Recent status and prospects of LHCf and RHICf

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Abstract

The Large Hadron Collider forward (LHCf) and the Relativistic Heavy Ion Collider forward (RHICf) experiments are dedicated to measure neutral particles produced around zero degree of the hadron interactions. In this paper, recent results of LHCf on photons, neutrons and π^0's mainly obtained from 13 TeV p-p collisions are summarized. Differential cross sections are compared with predictions of various event generators. Some new analyses such as the joint analyses with ATLAS, total energy and cross section as a function of pseudorapidity are also presented. A new result of RHICf for the first detection of a finite single-spin asymmetry of π^0 production at very forward pseudorapidity region, $\eta > 6$, in the polarized p-p collisions is also presented. Plan of the LHCf in LHC Run 3 is also introduced.

1 Introduction

Origin of cosmic rays is a long standing mystery in astrophysics [1]. Because of their power law energy spectrum, high-energy cosmic rays, typically above 10^{14} eV, have very low flux and they are observed through atmospheric air shower phenomenon that significantly enlarges the effective detection area. To estimate the fundamental properties of primary cosmic rays such as energy and particle type, it is required to compare the observed data of shower particles with Monte Carlo simulation. Therefore simulation needs a reliable hadronic interaction model, but the difficulty of modeling the forward particle production makes uncertainty large.

Thanks to the early LHC results, many generators are updated to so-called post-LHC models and discrepancy between predictions become smaller [2]. However, there are still apparent discrepancies between model predictions and data-model comparison. A recent hot topic in the air shower analyses is so-called muon excess (in experiment than simulation) problem [3]. The primary mass estimated using the surface detectors data and fluorescence telescope data are systematically different. Also the estimated average primary mass exceeds the mass of Iron in some cases, which is not naturally accepted according to the element abundance in the universe. These problems are solved if the simulation underestimates the number of muons.

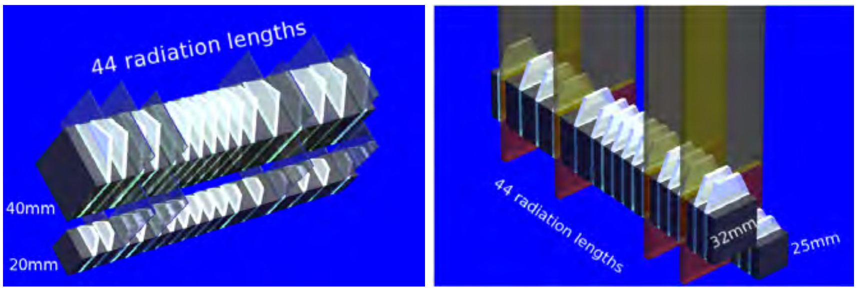

Figure 1: Schematic view of the LHCf Arm1 (left) and Arm2 (right) detectors.

Dedicated measurements at the current high-energy colliders allow access to the forward particle production in the laboratory energy of 10^{14} eV to 10^{17} eV, at RHIC and LHC, respectively. The LHCf and RHICf experiments were designed to measure very forward neutral particles to improve the knowledge of air shower development and hence the origin of cosmic rays. By using the polarized beam collisions at RHIC, measurements of spin asymmetry is another key science in RHICf.

2 LHCf and RHICf experiments

The Large Hadron Collider forward (LHCf) experiment was designed to measure the particles produced around zero degrees in the hadron collisions at LHC [4] [5]. Two independent detectors called Arm1 (IP8 side) and Arm2 (IP2 side) shown in Fig.1 were installed at 140 m from the interaction point 1 (IP1) where the ATLAS experiment is located. The detectors are located in the Target Neutral Absorbers (TANs) downstream of the beam separation dipole magnet and only neutral particles, predominantly photons and neutrons, are observed. Each detector is composed of two independent sampling calorimeter towers with position sensitive layers. By determining the invariant mass of two photons simultaneously observed, π^0's and η's immediately decayed into photon pairs near the interaction point are identified and their momenta are also reconstructed.

The Relativistic Heavy Ion Collider forward (RHICf) experiment was designed to install the LHCf Arm1 detector at the interaction point of the STAR experiment at RHIC [6] [7]. Because the installation slot at RHIC is 18 m from the interaction point, the coverage of transverse momentum p_T is equivalent to that in LHC although the collisions energy is 510 GeV. Thanks to this advantage particle production can be compared in a same x_F-p_T phase space, where x_F is Feynman x. Another unique point of RHIC is to collide polarized beams. It is known that in the collisions of transversely-polarized protons cross section of the forward particle production exhibits right-left asymmetry with respect to the polarization direction. Asymmetry of very forward neutron production is well measured [8] and even used to measure the polarization of the beams. While the π^0 or photon asymmetry is measured up to the pseudorapidity η ∼4 [9] [10] [11], no finite asymmetry is detected at more forward region [12]. RHICf is expected to measure the neutron asymmetry in wider phase space than the previous measurements and the π^0 asymmetry with a higher sensitivity to detect finite asymmetry for the first time in this pseudorapidity.

LHCf started its data taking at LHC in 2009 and until 2016 data were collected at various operation conditions at LHC. RHICf took data in 2017. Table 1 summarizes the operation of LHCf and RHICf.

Table 1: Summary of the data taking period and condition for LHCf and RHICf.

Year	Experiment	$\sqrt{s_{NN}}$	particles
2009	LHCf	900 GeV	p-p
2010	LHCf	7 TeV, 900 GeV	p-p
2013	LHCf (Arm2 only)	2.76 TeV	p-p
2013	LHCf (Arm2 only)	5.02 TeV	p-Pb
2015	LHCf	13 TeV	p-p
2016	LHCf (Arm2 only)	8.16 TeV	p-Pb
2017	RHICf (Arm1 only)	510 GeV	p-p (polarized)

3 Recent results of LHCf

3.1 Photons in 13 TeV collisions

Differential cross sections, $d\sigma/dE$, of photon production at pseudorapidity η >10.94 and 8.81< η <8.99 are reported [13]. Most of these photons are supposed to be produced as decay products of π^0. The results are compared with various generator predictions and it is found that the generators tuned with the early LHC results such as EPOS-LHC [14] and QGSJET II-04 [15] popular in the CR researches show reasonable agreements with the experimental results.

On the other hand, PYTHIA 8.212 [16] shows a significant excess in the very high energy photon production at η >10.94. The origin of this excess was studied and it was found that the diffractive processes are dominant source of high-energy photons in PYTHIA [17]. To experimentally elucidate the contribution of diffractive process as proposed in [17], a joint analysis of ATLAS and LHCf was performed [18]. Because the diffractive process produces less particles in the central region, using the number of particles detected in the ATLAS tracker, photons observed in the LHCf detector are classified into diffractive-like and non-diffractive-like categories. Although the diffractive-like events in the η >10.94 region are found to have a flatter spectrum than the inclusive events, the excess in the PYTHIA prediction is still obvious. On the other hand, PYHIA gives the best prediction of diffractive-like events in the 8.81< η <8.99 region. Angular dependence of modeling the diffractive process can be improved using these measurements.

3.2 Neutrons in 13 TeV collisions

Neutrons, or stable hadrons, are important to determine the core structure of air showers. Differential cross sections of forward neutron production at η >10.76, 8.99< η <9.22 and 8.81< $\eta < 8.99$ are reported [19]. The spectral shapes are very different between the most forward region η >10.76 and the others. The result of η >10.76 is shown in Fig.2 (left). A characteristic peak at 5 TeV is observed and none of the compared generators can explain this structure. Similar spectra reported by the PHENIX experiment at RHIC $\sqrt{s}$=200 GeV p-p collisions together with the lower energy data reported from the ISR experiment at $\sqrt{s}$=30-60 GeV shown in Fig.2 (right) exhibit a same peak position at x_F ~0.8 [8]. Already in the report of the ISR result [20] one pion exchange process is proposed to explain this peak. It is interesting if a same fundamental process dominates the particle production in a wide range of collision energy corresponding to a factor 13 TeV/30 GeV = 430.

Recently LHCf published the neutron cross sections with extended pseudorapidity regions [21]. New analyses are also performed to extract the total neutron energy and cross section as a function of pseudorapidity as shown in Fig.3, and an average inelasticity defined by neutrons. It is clear that the energy flow peaks at around η=9.5.

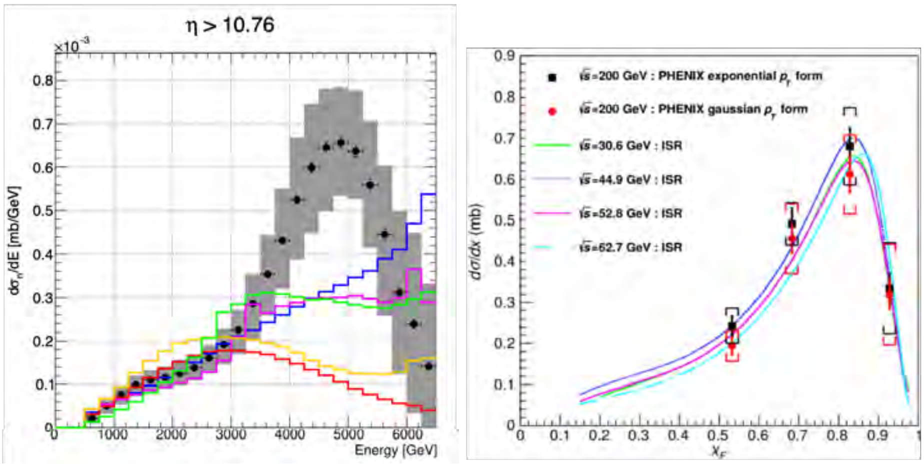

Figure 2: Energy (x_F) spectra of neutrons around zero degrees. (Left) Result of LHCf at $\sqrt{s}$=13 TeV p-p collisions for p$_T$<0.28x_F GeV/c [19]. (Right) Results of PHENIX and ISR at $\sqrt{s}$=30-200 GeV p-p collisions for p$_T$<0.11x_F GeV/c [8].

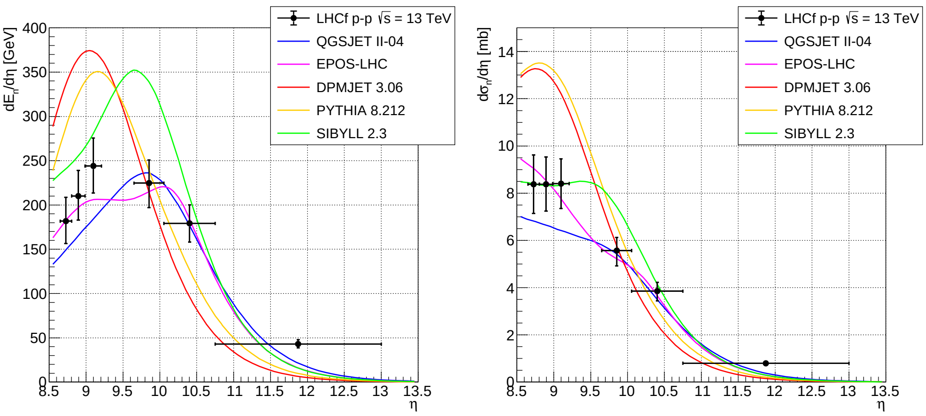

Figure 3: Total energy (left) and cross section (right) of forward neutrons as a function pseudorapidity η measured by LHCf at $\sqrt{s}$=13 TeV p-p collisions [21].

3.3 π^0's in 13 TeV collisions

π^0 is the main source of photons discussed in Sec.3.1 and the source of electro-magnetic component in air showers that determines the number of particles and hence represents the energy of primary particle. From the analyses of 2.76 TeV and 7 TeV p-p collision data, LHCf so far reported the production cross sections of π^0 and found a x_F scaling in this energy range as shown in Fig.4 [22] [23].

Analysis on 13 TeV data is on going and a preliminary result of p_T spectra at various x_F ranges is shown in Fig.5 [24]. Type 1 (black) and Type 2 (red and blue) indicate the events with two photons in two towers and two photons in a single tower, respectively. The latter having small opening angles are sensitive to the high energy (x_F) π^0's. By using the event with different categories, the coverage in phase space is enlarged. Smooth connection between different colors assures the validity of the analysis. More detail of this analysis is found in [24]. Extension of the scaling study

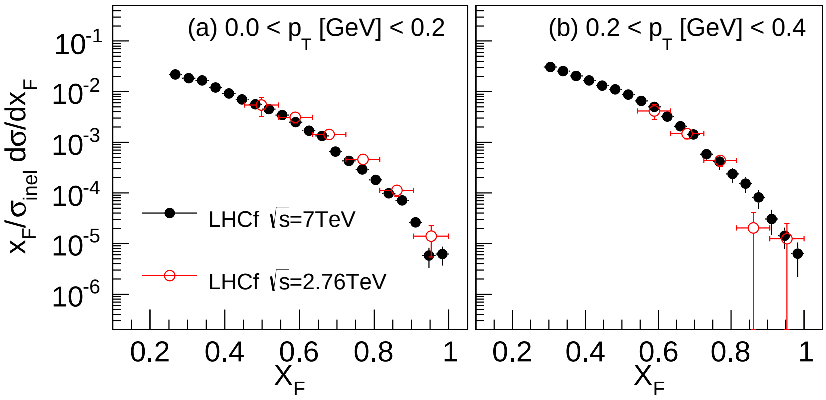

Figure 4: π^0 production cross sections as a function of x_F for two p_T ranges [23]. Results of 7 TeV and 2.76 TeV p-p collisions are plotted in black and red markers, respectively.

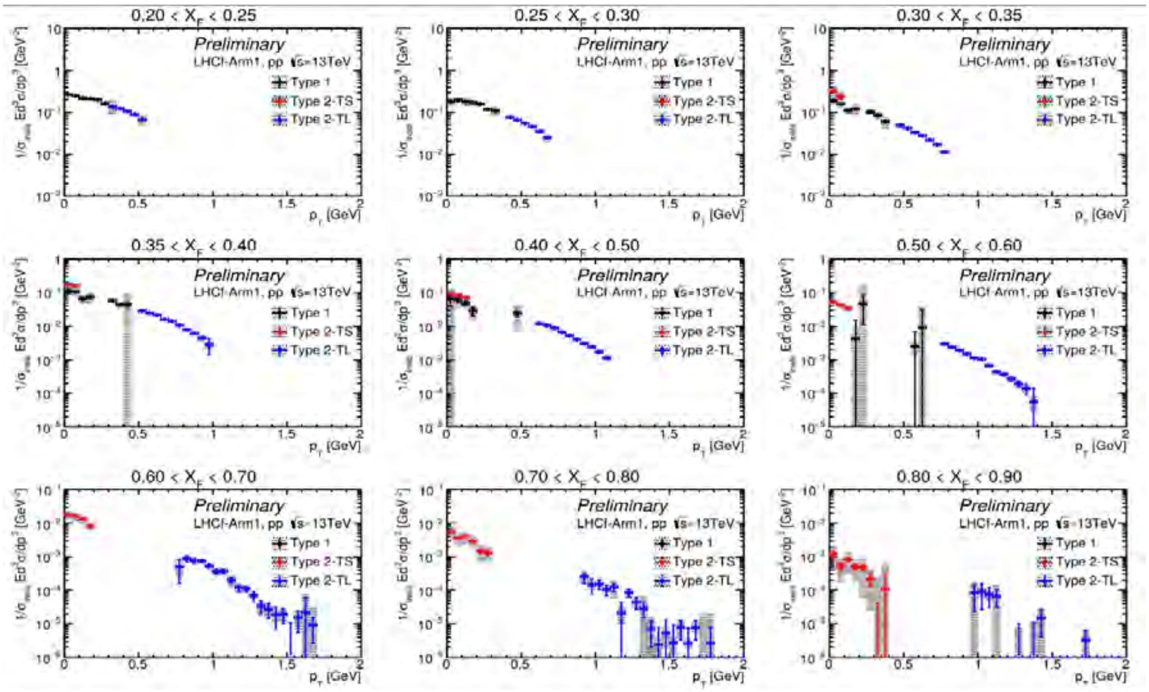

Figure 5: Preliminary p_T spectra of forward π^0 production at $\sqrt{s}$=13 TeV measured by LHCf [24]. Different panels show the results at different x_F ranges. Colors of markers indicate the different categories of event. See text and [24] for more detail.

shown in Fig.4 from $\sqrt{s}$=510 GeV to 13 TeV using the RHICf and latest LHCf results are foreseen as the next step.

4 Recent results of RHICf

RHICf analyzed the transverse single-spin asymmetry, A_N, of π^0 production as shown in Fig.6 [25]. Previous experiments reported finite A_N at moderately forward pseudorapidity, η ∼3, and the

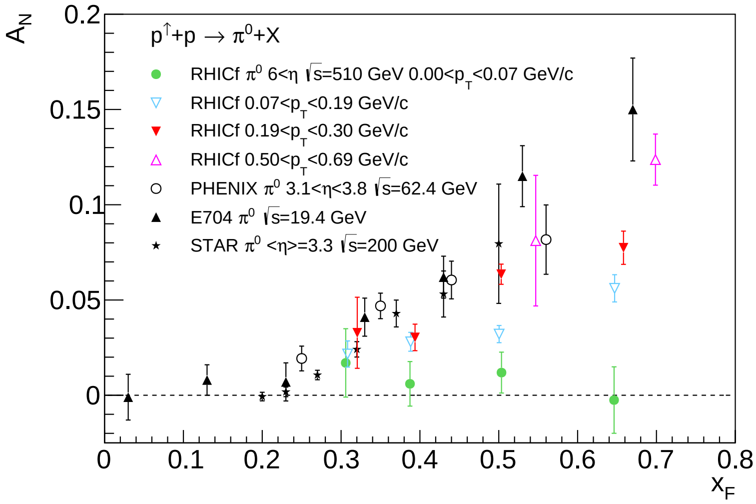

Figure 6: Transverse single-spin asymmetry, A_N, of π^0 production measured by RHICf (colors) compared with previous experiments (black) [25].

RHICf result at high p_T (η ~6.5) shows a good agreement with them. RHICf first time succeeded to measure finite A_N in more forward region. Around zero degree region A_N is consistent with zero (green points) as expected and it gradually increases with p_T. Though large asymmetry known near the central region has been explained by hard processes, recent measurements suggested contributions from soft processes such as diffractive processes are important in the forward region [11] [10]. The result of RHICf supports this idea. Because the particle production in the RHICf phase space has a larger contribution from diffractive processes, this observation will shed light on the nature of asymmetry. More detail analyses by classifying the events in diffractive and non-diffractive processes are planned using the information from the STAR detector. Data of TPC, TOF, BBC, ZDC and Roman Pots are stored when RHICf triggered high-energy event in its detector. Event matching of this common trigger is already confirmed.

5 Plan in LHC Run 3

LHCf is planning to take data in Run 3 starting in 2021. Detail ideas and technical discussions are found in the Technical Report [26]. Here summarizes two main ideas in this operation.

- Data taking with $\sqrt{s}$=14 TeV p-p collisions.
- Data taking with $\sqrt{s_{NN}}$=9.9 TeV p-O collisions, where O designates Oxygen beam.

The latter is an ideal collision for cosmic-ray physics to realize the collisions between cosmic-ray nucleon and atmosphere. By taking into account the early LHC data, so-called post-LHC generators show reasonable agreements in particle productions in p-p collisions. On the other hand, still sizable differences exist between the predictions of p-O collisions [2]. Study of the nuclear effects in the condition close to the atmosphere gives a new and direct impact on the CR physics. Note that LHCf already published the results of forward π^0 production in p-Pb collisions, where the generators reasonably described the LHCf results [27] [23]. However in this data half of the observed π^0's are produced through the Ultra Peripheral Collisions between the proton and virtual photons around the Pb nuclei. To test the hadronic interaction, a subtraction of UPC contribution by calculation is required and it is the dominant source of uncertainty in the final result. In case of light ion collisions like Oxygen, contribution from UPC is largely suppressed and uncertainty to study the hadronic interaction is also reduced. General physics motivations of heavy and light ion collisions in Run 3 and Run 4 are summarized in [28].

Though the energy of p-p collisions does not change significantly from Run 2 to Run 3, new programs are planned. Because of steep energy spectra especially in photons and π^0's, the LHCf results have large statistical errors in high-energy range. A new and simple trigger logic that preferentially selects high-energy electromagnetic showers was successfully implemented in the operation of RHICf. By applying the same trigger logic in the LHCf Run 3 operation with a slightly higher luminosity than Run 2, LHCf can accumulate more high-energy events. To accommodate to the limited data taking speed, low energy trigger events will be prescaled. At the same time, an upgrade for speed up of the data taking system is also in progress. High-energy and high-speed data taking allows analysis of η and K meson productions. Detection of η was already confirmed with the LHCf Run 1 and Run 2 data, but because the detector is sensitive only above 2 TeV, the event statistics was limited.

Finally new possibilities are open for the common data taking and analyses with ATLAS. As described in Sec.3.1, common data taking was already successfully performed and initial analyses are ongoing. However because of the short preparation time only central detectors were included in the past operation. By including the other forward detectors such as ZDCs (behind the LHCf detectors) and roman pots, more interesting possibilities in forward physics analyses will be available. More details of the ideas are shown in [26].

6 Summary

LHCf was motivated to improve the knowledge of forward particle productions, which is directly connected to the developments of cosmic-ray induced air showers and hence the high-energy astrophysics. LHCf so far succeeded data taking at various run conditions at LHC. Results are first presented in the form of differential cross sections such as $d\sigma/dE$, $d\sigma/dp_T$ as well as invariant cross sections $Ed^3\sigma/dp^3$ for photons, neutrons and π^0's. Results are compared with the predictions of generators popular in the air shower studies and also PYTHIA. Generally EPOS-LHC model shows a good agreement with the LHCf results, but depending on the particle type and phase space to be compared different models are preferred.

Not only deriving the cross sections, LHCf also continues further studies such as

- Test of x_F scaling comparing the data at different $\sqrt{s}$
- Event-by-event classification into diffractive and non-diffrative origins collaborating with ATLAS
- Analysis of total energy and cross section as a function of η
- Analysis of elasticity carried by forward neutrons

LHCf is also preparing data taking during LHC Run 3 starting from 2021. Using a special trigger logic and updated system, more events will be collected especially in high-energy range. This allows, even under a short operation period, analyses of high-energy photons and π^0, η and K mesons with sufficient statistics. Thanks to the successful operation and first analysis with ALTAS in Run 2, more subdetectors will join the common data taking. Participation of ZDC and roman pots are of prime interest. Highlight in Run3 is possible operation of Oxygen beam. Either p-O and

O-O collisions realize the collisions really happening in the atmosphere hit by cosmic-ray particles. Still unknown nuclear effects at high-energy collisions will be understood in these operation.

One of the LHCf detectors, Arm1, was transported beyond the Atlantic ocean and used as the RHICf detector at RHIC. Not only to enlarge the $\sqrt{s}$ coverage, the spin physics is one of the main targets. The data taking at $\sqrt{s}$=510 GeV with transversely polarized proton beams was successfully done in 2017. The first impressive result is recently published. RHICf first time detected the finite single-spin asymmetry of very forward π^0 production and also its onset by reducing the p_T coverage down to zero. A good agreement between the previous experiments at $\eta \sim$3 and RHICf result at $\eta \sim$6.5 indicates an importance of soft processes such as diffractive dissociation in a wide pseudorapidity range. Further analyses with the STAR experiment are on going.

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