NPQCD 2015 workshop, Cortona 20-22 April 2015

Results from forward detectors @ LHC and their impact in the study of High Energy Cosmic Rays

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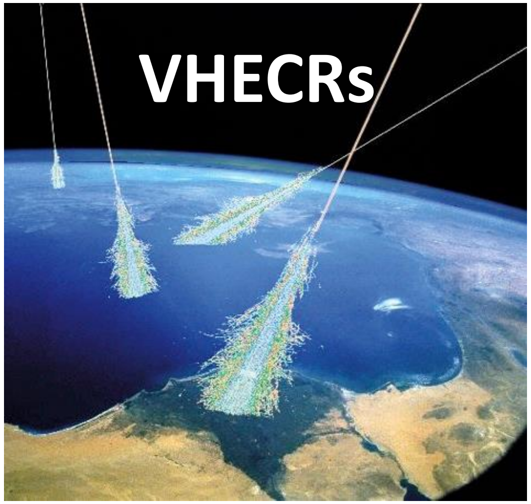
On behalf of the LHCf Collaboration

Outline

- INTRODUCTION
  i. Forward physics and VHECR
- FORWARD DETECTORS IN LHC EXPERIMENTS
- CASE I: IP5 → TOTEM & CMS – some results
  i. Measurement of cross section
  ii. Measurement of particle pseudorapidity distrib.
- CASE II: IP8 → LHCb
  i. Measurement of the forward energy flow
- FOCUS ON CASE III: IP1 → LHCf & ATLAS
  i. Introduction to the LHCf experiment
  ii. Details of detectors
  iii. Physics program
  iv. Main results
- SUMMARY

Study of Very High Energy Cosmic Rays



CR @ E > 100 TeV requires studying EAS development

Observation at ground level of the products of extensive air showers

- longitudinal distribution
- lateral distribution
- Arrival direction

Reconstruction of particle params and astrophysical quantities

- Energy spectrum
- Composition
- Source distribution

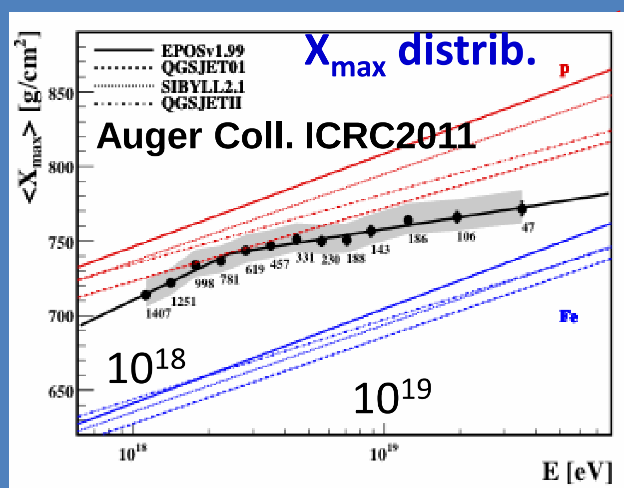
Example: study of the composition of primary CR with the variable X_{max}

(depth of air shower maximum in the atmosphere)

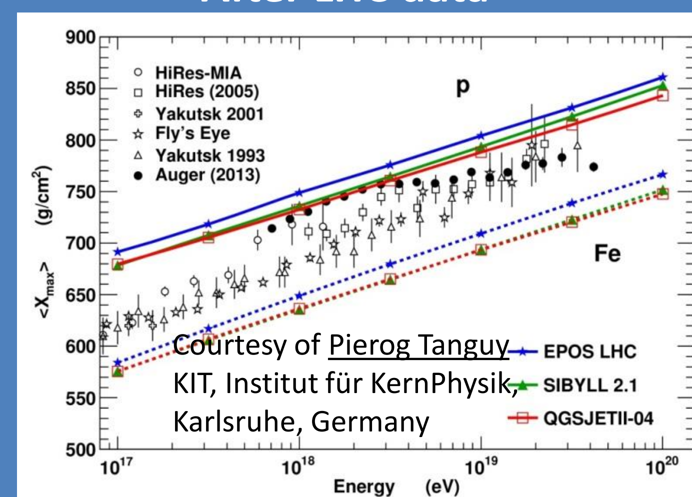
Uncertainty of hadron interaction models

Uncertainty in the interpretation of $<X_{max}>$ data

Before LHC data

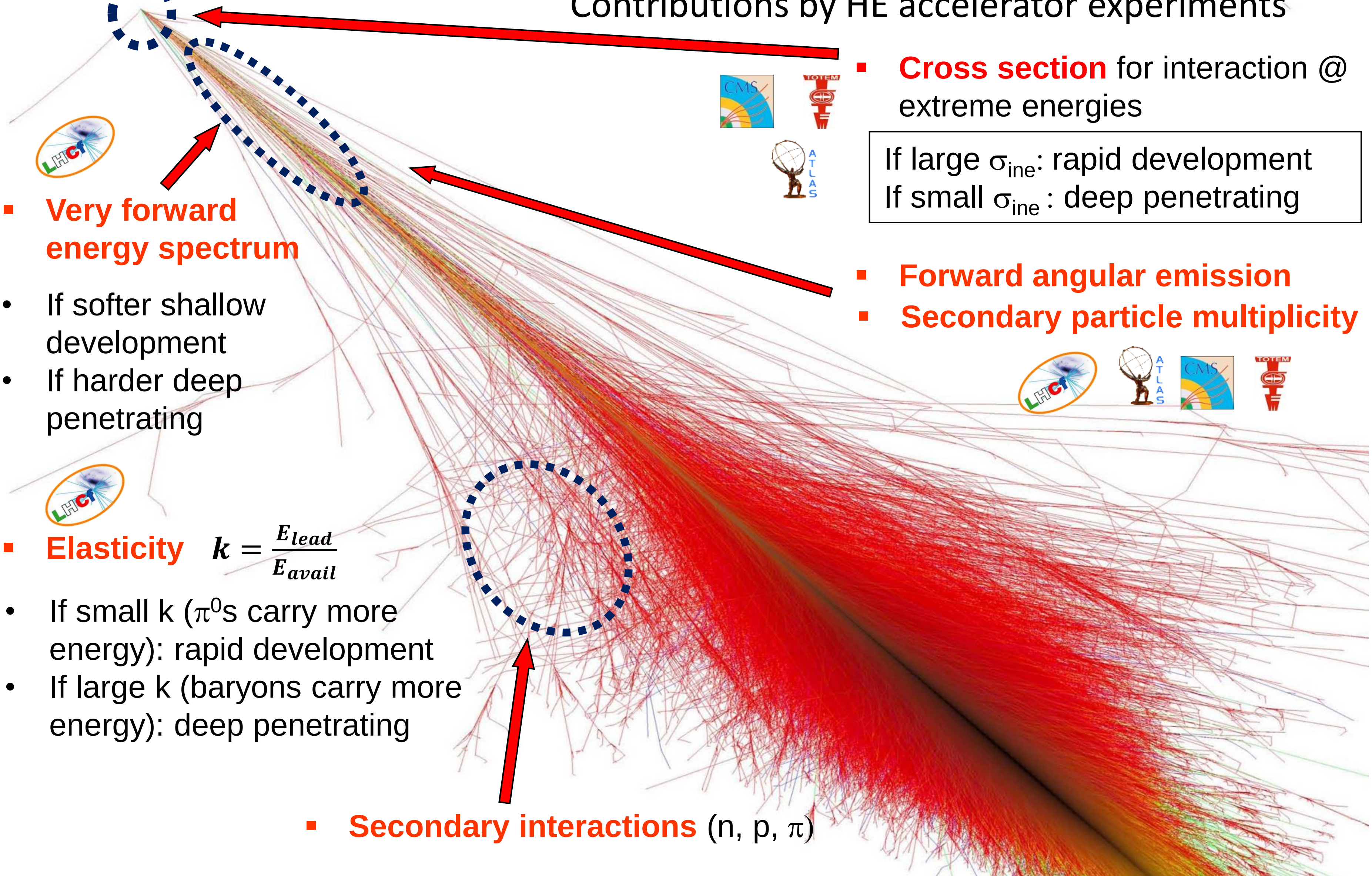


After LHC data



Study of Very High Energy Cosmic Rays

Contributions by HE accelerator experiments



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

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

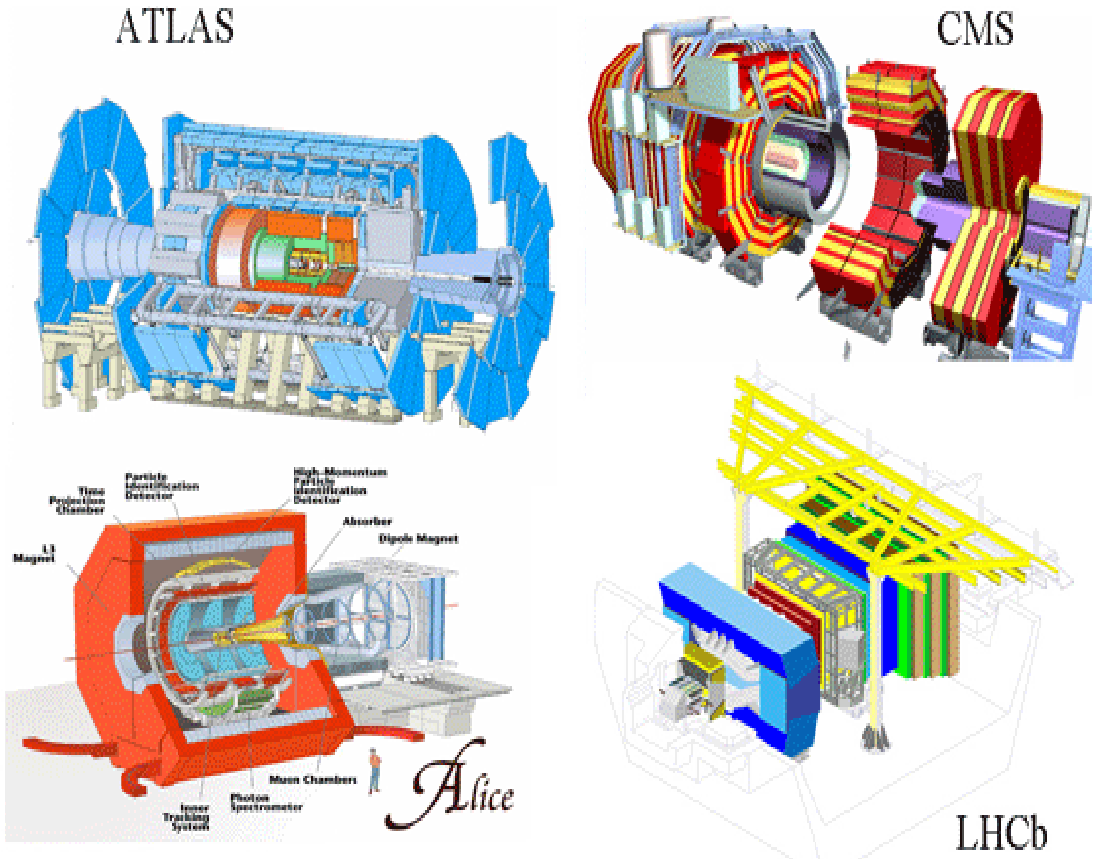
- **Very forward energy spectrum**
  - If softer shallow development
  - If harder deep penetrating

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

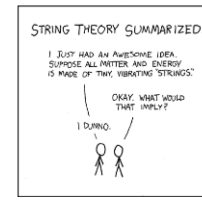
- **Elasticity** $k = \frac{E_{lead}}{E_{avail}}$
  - If small k (π^0s carry more energy): rapid development
  - If large k (baryons carry more energy): deep penetrating

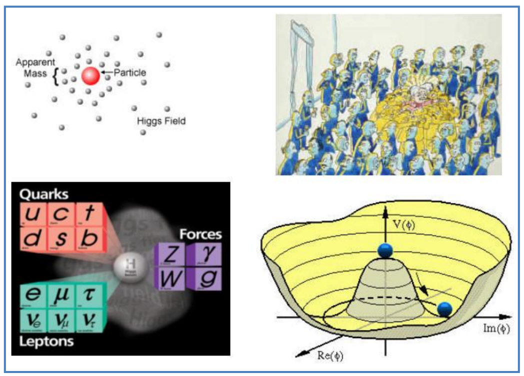
- **Secondary interactions** (n, p, π)

Impressive coverage of the central region



- The largest detectors for particle physics
- Surrounding the LHC Interaction Points
- Covering many fundamental physics items
- Designed for discoveries!





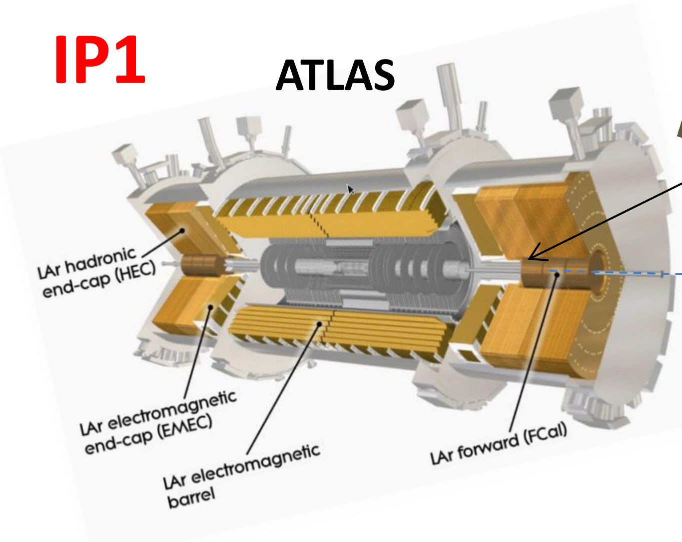
General purpose detectors (ATLAS, CMS,...) cover the spatial region at low rapidity.

Special detectors to access forward particles are necessary!

Fwd detectors: instrumentation at two IPs

IP1

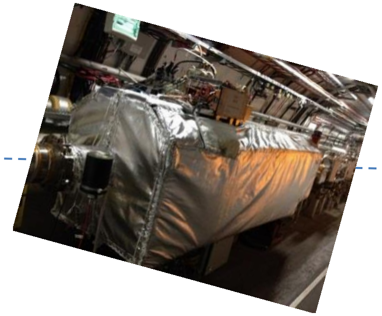
ATLAS



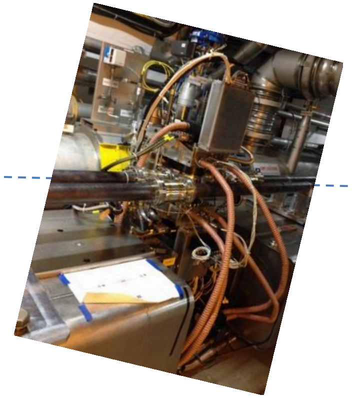
ATLAS LUCID
5.5 < |η| < 6

ATLAS FCAL
3 < η < 5

LHCf and ATLAS ZDC
(± 140 m); |η| > 8.4

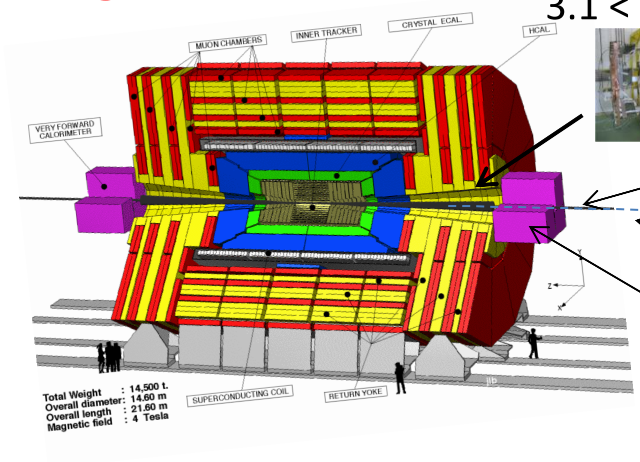


ATLAS ALFA RPs (± 240 m)
10.6 < η < 13.5

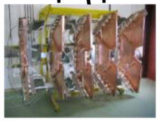


IP5

CMS

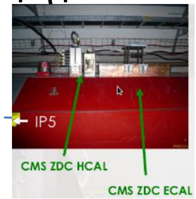


TOTEM T1 (CSC)
3.1 < |η| < 4.7

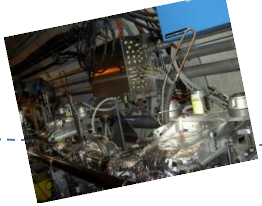


TOTEM T2 (GEM)
5.3 < |η| < 6.5

CMS ZDC (±140 m)
|η| > 8.4



TOTEM RPs
(±150 and ±220 m)



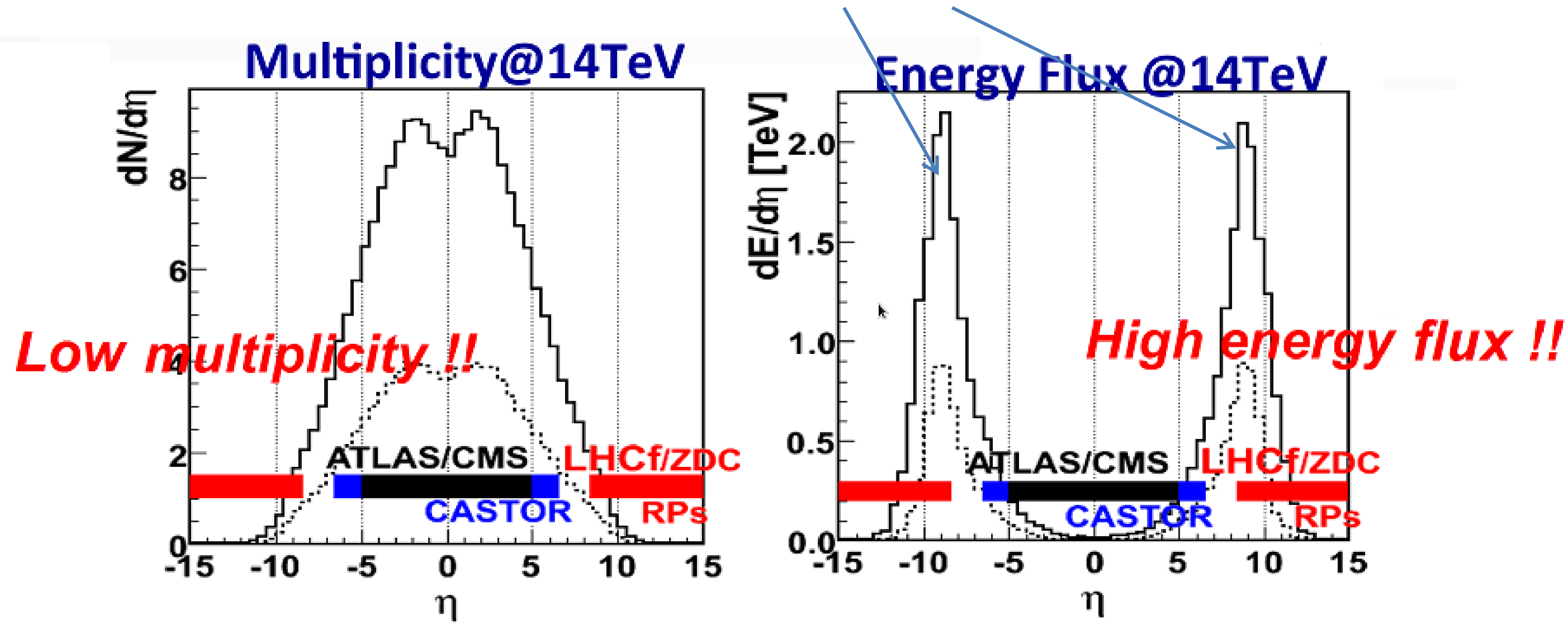
CMS HF
2.9 < |η| < 5.2

CMS CASTOR
5.1 < |η| < 6.6

W/quartz
Cherenkov calo

Energy and particle flow at LHC for pp @ 14 TeV

- High particle multiplicity in the central region
- High energy flux is in the forward region
  - Central detectors loose the peak of the energy flow

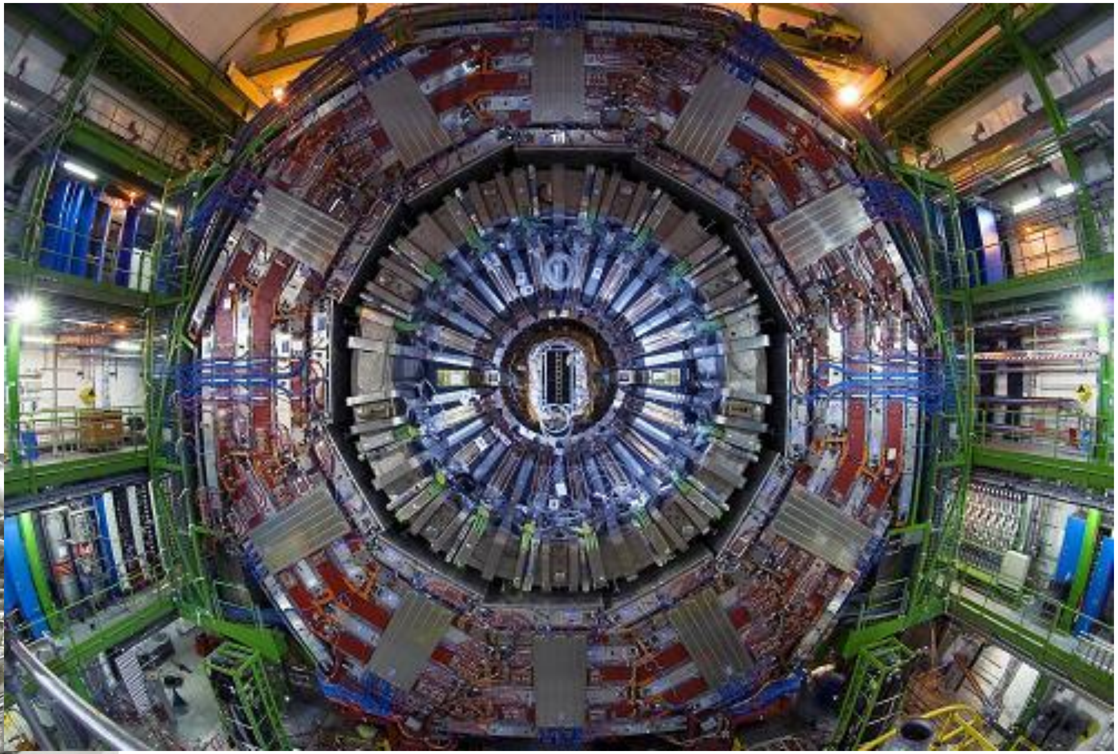


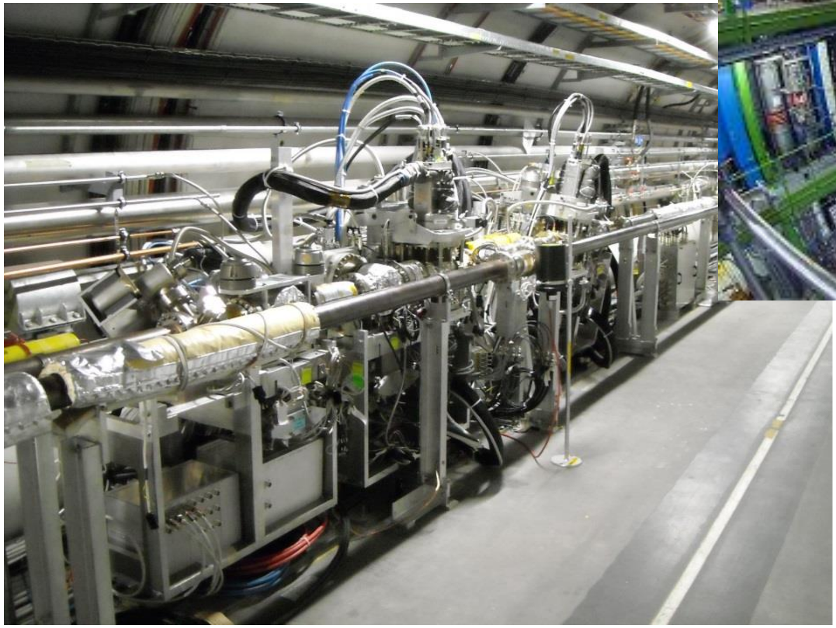
LHCf acceptance cover the region for $|\eta| > 8.4$

CASE I - IP5: TOTEM and CMS

TOTEM MAIN TOPICS

- total cross section
- elastic scattering
- diffraction





CMS

General purpose detector

TOTEM tracking components installed during LS1

TOTEM: measurement of cross section

Phys. Rev. Lett. 111, 012001 (2013)

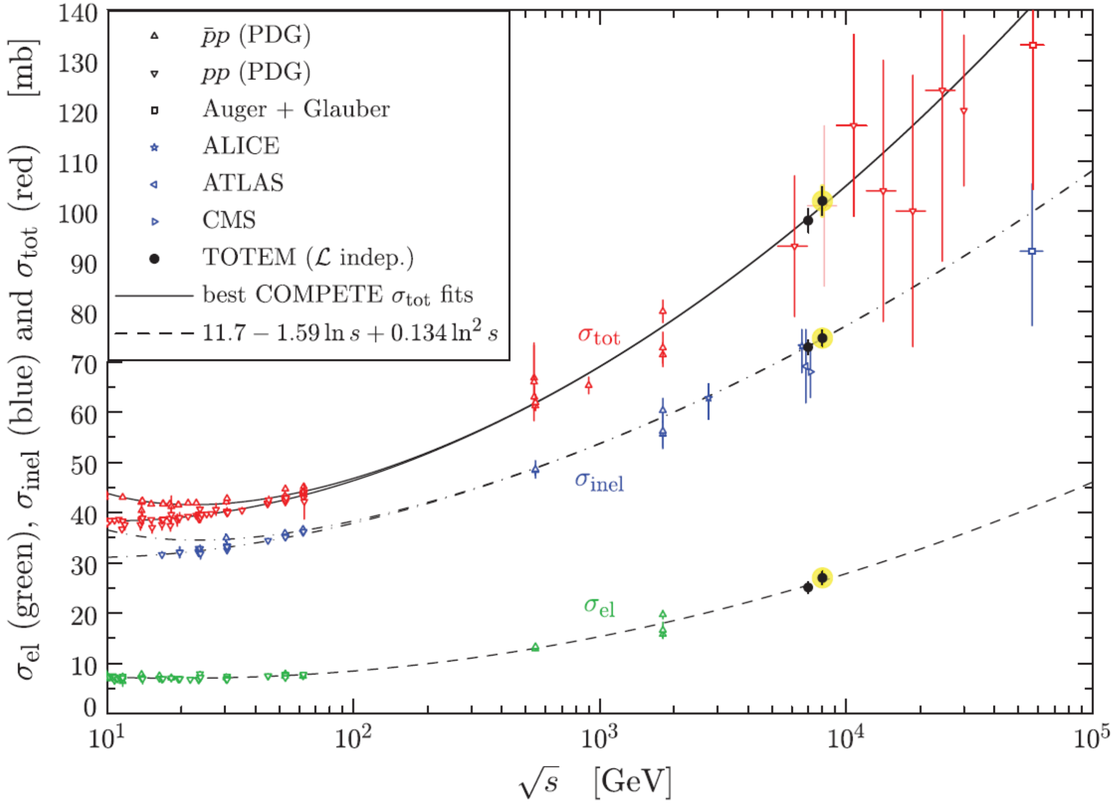
ELASTIC CROSS SECTION:

- Events triggered by RPs in coincidence on both sides

INELASTIC CROSS SECTION:

- Events triggered by the T2 tracker on either arm

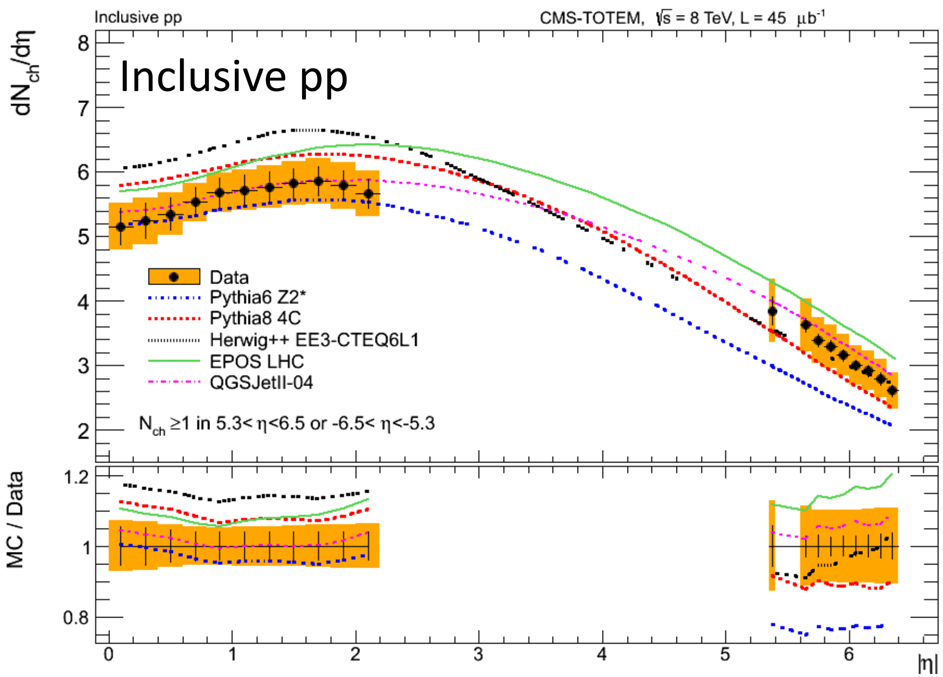
Triggers taken in random bunch crossings used for calibration.

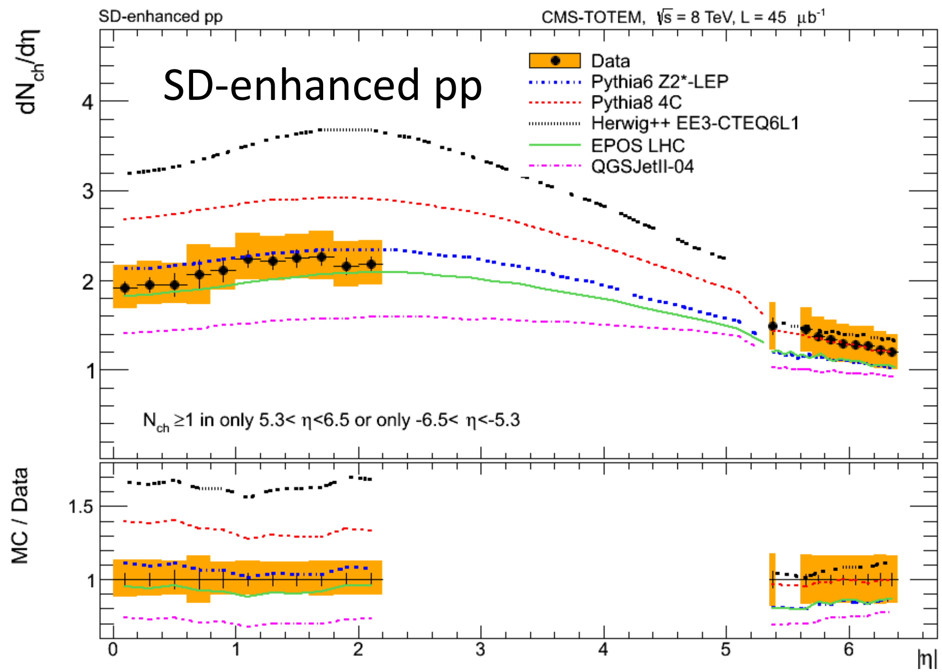


Compilation of the total (σ_{tot}), inelastic (σ_{inel}) and elastic (σ_{el}) cross-section measurements: the TOTEM measurements are highlighted. The continuous black lines (lower for pp, upper for $\bar{p}p$) represent the best fits of the total cross-section data by the COMPETE collaboration. The dashed line results from a fit of the elastic scattering data. The dash-dotted lines refer to the inelastic cross section and are obtained as the difference between the continuous and dashed fits.

TOTEM+CMS: measurement of pseudorapidity distrib.

EPJC 74 (2014) 3053 pp @ 8 TeV



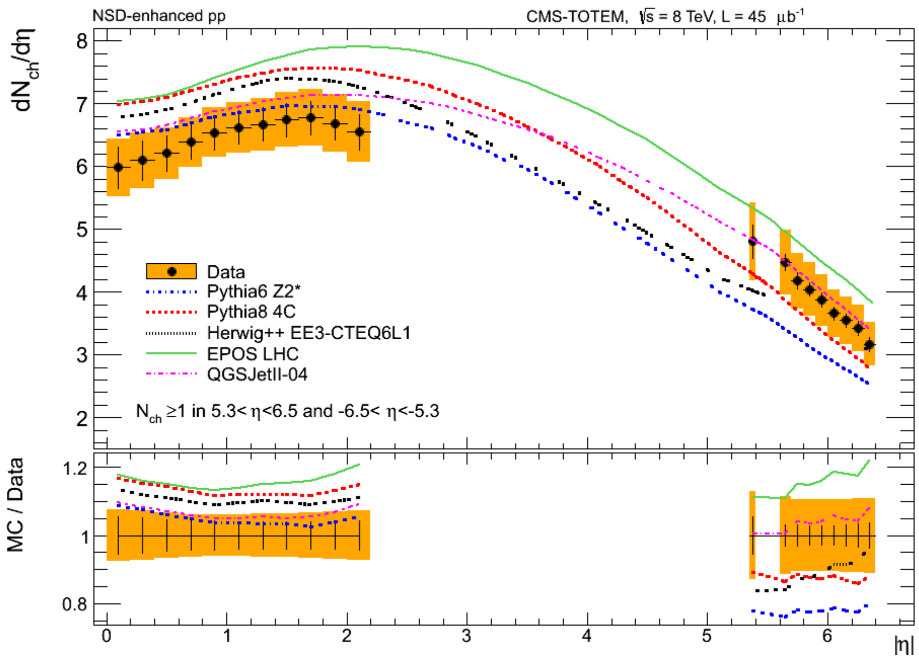


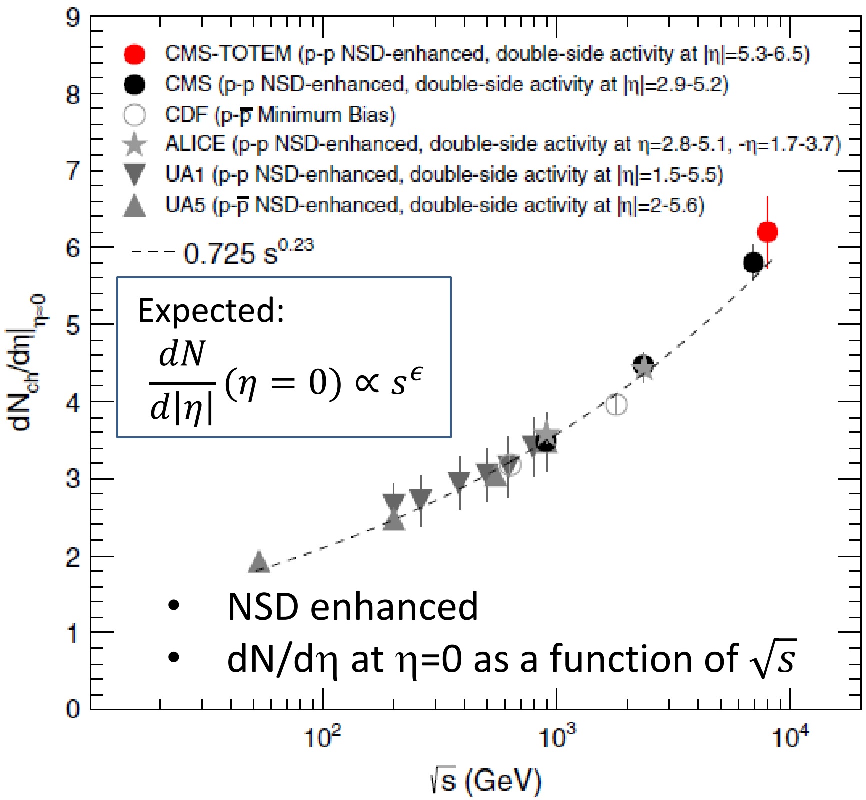
- Totem trigger – at least a charged particle in 5.3<|h|<6.5 (T2).
- Inclusive sample, 91–96 % of the total inelastic proton–proton cross section.

- Totem trigger – at least a charged particle only in 5.3<h<6.5 or only in -6.5<h<-5.3.
- Single diffractive enhanced sample.

TOTEM+CMS: measurement of pseudorapidity distrib.

NSD-enhanced pp EPJC 74 (2014) 3053





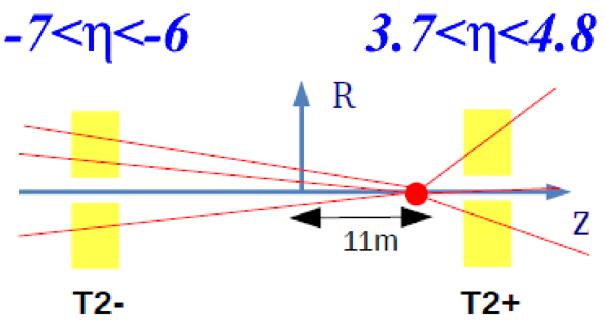
- Totem trigger – at least a charged particle in 5.3<η<6.5 and in
- -6.5< η <-5.3.

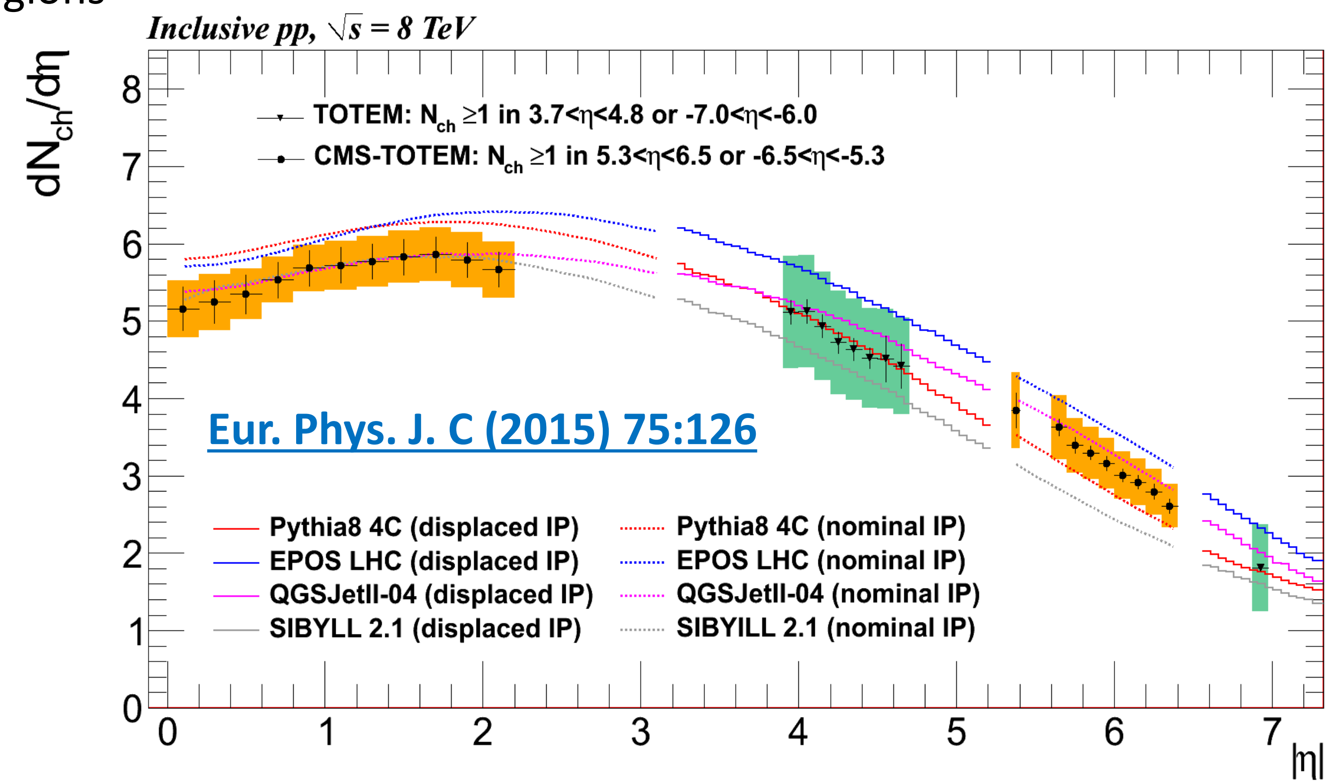
- Non Single Diffractive enhanced sample.

Value of dNch/dη at η =0 as a function of the centre-of-mass energy in pp and $\bar{p}p$ collisions. Shown are measurements performed with different NSD event selections from UA1, UA5, CDF, ALICE, CMS. The dashed line is a power-law fit to the data.

TOTEM+CMS: measurement of pseudorapidity distrib.

- Data were collected in a low intensity LHC run with collisions occurring **11.25 m far from the nominal interaction point**.
- The data sample is expected to include 96–97 % of the inelastic pp interactions.
- The measurement considers charged particles with $p_T > 0$ MeV/c, produced in inelastic interactions with at least one charged particle in the regions
  $-7 < \eta < -6$ or
  $3.7 < \eta < 4.8$.

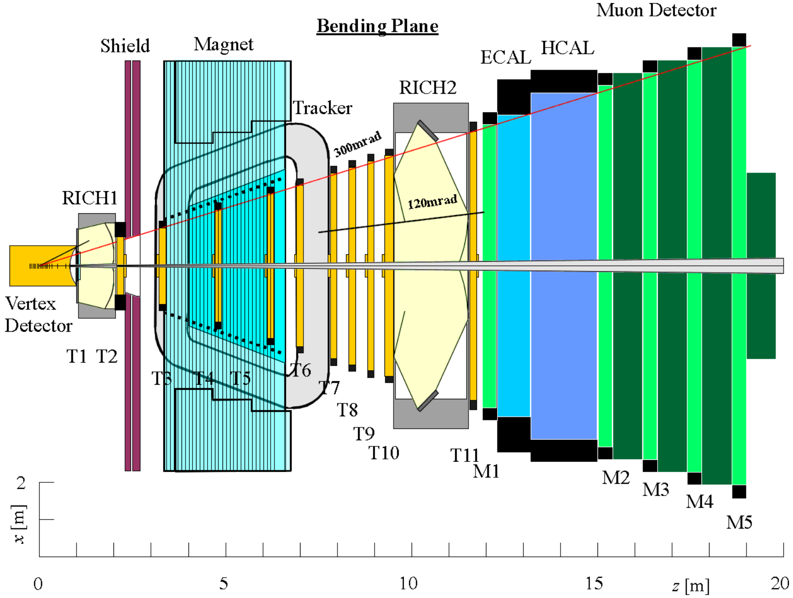


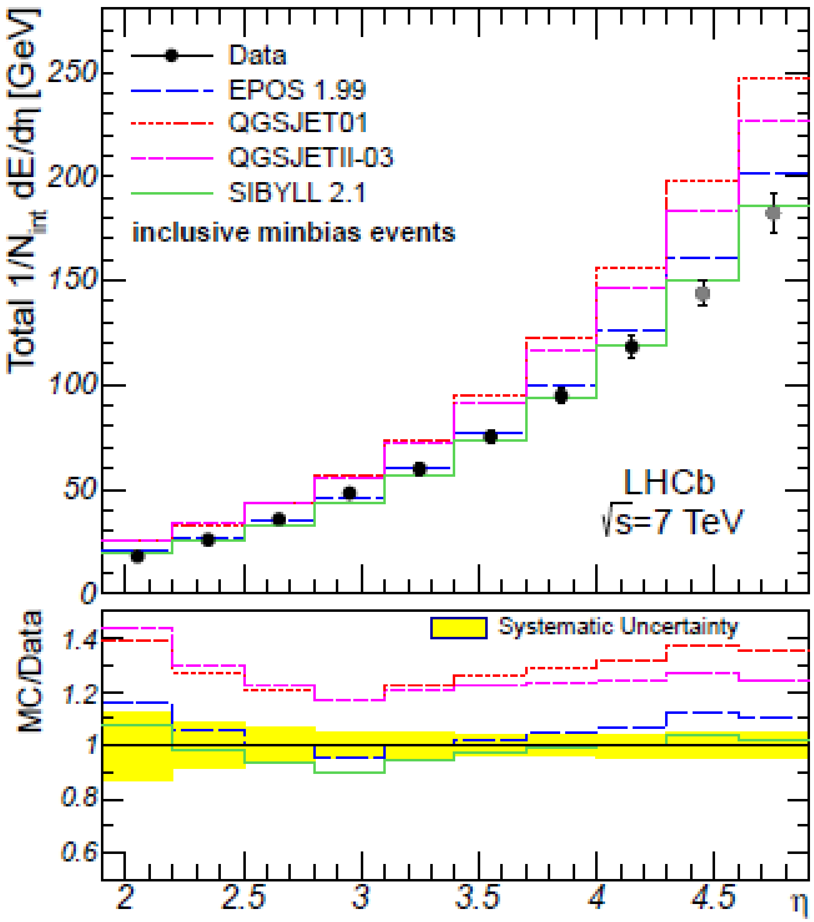


CASE II: LHCb - forward energy flow

EPJC 73 (2013) 2421

Measurement of energy flow at 1.9 < |η| < 4.9 (evets triggered by VELO, VErtex LOcator)





Upper figure: total measured energy flow as a function of η compared with predictions by hadronic interaction models.

The error bars represent the systematic uncertainties. The statistical uncertainties are negligible.

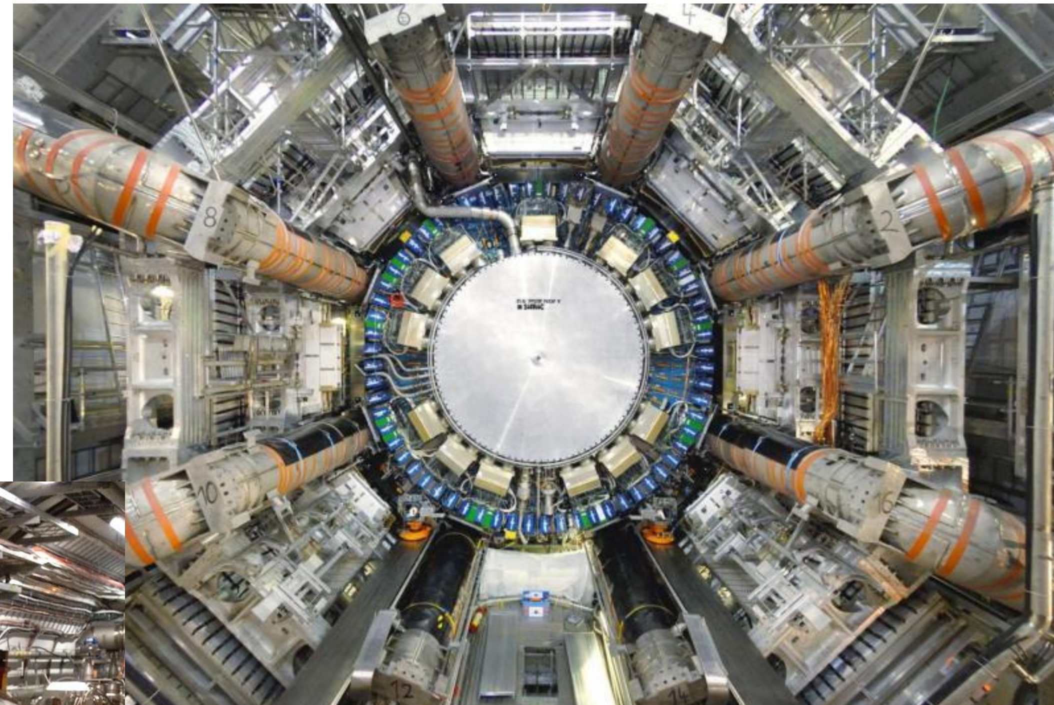
Lower figure: ratios of MC predictions to data.

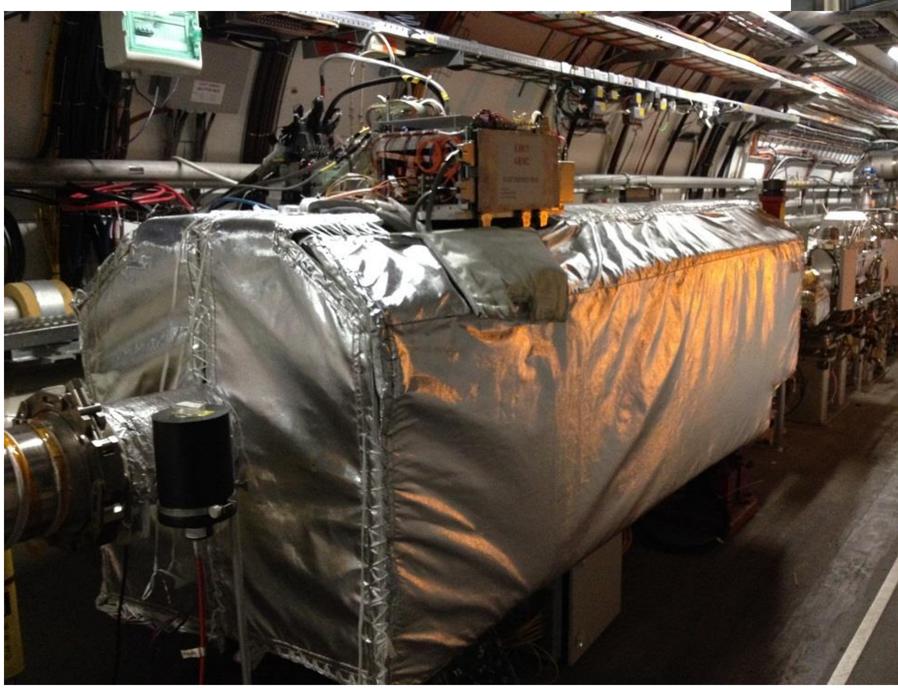
FOCUS ON CASE III - IP1: ATLAS and LHCf

LHCf MAIN TOPICS

Calibration of hadronic interaction models used in CR physics:

- fwd study of neutral particles
- energy and pt spectra
- pseudorapidity dependencies

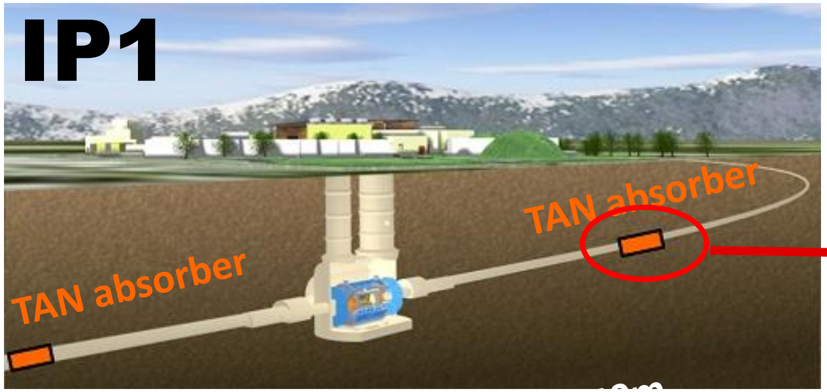




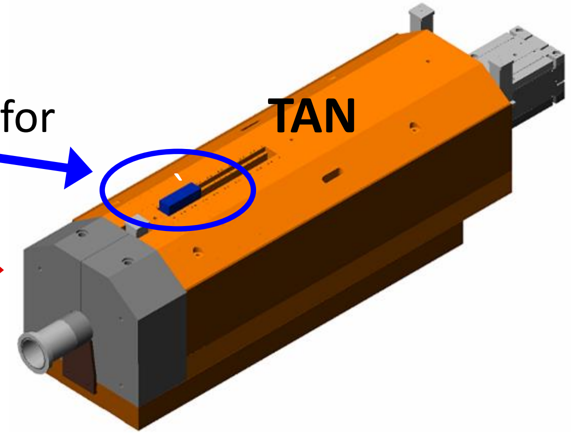
ATLAS

General purpose detector

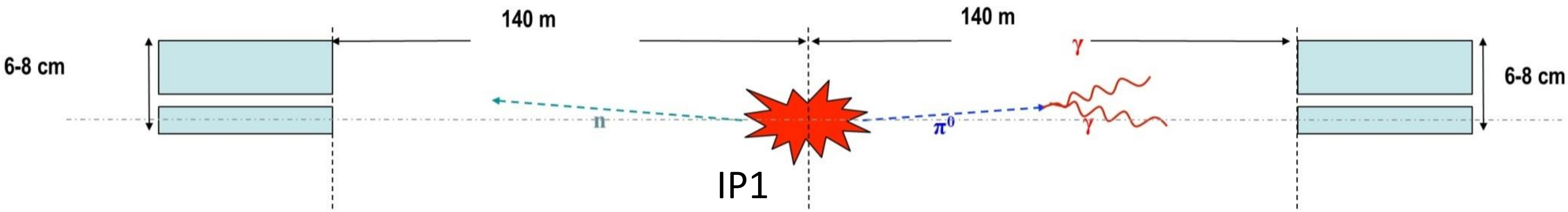
Overview of the LHCf experiment



Detectors are located inside the TAN absorber for neutral particles

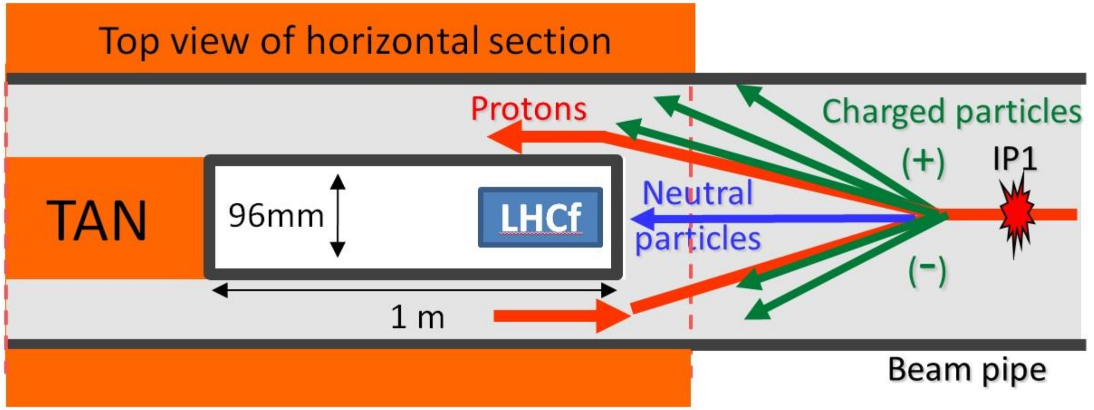


The LHCf detectors measure energy and impact point of γ and **n** → **e.m. calo + tracking layers**



Two independent detectors on both sides of IP1

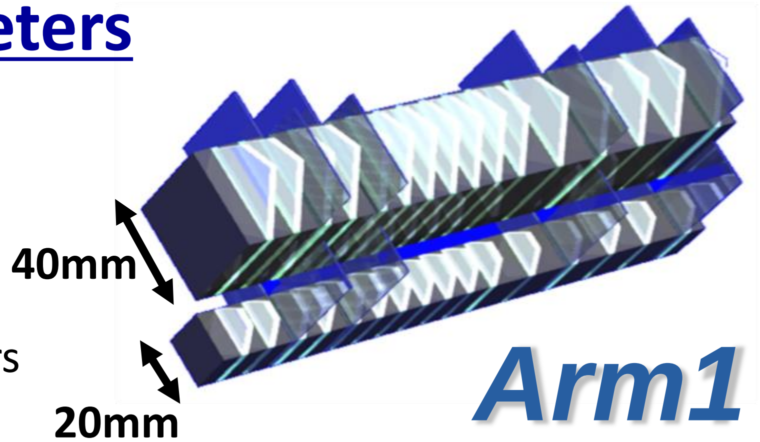
- ✓ Redundancy
- ✓ Coincidence
- ✓ Background rejection (esp. beam-gas)



Sampling and imaging E.M. calorimeters

- **Absorber**: W layers (**44 r.l. , 1.55λ_I** in total)
- **Energy measurement**: plastic scintillator tiles
- **4 tracking layers** for imaging:
  XY-SciFi(Arm1) and XY-Silicon μ-strip(Arm2)
- Each detector has two independent calorimeter towers

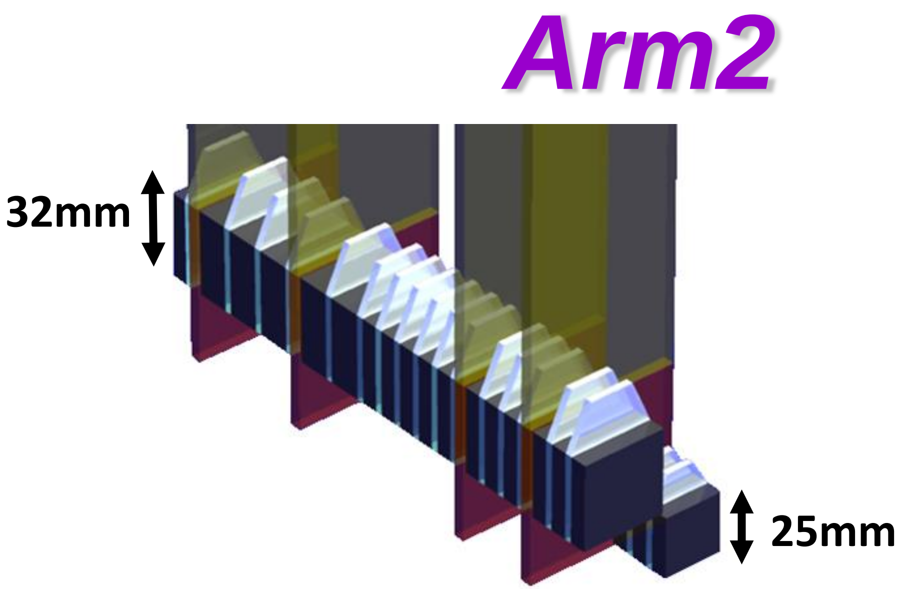
→ **reconstruction of $\pi^0 \to \gamma\gamma$ events**



Performance

Energy resolution (> 100 GeV)
< 5% for γ and ~ (35 ÷ 40)% for **n**

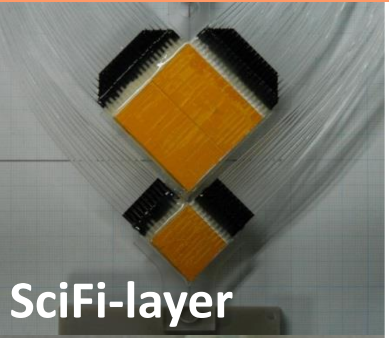
Position resolution
< 200µm (Arm1) and ~ 40µm (Arm2)

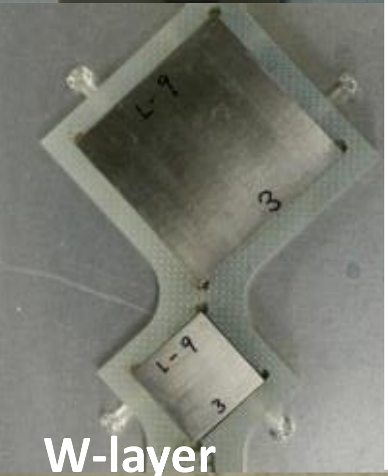


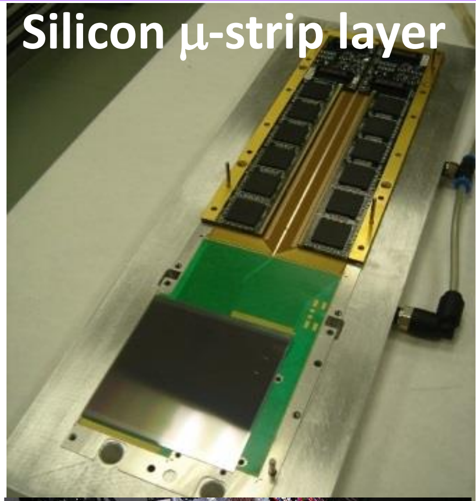
Front Counter scintillators

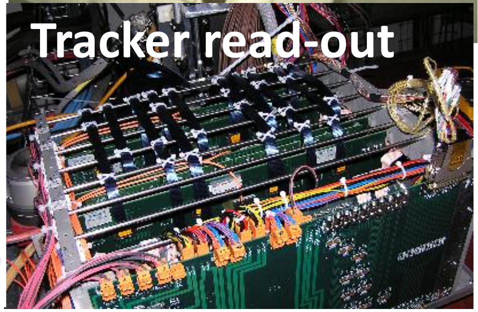
- thin scintillators 80x80 mm fixed upstream the main detectors
- **monitoring of beam condition**
- **background rejection**
- **Van der Meer scan**

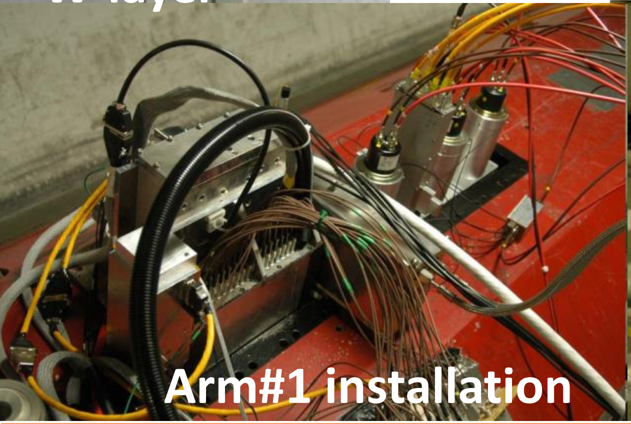
The LHCf detectors for phase I





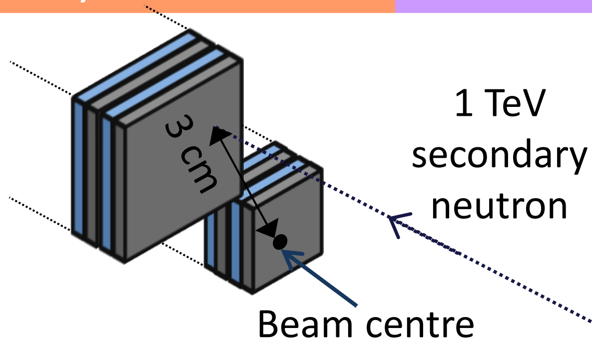






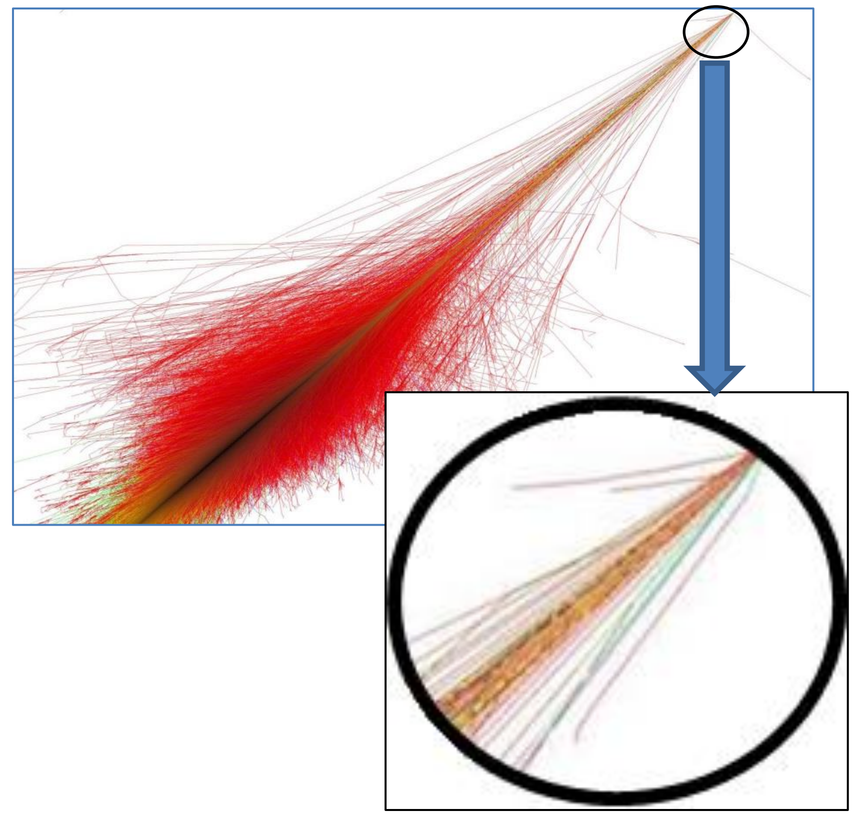
Overview of the LHCf experiment

Example:
pp @ 13 TeV



- *LHC frame*
Detecting a **1 TeV neutron** hitting one LHCf calorimeter tower at **3 cm from beam line**.
Angle wrt the interaction line = $2 \cdot 10^{-4}$ rad.

- *LAB frame* (CR interaction in the atmosphere)
Going from LHC to the LAB frame it corresponds to a $\mathbf{1.3 \cdot 10^{16}}$ **ev neutron.**
Angle wrt to the interaction line = $1.5 \cdot 10^{-8}$ rad.
After 100 m in atmosphere it would be 1.5 μm from the interaction line.



We are studying very high energy secondary particles emitted in a really narrow angular region of the central core of an atmospheric shower.
LHC works as a powerful angular amplifier or microscope.

Physics program and table of publications

	year		Equivalent proton energy in LAB (eV)	γ	n	π^0
PHASE I		SPS test beams		NIM A 671 129 (2012)	JINST 9 P03016 (2014)	
PHASE I	2009	p-p 900 GeV	4.3×10^{14}	PLB 715 298 (2012)		
PHASE I	2009/2010	p-p 7 TeV	2.6×10^{16}	PLB 703 128 (2011)	In preparation	PRD 86 092001 (2012)
PHASE I	2013	p-p 2.76 TeV	4.1×10^{15}			Phys. Rev. C 89, 065209 (2014)
PHASE I	2013	p-Pb 5.02 TeV	1.3×10^{16}			
PHASE II	2015	p-p 13 TeV	9.0×10^{16}	Upgraded detectors / waiting for low mu run in June		
PHASE II	2016 (?)	p-p 500 GeV	1.3×10^{14}	Run @ RHIC under discussion (RHICf)		

LHCf Results

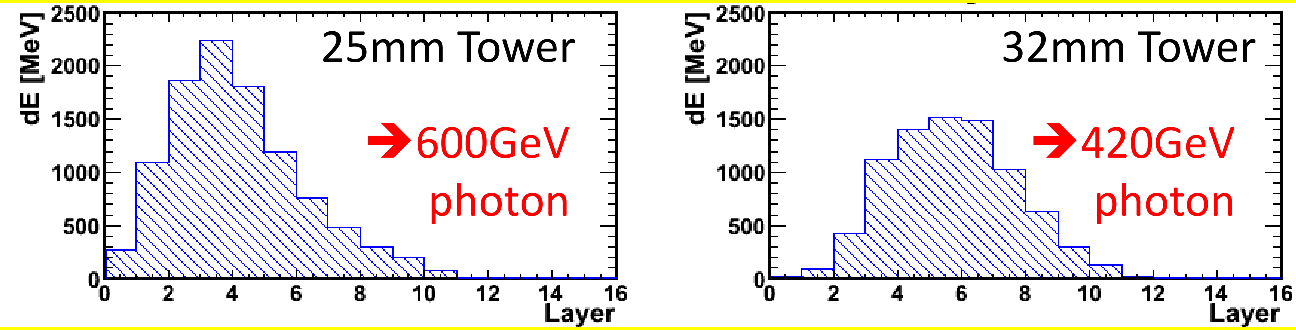
- O. Adriani, et al., “Measurement of zero degree single photon energy spectra for $\sqrt{s}$ = 7 TeV proton-proton collisions at LHC”, PLB 703-2, p. 128-134 (09/2011)
- O. Adriani, et al.,“Measurement of zero degree inclusive photon energy spectra for $\sqrt{s}$ = 900 GeV proton-proton collisions at LHC”, PLB 715, p. 298-303 (2012)
- O. Adriani, et al.,“Measurement of forward neutral pion transverse momentum spectra for $\sqrt{s}$ = 7TeV proton-proton collisions at LHC”, PRD 86,092001 (2012)
- O. Adriani, et al.,“Transverse-momentum distribution and nuclear modification factor for neutral pions in the forward-rapidity region in proton-lead collisions at $\sqrt{s_{NN}}$ = 5.02 TeV”, PRC 89 (2014) 6, 065209

SOME RECENT RESULTS

- Neutrons in $\sqrt{S}$ =7 TeV p-p collisions (preprint submitted to PLB, arXiv:1503.03505)

Results

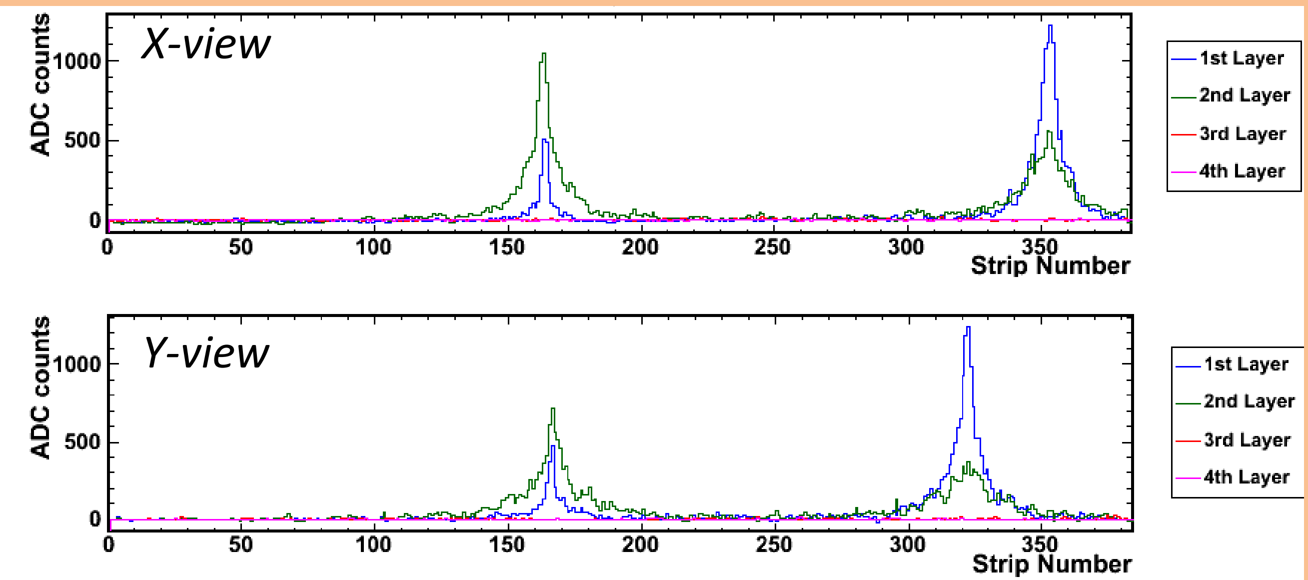
Longitudinal development measured by scintillator layers



Determination of **energy** from total energy release

PID from shape

Transverse profile measured by silicon μ–strip layers



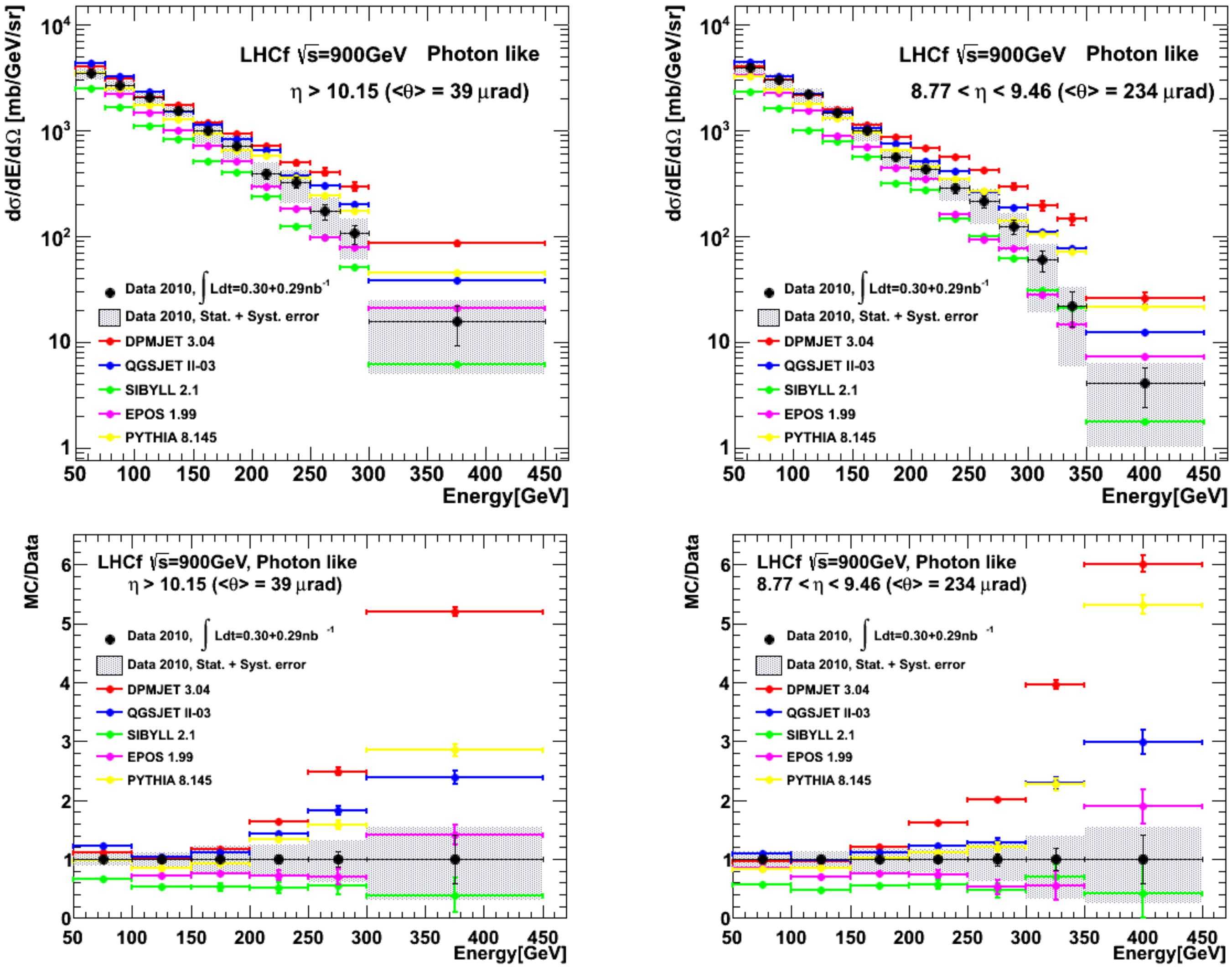
Determination of the **impact point**

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

Identification of **multiple hit**

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

Comparison of single γ data for pp @ 900 GeV with hadronic interaction models (pre-LHC versions)



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

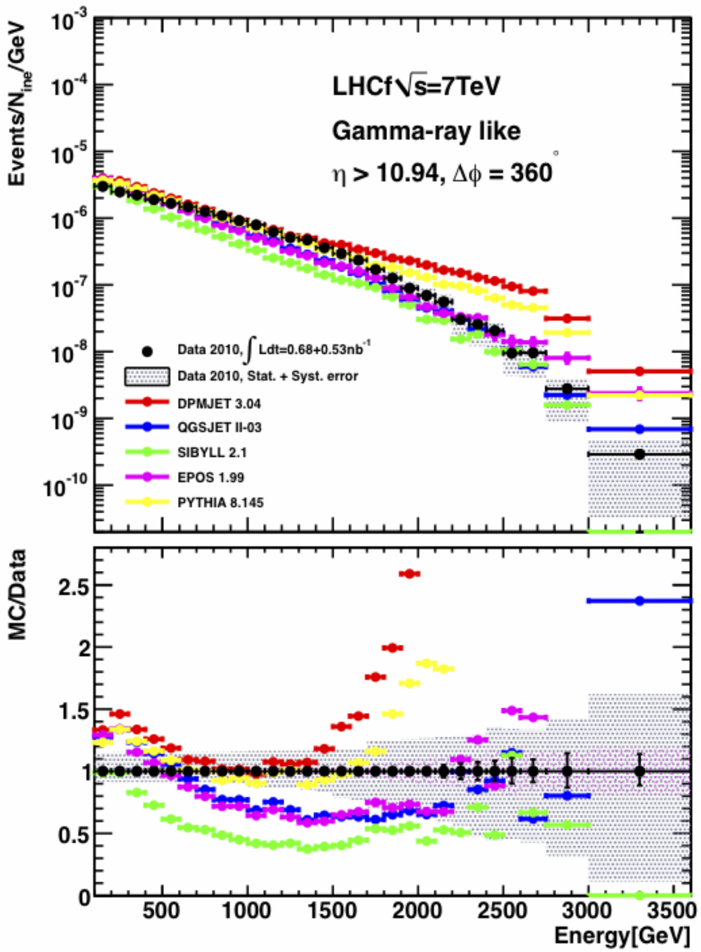
Syst.+Stat.

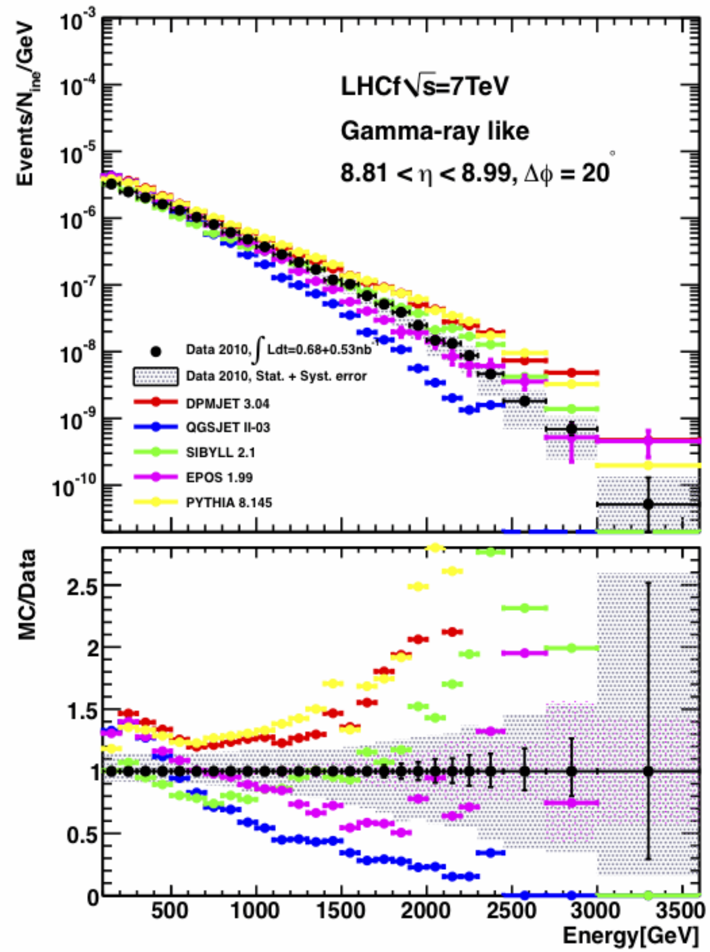
No strong evidence of η-dependence

DPMJET and **SYBILL** show reasonable agreement of shape

None of the models reproduces the data within the error bars

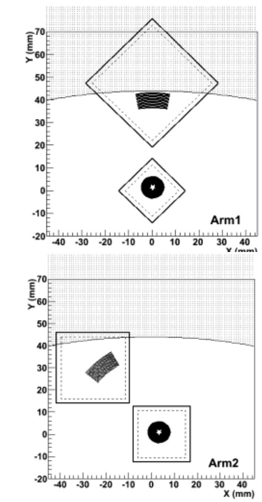
Comparison of single γ data for pp @ 7 TeV with hadronic interaction models (pre-LHC versions)





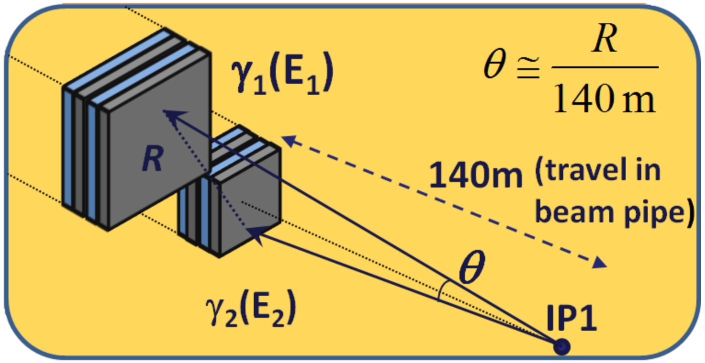
DATA
DPMJET 3.04
QGSJET II-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145

Syst.+Stat.

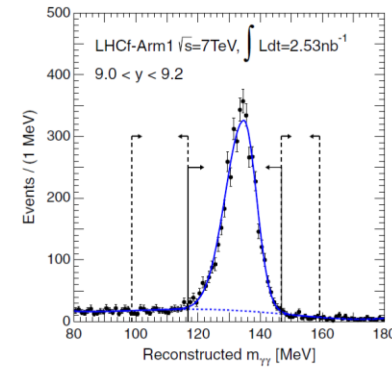


- No model can reproduce the **LHCf data** perfectly.
- DPMJET and PYTHIA are in good agreement at high-η for E_γ<1.5TeV, but harder in E>1.5TeV.
- QGSJET and SIBYLL shows reasonable agreement of shapes in high-η but not in low-η
- EPOS has less η dependency against the LHCf data.

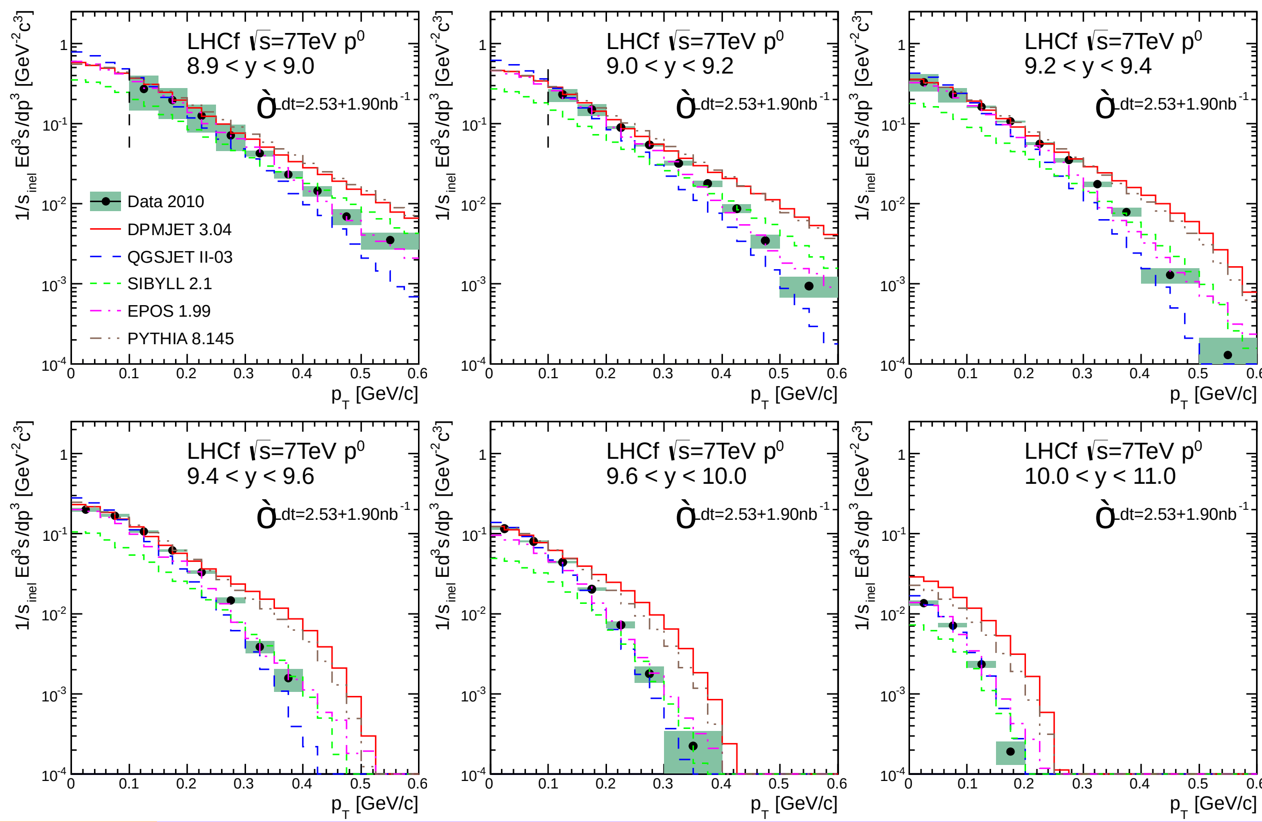
Comparison of π^0 data for pp @ 7 TeV with hadronic interaction models (pre-LHC versions)



Reconstruction of the invariant mass of two-photon events

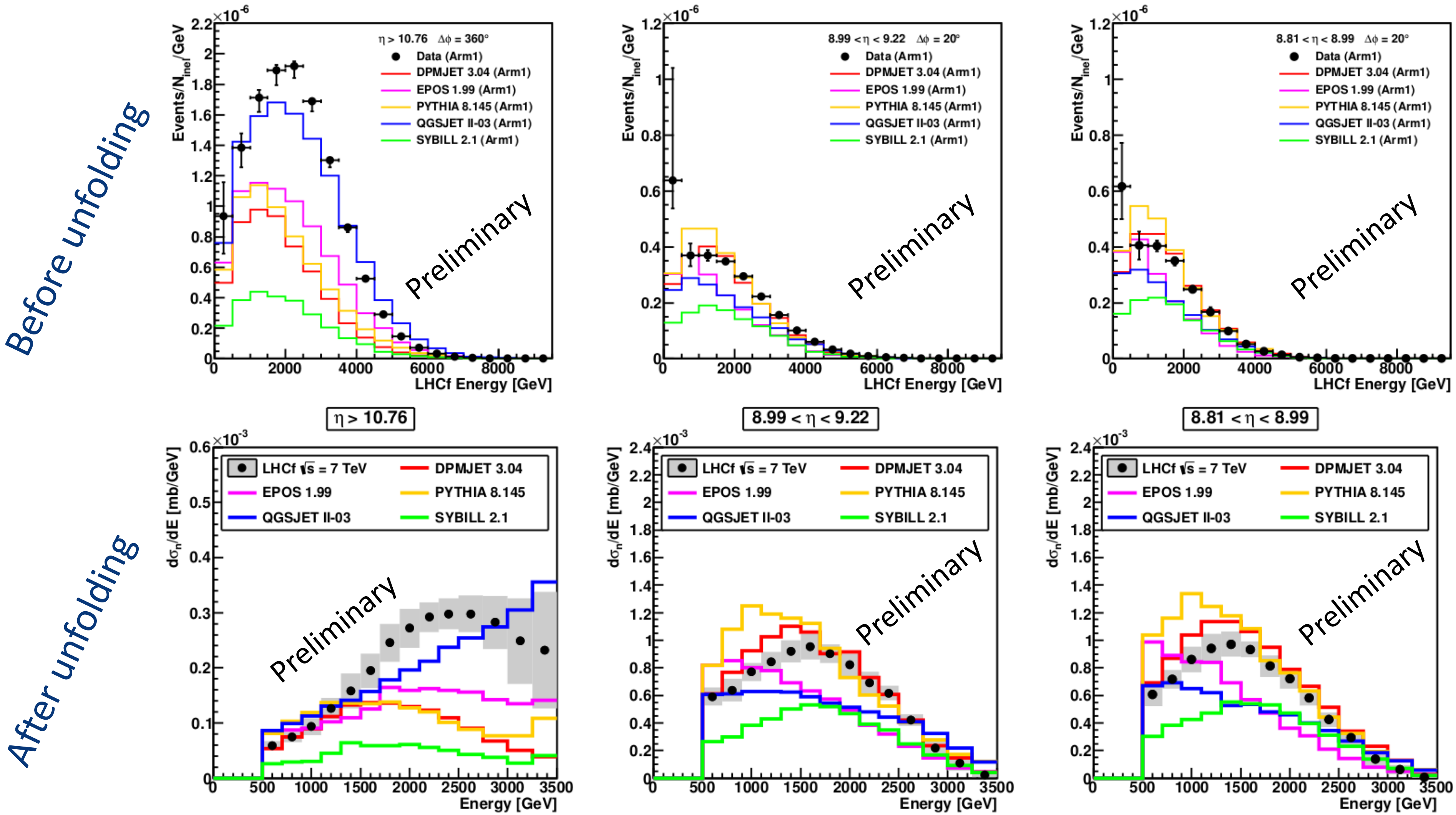


Identification of events with two particles hitting the two towers



- **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)

More recent analysis: neutron energy spectra before and after unfolding (pp @ 7 TeV)

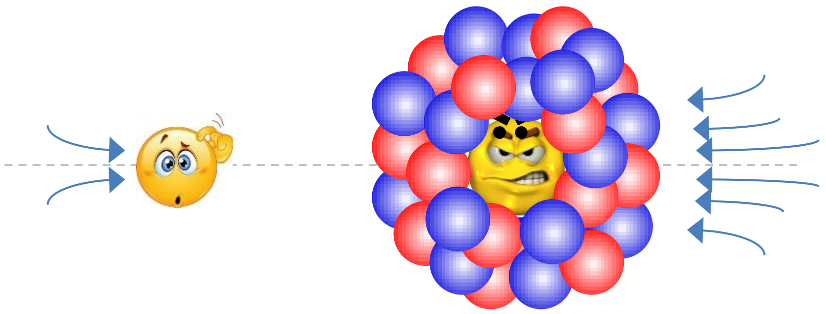


Very large high energy peak in the η>10.76 (predicted only by QGSJET)

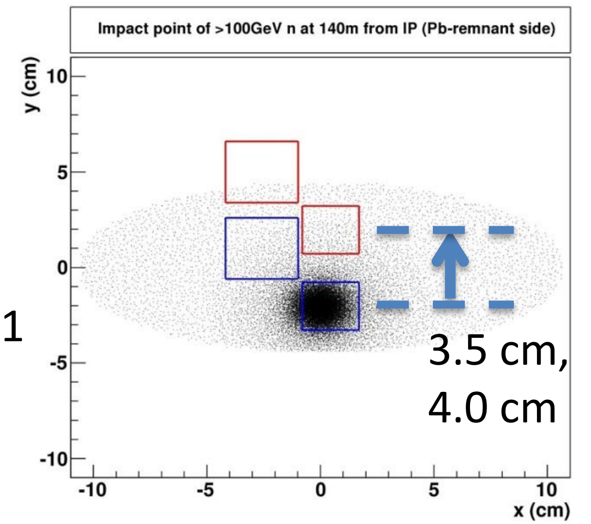
→ Small inelasticity in the very forward region!

Preprint submitted to PLB

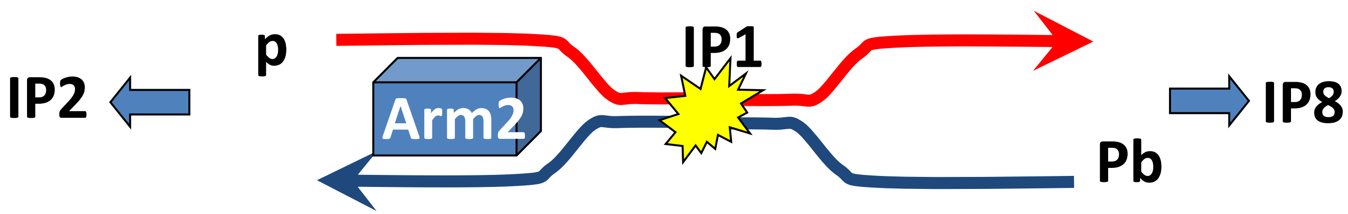
The LHC proton-Lead run on 2013 at $\sqrt{S_{NN}} = 5$ TeV



- Motivation: study of nuclear effects for CR interactions
- 2013 Jan-Feb for p-Pb/Pb-p collisions
  - Installation of the **only Arm2** at one side (silicon tracker good for multiplicity)
  - Data both at **p-side** (20Jan-1Feb) and **Pb-side** (1fill, 4Feb), thanks to the **swap of the beams**

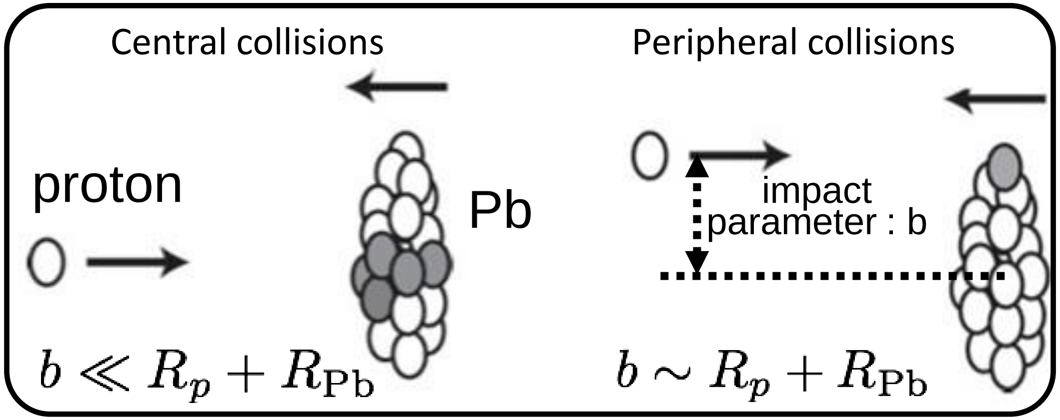


- Details of beams and DAQ
  - L = $1 \times 10^{29} - 0.5 \times 10^{29} cm^{-2}s^{-1}$
  - ~200.10^6 events
  - β^* = 0.8 m, 290 µrad crossing angle
  - 338p+338Pb bunches (min.ΔT = 200 ns), 296 colliding at IP1
  - 10-20 kHz trig rate downscaled to approximately 700 Hz
  - 20-40 Hz ATLAS common trig. Coincidence successful!
  - p-p collisions at 2.76 TeV have also been taken

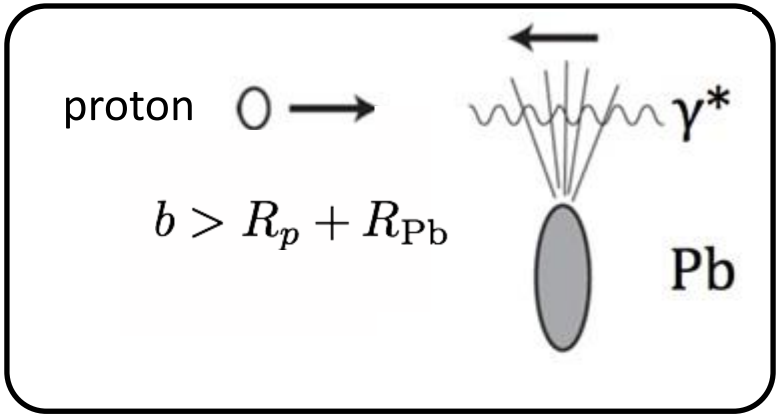


E.M. contribution to fwd particle production (p-Pb)

(Soft) QCD :
central and peripheral collisions



Ultra peripheral collisions :
virtual photons from rel. Pb collides a proton



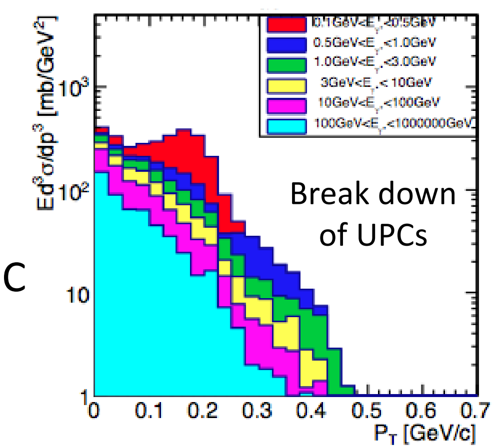
Estimation of momentum distribution of the UPC induced secondary particles (Lab frame+Boost):

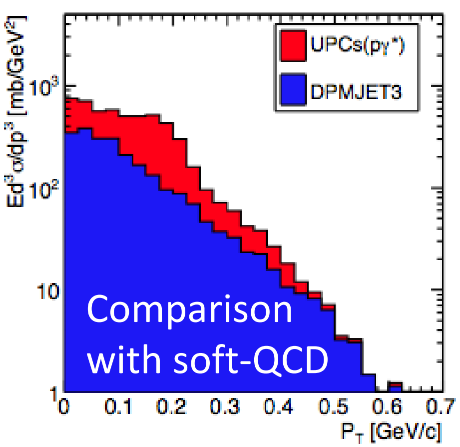
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation
2. photon-proton collisions are simulated by the SOPHIA model (E_γ > pion threshold)

Dominant channel to forward π^0 is

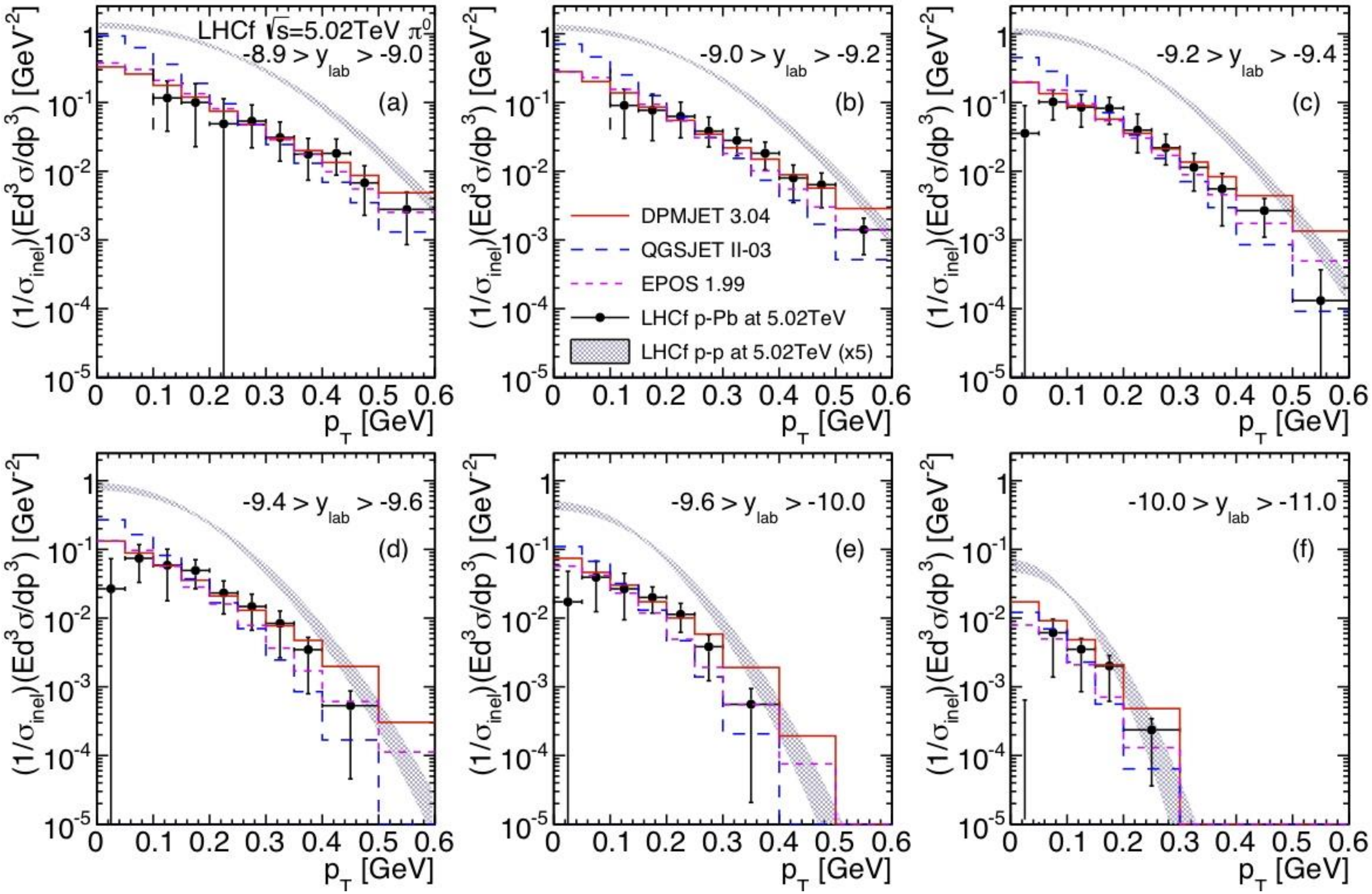
$$\gamma + p \to \Delta(1232) \to p + \pi^0$$

About half of the observed π^0s originate from UPC
About half is from soft-QCD
Need to subtract UPC component



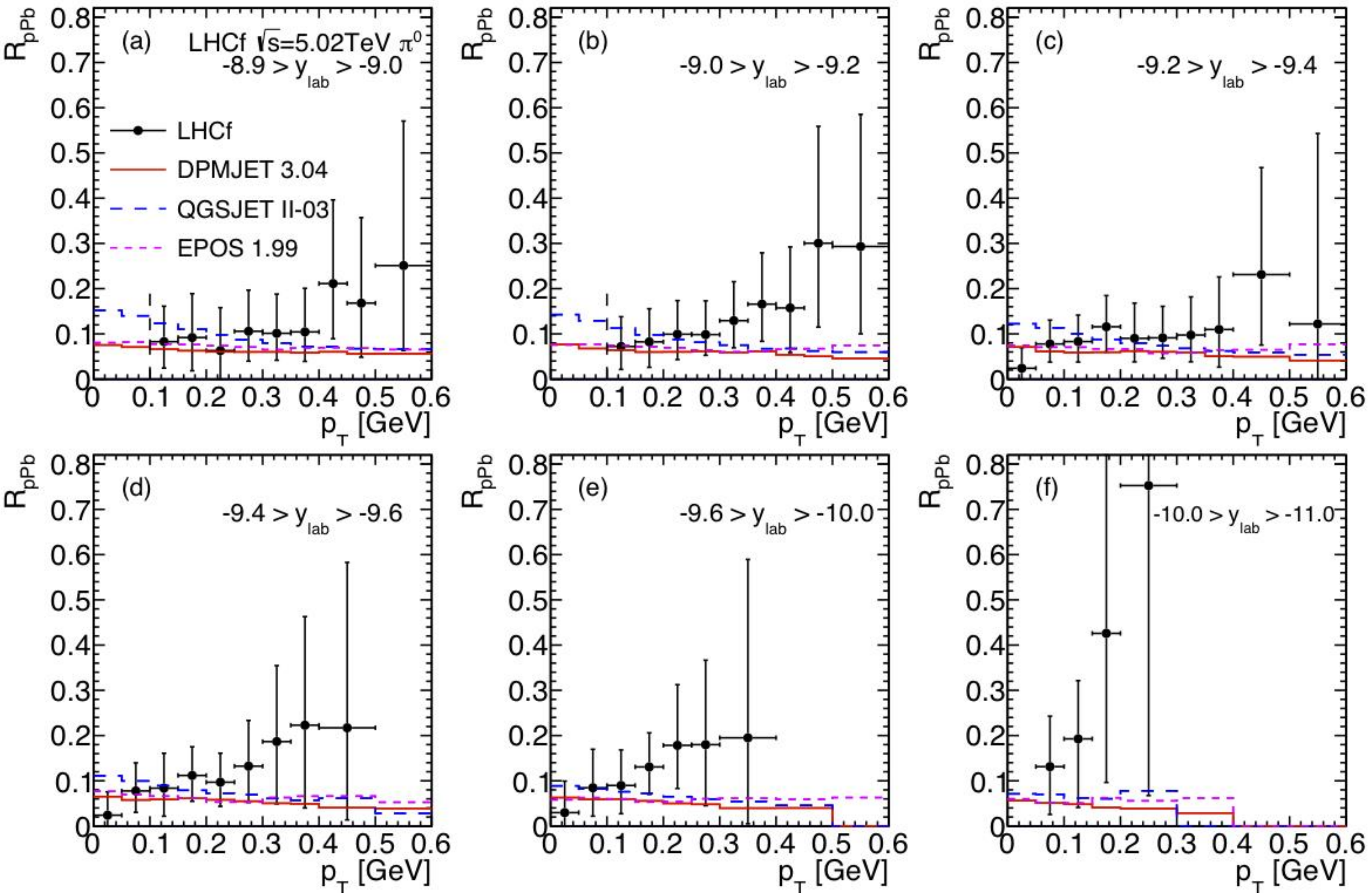


Invariant cross section for π^0 production (p-Pb)



- 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.

Nuclear Modification Factor for π^0 production (p-Pb)



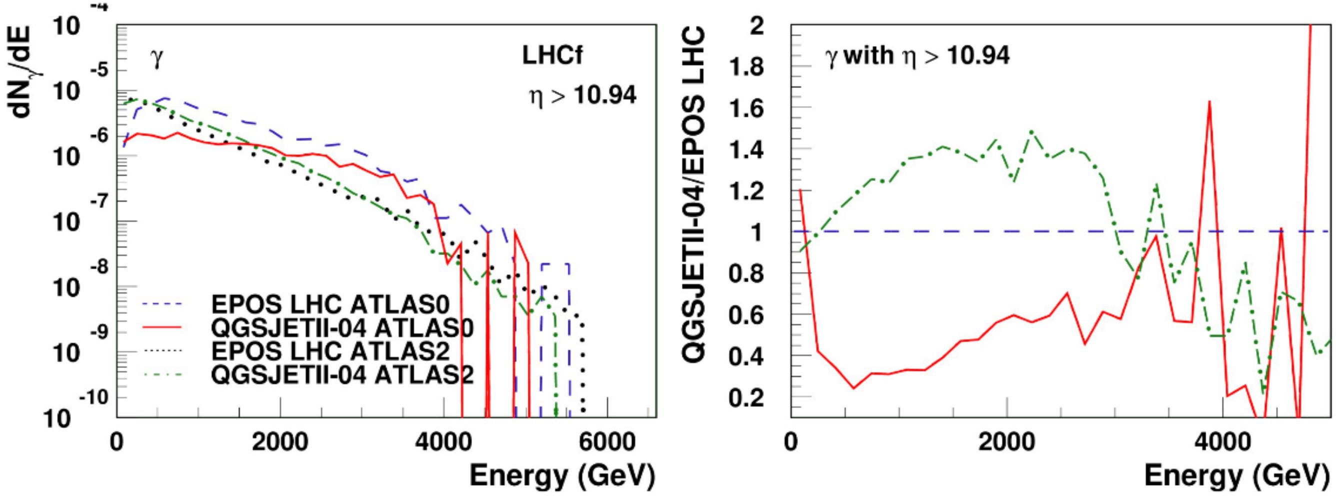
$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) \equiv \frac{\sigma^{\mathrm{pp}}_{\mathrm{inel}}}{\langle N_{\mathrm{coll}}\rangle \sigma^{\mathrm{pPb}}_{\mathrm{inel}}} \frac{Ed^3\sigma^{\mathrm{pPb}}/dp^3}{Ed^3\sigma^{\mathrm{pp}}/dp^3}$$

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

- Both LHCf and MCs show strong suppression.
- NMF grows with increasing p_T, as can be expected by the p_T spectrum that is steeper in p-p 5 TeV than in p-Pb 5 TeV collisions

Combined analysis with ATLAS

- During the 2013 p-Pb run LHCf trigger was used for triggering the ATLAS detector. Combined data taking is foreseen also for the next run (pp @ 13 TeV).
- Activity in the central detector can be used to separate diffractive and non diffractive events. It will be used also to remove the UPC events (which give no activity in ATLAS) for the analysis of p-Pb data.
- Important for improving the quality of the hadronic interaction models, where diffractive and non diffractive events have completely separate treatments.



ATLAS0 = no charge particle particle with |η|<2.5 and p_t>0.1 GeV/c

ATLAS2 = at least 2 charged particles particle with |η|<2.5 and p_t>0.1 GeV/c

Courtesy of Tanguy Pierog

SUMMARY & ACKNOWLEDGEMENTS

- **Improving hadronic interaction models**: still necessary after years of LHC
- Many aspects of the study of EAS still require more reliable models for a clear interpretation of experimental data
- All **LHC experiments** produce information on different aspects which are relevant for EAS simulations
- In particular **LHCf** is a dedicated experiment which measures neutral secondary particles for $|\eta|>8.4$ (many results already published)
- In June 2015 a **special low luminosity and low pile-up special run** is scheduled for LHCf
- Combined data taking with ATLAS already performed in p-Pb 2013 will be done also in p-p 2015
  - Important to separate diffractive from non-diffractive events

I would like to thank Simone Giani, Beatrice Bressan and Mirko Berretti for providing material for the TOTEM experiment.