Neutral particles energy spectra for 900 GeV and 7 TeV p-p collisions, measured by the LHCf experiment

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1 Abstract

LHCf is an experiment designed to study the production in the very forward direction of neutral particles produced in collisions at the LHC. Its results are and will be used to calibrate the hadron interaction models of the Monte Carlo codes which allow the interpretation of energy spectrum and composition of high-energy cosmic rays as measured by air-shower ground detectors. The experiment has already completed data taking in proton-proton collisions at $\sqrt{s} = 900$ GeV and at $\sqrt{s} = 7$ TeV during 2009 and 2010. At the beginning of 2013 the experiment will take data again with p-Pb collisions, and then the detectors will be upgraded for the $\sqrt{s} = 14$ TeV collisions in 2014.

2 Introduction

The physics case for LHCf lies in the energy spectra and composition of cosmic rays. The AGASA [1] and HiRes [2] experiments showed a marked discrepancy in results 10 years ago over the energy spectrum at extremely high energies (the ankle region) as shown at the left in Figure 1. Recent results the Pierre Auger Collaboration [3], HiRes (final), and Telescope Array Collaboration [4] however seem to indicate the presence of a GZK cutoff. In fact the uncertainty caused by the poor knowledge of the characteristics of the interaction of particles with the Earths atmosphere at such high energies remains an important source of systematic error in the determination of energy and also of chemical composition of primary particles (right part of Figure 1).

The aim of the LHCf experiment [5, 6] is to provide experimental results useful for testing and calibrating hadronic interaction models used in Monte Carlo (MC)

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simulation of extensive air showers, by measuring the energy spectra and the transverse momentum of neutral particles in a very high pseudo-rapidity region ($\eta > 8.4$, ‘forward’ region) at the Large Hadron Collider (LHC). The LHC provides the unique opportunity of studying the energy dependence of hadron interaction processes up to equivalent fixed-target energy of 10^{17} eV (at its design center-of-mass energy $\sqrt{s} = 14$ TeV), which corresponds to the region between the knee and the GZK cut-off of the cosmic ray spectrum.

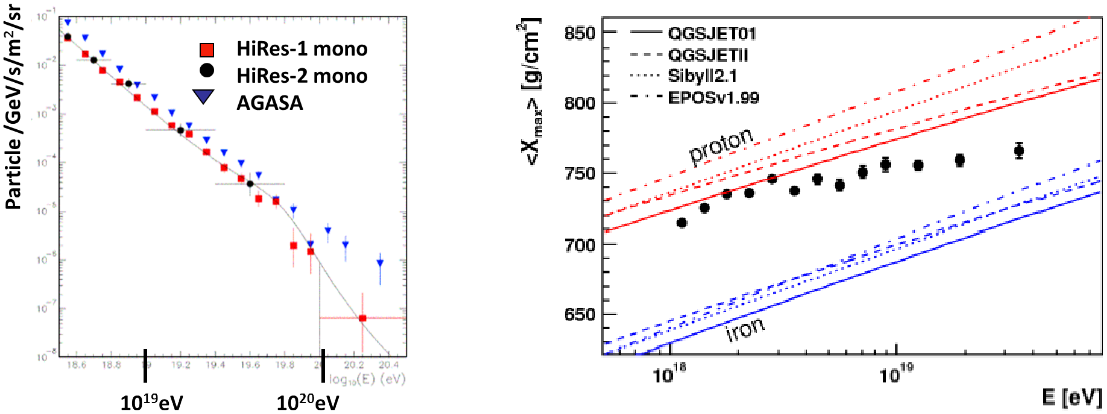

Figure 1: Energy spectra of cosmic rays as measured by the AGASA and the HiRes experiments (left). On the right, the energy spectra of cosmic rays as measured by the Auger collaboration, compared to different model expectations. Depending on the model chosen the favoured composition goes from proton to iron.

3 Detector

The LHCf experiment is based on two similar detectors, i.e. two electromagnetic sampling calorimeters, made of plastic scintillator and tungsten layers, complemented by a tracking system. Each detector, respectively called Arm1 and Arm2, consists of two independent calorimeter towers enclosed in a box which contains also part of the front-end electronics (see Figure 2. Detailed information about these detectors can be found in references [5, 6]. During data taking the detectors are positioned in such a way that one of the calorimeter towers, the smallest one, lies directly along the beam line at zero degrees. The LHCf standard run configuration, established for the past running and foreseen also for the future 14 TeV pp run, requires the installation of both detectors inside the reserved slots of the two TAN absorbers located 140 m on opposite sides of Interaction Point 1 (IP1) (as shown in Figure 3. This not only allows a comparison of the results between the two detectors which is very useful for systematic error checking, but also allows the study of double diffractive events.

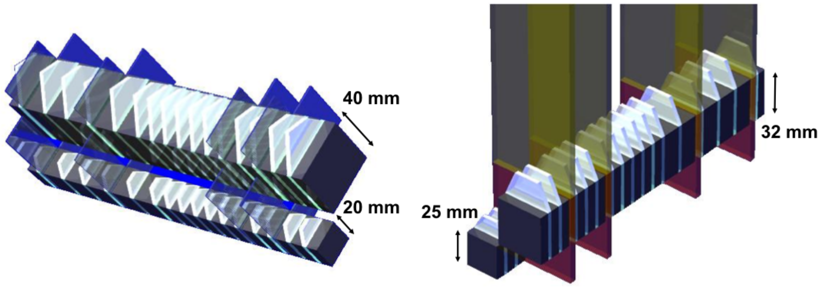

Figure 2: Schematic view of the LHCf detectors: Arm1 calorimeter to the left, Arm2 on the right. Plastic scintillators (light blue) are interleaved with tungsten blocks (dark grey). Four couples of position sensitive layers, scintillating fibres in Arm1 and silicon micro-strip detectors in Arm2, are present in each calorimeter.

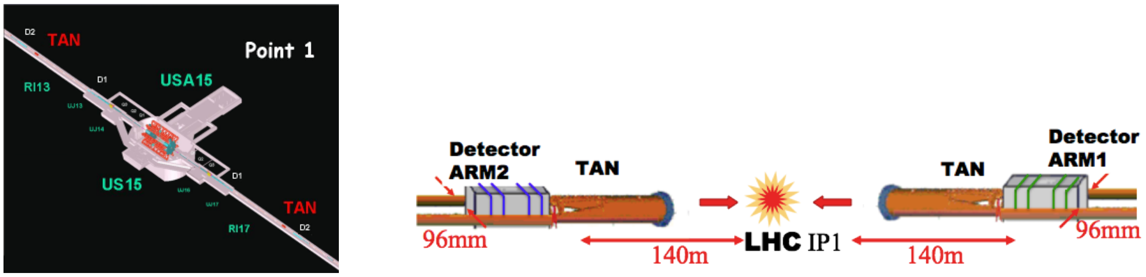

Figure 3: Schematic view of IP1 (LEFT), where the ATLAS experiment is, and the positions where the TAN and the Arm1 and Arm2 are placed (RIGHT).

4 Data taking and results

LHCf took data with stable beams at 900 GeV from December 6th to December 15th 2009 and from May 2nd to May 27th 2010. It then took data at 7 TeV from March 30th to July 19th 2010. Data was taken at 0 and 100 μrad crossing angle for different vertical detector positions. Table 1 summarises the acquired triggers and the type of events acquired. Details on event selection and analysis are provided in [7]. Basically the energy of photons is determined from the signals produced in

	Showers	γ	Hadrons	n
ARM1 (900 GeV)	46,800	4,100	11,527	
ARM2 (900 GeV)	66,700	6,158	26,094	
ARM1 (7 TeV)	172,263,255	56,846,874	111,971,115	344,526
ARM2 (7 TeV)	160,587,306	52,993,810	104,381,748	676,157

Table 1: Number of events acquired and then selected as photons or hadrons (neutrons).

the scintillators, after applying corrections for the non-uniformity of light collection and for particles leaking in and out of the edges of the calorimeter towers. In order to correct for these effects and to reject events with more than one shower inside the same tower (multi-hit events) the transverse impact position of showers provided by the position sensitive detectors is used. Events produced by neutral hadrons are selected by simple identification criteria based on the longitudinal development of the shower. Figure 4 shows the single photon spectra measured by LHCf in the two

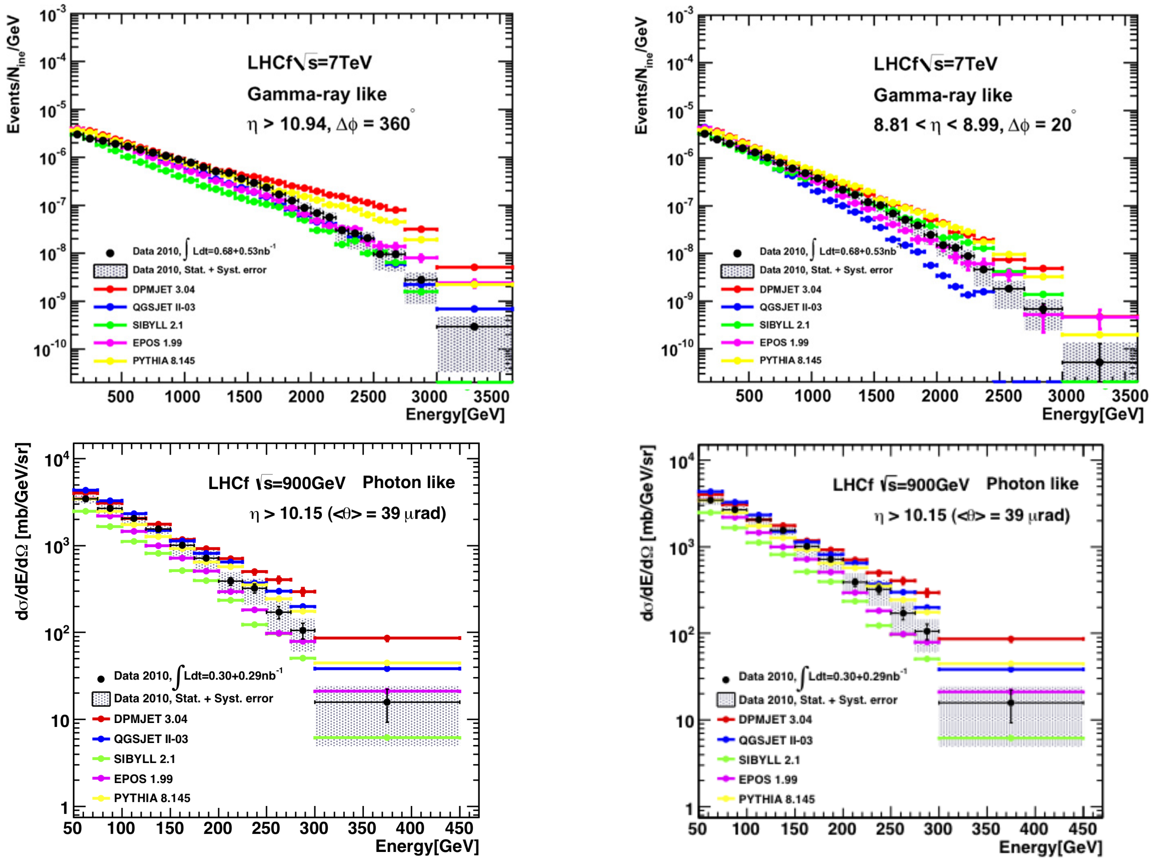

Figure 4: Single photon energy spectra measured by LHCf (black dots) for $\eta > 10.94$ (top left) and $8.81 < \eta < 8.99$ (top right) in 7 TeV proton-proton collisions, and for $\eta > 10.15$ (bottom left) and $8.77 < \eta < 9.46$ (bottom right) in 900 GeV proton-proton collisions. The MC results predictions for DPMJET III 3.04 (red), QGSJET II-03 (blue), SIBYLL 2.1 (green), EPOS 1.99 (magenta) and PYTHIA 8.145 (yellow) are shown. Error bars show the statistical error and the grey shaded areas the systematic error for experimental data. Figures from [8, 9].

pseudo-rapidity regions for 7 TeV and 900 GeV p-p collisions (roughly corresponding to the small calorimeter tower and the larger one respectively), compared with results predicted by MC simulations using different models, namely DPMJET III-3.04 [10], QGSJET II- 03 [11], SIBYLL 2.1 [12], EPOS 1.9 [13] and PYTHIA 8.145 [14]. Statical errors and systematic uncertainties are also plotted. A careful study of systematic uncertainties has been done and conservative estimates have been taken into account. Further details can be found in [8, 9]. A clear discrepancy is present between the experimental results and the predictions of the models in particular at high energies.

The LHCf experiment has recently finished the analysis of the transverse momentum spectra for π^0 produced in 7 TeV proton collisions at LHC [16]. The integrated luminosities corresponding to the data used in this analysis are 2.53 nb^{-1} (Arm1) and 1.90 nb^{-1}(Arm2).

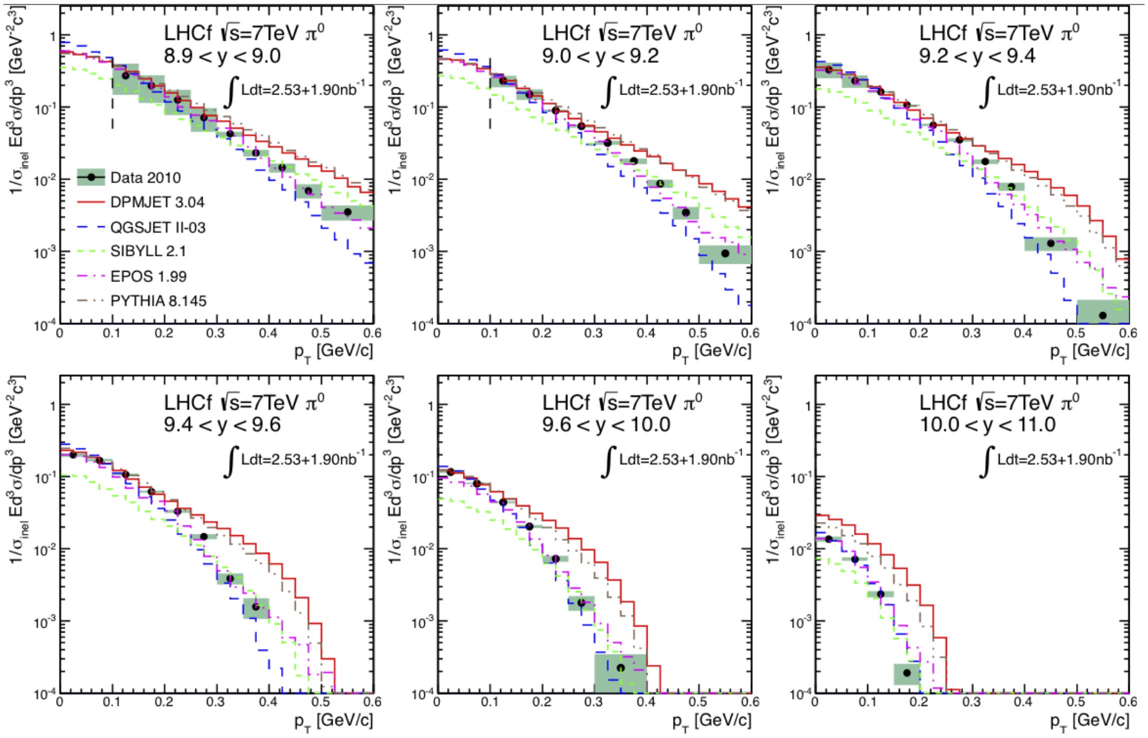

Figure 5: Combined p_T spectra of the Arm1 and Arm2 detectors [16] (black dots) and the total uncertainties (shaded triangles) compared with the predicted spectra by hadronic interaction models.

The π^0 are reconstructed in LHCf through the identification of their decays in two photons. Events are selected by requiring that each tower has only one well isolated photon. Because of the limited detector geometrical acceptance only photons from π^0 decays with an opening angle of $\theta < 0.4$ mrad can be detected. Energy, p_T and rapidity of the π^0 are reconstructed through the measurement of the photon energy and incident position in each calorimeter tower. Figure 5 shows the p_T spectra predicted by DPMJET 3.04, QGSJETII-03, SIBYLL 2.1, EPOS 1.99, and PYTHIA 8.145 (default parameter set) to the combined ARM1 and ARM2 p_T spectra (black dots), for different rapidity bins. Error bars take into account both statistical and systematic uncertainties. Among hadronic interaction models tested in this analysis, EPOS 1.99 shows the best overall agreement with the LHCf data. DPMJET 3.04 and PYTHIA 8.145 and SIBYLL 2.1 in general have harder spectra than the LHCf data.Finally, QGSJET II-03 predicts π^0 spectra that are softer than LHCf data and other models.

5 Conclusions and future activities

LHCf will measure very forward particle emission in the LHC p-Pb collisions at the beginning of 2013. The measurement is expected to constrain the nuclear effect for forward particle emission relevant to the CR-Air interactions, useful for model calibration [8]. Further improvements in data analysis for the 2009-2010 runs will provide the measurement of the neutral hadron spectra.

Also the LHCf collaboration is upgrading of the detector to improve the radiation resistance for the 14 TeV p-p run, currently foreseen in 2014. To this purpose the scintillating part of the detector is being replaced with GSO plates [16]. Planned improvements in the front-end electronics of the silicon position sensitive layers of ARM2 detectors to reduce the saturation effects, as well as an optimisation of the layout in the silicon layers will allow the use of the silicon strips also for calorimetry and not only for shower profile determination.

We acknowledge and are grateful to the LHC machine people who, through their constant and unrelenting effort, have allowed LHCf to achieve these results.

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