Status and Prospects of the LHCf and RHICf experiments

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Precise understanding of hadronic interactions at high energies is a key to improve mass composition measurements of very high energy cosmic-rays and to solve the muon excess issue observed in high energy cosmic-ray experiments using an air-shower technique. The LHCf and RHICf experiments measures the differential production cross sections of very forward neutral particle as photons, neutral pions and neutrons at LHC and RHIC, respectively. These data are critically important to test and tune hadronic interaction models used for air-shower simulations.

In this presentation, we introduce the recent results of both the experiments as well as our future operation plans. LHCf published an updated result of forward neutron measurement at pp, $\sqrt{s} = 13$ TeV. From the observed neutron energy spectra, we also obtained the average inelasticity, which is one of the key parameters for air shower development, as 0.536 ±0.031-0.037. In addition, several analysis are on-going; neutral pion measurement at pp, $\sqrt{s} = 13$ TeV, central-forward correlation analysis with LHCf+ATLAS, photon measurement by RHICf. LHCf plans to have operations at $pp$ and $pO$ during the LHC-Run3 period. At $pp$ collisions, new silicon readout system will be introduced to improve the read-out speed, and 10 times more statistics of the previous operation in 2015 will be obtained. Thanks to high statistics, rare particles such as $\eta$, $K^0_S$ and $\Lambda$ will be addressed also. We also plan another operation at RHIC in 2024 with a new detector. The detector, a calorimeter composed of tungsten, Si pad and pixel layers, will have a much wider acceptance and higher sensitivity of $K^0_S$ measurement than the current detector.

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1. Introduction

Precise understanding of hadronic interaction is an important key of very high energy cosmic-ray observations using extensive air shower technique. Mass composition of primary cosmic-rays is estimated from some shower parameters observed by ground detectors, for example, depth of maximum shower development $X_{\text{MAX}}$, muon production depth $X_{\mu \text{MAX}}$, and the number of muon $N_{\mu}$. However the estimated average mass numbers from these parameters are not compatible with each other, and the results strongly depend on the choice of hadronic interaction model used in the air shower simulations. To improve or solve the situation, accelerator data at high energy hadronic collisions for testing and tuning hadronic interaction models are necessary.

The LHC forward (LHCf) [1] and RHIC forward (RHICf) [2] experiments were designed to measure energetic photons, $\pi^0$'s and neutrons emitted in the very forward region of collisions, which play an important role in air shower developments, at LHC and RHIC. These accelerators provide collisions with a wide range of the center-of-mass collision energies $\sqrt{s}$ from 0.5 TeV up to 14 TeV, which correspond to $10^{14} - 10^{17}$ eV cosmic-ray interaction in the atmosphere. Both the experiments have obtained data in the last years, and several analysis results were published. In addition, they plan to have other operations near future. In this paper, we review recent results in Sec. 3 after briefly introducing the experimental setup in Sec. 2. In Sec. 4 we describe about the future operation plans, LHCf operations with $pp$ and $pO$ collisions and RHICf operation with a new detector, and then summarize in Sec. 5.

2. LHCf and RHICf experiments

The LHCf experiment consists of two independent detectors, called Arm1 and Arm2, installed ±140 m from the interaction point where the ATLAS detector installed as shown in Fig. 1. Each detector has two sampling and imaging calorimeter towers. Each tower is composed of tungsten plates, 16 GSO scintillator layers for sampling showers, and 4 position sensitive layers (GSO bar X-Y hodoscopes in Arm1 and X-Y silicon strip layers in Arm2) for imaging lateral shower distribution. The acceptances of the calorimeter towers are 20 mm × 20 mm and 40 mm × 40 mm in Arm1, and 25 mm × 25 mm and 32 mm × 32 mm in Arm2. The energy resolution for photos and neutrons are < 5% and 40%, respectively. More details of the detector performance can be found in [3, 4].

The LHCf detectors measures only neutral particles, photons, $\pi^0$, and neutrons, produced at the very forward region including zero degree of collisions because charged particles are swept out due to magnetic field of dipole magnets located between the interaction point and the detectors. The pseudorapidity coverage is $|\eta| > 8.4$.

The LHCf operations have performed with $pp$ collisions at several collision energies of $\sqrt{s} = 0.9, 2.76, 7$ and 13 TeV in the past. The luminosity during the operations was approximately $10^{29}$ or less, which is 5 orders of magnitude less than the LHC nominal luminosity at $pp$. Operations with $pPb$ collisions were also performed in 2013 and 2016. In the cases, only the Arm2 detector was installed into the beam line and measured particles produced in the proton-remnant side.

The RHICf experiment was performed using the LHCf Arm1 detector and the data acquisition (DAQ) system. The RHICf detector was installed at 18 m West from the STAR interaction point.
Figure 1: Location of the LHCf and RHICf detectors in the LHC/RHIC beam line. The LHCf detectors are located ±140 m far from the ATLAS interaction point. The RHICf (LHCf-Arm1) detector is installed at 18 m from the STAR interaction point. Only neutral particles generated at the interaction points can be reached because of magnetic field of dipole magnets located between the interaction point and the detector.

(Fig. 1). The operation was successfully completed with spin-polarized pp collisions at √s = 510 GeV in June 2017. The luminosity in the RHICf operation was set to approximately 10^{31} cm^2 s^{-1}, which is one order of magnitude lower than the nominal value of RHIC at pp collisions, to keep low collision pileup rate of 0.05 collision per bunch crossing.

3. Recent results and on-going analyses

Recently the neutron analysis at pp, √s = 13 TeV was upgraded with extension of analysis region and the elasticity k_n (or inelasticity 1 − k_n) was measured [5]. The inelasticity is an energy fraction used for secondary particle productions, and it is one of the most important parameters for air shower development. The inelasticity can be calculated from energetic neutron energies E_n measured by the LHCf detector, which are leading particle in most cases, as

\[ 1 - k_n = 1 - E_n/E_{\text{beam}} \]

where E_{\text{beam}} is the beam energy of 6.5 TeV. Figure 2 shows the measured k_n distribution (left) and average inelasticity \( <1-k_n> \) (right). The obtained average inelasticity is \( <1-k_n> = 0.536^{+0.031}_{-0.037} \), and it shows good agreements with model predictions except PYTHIA.

Preliminary result of \( \pi^0 \) analysis at pp, √s = 13 TeV was updated [6]. Using both the Arm1 and Arm2 data, a wide p_T region is covered. The other results, inclusive production cross sections of photon, \( \pi^0 \) and neutrons, published in the past can be found in [7–11]. In addition to them, joint analyses with ATLAS are on-going.

4. Future operations

LHCf plans to have two operations during LHC Run 3 (2022-2024) and RHICf will have an operation with a new detector in 2024. These future operations will provide not only increase of statistics, especially high energy \( \pi^0 \)s and common events with ATLAS, but also measurement of \( \eta \),...
Figure 2: Inclusive production cross section as a function of elasticity $k_n$ (left) and average inelasticity $<1-k_n>$ (right) obtained from the neutron measurement at $pp$, $\sqrt{s} = 13$ TeV. Black markers represent the experimental data, and solid lines (left) and filled circle (right) refer to model predictions at the generator level, obtained using only the events where the leading particle is a neutron. Open circle in the right figure show the value of $<1-k_n>$ obtained from any leading particles.

$K^0_s$ and $\Lambda$. $K^0_s$ is measured by detecting four photons from a $K^0_s$ decay: $K^0_s \rightarrow 2\pi^0 \rightarrow 4\gamma$. The kaon measurement is also important for improving predictions of high energy atmospheric neutrino flux.

4.1 LHCf operation at $pp$, $\sqrt{s} = 14$ TeV in 2022

The operation is scheduled for 2 days in the beginning of 2022. The collisions energy is requested to be $\sqrt{s} = 14$. The energy might be slightly lower than this value. The luminosity during the run is requested to be about $10^{30}$ cm$^{-2}$s$^{-1}$, which will be factor 10 higher than that of the last operation, to record factor 10 larger statistics of high energy $\pi^0$ events and several hundreds of $K^0_s$ events. In this operation, a joint operation with ATLAS ZDC detectors will be performed. The ZDC hadron module will be installed behind each LHCf detector, and it can measure the leaked-out particles of hadronic showers from the LHCf detector. Combining the data of two detectors the energy resolution for neutrons will be improved from 40% to 20%. This good resolution is important to select events of one-pion-exchange process, as discussed in [12], as well as improvement of the inclusive neutron measurements. The ATLAS roman pot detectors, ALFA and AFP, will join the operation also.

The preparation for the operation is on-going. To obtain the high statistics data in the limited beam time, the readout system of Arm2 silicon detector is upgraded. In the old system, the silicon data sent from the tunnel is stored in a VME board and the readout time of one silicon event with 3k channels and 1.3 k byte is 0.8 msec via the VME bus, which mainly limited the total DAQ rate. In the new system, the data are directly read from a frontend computer via TCP/IP connections (Fig. 3), and the readout time will be dramatically reduced to 0.1 msec. Considering the readout of other devices the maximum DAQ rate will be improved from 800 Hz to 2 kHz. This upgrade also solves other issues like instability of optical connections due to radiation damage and aging of the
Figure 3: Schematic view of the new silicon readout system. The MDAQ boards and PS-CLK board are newly designed, which work for digitization and data transfer, and for clock and trigger distribution to the MDAQ boards, respectively. The CLK-GEN transfers clock and trigger signals from the central DAQ system and is implemented on a FPGA board.

Figure 4: A photo of new MDAQ board. Analog signals transferred from PACE 3 chips are digitized in this board located near the Arm2 detector, and the data is sent to a counting room via 1 Gbps optical link with TCP/IP protocol.

system. Figure 4 shows a photo of new MDAQ board. We are now doing final tests of produced boards.

4.2 LHCf operation with pO collisions

Proton and Oxygen nucleus collisions are the best and ideal condition to study the hadronic interaction by high-energy cosmic-rays happened in the atmosphere. As a first approximation, a high energy proton-ion or ion-ion collisions is described as a superposition of well studied pp collisions at LHC. It is not enough to describe the energy spectra of particle productions precisely, and the forward particle production is suppressed due to shadowing of nucleons located behind and interactions of produced particles in the nucleus matter, so called nuclear effect. LHC have provided pPb collisions during Run 1 and 2, and LHCf measured the nuclear effect at pPb collisions for forward $x^0$ production [10]. However, Pb is too heavy to estimate the nuclear effect and there was a large background of photons and neutrons in the forward region due to interactions between
a proton and electromagnetic field of a Pb nucleus.

LHCf have continuously requested to have proton-ion collisions at LHC since several years ago. While a few technical discussions about oxygen beam were done in workshops, there was little progress to realize the pO collisions. We strongly requested them again to LHC committee because the beam line configuration will be changed to improve the radiation protection in LHC high luminosity phase, and the LHCf detectors cannot be inserted to the beam line after that. The LHCf operation with pO collisions is also strongly supported by people of the cosmic-ray and hadron communities. The technical and physics studies and discussions between LHC machine and experimental people were accelerated in last some months, and currently a short special run with pO and OO collisions becomes a new physics program during Run 3.

The schedule and operation condition is still under discussion. Currently the special run is scheduled for 7 days in 2023 or 2024 including the beam setup time. The beam energy is requested to 7 TeV for the pO run, which corresponds to the center-of-mass collisions energy per nucleon of $\sqrt{s} = 10$ TeV. The expected performances of LHCf at pO collisions can be found in [13].

### 4.3 RHICf II in 2024

The RHICf experiment also plans to have a next operation, called RHICf II. The main motivation of the operation is to increase statistics of high-\(X_F\) \(\pi^0\) events and measurement of strange hadrons \(K^0_s\) and \(\Lambda\) at \(p p\) collisions. We are also requesting an operation with proton and light collisions.

For the RHICf II operation a new detector will be used instead of the LHCf-Arm1 detector used in the last operation, and it is being developed using ALICE FoCal-EM technology [14]. The new detector consists of tungsten layers, silicon pad (one pad size of 1 cm$^2 \times 1$ cm$^2$) and silicon pixel (one pixel size of 30 $\mu$mm$^2 \times 30$ $\mu$mm$^2$) detectors as shown in Fig. fig:rhicf2, which are for shower absorbers, longitudinal shower sampling, and precise shower core determination. The acceptance of the detector is 8 cm$^3 \times 18$ cm$^3$, which is much larger than one of the old RHICf detector. The fine segmentation of each layer and wide acceptance of the detector allow us to precisely measure energies and impact positions of multi-particles in one event, for example four photons from a \(K^0_s\) decay, and they are essential to improve the sensitivity for \(K^0_s\) and \(\Lambda\) as well as for \(\pi^0\). Figure 6 shows the geometrical acceptance of the new detector for \(\pi^0\), \(K^0_s\), and \(\Lambda\). The acceptance values are much higher than those of the old detector, and the energy threshold of detection is also improved. For example, the detection threshold of \(\pi^0\) is improved from 60 GeV to 20 GeV.

The RHICf II operation is requested for RHIC Run in 2024. Thanks to good radiation hardness and fast DAQ system, a dedicated beam time with a special condition like low luminosity for the RHICf II operation is not requested, and the operation will be performed as a parasitic operation to other RHICf physics programs. The operation side, installation of STAR or sPHENIX interaction points, is under discussion. Currently an operation with \(p p\) collisions at $\sqrt{s} = 200$ GeV is scheduled for Run 2024, and possibly \(p A\) collisions will be done also.

### 5. Summary

The LHCf and RHICf experiment measured forward neutral particles at LHC and RHIC to study hadronic interaction for cosmic-ray air showers. Inelasticity at pp, $\sqrt{s} = 13$ TeV was measured using forward neutron data. Some other analyses, for example \(\pi^0\) measurement at pp, $\sqrt{s} = 13$ TeV
and joint analyses with ATLAS, are on-going. Both the experiments plan to have next operations, \( pp \) in 2022 and \( pO + O0 \) in 2023 or 2024 by LHCf, and \( pp (+ pA) \) in 2024 by RHICf. These focus more on studying detail physics processes, strange hadron measurements, and \( pA \) collisions with higher statistics data and better performance by a joint operation with ATLAS ZDC and roman pots, new detector in RHICf.

References


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