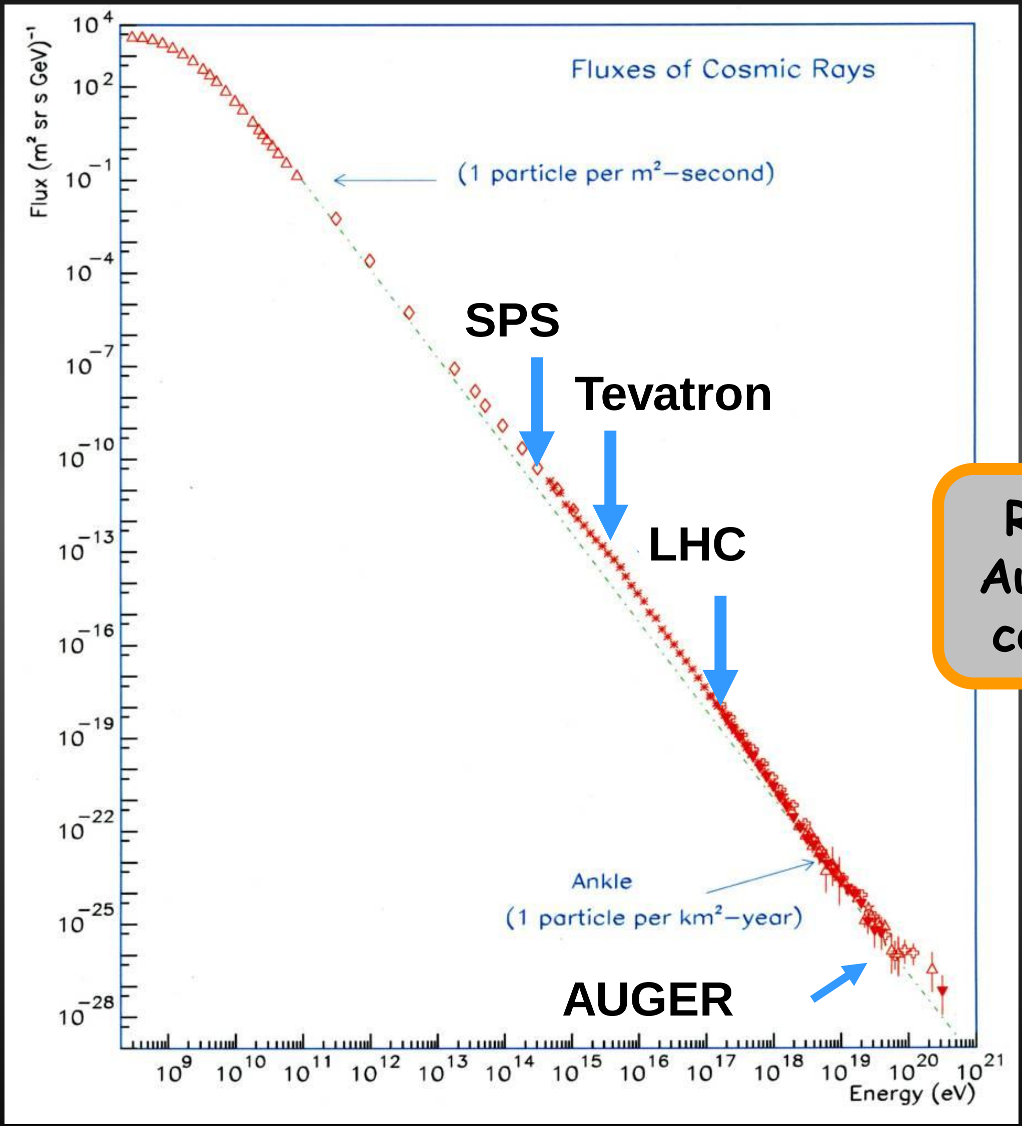
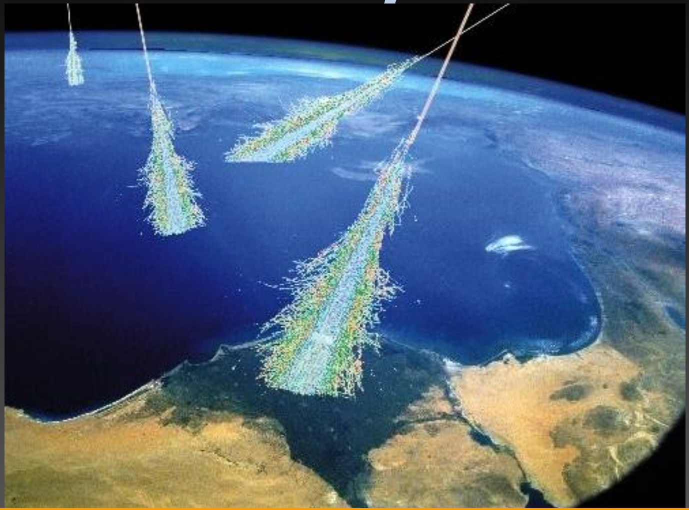
IFAE 2012
Ferrara, 11-13 Aprile 2012

Results from the LHCf experiment

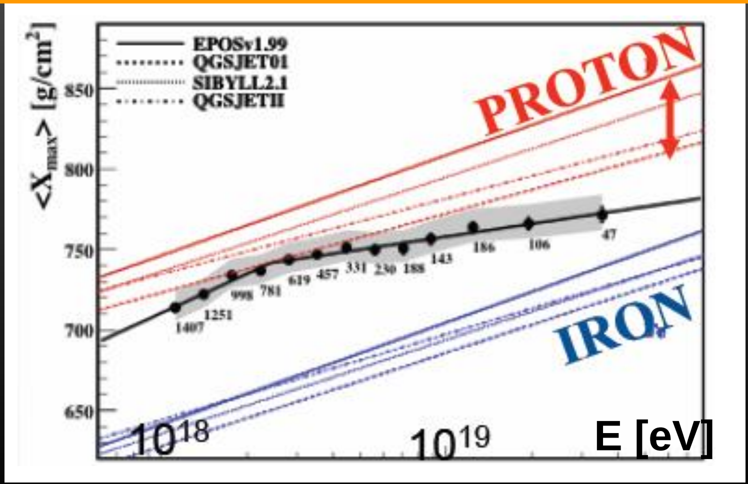
Massimo Bongi - INFN (Florence, Italy)
LHCf Collaboration

High-energy cosmic rays





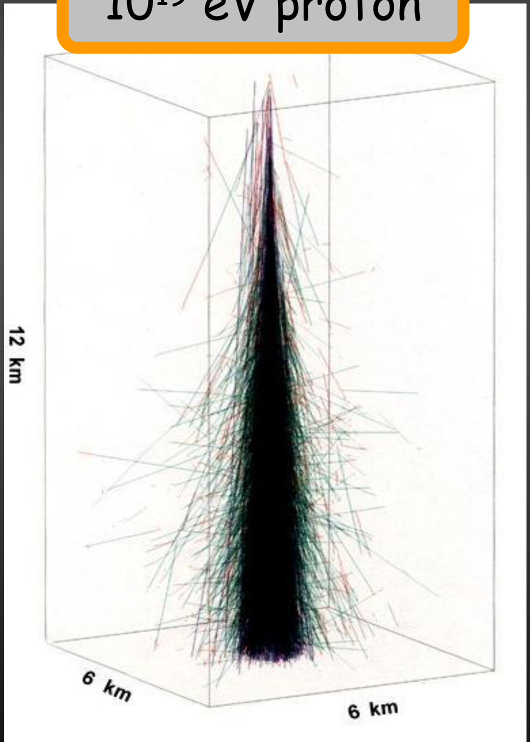
Recent excellent observations (e.g. Auger, HiRes, TA) but the origin and composition of HE CR is still unclear



Development of atmospheric showers

- The depth of the maximum of the shower X_{max} in the atmosphere depends on energy and type of the primary particle
- Several Monte Carlo simulations (different hadronic interaction models) are used and they give different answers about composition

10^{19} eV proton



Experimental tests of hadron interaction models are necessary

The dominant contribution to the shower development comes from particles emitted at low angles (forward region).

LHC gives us the unique opportunity to study hadronic interactions at 10^{17}eV

7 TeV + 7 TeV	$\rightarrow E_{lab} \approx 1 \times 10^{17}$ eV
3.5 TeV + 3.5 TeV	$\rightarrow E_{lab} \approx 3 \times 10^{16}$ eV
450 GeV + 450 GeV	$\rightarrow E_{lab} \approx 4 \times 10^{14}$ eV

LHC forward (LHCf) experiment

The LHCf collaboration

K.Fukatsu, T.Iso, Y.Itow, K.Kawade, T.Mase, K.Masuda, G.Mitsuka, Y.Muraki, T.Sako, K.Suzuki, K.Taki
Solar-Terrestrial Environment Laboratory, Nagoya University, Japan

H.Menjo *Kobayashi-Maskawa Institute, Nagoya University, Japan*

K.Kasahara, Y.Shimizu, T.Suzuki, S.Torii *Waseda University, Japan*

T.Tamura *Kanagawa University, Japan*

M.Haguenauer *Ecole Polytechnique, France*

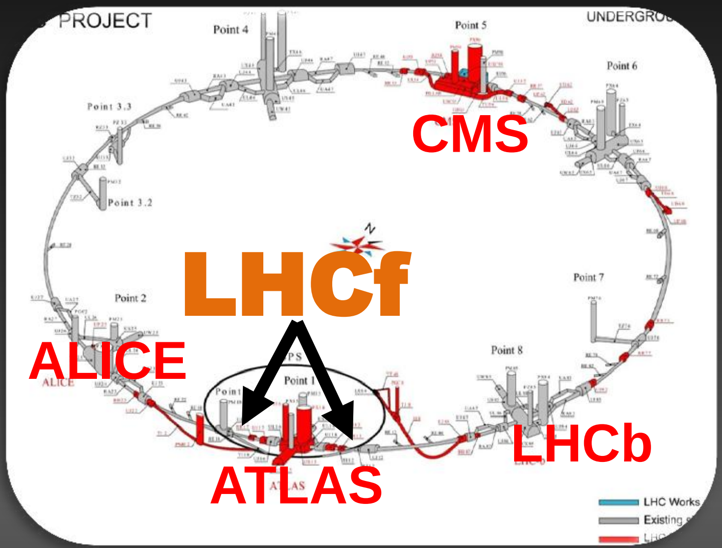
W.C.Turner *LBNL, Berkeley, USA*

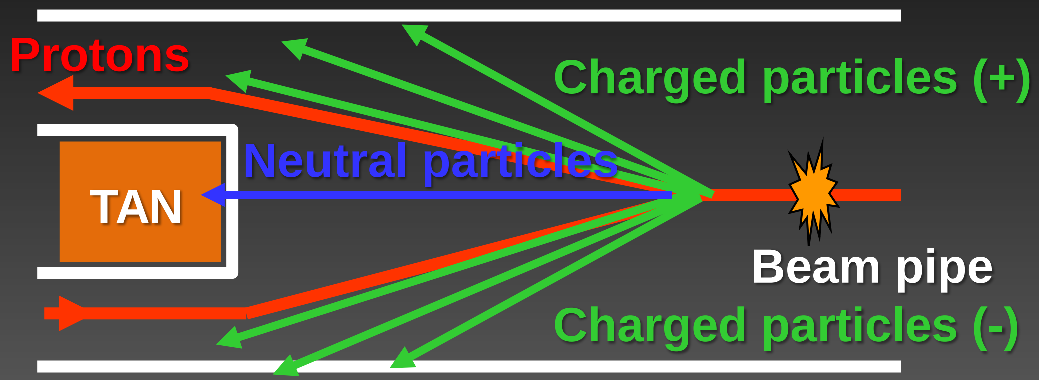
O.Adriani, L.Bonechi, M.Bongi, G.Castellini, R.D'Alessandro, P.Papini, S.Ricciarini, *INFN and Universita' di Firenze, Italy*

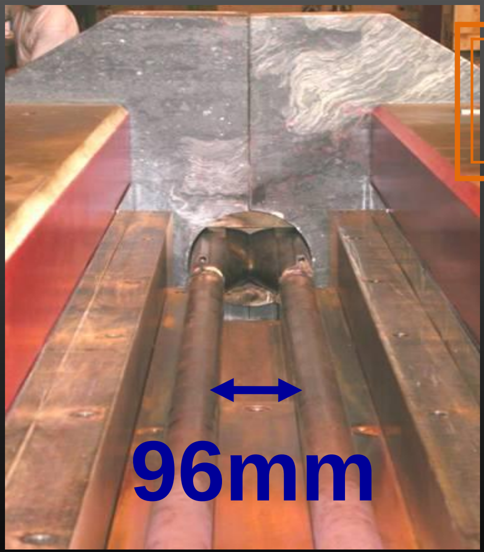
K.Noda, A.Tricomi *INFN and Universita' di Catania, Italy*

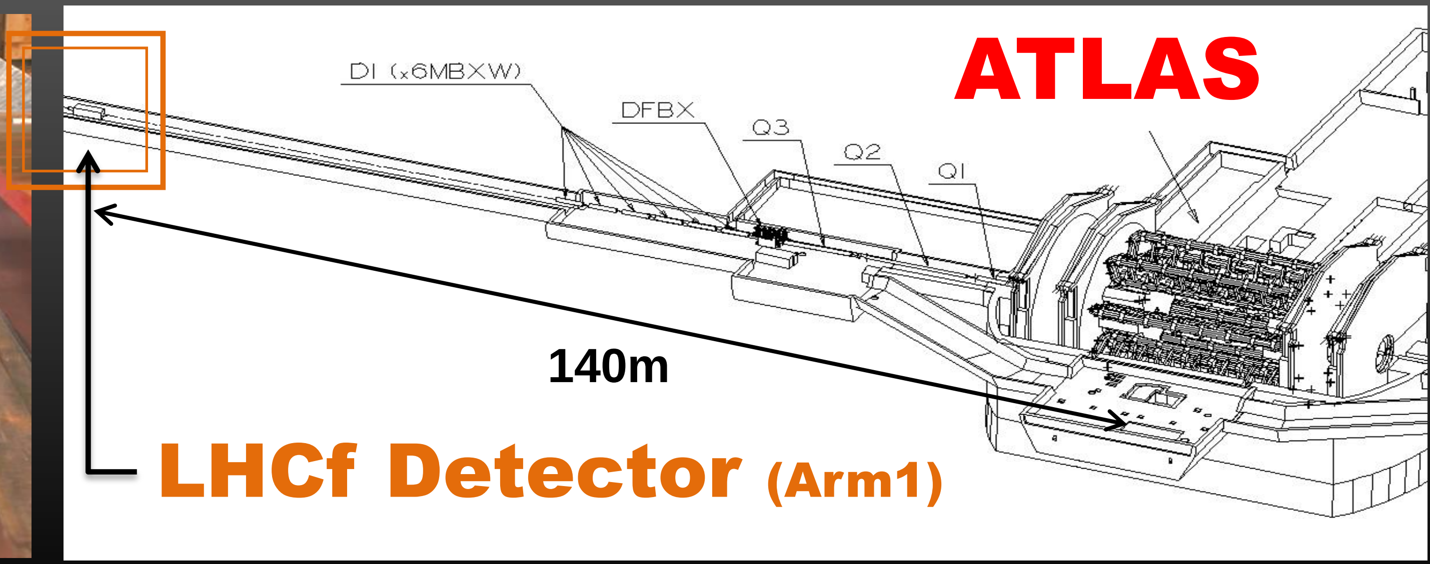
A-L.Perrot *CERN, Switzerland*

LHCf experimental set-up









Arm1 detector

- **Sampling e.m. calorimeters:**

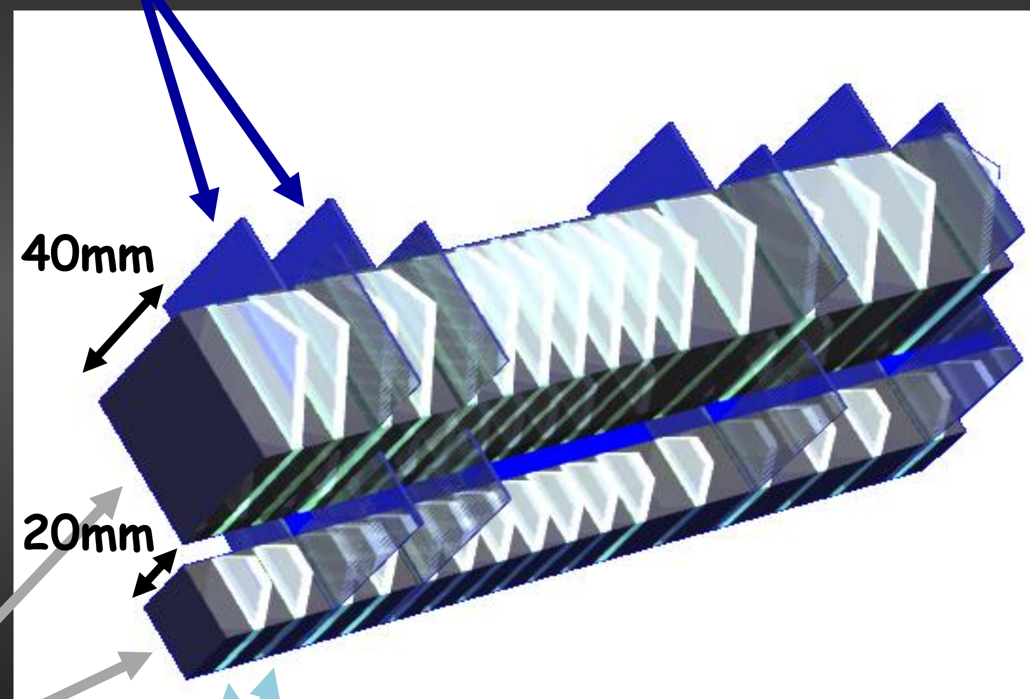
  each detector has two calorimeter towers which allow to reconstruct π^0

- ***Front counters:***

  thin plastic scintillators, 80x80 mm^2

  - monitor beam condition
  - estimate luminosity
  - reject background due to beam - residual gas collisions by coincidence analysis

Scintillating Fibers + MAPMT: 4 pairs of layers (at 6, 10, 30, 42 X_0), tracking measurements (resolution < 200 μm)



Absorber: 22 tungsten layers, 44 X_0, 1.55 λ

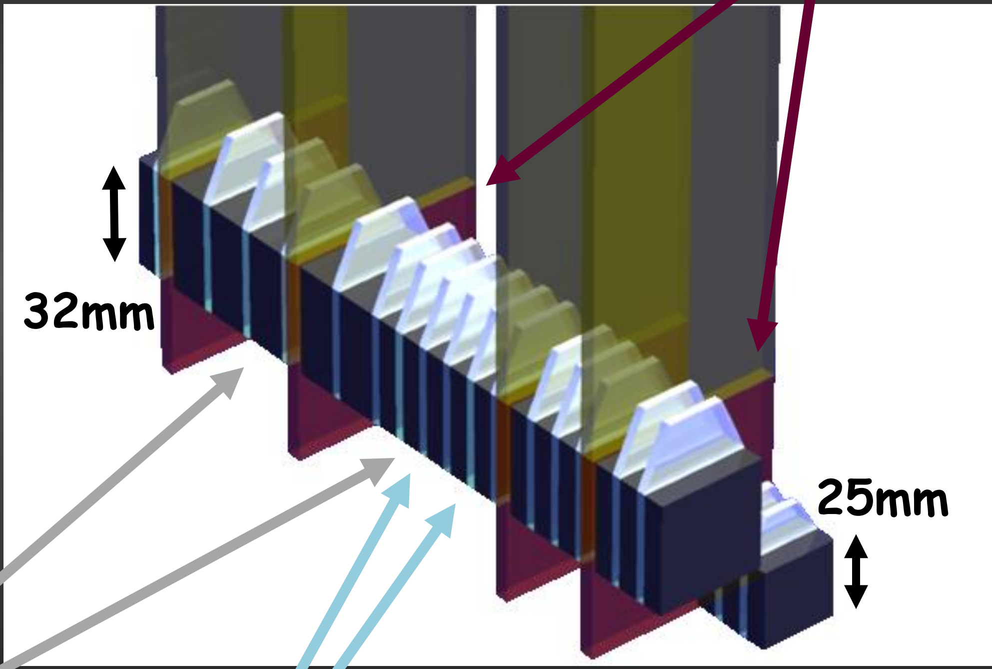
Plastic Scintillator: 16 layers, 3 mm thick, trigger and energy profile measurement

Arm2 detector

- **Sampling e.m. calorimeters:**

  each detector has two calorimeter towers which allow to reconstruct π^0

Silicon Microstrip: 4 pairs of layers (at 6, 12, 30, 42 X_0), tracking measurements (resolution ~ 40 μm)



- ***Front counters:***

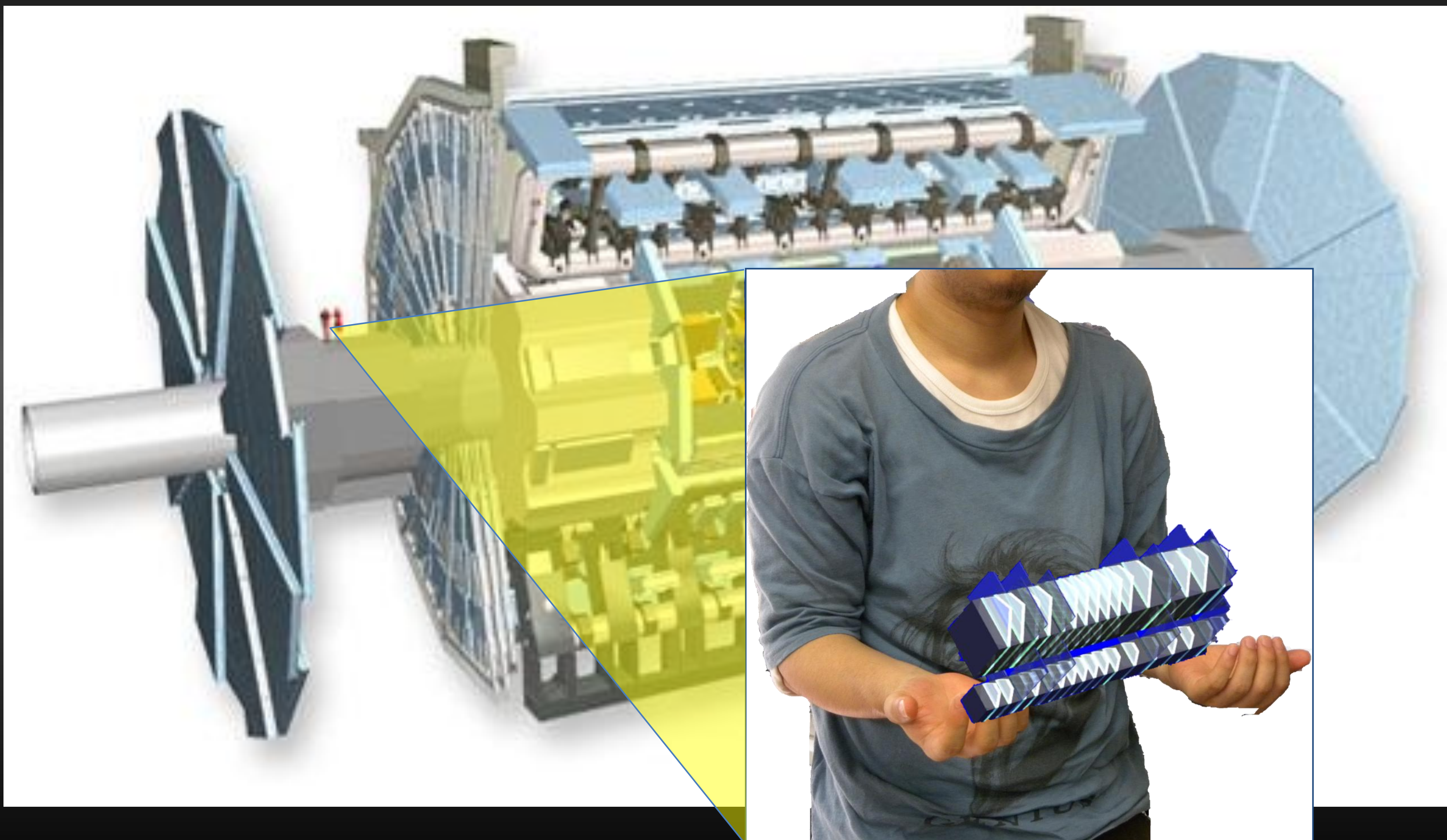
  thin plastic scintillators, 80x80 mm^2

  - monitor beam condition
  - estimate luminosity
  - reject background due to beam - residual gas collisions by coincidence analysis

Absorber: 22 tungsten layers, 44 X_0, 1.55 λ

Plastic Scintillator: 16 layers, 3 mm thick, trigger and energy profile measurement

ATLAS & LHCf




290mm
90mm
Arm1 detector

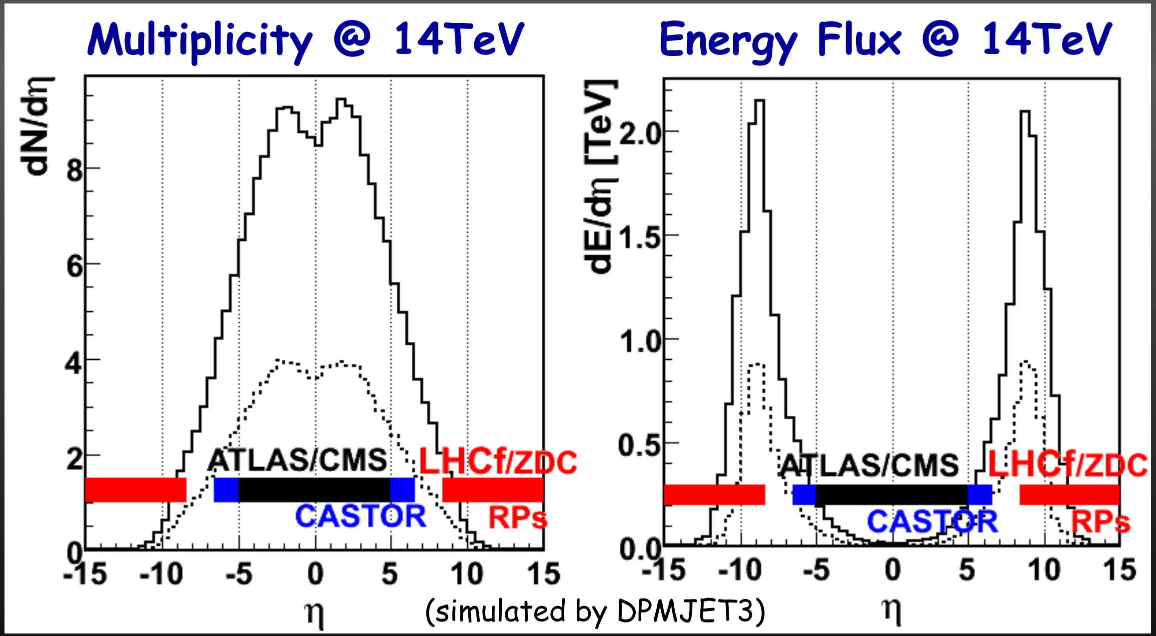

Arm2 detector

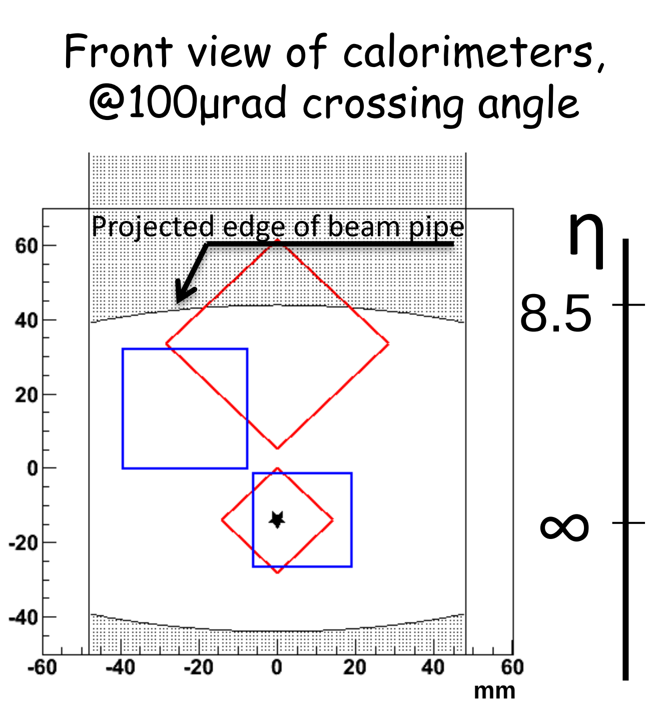
What LHCf can measure

Energy spectra and transverse momentum distribution of:

- gamma rays (E>100 GeV, dE/E<5%)
- neutral hadrons (E>few 100 GeV, dE/E~30%)
- π^0 (E>600 GeV, dE/E<3%)

in the pseudo-rapidity range η>8.4

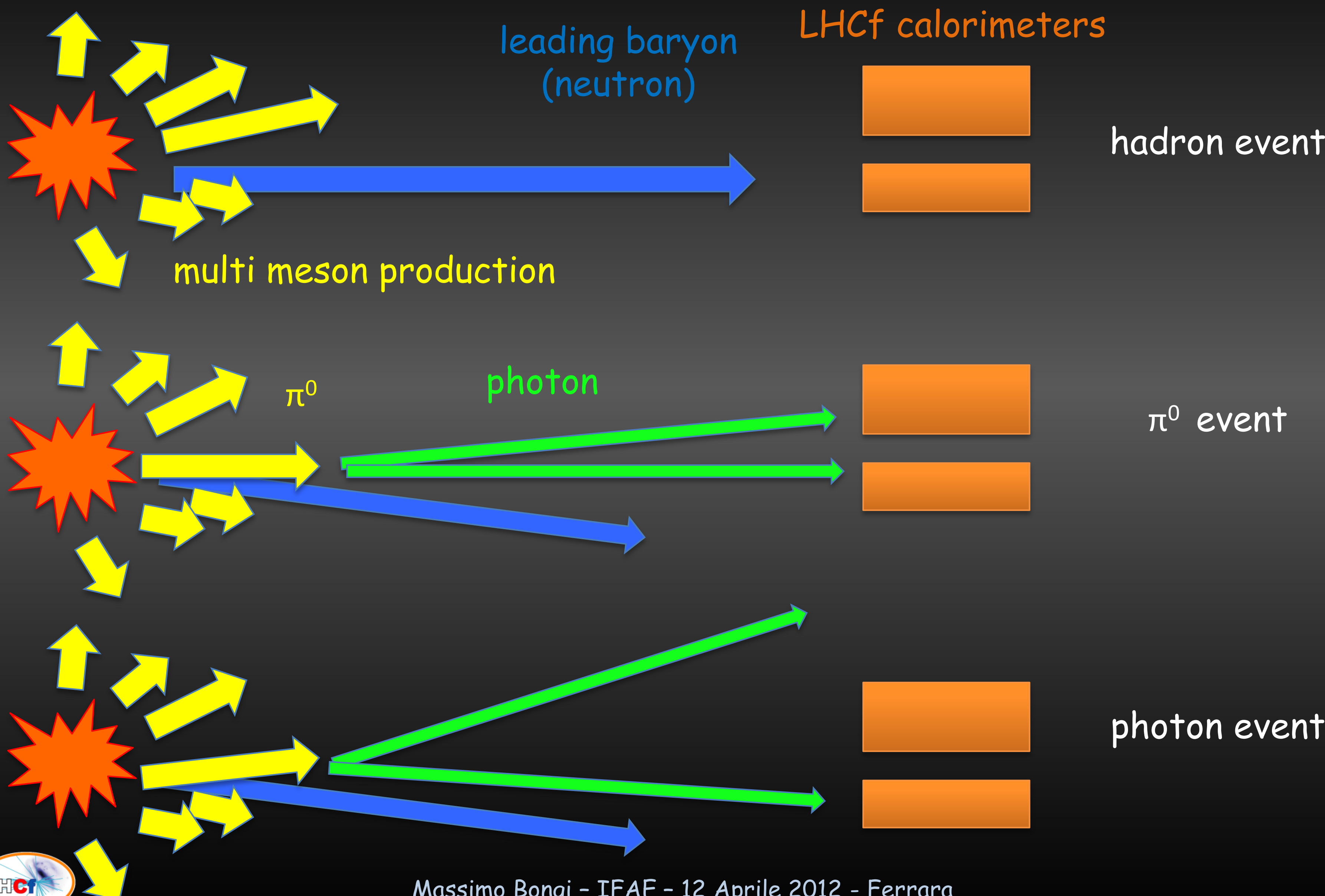




Low multiplicity

High energy flux

Event categories



Summary of operations

With stable beams at sqrt(s) = 900 GeV

- Total of 42 hours for physics (6^{th}–15^{th} Dec. 2009, 2^{nd}-3^{rd},27^{th}May 2010)
- ~ 10^5 showers events in Arm1+Arm2

With stable beams at sqrt(s) = 7 TeV

- Total of 150 hours for physics (30^{th} Mar.-19^{th} Jul. 2010)
  - Different vertical positions to increase the accessible kinematical range
  - Runs with or without beam crossing angle
- ~ $4 \cdot 10^8$ shower events and ~ 10^6 π^0 events in Arm1+Arm2

Hardware status and outlook

- 2009 and 2010: completed program for sqrt(s) = 900 GeV and sqrt(s) = 7 TeV
  - Removed detectors from tunnel in July 2010 (luminosity >10^{30} $cm^{-2}s^{-1}$)
- 2011 and mid 2012: upgraded Arm1 to more rad-hard detectors (GSO)
- 2012: Arm1 test beam at SPS (August),
  Arm2 reinstallation in LHC tunnel for p-Pb run (end of the year)
- 2013 and 2014: upgrade of Arm2,
  Arm2 test beam at SPS
- 2014: back on LHC beam for data taking at sqrt(s) = 14 TeV!
- 2015: possible run at RHIC, with p-p and d-N at sqrt(s) = 500 GeV

Single photon energy spectra @ sqrt(s) = 7 TeV

EXPERIMENTAL DATA

- p-p collisions at $\sqrt{s}$ = 7 TeV, no crossing angle (Fill# 1104, 15th May 2010 17:45-21:23)
- Luminosity: (6.3÷6.5) x 10^{28} $cm^{-2}s^{-1}$ (3 crossing bunches)
- Negligible pile-up (~0.2%)
- DAQ Live Time: 85.7% (Arm1), 67.0% (Arm2)
- Integrated luminosity: 0.68 nb^{-1} (Arm1), 0.53 nb^{-1} (Arm2)

MONTE CARLO DATA

- 10^7 inelastic p-p collisions at $\sqrt{s}$ = 7 TeV simulated by several MC codes:

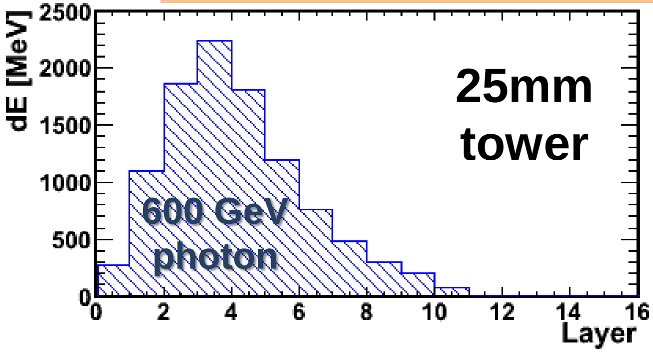
  DPMJET 3.04, QGSJET II-03, SYBILL 2.1, EPOS 1.99, PYTHIA 8.145
- Propagation of collision products in the beam pipe and detector response simulated by EPICS/COSMOS

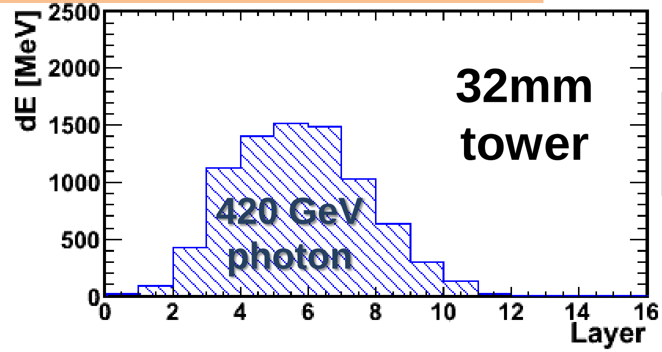
ANALYSIS PROCEDURE

1. Energy Reconstruction: total energy deposition in a tower (corrections for light yield, shower leakage, energy calibration, etc.)
2. Rejection of multi-hit events: transverse energy deposit
3. Particle identification (PID): longitudinal development of the shower
4. Selection of two pseudo-rapidity regions: $8.81 < \eta < 8.99$ and $\eta > 10.94$
5. Combine spectra of Arm1 and Arm2 and compare with MC expectations

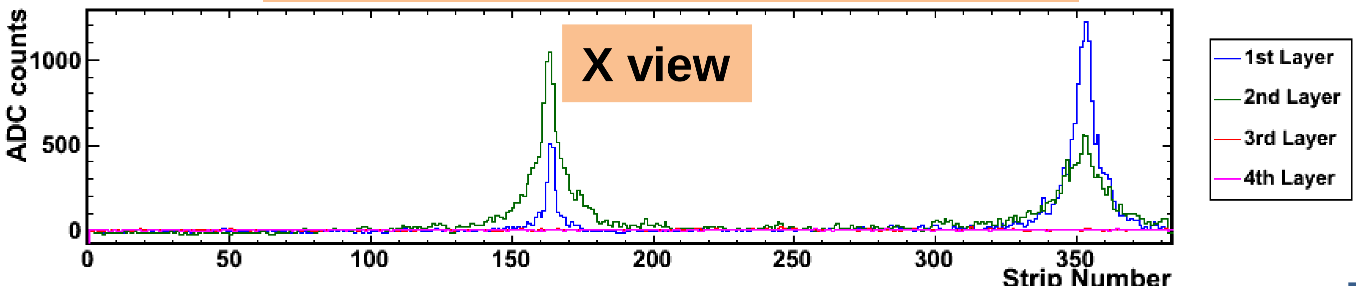
1 TeV π^0 candidate event

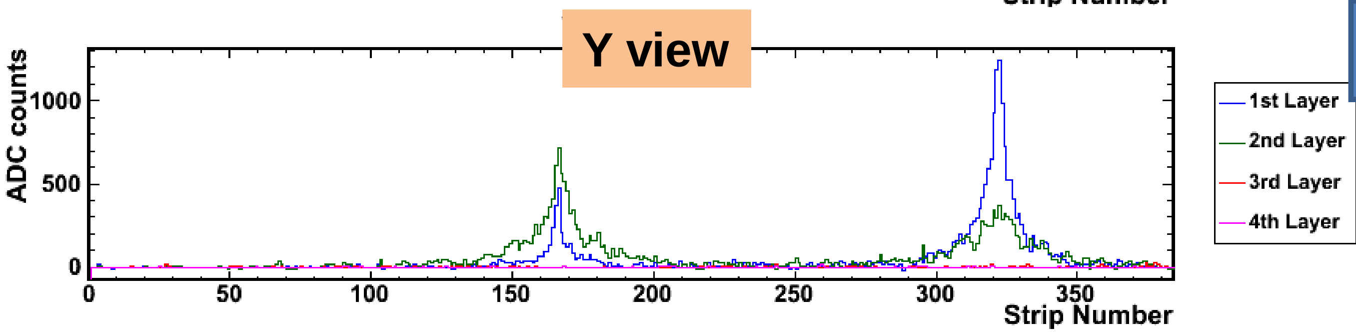
scintillator layers – longitudinal development





silicon layers – transverse energy





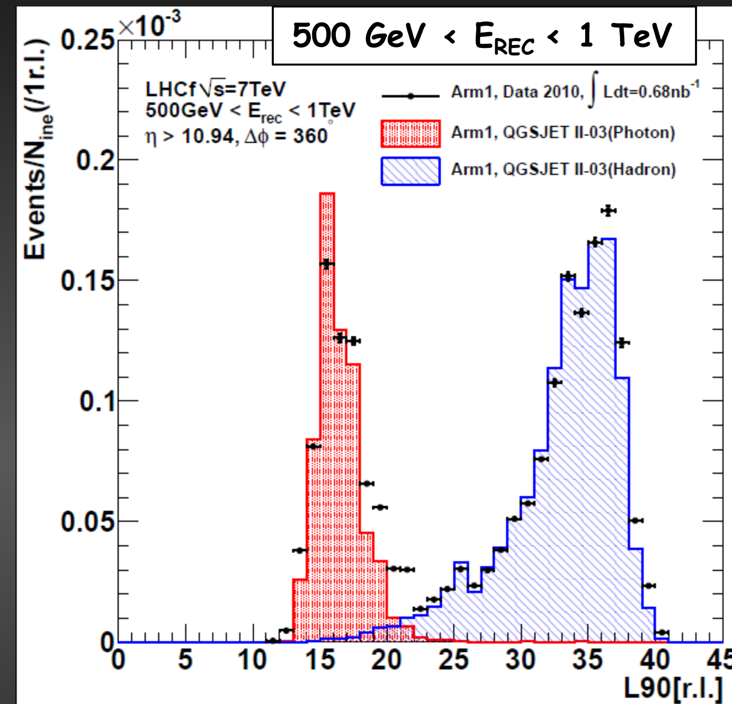
- Energy reconstruction
- PID

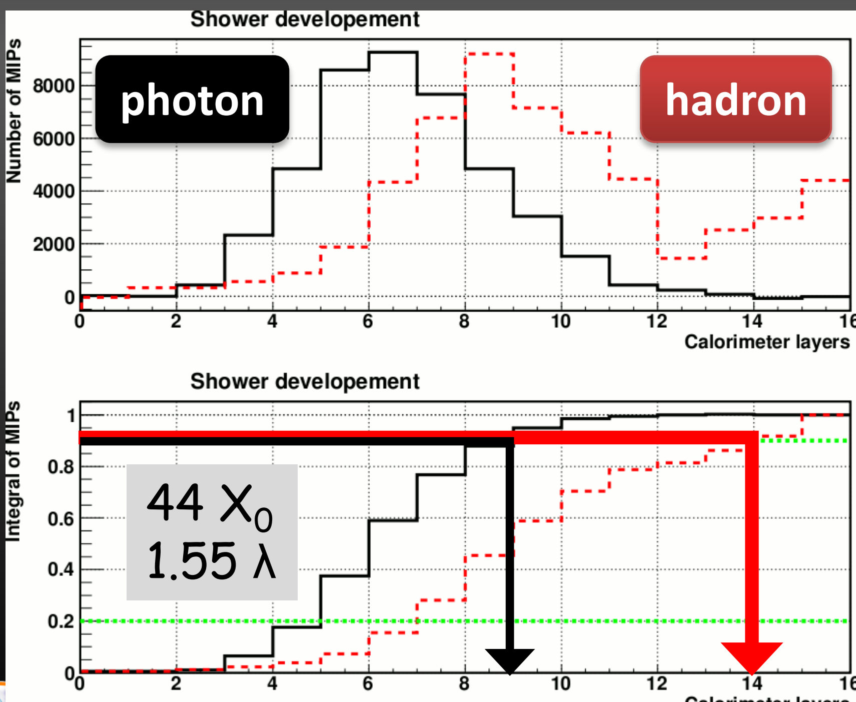
- π^0 mass reconstruction

- Hit position
- Multi-hit identification

Particle identification

- $L_{90\%}$: longitudinal position containing 90% of the shower energy
- Photon selection based on $L_{90\%}$ cut
- Energy dependent threshold in order to keep constant efficiency ε_{PID} = 90%
- Purity $P = N_{phot}/(N_{phot}+N_{had})$ estimated by comparison with MC
- Event number in each bin corrected by P/ε_{PID}





- MC photon and hadron events are independently normalized to data
- Comparison done in each energy bin
- LPM effects are switched on

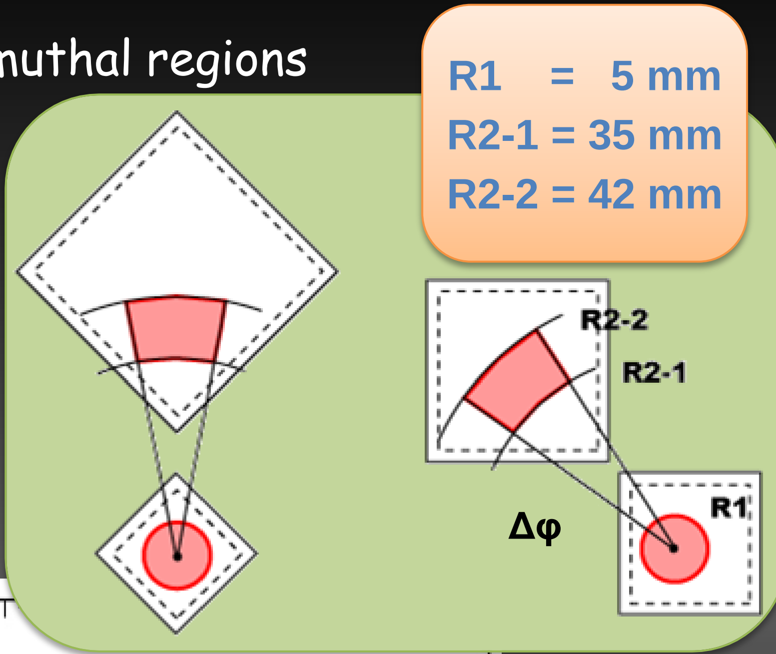
Comparison between the two detectors @ 7 TeV

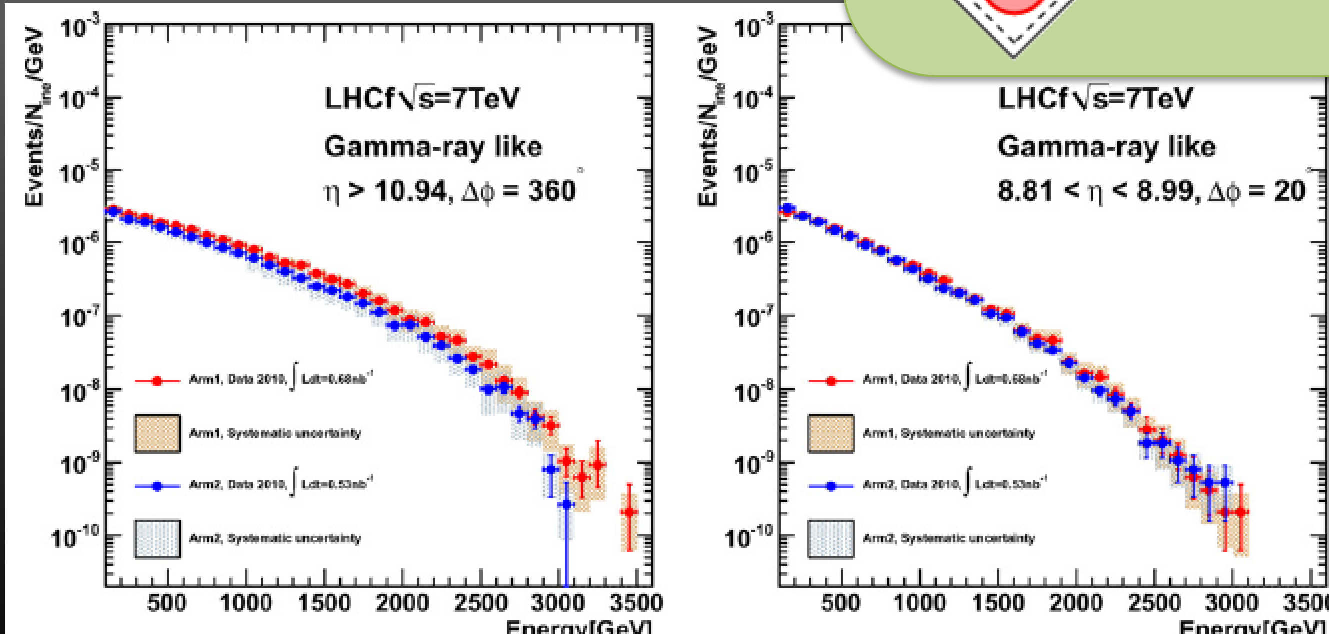
- We define two common pseudo-rapidity and azimuthal regions for the two detectors:

$8.81 < \eta < 8.99$, $\Delta\varphi = 20^\circ$ (large tower)

$\eta > 10.94$, $\Delta\varphi = 360^\circ$ (small tower)

- Normalized by the number of inelastic collisions (assuming σ_{ine} = 71.5 mb)
- General agreement between the two detectors





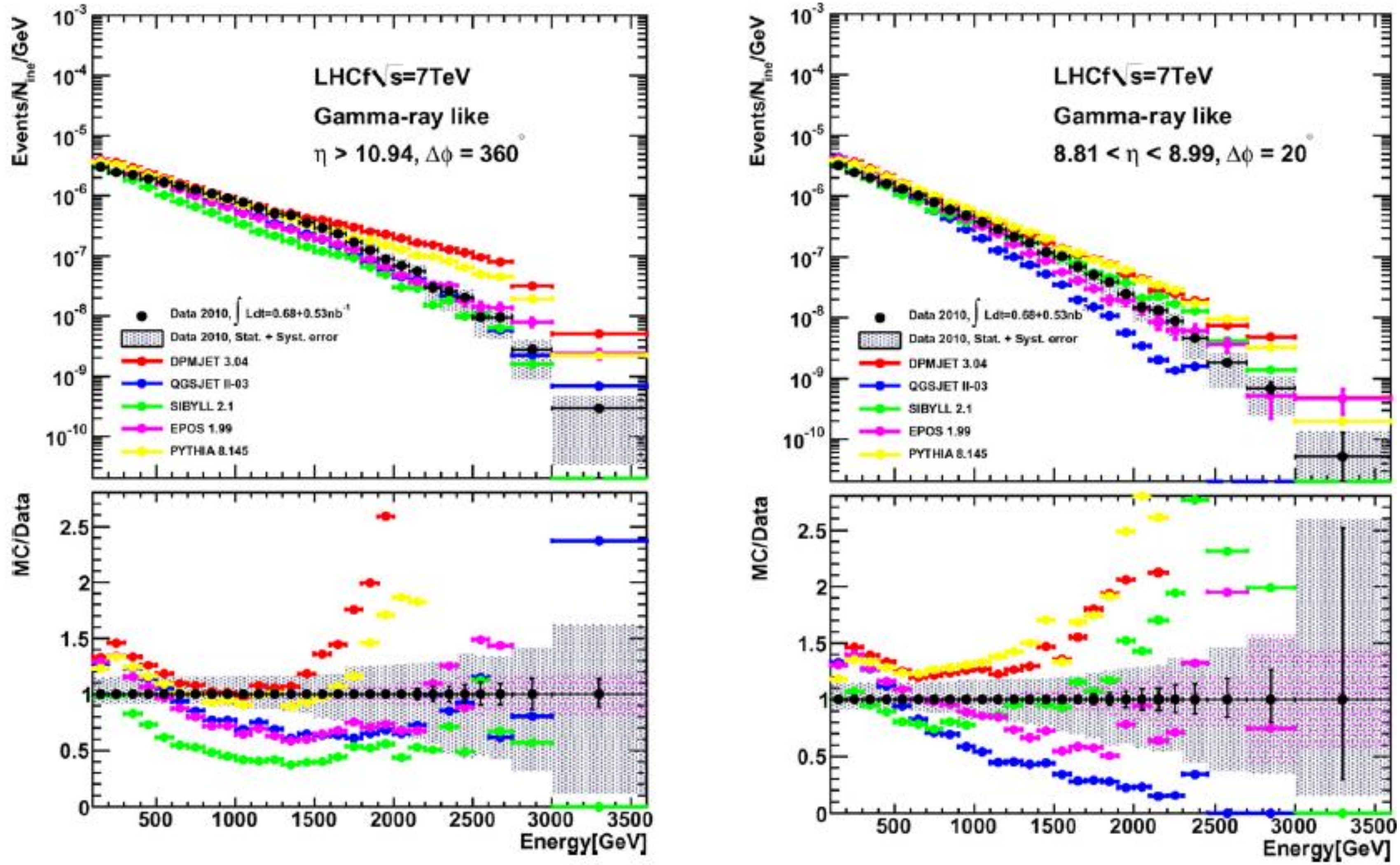
Red points: Arm1 detector **Blue points: Arm2 detector**

Filled area: uncorrelated systematic uncertainties

Single photon @ 7 TeV: comparison with MC

magenta hatch: MC statistical error

gray hatch: systematic error



DPMJET 3.04 QGSJET II-03 SYBILL 2.1 EPOS 1.99 PYTHIA 8.145

Physics Letters B 703 (2011) 128–134

Single photon energy spectra @ sqrt(s) = 900 GeV

EXPERIMENTAL DATA

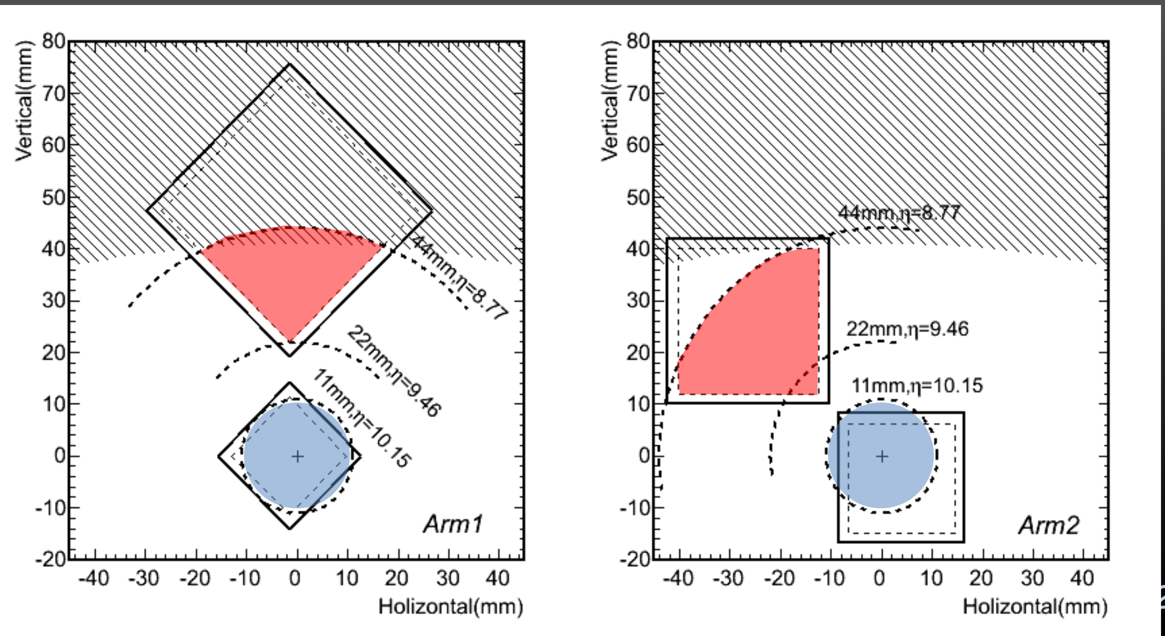
- p-p collisions at $\sqrt{s}$ = 900 GeV (2nd, 3rd and 27th May 2010)
- DAQ Live Time: 99.2% (Arm1), 98.0% (Arm2)
- Integrated luminosity: 0.30 nb^{-1}

MONTE CARLO DATA

- ~ 3 x 10^7 inelastic p-p collisions at $\sqrt{s}$ = 900 GeV simulated by several MC codes:

  DPMJET 3.04, QGSJET II-03, SYBILL 2.1, EPOS 1.99, PYTHIA 8.145

ANALYSIS PROCEDURE is similar to sqrt(s) = 7 TeV (no multi-hit cut is needed)



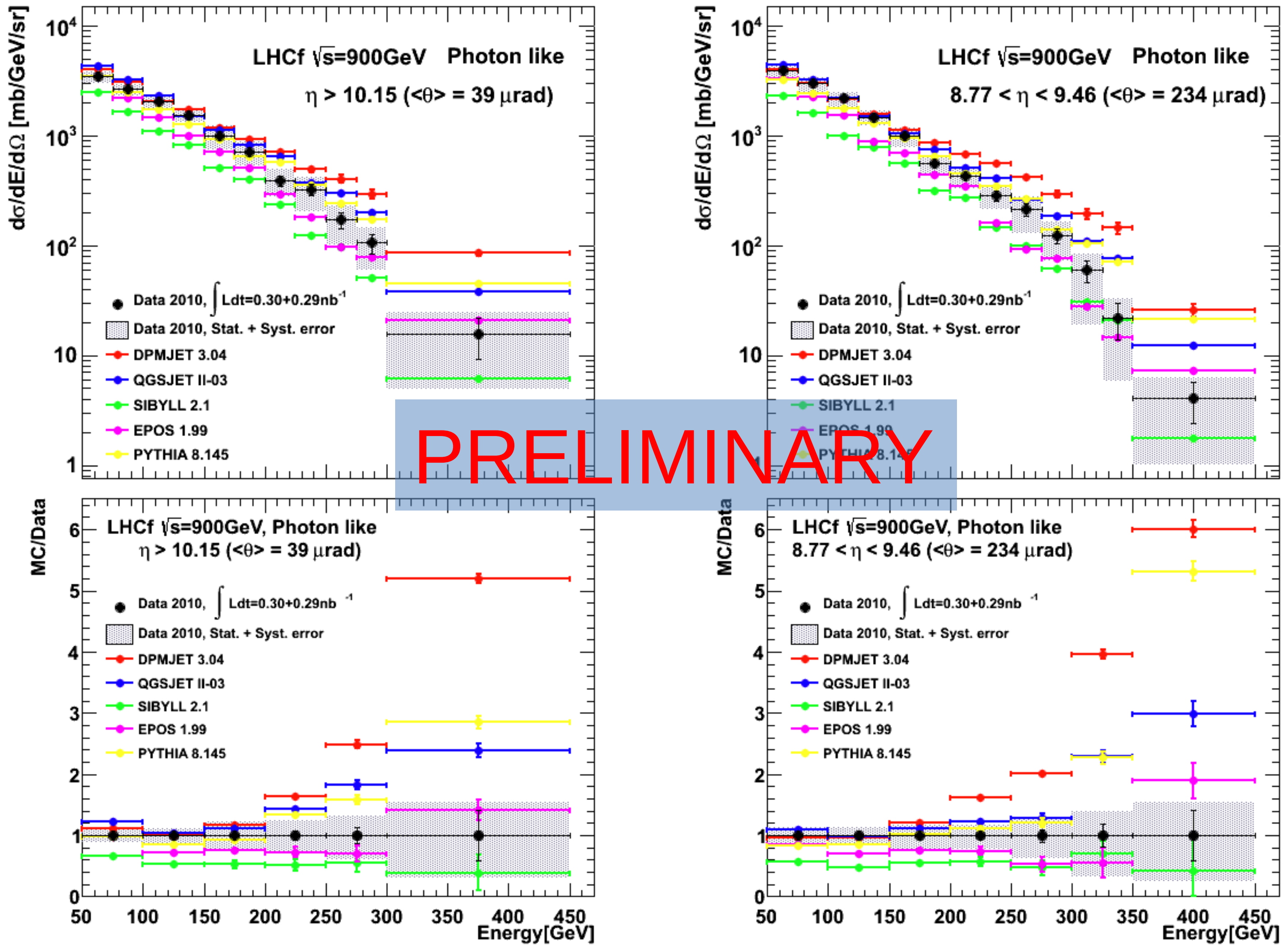
Common pseudo-rapidity regions:

$8.77 < \eta < 9.46$ (large tower)

$\eta > 10.15$ (small tower)

Single photon @ 900 GeV: comparison with MC

gray hatch: statistical + systematic error



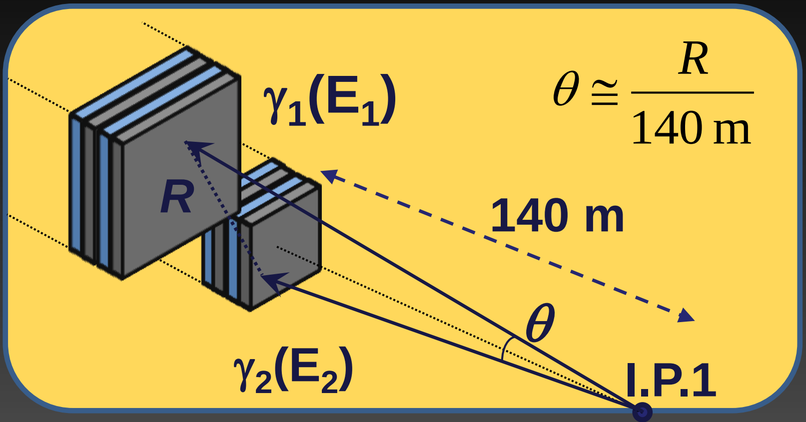
DPMJET 3.04 QGSJET II-03 SYBILL 2.1 EPOS 1.99 PYTHIA 8.145

Submitted to PLB, CERN-PH-EP-2012-048

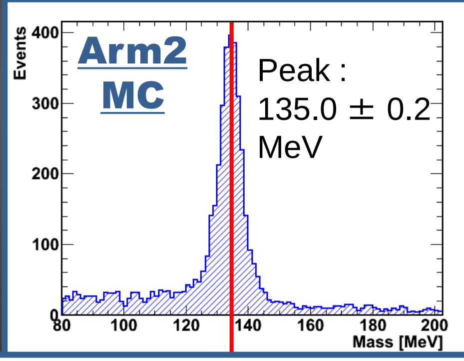
π^0 analysis

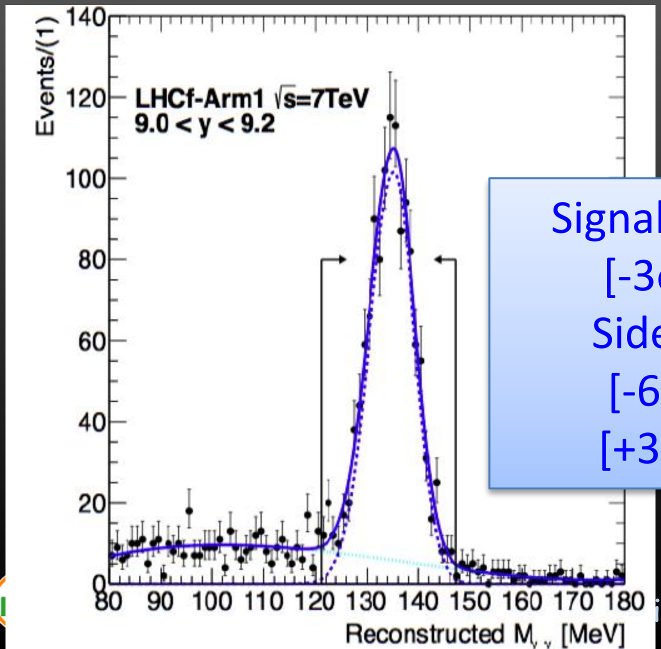
<u>Analysis procedure:</u>

- standard photon reconstruction
- event selection:
  - one photon in each calorimeter
  - reconstructed invariant mass (corrected for mass shift)
- background subtraction by using data (sidebands)
- unfolding of detector response
- acceptance correction

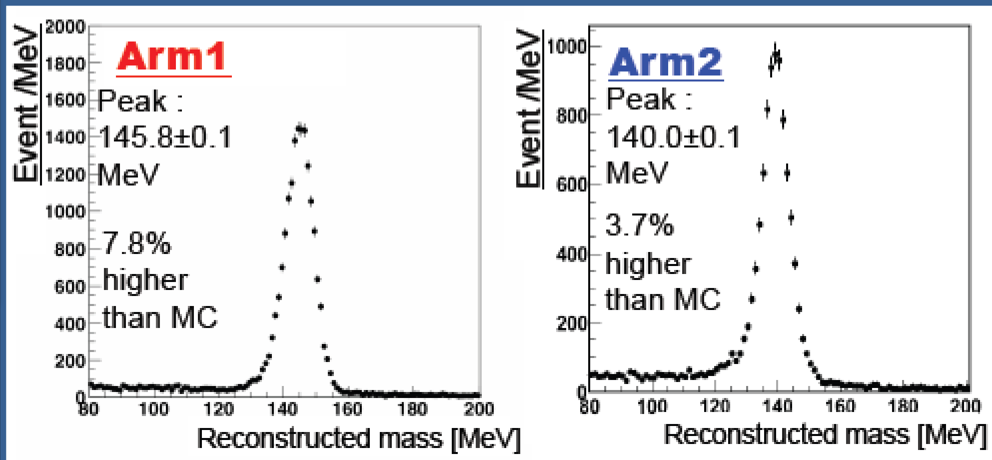


$$m \approx \theta\sqrt{(E_1 x E_2)}$$

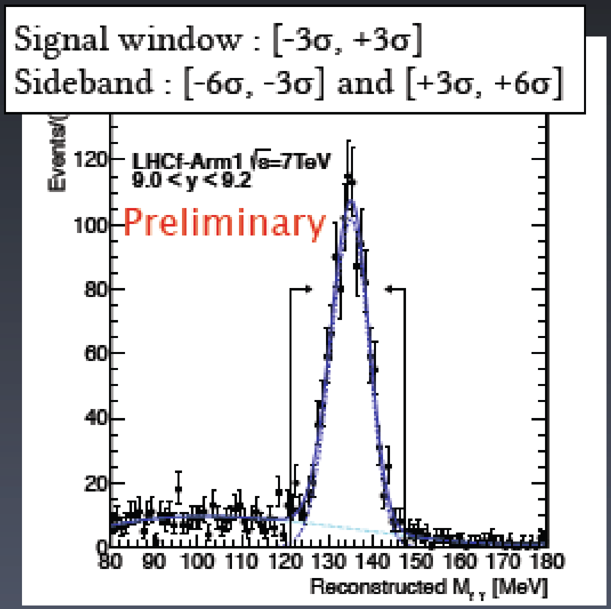




Signal window:
[-3σ, +3σ]
Sidebands:
[-6σ, -3σ]
[+3σ, +6σ]

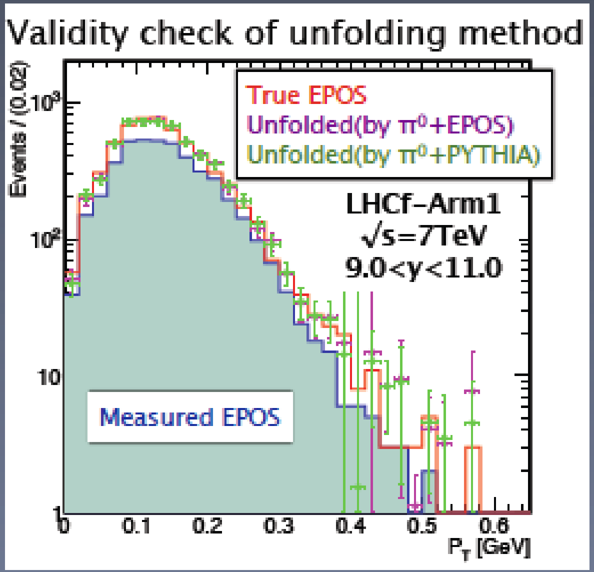


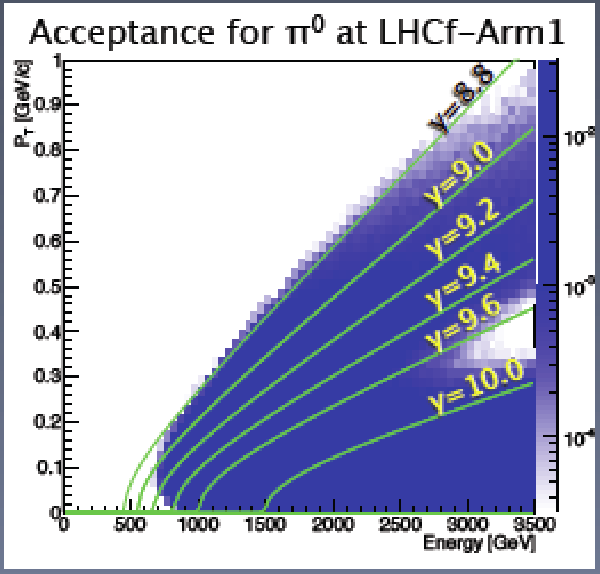
7TeV π^0 analysis



- Remaining background spectrum is estimated using the sideband information, then the BG spectrum is subtracted from the spectrum made in the signal window.

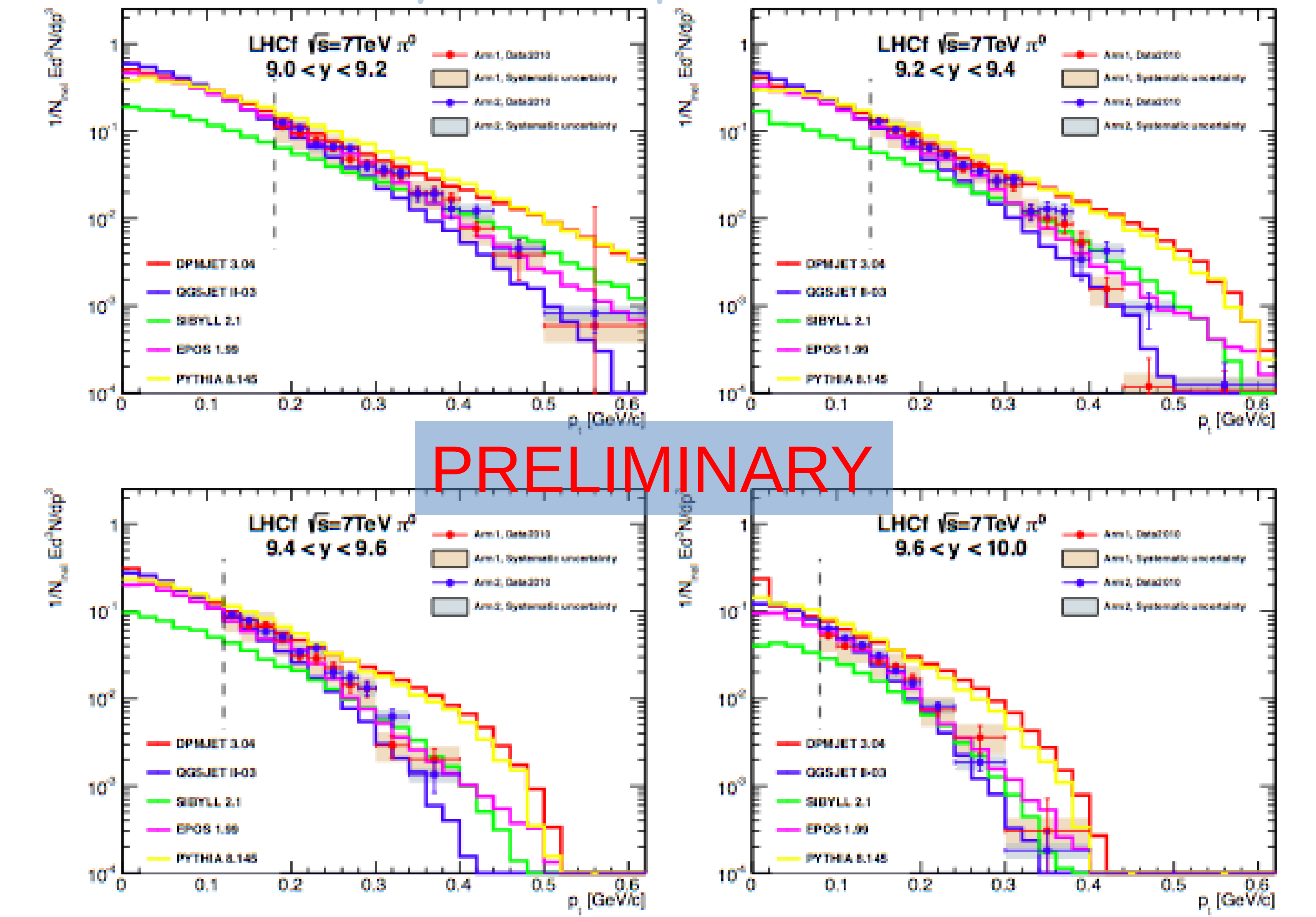
$$Signal = f(E, P_T)^{signal} - f(E, P_T)^{BG} \frac{\int_{\hat{M}-3\sigma_l}^{\hat{M}+3\sigma_u} \mathcal{L}_{BG} dM}{\int_{\hat{M}-6\sigma_l}^{\hat{M}-3\sigma_l} \mathcal{L}_{BG} dM + \int_{\hat{M}+3\sigma_u}^{\hat{M}+6\sigma_u} \mathcal{L}_{BG} dM}$$





- Detector responses are corrected by an unfolding process that is based on the iterative Bayesian method. (G. D'Agostini NIM A 362 (1995) 487)
- Detector response corrected spectrum is proceeded to the acceptance correction.

π^0 analysis: comparison with MC

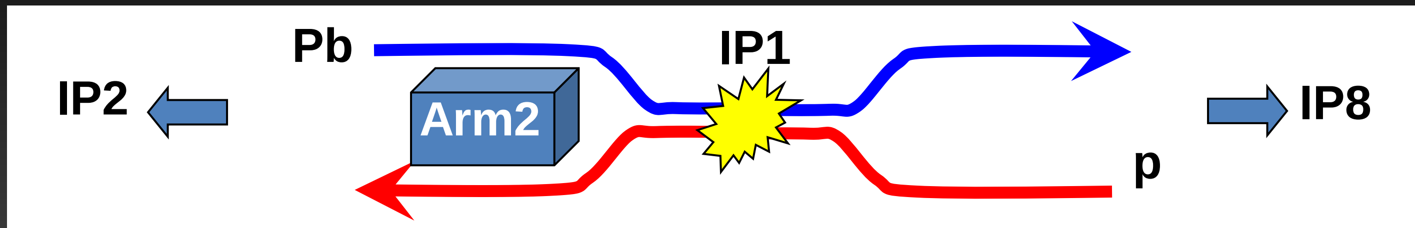


DPMJET 3.04 QGSJET II-03 SYBILL 2.1 EPOS 1.99 PYTHIA 8.145

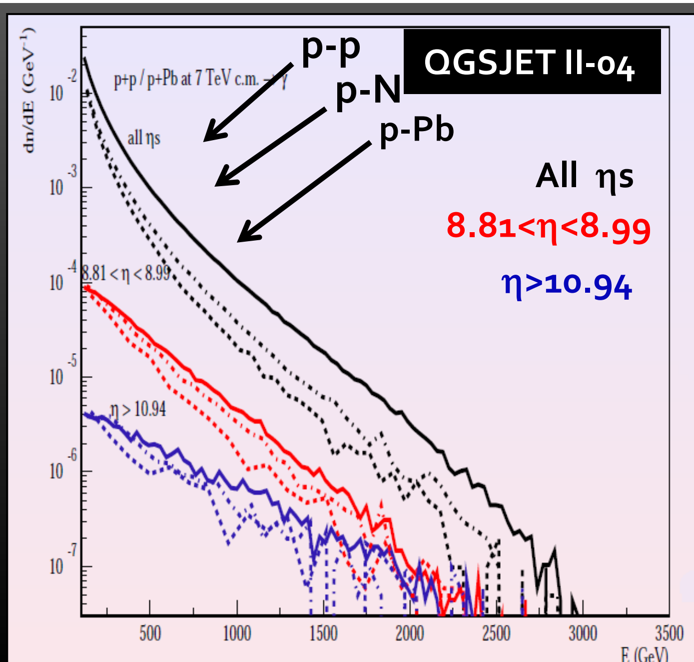
To be submitted soon

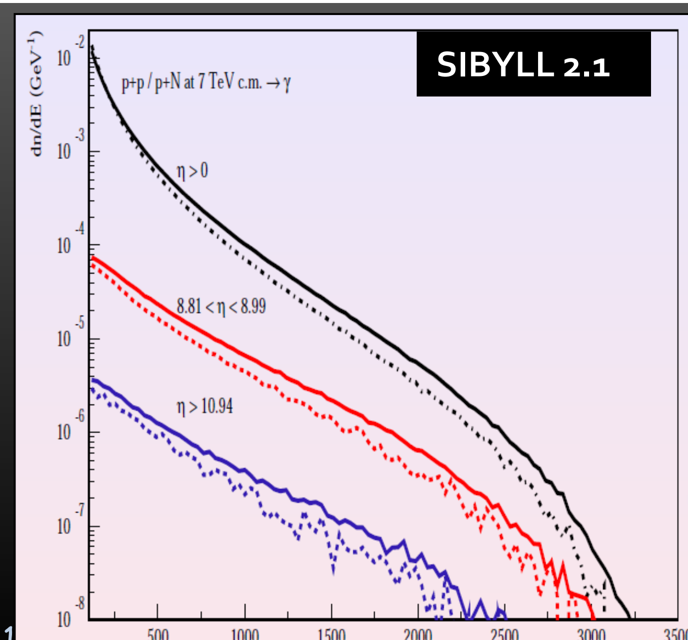
Proton-Lead run at the end of 2012

- Letter of Intent submitted to LHCC at the end of 2011
- reinstallation of Arm2 in LHC tunnel (proton remnant side)



- Photon energy distribution in different η intervals at $\sqrt{s_{NN}}$ = 7 TeV
- Comparison of p-p / p-N / p-Pb
- Larger suppression at high energy for heavier nuclei





Courtesy of S. Ostapchenko

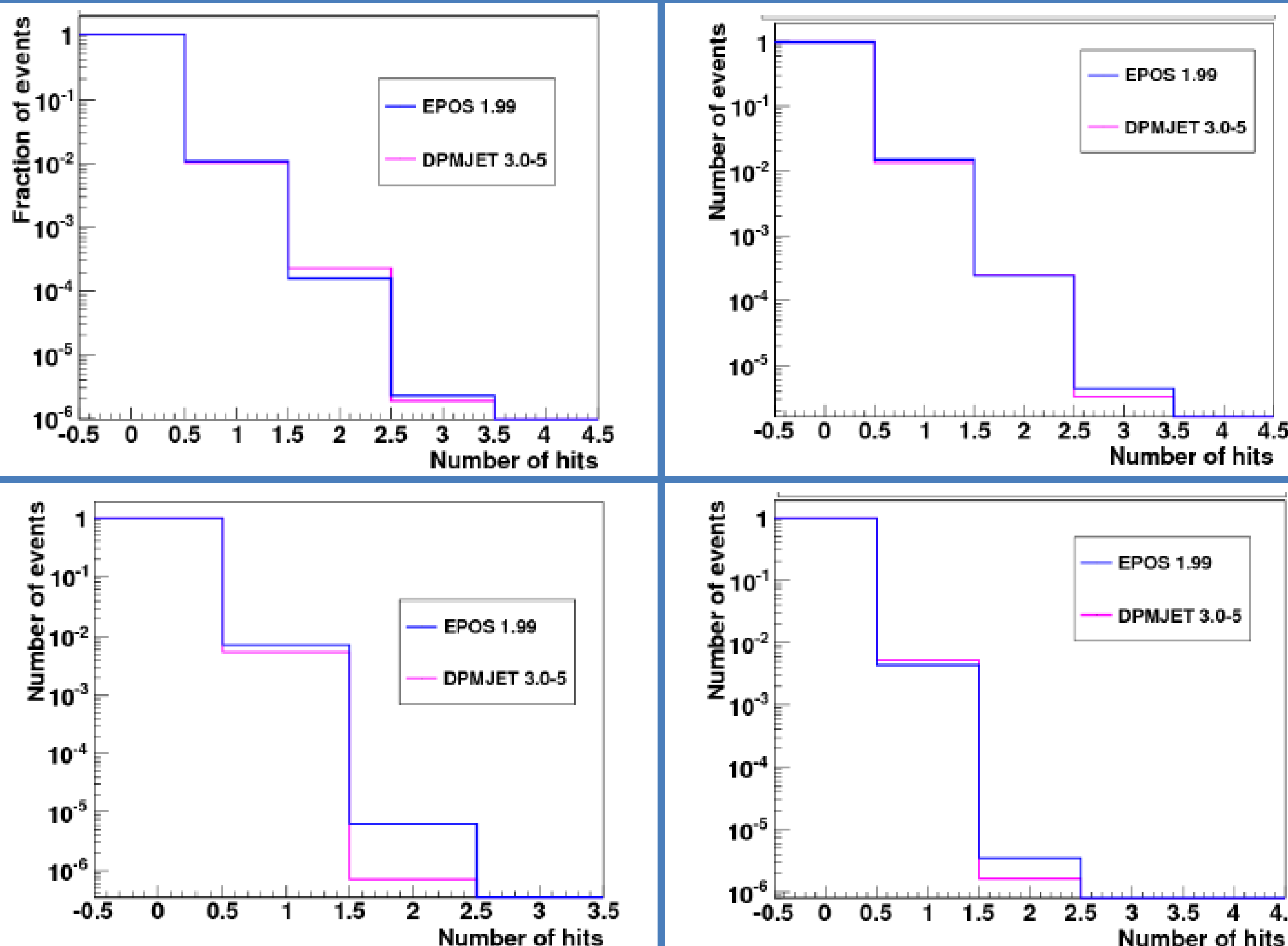
Proton-remnant side – photon multiplicity

MC simulation: 10^7 events

E_p = 3.5 TeV (actually 4 TeV)

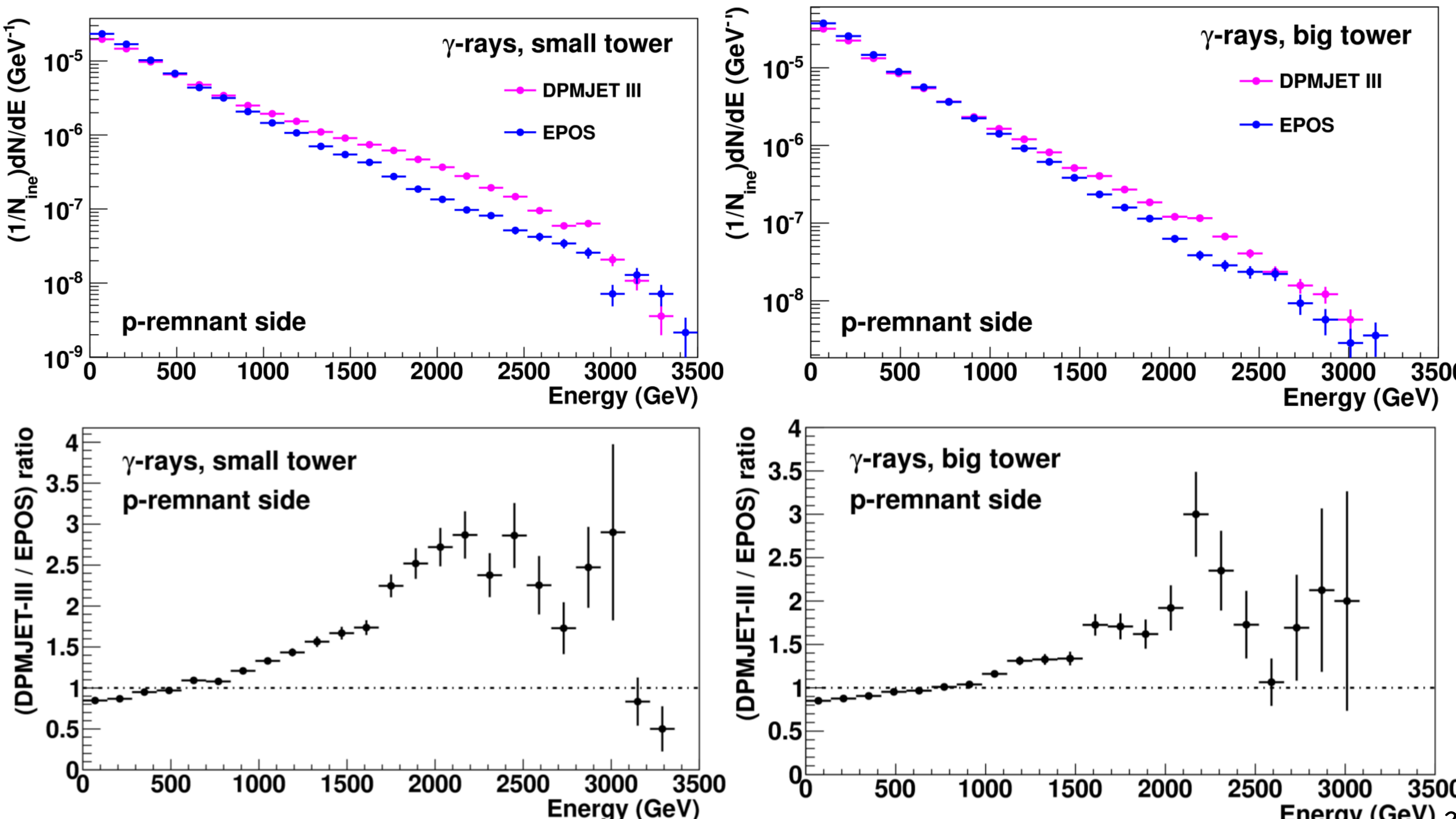
E_N = Z/A E_p = 1.38 TeV/Nucl.

	Small tower	Big tower
γ		
n		



Proton-remnant side – photon spectrum

small tower **big tower**



Analysis summary and outlook

- **Single photon analysis at sqrt(s) = 7 TeV and 900 GeV:**
  - first comparison of various hadronic interaction models with experimental data in a challenging phase space region
  - <u>no model perfectly reproduces LHCf data, especially at high energy</u>
    - ✓new input data for model developers
    - ✓implications for HE CR physics
- **Neutral pion analysis at sqrt(s) = 7 TeV:**
  - finalizing the analysis, almost ready to submit the paper
  - include events with two gammas hitting the same tower
  - the same analysis can be extended to η and K_0 particles
- **proton-Lead operation:**
  - physics case has been studied by MC simulations
  - Letter of Intent approved by LHCC
  - optimizing the procedures for a quick reinstallation in the tunnel
- **Other analysis:** neutrons, transverse momentum distribution of photons, extend pseudo-rapidity range,...