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Recent status of LHCf to improve the cosmic-ray air shower modeling

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The Large Hadron Collider forward experiment was motivated to test the hadronic interaction models used to describe the cosmic-ray induced air showers. In this paper, results of the LHCf for forward particle spectra measured in the LHC 0.9 and 7TeV p-p collisions and 5TeV p-Pb collisions are presented together with the future plan of the experiment.

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1. Introduction

Origin of cosmic rays is one of the long-standing mysteries in astrophysics. Energy spectrum of cosmic rays is measured over a wide range spanning from 10^{10} eV to 10^{20} eV. There are a few well-known structures, named *knee* at 10^{15} eV, *ankle* at 10^{18} eV and a recently established cutoff at 10^{20} eV [1]. These structures are explained as following. At around 10^{15} eV major galactic cosmic-ray source, supernova remnants, reaches at the acceleration limit of protons. Because heavier nuclei with charge Z can be accelerated to Z times higher energy than protons, the chemical composition of cosmic ray becomes heavier beyond the knee. Once the heaviest cosmic-ray particles meet their acceleration limit, the extragalactic cosmic rays become dominant in the flux and this transition produces the ankle structure. The ankle is also explained by e^+e^- production from the interaction between extragalactic protons and the cosmic microwave background [2]. Finally at around 10^{20} eV, a famous GZK mechanism [3] to protons or nuclei produces a cutoff. The cutoff can be a simply the result of the acceleration limit of the extragalactic sources. This rough scenario predicts a energy-dependent chemical composition and it is observationally supported. However the determination of the chemical composition needs a help of hadronic interaction models because the observations at such high energy are based on the detection of air showers. This results a large uncertainty depending on the choice of the interaction model in the interpretation [4].

The Large Hadron Collider forward (LHCf) experiment [5] was designed to reduce the uncertainty of the models by measuring the forward particle production at the LHC where the maximum collision energy $\sqrt{s}$=14 TeV corresponds to the laboratory energy of 10^{17} eV. In this paper, the results of LHCf and future plans are presented after a brief introduction of the experiment.

2. LHCf

2.1 Experimental Overview

The LHCf has installed two independent detectors called Arm1 and Arm2 at $\pm$140 m from the interaction point 1 (IP1) at the LHC. The detectors were installed inside the Target Neutral Absorbers (TANs) where the neutral particles produced around zero degrees at IP arrive while the charged particles are swept away by the dipole magnet between the TANs and the IP. Each of the LHCf detectors is composed of two small sampling shower calorimeters with position sensitive detectors, SciFi in Arm1 and silicon strip sensors in Arm2. The transverse sizes of the calorimeters in Arm1 are 20 mm$\times$20 mm and 40 mm$\times$40 mm while they are 25 mm$\times$25 mm and 32 mm$\times$32 mm in Arm2. The detail of the detector design and their performances are described in [6] [7] [8] [9] [10] [11] [12].

The data taking of the LHCf at the LHC have been performed in three periods. 1) Immediately after the first proton-proton collision at the LHC in 2009. Operation at $\sqrt{s}$ = 900 GeV with limited statistics. 2) Operations at $\sqrt{s}$ = 7 TeV proton-proton collisions from March to July 2010. The data corresponding to the delivered luminosity of 350 nb^{-1} were obtained. A few days of operation at $\sqrt{s}$ = 900 GeV but with larger statistics than 2009 was performed in the same period. 3) Operations at $\sqrt{s_{NN}}$ = 5 TeV proton-Lead collisions from January to February 2013 together with a short operation at $\sqrt{s}$ = 2.76 TeV proton-proton collisions. Only the Arm2 detector was used in this operation.

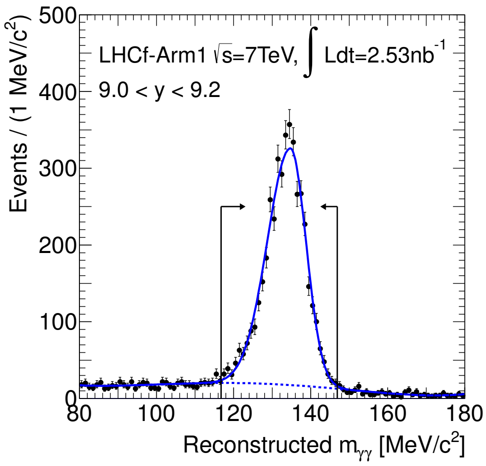

Figure 1: The invariant mass distribution in the 7 TeV data [16].

2.2 LHCf Results

Because of the excellent performance of the LHCf detectors for photons, the LHCf first analyzed the spectra of photons at 7 TeV and 900 GeV collisions [13] [14]. The energy spectra at p_T <1.0×x$_F$ GeV/c and p_T <0.14×x$_F$ GeV/c were extracted from the data at the two collision energies, respectively. Here p_T and x$_F$ designate the transverse momentum and the energy normalized by the beam energy, respectively. The experimental results were compared with the predictions from the various hadronic interaction models. In both collision energies, none of the models can explain the experimental results, but the data points distributed within the variation of the model predictions.

The spectra obtained from the two collision energies were compared in a same phase space and showed a good agreement [15]. This indicates a scaling of the spectral shape that is important to extrapolate our knowledge to the energy beyond the LHC. However, because the phase space available in this comparison was limited by the 900 GeV data and it is difficult to conclude about the general behavior of the forward particle production.

The LHCf has also published π^0 spectra from the 7 TeV data [16]. Thanks to the two calorimeter structure and the position sensors, invariant mass of the two photon events can be reconstructed by assuming the vertex were at the IP. In the distribution of the invariant mass, a peak at the rest mass of π^0 is identified as shown in Fig.1. From the candidate events of π^0 and the estimated background from the sideband events in the mass spectrum, the p$_T$ spectra at six rapidity ranges were obtained as shown in Fig.2. The results were compared with the predictions of models and the EPOS 1.99 model showed the best agreement with the experimental results.

2.3 LHCf Plan

2.3.1 Analysis

LHCf now proceeds the analysis of the forward neutron spectra. This is expected to provide an important hint for the problem of cosmic-ray muon excess [18] [19]. Because the LHCf detectors

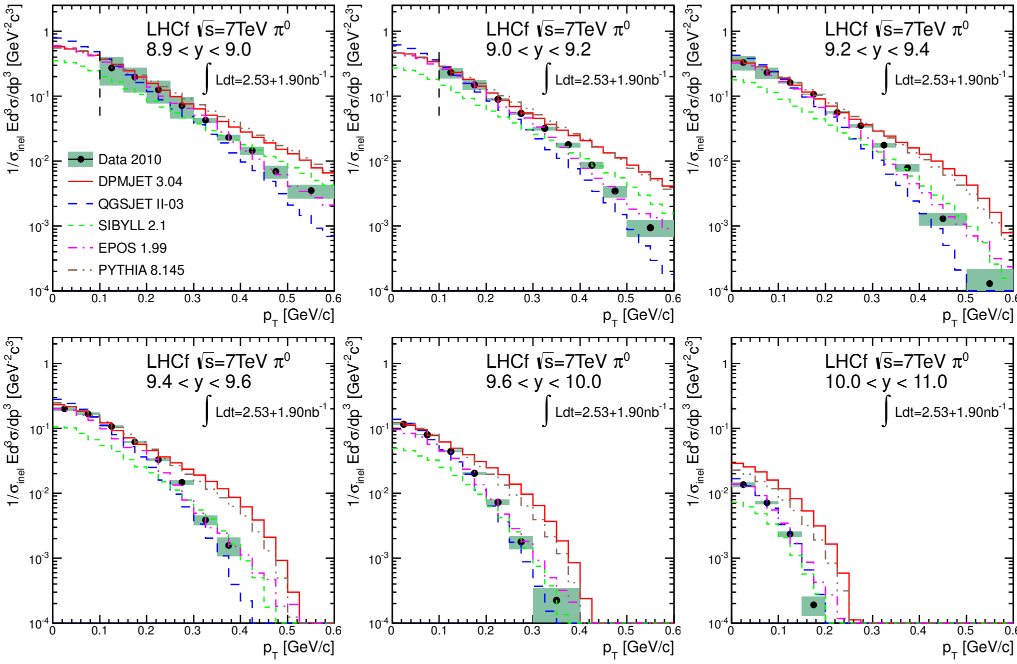

Figure 2: The π^0 spectra from the 7 TeV data compared with the various models [16].

were optimized to the measurement of electro-magnetic showers, the performance for the hadronic showers were carefully studied [12]. As a preliminary result of the 7 TeV data analysis LHCf found a higher yield of neutrons than any major models [17].

The interaction between cosmic-ray particles and earth's atmosphere is always between proton and nucleus or between nucleus and nucleus, where one of the nucleus is light component. Because so far any collider operations of ion collisions used heavy ions except d-Au collisions at RHIC, cosmic-ray models translate the results of p-p collision data into nuclear collisions. It is expected the measurements at the proton remnant side of p-Pb collisions at the LHC provide a new information of the nuclear effect in the forward particle production [20]. The analysis of the forward π^0 production in the LHC 5 TeV p-Pb collisions is ongoing and will be published soon. The comparison with the p-p collision data interpolated to 5 TeV from the results of 2.76 TeV and 7 TeV, *nuclear modification factor*, will be also derived.

2.3.2 Experiment

The prime target of the LHCf is an operation at the highest collision energy at the LHC, 14 TeV. LHCf is ready to take data at the early stage of the LHC Run2 starting from April 2015. Because the Run2 operation starts from 13 TeV collisions, this will be our maximum energy. At the high energy operation, the radiation dose becomes severe. This drove the LHCf to replace the plastic scintillators with radiation-hard Gd_2SiO_5 (GSO) scintillators [21] [22]. The special low luminosity operation for the LHCf in the early stage of Run2 is planned in the LHC operation. As discussed in Sec.2.2, the former results indicate a scaling of the spectral shape. The data from 13 TeV collisions enable us a comparison with the 7 TeV data in a wide phase space and a reliable extrapolation to the energy beyond the LHC.

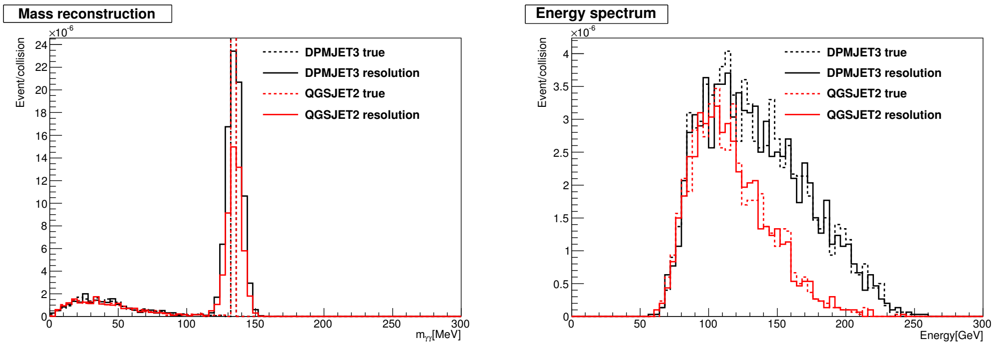

Figure 3: Simulated π^0 spectra at the RHIC 500 GeV p-p collision.

To test the scaling, experiments in a wide $\sqrt{s}$ coverage is important. However because of the geometrical constraint, the measurements at LHC at low energy is limited in the phase space. We found that the RHIC, where the detector installation slot is located at 18m from IP, enables us to cover a same phase space like the LHC 7 TeV data when operated at $\sqrt{s}$ = 500 GeV. Fig.3 shows results of simulation at RHIC 500 GeV proton-proton collision using one of the LHCf detectors. After a 8 hours of operation at a luminosity 1×10^{31} cm^{-2}s^{-1}, we can clearly test the two models studied here. The idea of the RHICf experiment is proposed [23] and discussion to realize the measurement is on going.

3. Summary

The LHCf published the key results from the data taken in the LHC 7 TeV and 900 GeV proton-proton collisions. Though so far there is no big surprise to change our knowledge about hadronic interaction, our data will constrain the future model improvement and reduce the uncertainty of interpretations. The LHCf is also continuing challenging analyses for hadronic events and nuclear effect. The results from these analyses will be published in early 2014. The prime target of the LHCf, operation at the highest energy, is also scheduled in 2015. Upgrade of the detectors for this operation is ongoing. To attack the energy beyond the LHC, providing uniform dataset from the different collision energies not only from the LHC, but also from the RHIC is our next target.

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