Overview of the latest physics results of the LHCf experiment

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on behalf of the LHCf Collaboration

Workshop on forward physics and high-energy scattering at zero degrees 2017

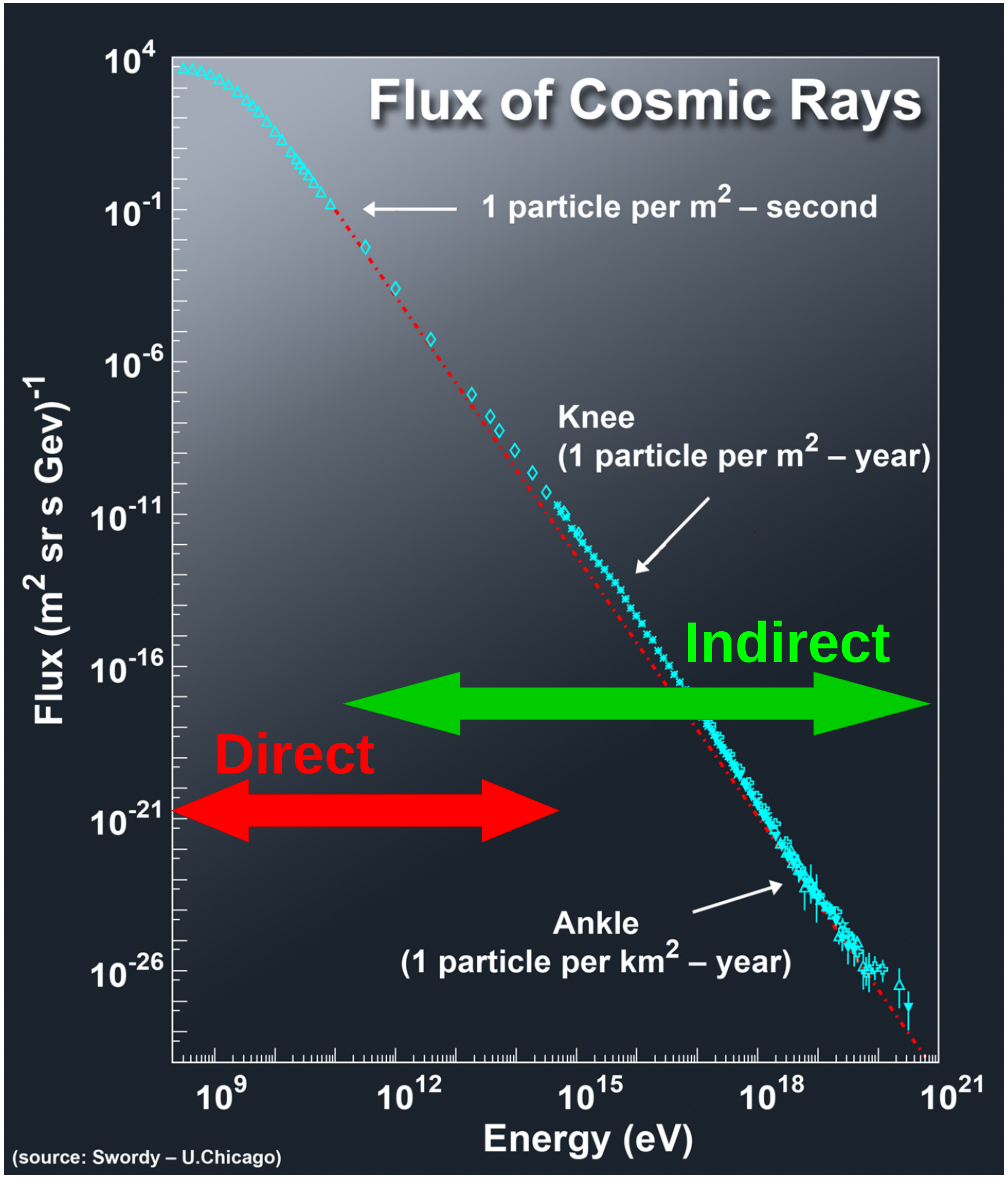
Nagoya, 26nd-29th September 2017

Outline

- Physics motivations
- The LHCf experiment
- Physics results
  - π^0 in p-p at 7 TeV and p-Pb at 5 TeV
  - photons in p-p collisions at 13 TeV
  - neutrons in p-p collisions at 13 TeV
- Ongoing activities

Physics motivations

Cosmic rays: spectrum

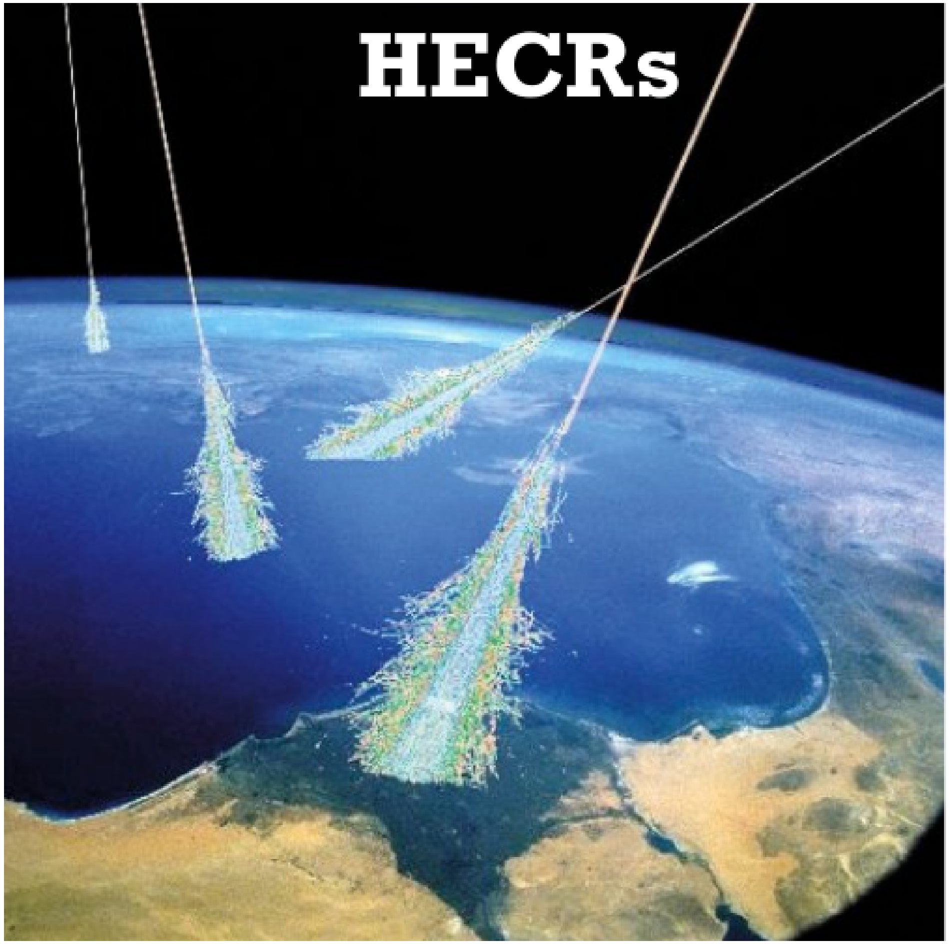


Credit: ASPERA/G.Toma/A.Saftoiu

- 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:

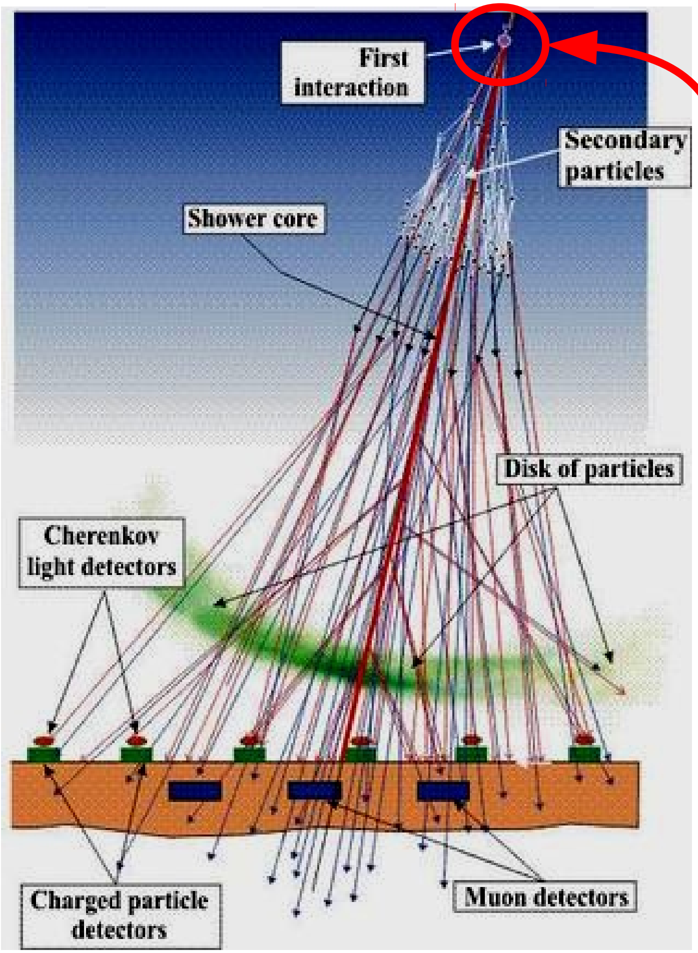
- Longitudinal distribution
- N° of particles at ground
- Arrival direction

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**

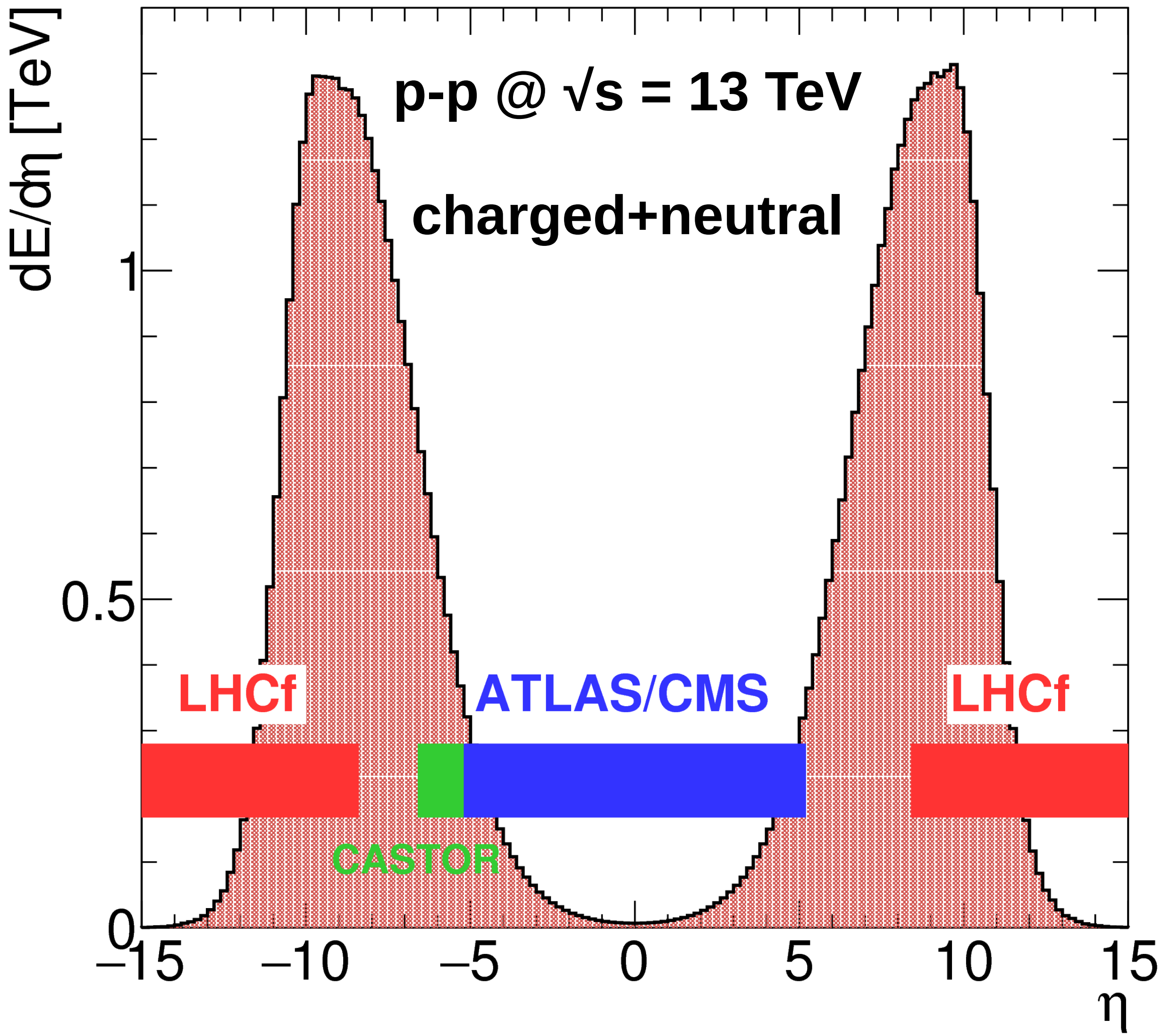
Energy flow in the very-forward region

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

LHCf acceptance covers the energy peak

Pseudo-rapidity

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

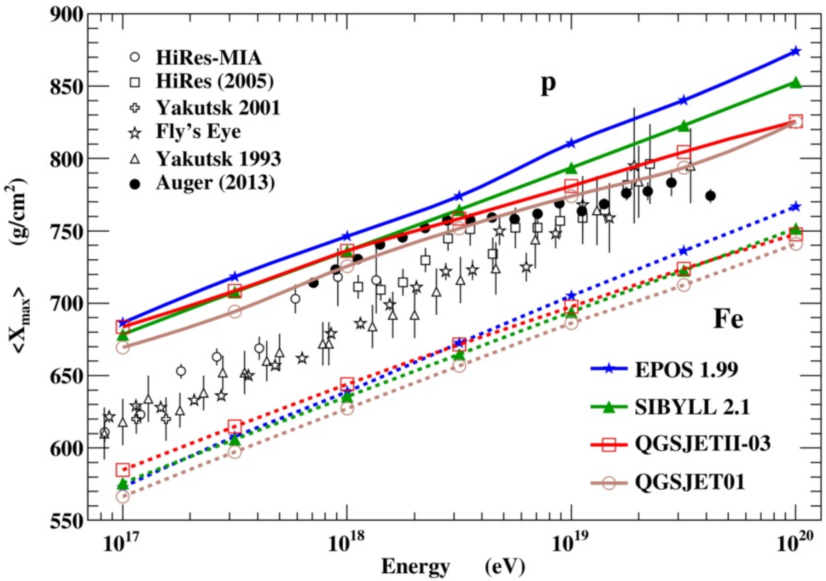


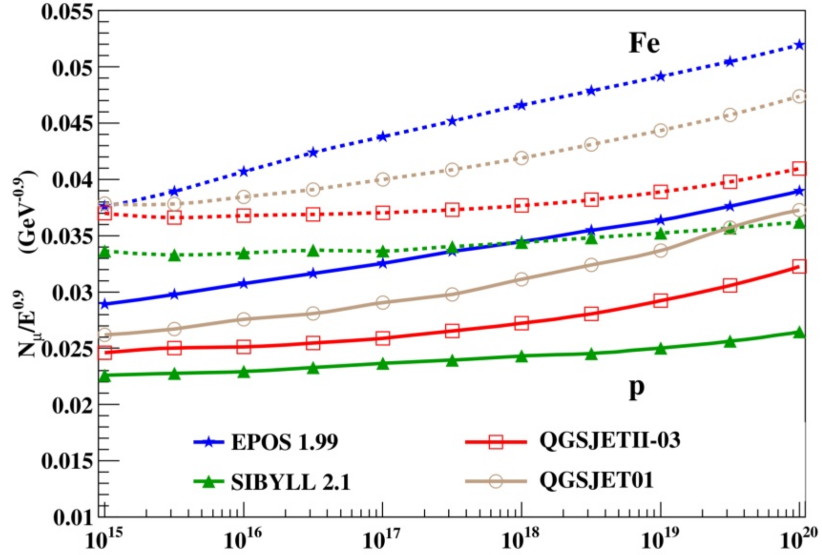
LHC contribution to models

Mean depth of shower maximum

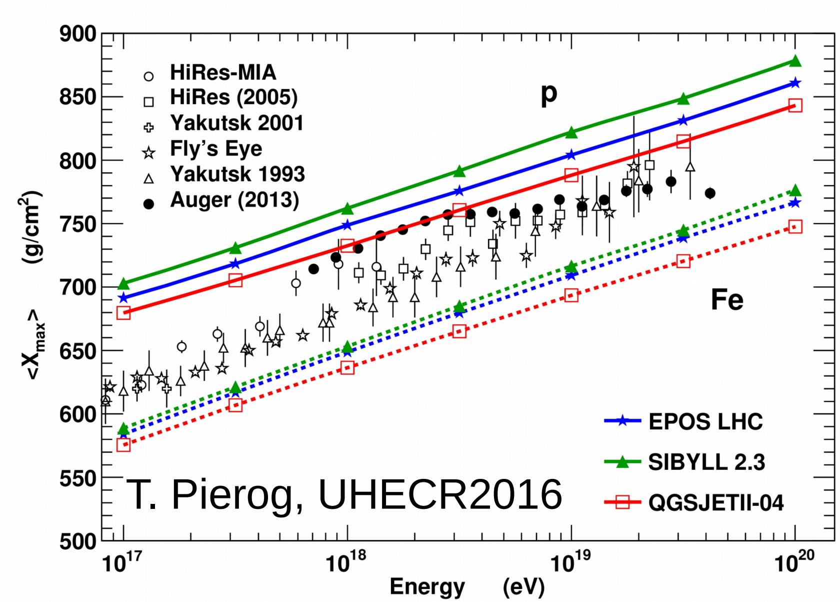
N° of muons at ground

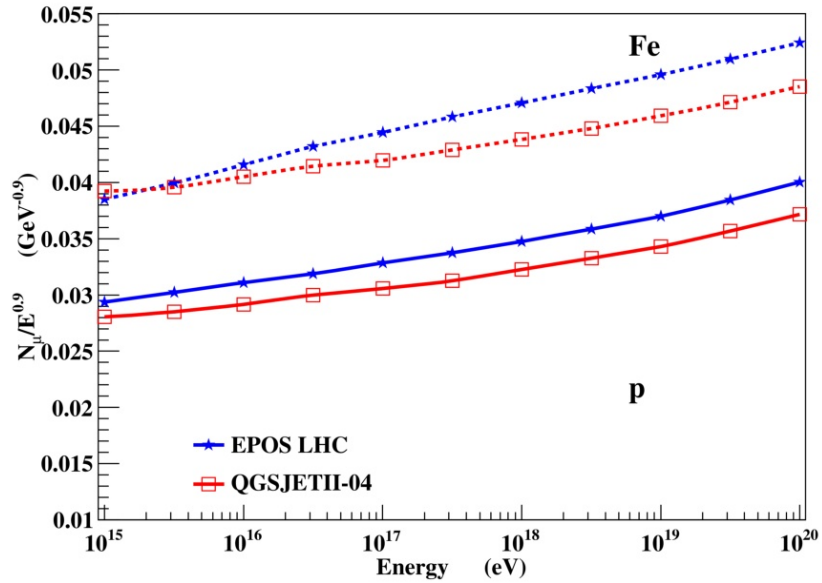
Pre-LHC





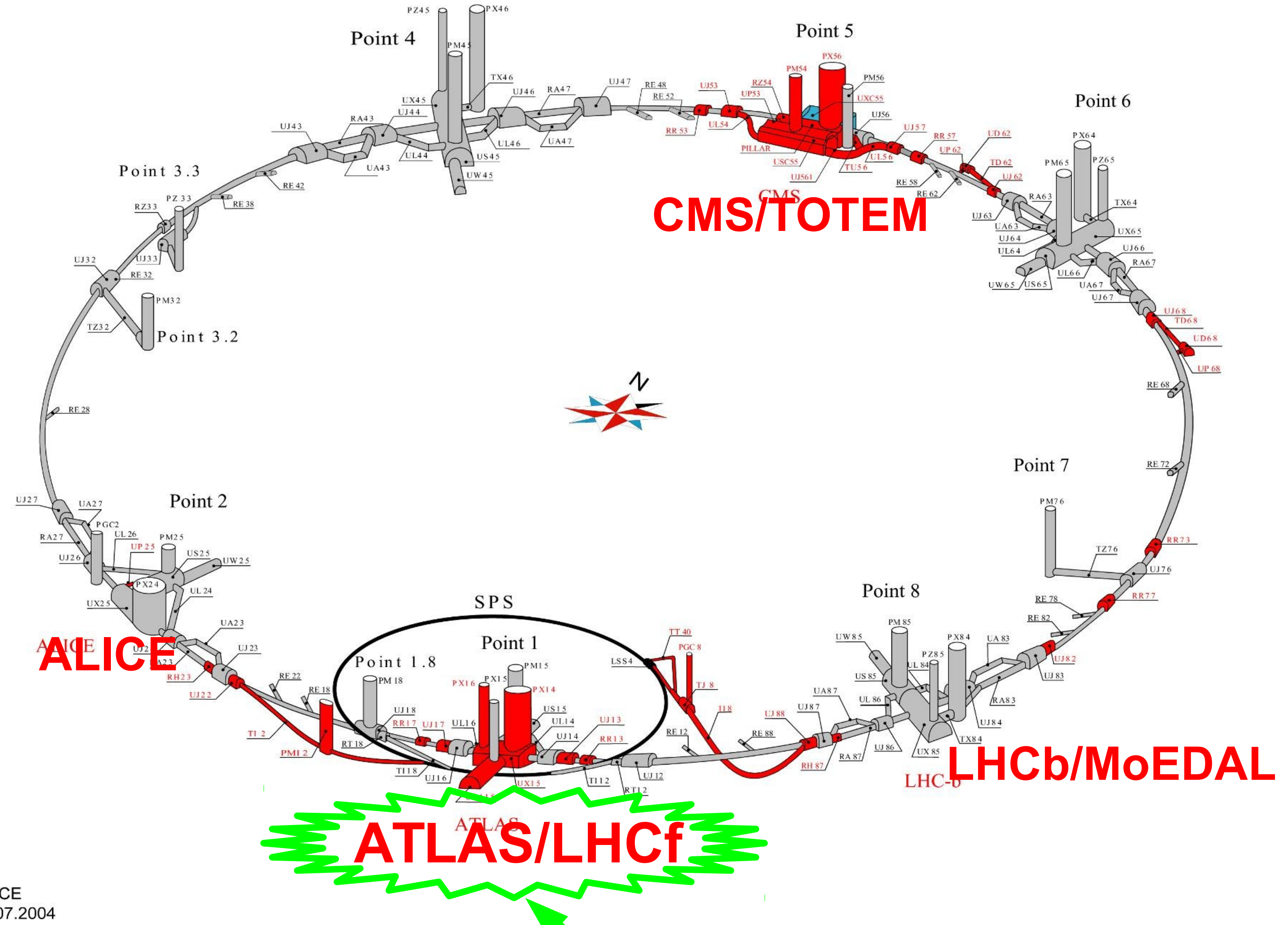
Post-LHC





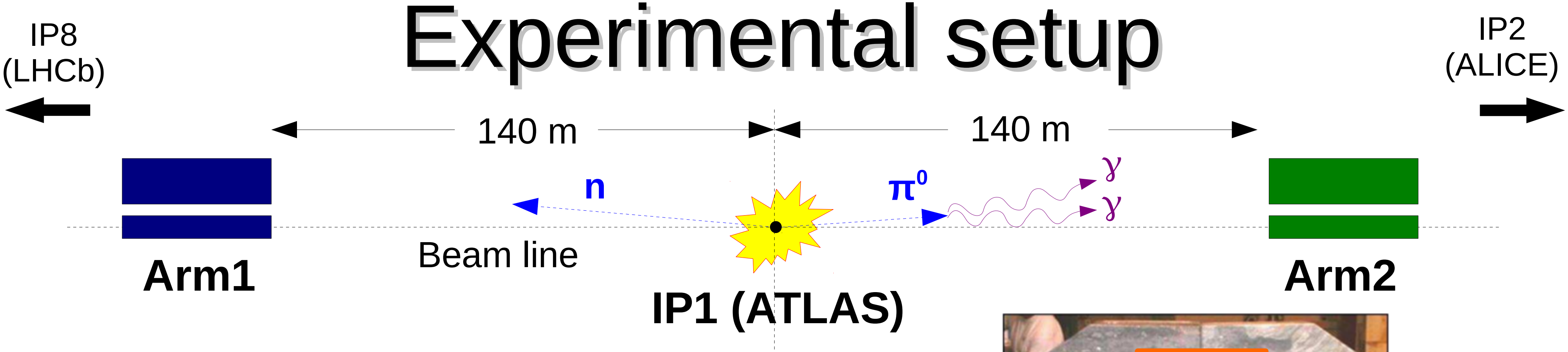
The LHCf experiment

LHCf at the Large Hadron Collider



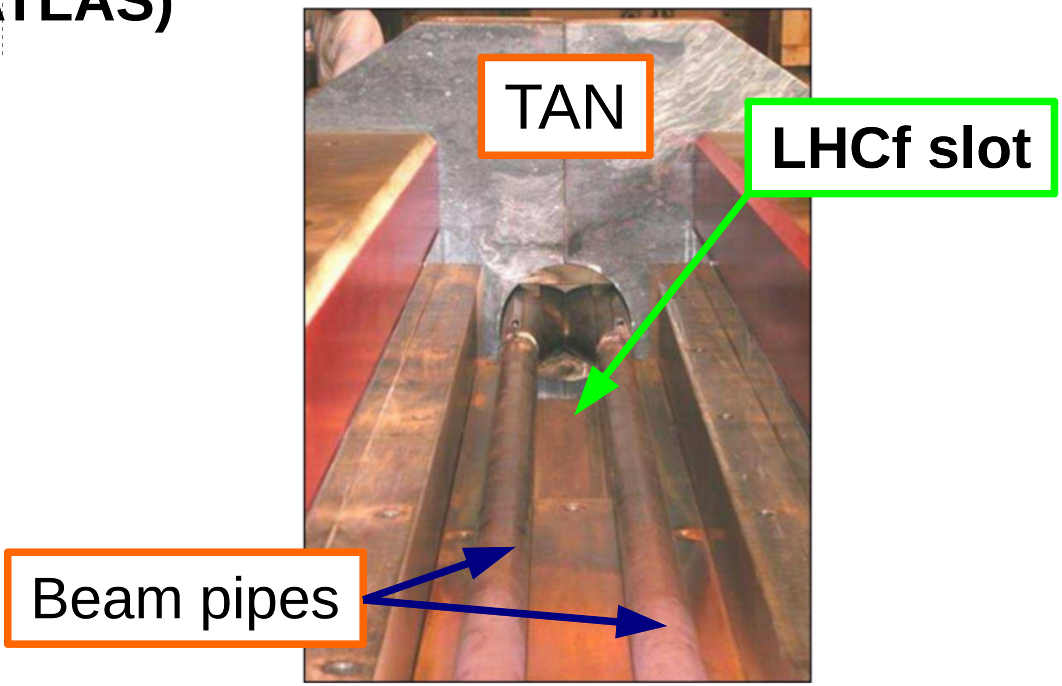
Two independent detectors are located 140m away from ATLAS (Interaction Point 1) along the beam line

Experimental setup



LHCf is located in TAN slot

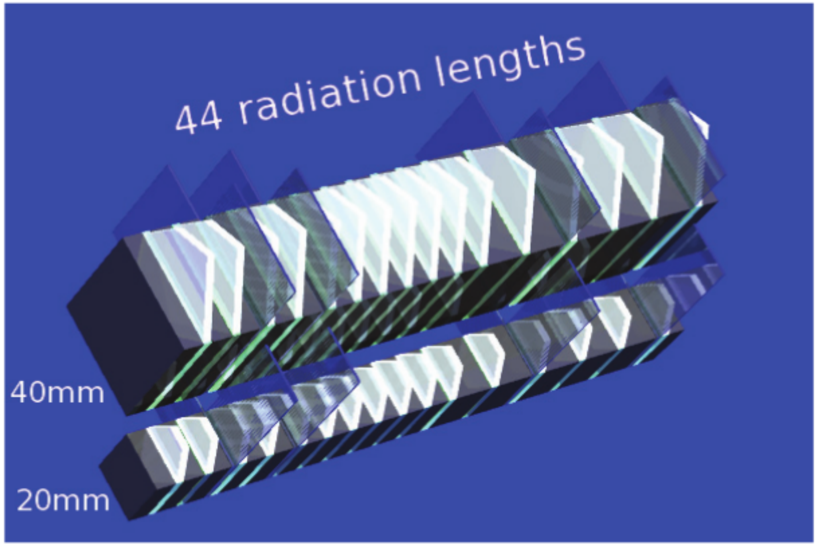
Zero degree particles!
Coverage from **η = 8.4**
(with 140 urad crossing
angle) to **∞**

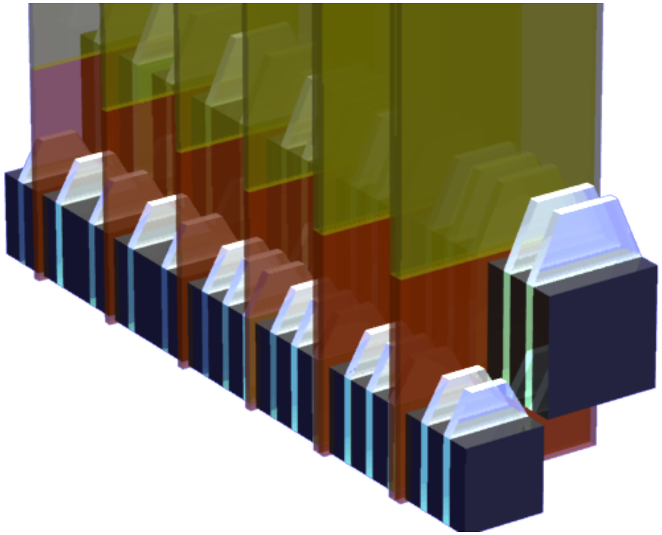


Charged particles are deflected by D1 dipole magnet

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

Detectors performance





Arm 1

- 20 x 20 mm^2 and 40 x 40 mm^2 sampling calorimeters: tungsten and **GSO scintillators**
- Depth: 44 X_0, 1.6 λ
- 4 x-y **GSO bars** tracking layers
- Position resolution: < 200 μm
- Energy resolution:
  - < 2% (photons)
  - ~ 40% (neutrons)

Arm 2

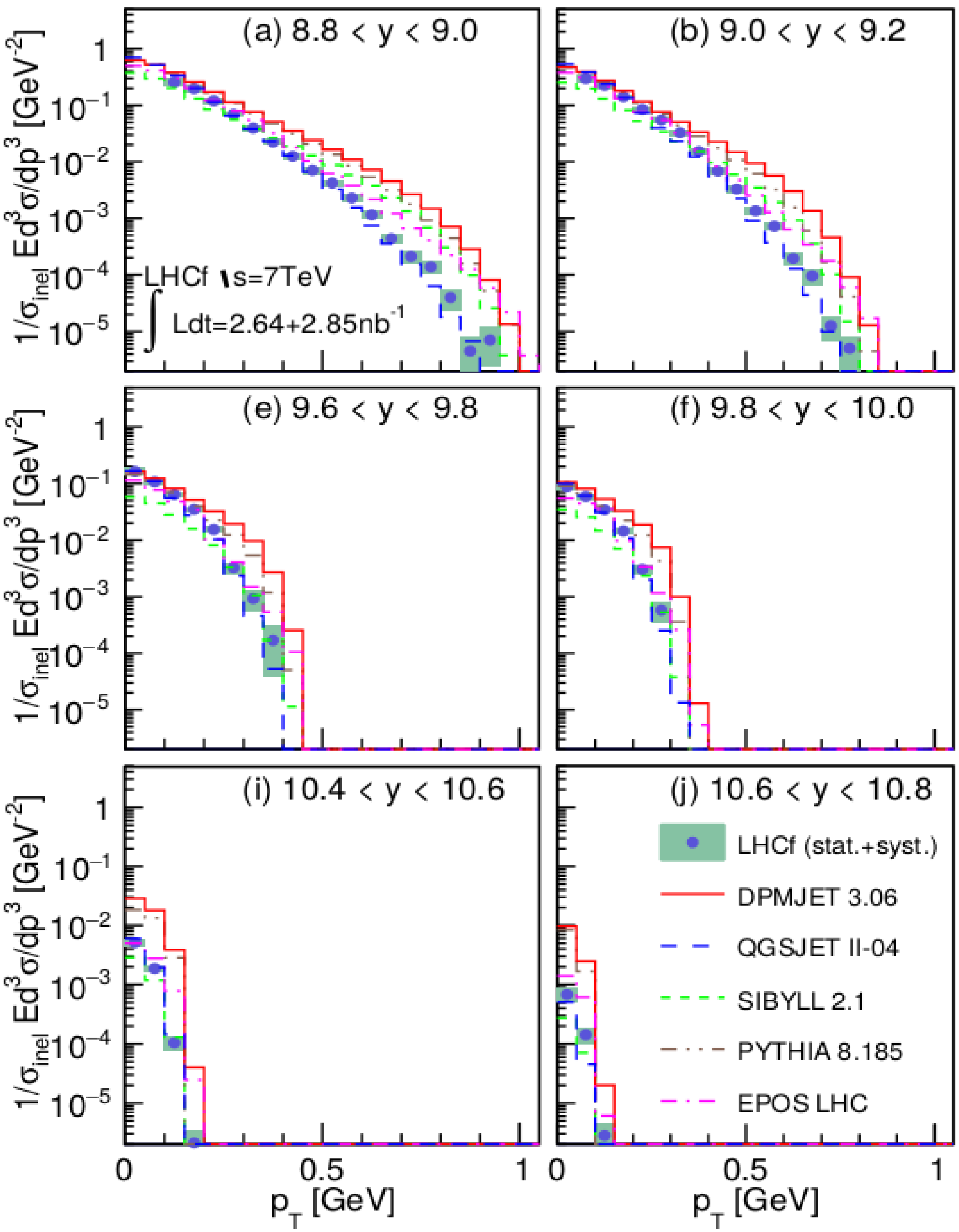
- 25 x 25 mm^2 and 32 x 32 mm^2 sampling calorimeters: tungsten and **GSO scintillators**
- Depth: 44 X_0, 1.6 λ
- 4 x-y **silicons microstrip** tracking layers
- Position resolution: 40 μm
- Energy resolution:
  - < 2% (photons)
  - ~ 40% (neutrons)

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: π^0

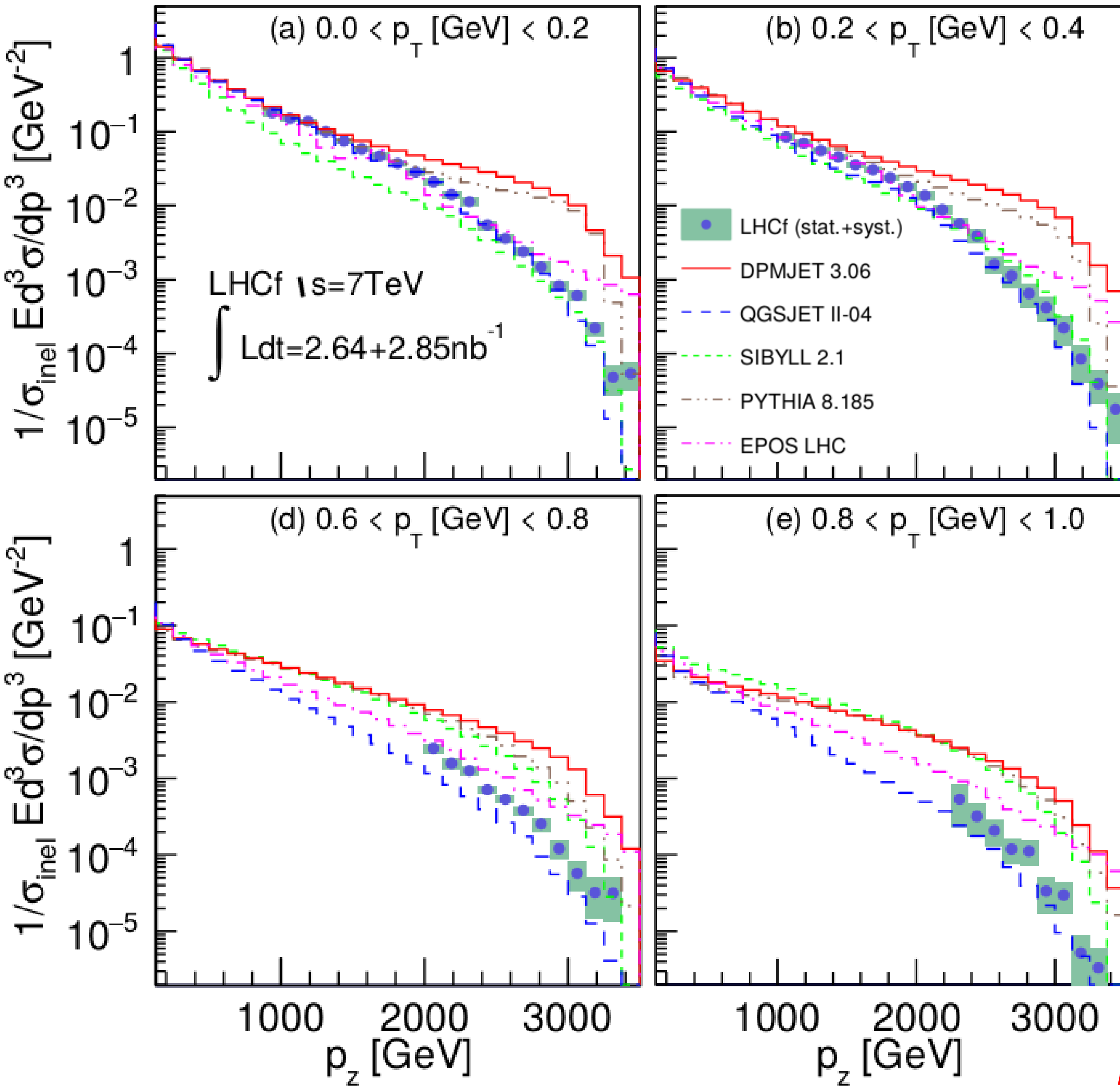
Inclusive π^0 P_T spectra in p-p @ 7 TeV



- Good agreement of QGSJET II-04
- EPOS-LHC slightly harder at $P_T > 0.5$ GeV
- Sibyll OK at $8.8 < y < 9.2$ and $P_T < 0.4$ GeV, low yield at $y > 9.2$
- DPMJET and Pythia OK at $9.0 < y < 9.8$, and $P_T < 0.2$ GeV, harder at $P_T > 0.2$ GeV

PRD 94, 032007 (2016)

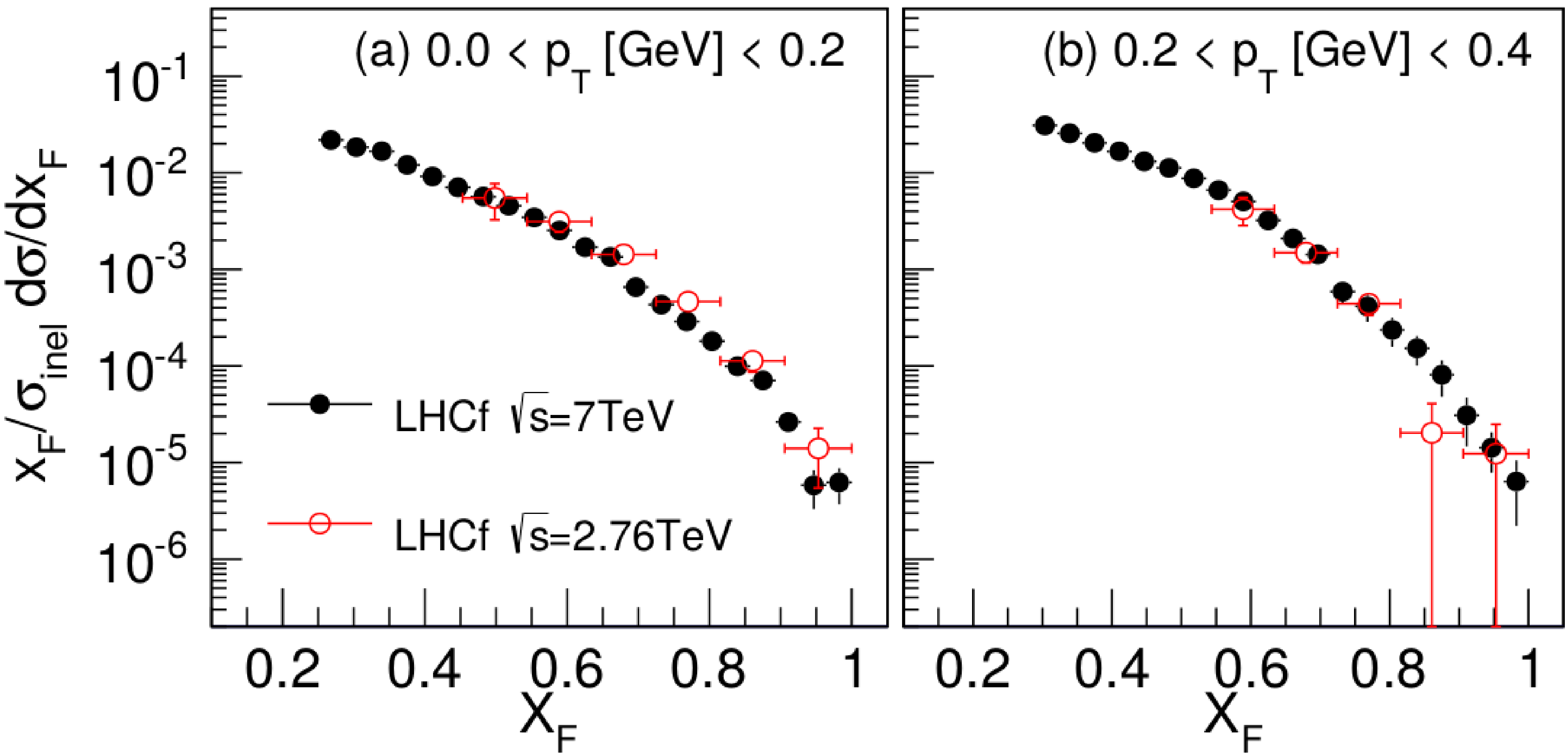
Inclusive π^0 P_Z spectra in p-p @ 7 TeV



- Good agreement of QGSJET II-04
- EPOS-LHC harder at $P_Z > 2$ TeV
- DPMJET and Pythia OK at $P_T < 0.2$ GeV and $P_Z < 1.6$ TeV, harder at $P_Z > 1.6$ TeV
- SIBYLL similar to DPMJET and PYTHIA increasing P_T, low yield at $P_T < 0.2$ GeV

PRD 94, 032007 (2016)

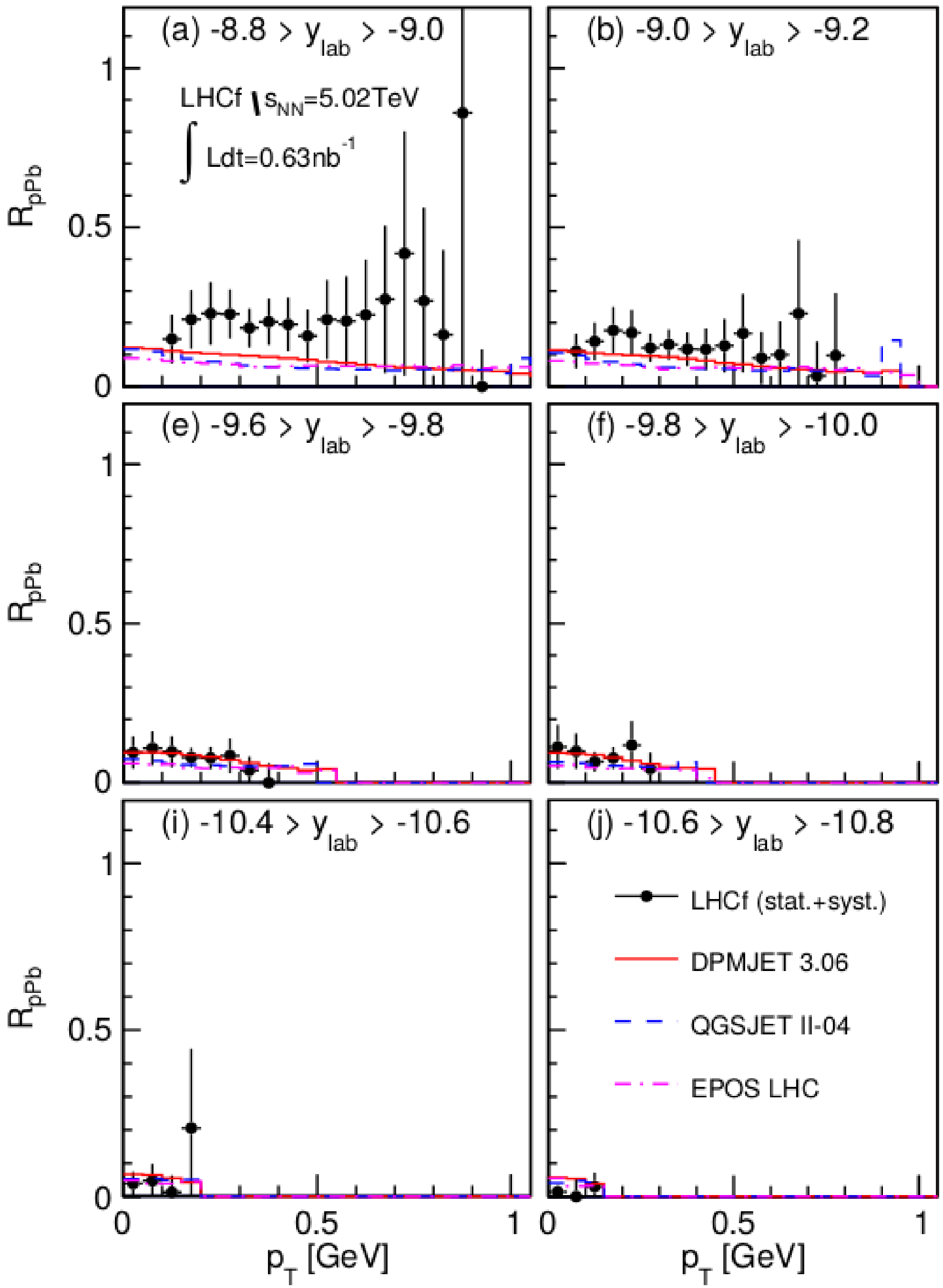
π^0: Feynman scaling hypothesis



- Hypothesis: cross section of secondary particles as a function of $X_F = 2\ P_Z / \sqrt{s}$ is independent of $\sqrt{s}$ for $X_F > 0.2$
- Feynman scaling holds at the ~20% level

PRD 94, 032007 (2016)

π^0: nuclear modification factor in p-Pb



$$R_{\rm pPb}(p_{\rm T}) \equiv \frac{\sigma_{\rm inel}^{\rm pp}}{\langle N_{\rm coll}\rangle \sigma_{\rm inel}^{\rm pPb}} \frac{Ed^3\sigma^{\rm pPb}/dp^3}{Ed^3\sigma^{\rm pp}/dp^3}$$

$$\langle N_{\rm coll}\rangle = 6.9$$

interpolated at 5.02 TeV using 7 TeV and 2.76 TeV data

- Both data and MC show a strong suppression
- Overall good agreement between data and MC

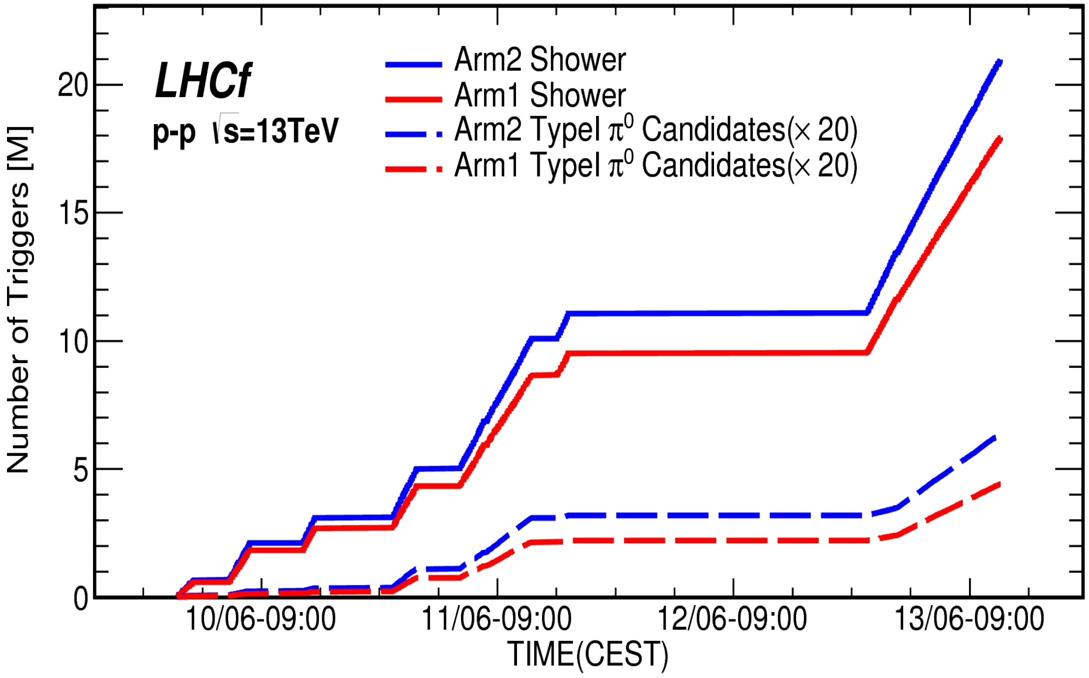
PRD 94, 032007 (2016)

Physics results: photons

LHCf run at 13 TeV

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

- **$\sqrt{s}$ = 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**



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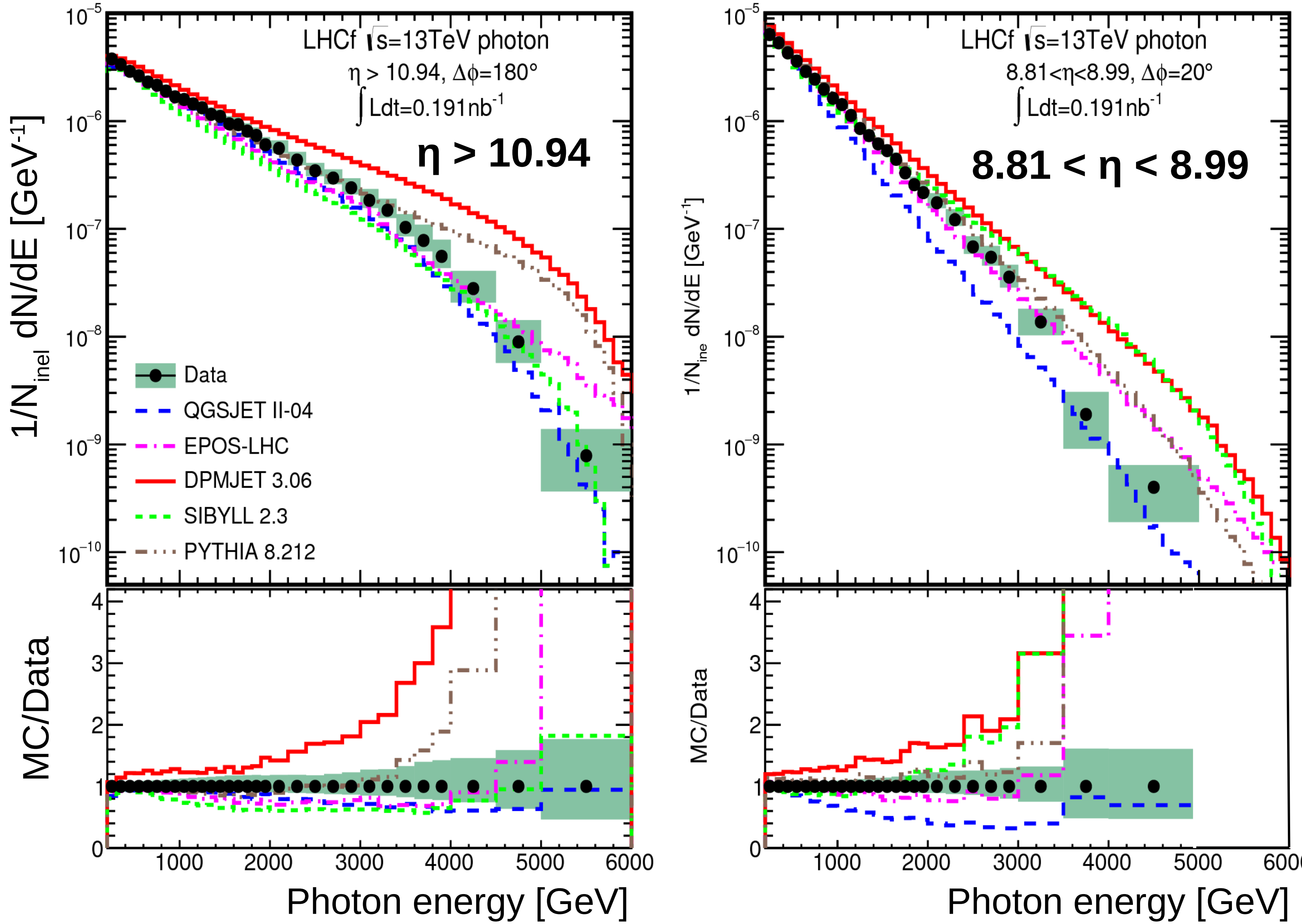
- **Pile-up:** 0.01 - 0.03
- 4 · 10^7 **events**
  5 · 10^5 **π^0s**
- Trigger exchange with **ATLAS**

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:** 0.191 nb^{-1}
- 3.9 · 10^6 **events**

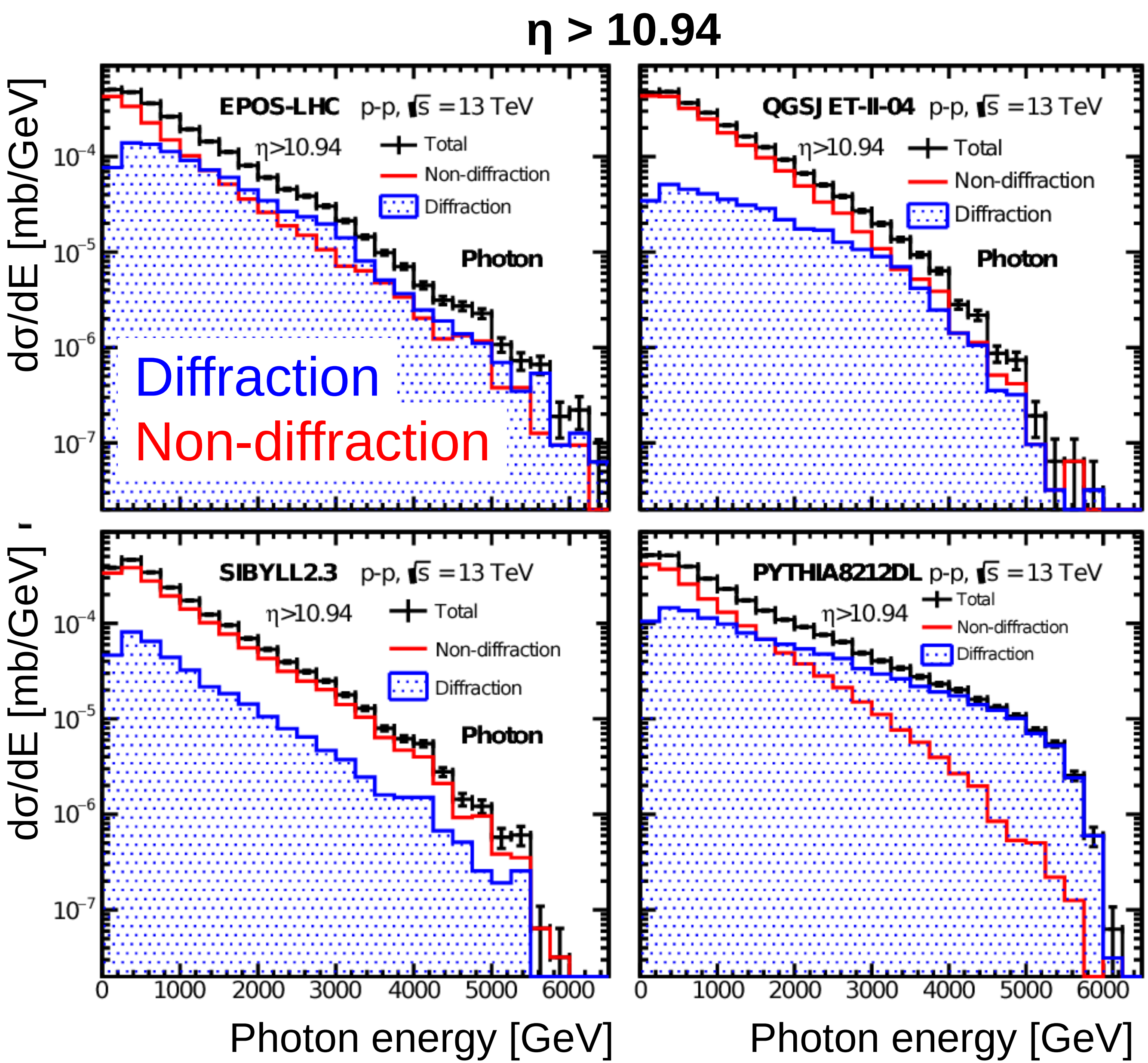
Photon spectrum in p-p at 13 TeV



CERN-EP-2017-051

- 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



Hadronic interaction models predict different contributions from diffraction

Central detectors can give useful information to identify diffractive events

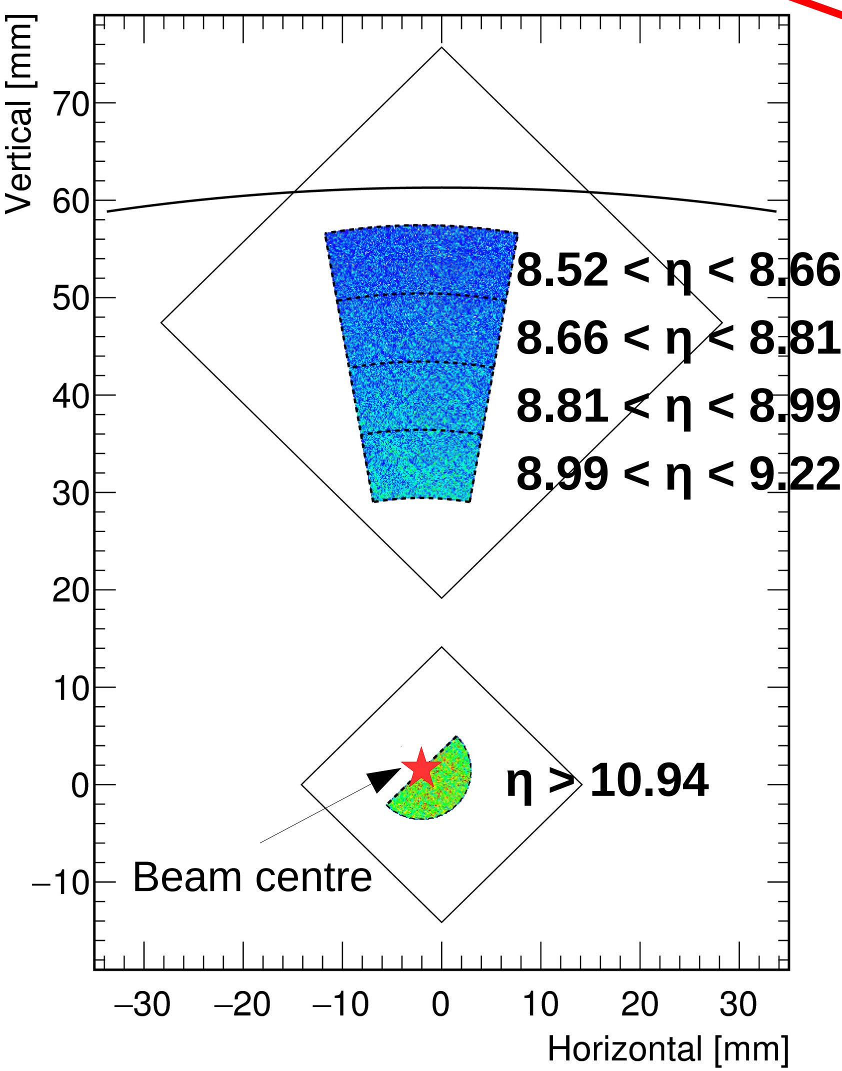
LHCf+ATLAS
combined analysis

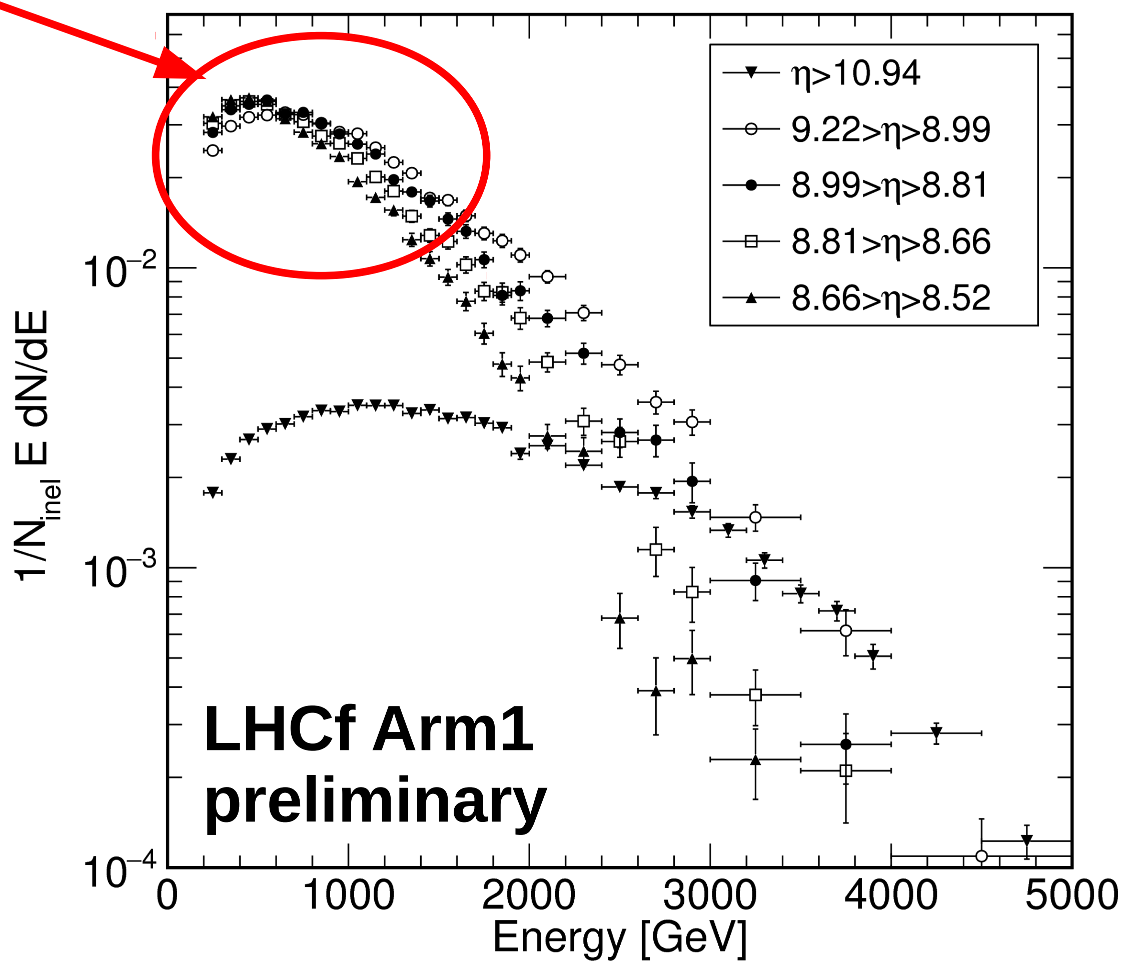
Zhou's presentation!

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

Acceptance extension

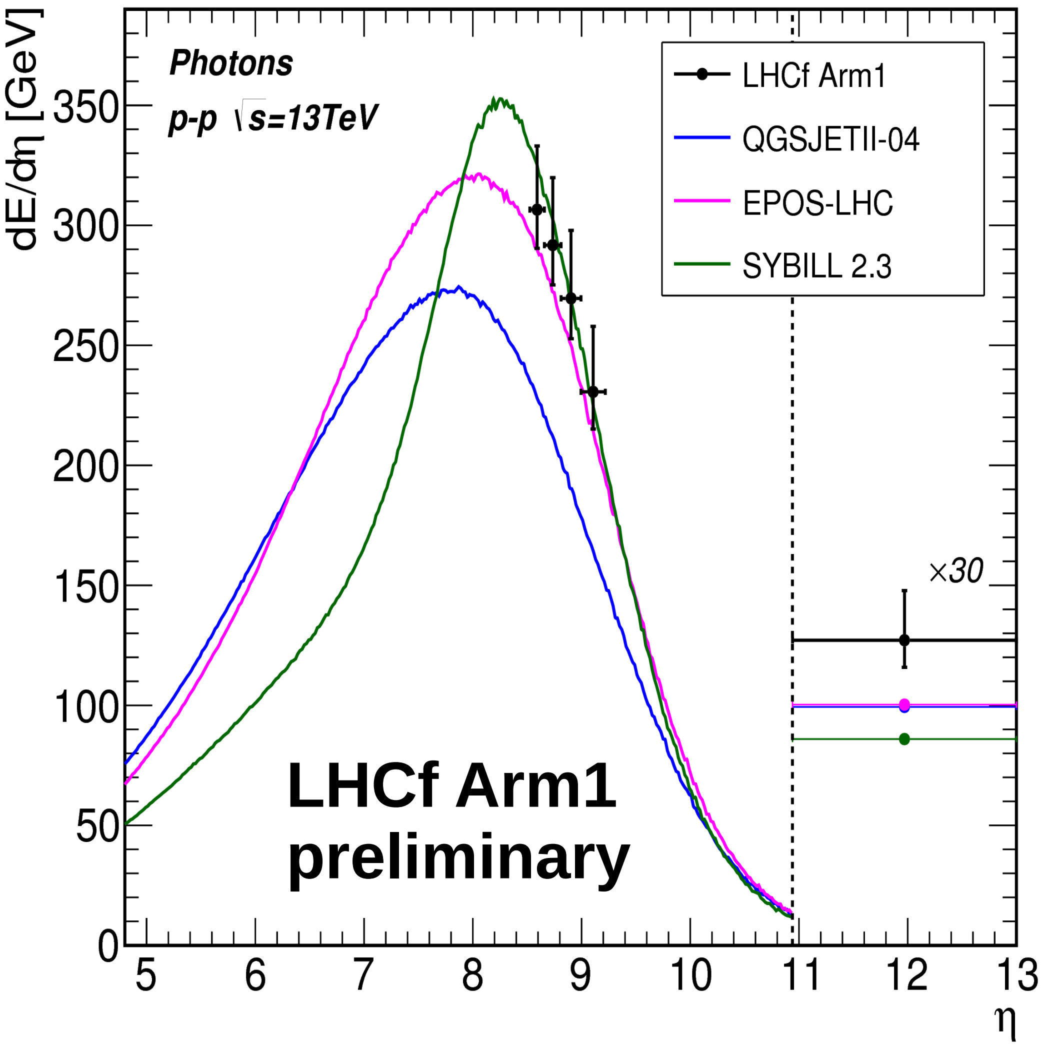
- Acceptance region extended to study the η dependence of energy flow
- Low energy region of the spectrum gives the dominant contribution for $8.52 < \eta < 9.22$





CERN-THESIS-2017-049

Electromagnetic energy flow



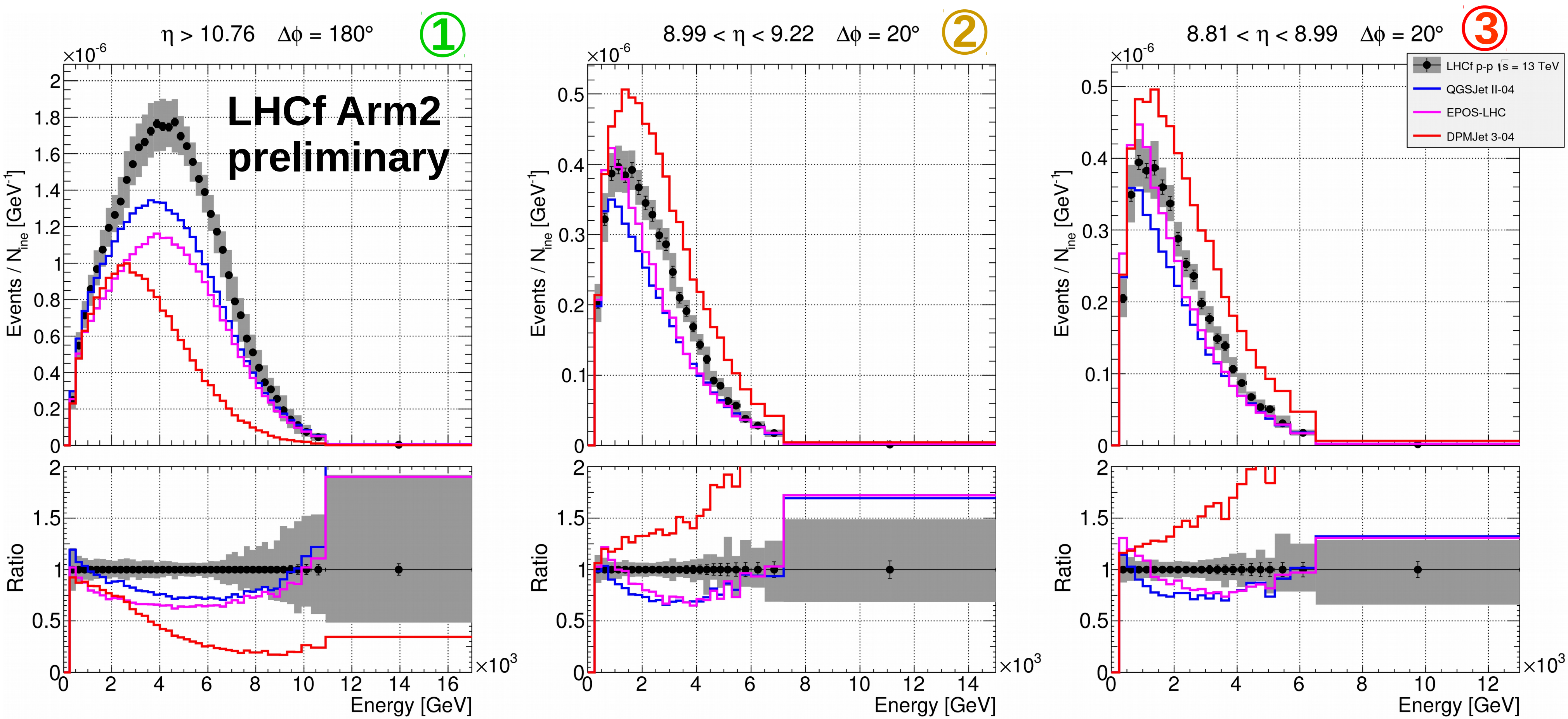
- Integrated from measured spectrum
- Low-η acceptance region extended: 8.52 < η < 9.22
- Best agreement with **SIBYLL 2.3** and **EPOS-LHC**
- **QGSJET II-04** predicts a less forward-peaked energy flow
- All models underestimate the flow in the η > 10.94 region

CERN-THESIS-2017-049

Physics results: neutrons (preliminary!)

Neutron energy spectrum (before unfolding)

$$\frac{1}{N_{inel}}\frac{dN}{dE}[\mathrm{GeV}^{-1}]$$

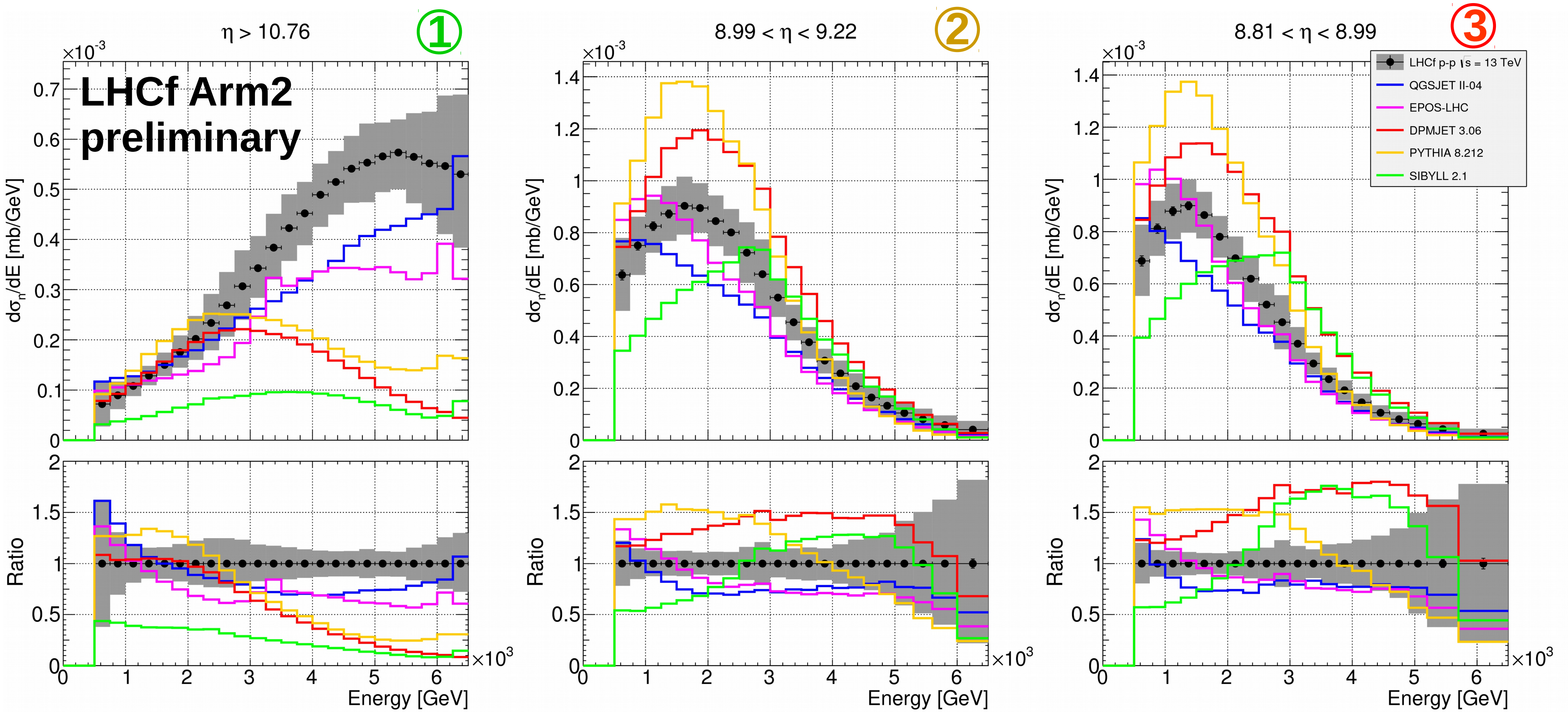


QGSJET II-04 and **EPOS-LHC** have similar shape but lower yield
DPMJET 3.04 have very different shape and yield

CERN-THESIS-2017-035

Neutron energy spectrum

$$\frac{d\sigma}{dE}[\mathrm{mb/GeV}]$$

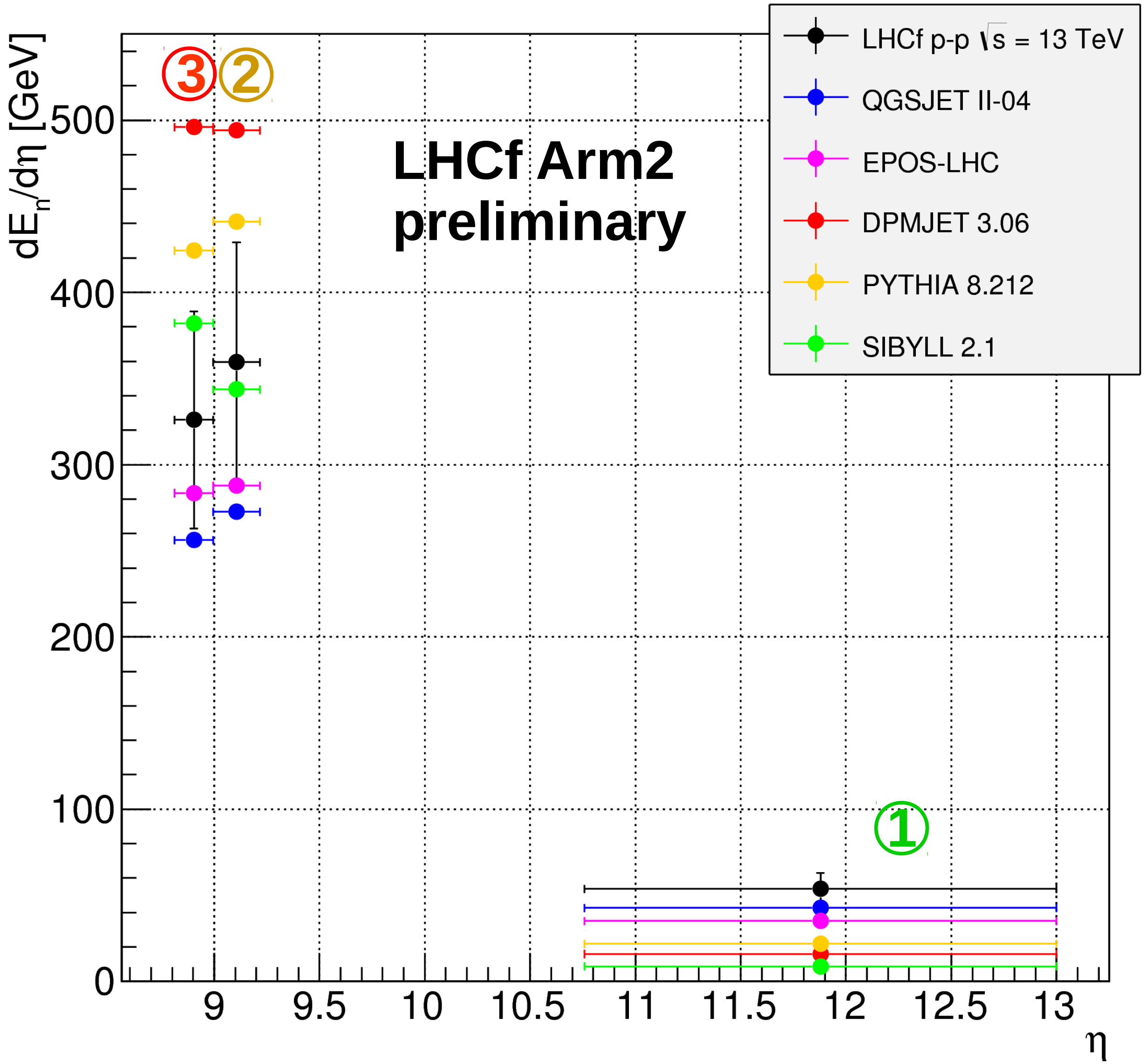


Only **QGSJET II-04** qualitatively reproduces behavior of data in η > 10.76
EPOS-LHC has similar shape in 8.81 < η < 9.22, but lower yield

CERN-THESIS-2017-035

Hadronic energy flow

dE/dη vs **η**

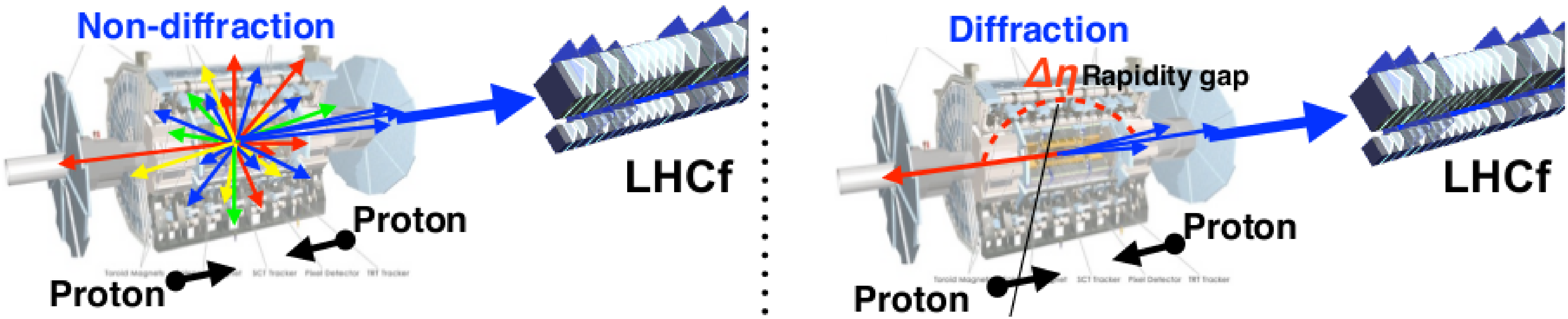


- Only hadrons with E > 500 GeV are considered
- **SIBYLL** and **EPOS** are consistent with data in the 8.81 < η < 9.22 regions (2 and 3)
- In the η > 10.76 region (1) all models underestimate the energy flow

CERN-THESIS-2017-035

Ongoing activities

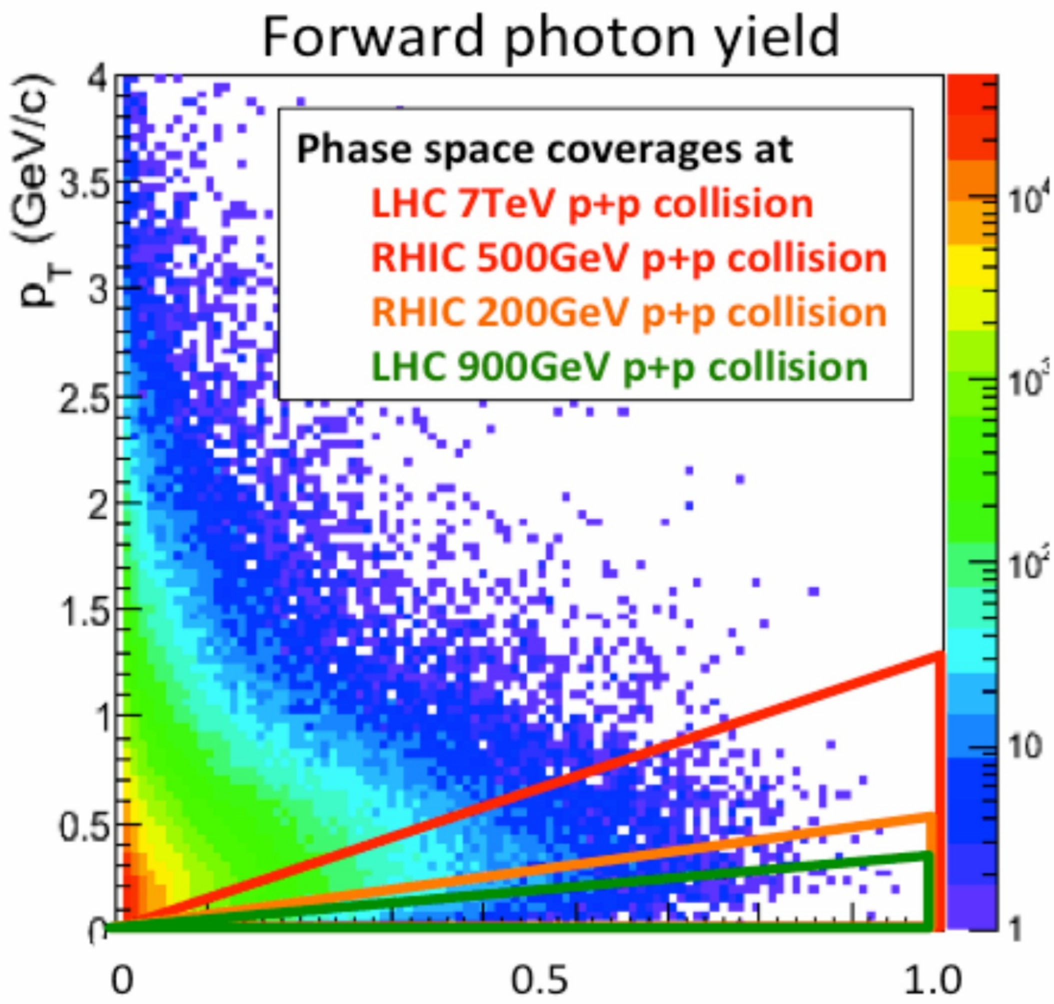
ATLAS+LHCf



- 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
- First analysis done with p-Pb data at 5.02 TeV (*ATL-PHYS-PUB-2015-038*)
- Analysis of 13 TeV data is ongoing

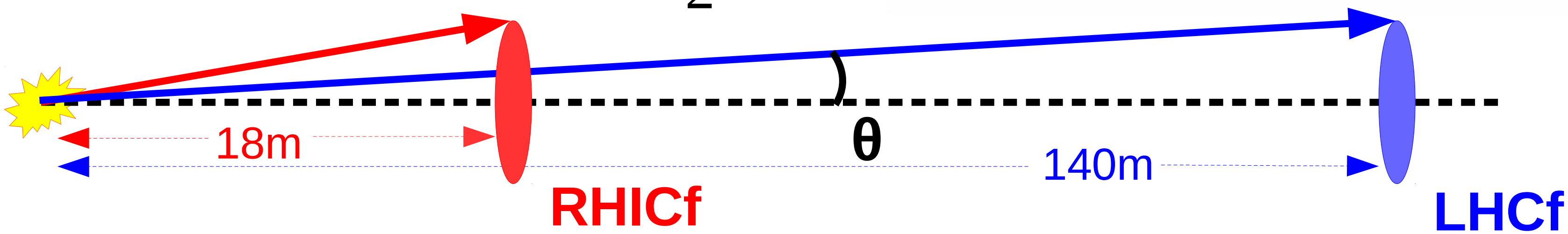
RHICf

- Run with p-p collisions at √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 (very important to extrapolate models beyond LHC energy)

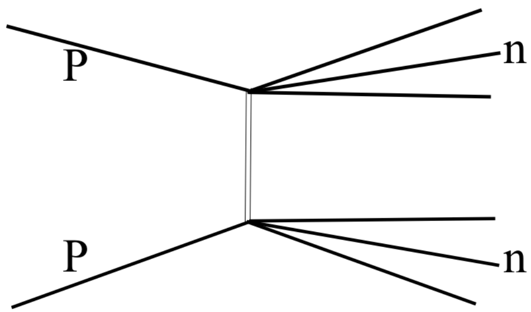


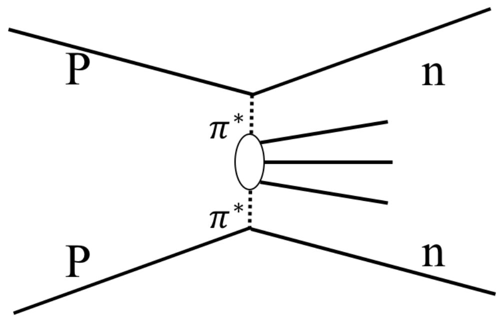
$$P_T \leq \frac{\sqrt{s}}{2} \sin\theta$$

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

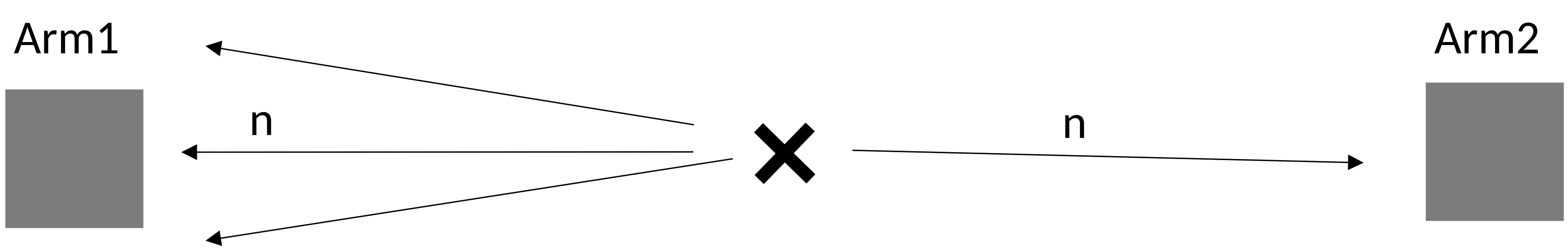


"Double Arm" analysis





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

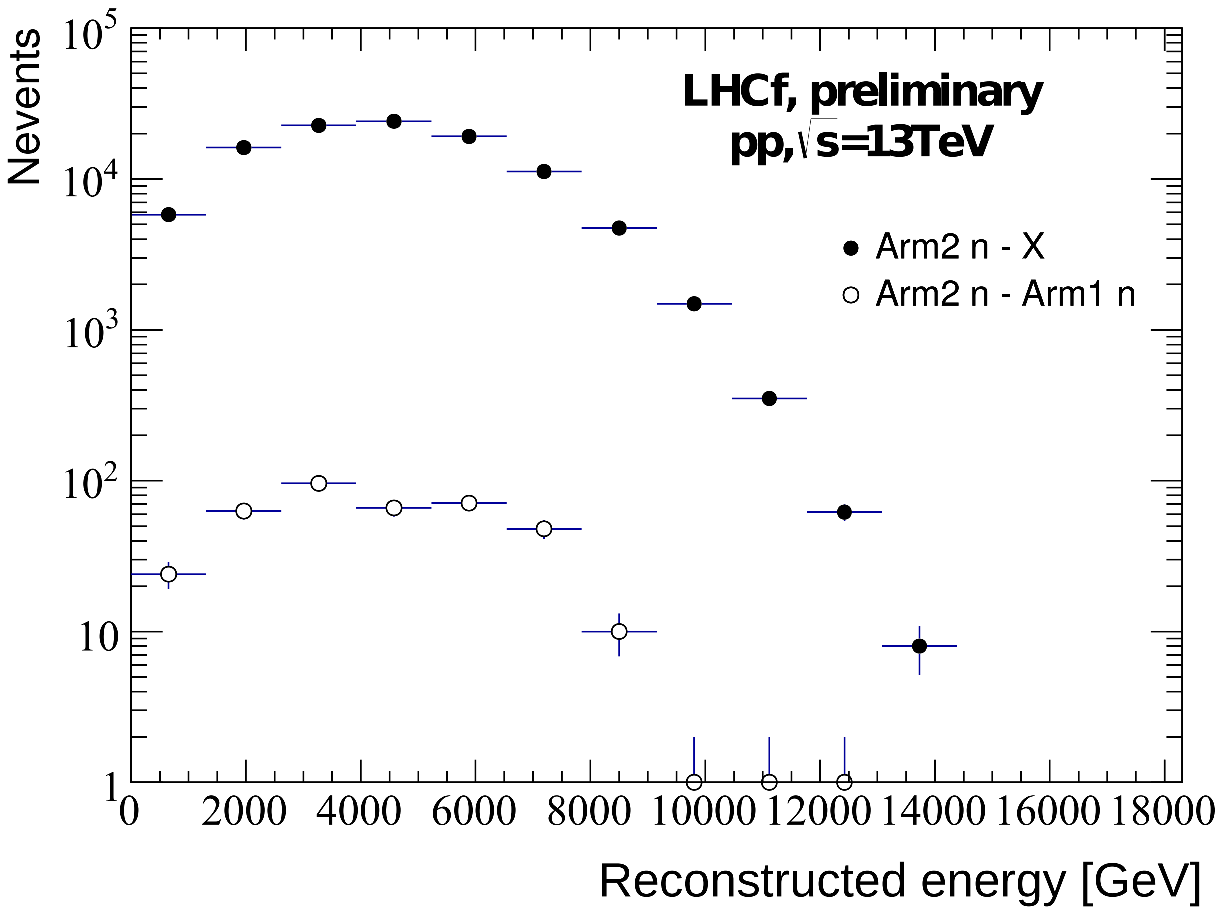


If hadron shower events are detected in both arms, what can we see?

Data sample:
about 1000 events
(η > 10.60)

“Double Arm” analysis

Spectrum of Arm2 with and without Arm1 event selection



Arm1 event selection:

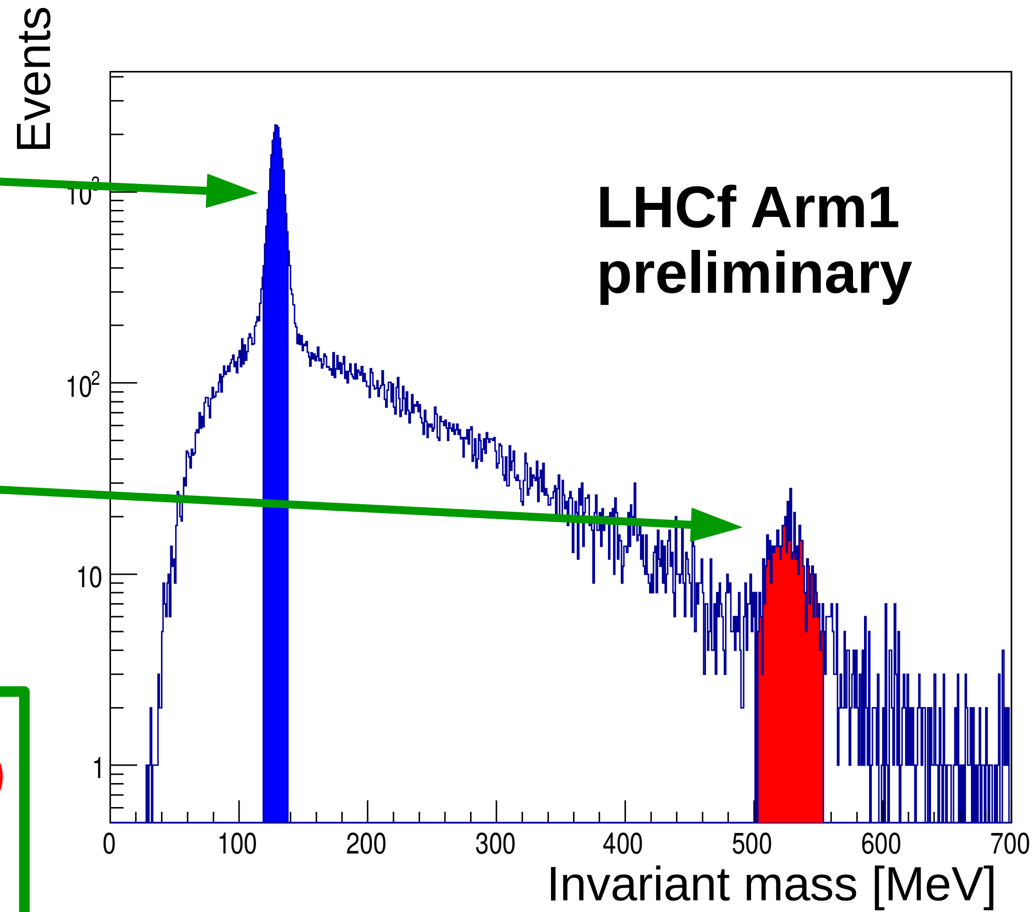
- Hadron shower
- E > 500 GeV
- $\eta > 10.94$
- $\Delta\varphi = 180°$

Arm2 event selection:

- Hadron shower
- E > 500 GeV
- $\eta > 10.94$
- $\Delta\varphi = 180°$

Next targets

- π^0 analysis in p-p at $\sqrt{s}$ = 13 TeV
- η meson analysis in p-p at $\sqrt{s}$ = 13 TeV
- Photon analysis in **p-Pb** at $\sqrt{s_{NN}}$ = 8.16 TeV



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

Summary

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

- Very forward neutral particles production in p-p and p-Pb collisions at the LHC:
  - π_0 P_T and P_Z spectra in p-p at **7 TeV** and p-Pb at **5.02 TeV**
  - **Photon** energy spectrum in p-p at **13 TeV**
  - **Neutron** energy spectrum in p-p at **13 TeV**

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

Backup

The LHCf collaboration

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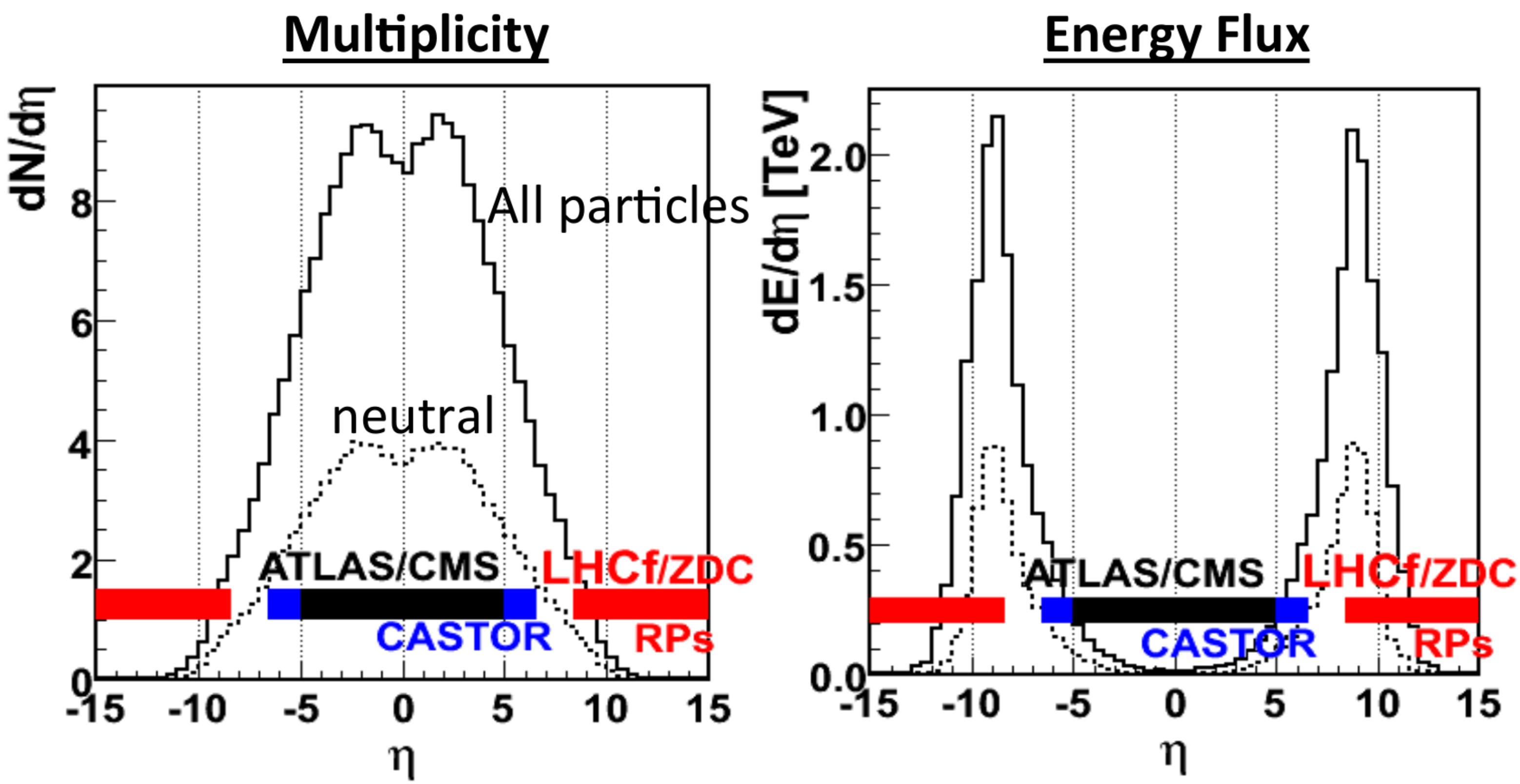
Published results

- **Photons**
  - Energy spectra in p-p @ √s = 7 TeV [*PLB 703 (2011), 128-134*]
  - Energy spectra in p-p @ √s = 900 GeV [*PLB 715 (2012), 298-303*]
- **π^0**
  - P_T spectra in p-p @ √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 @ √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 @ √s = 7 TeV [*PLB 750 (2015), 360-366*]

Forward energy flux @ LHC

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



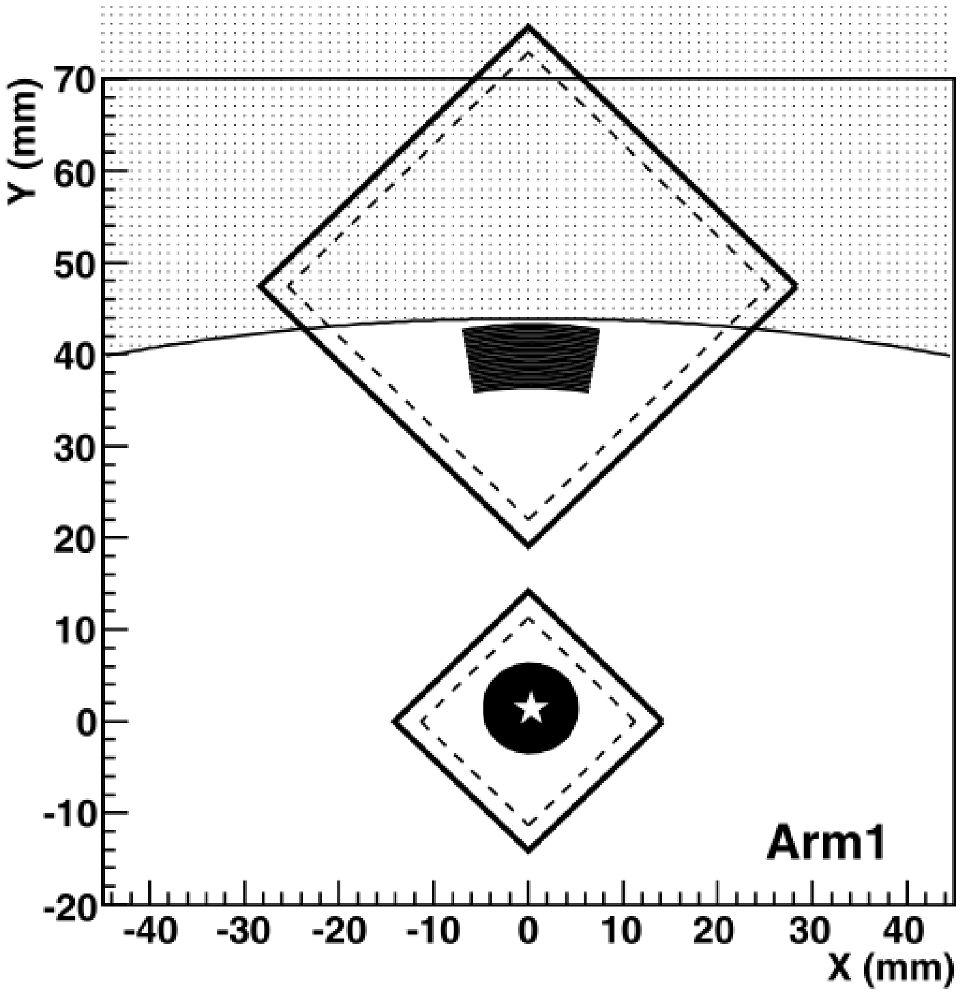
LHCf pseudo-rapidity range: η > 8.4
(with 140 μrad beam crossing angle)

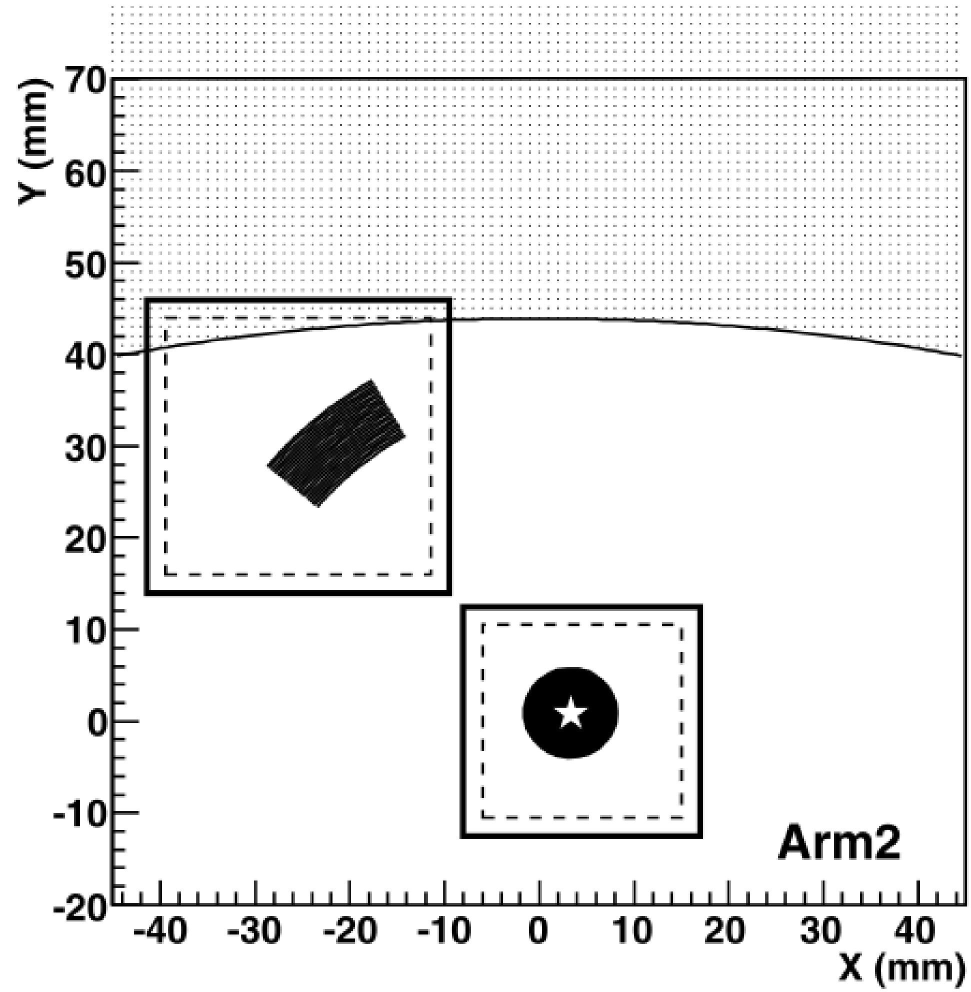
Pseudo-rapidity

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

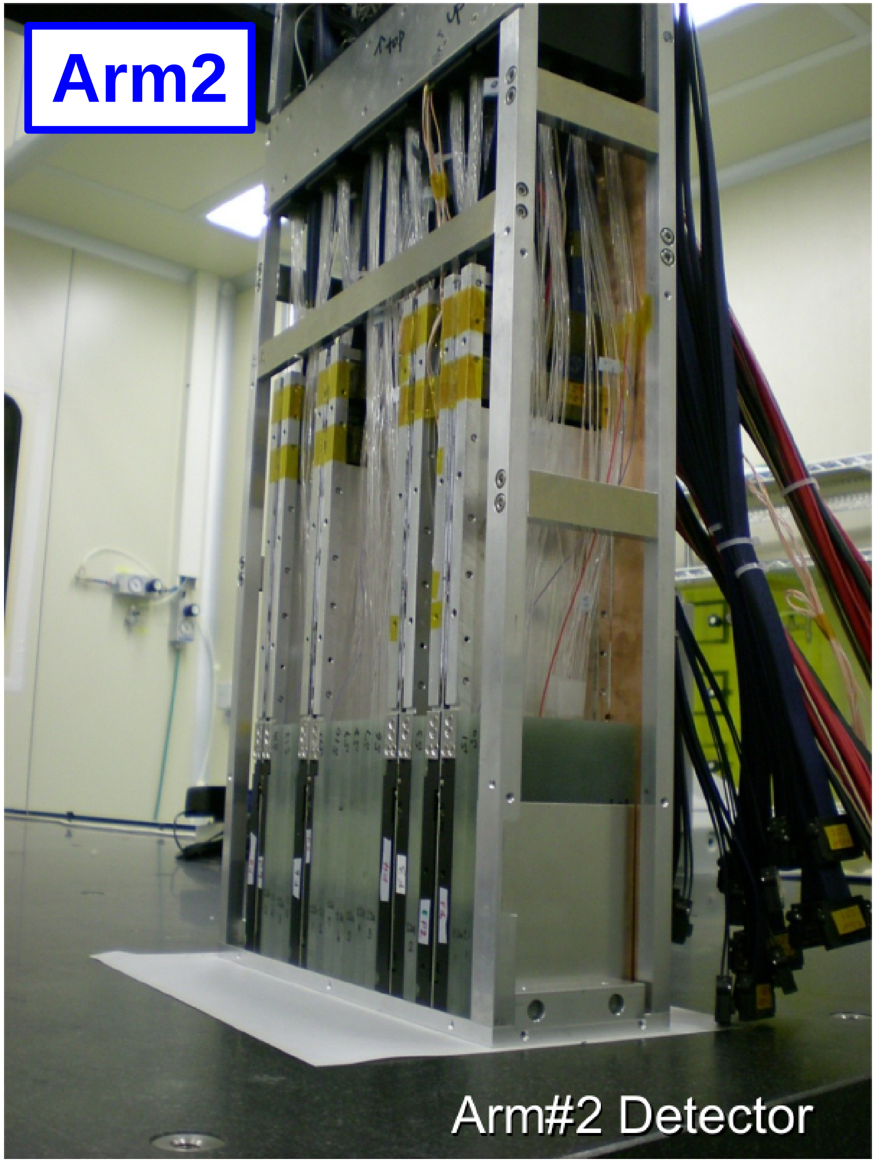
<u>LHCf covers the peak of energy flow</u>

Detectors cross section

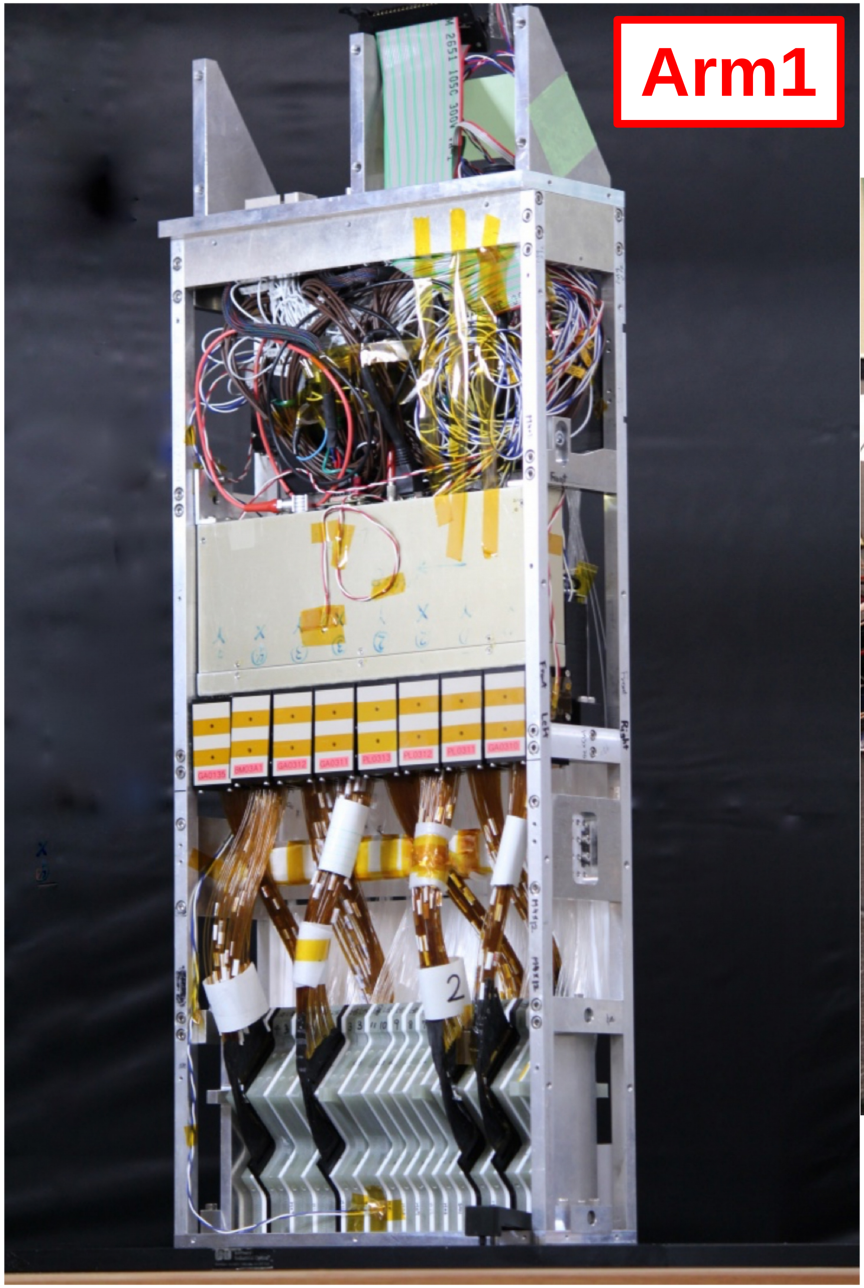


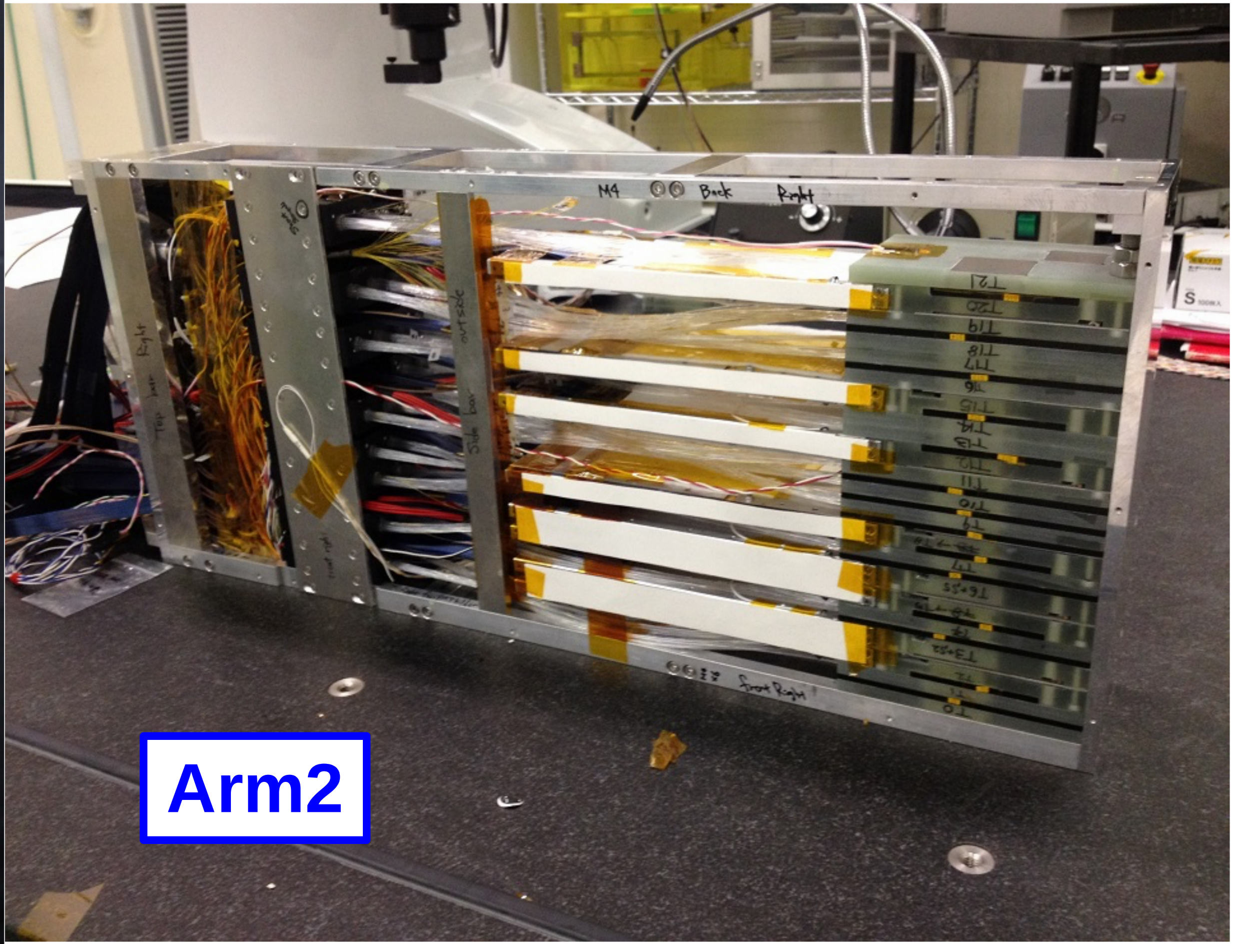


Arm1 and Arm2 (old)



Upgraded Arm1 and Arm2



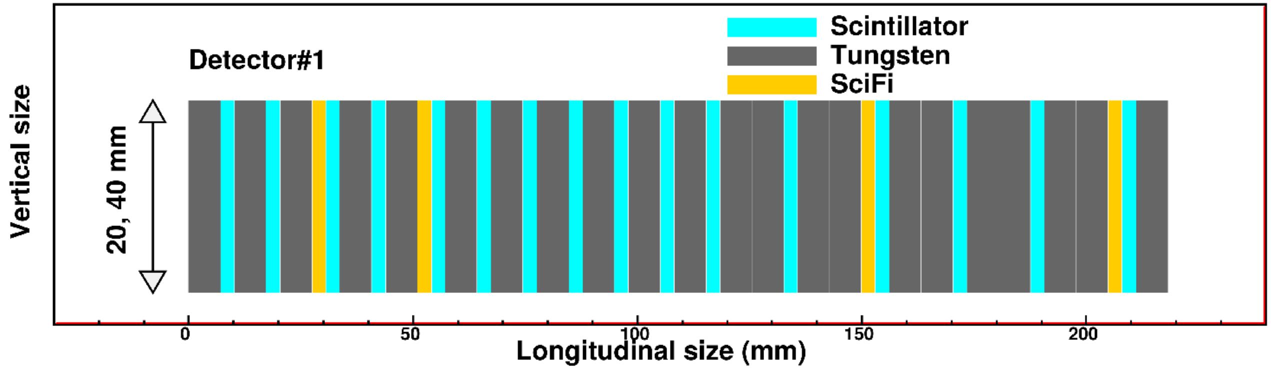


Upgrades for 13 TeV operations

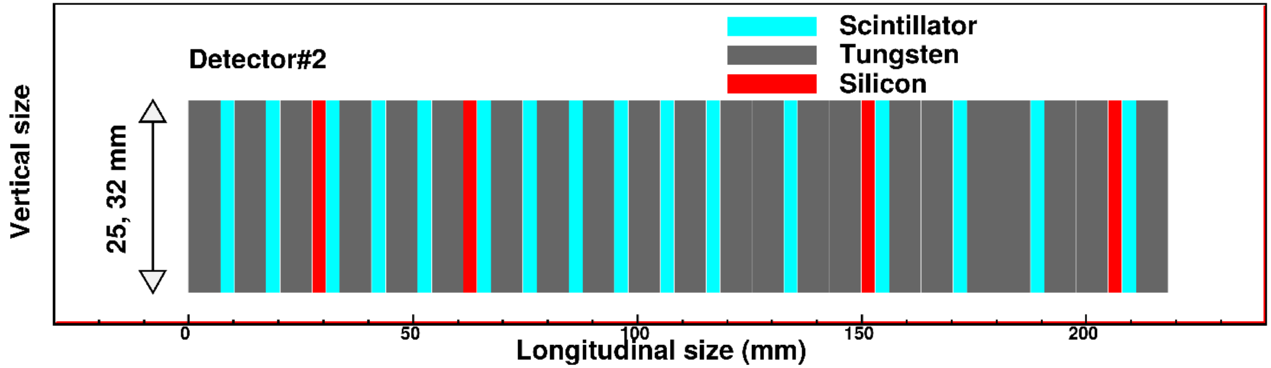
- More radiation damage is expected: 0.2 Gy/nb @ 7 TeV, 2-3 Gy/nb @ 13 TeV
  - All plastic scintillators have been substituted with **GSO scintillators** (can survive up to 10^6 Gy)
  - In Arm1, scintillation fibers were replaced with **GSO bars** (1 x 1 x 20 mm^3 and 1 x 1 x 40 mm^3 for small and large 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

Longitudinal structure

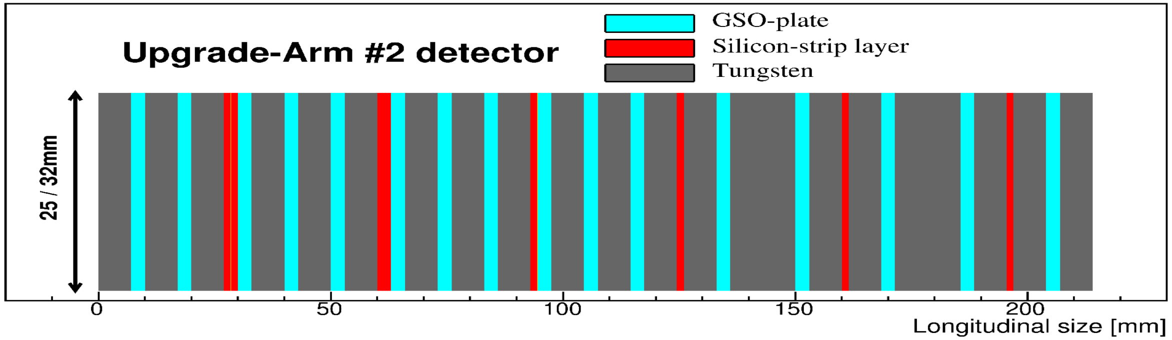
Arm1



Arm2 (Old)



Arm2 (New)



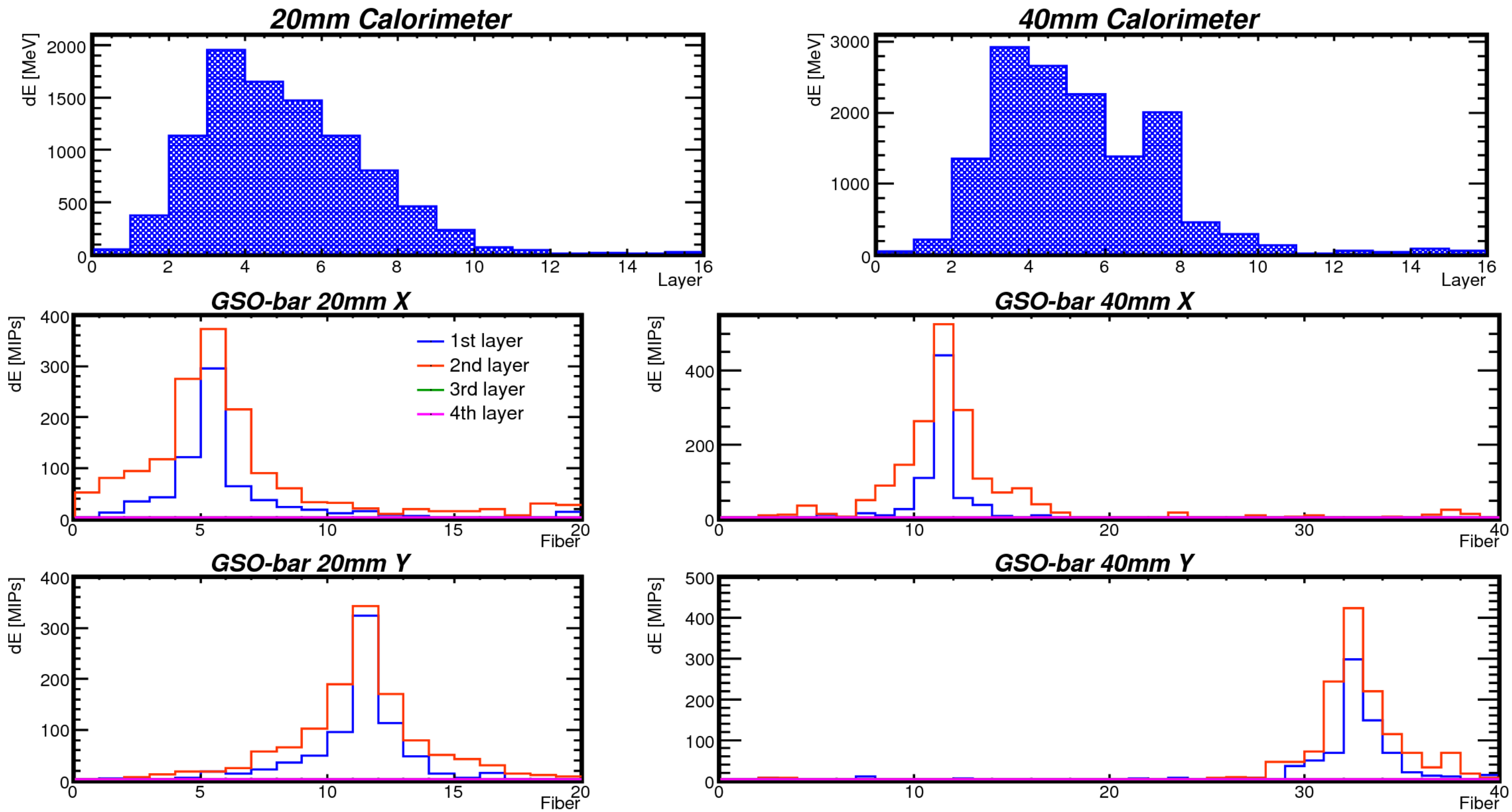
Arm 1 π^0 event

LHCf Arm1 Detector

π^0 Candidate Event

LHC p-p, $\sqrt{s}$ = 13 TeV Collisions

RUN: 44299
NUMBER: 4990
TIME: 1434141164
FILL: 3855
E_{20mm}: 323 GeV
E_{40mm}: 407 GeV
$M_{\gamma\gamma}$: 138 MeV



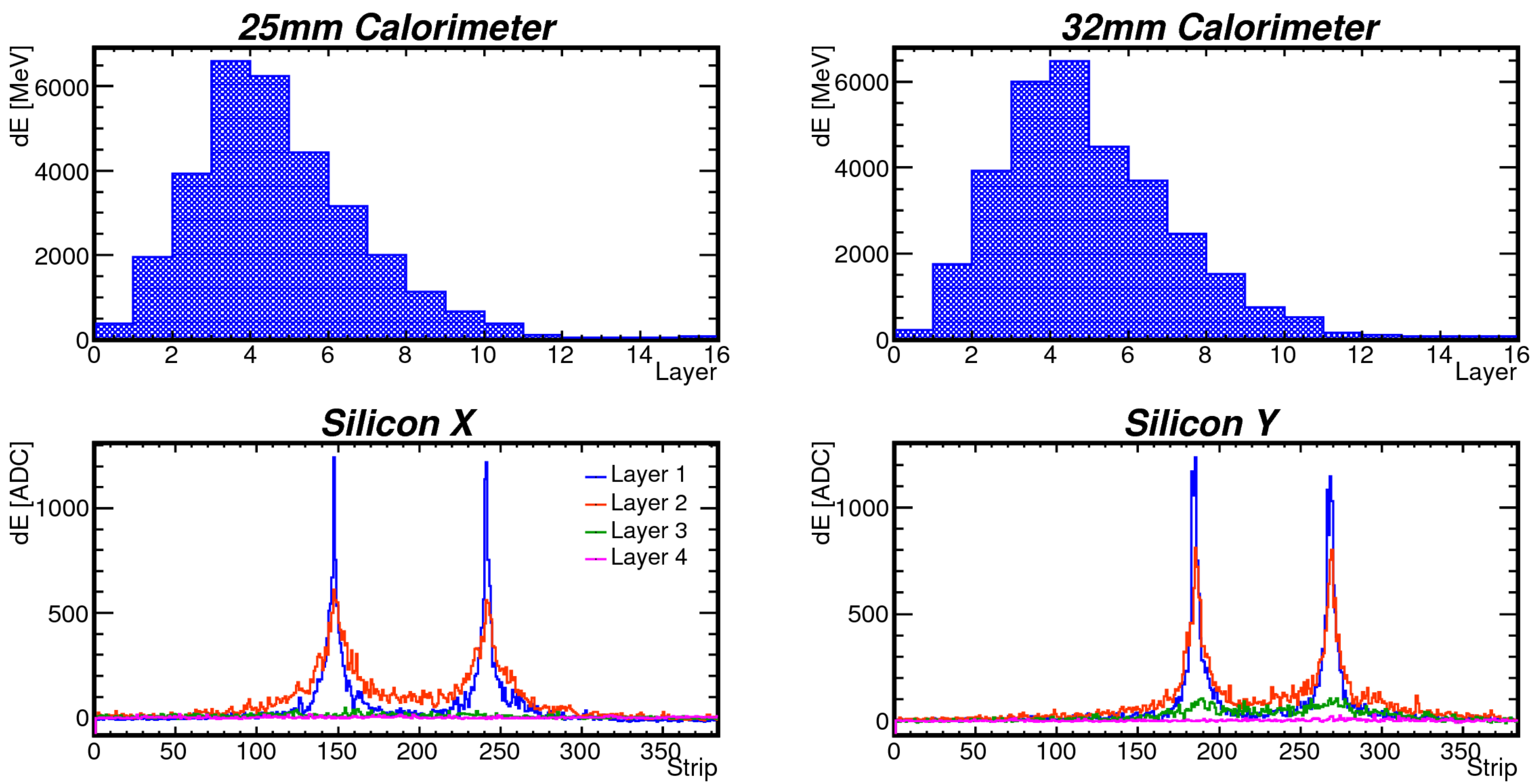
Arm 2 π^0 event

LHCf Arm2 Detector

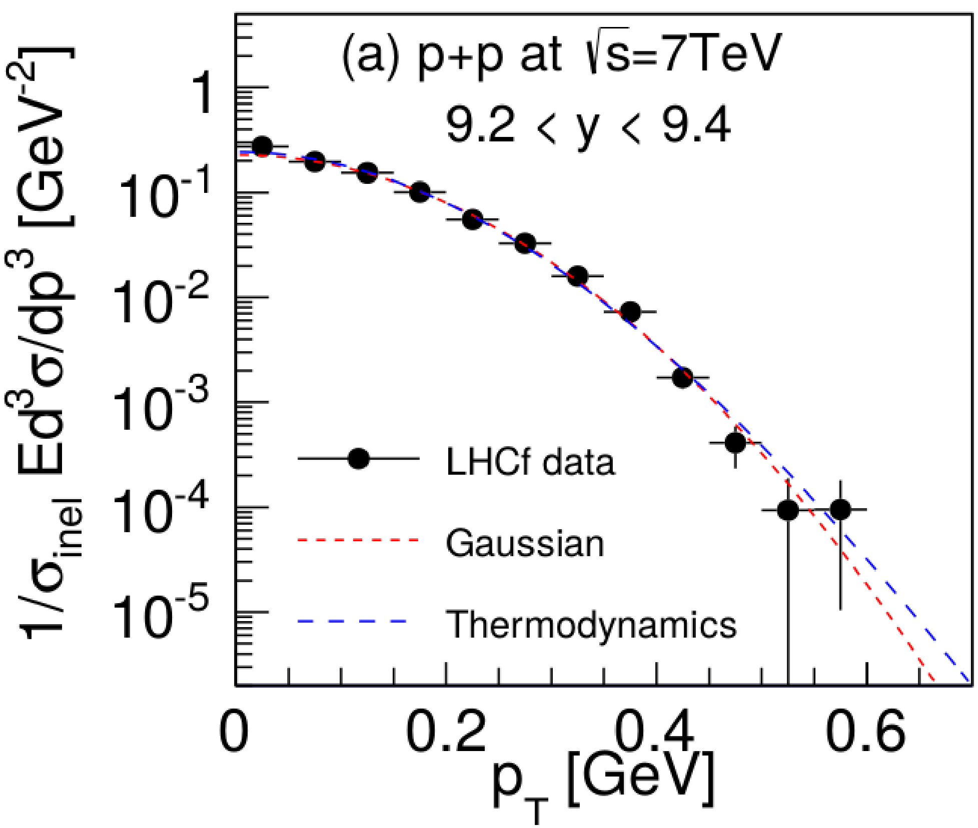
π^0 Candidate Event

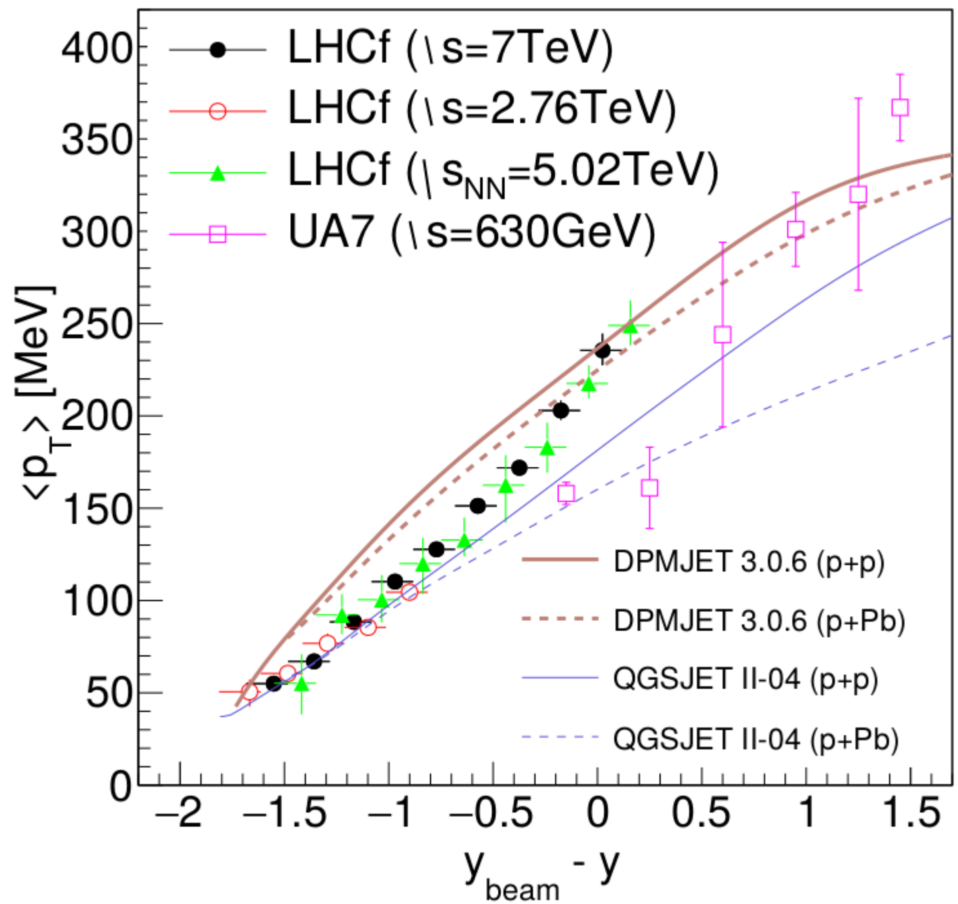
LHC p-p, $\sqrt{s}$ = 13 TeV Collisions

RUN: 44484
NUMBER: 3010
TIME: 1434152507
FILL: 3855
E_{25mm}: 1014 GeV
E_{32mm}: 1021 GeV
$M_{\gamma\gamma}$: 147 MeV



π^0: < P_T > scaling





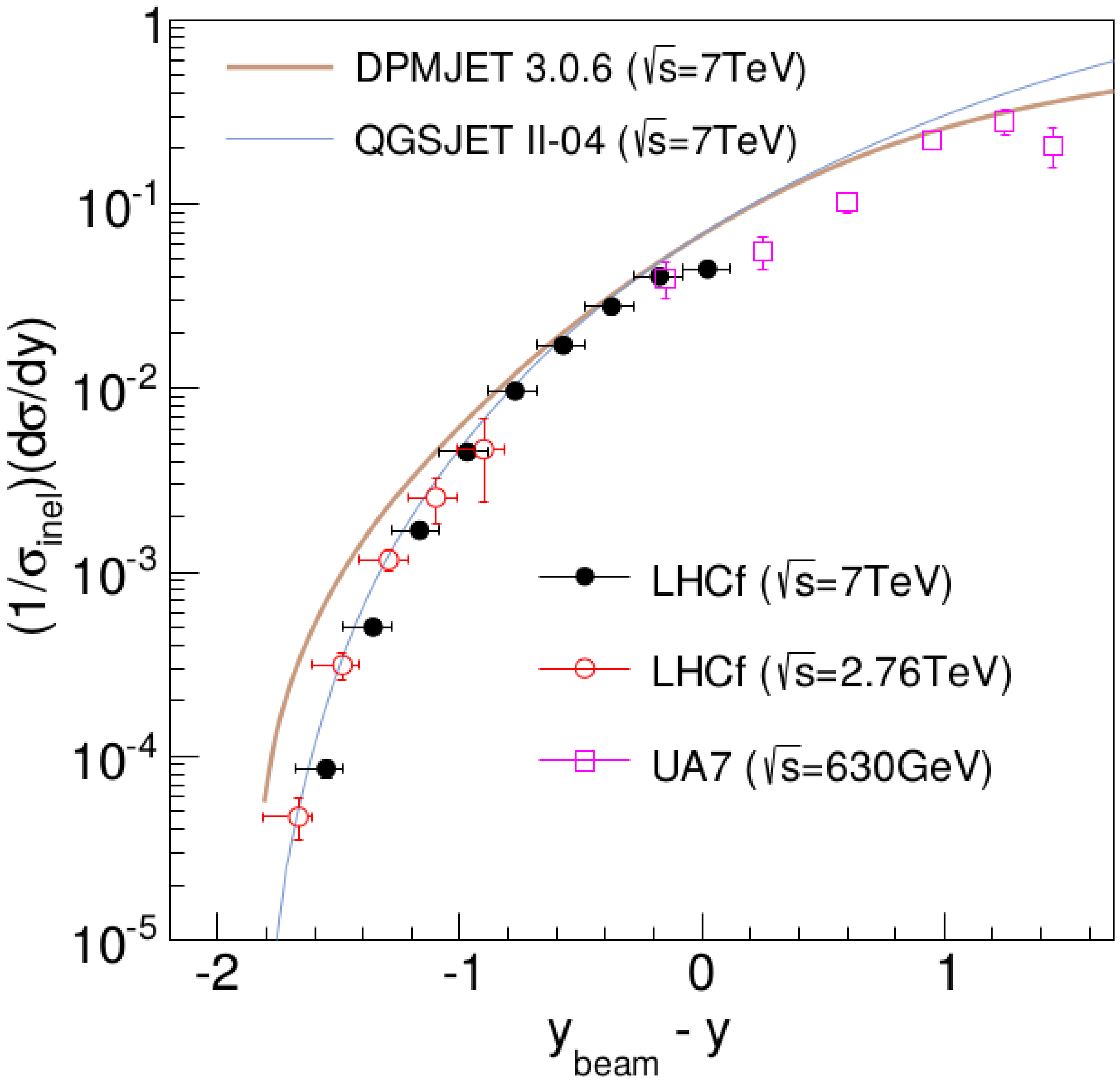
Derivation of mean PT:

- Fit with Gaussian
- Fit with thermodynamical model
- Numerical integration

- LHCf results consistent within ~ 10 %

PRD 94, 032007 (2016)

π^0: limiting fragmentation hypothesis



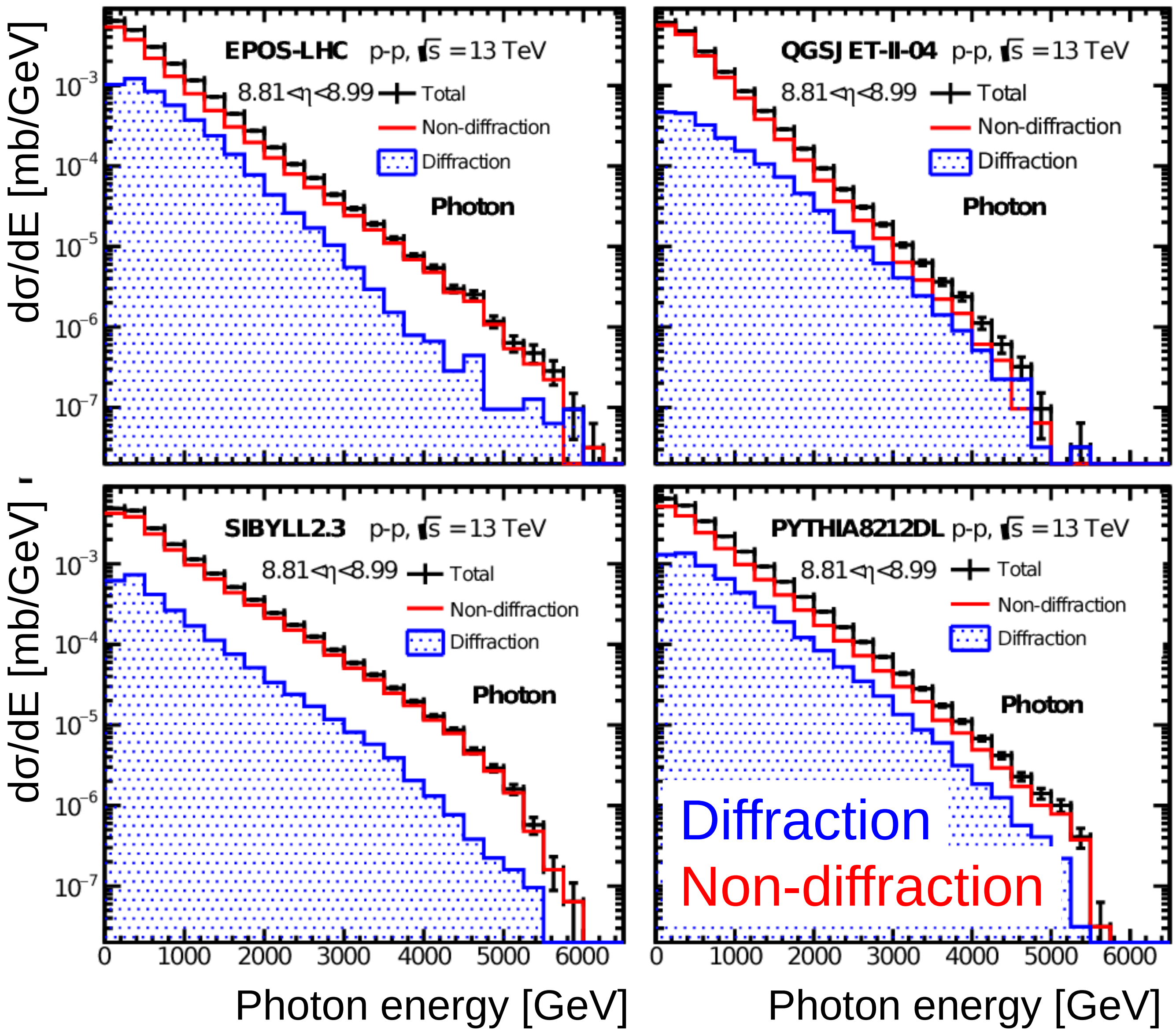
- Hypothesis: fragments of a colliding hadron follow a limiting rapidity distribution in the target frame

  rapidity distribution of secondary particles is independent of √s
- Limiting fragmentation hypothesis holds at ~15% level

PRD 94, 032007 (2016)

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

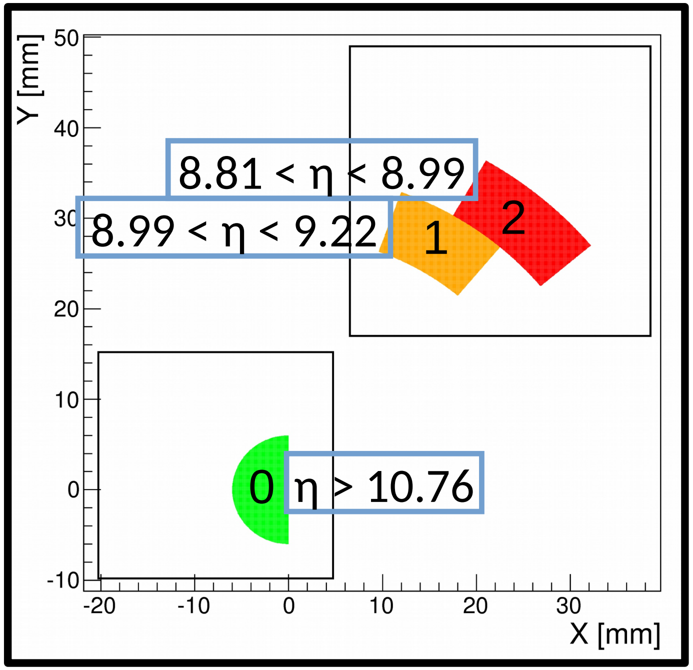
Analysis data set (neutrons)

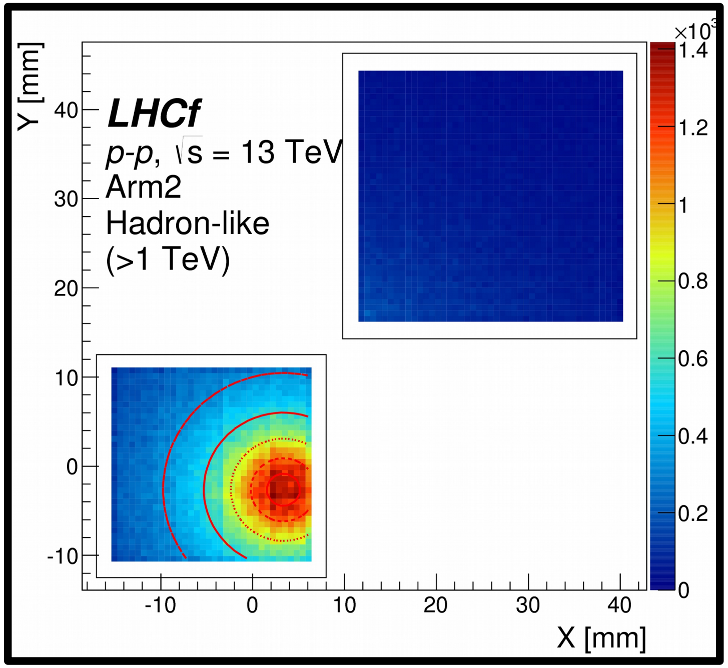
Data set

- 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

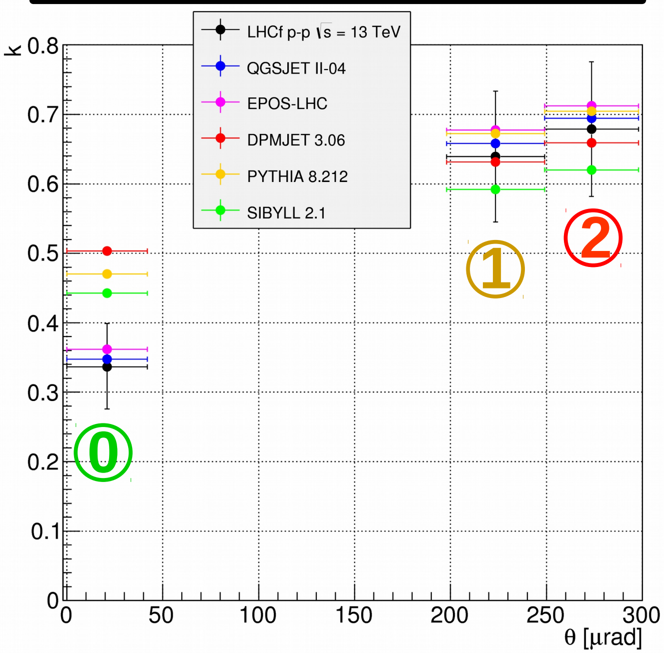
- Neutrons peaked along beam direction
- Perform a fit on 2D distribution
- Beam center is (+3.3, -2.7) mm
- Uncertainty is 0.3 mm for both x and y





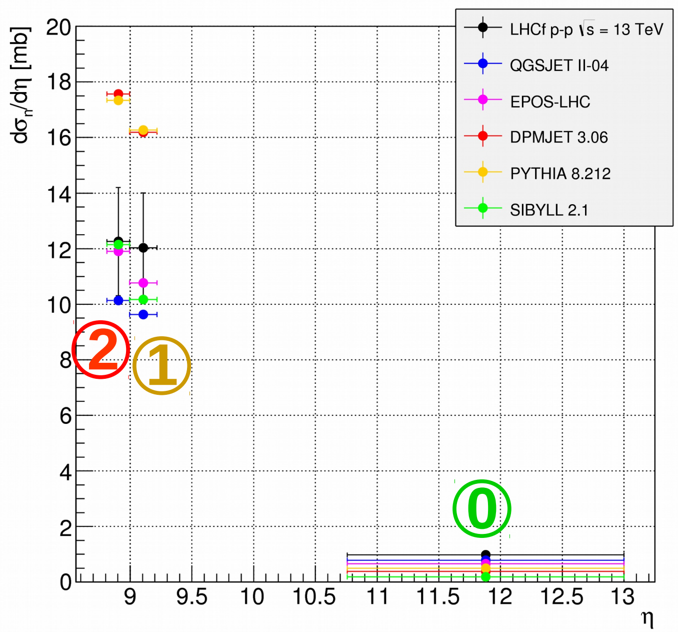
Measurements of interesting quantities in CR physics

Inelasticity VS θ



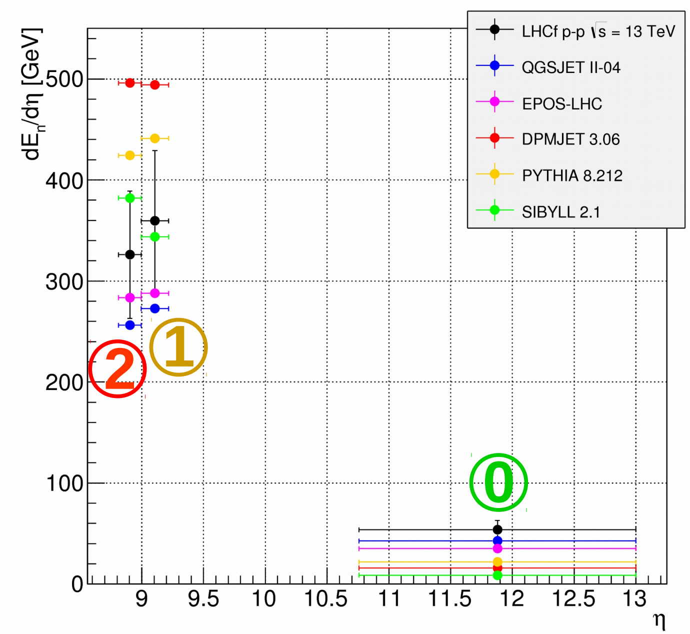
All models overestimate inelasticity in the most forward region even if **QGSJET II-04** and **EPOS-LHC** are consistent within the error bars

dσ/dη VS η



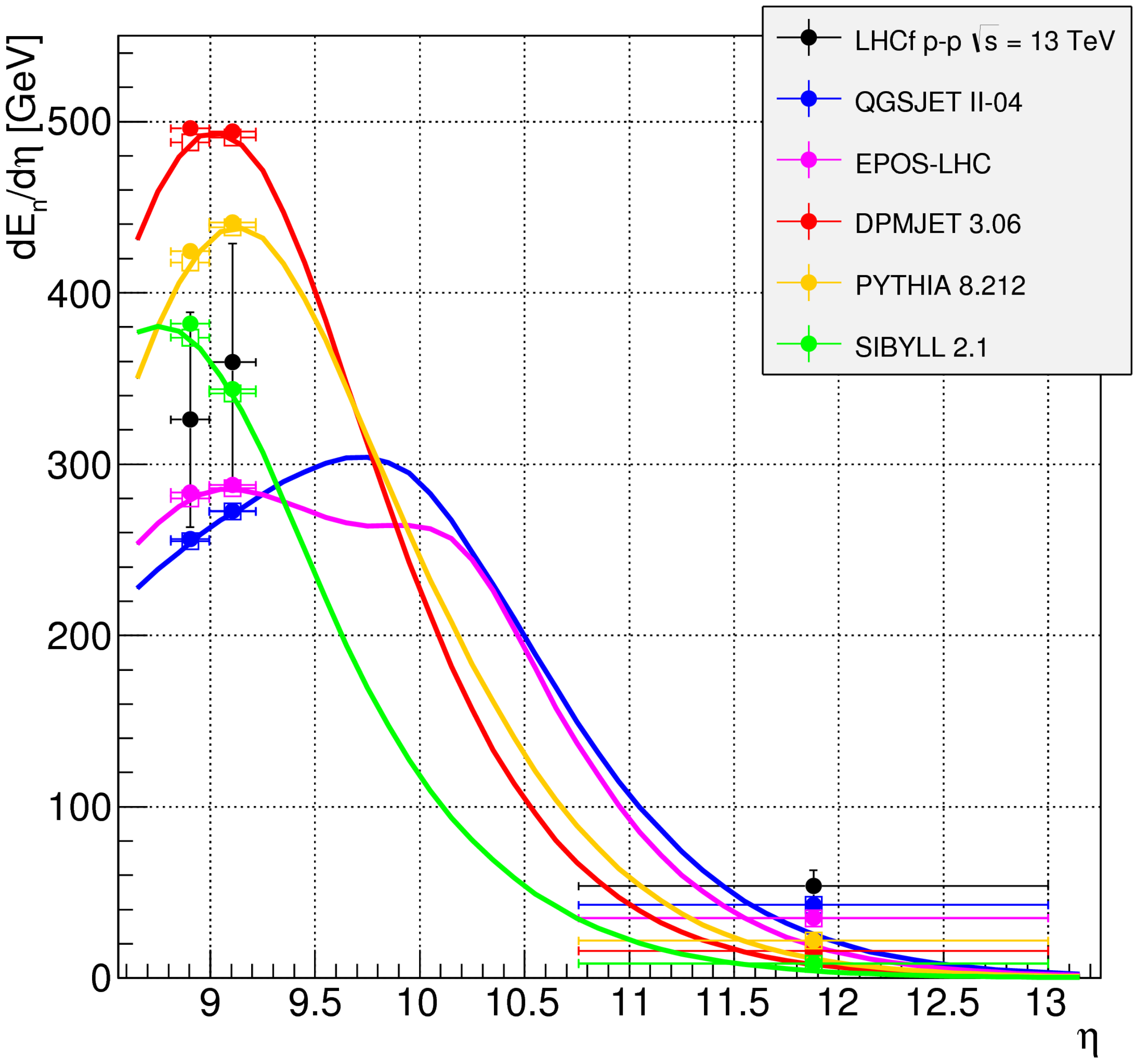
EPOS-LHC and **SIBYLL 2.1** reproduce enough well the measured total differential cross section except in the most forward region

dE/dη VS η



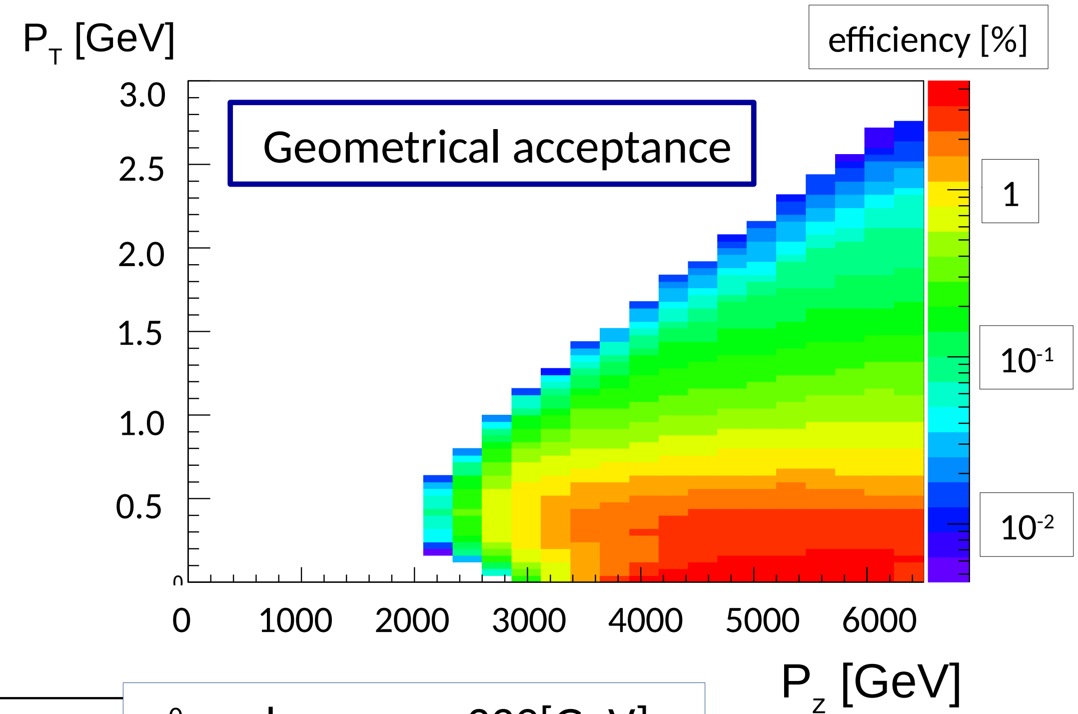
Where the energy flux is high, the agreement between experimental measurements and **SIBYLL 2.1**/**EPOS-LHC** is quite good

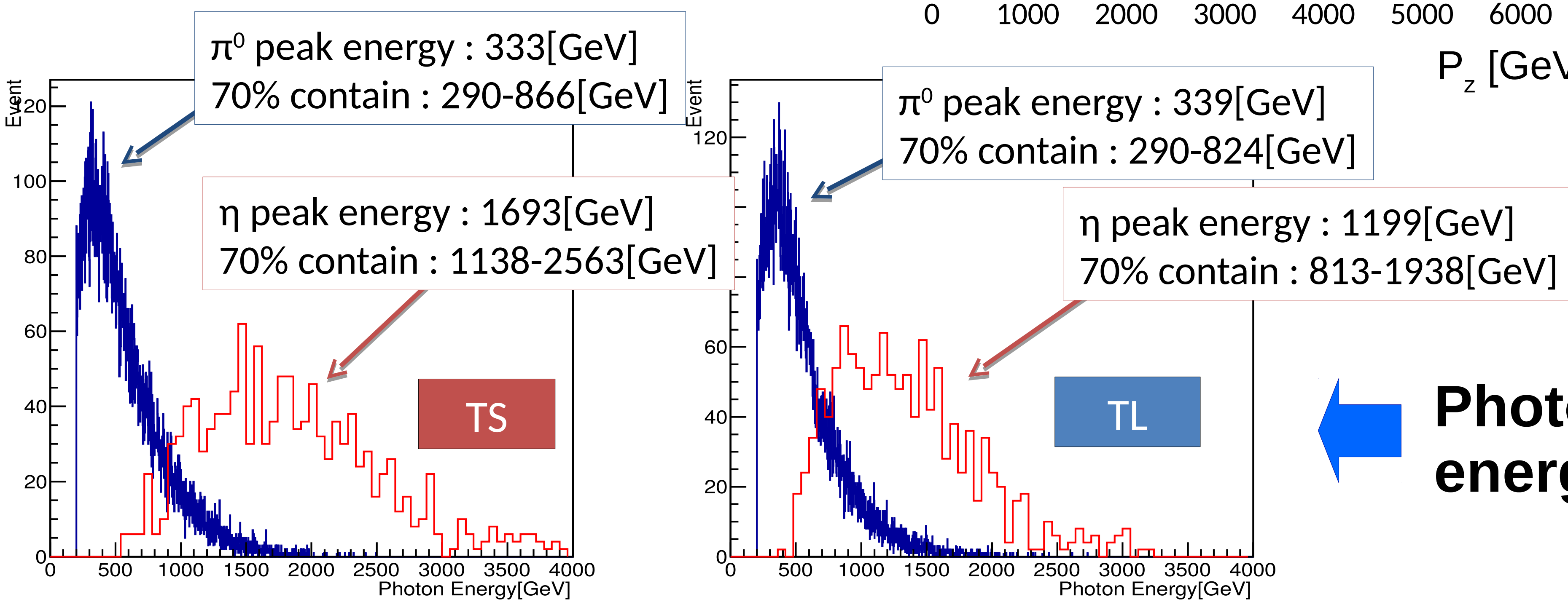
Hadronic energy flow vs η



η analysis

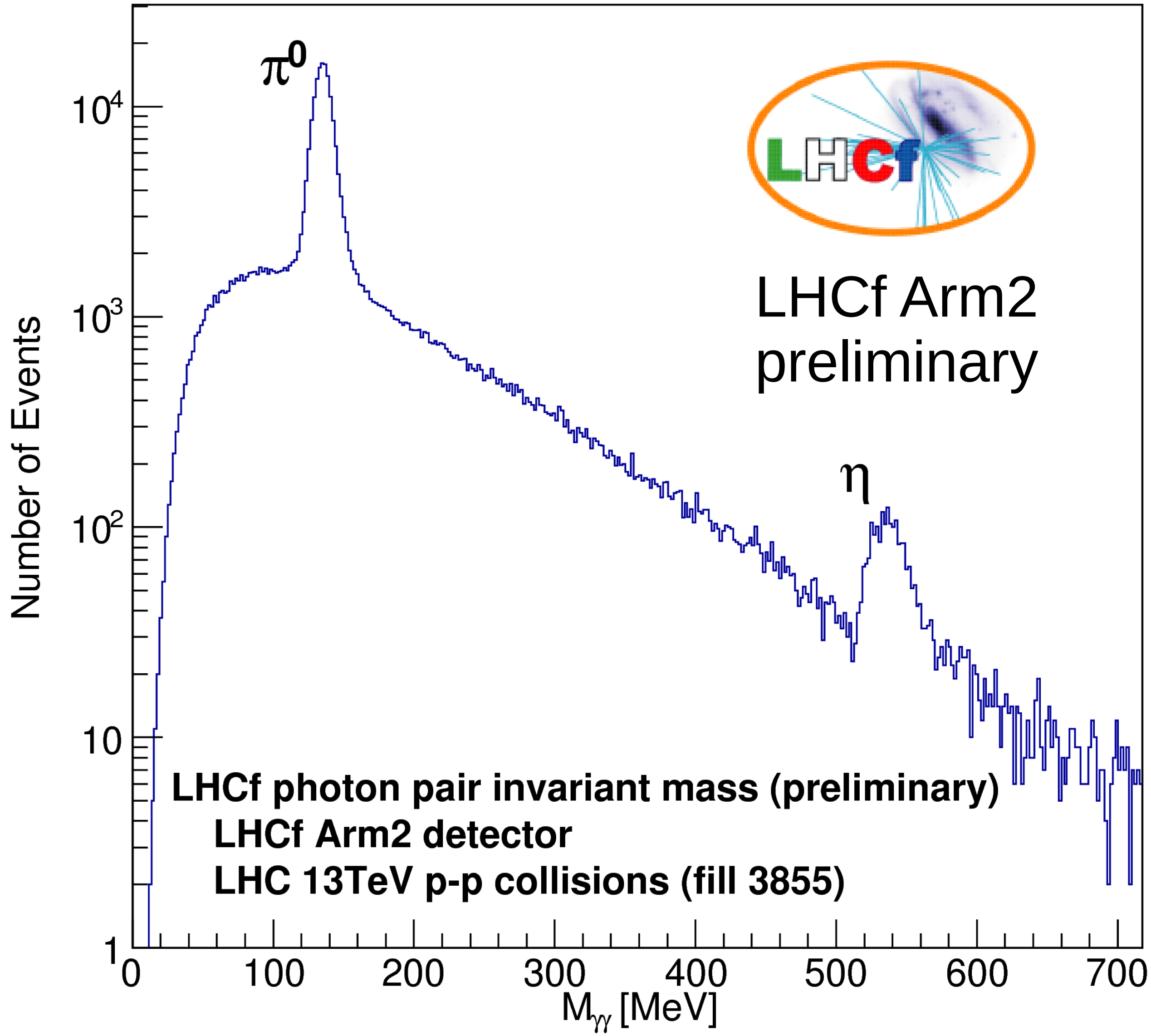
- Data sample:
  Fill #3855
  Entries: 53539 events
  π^0 meson: 23247 events
  η meson: 467 events



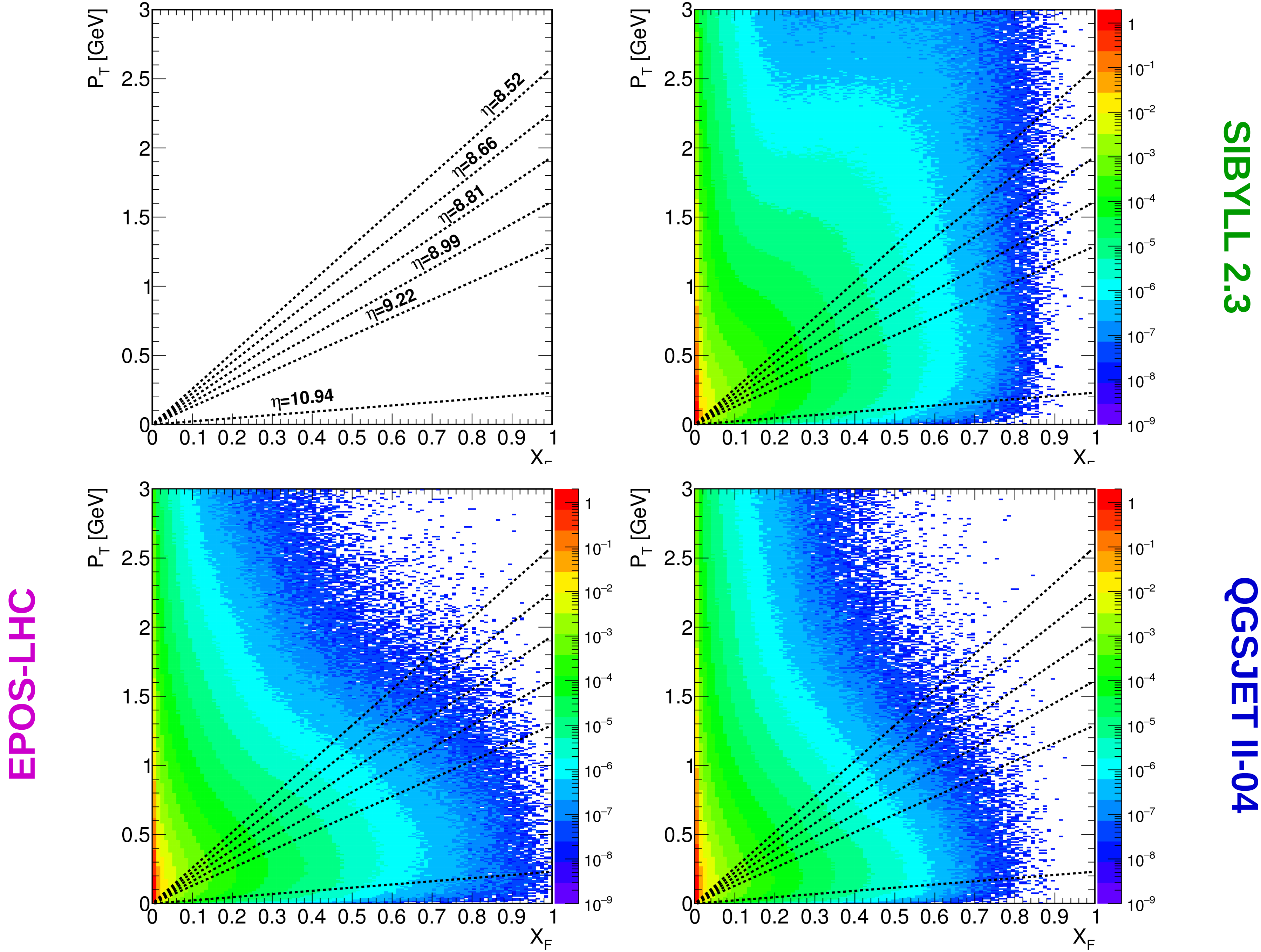


Photon energy

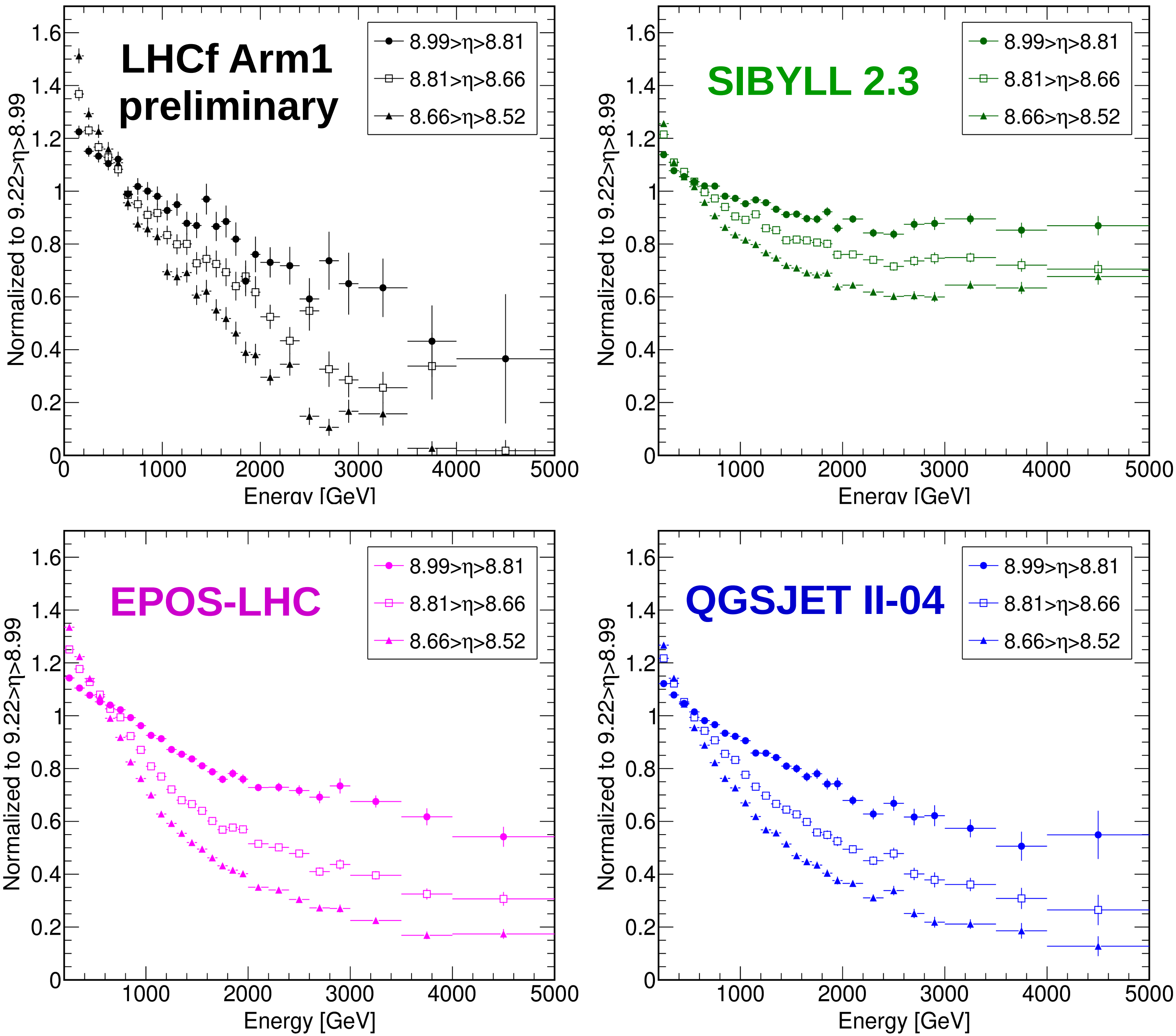
Photon pairs invariant mass at 13 TeV



P_T vs X_F photons yield

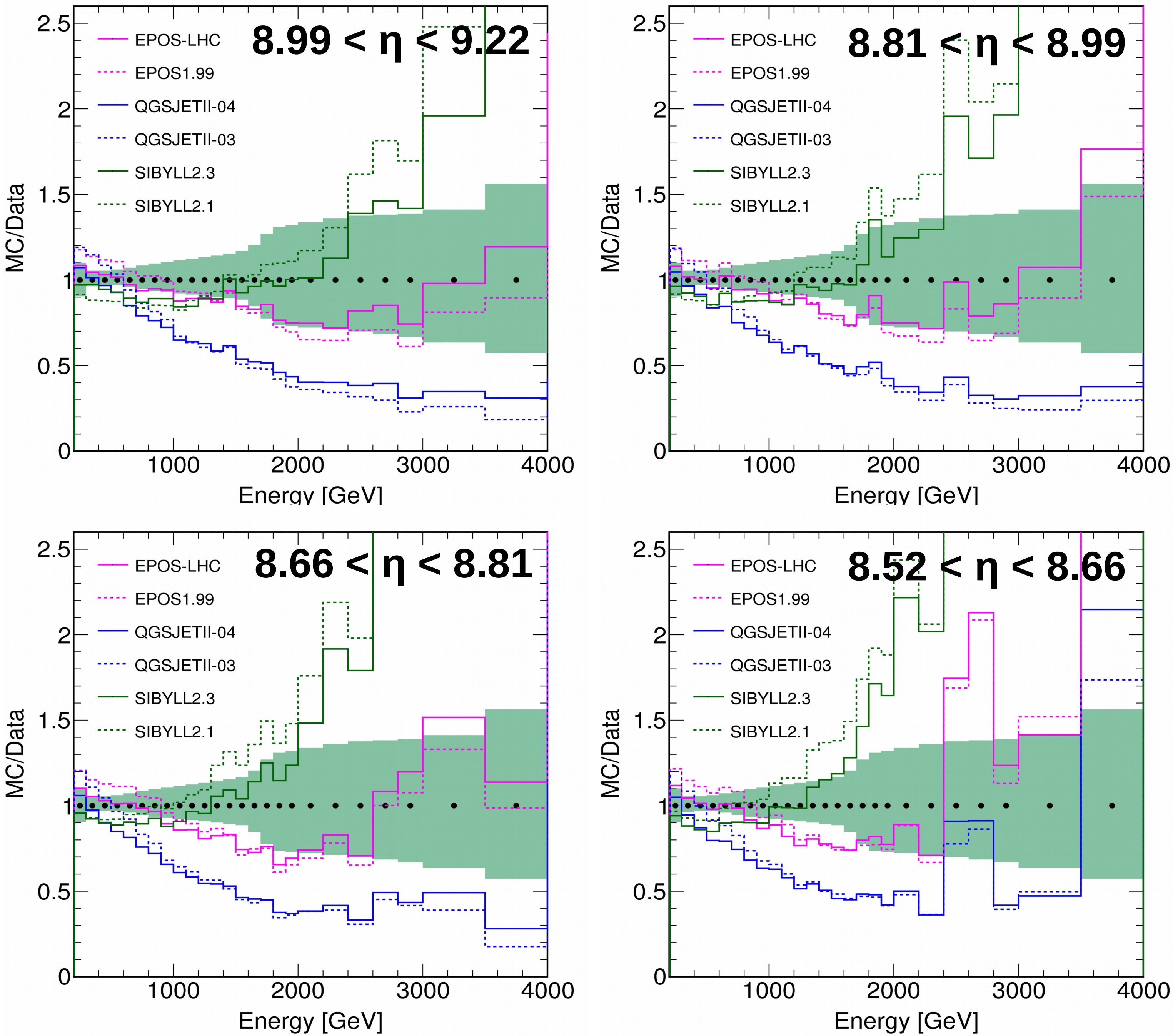


η-dependence of spectrum

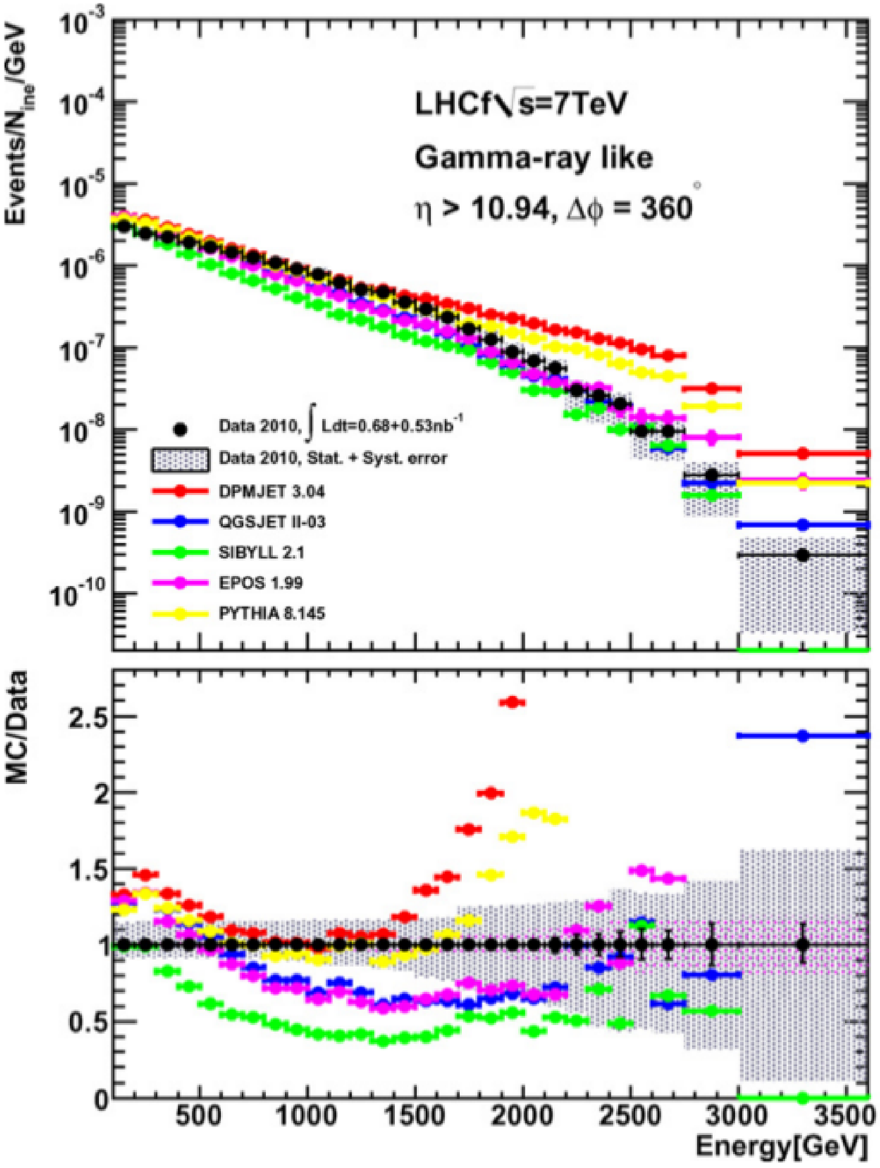


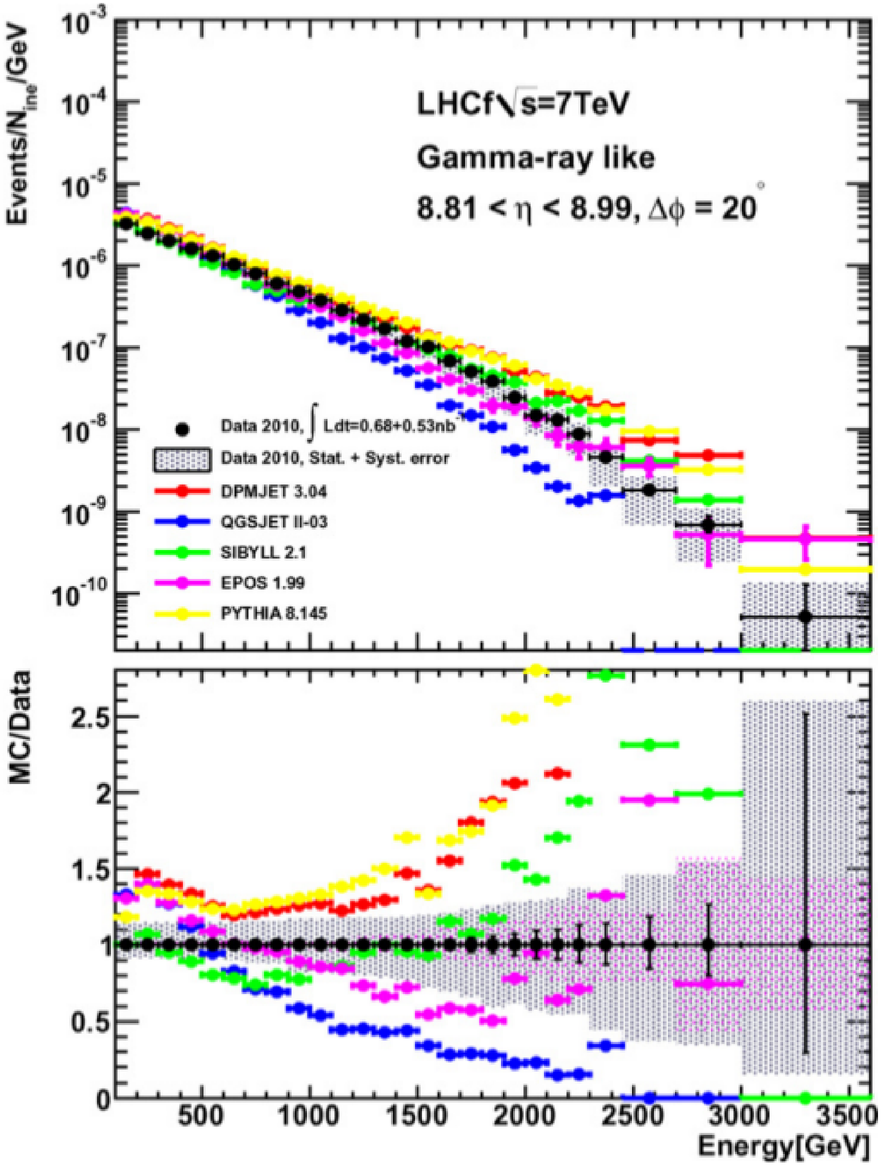
Data vs models: η dependence

LHCf Arm1 preliminary



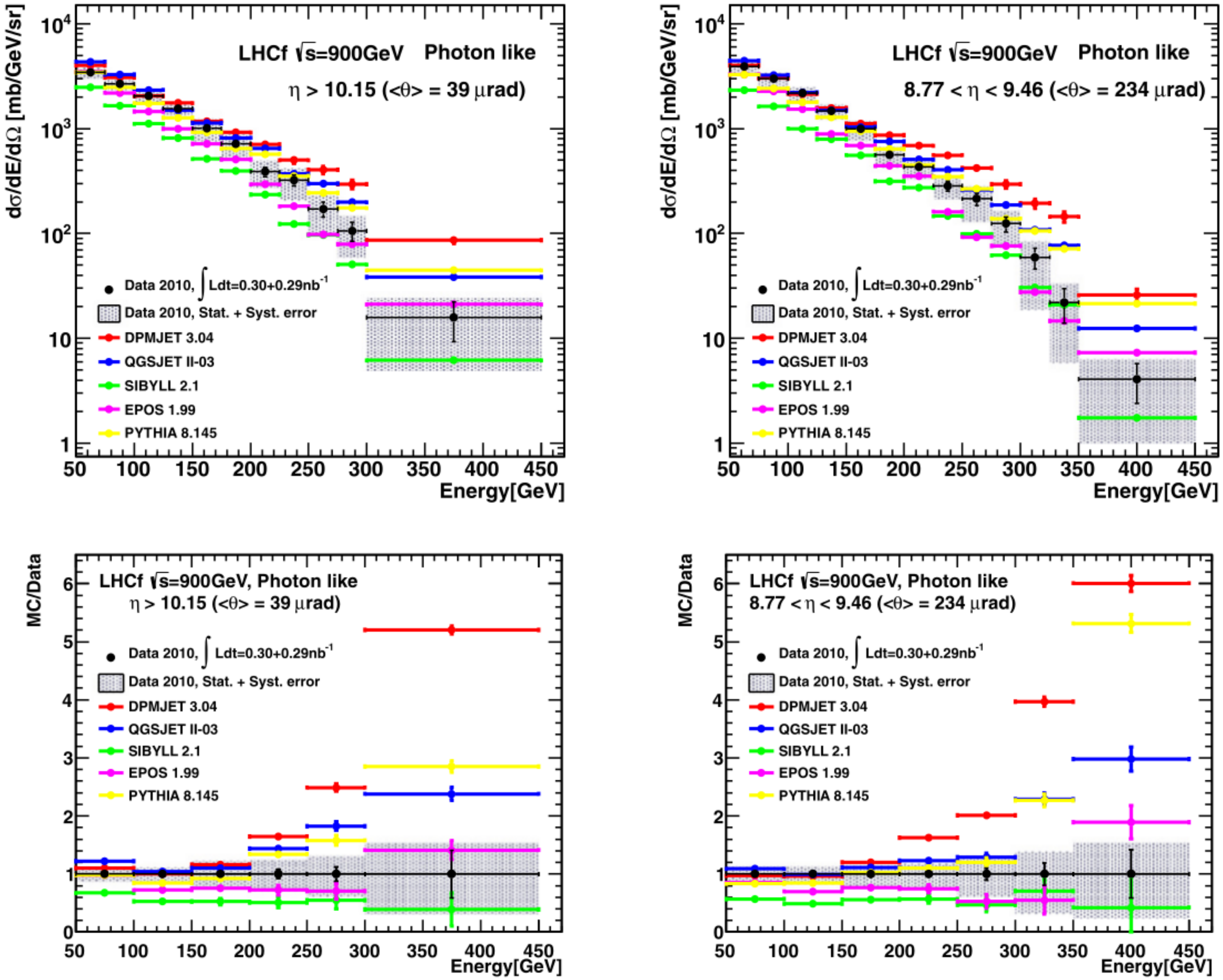
Photons spectrum in p-p at 7 TeV





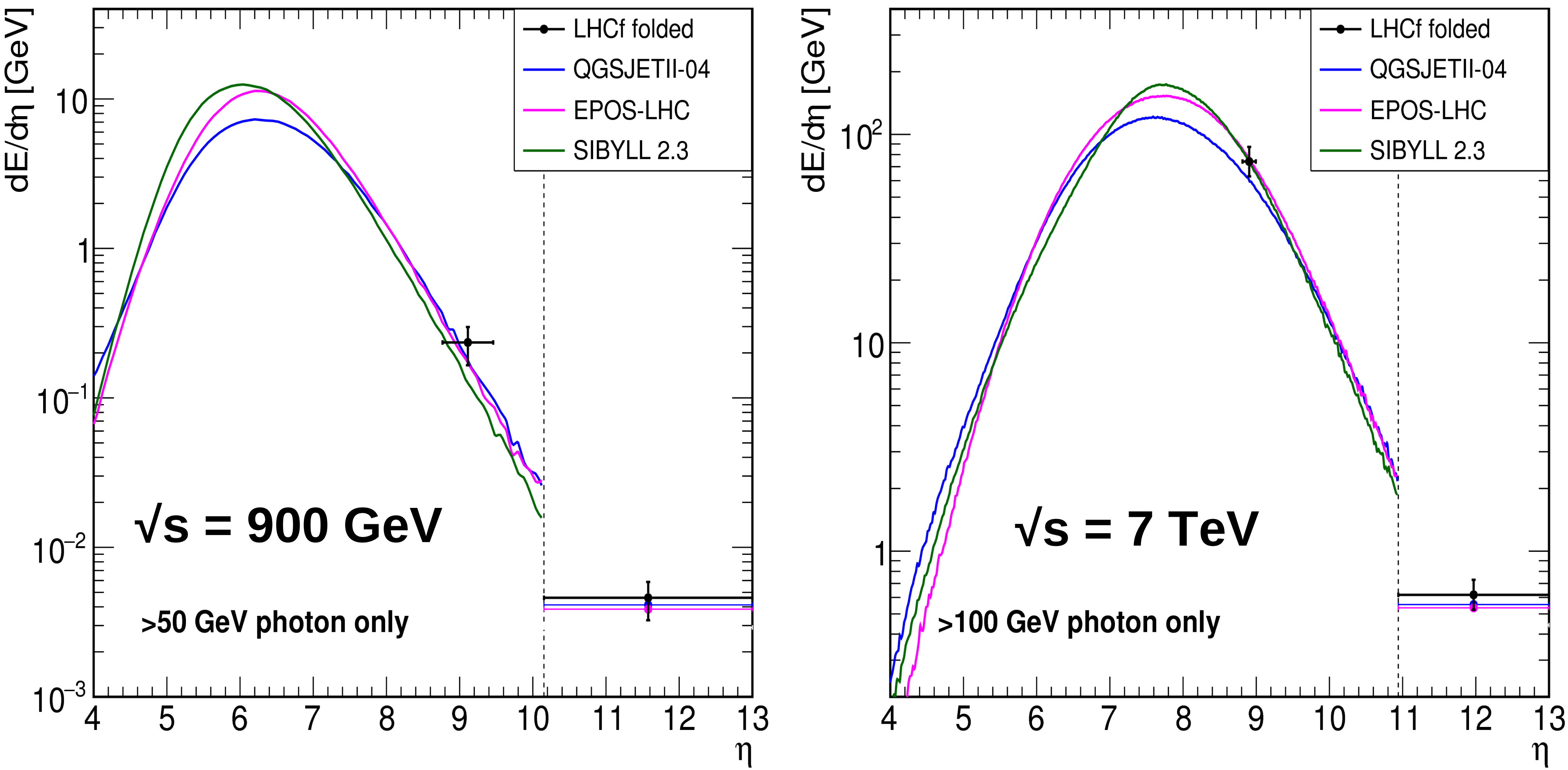
PLB 703 (2011), 128-134

Photons spectrum in p-p at 900 GeV



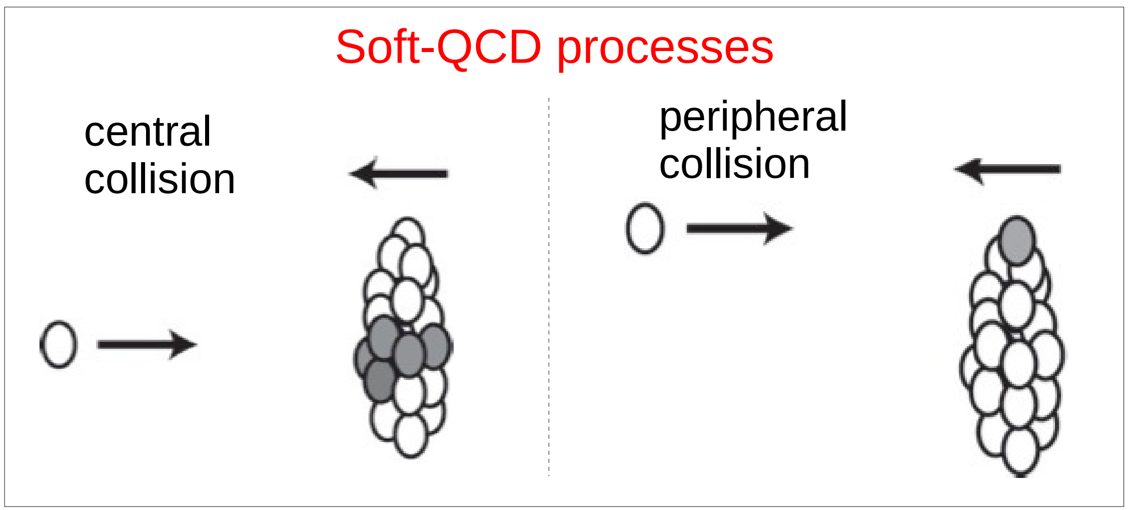
PLB 715 (2012), 298-303

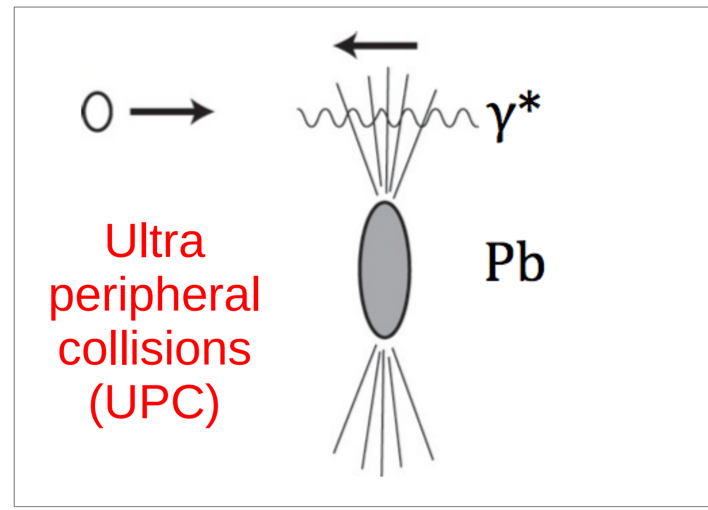
Energy flow: results at √s = 0.9, 7 TeV



π^0 analysis in p-Pb collisions at 5.02 TeV

- Only **Arm2** installed (better position resolution than Arm1)
- Data taken both at **p**-side and **Pb**-side (swapping beams)



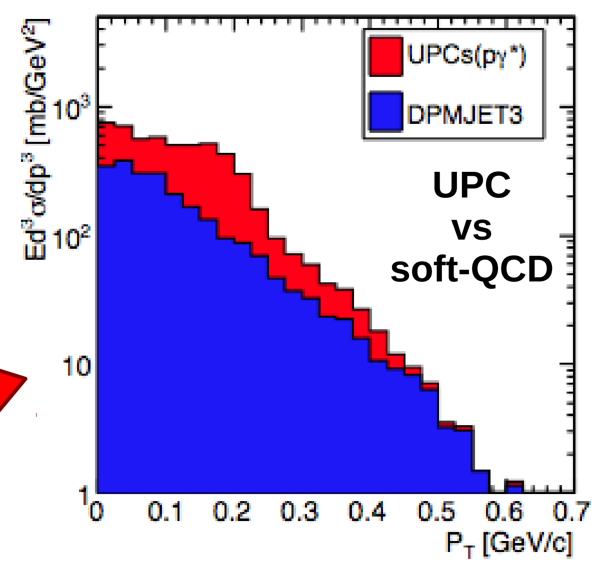


About half of the observed π^0 originates from UPC, another half is generated in soft-QDC processes

Dominant channel for forward π^0 production:

$$p + \gamma^* \rightarrow \Delta(1232) \rightarrow p + \pi^0$$

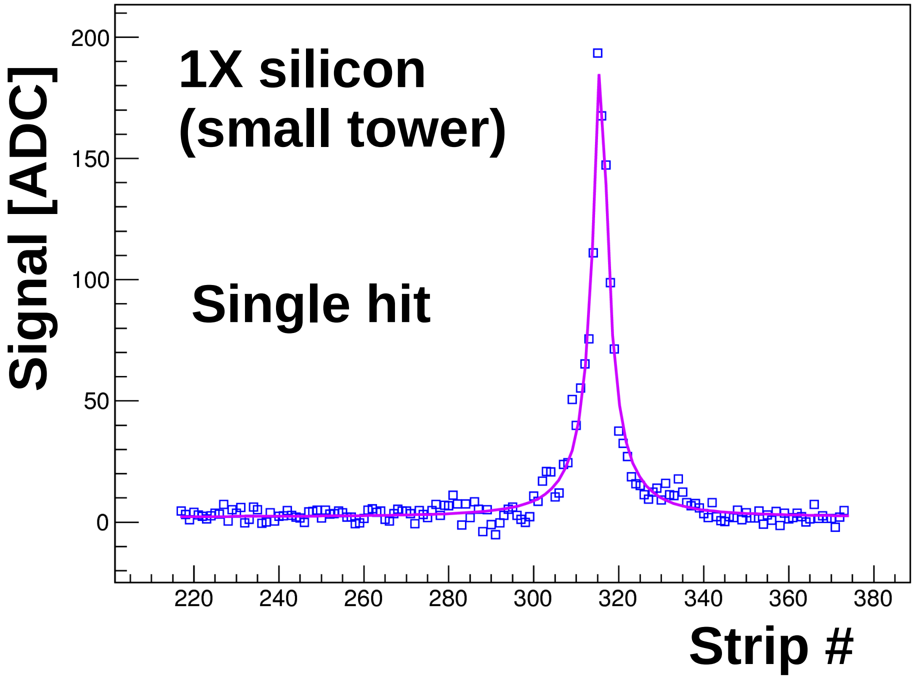
UPC contribution to P_T spectra is estimated from MC simulations (using Weizsacker Williams approximation for γ* spectrum and SOPHIA model for p-γ* collision)

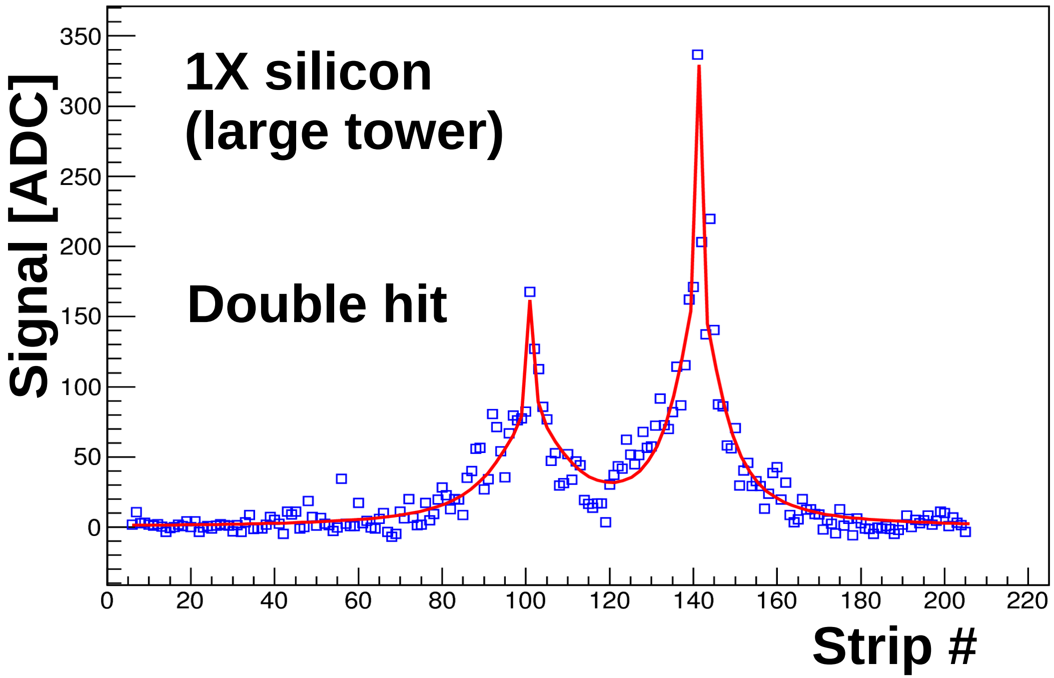


Position reconstruction

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

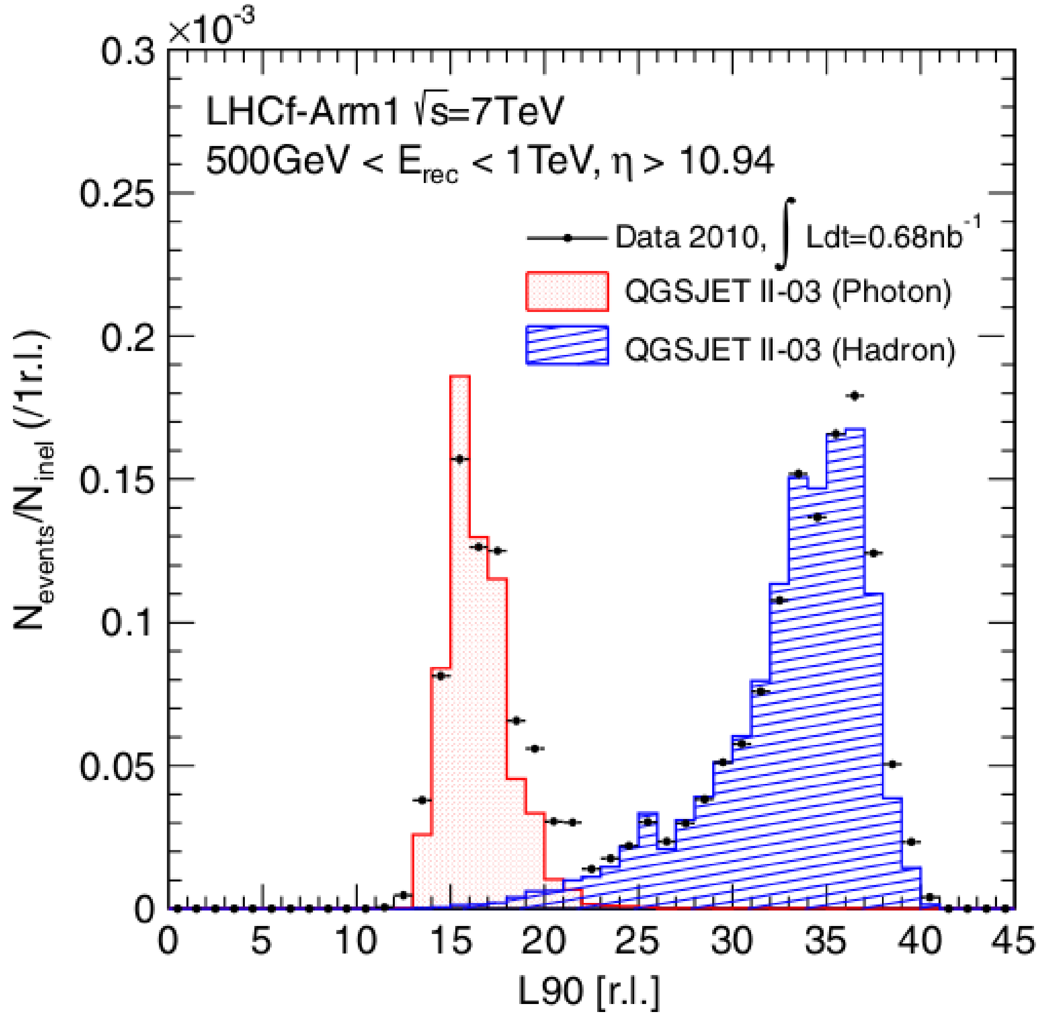
$$f(x) = p_0 \left[\frac{p_2}{\frac{(x-p_1)^2}{p_3} + p_3} + \frac{p_4}{\frac{(x-p_1)^2}{p_5} + p_5} + \frac{1-p_2-p_4}{\frac{(x-p_1)^2}{p_6} + p_6} \right]$$



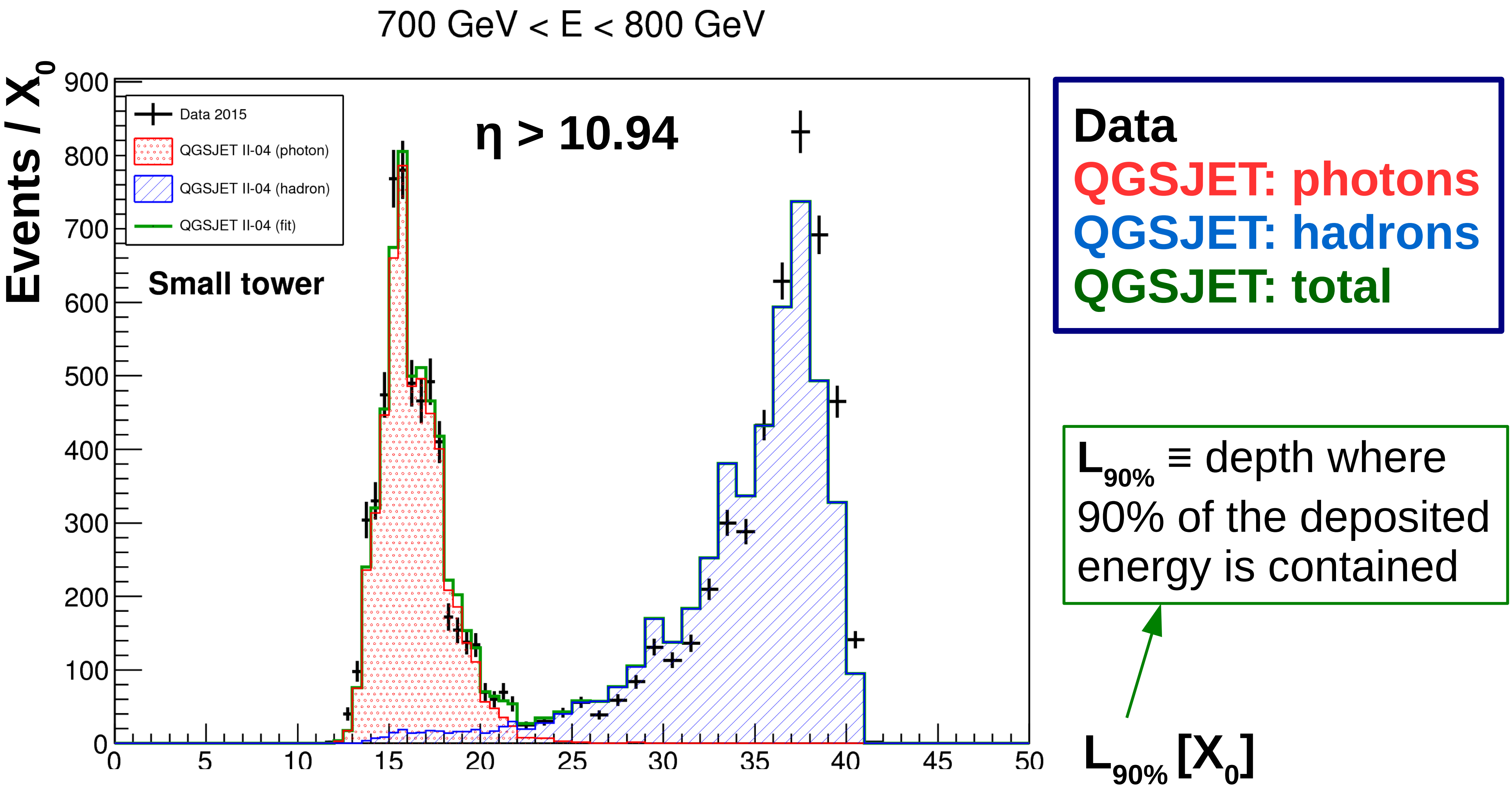


Photons selection

- **$L_{90\%}$**: 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

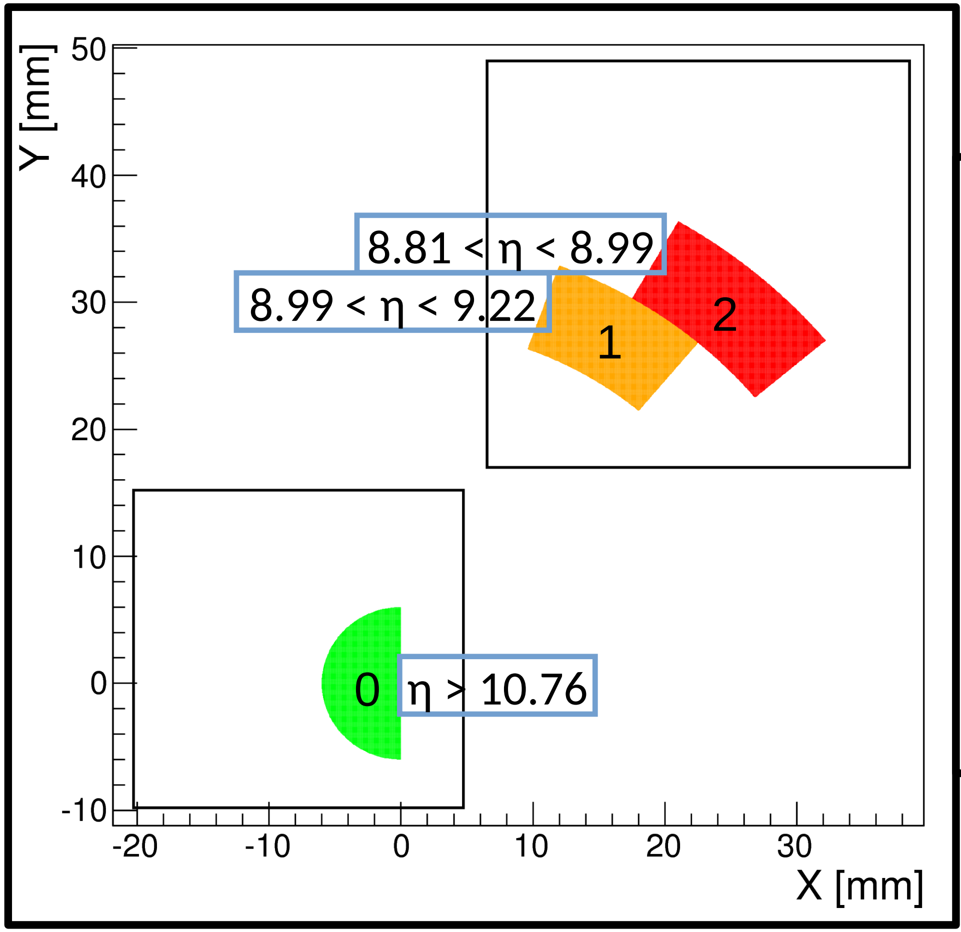


Template fit (photons)



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

Event selection (neutrons)

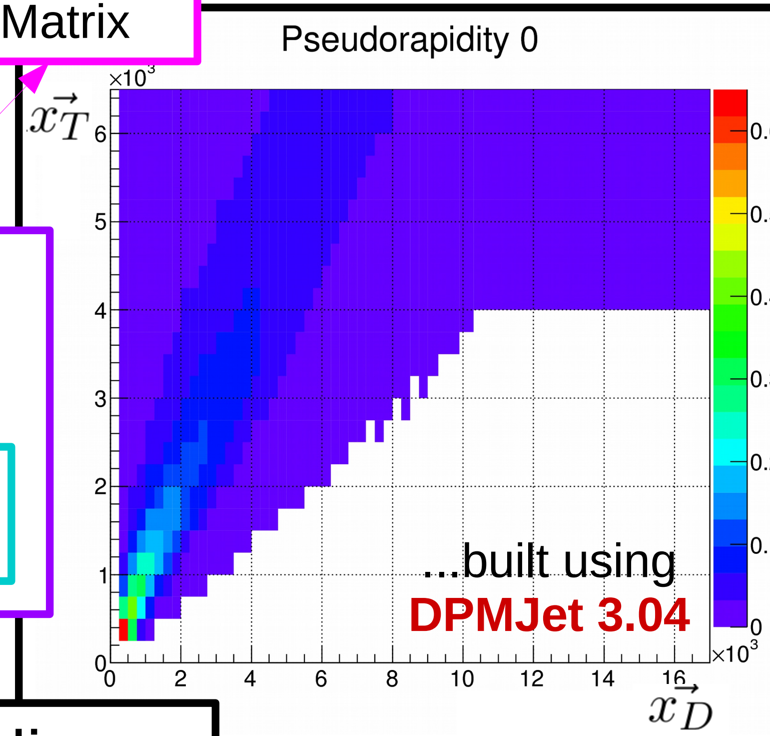


Event selection criteria:

- **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

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

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

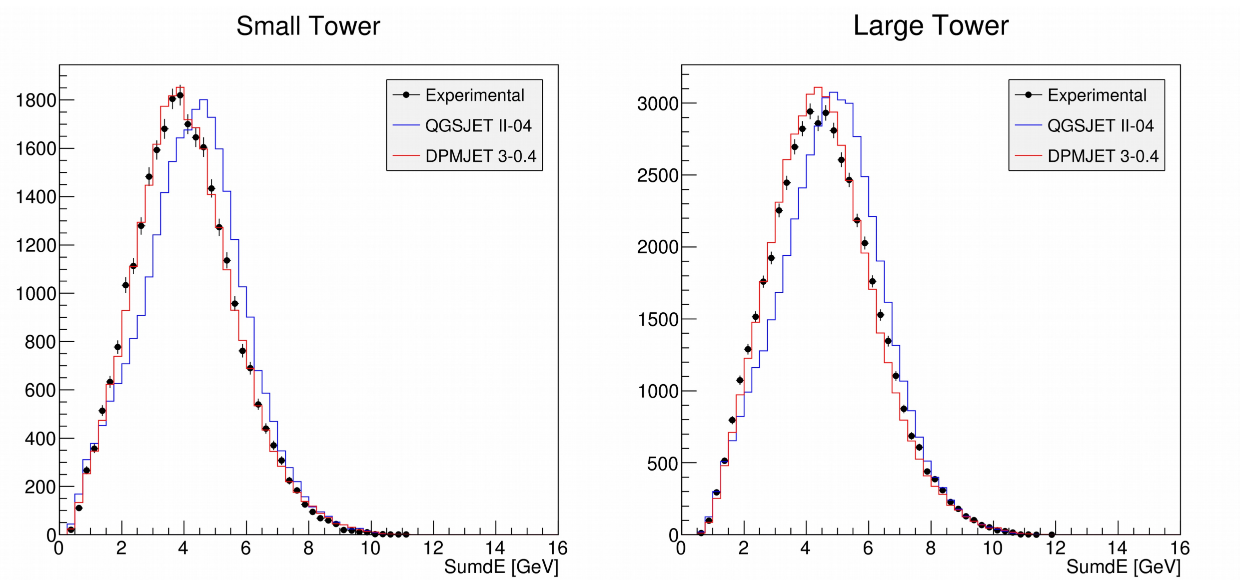
from MC

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

SPS beam test (protons): data vs MC



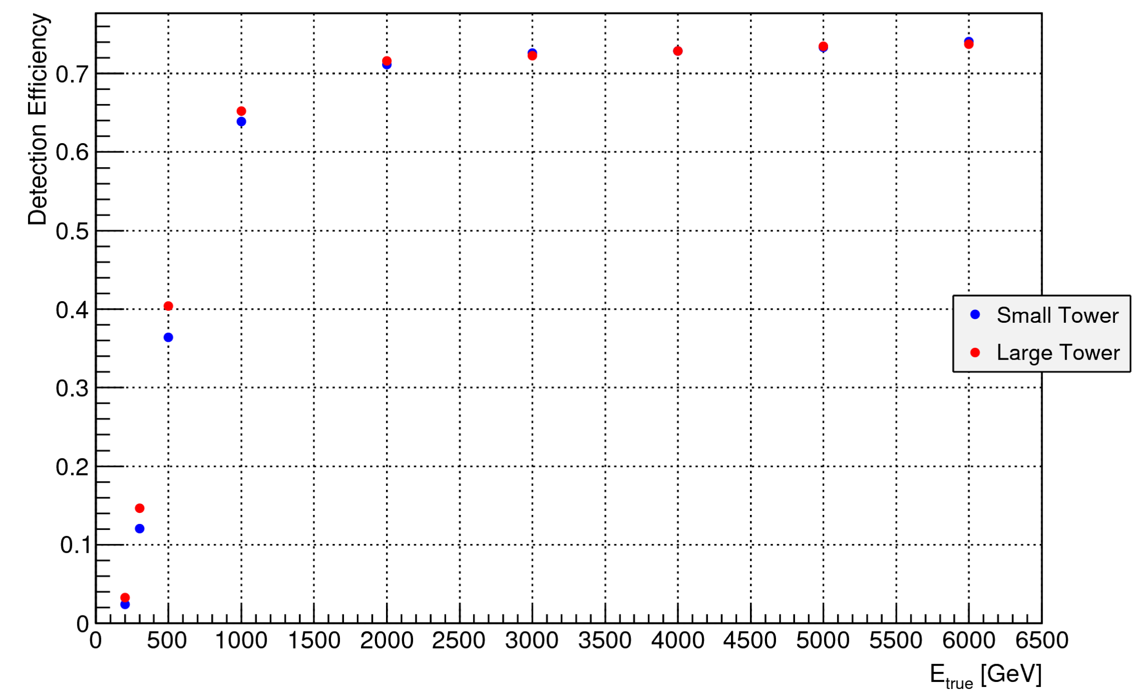
		Mean [GeV]	σ/Mean [%]	Ratio
Small tower	Experiment	4.041	39.283	-
	QGS	4.310	38.174	1.067
	DPM	4.065	39.430	1.006
Large Tower	Experiment	4.571	36.899	-
	QGS	4.820	34.594	1.055
	DPM	4.542	36.253	0.994

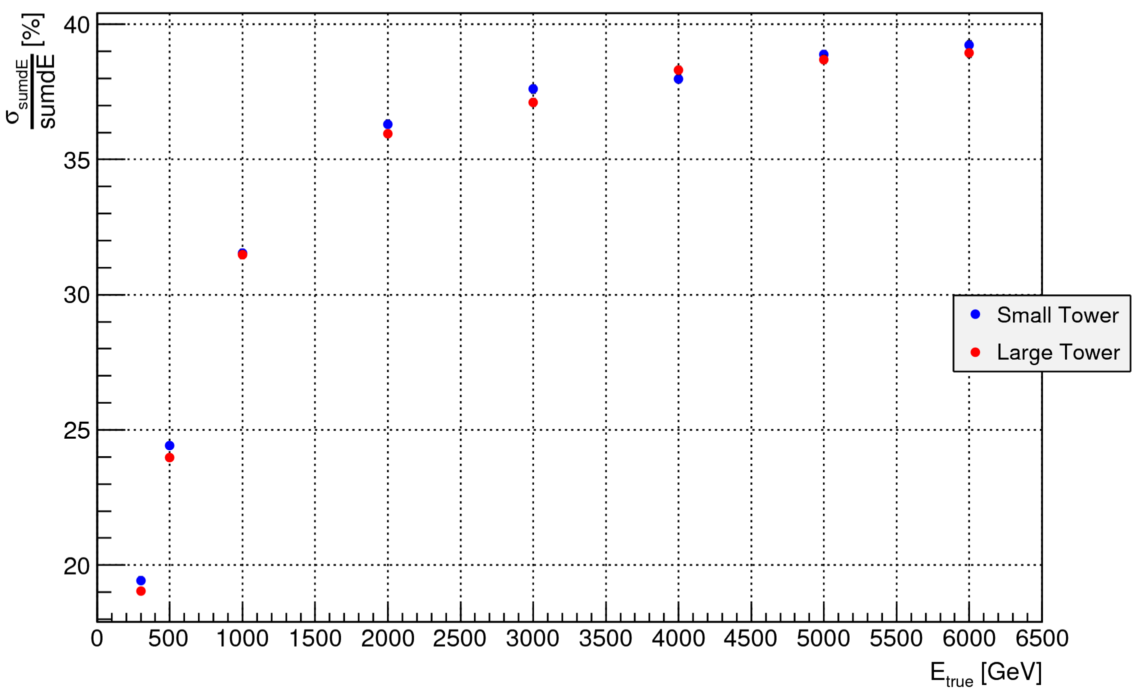
DPM model reproduces very well experimental results

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

350 GeV proton beam

Performances (neutrons)





Detection efficiency

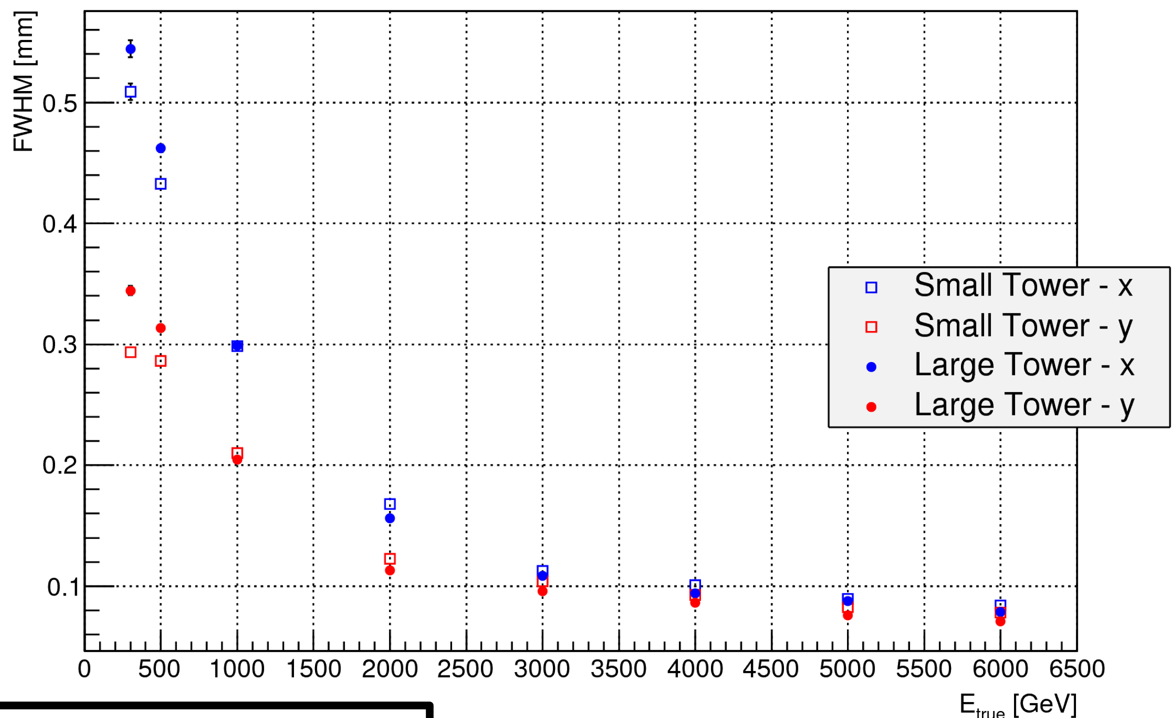
Making use of dE^{thr} = 600 MeV detection efficiency is very small below 500 GeV and reaches an almost constant value of ~70% above 2 TeV

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

Performances (neutrons)



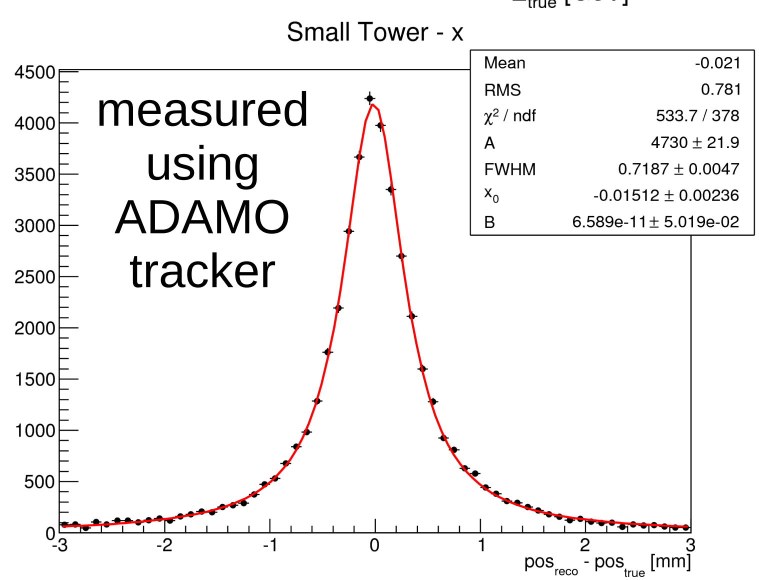
Position resolution

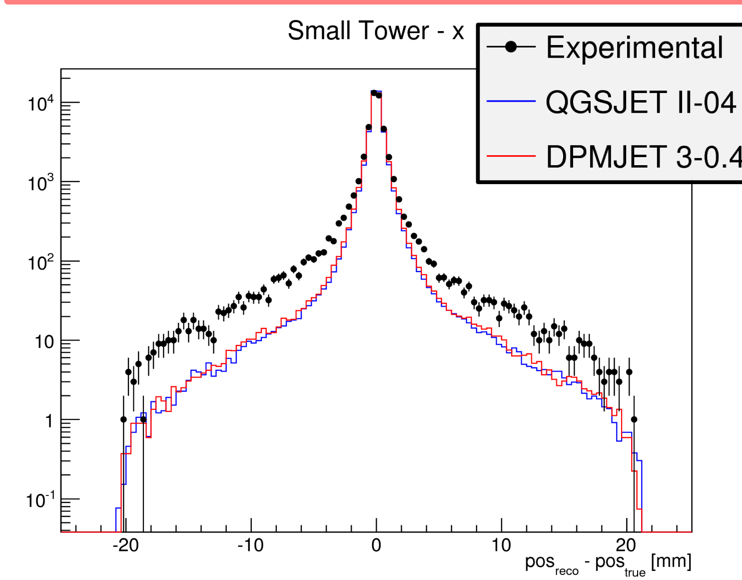
Position resolution, slightly different at low energy between x and y view, is better than 300 and 200 μm respectively above 1 TeV

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

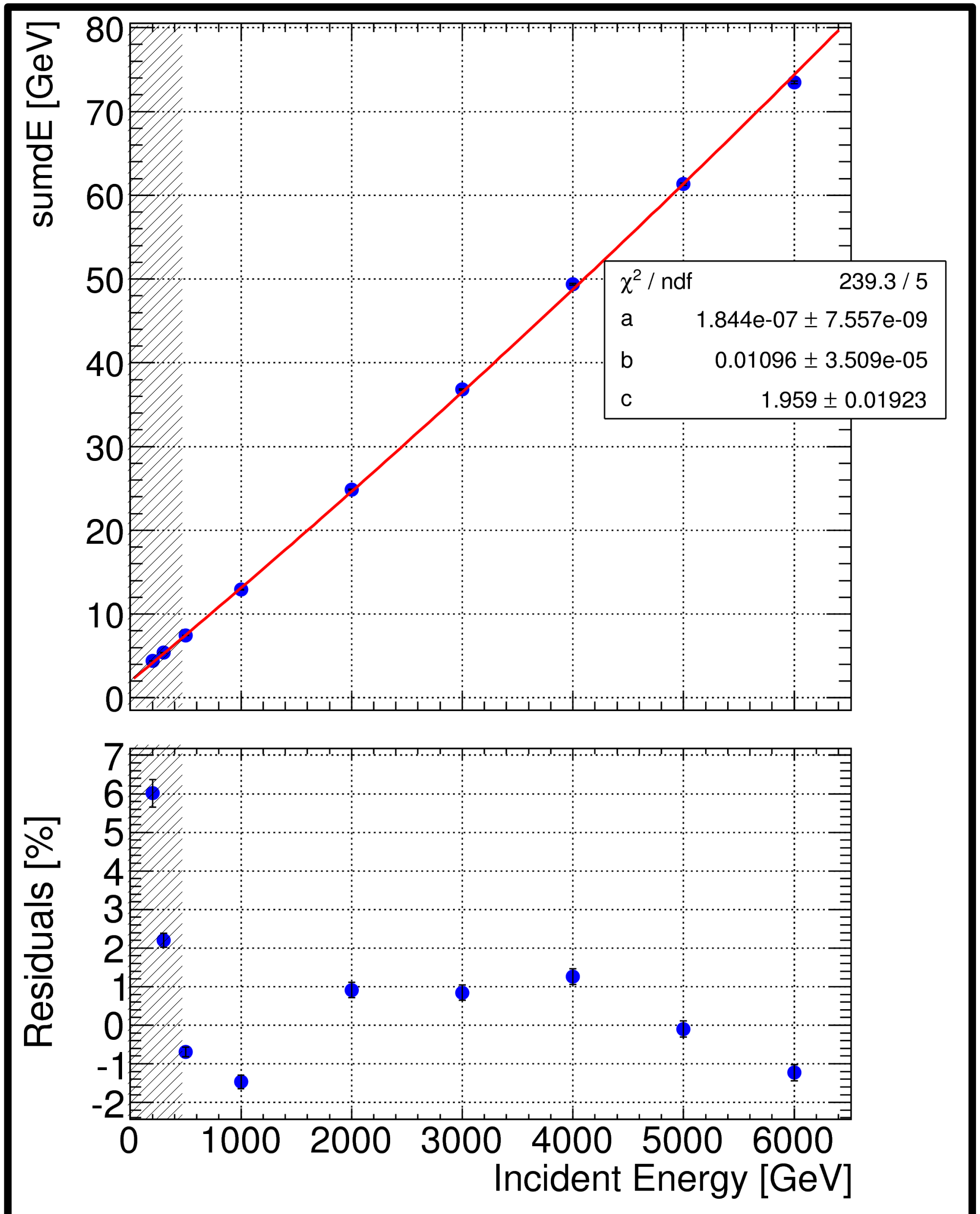
Resolution between 600 and 800 μm but long tails absent in MC

using 350 GeV proton beams beam test data





Energy conversion coefficients (neutrons): 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