PROCEEDINGS OF SCIENCE

LHCf and RHICf, collider experiments to reveal the nature of high-energy cosmic rays

Takashi Sako[*]
KMI/ISEE Nagoya University
E-mail: sako@isee.nagoya-u.ac.jp

for the LHCf and RHICf Collaborations

To understand the forward particle production in hadronic collisions, the Large Hadron Collider forward (LHCf) experiment has performed measurements at the LHC under various collision condition. The data of particle production at the highest accelerator energy are expected to improve the interpretation of the cosmic-ray air shower observation data, and hence to improve the knowledge of the cosmic-ray origin. Brief overview of the LHCf results obtained from the proton-proton collisions at $\sqrt{s}$=0.9, 2.76, 7 and 13 TeV and results from the proton-lead collisions at $\sqrt{s}$=5.02 TeV are presented. To explore the lower collision energy, $\sqrt{s}$=510 GeV, preparation of a new experiment the Relativistic Heavy Ion Collider forward (RHICf) is on going. Physics motivations and status of the RHICf are also presented.

The 3rd International Symposium on " Quest for the Origin of Particles and the Universe"
5-7 January 2017
Nagoya University, Japan

[*]Speaker.

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

1. Introduction

The origin of cosmic rays with energy extending up to 10^{20} eV is a long-standing problem in the astrophysics. To solve the problem, observations of cosmic-ray energy and particle type, or chemical composition, are important. Because of the very low flux of the high-energy cosmic rays, observations are performed using the atmospheric air shower technic that measures secondary particles produced in the atmosphere. In the analyses of observed data, comparison with Monte Carlo simulations of air showers is unavoidable, and the results are sensitive to the choice of hadronic interaction model used in the simulation [1].

Since the beginning of the operation in 2009, the Large Hadron Collider has been extensively used to test and tune the hadronic interaction models used for the cosmic-ray physics [2]. The maximum so far achieved collision energy of 13 TeV corresponds to the equivalent cosmic-ray energy hitting the atmosphere of 0.9×10^{17} eV. This is the first time that the accelerator energy exceeds the energy of the *knee* found in the cosmic-ray energy spectrum at 4×10^{15} eV.

Thanks to the mainly LHC Run1 data, some interaction models are updated, and the dispersion found in the predictions of air shower observables decreased. However there is still significant difference between the model predictions, and even some analyses conclude non-realistic interpretations [3]. More tunings of the models especially using the forward particle production are necessary. Because the forward particles carry a large fraction of collision energy, they are responsible to determine the shape of air showers [4].

In this paper, the results and the status of the LHC forward (LHCf) experiment dedicated to measure very forward particles at LHC are reviewed. As an extension of the LHCf, preparation of a new experiment RHICf forward (RHICf) at the Relativistic Heavy Ion Collider is ongoing. The physics targets, the status and the plan of the RHICf are also presented.

2. Results of the LHCf experiment

2.1 LHCf overview

The LHCf experiment installed two compact detectors either side of the interaction point (IP) 1 at LHC sharing the collisions with the ATLAS [5]. Each detector consists of two sampling calorimeters with the transverse sizes ranging from 20 mm×20 mm to 40 mm×40 mm. Because the location of the detectors are behind the dipole magnets when looking from the IP, only neutral particles such as photons and neutrons enter the detectors. By detecting photon pairs simultaneously by the two calorimeters, processes like $\pi^0 \to 2\gamma$ and $\eta \to 2\gamma$ are also identified by reconstructing the invariant mass of the photon pairs. The LHCf has collected the data during the proton-proton collision periods at $\sqrt{s}$=0.9 TeV (2009 and 2010), 2.76 TeV (2013), 7 TeV (2010) and 13 TeV (2015) as well as the proton-lead collision periods at $\sqrt{s_{NN}}$ = 5.02 TeV (2013 and 2016) and 8.16 TeV (2016).

Photon spectra at pseudorapidity η larger than 8.8 were published for the proton-proton collision data taken at $\sqrt{s}$= 0.9 TeV [6], 7 TeV [7] and 13 TeV [8]. The results were compared with the predictions by several hadronic interaction models, and it was found none of the models can perfectly match with the experimental results. On the other hand, experimental results are within the variation of the various model predictions.

PoS(KMI2017)031

Production cross sections of π^0 were published for the proton-proton collisions at $\sqrt{s}$=7 TeV [9] and proton-lead collisions at $\sqrt{s_{NN}}$=5.02 TeV. Summary of π^0 cross sections with full acceptance analyses including 2.76 TeV proton-proton collisions is published in [11]. The double differential cross sections of π^0 production at 7 TeV reported in [11] are visualized in Fig.1 both for the LHCf result and the model predictions. The ratio of the model predictions to the LHCf result is plotted in Fig.2. In Fig.2 difference between models to the experimental result is clearly identified. For EPOS-LHC [12], in the middle p_z range, the ratio is around unity but it increases at high p_z. In case of QGSJET II-04 [13], the ratio is flat, meaning the spectral shape has a good agreement with data, but it is less than unity, meaning the totally less π^0 production. Sibyll 2.1 [14] shows similar tendency to EPOS-LHC, but overestimates at high p_T rather than high p_z. Same trend in the different models is found in the photon spectra.

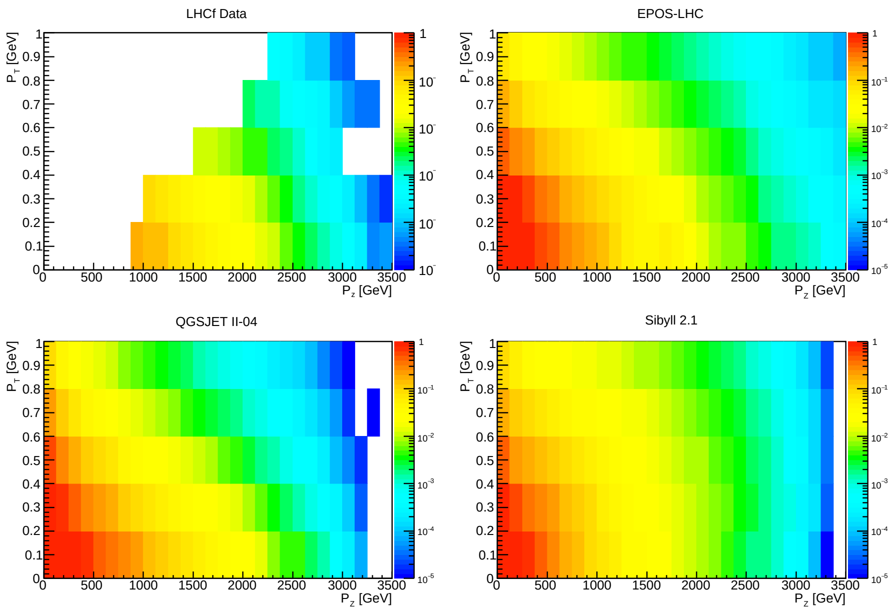

Figure 1: π^0 production cross sections at 7 TeV proton-proton collisions as a function of the longitudinal momentum p_z and the transverse momentum p_T. The results of the LHCf (left-top), the predictions of the EPOS-LHC model (right-top), the QGSJET II-04 model (left-bottom) and the SIBYLL 2.1 model (right bottom) are presented. Color scale indicates the normalized invariant cross section $\frac{1}{\sigma_{ine}} E \frac{d^3\sigma}{dp^3}$ [GeV^{-2}].

Production cross sections of neutrons were also published using the 7 TeV proton-proton collision data [15]. The result covering 0 degree production angle showed a characteristic peak at 2,500 GeV, and such high-energy excess was qualitatively explained by the QGSJET II-03 model. All the other models studied here under-predict the LHCf result. At the off-0 degree, $8.81 < \eta < 9.22$, all comtemporary cosmic-ray models EPOS, QGSJET and SIBYLL under-predict the LHCf results while the relatively old DPMJET model [16] well explained the LHCf results. The LHCf results showed that the ratio of energies carried by the neutrons to the photons is largest in the experimental data than any model predictions.

Production cross section of π^0 in the $\sqrt{s_{NN}}$=5.02 TeV proton-lead collisions was published in [11]. The measurement was carried out when the LHCf detector was located at the downstream of

PoS(KMI2017)031

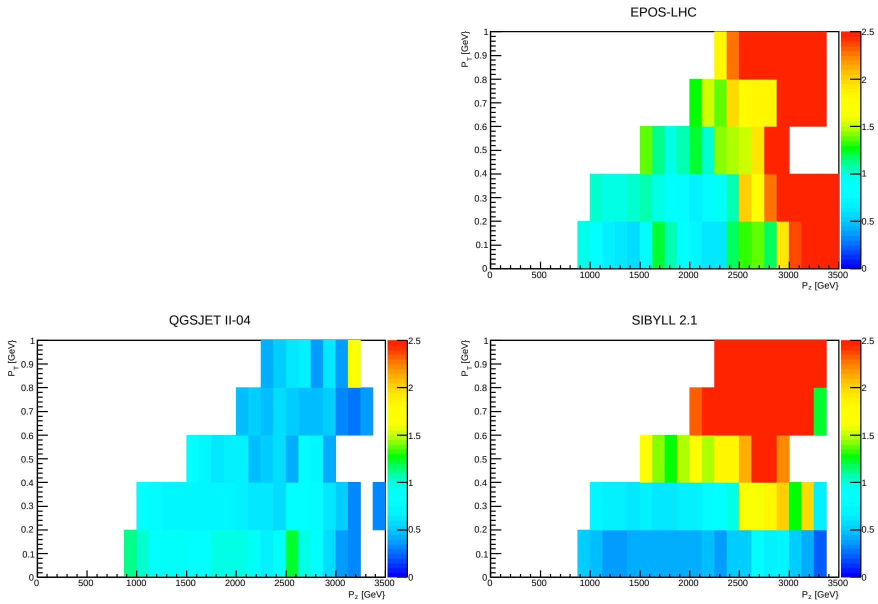

Figure 2: Ratio of the model predictions to the LHCf result for π^0 production cross section at 7 TeV proton-proton collisions. See also caption of Fig.1.

the proton beam. About half of π^0 production was explained by ultra-peripheral collisions (UPC) where projectile protons interact with strong electromagnetic field around the lead nuclei. After subtracting this electromagnetic production according to the calculation, hadronic production of π^0 was extracted. Then the cross section of the hadronic π^0 production was compared with that in the proton-proton collisions at $\sqrt{s}$=5.02 TeV deduced by interpolating the results at 2.76 TeV and 7 TeV. The result was expressed by so-called nuclear modification factor, and it was consistent with the model predictions while the uncertainty was large.

2.2 Verification of $\sqrt{s}$ dependence

Collision energy dependence of production cross sections is of great interest for the cosmic-ray physics. The π^0 cross sections at $\sqrt{s}$=2.76 TeV and 7 TeV proton-proton collisions were compared after normalizing the longitudinal momentum to the Feynman x, $x_F = 2p_z/\sqrt{s}$, and selecting the data in the same p_T ranges [11]. It is found that within $p_T < 0.4$ GeV and $x_F > 0.4$ the invariant cross sections agreed within the $\pm 20\%$ level. Test of scaling will be extended using the data taken in the13 TeV proton-proton collisions and the RHICf experiment at 510 GeV as explained in Sec.3.

Another scaling was studied using the neutron production. Before LHCf, a scaling of very forward neutron production from 30 GeV to 200 GeV proton-proton collisions was reported using the data from the ISR and the PHENIX experiment [17]. The result from the LHCf was compared with these data, and it was suggested that the LHCf result has a peak at lower energy than the previous experiments [18]. Though it was not conclusive due to a large systematic uncertainty, further test is expected using the 13 TeV data. In case the scaling break is observed, the data at 510 GeV by the RHICf will provide a hint of the turning energy.

PoS(KMI2017)031

2.3 Joint analyses with ATLAS

The LHCf has so far tested the hadronic interaction models in the almost unexplored forward phase space. In this region, the processes responsible to the particle production are shared roughly half and half by the diffractive dissociation and the non-diffractive process. Because very different theoretical approaches are required to describe these processes, classification of the LHCf events into two categories is useful to improve the hadronic interaction models. Based on the fact that the diffractive process, especially in the low mass diffraction, is associated with large rapidity gap in the central rapidity, the usage of the ATLAS information is a powerful tool of classification. A Monte Carlo study for the potential of the ATLAS-LHCf joint analysis was reported by [19] and real analysis started using the common operation data taken in 2015.

A technical feasibility of the joint analysis was already reported using the data in 5.02 TeV proton-lead collisions [20]. In this analysis, event identification using the ATLAS L1T event number and the bunch ID were confirmed. Using the number of charged particles in the ATLAS tracker, neutrons produced through UPC and hadronic process are clearly separated.

3. The RHICf experiment

3.1 Basic ideas of RHICf

As discussed in Sec.2.2, an indication of a scaling in the π^0 production and an indication of a scaling break in the neutron production are reported. As well as the highest collision energy $\sqrt{s}$=13 TeV at the LHC, data from the intermediate energy 510 GeV realized by RHIC is interesting to test these scaling and scaling break. The RHICf experiment is in preparation using one of the LHCf detectors at the interaction point of the STAR experiment. The detector will be installed 18 m west from the IP and the neutral particles emitted at $\eta > 6$ can be observed. Using this configuration, particles with $p_T < 1.2x_F$ GeV can be detected, that is equivalent to the coverage of the LHCf $\sqrt{s}$=7 TeV operation.

3.2 Expected results in the cross section measurements

Numbers of photons, neutrons and π^0 expected in an 12 hours operation are shown in Fig.3. In this calculation, the EPOS-LHC model [12] was used as an event generator. To increase the detection rate of π^0, 18 kHz event rate of single photons and neutrons was assumed at the detector level, but only 5% of them are recorded limited by the readout speed. Instead, all the photon pair events that are candidates of $\pi^0 \rightarrow \gamma\gamma$ are recorded at about 100 Hz without prescaling. It was assumed that the data were taken at three different detector positions. Characteristic shape found especially in the neutron spectra is due to the combination of the different positions and the shape of the calorimeters. Except at the high energy end of the photon spectra, more than 10^4 events are expected for photons and neutrons, that reduces the statistical uncertainty at less than 1% that will be sufficiently smaller than possible systematic uncertainty. About π^0 1% to 10% statistical uncertainties are expected in a wide energy and p_T range. By introducing a special trigger of high-energy photons, number of events in high-energy region will be increased.

PoS(KMI2017)031

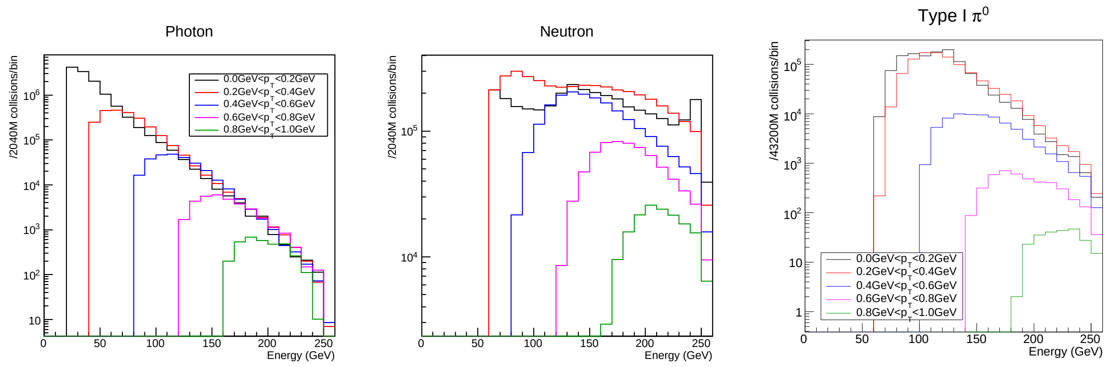

Figure 3: Numbers of photons, neutrons and π^0 expected in an 12 hours operation of the RHICf experiment.

3.3 Expected results in the spin asymmetry measurements

The RHIC can collide protons as spin-polarized beams. From the transversely polarized proton collisions, the RHIC IP12 experiment discovered an asymmetrical production of neutrons at very forward region [21] that is now used as the principle of polarization measurement. The PHENIX reported the amplitude of the asymmetry at p_T <0.4 GeV is proportional to p_T [22] and it was theoretically explained as a consequence of interference between π and a_1 meson exchange [23]. However, because the PHENIX result was obtained by collecting the results at different $\sqrt{s}$, it is not clear if the scaling appears in p_T or in $\sqrt{s}$. Measurements of single-spin asymmetry in wide p_T range at a single $\sqrt{s}$ is desired.

The limited p_T coverage by the PHENIX was due to the limited position resolution of the detector. Using the RHICf detector, that has 10 times better position resolution, asymmetry measurement with a wide p_T coverage can be realized. Also by moving the detector vertically, asymmetry up to 1.2 GeV will be measured. According to the same operation condition discussed in Sec.3.2, amplitude of asymmetry can be determined with better than 1% statistical errors from the p_T bin 0.0–0.1 GeV to 0.8–1.2 GeV. Because the asymmetry amplitude reported by the PHENIX amounts to 13% at p_T=0.3 GeV, it is sufficient resolution.

3.4 Status and plan

A week of dedicated machine time is approved for the RHICf experiment from the end of May to early June in 2017. To make the beams colliding as parallel as possible, a higher β^*=10 m than the usual RHIC operation are requested. Also to maximize the sensitivity to the transverse spin asymmetry, the beams will be polarized in the radial direction while it is usually in the vertical. To setup these dedicated beam condition, two days are expected. To collect sufficient number of events, another two days are expected. Including the contingency, all the operation will be completed in one week.

Test of installation and data taking without beam were performed until the end of 2016. The RHICf detector fit with the space between two beam pipes using a newly constructed structure as shown in Fig.4 that allows the detector to move vertically. Test for data taking was continued after the first collision in 2017 at RHIC. Immediately after the collision was established on 20 Feb., the

PoS(KMI2017)031

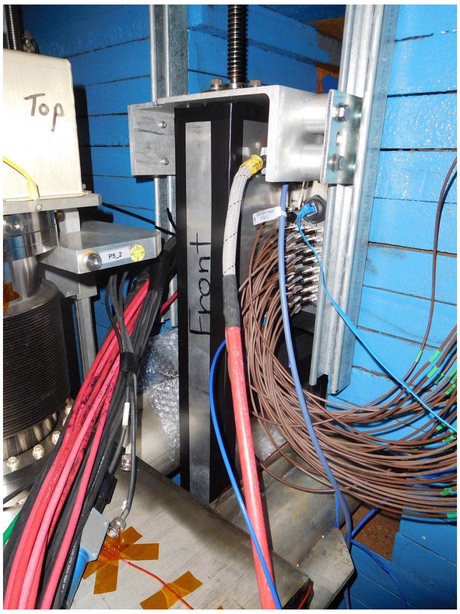

Figure 4: The RHICf detector installed between two beam pipes 18 m west from the STAR IP.

RHICf detector successfully detected shower events. In the next few days, common data taking with the STAR detectors was also commissioned. Once the RHICf identifies a shower event, the trigger signal is sent to the STAR and the STAR records the signal as if the RHICf is a subdetector. The event number (token) is sent back to the RHICf and RHICf sends its data to the STAR with the token number. Finally the STAR records the data with same token number all together. This common operation system was tested using the first collision and was successful. It is expected that a similar analysis like the ATLAS-LHCf case will be easily performed. Adding the deposited energy in the RHICf and the STAR ZDC, neutron measurements with high p_T and high energy resolutions are also expected.

4. Summary

The LHCf experiment has successful operations at various collision conditions at LHC. They provided the highest energy data at the unexplored forward region to constrain the particle production relevant to the cosmic-ray physics. Their so far published photon, neutron and π^0 results are compared with the interaction models and the models are being tuned. The comparisons between the data at different collision energies reveal the scaling or scaling break of the partile spectra. The LHCf indicates the scaling of π^0 at $\sqrt{s}$=2.76 and 7 TeV, while the ISR, PHENIX and LHCf indicate a scaling break of neutron spectra between 200 GeV and 7 TeV.

A new experiment RHICf is being prepared to test the scaling (and break) at $\sqrt{s}$=510 GeV at RHIC. The experiment uses one of the LHCf detector, and the data taking is scheduled in early June 2017. The RHICf can also measure the single-spin asymmetry of the very forward particle using the transversely polarized proton beam. Thanks to the excellent position resolution of the RHICf detector, the measurement will reveal the mechanism of the asymmetrical particle production.

PoS(KMI2017)031

References

[1] K.-H. Kampert and M. Unger, Astropart. Phys., 35 (2012) 660.

[2] D. d'Enterria et al., Astropart. Phys., 35 (2011) 98.

[3] Pierre Auger Collaboration, Phys. Rev. D 90, 122005 (2014).

[4] K. Akiba et al., J. Phys. G: Nucl. Part. Phys. 43 (2016) 110201.

[5] The LHCf Collaboration, JINST, 3, S08006 (2008).

[6] The LHCf Collaboration, Phys. Lett. B 715 (2012) 298.

[7] The LHCf Collaboration, Phys. Lett. B 703 (2011) 128.

[8] The LHCf Collaboration, arXiv:1703.07678.

[9] The LHCf Collaboration, Phys. Rev. D 86, 092001 (2012).

[10] The LHCf Collaboration, Phys. Rev. C 89, 065209 (2014).

[11] The LHCf Collaboration, Phys. Rev. D 94, 032007 (2016).

[12] K. Werner, F.-M. Liu, and T. Pierog, Phys. Rev. C 74, 044902 (2006).

[13] S. Ostapchenko, Nucl. Phys. B, Proc. Suppl. 151, 143 (2006).

[14] E.-J. Ahn, R. Engel, T. K. Gaisser, P. Lipari, and T. Stanev, Phys. Rev. D 80, 094003 (2009).

[15] The LHCf Collaboration, Phys. Lett. B 750 (2015) 360.

[16] F.W. Bopp, J. Ranft, R. Engel, S. Roesler, Phys. Rev. C 77 (2008) 014904.

[17] A. Adare, et al., Phys. Rev. D 88 (2013) 032006.

[18] K. Kawade, PhD thesis, Nagoya University (2015).; CERN-THESIS-2014-315.

[19] Q. D. Zhou, Y. Itow, H. Menjo, and T. Sako, Eur. Phys. J. C (2017) 77:212.

[20] The ATLAS and the LHCf Collaborations, ATL-PHYS-PUB-2015-038.

[21] Y. Fukao et al., Phys. Lett. B 650 (2007) 325.

[22] The PHENIX Collaboration, Journal of Physics: Conference Series 295 (2011) 012097.

[23] B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt, Phys. Rev. D 84, 114012 (2011).

PoS(KMI2017)031