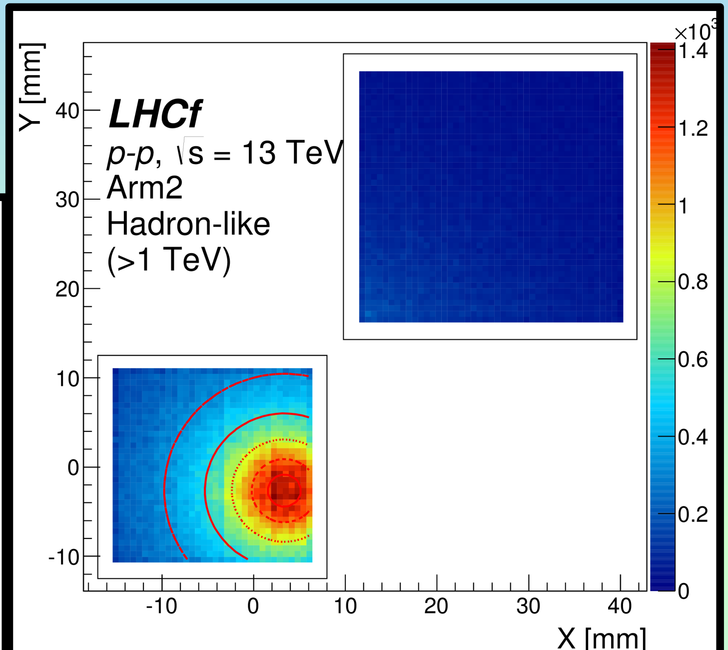
Measurements of the energy spectra relative to neutrons produced in $\sqrt{s}$ = 13 TeV p-p collisions using the LHCf Arm2 detector

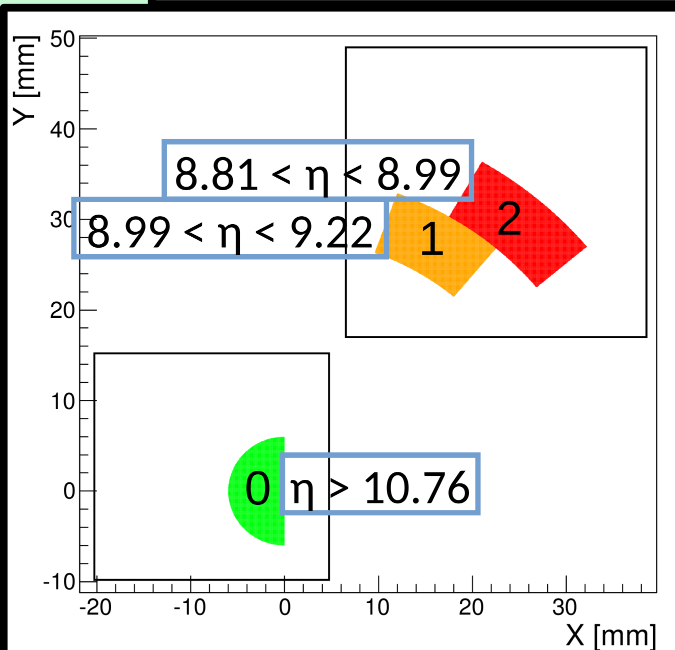
Eugenio Berti

LHCf collaboration meeting
Firenze 26th November 2018

Data set and Event selection



Data set
- 12 July 2015,
  22:32-1:30
- Fill # 3855
- μ = 0.01
- $\int L dt$ = 0.194 nb^{-1}
- σ_{ine} = 78.53 mb



Event selection
- **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

Bold indicates main differences from neutron analysis relative to p-p collisions at 7 TeV

Raw energy spectra

Reconstructed energy spectra

Iterative Bayesian Unfolding

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)

Hadron contamination correction (mainly Λ^0 and K^0_L)

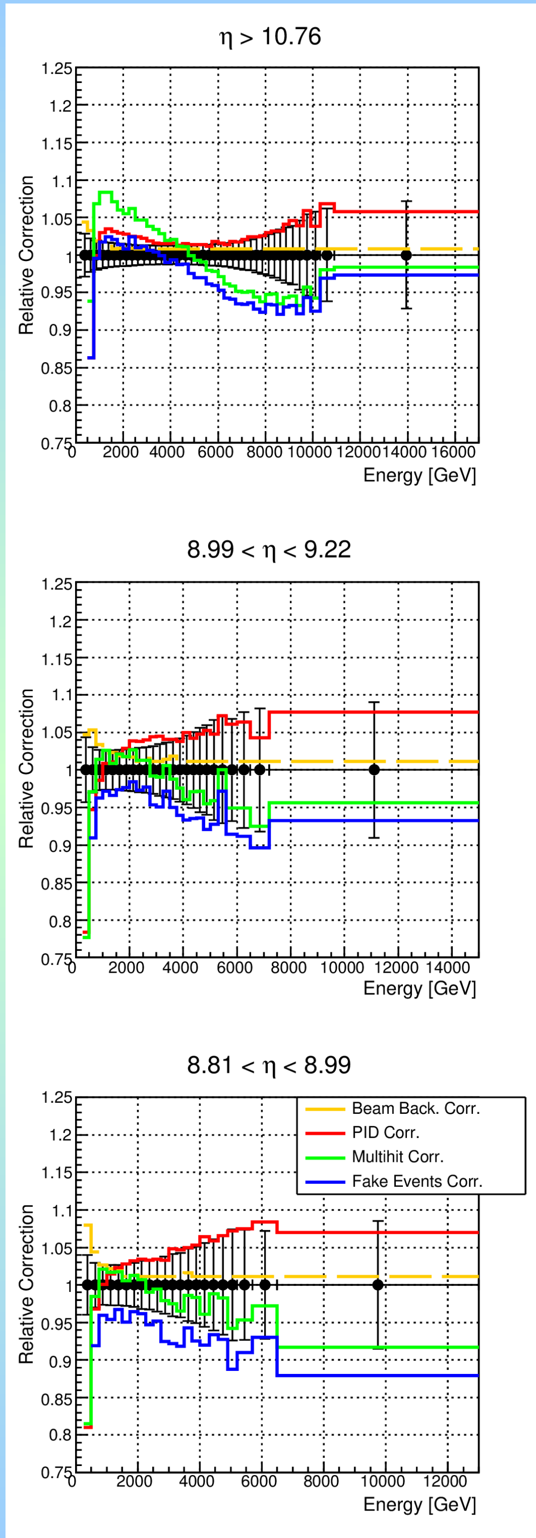
Missed events correction (mainly detection inefficiency)

$d\sigma_n/dE$

Found Mistake -> Erratum needed

Unfolded energy spectra

Correction Factors

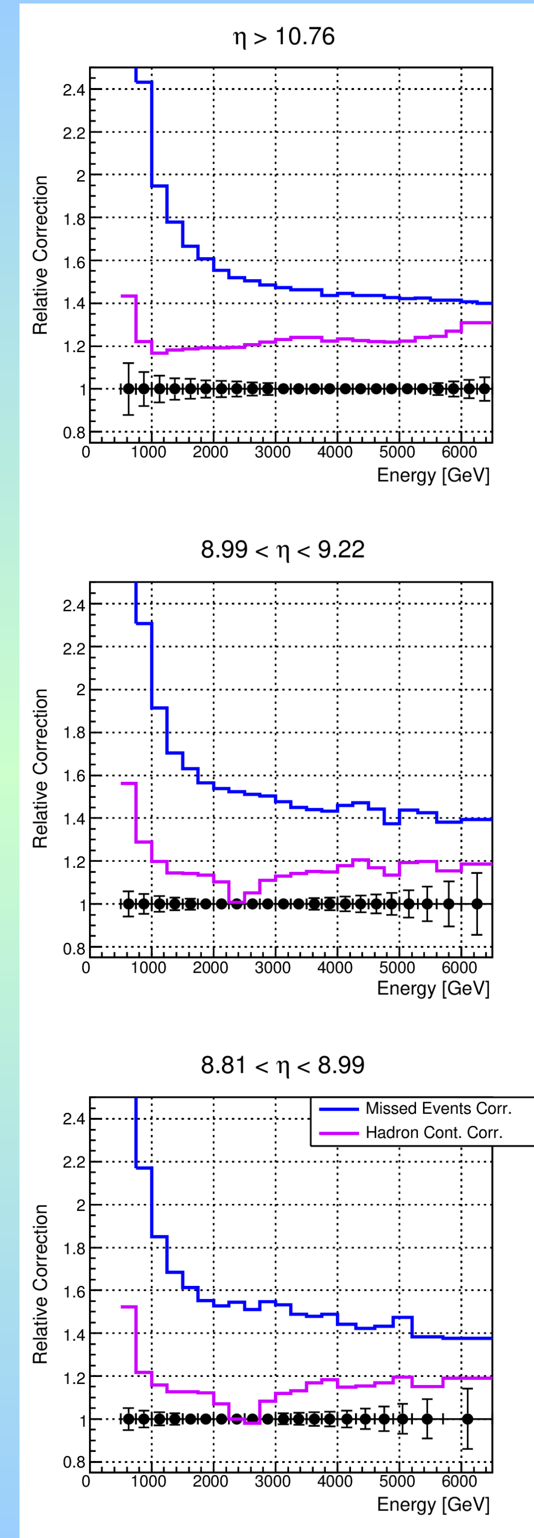


All correction factors have been determined using **QGSJet II-04** and **EPOS-LHC** generators and **full detector simulation**.

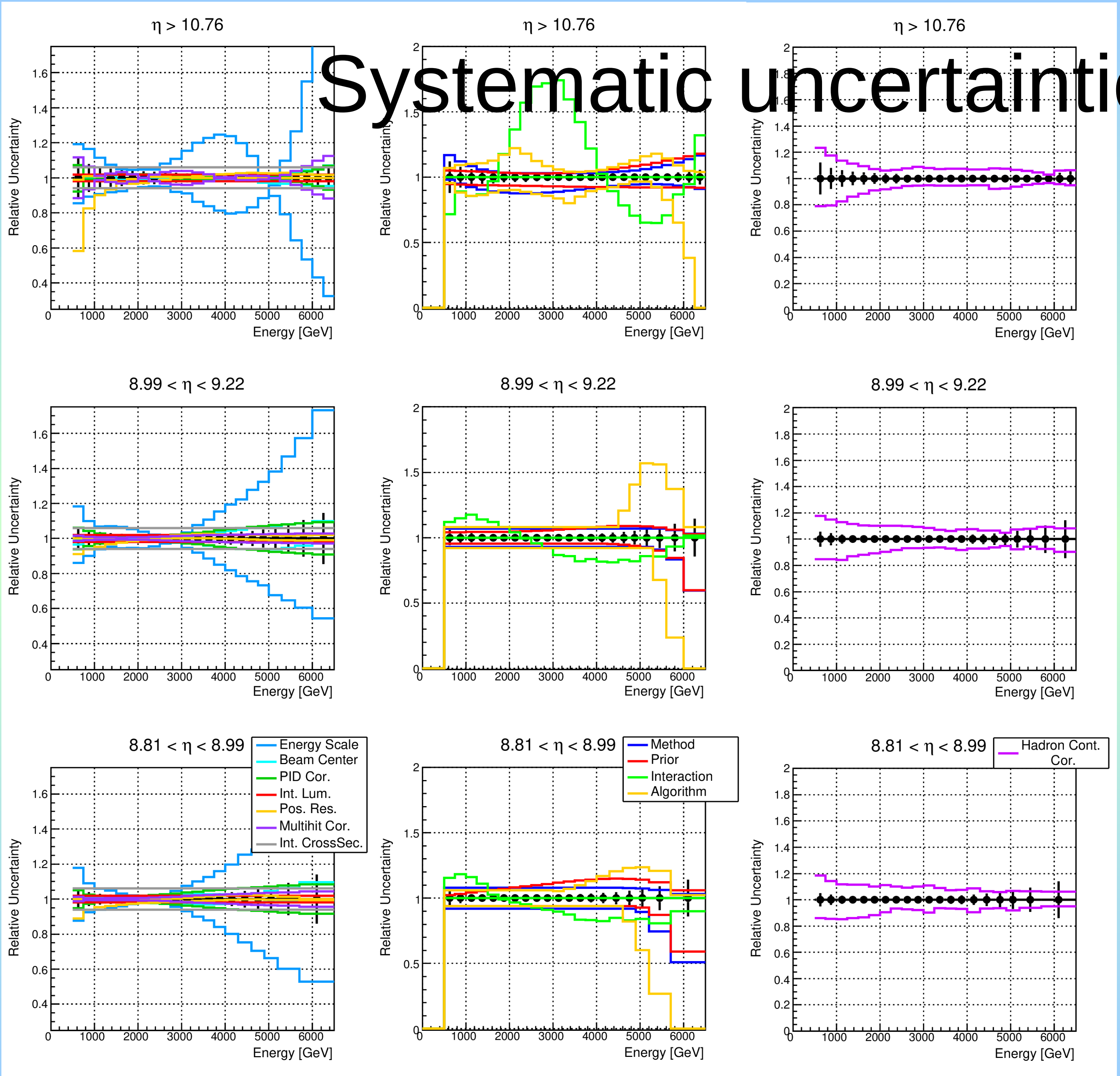
Multihit correction is the only generator-dependent correction. Multithit were considered both as a source of correction and uncertainty.

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

Hadron contamination correction remove neutrons that were not generated from collisions or from decay of short-life particles



Systematic uncertainties



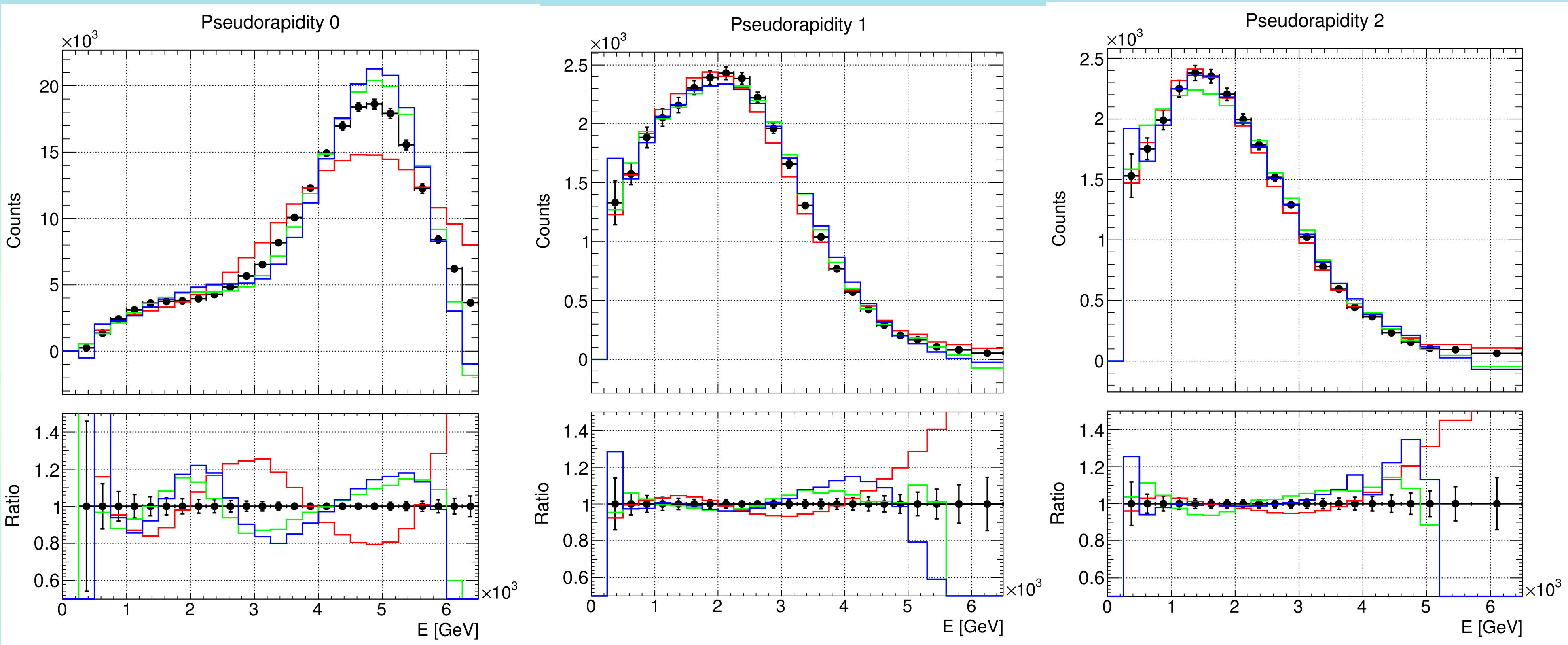
The dominant contribution is the **Energy systematic**

Unfolding process has significant systematics

Systematics due to **correction factors** (PID, Multihit, Hadron Contamination), **beam parameters** (Beam center, Luminosity) or **detector performances** (Position Resolution), are mostly below 5%

Key points of unfolding: Algorithm and Convergence

SVD
TUnfold
Bayes $\Delta\chi^2<1$
Bayes $\Delta\chi^2<10$



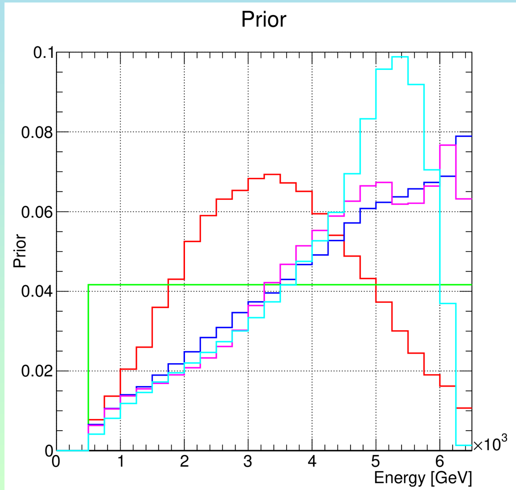
Bayesian unfolding converges very slowly in Region 0 because of spectral shape.

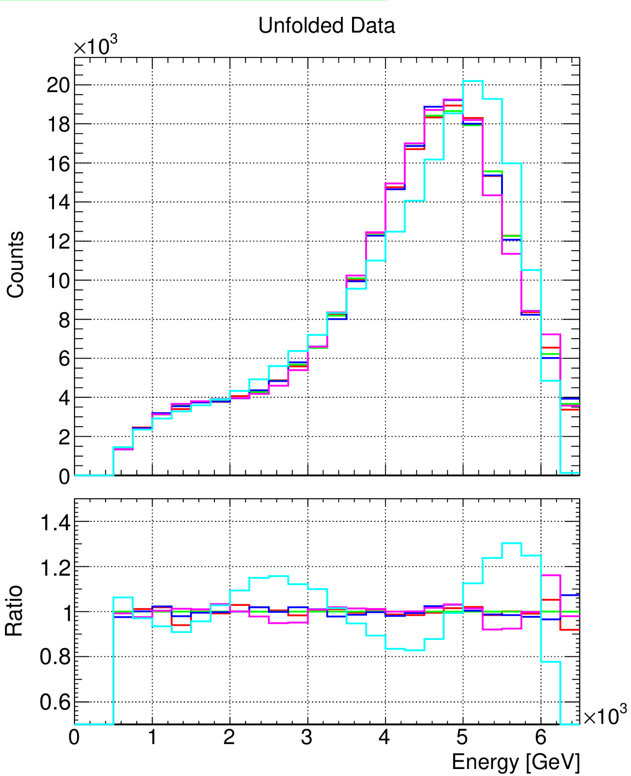
This high number of iterations is mandatory to avoid prior bias, so, assuming a **convergence criteria of $\Delta\chi^2<1$**, 51, 12 and 10 iterations are needed for Region 0, 1 and 2

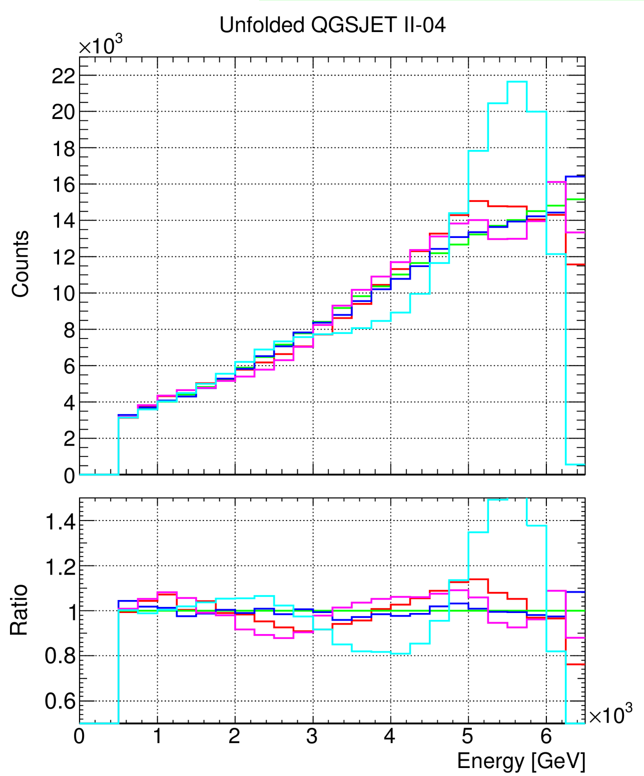
The **dependence on the algorithm** and related systematic uncertainty is below 20% if we consider **Bayesian unfolding with convergence criteria of $\Delta\chi^2<1$**

Key points of unfolding: Choice of the prior

- using Flat prior (green)
- using QGSJet II-04 prior (blue)
- using EPOS-LHC prior (magenta)
- using DPMJet 3.06 prior (red)
- using ISR-derived prior (cyan)







Bayesian unfolding gives a stable result and consistent with MC true if we use **convergence criteria as $\Delta\chi^2<1$**

We considered all priors from the **main models and ISR derived-prior** (derived from ISR measurements as PHENIX did)

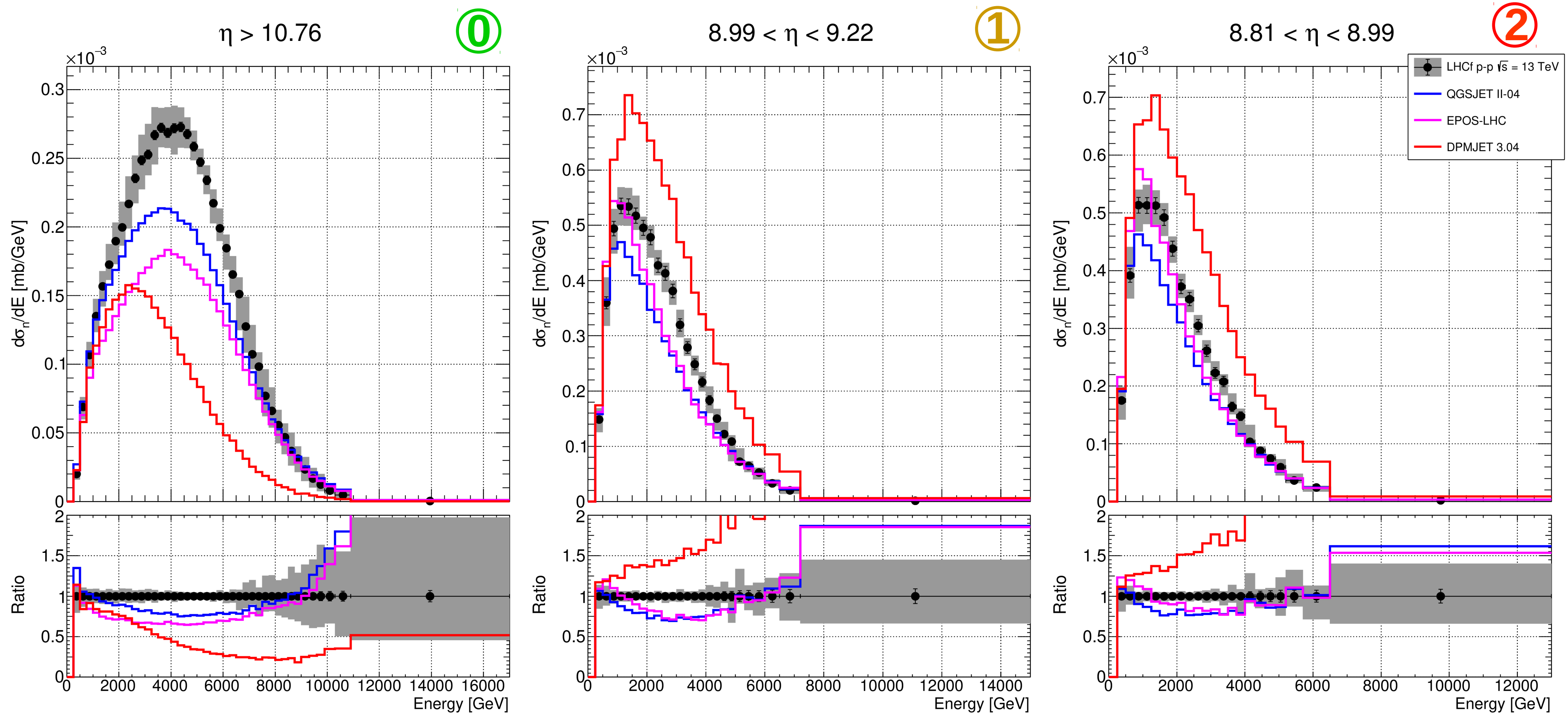
The **dependence on the prior** and the related systematic uncertainty is below 20%, except for ISR-derived one

Because of this reason we excluded this ISR-derived prior and **we can not conclude anything on Feynman scaling**

Reconstructed energy spectra

Differential production cross section

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

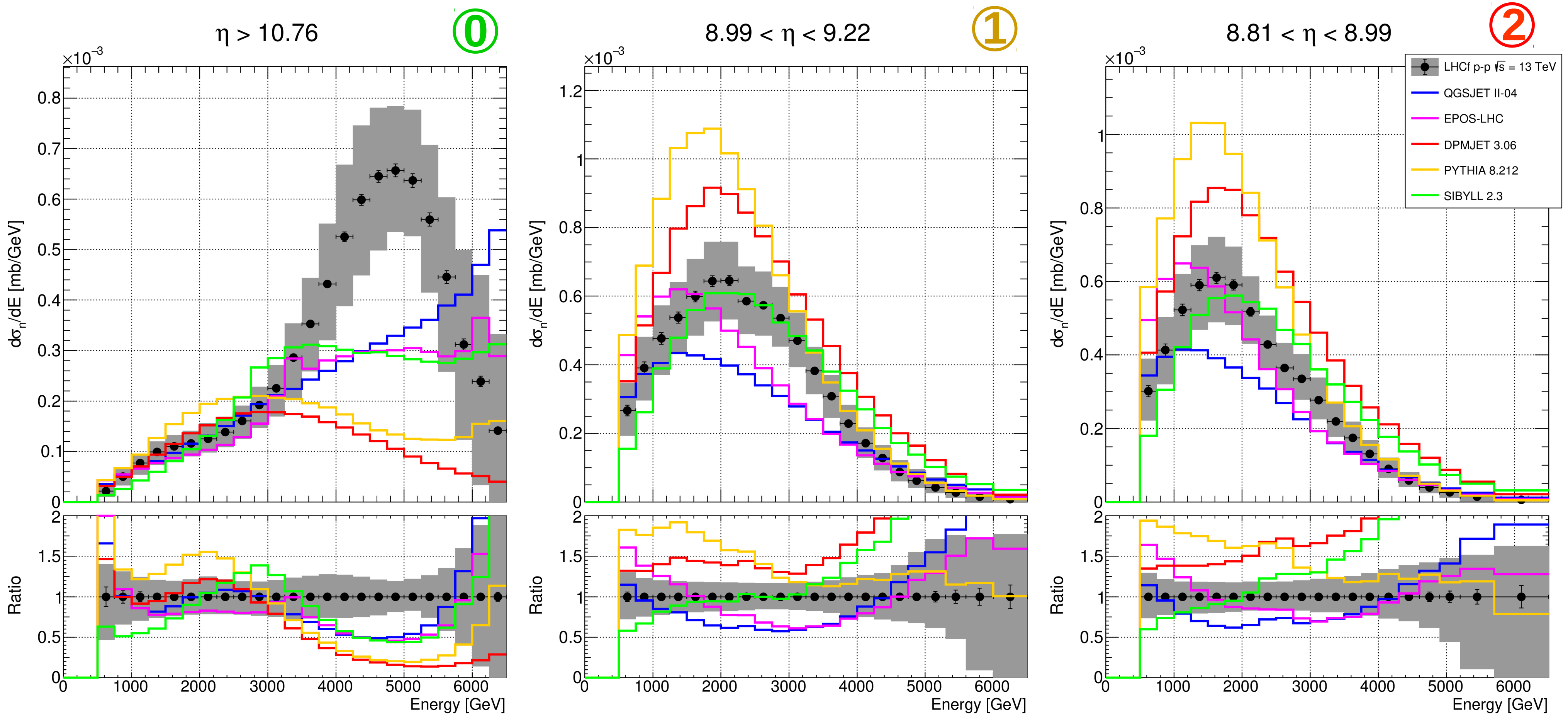


QGSJET II-04 and **EPOS-LHC** have similar shape but lower yield
DPMJET 3.04 have very different shape and yield

Unfolded energy spectra

Differential production cross section

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



Large discrepancy between data and model in Region 0
Nice agreement of **SIBYLL 2.3** and **EPOS-LHC** in Region 1 and 2

About mistake

In the 13 TeV neutron analysis, differently from the 7 TeV case, we decided to **apply a generator-based correction factor in order to measure the distributions of neutrons produced at the IP**, removing the effect of propagation through the beam pipe (particle decays and magnet bending).

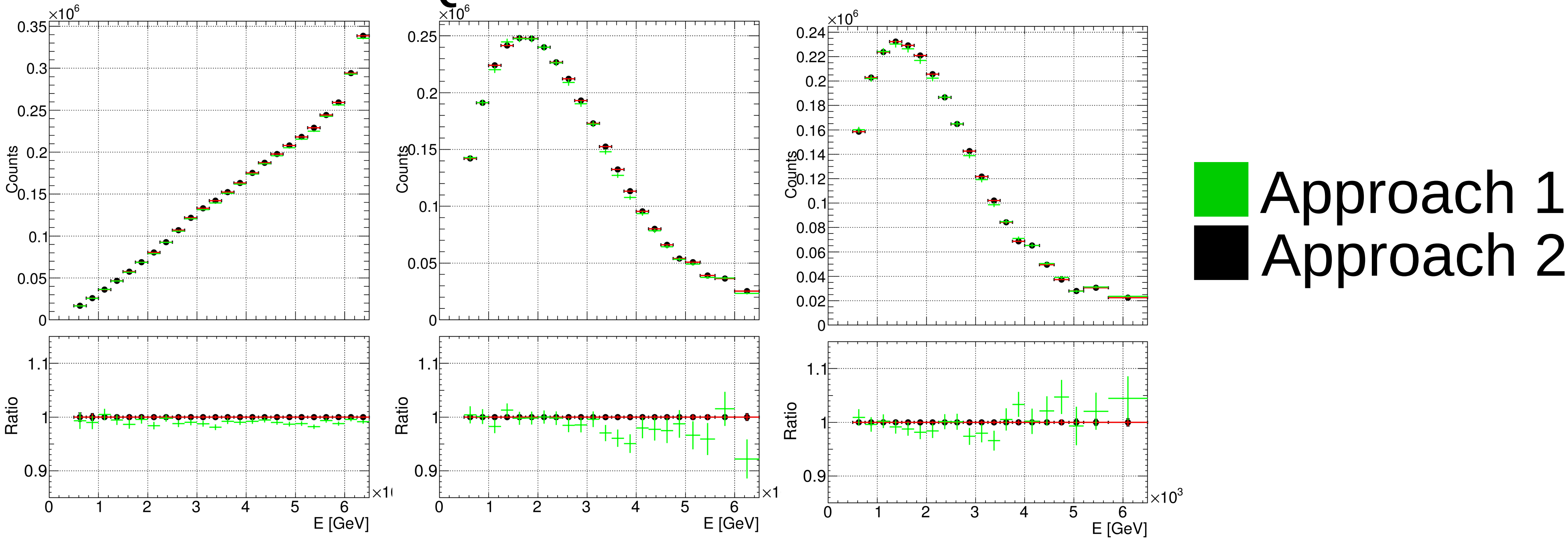
This choice was dictated by the idea to give an **easy-to-interpret result** to theorists for model development (and implementation in Rivet code).

However, because of **my mistake**, our final results (and the models with whom we compared them) include antineutrons as well, so I believe that it is important to **send Addendum** (or Erratum, we may discuss about) with the distributions relative to neutron production only.

Note that this affects not only out measurements (via the hadron contamination correction factors) but also the final comparison with data.

About MC for final comparison

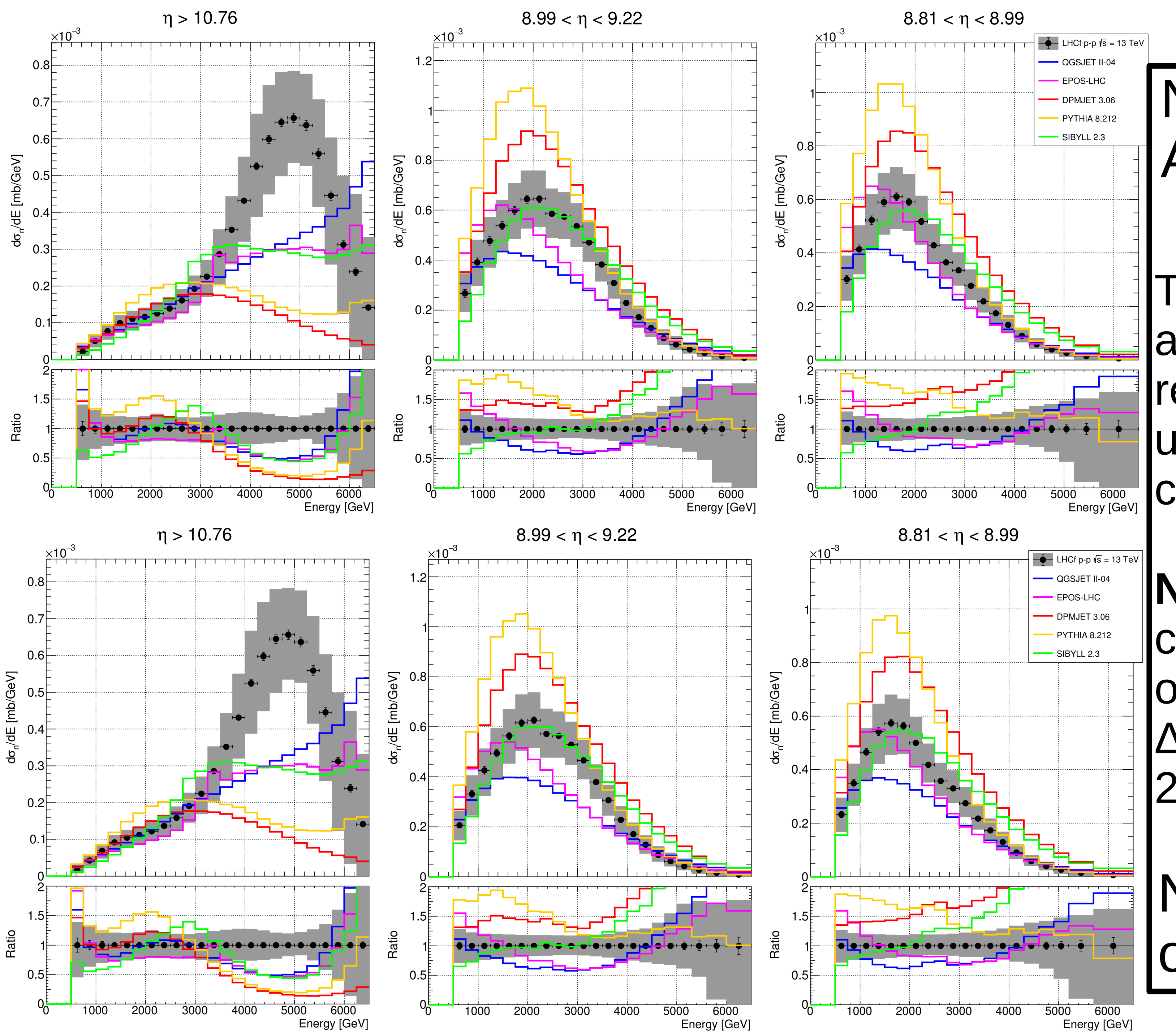
QGSJet II-04



For the final comparison of models with measurements:

- in the paper we followed **Approach 1**, i.e. we used Δφ=180° (ST) and 20° (LT) at IP rescaling for Δφ coverage, consistent with hadron contamination corrections, but with not negligible statistical uncertainty
- in the addendum, we may think about **Approach 2**, i.e. we use Δφ=360° including both positive (“Arm1”) and negative (“Arm2”) z direction, with negligible statistical uncertainty, but inconsistent approach respect to paper

Change in the final result



Neutrons+ Antineutrons

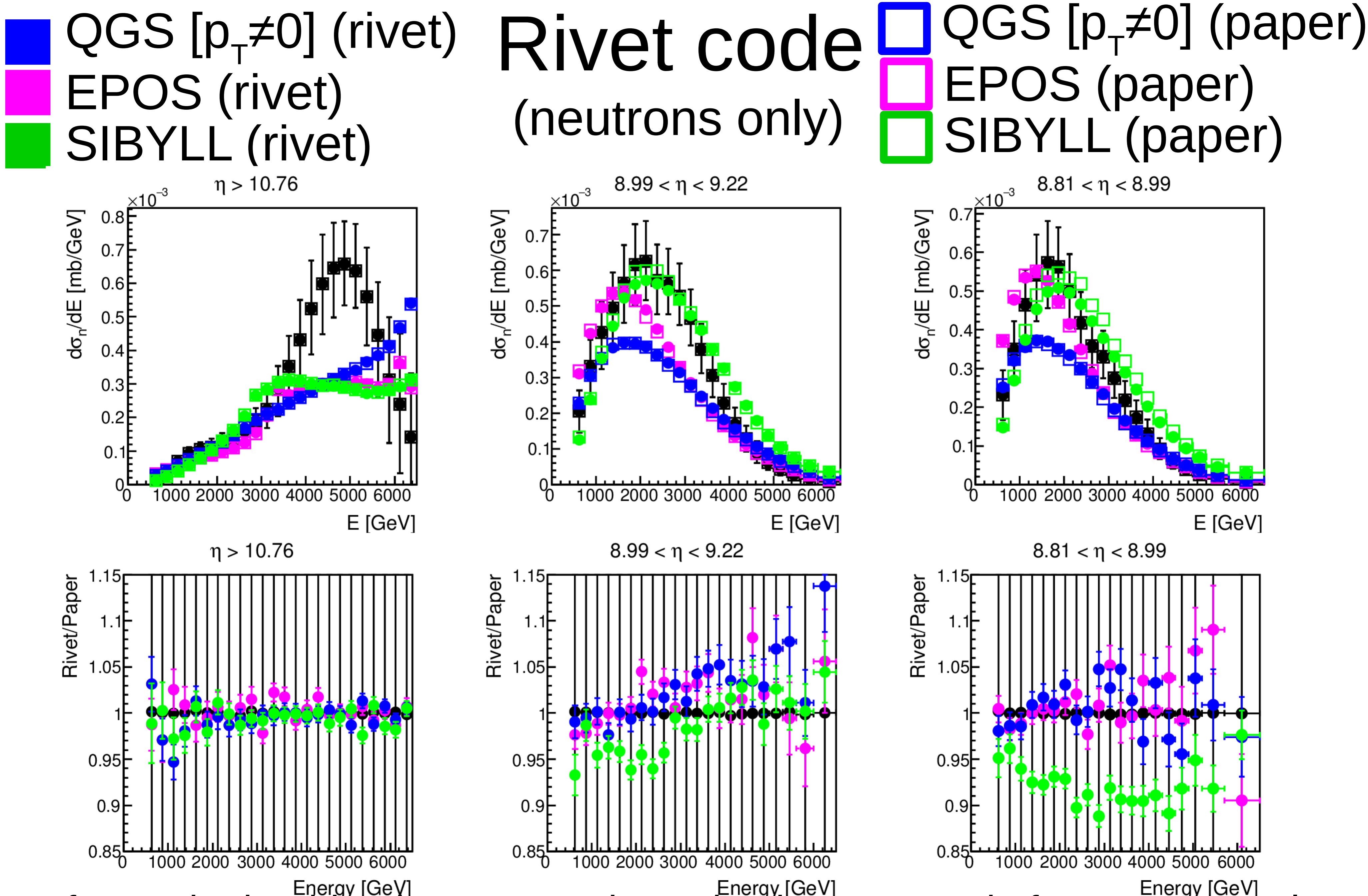
The change affects both our results and MC used for final comparison

NB: MC for final comparison were obtained using Δφ=180° (ST) and 20° (LT) at IP

Neutrons only

Rivet code

(neutrons only)



If we submit addendum we need to write the RIvet code for neutrons only

Future plans

LHCf/ATLAS

Use Arm2 results in Region 0, 1 and 2 with ATLAS central veto to separately measure diffractive and non-diffractive forward neutron production

Menjo, Ohashi, Eugenio?

Menjo-san's talk

LHCf alone

Repeat Arm2 analysis with Arm1 detector in Region 0, 1 and 2 and eventually extend pseudorapidity coverage to other areas

Eugenio?

Next slides

Extension of Arm2 analysis to Arm1

In my feeling, the bottleneck is to complete the calibration of the Arm1 detector

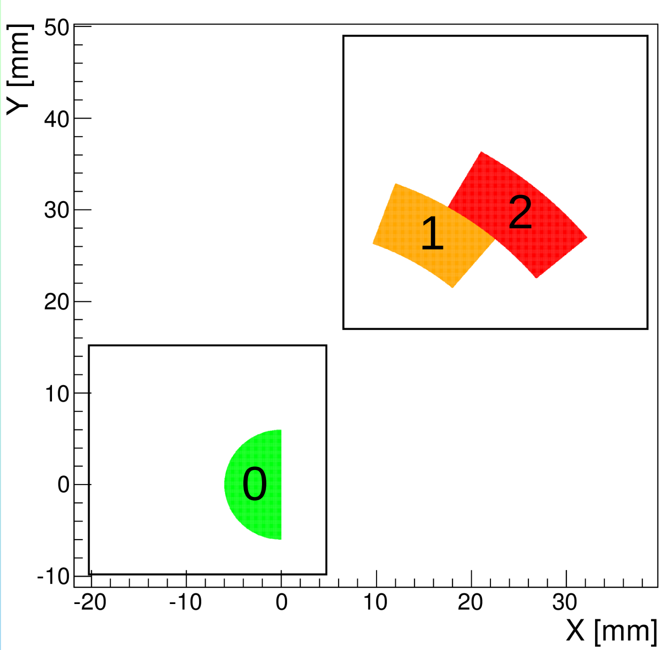
- ✔ Compute sumdE to E conversion factors (Ueno)
- ✔ Evaluate position dependent correction factors (Zhou)
- ✔ Calibrate the gains of the last GSO layers (Eugenio)
- ◆ Check detector performance using simulation (Zhou)
- ✗ Compare sumdE distributions between MC and data (Eugenio?)
- ✗ Calibrate the last two x-y GSO bars layers (Eugenio?)
- ✗ Optimize the vertex reconstruction method (Eugenio?)
- ✗ Implement everything in new software (Alessio?)

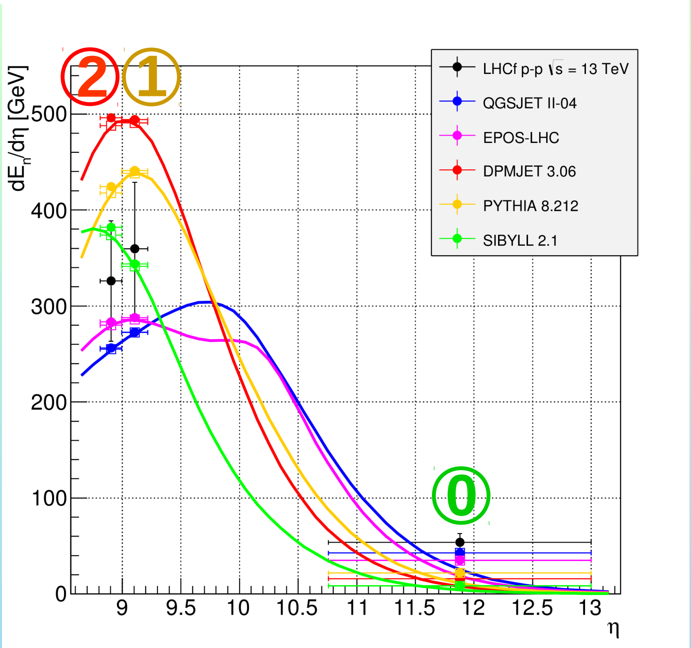
The calibration of the last two x-y **GSO bars layers** and the optimization of the **vertex reconstruction method** are the most time-consuming tasks.
Even if I have no experience in GSO-bars, I can work on these two tasks if someone from Japanese side can explain me how to do.

The implementation of everything in the **new software** is mandatory, because currently we can not use “Italian” old software with upgraded detector.
In principle we can change that software, but it doesn't worth considering that we are going to replace it with the new one.

Why to extend pseudorapidity coverage?

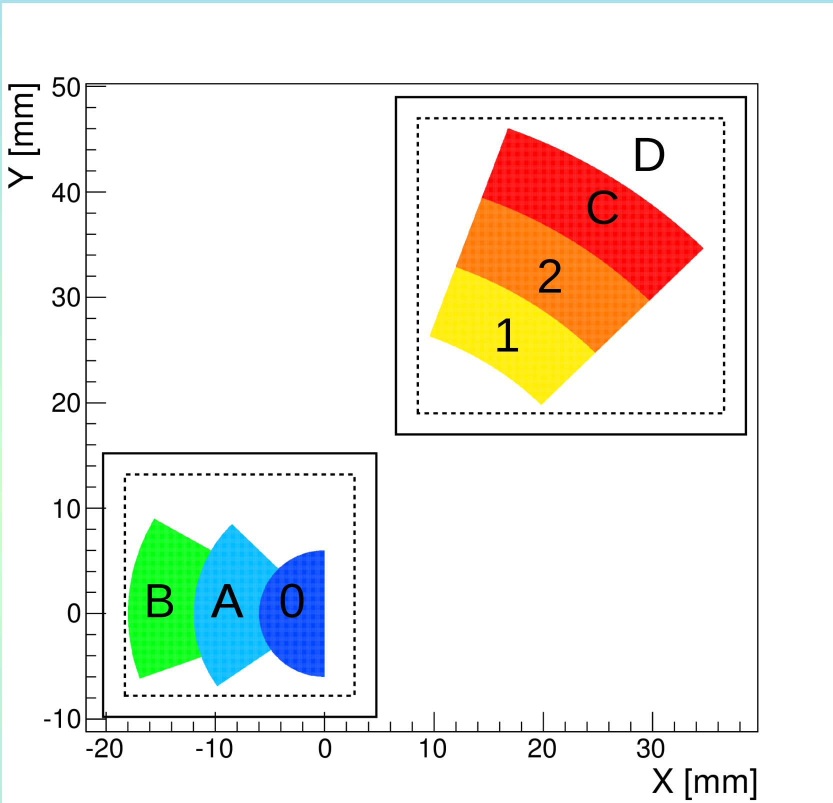
	Rapidity 0		Rapidity 1		Rapidity 2	
η	∞	10.76	9.22	8.99	8.99	8.81
r (mm)	0	6	28	35	35	42
θ (μrad)	0	42	198	249	249	298
φ (°)	90	180	50	70	40	60

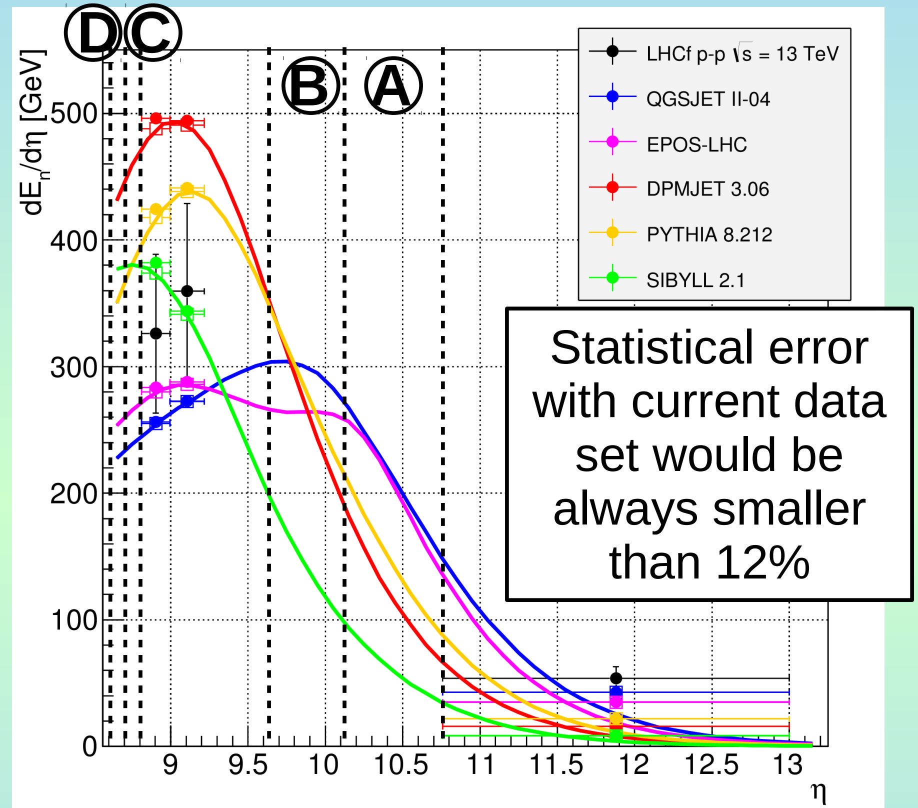




With the current measurement we sampled the two regions 1 and 2 where the energy flow is significant, but we are not sure to what happens between region 0 and 1

What if we add four more regions?





	Rapidity A		Rapidity B		Rapidity C		Rapidity D	
η	10.76	10.07	10.07	9.66	8.81	8.66	8.66	8.52
r (mm)	6	12	12	18	42	49	49	56
θ (μrad)	42	80	85	128	298	347	347	397
φ (°)	135	215	150	200	45	70	45	70

Arm2

Arm1

Summary

The measurement of inclusive differential neutron production cross section in p-p collisions at 13 TeV was carried on using the Arm2 detector only in $\eta > 10.76$, $8.99 < \eta < 9.22$ and $8.81 < \eta < 8.99$.
After **publication on JHEP journal**, I found my mistake in the definition of neutrons (antineutrons were included as well) and I would like to go for **submission of erratum** to avoid confusion between model developers.

There are two important **next steps** that can be carried on at the same time:

- **study diffractive and non-diffractive production using LHCf/ATLAS analysis**
- **repeat the analysis for Arm1 and extend the pseudorapidity coverage**

Focusing on including Arm1 and enlarging coverage:

- it requires to complete the calibration of Arm1 for hadronic showers
- it involves regions that are really relevant for neutron production
- **it definitely worths** considering that, after long efforts, we now have a quite well established analysis and that this analysis can exploit the most of the potential of our data, providing a very detailed information about forward neutron production at the highest energy available

Back Up

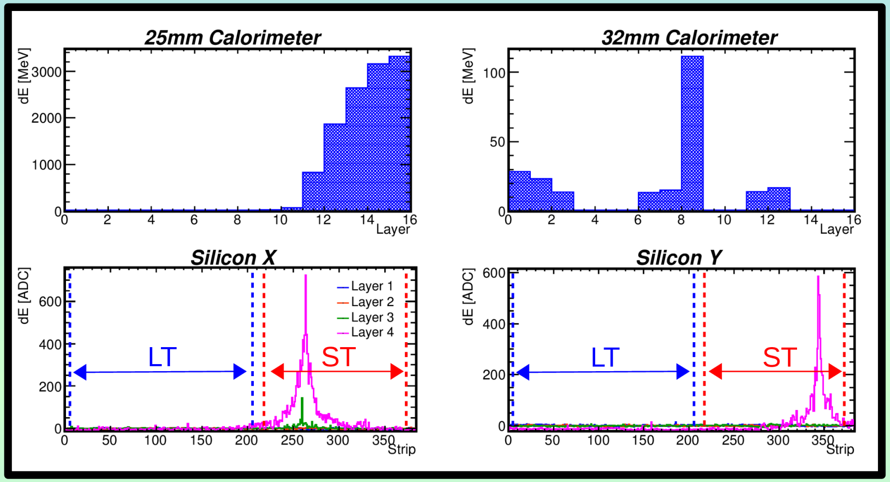
Event reconstruction

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*

Spectra unfolding

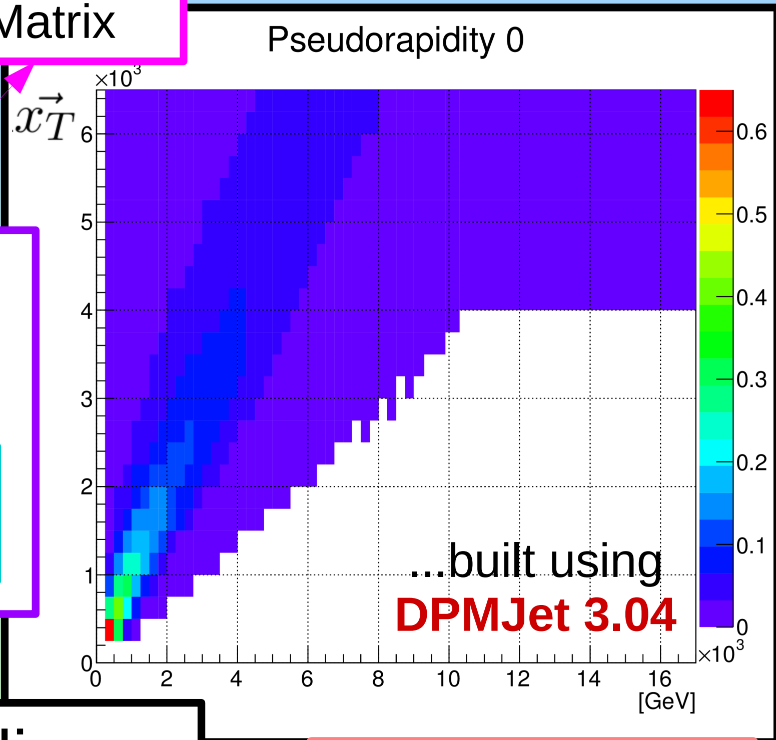
The limited energy resolution strongly affect the measured spectra.
It is necessary to unfold the reconstructed spectra using detector response.

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

Reconstructed spectra

True spectra

Response Matrix



Iterative Bayesian Unfolding

Input prior

Prior $P(T_i)$

Bayes theorem

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

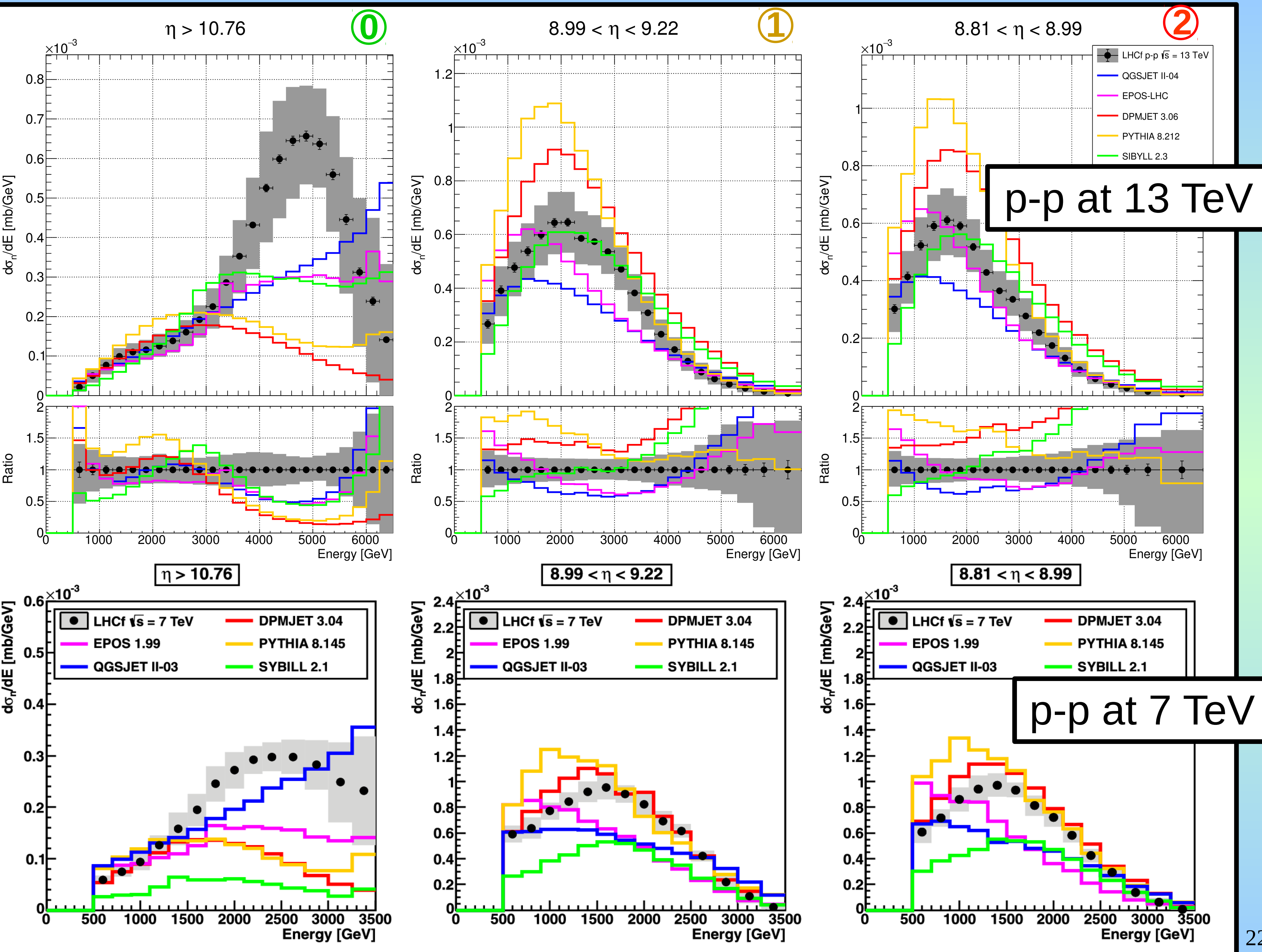
wit
h $\lambda_{ji} \equiv P(D_j|T_i)$
from MC

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

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


η > 10.76
8.99 < η < 9.22
8.81 < η < 8.99
LHCf p-p √s = 13 TeV
QGSJET II-04
EPOS-LHC
DPMJET 3.06
PYTHIA 8.212
SIBYLL 2.3
p-p at 13 TeV
dσn/dE [mb/GeV]
Ratio
Energy [GeV]
LHCf √s = 7 TeV
DPMJET 3.04
EPOS 1.99
PYTHIA 8.145
QGSJET II-03
SYBILL 2.1
p-p at 7 TeV

ISR extrapolation

PHENIX paper

A. Adare, et al., Phys. Rev. D, 88, 032006 (2013).

Invariant cross sections measured at the ISR experiment were converted to differential cross sections for the comparison with the PHENIX data. The conversion formula from the invariant cross section $Ed^3\sigma/dp^3$ to $d\sigma/dx_F$ is described with the approximation in the forward kinematics as

$$\frac{d\sigma}{dx_F} = \frac{2\pi}{x_F}\int_{Acc.} E\frac{d^3\sigma}{d^3p}p_T dp_T, \quad (8)$$

where $Acc.$ means the p_T range of the PHENIX acceptance cut; $0 < p_T < 0.11x_F$ GeV/c for the $r < 2$ cm cut. As a p_T shape, we used an exponential form $\exp(-4.8p_T)$ which was obtained from the $0.3 < x_F < 0.7$ region from the ISR results [2, 3].

ISR paper

J. Engler et al., Nucl. Phys. B 84, 70 (1975).

tum. One observes an exponential decrease with the same slope in both cases. If, for $0.2 \leqslant p_\perp \leqslant 1.0$ GeV/c a parametrization

$$E\frac{d^3\sigma}{dp^3} = a\,e^{-bp_\perp}$$

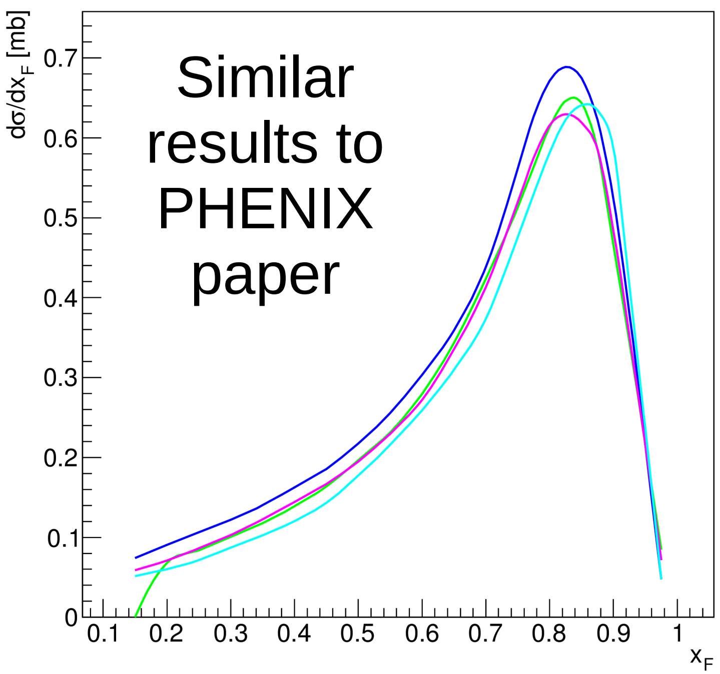
is chosen, the parameter $b = (4.8 \pm 0.3)$ GeV/c^{-1} is found to be independent of s and x in the range $0.2 \leqslant x \leqslant 0.7$ within the errors. For inclusive proton spectra

ISR paper

W. Flauger and F. Monnig, Nucl. Phys. B 109, 347 (1976).

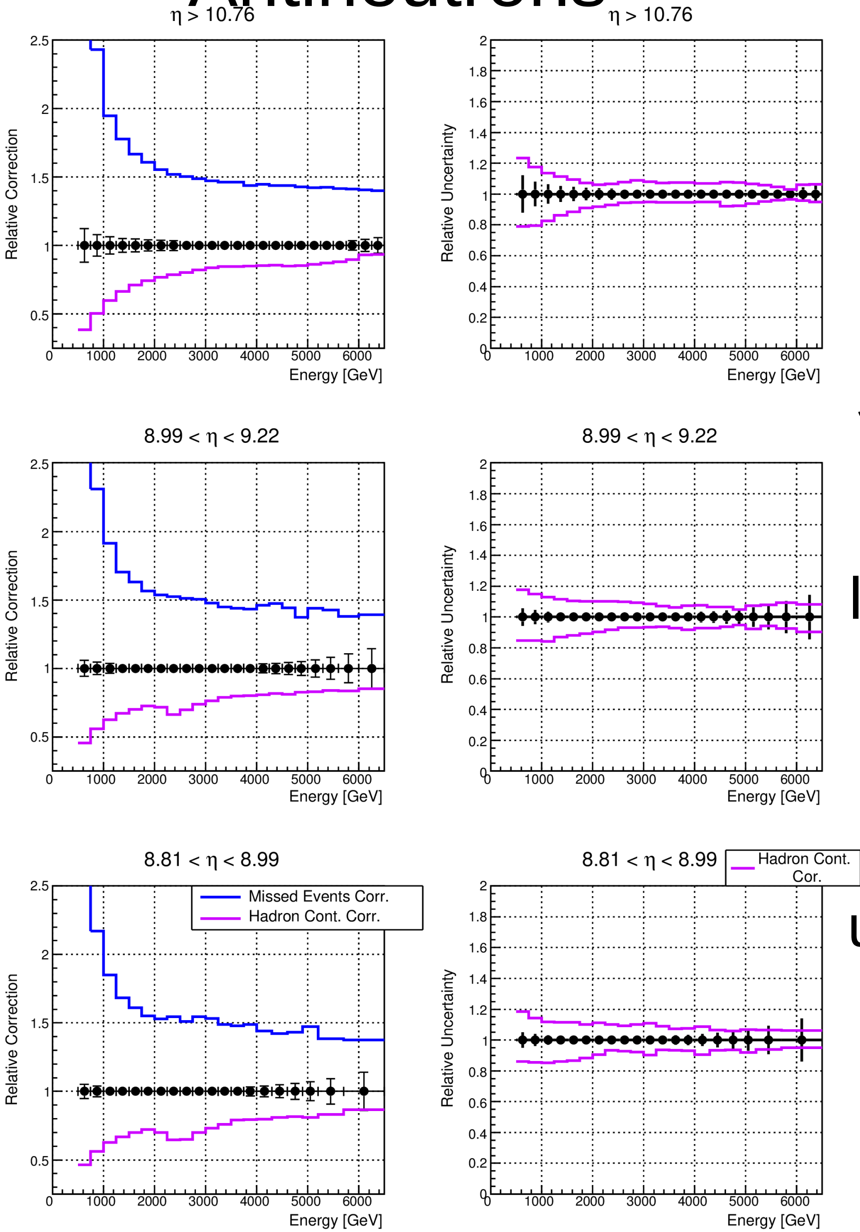
Invariant cross-sections for pp → nx at 0° production angle

x	E $d^3\sigma/dp^3$ [mb/(GeV^2/c^3)]			
	$\sqrt{s}$ = 30.6 GeV	$\sqrt{s}$ = 44.9 GeV	$\sqrt{s}$ = 52.8 GeV	$\sqrt{s}$ = 62.7 GeV
0.15		13.7 ± 1.5	10.9 ± 1.4	9.5 ± 1.2
0.2	9.6 ± 1.6	12.8 ± 1.4	10.0 ± 1.3	8.5 ± 1.1
0.25	9.6 ± 1.4	12.2 ± 1.3	9.9 ± 1.2	8.2 ± 1.0



Change in Hadron Contamination

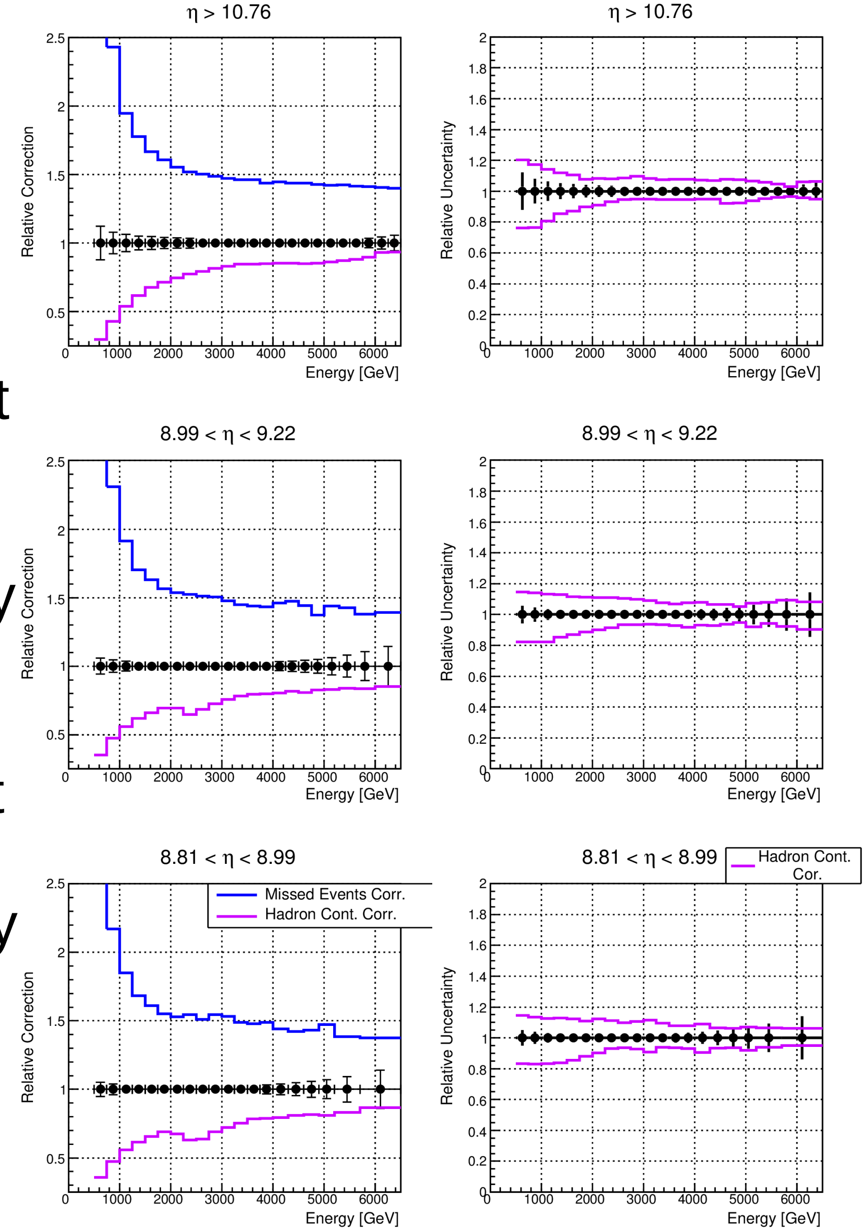
Neutrons
+
Antineutrons



Significant change in factors at low energy

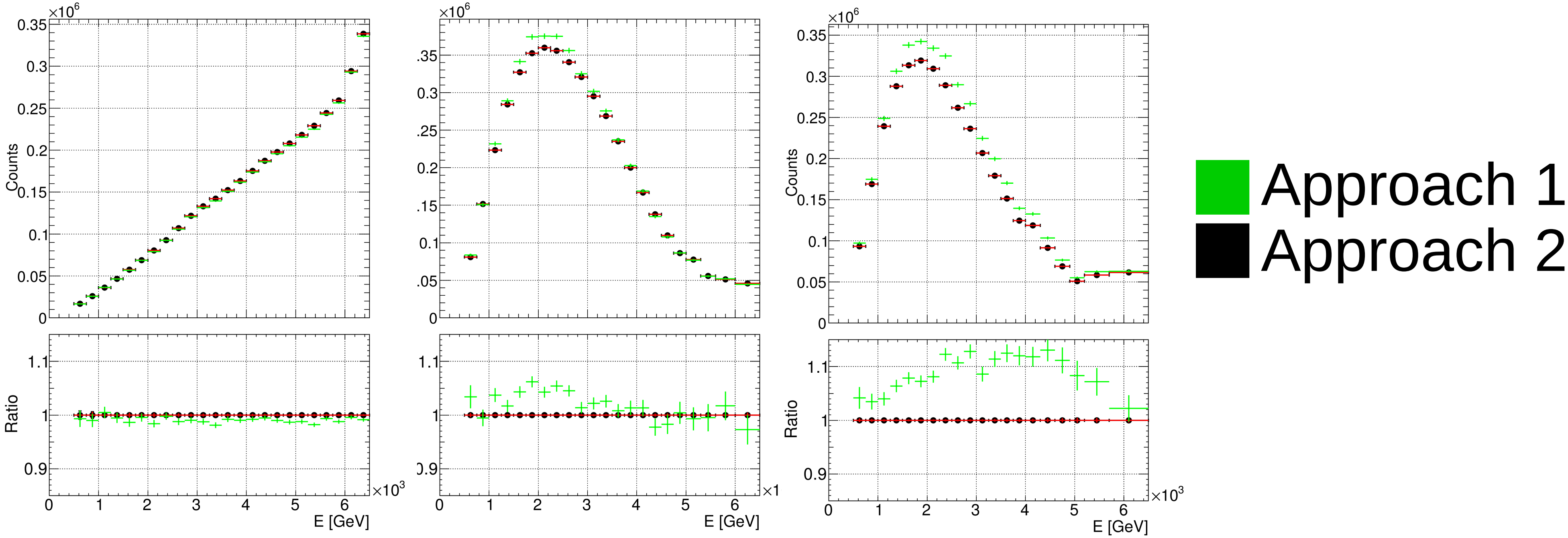
No significant change in uncertainty

Neutrons only



About MC for final comparison

SIBYLL 2.3



Approach 2 is particularly convenient when considering SIBYLL 2.3, because of its Δφ asymmetry, but take into account that, when used to estimate hadron contamination correction factors, SIBYLL 2.3 still exhibits this problem...

NB: In the implementation of the Rivet code we will likely follow Approach 2 because otherwise a lot of statistics is required, but I anyway prefer to keep Approach 1 in the addendum for consistency with the one used in the paper

Arm2 distributions in extended pseudorapidity regions