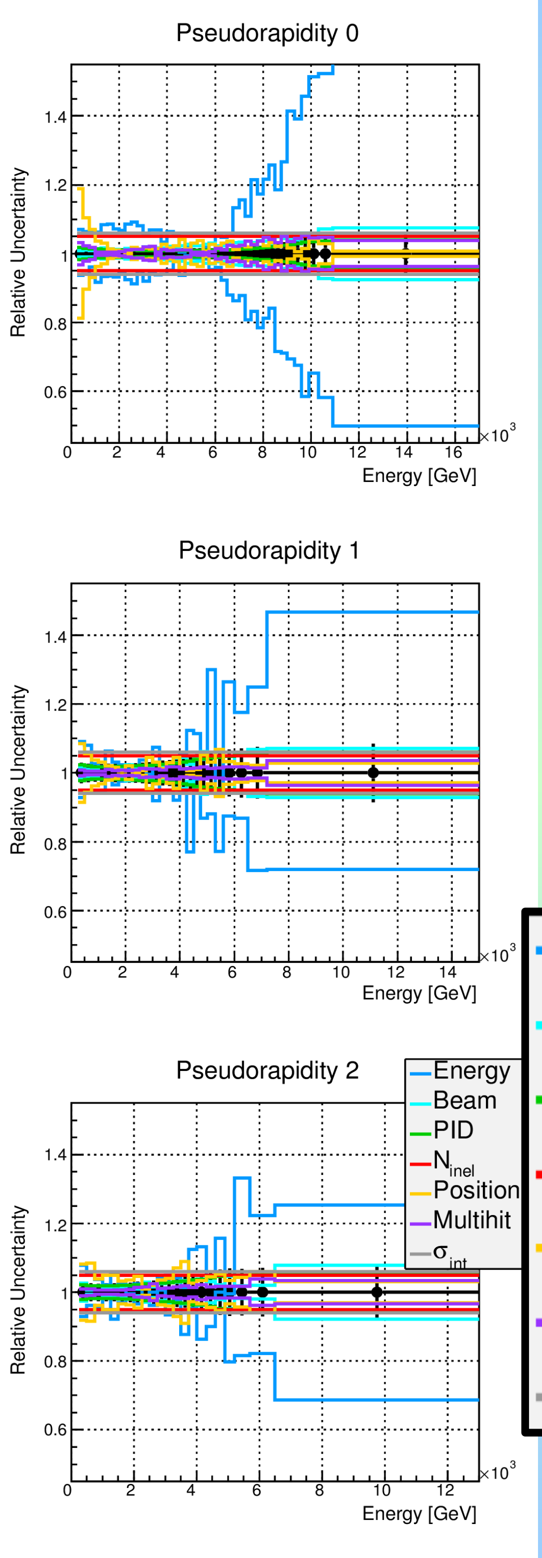


calibration effect = 3.5%
hardware effect = 2%
π^0 mass shift = 2.15%
$\sigma_{energy} = \sqrt{\sigma_{cal}^2 + \sigma_{hw}^2 + \sigma_{\pi^\circ}^2} = 4.5\%$

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

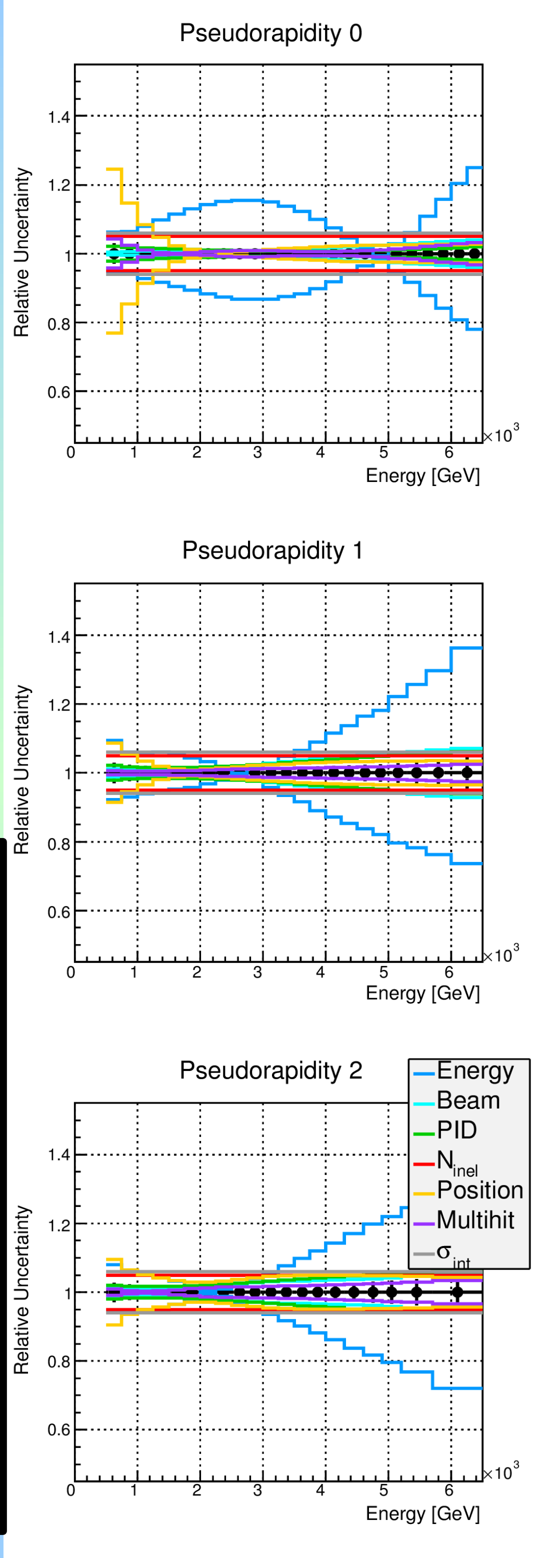
We **manually** propagated uncertainties through the unfolding

🟦 Energy
🟦 Beam
🟩 PID
🟥 N_{inel}
🟨 Position
🟪 Multihit
⬜ σ_{int}

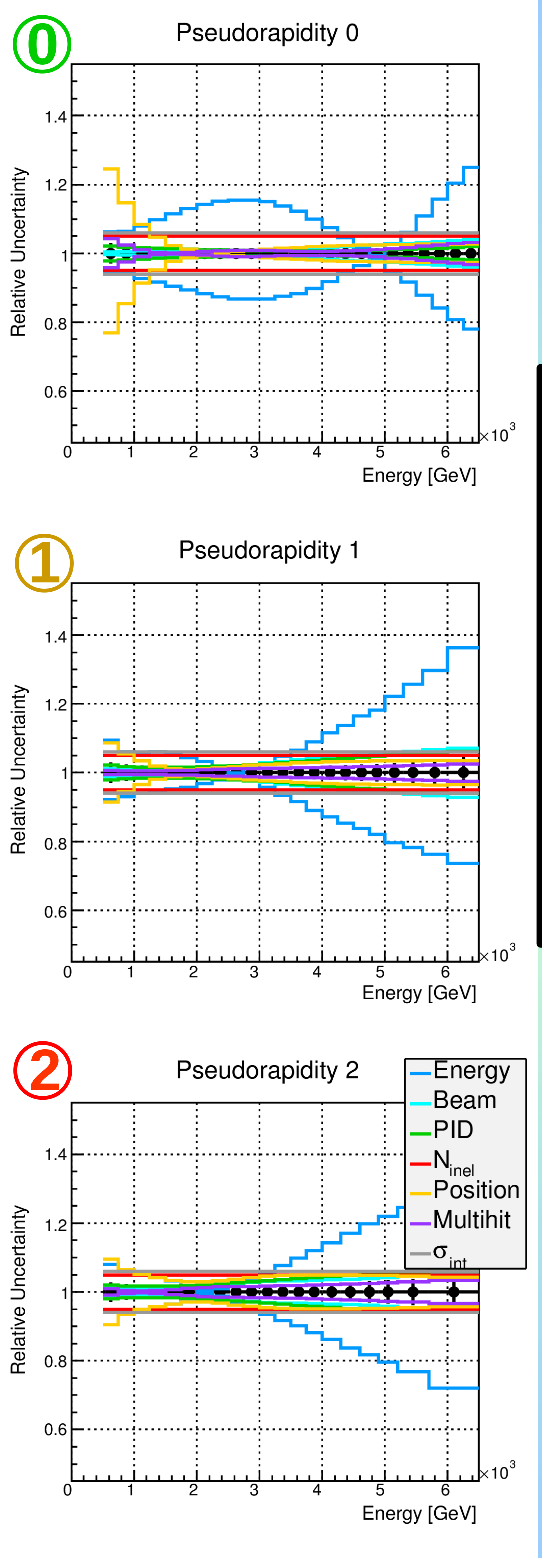
For each systematic:

- 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

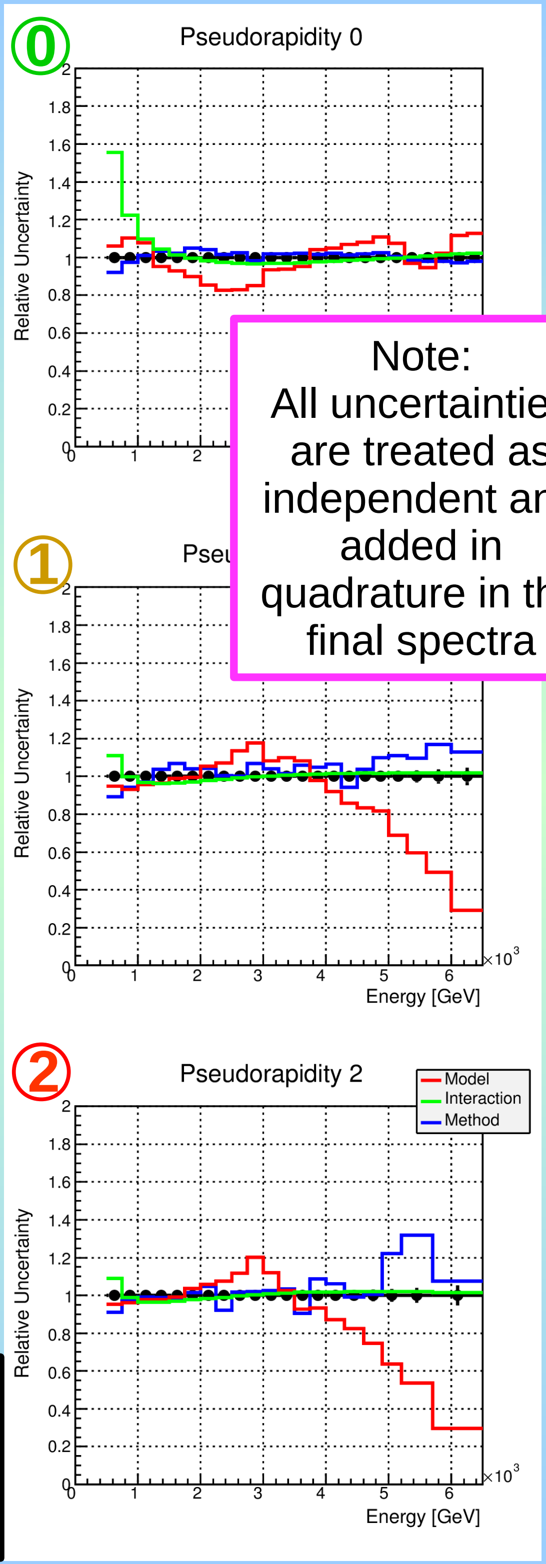


- 🟦 Energy
- 🟦 Beam
- 🟩 PID
- 🟥 N_{inel}
- 🟨 Position
- 🟪 Multihit
- ⬜ σ_{int}

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%

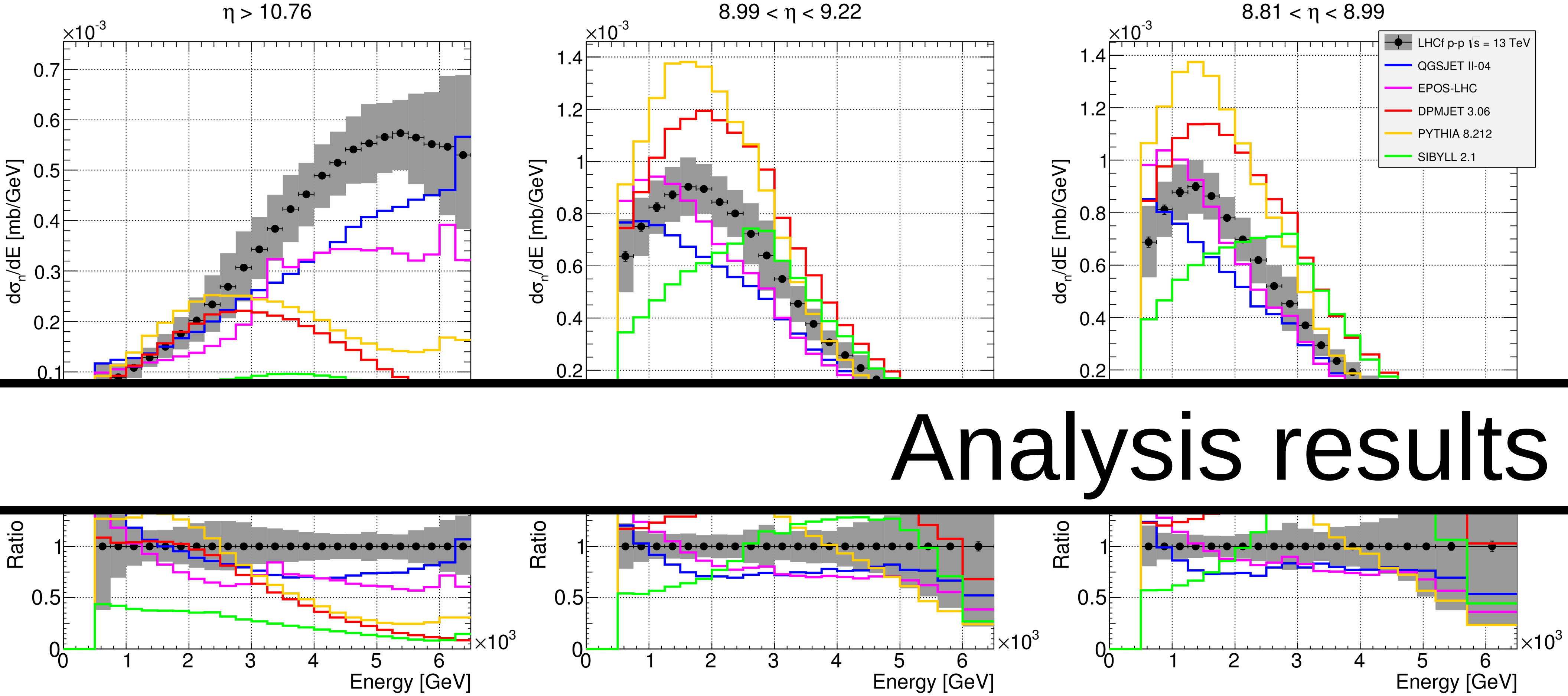
The dominant contribution related to the unfolding process is **Model systematic**, due to the large dependence on the generator used for training of unfolding algorithm

- 🟥 Model
- 🟩 Interaction
- 🟦 Method



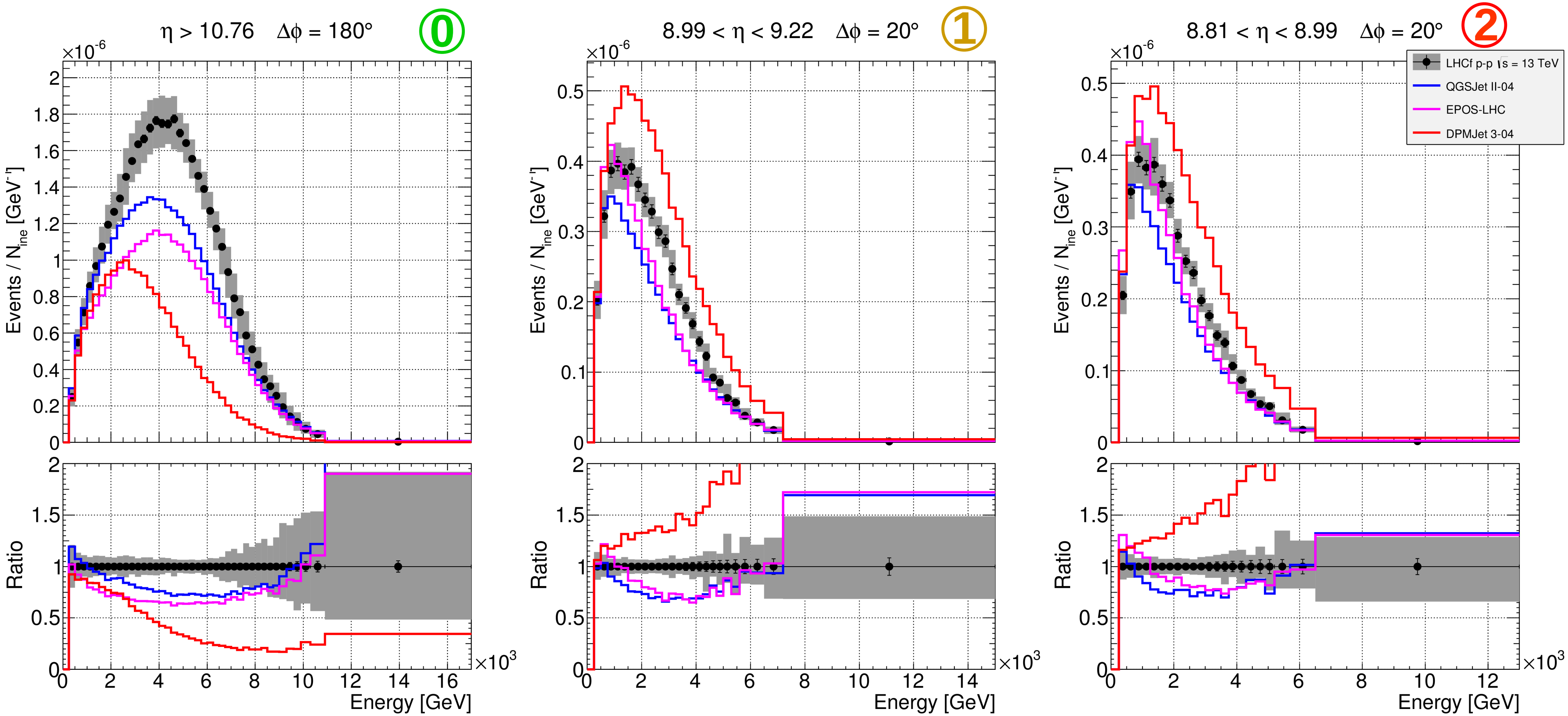
Note:
All uncertainties are treated as independent and added in quadrature in the final spectra

Analysis results



Reconstructed energy spectra

Events / N_{ine} / dE

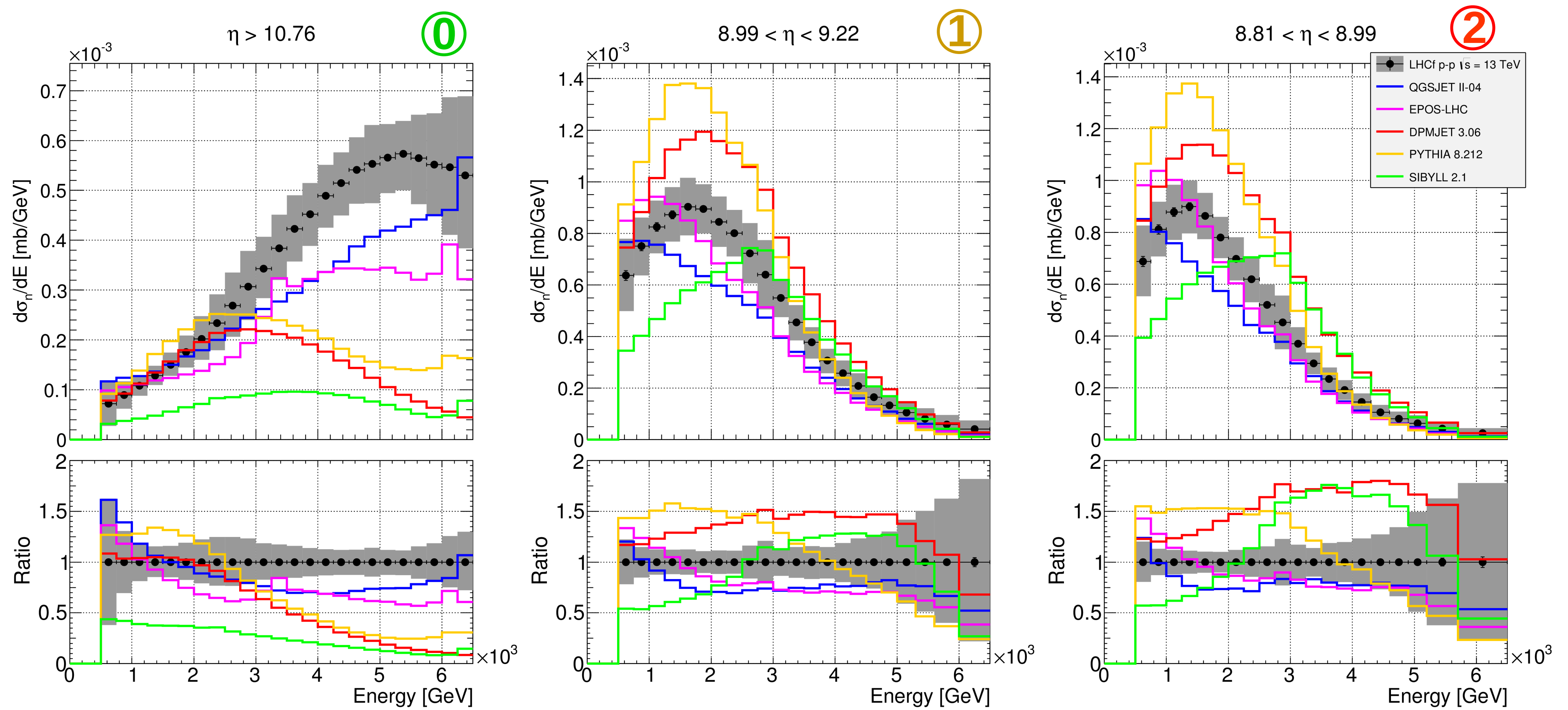


QGSJET II-04 and **EPOS-LHC** have similar shape but lower yield
DPMJET 3.04 have very different shape and yield

Unfolded energy spectra

Differential production cross section

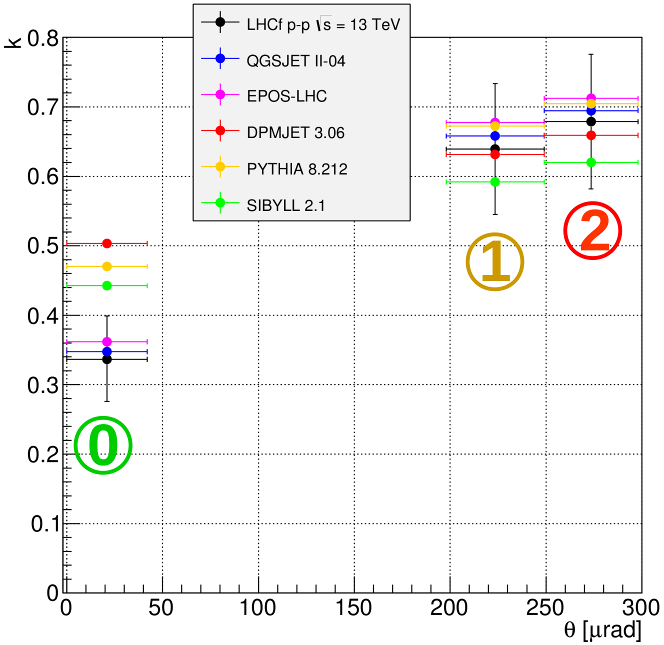
$$d\sigma_n/dE = \frac{dN(\Delta\eta,\Delta E)}{E}\frac{1}{L}\times\frac{2\pi}{d\varphi}$$



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

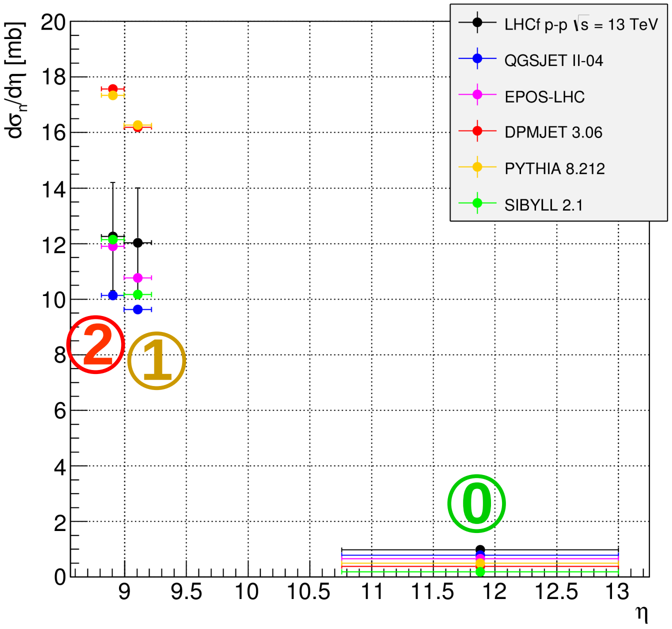
Measurements of interesting quantities in CR physics

Inelasticity VS θ



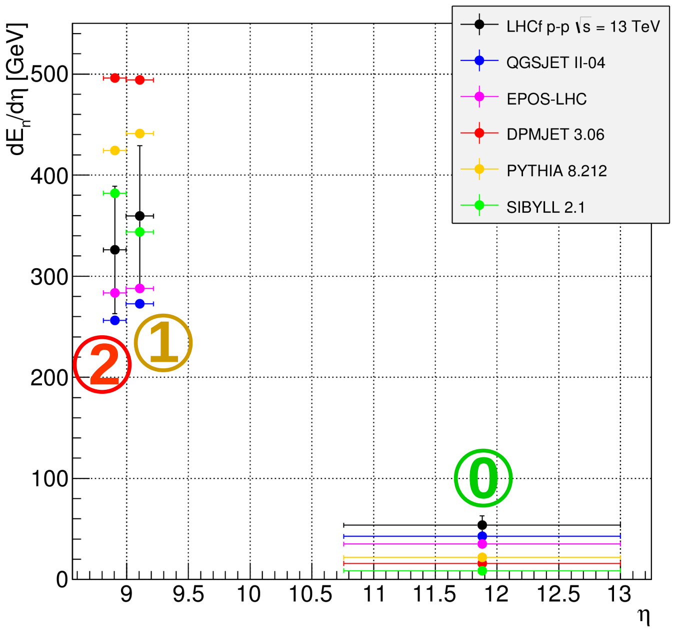
All models overestimate inelasticity in the most forward region even if **QGSJET II-04** and **EPOS-LHC** are consistent within the error bars

dσ/dη VS η



EPOS-LHC and **SIBYLL 2.1** reproduce enough well the measured total differential cross section except in the most forward region

dE/dη VS η



Where the energy flux is high, the agreement between experimental measurements and **SIBYLL 2.1**/**EPOS-LHC** is quite good

Test of Feynman scaling

Approximations:

- $p_Z \sim E$
- $p_T^{MAX} \sim \theta \times \sqrt{s}/2$

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 √s if we consider the same p_T interval

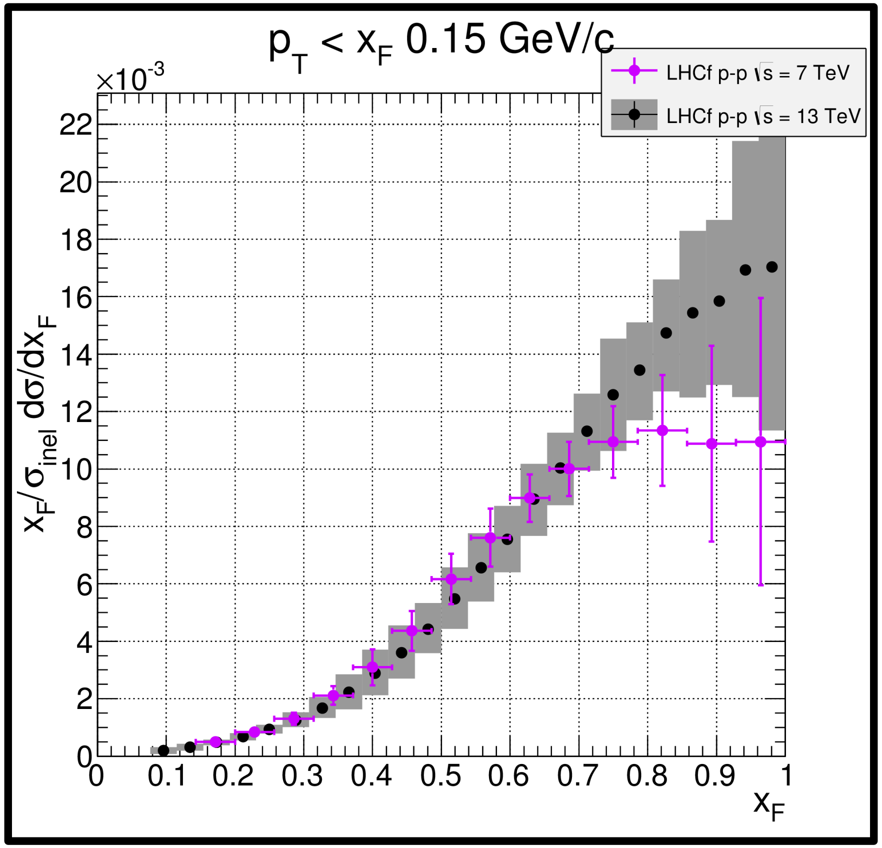
Idea

Use neutron production cross section measured in case of p-p collisions at √s=7 and 13 TeV to test Feynman scaling hypothesis

How to Proceed

In case of √s=7 TeV, the region $\eta > 10.76$ corresponds to $p_T^{MAX} < 0.15$ GeV/c

The analysis at √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 $0.2 < x_F < 0.75$

Summary

In this work we presented two results relative to Arm2 upgraded detector:

- **Calibration of the detector for the reconstruction of hadronic showers**
  - Calibration of energy scale involved determination of channels gains, conversion coefficients and correction factors, leading to a ***final uncertainty of 3.5%***
  - For neutrons above 2 TeV, we found a ***detection efficiency of 70%, an energy resolution of 40% and a position resolution of 0.1 mm***
- **Measurement of energy spectra of neutrons from √s=13 TeV p-p collisions**
  - The analysis required the application of correction factors, the estimation of systematic uncertainties and the use of an unfolding technique
  - 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 **SIBYLL 2.1** reproduces enough well the total differential cross section and the energy flux in the region ***$8.81 < \eta < 9.22$***
  - A ***test of Feynman scaling*** using data relative to √s=7 and 13 TeV showed that the hypothesis holds within the uncertainties

Back Up

MonteCarlo status

		Arm1			Arm2		
		QGSJet	DPMJet	Time needed (assuming 200 CPU)	QGSJet	DPMJet	Time needed (assuming 200 CPU)
	350 GeV p	1000k (TS) 2000k (TL)	500k+500k (TS) 1000k+1000k (TL)	~ 1 week (3.5k/day/CPU)	1600k (TS) 3200k (TL)	1600k (TS) 3200k (TL)	X
Calibration	monoenergetic neutrons at tower center	X	10k+115k below 1 TeV (for each tower), 10k above 1 TeV (for each tower)	< 1 week (1.7k/day/CPU)	125k below 1 TeV (for each tower) 50k above 1 TeV (for each tower)	125k below 1 TeV (for each tower) 50k above 1 TeV (for each tower)	X
	1 TeV neutrons on all tower area	X	4000k (TS) 5000k+3000k (TL)	~ 2 weeks (1.0k/day/CPU)	X	1500k+3000k (TS) 2400k+4800k (TL)	~ 1 month (1k/day/CPU)
Analysis	Flat energy - Flat position neutron spectra	X	10000k (for each tower)	~ 1 month	10000k (for each tower)	14000k (for each tower)	~ 1 month

Two months in Nagoya

Two months in Firenze