Very forward neutral particles production measured by the LHCf experiment

Alessio Tiberio
University of Florence and INFN
on behalf of the LHCf Collaboration

LHC Working Group on Forward Physics and Diffraction

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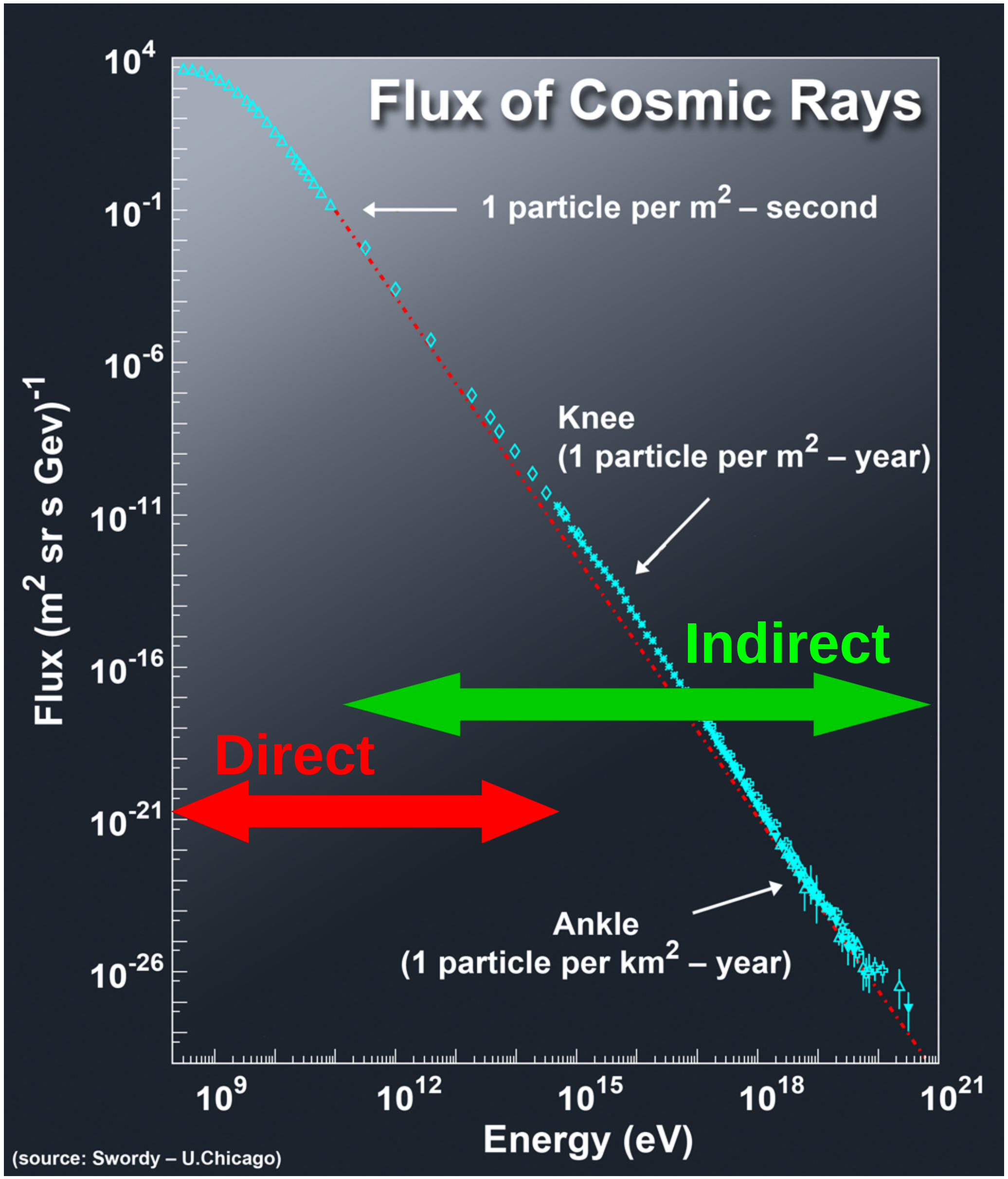
Outline

- Physics motivations
- The LHCf experiment
- Physics results
  - photons in p-p collisions at 13 TeV
  - photons in p-Pb collisions at 8.16 TeV
  - neutrons in p-p collisions at 13 TeV
- Ongoing activities

Physics motivations

Cosmic rays: spectrum

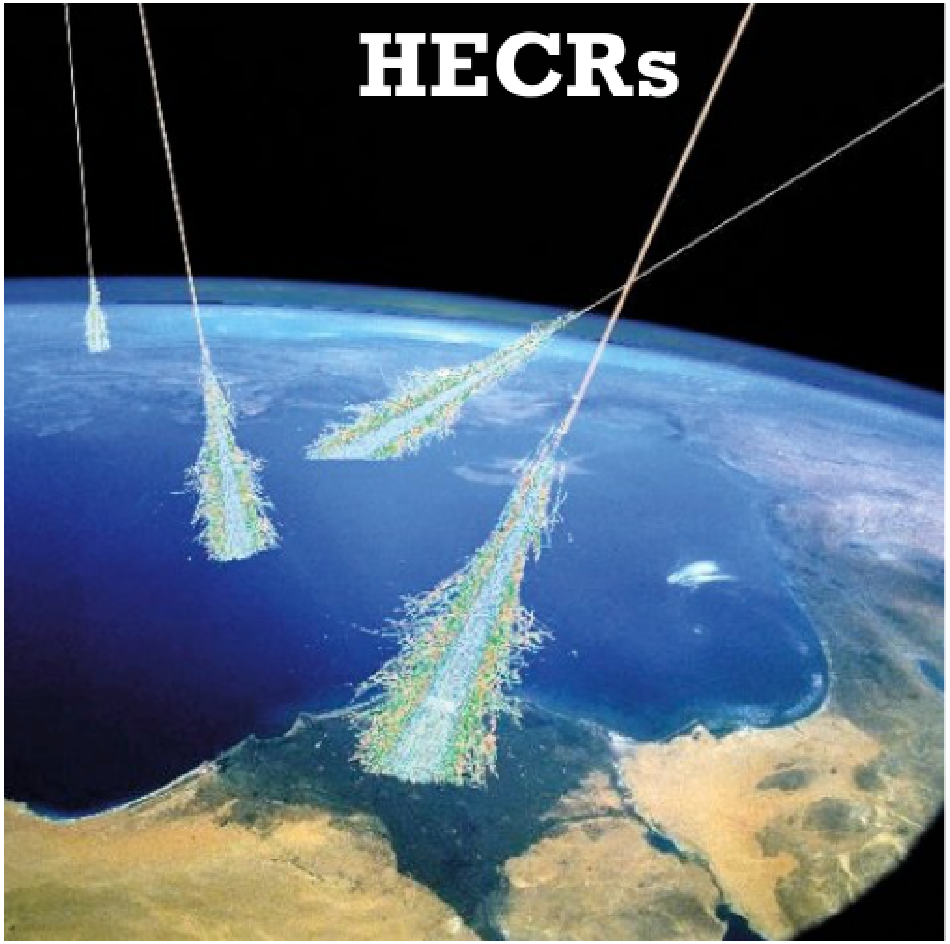


Credit: ASPERA/G.Toma/A.Saftoiu

- Cosmic rays spectrum falls as a power law: $F(E) \sim E^{-\alpha}$
  - $\alpha \sim 2.7$ ($E < 10^{16}$)
  - $\alpha \sim 3$ ($10^{16} < E < 10^{18.5}$)
  - $\alpha \sim 2.7$ ($E > 10^{18.5}$)
- **Direct measurements** limited by low flux of particles at high energies
- Above ~10^2 GeV **indirect measurements** (with ground based experiments) become possible

Only **indirect measurements** are possible above ~10^{14}-10^{15} eV

Cosmic rays: indirect measurements



Air showers measurements:

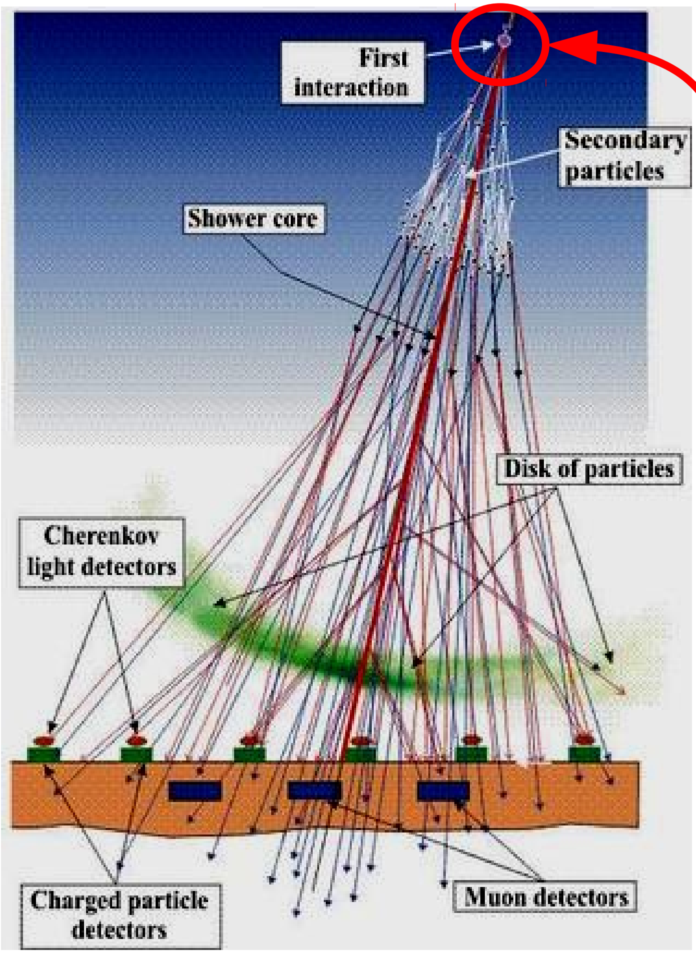
- Longitudinal distribution
- N° of particles at ground
- Arrival direction

Astrophysical parameters:

- Spectrum
- Composition
- Sources distribution

Monte Carlo simulations of air showers with accurate hadronic interaction models are very important

Contribution from accelerator experiments



$\sqrt{s}$ = 13 TeV → $E_{CR} = 9 \cdot 10^{16}$ eV

First interaction

- **Inelastic cross section**
- **Multiplicity**
- **Inelasticity $k = 1 - p_{lead} / p_{beam}$**
- **Forward energy spectrum**

} **LHCf: neutrons photons π^0**

- **Nuclear effects** → **p-Pb collisions**

- Soft interactions dominate (non perturbative QCD)
- Several phenomenological models based on Gribov-Regge theory are proposed

→ **Inputs from experimental data are fundamental**

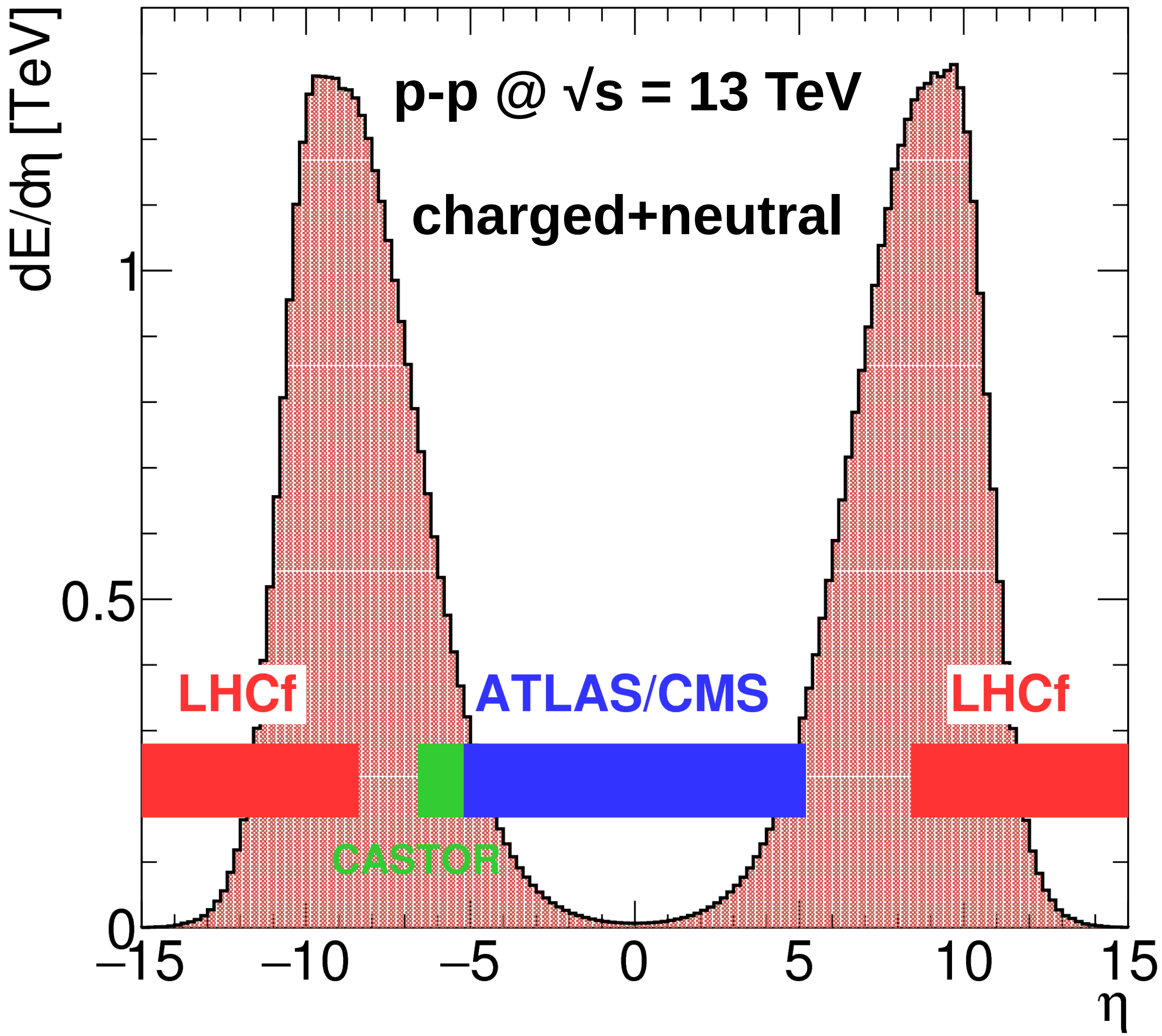
Why forward region?

The peak of energy flow is around η ~ 9 (θ ~ 0.25 mrad)

LHCf acceptance covers the energy peak

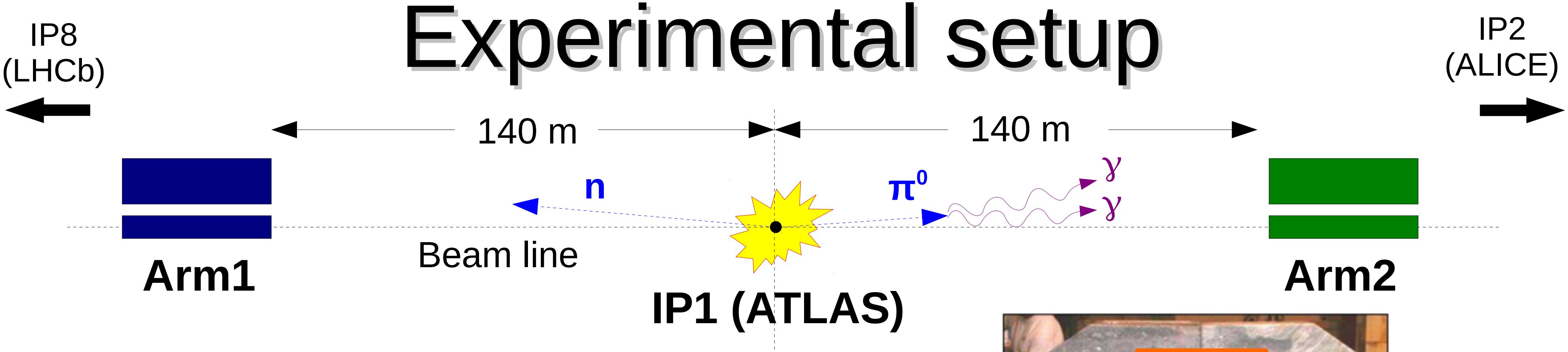
Pseudo-rapidity

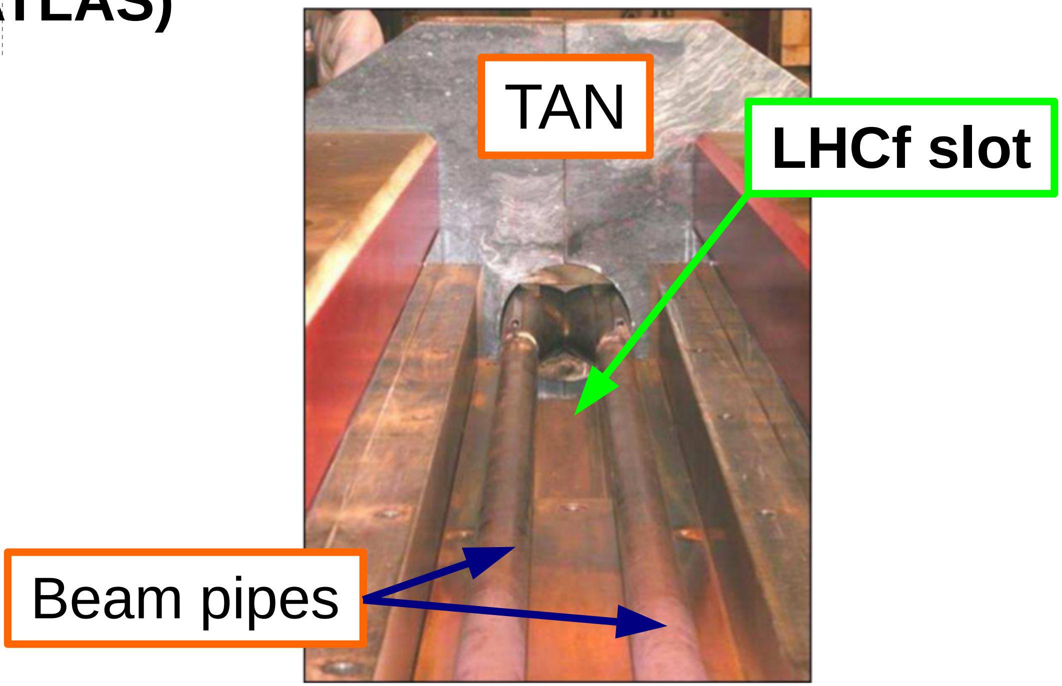
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



The LHCf experiment

Experimental setup





LHCf is located in TAN slot

Zero degree particles!
Coverage: **η > 8.4** (with 140 urad crossing angle)

Charged particles are deflected by D1 dipole magnet

Only neutral particles (**photons** and **neutrons**) are detected

Detectors performance

- Two sampling and position sensitive calorimeters
- Tungsten + **GSO scintillators**
- Depth: 44 X_0, 1.6 λ
- Energy resolution:
  - < 3% (photons, E > 200 GeV)
  - ~ 40% (neutrons)

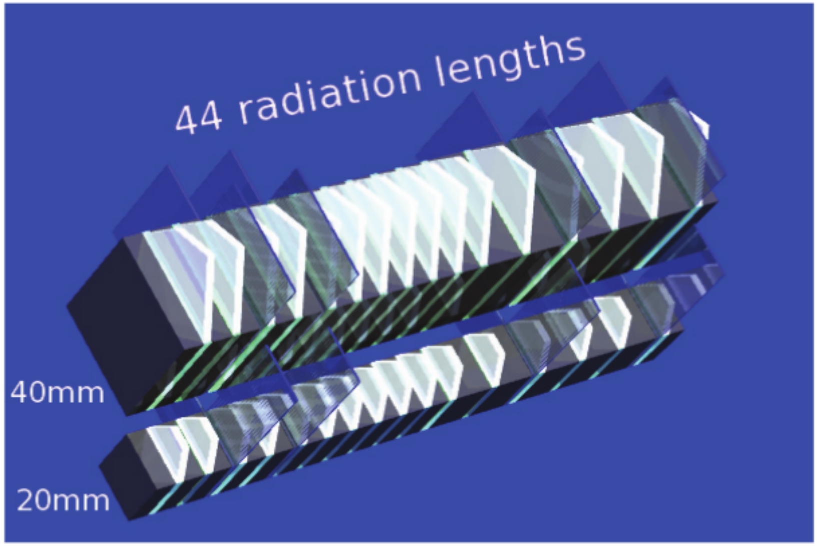
Arm 1

- Transverse size: 20 x 20 mm^2 and 40 x 40 mm^2
- 4 x-y **GSO bars** tracking layers
- Position resolution: < 200 μm

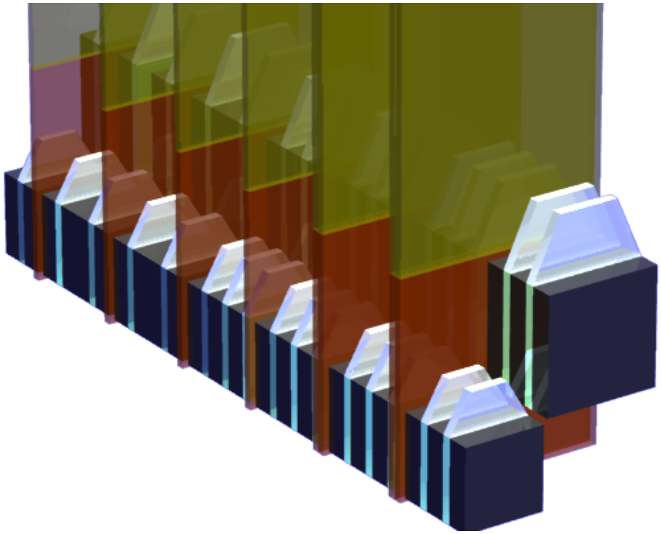
Arm 2

- Transverse size: 25 x 25 mm^2 and 32 x 32 mm^2
- 4 x-y **silicons microstrip** tracking layers
- Position resolution: 40 μm

Arm 1



Arm 2



Operations history at LHC

- December 2009 - July 2010
  - **p-p** collisions at $\sqrt{s}$ = **900 GeV**
  - **p-p** collisions at $\sqrt{s}$ = **7 TeV**
- January - February 2013 (only Arm 2)
  - **p-Pb** collisions at $\sqrt{s_{NN}}$ = **5.02 TeV**
  - **p-p** collisions at $\sqrt{s}$ = **2.76 TeV**
- June 2015
  - **p-p** collisions at $\sqrt{s}$ = **13 TeV**
- November 2016 (only Arm2)
  - **p-Pb** collisions at $\sqrt{s_{NN}}$ = **8.16 TeV**

Physics results: photons

LHCf p-p run at 13 TeV

- Low luminosity dedicated run for LHCf: 9th – 13th of June 2015

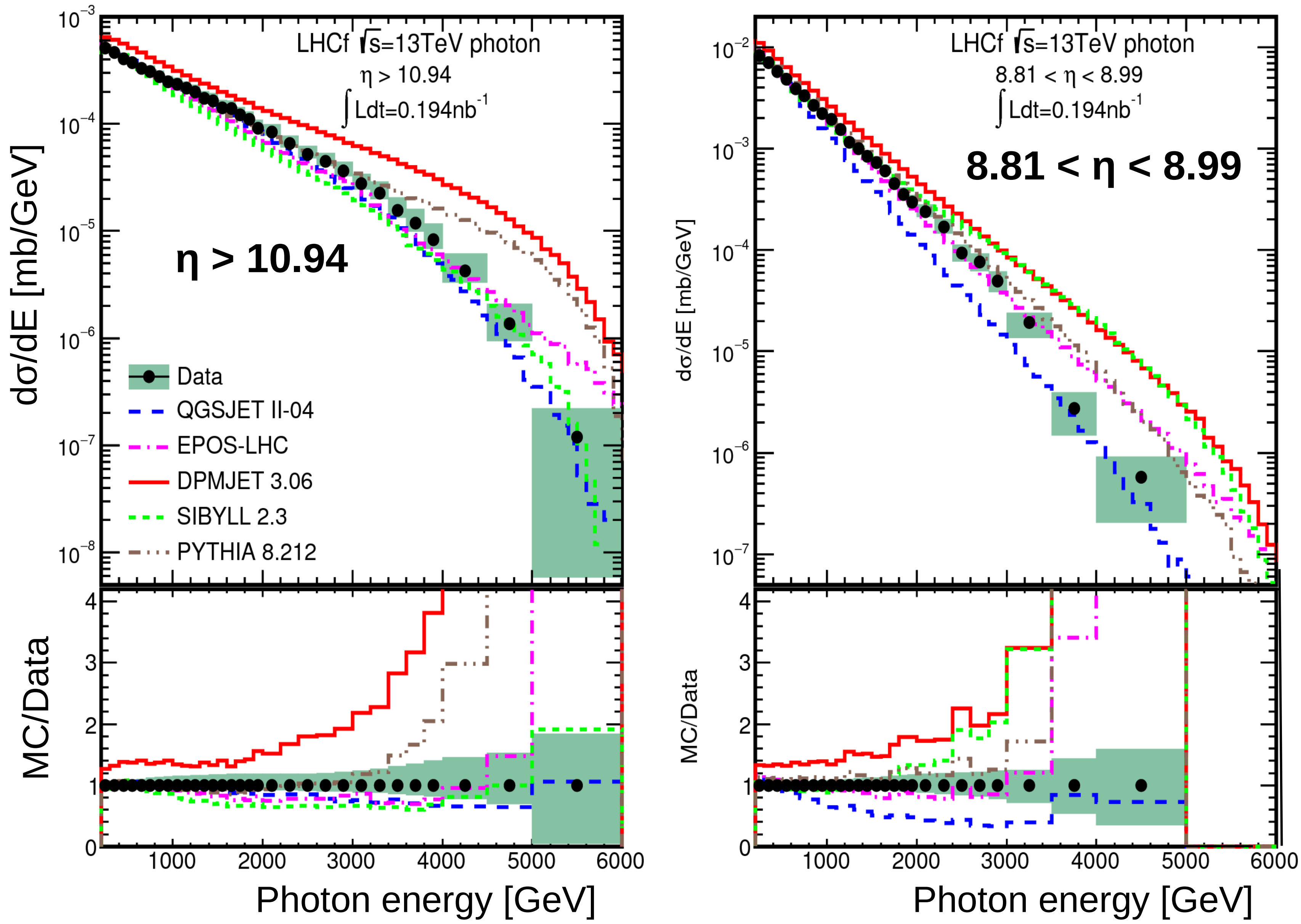
LHCf run:

- **$\sqrt{s}$ = 13 TeV**
- ~ 27 hours of operation
- **Luminosity:** 0.3 - 1.6 · 10^{29} cm^{-2} s^{-1}
- **Pile-up:** 0.01 - 0.03
- 4 · 10^{7} **events**
  5 · 10^{5} **π^0s**
- Trigger exchange with **ATLAS**

Analysis data set:

- ~ 3 hours of operation
- **Luminosity:** 0.3 - 0.5 · 10^{29} cm^{-2} s^{-1}
- **Pile-up:** 0.007-0.012
- **Integrated luminosity:** 0.194 nb^{-1}
- 4 · 10^{6} **events**

Photon spectrum in p-p at 13 TeV

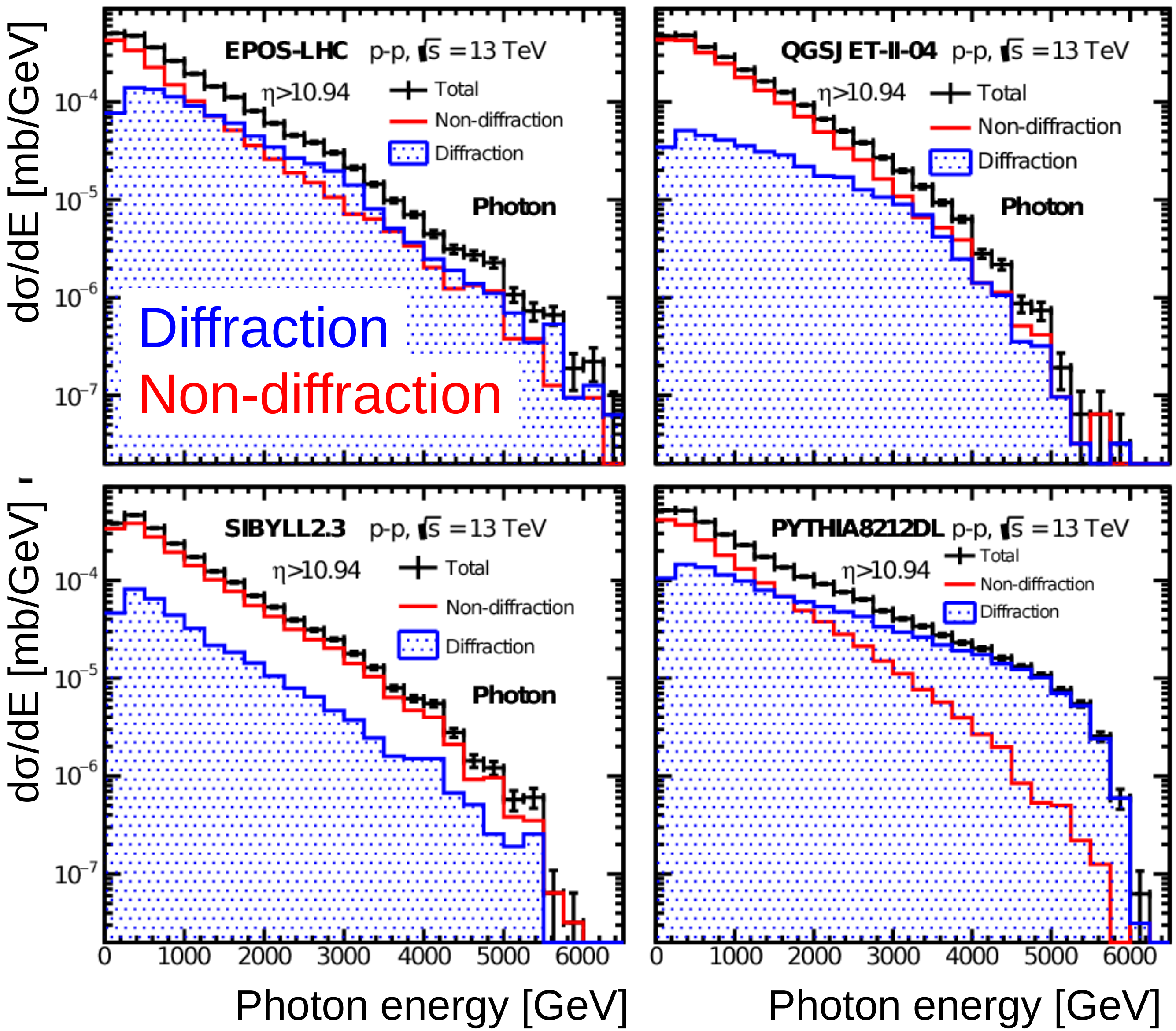


PLB 780 (2018) 233–239

- **EPOS-LHC**: good agreement for E < 3-4 TeV in both pseudorapidity regions
- **QGSJET II-04**: good overall agreement for high-η, softer spectrum in low-η

Diffractive events contribution

η > 10.94



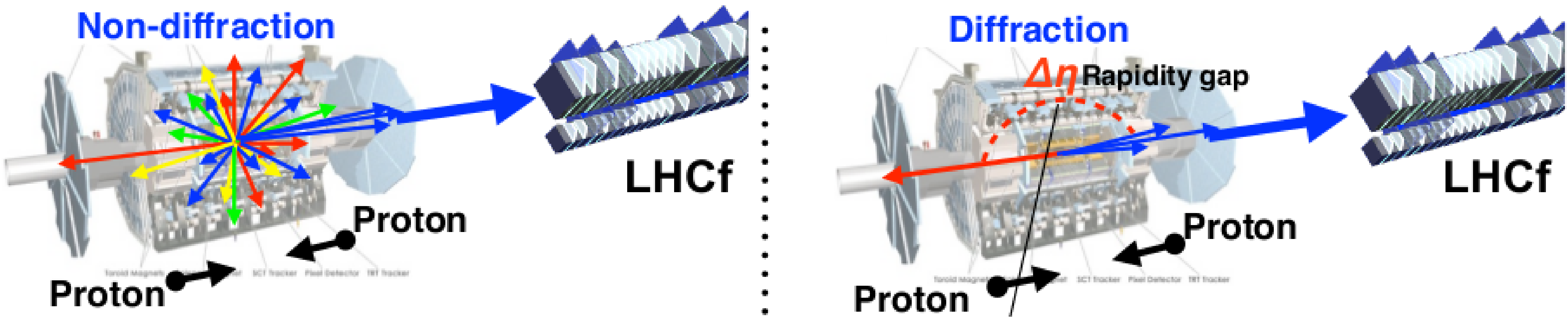
Hadronic interaction models predict different contributions from diffraction

Central detectors can give useful information to identify diffractive events

LHCf+ATLAS combined analysis

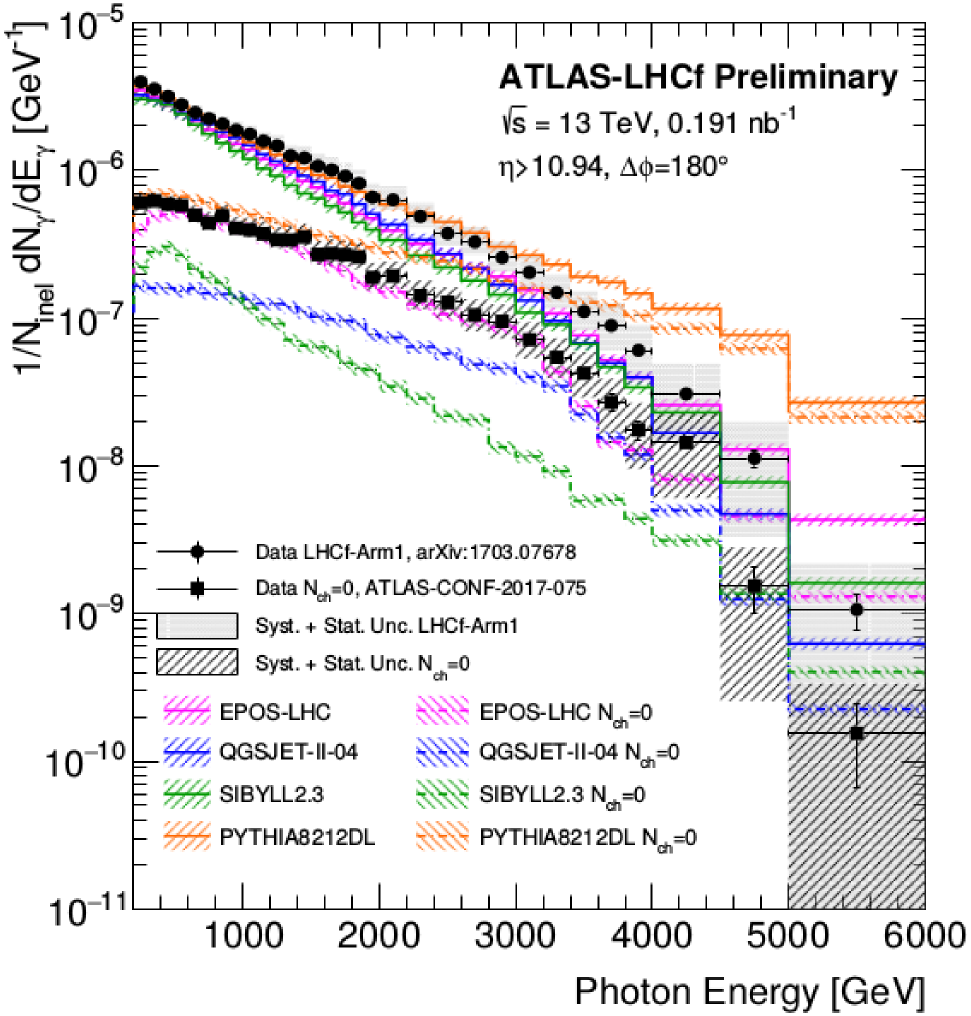
Eur. Phys. J. C (2017) 77:212

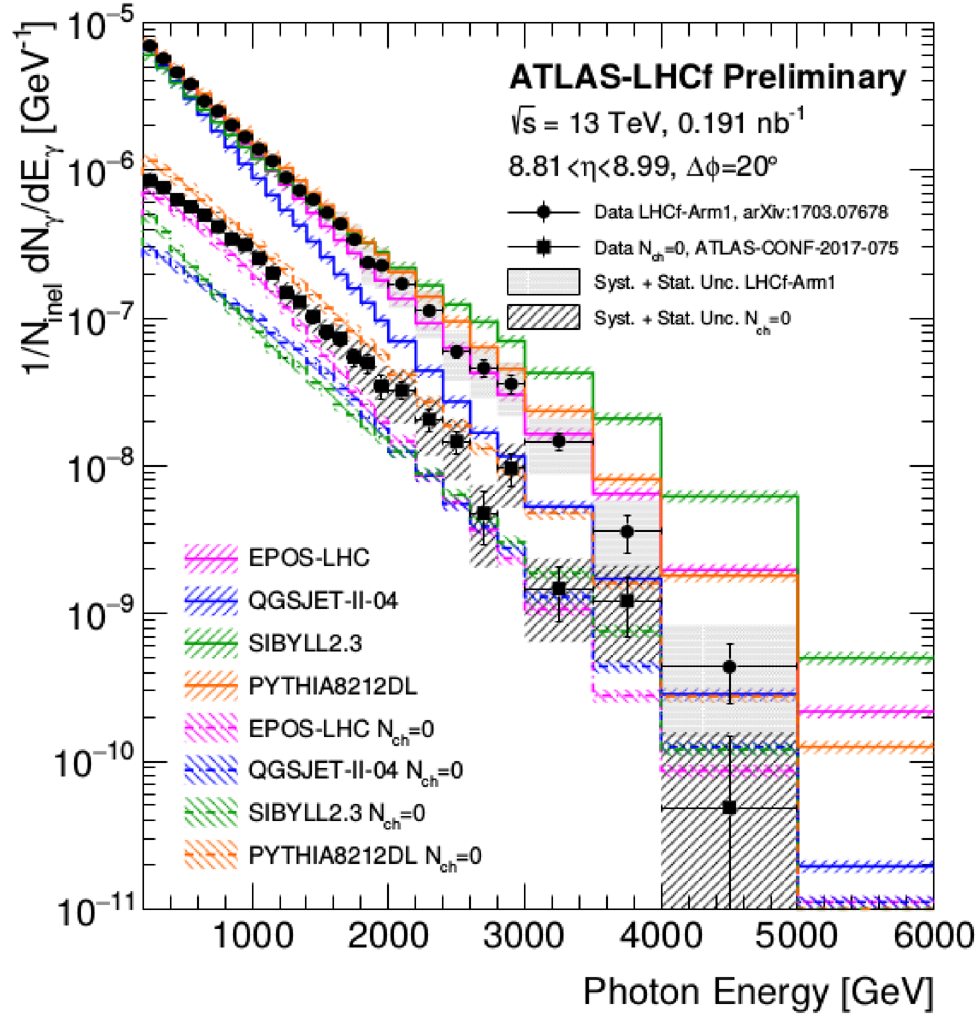
ATLAS+LHCf



- Trigger exchanged with ATLAS during p-p operation at 2.76, 13 TeV and p-Pb operation at 5.02, 8.16 TeV
- The number of tracks in the central region identifies the type of the event
- A preliminary analysis was done with p-Pb data at 5.02 TeV (*ATL-PHYS-PUB-2015-038*)
- First analysis of 13 TeV data: *ATLAS-CONF-2017-075*

Combined analysis results





(Presented by Q. D. Zhou on last working group meeting in December)

ATLAS-CONF-2017-075

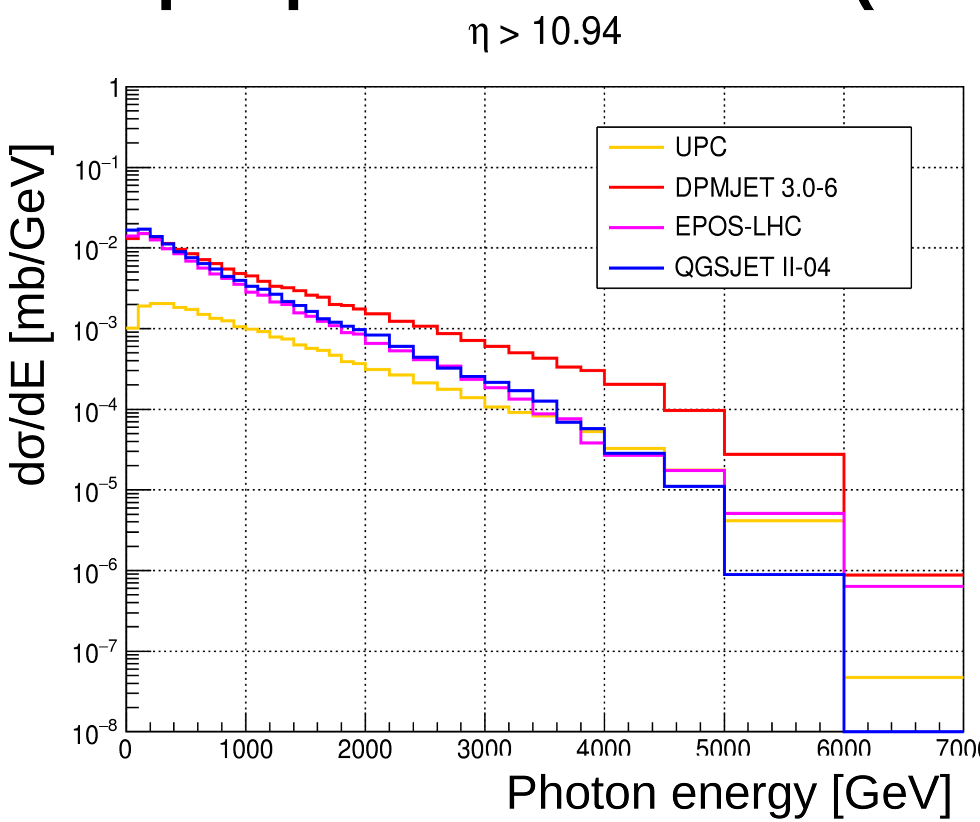
LHCf p-Pb run at 8.16 TeV

- Low luminosity dedicated run for LHCf: 25th of November 2016 (~9 hours)

Analysis data set:

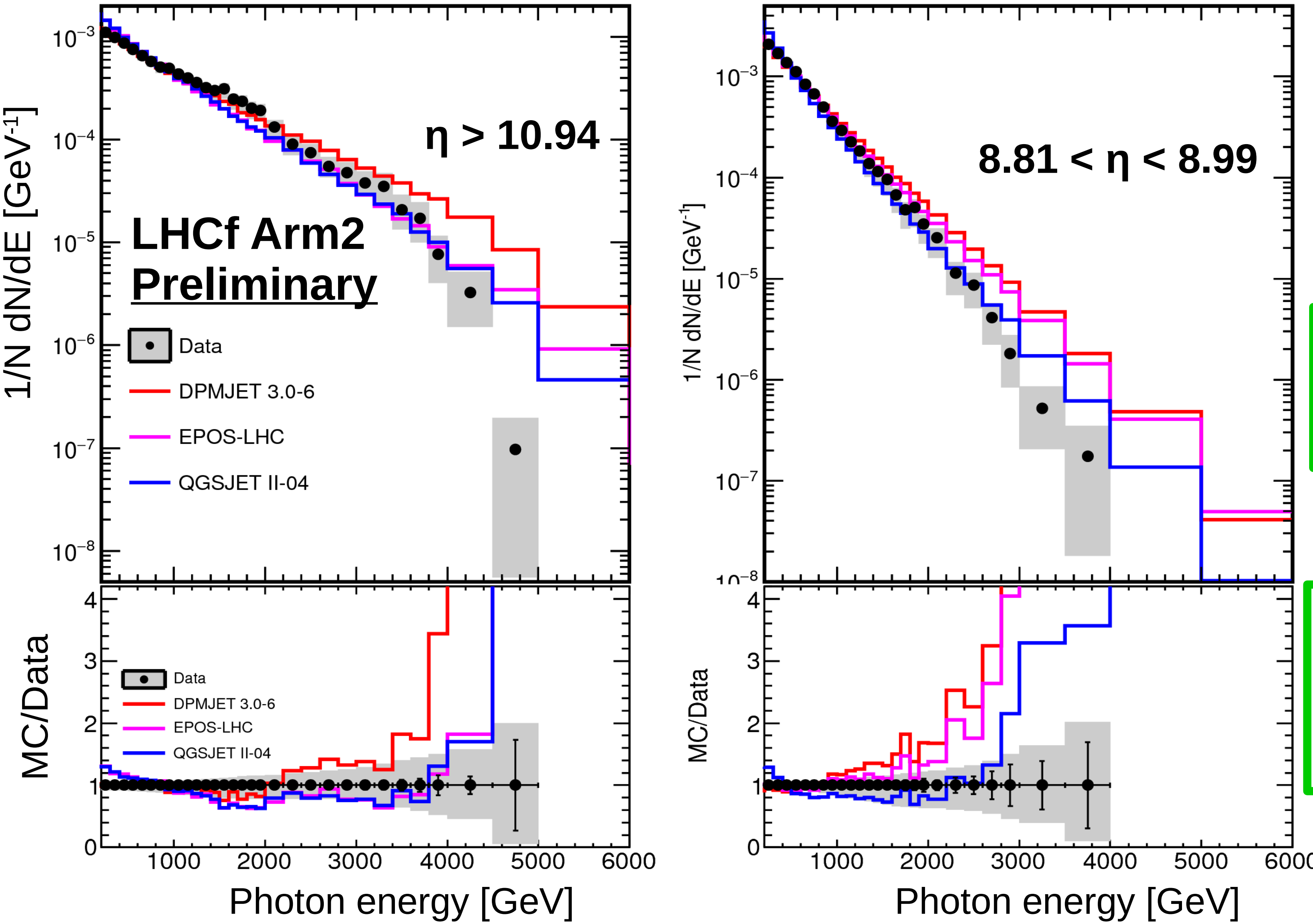
- ~ 2 hours of operation
- **Luminosity:** ~ 0.8 · 10^{28} cm^{-2} s^{-1}
- **Pile-up:** 0.01
- 3 · 10^{6} **events**
- Integrated luminosity not available yet...

Ultra peripheral collisions (UPC)



UPC simulation → STARLIGHT + SOPHIA/DPMJET

Photon spectrum in p-Pb at 8.16 TeV



UPC added to MC simulations

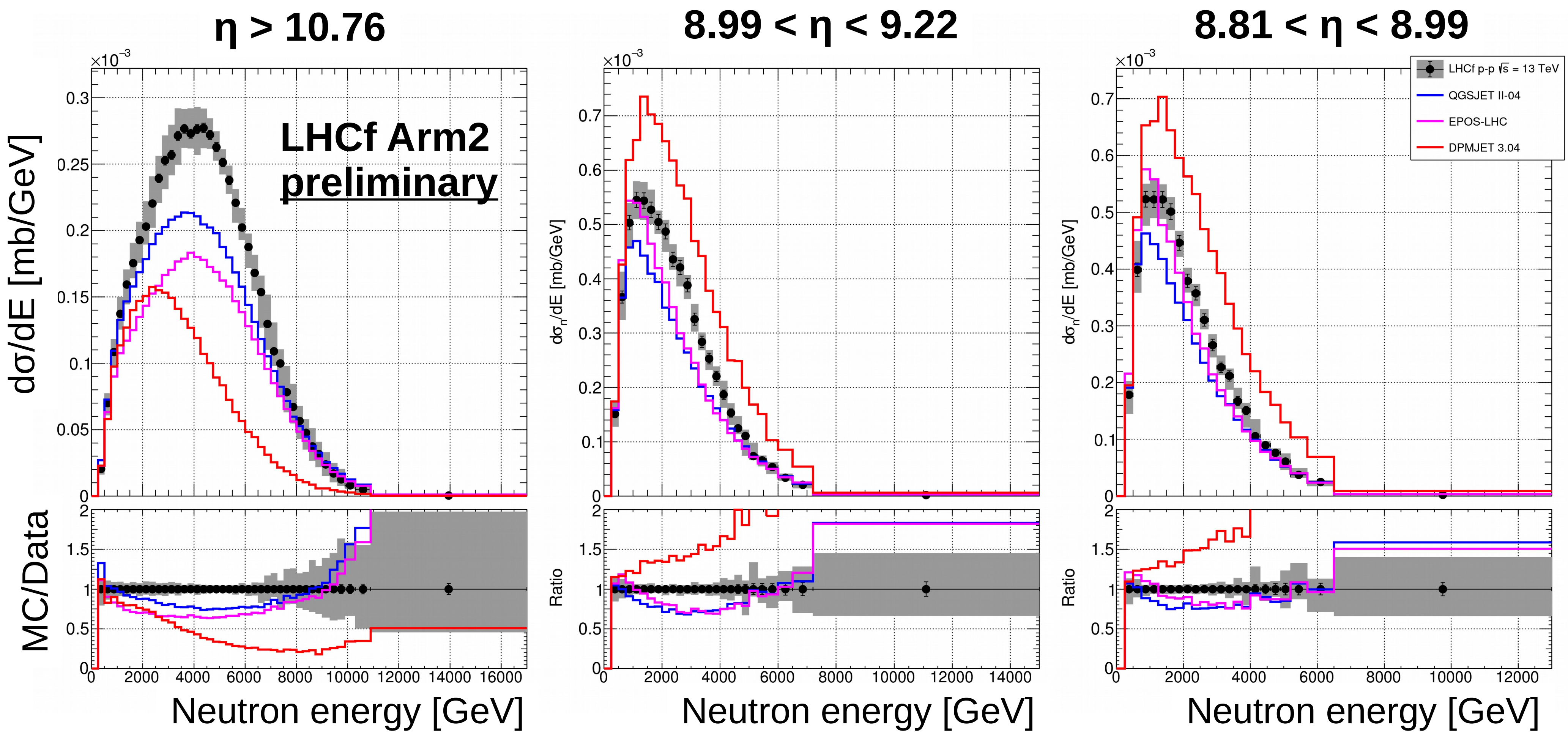
All spectra normalized to their integral

Only "shape" comparison (not cross section)

- η > 10.94: good agreement of **EPOS-LHC** and **QGSJET II-04**
- 8.81 < η < 8.99: all models predict an harder spectrum

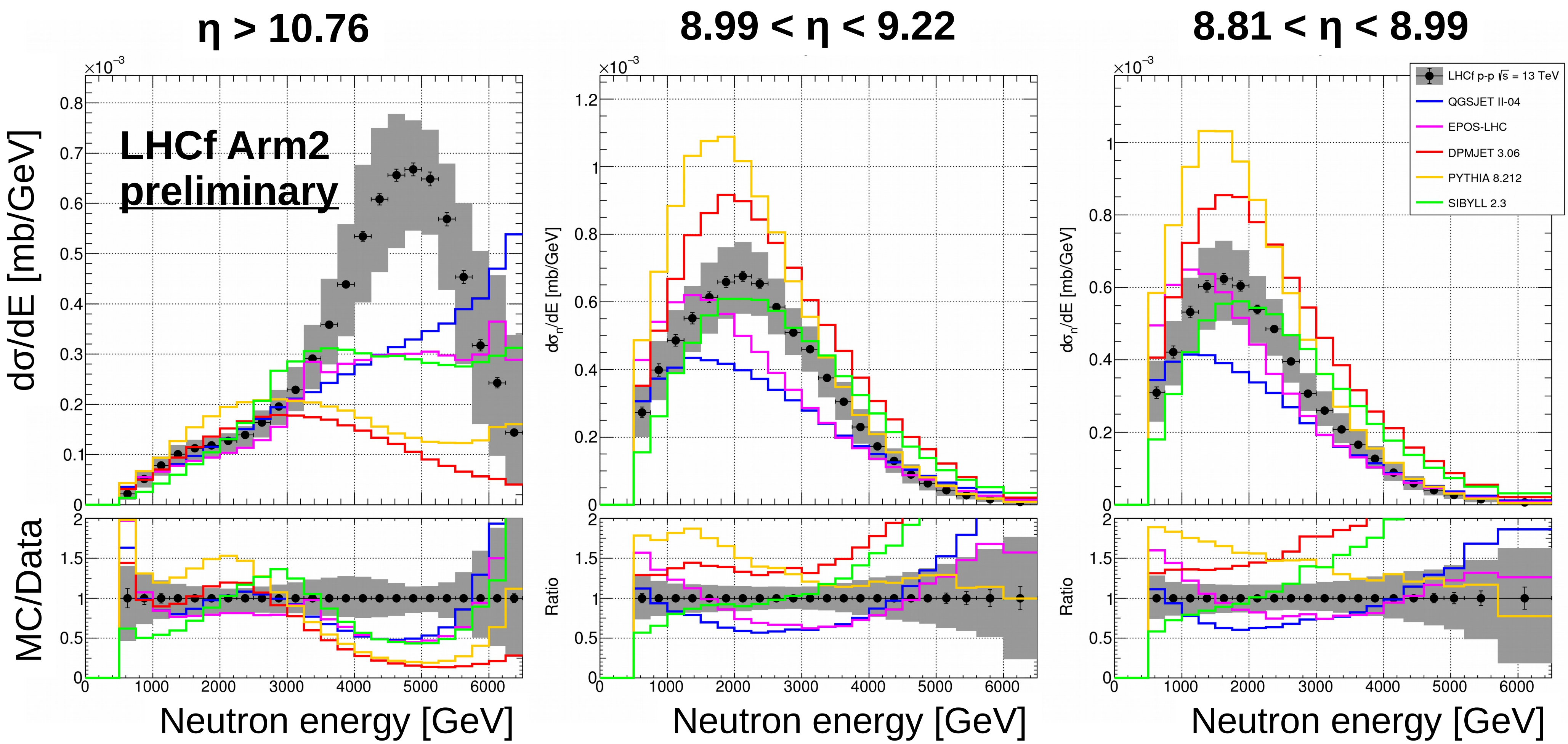
Physics results: neutrons (preliminary!)

Neutron energy spectrum (before unfolding)



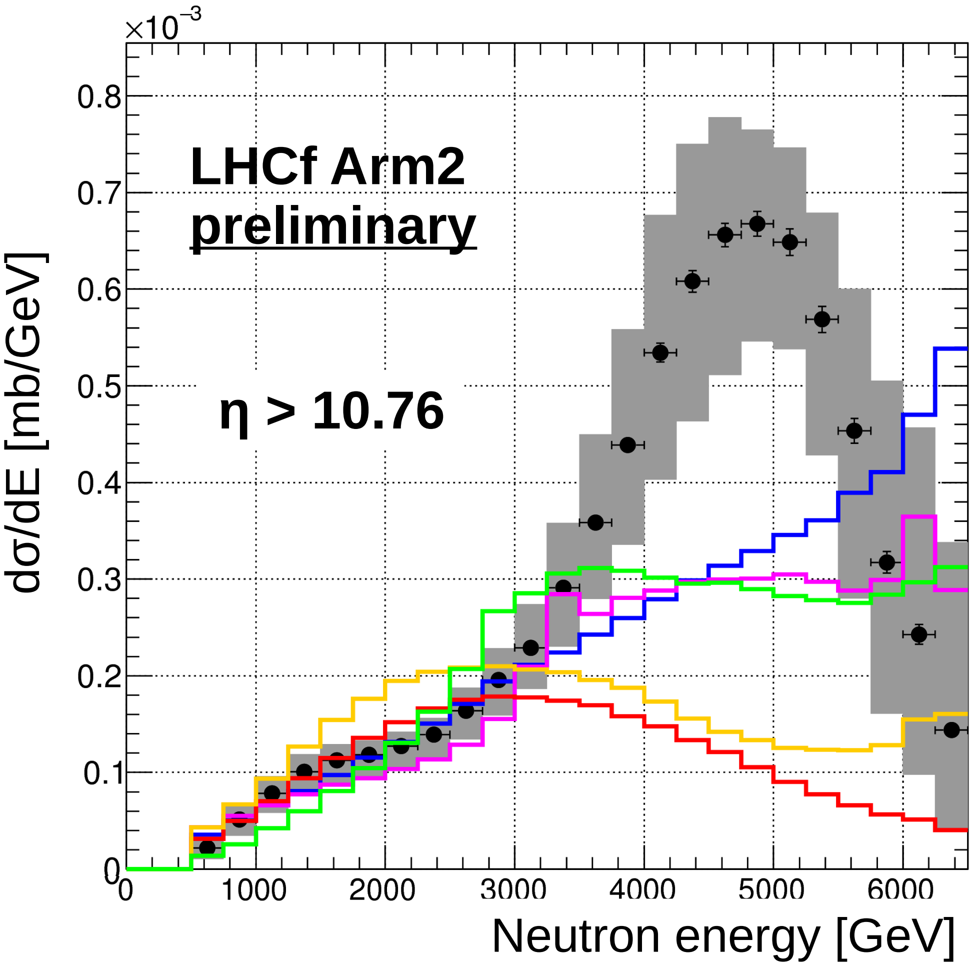
- **QGSJET II-04** and **EPOS-LHC** have similar shape but lower yield
- **DPMJET 3.04** have very different shape and yield

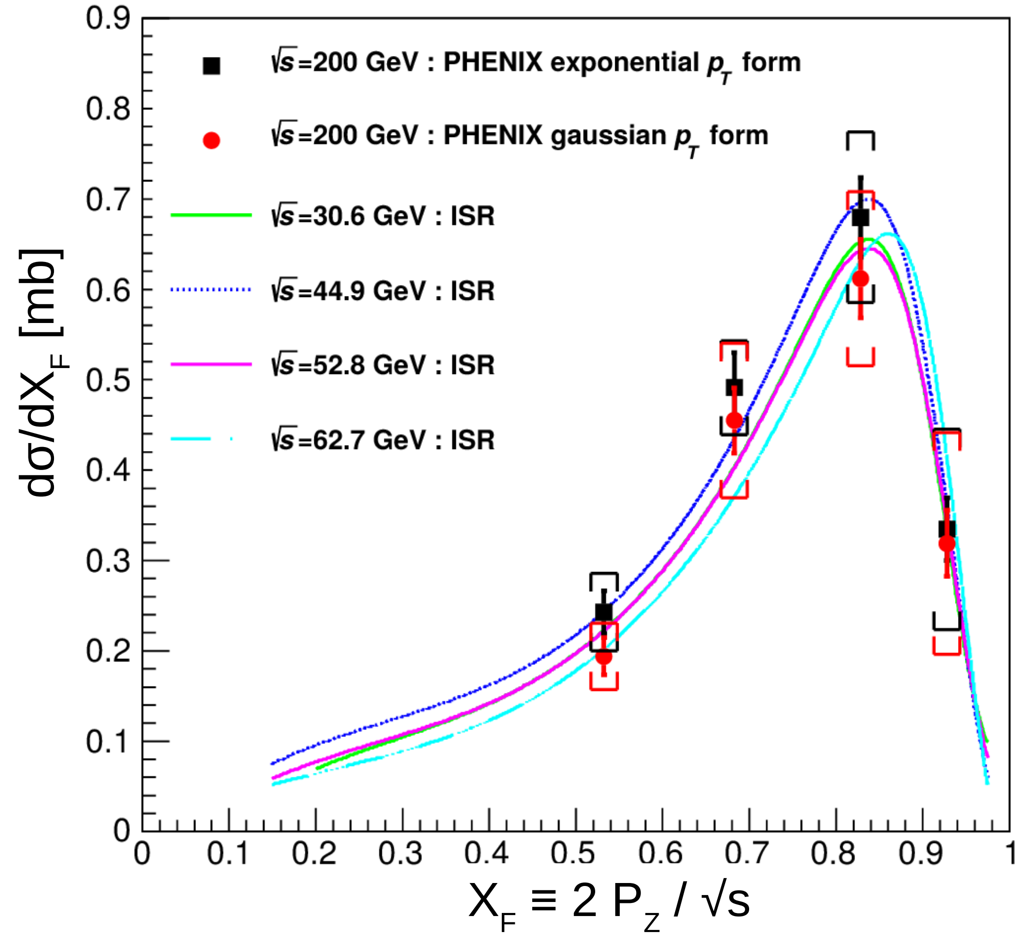
Neutron energy spectrum



- η > 10.76: huge neutron production compared to all models predictions
- 8.81 < η < 9.22: **EPOS-LHC** and **SIBYLL 2.3** show a better agreement than other models

Comparison with PHENIX and ISR





$0 < P_T < 0.28\, X_F$ GeV/c **$0 < P_T < 0.11\, X_F$ GeV/c**

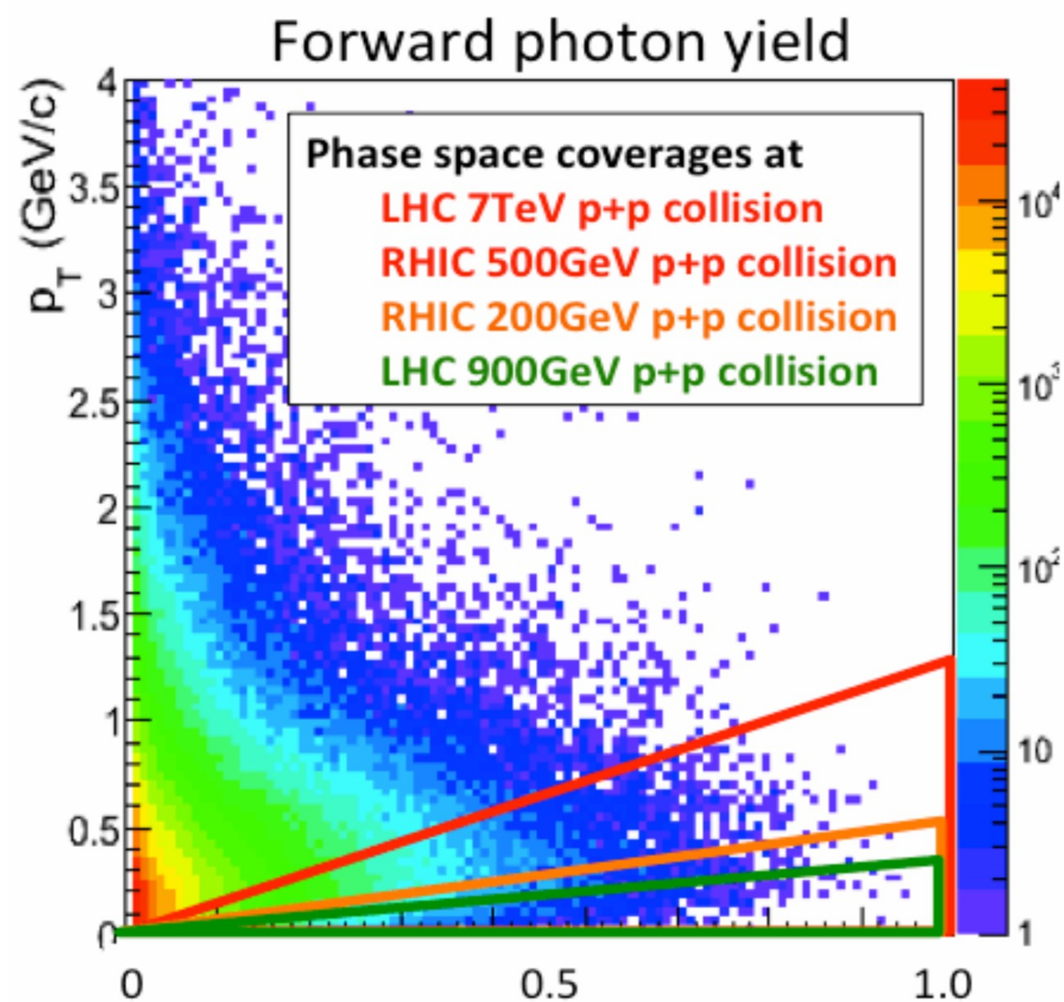
Different P_T coverage!

Same structure observed by PHENIX and ISR (qualitatively)

Ongoing activities

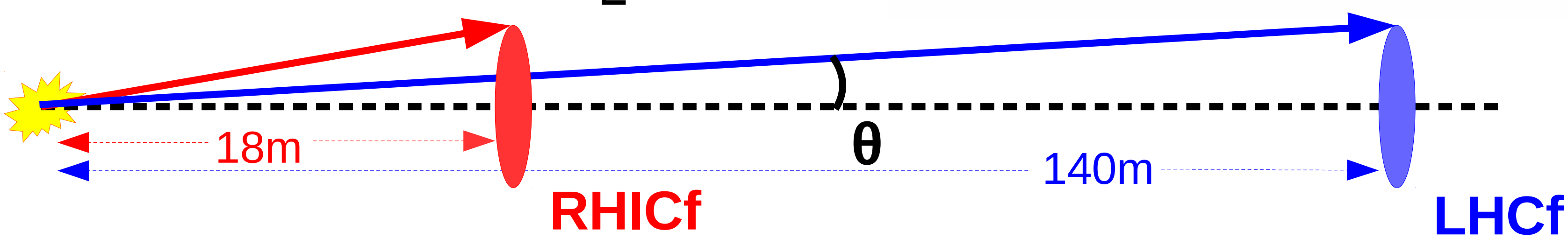
RHICf

- Run with p-p collisions at $\sqrt{s}$ = 510 GeV performed on June 2017
- Arm1 detector 18 m away from STAR interaction point
- Same P_T coverage as LHC at 7 TeV
- Test of Feynman scaling (extrapolation beyond LHC energy)



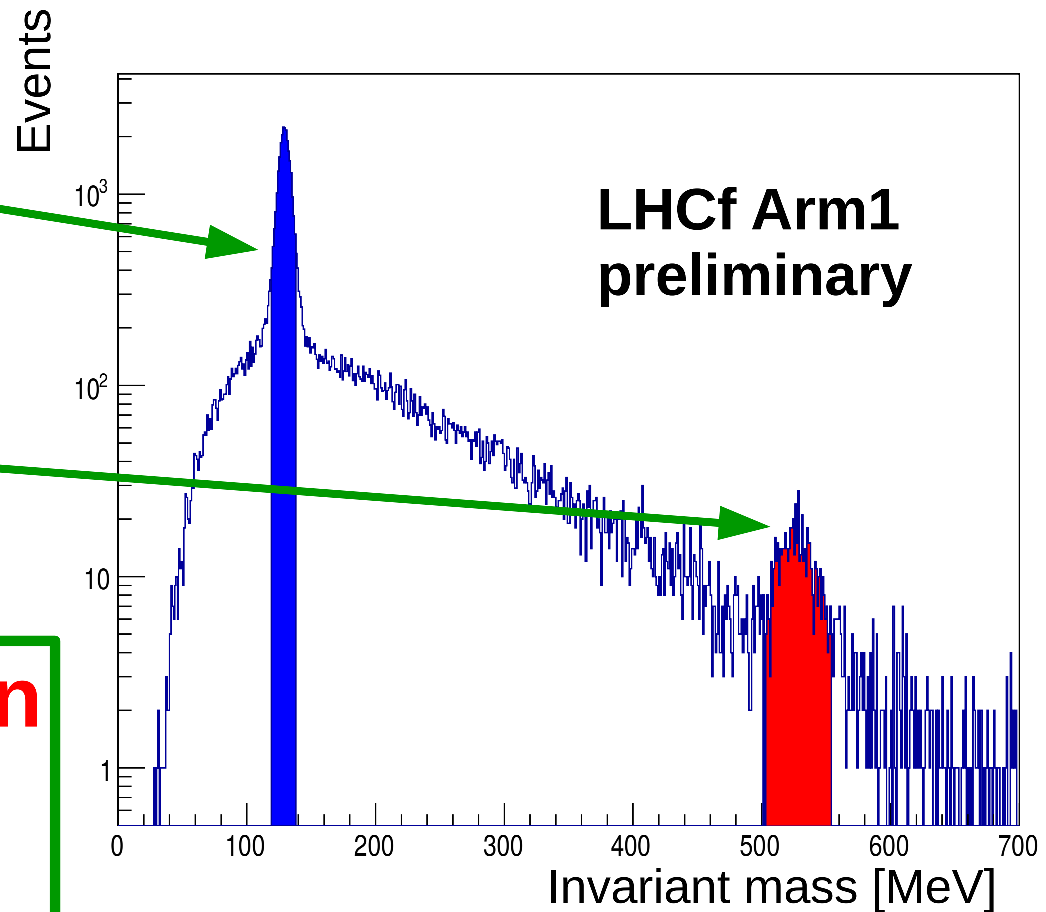
$$P_T \leq \frac{\sqrt{s}}{2} \sin\theta \cdot X_F$$

$$X_F = \frac{2P_Z}{\sqrt{s}}$$



Current targets

- **π⁰** analysis in p-p at √s = 13 TeV
- **η** meson analysis in p-p at √s = 13 TeV
- **Arm1-Arm2 correlation** (double diffraction, pion-pion exchange)



- Proposal: **proton-light ion** collisions at LHC

Summary

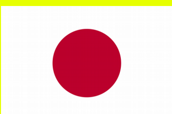
- **LHCf** can contribute to reduce systematic uncertainties on hadronic interaction models for air-showers

- Latest analysis results in p-p and p-Pb collisions at the LHC:
  - **Photon** energy spectrum in p-p at **13 TeV** and p-Pb at **8.2 TeV**
  - **Neutron** energy spectrum in p-p at **13 TeV**

- Other activities:
  - **ATLAS-LHCf** combined analysis
  - Operation at RHIC accelerator with p-p at $\sqrt{s}$ = **510 GeV** (***RHICf***) successfully performed
  - π^0 meson analysis
  - **η** meson analysis
  - **“Double Arm”** correlation analysis

Backup

The LHCf collaboration



Y. Itow[1, 2], Y. Makino[1], K. Masuda[1], Y. Matsubara[1], E. Matsubayashi[1], H. Menjo[3], Y. Muraki[1], T. Sako[1, 2], K. Sato[1], M. Shinoda[1], M. Ueno[1], Q. D. Zhou[1]

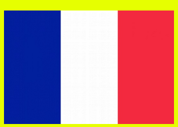
[1] Institute for Space-Earth Environmental Research, Nagoya University, Japan
[2] Kobayashi-Maskawa Institute, Nagoya University, Japan
[3] Graduate school of Science, Nagoya University, Japan

K. Yoshida *Shibaura Institute of Technology, Japan*

T. Iwata, K. Kasahara, T. Suzuki, S. Torii *Waseda University, Japan*

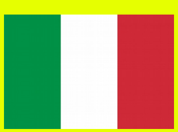
Y. Shimizu, T. Tamura *Kanagawa University, Japan*

N. Sakurai *Tokushima University, Japan*



M. Haguenauer *Ecole Polytechnique, France*

W. C. Turner *LBNL, Berkeley, USA*



O. Adriani[4, 5], E. Berti[4, 5], L. Bonechi[4], M. Bongi[4, 5], G. Castellini[6], R. D'Alessandro[4, 5], P. Papini[4], S. Ricciarini[4, 6], A. Tiberio[4, 5]

[4] INFN section of Florence, Italy
[5] University of Florence, Italy
[6] IFAC-CNR, Florence, Italy

A.Tricomi *INFN and University of Catania, Italy*

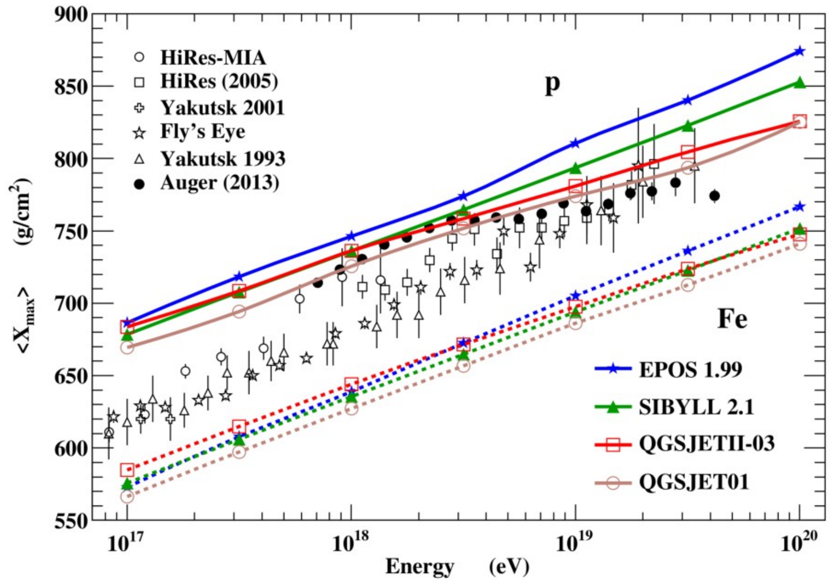
Published results

- **Photons**
  - Energy spectra in p-p @ $\sqrt{s}$ = 7 TeV [*PLB 703 (2011), 128-134*]
  - Energy spectra in p-p @ $\sqrt{s}$ = 900 GeV [*PLB 715 (2012), 298-303*]
  - Energy spectra in p-p @ $\sqrt{s}$ = 13 TeV [*PLB 780 (2018) 233–239*]
- **π^0**
  - P_T spectra in p-p @ $\sqrt{s}$ = 7 TeV [*PRD 86, 092001 (2012)*]
  - P_T spectra in p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV [*PRC 89, 065209 (2014)*]
  - P_T and P_Z spectra in p-p @ $\sqrt{s}$ = 7 TeV and 2.76 TeV, p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV [*PRD 94, 032007 (2016)*]
- **Neutrons**
  - Energy spectra in p-p @ $\sqrt{s}$ = 7 TeV [*PLB 750 (2015), 360-366*]

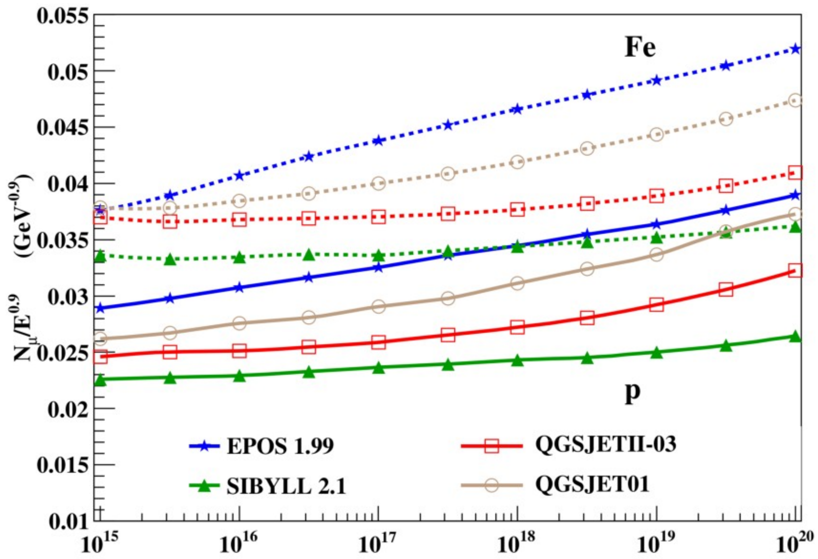
LHC contribution to models

Pre-LHC

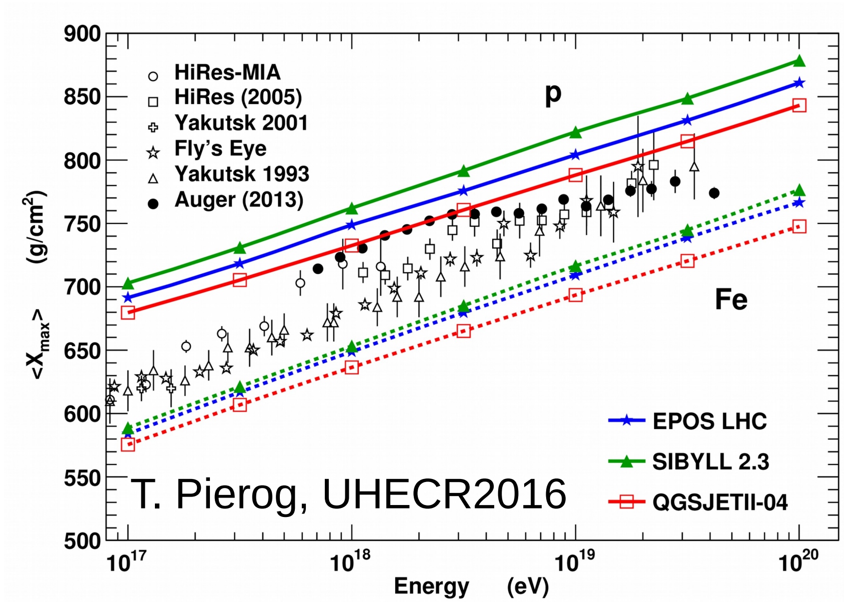
Mean depth of shower maximum

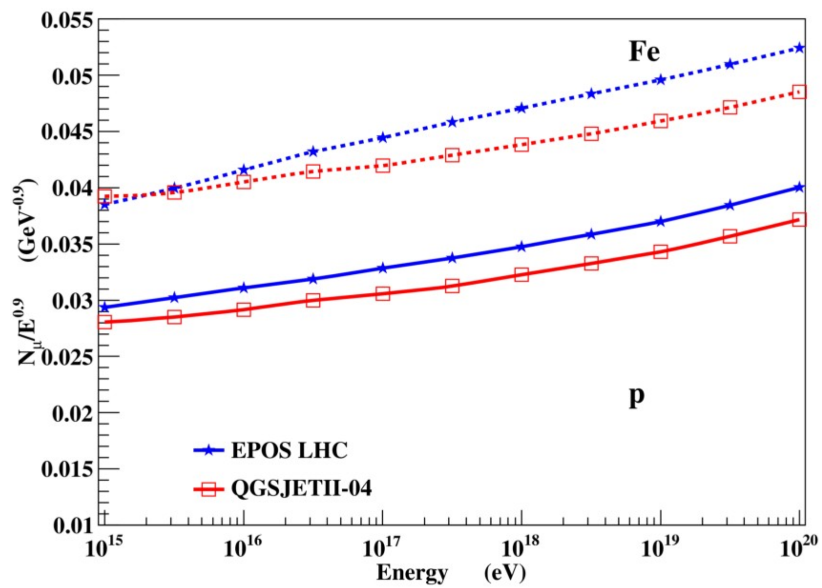


N° of muons at ground



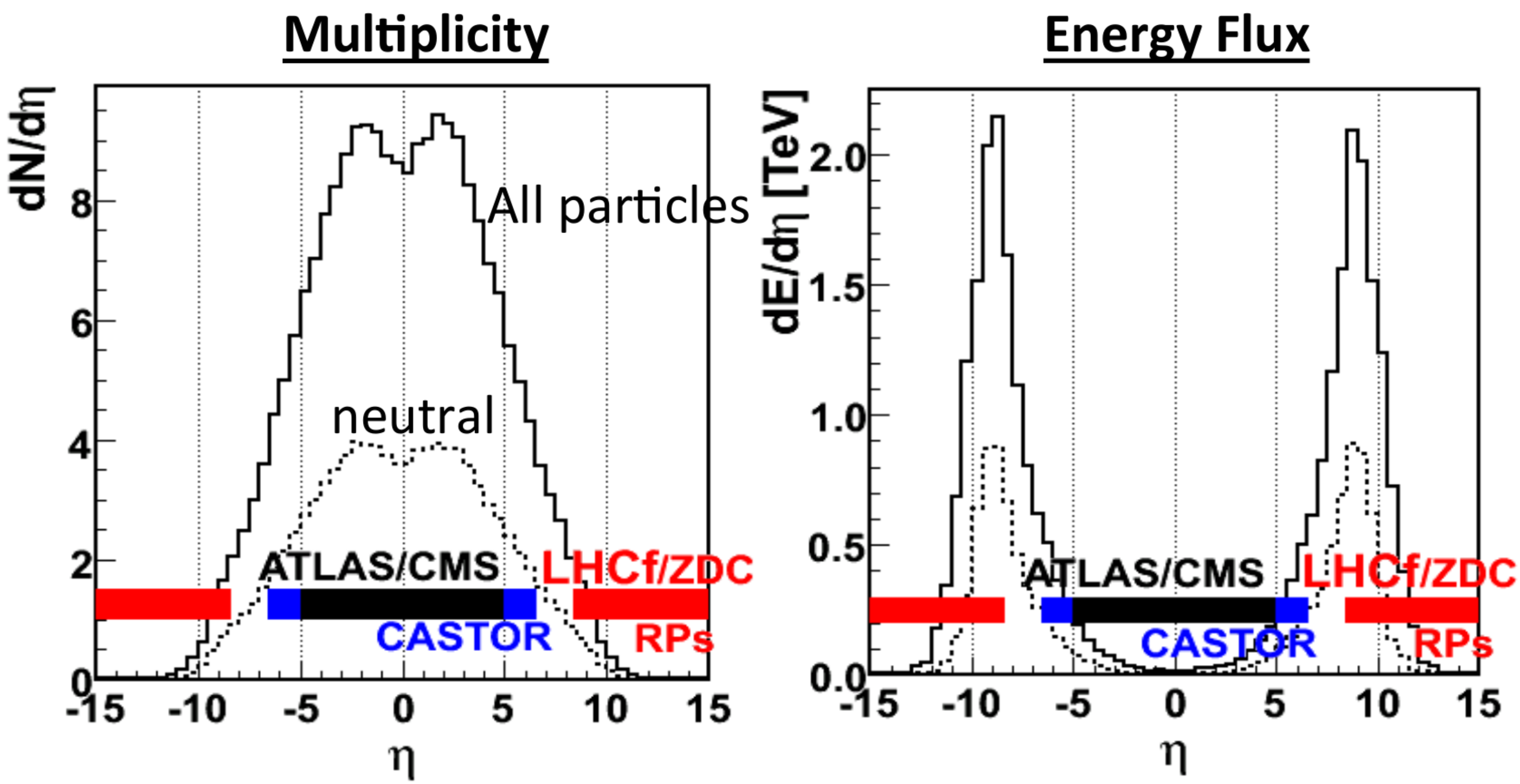
Post-LHC





Forward energy flux @ LHC

p-p collisions @ $\sqrt{s}$ = 14 TeV → $E_{CR} = 10^{17}$ eV



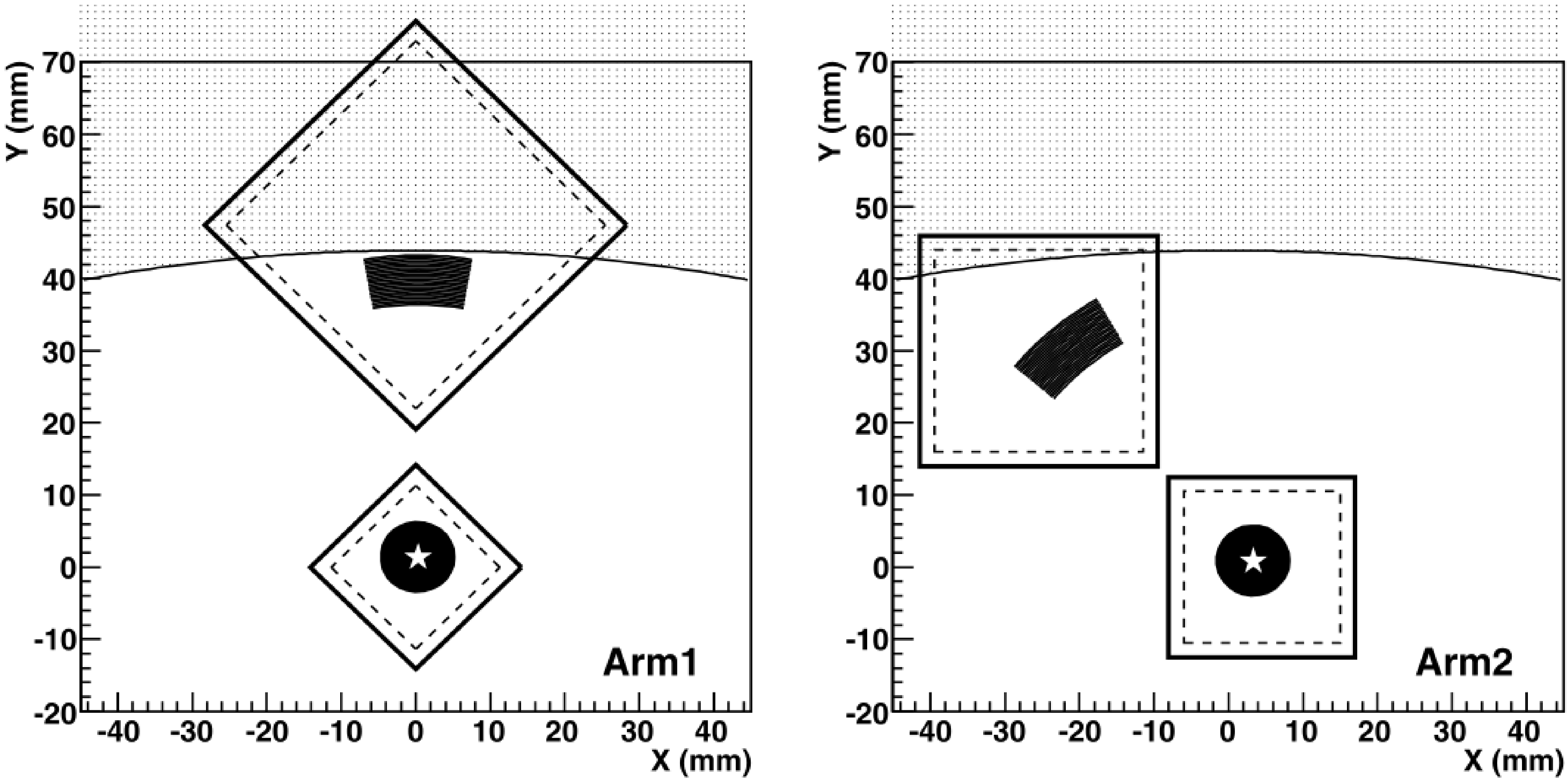
LHCf pseudo-rapidity range: η > 8.4
(with 140 μrad beam crossing angle)

Pseudo-rapidity

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

<u>LHCf covers the peak of energy flow</u>

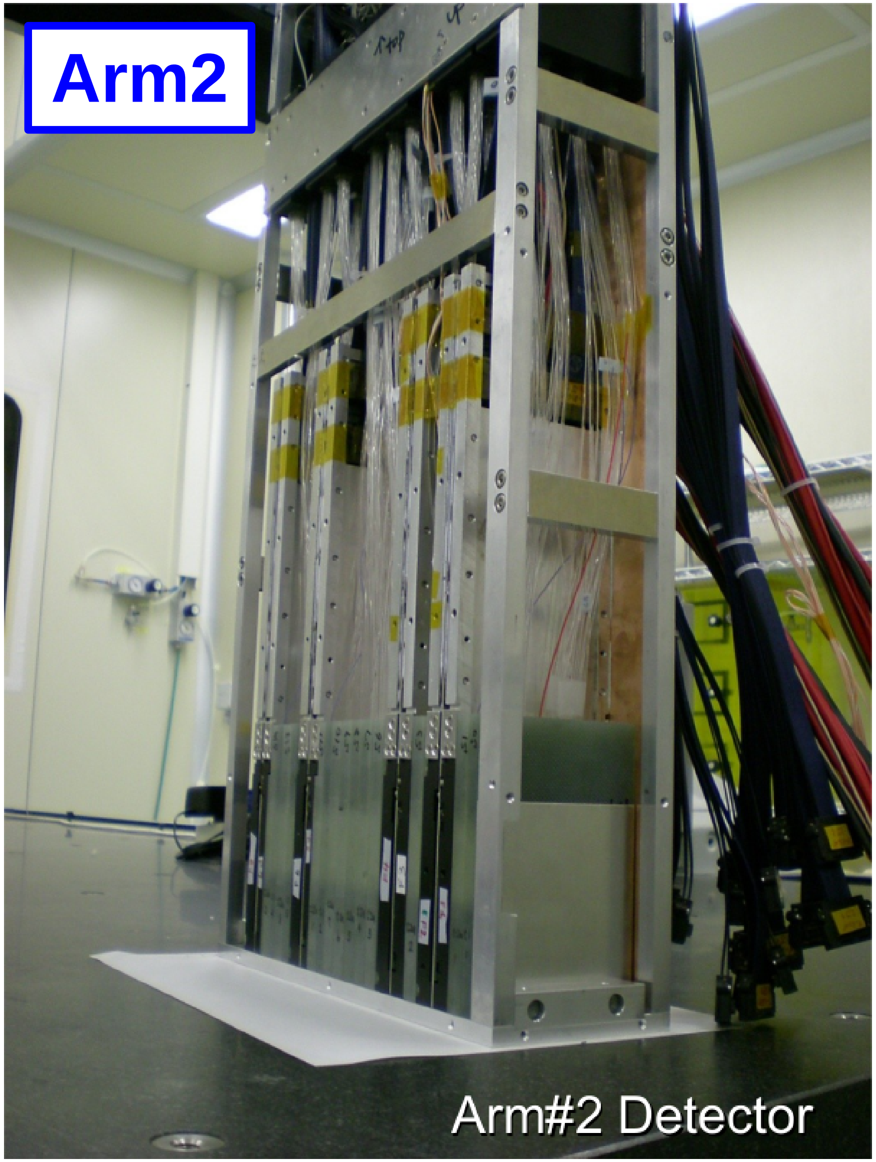
Detectors cross section



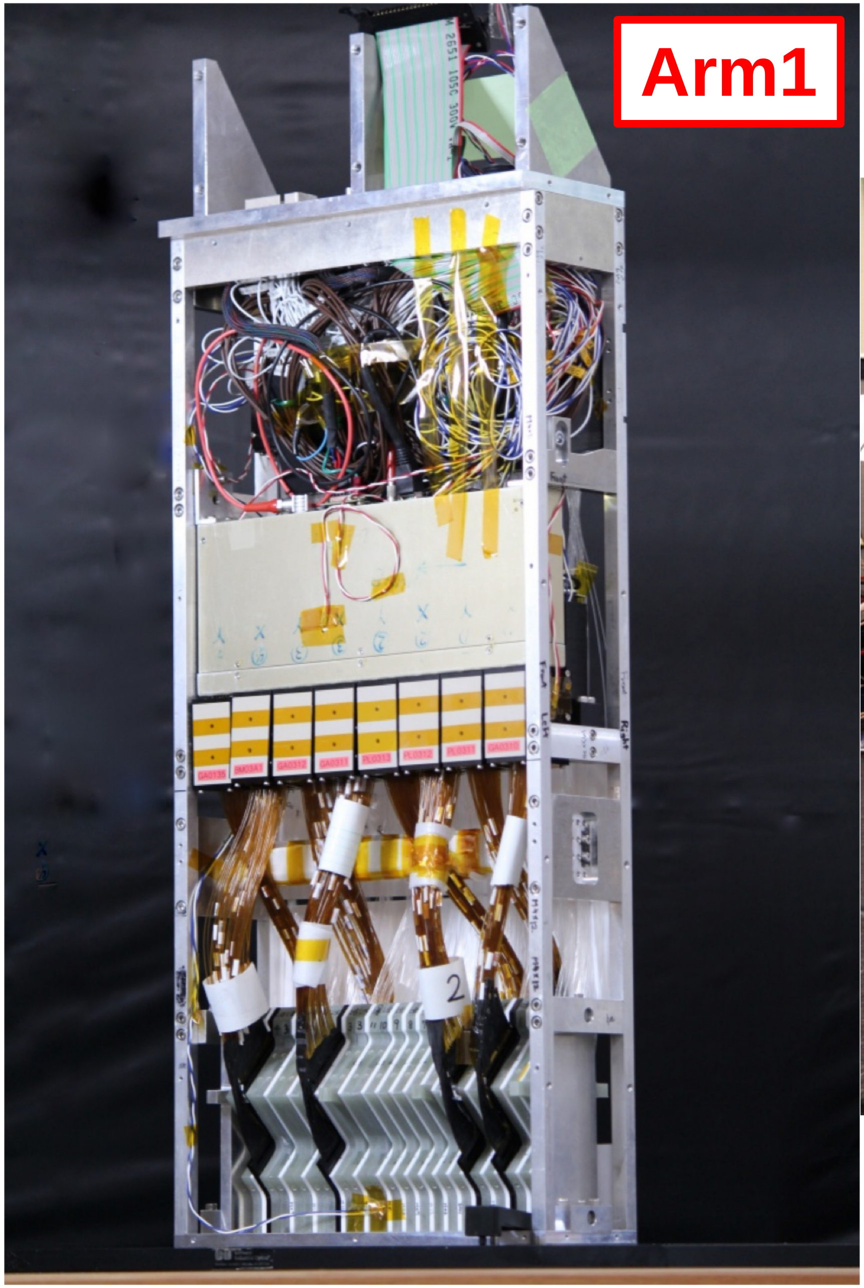
Upgrades for 13 TeV operations

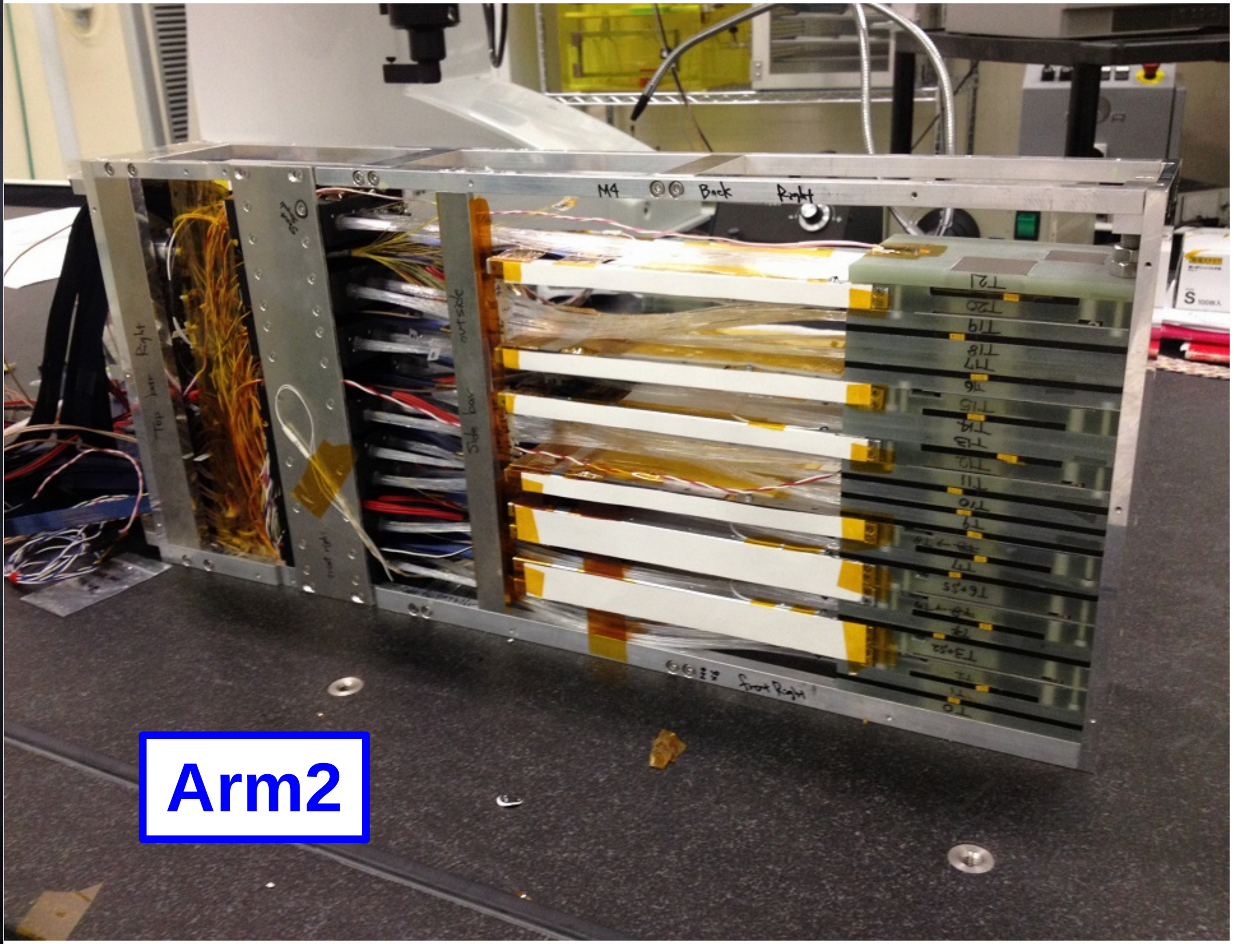
- More radiation damage is expected: 0.2 Gy/nb^{-1} @ 7 TeV, 2-3 Gy/nb^{-1} @ 13 TeV
  - All plastic scintillators have been substituted with **GSO scintillators** (can survive up to 10^6 Gy)
  - In Arm1, scintillation fibers were replaced with **GSO bars** ($1 \times 1 \times 20\ mm^3$ and $1 \times 1 \times 40\ mm^3$ for small and large tower respectively)
- In old configuration, silicons detectors in Arm2 saturate for photons with energy > 1.5 TeV
  - **Silicon signal reduced** (~ 60%) by using a new bonding scheme of silicon strips
- Silicon detectors **longitudinal positions** were changed to better catch E-M and hadronic showers → possibility to use silicon detectors to reconstruct energy → cross check with calorimeter

Arm1 and Arm2 (old)



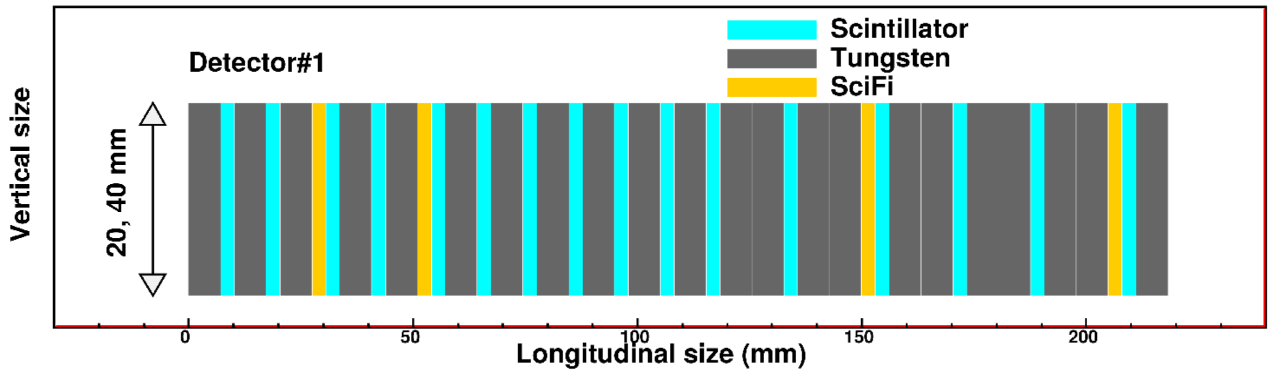
Upgraded Arm1 and Arm2



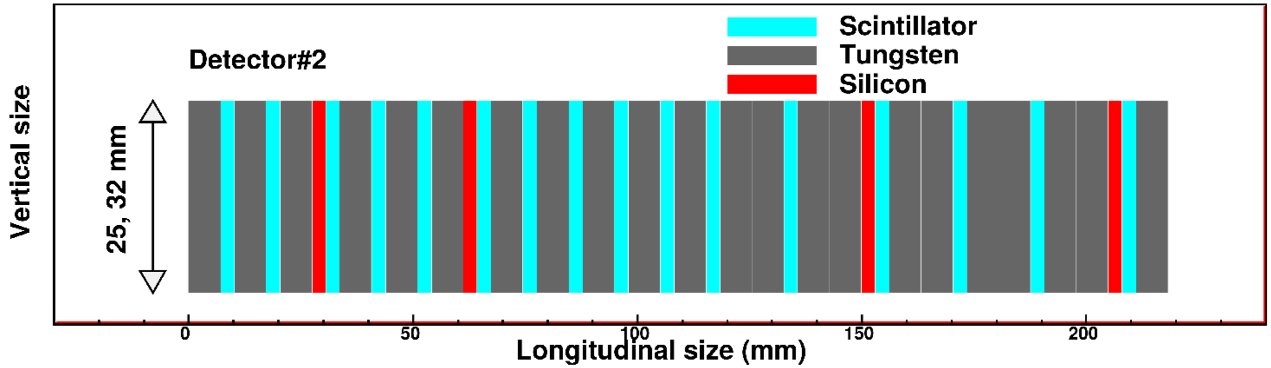


Longitudinal structure

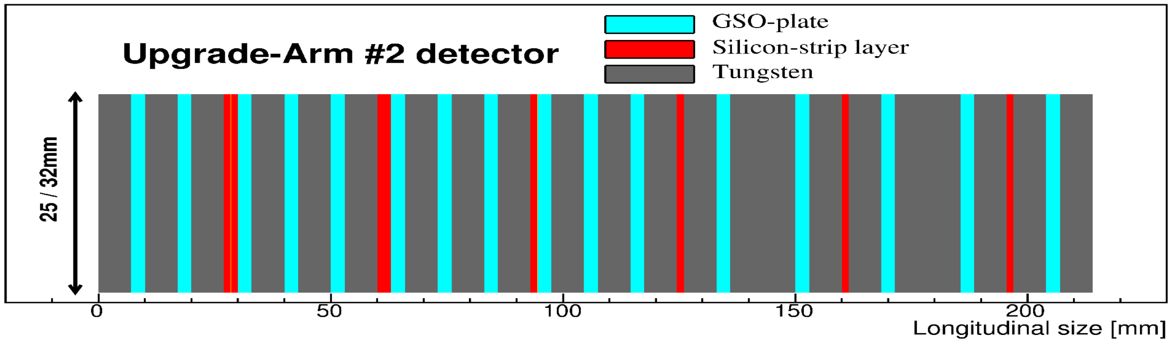
Arm1



Arm2 (Old)

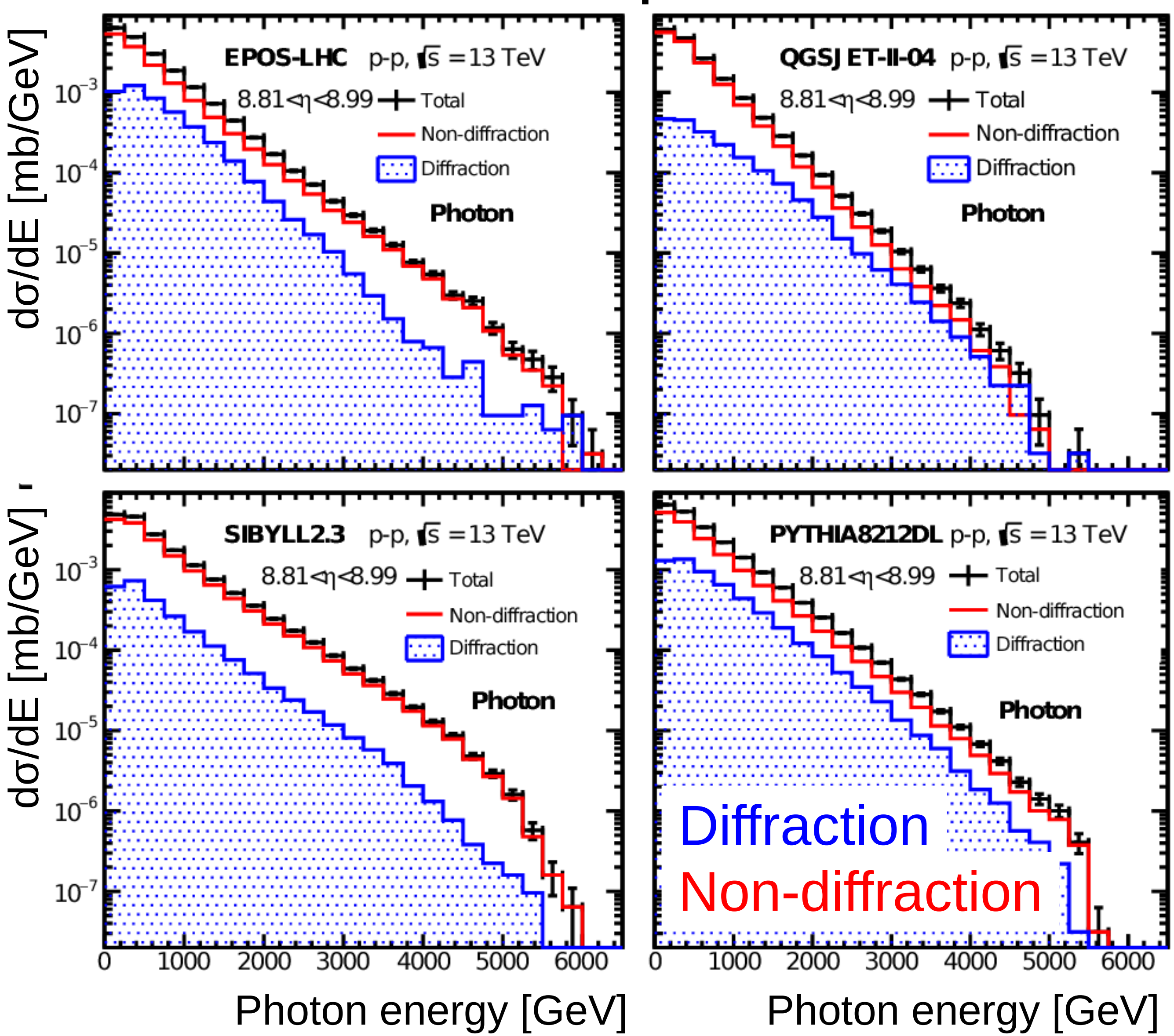


Arm2 (New)



Diffractive events contribution

8.81 < η < 8.99



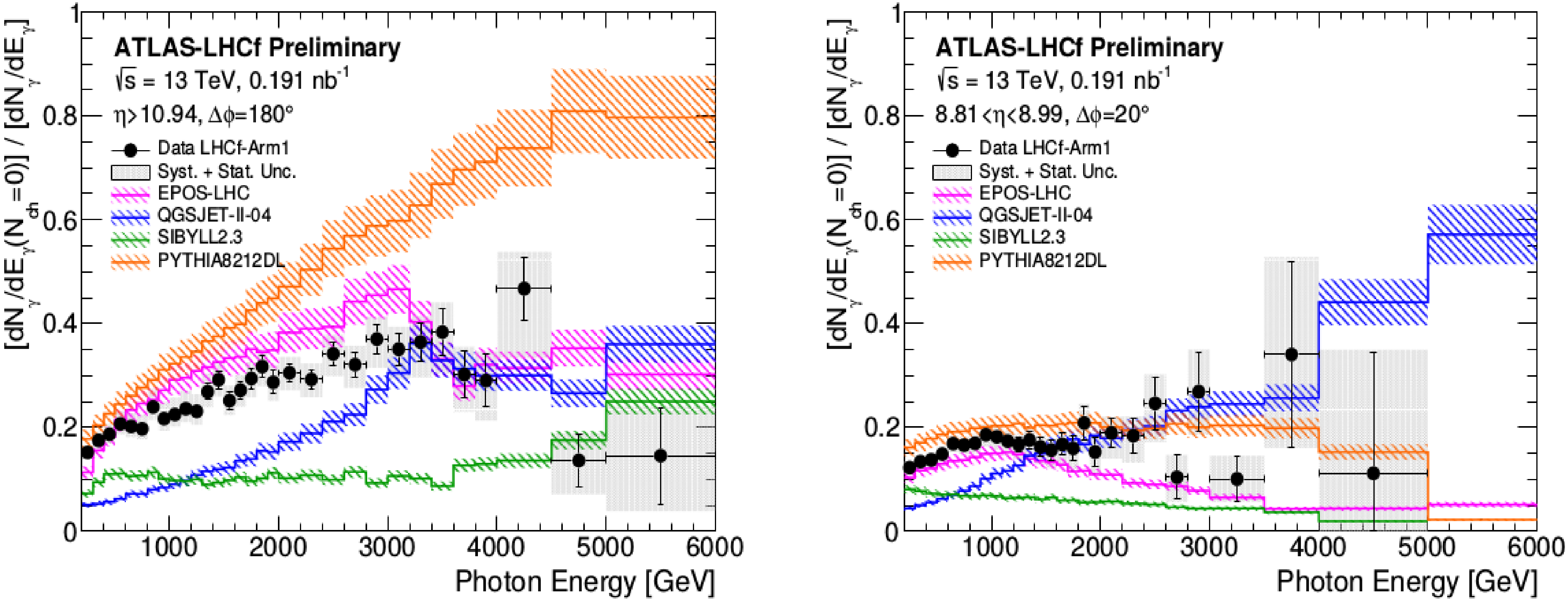
Hadronic interaction models predict different contributions from diffraction

Central detectors can give useful information to identify diffractive events

LHCf+ATLAS
combined analysis

Eur. Phys. J. C (2017) 77:212

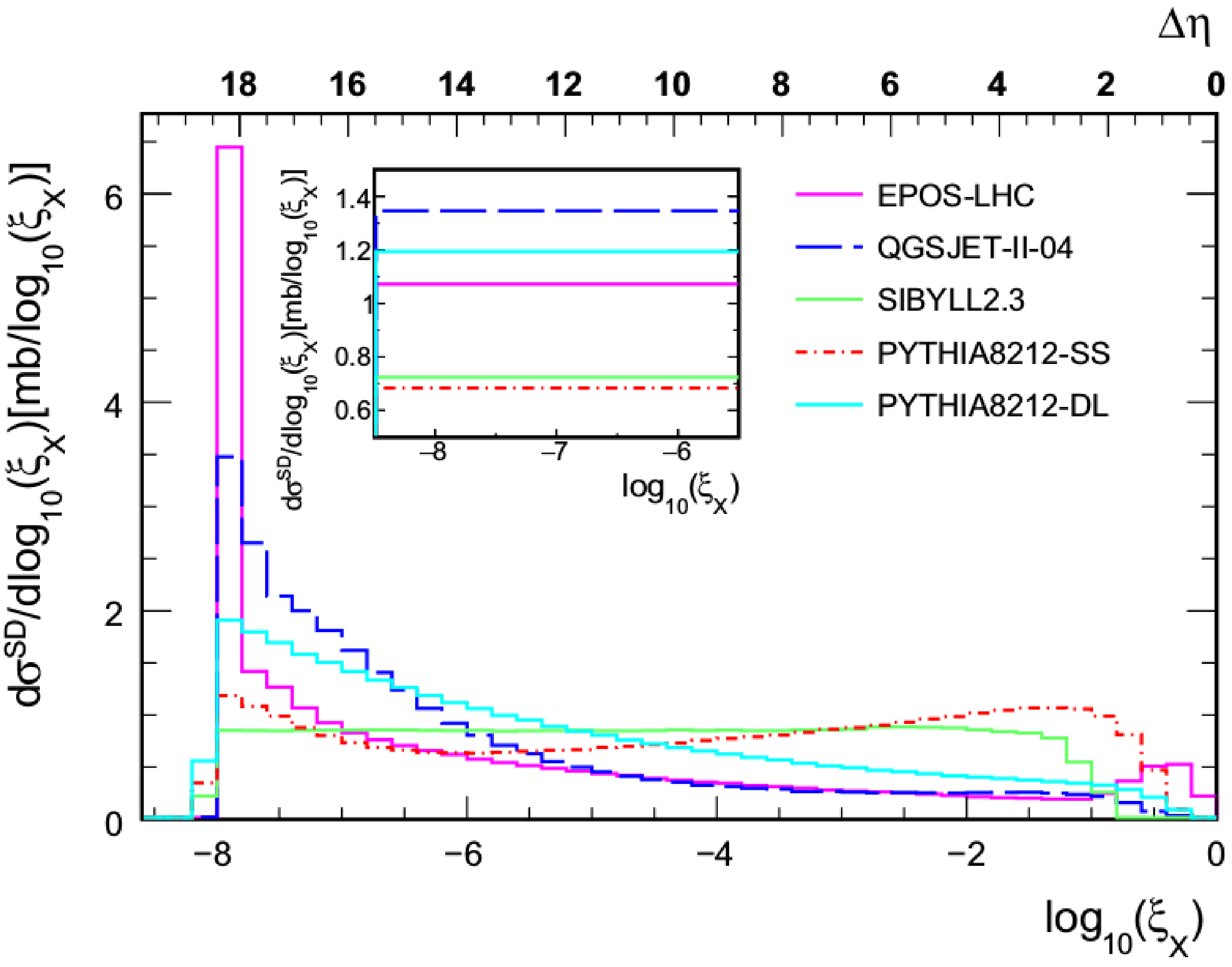
Combined analysis results



(Presented by Q. D. Zhou on last working group meeting in December)

ATLAS-CONF-2017-075

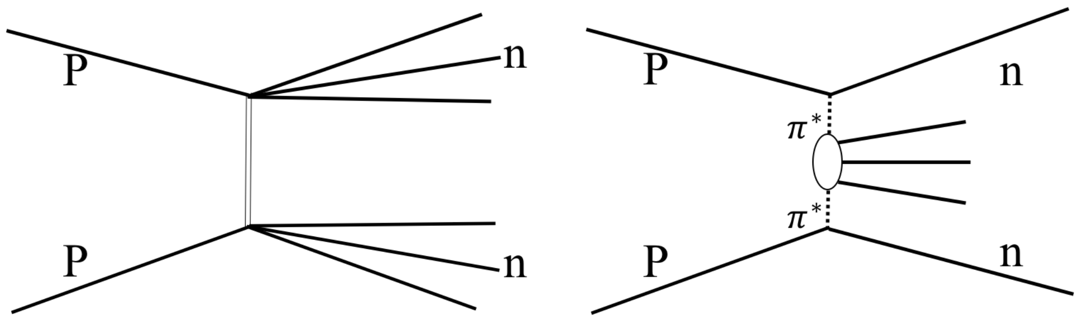
Diffraction mass distribution



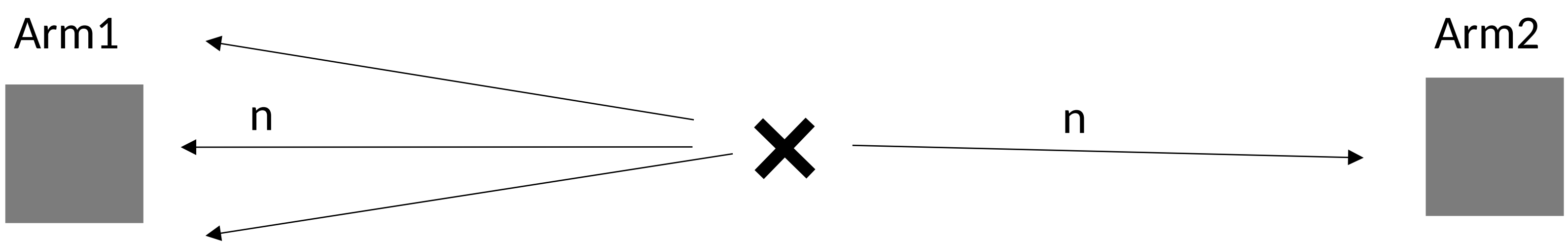
$$\xi_X = \frac{M_X^2}{s}$$

$$\Delta\eta \simeq -\ln(\xi_X)$$

“Double Arm” analysis



Double diffractive or pion-pion exchange can produce neutrons in both side of very forward region, which can be detected by LHCf detectors.

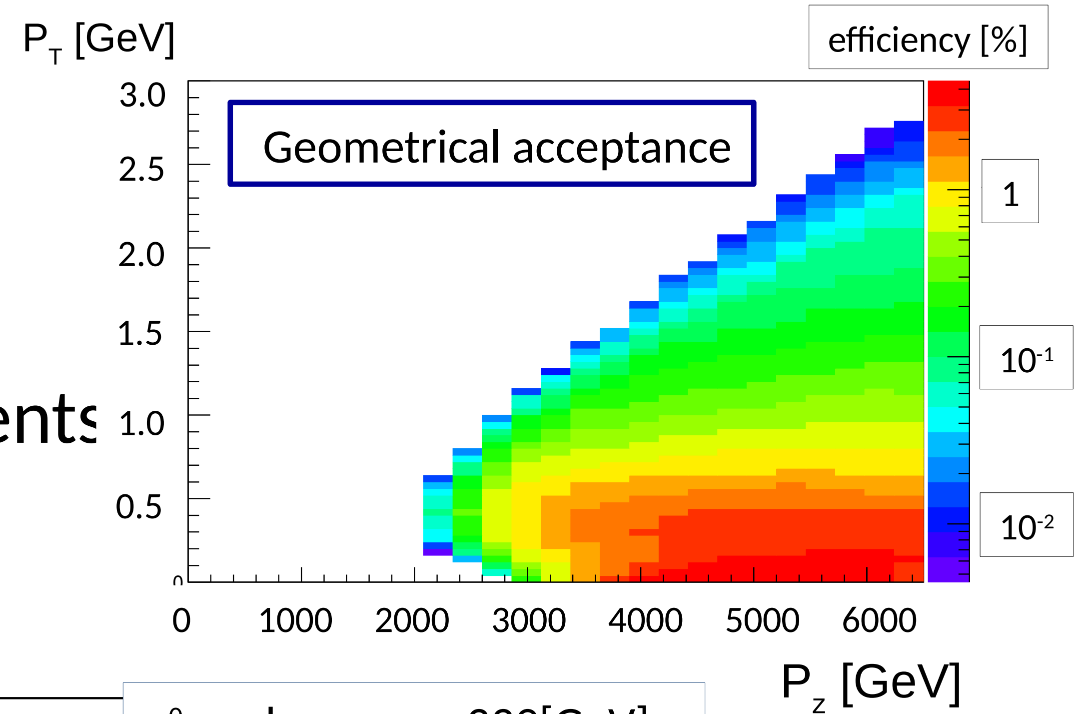


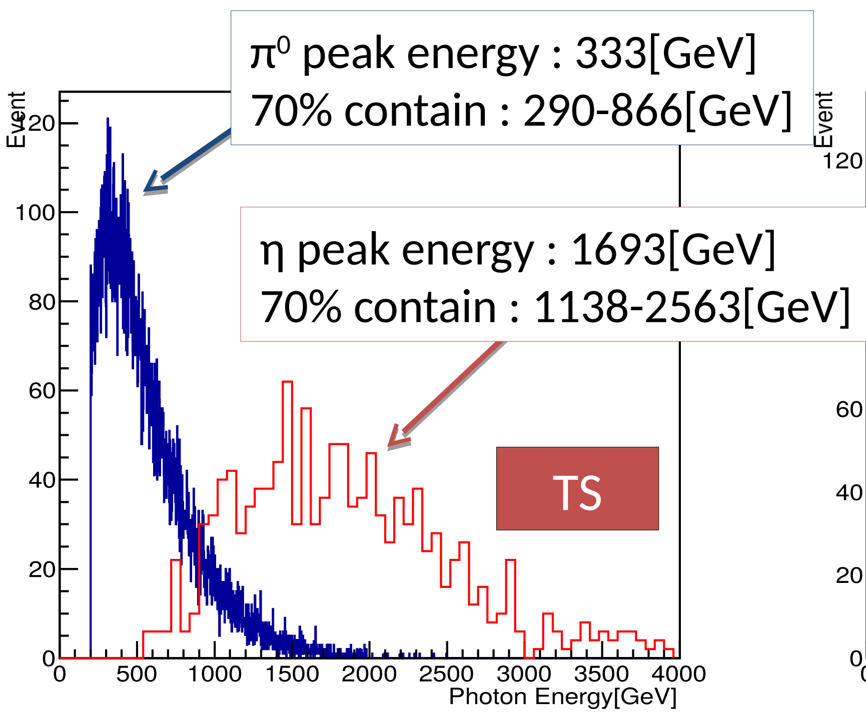
If hadron shower events are detected in both arms, what can we see?

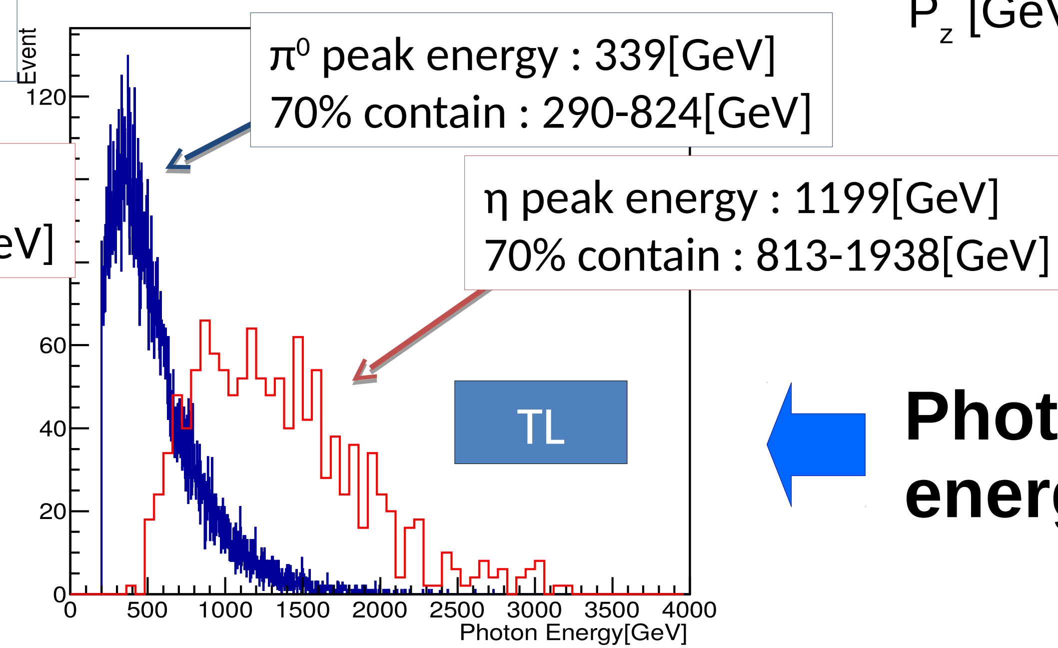
Data sample:
about 1000 events
($\eta > 10.60$)

η analysis

- Data sample:
  Fill #3855
  Entries: 53539 events
  π^0 meson: 23247 events
  η meson: 467 events

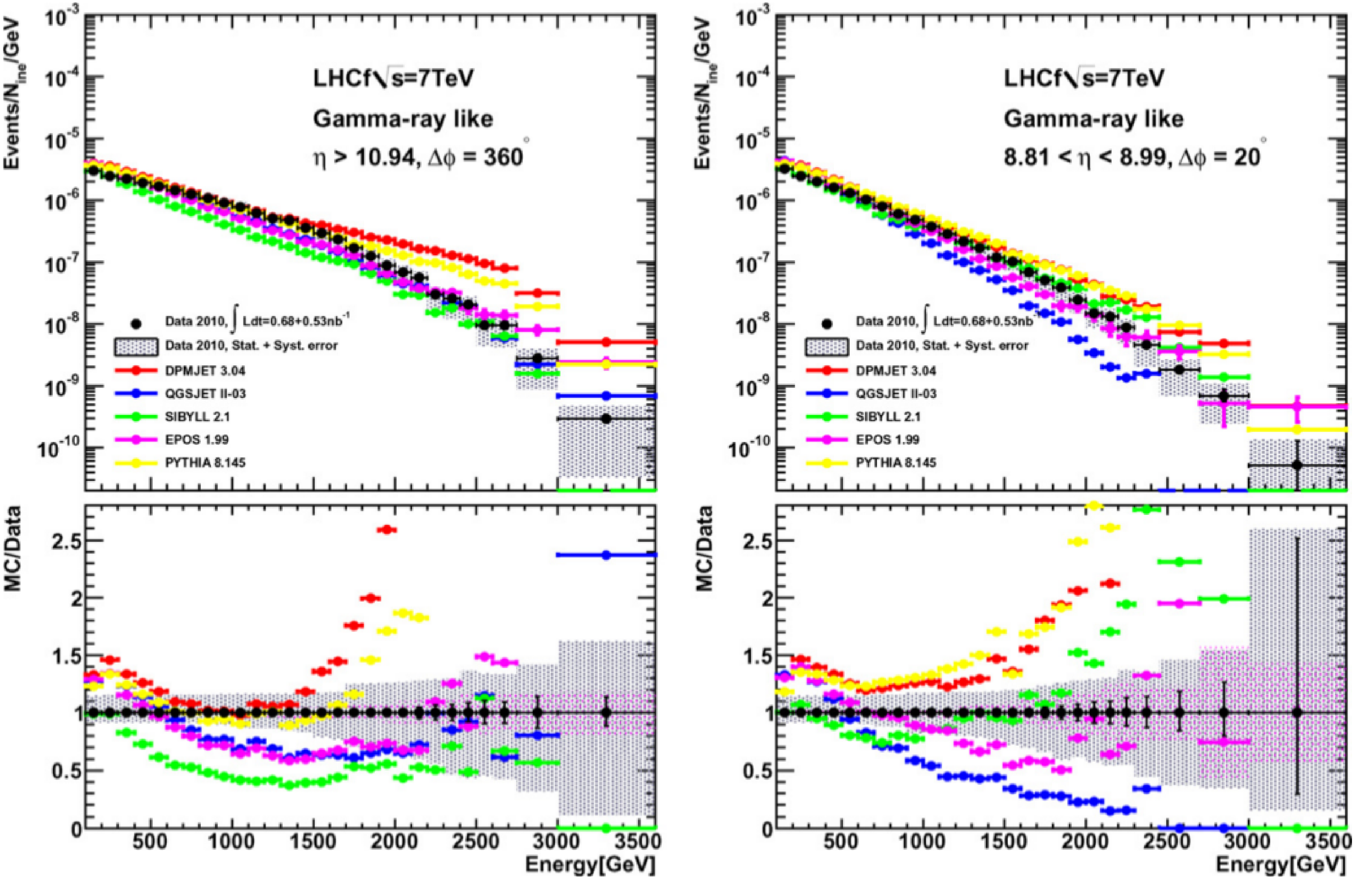






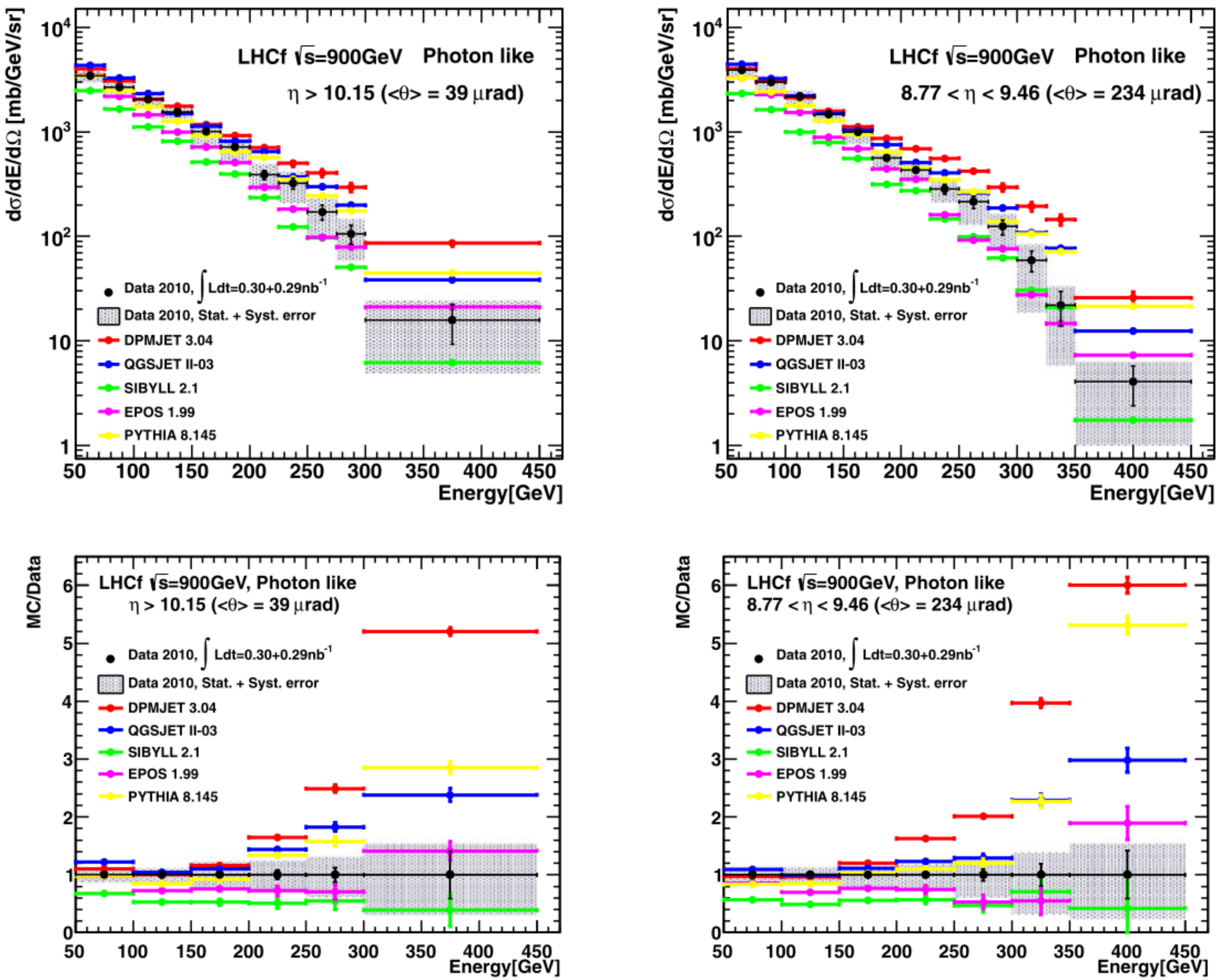
Photon energy

Photons spectrum in p-p at 7 TeV



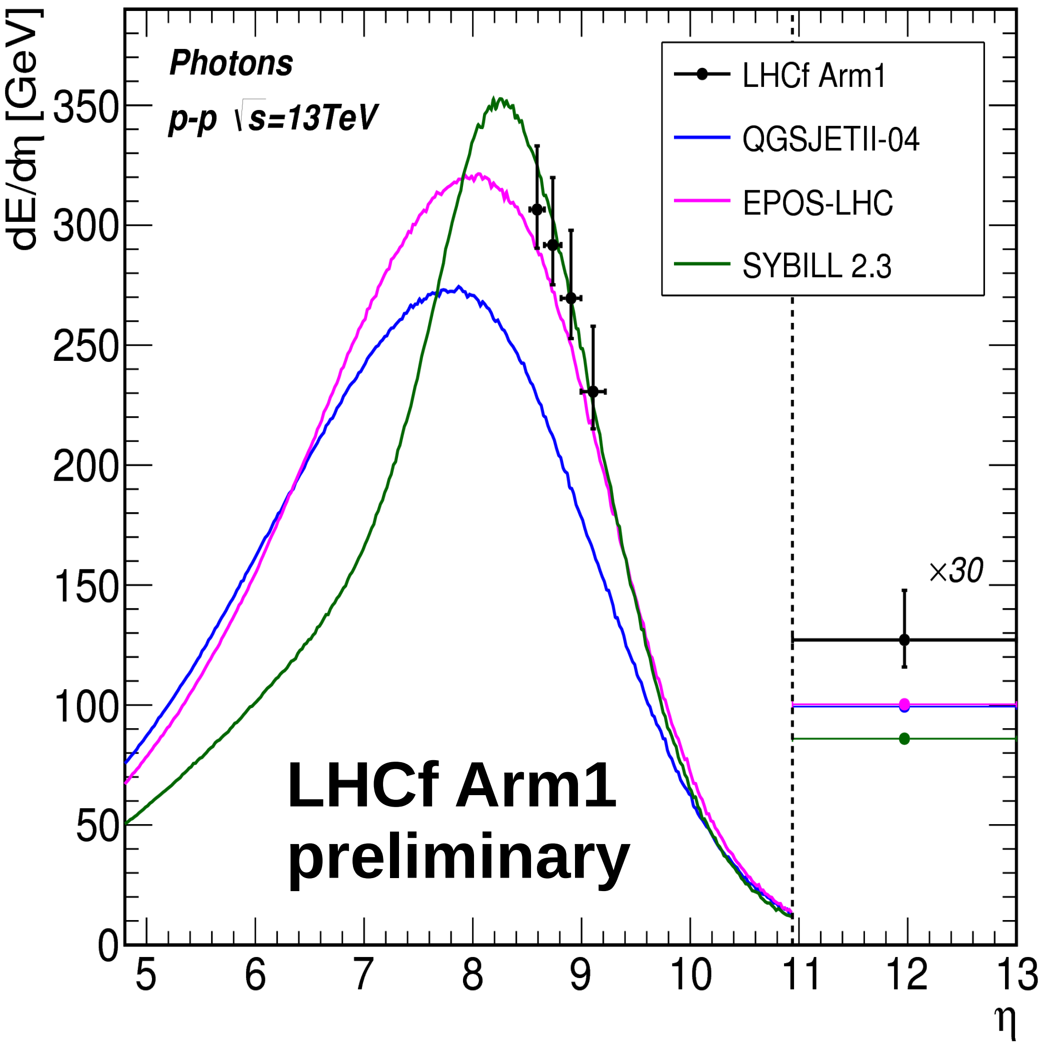
PLB 703 (2011), 128-134

Photons spectrum in p-p at 900 GeV



PLB 715 (2012), 298-303

Electromagnetic energy flow



- Integrated from measured spectrum
- Low-η acceptance region extended: 8.52 < η < 9.22
- Best agreement with **SIBYLL 2.3** and **EPOS-LHC**
- **QGSJET II-04** predicts a less forward-peaked energy flow
- All models underestimate the flow in the η > 10.94 region

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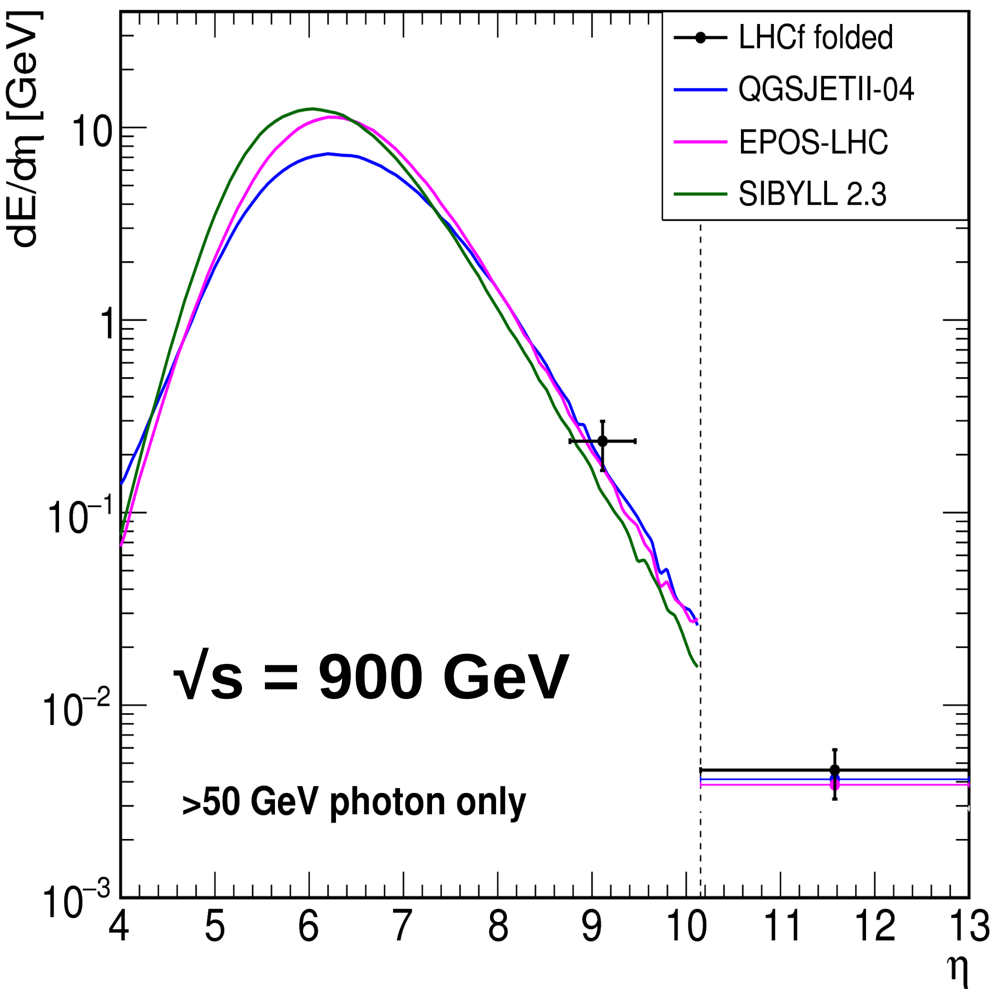
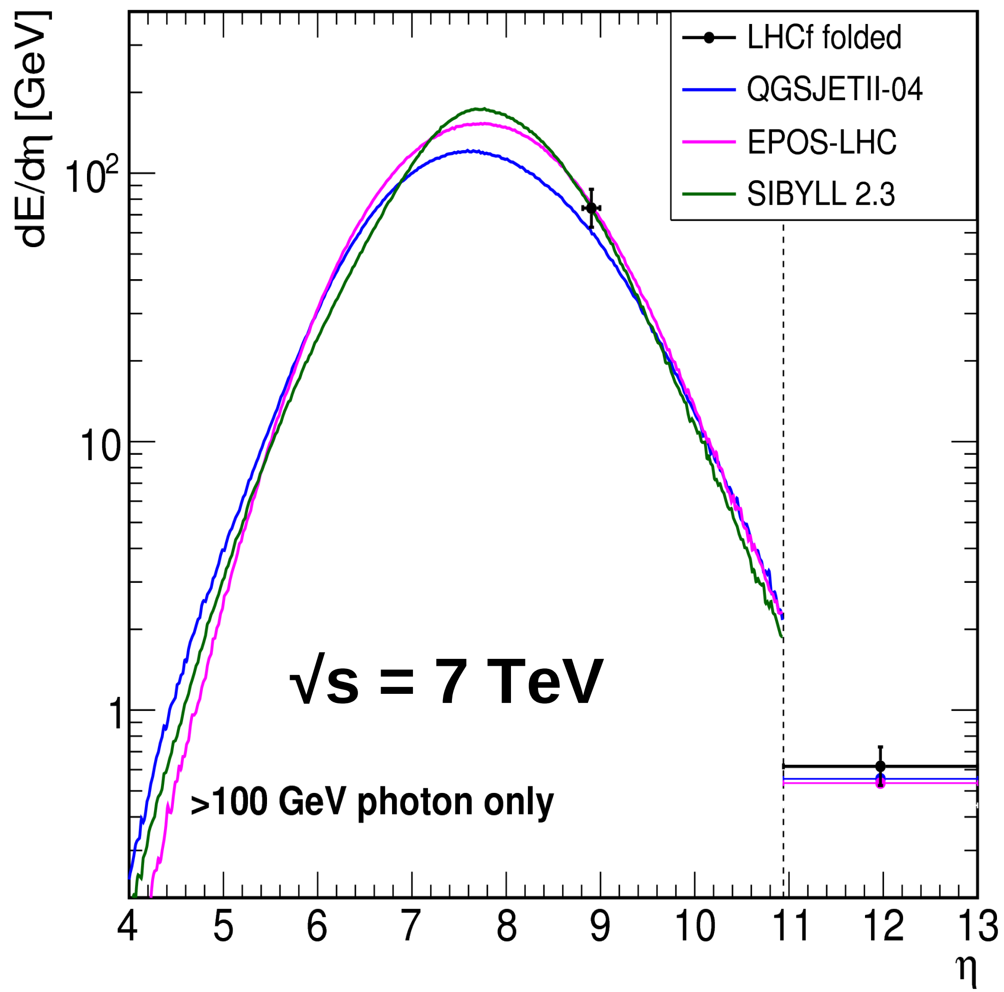
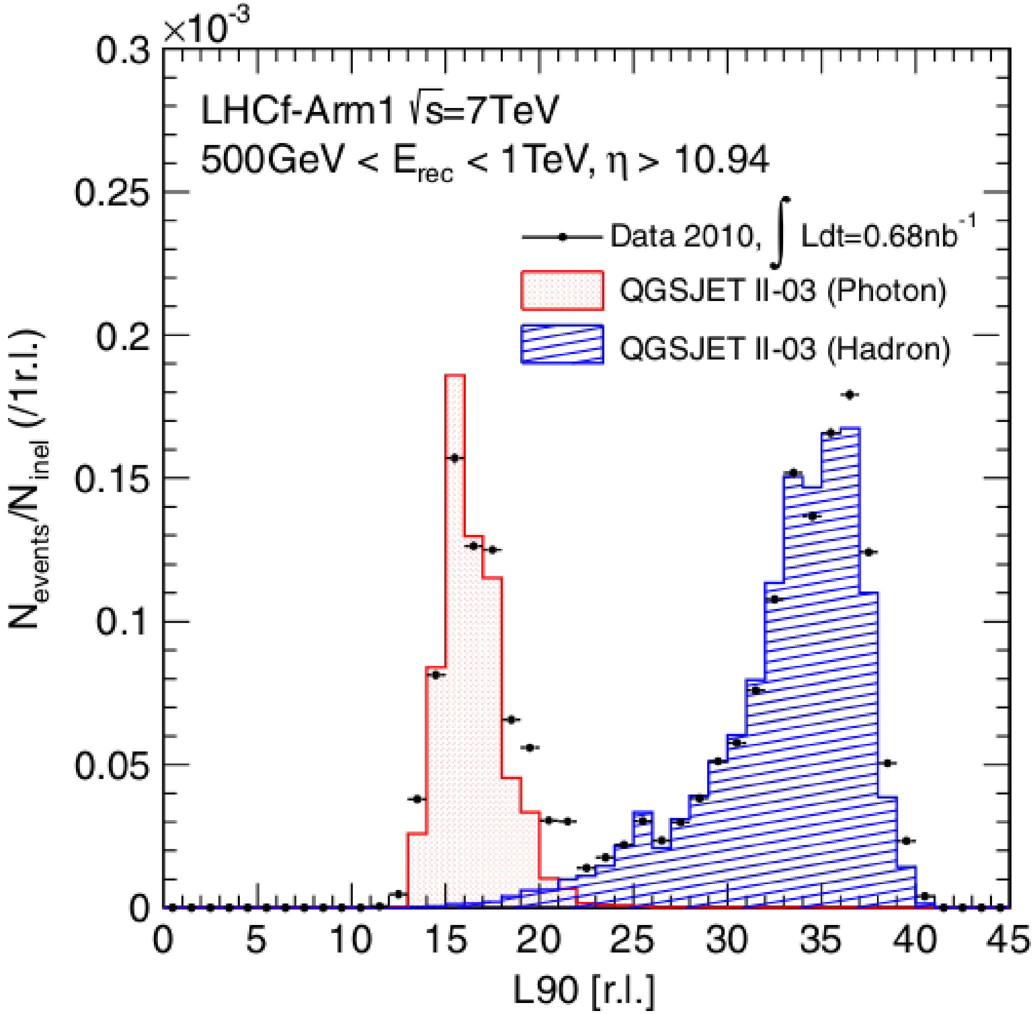
Energy flow: results at √s = 0.9, 7 TeV



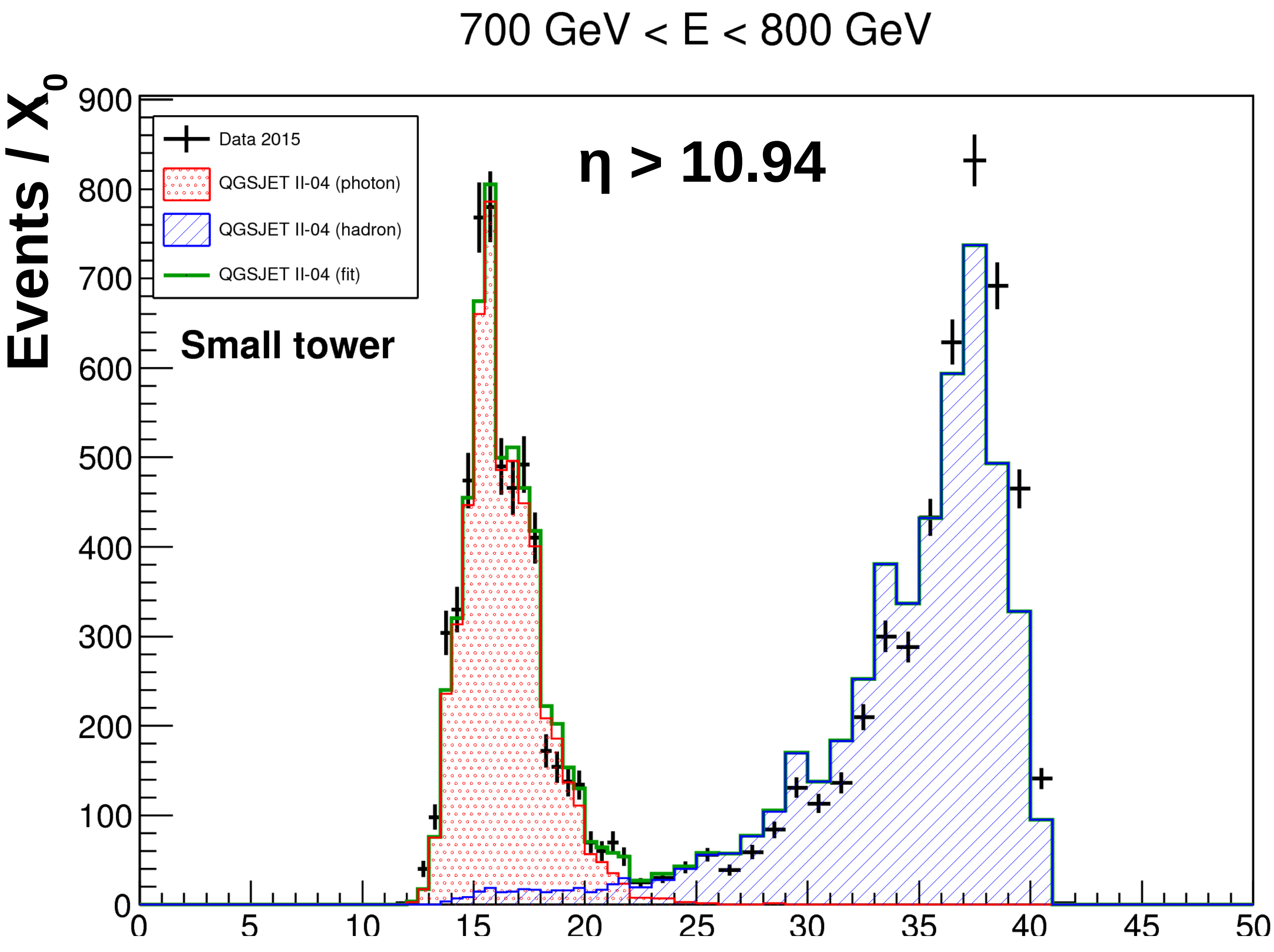


Photons selection

- $L_{90\%}$: depth where 90% of the deposited energy is contained
- Energy-dependent threshold to keep photon detection efficiency at 90%
- Events with $L_{90\%}$ less than the threshold are recognized as photons



Template fit (photon analysis)



Data
QGSJET: photons
QGSJET: hadrons
QGSJET: total

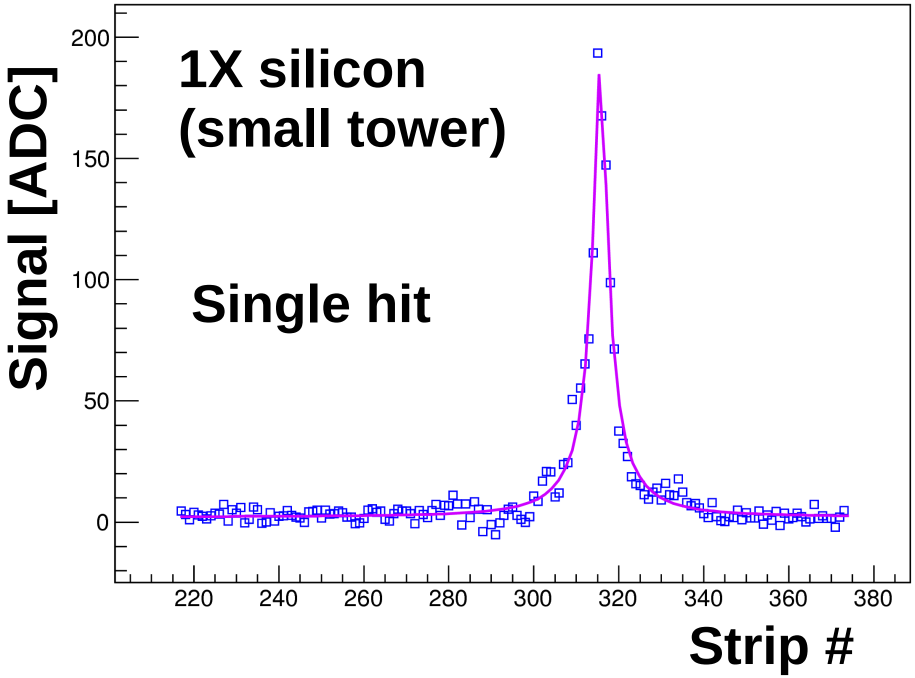
$L_{90\%}$ ≡ depth where 90% of the deposited energy is contained

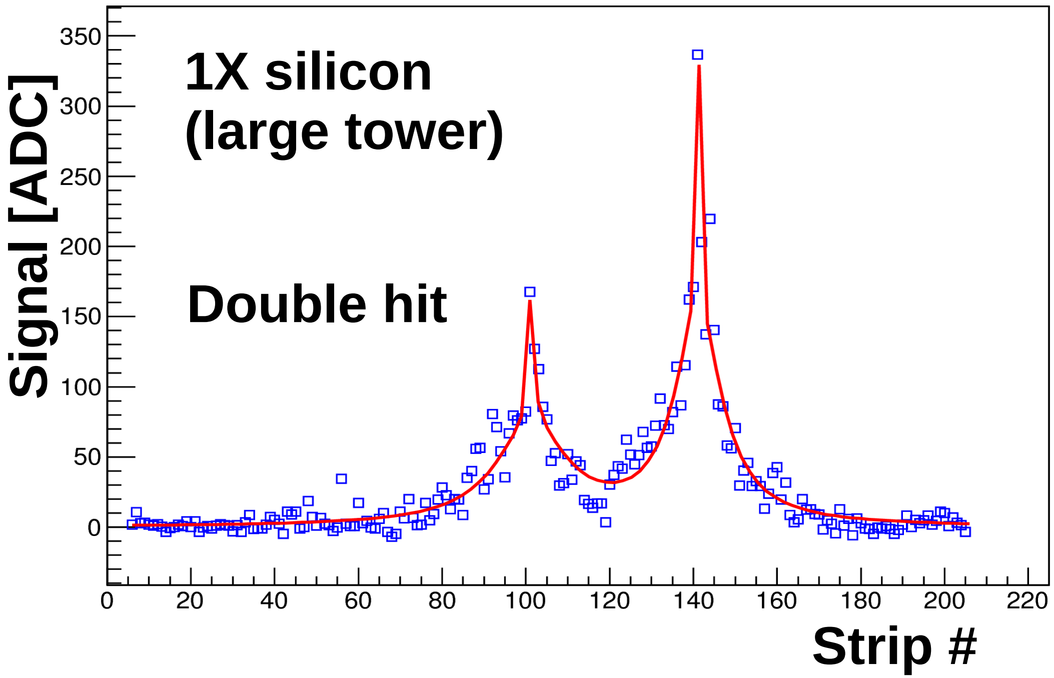
- Photon and hadron distributions are independently scaled to reproduce measured distribution

Position reconstruction

- Fit on transverse distribution of energy deposit (Arm1 → GSO bars, Arm2 → silicon microstrip)
- 3-components Lorentzian function

$$f(x) = p_0 \left[\frac{p_2}{\frac{(x-p_1)^2}{p_3} + p_3} + \frac{p_4}{\frac{(x-p_1)^2}{p_5} + p_5} + \frac{1-p_2-p_4}{\frac{(x-p_1)^2}{p_6} + p_6} \right]$$





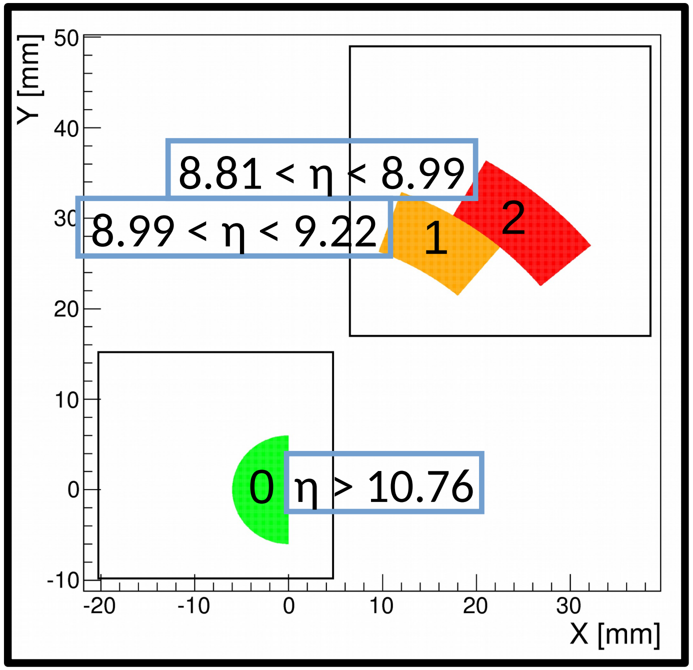
Analysis data set (neutrons)

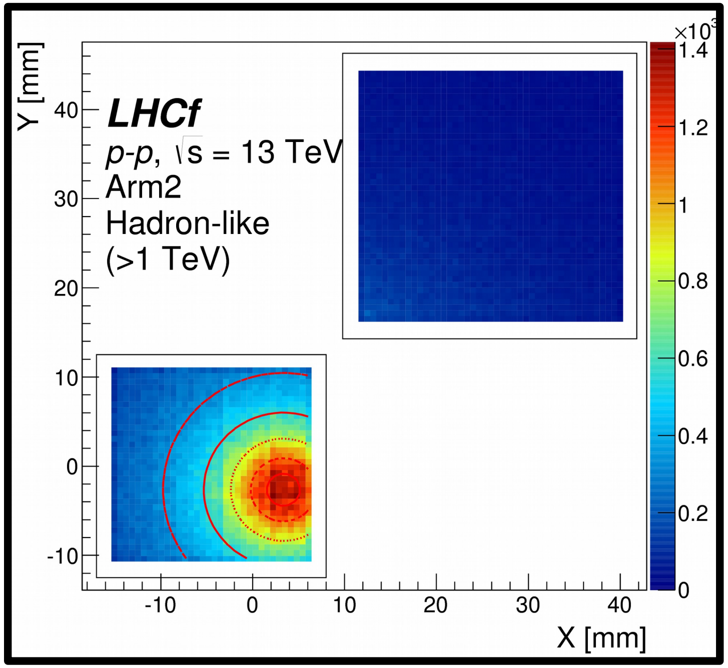
Data set

- 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

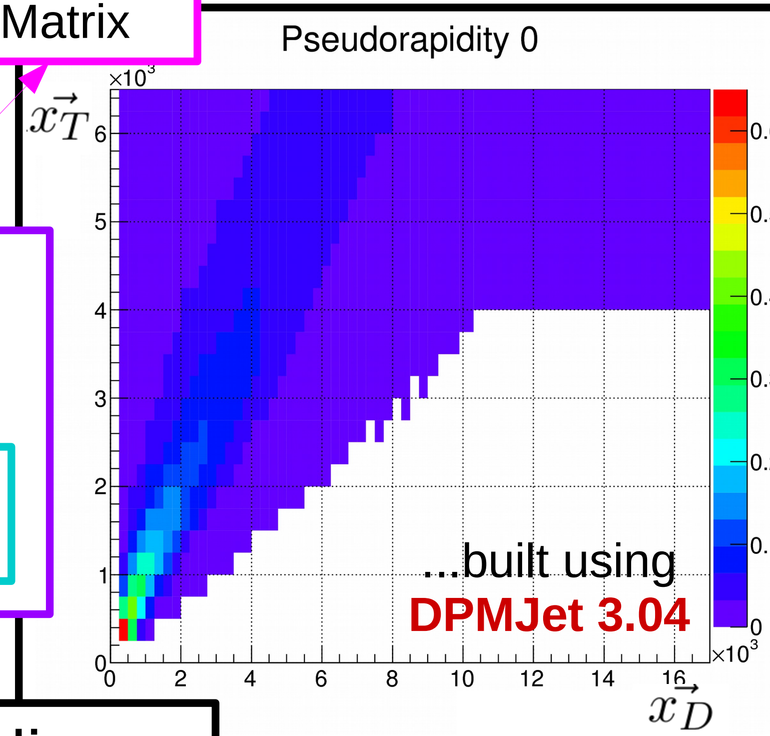
- Neutrons peaked along beam direction
- Perform a fit on 2D distribution
- Beam center is (+3.3, -2.7) mm
- Uncertainty is 0.3 mm for both x and y





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

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

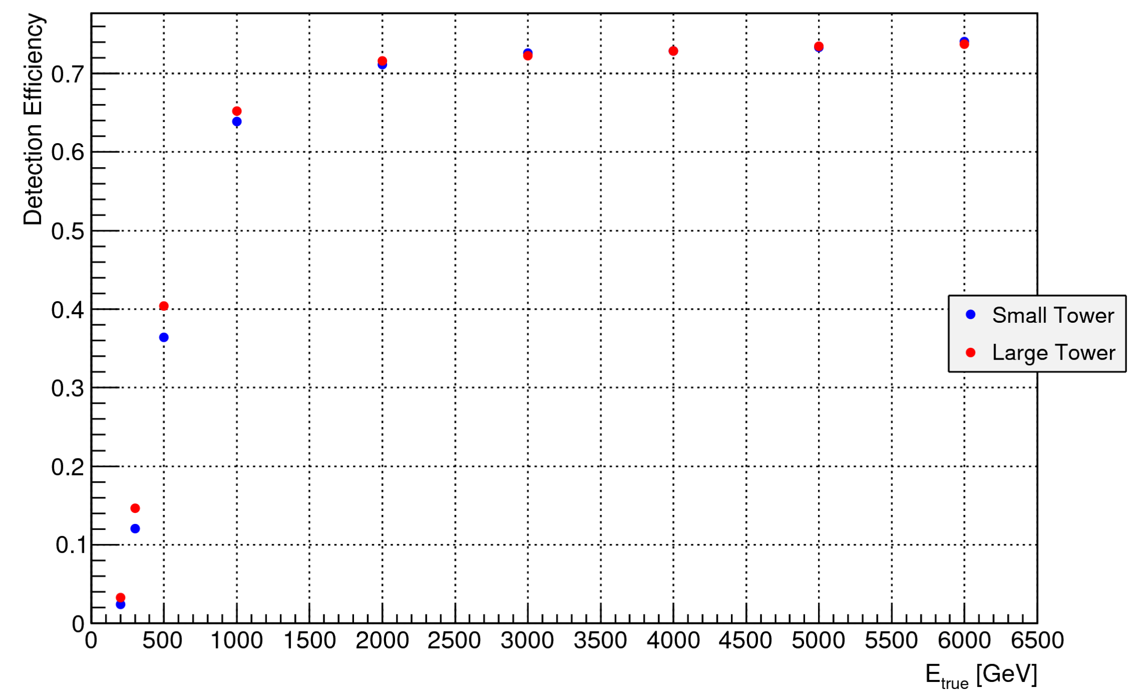
from MC

Unfolded spectra

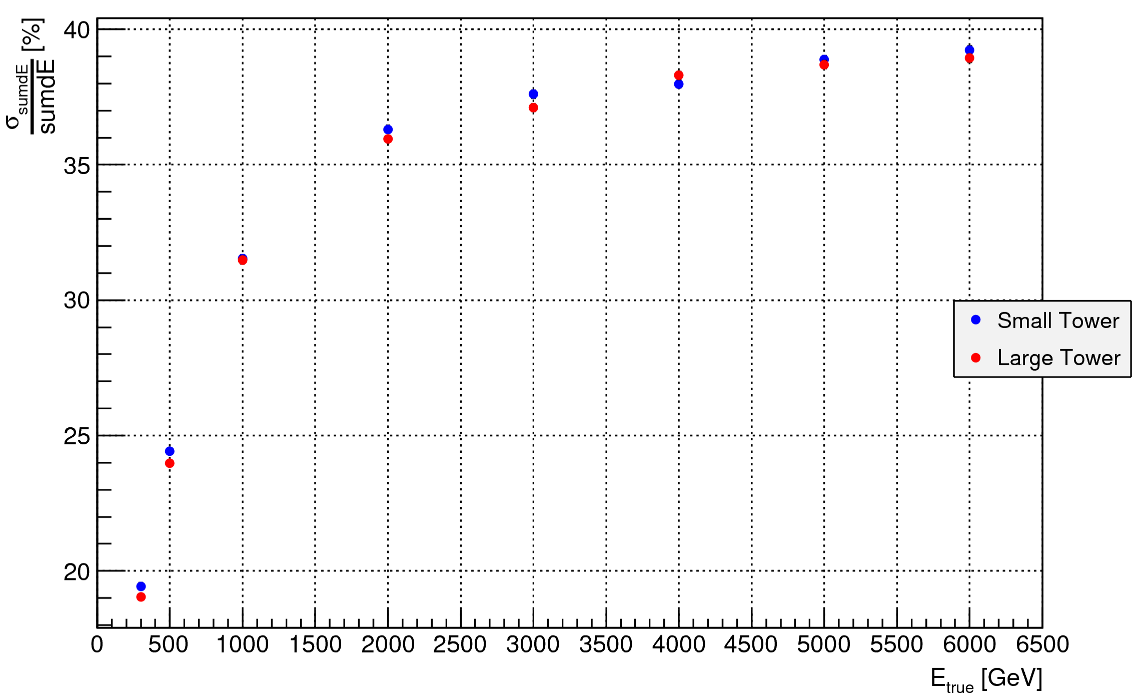
$$x_{T_i} = \frac{1}{\epsilon_i} \sum_{j=1}^{N_D} \theta_{ij} x_{D_j}$$

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

Performances (neutrons)



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