QCD at LHC: forward physics and UPC collisions of heavy ions

Trento, 26-30 September 2016

Overview of the forward measurement by the LHCf detector at LHC

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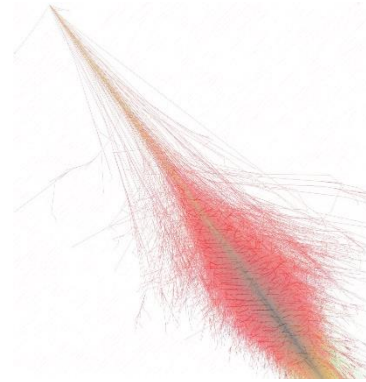
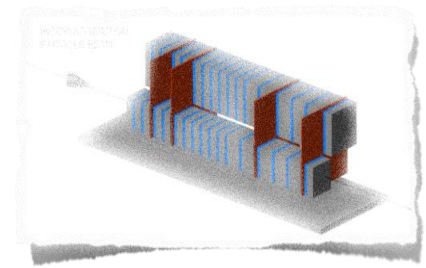
on behalf of the LHCf Collaboration

INFN Istituto Nazionale di Fisica Nucleare

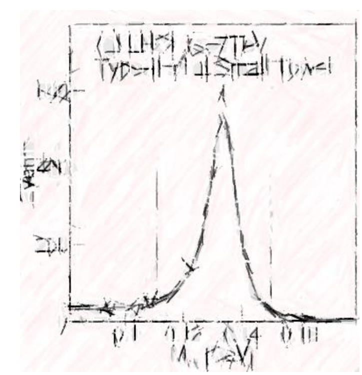
Outline…



- Introduction
  - Cosmic rays and forward physics
  - The LHCf experiment
    - Purpose, Method, Collaboration and Apparatus



- Data analysis
  - Overview of the achieved results
  - Status of the on-going analysis and preliminary results

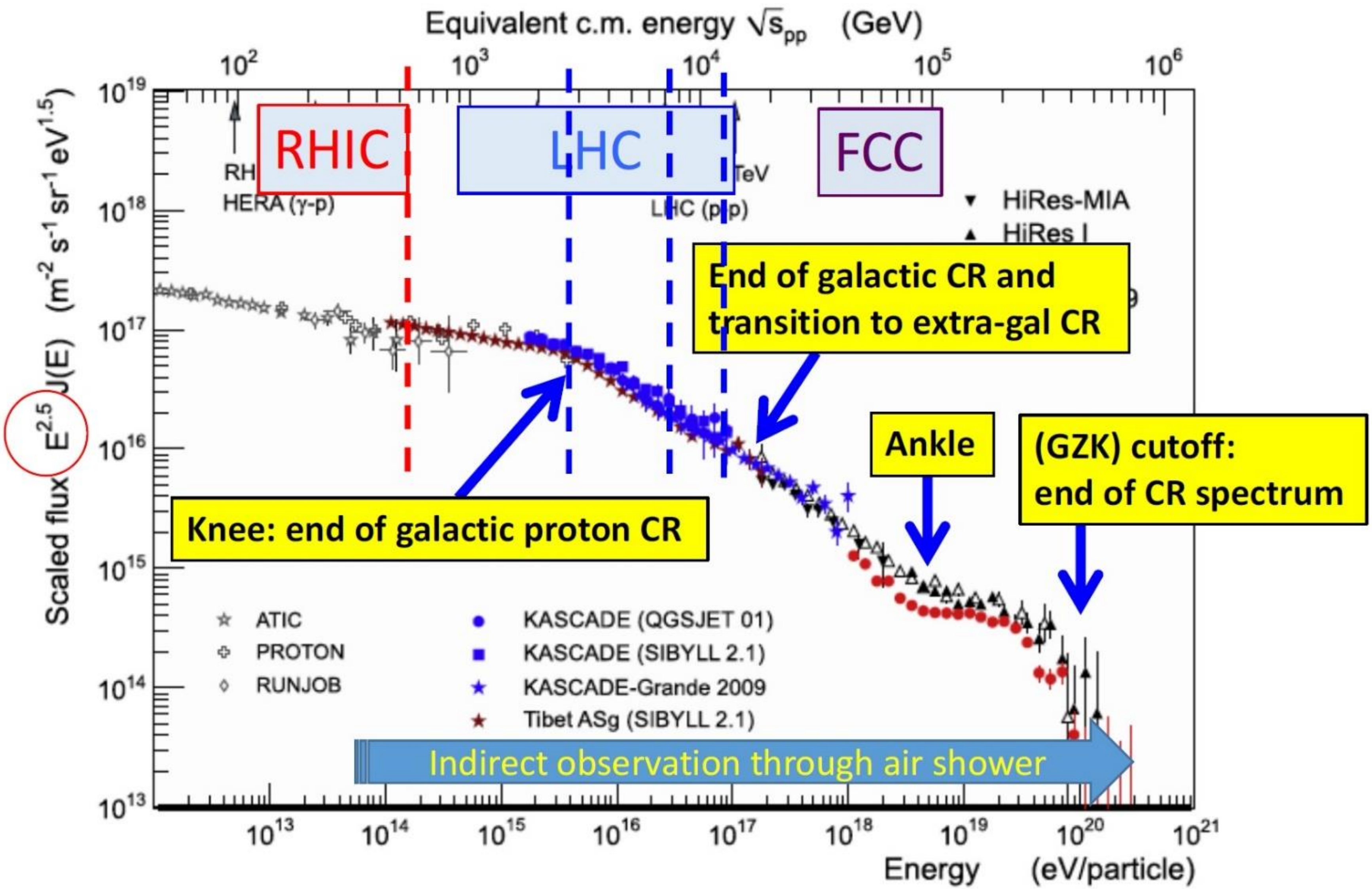


- Future activities
  - 2016 p+Pb collisions @ LHC
  - 2017 RHICf run @ RHIC
  - 20?? p+Light Ion @ LHC

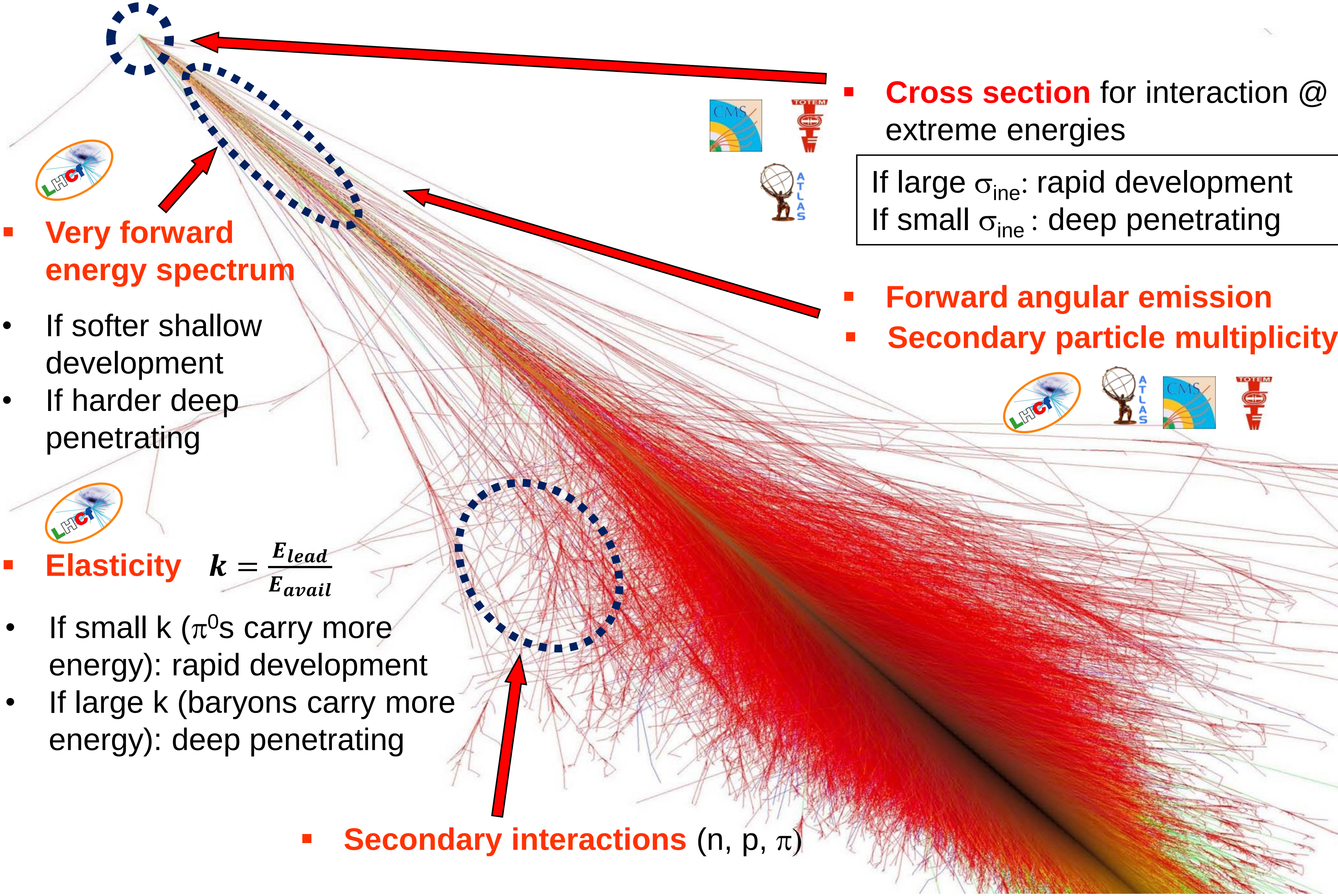
?

Introduction

Spectrum of cosmic rays



Cosmic ray shower



- **Cross section** for interaction @ extreme energies

If large σ_{ine}: rapid development
If small σ_{ine} : deep penetrating

- **Very forward energy spectrum**
  - If softer shallow development
  - If harder deep penetrating

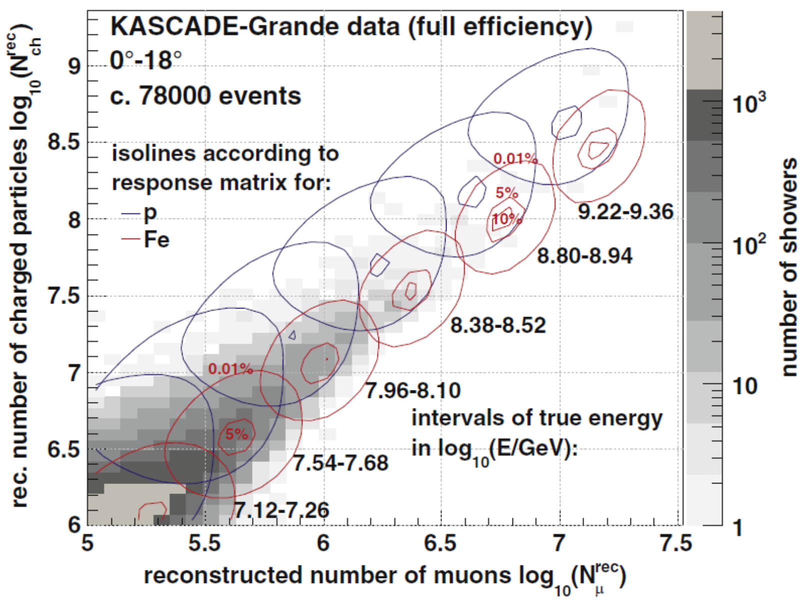
- **Forward angular emission**
- **Secondary particle multiplicity**

- **Elasticity** $k = \frac{E_{lead}}{E_{avail}}$
  - If small k (π^0s carry more energy): rapid development
  - If large k (baryons carry more energy): deep penetrating

- **Secondary interactions** (n, p, π)

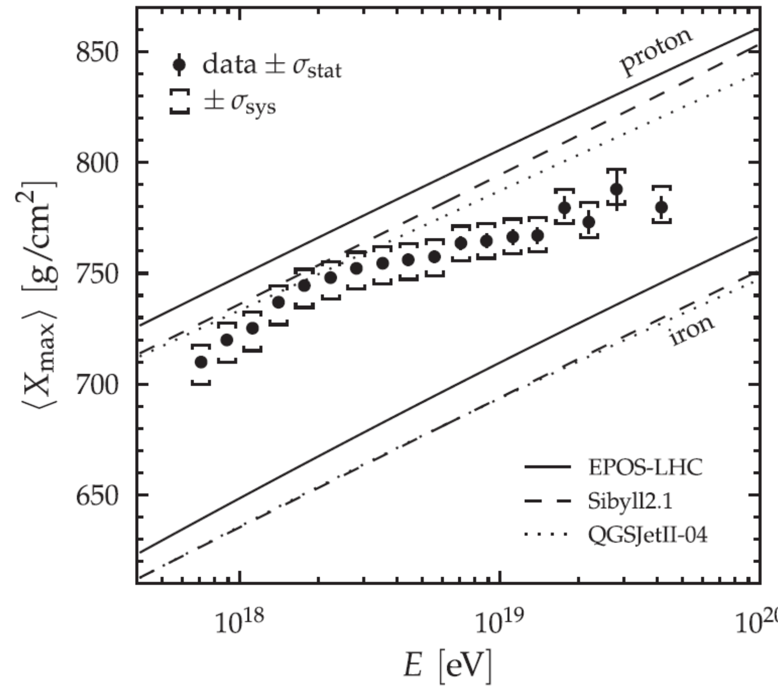
Study of the composition of CR

KASCADE Grande, Astropart. Phys., 47 (2013) 54-66



Response (color contours) was calculated using QGSJET II-02 + FLUKA 2002.4

PAO, PRD, 90, 122005 (2014)



Estimation of chemical composition:

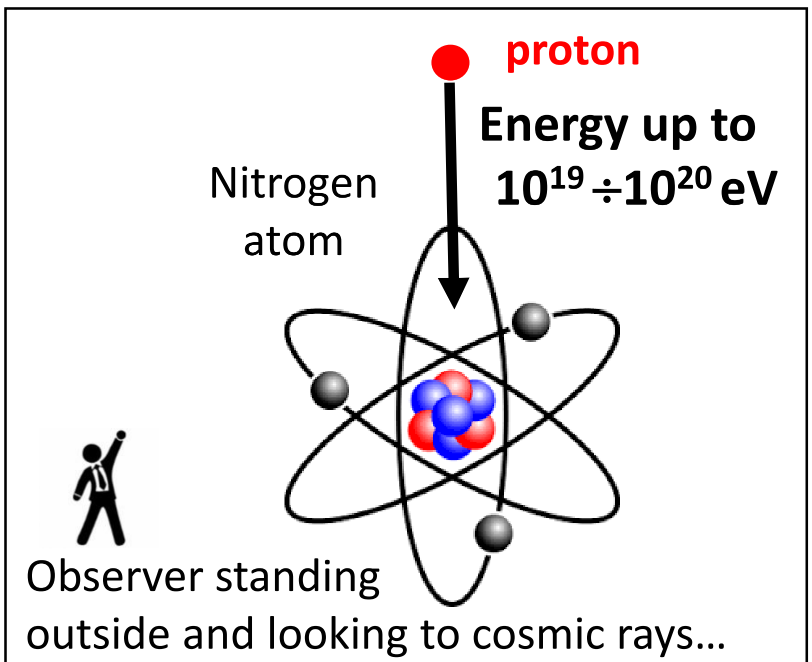
- From Knee to Ankle: N_μ
- From Ankle to the highest energies: $\langle X_{max} \rangle$

Interpratation is based on predictions by MC using a particular hadronic interaction model

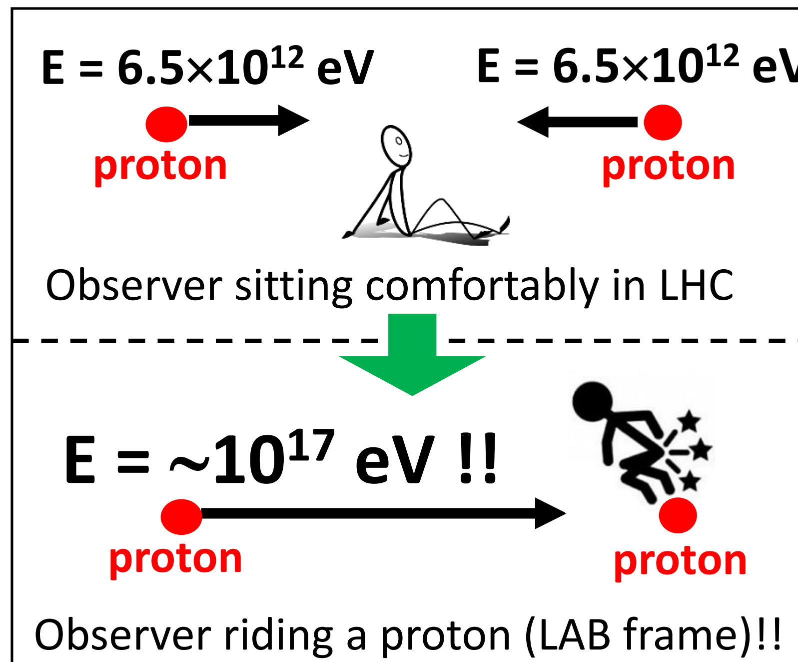
LHCf and Cosmic Ray Physics

- Possibility to study particles in the **forward direction** at LHC (neutrals: γ, π^0, n)
  - Forward secondary particles carry a great fraction of the primary energy
- 6.5 TeV + 6.5 TeV in the LHC frame → **~10^{17} eV** in the laboratory frame (LAB)
- Calibration of **hadronic interaction models** used for the simulation of atmospheric showers

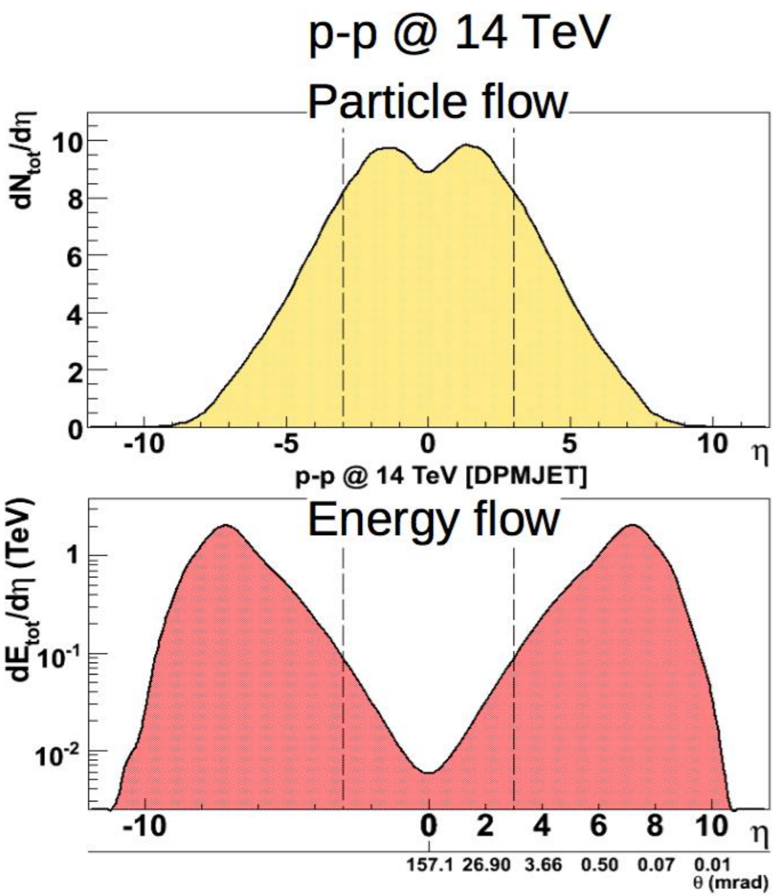
COSMIC RAYS

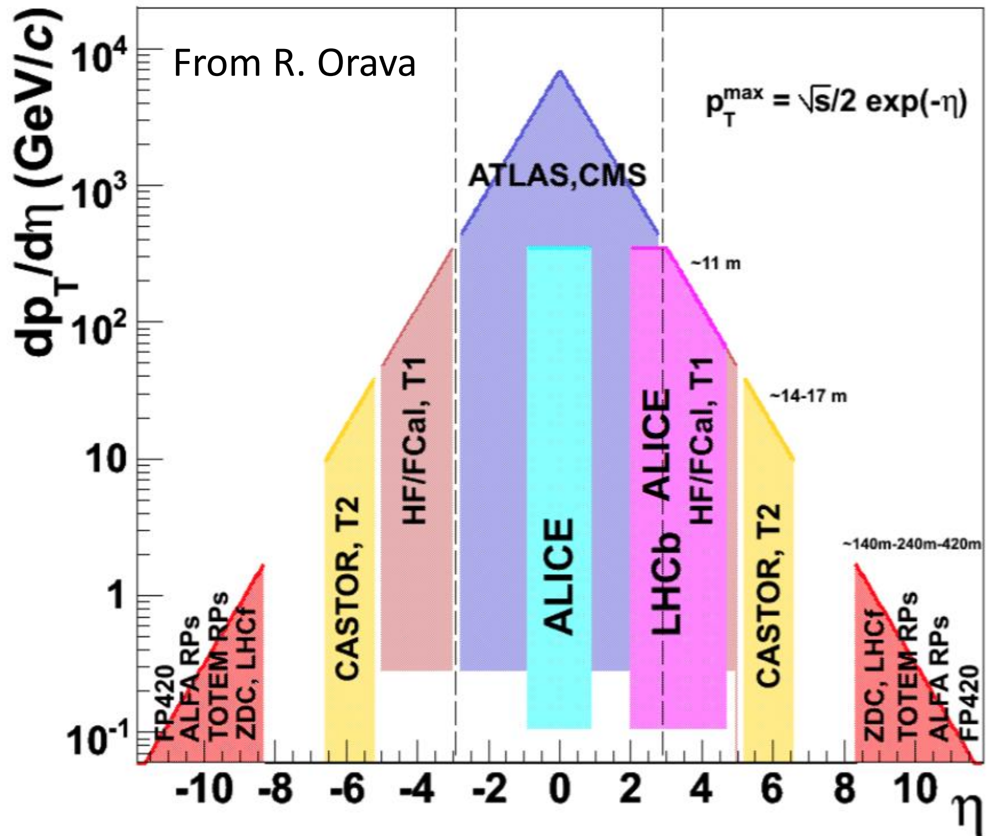


LHC



LHC phase space coverage

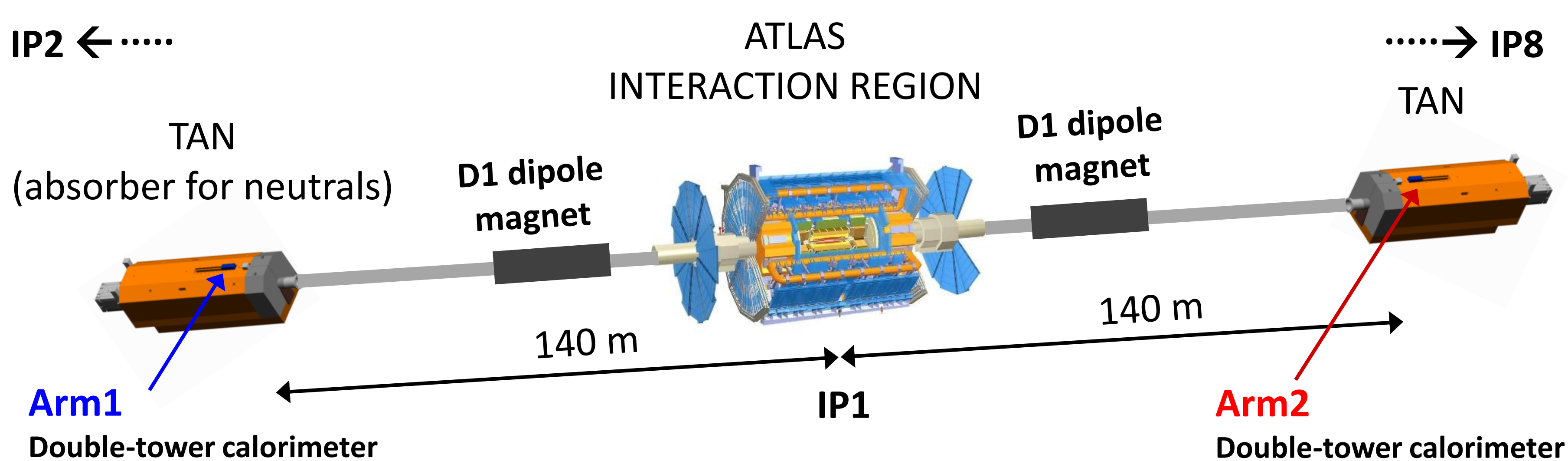




We profit of the very broad coverage!

LHCf is a dedicated forward detector for a better measurement of the energy flow

The experimental side



Position resolution: < 200 μm (Arm1) and 40 μm (Arm2)

Energy resolution: < 5% for photons; 30% for neutrons

Pseudo-rapidity range:

η > 8.7 @ zero X-ing angle

η > 8.4 @ 290 μrad (total)

Arm1 Detector

2cm x 2cm + 4cm x 4cm

GSO tiles (e.m. calo)

4 X-Y tracking layers (**GSO bars**)

Arm2 Detector

2.5cm x 2.5cm + 3.2cm x 3.2cm

GSO tiles (e.m. calor)

4 X-Y tracking layers **(silicon microstrip)**

44 X_0
~1.5 λ_{int}

Details of detectors

ARM1

2 towers 24 cm long stacked vertically with 5 mm gap

Lower: 2 cm x 2 cm area

Upper: 4 cm x 4 cm area

ARM2

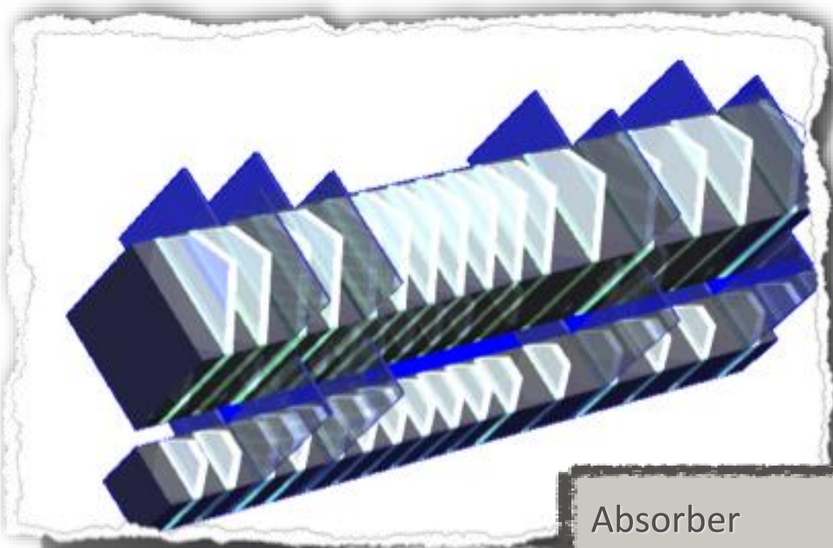
2 towers 24 cm long stacked on their edges and offset from one another

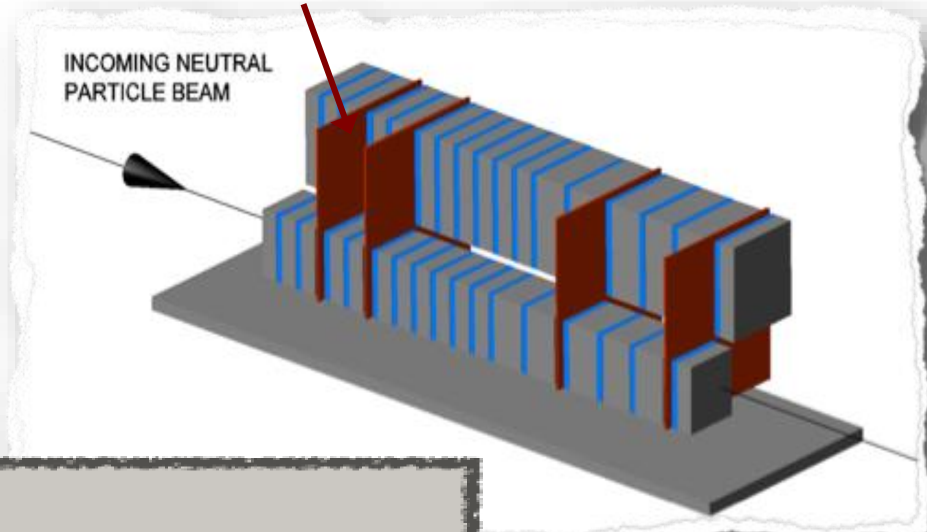
Lower: 2.5 cm x 2.5 cm

Upper: 3.2 cm x 3.2 cm

4 pairs of scintillating fiber/GSO bars layers for tracking purpose

4 pairs of silicon micro-strip layers for tracking purpose (X and Y directions)





Absorber
22 tungsten layers 7mm – 14 mm thick (2-4 r.l.)
(W: X_0 = 3.5mm, R_M = 9mm)

The LHCf collaboration today (32 members)

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N. Sakurai[i], Y. Shimitsu[j], M. Shinoda[e], T. Suzuki[g], T. Tamura[j], A. Tiberio[a,b], S. Torii[g],

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k) *University of Catania, Italy*
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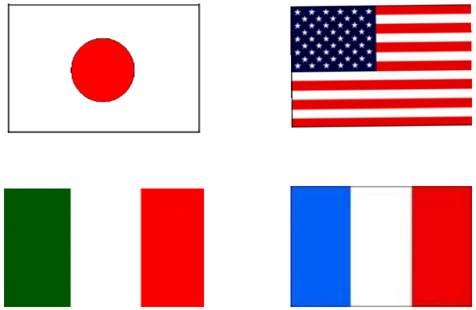


Brief history of LHCf

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

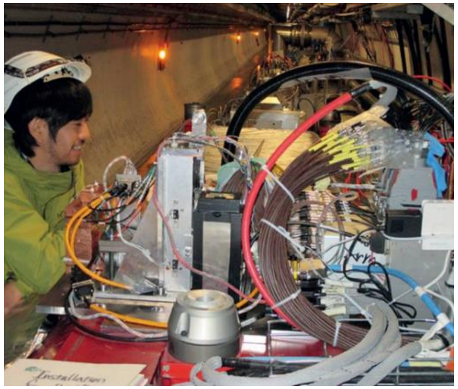
Jul 2006
construction

Aug 2007
SPS beam test

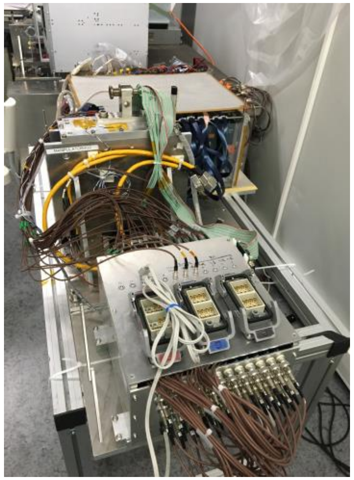
Jan 2008
Installation
Sep
1st LHC beam

Dec- Jul 2010
0.9TeV& 7TeV pp
(detector removal)

Dec 2012- Feb 2013
5TeV/n pPb, 2.76TeVpp
Arm2 only
(detector removal and <u>upgrade</u>)



May-June 2015
13 TeV dedicated pp
(detector removal)

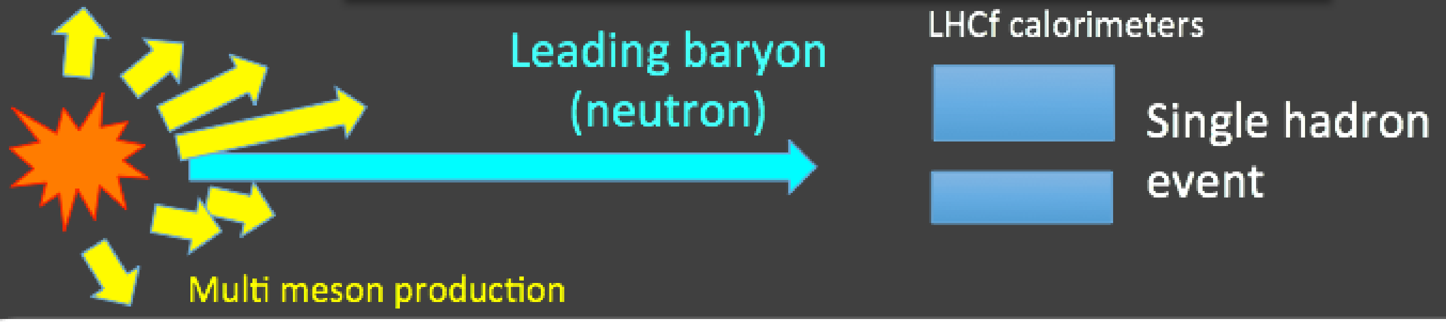


Sept. 2016
Preparation to p+Pb
@ 8 TeV

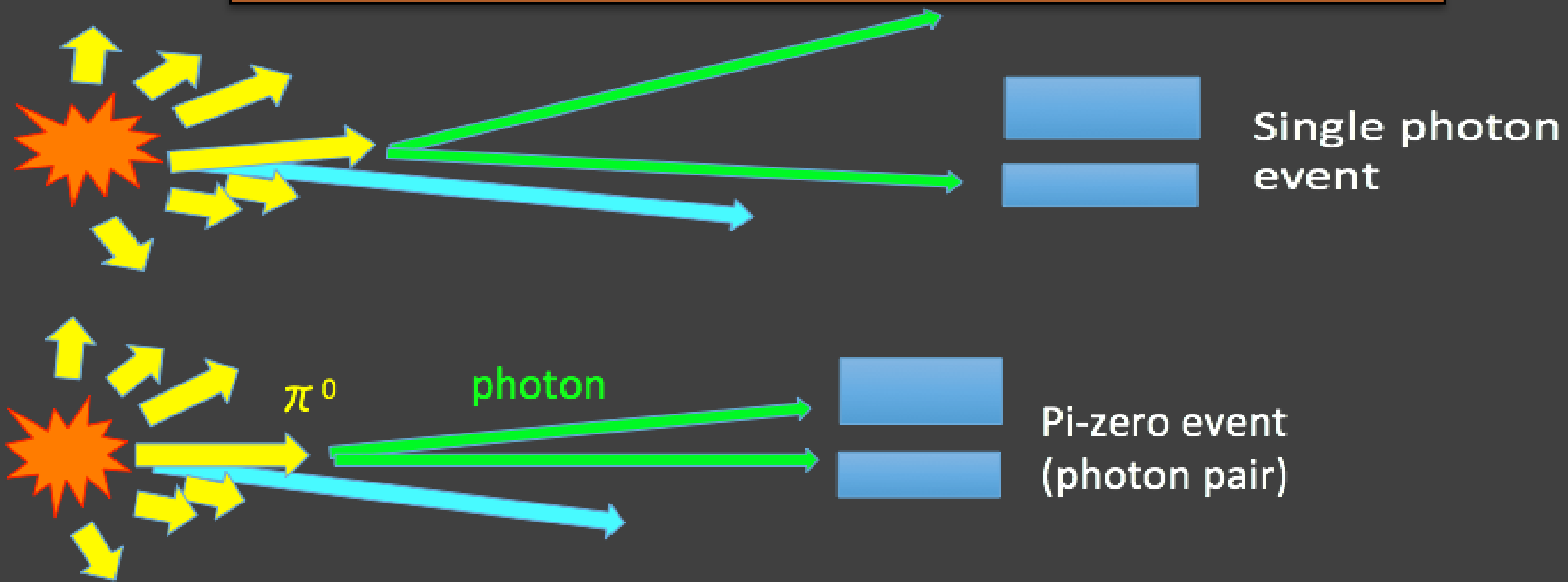
Overview of the LHCf results

Relevant type of events in LHCf

Responsible for air shower core (elasticity)



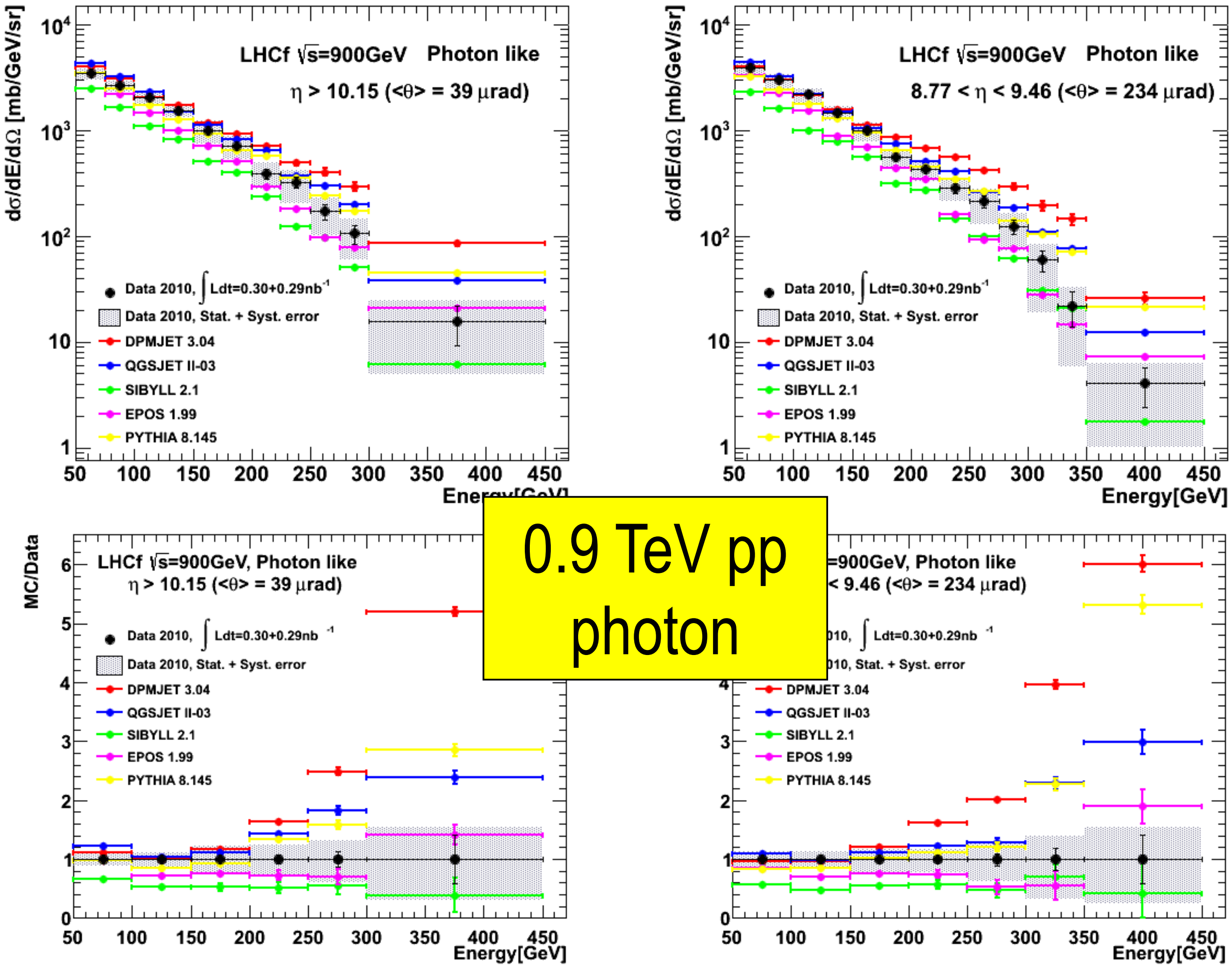
Responsible for EM air shower component (inelasticity)



Achieved results & others

RUN	Proton E_{LAB} (eV)	γ	n	π^0 limited acceptance	π^0 full acceptance	Performance
SPS test beam		NIM A, 671, 129 (2012)	JINST 9 P03016 (2014)			
p+p 900 GeV	4.3×10^{14}	PLB 715, 298 (2012)				IJIMPA 28 (2013) 1330036
p+p 7 TeV	2.6×10^{16}	PLB 703, 128 (2011)	PLB 750 (2015) 360-366	PRD 86, 092001 (2012)	PRD 94 032007	
p+p 2.76 TeV	4.1×10^{15}			PRC 89, 065209 (2014)		
p+Pb 5 TeV	1.4×10^{16}					
p+p 13 TeV	9.0×10^{16}	Data taken in June 2015 - Preliminary analysis				
p+Pb 8.1 TeV	3.6×10^{16}	Scheduled in November 2016				

Old LHCf results: single γ energy - p+p @ 900 GeV



0.9 TeV pp photon

DATA
DPMJET 3.04
QGSJET II-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145

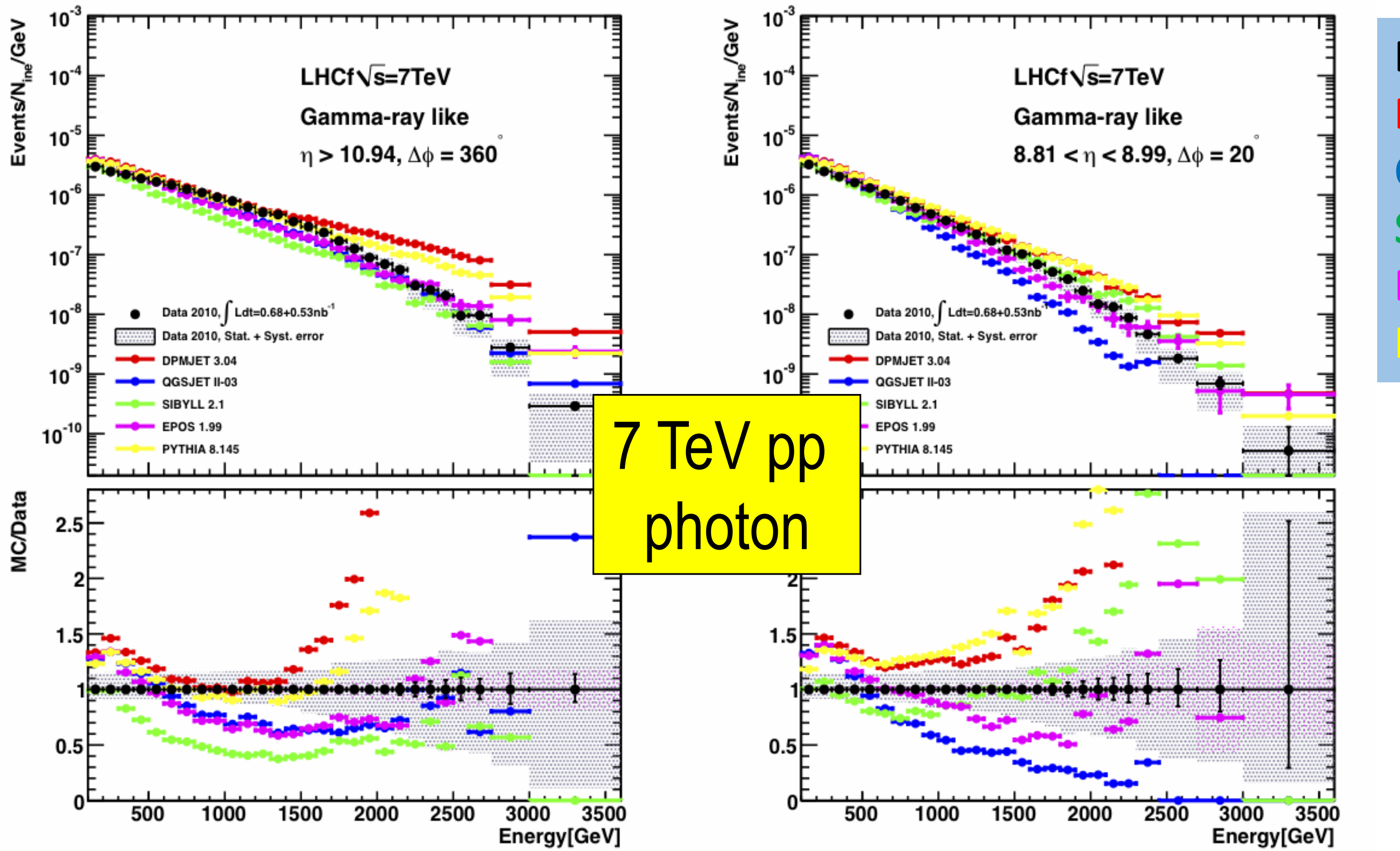
Syst.+Stat.

No strong evidence of η-dependence

EPOS and SIBYLL show reasonable agreement of shape

None of the models reproduces the data within the error bars

Old LHCf results: single γ energy - p+p @ 7 TeV



DATA
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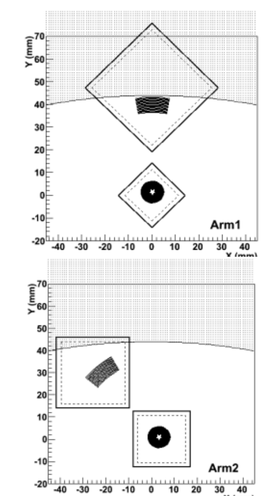
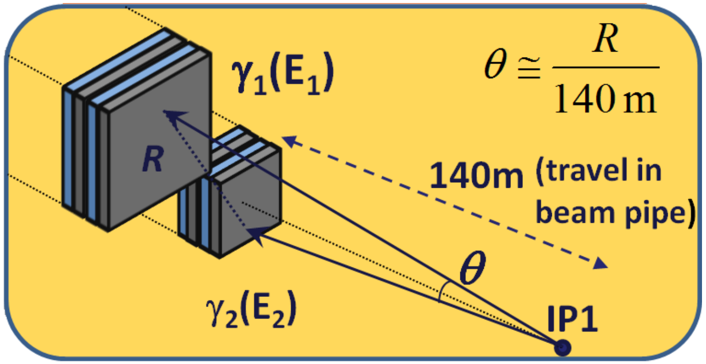
EPOS 1.99
PYTHIA 8.145

Syst.+Stat.



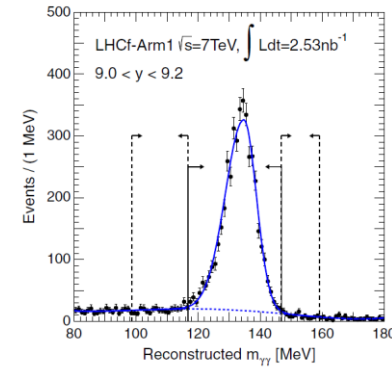
- No model can reproduce the **LHCf data** perfectly.
- **DPMJET** and **PYTHIA** are in good agreement at high-η for E_γ<1.5TeV, but harder in E>1.5TeV.
- **QGSJET** and **SIBYLL** shows reasonable agreement of shapes in high-η but not in low-η
- **EPOS** has less η dependency against the LHCf data.

Old LHCf results: π^0 p_t - p+p @ 7 TeV



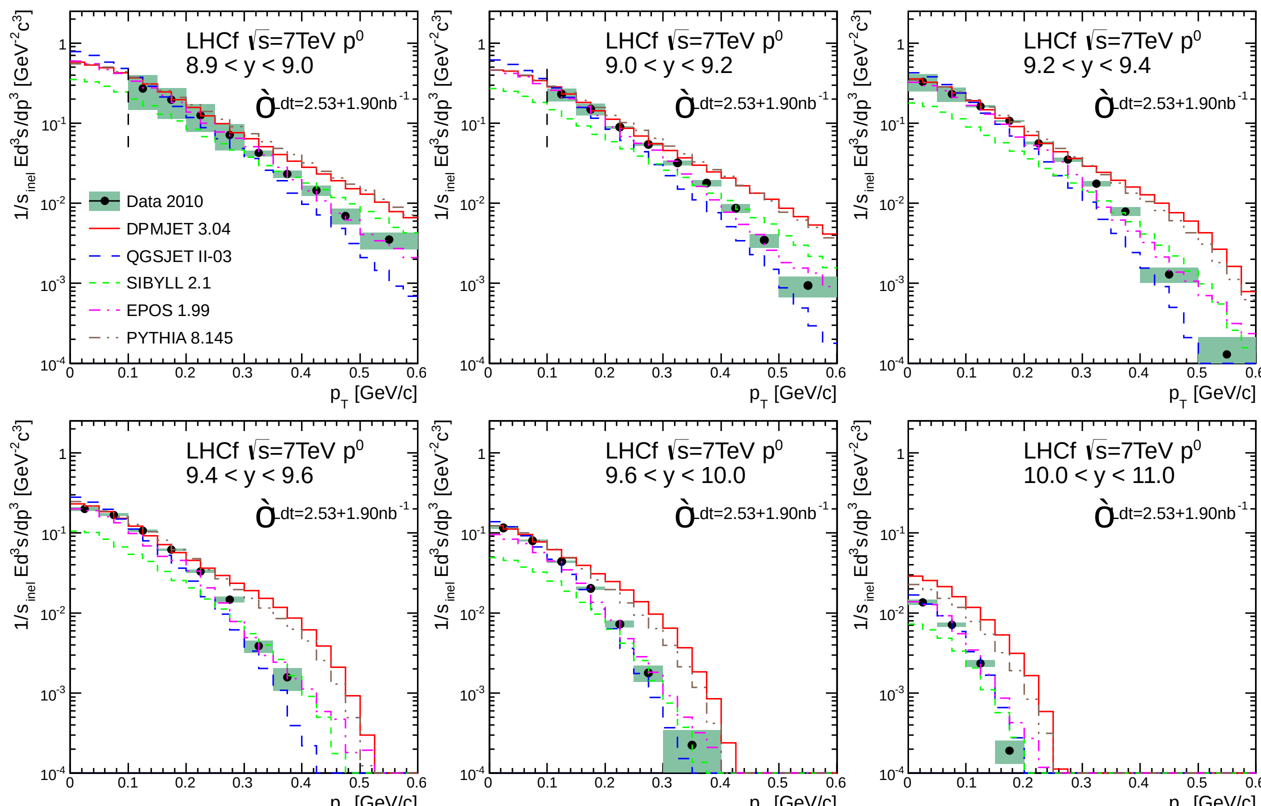
Reconstruction of the invariant mass of two-photon events

7 TeV pp π^0

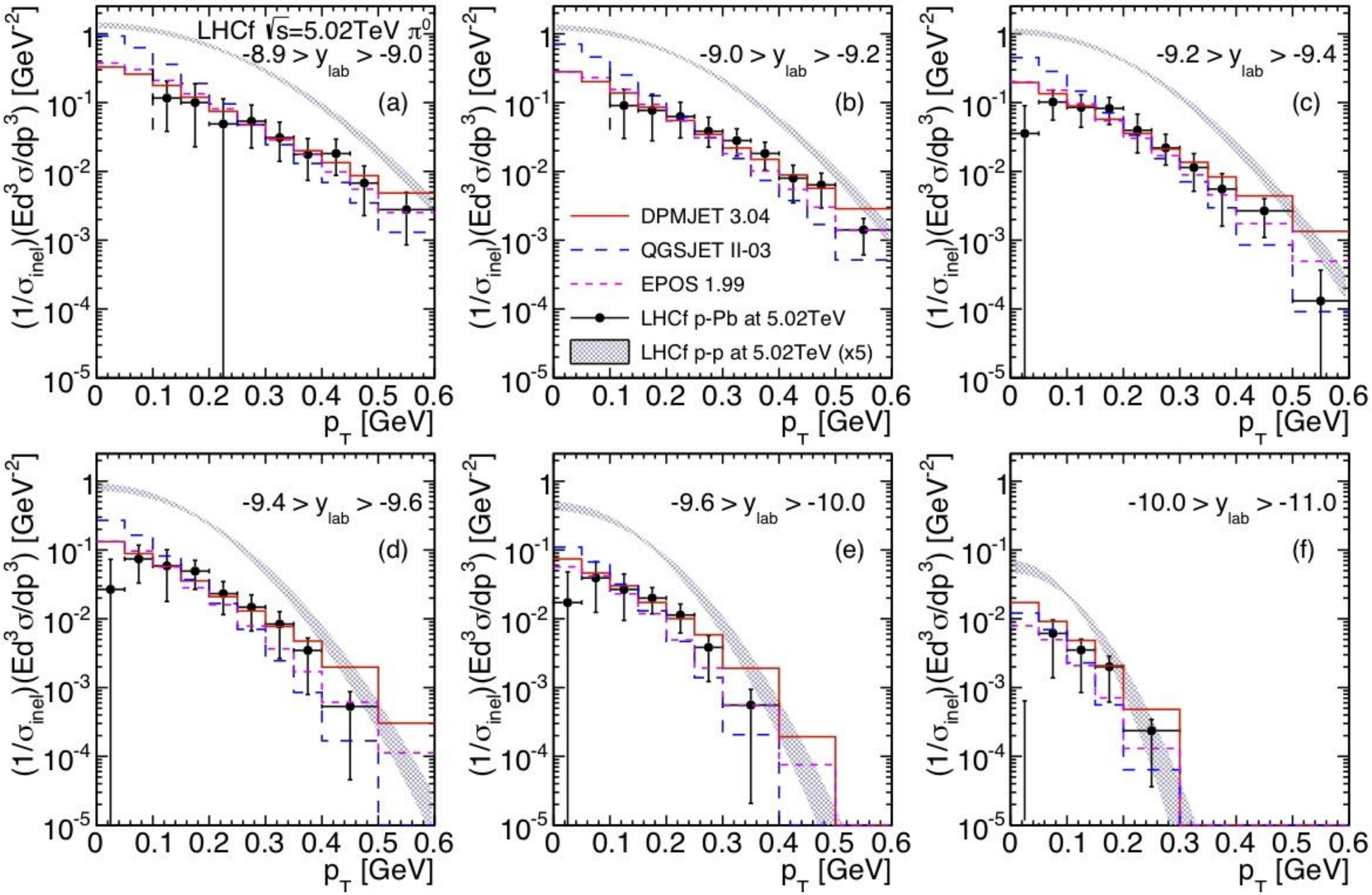


Identification of events with two particles hitting the two towers

- **EPOS1.99** show the best agreement with data in the models.
- **DPMJET** and **PYTHIA** have harder spectra than data ("popcorn model")
- **QGSJET** has softer spectrum than data (only one quark exchange is allowed)



Old LHCf results: π^0 p_t - p+Pb 2013 @ 5 TeV



- LHCf data in p-Pb (filled circles) show good agreement with DPMJET and EPOS.
- LHCf spectra in p-Pb are clearly less steep than the LHCf data in p-p at 5.02 TeV (shaded area, spectra multiplied by 5). The latter is interpolated from the results at 2.76 TeV and 7 TeV.

Most recent results

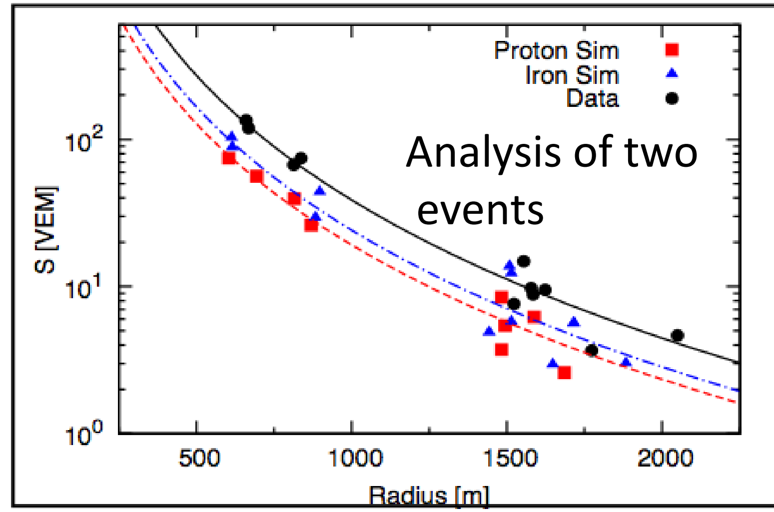
Forward hadrons and Cosmic Rays

Motivations:

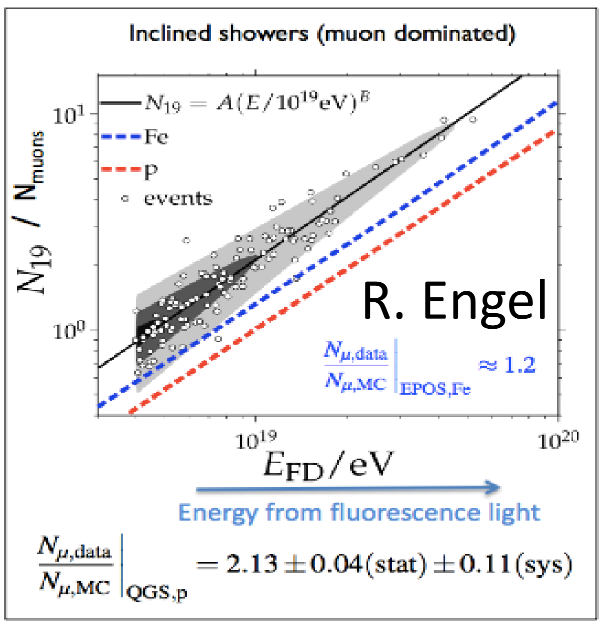
Inelasticity measurement $k=1-p_{leading}/p_{beam}$

Muon excess at Pierre Auger Observatory

- cosmic rays experiment measure PCR energy from muon number at ground and florescence light
- 20-100% more muons than expected have been observed



[J.Allen, et al. ICRC2011 Proceedings]



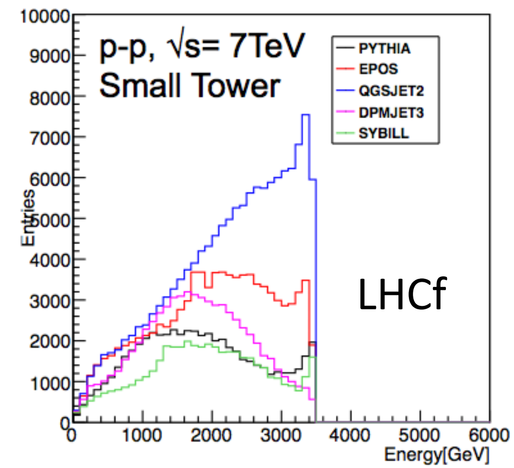
Number of muons depends on the energy fraction of produced hadron

Muon excess in data even for Fe primary MC

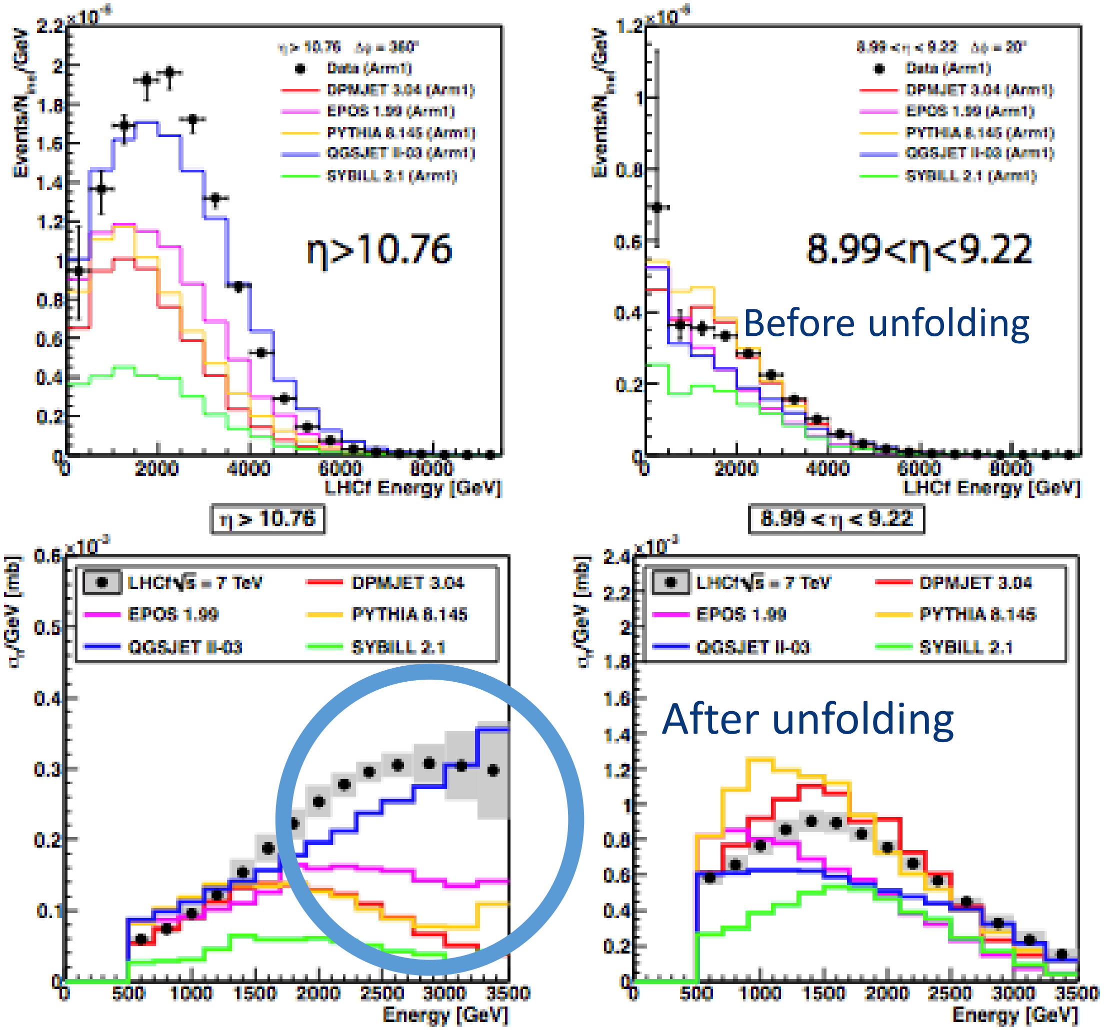
EPOS predicts more muon due to larger baryon production

Importance of baryon measurement!

Neutron spectra predicted by interaction models



Inclusive hadron spectra (LHCf @ 7 TeV pp)



n / γ ratio

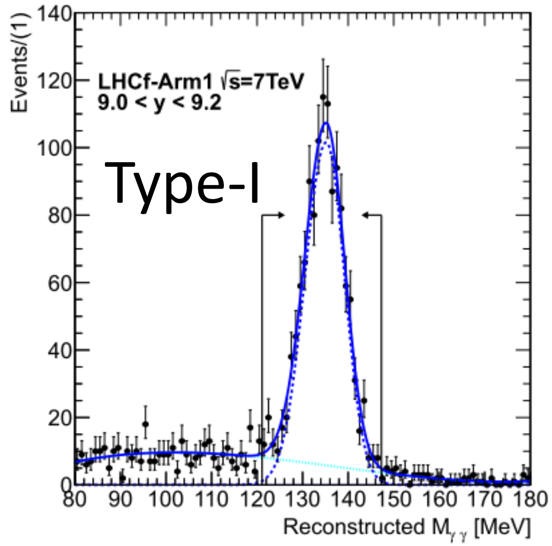
Data (η>10.76)	3.05 ± 0.19
DPMJET3.04	1.05
EPOS 1.99	1.80
PYTHIA 8.145	1.27
QGSJET II-03	2.34
SYBILL 2.1	0.88

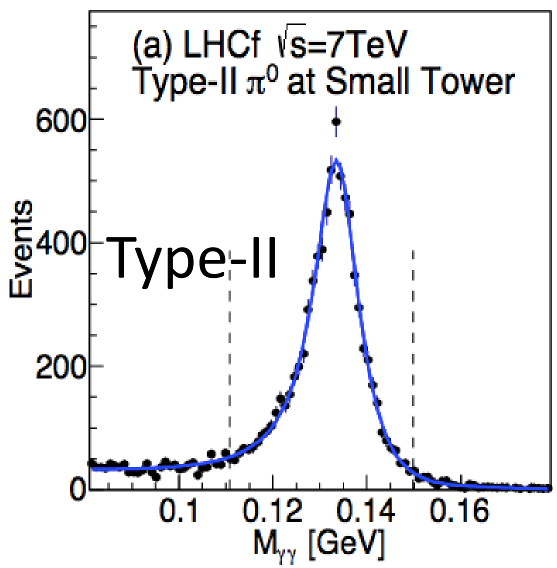
n / γ ratio

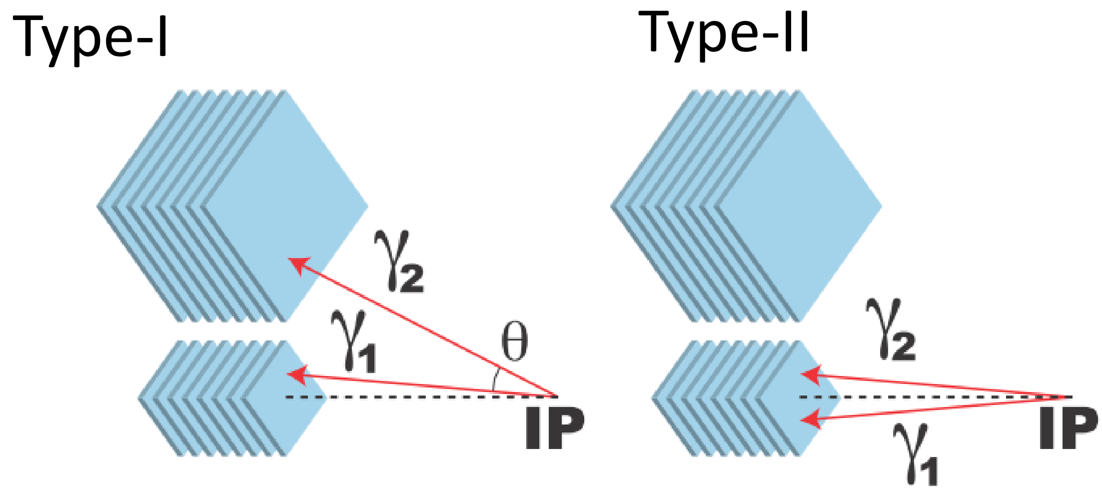
Data (8.99<η<9.22)	1.26 ± 0.08
DPMJET3.04	0.76
EPOS 1.99	0.69
PYTHIA 8.145	0.82
QGSJET II-03	0.65
SYBILL 2.1	0.57

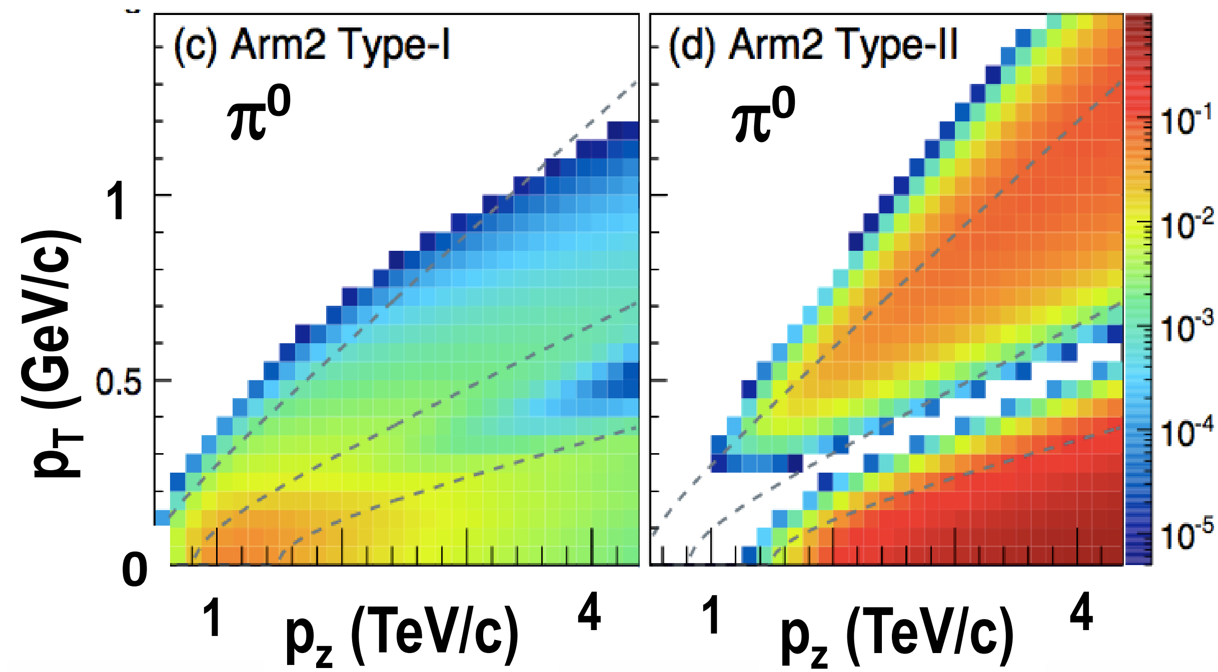
Very large high energy peak in the η>10.76 (predicted only by QGSJET)
→ Small inelasticity in the very forward region!

LHCf Type-I and Type-II π^0 analysis

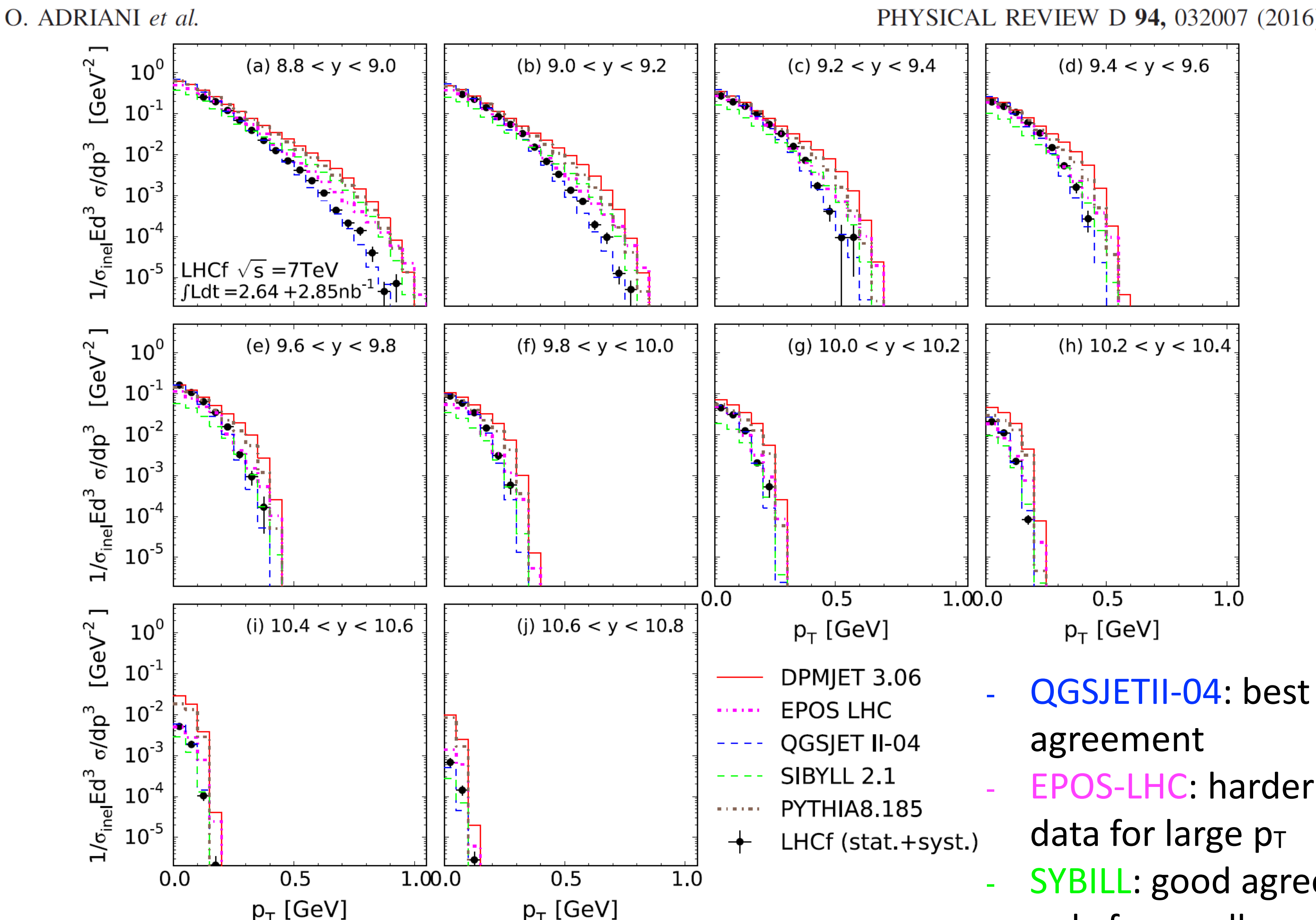








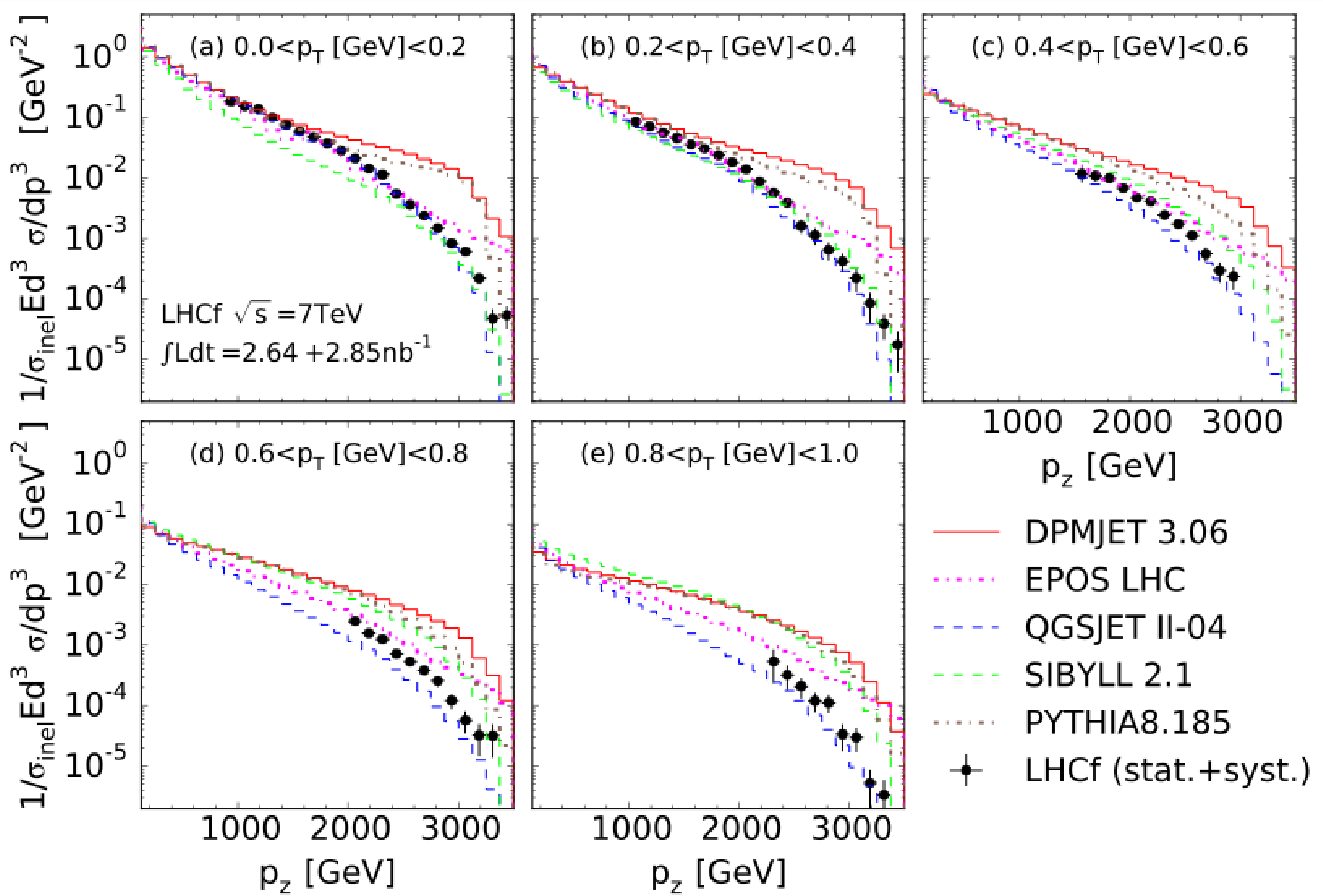
π^0 p_T spectra in 7 TeV pp collisions



- QGSJETII-04: best agreement
- EPOS-LHC: harder than data for large p_T
- SYBILL: good agreement only for small y

π^0 p_z spectra in 7 TeV pp collisions

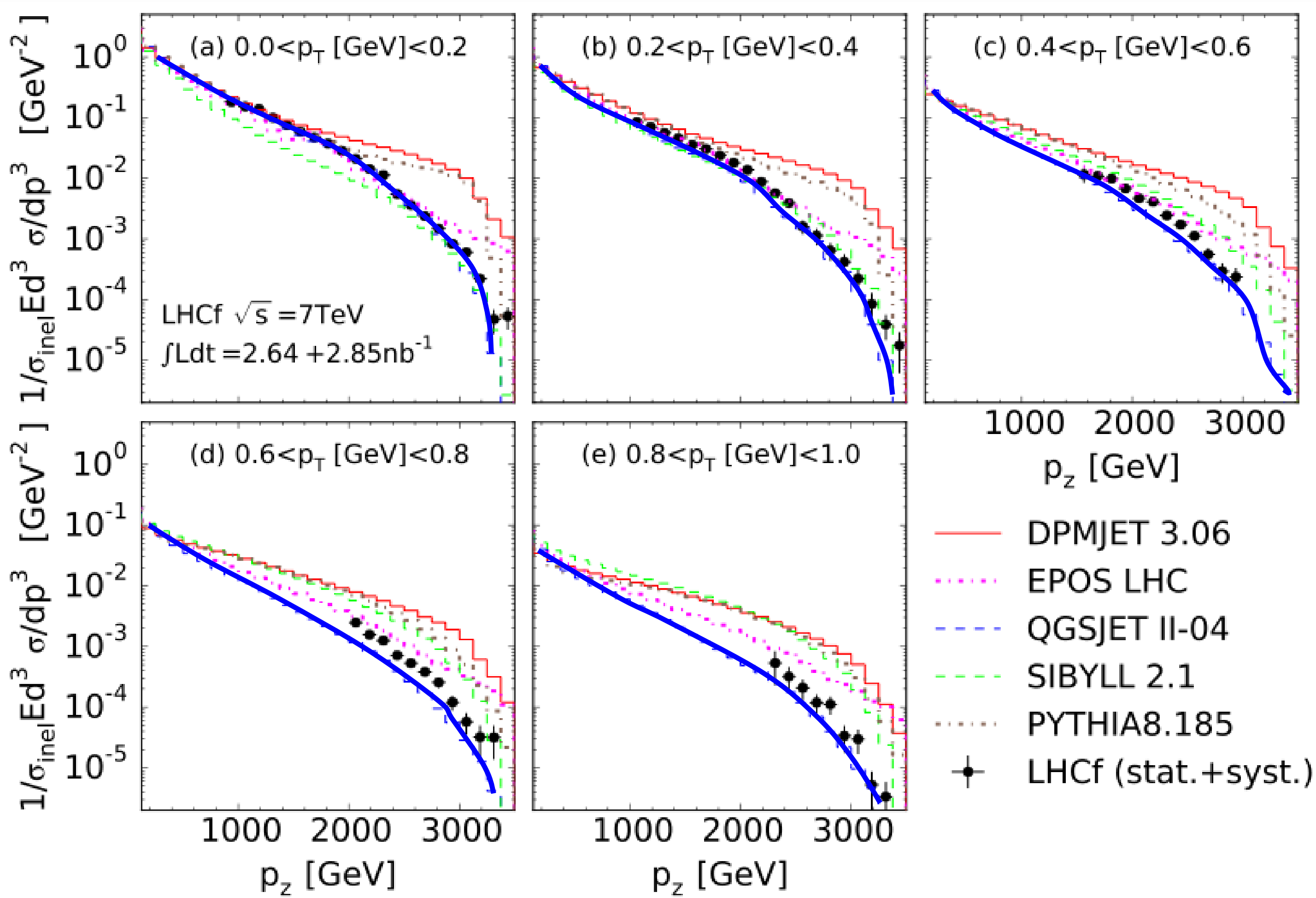
PRD 94 (2016) 032007



DPMJET and Pythia overestimate over all E-p_T range

π^0 p_z spectra in 7 TeV pp collisions → QGSJET

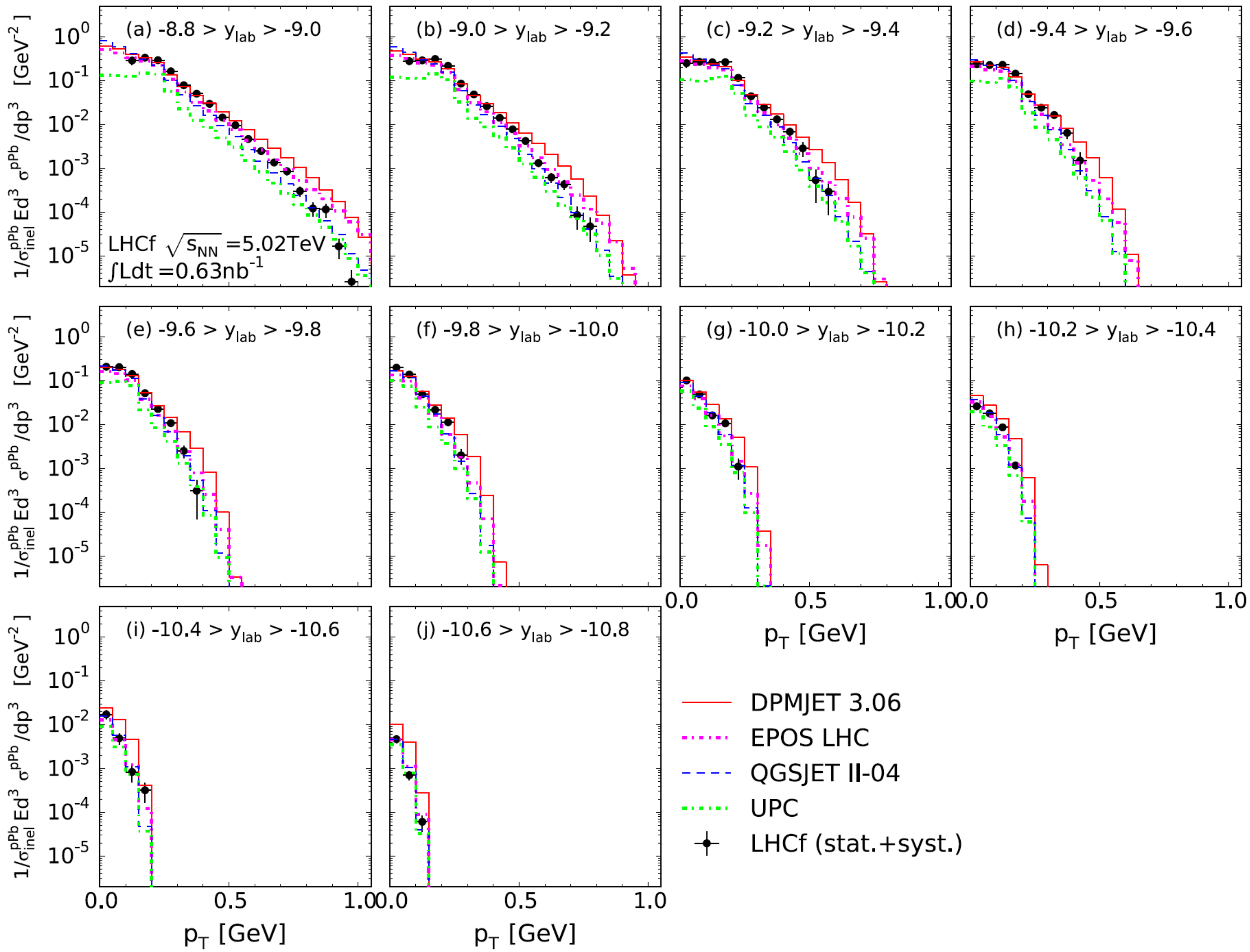
PRD 94 (2016) 032007



- Very good agreement in shape, slightly underestimate at high p_T
- Totally slightly underestimate

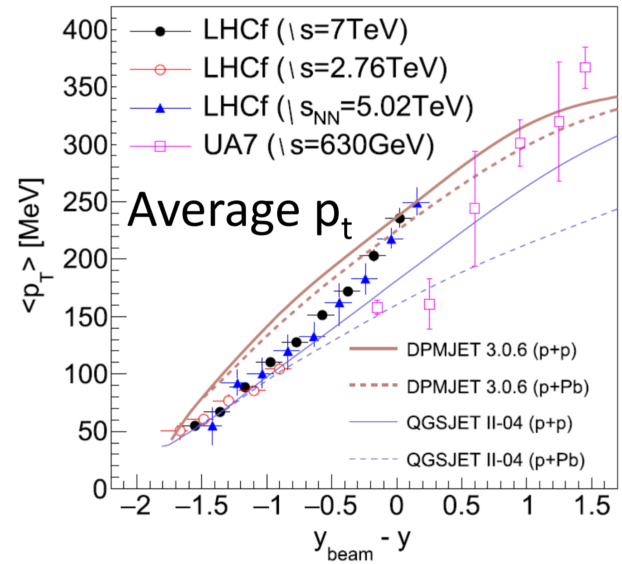
Neutral pions in p+Pb @ 5 TeV (2013 run)

MEASUREMENTS OF LONGITUDINAL AND TRANSVERSE … PHYSICAL REVIEW D **94,** 032007 (2016)



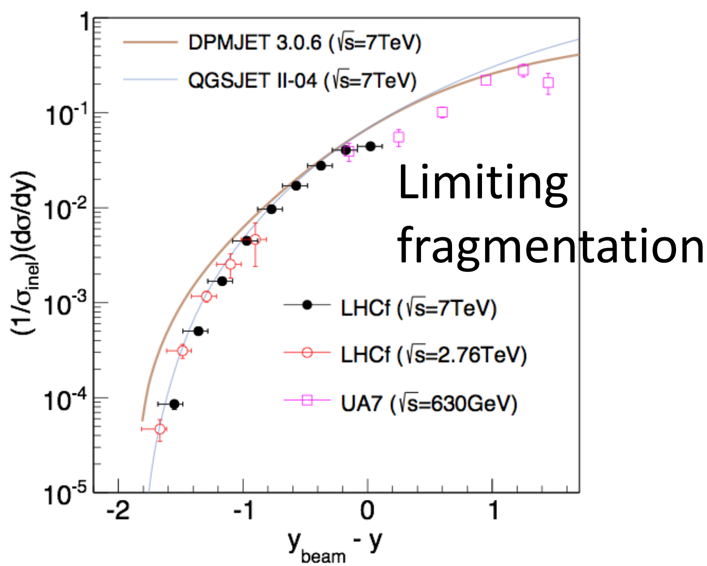
Scaling for neutral pions

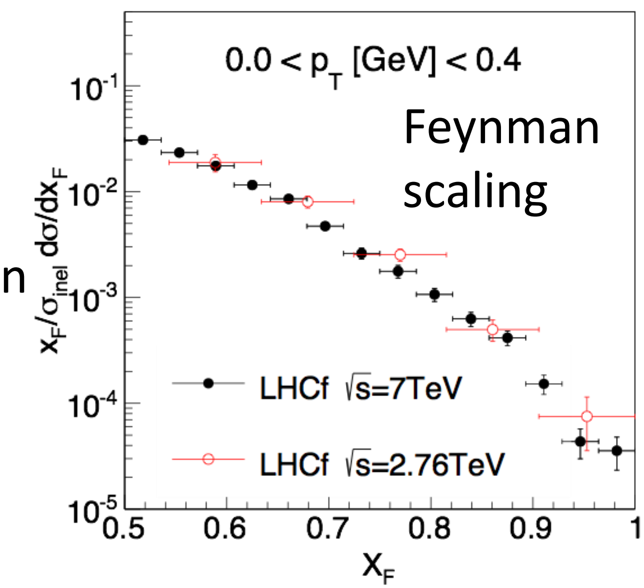
PHYSICAL REVIEW D **94,** 032007



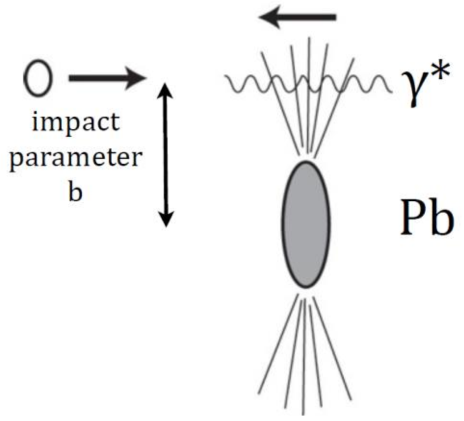
- Scaling laws are a fundamental tool to safely extrapolate predictions to the UHECR regime
- Tested $<p_T>$, limiting fragmentation and feynman scaling @ 2.76TeV —5.02 TeV– 7TeV
- good scaling within uncertainties
- Wider coverage expected in y and p_T with 13TeV data
- Wider √s coverage with RHICf experiment in 2017 at √s=510GeV
- RHICf results useful also to understand discrepancies with UA7 results

Reasonable scaling can be inferred from the data ~ 10-20%





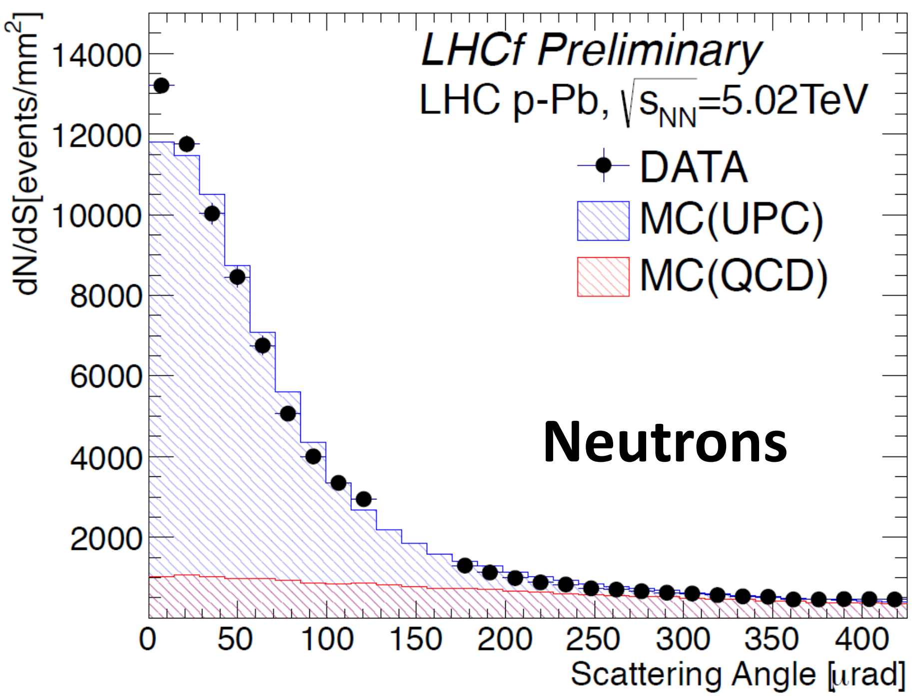
UPC contributions in the LHCf data



$$p\text{+Pb} \longrightarrow \text{X+ Pb} \Leftrightarrow p + \gamma^* \longrightarrow \text{X}$$

Estimation of contributions from UPC:

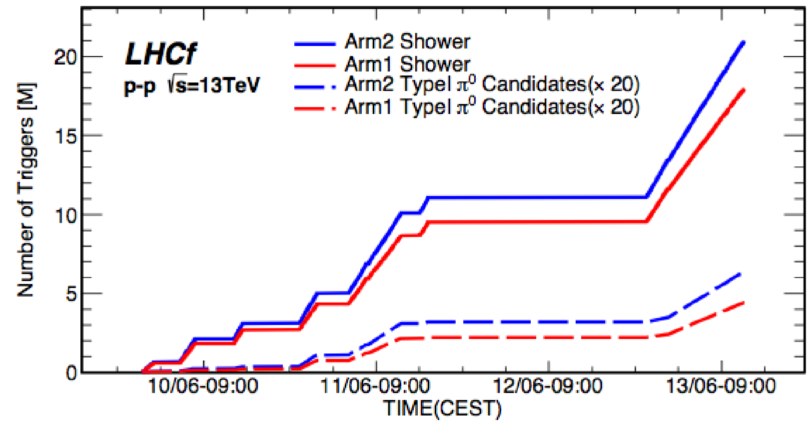
- STARLIGHT to simulate the vitual photon flux
- SOPHIA for the low energy photon-proton Interactions
- PHYTIA and DPMJET for the low energy photon-proton Interactions



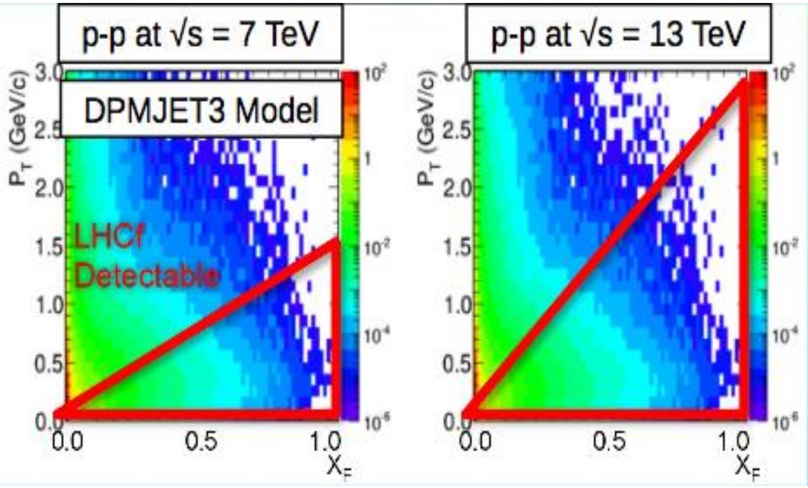
Last LHCf run: p+p @ 13 TeV (2015)

1) Single Photon analysis

2) Hadron analysis

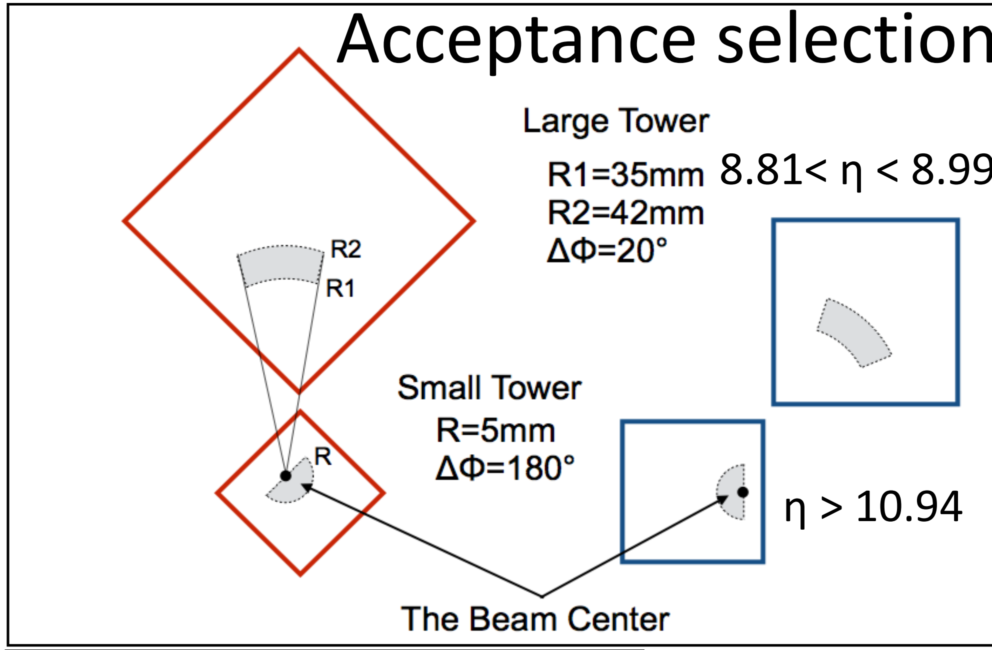


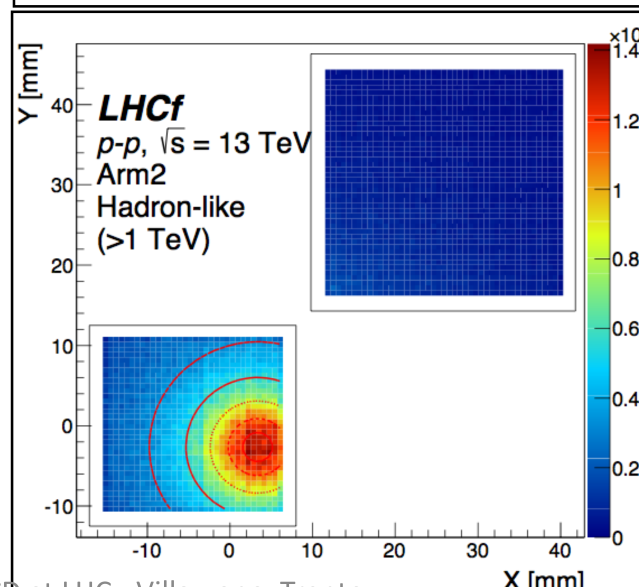
- During Week 24, June 9-13 2015, LHCf dedicated low-lumi run
- Total 26.6 hrs with $L=0.5\sim1.6.10^{29}$ $cm^{-2}s^{-1}$ ($16\ nb^{-1}$)
- ~39 M showers, 0.5 M π^0 obtained
- Trigger exchange with ATLAS
- Detector removal on June 15th during TS1
- Run was very successful!!!!



Single photon analysis for pp 13 TeV

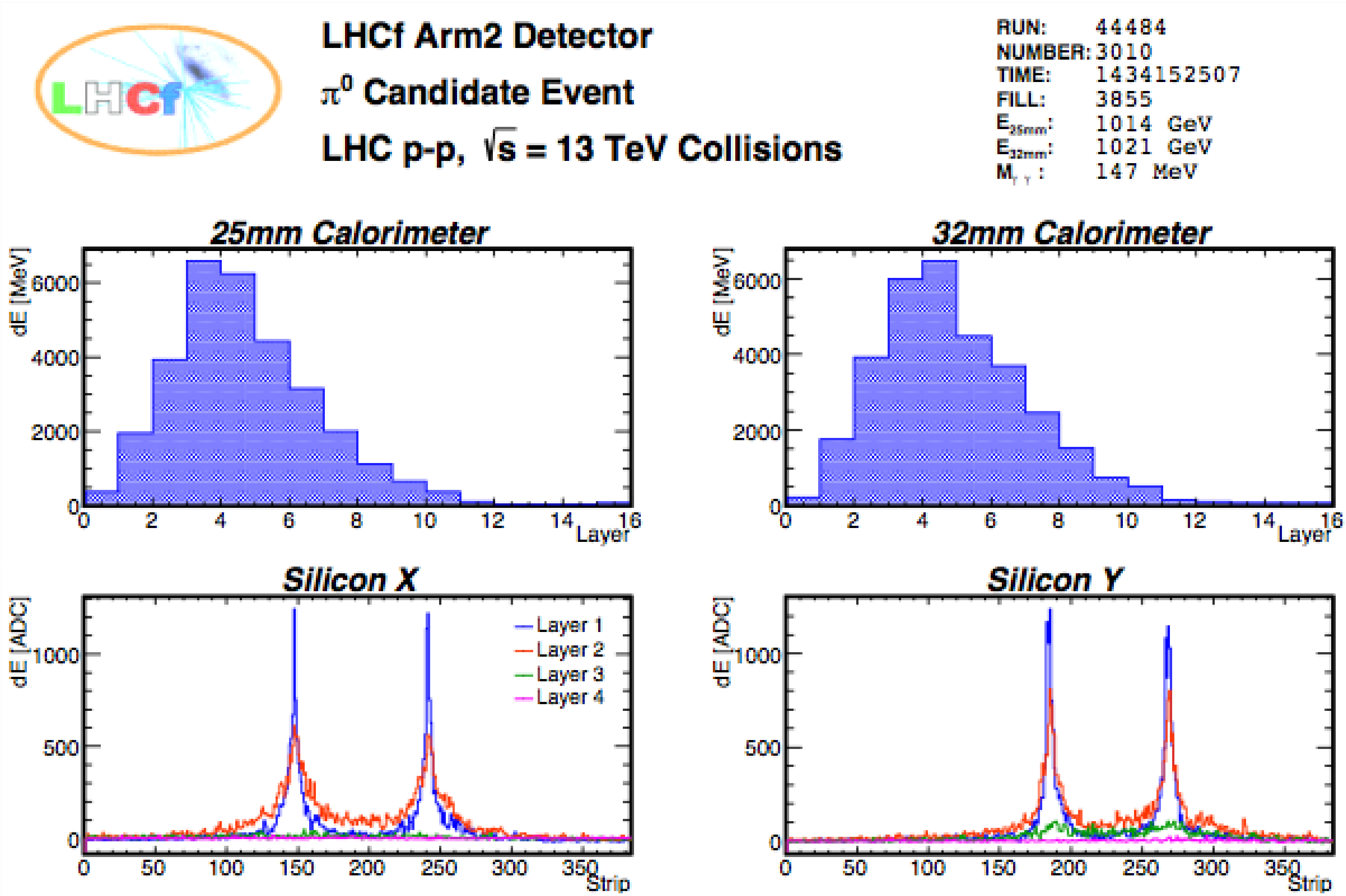
- Data set :
  - 12 June 22:32-1:30 (3 hours)
  - Fill # 3855, μ ~ 0.01
  - $\int L dt = 0.191\ nb^{-1}$ for both detectors
- On-going analysis
  - Event Selection
    - Photon/hadron selection
    - Multi-Hit event rejection
  - Corrections
    - PID correction
    - Multi-Hit correction
    - Unfolding
  - Combination of Arm1 and Arm2 spectra considering all the systematics



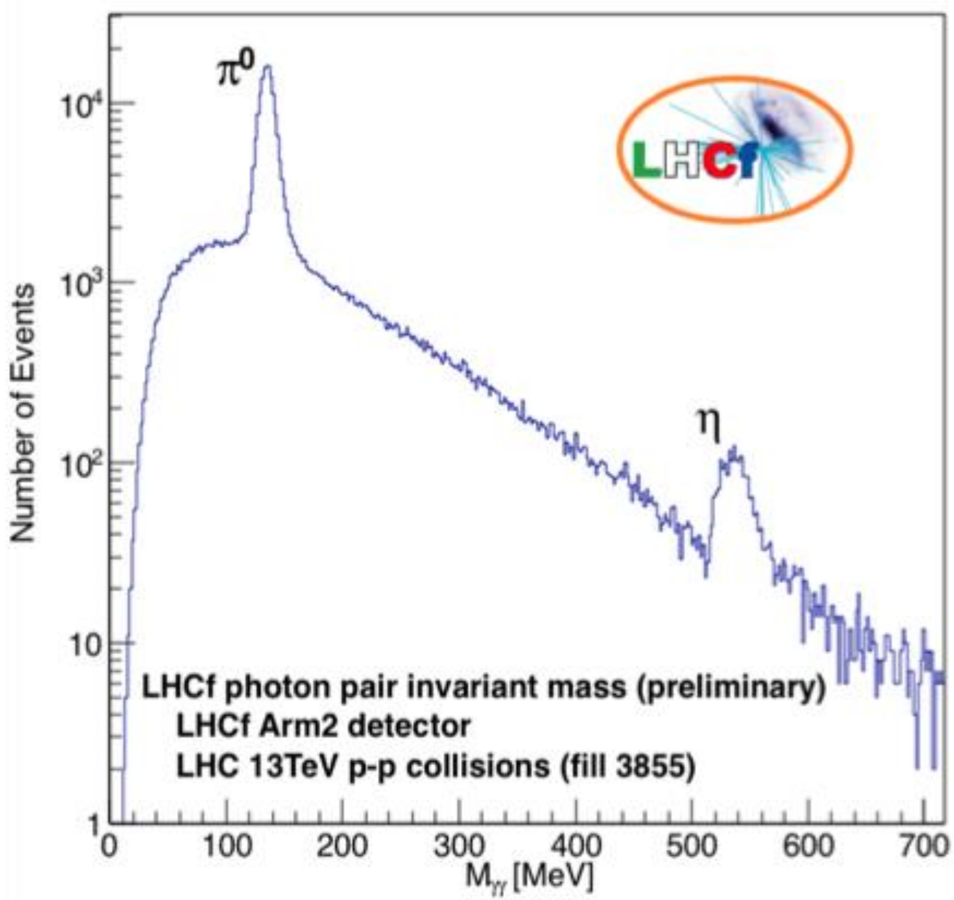


Beam center was estimated from the hit-map of high energy hadron events

Very high energy pions!

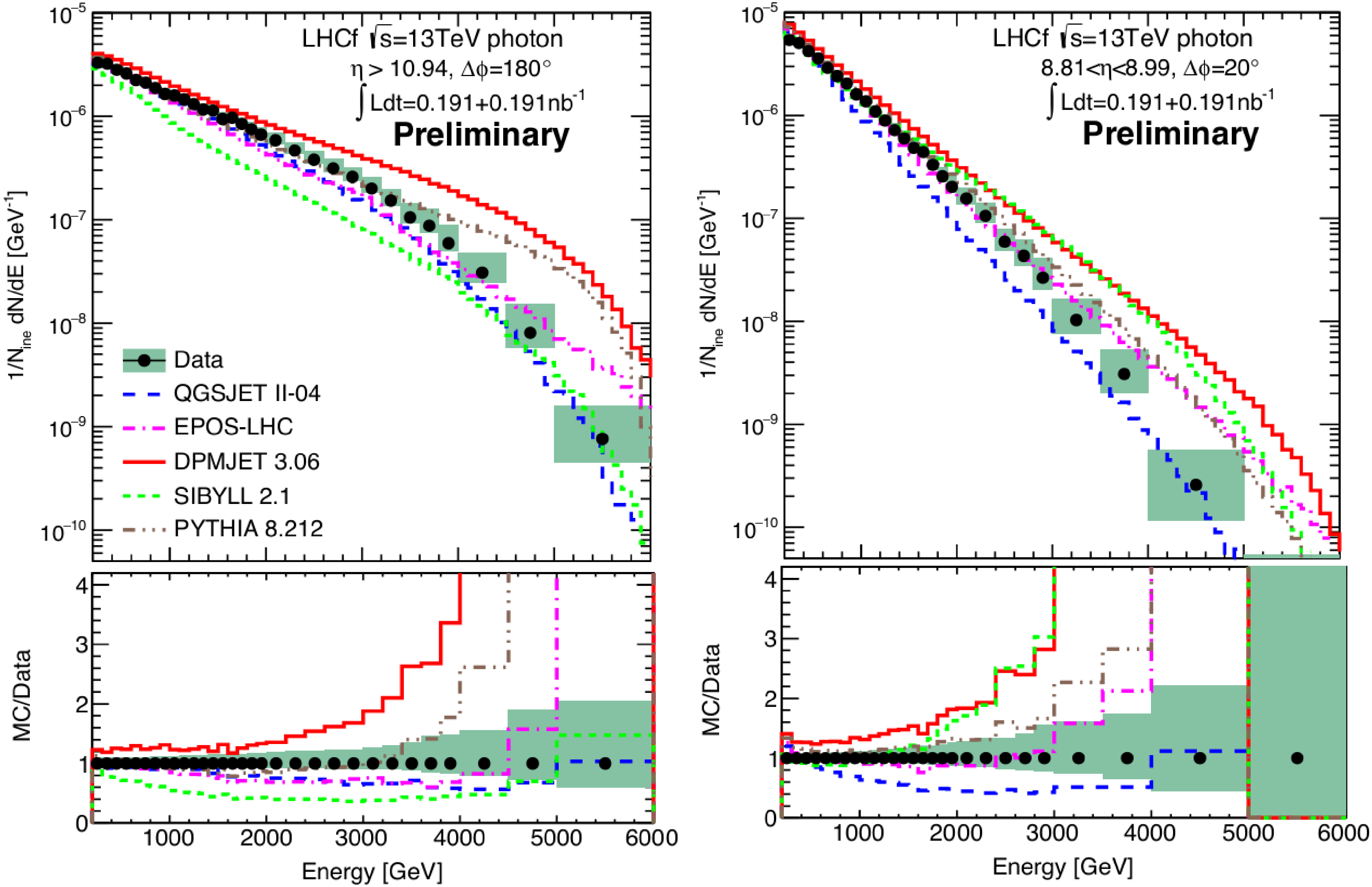


Photon pairs - invariant mass



- Mandatory tool for energy scale calibration
- Importance of η due to also charged decay mode
- We proposed to use also to calibrate models for muon-neutrino flux
- Big interest from model developers

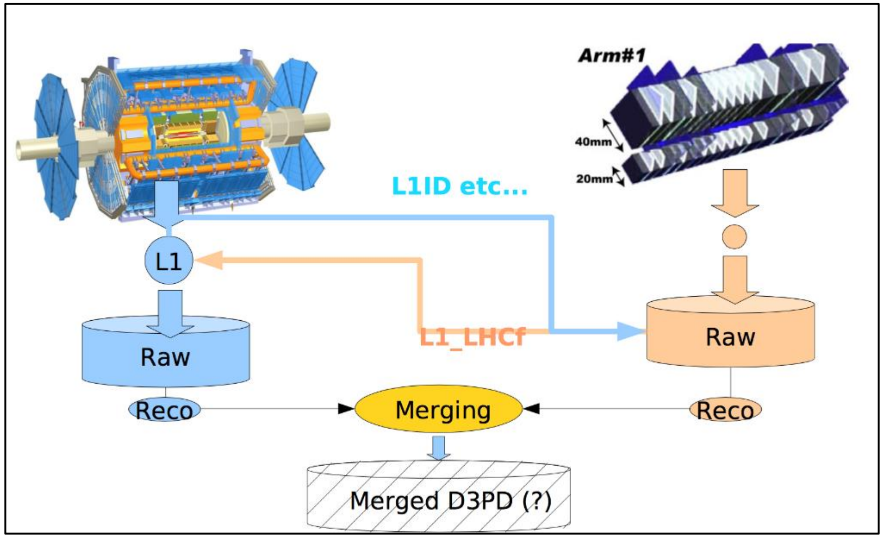
Preliminary photon energy spectra in pp 13 TeV

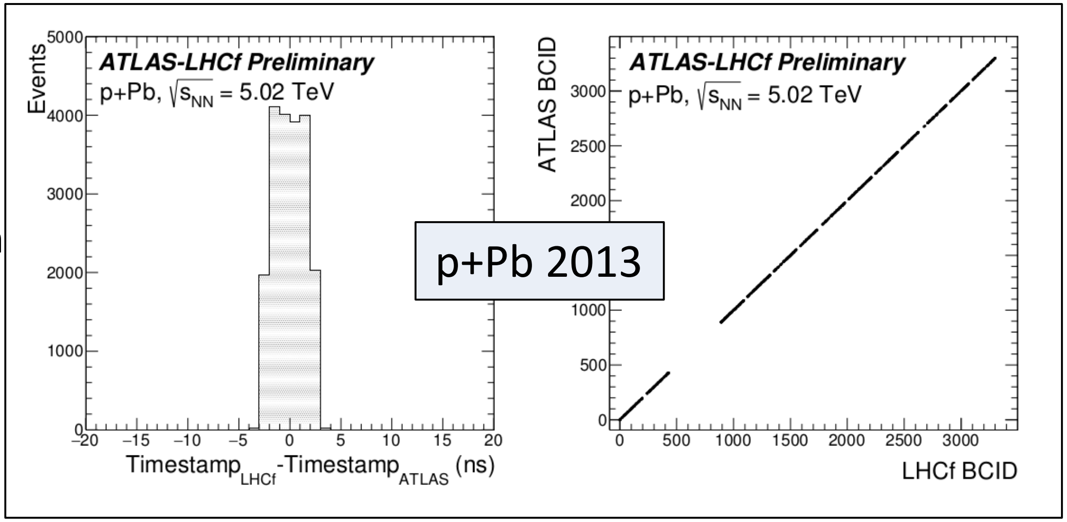


ATLAS-LHCf combined data analysis

- Trigger sharing with ATLAS at ~100 Hz in 2015 p+p (10 Hz in 2013 p+Pb)
- Off-line event matching
- **Status** (p+p 2015)
  - Event matching successfully verified
- Internal note (p+Pb 2013)
  - **ATL-PHYS-PUB-2015-038**
- Important to separate the contributions due to diffractive and non-diffractive collisions
  - It makes more easy for developers improving the hadronic interaction models

... + ALFA !!!





+ A commonly triggered event

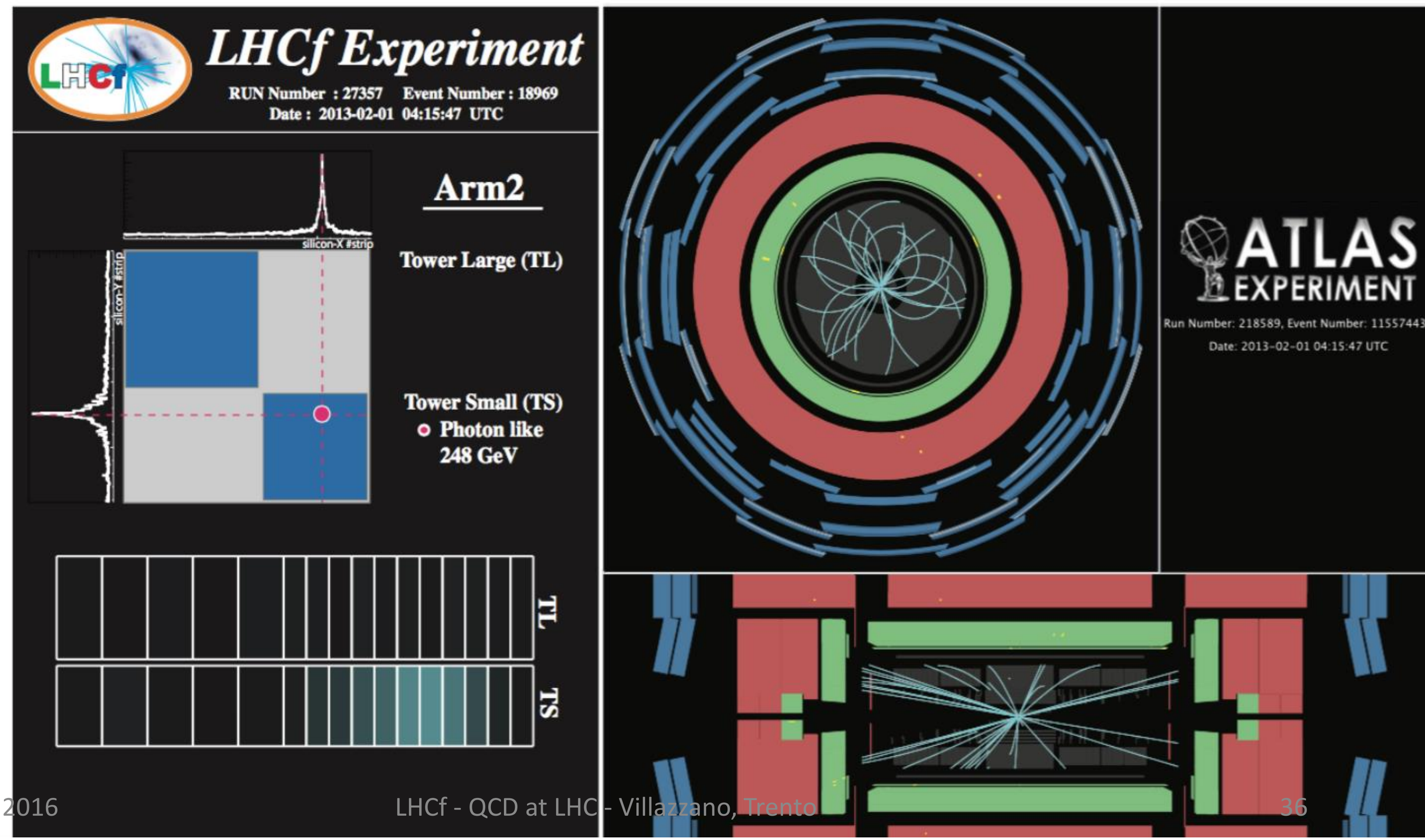
ATLAS LHCf NOTE

August 26, 2015

ATL-PHYS-PUB-2015-038
30 August 2015

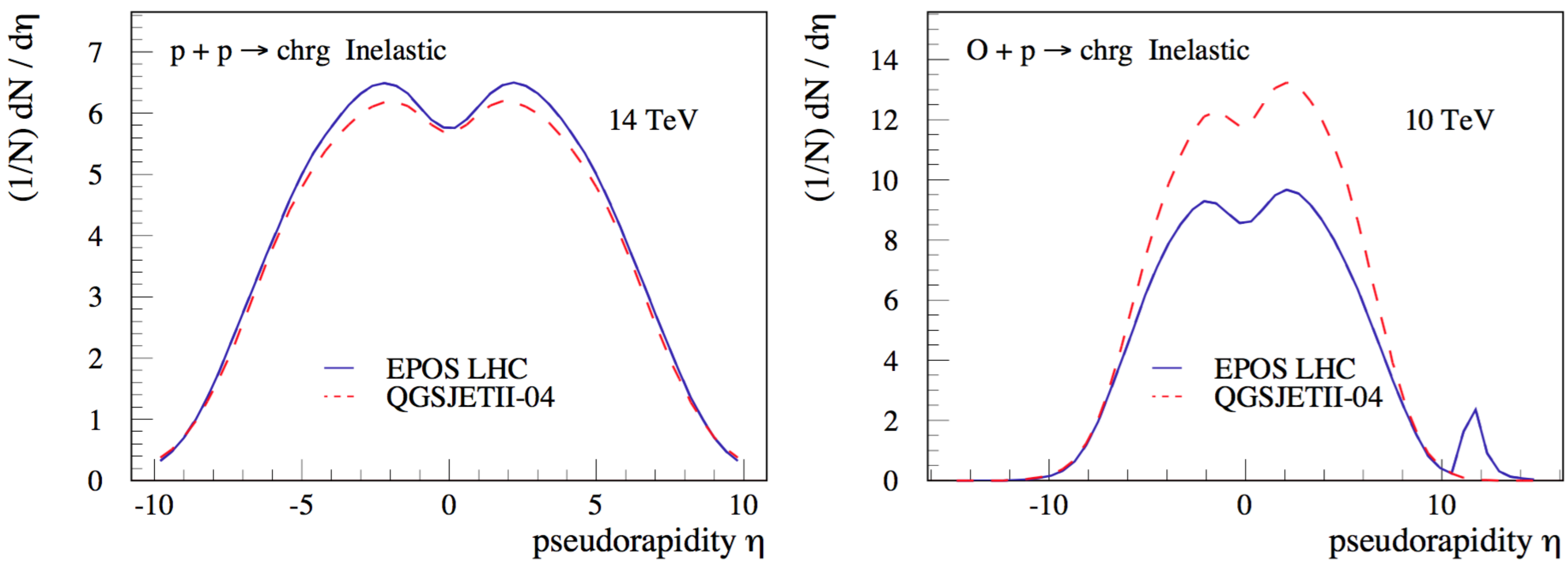
Classification of Events in the Combined ATLAS-LHCf Data Recorded During the p+Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

The ATLAS and the LHCf Collaborations



The far future @ LHC

- The most promising future at LHC for LHCf involve the proton-light ions collisions
- To go from p-p to p-Air is not so simple….
    - Comparison of p-p, Pb-Pb and p-Pb is useful, but model dependent extrapolations are anyway necessary
- Direct measurements of p-O or p-N could significantly reduce some systematic effects

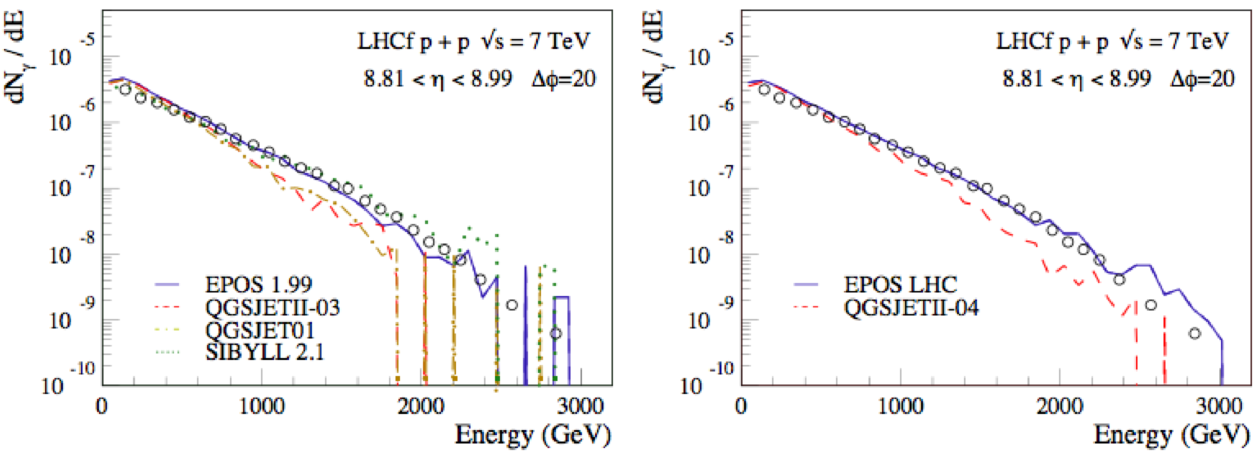


Conclusions

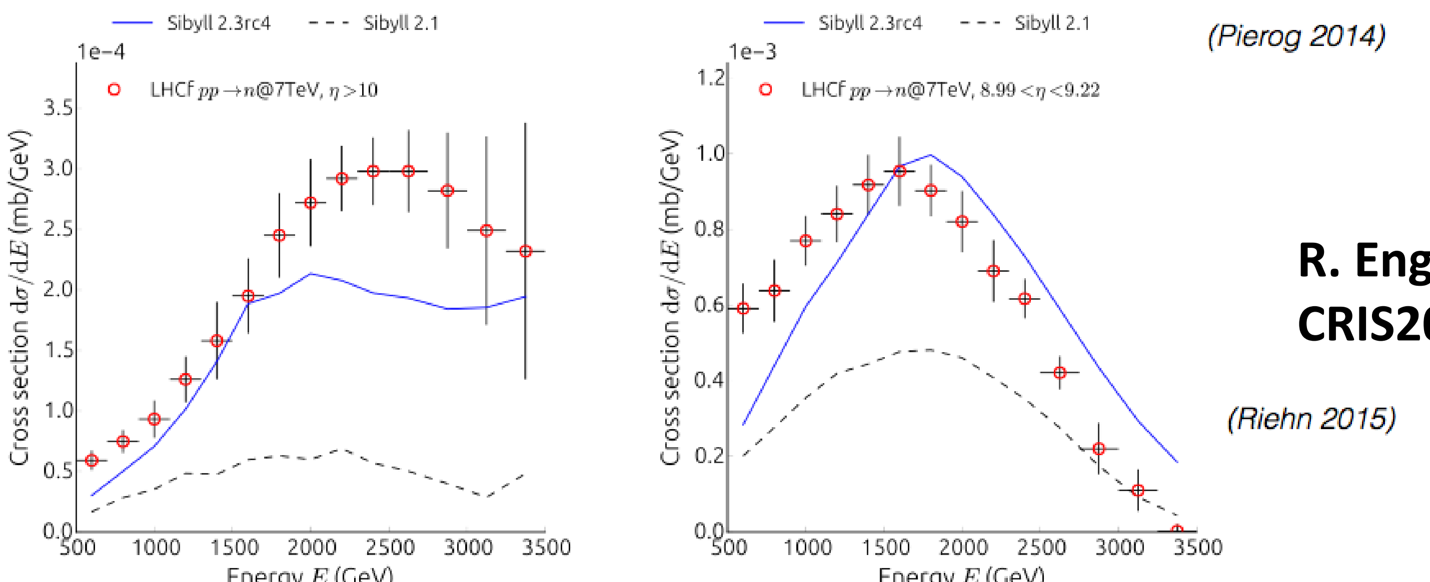
- LHCf has measured precisely very forward γ, n and π^0 production in p-p and p-Pb collision at $E_{CM} \leq 7$ TeV
  - Improving the **knowledge of hadronic interaction models** for HECR Physics
  - Results with **hadrons** interesting for the **muon excess** “problem” in EAS
  - Verification of **scaling hypothesis** important for extrapolating at higher energy
  - p+Pb results important to understand **nuclear medium effects**
- Very successful **13 TeV pp run** in June 2015
  - **Preliminary photon spectra** ready, other analyses are on going
- Intensive 2016-2017 program:
  - 8.1 TeV (and 5 TeV) p+Pb collisions at LHC in November 2016
  - 510 GeV p+p with polarized beam at RHIC in May-July 2017
- More results will come in the next years… while **waiting for p+Light Ion run** at LHC

Backup slides

Tuning of hadronic interaction model with LHCf data



(Pierog 2014)



(Riehn 2015)

R. Engel CRIS2016

Absolute energy scale uncertainty (pp 13 TeV)

The uncertainty of energy scale is the largest contribution to the systematic uncertainty of the final spectra. The energy scale of detector is checked by using $M_{\gamma\gamma}$ peak of π^0

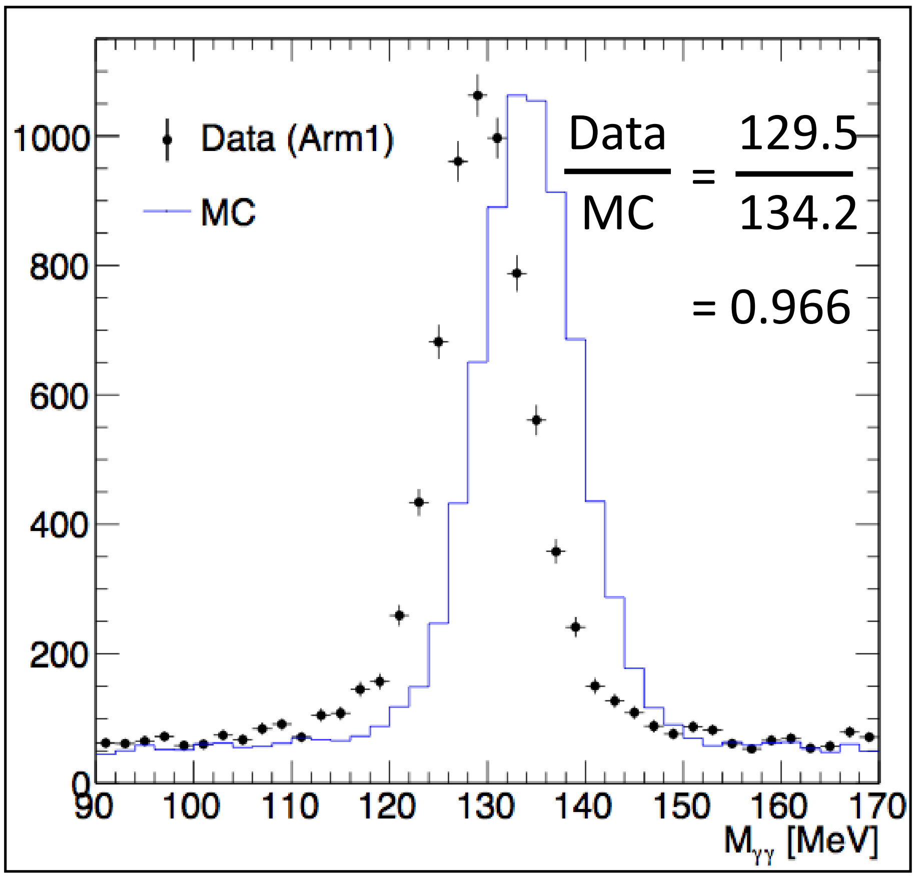


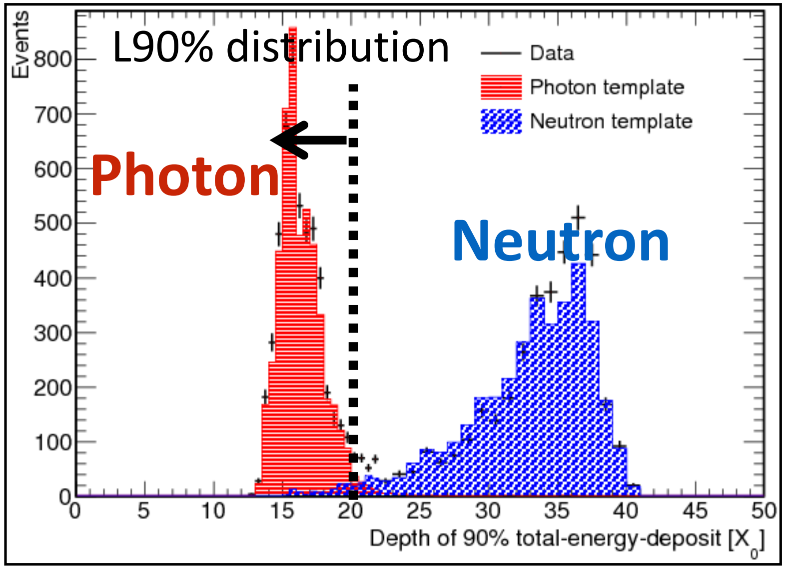
Table: shift of π^0 mass peak

	New detector	Old detector
Arm1	**-3.4%**	+7.8%
Arm2	**-2.1%**	+3.7%

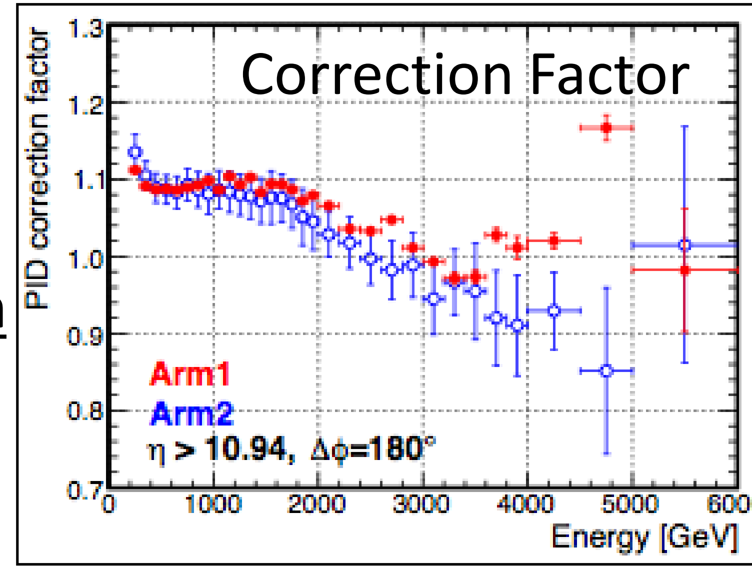
Thank to the careful energy-calibration of detector by the CERN-SPS beam test, the shift of π^0-mass-peak is reasonable compared to the uncertainty of calibration, 3.5%. The systematic error is expected to be smaller than at the previous result at √s=7TeV

Corrections: particle ID and multiple hits

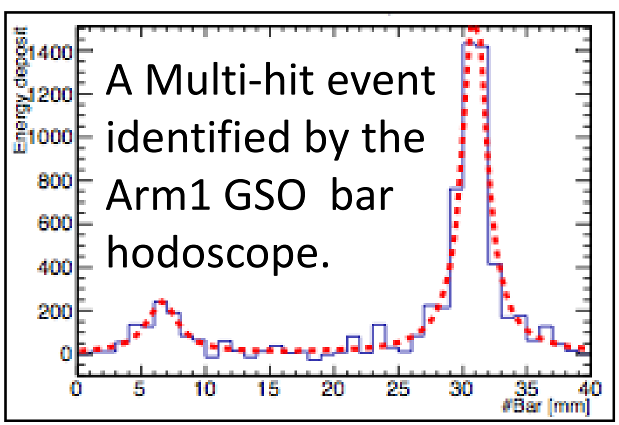
The correction factor was driven from the template fitting method of L90% distribution



PID correction

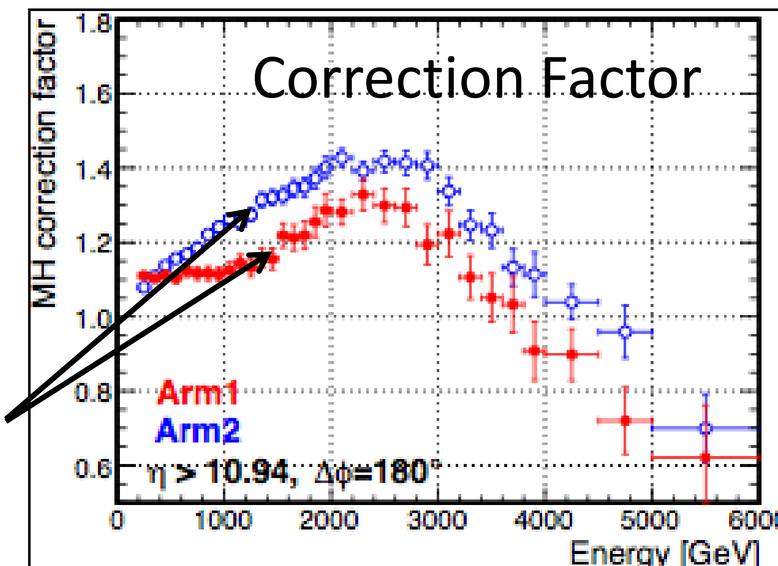


Effect of the multi-hit event cut is estimated based on MC with QGSJET2 model

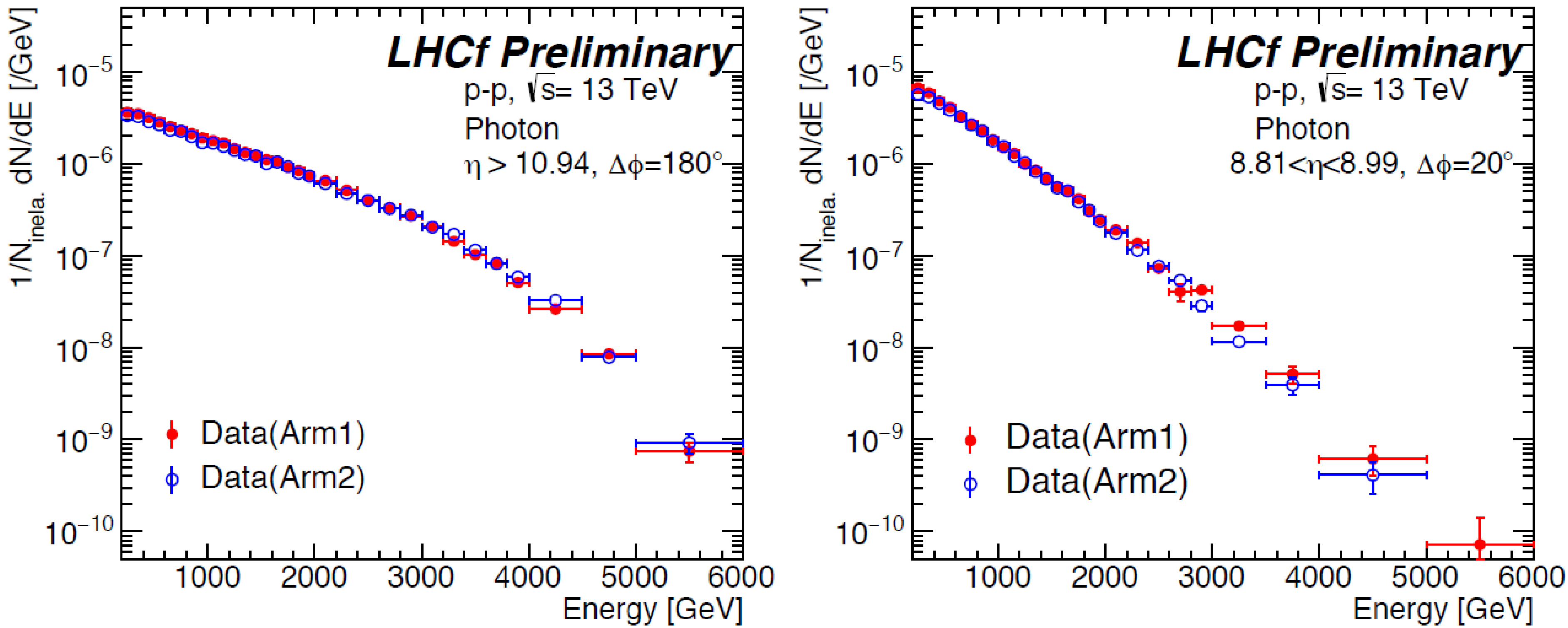


Multi-hit correction

Difference due to the different geometrical shape of calorimeters



Comparison Arm1/Arm2

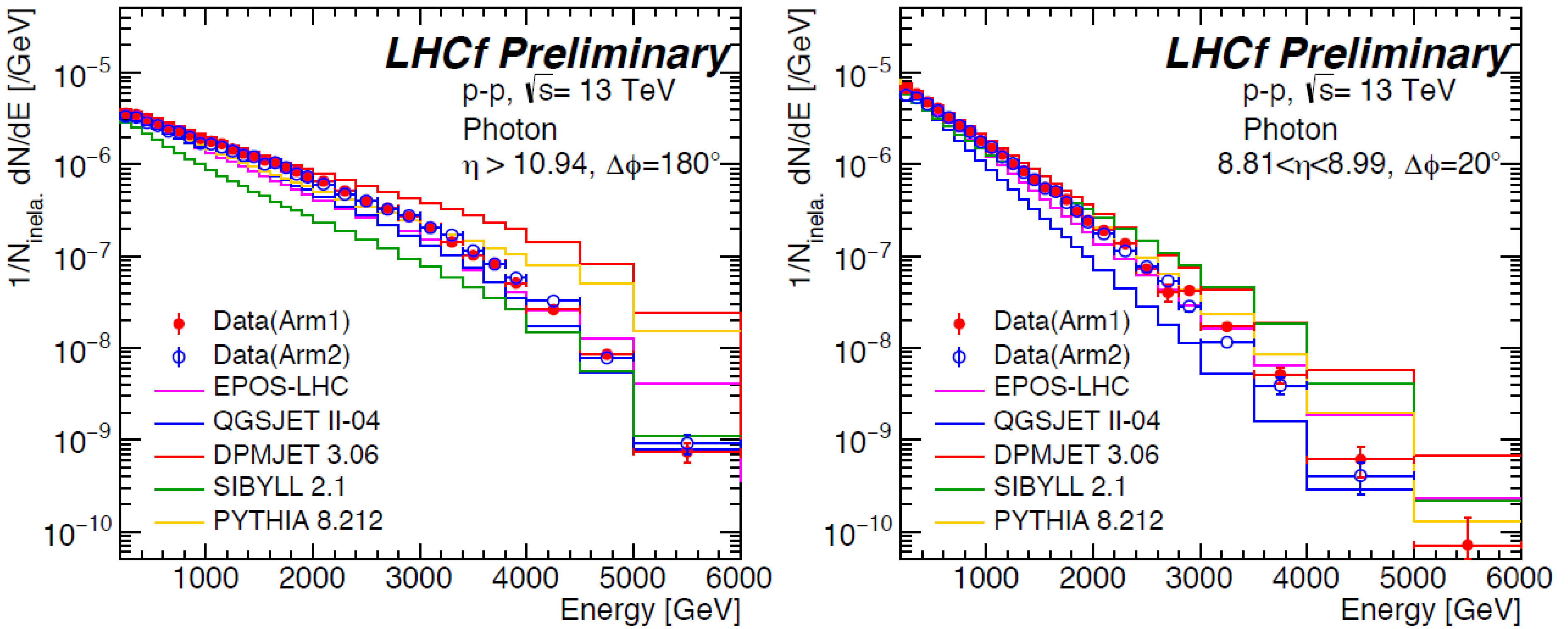


Error bars show only the statistical errors.

The evaluation of the systematic uncertainties is in progress

We would like to acknowledge the ATLAS collaboration for providing the measurement of the luminosity and of the cross section.

Preliminary comparison with models



Error bars show only the statistical errors.

Impact of common ATLAS-LHCf trigger

PYTHIA MC study @ 14 TeV. Diffractive event selection efficiency and purity:dropping events with (PT > 100 MeV/c & Nch>1 in |η|<2.5) @ATLAS

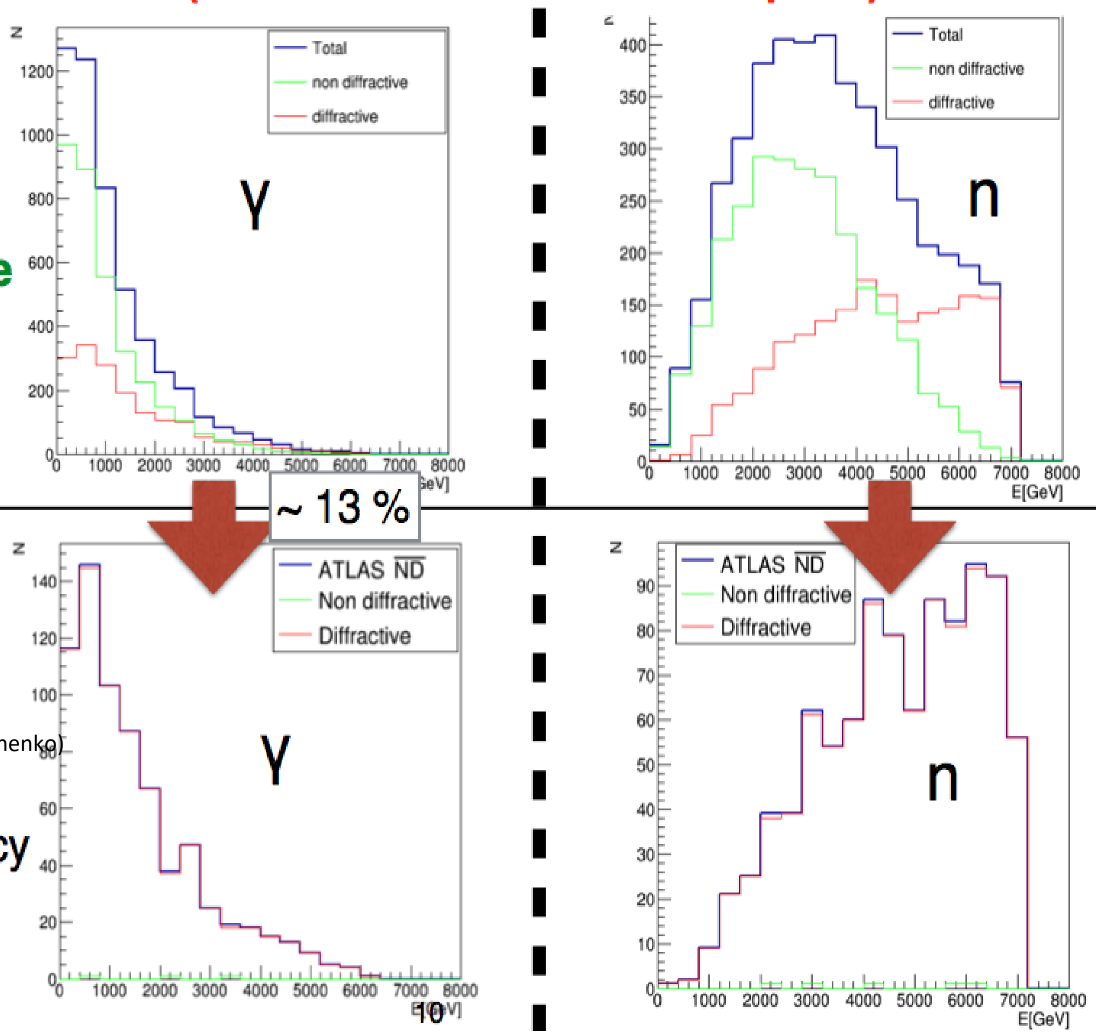
All events

in MC true,
Non-diffractive
Diffractive

w/ event selection (not ND)

key: low mass diffraction (Ostapchenko)

For diff. events,
35-40% efficiency
99 % purity

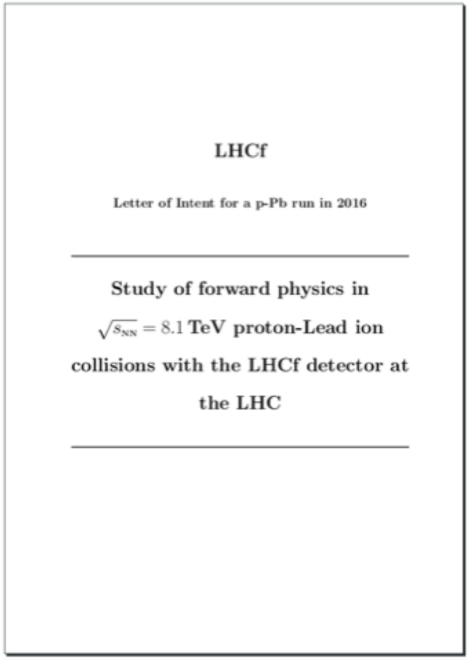


p-Pb at 8.1 TeV

Ony ARM2 Detector

Motivations:

- Statistics:
  - Measure π^0 with increased statistics wrt 2013 run
  - Possibility to detect the η meson
  - Combined ATLAS-LHCf data taken (very limited in 2013)
- Phase space
  - extend up to p_T>1 GeV/c
    - deviations from models suggested from 2013 data at high p_T
    - investigate pQCD phase-space region
- Scaling properties
  - Factor ~3 in energy (LAB ref.)
  - Extrapolation at extreme CR energies
  - Feynman scaling: spectra in x_F



LHCf

Letter of Intent for a p-Pb run in 2016

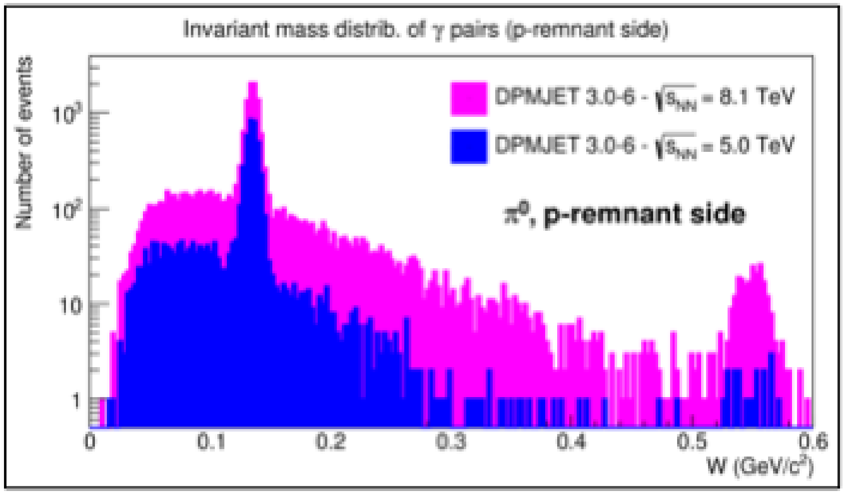
Study of forward physics in $\sqrt{s_{NN}} = 8.1$ TeV proton-Lead ion collisions with the LHCf detector at the LHC

The LHCf collaboration

O. Adriani[1,2], E. Berti[1,2], L. Bonechi[1], M. Bongi[1,2], G. Castellini[3], R. D'Alessandro[1,2], M. Haguenauer[4], Y. Itow[5,6], T. Iwata[7], K. Kasahara[7], Y. Makino[5], K. Masuda[5], E. Matsubayashi[5], Y. Matsubara[5], H. Menjo[8], Y. Muraki[5], Y. Okuno[5], P. Papini[1], S. Ricciarini[3], T. Sako[5,6], N. Sakurai[9], T. Suzuki[7], Y. Shimizu[10], T. Tamura[10], A. Tiberio[1,2], S. Torii[7], A. Tricomi[11,12], W. C. Turner[13], M. Ueno[5], K. Yoshida[14], and Q.D. Zhou[5]

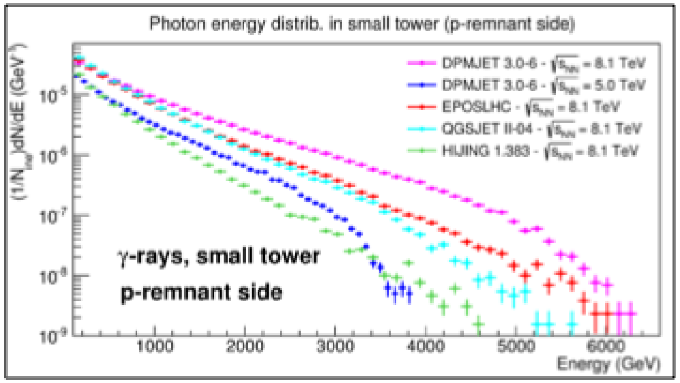
[1]INFN Florence, Italy
[2]University of Florence, Italy
[3]IFAC-CNR, Florence, Italy
[4]École-Polytechnique, Paris, France
[5]Institute for Space-Earth Environmental Research, Nagoya University, Japan
[6]Kobayashi Maskawa Institute for the Origin of Particles and the Universe, Nagoya, Japan
[7]Waseda University, Tokyo, Japan
[8]Graduate School of Science, Nagoya University, Japan
[9]Tokushima University, Japan
[10]Kanagawa University, Yokohama, Japan
[11]INFN Catania, Italy
[12]University of Catania, Italy
[13]LBNL, Berkeley, California, USA
[14]Shibaura Institute of Technology, Japan

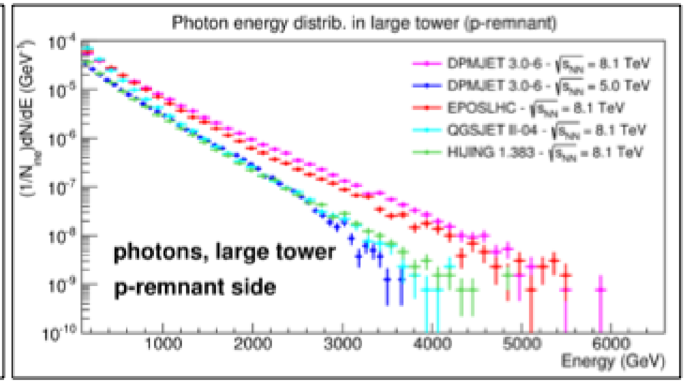
February 28, 2016



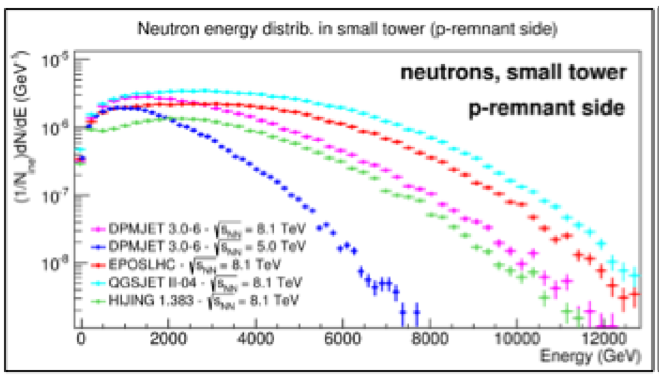
p-Pb at 8.1 TeV: γ & n spectra

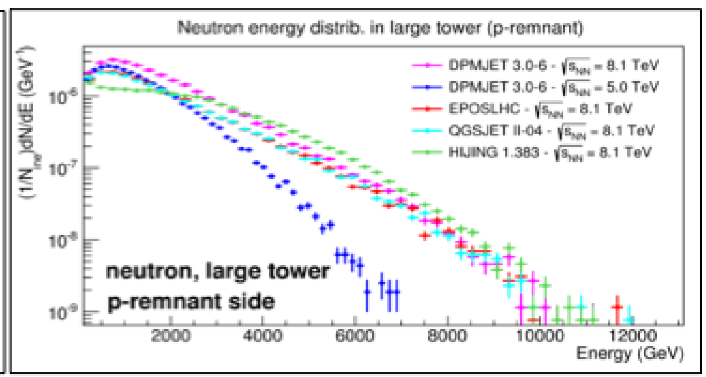
Expected **photon** distribution





Expected **neutron** distribution (35% energy resolution)





(CRMC)* framework has been used to simulate 10^7 collisions with 4 different hadronic interaction models:

- DPMJET 3.0-6 p+Pb
- EPOS-LHC p+Pb
- QGSJET II-04
- HIJING 1.383

Small calorimeter tower centered on the beam spot

Only p-remnant side considered

* We acknowledge T. Pierog, C. Baus and R. Ulrich for support

p-Pb at 8.1 TeV: run conditions

Beam conditions

- $L=10^{28}\text{-}10^{29} cm^{-2}s^{-1}$
- filling scheme will be chosen after PS and SPS beam commissioning
- proton bunch spacing 100 ns (we can afford!)
- Pb bunch spacing 100 ns but not all bunches will collide
- β^* ~ 0.6 m same as in high luminosity 8 TeV run
- crossing angle in IP1 (IP5) changed from 370 μrad to ~ 280 μrad (up2down)

Data Taking request based on simulation estimates

- Minimum integrated luminosity to detect $4*10^4$ π^0 ATLAS-LHCf common events for physics and energy calibration
- Data acquisition time depends on the bandwidth allowed by ATLAS for common data taking
  - 100 Hz common rate —>~1 day
  - 400 Hz common rate —>~12 h taking data in two different acceptance region

p-Pb run schedule

- 31/10 – 04/11: technical stop
  —> installation of Arm2 detector
- 10/11 – 15/11: 5 TeV operations
  —> possible run for LHCf
- 20/11 – 26/11: 8 TeV operations
  —> LHCf dedicated run between 25/11 and 26/11

Common acquisition with ATLAS during all operation:

- 100% of LHCf triggers acquired by ATLAS
- rate of 400 Hz (maximum rate for LHCf: 500-600 Hz)

p-Pb at 8.1 TeV: preparation

- ARM2 electronics reconditioned
- Setup in USA15 ready
  - all the cabling done
  - tuning of DAQ logic with 100 ns bunch spacing done
  - test of common operation with ATLAS successful
- Detector ready to be installed
  - cabling completed
  - test of silicon readout done
  - PMT signals checked