# L'esperimento LHCf

## Motivazioni scientifiche e risultati recenti

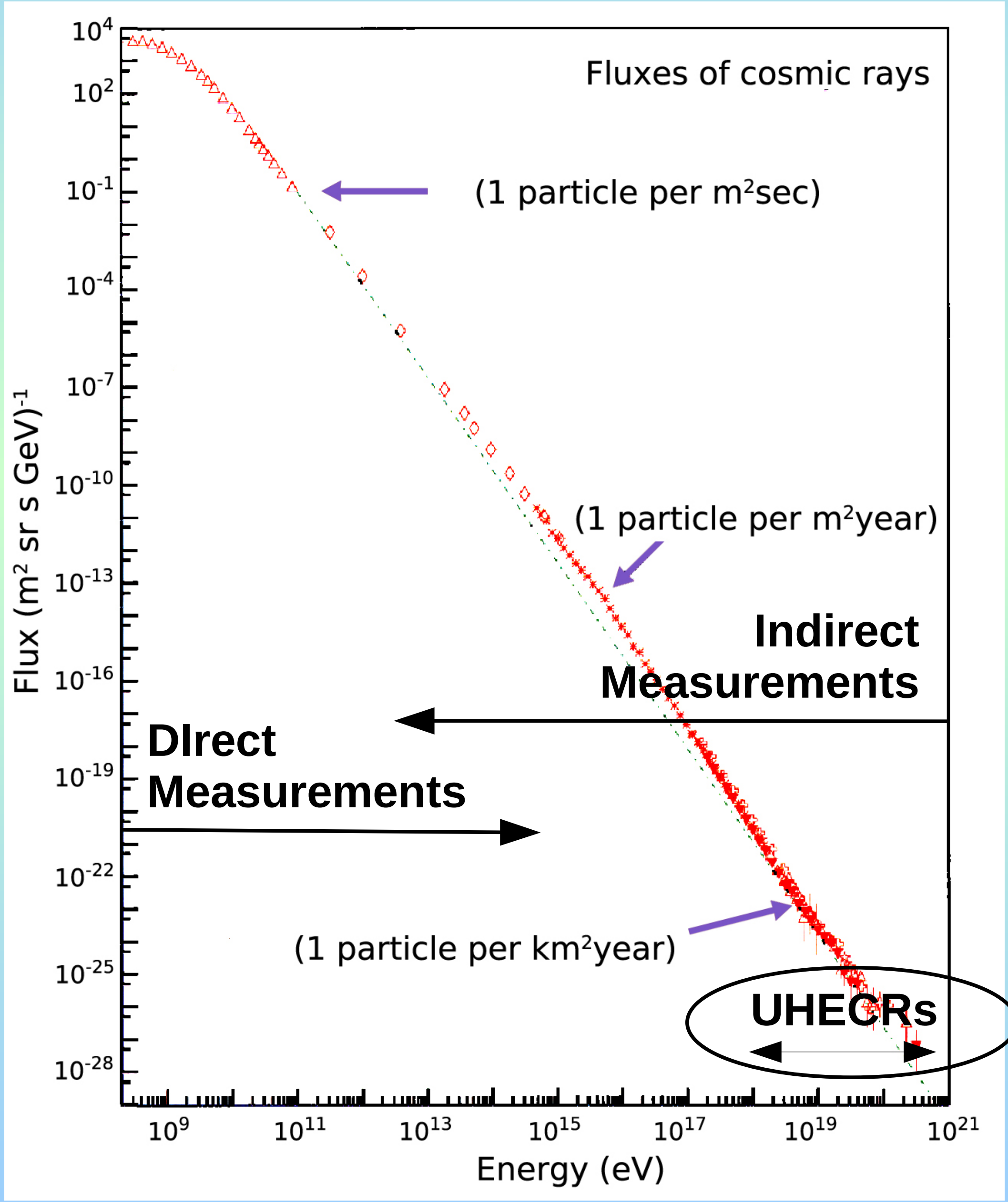
E. Berti

Consiglio di sezione
Firenze, 6 Dicembre 2016

# Introduction

## From Cosmic Rays to LHC

# Ultra High Energy Cosmic Rays (UHECRs)



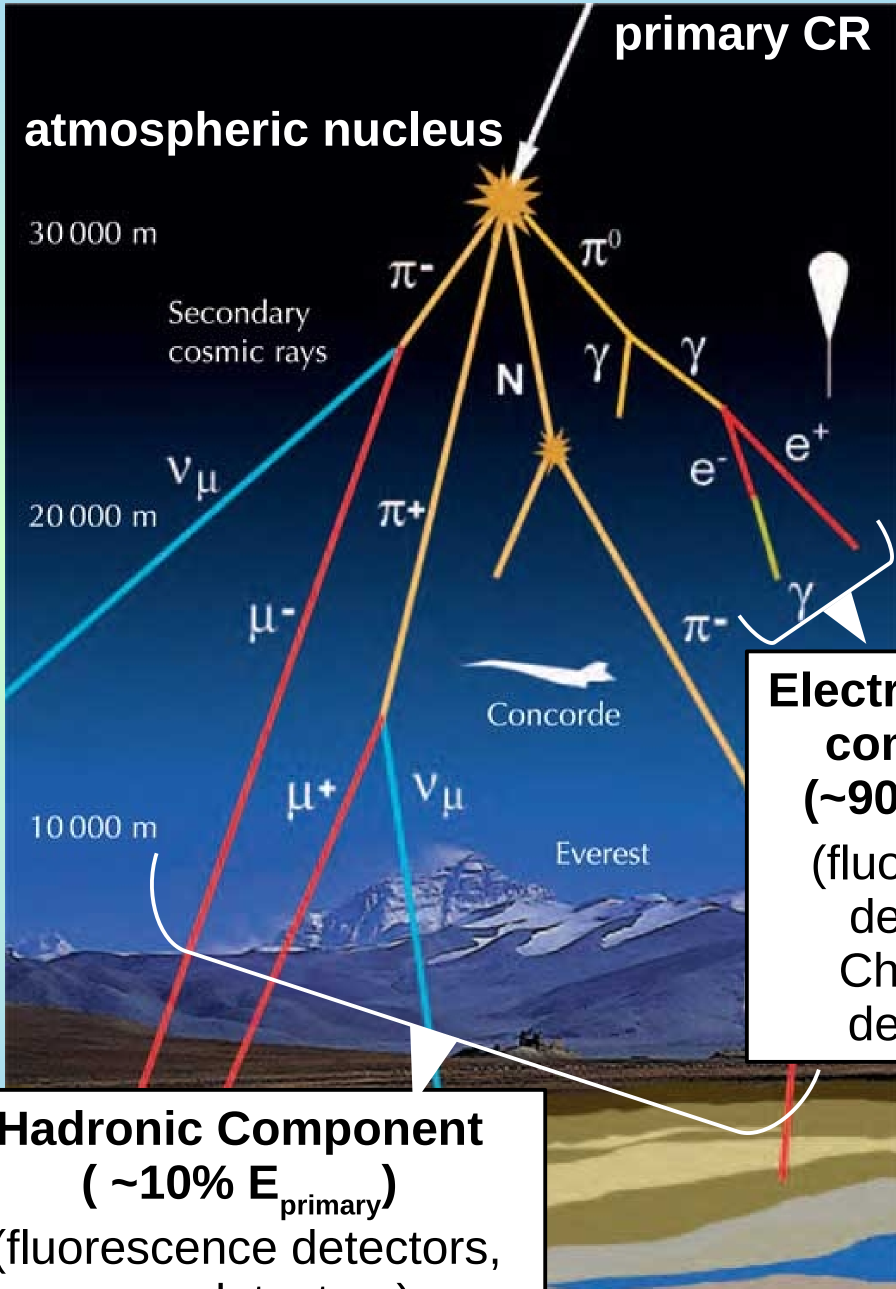

**Purpose**
Understand cosmic rays propagation and acceleration mechanism

Accurate measurements of flux and composition as a function of energy

**Direct measurements** (stratospheric balloons, satellites)

**Indirect Measurements** (large detector arrays at ground)

# Detection of UHECRs




**Electromagnetic component (~90% $E_{primary}$)**
(fluorescence detectors, Cherenkov detectors)

**Hadronic Component ( ~10% $E_{primary}$)**
(fluorescence detectors, muon detectors)

**Extensive Air Showers (EASs)**
Showers formed by the interaction of the primary CR with the atmosphere

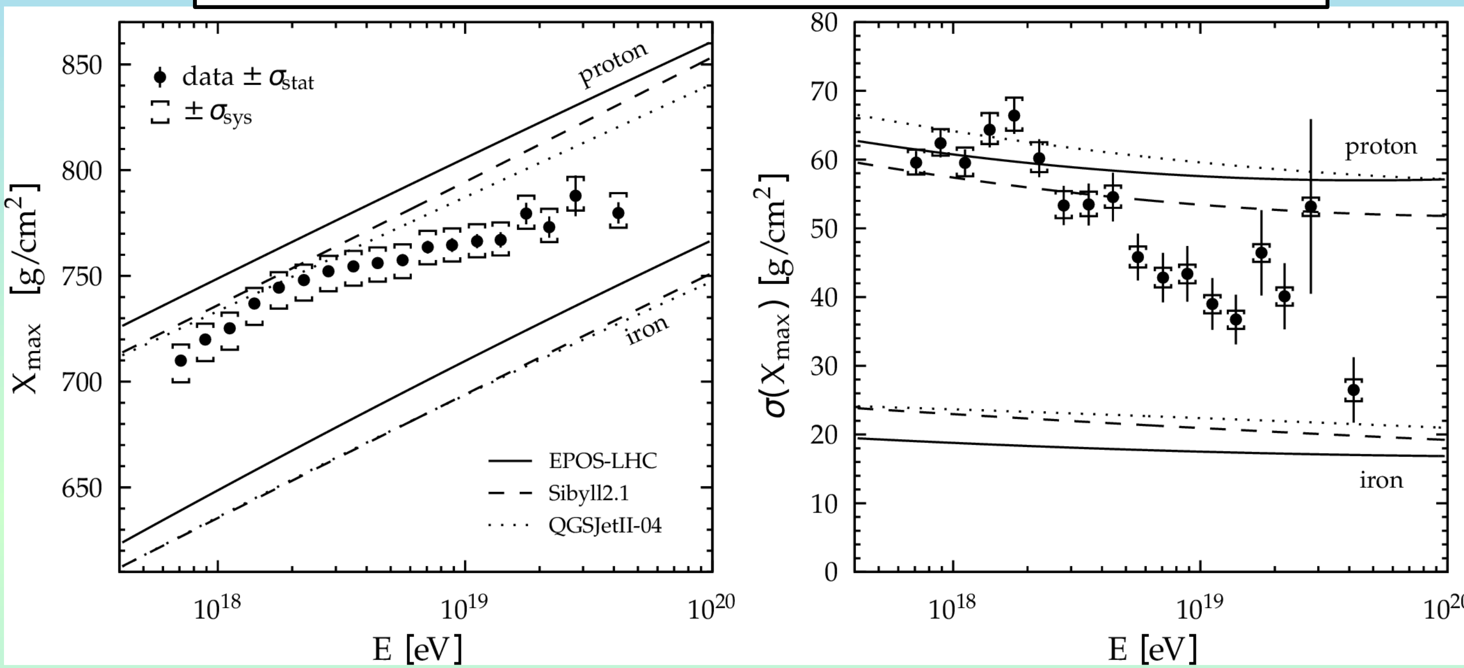
The largest fraction of the primary energy is carried by **forward secondary particles**

**Hadronic interaction models**
Hadronic interaction models are mandatory for the analysis of UHECRs composition

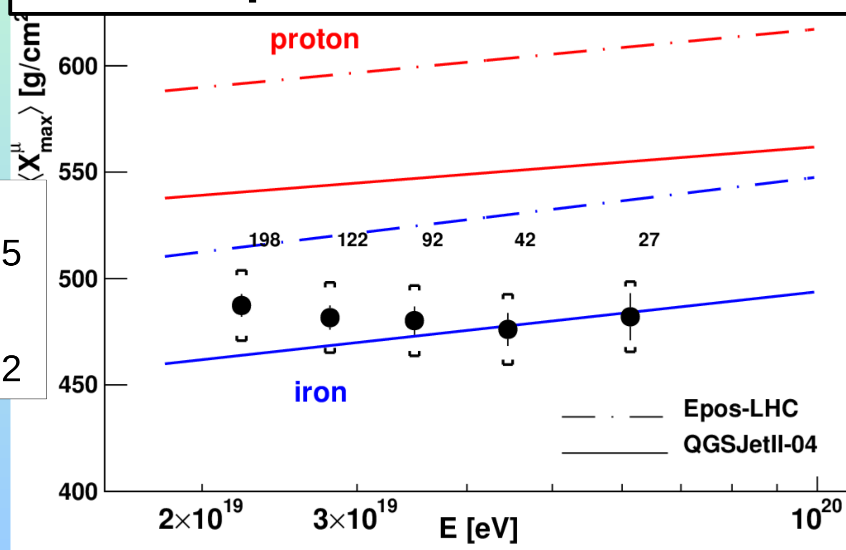
Large discrepancies between models in the forward region imply **large uncertainties**

# Agreement between models

**Mean and RMS depth of shower maximum**




**Mean depth of muon maximum**



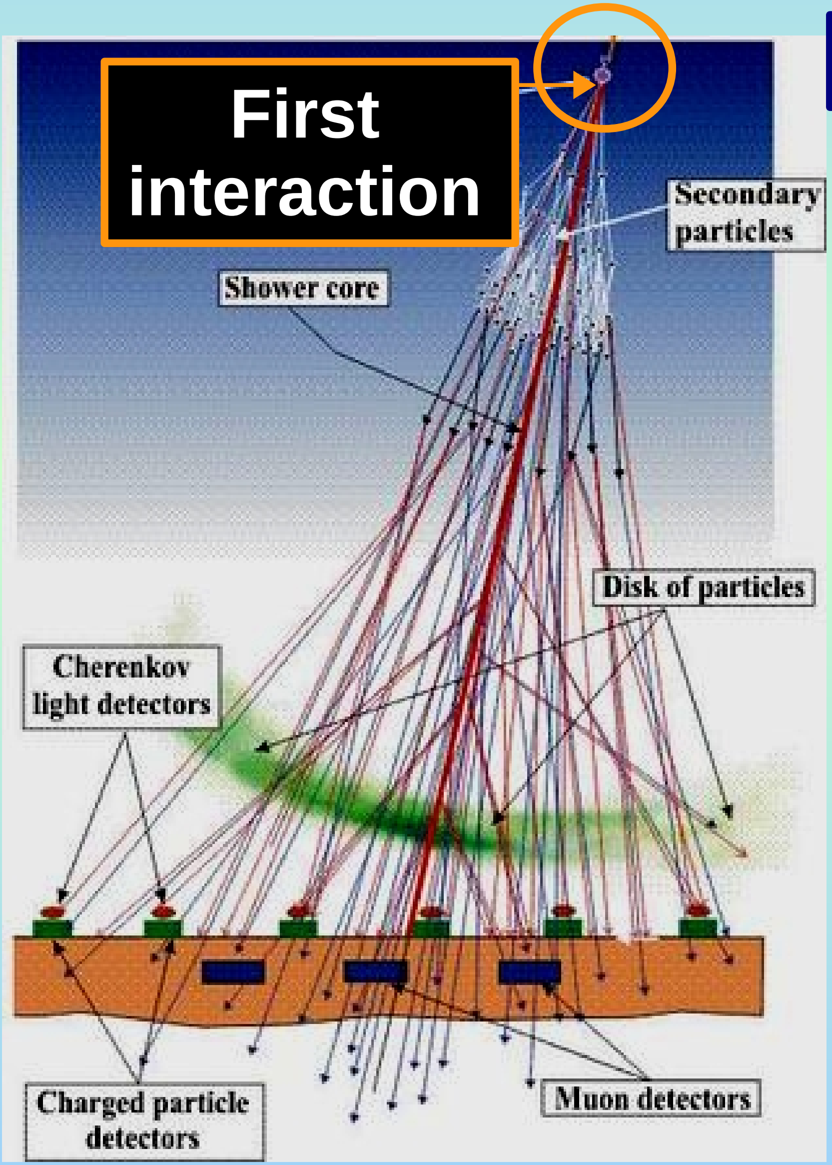


A. Aab et al. (Pierre Auger Collaboration) Phys. Rev. D 90, 122005

A. Aab et al. (Pierre Auger Collaboration) Phys. Rev. D 90, 012012


**Large discrepancies** between models, especially for the **muon component**

# Contributions from LHC experiments to models calibration




p-p at $\sqrt{s}$ = 13 TeV ⇒ $E_{LAB} = 9 \cdot 10^{16}$ eV

- **Inelastic cross section**
  large → rapid development
  small → deep penetrating
  (TOTEM, ATLAS, CMS, ...)
- **Multiplicity**
  large → rapid development
  small → deep penetrating
  (ATLAS, CMS ,..)
- **Inelasticity $k = 1 - p_{lead} / p_{beam}$**
  large → rapid development
  small → deep penetrating
- **Forward energy spectrum**
  softer → rapid development
  harder → deep penetrating

$\left.\right\}$ LHCf : neutrons photons $\pi^0$

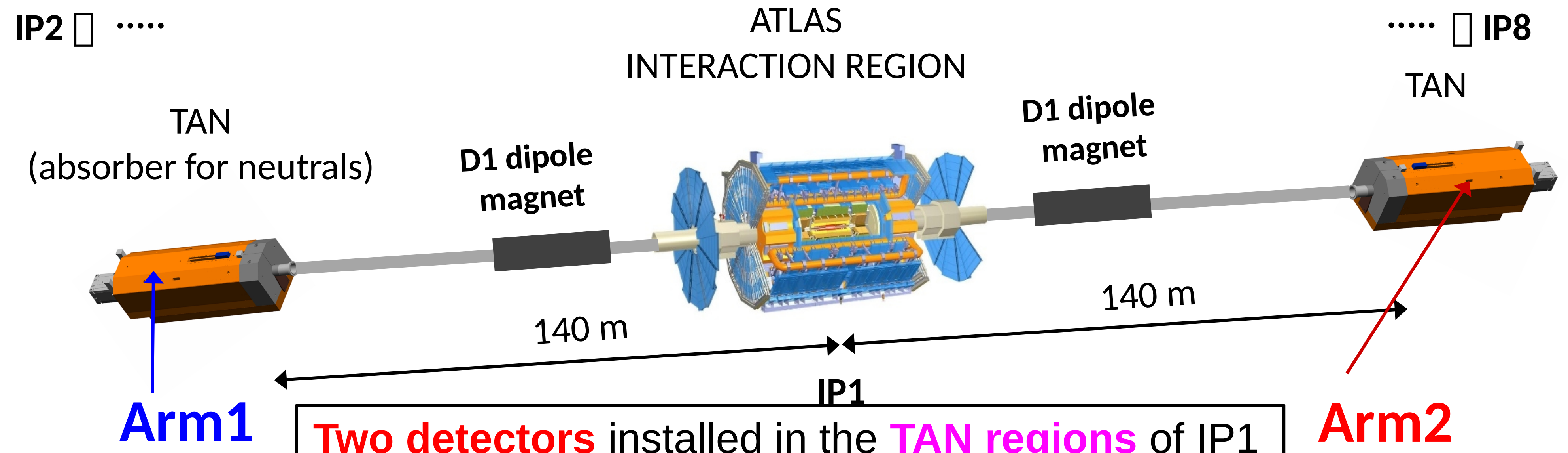
- **Nuclear effects** — LHCf : p-Pb collisions
- **Extrapolation to E > $10^{17}$eV**
- Test of scaling laws (Feynman scaling)

LHCf : p-p collisions at different $\sqrt{s}$

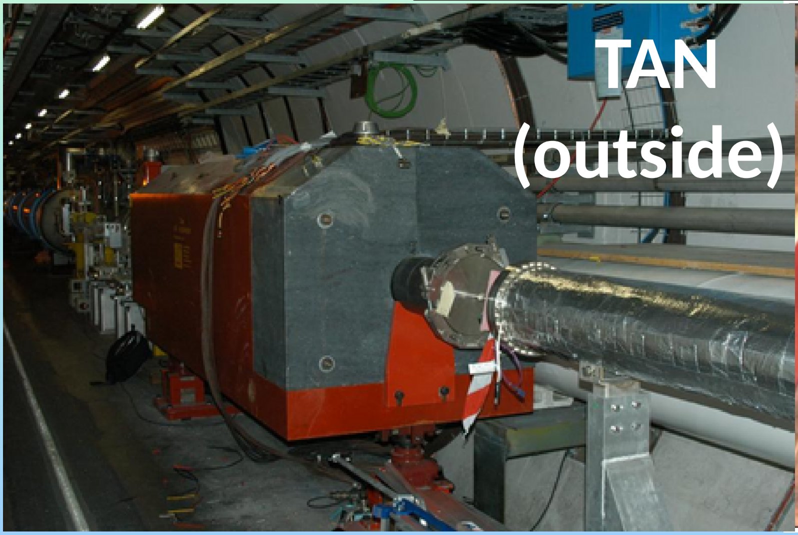
# The LHCf Experiment

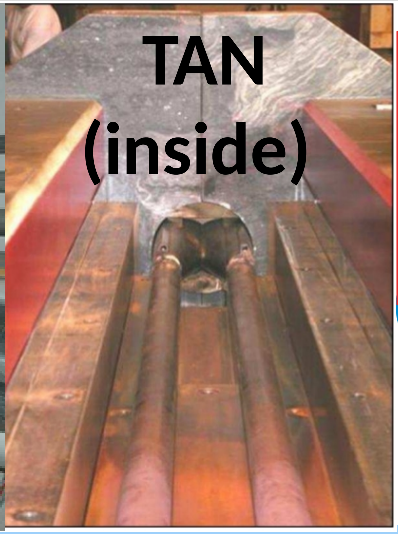
# The LHCf Experiment

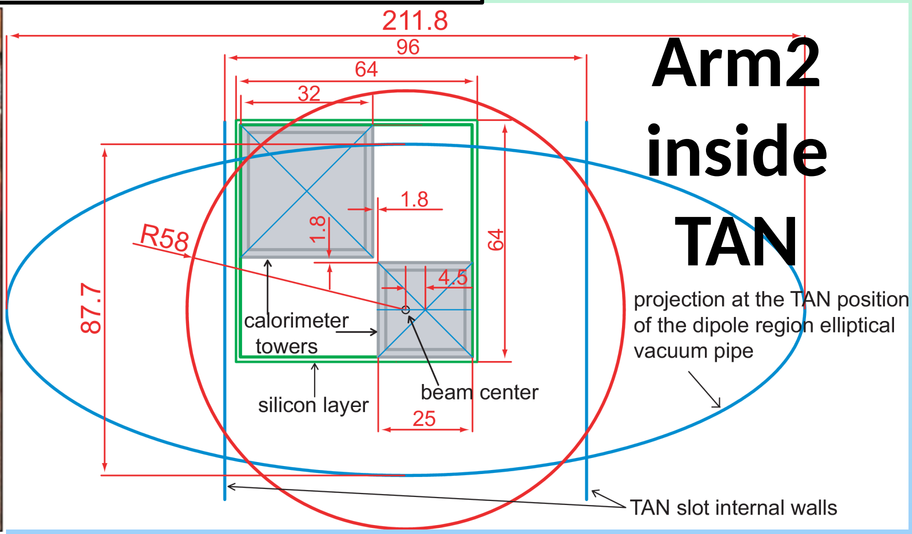
Detection of **neutral particles** having **pseudorapidity η > 8.4**




**Two detectors** installed in the **TAN regions** of IP1

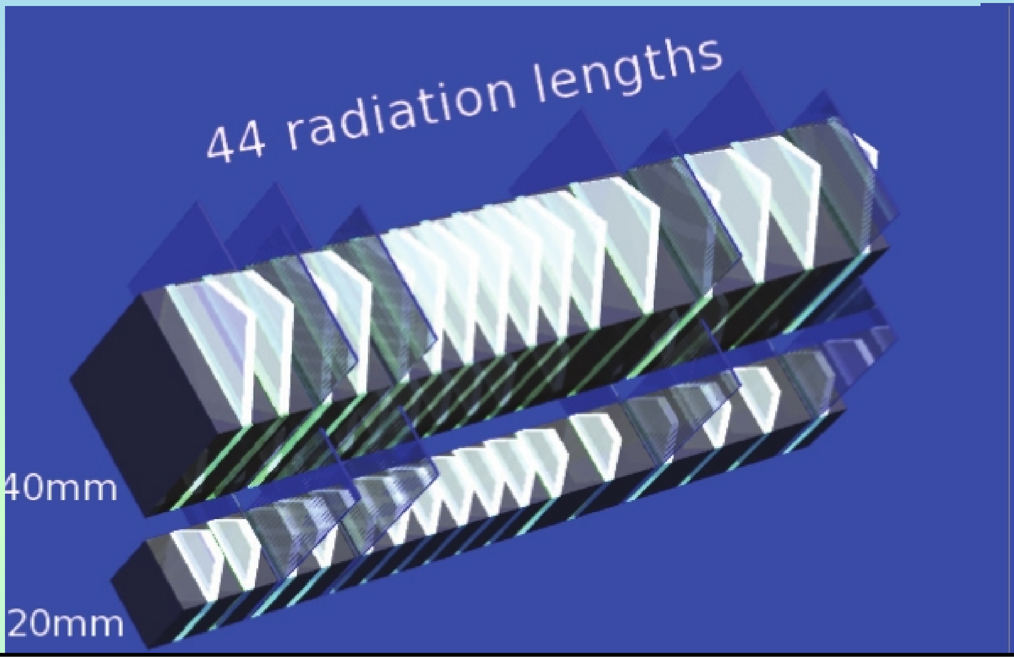


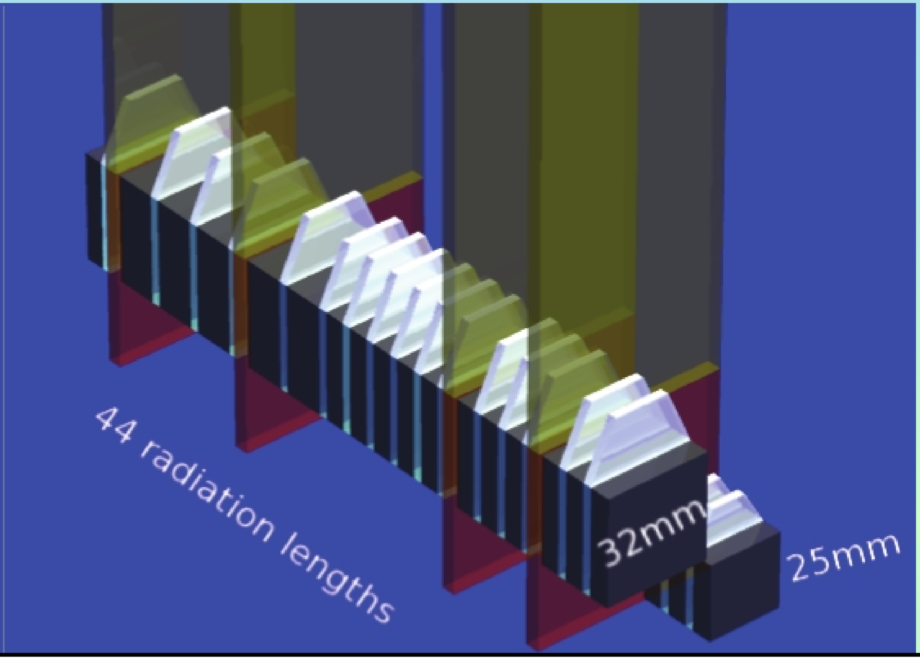



# LHCf detectors

**Arm1**




**Arm2**




**Two sampling calorimeters**

**Towers Size**:

20 x 20 and 40 x 40 mm$^2$

**Imaging layers:**

4 x-y SciFi

**Position resolution**:

< 200 μm (photons)

< 1 mm (hadrons)

**Two towers**: 22 tungsten and 16 scintillators layers

**Depth**: 21 cm, 44 $X_0$, 1.6 $\lambda_I$

**Energy resolution**:

< 2% (photons)

~ 40% (neutrons)

**Towers Size**:

25 x 25 and 32 x 32 mm$^2$

**Imaging layers:**

4 x-y silicon microstrip

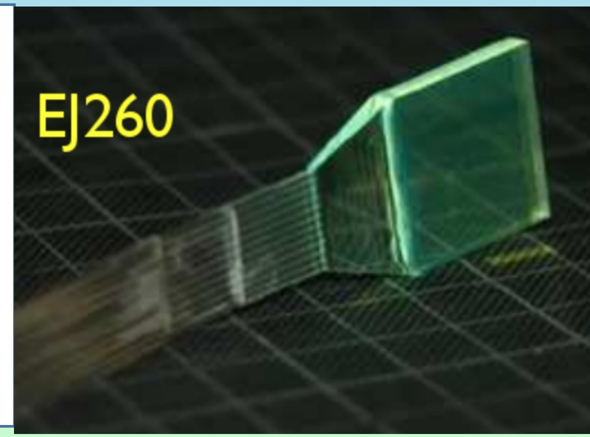
**Position resolution**:

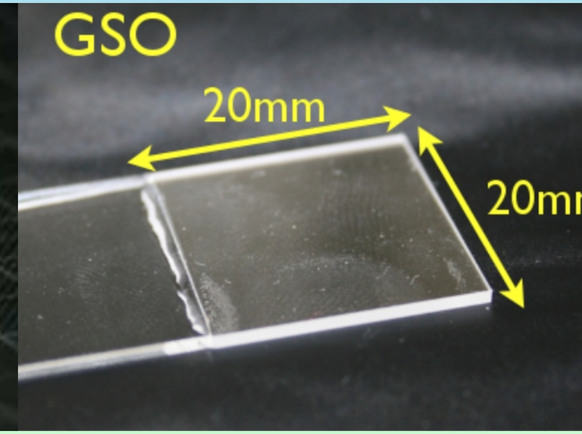
< 40 μm (photons)

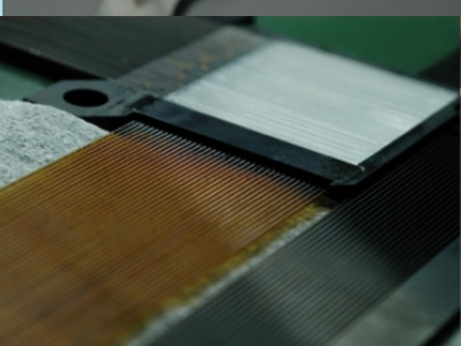
< 800 μm (hadrons)

# LHCf upgrade after Run I

**Arm1 and Arm2**
Replace **EJ-260** ($10^2$ Gy) with **GSO** ($10^6$ Gy) scintillators to improve radiation hardness (30 Gy/$nb^{-1}$ expected dose rate at $\sqrt{s}$ = 13 TeV)

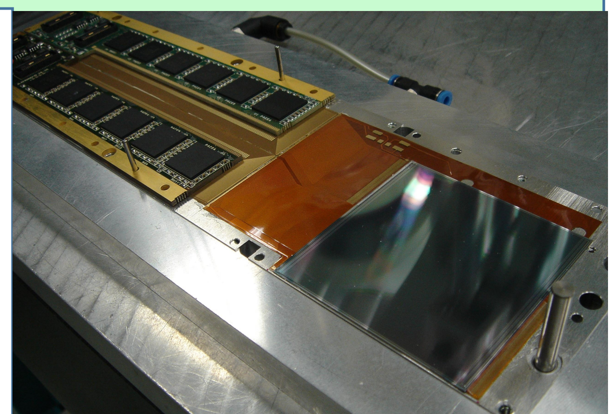


**Arm1**

Replace **SciFi** with **GSO bars hodoscope**

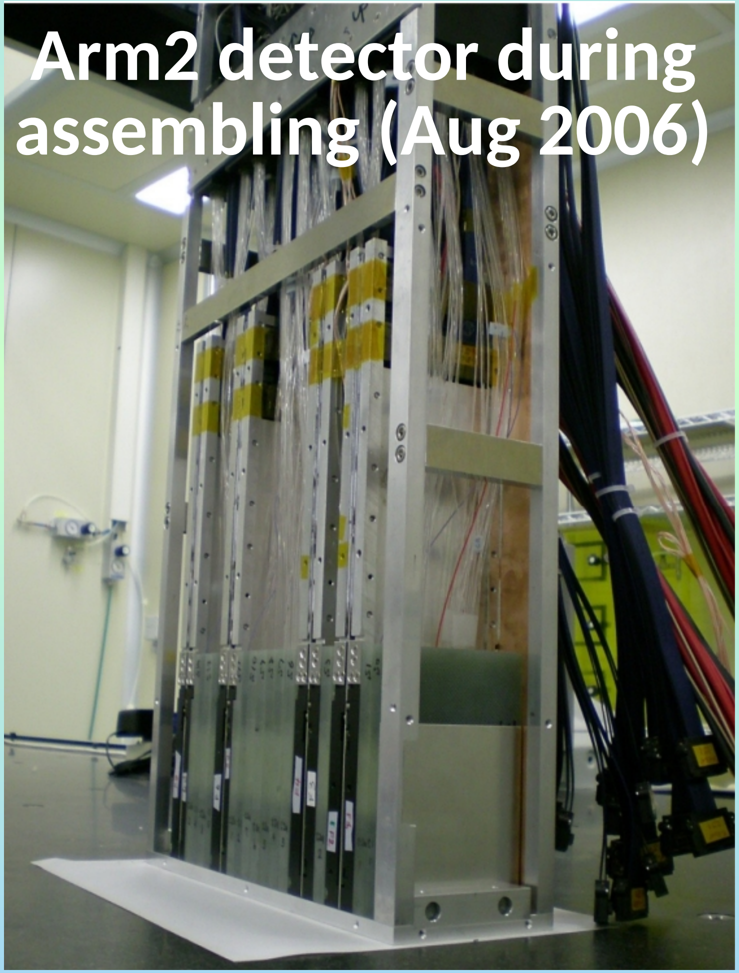


**Arm2**

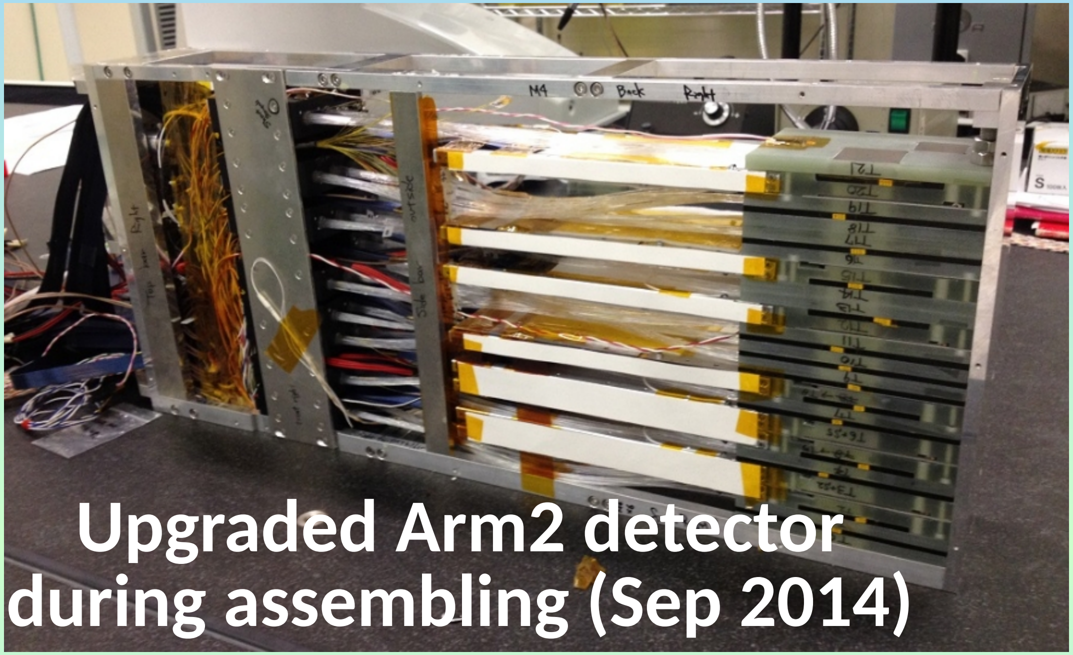
Optimize the silicon layers position for the **reconstruction of energy** in imaging layers

Modify the bonding of the silicon microstrip detectors to **improve the dynamic range**

# Arm2 detector



Arm2 detector during assembling (Aug 2006)



Upgraded Arm2 detector during assembling (Sep 2014)

Upgraded Arm2 detector installed (Nov 2014)

# Analysis results

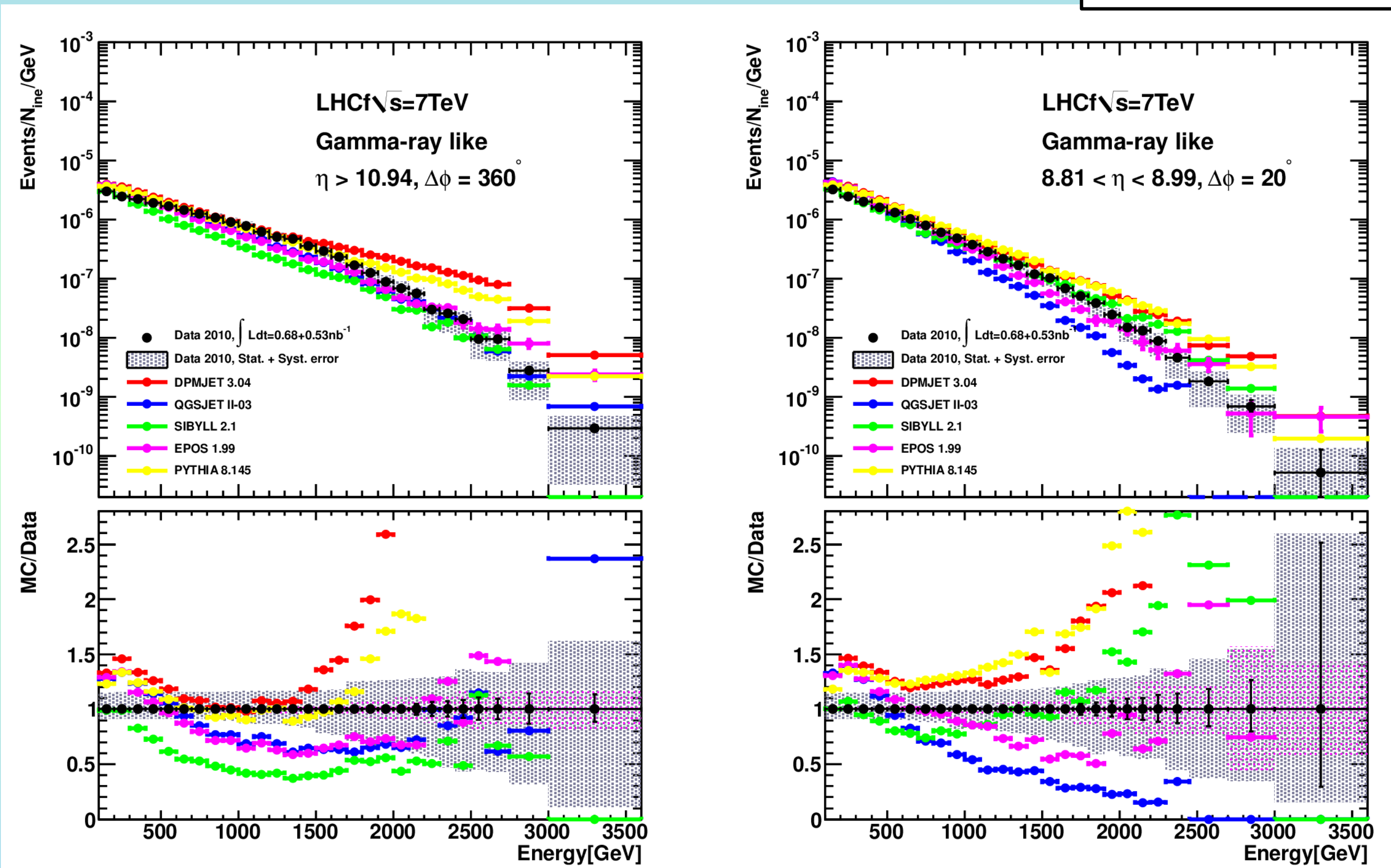
# Acquired data and published results

| | Proton equivalent energy in LAB (eV) | $\gamma$ | n | $\pi^0$ |
|---|---|---|---|---|
| SPS test beam | | NIM A, 671, 129 (2012) + submitted to JINST (upgrade) | JINST 9 P03016 (2014) | |
| p+p 900 GeV | $4.3 \times 10^{14}$ | Phys. Lett. B 715, 298 (2012) | | |
| p+p 7 TeV | $2.6 \times 10^{16}$ | Phys. Lett. B 703, 128 (2011) | Phys. Lett. B 750 (2015) 360-366 | Phys. Rev. D 86, 092001 (2012) + Phys. Rev. D 94 032007 (2016) |
| p+p 2.76 TeV | $4.1 \times 10^{15}$ | | | Phys. Rev. C 89, 065209 (2014) + Phys. Rev. D 94 032007 (2016) |
| p+Pb 5.02 TeV | $1.4 \times 10^{16}$ | | | |
| p+p 13 TeV | $9.0 \times 10^{16}$ | Analysis almost concluded, it will be submitted soon | Analysis ongoing | |
| p+Pb 8.16 TeV | $3.6 \times 10^{16}$ | Data taking completed in November 2016 | | |

# Photons energy spectra

## p-p √s = 7 TeV

PLB 715 (2012), 298-303




**DPMJET 3.04** and **PYTHIA 8.146** are in good agreement only in 0.5 TeV < E <1.5TeV for η>10.94

**QGSJET II-03**, **EPOS 1.99** and **SIBYLL 2.1** have similar shape but different yield

# Neutrons energy spectra

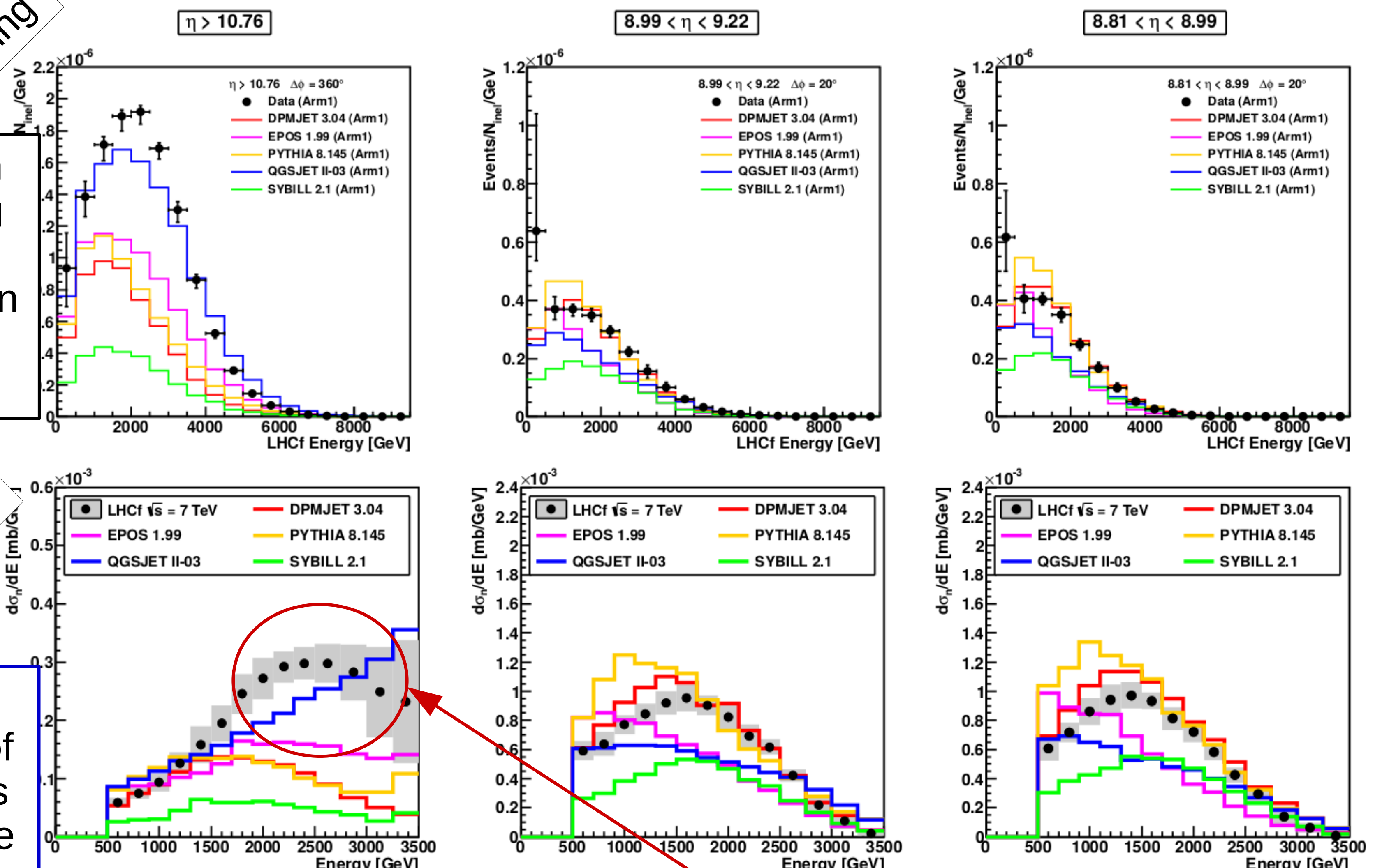
p-p $\sqrt{s}$ = 7 TeV

PLB 750 (2015), 360-366

Before unfolding

After unfolding

Being resolution ~40%, unfolding is needed to obtain information for models developers




**Motivation**

Measurements of forward neutrons spectra can solve the muon excess problem observed by ground-based CR experiments

**η > 10.76**

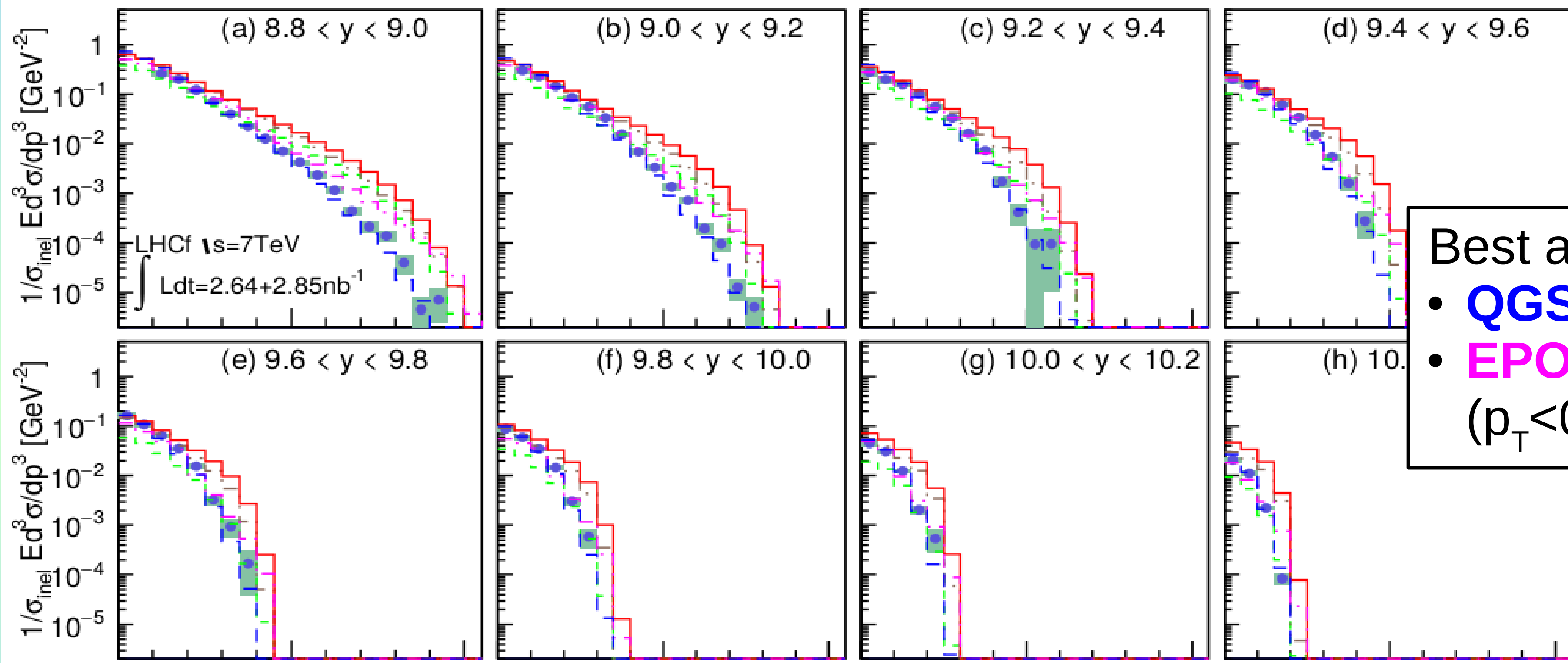
High production rate at high energies ⟶ Small inelasticity

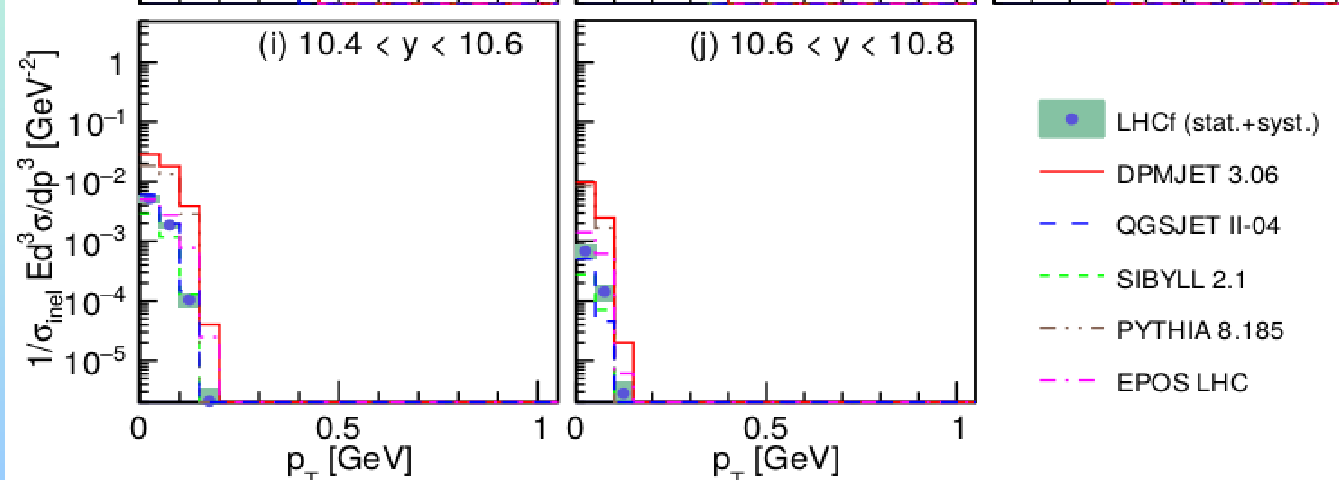
Shape qualitatively reproduced by **QGSJET II-03** only

# $\pi^0$ $p_T$ spectra for different rapidity

## p-p $\sqrt{s}$ = 7 TeV

PRD 64 (2016), 032007

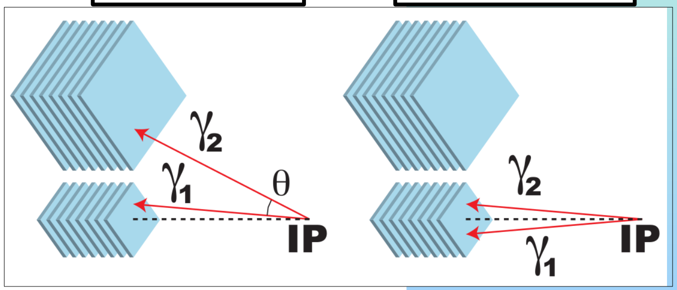



Best agreement:
- **QGSJet II-04**
- **EPOS-LHC**
  ($p_T$<0.5 GeV/c)

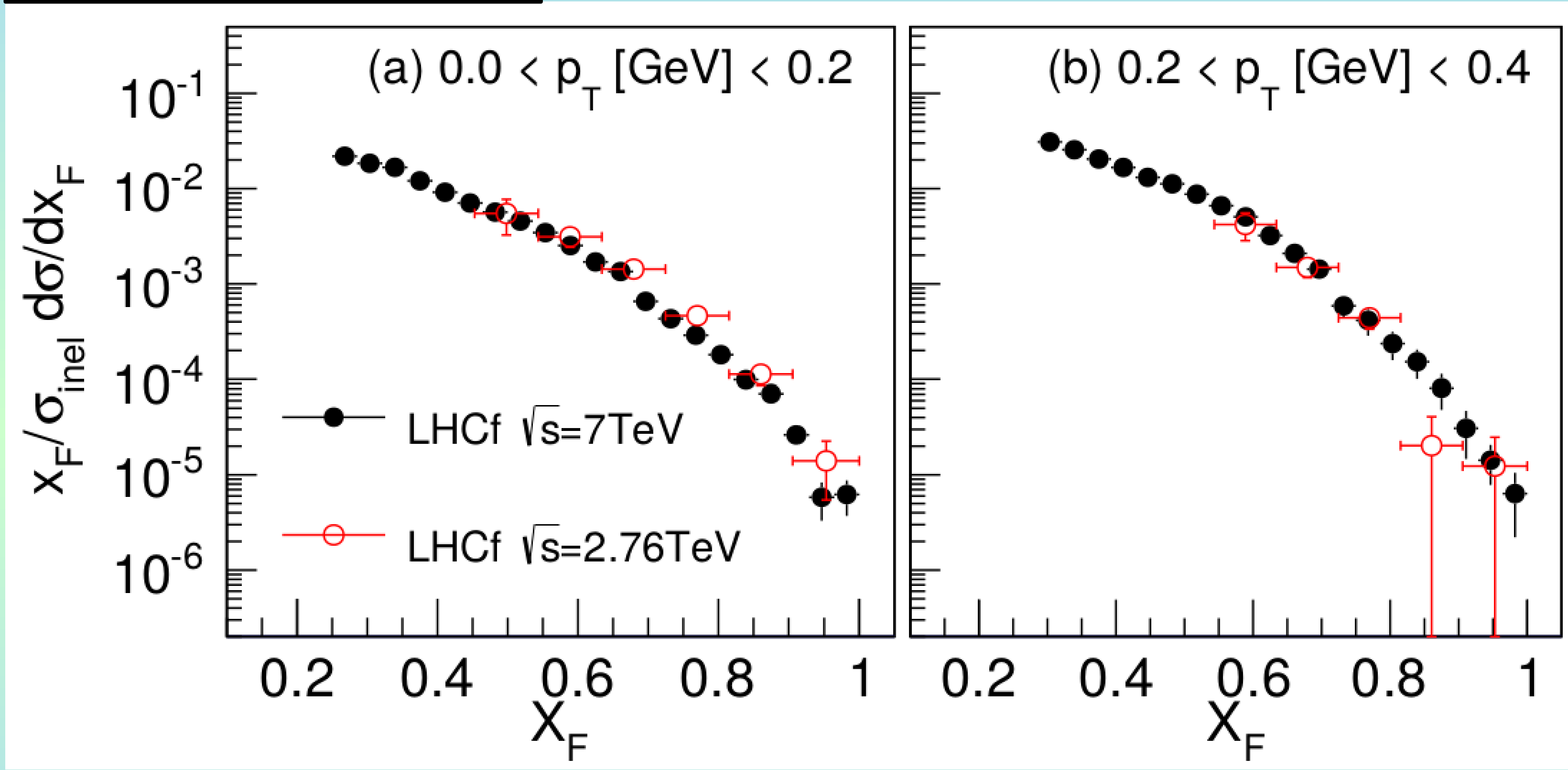
Type-I

Type-II



# Feynman scaling

PRD 64 (2016), 032007




**Feynman scaling** in the forward rapidity region inclusive production cross section expressed as a function of Feynman $x_F$ is independent from $\sqrt{s}$

$$x_F = 2p_Z/\sqrt{s}$$

**Validity tested by LHCf**

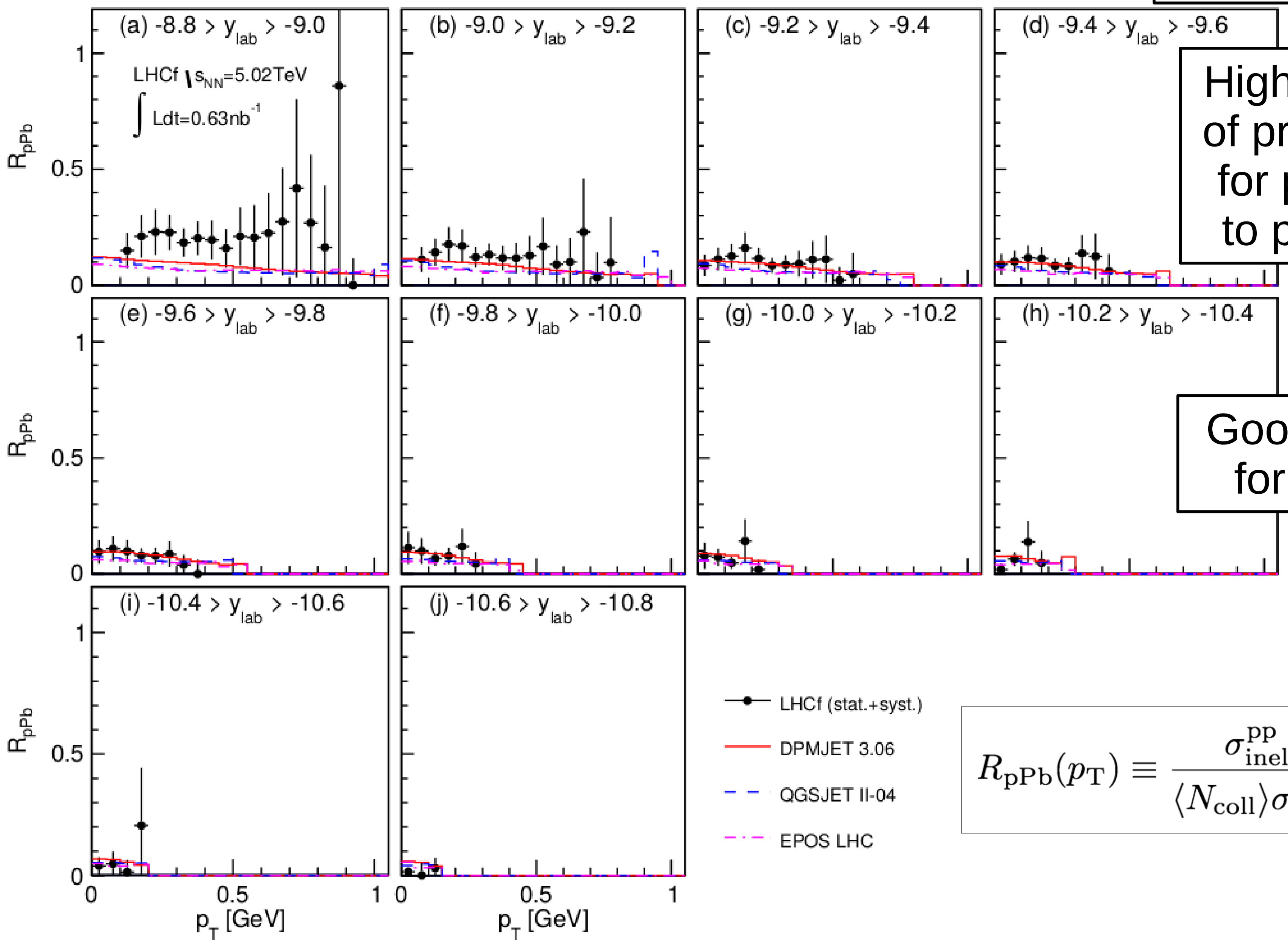
**$\langle p_T \rangle$ scaling** ±10%

**limiting fragmentation** ±15%

**Feynman scaling** ±20%

# Nuclear modification factor

PRD 64 (2016), 032007




High suppression of production rate for p-Pb respect to p-p collisions

Good agreement for all models

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

# Ongoing analyses

# Analysis of photon energy spectra

## p-p at √s = 13 TeV

**Data set**

- 12 July 22:32-1:30 (3 hours)
- Fill # 3855,  μ ~ 0.01
- $\int L dt = 0.19\ nb^{-1}$
- $\sigma_{ine} = 78.53$ mb

**Ongoing analysis**

Event Selection

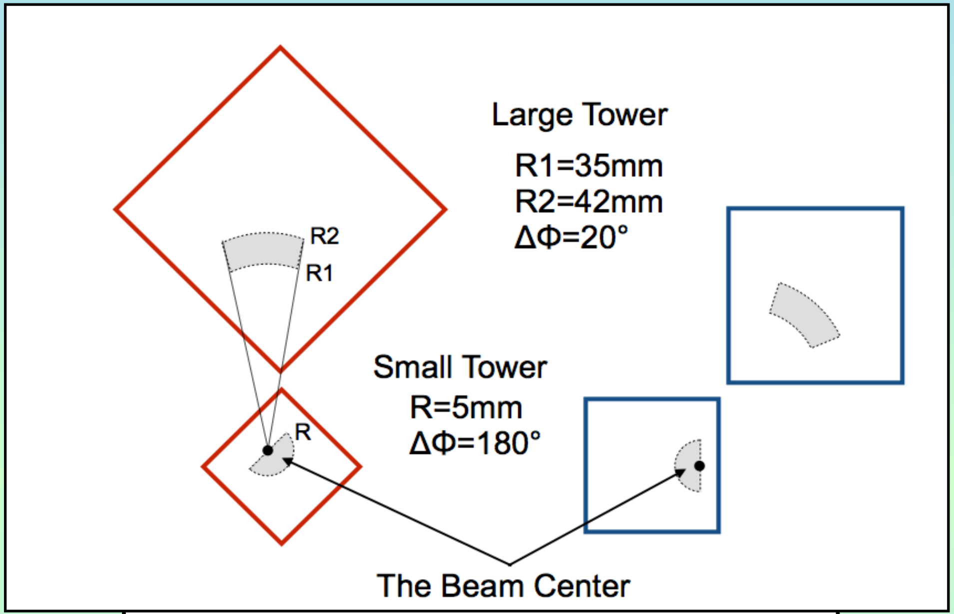
- Photon/hadron selection
- Multi-Hit event rejection

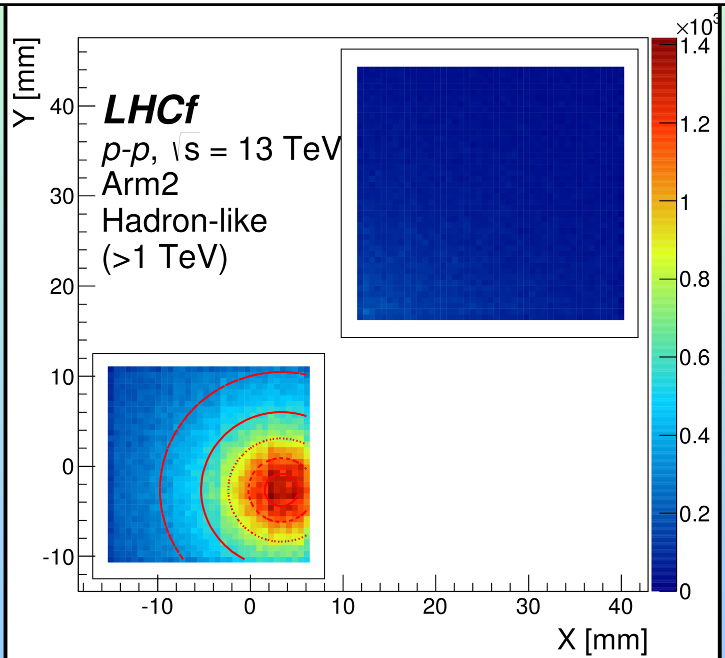
Corrections

- PID correction
- Multi-Hit correction

Unfolding

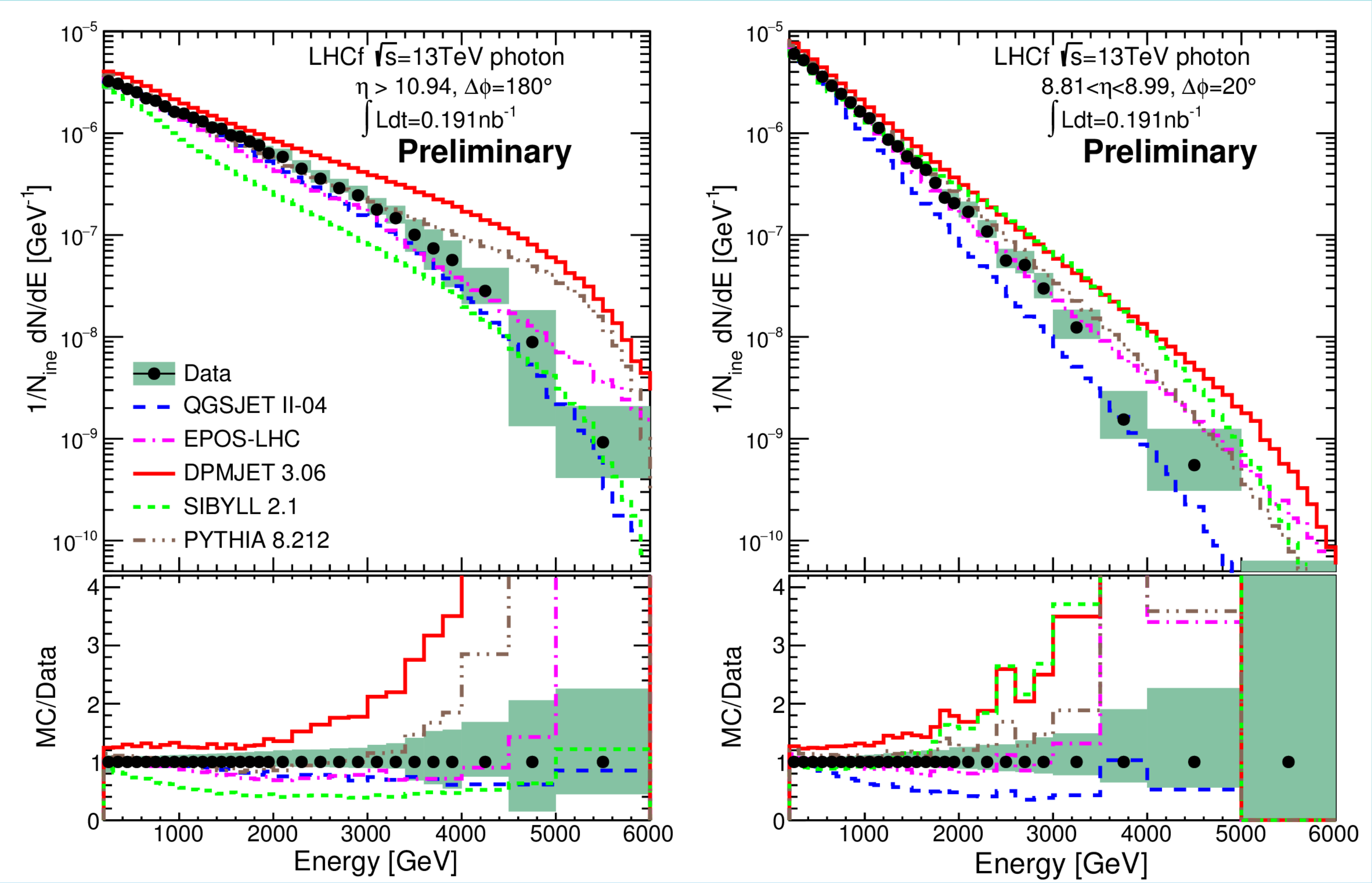
Combination of Arm1 and Arm2 spectra considering systematic



# Preliminary photons energy spectra

## p-p √s = 13 TeV



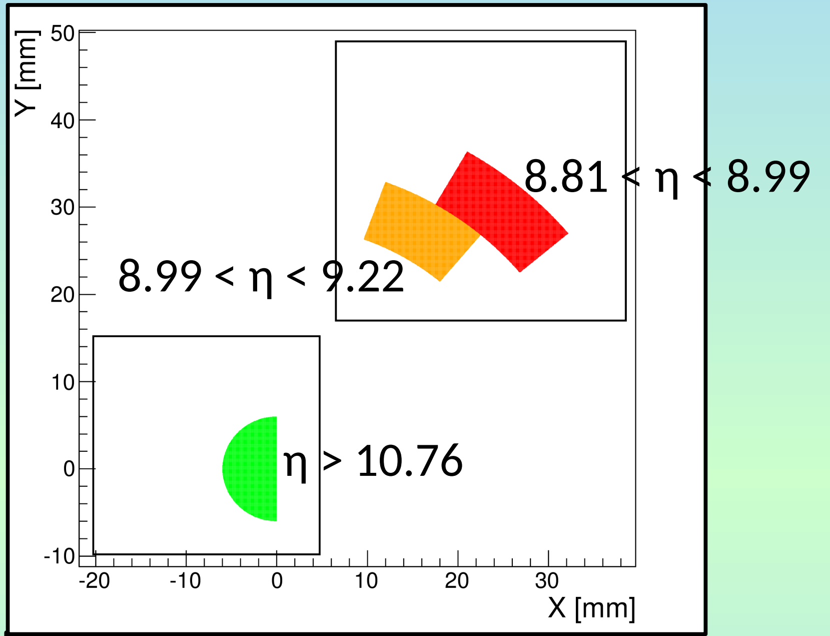

**QGSJET II-04** is in good agreement for η>10.94,
but leads to lower yield in the other case
**EPOS-LHC** is good below 3-5 TeV, otherwise harder

# Analysis of neutron energy spectra

## p-p at √s = 13 TeV

**Data set**

- 12 July 22:32-1:30 (3 hours)
- Fill # 3855, μ ~ 0.01
- $\int L dt = 0.19\ nb^{-1}$
- $\sigma_{ine} = 78.53$ mb




**Ongoing analysis (Arm2 only)**

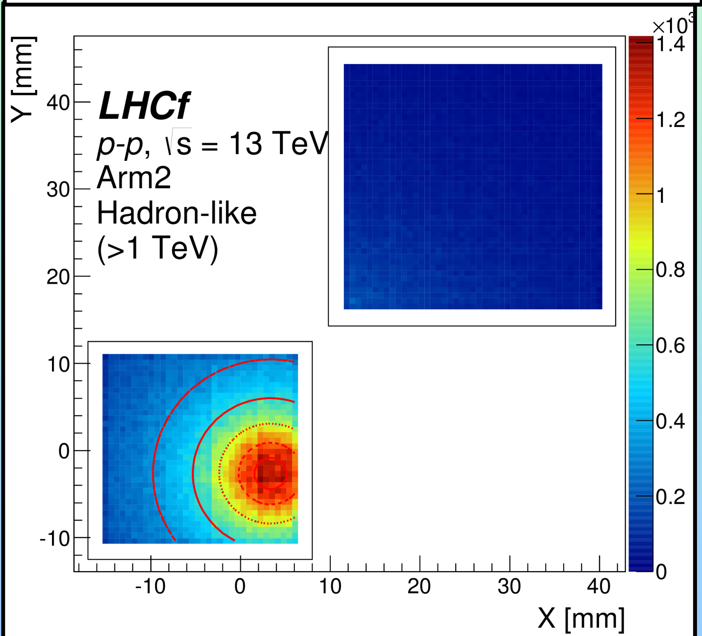
Event Selection

- Photon/hadron selection

Corrections

- PID correction
- Multi-Hit correction
- Detection efficiency correction

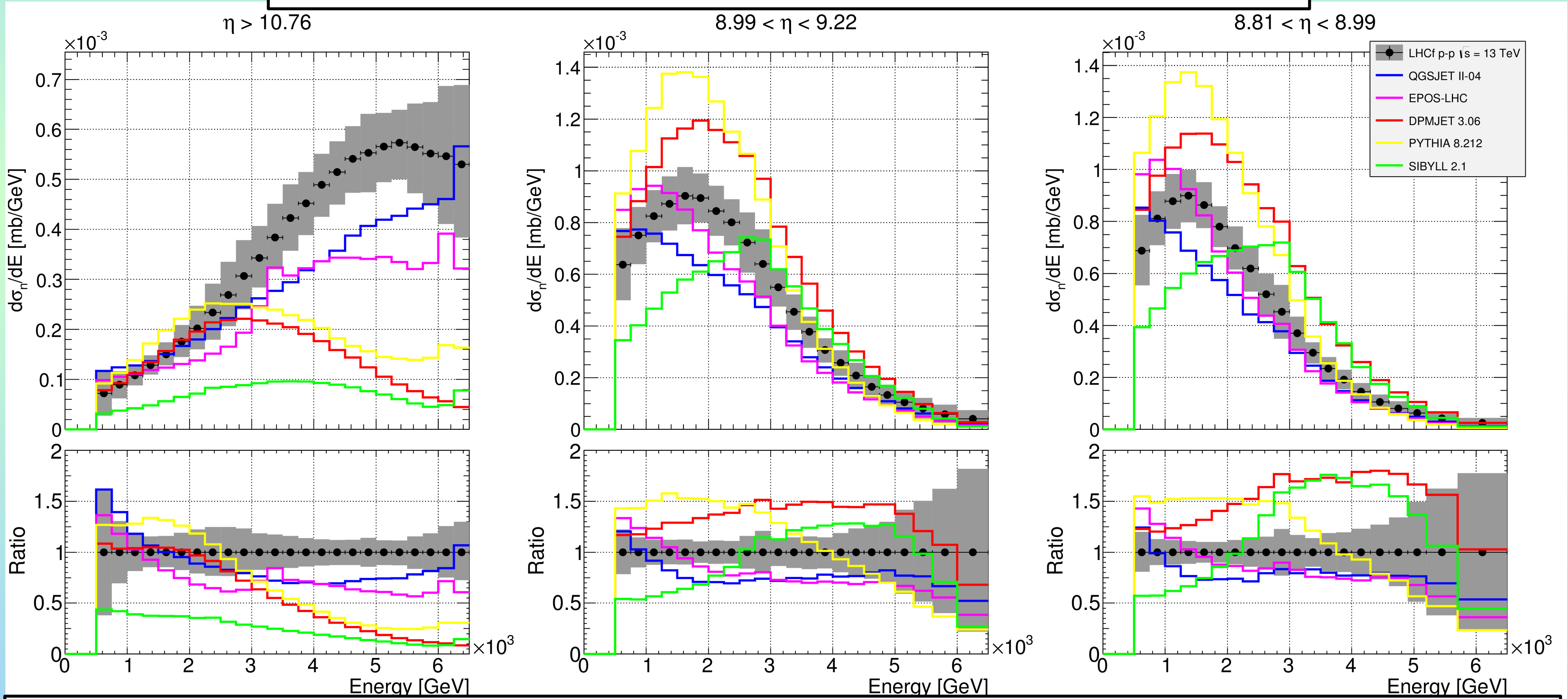
Unfolding



# Arm2 preliminary unfolded spectra

Differential neutron production cross section

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

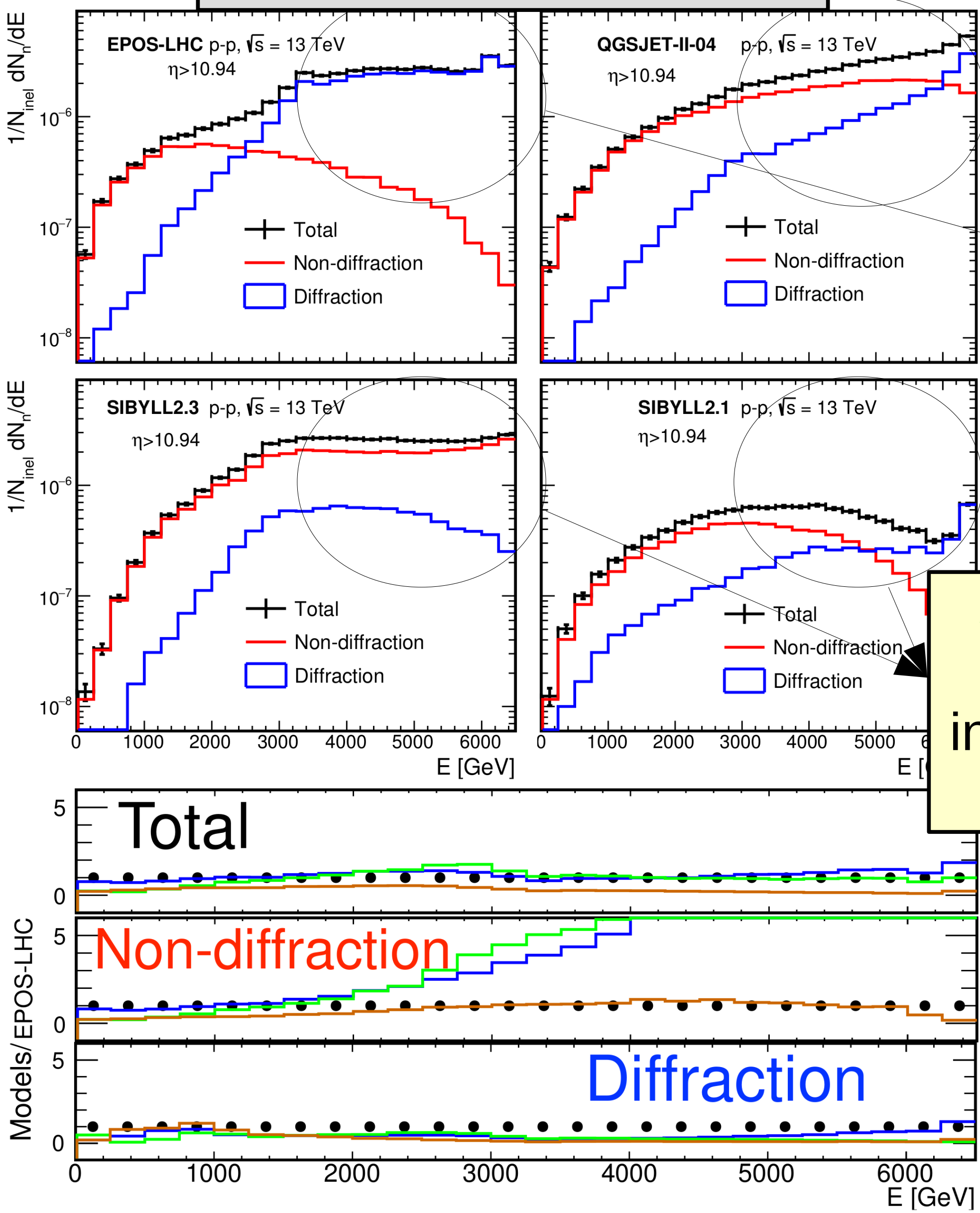



Only **QGSJET** qualitatively reproduces behavior of data in η > 10.76
**EPOS-LHC** has similar shape in 8.81 < η < 9.22, but lower yield

# ATLAS-LHCf common operations

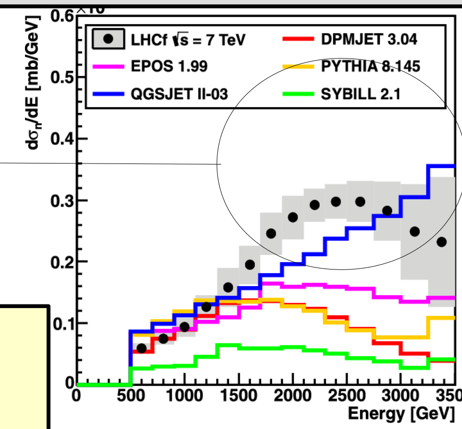
# Motivations

$\sqrt{s}$ = 13 TeV - η > 10.94




**Diffractive** and **non-diffractive** events are treated separately in hadronic interaction models

$\sqrt{s}$ = 7 TeV - η > 10.76



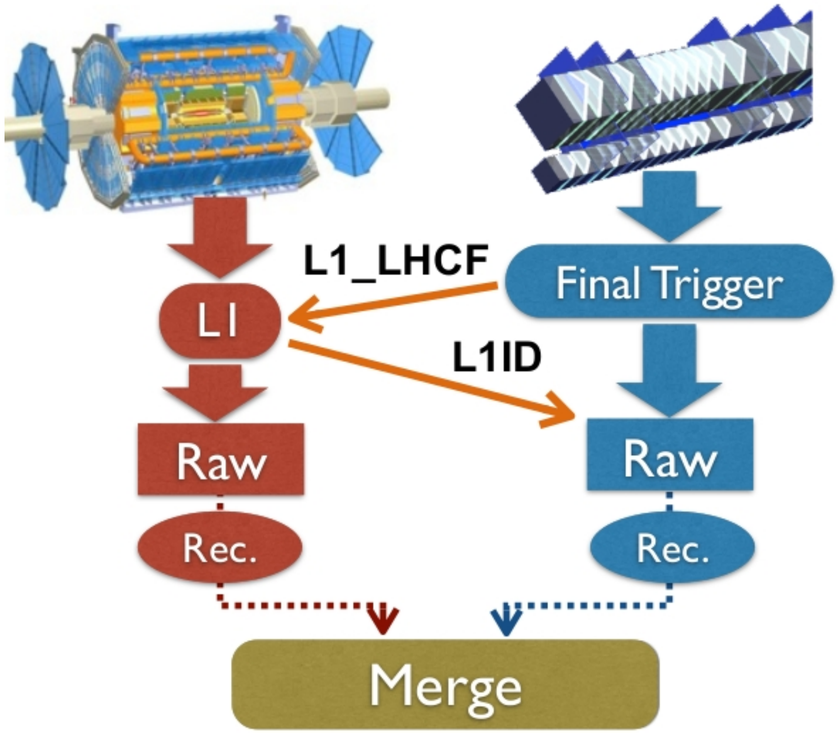

Is this difference dominated by diffractive or non-diffractive events?

**SIBYLL 2.3** was tuned on 7 TeV results increasing non-diffractive production

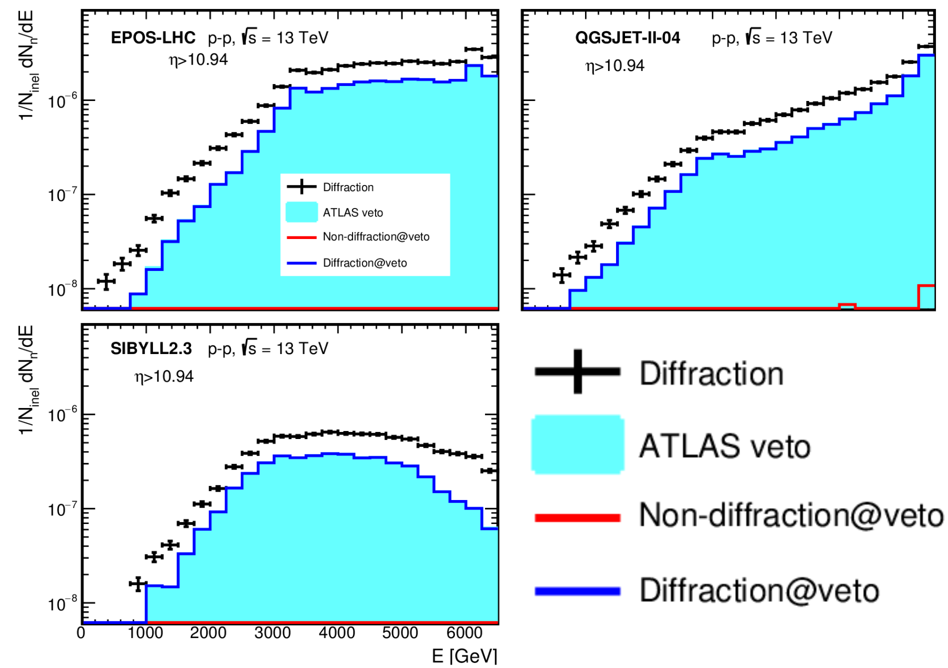
In order to improve hadronic interaction models we need to separate **diffractive** and **non-diffractive** events

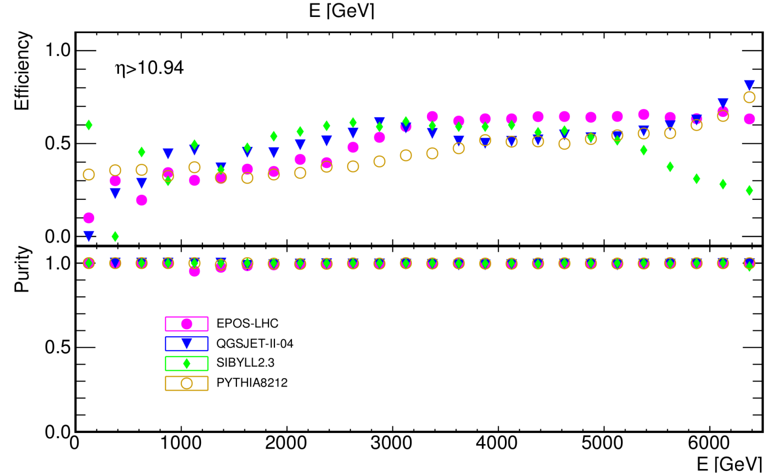
# LHCf-ATLAS common operations

After a preliminary test in 2013, in 2015 and 2016 LHCf and ATLAS had **common operations**.




Diffractive events can be indentified by **ATLAS veto** : tracks=0 at |η|<2.5




Diffractive event identification :

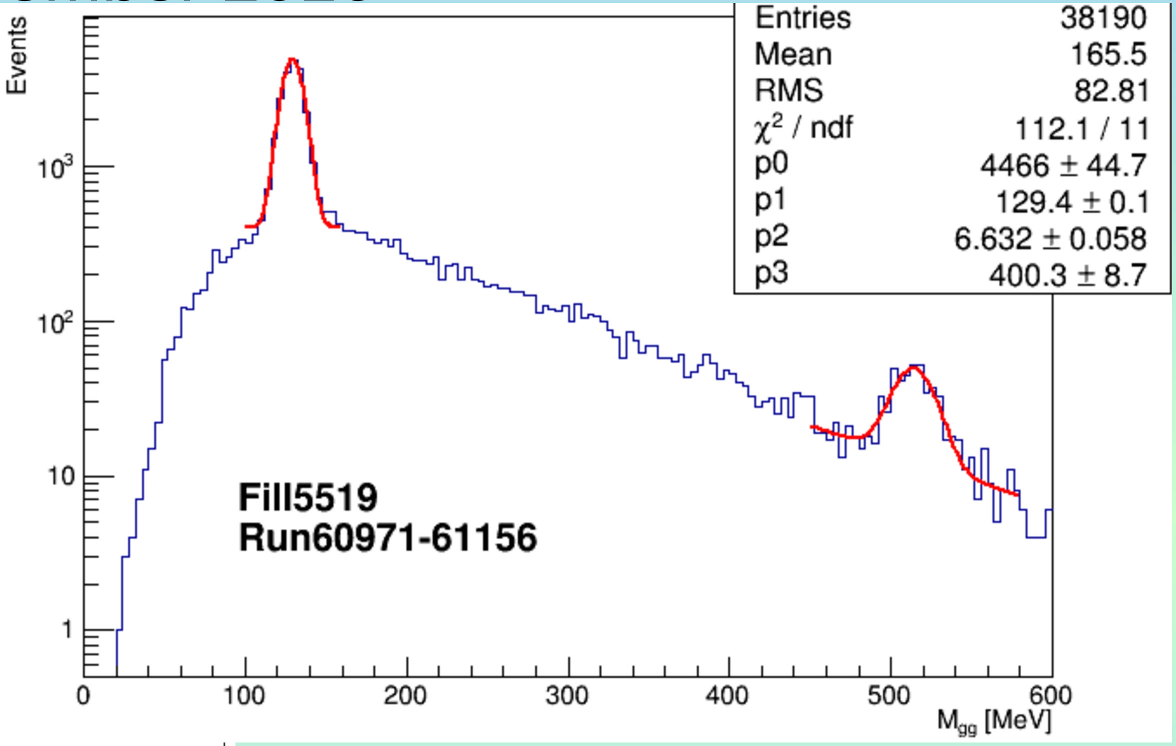
- efficiency about 50%
- purity almost 100%

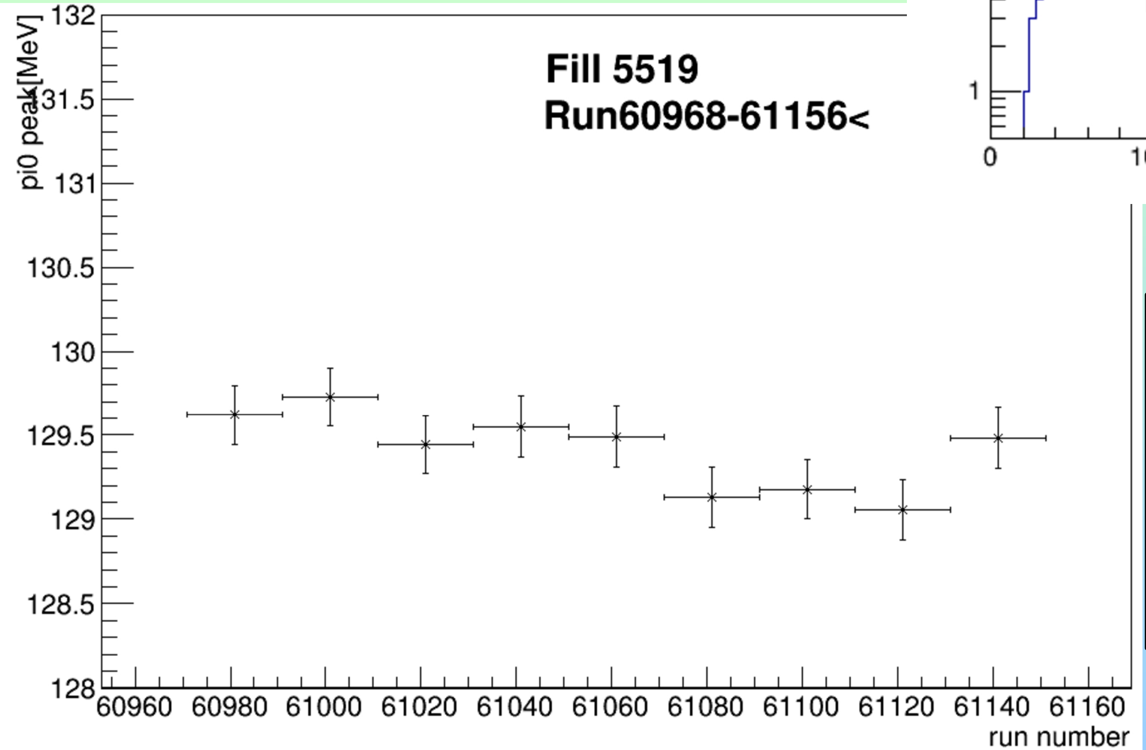
# Latest LHCf operations

November 2016

p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

- ATLAS-LHCf events : 25 M
  - of which $\pi^0$ trigger : 0.5 M




p-Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV

- ATLAS-LHCf events : 16.73 M
  - of which $\pi^0$ trigger : 1.0 M

# Summary

So fat results published by LHCf are relative to **photons, $\pi^0$s** and **neutrons:**

- in all cases **no model perfectly reproduces LHCf data**
- scaling laws tested hold at a 20% level in the worst case
- strong suppression in production spectra was found in case of p-Pb

In the last two years LHCf acquired data from:

- p-p collisions at $\sqrt{s}$ = 13 TeV
- p-Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV

Analysis of  p-p collisions at $\sqrt{s}$ = 13 TeV is ongoing:

- **photon energy spectra** (analysis almost finished)
- neutron energy spectra
- LHCf - ATLAS joint analysis has just started