The results from LHCf: very forward measurements for cosmic ray interactions

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Abstract: The LHCf experiment is an unique dedicated experiment for measurement of very forward particle production relevant to cosmic-ray air shower developments by using small electromagnetic imaging calorimeters at the zero degree of the LHC interaction point, IP1. The operationa with *p-p* collisions at $\sqrt{s} = 900\,\text{GeV}$ and 7 TeV have been done in 2009 and 2010. The results of forward production spectra of photons and π^0s are compared with the existing cosmic ray interaction models, SYBILL, QGSJETII, DPMJET3, and EPOS1.99. None of them could completely reproduce the data. On-going hadron analysis will be also important to understand inelasticity of collisions. LHCf has also completed data taking for LHC *p-Pb* collisions to study nuclear effect relevant to air shower development. This is also very important to validate composition measurements by air-shower experiments based on X_{MAX}. Current achievement of the LHCf experiment and possible future experiments at *p-A* and/or *A-A* collisions at LHC and RHIC are presented.

Keywords: LHC, Hadron interaction, UHECR.

1 Introduction

The origin of Ultra High Energy Cosmic Rays (UHECRs) are one of the quests of current science. Recently the Pierre Auger observatory and the Telescope Array experiment are observing UHECRs by using the hybrid technique of florescence telescopes and grand array detectors. They are providing the exciting results[1, 2]. Average and RMS of the measured X_{MAX} are good indicators of the composition of UHECRs[3]. However the predictions of X_{MAX} by air-shower simulations depend on the hadron interaction model used in the simulation. Large Hadron Collider (LHC), the most powerful and energetic hadron collider, gives us a unique opportunitie to calibrate hadron interaction models at the collision energy of $\sqrt{s} = 13\,\text{TeV}$, which is equivalent to 9×10^{16} eV in the laboratory frame. After LHC operation, hadron interaction models have been turned by using the several results of LHC experiments and the difference of X_{MAX} predictions between interaction models got smaller than ones before the starting of LHC[4]. However the observed results by the UHECR experiments is not consistently understood yet.

The LHCf experiment[5] is one of the seven physics experiments at LHC. The LHCf experiment measures energy and transverse momentum spectra of photons, π^0s and neutrons scattered to the very forward region by the LHC interactions. These energetic particles make an important role in the air shower development. In this paper, we presented the results at $\sqrt{s} = 900\,\text{GeV}$ and 7 TeV *p-p* collisions in Section 3 and future operations in Section 4.

2 The LHCf experiment

The LHCf experiment has two independent detectors (Arm1 and Arm2). Each detector has two sampling and imaging calorimeter towers that are composed of tungsten layers, 16 plastic scintillator layers for energy measurement and four position sensitive layers for impact position determination of showers. The position sensitive layers of Arm1 and Arm2 are X-Y scintillating fiber (SciFi) hodoscopes and X-Y silicon strip detectors, respectively. The transverse cross sections of calorimeter towers are $20\times20\,\text{mm}^2$ and $40\times40\,\text{mm}^2$ in Arm1 and $25\times25\,\text{mm}^2$ and $32\times32\,\text{mm}^2$ in Arm2. Figure 1 shows the schematic view of the Arm1 detector. The detectors are installed 140 m away from the LHC interaction point, IP1, where the ATLAS detector has been installed. At that point, the

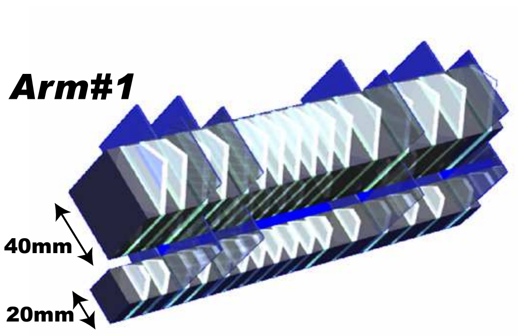

Fig. 1: Schematic view of the LHCf-Arm1 detector

beam pipe makes transition from a big beam pipe to small two beam pipes (Y-chamber). The detectors are installed into the narrow gaps of beam pipes and view zero degree of collisions. Because dipole magnets are located between IP1 and the detectors, charged particles are swept away and neutral particles, photons and neutrons, are able to be detected by the detectors. The unique location covers the pseudo-rapidity range of $\eta = 8.4$ to infinite. Additionally thin scintillator detectors which have the large acceptance of $8 \times 8\,\mathrm{cm}^2$ are installed in front of the calorimeter detectors for monitoring the luminosity during operation and coincidence analysis between both sides [6].

The energy resolution of the detectors for photons and neutrons is 5% and 35%, respectively. 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 [7, 8, 9].

3 Results at *p*-*p* collisions $\sqrt{s}=$ 900 GeV and 7 TeV

The LHCf-Phase 1 operation was successfully done in 2009 and in 2010. In December 2009, the first LHC physics operation was started with *p*-*p* collisions at $\sqrt{s} = 900$ GeV and LHCf took about 3 K shower events at each arm. From March 2010, LHC started the physics operation at the increased collision energy of $\sqrt{s} = 7$ TeV . LHCf operated in this initial stage of LHC, during the commissioning of the LHC machine, and continued until July 2010 with increasing luminosity to a few $10^{30} cm^{-2}s^{-1}$. In total, 200 M shower events were taken in this Phase 1 operation. The energy scale of calorimeters was monitored during the operation by a UV pulse laser and by the peak position of reconstructed invariant mass corresponding to π^0 and the stability was 5%. In addition to 7 TeV, LHC provided $\sqrt{s} = 900$ GeV *p*-*p* collisions for a few days in this period. Because the luminosity in 2010 was higher than in 2009, about 50 K shower events at each arm were taken.

The spectra of forward photons and π^0s at $\sqrt{s} = 7$ TeV *p*-*p* collisions and the spectrum of photons at $\sqrt{s} = 900$ GeV and 7 TeV were published [10, 11, 12]. Figure 2 shows the transverse momentum spectra of forward π^0s measured by LHCf with comparing with the predictions by several hadron interaction models. Although no model is able to reproduce the LHCf data perfectly, the LHCf data is on the middle of model predictions. DPMJET3.03[13] and PYTHIA8.145[14] show harder spectra than data and EPOS1.99[15] shows the best overall agreement with data in the tested models. These tendencies were also found in

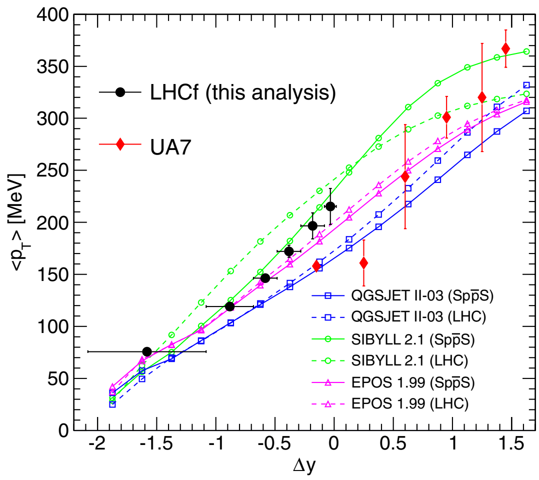

Fig. 3: Average transverse momentum as a function of $\Delta y (= y - y_{beam})$, where y_{beam} is the rapidity of proton beam. The colored solid lines and dashed lines indicate the predictions of models at LHC($\sqrt{s} = 7$ TeV) and S$p\bar{p}$S ($\sqrt{s} = 630$ GeV) energies, respectvely.

the photon results both at 900 GeV and at 7 TeV. it is reasonable because most of photons are produced by decays of π^0s generated at the collisions.

Figure 3 shows the average transverse momentum $< p_T >$ measured by LHCf together with the UA7 data measured at S$p\bar{p}$S ($\sqrt{s} = 630$ GeV) [18] as a function of $\Delta y (= y - y_{beam})$, where y_{beam} is the rapidity of proton beam. The LHCf and the UA7 data mostly appear to lie along a common curve and it may indicate the energy scaling of forward π^0 production.

Another interesting and important data, production of forward energetic baryons at *p*-*p* collisions, can be provided by LHCf via neutron measurement. The preliminary result of neutron analysis at $\sqrt{s} = 7$ TeV is presented in this conference [19].

4 Operation in early 2013 and Future operations

4.1 *p*-*Pb* collision in early 2013

LHC is able to provide different particle spices collisions, *p*-*Pb*, as well as *p*-*p* and *Pb*-*Pb* collisions. In January and February 2013, LHCf took data with *p*-*Pb* collisions at the center-of-mass collision energy per nucleon of $\sqrt{s_{NN}} =$ 5 TeV. Only the Arm2 detector was used for the operation because the Arm1 detector is in upgrading for the future operations. In most of the operation time, the detector was located on the *p*-remnant side. The measurement is to check the nuclear effect on the production of forward energetic particles. It is one of the important effects for modeling interactions between cosmic-rays and atmosphere. In addition, the short operations, the operation on the *Pb*-remnant side and the operation with *p*-*p* at $\sqrt{s} = 2.76$ TeV, have been successfully completed in this period. Figure 4 show an event sample with multiple showers in the calorimeter taken at the operation in the *Pb*-remnant side.

During operations with *p*-*Pb* collisions, LHCf have common operation with ATLAS in the trigger level. LHCf sent the final trigger signals to the ATLAS DAQ system

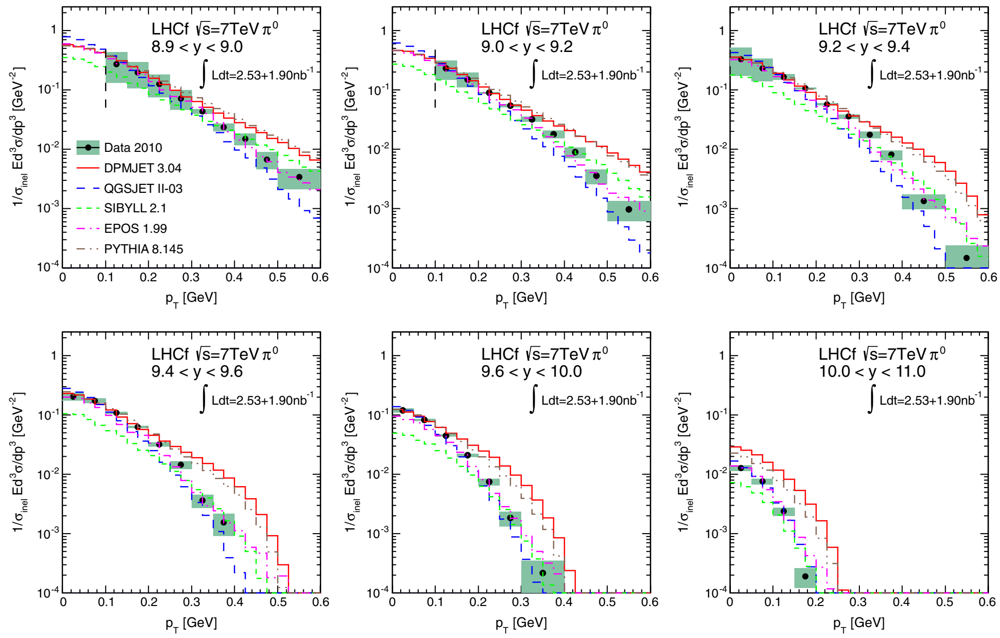

Fig. 2: Transverse momentum spectra of forward π^0 in each rapidity bin. The black dots and the shaded area show LHCf data and the uncertainties. The color lines indicate the predictions by several hadron interaction models [13, 14, 15, 16, 17].

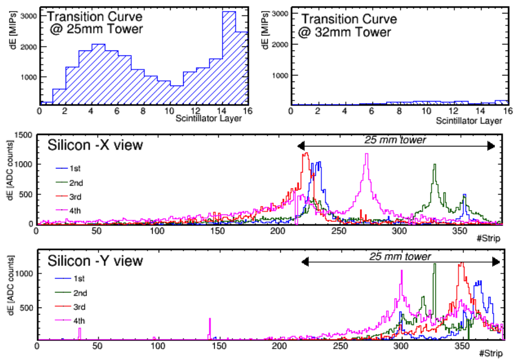

Fig. 4: Event Sample with multiple showers measured at the Pb-remnant side.

and ATLAS was triggered by the LHCf signals downscaled from about 700 Hz to between 20 and 40 Hz. The information at the central region measured by the ATLAS detector is quite helpful to study the production mechanism of forward particles.

4.2 *p-p* collision at $\sqrt{s} = 13$ TeV in 2015

After the long shutdown of LHC until the end of 2014, LHC will re-start its operation with *p-p* collisions at the highest collision energy of $\sqrt{s} = 13$ TeV. The LHCf detectors will be re-installed inside the LHC tunnel in the end of 2014 and will have operation for about one week in the initial stage of the LHC physics operation in early 2015. Figure 5 shows the transverse momentum coverage for photons as a function of Feynman X (X_F: the longitudinal momentum of a particle normalized with the beam momentum). The color map in Fig. 5 shows the energy-P_T distribution of photons generated at $\sqrt{s} = 7$ TeV *p-p* collisions by the DPMJET3.03 model as a reference. The transverse momentum coverage at $\sqrt{s} = 13$ TeV is the widest in the operations thanks to about two times higher boosting factor than one at $\sqrt{s} = 7$ TeV.

Both the detectors are upgraded before the operation in 2015. Because the radiation dose of detectors at $\sqrt{s} = 13$ TeV is about 8 times higher than at $\sqrt{s} = 7$ TeV, all plastic scintillators of detectors are replaced with crystal scintillators of Gd_2SiO_5 (GSO). The SciFi hodoscopes are also replaced with GSO bar bundles. The radiation hardness of GSO scintillators has been checked by using high intensity carbon beams with 400 MeV/n [20]. The beam tests for calibrations and performance studies with the upgraded Arm1 detector have been done with carbon beams [21, 22] and with electron, proton and muon beams at CERN SPS.

4.3 p-light nucleus collisions at LHC.

Because lead is too heavy, the best way to study the nuclear effect for cosmic-ray point of view is to make collisions between proton (or Iron) and light nucleus (Nitrogen or Oxygen) directly at LHC. Oxygen beam may be possible in LHC [23]. For the moment, the LHC schedule is fully booked for operations with *p-p* and *Pb-Pb* collisions until 2019. To have operations earlier than 2019, we have to present the importance of *p*-light nucleus collisions with support of the cosmic-ray community.

4.4 Operations at RHIC

Another possibility to study the nuclear effect relevant to air shower development is operations at RHIC, which is located in Long Island, USA. RHIC have never made *p*-light nucleus collisions, however, there is no big technical problem to make them, such as *p-N*, and also *N-N* and *N-Fe* at $\sqrt{s_{NN}} = 200$ GeV. There are the Y-chambers with the beam pipe gap of 10 cm at the locations of 18 m from the interaction points and the LHCf detector can fit the narrow gap perfectly. The location covers the pseudorapidity range of $\eta > 6$. Figure 6 shows prediction of the nuclear modifica-

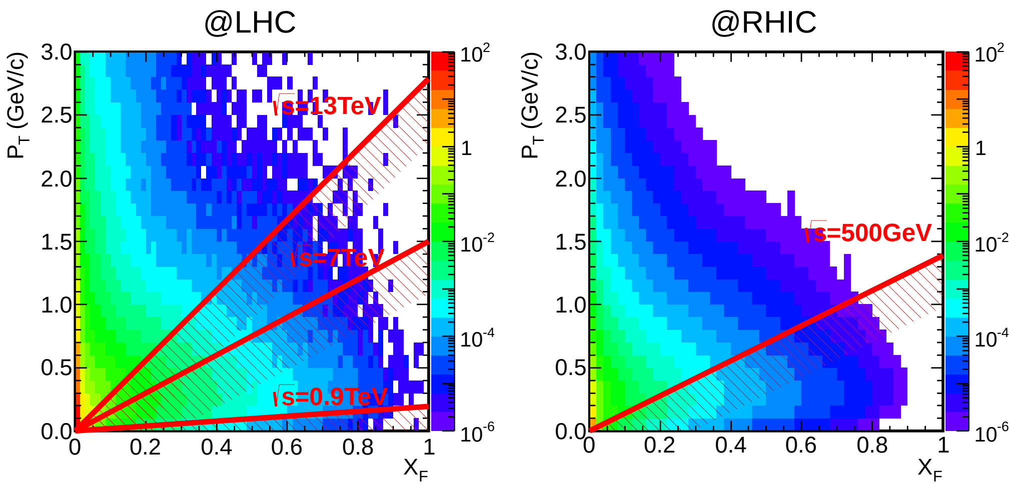

Fig. 5: Transverse momentum coverages of the LHCf detectors at several collisions energy at LHC(900 GeV, 7 TeV and 13 TeV) and at RHIC (500 GeV). The color maps show 2D histograms of energy v.s. P_T for photons generated by DPMJET3.03 at $\sqrt{s} = 7$ TeV (left) and at $\sqrt{s} = 500$GeV (right).

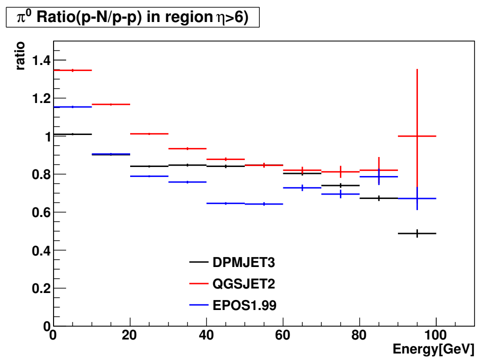

Fig. 6: Nuclear modification factors of forward π^0s ($\eta > 6$) at $\sqrt{s_{NN}} = 200$ GeV expected by interaction models.

tion factor of forward π^0 productions by several interaction models at *p-N* collisions. Operation with $\sqrt{s} =$ 500 GeV *p-p* collision at RHIC is also important for studying the energy scaling of forward particle productions. The coverage of the transverse momentum is wide and it is mostly same as at $\sqrt{s} =$ 7 TeV of LHC as shown in Fig. 5. These plans was proposed to the RHIC committee as "Letter of Intent; Precise measurement of forward particle production at RHIC", which was submitted in the end of May 2013.

5 Summary

The LHCf experiment has successfully completed the phase-1 operation with $\sqrt{s} = 900$ GeV and 7 TeV *p-p* collisions in 2009 and 2010 and published the results of forward photon and π^0 spectra. No hadron interaction model was found to reproduce the LHCf data perfectly, however, some of them have reasonable agreement with data. Data taken at p-Pb collisions in early 2013 and data that will be taken by future operations, $\sqrt{s} = 13$ eV p-p, p-light nucleus and operations at RHIC are critical to verify hadron interaction models and it helps greatly to study high energy cosmic ray physics.

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