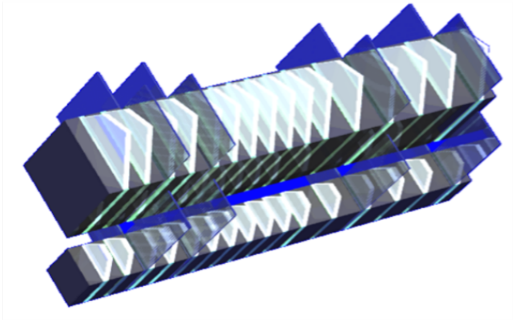
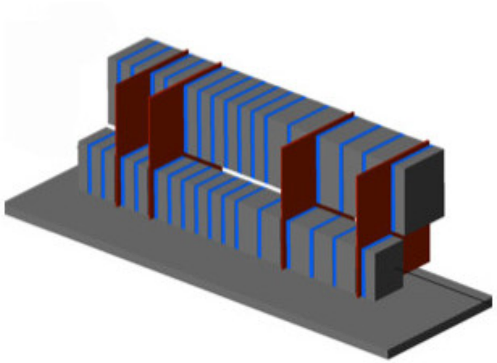




LHCf experiment: forward physics at LHC for cosmic rays study

Marina Del Prete (University and INFN of Florence)
on behalf of the LHCf collaboration

International Conference on New Frontiers in Physics
23 August 2015 – 30 August 2015 Kolymbari (Crete)

OUTLINE

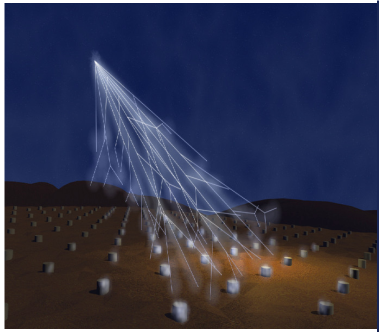
- Physics motivations of LHCf
- Experimental setup
- Latest analysis:
  - neutron energy spectra in 7 TeV p-p collisions
  - π^0 P_T spectra in 5.02 TeV p-Pb collisions
  - Feynman Scaling
  - LPM Effect
- Run 13 TeV 2015
- Conclusion and Future plan

High Energy Cosmic Rays

High energies -> low flux and indirect measurements

Extensive air shower observation:

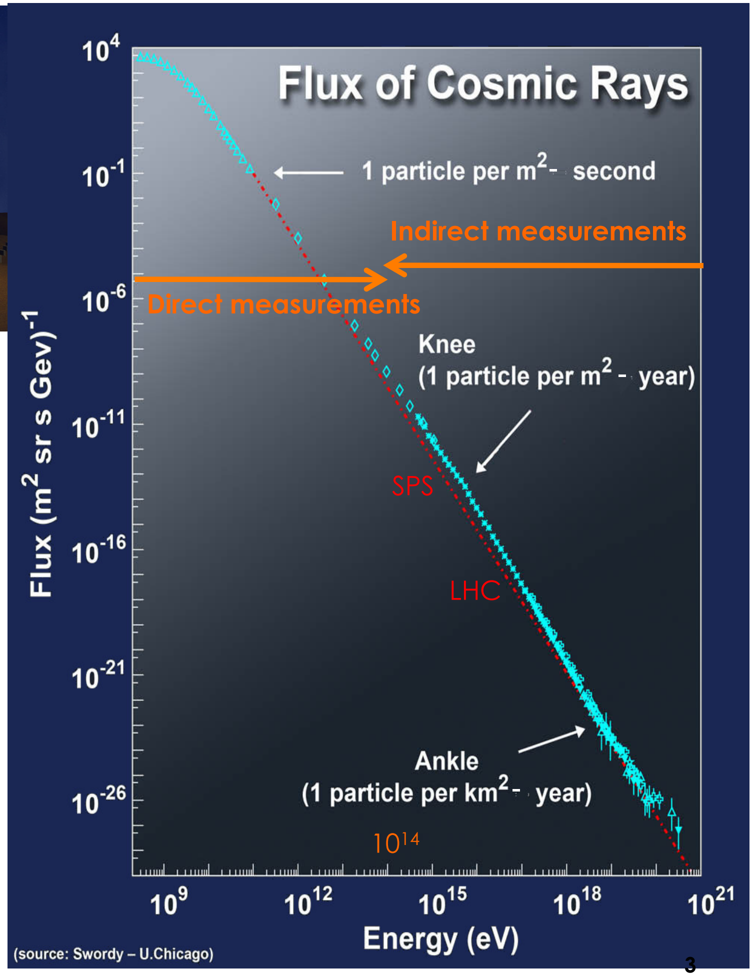
- Longitudinal distribution
- Lateral distribution
- Arrival direction



Astrophysical parameters:

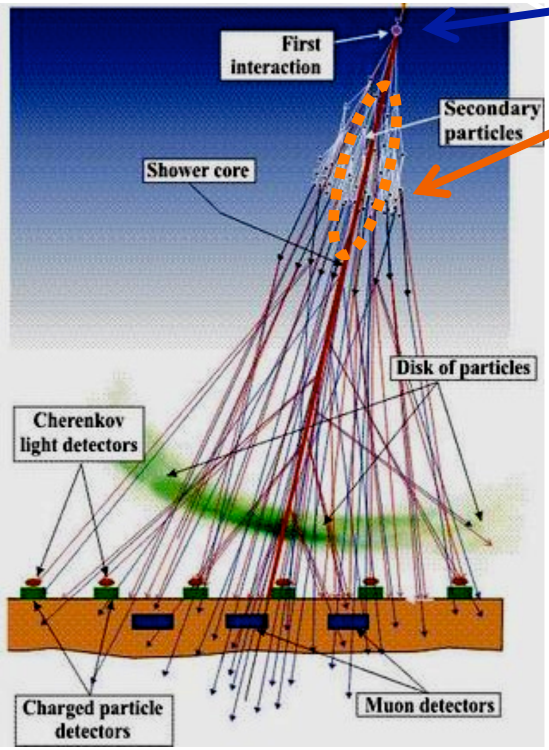
- Spectrum
- Composition
- Source distribution

Uncertainty of hadron interaction models
-> uncertainty of results interpretation



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

The role of the accelerators experiments



Inelastic cross section by Totem

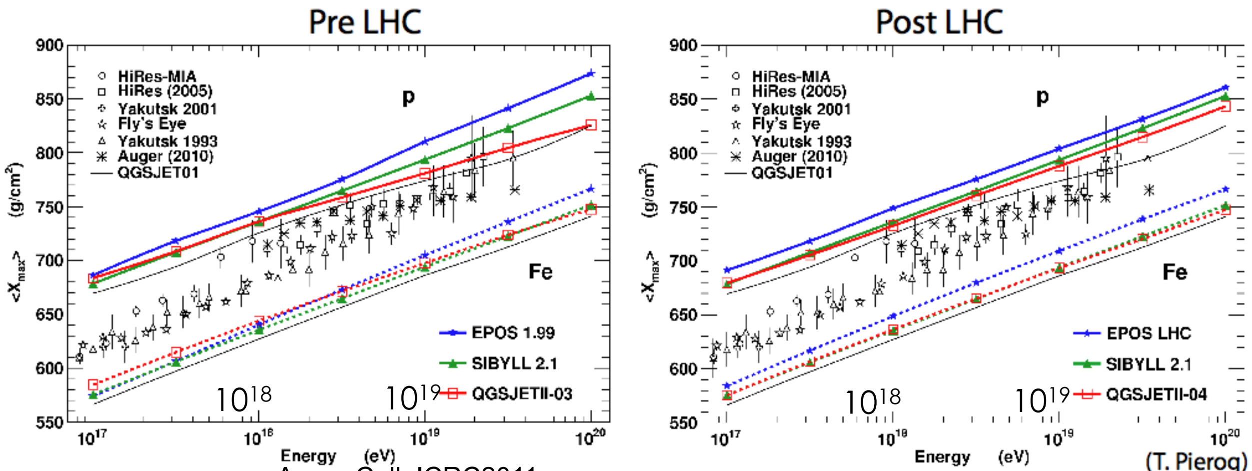
Forward energy spectrum
- if softer shallow development
- If harder deep penetrating

Inelasticity $k = 1 - E_{lead.} / E_{beam}$
- If large k (π^0s take more energy) -> rapid development
- If small k (baryons take more energy) -> deep penetrating

by LHCf studing
neutrons
photons
π^0

Nuclear effects by LHCf: study of p-Pb collisions

X_{MAX} is depth of air shower maximum in atmosphere -> depends on **energy** and **type** of primary particle

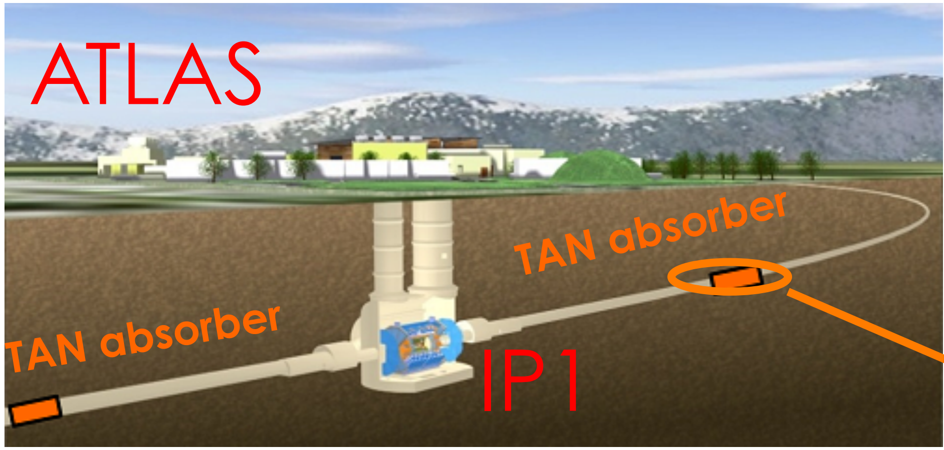


Auger Coll. ICRC2011

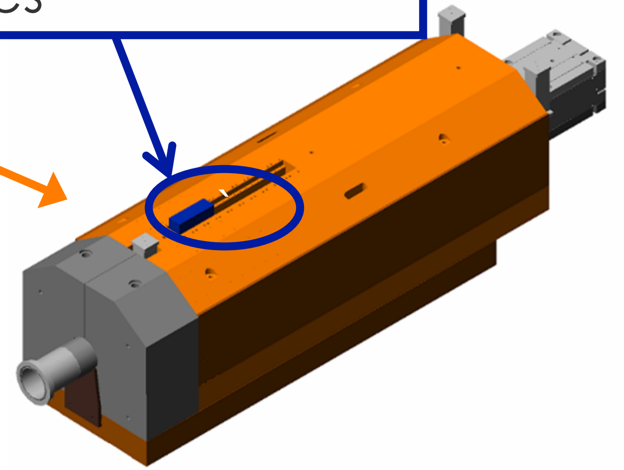
(T. Pierog)

LHCf: experimental setup

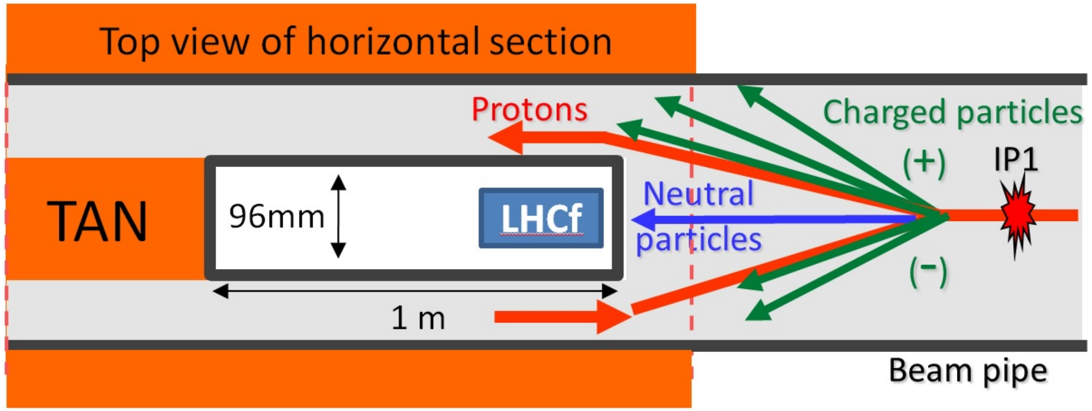
LHCf has the aim to understand the hadronic interactions in the collisions between high-energy CR and earth atmosphere



LHCf detectors are located inside the TAN absorbers for neutral particles

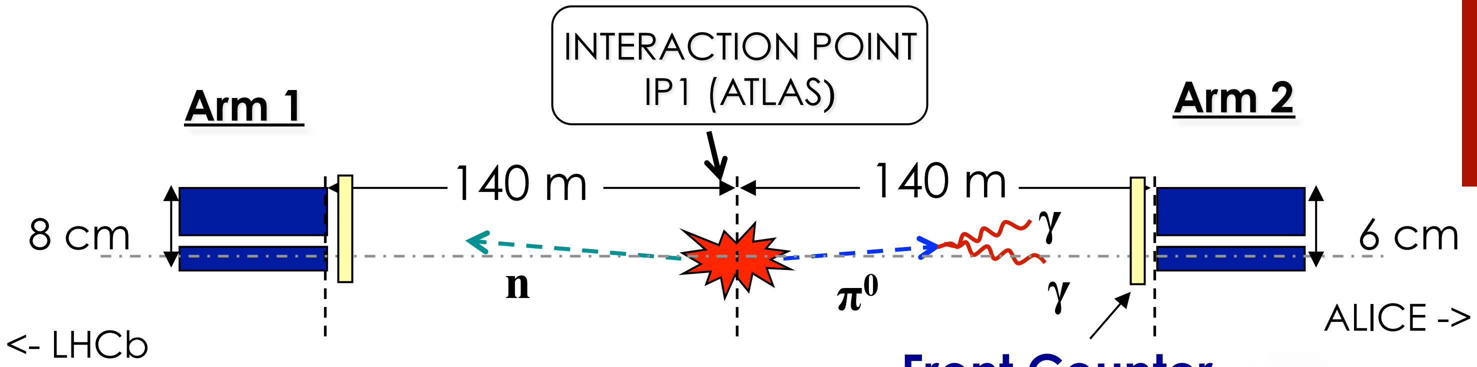


Charged particles are deviated by D1 dipole magnets

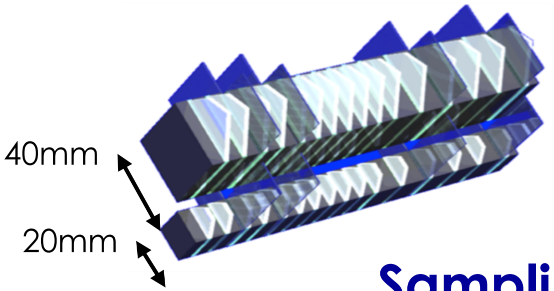


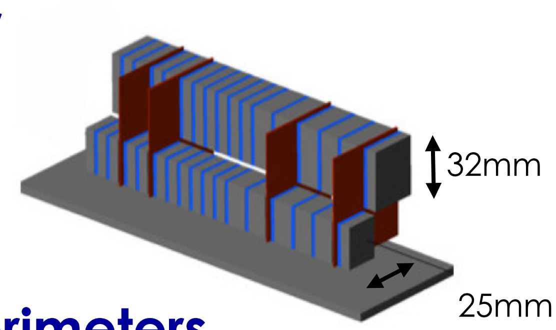
The LHCf detectors measure energy and impact point of γ and n

LHCf: experimental setup



Front Counter
thin scintillators 80x80 mm
monitoring beam condition
rejecting background





Sampling and imaging E.M. calorimeters

Absorber: 16 W layers (44 r.l., 1.55λ_I in total)
Energy measurement: plastic scintillator tiles ->
Resolution (>100 GeV) < 5% for γ and ~ (35 ÷ 40)% for n
4 tracking layers: XY-SciFi(Arm1) -> Position resolution < 200μm
XY-Silicon μ-strip(Arm2) -> Position resolution ~ 40μm
Detectors has two independent calorimeter towers → **reconstruction of the mass of $\gamma\gamma$ system**

LHCf collaboration

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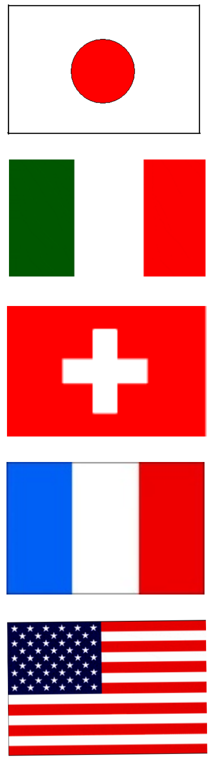
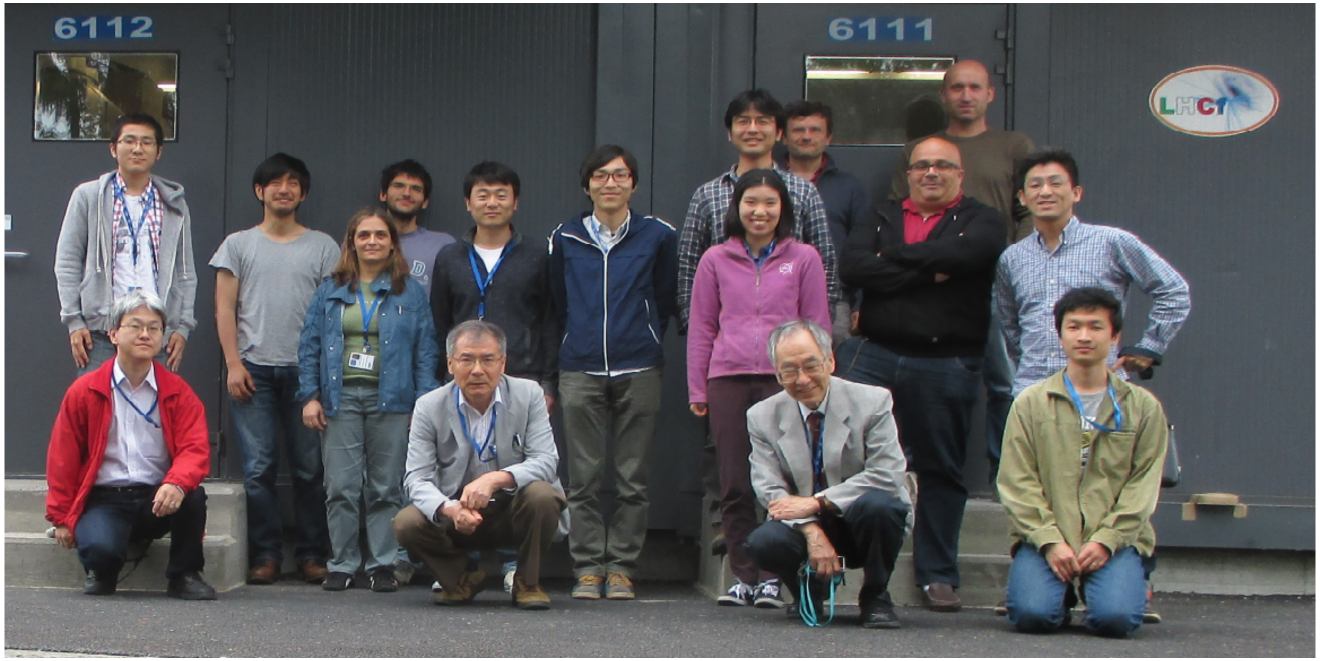
j) Kanagawa University, Japan
k) University of Catania, Italy
l) INFN Section of Catania, Italy
m) LBNL, Berkeley, California, USA
n) Shibaura Institute of Technology, Japan



LHCf collaboration at CERN

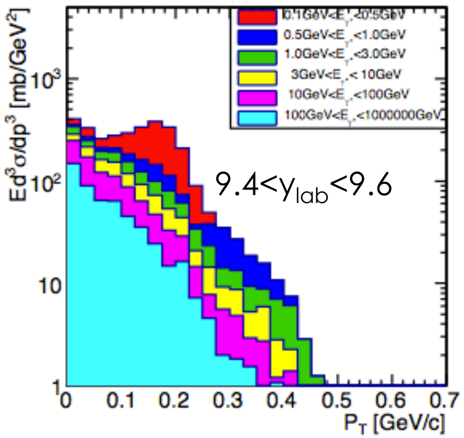


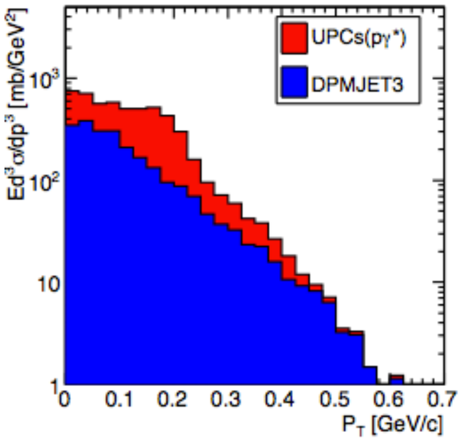
- In front of LHCf control room at IP1 in June 2015

- In LHCf control room at IP1 in June 2015 … meeting and shift for special Run p-p 13 TeV

π^0 analysis in p-Pb collisions at 5.02 TeV (1.3x10[16] eV proton hitting the atmosphere)

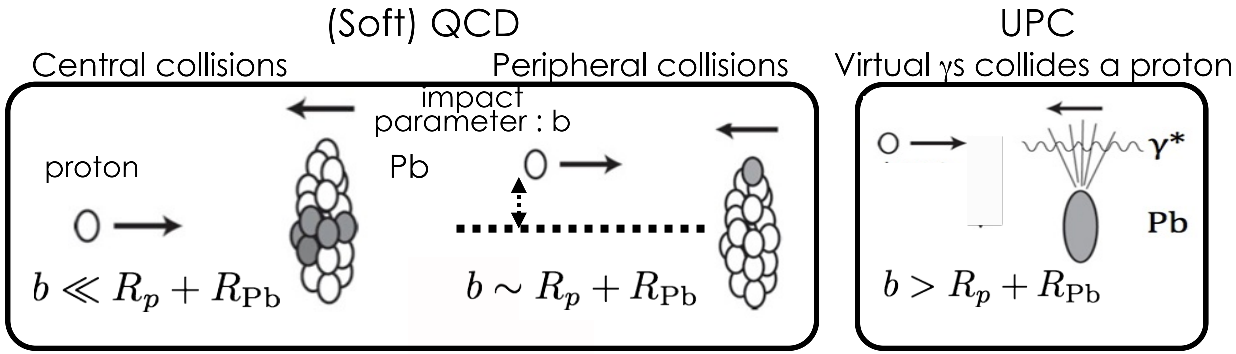
- Only Arm2 installed (better position resolution than Arm1)
- Data both at p-side (20Jan-1Feb) and Pb-side (1fill, 4Feb), thanks to the swap of the beams





Dominant channel for forward π^0 production:

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



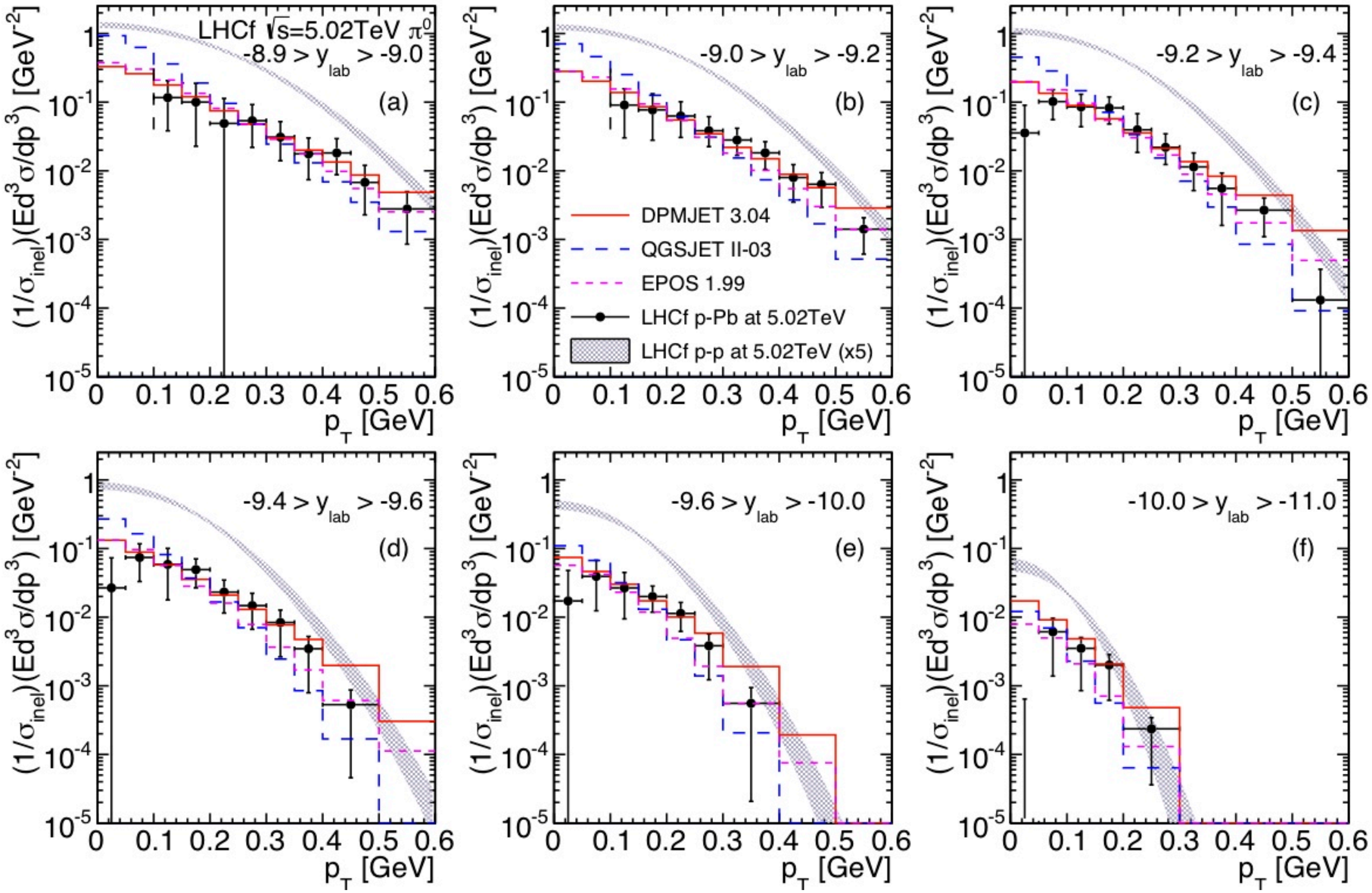
UPC contribution to P_T spectra is estimated from MC simulations (using Weizsacker Williams approximation for γ^* spectrum and SOPHIA model for p-γ^* collisions)

About half of the observed π^0s originate from UPC

Need to subtract UPC component

π^0 analysis in p-Pb collisions at 5.02 TeV and p-p collisions at 2.76 and 7 TeV

(4.1x10[15] and 2.6x10[16] eV proton hitting the atmosphere)



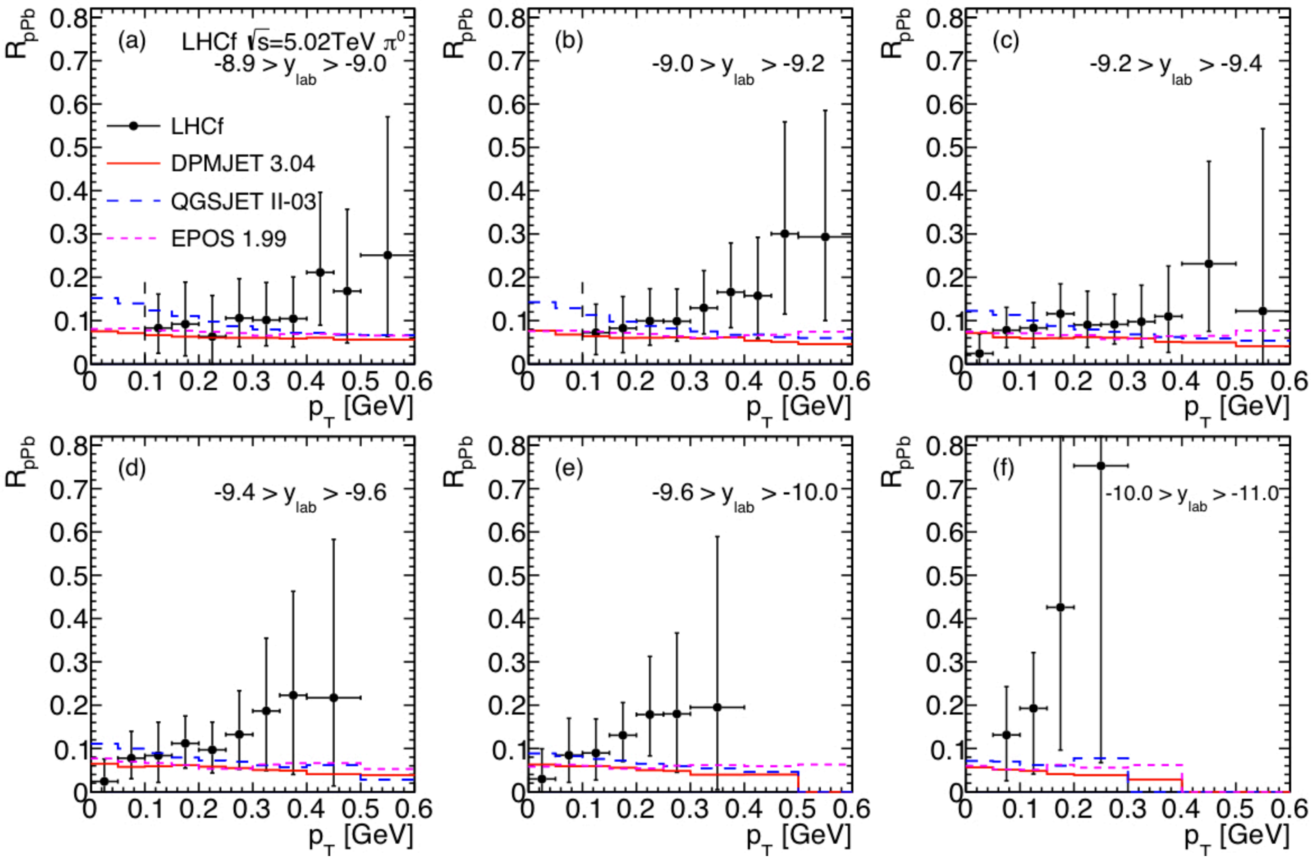
- The p-p 5.02 TeV LHCf data are obtained from the results of run:
  - 2.76 TeV (2013)
  - 7 TeV (2010).
- The spectra of p-p 5.02 TeV are multiplied by 5

Phys. Rev. C 89, 065209 (2014)

- **p-Pb Data (filled circles) are in good agreement with DPMJET and EPOS**
- **p-Pb spectra are harder than p-p spectra.**

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

Nuclear Modification Factor for π^0 production



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

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

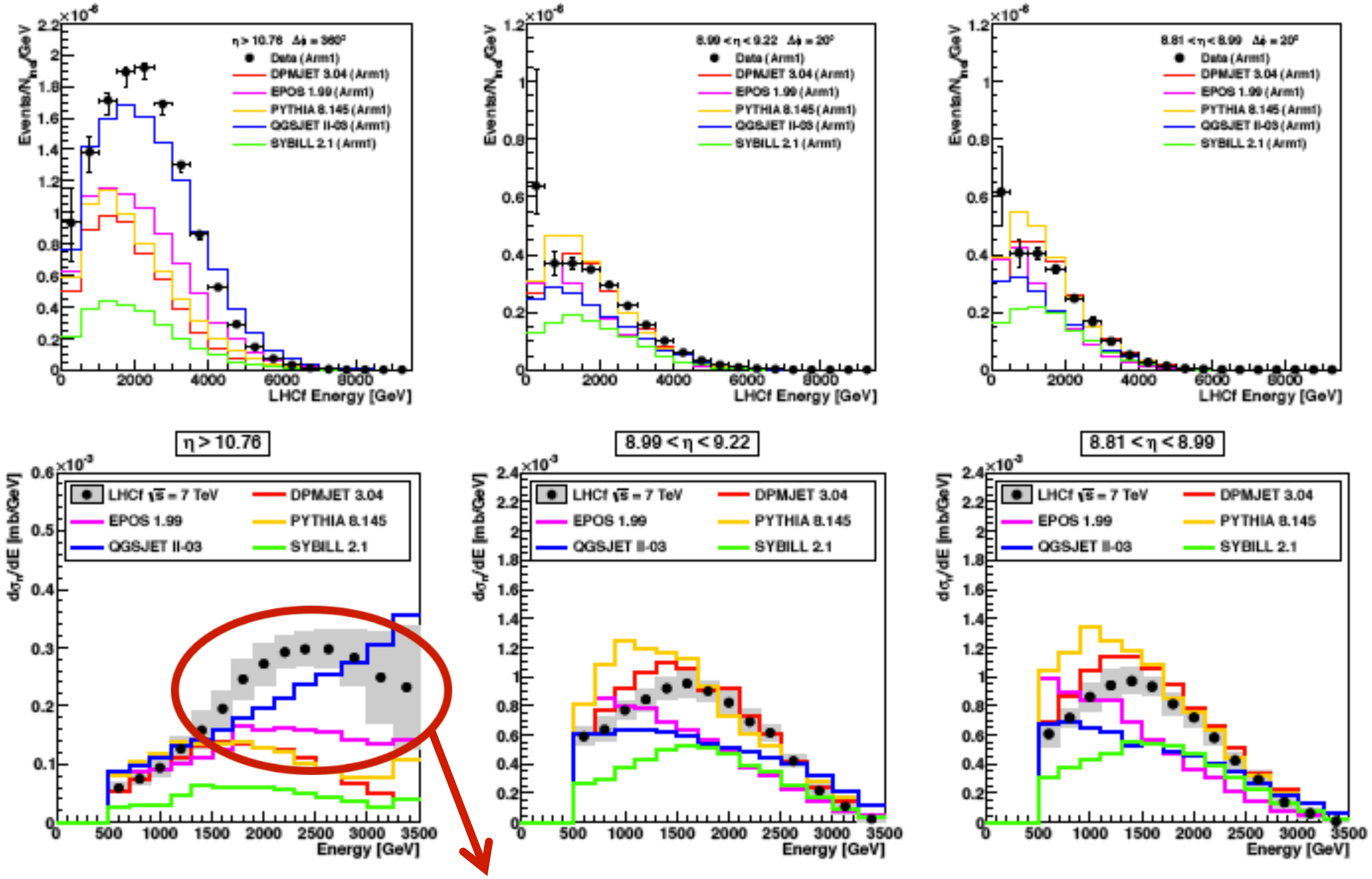
Large y_{lab} -> large experimental uncertainty.

Better results with ATLAS combined analysis: ATLAS does not detect the diffractive events

- **Data and MC shows strong suppression**
- **NMF grows with PT as expected (p-Pb spectra are harder than p-p spectra)**

Neutrons analysis in p-p collisions at 7 TeV

(2.6x10^{16} eV proton hitting the atmosphere)



Events vs Energy Before Unfolding

Cross Section vs Energy After Unfolding

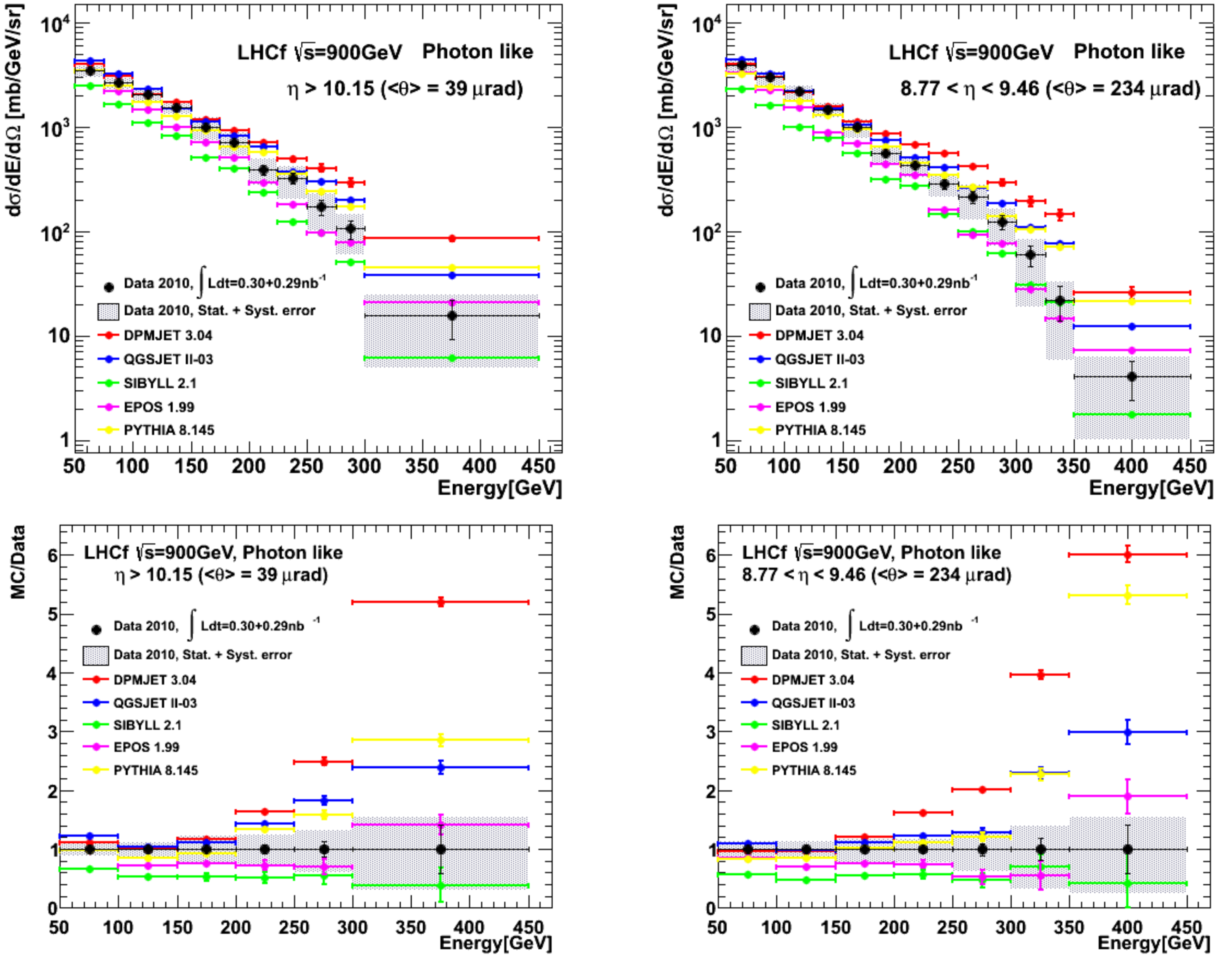
Large amount of high energy neutrons for η > 10.76 (only predicted by QGSJET) -> small inelasticity in the very forward region

JINST 9 P03016 (2014), hep-ex:1503.03505

LHCf: p-p run 0.9 and 7 TeV

Photons spectra in p-p at **900 GeV**

(4.3×10^{14} eV proton hitting the atmosphere)



- **DPMJET** - **SYBILL** show reasonable agreement of shape
- None of the models reproduces the data within the error bars

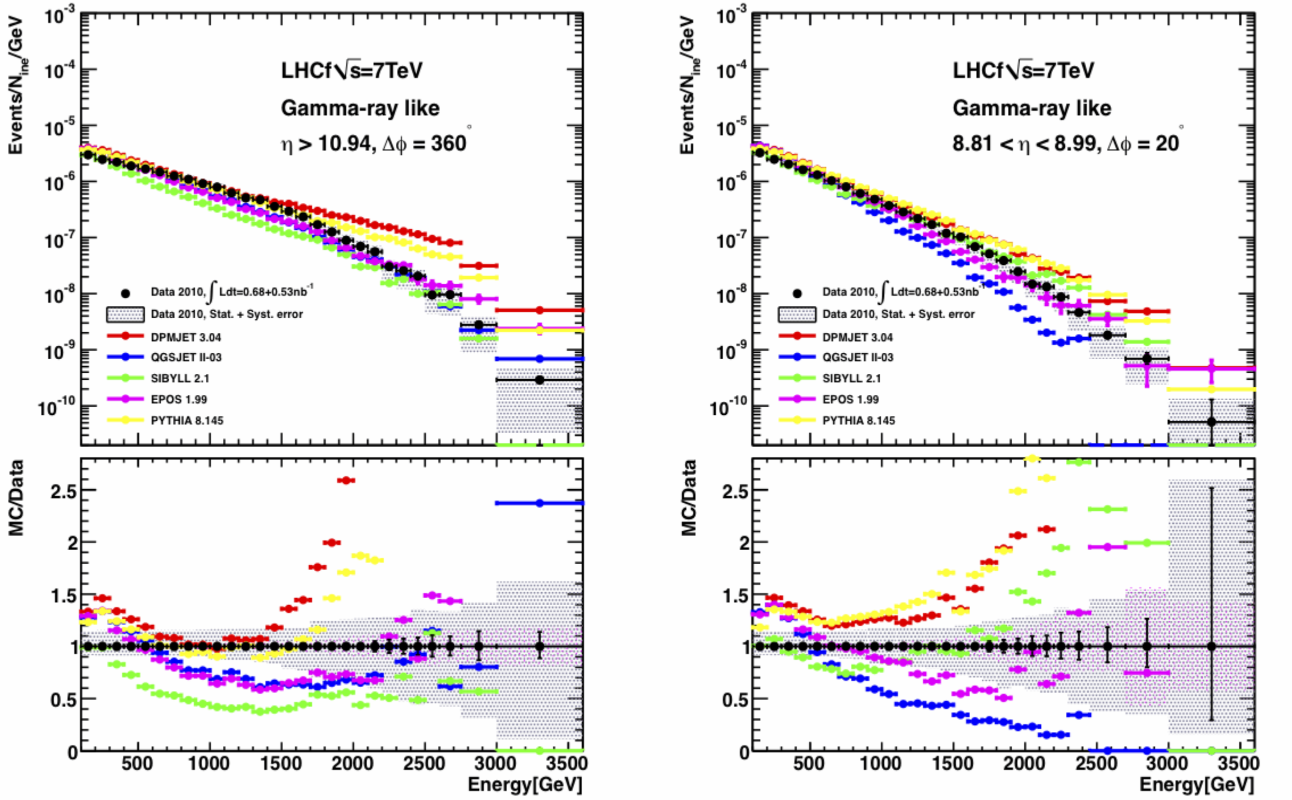
PLB 715 298 (2012)

No strong evidence of η-dependence

LHCf: p-p run 0.9 and 7 TeV

Photons spectra in p-p at **7 TeV**

(2.6x10^{16} eV proton hitting the atmosphere)



- **DPMJET** - **PYTHIA** are in good agreement at high- η only for E_γ<1.5TeV .
- **QGSJET** – **SIBYLL** are in reasonable agreement for high- η
- **EPOS** has less η dependency.

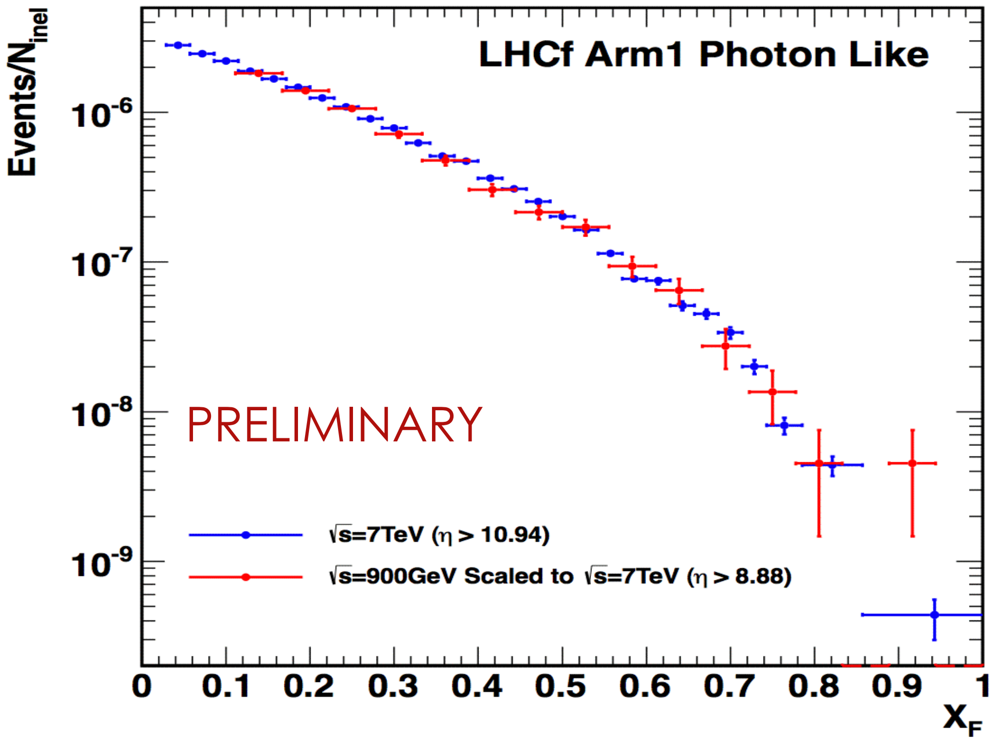
No models reproduce the LHCf data perfectly

PLB 703 128 (2011)

LHCf: p-p run 0.9 and 7 TeV

Feynman X_F scaling

The Feynman scaling is important to extrapolate the cross sections information at cosmic ray high energy.



- p-p runs: at √s= 7 TeV and at √s = 900 GeV spectrum.
- the two spectra were normalized by the inelastic events for $X_F > 0.1$

hep-ex: 1507.08764

- **Forward photon spectra measured by LHCf at 7 TeV and 900 GeV support X_F scaling**
- **The same analysis will be done for RICHf at 510 GeV**

LPM effect **(PRELIMINARY)**

At high energies multiple scattering reduces the cross sections for bremsstrahlung and pair production processes (the Landau Pomeranchunk Migdal effect)

-> Delay and significant elongation of electromagnetic shower.

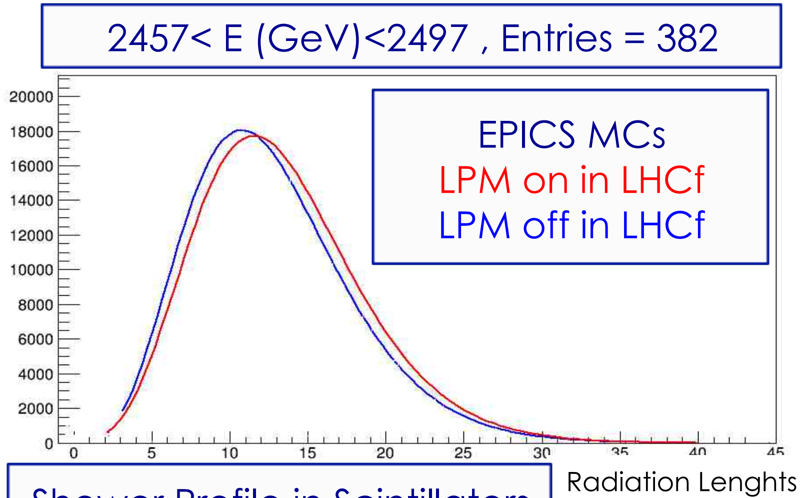
LPM effect is evident for $k > E_{LPM}$

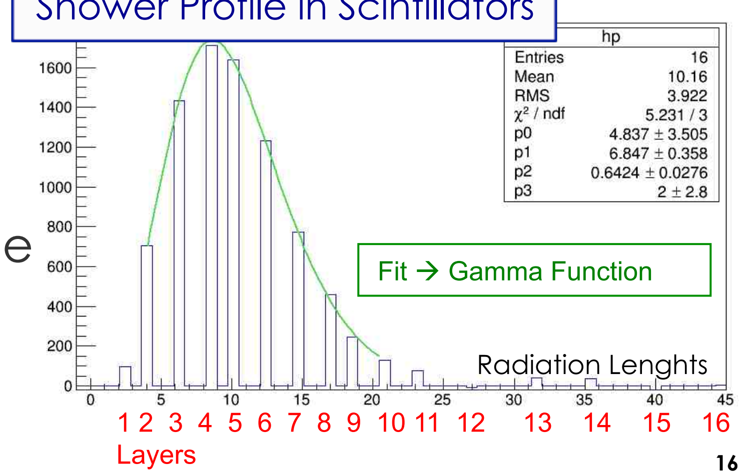
- $E_{LPM} = m^2c^3 \alpha X_o / 4\pi\hbar$
- k= photon energy

And small emission angle θ ->

LHCf has the optimal set up to detect It directly (by measuring the shape of longitudinal profile of the shower):

we use EPICS software for simulations with and without LPM effect and parametrize the shower shape using the scintillators signal in the layers of ARM2





LPM effect **(PRELIMINARY)**

SIn= S2+S3 -> more in the poster session

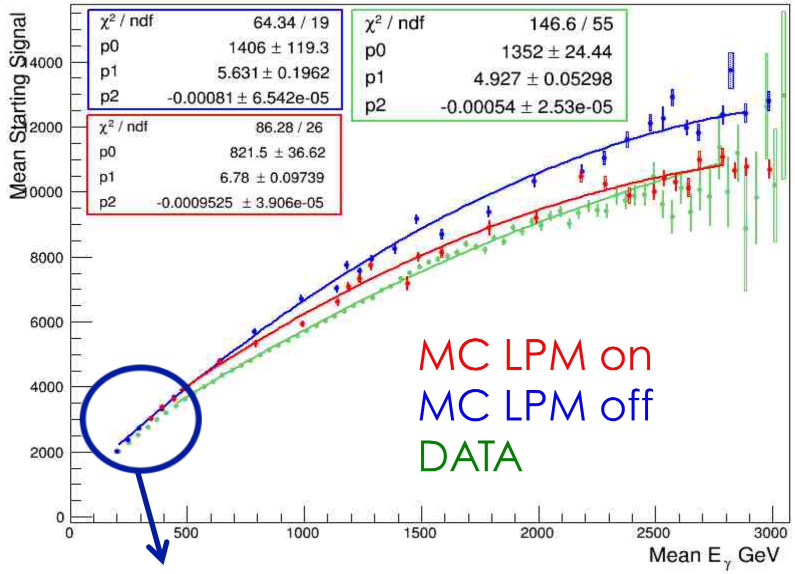
We define the beginning of shower as the signals recorded in Layer 2 and 3

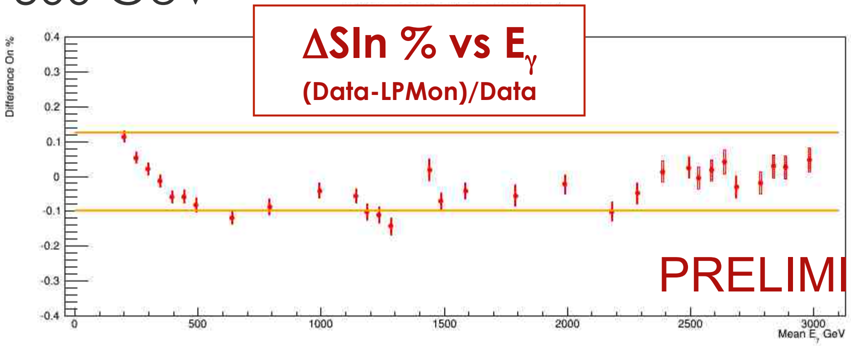
It will be smaller for LPM on than LPM off because of shower delay

MCs do not reproduce the Data at low energy (<600 GeV)

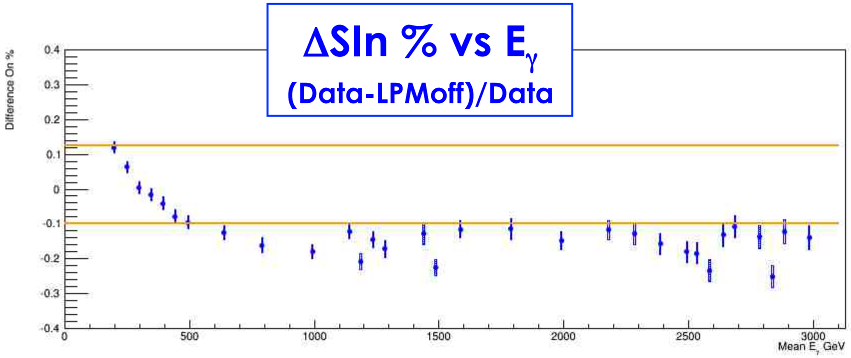
MCs are tested for LPM effect up to energies of ~300 GeV

SIn vs E$_\gamma$





PRELIMINARY



Define a compatibiliy range where MC LPM on and off are equal

LHCf: p-p run at 13 TeV

($9x10^{16}$ eV proton hitting the atmosphere)

Special physics run from 8 to 12 June: low luminosity (10^{29} $cm^{-2}s^{-1}$, 5 orders of magnitudes below the nominal one of LHC) to avoid pileup and improve angular precision

- First collisions for physics (STABLE BEAMS) were at the midnight of 10 June and until morning of 13 June: **6 STABLE BEAM PERIODS**

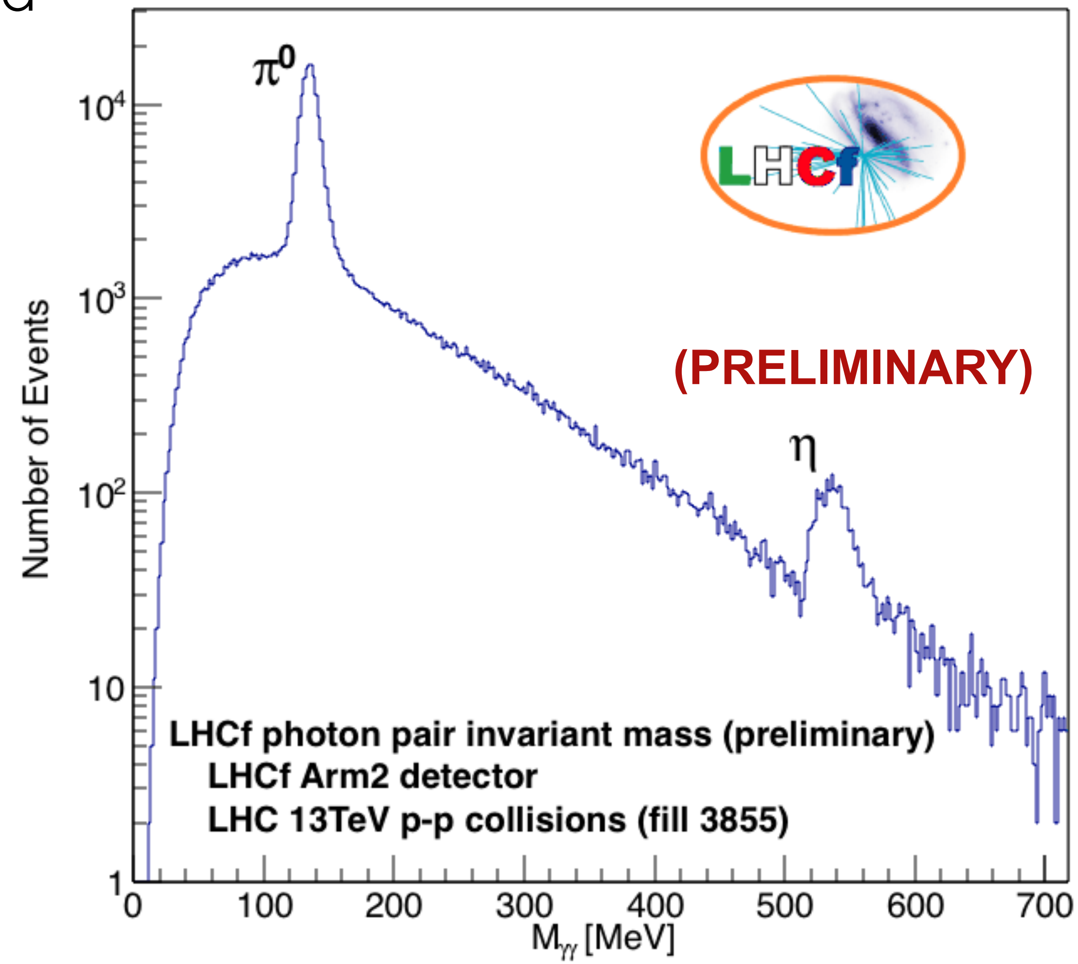
LHCf takes successfully more than 32 hours of physics Data.

- **This operation was in collaboration with the ATLAS experiment**, the trigger signals of LHCf were sent to ATLAS that recorded their data accordingly. The analyses of common events will permit to classify the events based on the nature of the processes (diffractive dissociation and non-diffractive).
- The LHCf detectors were uninstalled from the LHC tunnel on 15 June during the first technical stop of LHC to avoid radiation damage expected with the higher luminosity lasting in the LHC RUN2.

LHCf: p-p run at 13 TeV

(9×10^{16} eV proton hitting the atmosphere)

With a preliminary analysis during the operation not only π_0 mesons but also η mesons were clearly detected



Conclusion and Future plan

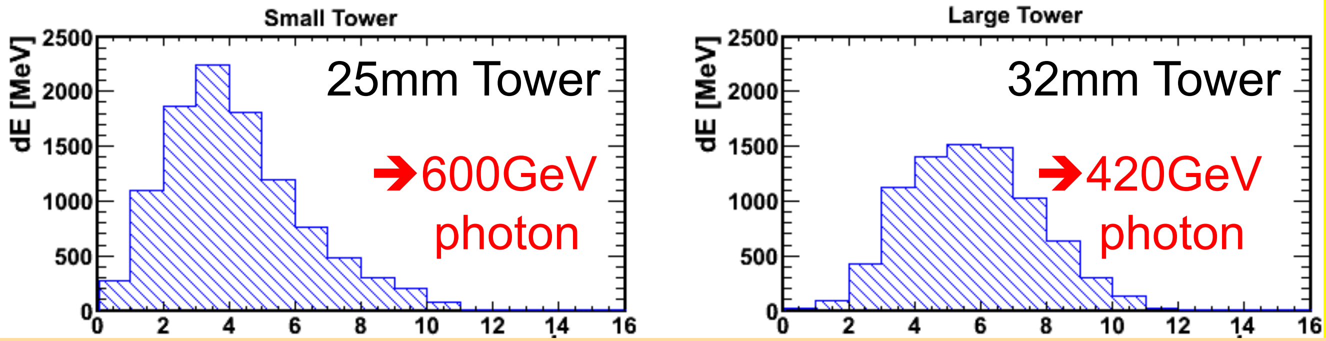
LHCf is a small experiment with the aim to understand the hadronic interaction taking place in the collisions between high-energy cosmic rays and earth's atmosphere:

- We measured photons, neutral pions and neutrons for p-p interactions at $\sqrt{s}$= 900 GeV, 2.76 TeV, 7 TeV, 13 TeV and p-Pb interactions at $\sqrt{s}$=5.02 TeV
- The analysis of hadronic component for p-p 7TeV is completed
- The π_0 analysis (NMF) for p-Pb run is already published
- Atlas/LHCf common analysis on data taking in 2013 is ongoing. Its follow up in the 2015 is under discussion
- The analysis of data taken in p-p run at 13 TeV is ongoing
- Data taking p-Pb at LHC (2016-2017) is been considered
- LHCf->RICHf: operation at RICH for p-p at 510 GeV (2017)

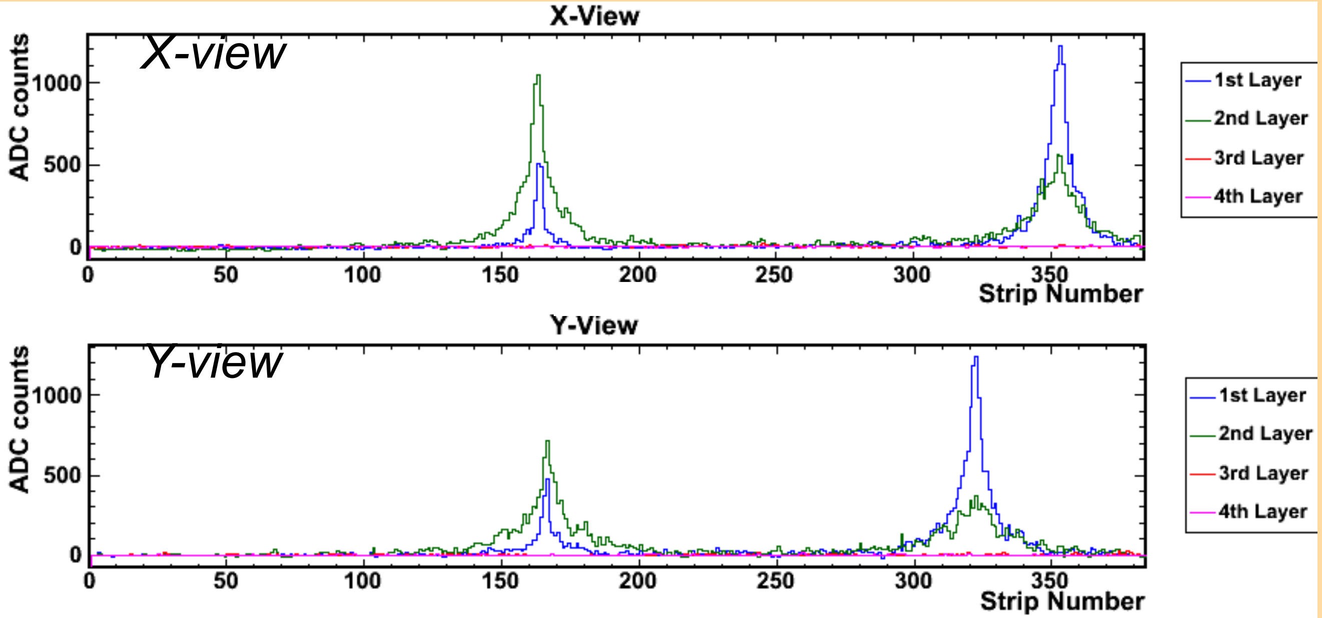
Bk Slides

π^0 analysis reconstruction

Longitudinal development measured by scintillator layers



Transverse profile measured by silicon μ–strip layers



Reconstruction of π^0 mass $M_{\pi 0} = \sqrt{E_{\gamma 1} E_{\gamma 2}} \cdot \theta$

Determination of **energy** from total energy release

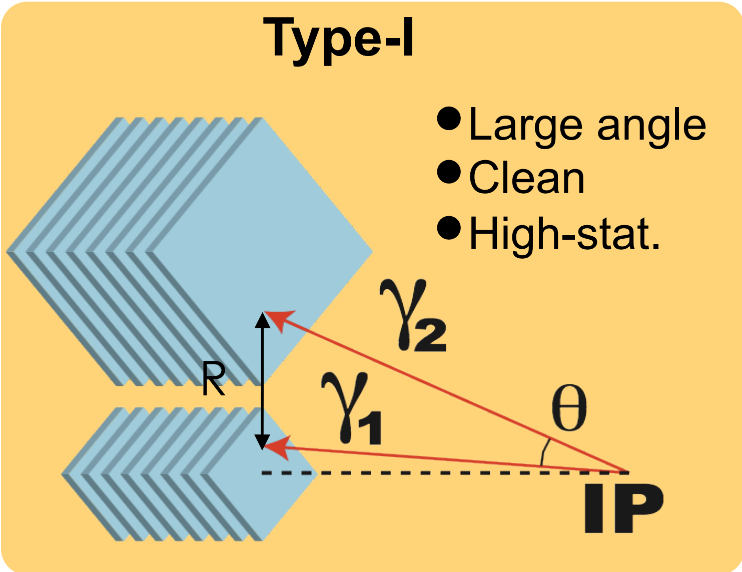
PID from shape

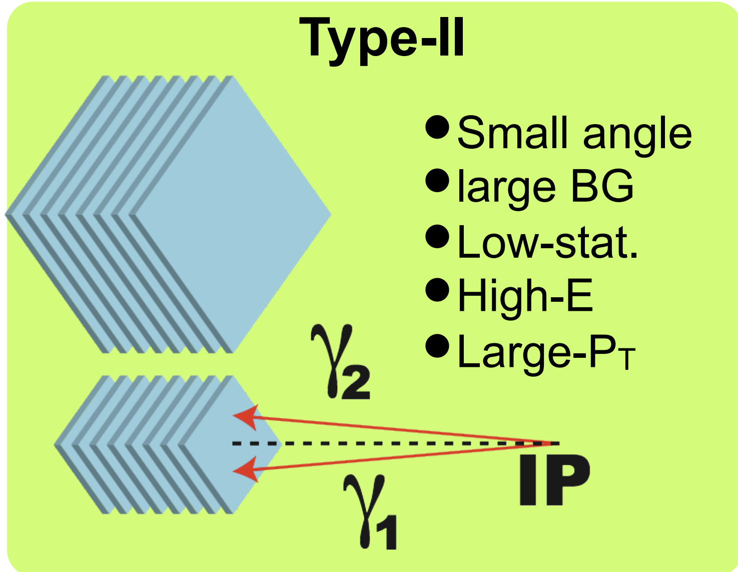
Determination of the **impact point**

Measurement of the **opening angle** of gamma pairs

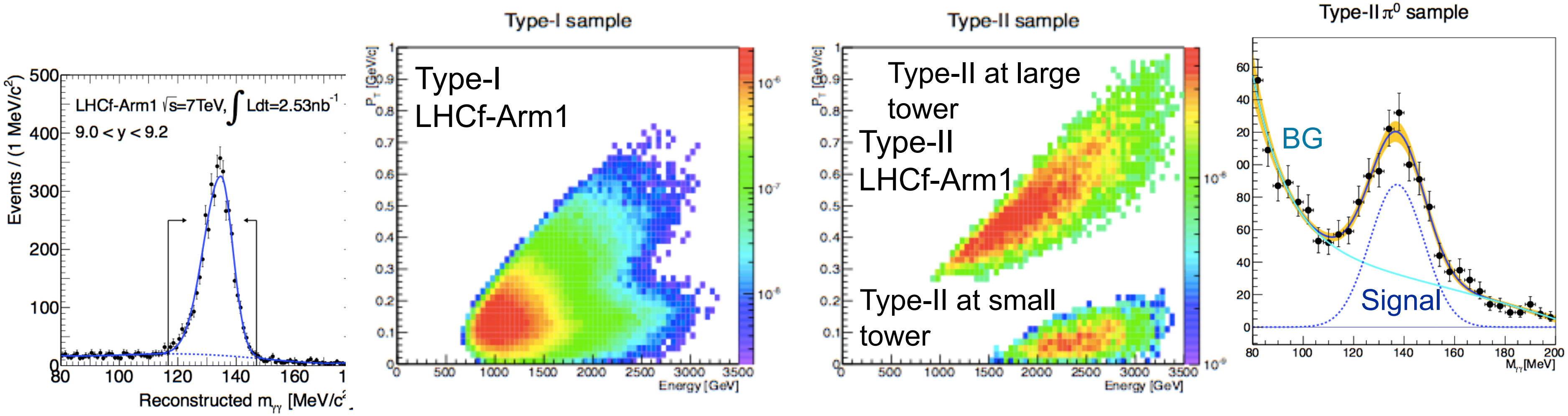
Identification of **multiple hit**

π^0 analysis reconstruction

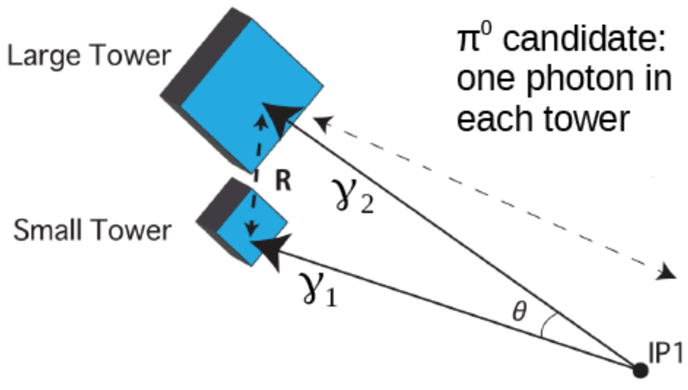




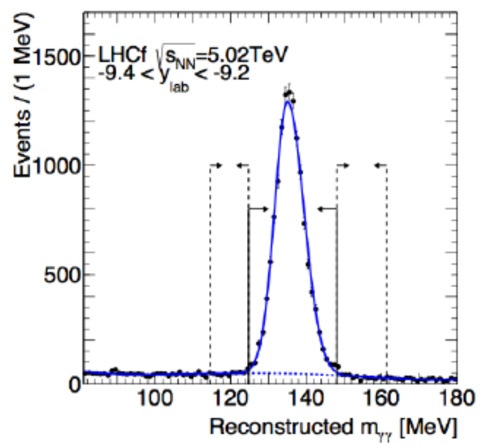
$$\theta = \frac{R}{140\ \text{m}}$$



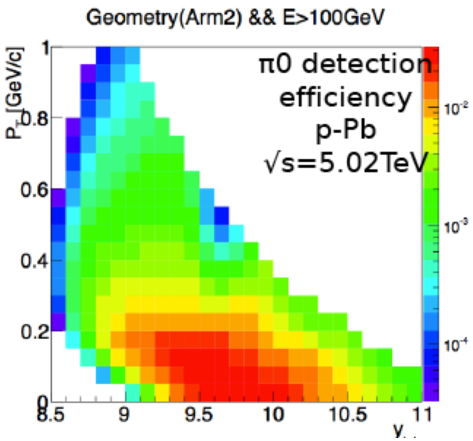
π^0 analysis reconstruction



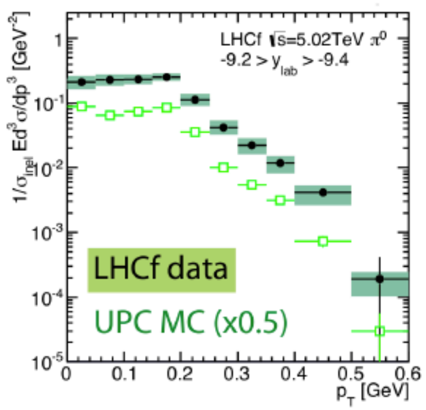
BG subtraction by sideband



Unfolding the smeared P_T spectra and correction for geometrical inefficiency



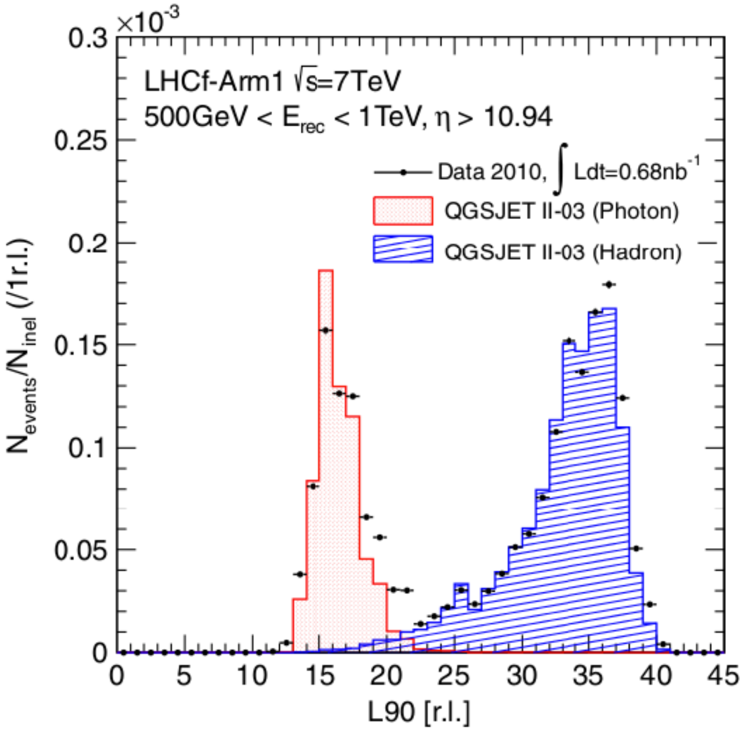
UPC subtraction



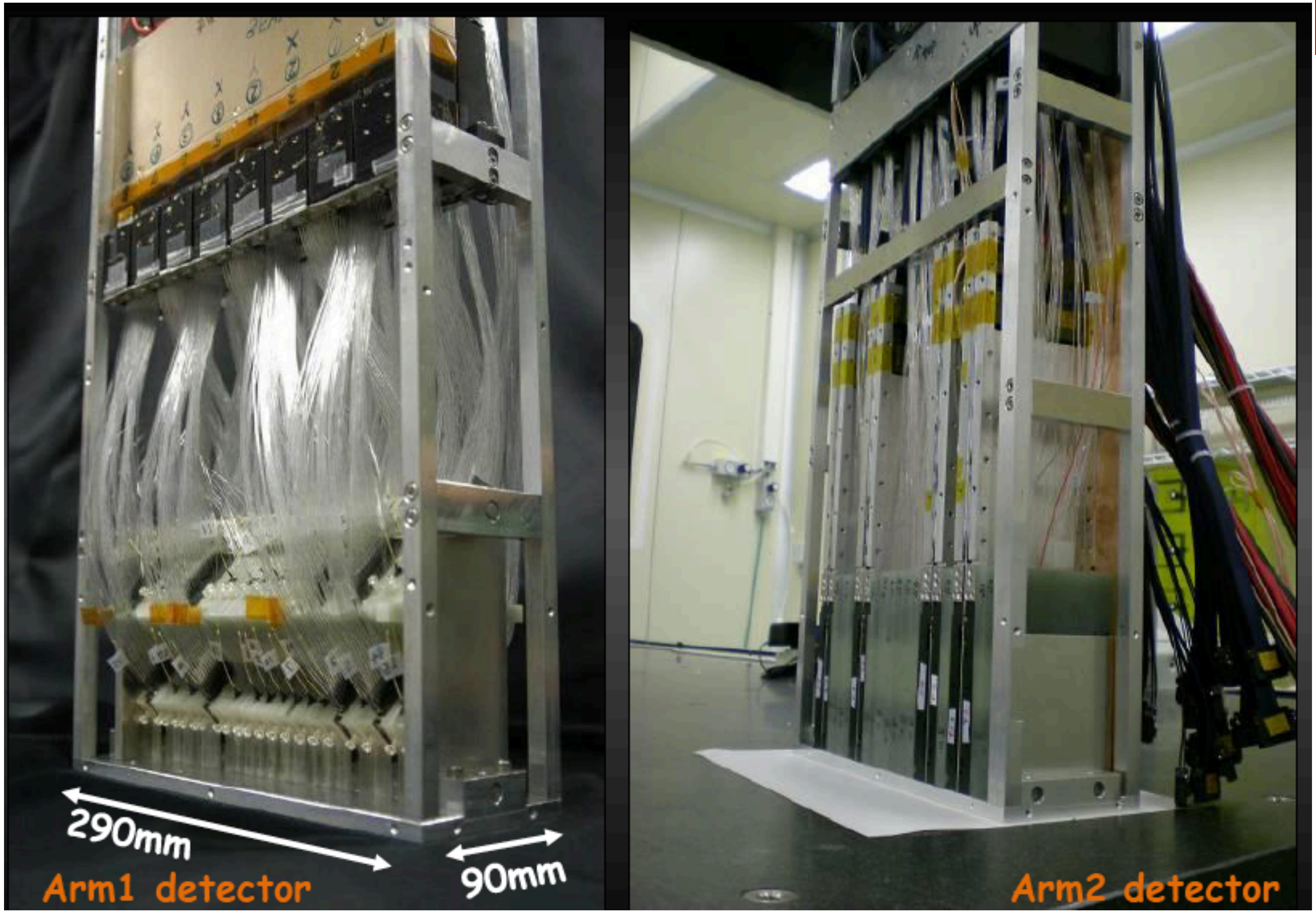
Photons and hadron selection

EM and hadronic showers are separated with a method based on a difference of the longitudinal shower development

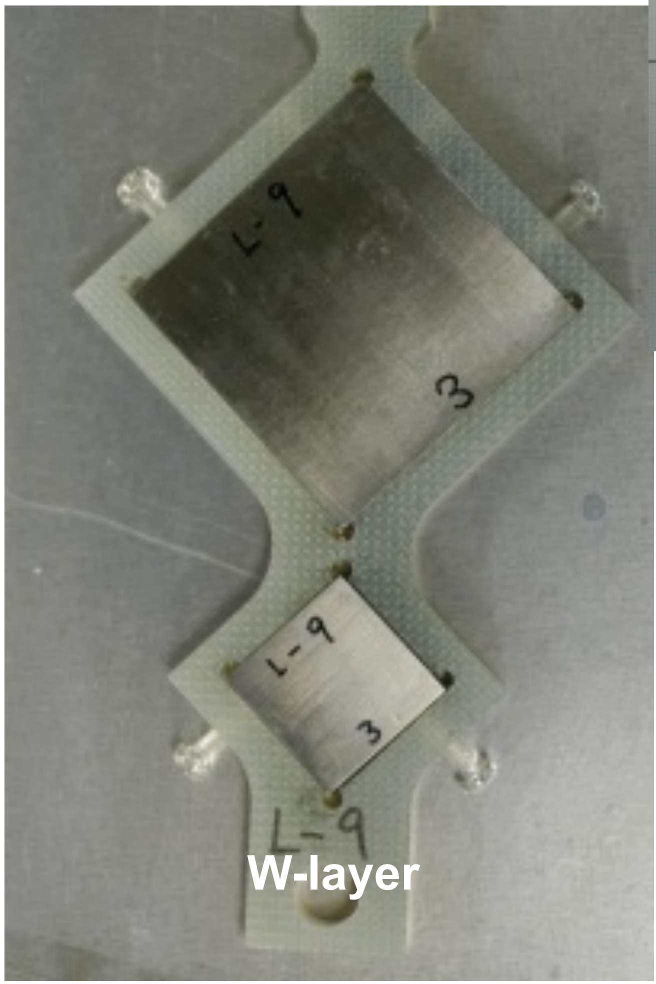
- **L90%**: depth in X_0 where 90% of the deposited energy is contained
- Energy-dependent threshold to keep photon detection efficiency at 90%
- Events with L90% less than threshold are recognized as photons

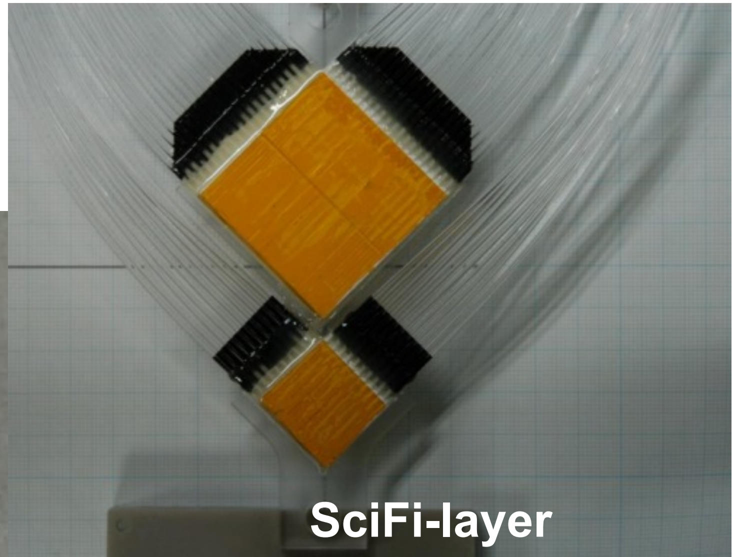


PHOtOS



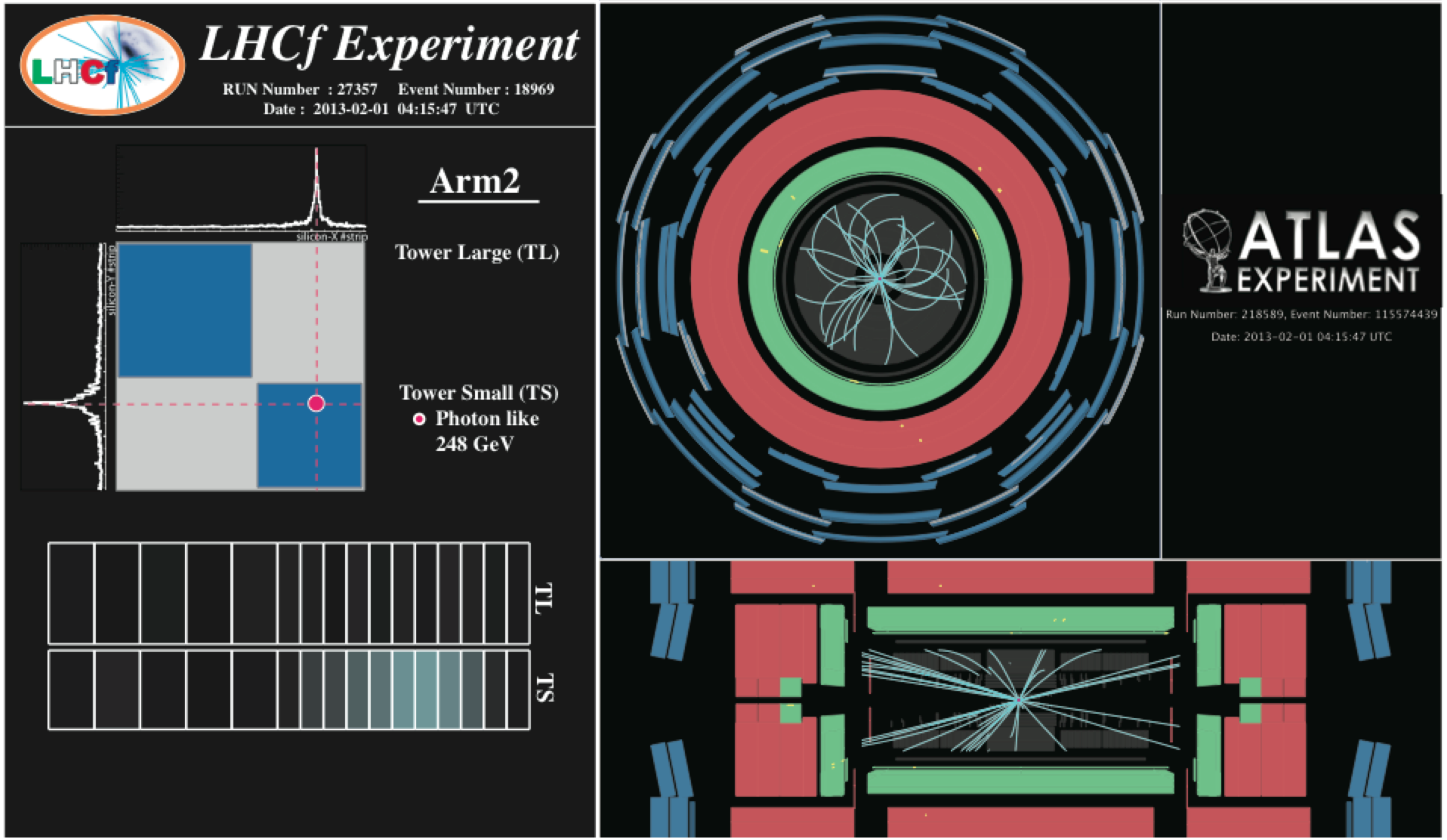
PHOtOS





year		Equivalent proton energy in LAB (eV)	γ	n	π^0
	SPS test beams		NIM A 671 129 (2012)	JINST 9 P03016 (2014)	
2009	p-p 900 GeV	4.3×10^{14}	PLB 715 298 (2012)		
2009/2010	p-p 7 TeV	2.6×10^{16}	PLB 703 128 (2011)	In preparation	PRD 86 092001 (2012)
2013	p-p 2.76 TeV	4.1×10^{15}			Phys. Rev. C 89, 065209 (2014)
2013	p-Pb 5.02 TeV	1.3×10^{16}			
2015	p-p 13 TeV	9.0×10^{16}	Data taken		

Display


LHCf Experiment
RUN Number : 27357 Event Number : 18969
Date : 2013-02-01 04:15:47 UTC
Arm2
Tower Large (TL)
Tower Small (TS)
Photon like
248 GeV
silicon-X #strip
silicon-Y #strip
TL
TS
ATLAS
EXPERIMENT
Run Number: 218589, Event Number: 115574439
Date: 2013-02-01 04:15:47 UTC

Neutrons analysis in p-p collisions at 7 TeV

(2.6x10[16] eV proton hitting the atmosphere)

- **Performance for 1.5 TeV neutrons:**
  - Δx ~ (0.2÷1)mm
  - ΔE/E ~(35 ÷ 40)% -> high leakage
- **True spectrum is smeared by detector response**
  - Unfolding is needed to extract physics results