PROCEEDINGS OF SCIENCE

# Measurement of very forward particle production at RHIC with $\sqrt{s}$=510 GeV proton-proton collisions

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The Relativistic Heavy Ion Collider forward (RHICf) experiment has measured neutral particles produced in the very forward direction in the $\sqrt{s}$=510 GeV proton-proton collisions at RHIC in June 2017. The production cross sections of these particles are crucial to understand the hadronic interaction relevant to the air shower development at the cosmic-ray equivalent energy of $1.4\times10^{14}$ eV, just below the energy of the knee. Together with the data at LHC, accelerator data can cover the interaction in the cosmic-ray energy of $10^{14}$ eV to $10^{17}$ eV. In addition, RHICf is able to improve the former measurements of single-spin asymmetry in the polarized proton-proton collisions that is sensitive to the fundamental process of the meson exchange. Common data taking with the STAR experiment will shed light on the unexplored low mass diffraction process.

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## 1. Introduction

Interpretations of air shower measurements rely on the Monte Carlo simulation [1]. Hadronic interaction, especially the forward particle production [2], is a key to determine the structure of air showers. Though it is extensively studied using the LHC data with corresponding cosmic-ray energy of $10^{16}$ to $10^{17}$ eV [3], study at lower energy is sperse. To extrapolate the knowledge at the LHC energy to higher energy, or even to interpolate to lower energy, lower energy data is critical. The LHCf experiment reported a scaling of forward $\pi^0$ production cross sections at $\sqrt{s}$=2.76 TeV and 7 TeV [4]. Similar scaling was also reported in the forward neutron production cross sections between ISR and PHENIX [5] from $\sqrt{s}$=30 GeV to 200 GeV, while LHCf indicates a break of such scaling at 7 TeV and 13 TeV[6] [7].

The Relativistic Heavy Ion Collider (RHIC), colliding the proton beams at $\sqrt{s}$=510 GeV, provides the best opportunity to study the hadronic interaction corresponding to the cosmic-ray energy of $1.4\times10^{14}$ eV. This paper describes the experimental idea of the RHIC forward (RHICf) experiment that used one of the former LHCf detectors [8]. RHICf successfully completed its data taking at RHIC by 27 June, 2017. Very first obtained data are presented here.

A strong advantage to use RHIC is that protons can be collided as polarized beams. Asymmetrical production of forward neutrons with respect to the polarization direction was discovered by an experiment at RHIC [9]. The PHENIX measurements suggest that the amplitude of the asymmetry is proportional to the transverse momentum $p_T$ [10]. This behavior is theoriticaly well explained by an interference between pion exchange and $a_1$ meson exchange [11]. Using this kind of study, forward particle productions will be understood from more fundamental processes. RHICf is able to improve the former measurements at RHIC.

## 2. The RHICf experiment

Detailed introduction to the RHICf experiment and its operation plan at RHIC were summarized in [12]. Finally realized setup are described here.

### 2.1 Setup

The RHICf detector shown in Fig.1 is the former LHCf Arm1 detector [8]. It is composed of two compact electro-magnetic calorimeters with dimensions 20 mm$\times$20 mm and 40 mm$\times$40 mm transverse to the incoming particles. Each calorimeter is composed of 44 radiation lengths of tungsten and 16 sampling scintillators read by PMT. Array of thin scintillator bars read by a MAPMT consists a position sensitive layer and 4 X-Y pairs of such array is inserted in each calorimeter [13]. Detail of the detector [8] and its performance measured at the CERN SPS fixed target experiment facility [14] [15] and during the LHC operation in 2009-2010 [16] are found elsewhere. Because the RHIC beam energy, 255 GeV, coincides with the beam energy at SPS, calibration at SPS is directly applicable for the RHICf operation.

The RHICf detector was installed in front of the Zero Degree Calorimeter (ZDC) at 18 m west of the STAR interaction point as shown in Fig.2. A photo taken on 22 June, 2017, the day of installation, is shown in Fig.3. Because this installation slot is located behind the beam separation DX dipole magnet when seen from the interaction point, charged particles produced in the collisions

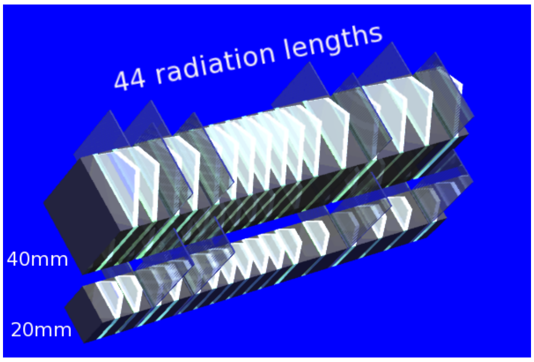


**Figure 1:** Schematic view of the RHICf detector composed of two compact sampling calorimeters.

are swept away and only neutral particles produced around zero degree arrive at the detector. The detector is fixed on the vertically movable structure. By moving the detector vertically, measurable phase space, or angle, can be maximized. Limited by the beam pipe between the interaction point and the detector, the maximum observable angle is 5 mrad, corresponding to the pseudorapidity $\eta$ of 6.

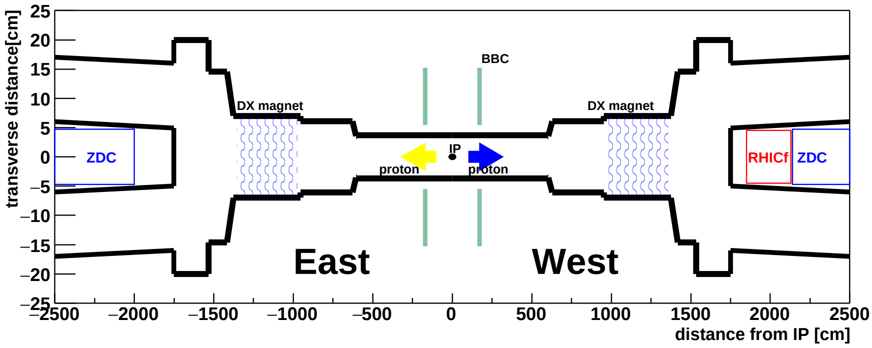


**Figure 2:** Location of the RHICf detector in the vicinity of the STAR experiment.

Once a neutral particle, essentially photon or neutron, enters one of the RHICf calorimeters, it develops a cascade shower in the tungsten. When more than 45 MeV, roughly equivalent to 45 MIPs, of energy deposition is observed in a scintillator layer, a hit signal is generated. When successively 3 or more layers generate hit signals, a trigger signal is issued to record the event. Using this trigger condition, as shown in Fig.4, trigger efficiency reaches above 98% for photon with energy more than 50 GeV. For neutrons, trigger efficiency reaches at 60% at 100 GeV and weakly increases above that energy. This is because the thickness of the calorimeter corresponds to 1.6 hadronic interaction lengths.

When each calorimeter records a single photon simultaneously, invariant mass of this photon pair, $M_{\gamma\gamma}$, is calculated assuming they are produced at the interaction point. If the photon pair is produced by decay of a single $\pi^0$, $M_{\gamma\gamma}$ becomes 135 MeV. Because the event rate of $\pi^0$ is expected at 1% of the event rate of single shower events, special trigger to enrich the double-photon showers was implemented. As the photons are known to have a steep energy spectrum, another special

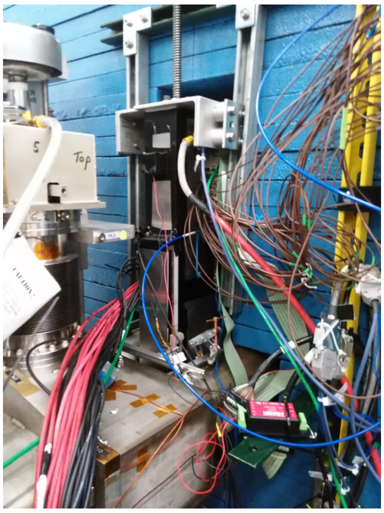

**Figure 3:** The RHICf detector installed in the RHIC tunnel.

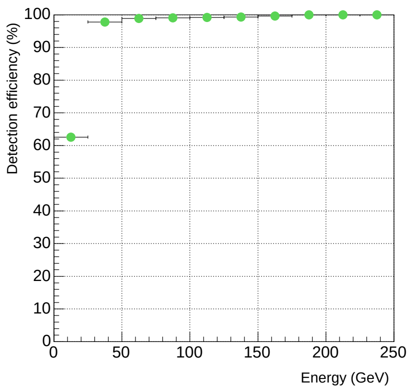


**Figure 4:** Detection efficiency in percent for photon incident as a function of photon energy in GeV.



trigger for high-energy photons was also implemented.

RHICf recorded the events together with the STAR detector. Most of the STAR sub-detectors including ZDC, beam-beam counters (BBC), roman pots, TOF counters covering the central rapidity recorded their data triggered by RHICf. In 10% of RHICf triggered events, information of the Time Projection Chamber (TPC) were also recorded that allows to determine the momenta of individual particle at the central rapidity.

### 2.2 Targets of RHICf

**Cross section measurements**

Prime target for the cosmic-ray physics is to determine the differential production cross sections, $d^2\sigma/dEdp_T$ or $d^2\sigma/dEd\eta$, of photons, neutrons and $\pi^0$. According to the model predictions shown in Fig.5, there are still significant differences between models. The trend found between the EPOS and QGSJET II models, *i.e.* good agreement at large $\eta$ and softer in QGS at small $\eta$, is similar to the trends at $\sqrt{s}$=7 and 13 TeV, which was constrained by LHCf [17] [18] [19]. Because the energy flux peaks at around $\eta$=5–6 in the RHIC energy, where the discrepancy between models is large, new constraint by the RHICf data is important for further model improvements.

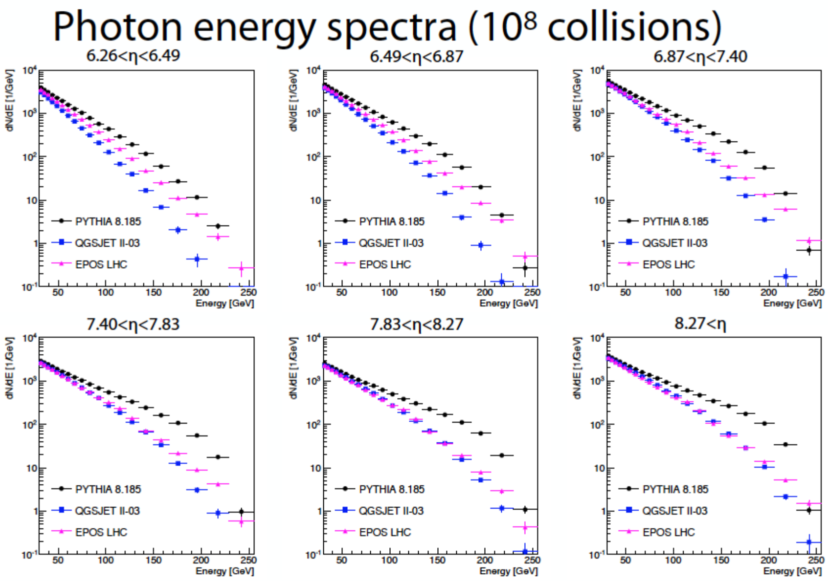


**Figure 5:** Model predictions of the photon energy spectra at different pseudorapidity $\eta$ ranges.

**Single-spin asymmetry measurements**

The $p_T$ dependence of the forward neutron asymmetry introduced in Sec.1 was discovered by PHENIX at $p_T$ <0.4 GeV by combining the data obtained at different $\sqrt{s}$. Because there is no overlap in $p_T$ coverage between the different data sets, it is not clear if the result really indicates the $p_T$ dependence or $\sqrt{s}$ dependence. The $p_T$ coverage in this measurement was limited by the position resolution of the detector, but it can be improved by using the RHICf detector. Because RHICf covered the $p_T$ range up to 1 GeV with a single collision condition $\sqrt{s}$=510 GeV, it is expected to test the $p_T$ dependence of the forward neutron asymmetry.

**Common data analyses**

Several interesting analyses are expected using the RHICf-STAR common data.

- Using the ZDC, thick hadron calorimeter behind the RHICf, energy resolution of the neutron measurement will be improved from 40% to 20%.
- Using the central detector information, classification of diffractive and non-diffrative events will be available as discussed in the case of LHCf-ATLAS [20].
- Using the combination with the roman pot detectors at the opposite side, that tags the intact proton in the single-diffraction event, diffractive mass of each event detected by the RHICf detector is determined.

Importance of the studies related to the diffraction dissociation in cosmic-ray physics was pointed out by [21]. RHICf has a unique sensitivity to the especially low mass diffraction, that produces high-energy particles in the very forward direction.

### 2.3 First data at RHIC

RHICf succeeded data taking at RHIC from 25 to 27 June, 2017. Proton beams with energy of 255 GeV were collided at $\sqrt{s}$=510 GeV. Each beam was radially polarized to maximize the single-spin asymmetry in the vertical direction to which the RHICf detector has the maximum sensitivity. Beams were weakly squeezed to $\beta^*$=8 m to collide the protons as parallel as possible. Collisions were realized with a luminosity at about $1\times10^{31}\,\mathrm{cm^{-2}s^{-1}}$. At this condition, RHICf observed single shower events at maximum 20 kHz and it was prescaled down to about 600 Hz. Instead, events with the $\pi^0$ trigger and high-energy photon trigger as introduced in Sec.2.1 were recorded with no or small prescaling factors to keep the total recording rate at 1 kHz.

Almost 90% of the RHICf triggered events was also recorded as the RHICf-STAR common data. Clear anti-correlation between the energies observed by RHICf and the west ZDC was confirmed while no correlation was found between RHICf and the east ZDC as expected (see Fig.2 for the RHICf-ZDC configuration). This assures correct event matching between two experiments.

To determine the production angle of each particle, the direction of the beam, zero degree, projected on the detector plain must be determined using the real data. Because the high-energy neutrons are known to concentrate around zero degree, hit map of the high-energy neutrons as shown in Fig.6 is used to define zero degree. The data clearly indicates the zero degree is located near the center of the small calorimeter as expected.

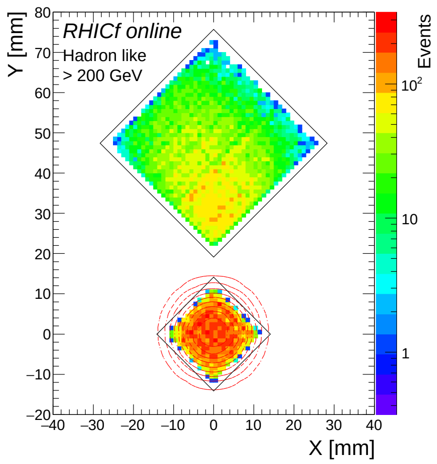


**Figure 6:** Hit map of high-energy neutrons when the small calorimeter was placed at the geometrical zero degree.

Fig.7 shows the invariant mass distribution of photon pair events observed in a small data set. A clear peak is found at $M_{\gamma\gamma}$=135 MeV meaning a successful detection of $\pi^0$'s and a correct energy calibration.

## 3. Summary

RHICf has successfully completed the data taking at RHIC using the $\sqrt{s}$=510 GeV proton-proton collisions in the end of June, 2017. The quality of the data at the first analysis stage is at the satisfactory level. By determining the production cross sections of forward photons, neutrons

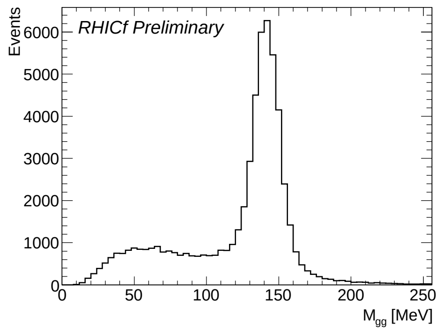


**Figure 7:** Distribution of invariant mass determined using photon pair events.

and $\pi^0$, hadronic interaction will be better understood and the uncertainty in the air shower interpretation will be reduced. The equivalent cosmic-ray energy $1.4\times10^{14}$ eV is just below the energy of the knee. Combining with the results at LHCf up to $10^{17}$ eV, forward particle production below and above the knee is understood first time and its energy evolution can be studied.

Not only the cross sections, RHICf measurements will shed light on the fundamental process of meson exchange between protons through the asymmetry analyses. Common operation with STAR is also important to study especially the low mass diffraction process, that is poorly studied by experiments so far but is known to be important in the air shower modeling.

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## References

[1] K.-H. Kampert and M. Unger, *Measurements of the cosmic ray composition with air shower experiments*, *Astropart. Phys.* **35** (2012) 660-678.

[2] K. Akiba et al., *LHC forward physics*, *J. Phys. G: Nucl. Part. Phys.* **43** (2016) 110201.

[3] D. d'Enterria et al., *Constraints from the first LHC data on hadronic event generators for ultra-high energy cosmic-ray physics*, *Astropart. Phys.* **35** (2011) 98-113.

[4] LHCf Collaboration, *Measurements of longitudinal and transverse momentum distributions for neutral pions in the forward-rapidity region with the LHCf detector*, *Phys. Rev.* **D 94**, 032007 (2016).

[5] PHENIX Collaboration, *Inclusive cross section and single transverse spin asymmetry for very forward neutron production in polarized p+p collisions at* $\sqrt{s}$*=200 GeV*, *Phys. Rev.* **D 88**, 032006 (2013).

[6] LHCf Collaboration, *Measurement of very forward neutron energy spectra for 7 TeV proton-proton collisions at the Large Hadron Collider*, *Phys. Lett.* **B 750** (2015) 360-366.; K. Kawade, *Measurement of neutron production in the very forward rapidity at LHC* $\sqrt{s}$ *= 7 TeV p-p collision* , PhD thesis, Nagoya University (2014).; CERN-THESIS-2014-315.

[7] E. Berti, *Measurement of energy spectra relative to neutrons produced at very small angle in $\sqrt{s}$=13 TeV proton-proton collisions using the LHCf Arm2 detector*, PhD thesis, University of Florence (2017).; CERN-THESIS-2017-035.

[8] LHCf Collaboration, *The LHCf detector at the CERN Large Hadron Collider*, *JINST* **3**, S08006 (2008).

[9] Y. Fukao et al., *Single transverse-spin asymmetry in very forward and very backward neutral particle production for polarized proton collisions at $\sqrt{s}$=200 GeV*, *Phys. Lett.* **B 650** (2007) 325-330.

[10] The PHENIX Collaboration, *Energy and transverse momentum dependence of single-spin asymmetry of very forward neutron in polarized pp collision*, *J. Phys. Conf. Ser.*, **295**, 012097 (2011).

[11] B. Z. Kopeliovich, I. K. Potashnikova, I. Schmidt and J. Soffer, *Single transverse spin asymmetry of forward neutrons*, *Phys. Rev.*, **D 84**, 114012 (2011).

[12] The RHICf Collaboration, *RHIC Beam Use Request for Run17*, *https://indico.bnl.gov/conferenceDisplay.py?confId=1761*

[13] T. Suzuki et al. *Performance of very thin $Gd_2SiO_5$ scintillator bars for the LHCf experiment*, *JINST*, **8**, T01007 (2013).

[14] Y. Makino et al., *Performance study for the photon measurements of the upgraded LHCf calorimeters with $Gd_2SiO_5$ (GSO) scintillators*, *JINST*, **12**, P03023 (2017).

[15] K.Kawade et al., *The performance of the LHCf detector for hadronic showers*, *JINST*, **9**, P03016 (2014).

[16] LHCf Collaboration, *LHCf DETECTOR PERFORMANCE DURING THE 2009-2010 LHC RUN*, *IJMPA*, **28**, 1330036 (2013).

[17] LHCf Collaboration, *Measurement of zero degree single photon energy spectra for $\sqrt{s}$= 7 TeV proton-proton collisions at LHC*, *Phys. Lett.* **B 703**, 128-134 (2011).

[18] LHCf Collaboration, *Measurement of forward photon-energy spectra for $\sqrt{s}$ = 13 TeV proton-proton collisions with the LHCf detector*, *CERN-EP-2017-051*; [hep-ex/170307678].

[19] Y. Makino, *Measurement of the very-forward photon production in 13 TeV proton-proton collisions at the LHC*, PhD thesis, Nagoya University (2017); CERN-THESIS-2017-049.

[20] Q.D. Zhou, Y. Itow, H. Menjo and T. Sako, *Monte Carlo study of particle production in diffractive proton-proton collisions at $\sqrt{s}$=13 TeV with the very forward detector combined with central information*, *Eur. Phys. J.* **C 77**, 212 (2017).

[21] S. Ostapchenko, *LHC data on inelastic diffraction and uncertainties in the predictions for longitudinal extensive air shower development*, *Phys. Rev.* **D 89**, 074009 (2014).