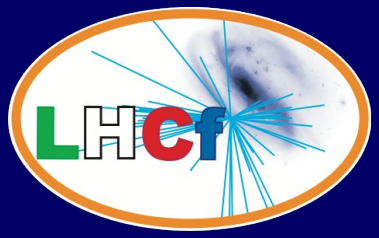


Very-forward photon production in p-p and p-Pb collisions measured by the LHCf experiment

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

PHOTON 2019

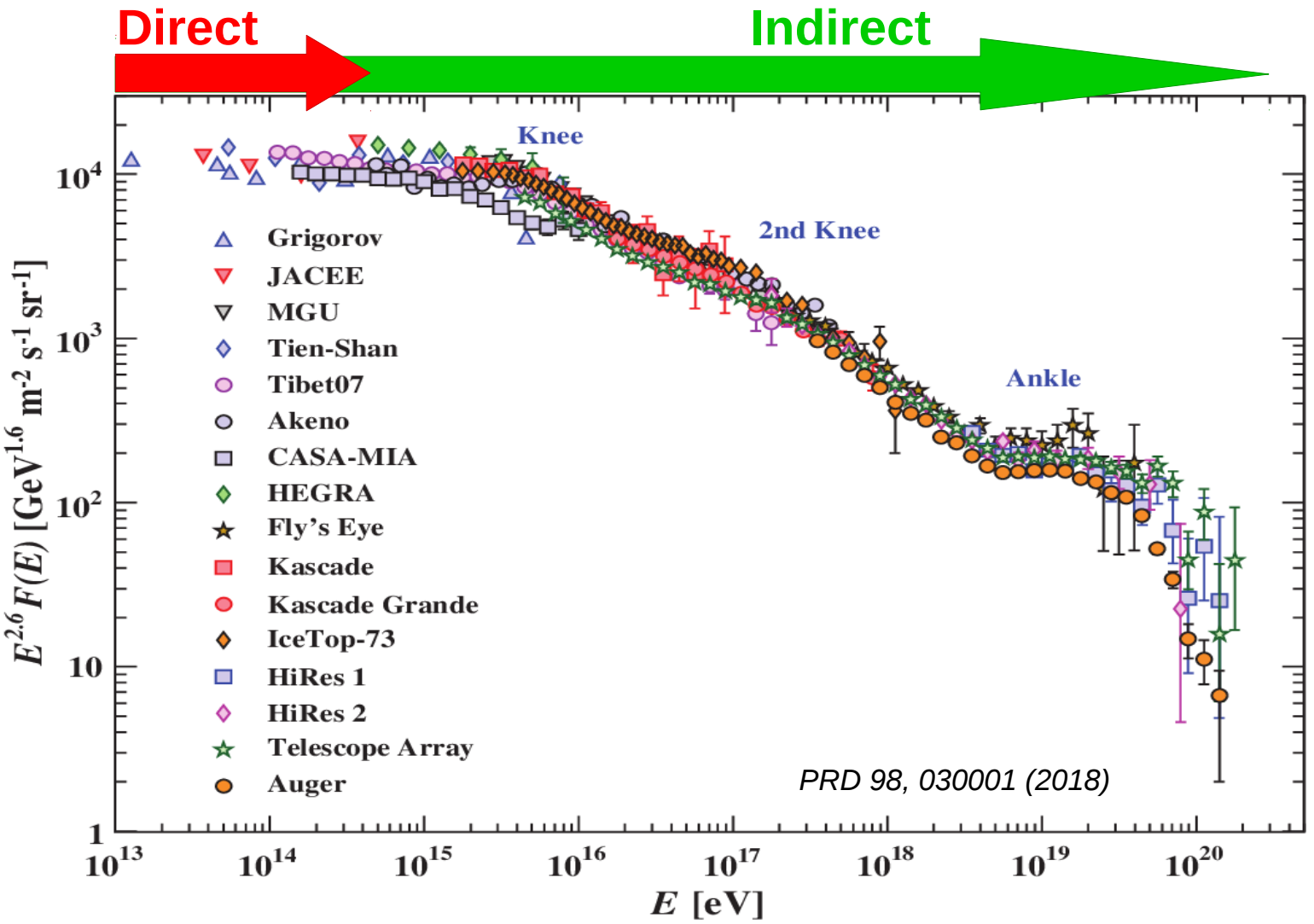
Frascati, 3-7 June 2019

Outline

- Physics motivations
- The LHCf experiment
- Physics results
  - photons in **p-p** at **13 TeV**
  - **LHCf-ATLAS** combined analysis
  - photons in **p-Pb** at **8.16 TeV** **preliminary!**

Physics motivations

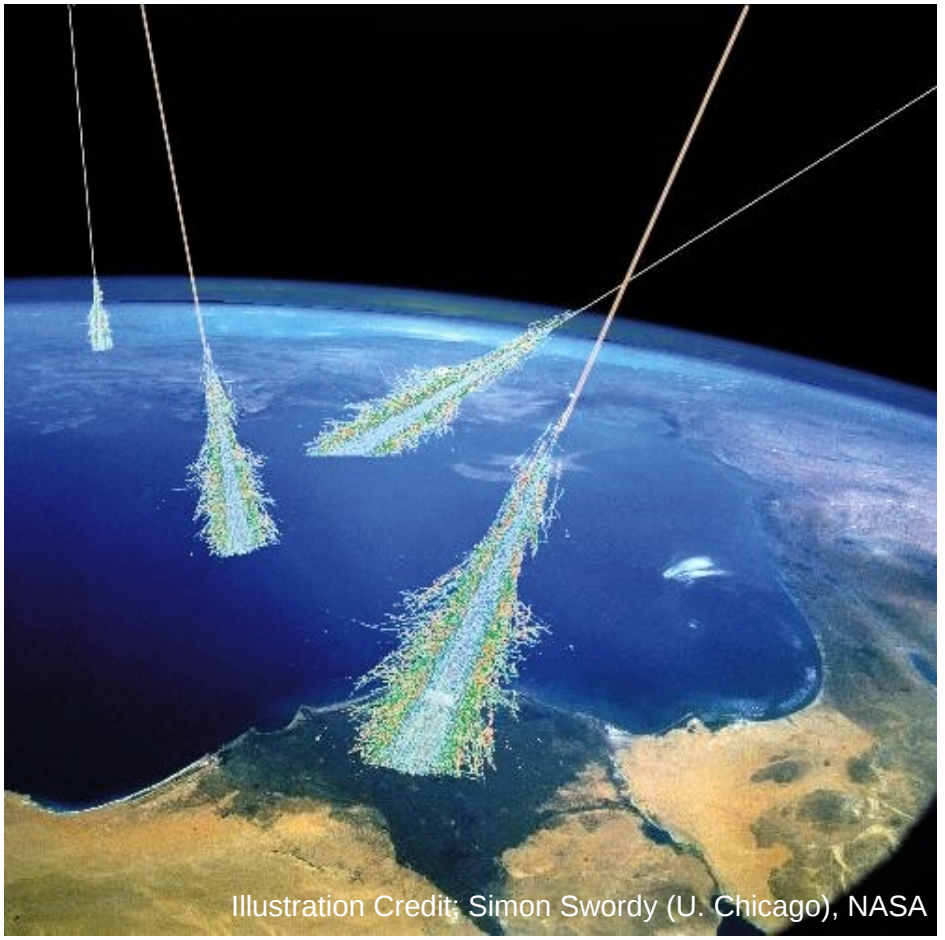
Cosmic rays spectrum



- **Direct measurements** limited by low flux of particles at high energies

- Only **indirect measurements** (with ground based experiments) are possible above ~10^{14}-10^{15} eV

Cosmic rays: indirect measurements



Air showers measurements:

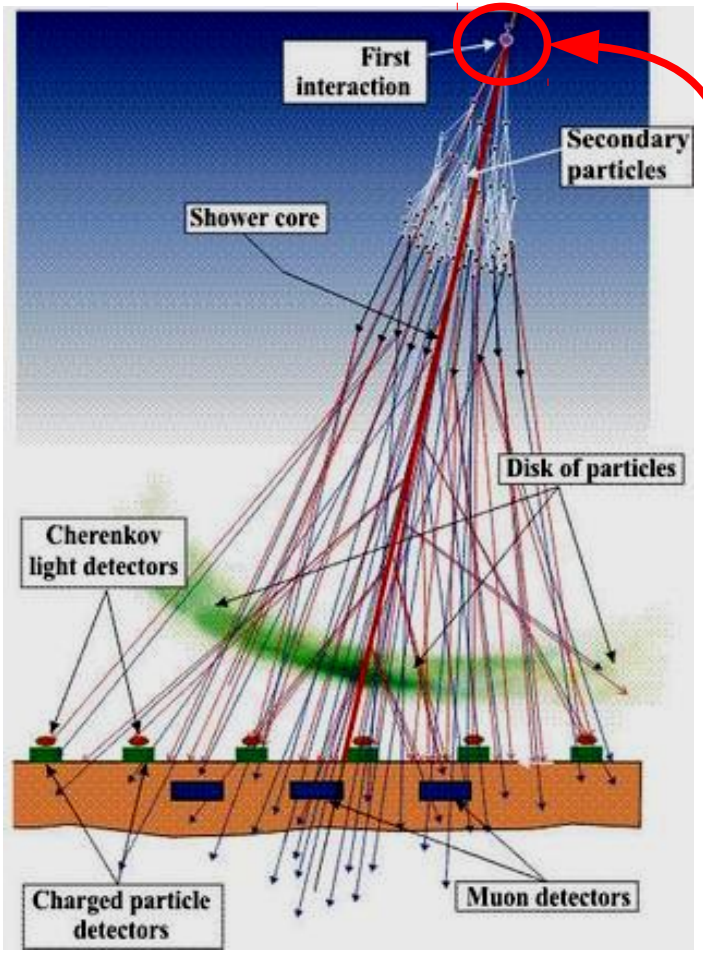
- Longitudinal distribution
- N° of particles at ground
- Arrival direction

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 → $E_{CR} = 0.9 \cdot 10^{17}$ eV

First interaction

- **Inelastic cross section**
- **Multiplicity**
- **Elasticity = 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

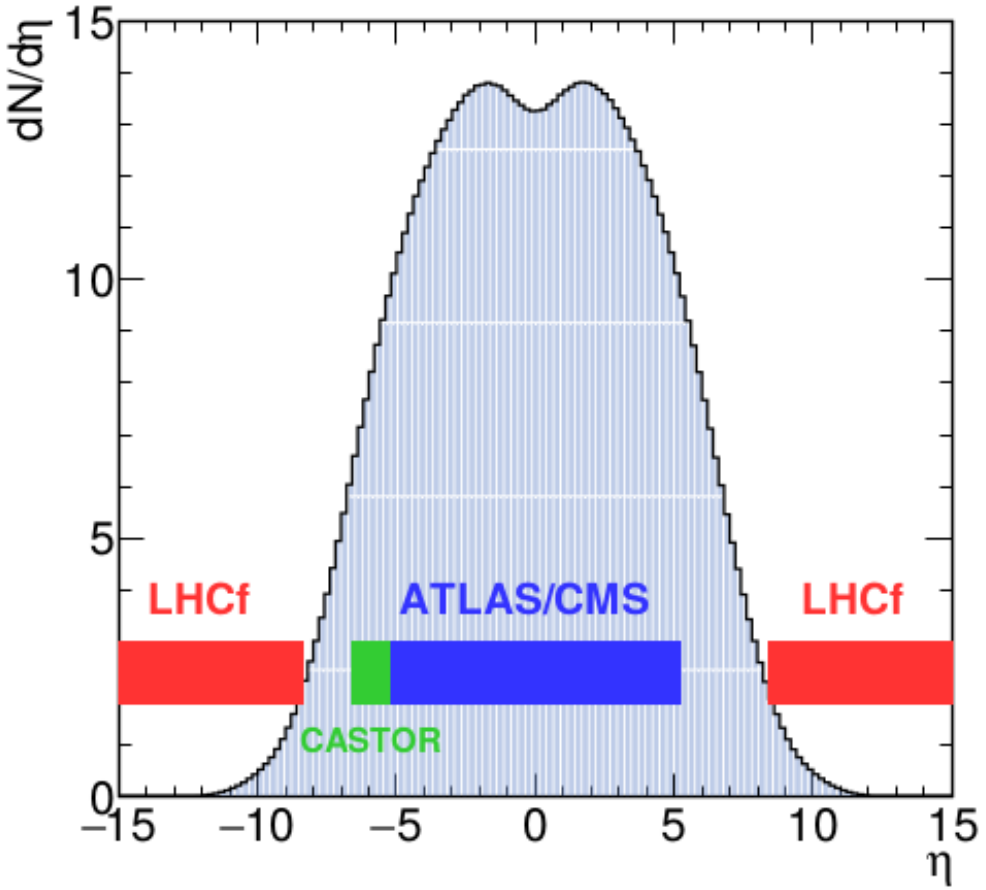
→ **Inputs from experimental data are fundamental**

Why forward region?

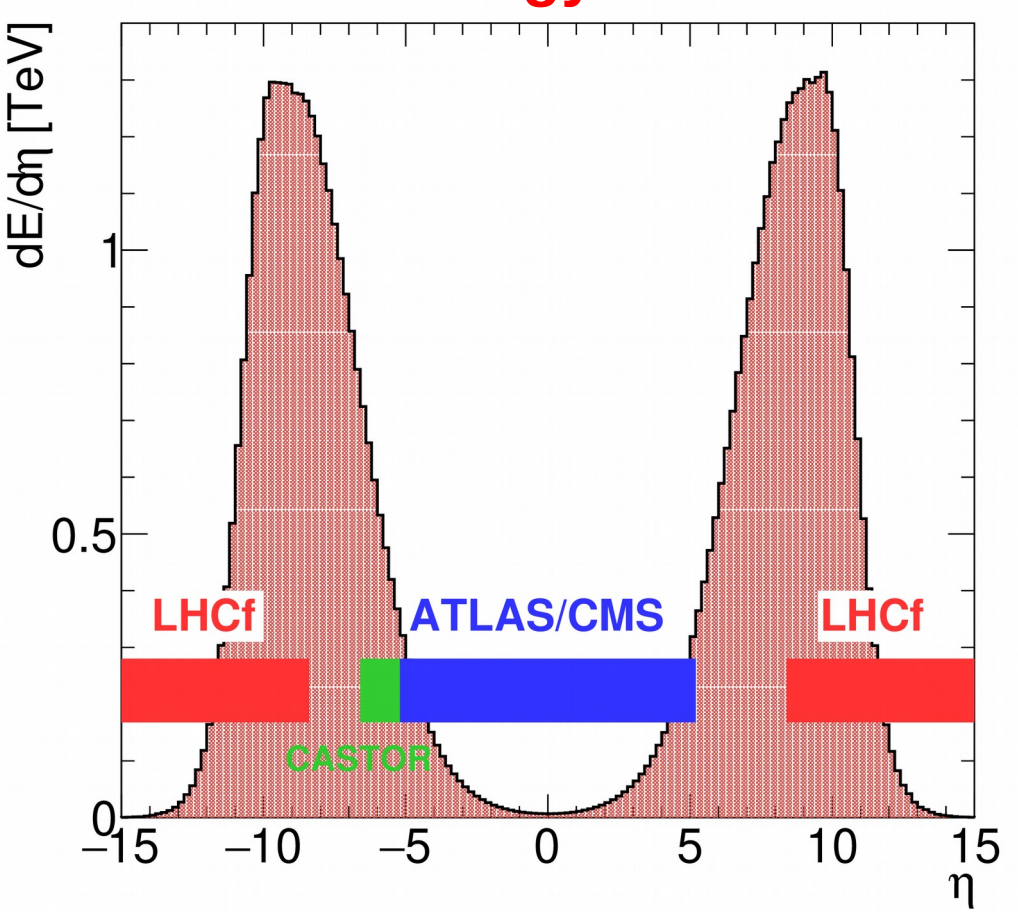
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

p-p @ √s = 13 TeV

Multiplicity



Energy flow

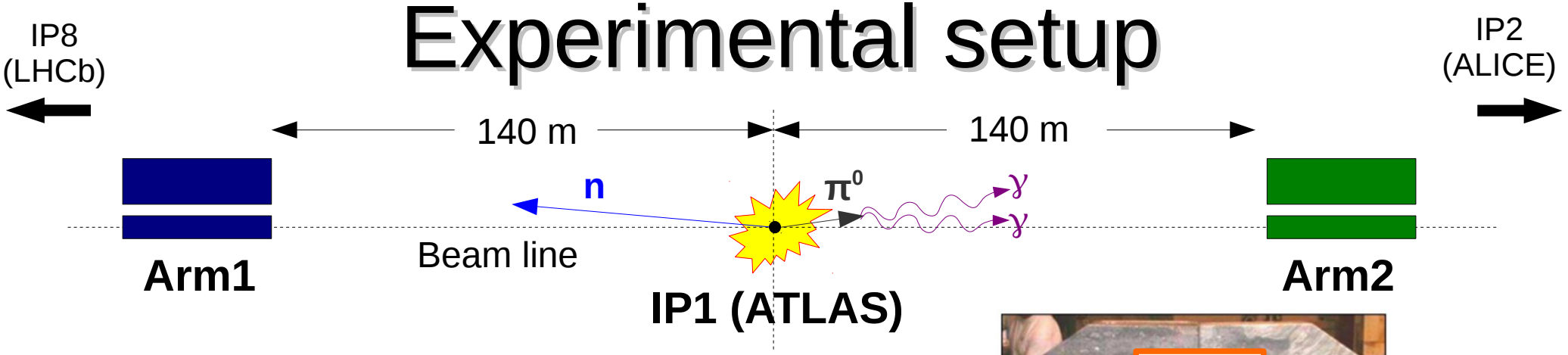


Maximum multiplicity in the central region

Peak of energy flow around η ~ 9 (θ ~ 0.25 mrad)

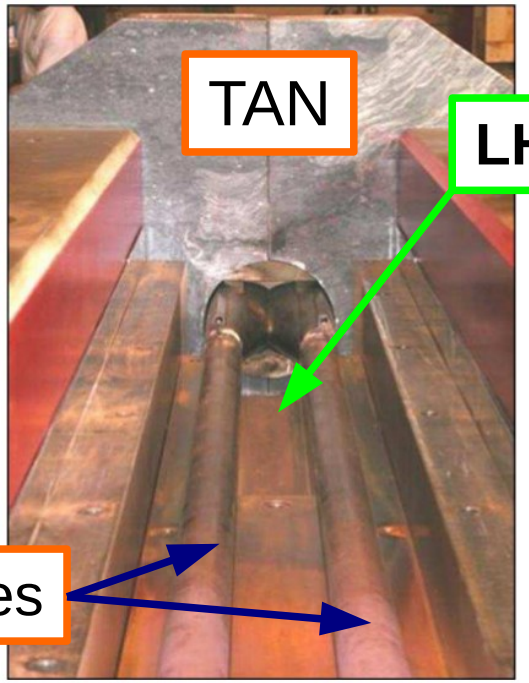
The LHCf experiment

Experimental setup



LHCf is located in TAN slot

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



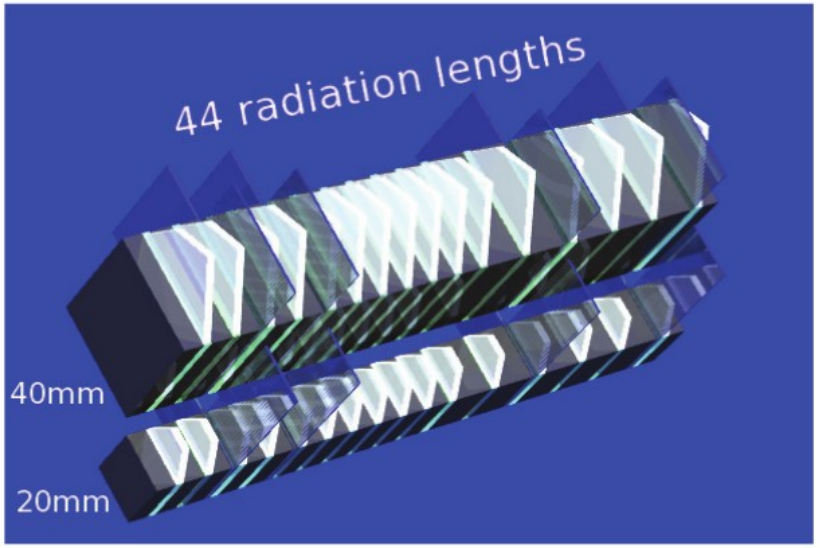
Charged particles are deflected by D1 dipole magnet

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)

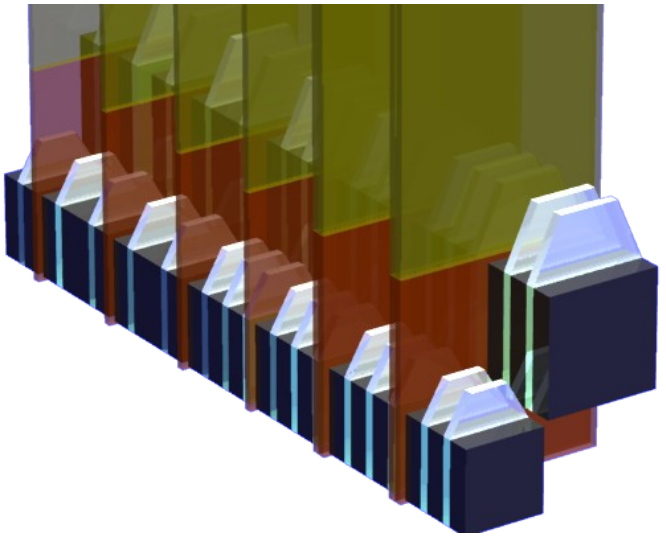
Arm 1



Arm 1

- Transverse size: 20 x 20 mm^2 and 40 x 40 mm^2
- 4 x-y **GSO bars** layers
- Position resolution: 100 μm (photons, E > 200 GeV)

Arm 2



Arm 2

- Transverse size: 25 x 25 mm^2 and 32 x 32 mm^2
- 4 x-y **silicon μstrip** layers
- Position resolution: 40 μm (photons, E > 200 GeV)

Operations history at LHC

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

Physics results: photons in p-p

LHCf p-p run at 13 TeV

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

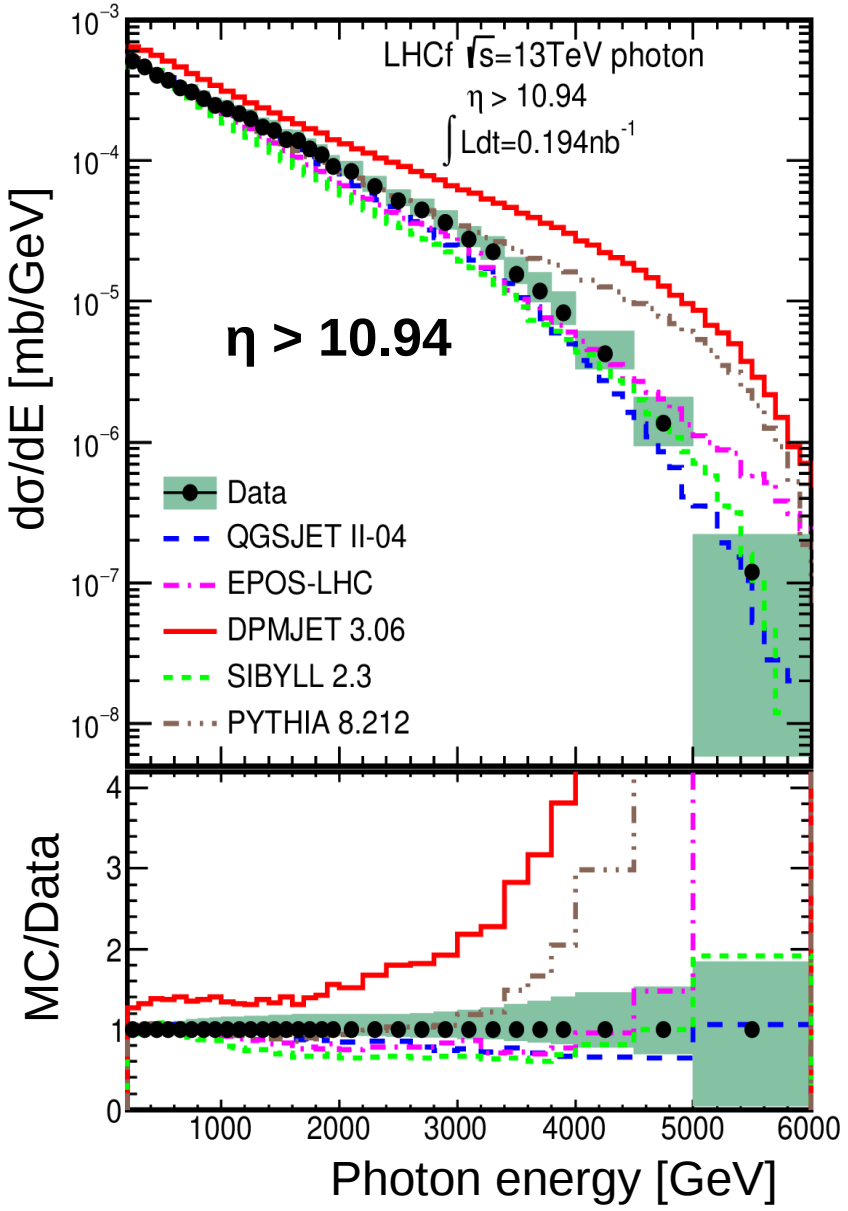
LHCf run:

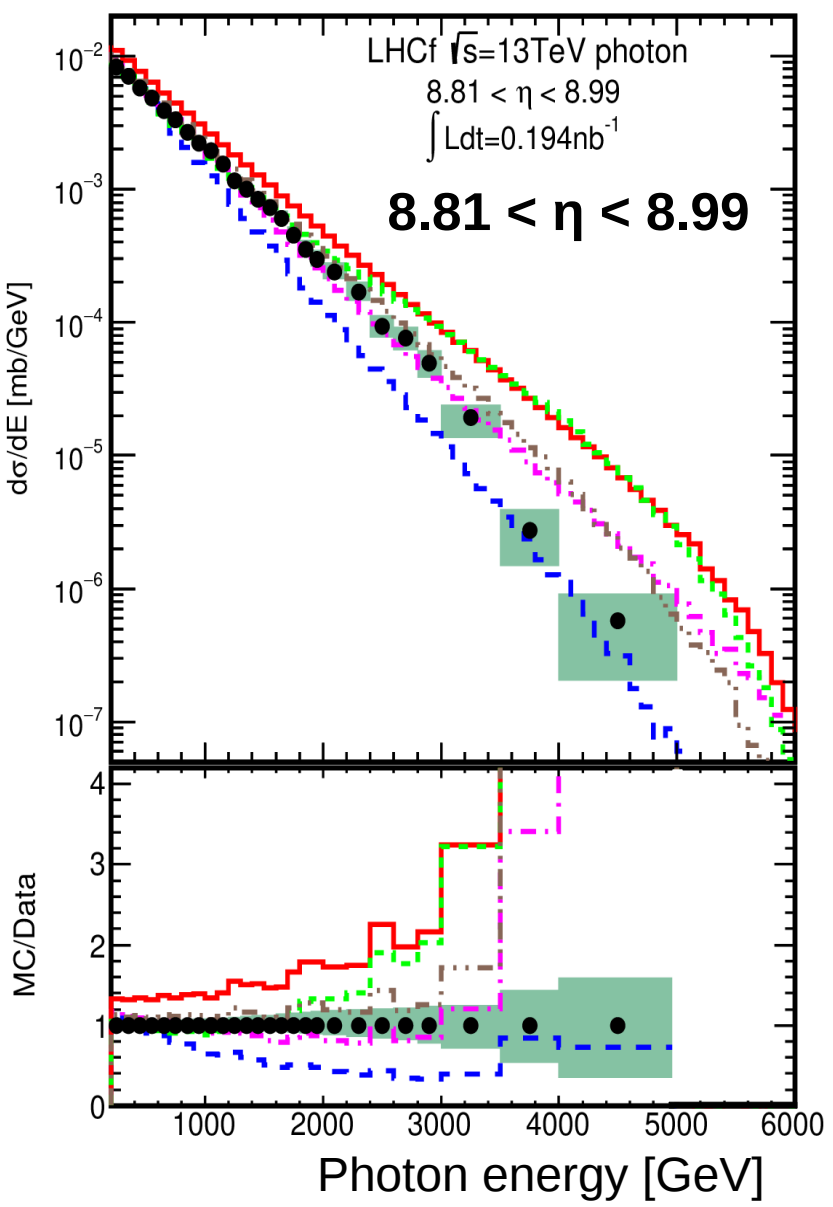
- **$\sqrt{s}$ = 13 TeV**
- ~ 27 hours of operation
- **Luminosity:** 0.3 - 1.6 · 10^{29} cm^{-2} s^{-1}
- **Pile-up:** 0.01 - 0.03
- 4 · 10^{7} **events**
  5 · 10^{5} **π^0s**
- Trigger exchange with **ATLAS**

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

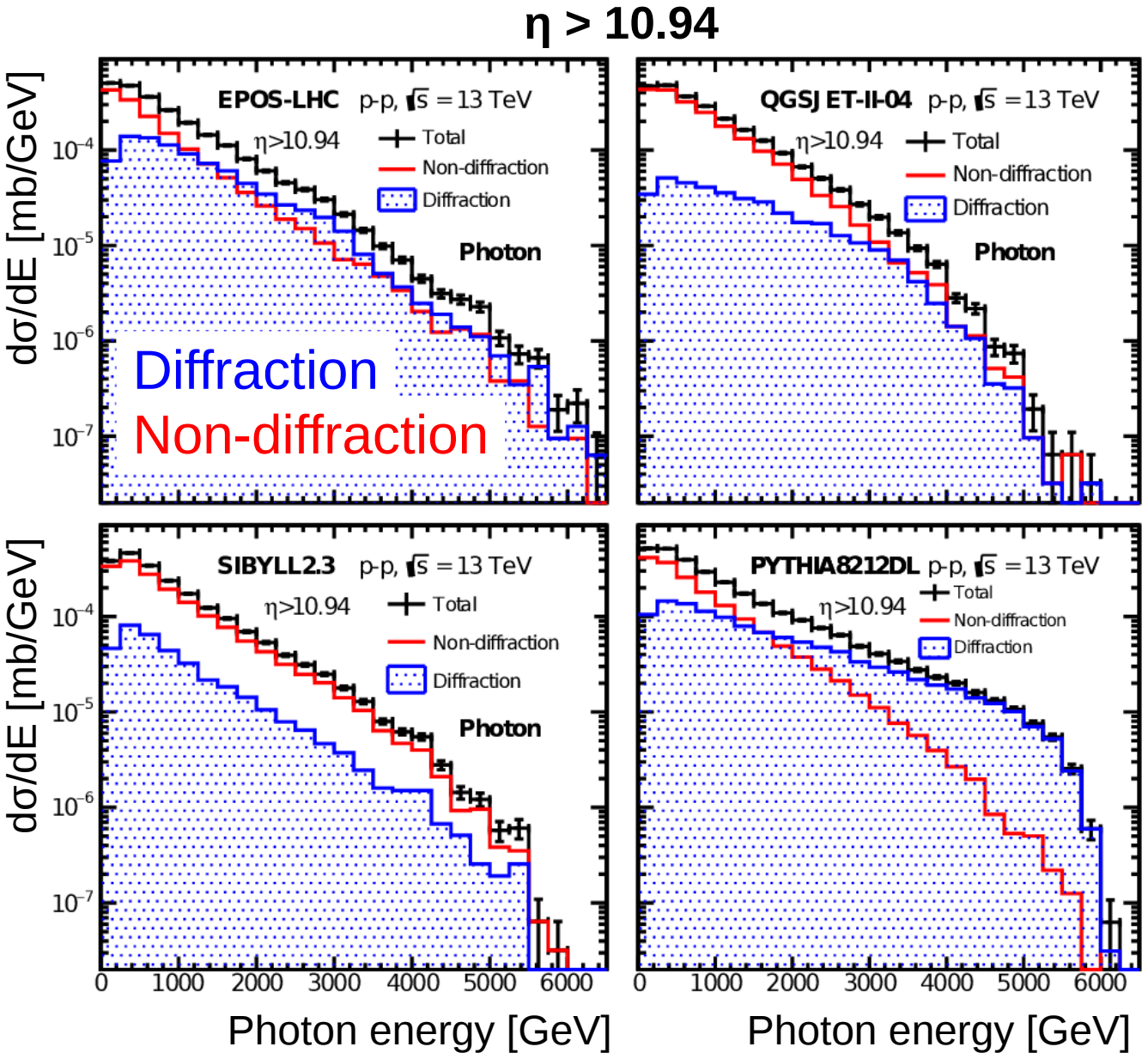




O. Adriani et al., PLB 780 (2018) 233–239

- **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



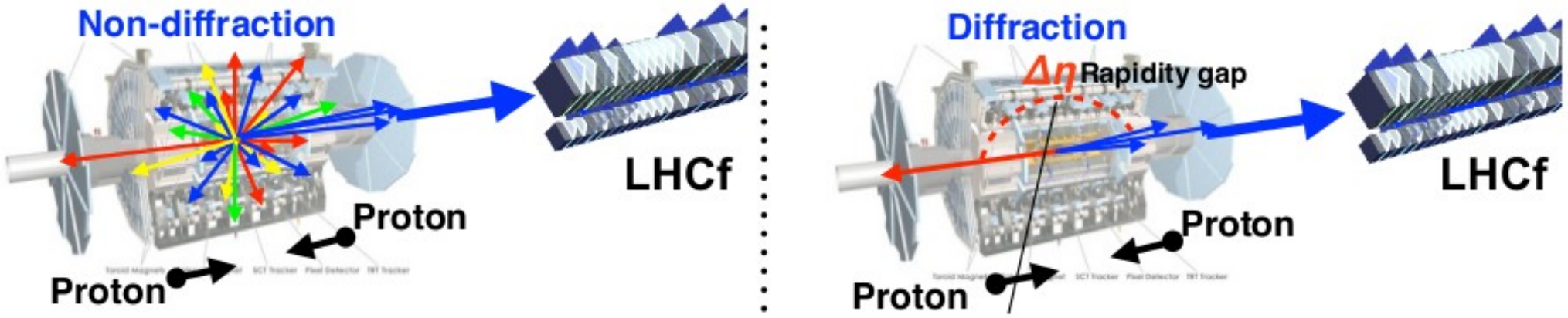
Hadronic interaction models predict different contributions of diffraction

Central detectors can give useful information to identify diffractive events

LHCf+ATLAS combined analysis

Q. D. Zhou et al., Eur. Phys. J. C (2017) 77:212

ATLAS+LHCf

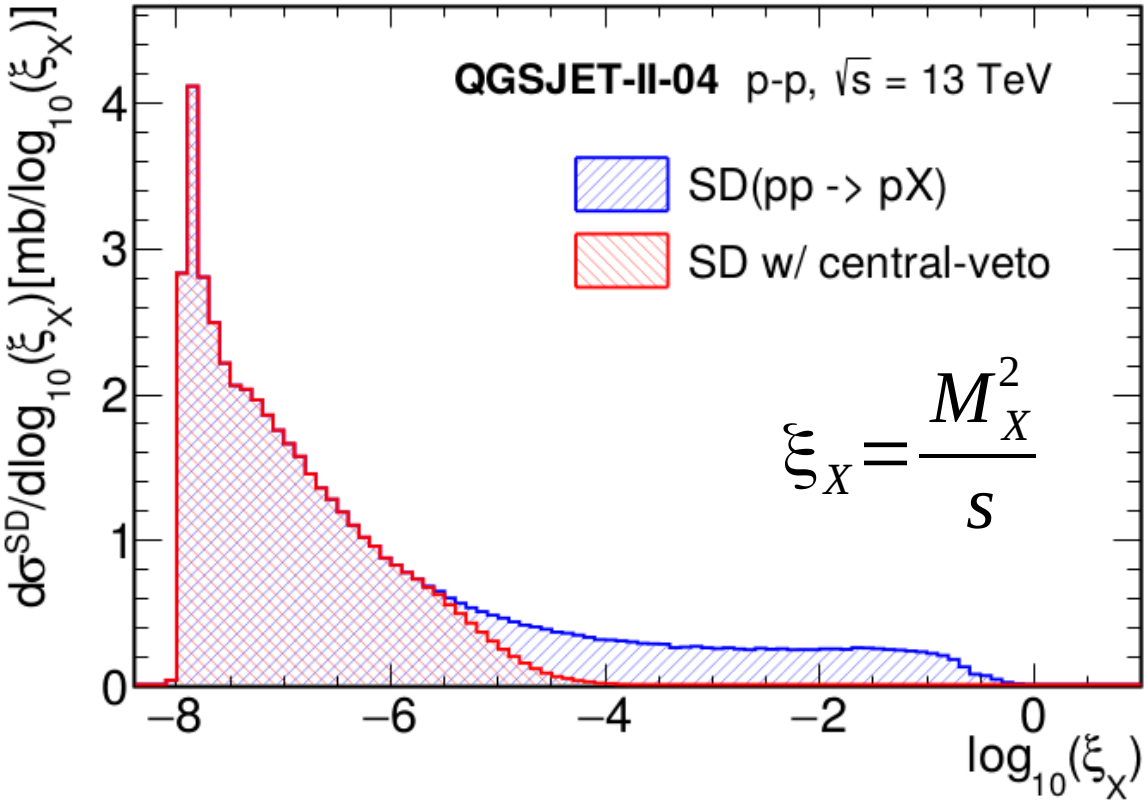


- Trigger exchanged with ATLAS during p-p operation at 2.76, 13 TeV and p-Pb operation at 5.02, 8.16 TeV
- The number of tracks in the central region identifies the type of the event
- A preliminary analysis was performed with p-Pb data at 5.02 TeV (*ATL-PHYS-PUB-2015-038*)
- First analysis of 13 TeV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

Diffractive event selection

Central veto: no charged particles in ATLAS with

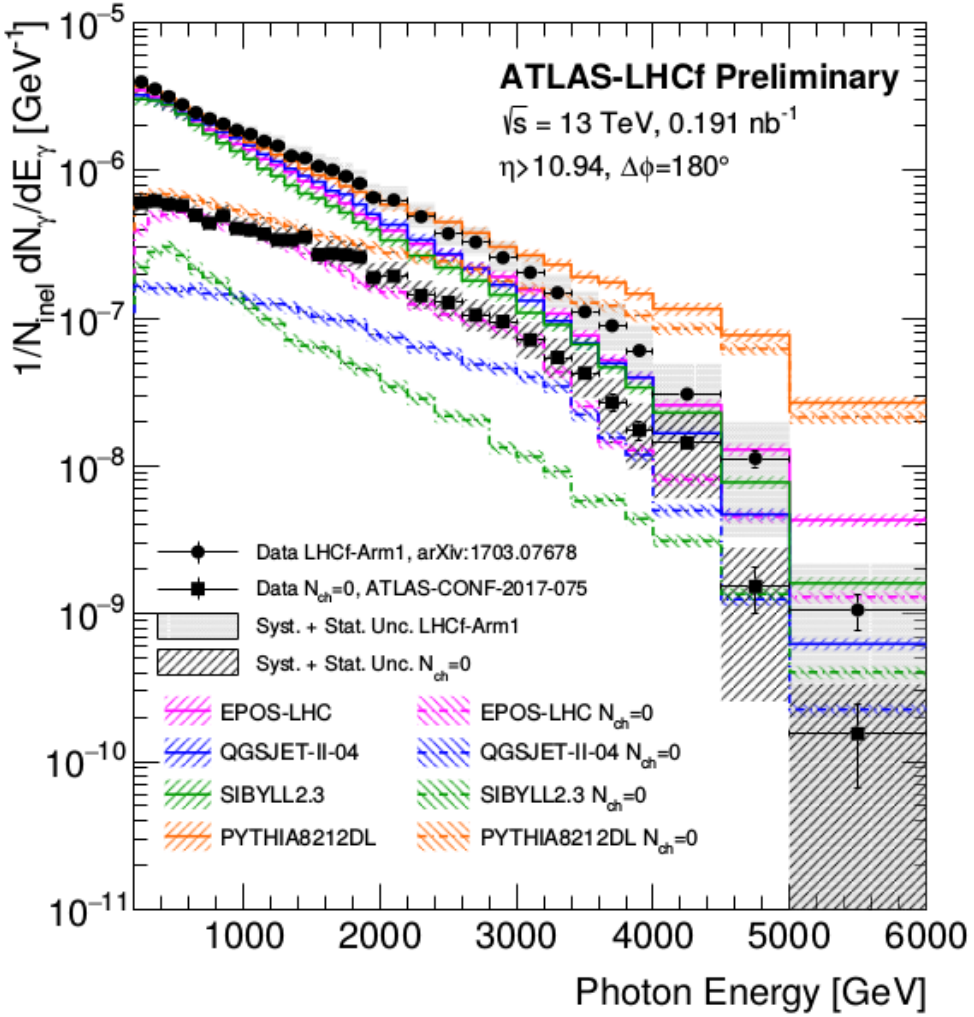
- $-2.5 < \eta < 2.5$
- $P_T > 100$ MeV

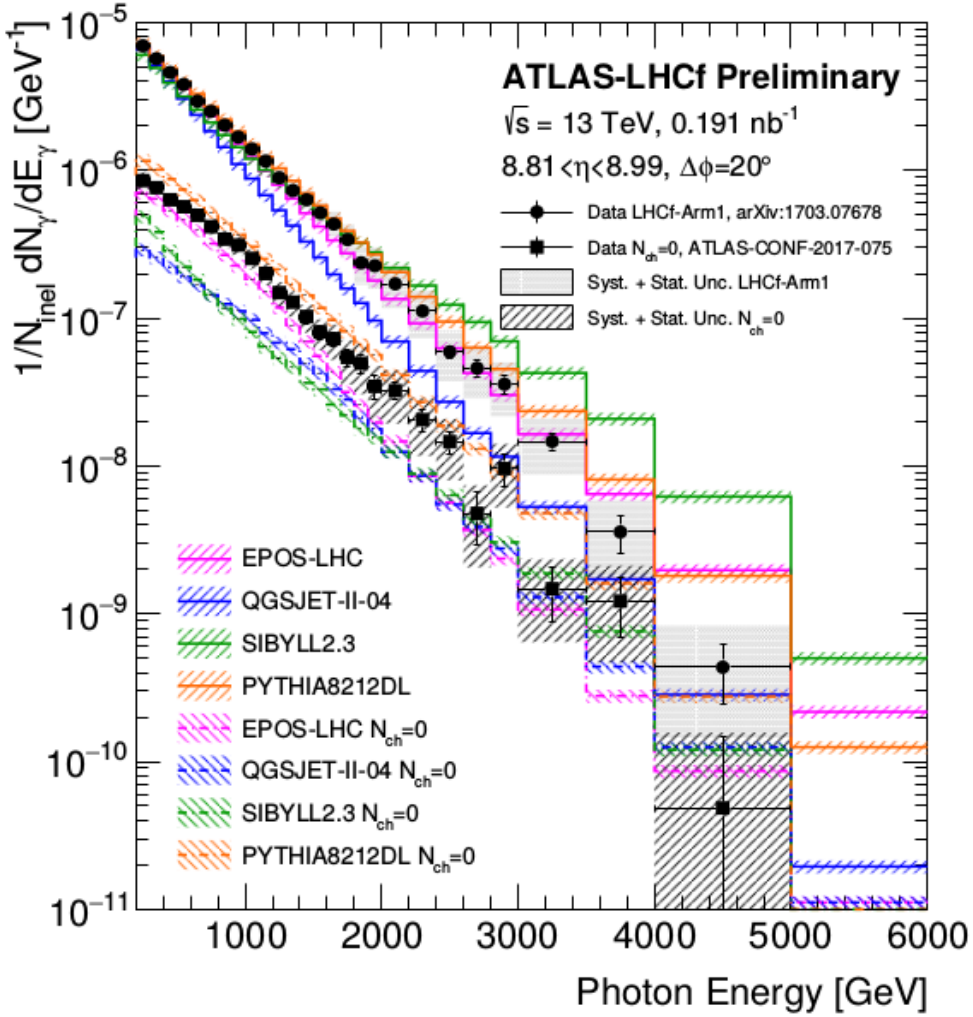


Central veto selects low-mass diffractive events (M_X < ~20 GeV)

Q. D. Zhou et al., Eur. Phys. J. C (2017) 77:212

Combined analysis results

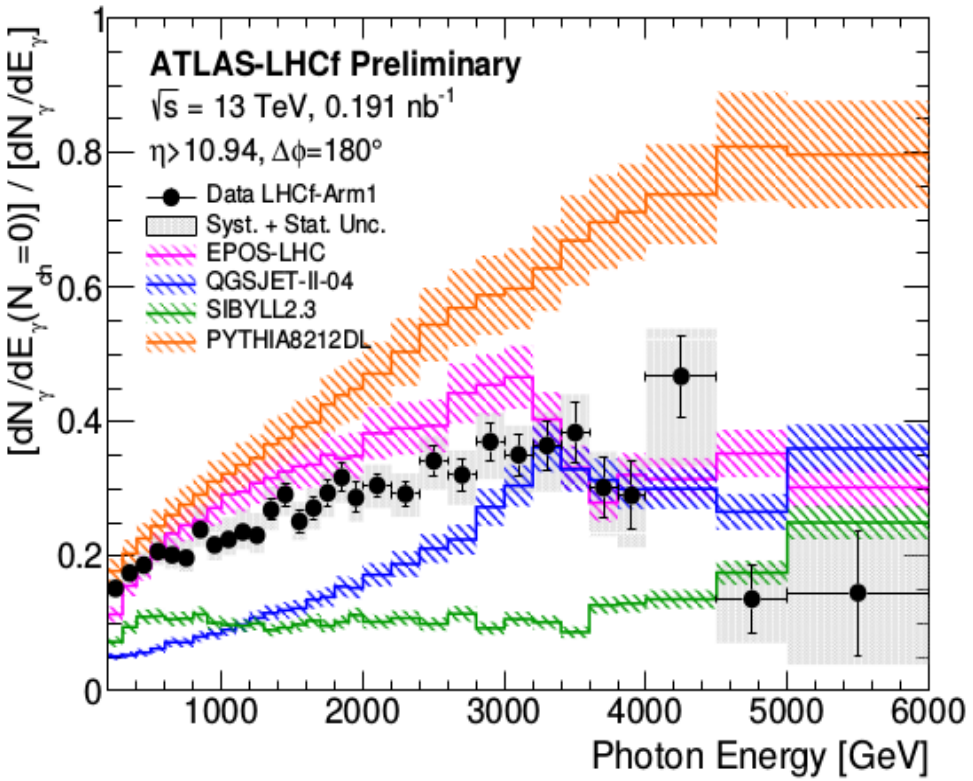


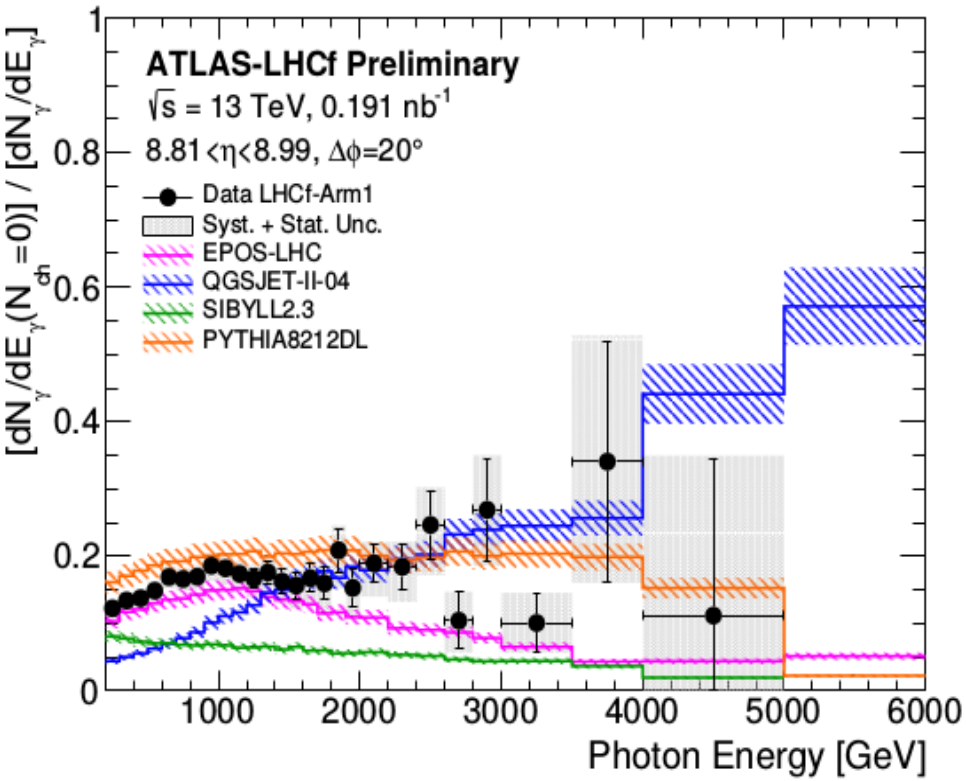


- Good agreement of **EPOS-LHC** model in both regions
- **PYTHIA** has a good agreement at low energies
- **QGSJET** and **SIBYLL** predict a lower yield

ATLAS-CONF-2017-075

Combined analysis results: diffraction ratio





- Good agreement of **EPOS-LHC** for η > 10.94
- **PYTHIA** has a good agreement in 8.81 < η < 8.99 region

ATLAS-CONF-2017-075

Physics results: photons in p-Pb

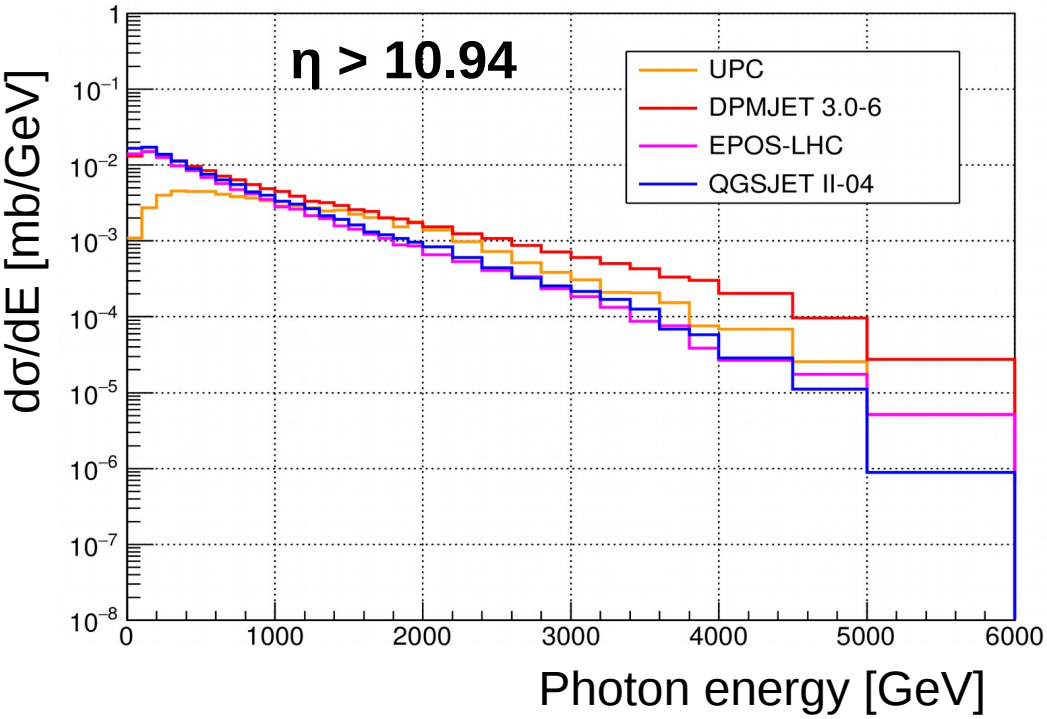
LHCf p-Pb run at 8.16 TeV

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

Analysis data set:

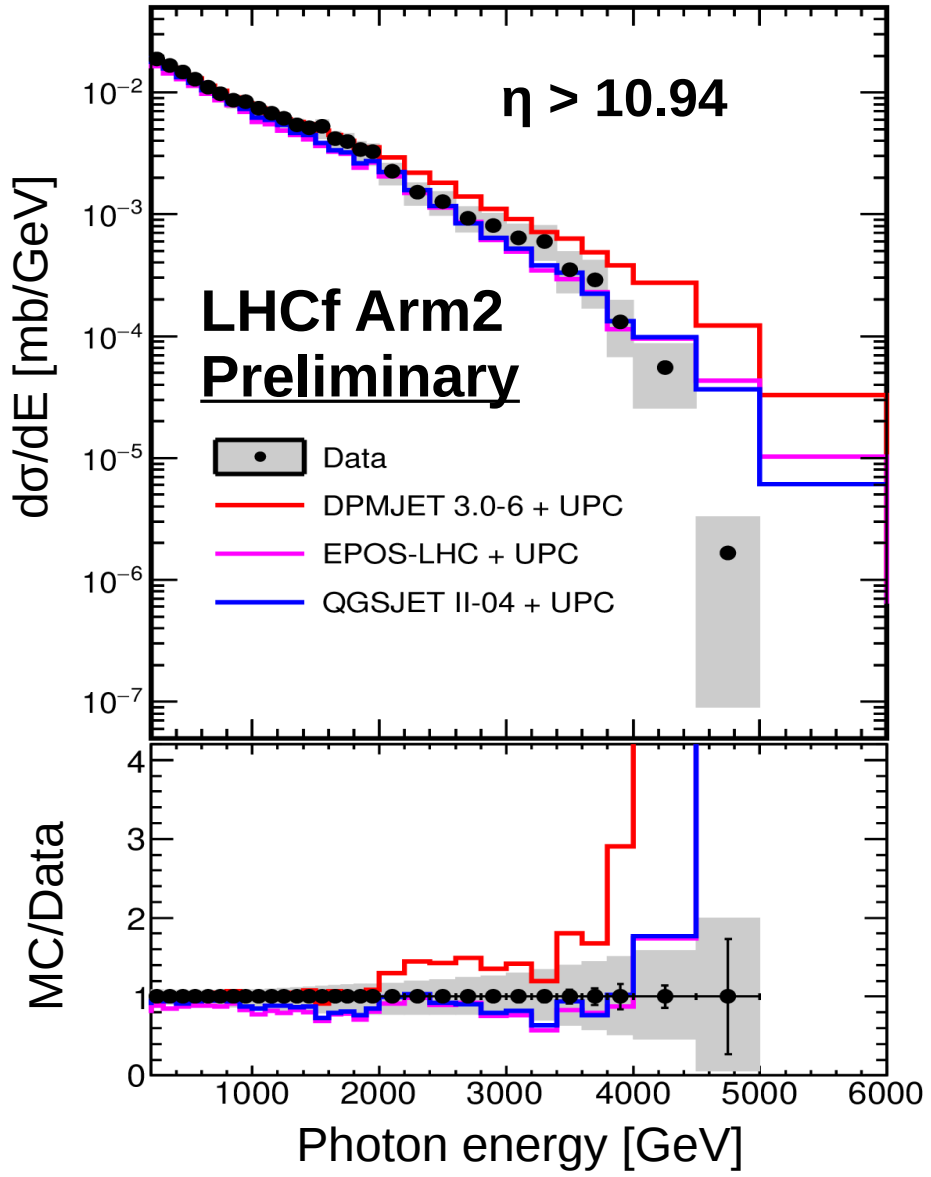
- ~ 2 hours of operation
- **Luminosity:** ~ $0.8 \cdot 10^{28}$ cm^{-2} s^{-1}
- **Pile-up:** 0.01
- $3 \cdot 10^{6}$ **events**
- **Integrated luminosity:** 8.1 μb^{-1}

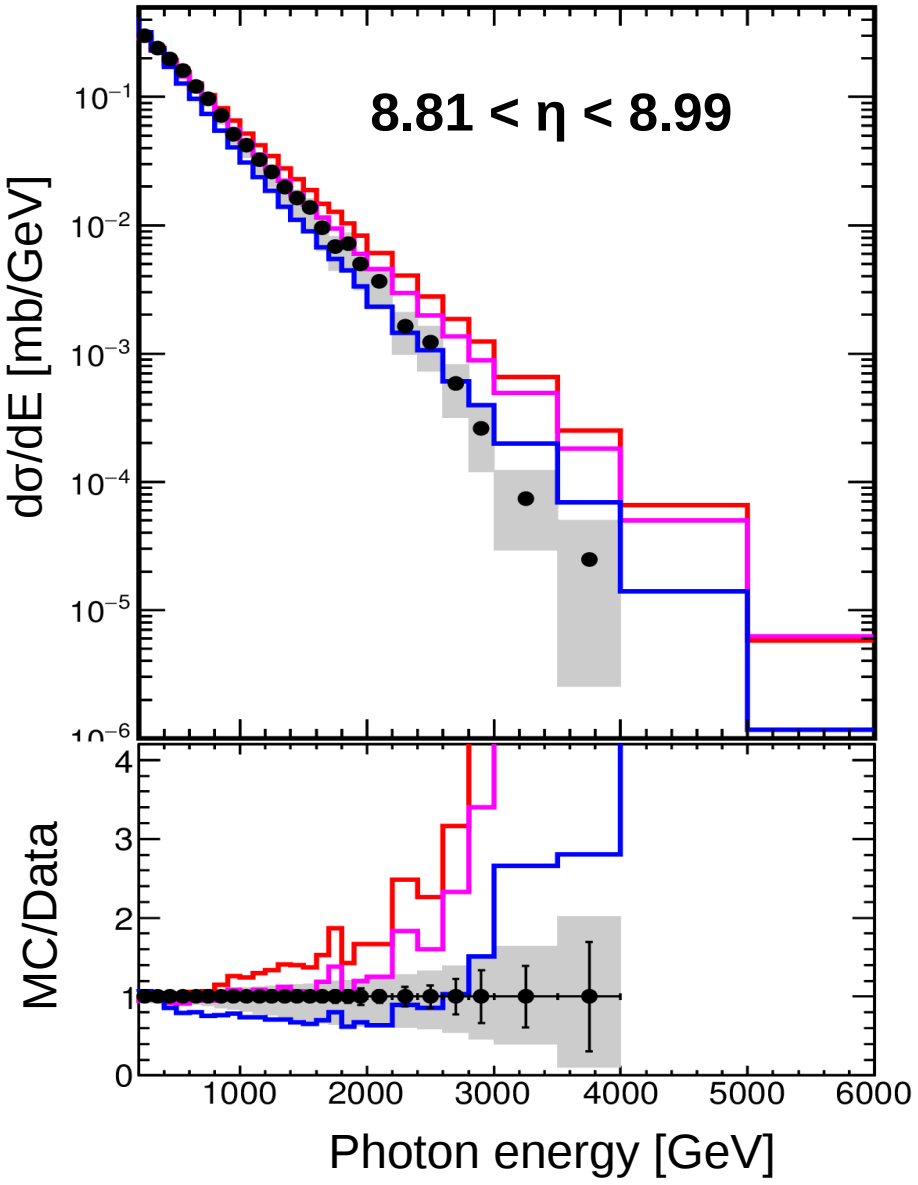
Ultra peripheral collisions (UPC)



UPC simulation → STARLIGHT + SOPHIA/DPMJET

Photon spectrum in p-Pb at 8.16 TeV





UPC added to MC

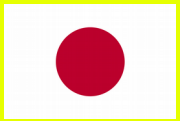
- η > 10.94: good agreement of **EPOS-LHC** and **QGSJET II-04**
- 8.81 < η < 8.99: all models predict an harder spectrum

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:
  - Photon energy spectrum in **p-p** at **13 TeV**
    - combined analysis with **ATLAS** experiment
  - Photon energy spectrum in **p-Pb** at **8.16 TeV** (preliminary)
- Future prospects:
  - p-p at 14 TeV (increase of statistics for π^0 analysis)
  - possibility of a p-O run (under discussion)

Backup

The LHCf collaboration



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N. Sakurai — *Tokushima University, Japan*

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

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M. Haguenauer — *Ecole Polytechnique, France*

W. C. Turner — *LBNL, Berkeley, USA*

Published results

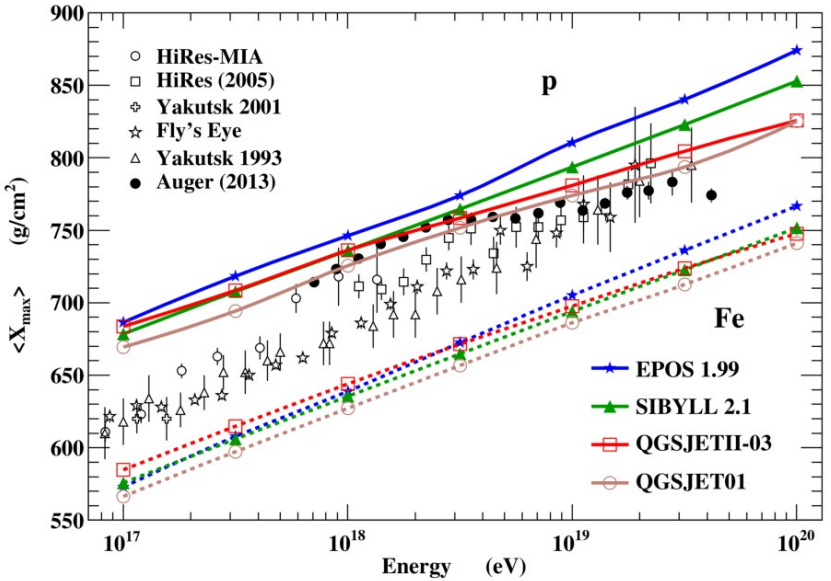
- **Photons**
  - Energy spectra in p-p @ $\sqrt{s}$ = 7 TeV [*PLB 703 (2011), 128-134*]
  - Energy spectra in p-p @ $\sqrt{s}$ = 0.9 TeV [*PLB 715 (2012), 298-303*]
  - Energy spectra in p-p @ $\sqrt{s}$ = 13 TeV [*PLB 780 (2018) 233–239*]
- **π^0**
  - P_T spectra in p-p @ $\sqrt{s}$ = 7 TeV [*PRD 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*]
  - Energy spectra in p-p @ $\sqrt{s}$ = 13 TeV [*JHEP (2018) 2018: 73*]

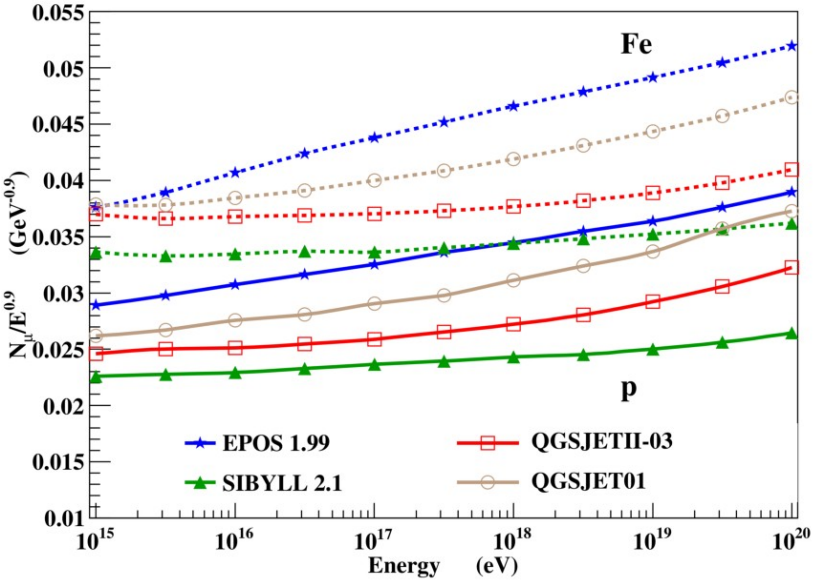
Models improvement after LHC Run1

Mean depth of shower maximum

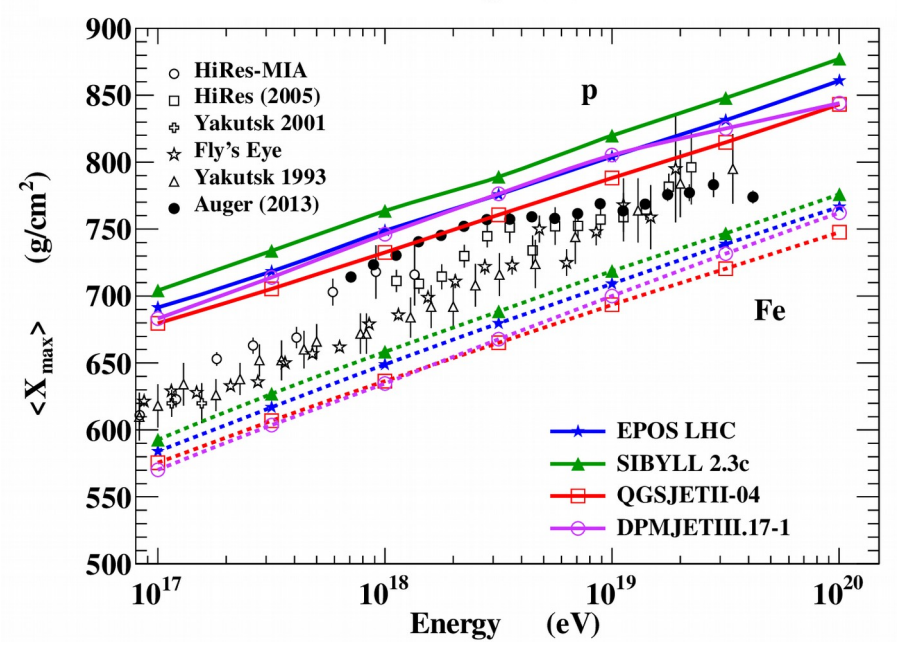
N° of muons at ground

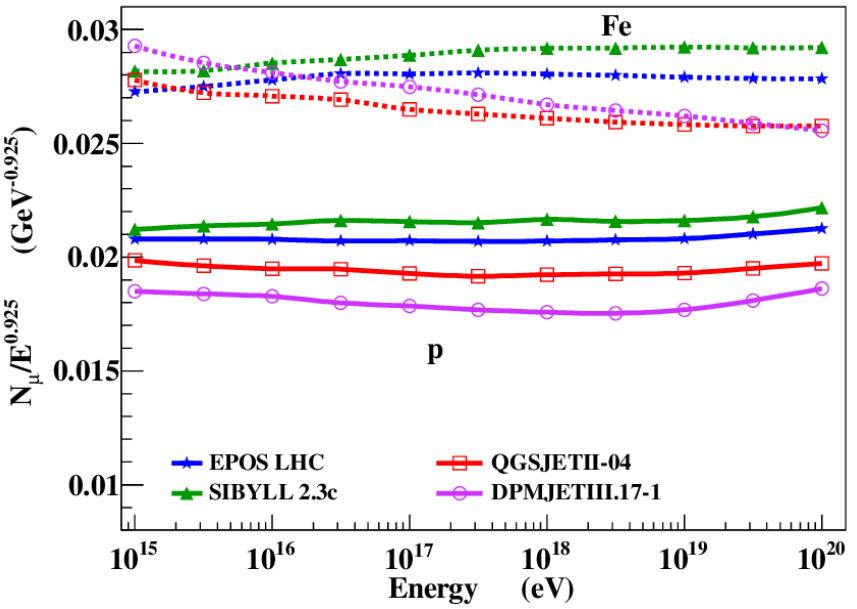
Pre-LHC



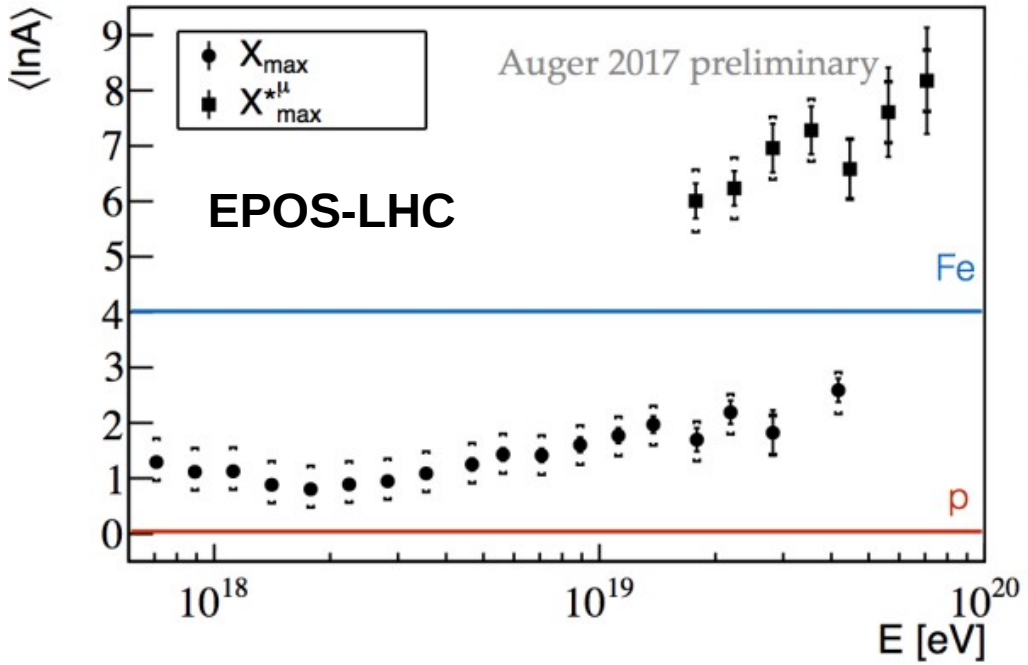


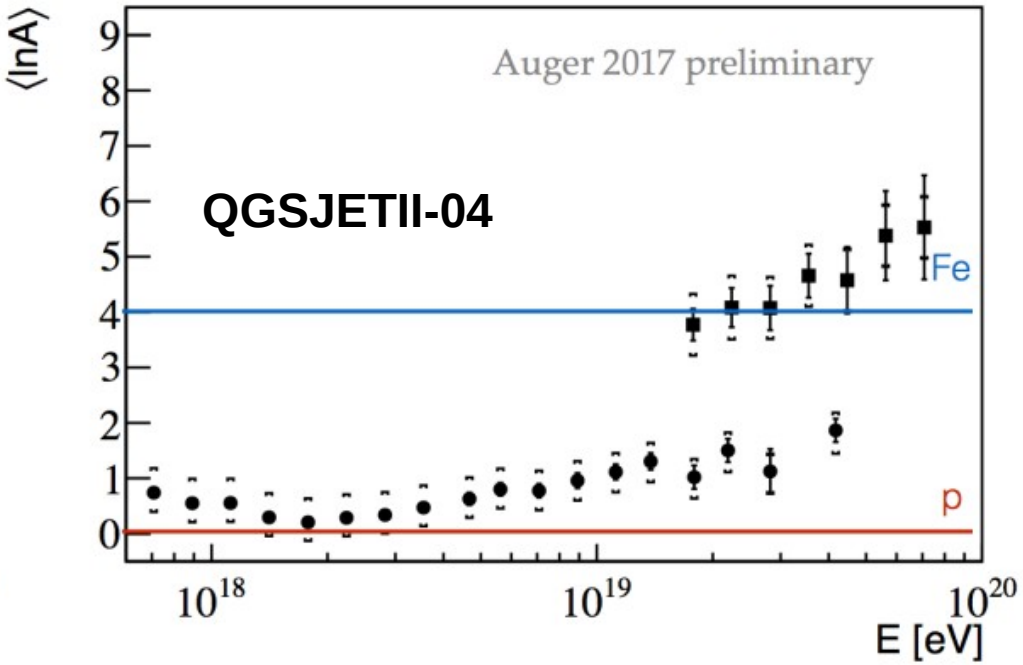
Post-LHC





Muon excess problem

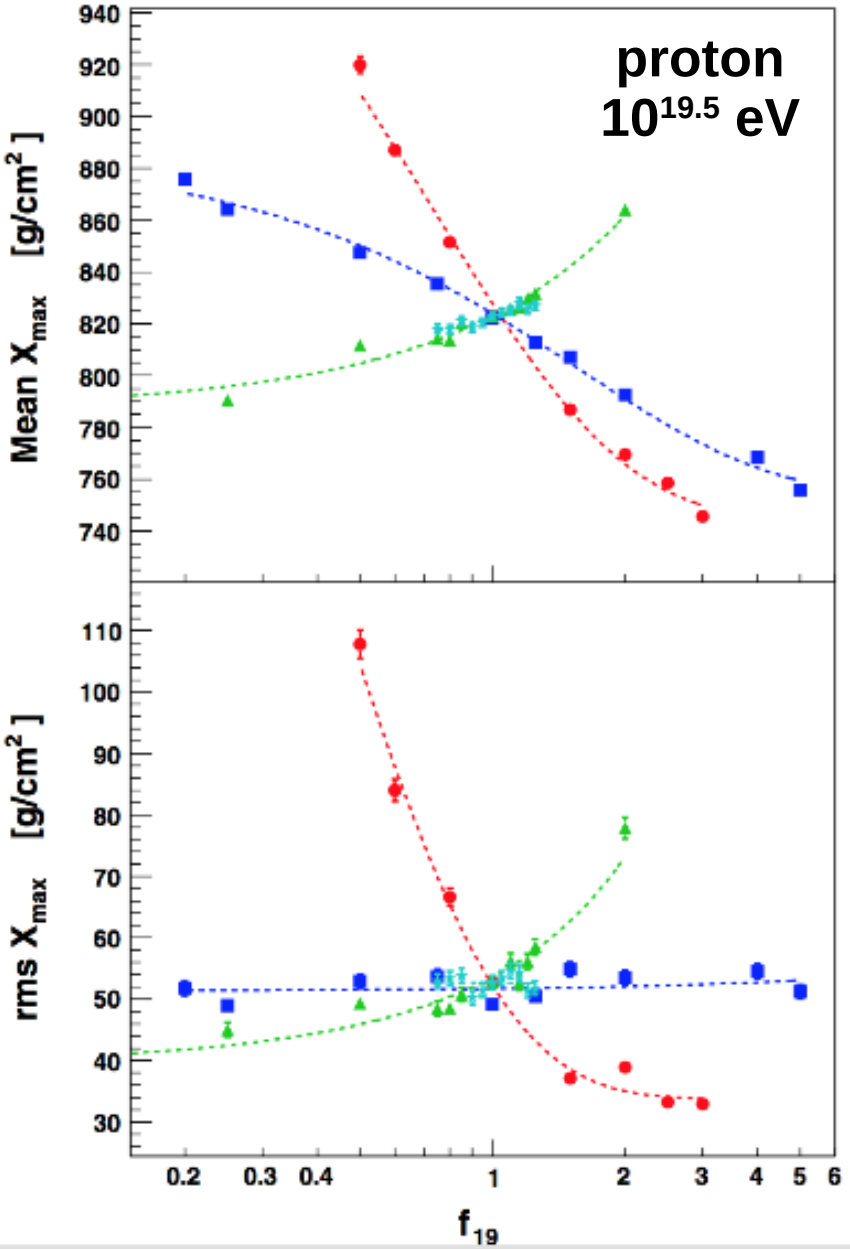


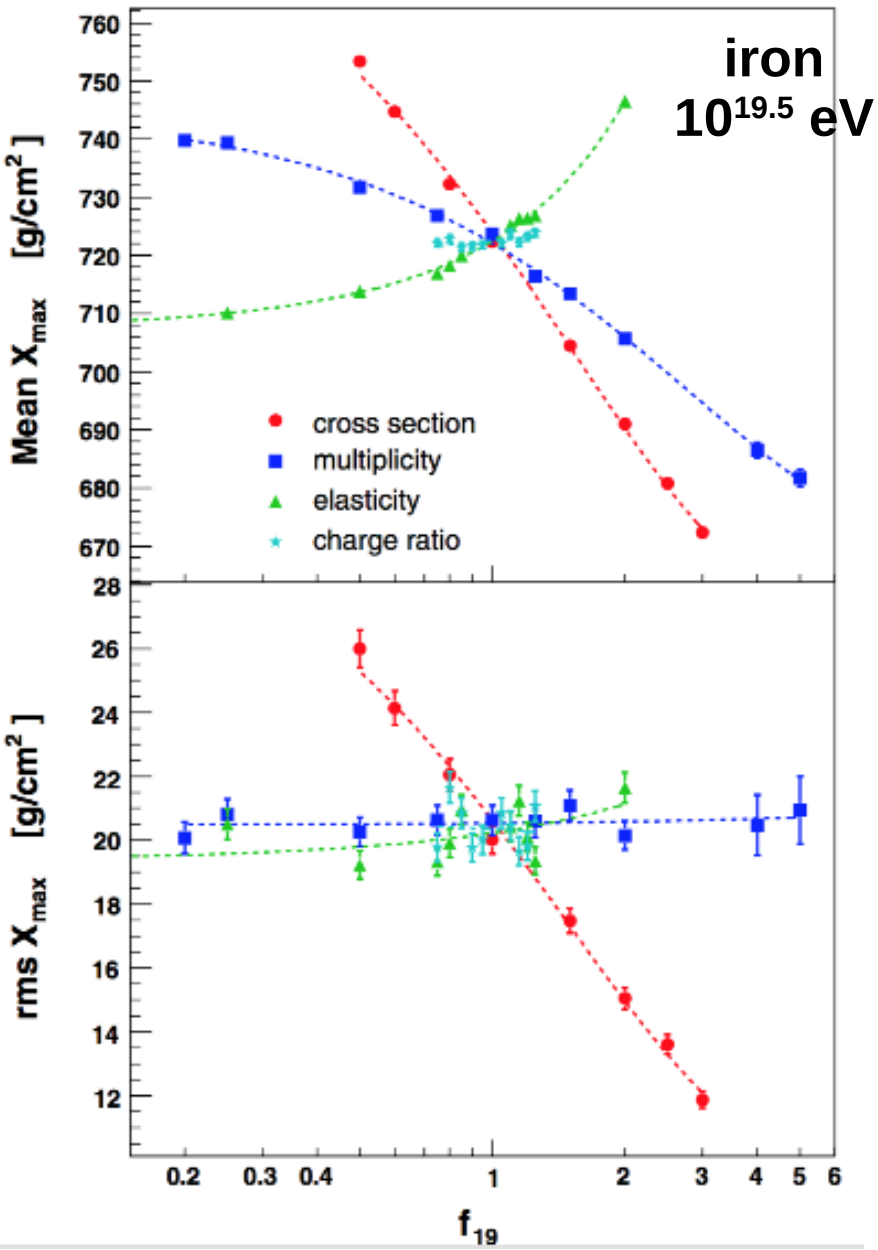


M. Mallamaci, ICRC2017

X_{max} vs parameters

SIBYLL 2.1

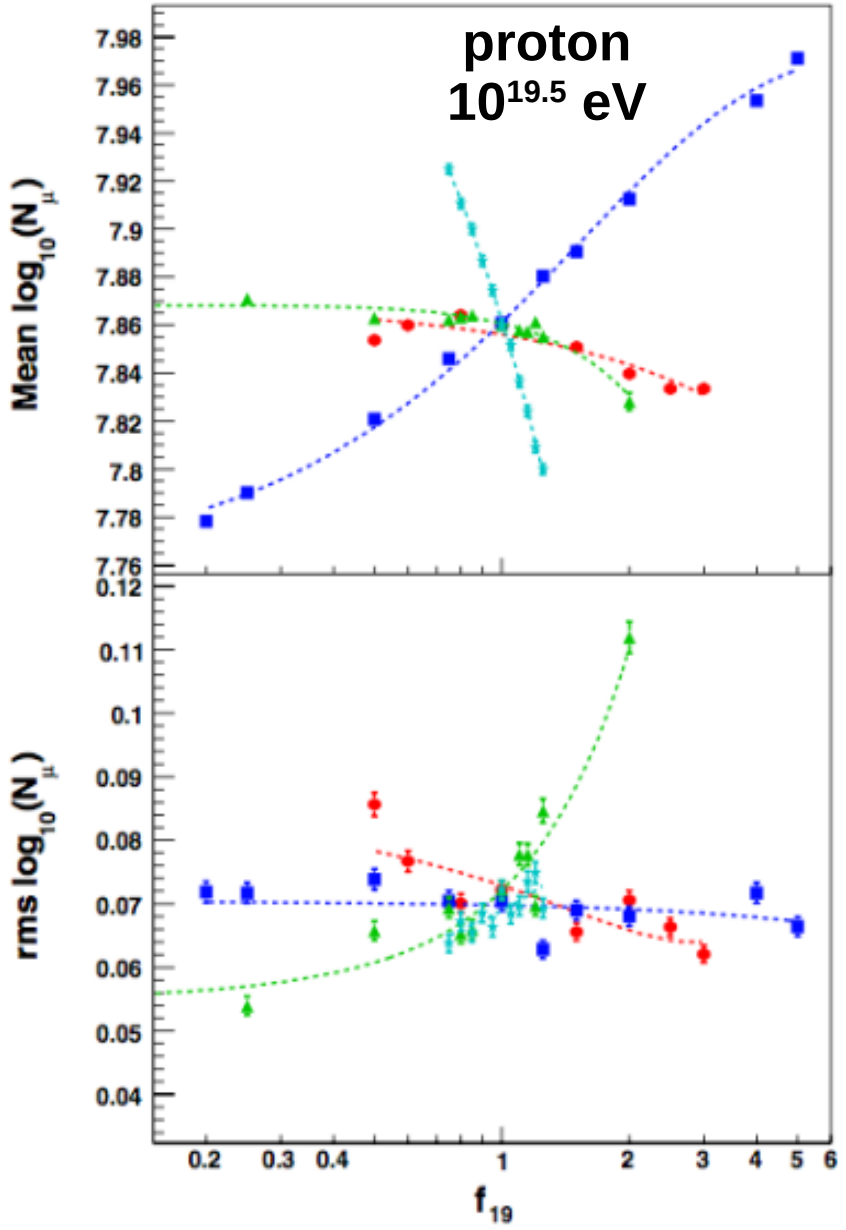


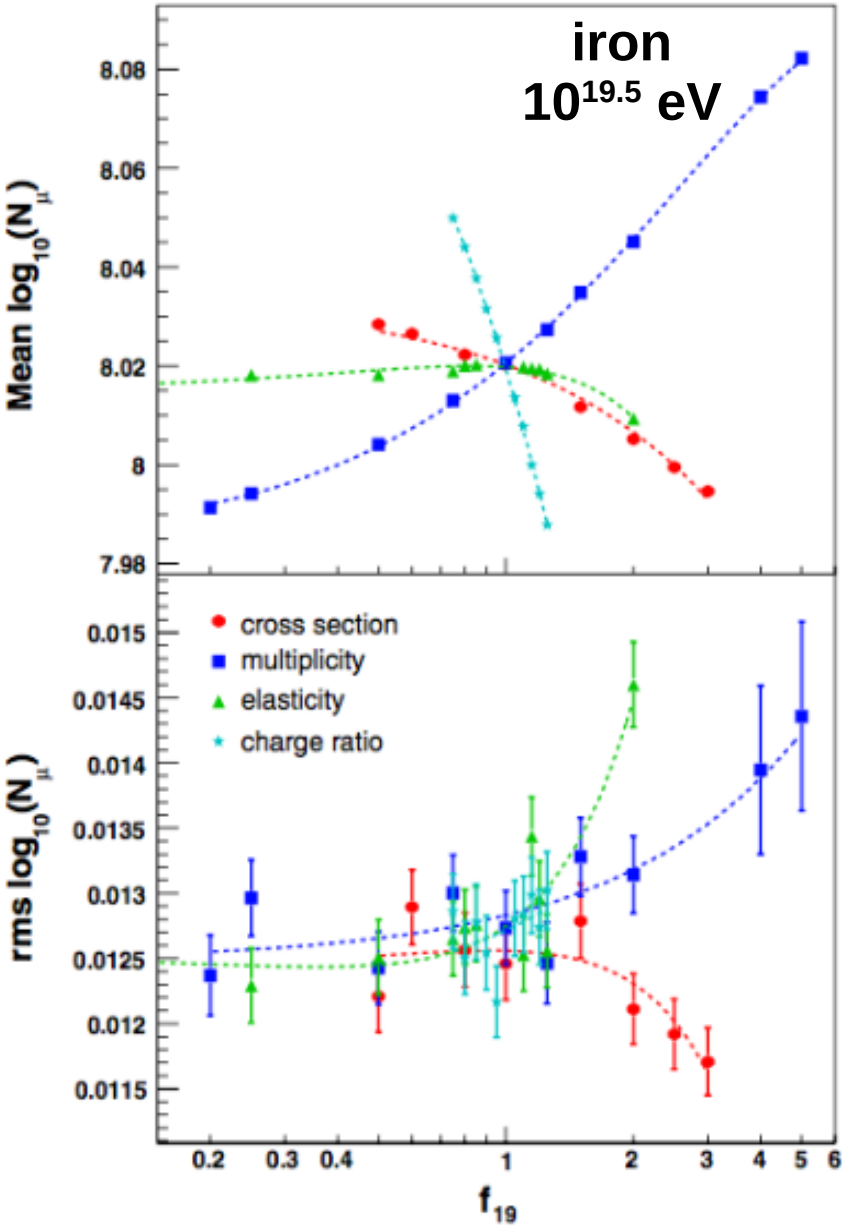


Phys. Rev. D83 (2011) 054026

N_μ vs parameters

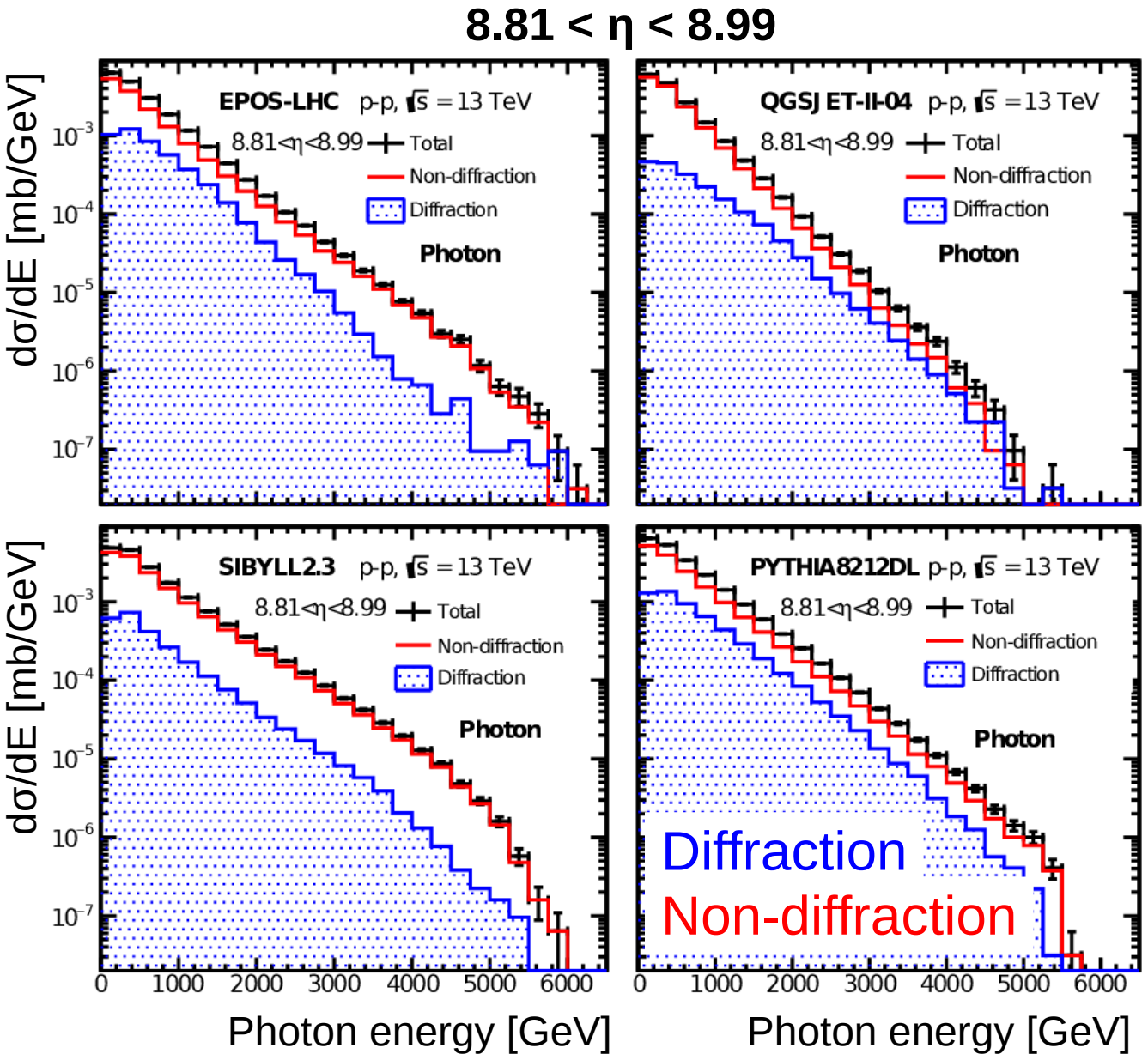
SIBYLL 2.1





Phys. Rev. D83 (2011) 054026

Diffractive events contribution



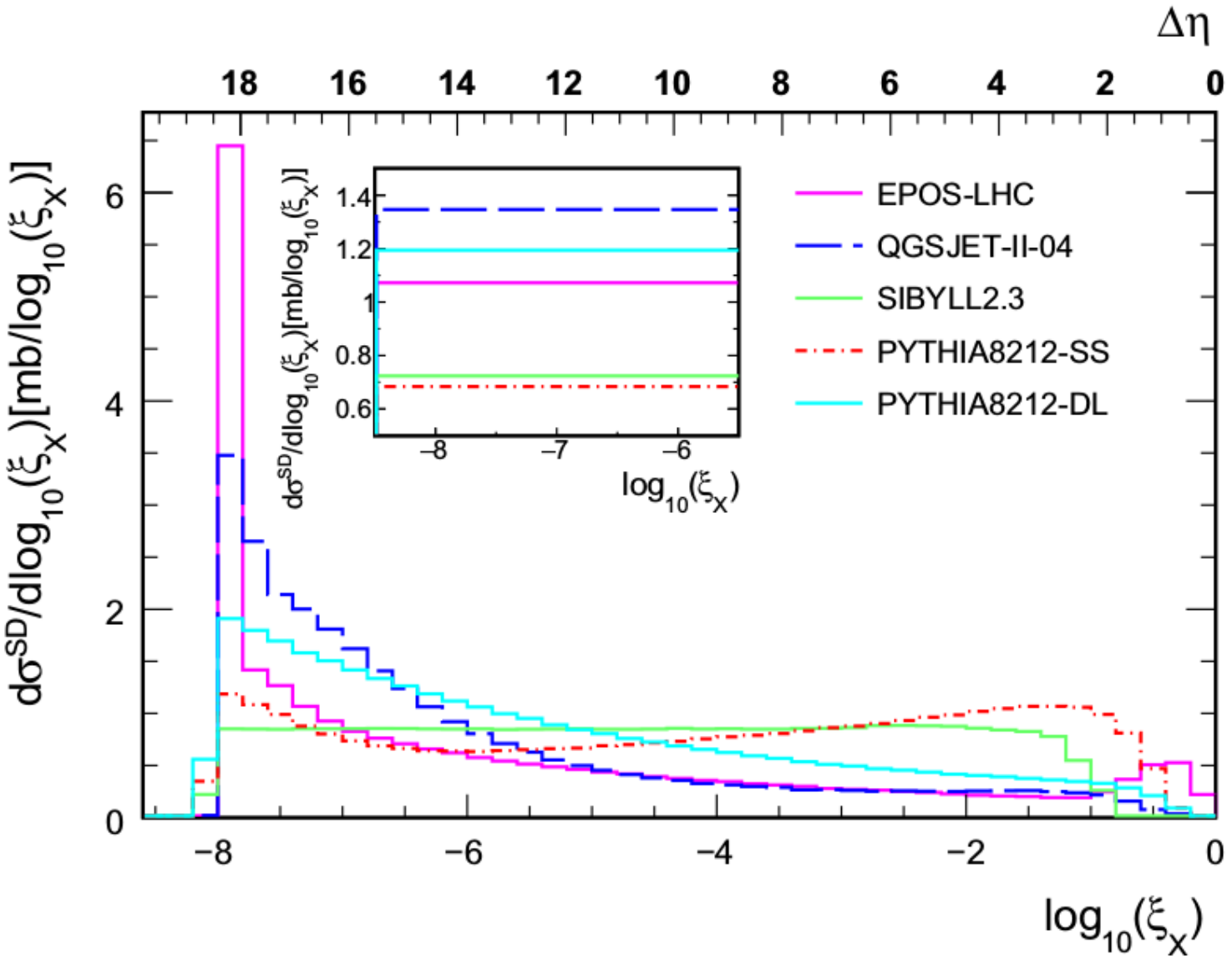
Hadronic interaction models predict different contributions of diffraction

Central detectors can give useful information to identify diffractive events

LHCf+ATLAS combined analysis

Q. D. Zhou et al., Eur. Phys. J. C (2017) 77:212

Diffraction mass distribution

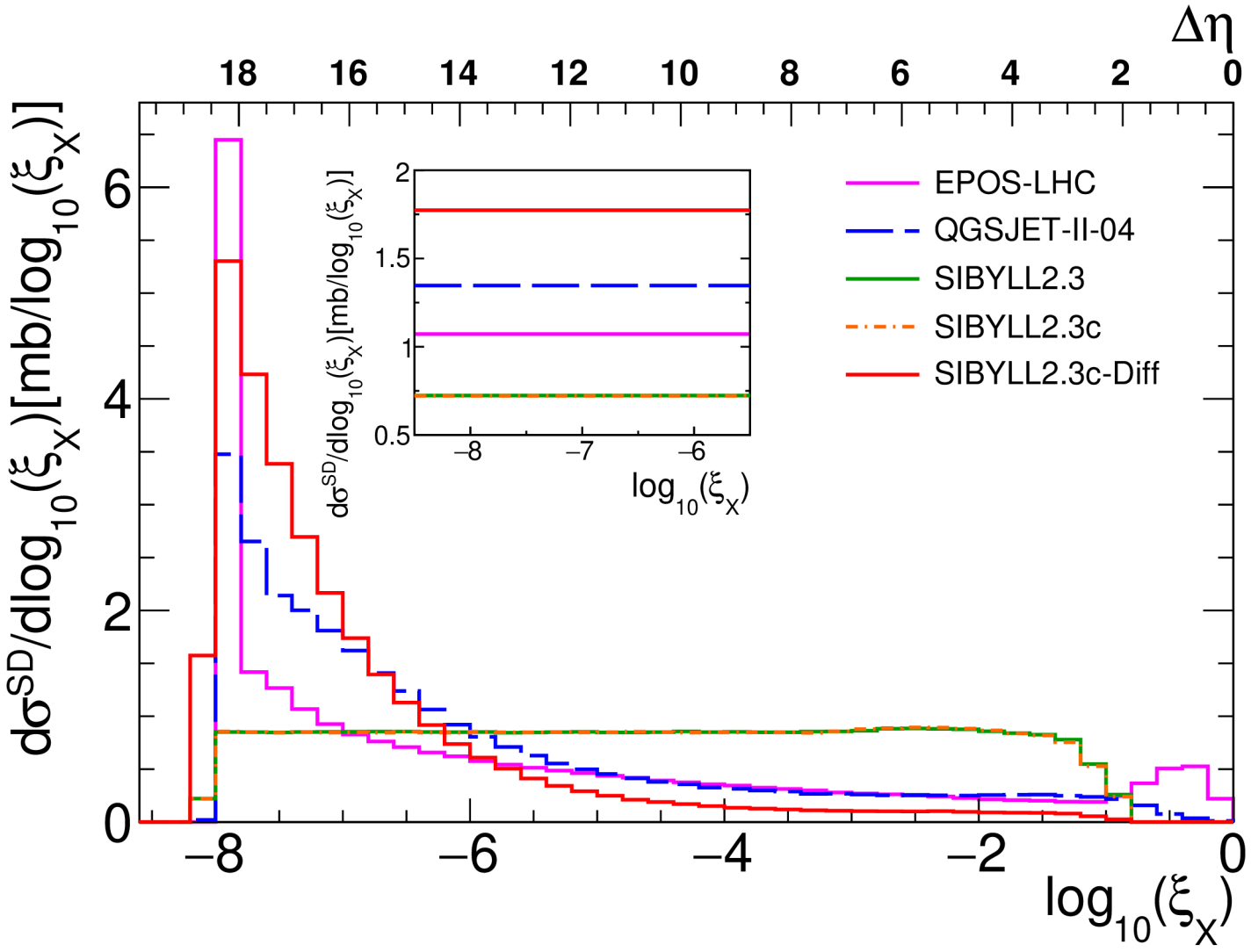


$$\xi_X = \frac{M_X^2}{s}$$

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

Q. D. Zhou et al., Eur. Phys. J. C (2017) 77:212

Tuning of SIBYLL 2.3c (by F. Riehn)

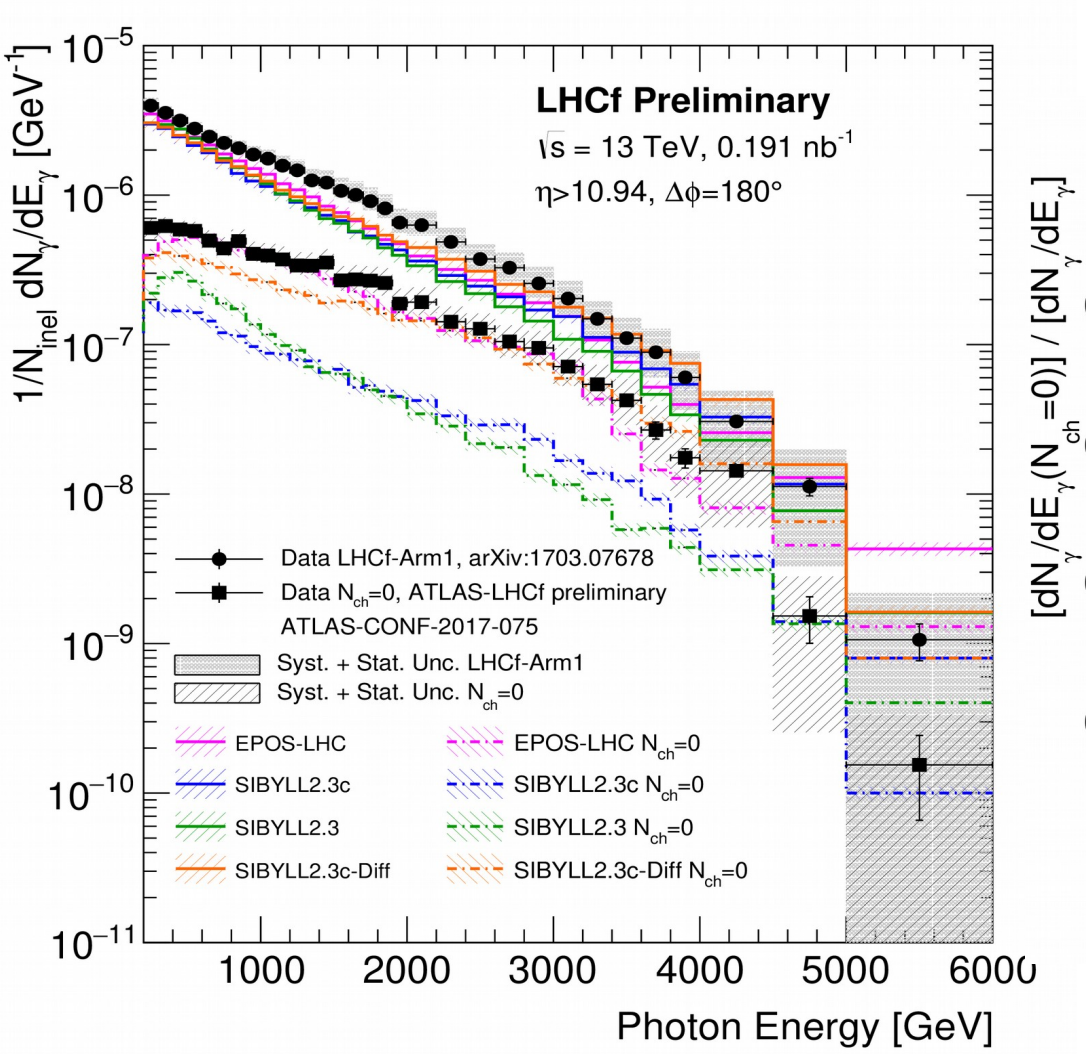


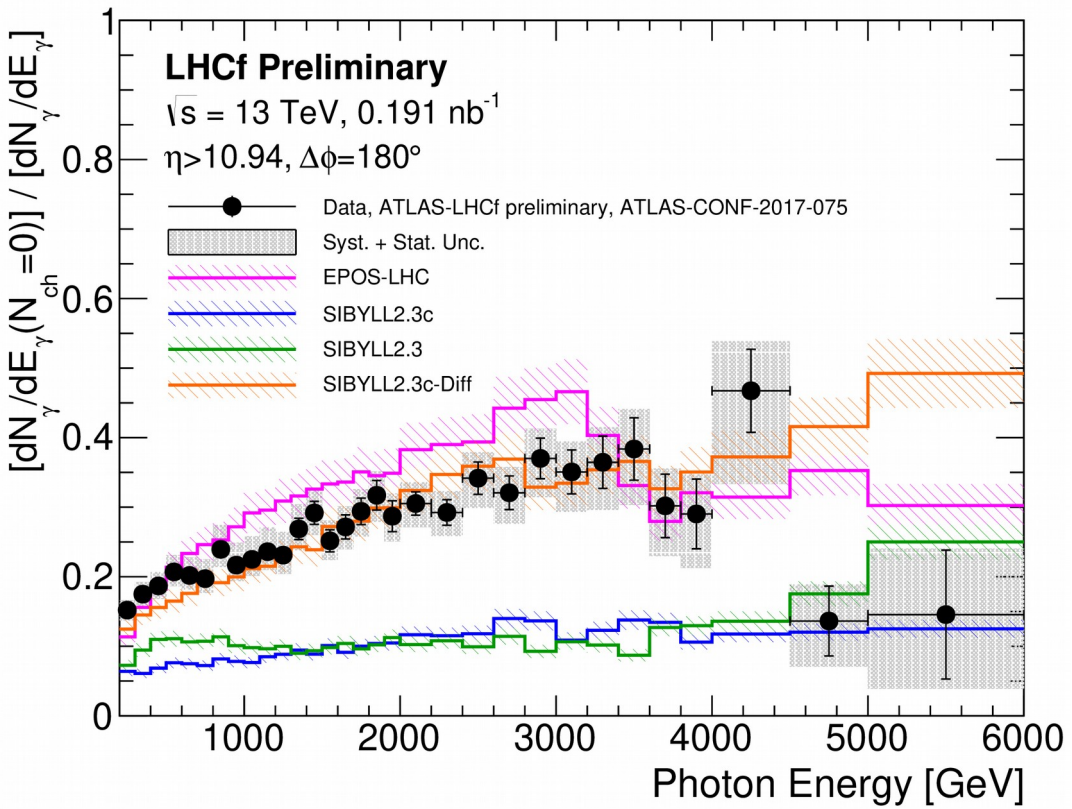
$$\xi_X = \frac{M_X^2}{s}$$

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

Tuning of the **SIBYLL2.3c** pomeron flux to get a more realistic diffractive cross section distribution

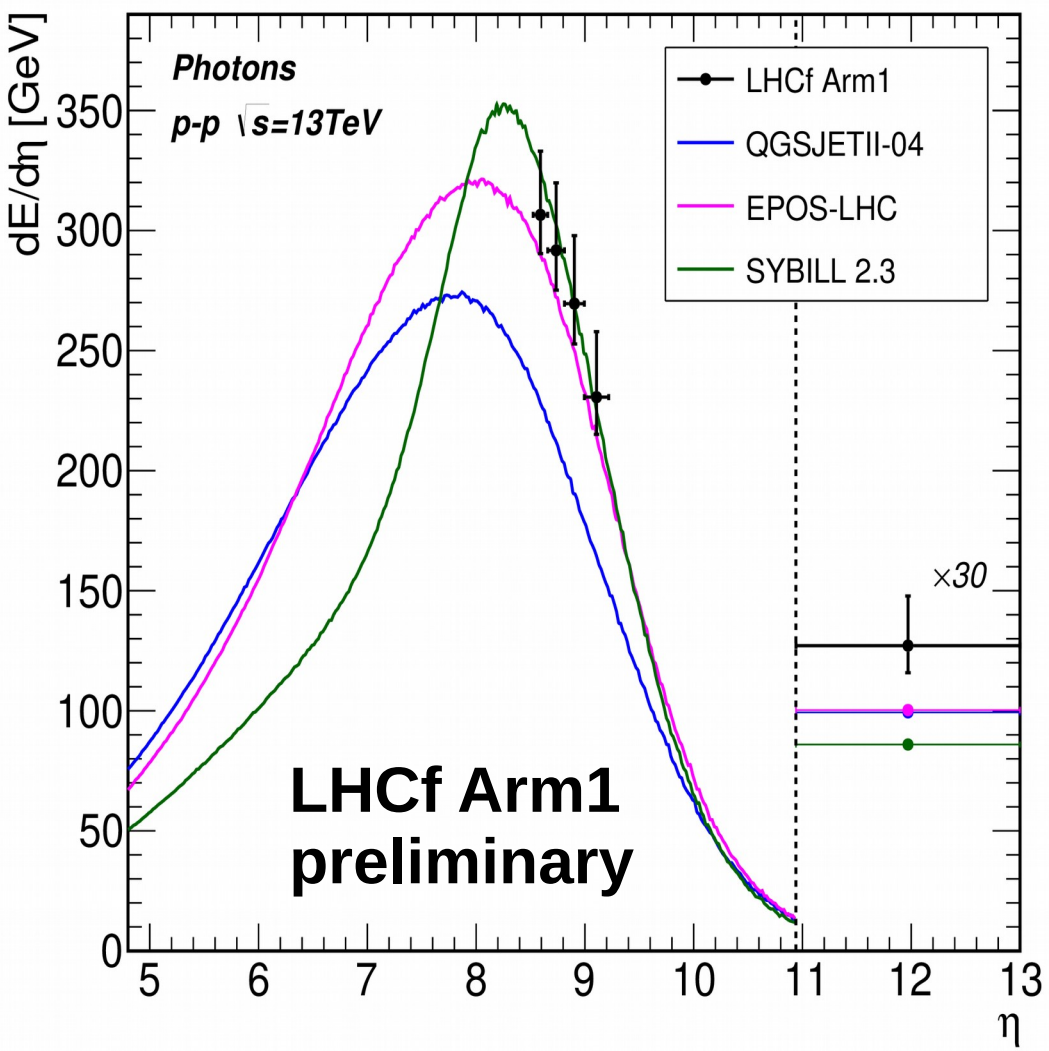
Tuned SIBYLL 2.3c: results





- Very good agreement of tuned **SIBYLL 2.3c-Diff** for low-mass diffraction spectrum and ratio

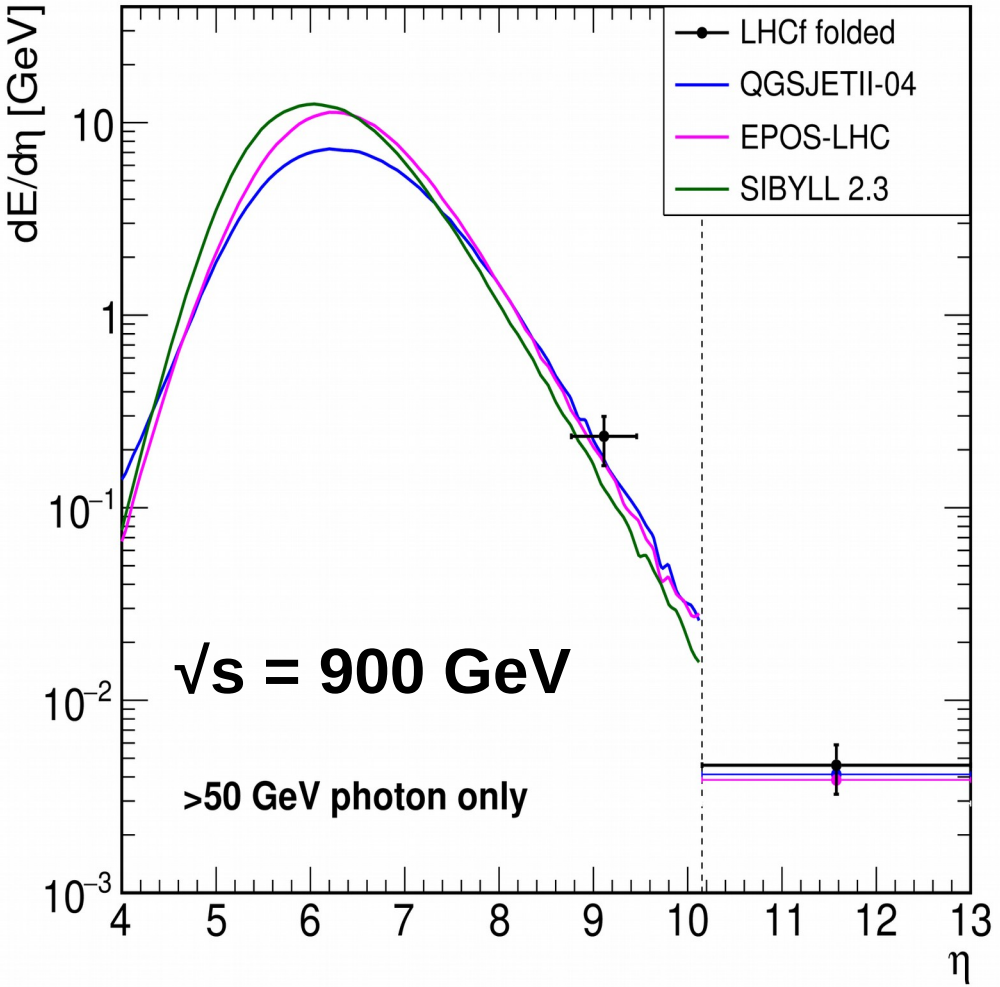
Electromagnetic energy flow

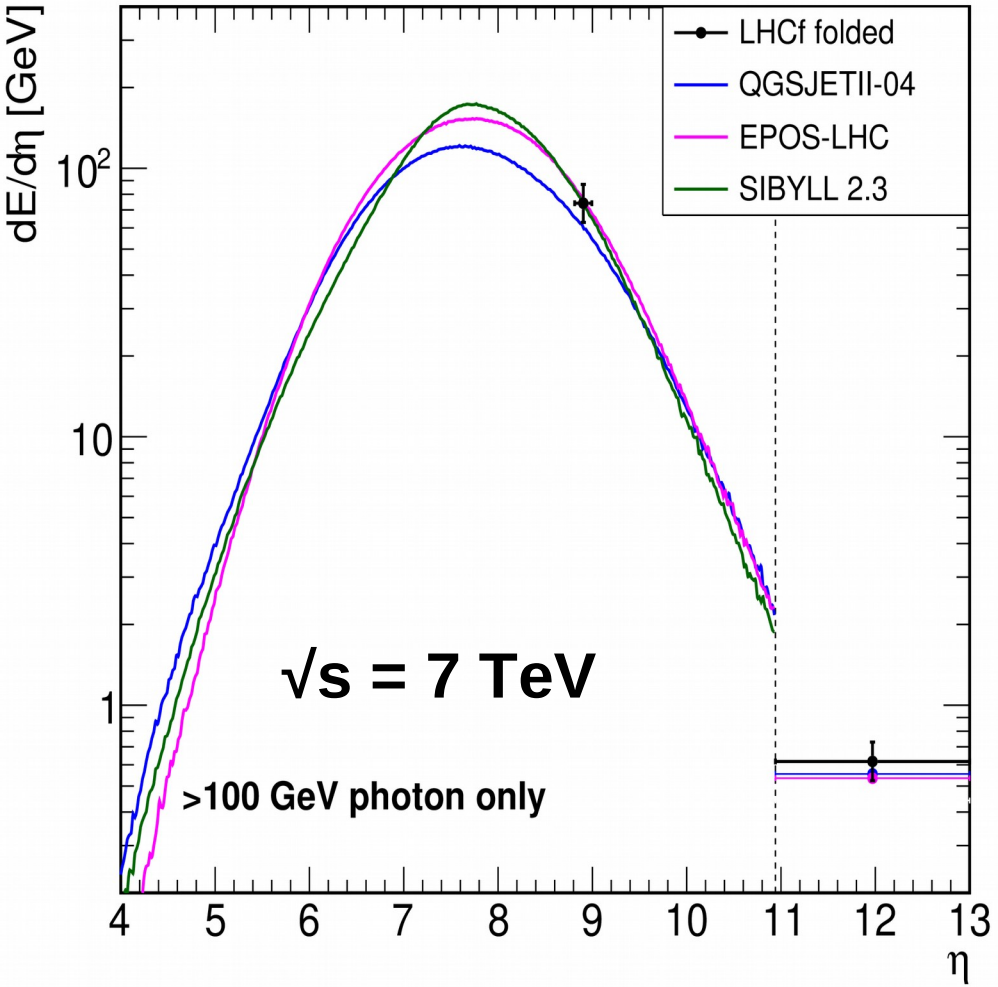


- Integrated from measured spectrum
- Low-η acceptance region extended: $8.52 < \eta < 9.22$
- Best agreement with **SIBYLL 2.3** and **EPOS-LHC**
- **QGSJET II-04** predicts a less forward-peaked energy flow
- All models underestimate the flow in the $\eta > 10.94$ region

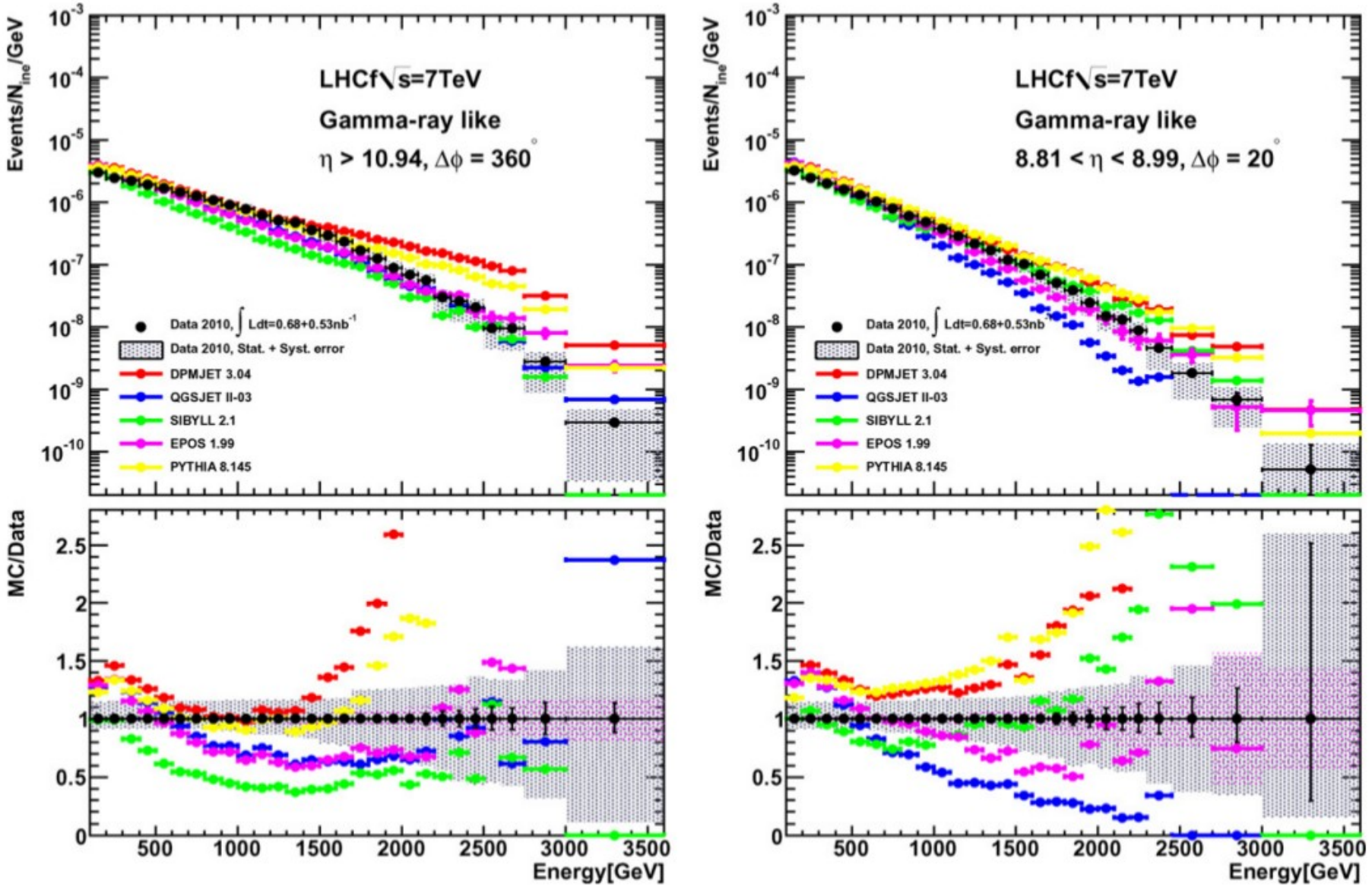
Y. Makino, CERN-THESIS-2017-049

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



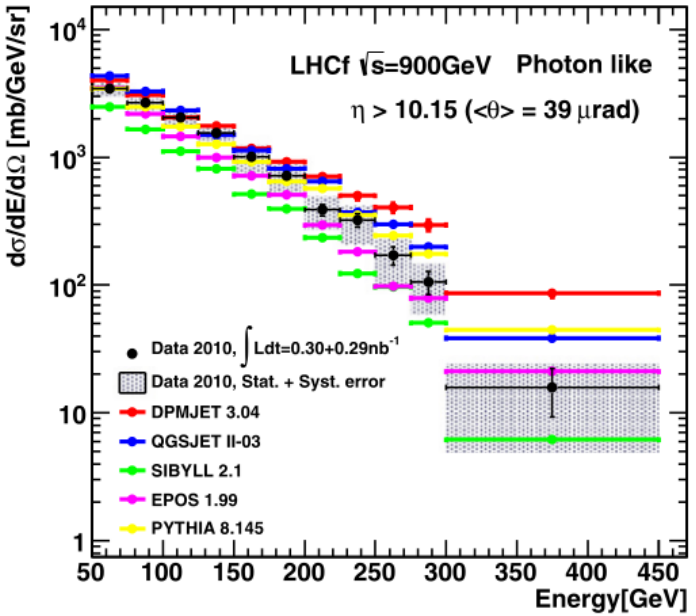


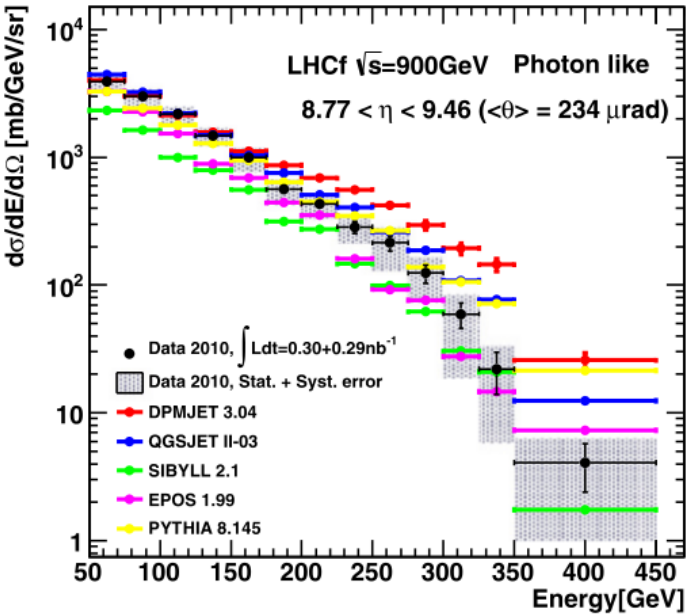
Photons spectrum in p-p at 7 TeV

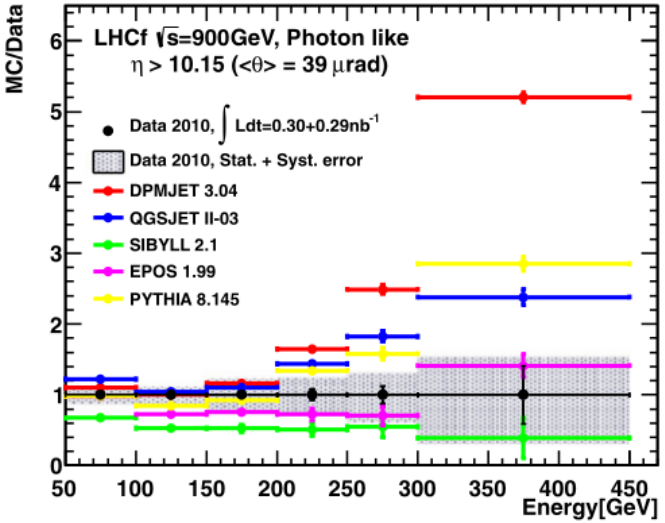


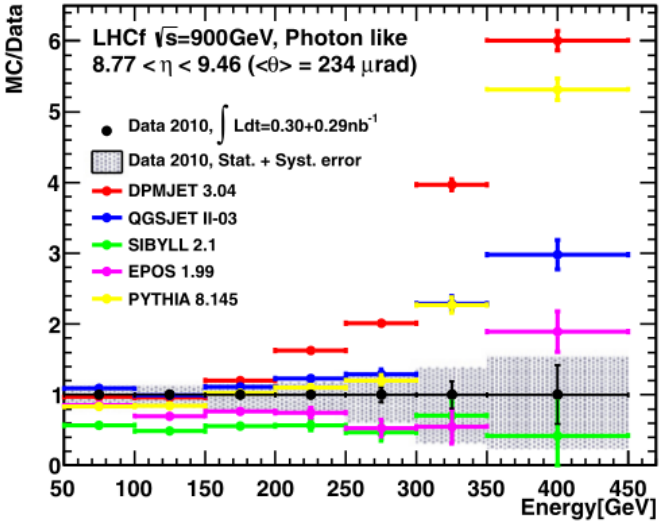
O. Adriani et al., PLB 703 (2011), 128-134

Photons spectrum in p-p at 900 GeV



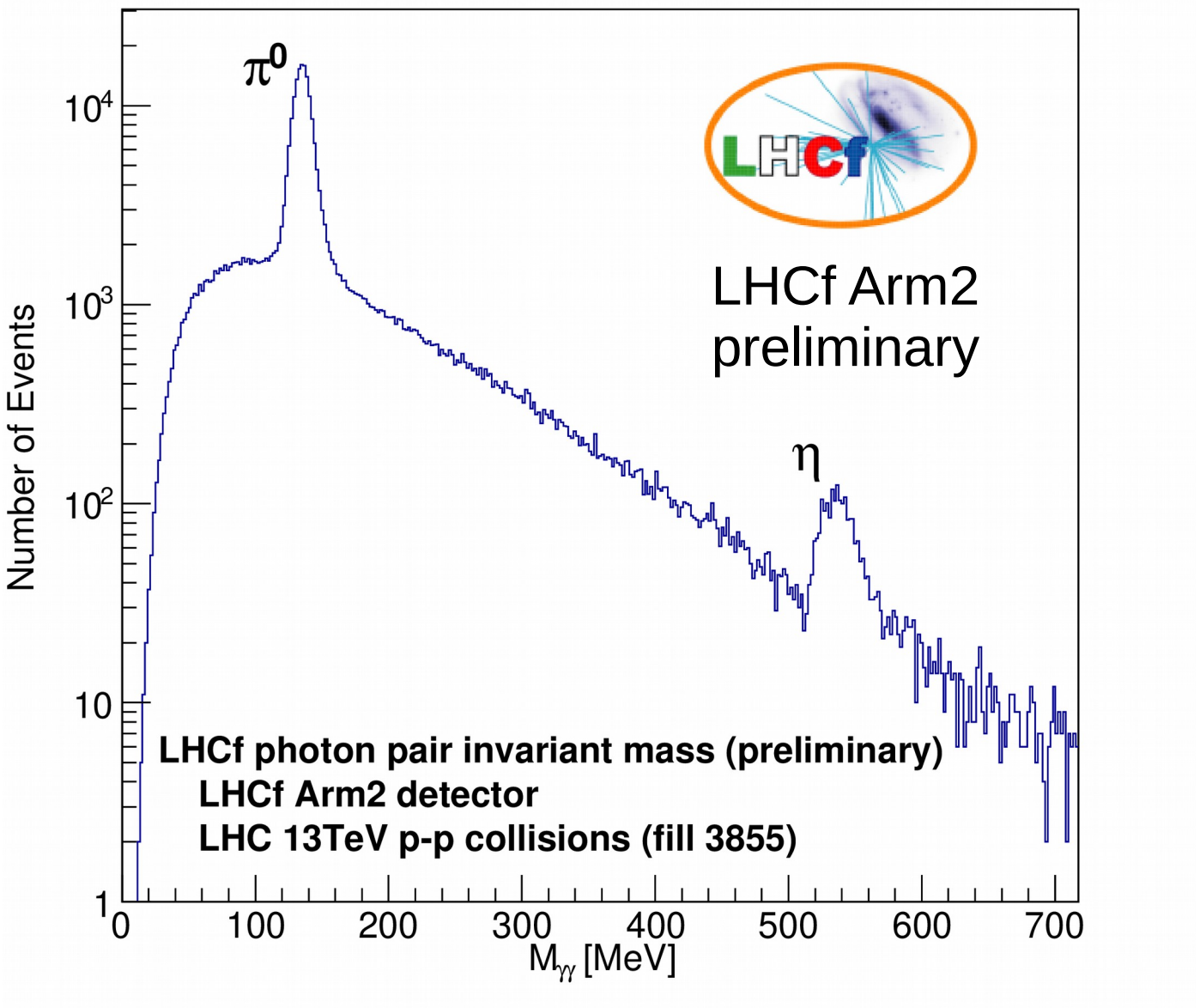






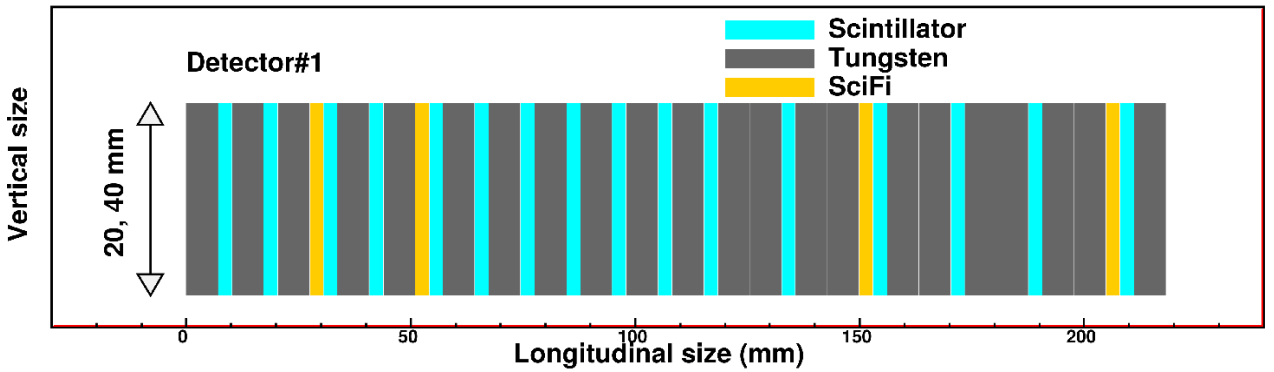
O. Adriani et al., PLB 715 (2012), 298-303

Photon pairs invariant mass at 13 TeV

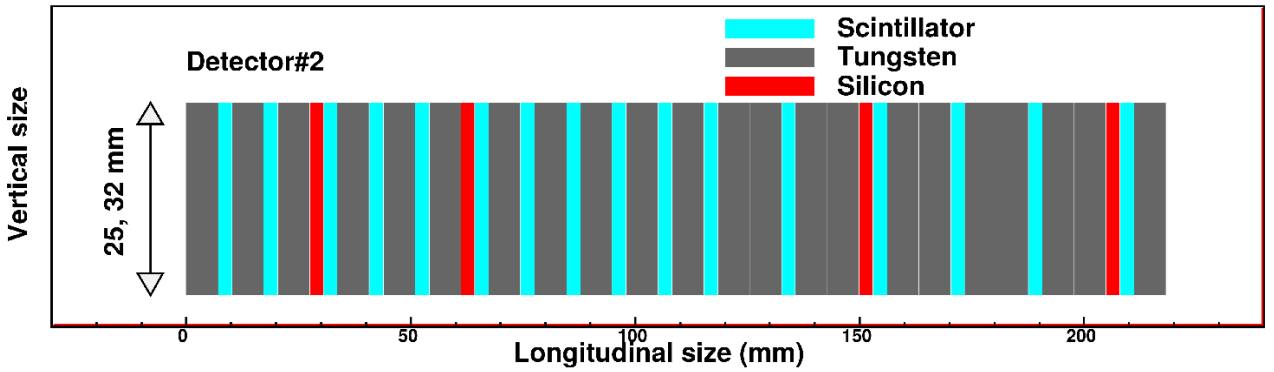


Longitudinal structure

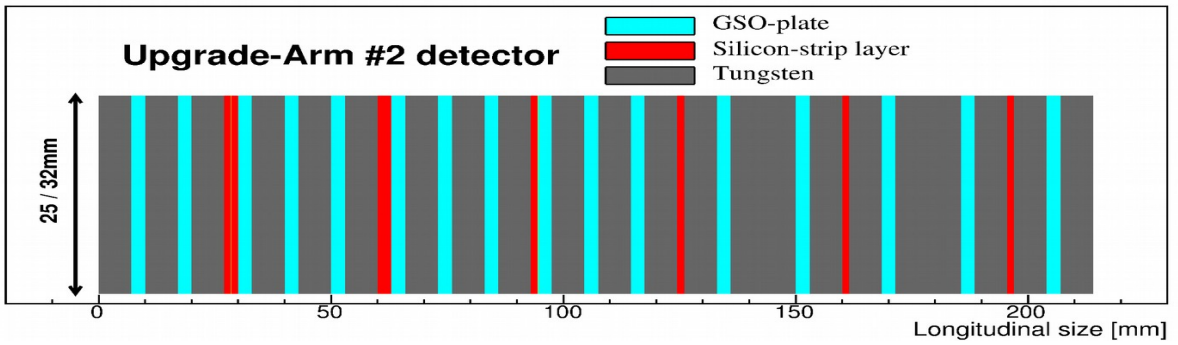
Arm1



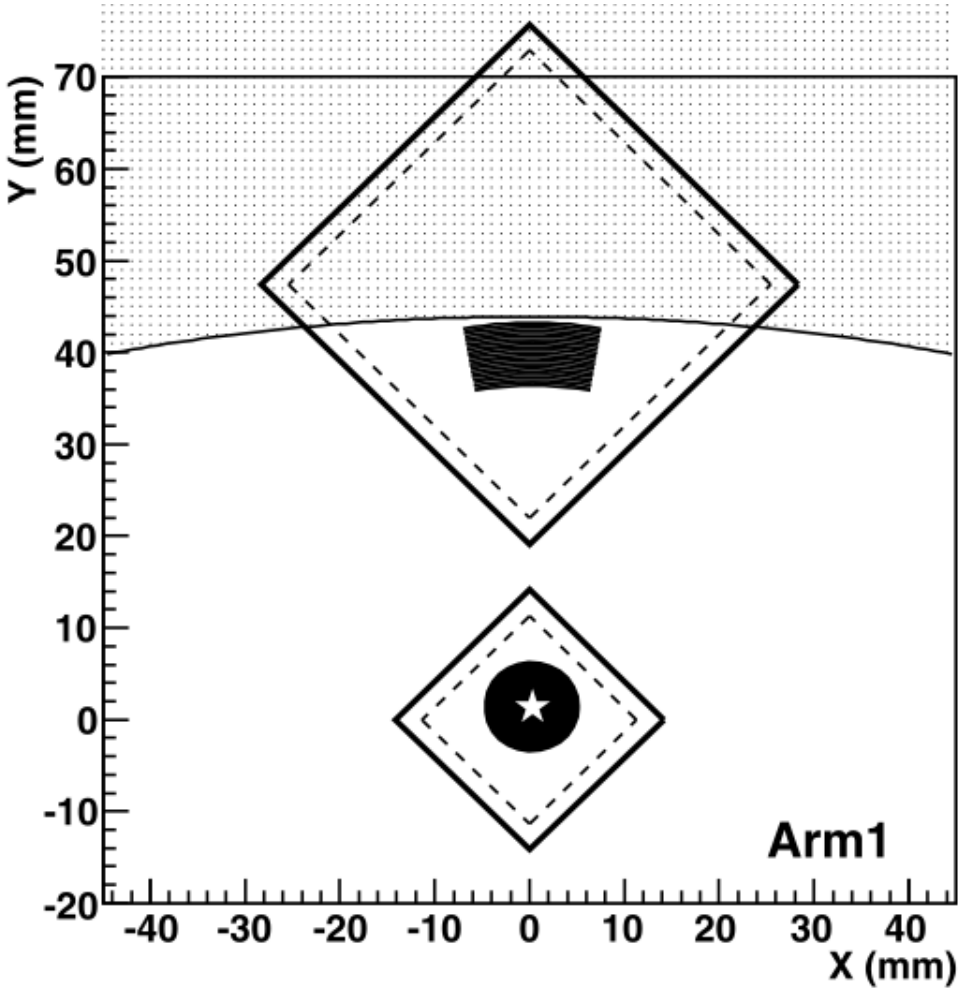
Arm2 (Old)

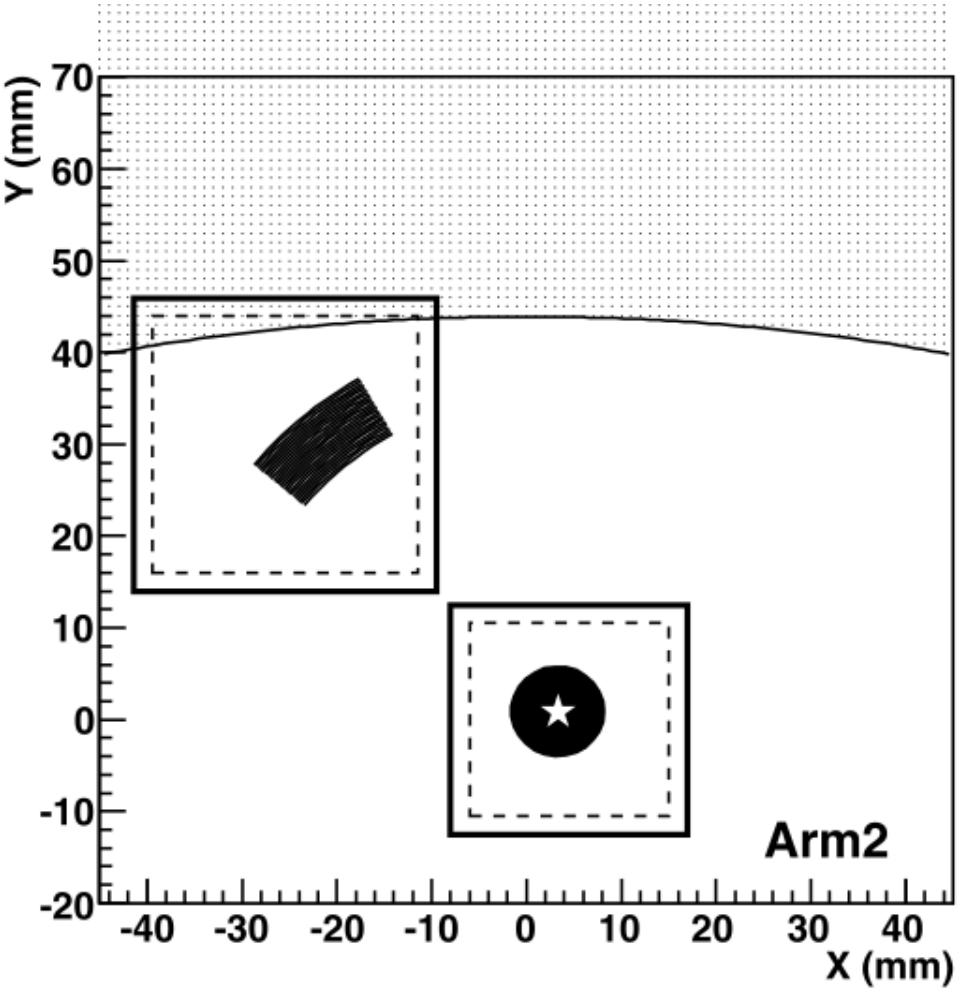


Arm2 (New)



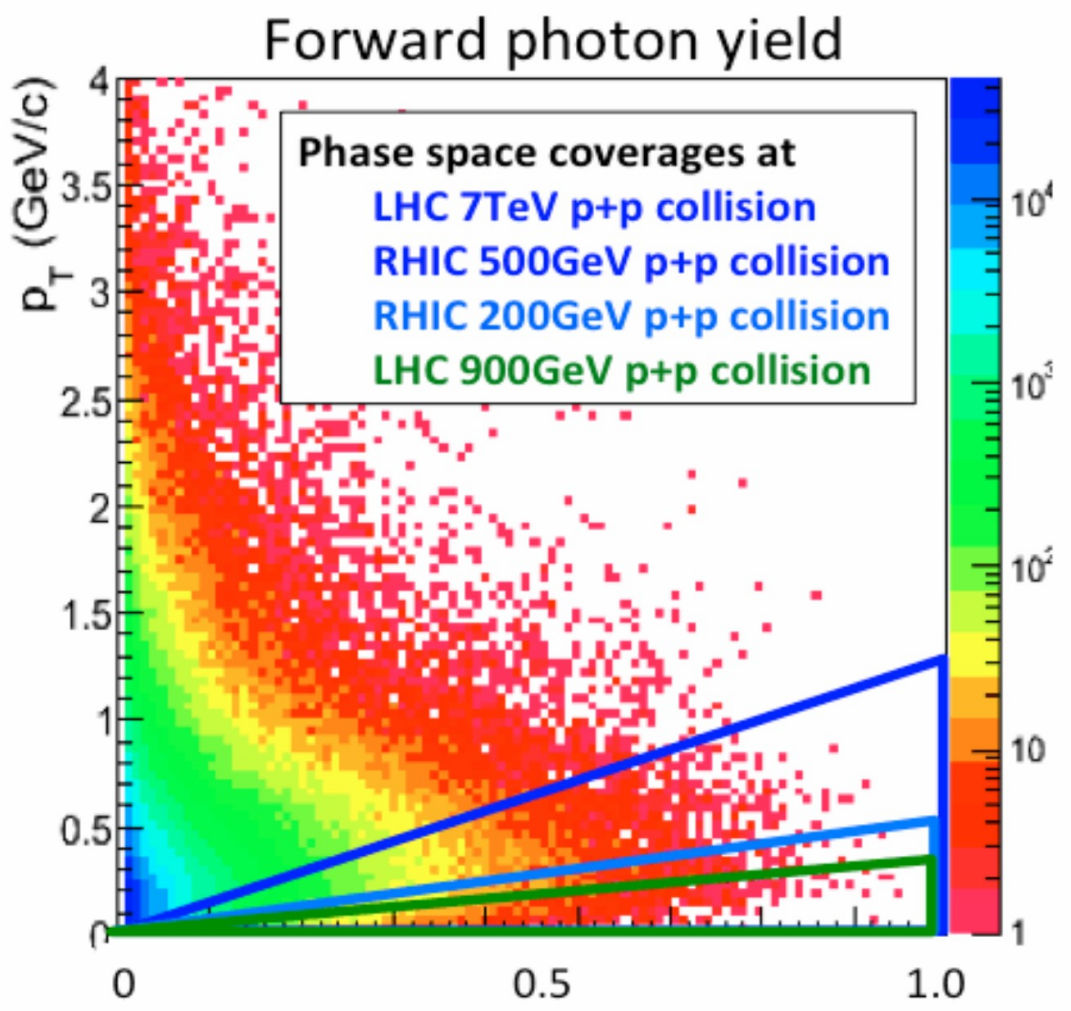
Detectors cross section





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 (extrapolation beyond LHC energy)



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

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