LHCf Run II physics results in proton-proton collisions at $\sqrt{s}$ = 13 TeV

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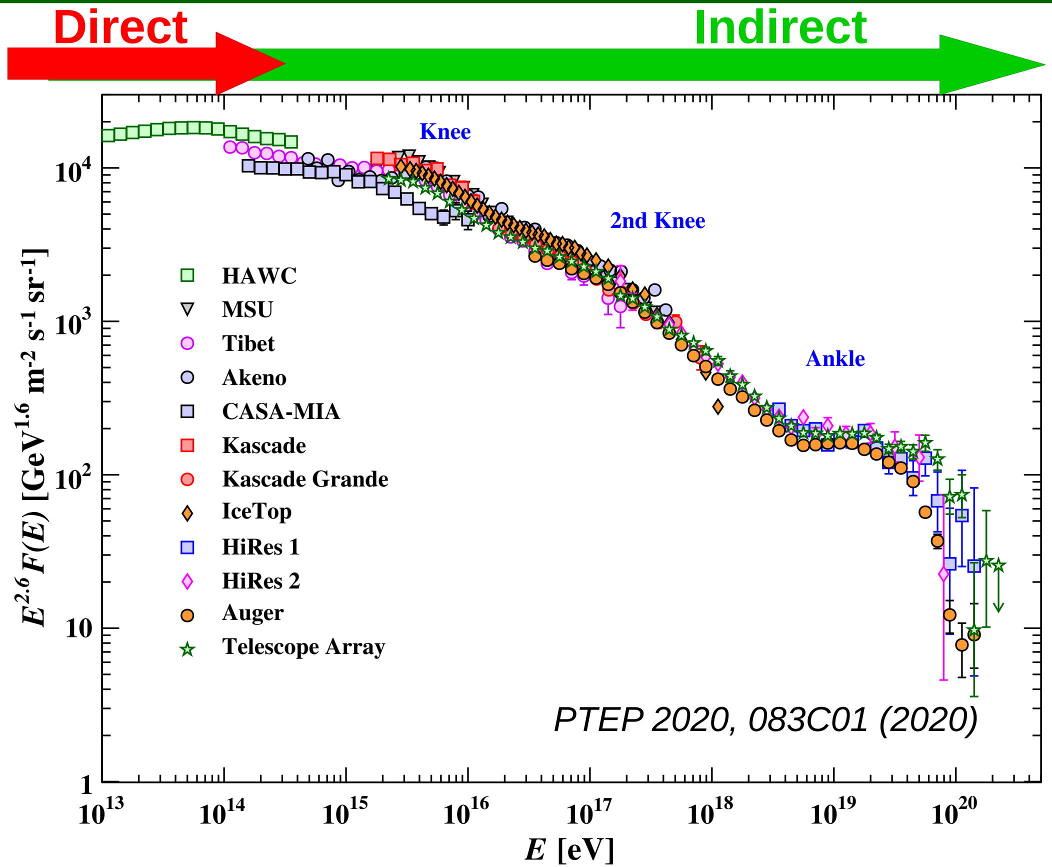
on behalf of the LHCf collaboration

ICHEP 2022, Bologna (Italy), July 6-13, 2022

Ultra-high-energy cosmic rays



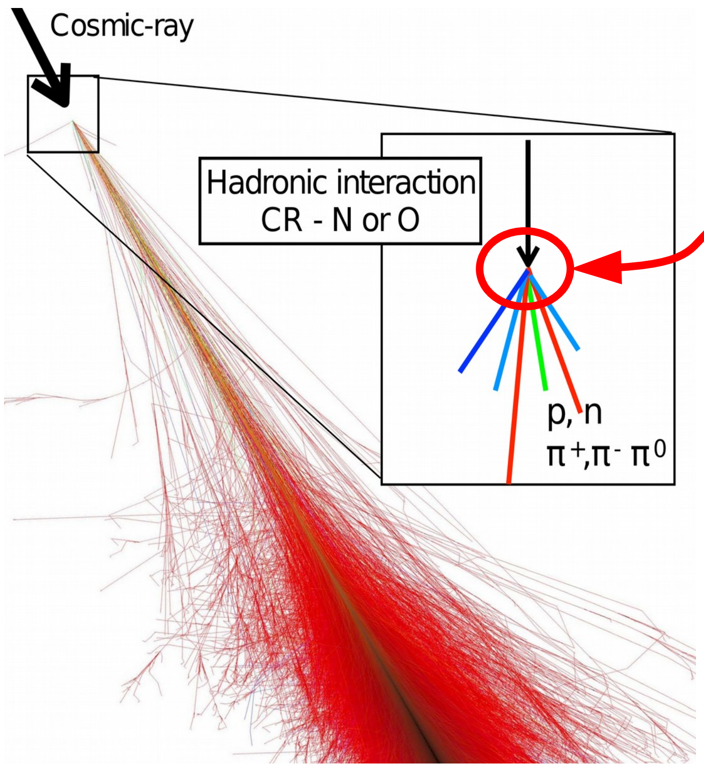
- **Direct measurements** limited by low flux of particles at high energies

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

  Observation of air showers of secondary particles

  Detailed MC simulations are fundamental

Contribution from accelerators



$\sqrt{s}$ = 13 TeV → $E_{CR} = 0.9 \cdot 10^{17}$ eV

First CR interaction

- **Inelastic cross section**
- **Multiplicity**
- **Elasticity = p_{lead} / p_{beam}**
- **Forward energy spectrum**
- **Nuclear effects**

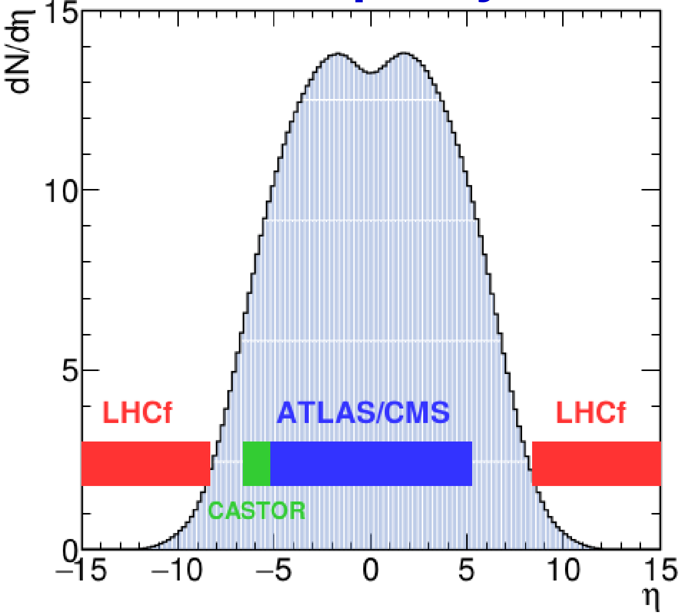
Elasticity and forward energy spectrum → **neutrons, photons, π^0, η**

Nuclear effects → **p-Pb collisions (p-O in 2023/24!)**

All of these → **LHCf**

Why forward?

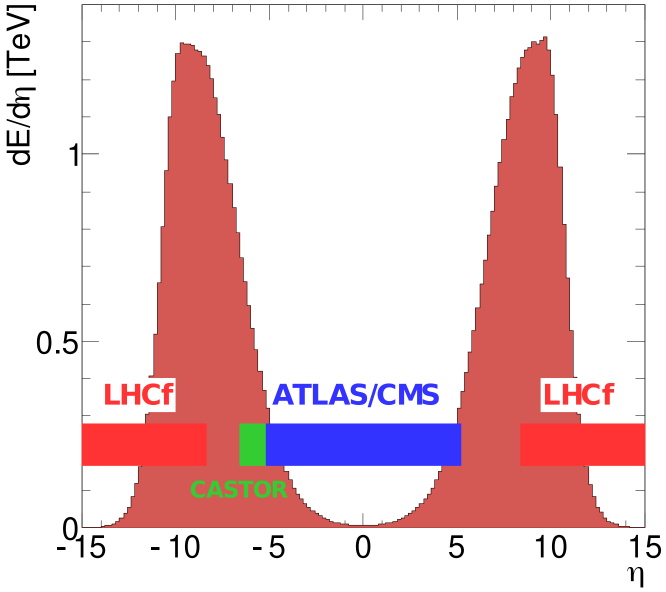
Multiplicity



p-p
√s = 13 TeV

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

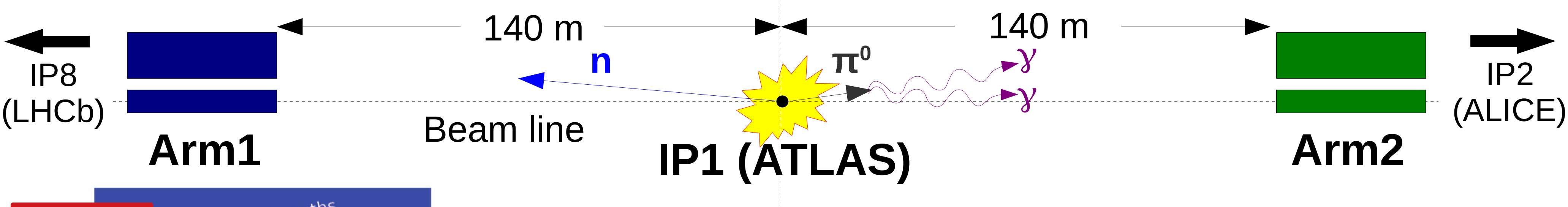
Energy flow



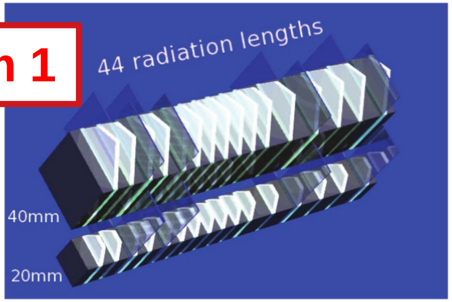
Maximum multiplicity in the central region

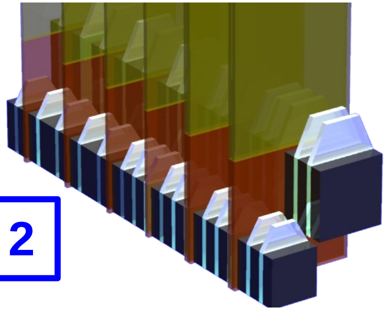
Peak of energy flow around
η ~ 9 (θ ~ 0.25 mrad)

Experimental setup



Arm 1





Arm 2

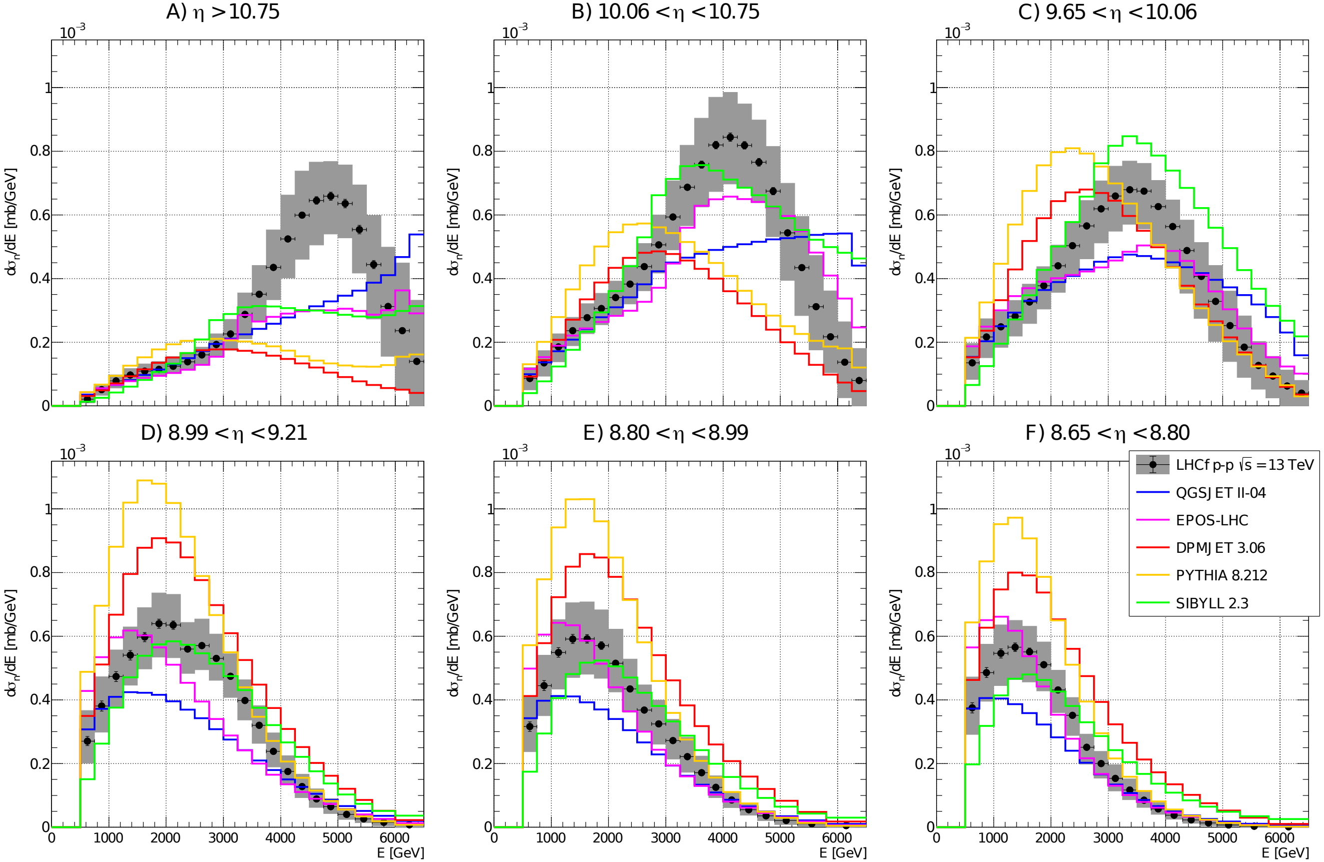
Zero degree particles!
Coverage: **η > 8.4** (with 140 μrad beam crossing angle)

Charged particles deflected by D1 dipole magnets

Neutral particles (**photons** and **neutrons**) detected

Neutrons in p-p at √s = 13 TeV

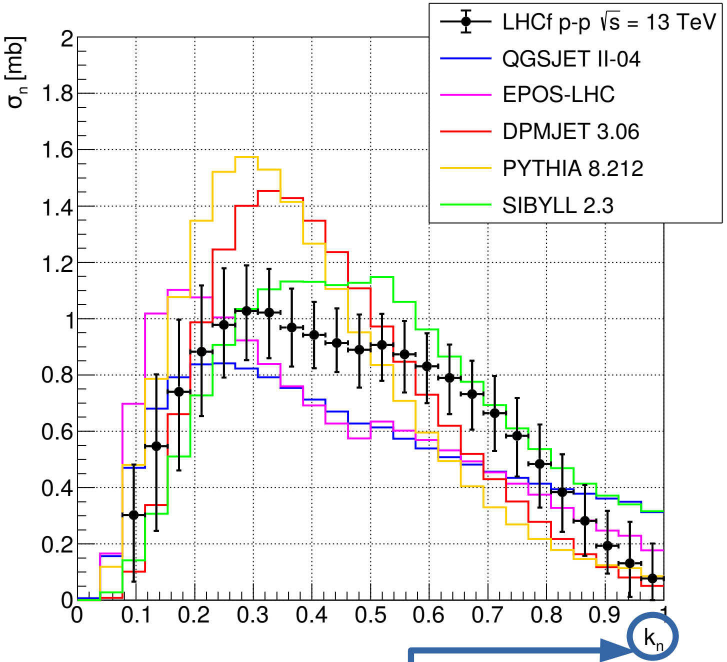
- Models do not reproduce the peak structure at η > 10.75 and underestimate the total cross section in this region
- For 8.65 < η < 10.75 either EPOS-LHC or SIBYLL 2.3 has the best agreement with data, depending on the pseudorapidity region



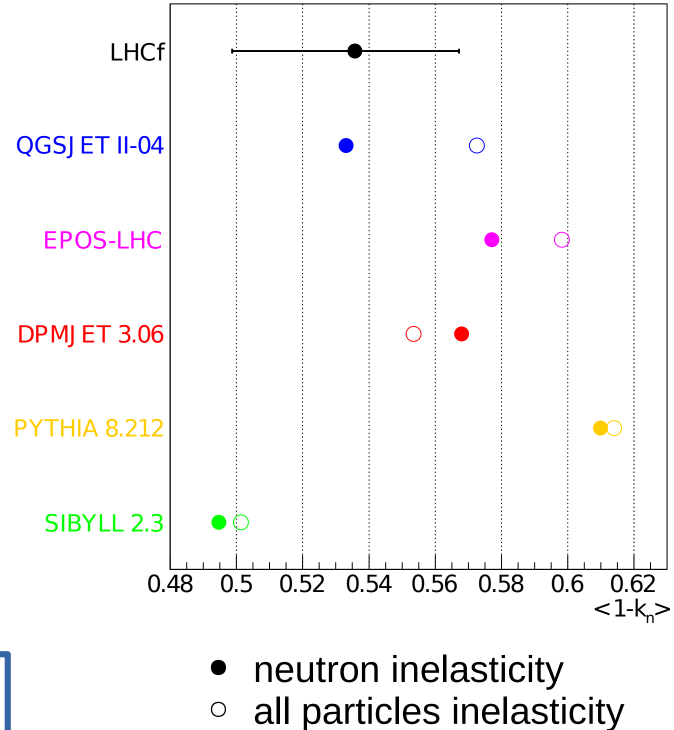
O. Adriani et al., JHEP07 (2020) 016

Inelasticity in p-p at √s = 13 TeV

- Neutron elasticity distribution is not well reproduced by any model (SIBYLL 2.3 better than others)
- Average neutron inelasticity is well reproduced with QGSJet II-04 and not far from the prediction of other models, except PYTHIA 8.212

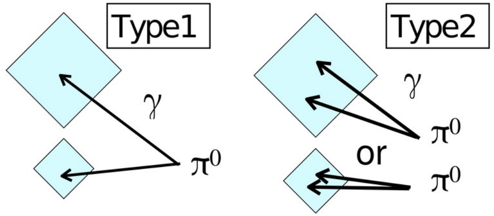


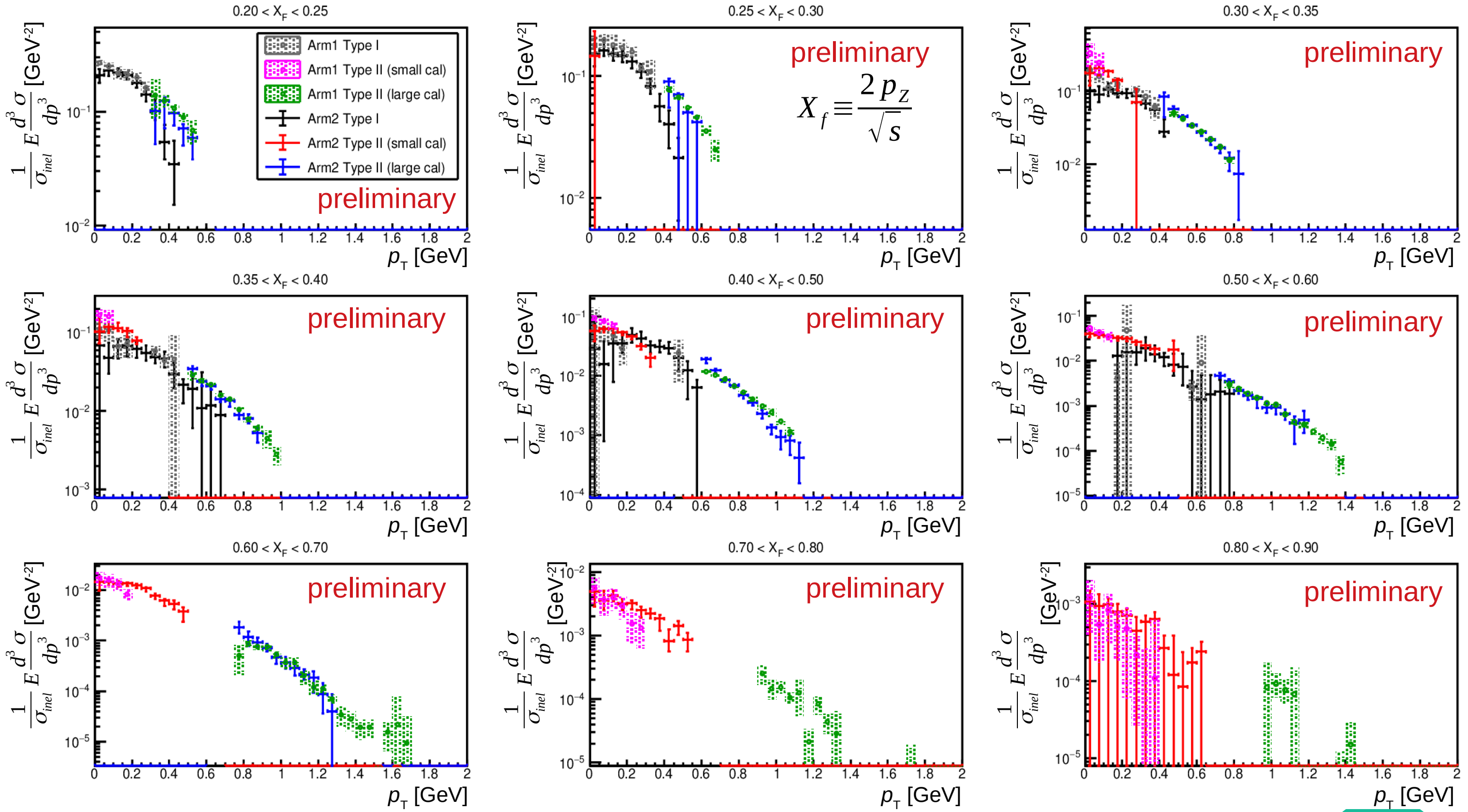
k_n ≡ elasticity in events where the leading particle is a neutron



O. Adriani et al., JHEP07 (2020) 016

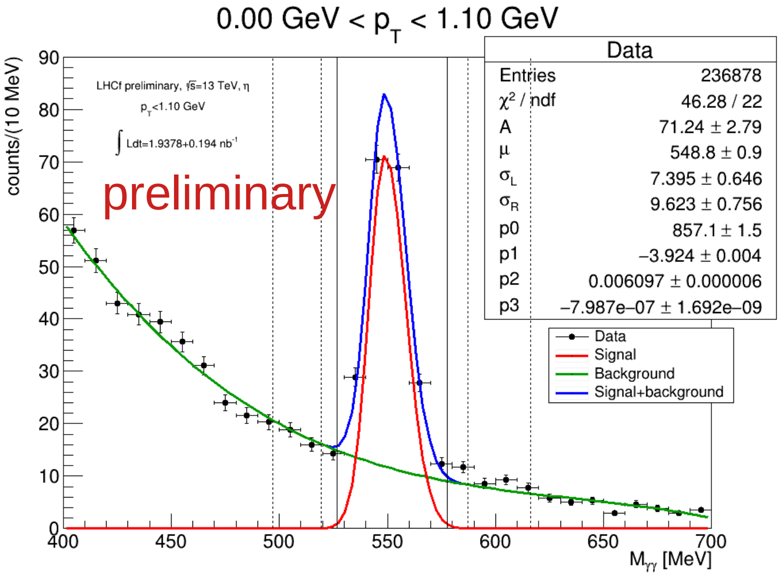
π^0 in p-p at $\sqrt{s}$ = 13 TeV (preliminary)

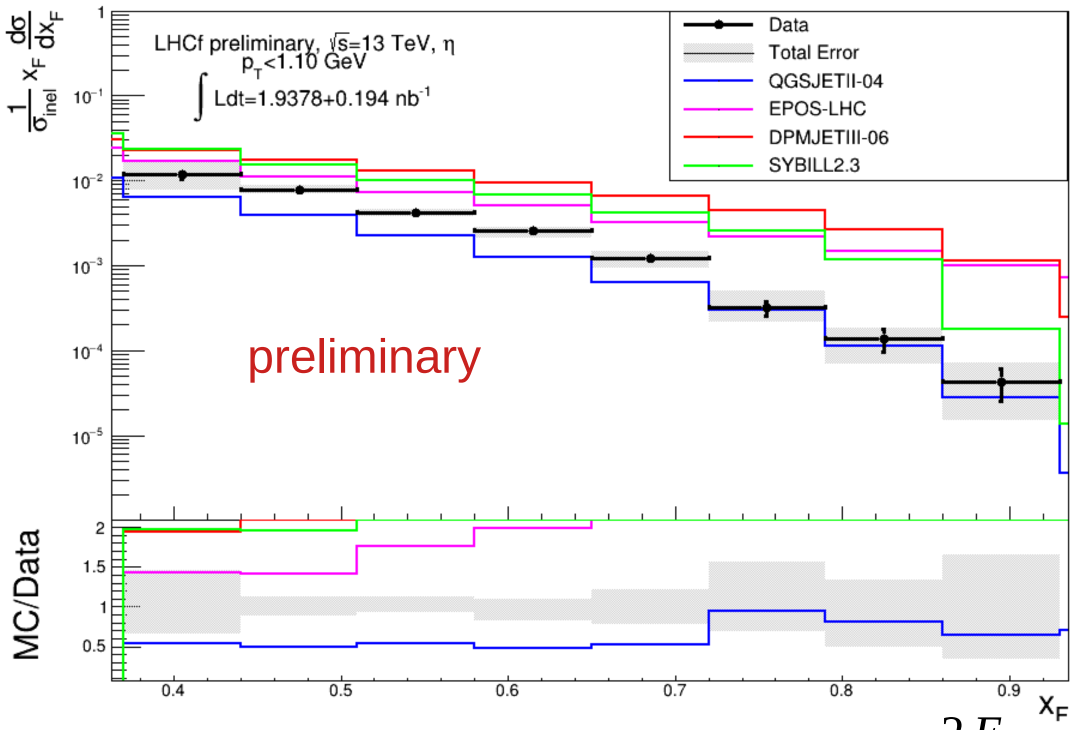




- **Good agreement** between Arm1 and Arm2 data and between “Type I” and “Type II” events
- Arm2 acceptance covers the gaps in Arm1 data for X_F < 0.6 and extends the low-p_T coverage for X_F > 0.6, while Arm1 extends the acceptance to higher p_T

η in p-p at √s = 13 TeV (preliminary)

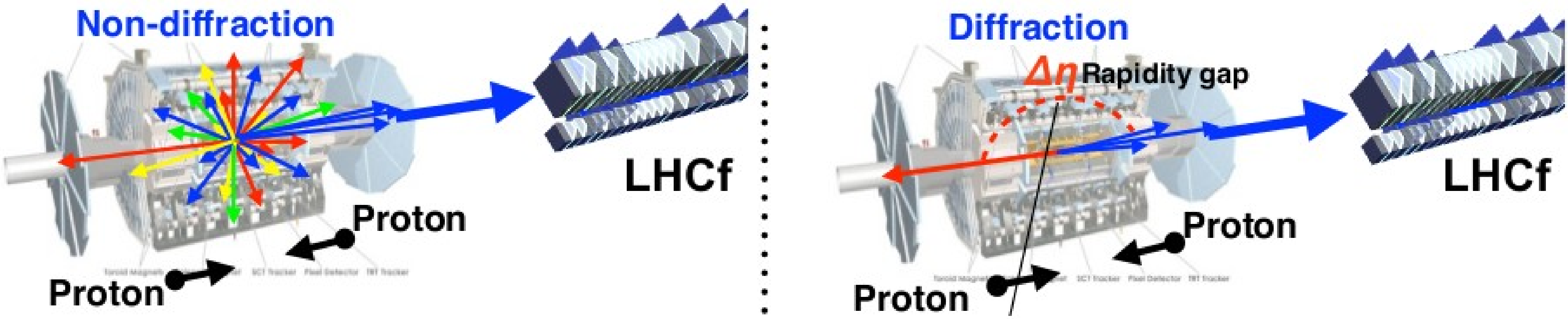




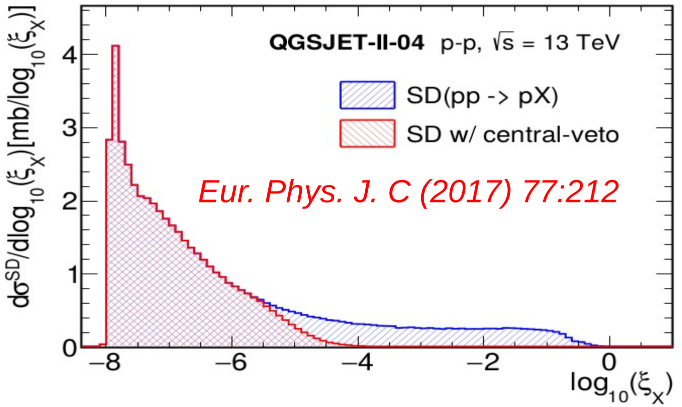
- Better agreement with QGSJET, but still a factor ~2 difference at low X_F

$$X_F \equiv \frac{2E}{\sqrt{s}}$$

ATLAS-LHCf combined analysis



- The number of tracks in the central region gives information on the type of collision
- Requiring no charged tracks in ATLAS for $|\eta| < 2.5$ a sample of low-mass diffractive events can be selected

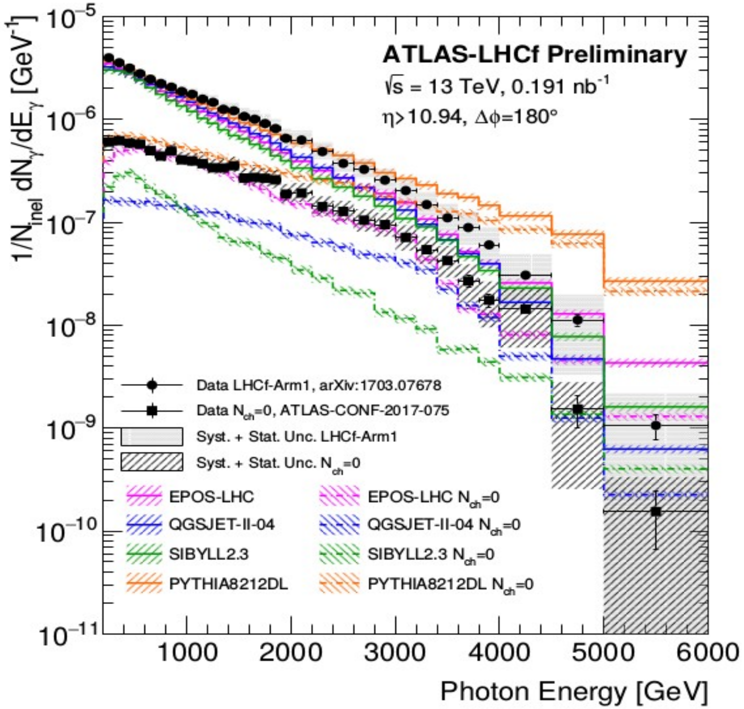


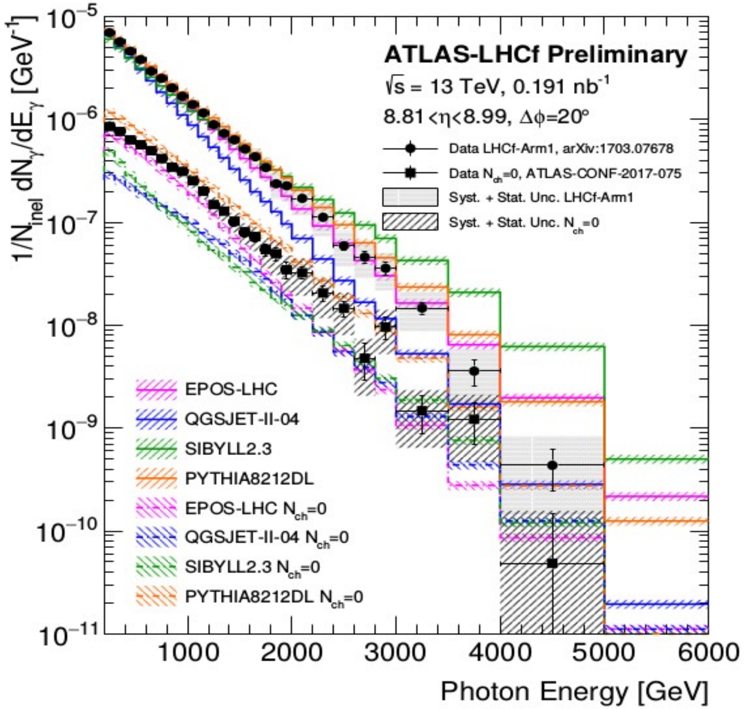
$$\xi_X = \frac{M_X^2}{s}$$

Combined analysis with ATLAS (photons in p-p at √s = 13 TeV)

- Good agreement with EPOS-LHC for η > 10.94

- Best agreement with EPOS-LHC and PYTHIA 8.212DL for 8.81 < η < 8.99

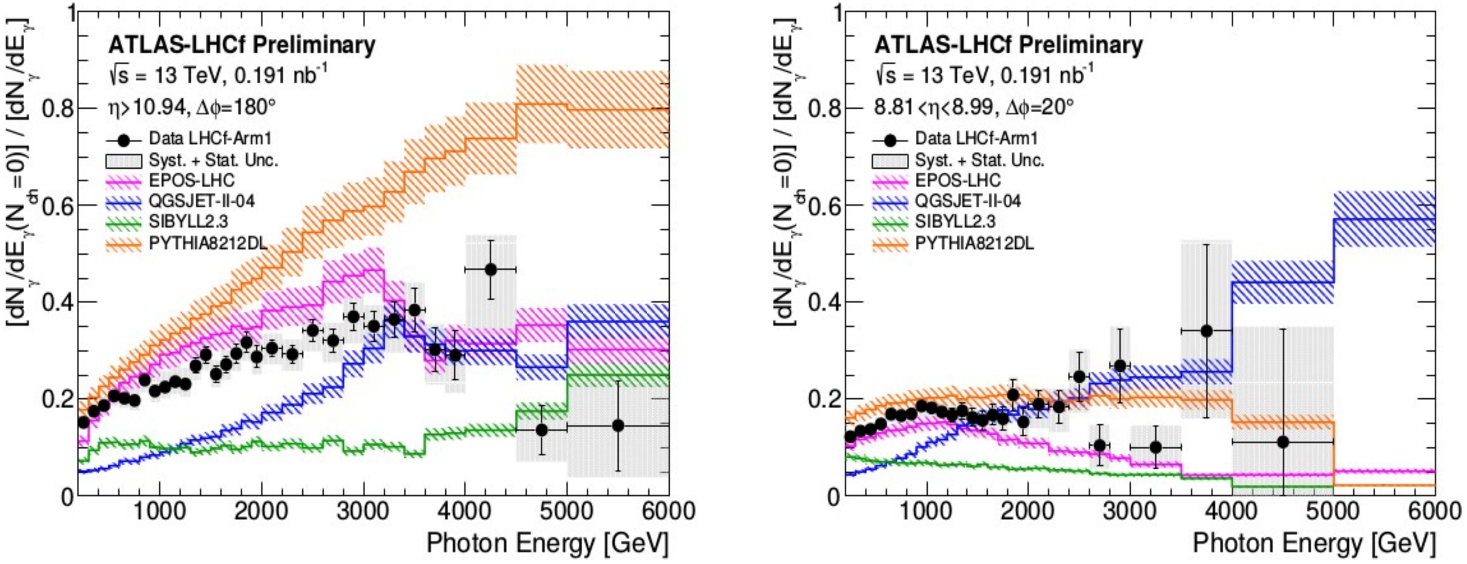




ATLAS-CONF-2017-075

Combined analysis with ATLAS (photons in p-p at √s = 13 TeV)

- The fraction of diffractive-like events differs between models
- Best agreement with EPOS-LHC for $\eta > 10.94$
- Best agreement with PYTHIA 8.212DL for $8.81 < \eta < 8.99$

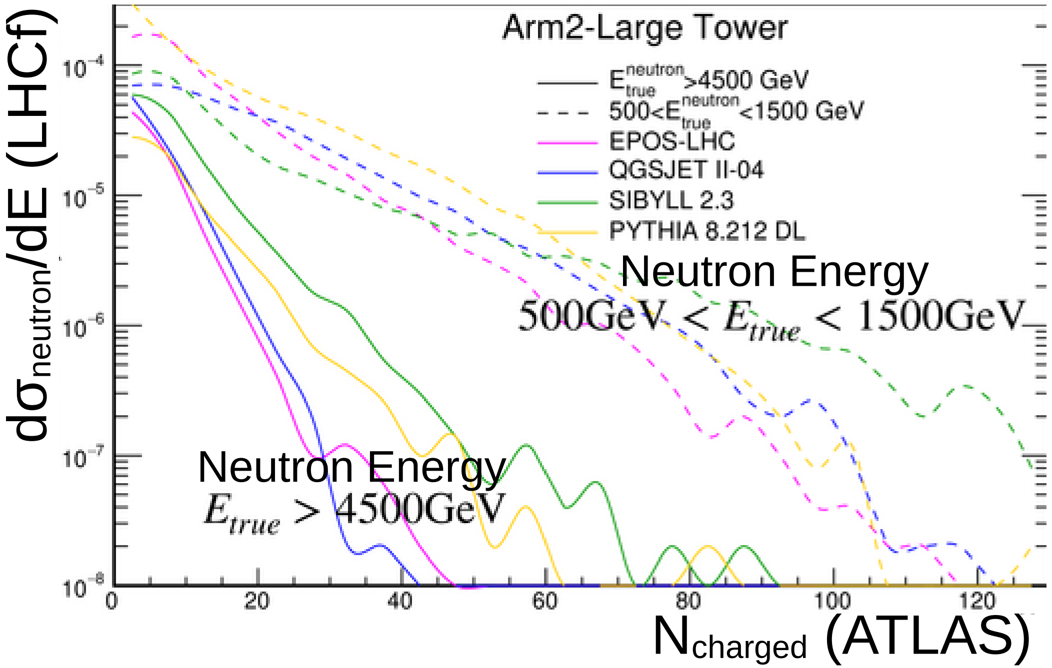


ATLAS-CONF-2017-075

Combined analysis with ATLAS: ongoing analysis

- Study of **multi parton interaction (MPI)**, as proposed in S. *Ostapchenko et al, Phys. Rev. D 94, 114026*

- Study of the correlation between the energy of a neutron detected by LHCf and the number of charged tracks detected by ATLAS in the central region



Future prospects

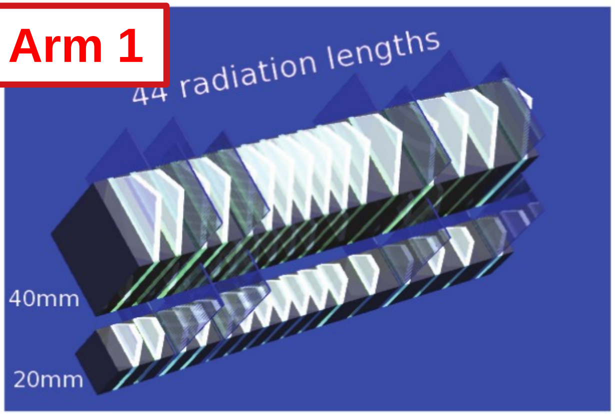
- Operation in **proton-proton** collisions at **$\sqrt{s}$ = 13.6 TeV**
  - Increase of π^0 and η statistics thanks to the upgrade of the readout electronics and a dedicated trigger scheme
  - Allow the K^0 analysis thanks to the increased statistics
  - Joint acquisition with ATLAS planned
    - operation with roman pots (ALFA and AFP): hadronization of single diffractive events and Δ resonance ($p+\pi^0$)
    - operation with ATLAS ZDC: improve hadron resolution from ~40% to ~20% (measurements of p-π cross section via one-pion exchange process)
- Operation in **proton-oxygen** and **oxygen-oxygen** collision (2023 or 2024)
  - best configuration to probe CR-atmosphere collision
  - direct measurement of nuclear modification factor (no background from ultra peripheral collisions as in p-Pb collisions)

backup

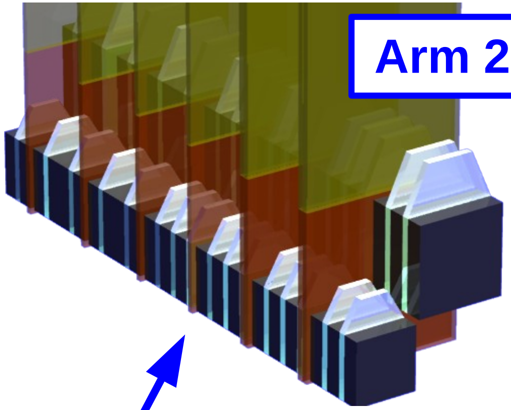
Detectors performance

- 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 2



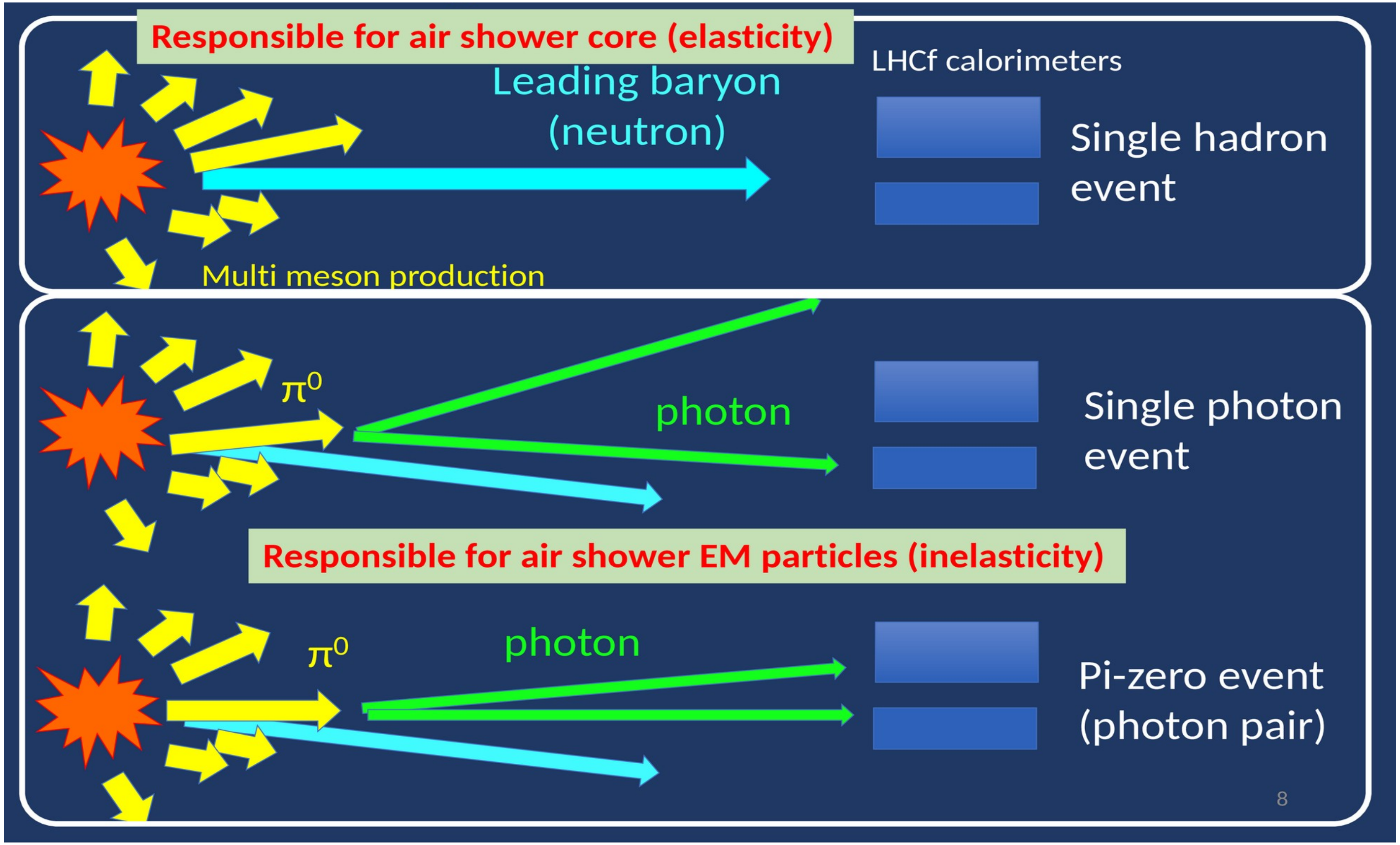
Arm 1

- 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

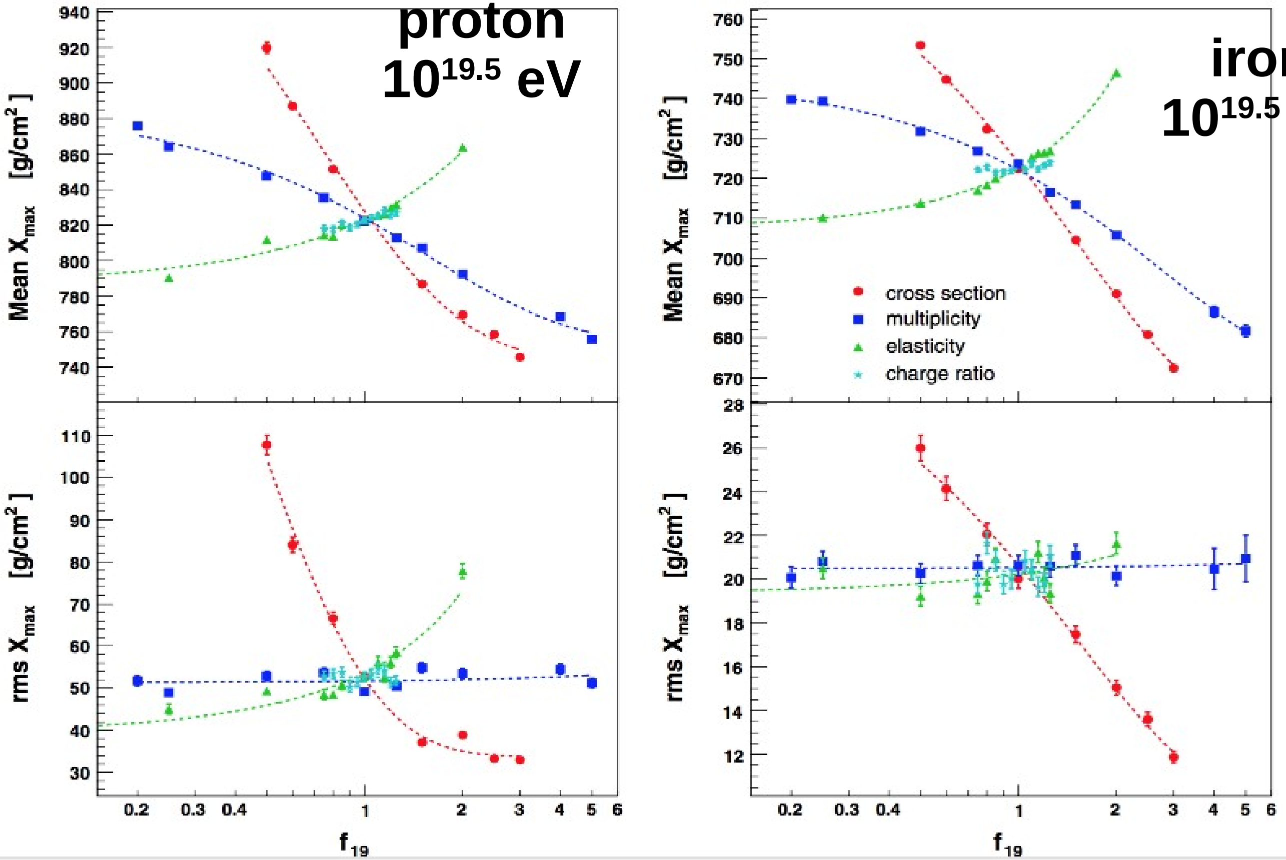
- Transverse size: 25 x 25 mm^2 and 32 x 32 mm^2
- 4 x-y **silicon µstrip** layers
- Position resolution: 40 µm (photons, E > 200 GeV)

Event categories



X_{max} vs parameters

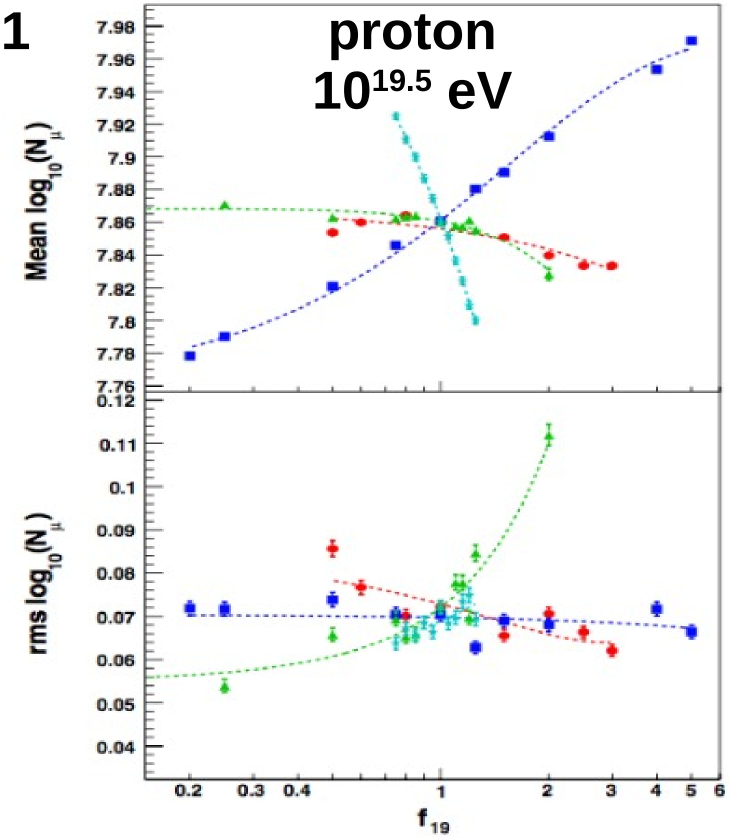
SIBYLL 2.1

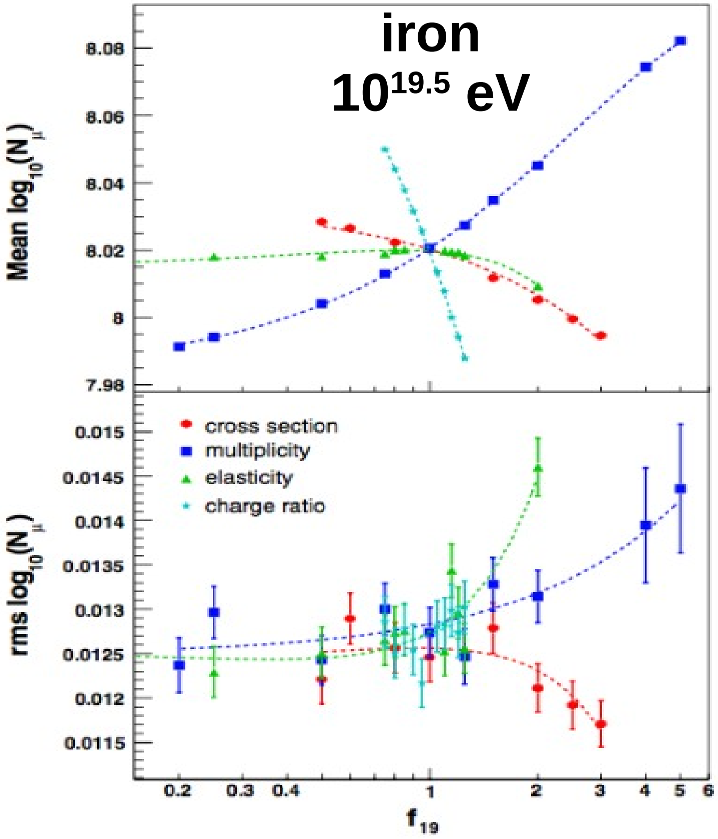


Phys. Rev. D83 (2011) 054026

N_μ vs parameters

SIBYLL 2.1

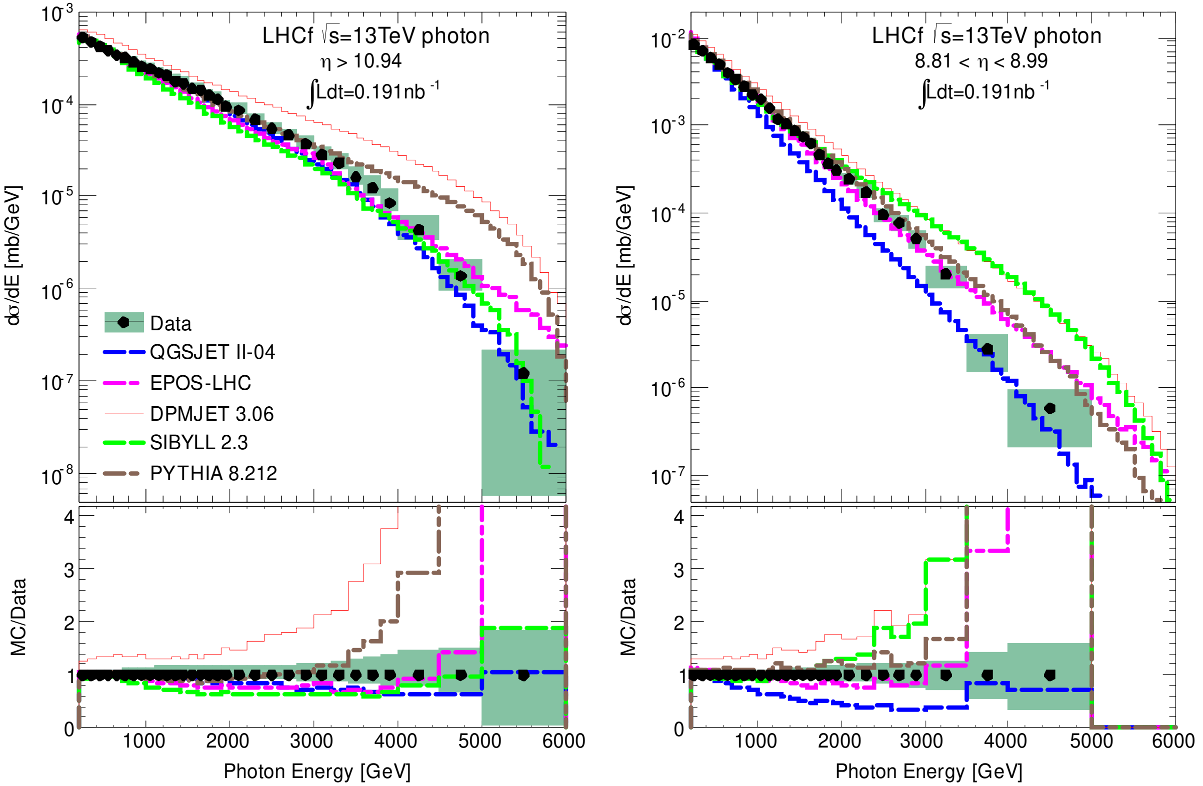




Phys. Rev. D83 (2011) 054026

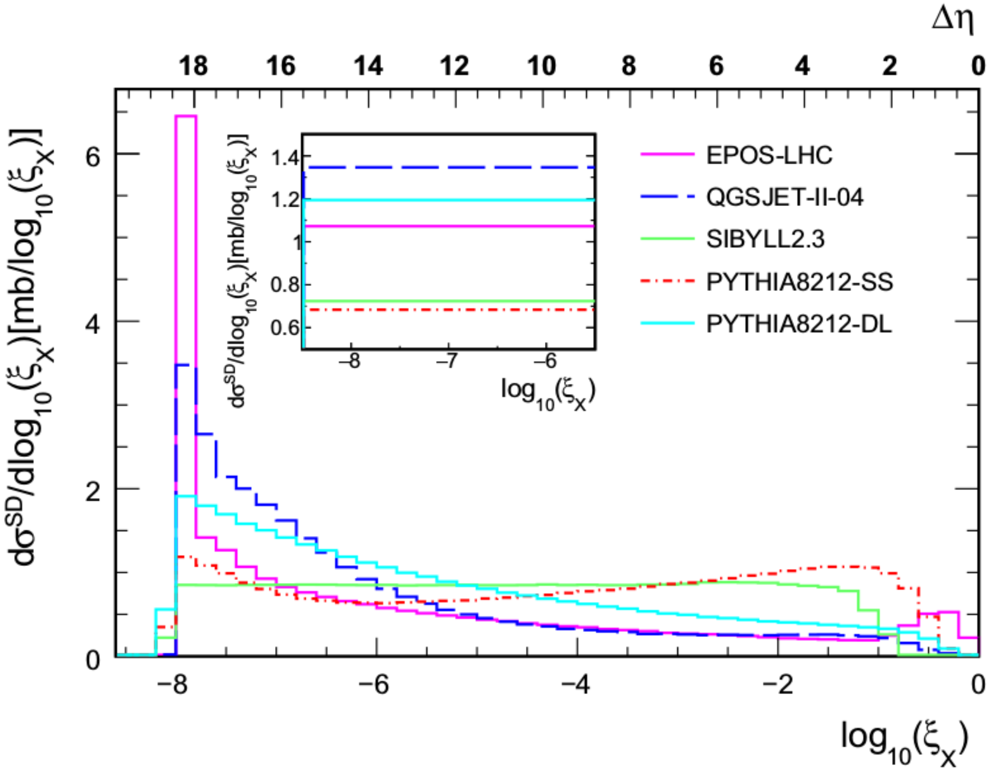
Photons in p-p at √s = 13 TeV

- Best agreement with QGSJET and EPOS-LHC for η > 10.94
- Good agreement with EPOS-LHC and PYTHIA 8.212 for 8.81 < η < 8.99 at energies below 3 TeV



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

Diffraction mass distribution

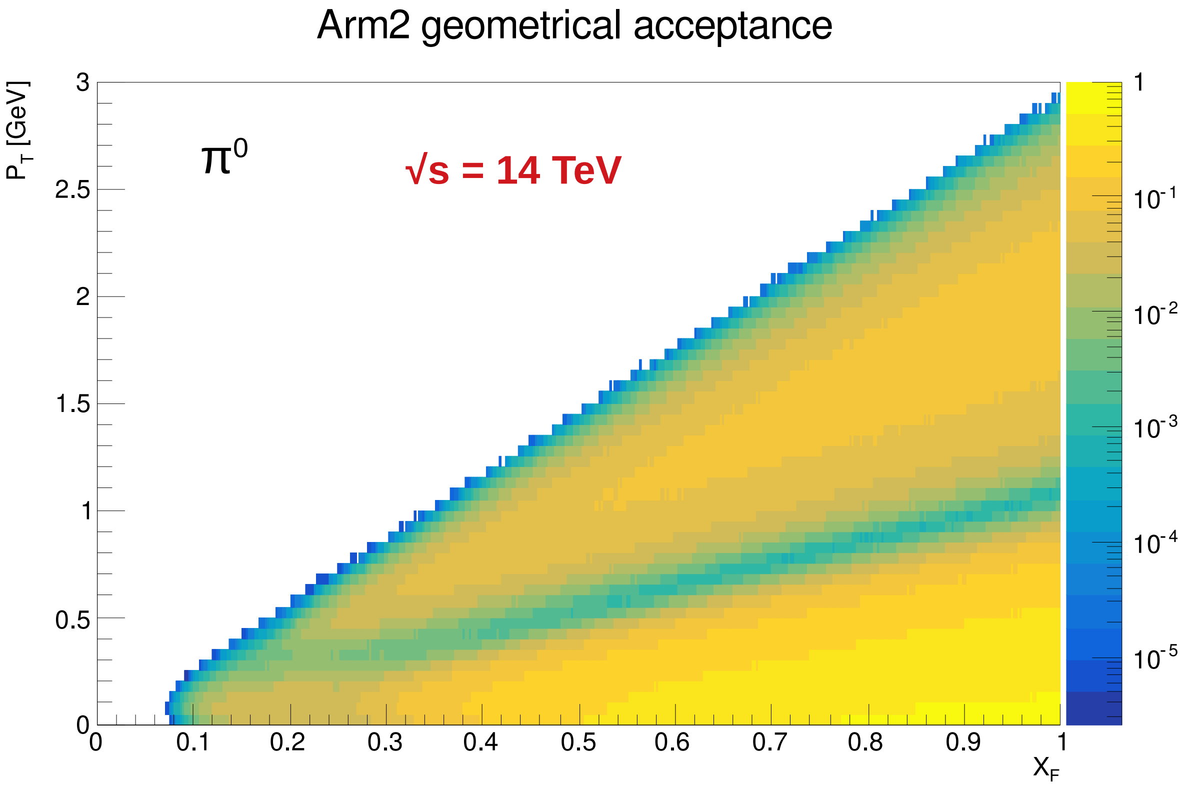


$$\xi_X = \frac{M_X^2}{s}$$

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

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

π^0 geometrical acceptance



Trigger logic

- "Shower" trigger
  - prescale factor: 14
  - ~100% efficiency for photons (E > 200 GeV)
  - ~70% efficiency for neutrons (E > 1 TeV)
- "Type I" trigger
  - prescale factor: 1
  - π^0 with one photon in each calorimeter (efficiency ~98%)
  - η
- "High EM" trigger
  - prescale factor: 1
  - high energy photons (E > 1 TeV)
  - π^0 with both photons in the same calorimeter (efficiency ~97%)

Arm2 DAQ upgrade

- **Replace aged electronics**
  - lack of replacements for FOXI optical transmitters/receivers, control ring boards, ...
- **Speed-up the readout by a factor ~10**
  - Arm2 silion DAQ gives the main contribution to dead time (~1 ms)
  - GbEthernet (~1 Gbps) protocol will be used instead of FOXIchip protocol (~100 Mbps)

Arm2 DAQ upgrade