Production spectra of zero-degree neutral particles measured by the LHCf experiment

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Outline

- Physics motivations of LHCf
- Experimental setup
- Latest published results:
  - neutron energy spectra in p-p @ 7 TeV
  - π^0 P_T and P_z spectra in p-p @ 7 TeV and 2.76 TeV and in p-Pb @ 5.02 TeV
- Preliminary results from Run II
  - photon energy spectra in p-p @ 13 TeV

The LHCf collaboration

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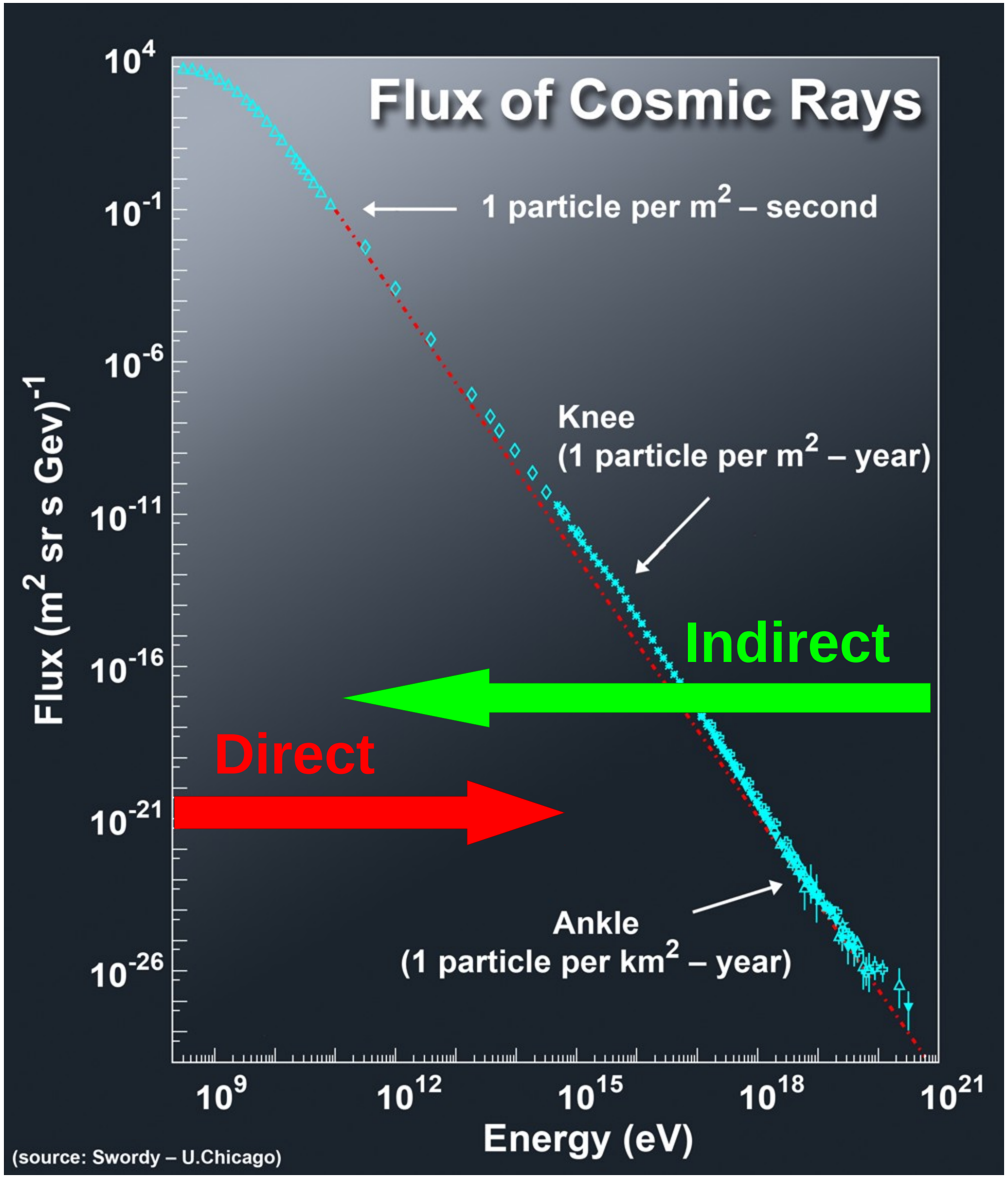
High energy cosmic rays

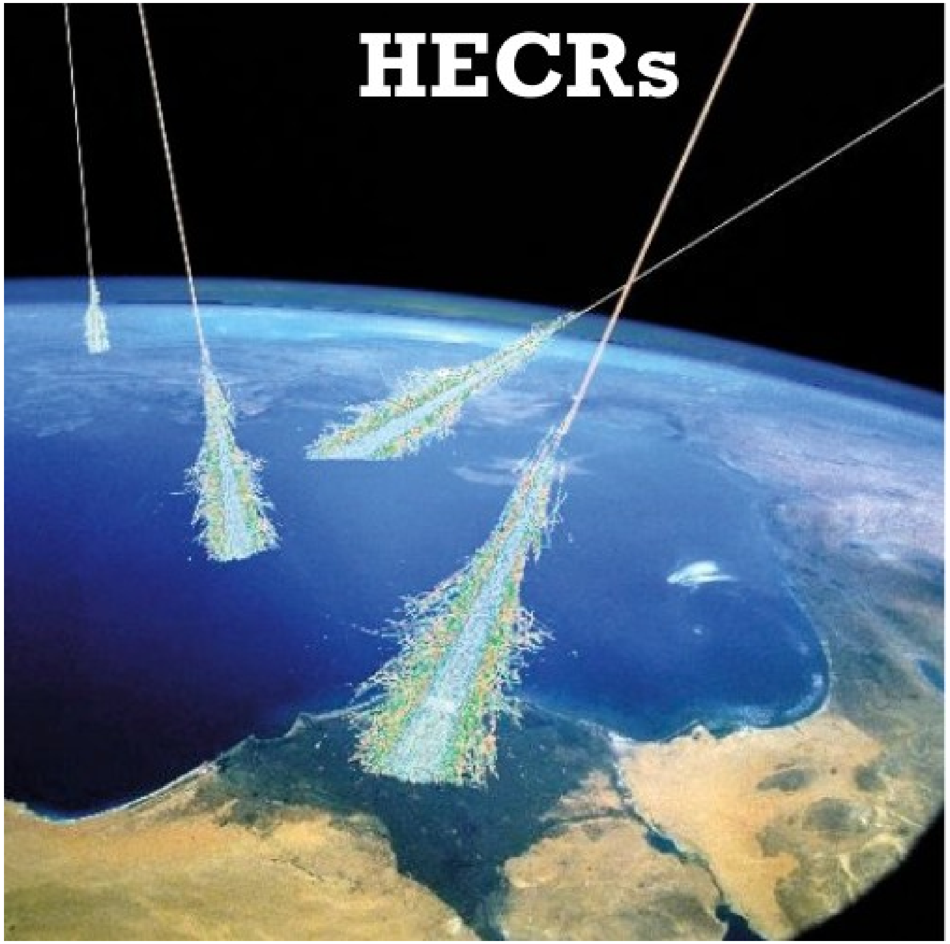


Credit: ASPERA/G.Toma/A.Saftoiu

- Cosmic rays spectrum falls as a power law ~ $E^{-2.7}$
- Direct measurements (with satellite experiments) are limited by the very low flux of particles at high energies
- At high energies indirect measurements (with ground based experiments) become possible

Only **indirect measurements** are possible above 10^{15} eV

Indirect measurements



Air showers measurements:

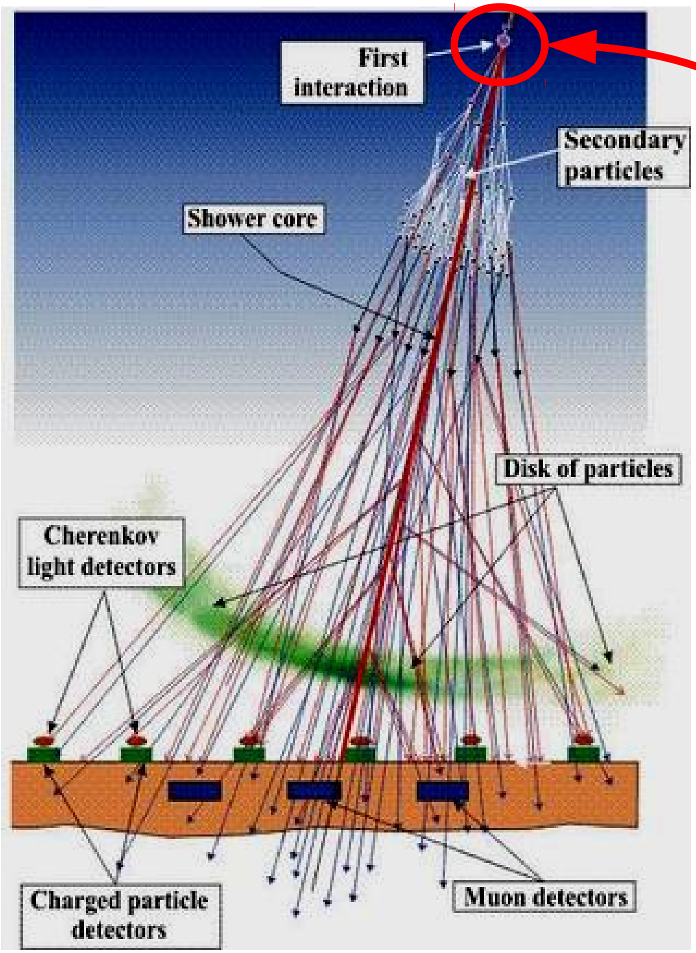
- Longitudinal distribution
- N° of particles at ground
- Arrival direction

Astrophysical parameters:

- Spectrum
- Composition
- Sources distribution

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

Contributions from accelerator experiments



First interaction

$\sqrt{s}$ = 13 TeV → E_{LAB} $9 \cdot 10^{16}$ eV

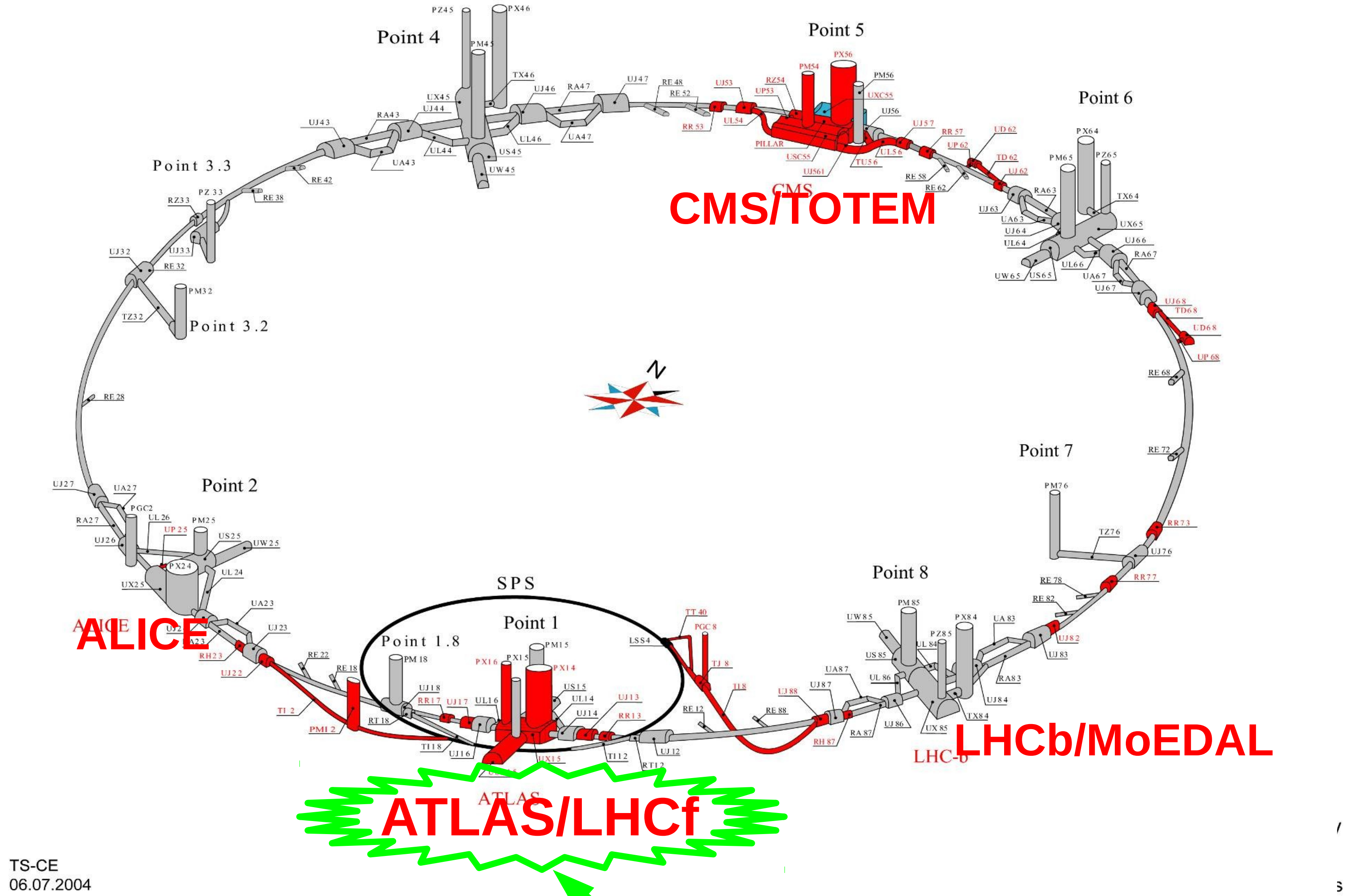
- **Inelastic cross section**
  large → rapid development
  small → deep penetrating
- **Multiplicity**
- **Inelasticity $k = 1 - p_{lead} / p_{beam}$**
  large → rapid development
  small → deep penetrating
- **Forward energy spectrum**
  softer → rapid development
  harder → deep penetrating
- **Nuclear effects** LHCf: p-Pb collisions

LHCf: neutrons photons π^0

- Soft interactions dominate (non perturbative QCD)
- Several phenomenological models based on Regge theory are proposed

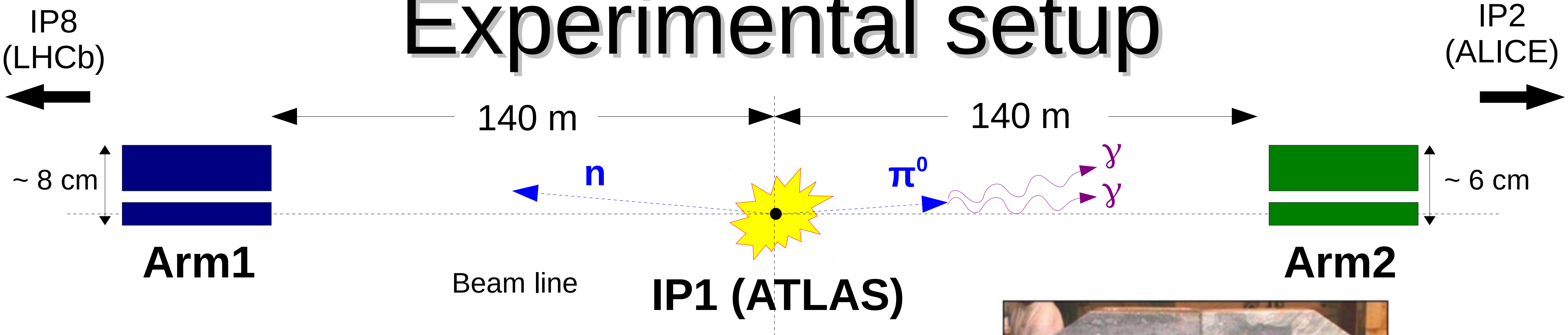
→ **Inputs from experimental data are very important**

LHCf at Large Hadron Collider

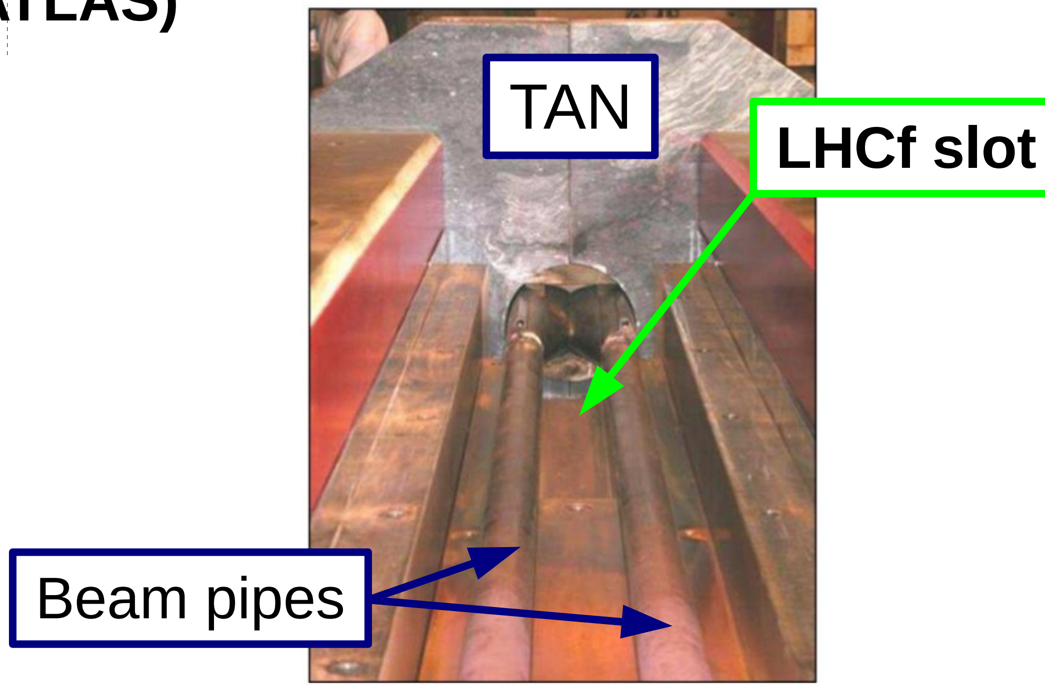


Two detectors are located 140m away from ATLAS (Interaction Point 1) along the beam line

Experimental setup



LHCf is located in TAN slot

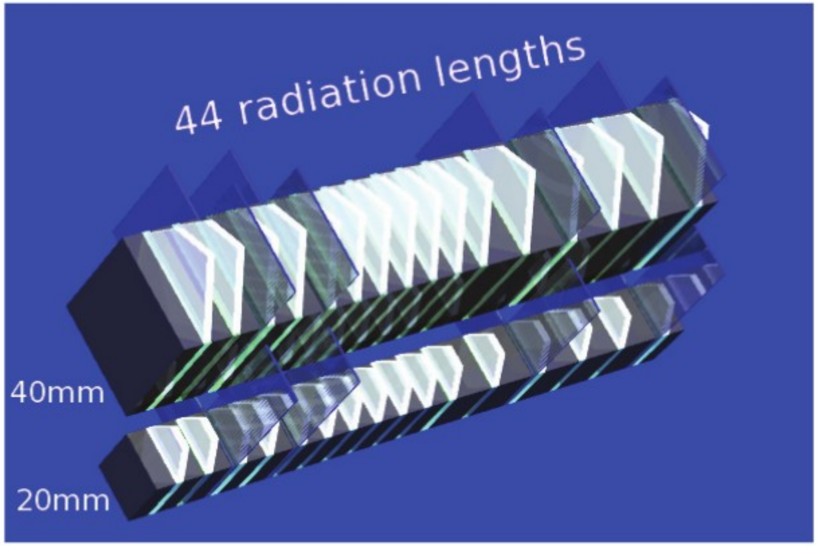


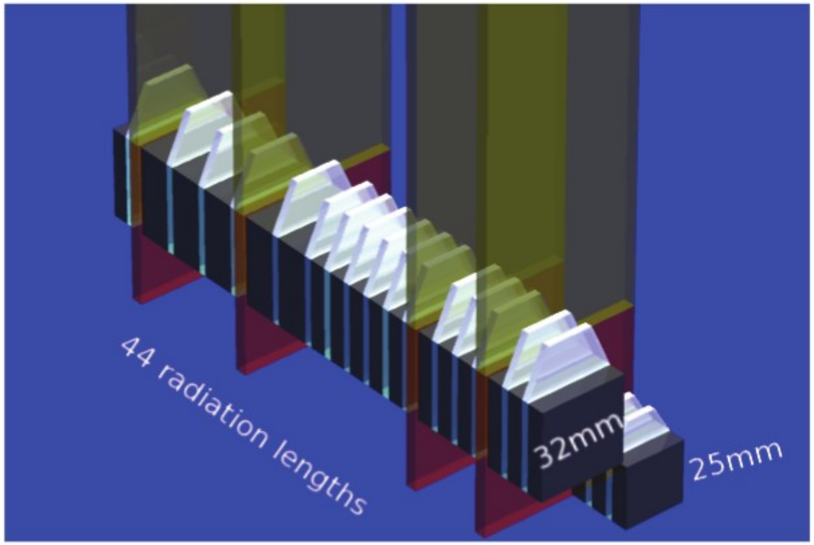
Zero degree particles!
Coverage from **η = 8.4**
(with 140 urad crossing angle) to **∞**

Charged particles are deflected by D1 dipole magnet

Only neutral particles (**photons** and **neutrons**) are detected

Detectors performance





Arm 1

- 20 x 20 mm^2 and 40 x 40 mm^2 sampling calorimeters: tungsten and plastic scintillators (EJ-260)
- Depth: 44 X_0, 1.6 λ
- 4 x-y **SciFi** tracking layers
- Position resolution: < 200 μm
- Energy resolution:
  - < 5% (photons)
  - ~ 40% (neutrons)

Arm 2

- 25 x 25 mm^2 and 32 x 32 mm^2 sampling calorimeters: tungsten and plastic scintillators (EJ-260)
- Depth: 44 X_0, 1.6 λ
- 4 x-y **silicons microstrip** tracking layers
- Position resolution: 40 μm
- Energy resolution:
  - < 5% (photons)
  - ~ 40% (neutrons)

Operations history at LHC

- December 2009 - July 2010
  - p-p collisions @ $\sqrt{s}$ = 900 GeV
  - p-p collisions @ $\sqrt{s}$ = 7 TeV
- January, February 2013 (only Arm 2)
  - p-Pb collisions @ $\sqrt{s_{NN}}$ = 5.02 TeV
  - p-p collisions @ $\sqrt{s}$ = 2.76 TeV
- June 2015
  - p-p collisions @ **$\sqrt{s}$ = 13 TeV**
- November 2016 (only Arm2)
  - p-Pb collisions @ **$\sqrt{s_{NN}}$ = 8.1 TeV**

Published results

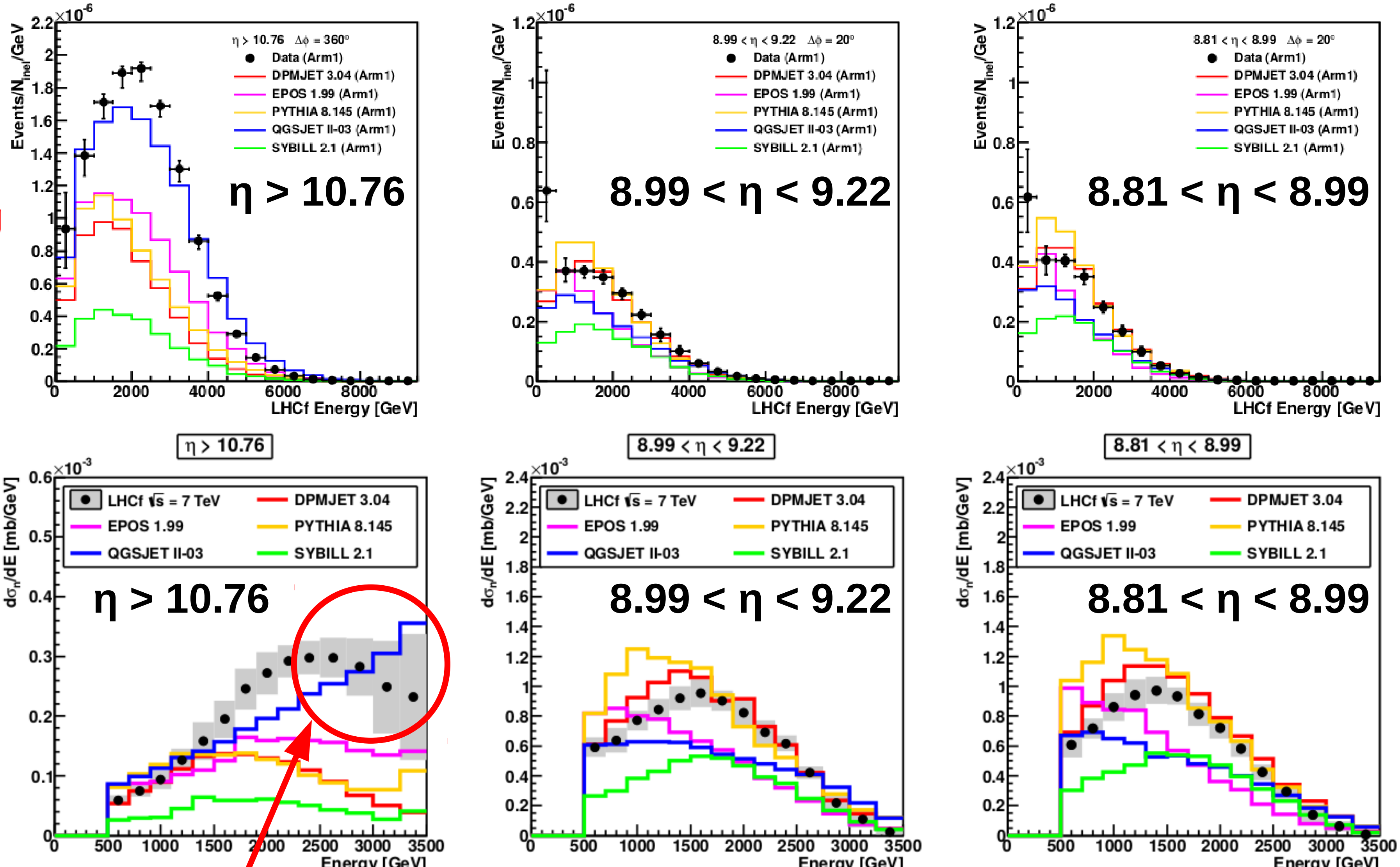
- Photons
  - Energy spectra in p-p @ $\sqrt{s}$ = 7 TeV [*PLB 703 (2011), 128-134*]
  - Energy spectra in p-p @ $\sqrt{s}$ = 900 GeV [*PLB 715 (2012), 298-303*]
- π^0
  - P_T spectra in p-p @ $\sqrt{s}$ = 7 TeV [*PRD 86, 092001 (2012)*]
  - P_T spectra in p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV [*PRC 89, 065209 (2014)*]
  - P_T and P_Z spectra in p-p @ $\sqrt{s}$ = 7 TeV and 2.76 TeV, p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV [*submitted to PRD*]
- Neutrons
  - Energy spectra in p-p @ $\sqrt{s}$ = 7 TeV [*PLB 750 (2015), 360-366*]

Neutron energy spectra in p-p at 7 TeV

PLB 750 (2015), 360-366

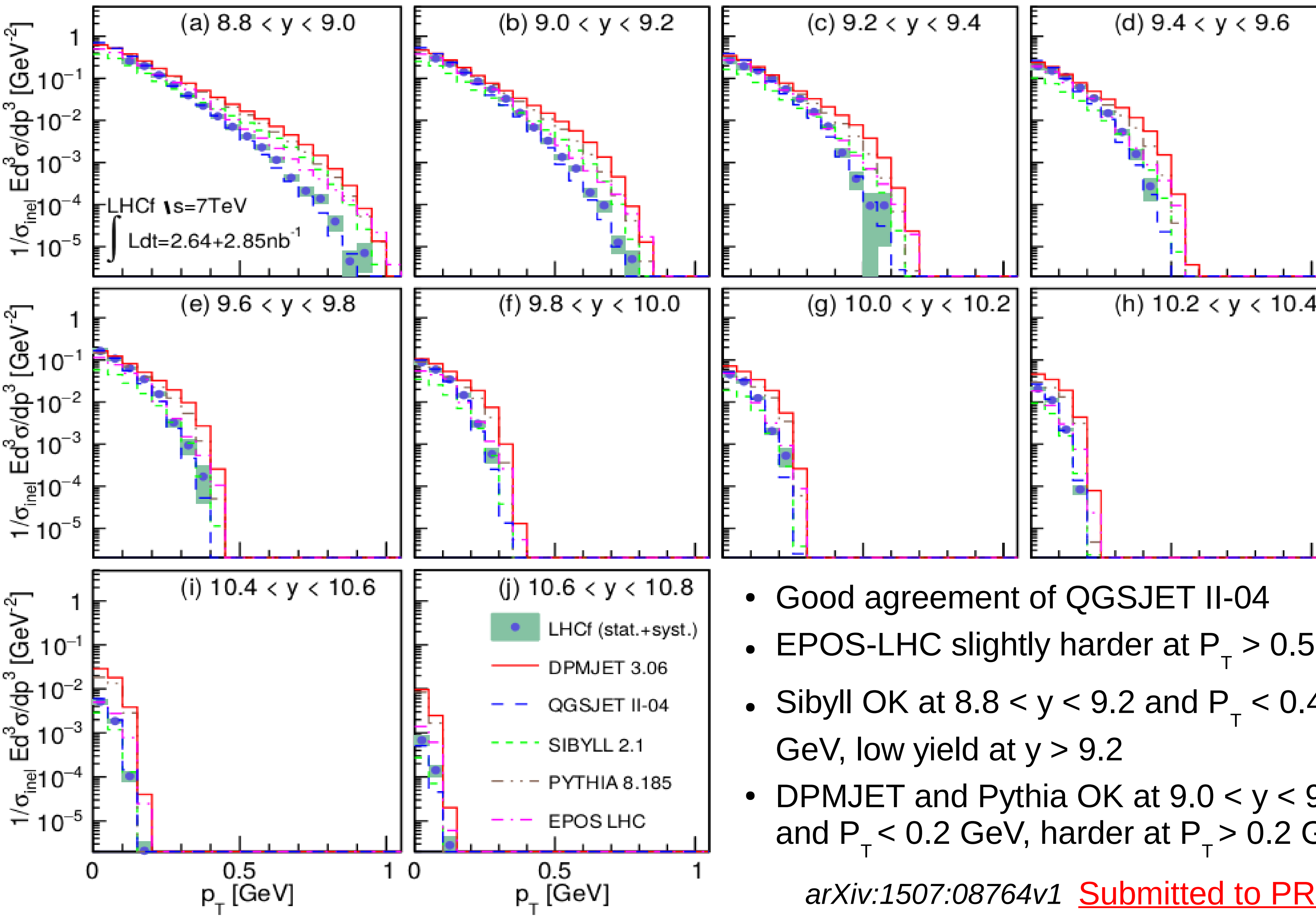
Before unfolding

After unfolding



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

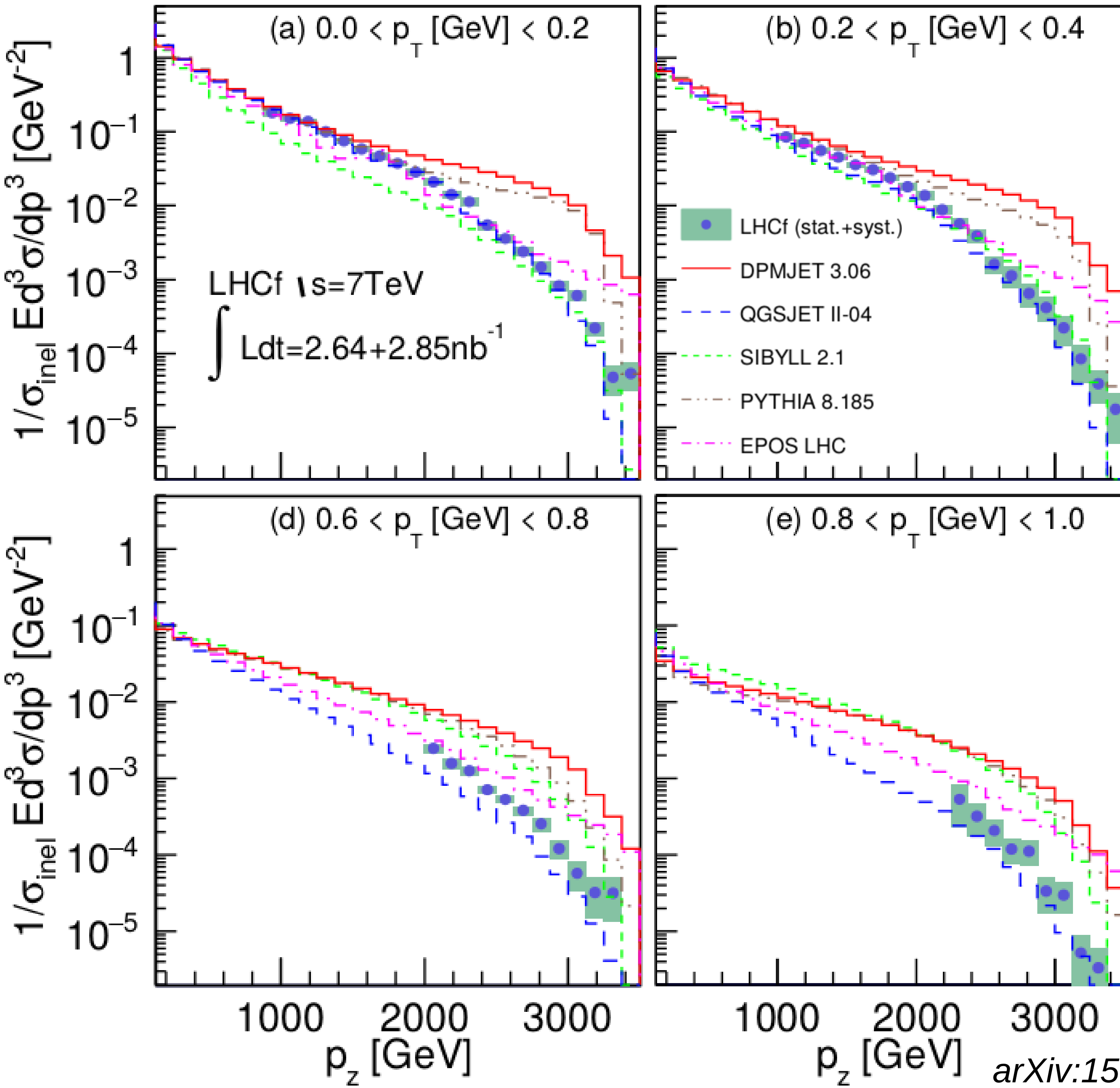
π^0 P_T spectra in p-p @ 7 TeV



- Good agreement of QGSJET II-04
- EPOS-LHC slightly harder at $P_T > 0.5$ GeV
- Sibyll OK at $8.8 < y < 9.2$ and $P_T < 0.4$ GeV, low yield at $y > 9.2$
- DPMJET and Pythia OK at $9.0 < y < 9.8$, and $P_T < 0.2$ GeV, harder at $P_T > 0.2$ GeV

arXiv:1507:08764v1 Submitted to PRD

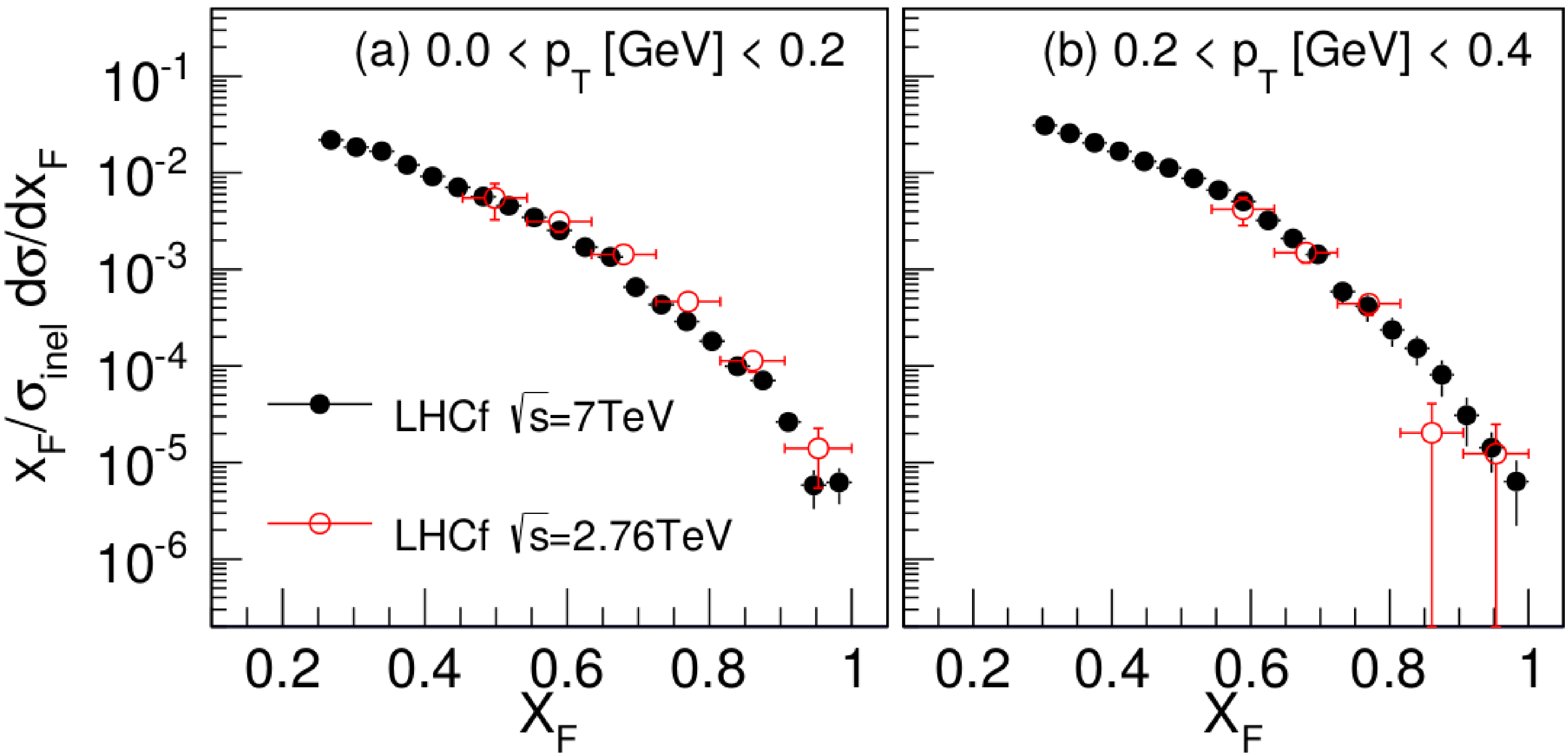
π^0 P_Z spectra in p-p @ 7 TeV



- Good agreement of QGSJET II-04
- EPOS-LHC harder at P_Z > 2 TeV
- DPMJET and Pythia OK at P_T < 0.2 GeV and P_Z < 1.6 TeV, harder at P_Z > 1.6 TeV
- SIBYLL similar to DPMJET and PYTHIA increasing P_T, low yield at P_T < 0.2 GeV

arXiv:1507:08764v1 Submitted to PRD

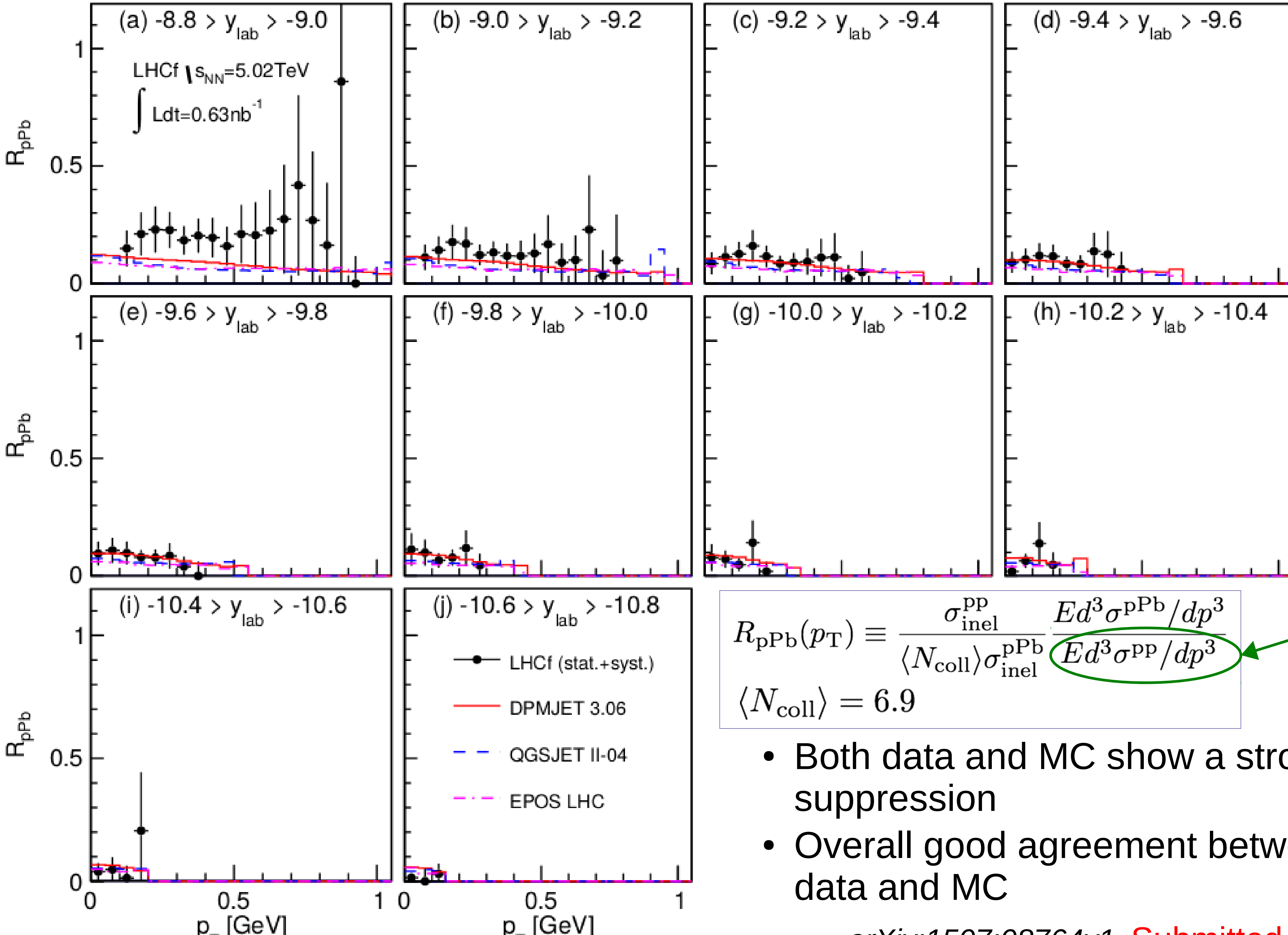
π^0: Feynman scaling hypothesis



- Hypothesis: cross section of secondary particles as a function of $X_F = 2 P_Z / \sqrt{s}$ is independent of $\sqrt{s}$ for $X_F > 0.2$
- Feynman scaling holds at the ~20% level

arXiv:1507:08764v1 Submitted to PRD

π^0: nuclear modification factor in p-Pb



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

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

interpolated at 5.02 TeV using 7 TeV and 2.76 TeV data

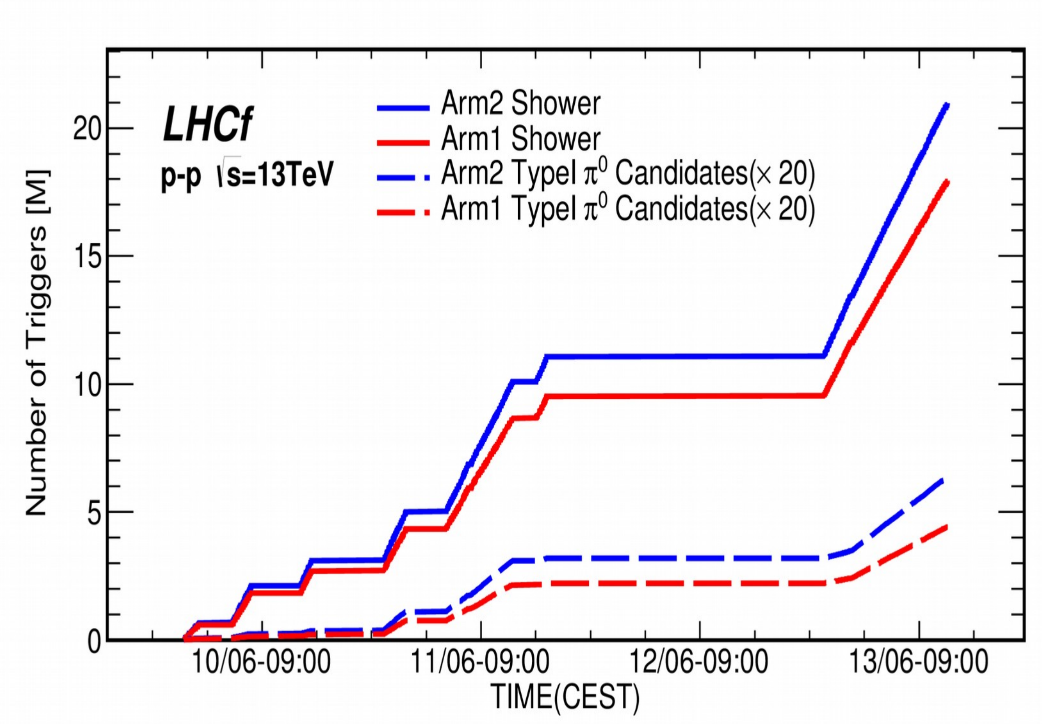
- Both data and MC show a strong suppression
- Overall good agreement between data and MC

arXiv:1507:08764v1 Submitted to PRD

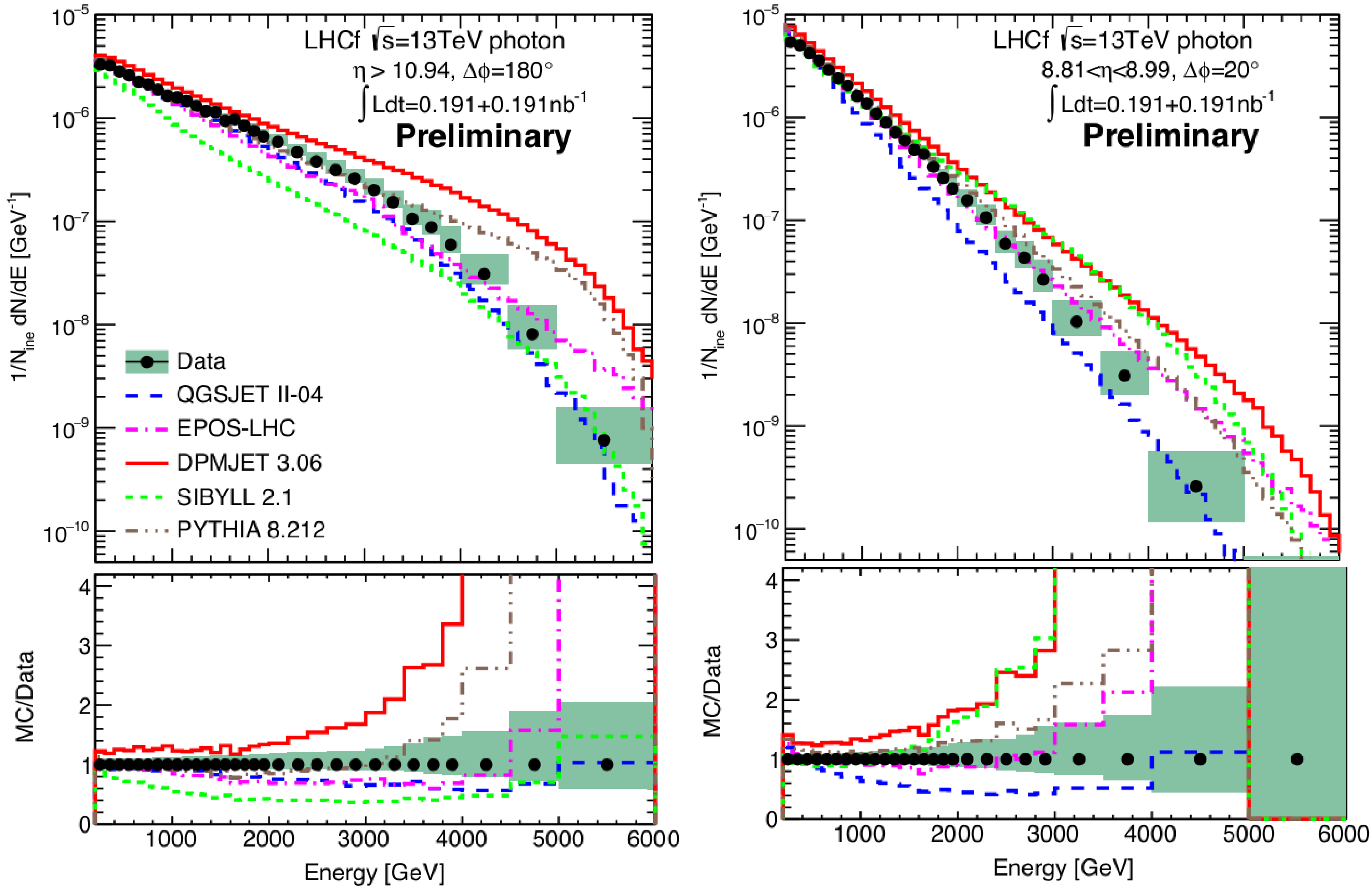
LHC operations in 2015

- Upgrade of the detector
  - plastic scintillators → GSO scintillators (radiation hardness)
  - scintillation fibres → GSO bars (radiation hardness)
  - reduction of silicon detectors signal (avoid saturation)
  - change of silicon detectors longitudinal position (energy reconstruction)

- LHCf low-luminosity dedicated run during week 24, June 9-13
  - $\sqrt{s}$ = 13 TeV
  - 26.6 hours with L = 0.5-1.6 · 10^{29} cm^{-2} s^{-1} with μ = 0.01, 0.03
  - 4 · 10^7 showers, 0.5 · 10^6 π^0 obtained
  - Trigger exchange with ATLAS



Photon spectra in p-p @ 13 TeV



- Data are not well reproduced by a single model
- QGSJET: good shape but low yield, EPOS: good except very high energy region

Summary and future plans

- LHCf can contribute to reduce systematic uncertainties on hadronic interaction models
- Data in p-p and p-Pb collisions are used to study both soft QCD processes and to estimate nuclear effects
- Very forward spectra of photons, π^0s and neutrons were measured
- LHC operations at $\sqrt{s}$ = 13 TeV in 2015 were successfully completed
- Analysis of Run II data is ongoing
  - photon and neutron energy spectra
  - combined analysis with ATLAS
- Operation at RHIC accelerator in 2017 with p-p collisions at $\sqrt{s}$ = 510 GeV (*RHICf*)

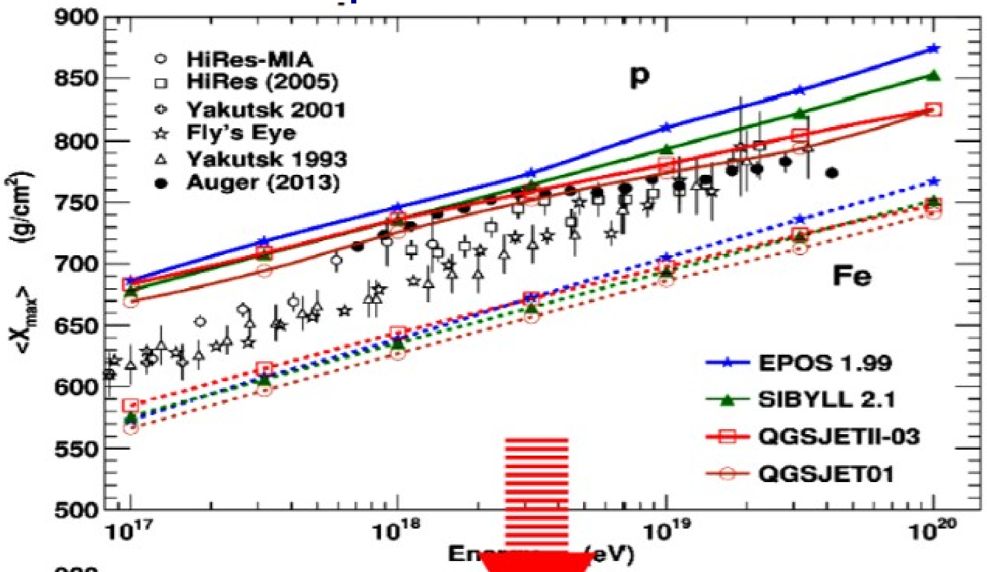
Backup slides

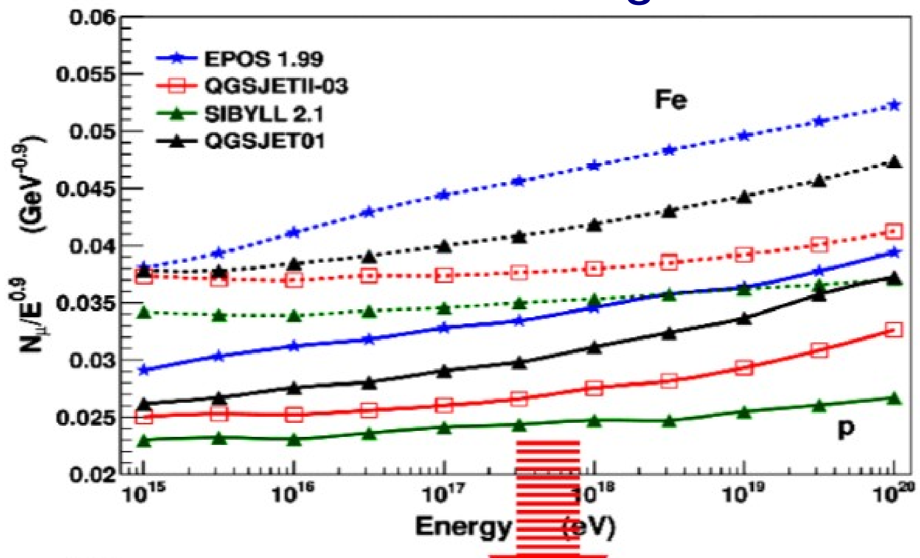
LHC contribution to models

Mean depth of shower maximum

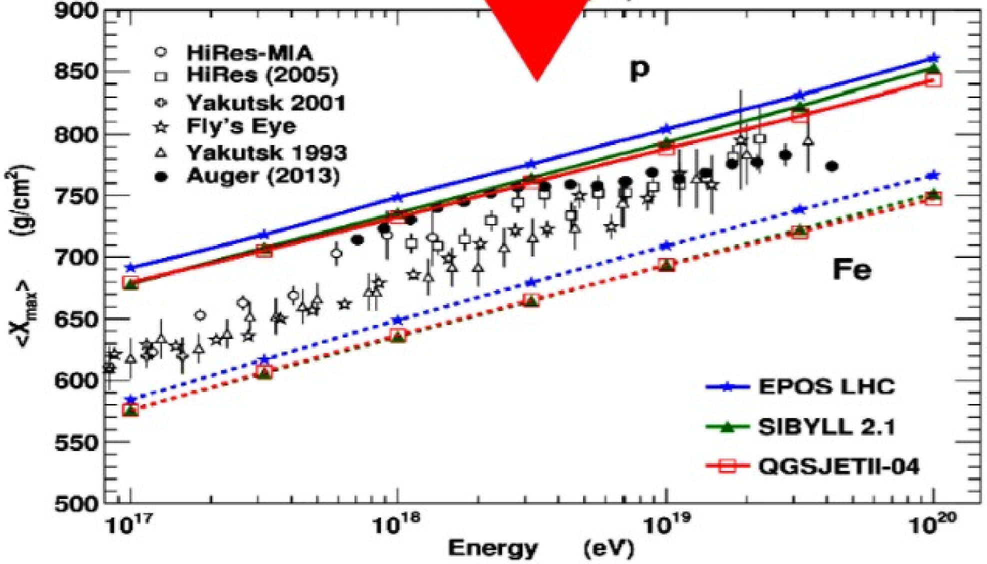
N° of muons at ground

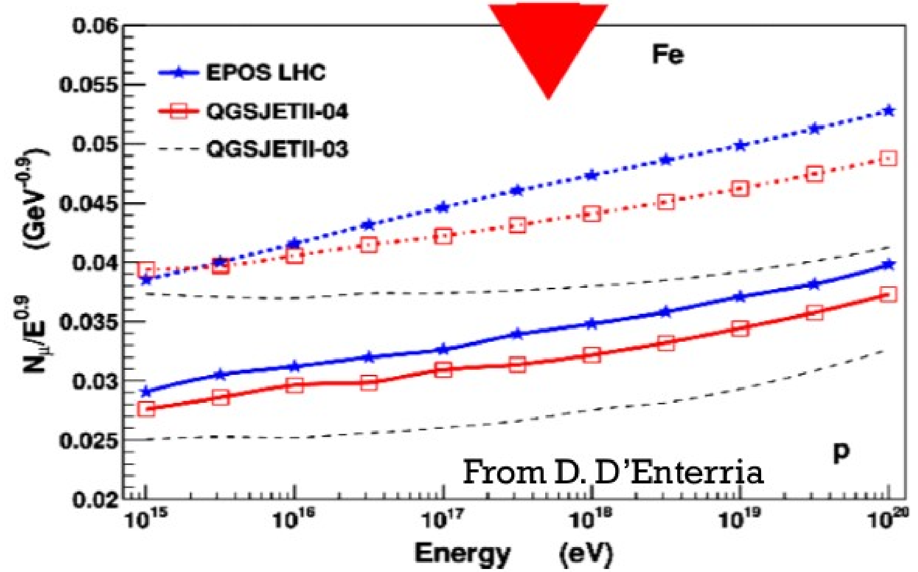
Pre-LHC





Post-LHC



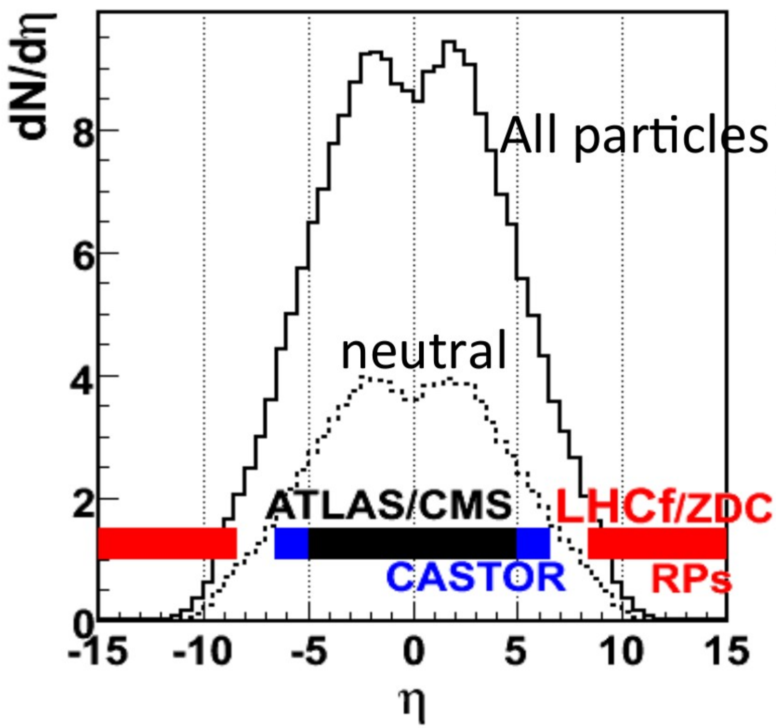


- Tuning by S. Ostapchenko and T. Pierog
- Reduction of systematic uncertainties between models

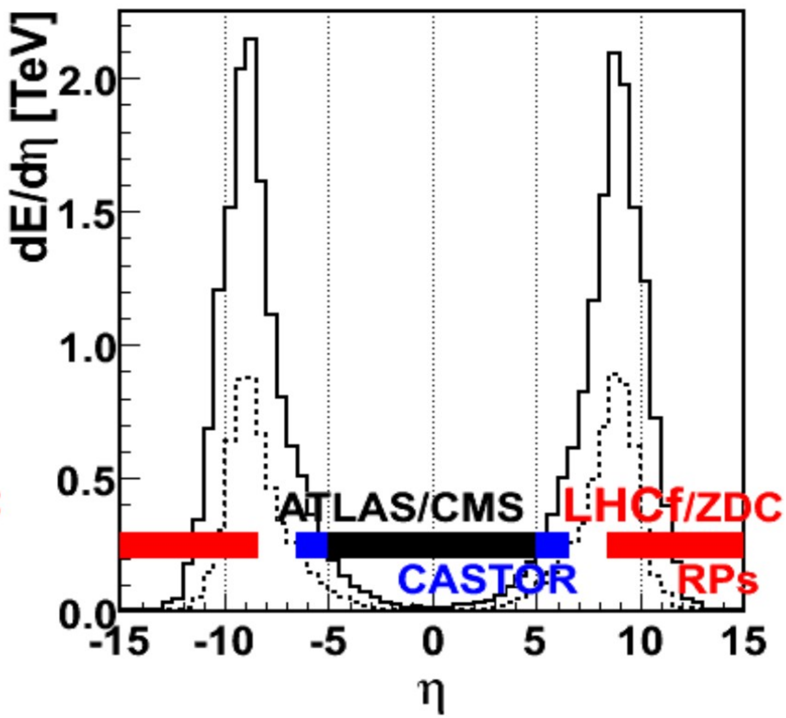
Forward energy flux @ LHC

p-p collisions @ $\sqrt{s}$ = 14 TeV → $E_{CR} = 10^{17}$ eV

Multiplicity



Energy Flux



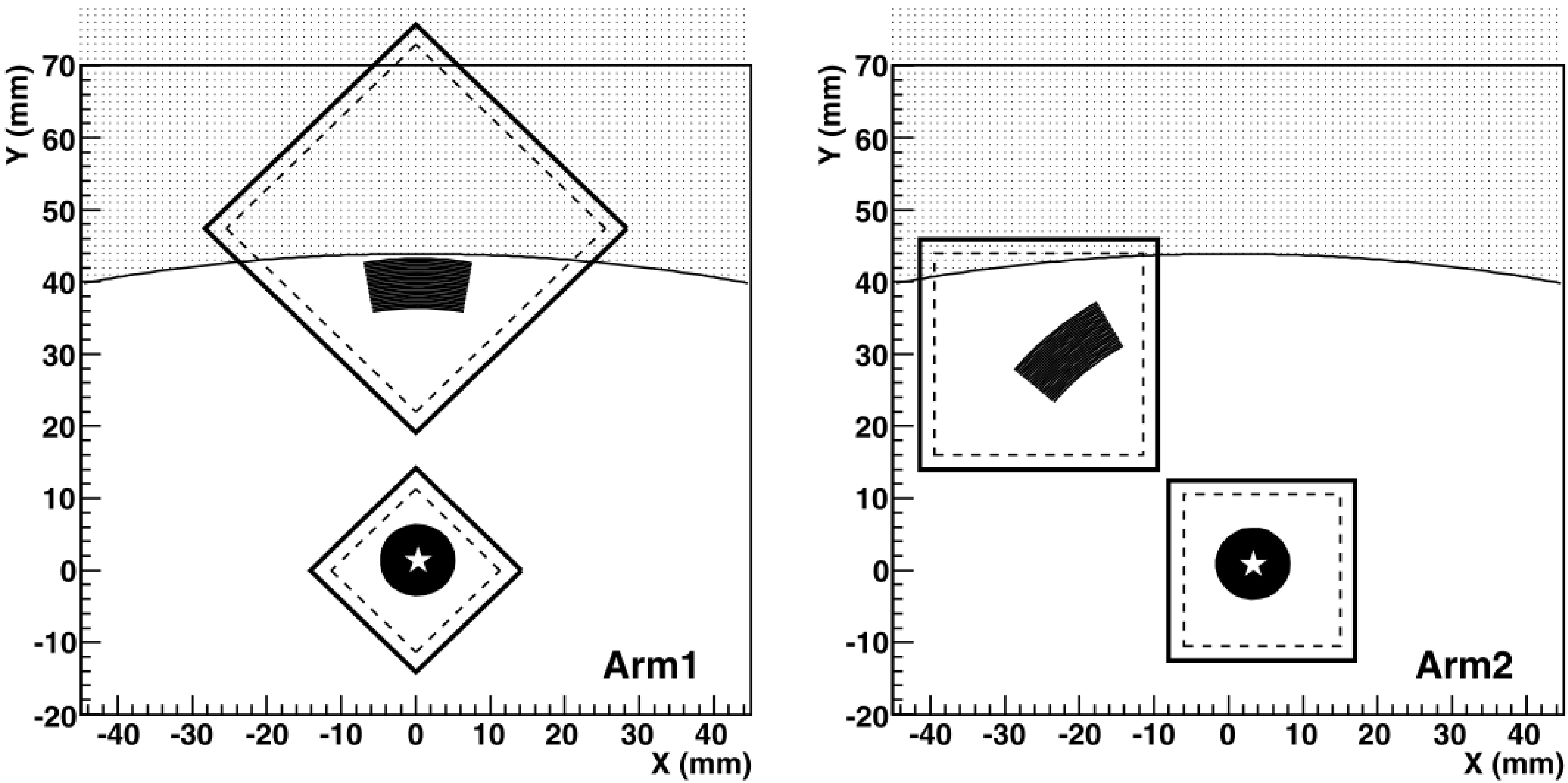
LHCf pseudo-rapidity range: η > 8.4
(with 140 μrad beam crossing angle)

Pseudo-rapidity

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

LHCf covers the peak of energy flow

Detectors cross section



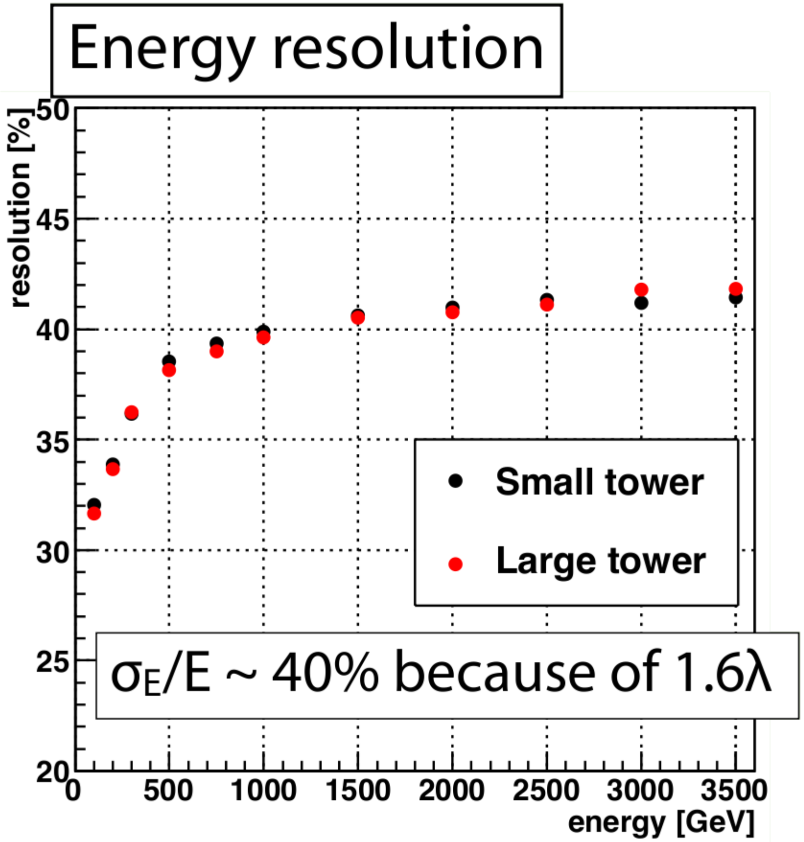
Arm 1 & Arm 2 detectors

Neutrons analysis in p-p collisions at 7 TeV

Energy resolution ~40%
above 500 GeV
(due to high leakage)

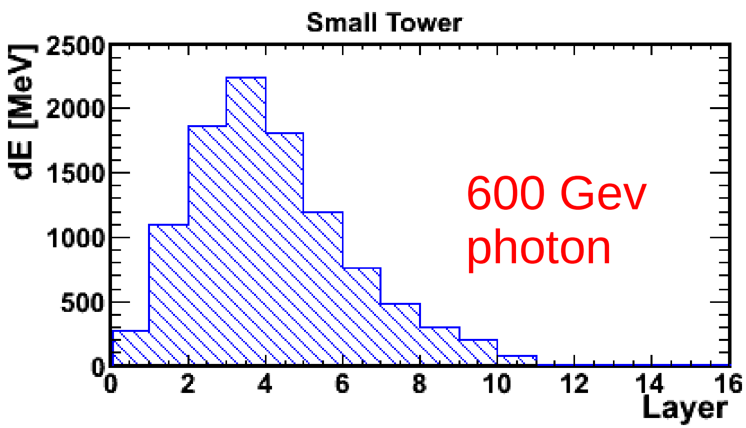
True spectrum is smeared
by detector response

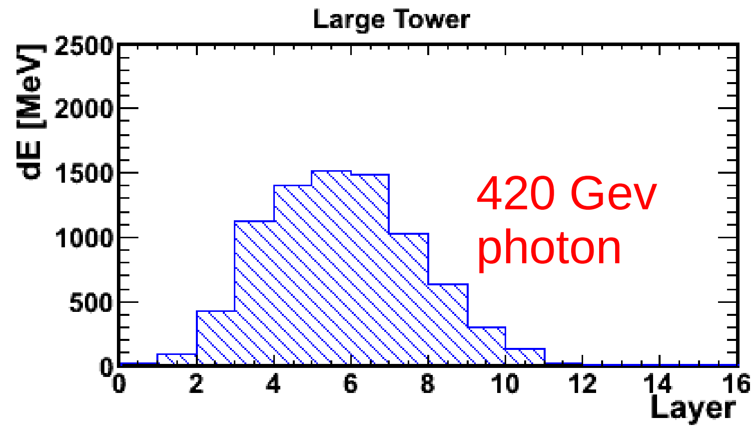
Unfolding is needed to extract physics results



Neutron measurements are important to study the **muon excess** observed in ground based experiments

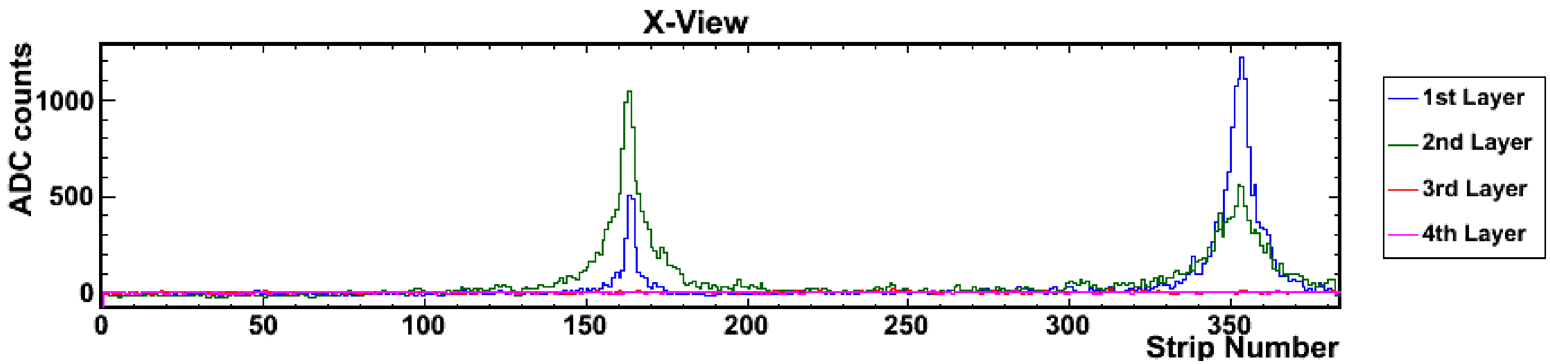
π^0 event

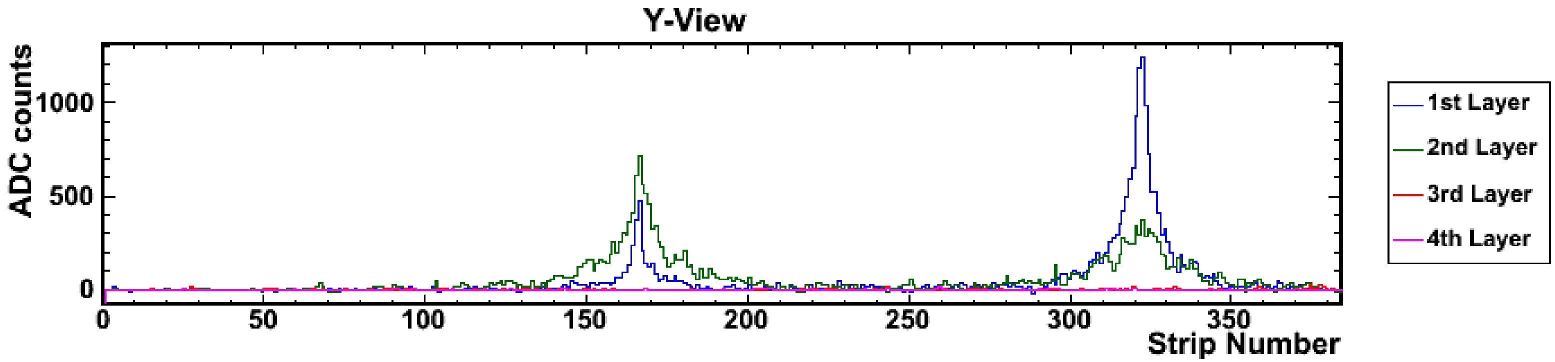




Scintillators:

- Energy measurement
- PID from shape



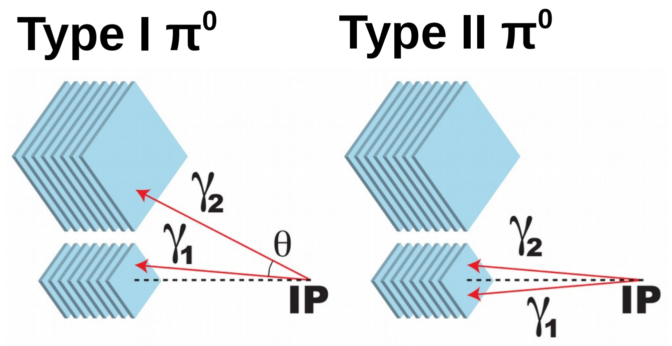


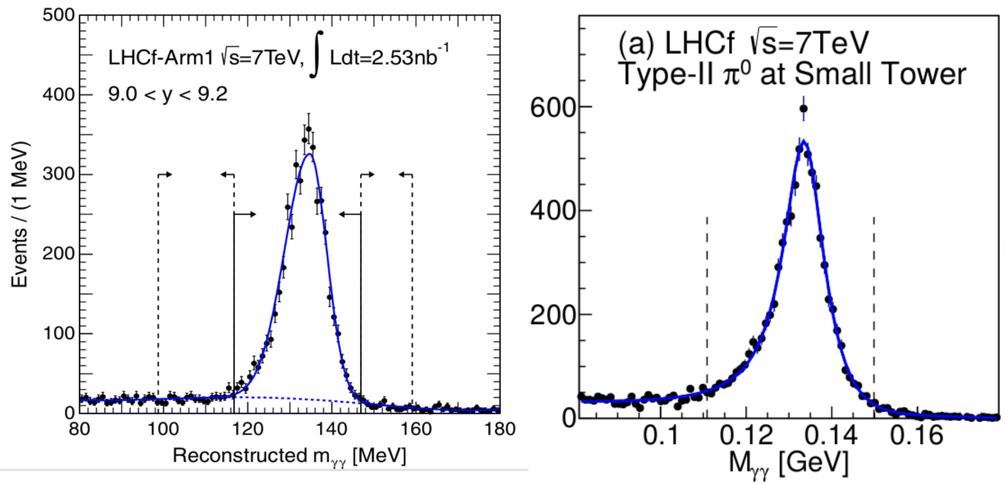
Silicon μ-strip:

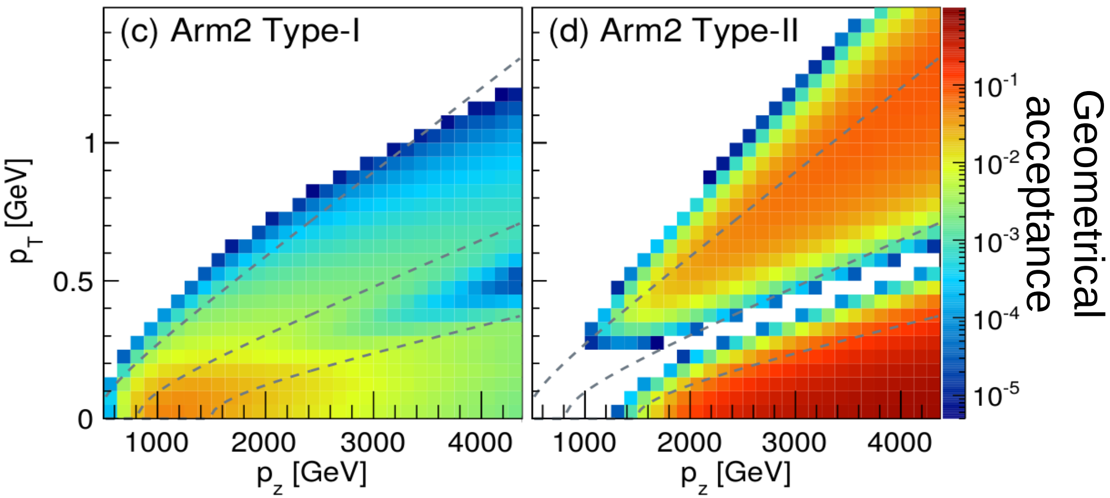
- Impact point and opening angle measurement
- Multi-hit identification

$$m_{\pi^0} = \sqrt{E_1 E_2}\,\theta$$

π^0 reconstruction



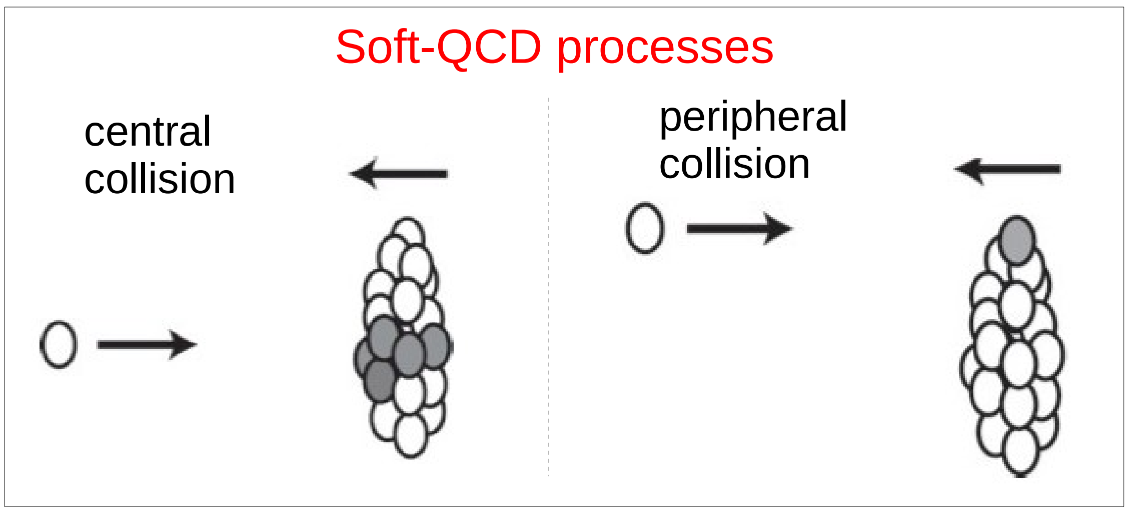


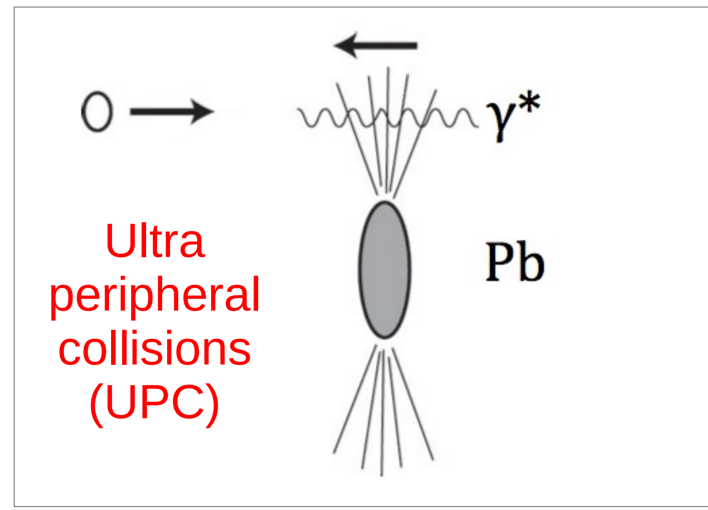


- P_T and P_Z of π^0 are reconstructed from energy and incident position of the photon pair
- Multihit events are excluded (i.e., events with a background particle in addition to the photon pair)
- Data are corrected for experimental effects:
  - background contamination
  - detector response and reconstruction efficiency (unfolding)
  - detector acceptance
  - multi hit rejection

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

- Only **Arm2** installed (better position resolution than Arm1)
- Data taken both at **p**-side and **Pb**-side (swapping beams)



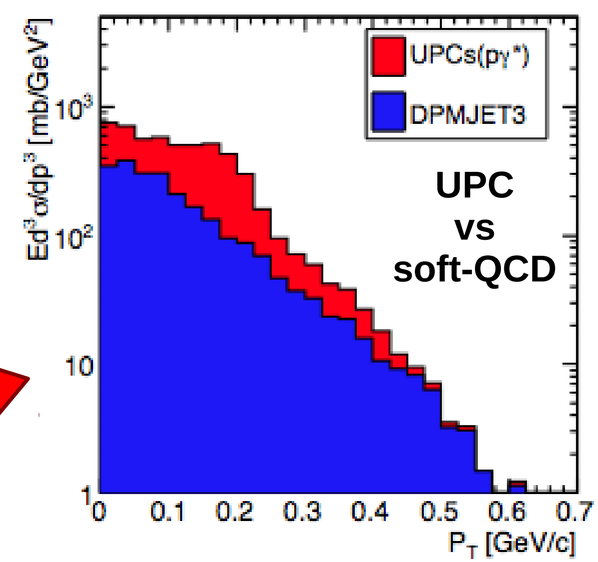


About half of the observed π^0 originates from UPC, another half is generated in soft-QDC processes

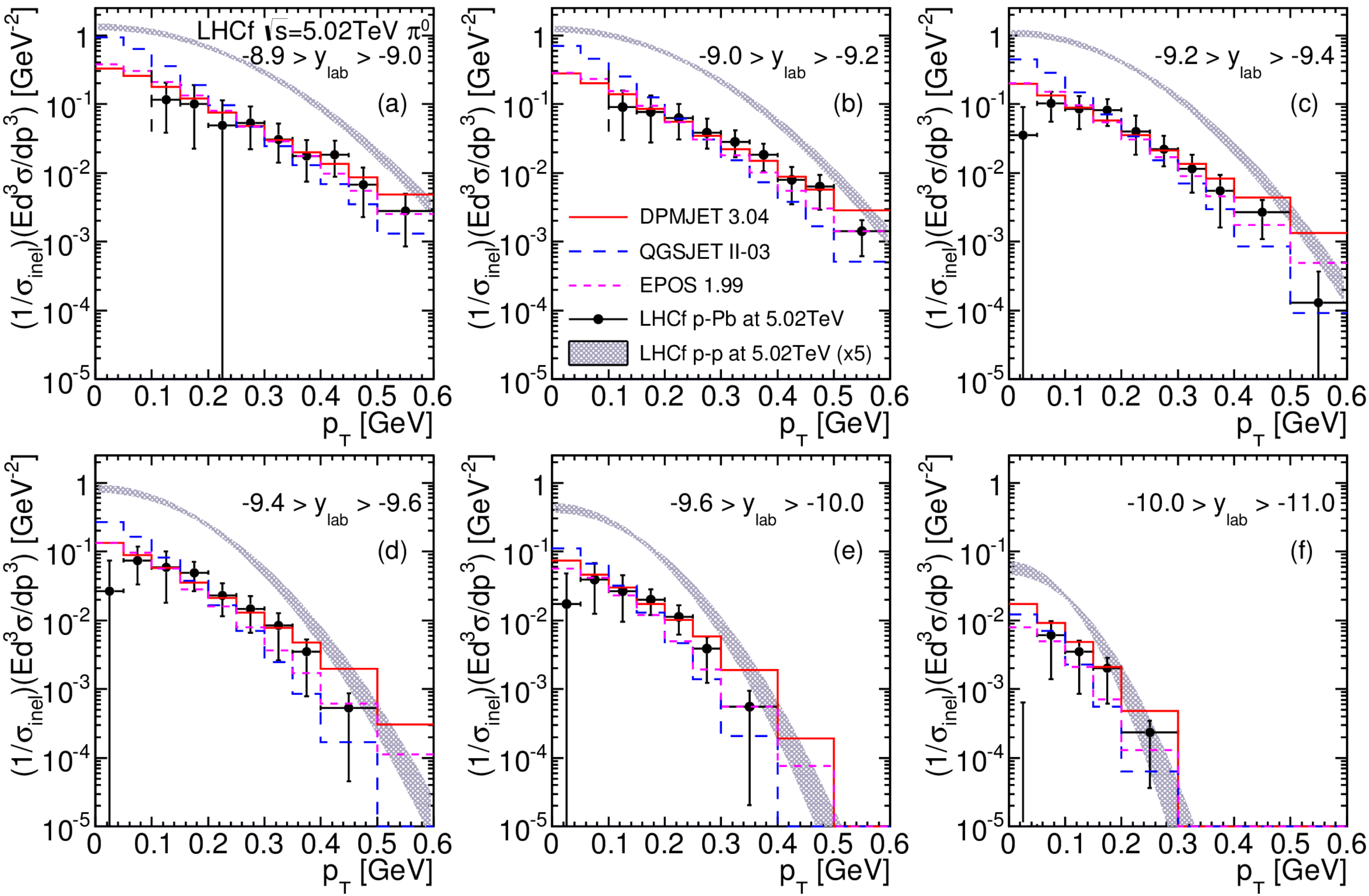
Dominant channel for forward π^0 production:

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

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



π^0 P_T spectra in p-Pb

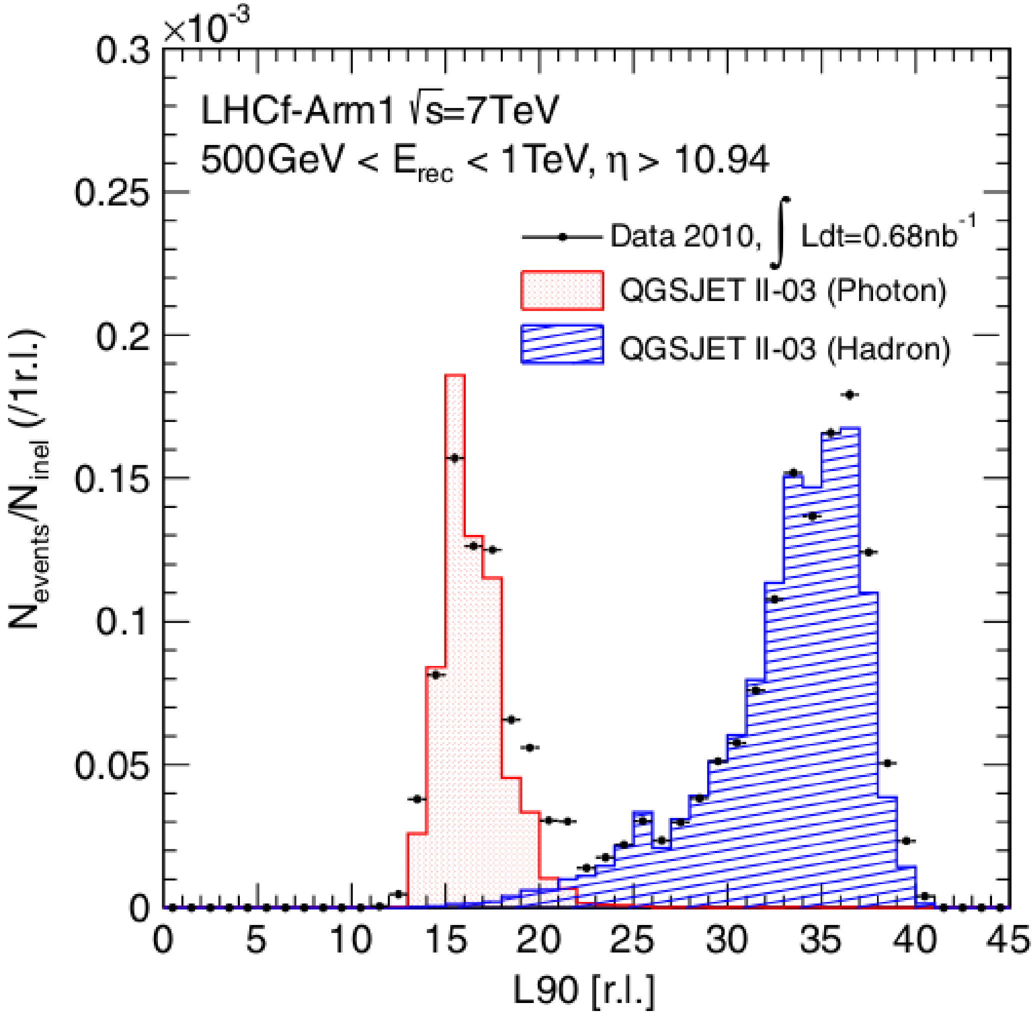


- p-p spectra at 5.02 TeV are interpolated from results at 2.76 and 7 TeV
- Data (filled circles) are in good agreement with DPMJET and EPOS
- p-Pb spectra are harder than p-p spectra (shaded area, multiplied by 5)

PRC 89, 065209 (2014)

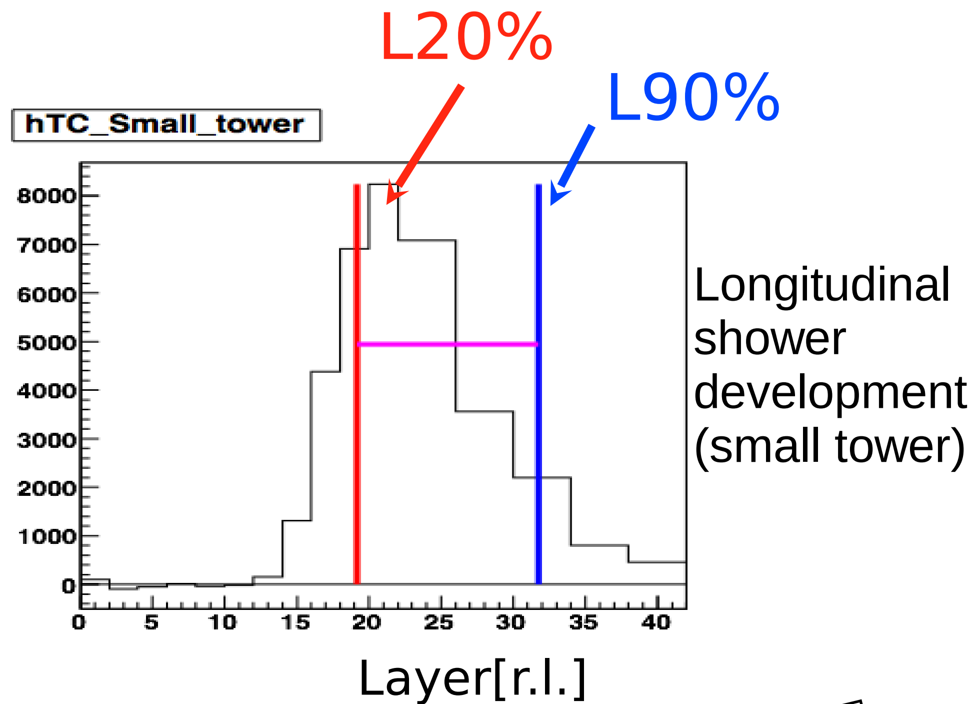
Photons selection

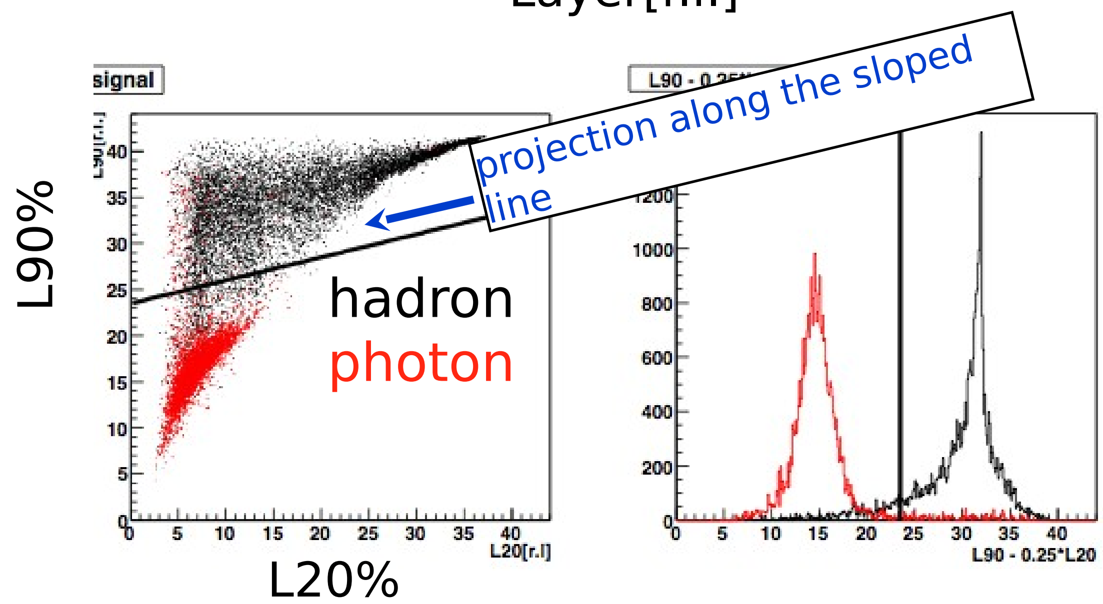
- **L90%**: depth in X_0 where 90% of the deposited energy is contained
- Energy-dependent threshold to keep photon detection efficiency at 90%
- Events with L90% less than threshold are recognized as photons



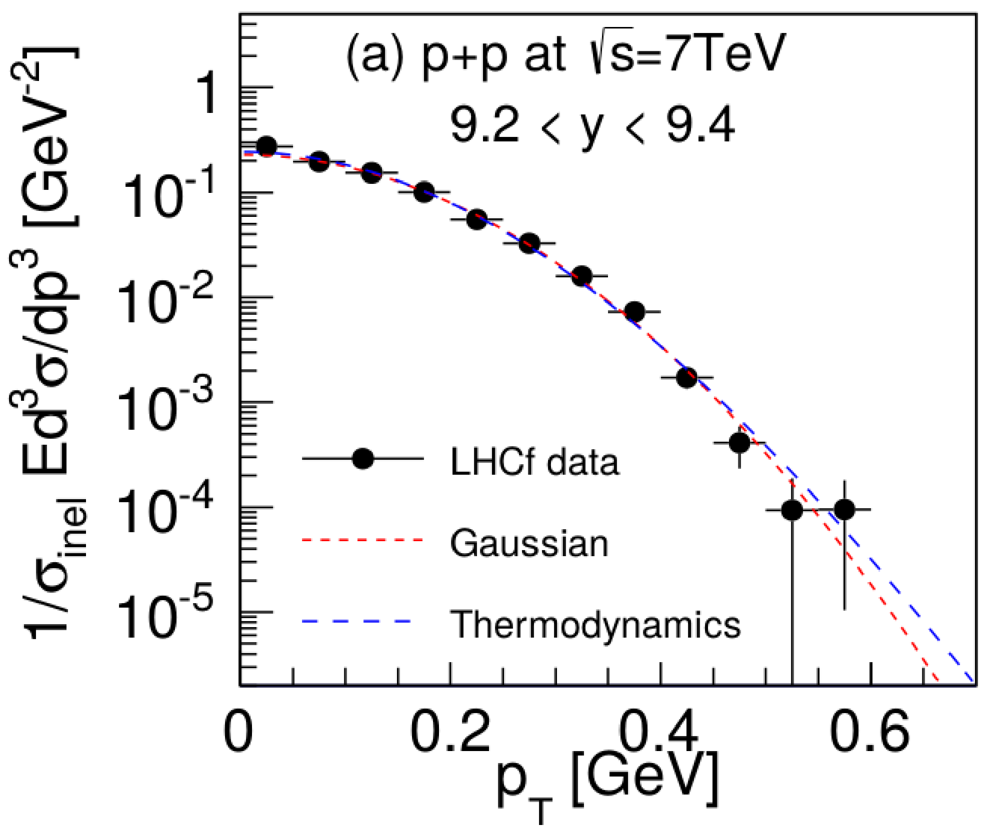
Neutrons selection

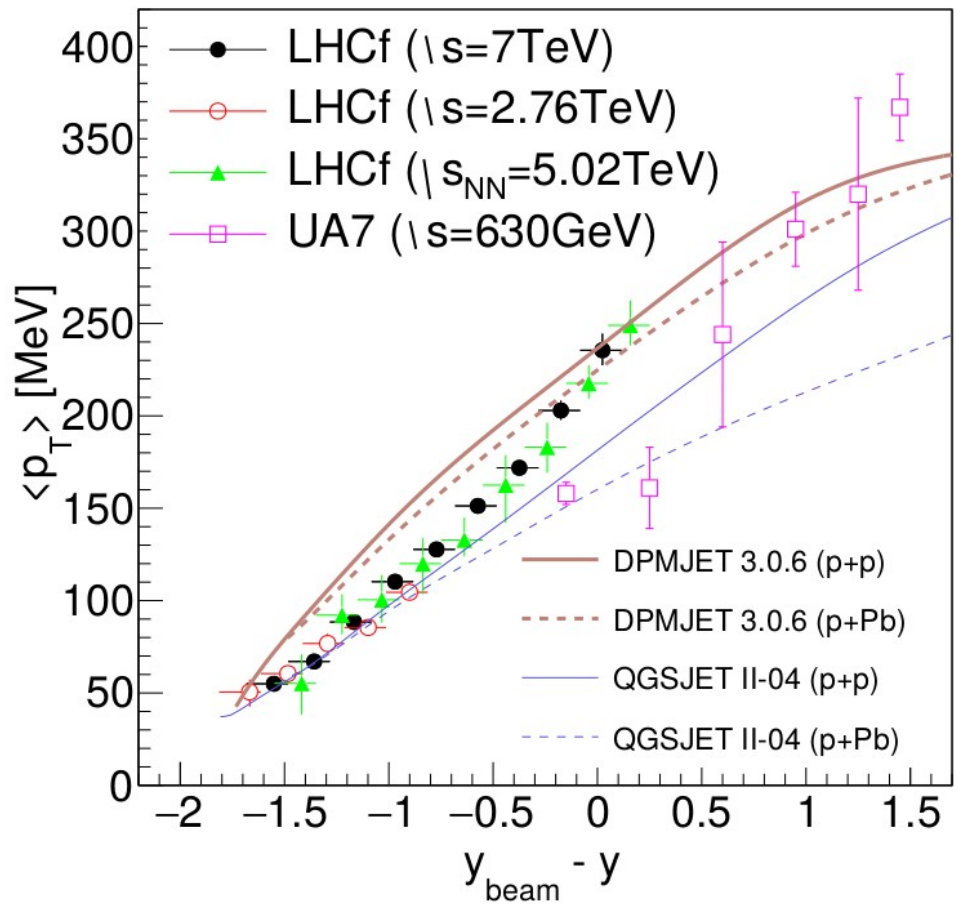
- A 2D method based on longitudinal shower development is used
- **L20%** (**L90%**): depth in X_0 where 20% (90%) of the deposited energy is contained
- $\mathbf{L_{2D}}$ = L90% - 0.25 · L20%
- Mean purity in the 0-10 TeV range: 95%
- Mean efficiency: ~90%





π^0: < P_T > scaling





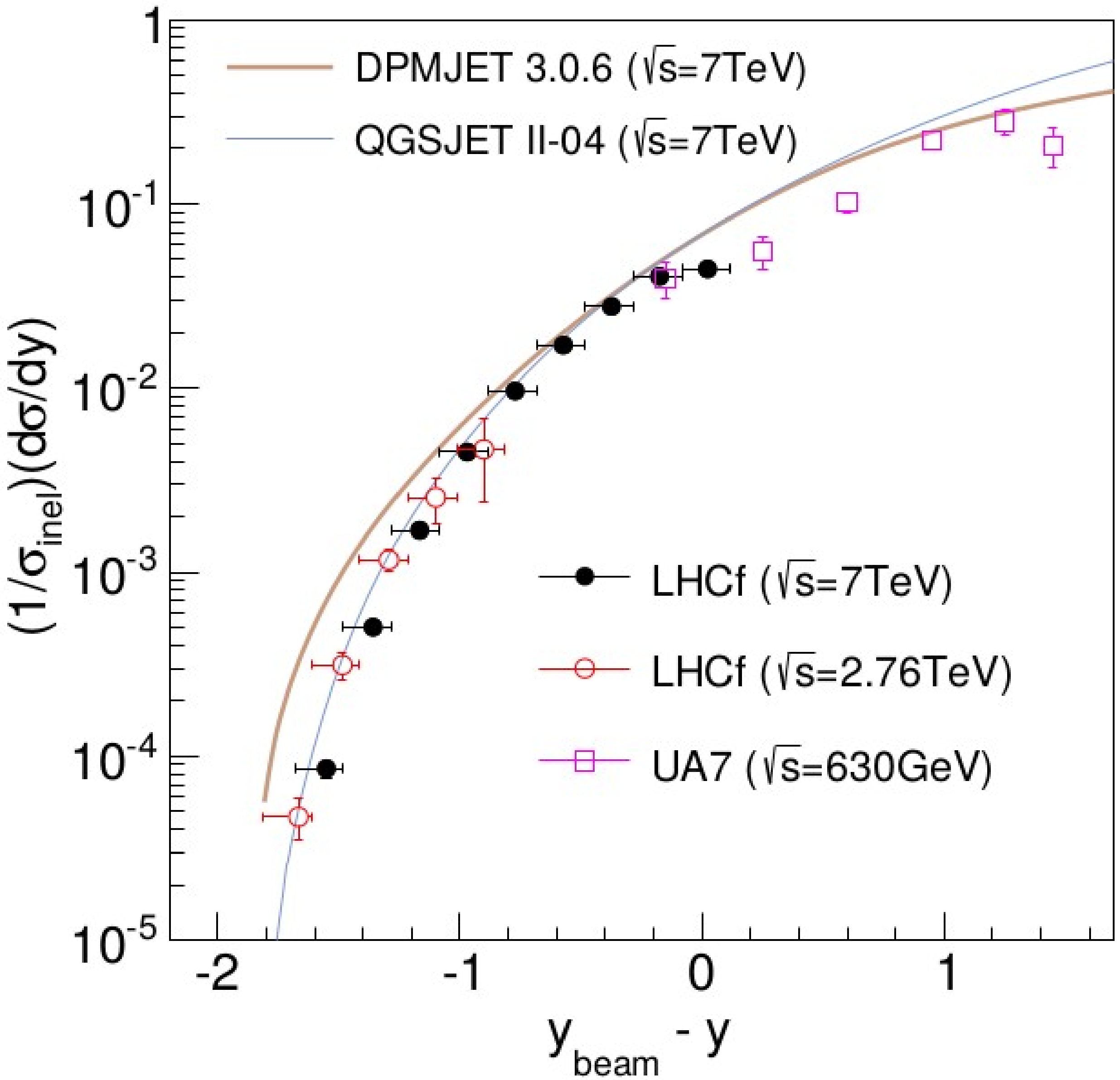
Derivation of mean PT:

- Fit with Gaussian
- Fit with thermodynamical model
- Numerical integration

- LHCf results consistent within ~ 10 %

arXiv:1507:08764v1 Submitted to PRD

π^0: limiting fragmentation hypothesis



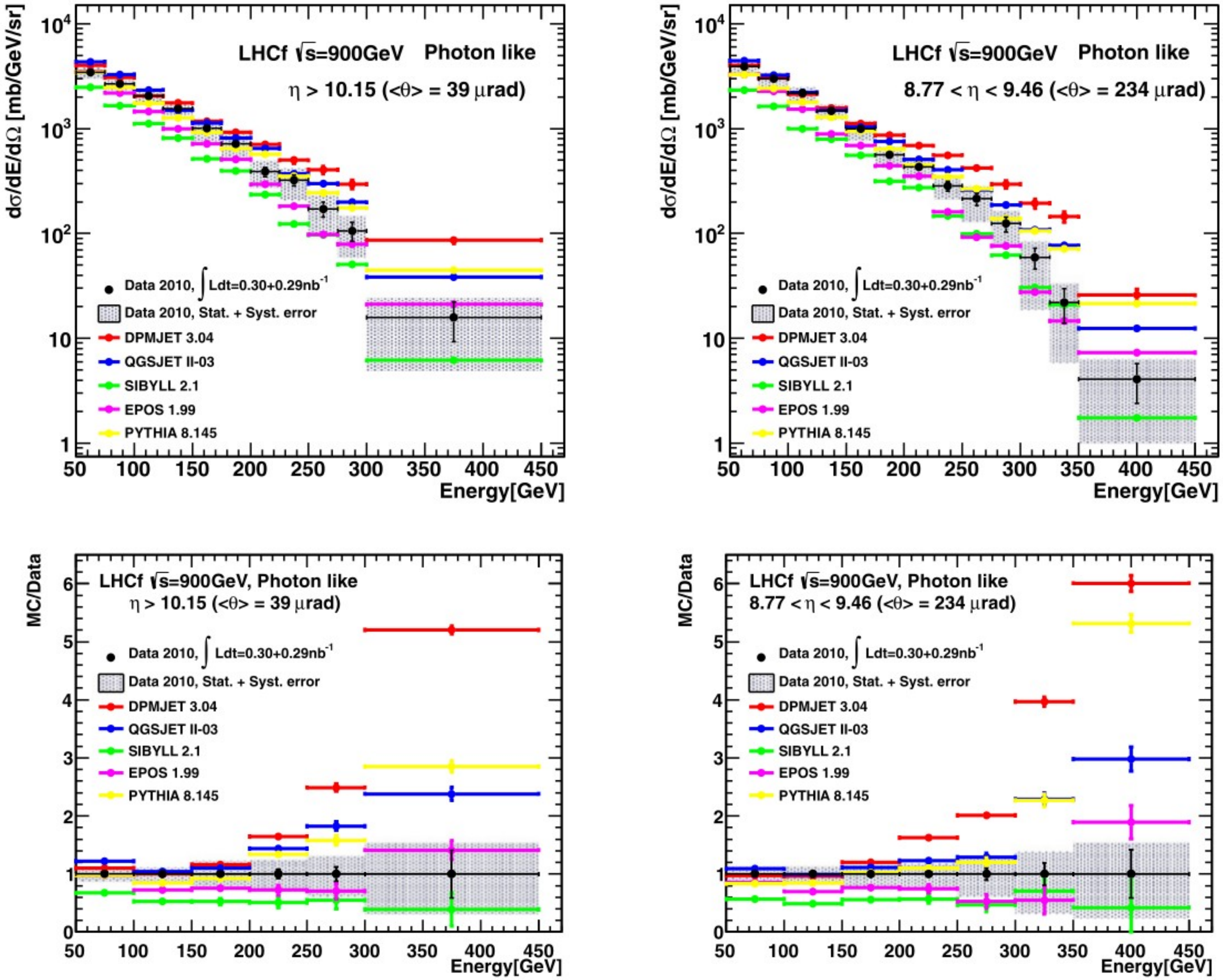
- Hypothesis: fragments of a colliding hadron follow a limiting rapidity distribution in the target frame

  ⬇

  rapidity distribution of secondary particles is independent of √s
- Limiting fragmentation hypothesis holds at ~15% level

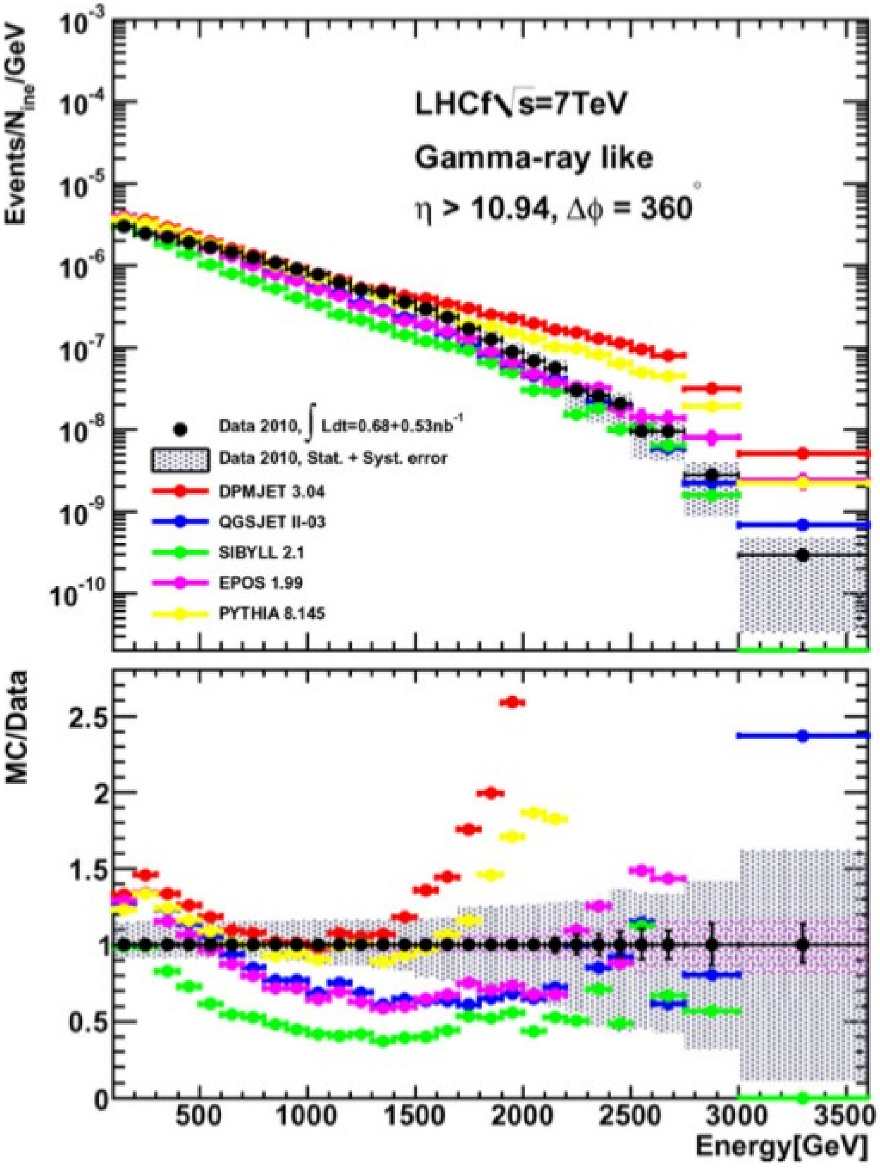
arXiv:1507:08764v1 Submitted to PRD

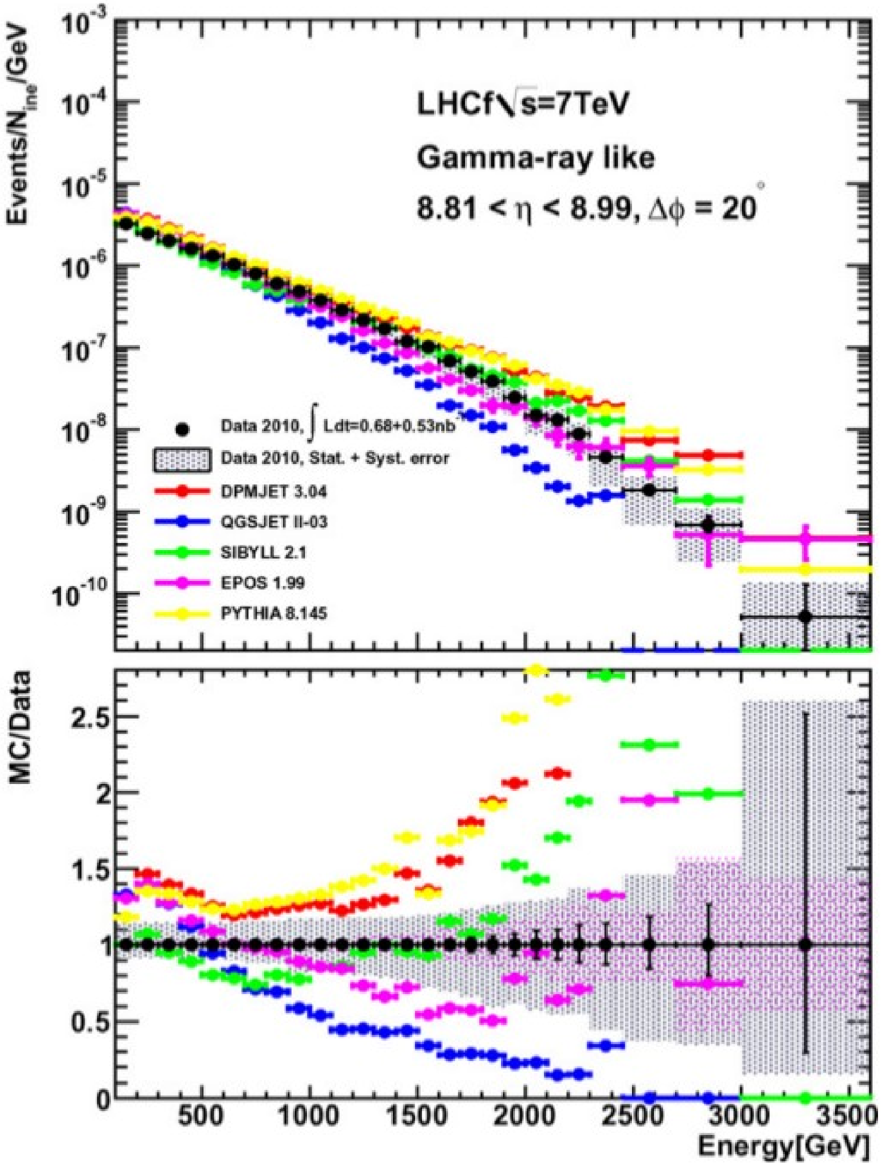
Photons spectra in p-p at 900 GeV



PLB 715 (2012), 298-303

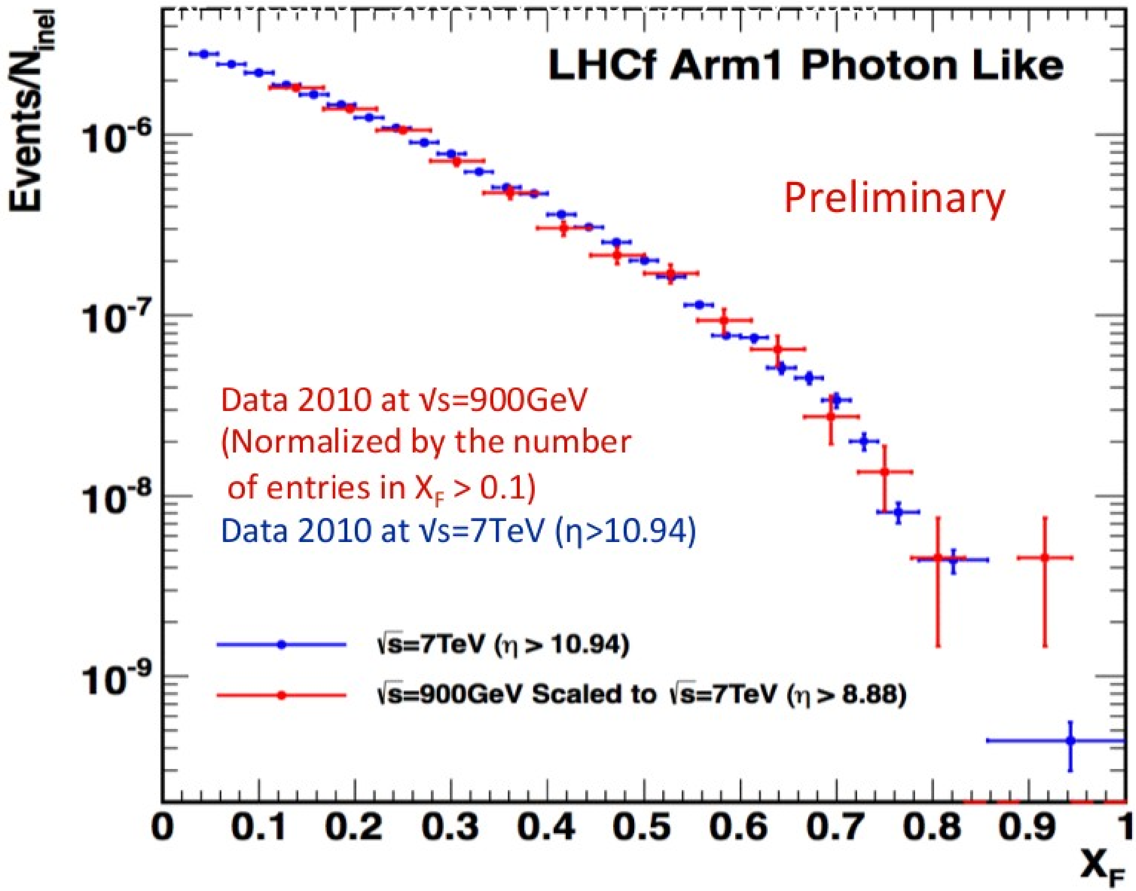
Photons energy spectra in p-p at 7 TeV





PLB 703 (2011), 128-134

Feynman scaling (photons)



- Comparison in the same P_T range ($P_T < 0.13\ X_F$ GeV/c)
- Normalized by # of events with $X_F > 0.1$
- Statistical error only

Upgrades for 13 TeV operations

- More radiation damage is expected: 0.2 Gy/nb @ 7 TeV, 2-3 Gy/nb @ 13 TeV
  - All plastic scintillators have been substituted with **GSO scintillators** (can survive up to 10^6 Gy)
  - In Arm1, scintillation fibers were replaced with **GSO bars** ($1 \times 1 \times 20\ mm^3$ and $1 \times 1 \times 40\ mm^3$ for small and large tower respectively)
- In old configuration, silicons detectors in Arm2 saturate for photons with energy > 1.5 TeV
  - **Silicon signal reduced** (~ 60%) by using a new bonding scheme of silicon strips
- Silicon detectors **longitudinal positions** were changed to better catch E-M and hadronic showers → possibility to use silicon detectors to reconstruct energy → cross check with calorimeter

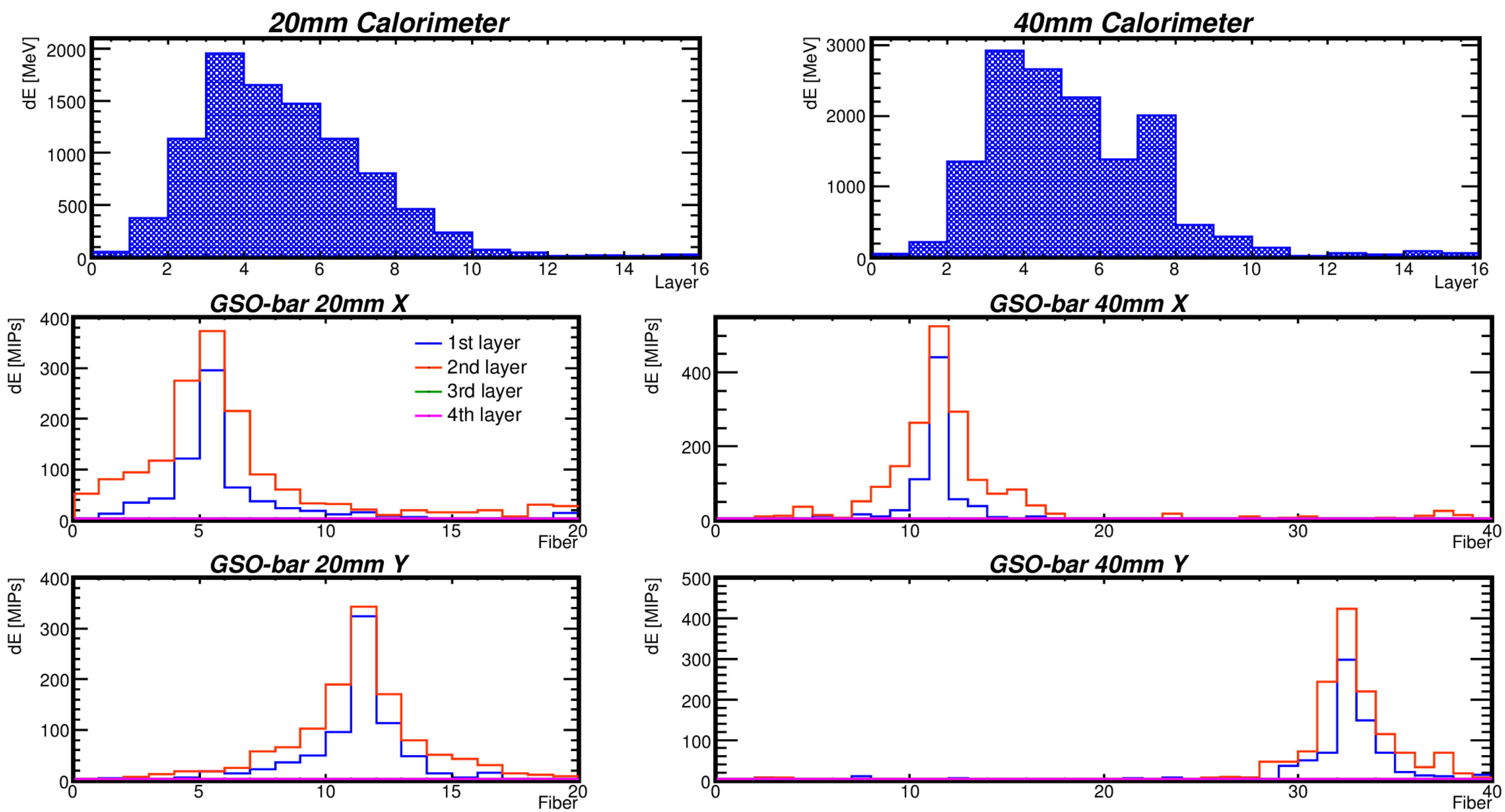
Arm 1 π^0 event

LHCf Arm1 Detector

π^0 Candidate Event

LHC p-p, $\sqrt{s}$ = 13 TeV Collisions

RUN:	44299
NUMBER:	4990
TIME:	1434141164
FILL:	3855
E_{20mm}:	323 GeV
E_{40mm}:	407 GeV
$M_{\gamma\gamma}$:	138 MeV



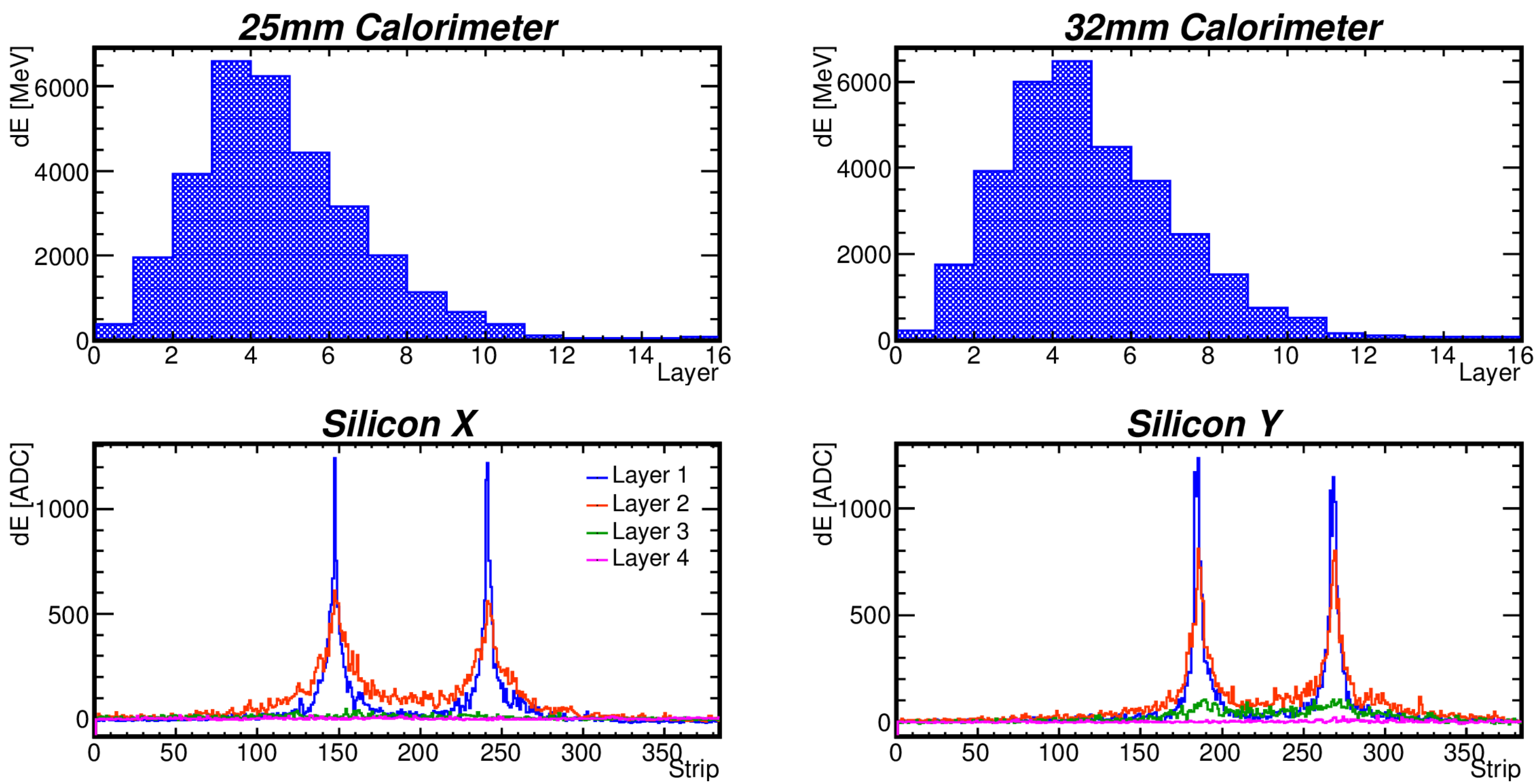
Arm 2 π^0 event

LHCf Arm2 Detector

π^0 Candidate Event

LHC p-p, $\sqrt{s}$ = 13 TeV Collisions

RUN: 44484
NUMBER: 3010
TIME: 1434152507
FILL: 3855
E_{25mm}: 1014 GeV
E_{32mm}: 1021 GeV
$M_{\gamma\gamma}$: 147 MeV



First look at 13 TeV data