IL NUOVO CIMENTO Vol. 36 C, N. 1 Gennaio-Febbraio 2013
DOI 10.1393/ncc/i2013-11420-y

Colloquia: IFAE 2012

Results from the LHCf experiment

M. Bongi(1)(2)(*), O. Adriani(1)(2), L. Bonechi(2), G. Castellini(2), R. D'Alessandro(1)(2), M. Haguenauer(3), T. Iso(4), Y. Itow(4)(5), K. Kasahara(6), K. Kawade(4), K. Masuda(4), H. Menjo(2)(5), G. Mitsuka(4), Y. Muraki(4), K. Noda(7), P. Papini(2), A.-L. Perrot(8), S. Ricciarini(2), T. Sako(4)(5), Y. Shimizu(6), T. Suzuki(6), T. Tamura(9), S. Torii(6), A. Tricomi(7)(10) and W. C. Turner(11)

(1) *Università di Firenze - Firenze, Italy*
(2) *INFN, Sezione di Firenze - Firenze, Italy*
(3) *Ecole Polytechnique - Palaiseau, France*
(4) *Solar-Terrestrial Environment Laboratory, Nagoya University - Japan*
(5) *Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University - Japan*
(6) *RISE, Waseda University - Japan*
(7) *INFN, Sezione di Catania - Catania, Italy*
(8) *CERN - Geneva, Switzerland*
(9) *Kanagawa University - Japan*
(10) *Università di Catania - Catania, Italy*
(11) *LBNL - Berkeley, CA, USA*

ricevuto il 31 Agosto 2012

Summary. — LHCf is an experiment designed to study the very forward emission of neutral particles produced in collisions at the LHC. Its results can 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 taking data in proton-proton collisions at $\sqrt{s} = 900\,\mathrm{GeV}$ and at $\sqrt{s} = 7\,\mathrm{TeV}$ during 2009 and 2010. The detectors are now being upgraded and they will be installed again in the LHC tunnel for proton-ion collisions and for operation with protons at $\sqrt{s} = 14\,\mathrm{TeV}$. In this paper results and comparisons with the predictions obtained from Monte Carlo simulations will be reported.

PACS `13.85.-t` – Hadron-induced high- and super-high-energy interactions (energy $> 10\,\mathrm{GeV}$).
PACS `13.85.Tp` – Cosmic-ray interactions.
PACS `29.40.Vj` – Calorimeters.

(*) E-mail: `massimo.bongi@fi.infn.it`

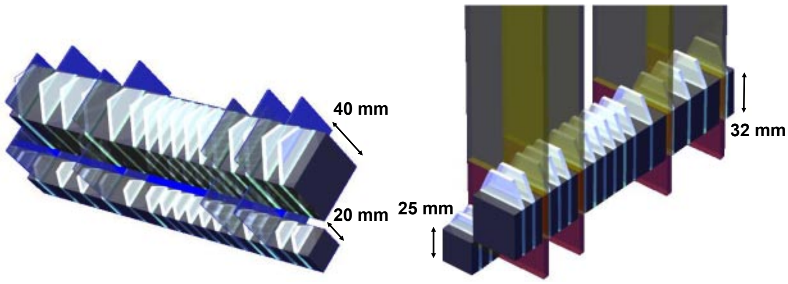

Fig. 1. – Schematic view of the LHCf detectors: *Arm1* calorimeter is depicted on the left, *Arm2* on the right. Plastic scintillators (light blue color) are interleaved with tungsten blocks (dark gray color). Four couples of position-sensitive layers (scintillating fibers in *Arm1*, dark blue color; silicon micro-strip detectors in *Arm2*, purple color) are present in each calorimeter.

1. – The LHCf experiment

Several extensive air shower experiments have strongly contributed to the understanding of high-energy cosmic ray physics in recent years. In particular the Pierre Auger Collaboration [1] and the Telescope Array Collaboration [2] are providing a deeper insight into the nature of high-energy cosmic rays. However, the uncertainty caused by the poor knowledge of the characteristics of the interaction of particles with the Earth's atmosphere at such high energies remains an important source of systematic error in the determination of energy and chemical composition of primary particles. The aim of the LHCf experiment [3] is to provide experimental results useful for testing and calibrating hadronic interaction models used in Monte Carlo (MC) 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 $\sqrt{s} = 14\,\text{TeV}$), which corresponds to the region between the *knee* and the *GZK cut-off* of the cosmic ray spectrum. The LHCf experiment uses two independent detectors (called *Arm1* and *Arm2*) installed in the LHC tunnel on both sides of the ATLAS detector, at a distance of 140 m and at zero-degree collision angle, in the regions where the single beam pipe coming from the interaction point splits to two separate tubes. Due to the presence of LHC dipole magnets, only neutral particles from the interaction point (mainly photons from π^0 decay, and neutrons) can reach these regions. Each detector has two sampling and imaging calorimeter towers (see fig. 1) whose transverse cross sections are $20 \times 20\,\text{mm}^2$ and $40 \times 40\,\text{mm}^2$ for *Arm1*, and $25 \times 25\,\text{mm}^2$ and $32 \times 32\,\text{mm}^2$ for *Arm2*. The two-tower structure helps in the detection of the π^0 decaying in two photons, hence providing a very precise absolute energy calibration for the experiment by reconstructing the π^0 invariant mass. The towers are composed of 16 plastic scintillators interleaved with tungsten absorbers which allow the reconstruction of the longitudinal development of showers induced by neutral particles, and amount to a total thickness of 44 radiation lengths and 1.7 interaction lengths. Four layers of position-sensitive detectors (scintillating fibers with 1 mm square-section in *Arm1*, and silicon micro-strip detectors with $160\,\mu$m readout pitch in *Arm2*) provide measurements of the transverse profile of showers. Two additional double-layer scintillators in front of each detector allow to monitor the quality of the beam and to estimate the luminosity of the LHC machine by the Van der Meer scan method [4]. In the range $E > 100\,\text{GeV}$, the

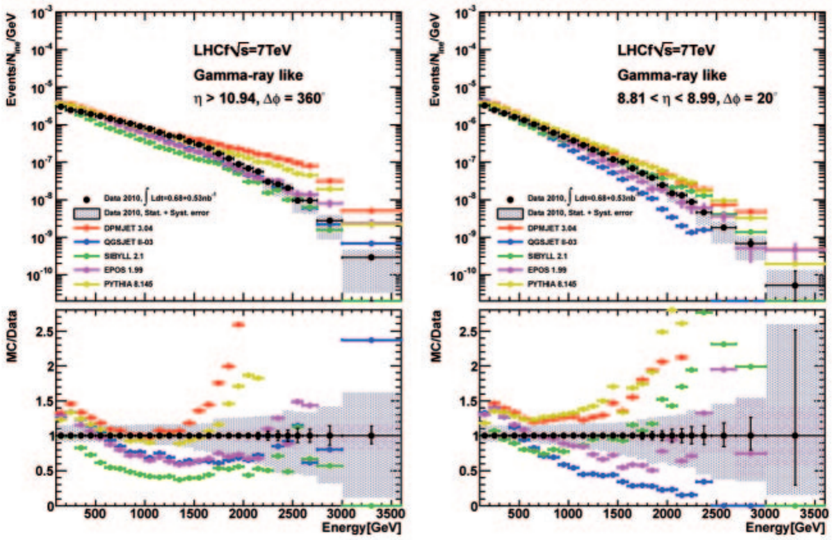

Fig. 2. – Single-photon energy spectra measured by LHCf (black dots) in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ and compared with the predictions of the following MC codes: DPMJET 3.04 (red), QGSJET II-03 (blue), SIBYLL 2.1 (green), EPOS 1.99 (magenta) and PYTHIA 8.145 (yellow). Top panels show the spectra and bottom panels show the ratio MC/data. Left and right panels refer to pseudo-rapidity ranges $\eta > 10.94$ and $8.81 < \eta < 8.99$, respectively. Error bars show the statistical error and gray-shaded areas the systematic error for experimental data. Magenta-shaded areas indicate the statistical error associated to MC simulations (using EPOS 1.99 as a representative of all the models).

LHCf detectors have energy and position resolutions for electromagnetic showers better than 5% and 200 μm, respectively, while hadronic showers of high-energy neutrons can be measured with an energy resolution of about 30%.

2. – LHCf operation at LHC and single-photon energy spectrum

Both LHCf detectors have been installed in 2008 in the LHC tunnel and they started taking data since the first physics run of the LHC in 2009 at a center of mass energy $\sqrt{s} = 0.9\,\text{TeV}$. From December 2009 until May 2010 (approximately 42 hours of effective data-taking time) LHCf recorded more than 10^5 single shower events. A run at $\sqrt{s} = 7\,\text{TeV}$ was completed between Mar and July 2010 (amounting to about 150 hours of effective data-taking time), and more than $3 \cdot 10^8$ showers were detected, thus allowing a precise measurement of the forward spectra of neutral particles. The detectors have been removed from the LHC tunnel during summer 2010, when the LHC luminosity increased above $10^{30}\,\text{cm}^{-2}\,\text{s}^{-1}$, in order to avoid significant radiation damage. LHCf will be reinstalled in the tunnel for the run at $\sqrt{s} = 14\,\text{TeV}$, currently foreseen in 2014, after an upgrade to replace its plastic scintillators and scintillating fibers with GSO scintillators, which will allow to improve significatively the detector's radiation hardness [5, 6]. The first physics result about the single-photon spectrum at $\sqrt{s} = 14\,\text{TeV}$ in two pseudo-rapidity bins has been published by the LHCf collaboration in 2011 [7]. For this analysis only a small subset of data has been used (corresponding to an integrated luminosity of $0.68\,\text{nb}^{-1}$ and $0.52\,\text{nb}^{-1}$ for *Arm1* and *Arm2*, respectively) in order to select the best running conditions and minimize backgrounds due to beam-gas interactions and pile-up effects. The energy of photons is determined from information on the signal produced in 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 discarded by simple identification criteria based on the longitudinal development of the shower. The two *Arms* have different geometrical configurations (see fig. 1), and in this analysis two pseudo-rapidity regions common to both the detectors have been selected ($\eta > 10.94$ for the small towers, $8.81 < \eta < 8.99$ for the large towers), in order to combine the spectra obtained from *Arm1* and *Arm2* without any acceptance correction. Further details about the analysis can be found in ref. [7]. Figure 2 shows the comparison of the experimental spectra with several MC simulations using different hadronic interaction models: DPMJET 3.04 [8], QGSJET II-03 [9], SIBYLL 2.1 [10], EPOS 1.9 [11] and PYTHIA 8.145 [12, 13]. None of the models is able to reproduce experimental data in the explored energy range from 100 GeV to 3.5 TeV: in particular a large discrepancy is present in the highest-energy region. Discussions with the community of people involved in the development of models have already started and improvements in the calibration of the models are expected in near future.

3. – Conclusions

LHCf has provided the first measurement of the spectrum of photons with $E >$ 100 GeV emitted in the very-forward region during proton-proton collisions at LHC. Comparison with hadronic interaction models calibrated at lower energies and used in simulations of high-energy cosmic-ray induced showers in the atmosphere seems to indicate that none of them reproduces experimental data within statistical and systematic uncertainties. Besides extending the result at higher energy when the $\sqrt{s} = 14\,\text{TeV}$ proton-proton run while take place at LHC, we plan to study also very forward production of particles in proton-ion collisions, in order to have a more complete picture of hadronic interactions in the atmosphere, where mainly nitrogen and oxygen nuclei are involved.

REFERENCES

[1] Kampert K.-H. for the Pierre Auger Collaboration, *Proc. of ICRC2011*, **12** (2011) 48.
[2] Tsunesada Y. for the Telescope Array Collaboration, *Proc. of ICRC2011*, **12** (2011) 58.
[3] Adriani O. *et al.*, *JINST*, **3** (2008) S08006.
[4] Taki K. *et al.*, *JINST*, **7** (2012) T01003.
[5] Kawade K. *et al.*, *JINST*, **6** (2011) T09004.
[6] Suzuki T. *et al.*, *Proc. of ICRC2011*, **5** (2011) 19.
[7] Adriani O. *et al.*, *Phys. Lett. B*, **703** (2011) 128.
[8] Bopp F. W. *et al.*, *Phys. Rev. C*, **77** (2008) 014904.
[9] Ostapchenko S. *et al.*, *Phys. Rev. D*, **74** (2006) 014026.
[10] Ahn E.-J. *et al.*, *Phys. Rev. D*, **80** (2009) 094003.
[11] Werner K. *et al.*, *Phys. Rev. C*, **74** (2006) 044902.
[12] Sjöstand T. *et al.*, *JHEP*, **0605** (2006) 026.
[13] Sjöstand T. *et al.*, *Comput. Phys. Commun.*, **178** (2008) 852.