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Recent results from LHCf

H. Menjo[1,a], O. Adriani[2,3], E. Berti[2,3], L. Bonechi[2], M. Bongi[2,3], G. Castellini[4], R. D'Alessandro[2,3], M. Del Prete[2,3], M. Haguenauer[5], Y. Itow[6,7], K. Kasahara[8], K. Kawade[6], Y. Makino[6], K. Masuda[6], E. Matsubayashi[6], G. Mitsuka[6], Y. Muraki[6], P. Papini[2], A.-L. Perrot[9], D. Pfeiffer[9], S. Ricciarini[2,4], T. Sako[6,7], Y. Shimizu[10], Y. Sugiura[6], T. Suzuki[8], T. Tamura[11], A. Tiberio[2,3], S. Torii[8], A. Tricomi[12,13], W.C. Turner[14], and Q. Zhou[6]

[1] Graduate school of Science, Nagoya University, Japan
[2] INFN Section of Florence, Italy
[3] Physics and Astronomy Department, University of Florence, Italy
[4] IFAC-CNR, Italy
[5] Ecole-Polytechnique, France
[6] Solar-Terrestrial Environment Laboratory, Nagoya University, Japan
[7] Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Japan
[8] RISE, Waseda University, Japan
[9] CERN, Switzerland
[10] JAXA, Japan
[11] Kanagawa University, Japan
[12] INFN Section of Catania, Italy
[13] University of Catania, Italy
[14] LBNL, Berkeley, USA

Abstract. The LHCf experiment is one of the LHC forward experiments. The aim of LHCf is to provide critical calibration data of hadronic intraction models used in air shower simulations. The LHCf has completed the operations for p-p collisions with a collision energy of $\sqrt{s} = 0.9$ and 7 TeV p-p in 2010 and for p-Pb collisions with a collision energy per nucleon of $\sqrt{s_{NN}} =$ 5.02. The recent LHCf result of forward neutron energy spectra at 7 TeV p-p collision and forward π^0 spectra at p-Pb collisions are presented in this paper.

1. LHCf experiment

The LHCf experiment is an LHC experiment dedicated to the measurement of very forward neutral-particle spectra. The aim is to provide critical date for the calibration of hadronic interaction models used in MC simulations of cosmic-ray induced air showers. One of the key parameters of air shower development is the energy spectra of the energetic secondaries produced in the forward region of hadronic interactions. The LHCf detectors were designed to measure such forward energetic particles of p-p and p-Pb collisions at an LHC interaction point. The pseudo-rapidity coverage of the detectors is more than 8.4 at the beam crossing angle of 140 μrad.

The LHCf has two independent detectors, so called Arm1 and Arm2, which were installed +/− 140 m from the ATLAS interaction point (IP1). Each detector has two sampling and imaging calorimeter towers. They consist of tungsten plates, 16 scintillator layers and four position sensitive layers. The scintillator layers were inserted between tungsten plates for shower sampling with 2 radiation length step. The position sensitive layers were developed to measure the shower impact position with different techniques of X-Y scintillating fiber hodoscopes and X-Y silicon strip detectors for Arm1 and Arm2, respectively. The transverse cross sections of calorimeters are 20×20 mm^2 and 40×40 mm^2 in Arm1 and 25×25 mm^2 and 32×32 mm^2 in Arm2. The total thickness of calorimeter towers is 44 radiation lengths and 1.7 interaction length. The LHCf detectors are able to measure only neutral particles like photons and neutrons because the charged particles produced at IP1 are swept out by the magnetic field of dipole magnets located between IP1 and the LHCf detectors. The energy resolution of detectors is about 5% for photons and 40% for neutrons. The position resolution is better than 200 μm for photons and a few mm for neutrons. More details of the detector performance were reported elsewhere [1,2].

The LHCf has successfully completed operating with proton-proton collisions at $\sqrt{s} = 0.9$, 7 TeV in 2010 and with proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV in 2013. The forward photon and π^0 spectra for proton-proton collisions has been published [3–5].

2. Neutron spectrum in $\sqrt{s} = 7$ TeV p-p collisions

The measurement of the neutron energy spectrum is a way to access one of the key parameters for air-shower

[a] e-mail: menjo@stelab.nagoya-u.ac.jp

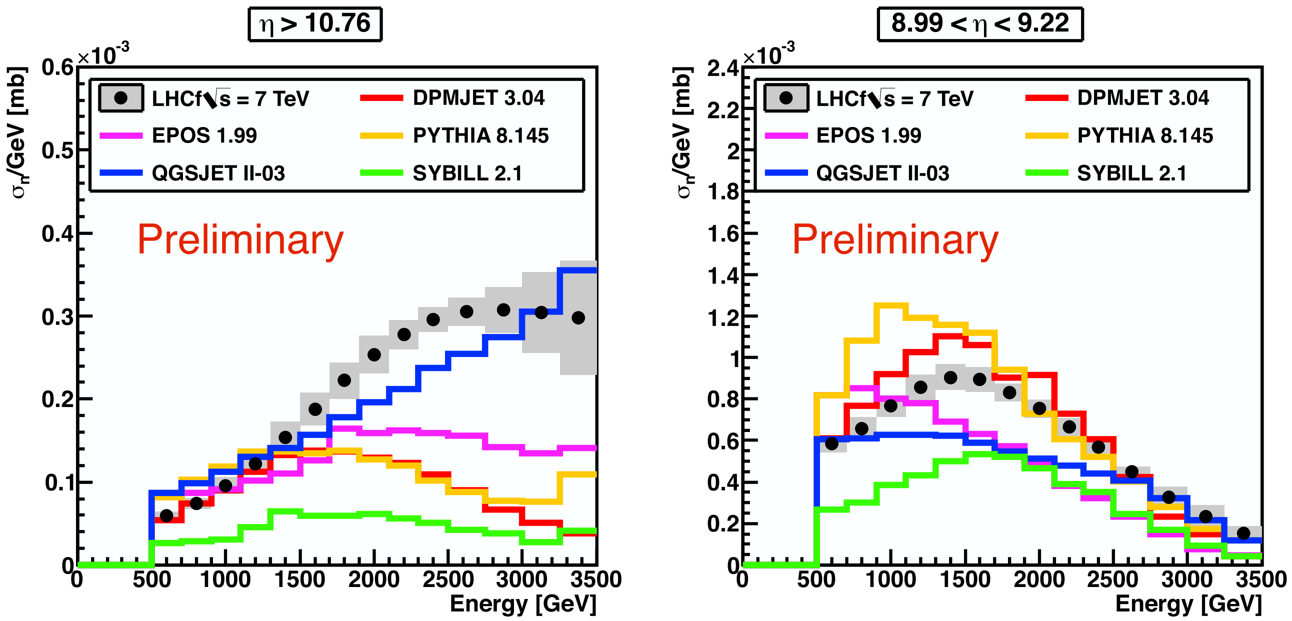

Figure 1. Forward neutron energy spectra at $\sqrt{s}\ =\ 7$ TeV p-p collisions measured for $\eta\ >10.76$ (left) and $8.99<\ \eta\ <9.22$ (right) [6]. The black dots and the shaded area show LHCf data and the uncertainties. The color lines indicate the predictions by several hadron interaction models [7–11].

development, the inelasticity of hadronic interaction. This parameter is estimated from the energy of leading baryons in collisions. The detection efficiency of LHCf detectors is 70% for neutrons above 500 GeV/c. The energy and position resolutions are 40% and 1 mm, respectively. Hadronic showers induced by neutral hadrons are well identified from electromagnetic showers induced by photons by using the transition shape of showers. Figure 1 shows the preliminary result of neutron energy spectra after the unfolding procedure for detector response [6]. The left and right figures are for pseudo-rapidity bins of $\eta > 10.76$ and $8.99 < \eta < 9.22$, respectively. The colored lines indicate the predictions of several hadronic interaction models [7–11]. We found that the spectrum for $\eta > 10.76$ was very hard like QGSJET2 while that for $8.99 < \eta < 9.22$ was in the middle of model predictions.

3. π^0 P_T spectrum in $\sqrt{s_{NN}}\ = 5.02$ TeV p-Pb collisions

The nuclear effect is another key of hadronic interaction playing important roles in air shower development. Collisions between high energy cosmic rays and atmospheric nuclei are not simple proton-proton collisions but proton(Fe)-light nucleus like nitrogen and oxygen. The LHC provided an opportunity to measure the nuclear effect with proton-lead collisions at a center-of-mass collision energy per nucleus of $\sqrt{s_{NN}} = 5.02$ TeV in early 2013 while the nuclear effect for p-Pb collisions is expected to be greater than one for p-N,O.

LHCf operated for such p-Pb collisions with detectors (Arm2). For most of the operation time, the Arm2 detector was located on the p-remnant side where proton beams passed from IP1. The LHCf operated at the Pb-remnant side for only some hours. In that time, the detector was located 4 cm up from zero degree of collisions to avoid too high multiplicity on the calorimeter towers. Figure 2 shows the transverse momentum spectra of π^0s in p-Pb collisions (the p-remnant side) [12]. The expected contribution of ultra peripheral collisions (UPCs) was already subtracted in these spectra. The thin lines indicate the predictions from the hadronic interaction models, DPMJET3, QGSJET2 and EPOS1.99. The transverse momentum spectra at proton-proton collisions at the equivalent energy of $\sqrt{s} = 5.02$ TeV were derived from the LHCf data taken at $\sqrt{s} =$ 0.9, 2.76 and 7 TeV proton-proton collisions and are shown as the gray hatched lines in Fig. 2. The nuclear modification factor, $\mathbf{R}_{\mathbf{pPb}}$, was defined as the ratio of the p-Pb result to the p-p result. $\mathbf{R}_{pPb}$ varies from 0.1 at $P_T \sim 0.1$ GeV/c to 0.3 at $P_T \sim 0.3$ GeV/c. This tendency is found in all the rapidity bins of Fig. 2. The hadronic interaction model reproduce the small factor of $\mathbf{R}_{\mathbf{pPb}} \sim 0.1$ constantly in the P_T range. They are in good agreement with the LHCf result within the errors.

4. Future prospects

The LHC restarts operation in 2015. A one-week special operation with very low-luminosity of $10^{30}\,\mathrm{cm^2\,s^{-1}}$ is planned in mid-May 2015. The LHCf will operate during the low-luminosity campaign period for proton-proton collisions with $\sqrt{s}\ =\ 13$ TeV. The collision energy is 0.9×10^{17} eV in the laboratory frame. It will be a unique data point of forward particle measurements at the highest collision-energy of collider experiments in the next decades. Comparison with the data taken for proton-proton collisions at $\sqrt{s}\ =\ 0.9, 2.76$ and 7 TeV in previous operations allows the energy scaling of forward particle production to be tested. The test with a wide collision energy of $10^{14} - 10^{17}$ eV in the laboratory frame is important because it covers the energy of the well-known

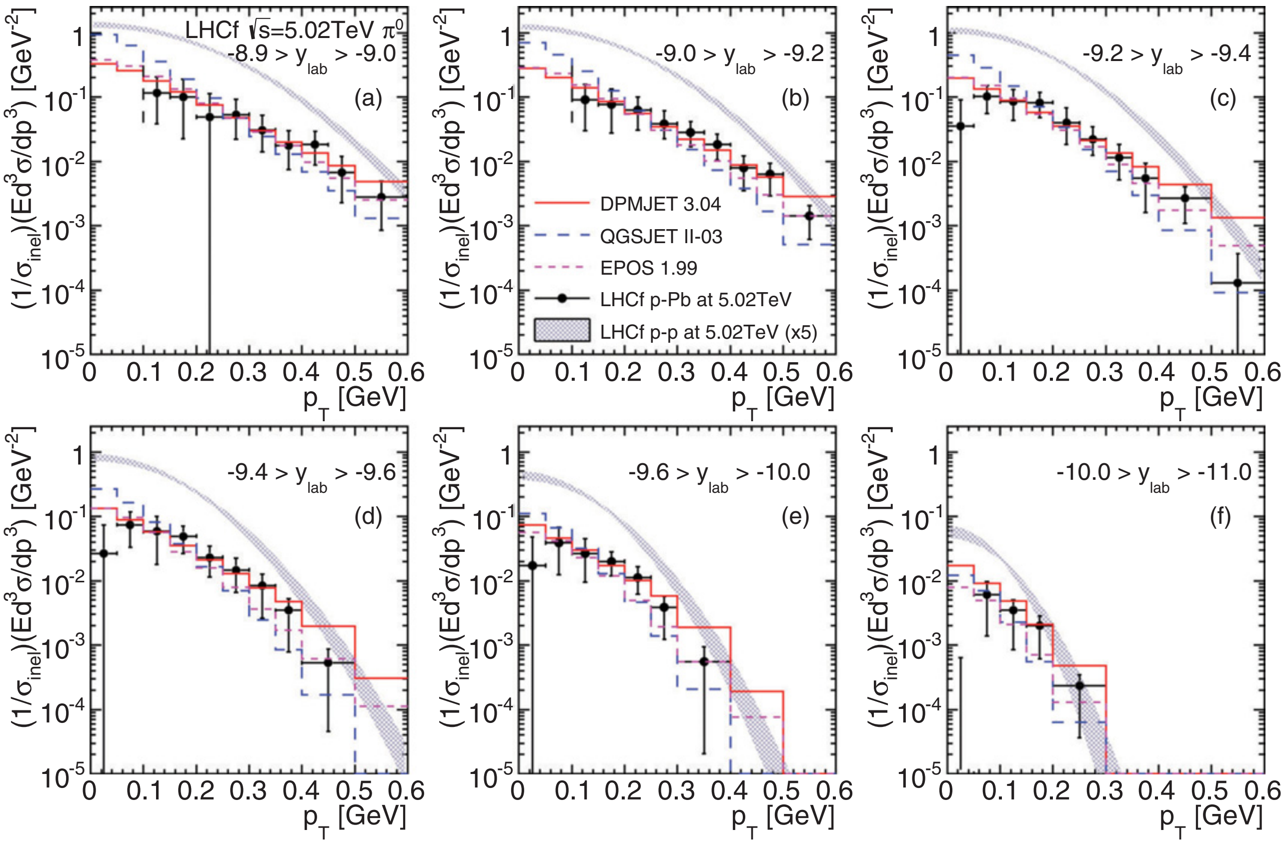

Figure 2. Transverse momentum spectra of forward π^0s for p-Pb collisions [12]. The black dots and the shaded area show LHCf data and the uncertainties. The color lines indicate the predictions by several hadron interaction models [7–11].

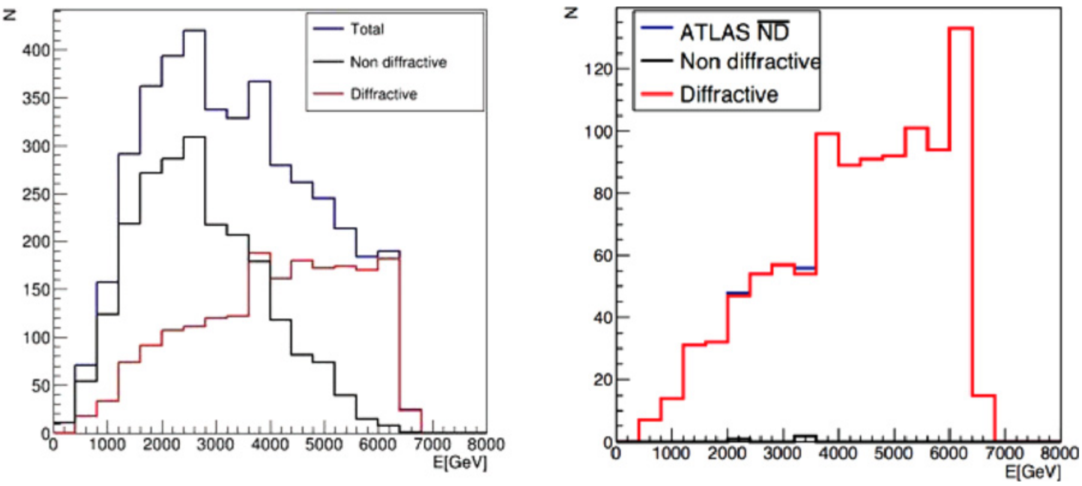

Figure 3. Neutron spectrum for p-p collisions at $\sqrt{s} = 13$ expected by LHCf-Arm1. The left and the right figures show the spectra without and with the event selection by the particle generation in $|\eta| < 2.5$, respectively. The blue and the red lines indicate the contribution of non-diffractive and diffractive events categorized in the event generator.

Knee kink of the cosmic-ray spectrum around 10^{15} eV. Additionally the operation is a good opportunity to study diffractive physics thanks to the common operation with the ATLAS experiment. The LHCf sends its final trigger signals to the ATLAS trigger system and triggers ATLAS after pre-scaling of the signals. A simple MC study was made with 10^5 inelastic-event generation by PYTHIA for confirming the capability of event selection for diffractive events with ATLAS event-by-event data [13]. Figure 3 shows the neutron spectra expected on the LHCf-Arm1 detector at 13 TeV p-p collisions. The left and right figure show the spectra without and with the event selected by ≥ 1 particle production with $P_T > 100\,\mathrm{MeV/c}$ in the pseudo-rapidity range of $|\eta| < 2.5$. The black and the red lines indicate the contribution of non-diffractive and diffractive events categorized in the event generator. The diffractive events are able to be selected with 35–40% efficiency and 99% purity.

After the operation in 2015, we propose to take one of the detectors to RHIC and to operate for proton-proton collisions at $\sqrt{s} = 0.5$ TeV. This will provide an opportunity to measure the forward production spectra with much wider P_T coverage than for LHC 0.9 TeV proton-proton collisions. It will be very useful to test energy scaling.

5. Summary

The LHCf experiment measured the forward neutron spectra at p-p collisions with the center-of-mass energy of $\sqrt{s} = 7$ TeV. The measured spectrum for $\eta > 10.76$ was harder than the all model predictions while the measured spectrum for $8.99 < \eta < 9.22$ was located in the middle of the model predictions. The nuclear modification factor of forward π^0 production spectra was measured as $\mathbf{R_{pPb}} \sim$ 0.1 to 0.3 from $P_T \sim 0.1$ GeV/c to 0.6 GeV/c. The small factor is consistent with the model prediction within the errors. The study of energetic particle production in the forward region is accelerated with the measurement for p-p collisions with $\sqrt{s} = 13$ TeV in 2015. The LHCf-ATLAS common operation helps us to understand the particle production mechanism in the soft hadronic interactions and to modify hadronic interaction models for cosmic-ray air showers.

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