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The resent results from the LHCf experiment

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The LHCf experiment is an LHC experiment dedicated to measure the production spectra of forward neutral particles, photons, π^0s and neutrons. The obtained results are very useful to test hadronic interaction models which are used in MC simulations for cosmic-ray air shower developments. The LHCf had an operation in 2015 with *p*-*p* collisions at $\sqrt{s}$= 13 TeV, which corresponds to the collision energy of 0.9×10^{17}eV in the laboratory frame. We discuss the results of the inclusive energy spectra for forward photons obtained at *p*-*p*, $\sqrt{s}$= 13 TeV data as well as π^0 results taken at *p*-*p*, $\sqrt{s}$= 7 TeV. In addition we introduce future prospects of LHCf analyses and activities.

KEYWORDS: LHC, UHECRs, Hadronic interaction models

1. Introduction

A hadronic interaction model is one of the key tools for ground-based cosmic-ray experiments. High energy cosmic-rays arriving at the earth interact atmosphere and induce extensive air-showers. High energy cosmic-ray experiments observe air showers and reconstruct energies arrival directions and chemical compositions of primary cosmic-rays from the data measured by ground-based detectors such as a particle detector array and/or Cherenkov telescopes. Hadronic interaction models are used in Monte Carlo (MC) simulations for air shower developments. These models were tuned and tested with many results of collider experiments. However, inconsistencies between observed data and MC simulation were reported [1].

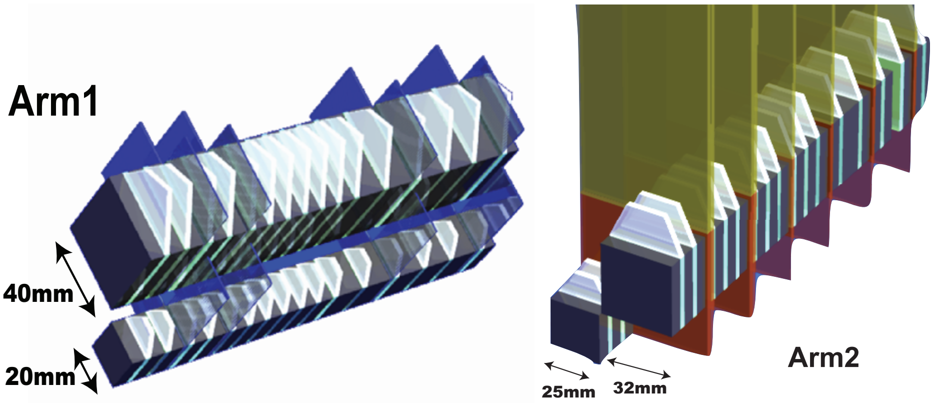

Fig. 1. Schematic views of the Arm1 (left) and Arm2 (right) detectors

Large Hadron Collider (LHC) started the operation at 2009. The collider provides unique opportunity to measure the hadronic collisions at the center-of-mass collision energy $\sqrt{s}$ =13 TeV, which corresponds to 0.9×10^{17} eV in the laboratory frame. The LHC forward (LHCf) experiment [2] is dedicated to measure the production of neutral particles in the very forward region of an LHC interaction point. Because most of energetic particles, which are important in air-shower development, produce in forward region, LHCf results will be critical data to test hadronic interaction models. The LHCf has obtained data with *p*-*p* collisions at several collision energies from 0.9 TeV to 13 TeV and with *p*-Pb collisions at $\sqrt{s_{NN}}$ =5 TeV. In this paper, we present LHCf's recent results and future prospects.

2. The experimental setup

The LHCf experiment has two independent detectors, so called Arm1 and Arm2. They were installed ±140 m from the ATLAS interaction point, IP1. At that point, the beam pipes makes a transition from a big-diameter pipe to two small-diameter pipes which connect to the LHC arc. The detectors were inserted into the 10 cm gap between the small-diameter pipes to view the zero degree of collisions. Because of the presence of dipole magnets located between IP1 and the detectors, the LHCf detectors were able to measure only neutral particles like photons and neutrons.

Each LHCf detector has two sampling and imaging calorimeter towers which are consisted of tungsten plates, 16 scintillator layers for shower sampling and four position sensitive layers for measurement of shower position [3]. The transverse sizes of the towers are 20 mm × 20 mm and 40 mm × 40 mm for Arm1 and 25 mm × 25 mm and 32 mm × 32 mm for Arm2. In nominal operations, the small-size calorimeters were located the zero degree of collisions. The pseudorapidity coverage of the detectors were $\eta > 8.4$.

Before the operation with *p*-*p* collisions at $\sqrt{s}$ =13 TeV in 2015, the detectors have been upgraded to improve their radiation hardness by replacing the plastic scintillators with Gd_2SiO_5 (GSO) scintillators [4] and the X-Y scintillating-fiber hodoscopes with X-Y GSO bar-bundle hodoscopes [5]. The silicon detectors inserted into the Arm2 detector has been upgraded also to improve the dynamic range and the performance of energy reconstruction by using the energy deposit on the silicon detectors.

Common operations with the ATLAS experiment, whose detector covers the central region of IP1, have been performed since the operation in 2013. LHCf final trigger signals were sent to the ATLAS DAQ system and their signals triggered the ATLAS DAQ after prescaled down to available DAQ rate in the ATLAS DAQ system for LHCf triggers.

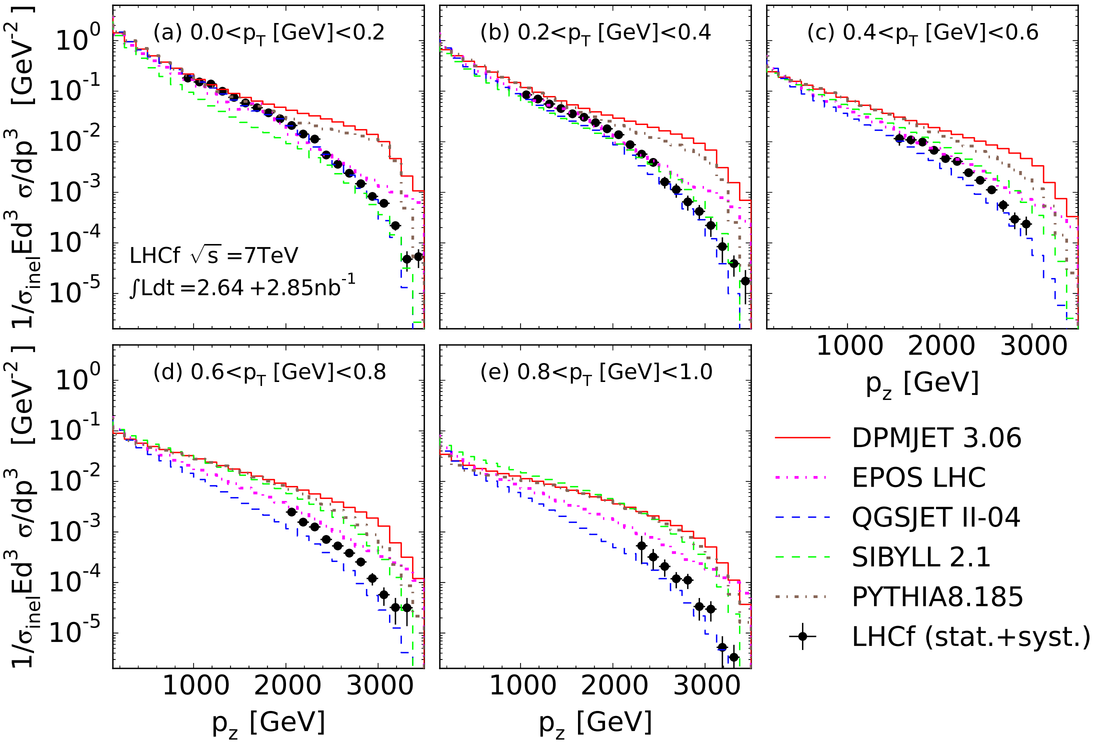

Fig. 2. Measured inclusive longitudinal momentum spectra of π^0s at p-p, $\sqrt{s}$ = 7 TeV. Each panel shows the result for each transverse momentum bin with 0.2 GeV step. The black points and the colored lines indicate the data and the MC predictions.

3. Recent results

3.1 *Forward π^0 measurements in LHC-Run1*

During LHC-Run1, LHCf had several operations with p-p collisions at $\sqrt{s}$= 0.9 TeV, 2.76 TeV and 7 TeV and with p-Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV. LHCf results of measurements of forward π^0 production cross section in LHC-Run1 were found in Ref. [6], except p-p at $\sqrt{s}$= 0.9 TeV because of zero acceptance for the detection. In the previous π^0 result paper for p-p at $\sqrt{s}$= 7 TeV [7], we analyzed the π^0 events, so called Type-I π^0 events, in which photon pairs were detected by the two calorimeter towers. After the publication of the papar, we developed a new method to reconstruct energies and p_T of π^0s in the events where photon pairs from π^0 decays hit one calorimeter tower. These events were called Type-II π^0 events. The energy threshold of these Type-II π^0 events is about 2 TeV, higher than the Type-I π^0 threshold 600 GeV, however, the acceptance for high energy or high transverse momentum π^0 events is much higher than Type-I π^0.

Figure 2 shows the measured inclusive longitudinal momentum spectra of π^0s at p-p, $\sqrt{s}$ = 7 TeV. Combining the results of the Type-I and Type-II events, we had high statistics data from low energy to more than 3 TeV/c. The colored lines indicate MC predictions. QGSJET II-04 [8] shows a best agreement with the data in the tested models. EPOS-LHC [9] well reproduces the data spectra below 2.5 TeV although it predicts higher flux than the data above 2.5 TeV.

3.2 *Forward photon energy spectrum at p+p $\sqrt{s}$ = 13 TeV*

The operation for p-p collisions at $\sqrt{s}$ =13 TeV has been performed in June 2015. A part of the data, taken on June 12 -13, was analyzed to measure the inclusive forward photon energy spectra. The

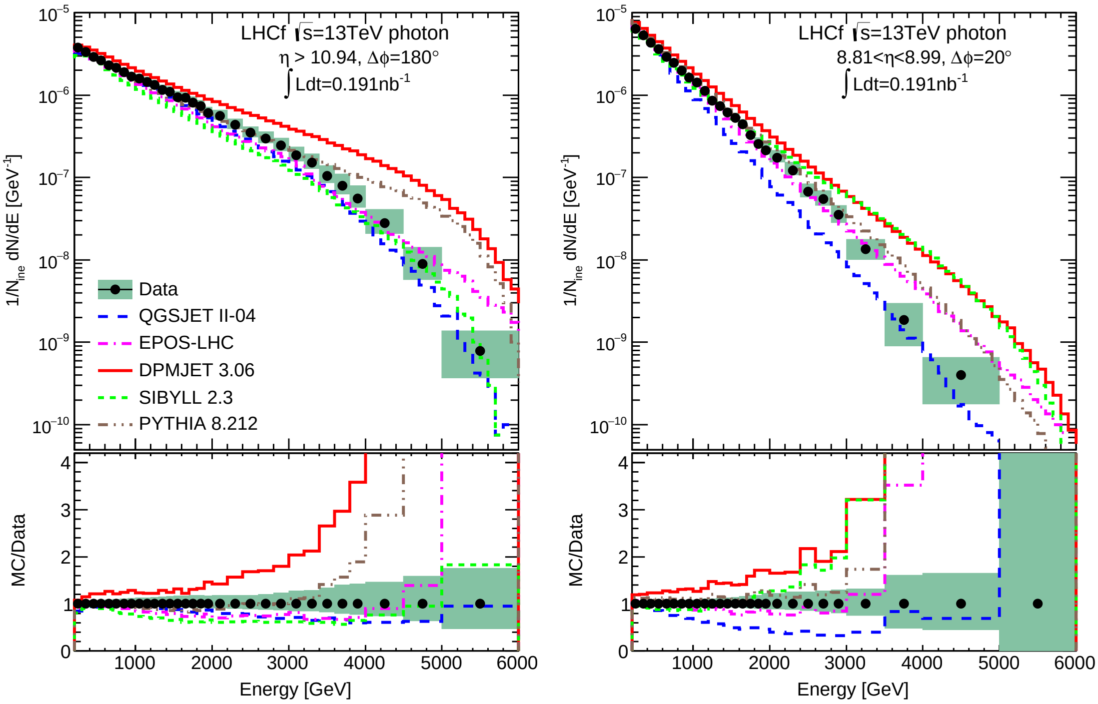

Fig. 3. Comparison of the inclusive photon spectra measured by LHCf at p-p, $\sqrt{s} = 13$ TeV with MC predictions [10]. The black dots and the colored lines show the data and MC predictions. The hatched areas indicate the total uncertainties of data including the statistical and the systematic uncertainties. The top panels show the energy spectra, and the bottom panels show the ratio of MC predictions to the data.

details of the analysis and the result are found in Ref. [10]. About 4% of the total events were multi-hit events, in which more equal than two particles hit a calorimeter. These multi-hit events were cut in this analysis. We performed a correction with the MC derived factors to recover the flux of photons rejected in the multi-hit event cut. After applying all corrections including the spectrum unfolding for the correction of the energy resolution, our results were able to be compared with MC predictions directly.

Figure 3 shows the measured inclusive photon energy spectra for the pseudo-rapidity regions $\eta > 10.94$ and $8.81 < \eta < 8.99$. The results were taken from the combination of the Arm1 and Arm2 results. The black dots show the experimental results and the colored lines show the predictions of several hadronic interaction models. As a general conclusion, we found no model can reproduce our data perfectly. In the pseudorapidity region $\eta > 10.94$ which covers the zero degree of collisions, the QGSJET II-04 and EPOS-LHC models show the best agreement overall with the data. PYTHIA 8.212 shows good agreement with the data from the lowest energy bin to near the 3 TeV bin although it clearly predicts higher flux than the data in the energy region greater than 3 TeV. In the pseudorapidity region $8.81 < \eta < 8.99$ which corresponds to a off-center region, the EPOS-LHC and PYTHIA 8.212 models show good agreement with the data except at the high-energy end above 3 TeV. QGSJET II-04 shows lower flux than the data. The trends of SIBYLL 2.3 from the data are different between the two rapidity regions. It is due to the SIBYLL's larger mean value of transverse momentum than both the data and the other models.

4. Future prospects

4.1 Joint analysis with the ATLAS experiment

A joint analysis with the ATLAS experiment was started. We exchanged the reconstructed event-by-event data between LHCf and ATLAS. Combining the LHCf data with information in the central region provided by ATLAS, we can study detailed hadronic processes of forward particle production. It is important to understand better about soft-QCD processes and to improve interaction models. The first target of this joint-analysis is to measure the contribution of diffractive processes on the forward particle production. The diffractive process is one of main processes for forward particle production and it has uncertainties, especially the cross section of low diffractive-mass (M_X) events, due to experimental difficulties of measurement. A simulation study shows that an artificial increase of the low diffractive-mass cross section in QGSJET II to fit the TOTEM result induces 10 g/cm change of X_{MAX} in the air shower simulation [11]. The LHCf experiment is able to access very low mass diffraction of $M_X < 20$ GeV. By selecting the events in which the ATLAS central tracker detected no particle, forward neutral particles from diffractive processes are able to be measured by the LHCf experiment with very high purity of more than 99% and reasonable survival efficiency of about 50%. A detailed simulation study is found in Ref. [12].

4.2 Operation in 2016; p+Pb collisions at $\sqrt{s_{NN}} = 8$ TeV

The LHCf experiment joined an LHC operation with *p*-Pb collisions in 2016. LHC provided *p*-Pb collisions with the collision energies per nucleon $\sqrt{s_{NN}} = 5$ TeV and 8 TeV. The physics motivation of the operation is to measure the nuclear modification factors of forward particle production at the LHC-maximum collision energy. Thanks to factor 1.6 higher collision energy than 5 TeV, the LHCf detector covered a wider range of transverse momentum than the past 5 TeV operation. The operation with $\sqrt{s_{NN}} = 5$ TeV was performed also to confirm the results of the past operation [6] with the upgraded detector. It helps also to reduce systematic uncertainties related to the detector performance in analyses of comparison of 8 TeV results with 5 TeV results to test energy dependencies of forward particle production.

The Arm2 detector was installed to the LHC tunnel again in the beginning of November 2016. The detector was located on the *p*-remnant side of collisions. The operation has been successfully completed. We recoded 25.3 M events and 16.7 M events with 5 TeV and 8 TeV collisions, respectively.

4.3 The RHICf experimet; p-p collisions at $\sqrt{s} = 510$ GeV

The RHIC forward (RHICf) experiment measures the forward particle production at the Relativistic Heavy Ion Collider (RHIC) located in Brookhaven National Laboratory (BNL), USA [13]. The maximum center-of-mass energy of *p-p* collisions at RHIC is 510 GeV, which is equivalent to 10^{14} eV in the laboratory frame. Comparing with the results of the LHCf experiment, we can test the dependency of forward particle production on the collision energy and test hadronic interaction models with the data in the wide energy range from 10^{14} eV to 10^{17} eV. It is important to extrapolate the LHCf-measured results from the LHC collision energy to the energy of UHECRs.

The RHICf operation is scheduled for June 2017 and the preparation is on-going. One of the LHCf detectors, Arm1, was delivered to BNL to be used for the RHICf experiment. The detector is installed 18 m far from a RHIC interaction point where the STAR detector was installed. The operation is performed for one week with low-luminosity beams. During the operation, the RHICf DAQ trigger signals are sent to the STAR DAQ system and their signals trigger the STAR DAQ. The common operation increases the physics potential of the RHICf experiment, for examples, diffractive study with the STAR central tracker and improvement of energy resolution for neutrons by combine-analysis with the STAR zero degree calorimeter.

5. Summary

The LHCf experiment had several operations with *p*-*p* and *p*-Pb collisions and tested hadronic interaction models used in MC simulation for cosmic-ray air showers. Post LHC models, QGSJET II-04 and EPOS-LHC show better agreement with the LHCf results for π^0s and photons than the other models. However, these model could not reproduce our data perfectly. Currently we are proceeding neutron analysis with a 13 TeV *p*-*p* data set. Results from LHCf-ATLAS joint analyses and a measurement at RHIC will be provided near future. They are important to understand a contribution of diffractive process and the energy scaling of forward particle production. LHCf keeps to provide critical data to test hadronic interaction models.

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