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The results and future prospects of the LHCf experiment

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The LHCf forward (LHCf) experiment measures the production cross sections of neutral particles emitted to the very forward region of an LHC interaction point in order to test the hadronic interaction models used in air-shower simulations. In this proceedings, we present the neutron and π^0 spectra measured in pp collisions at $\sqrt{s}$ = 13 TeV. In addition to them, many results will be delivered from currently on-going analyses of data obtained at LHCf-ATLAS common operation, and at the RHICf experiment with pp collisions at $\sqrt{s}$ = 510 GeV, as well as from future LHCf operations with pp and pO collisions at LHC.

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1. Introduction

The world-biggest particle accelerator, Large Hadron Collider (LHC), has delivered a lot of new results in particle physics and nuclear physics since its operation start-up in 2010. The data of hadronic interaction provided by LHC is also very useful for cosmic-ray physics, especially for very high energy cosmic-ray measurements using the extensive air-shower technique. The maximum LHC collision energy in the centre-of-mass system, $\sqrt{s}$ = 14 TeV, is equivalent to 10^{17} eV of cosmic-ray interactions in the atmosphere, and it is much higher than the knee energy of around 10^{15} eV and close to the Ultra-High Energy Cosmic-Ray (UHECR) energy region of more than 10^{19} eV. Using the data obtained by the LHC experiments in the early phase of the LHC operation, hadronic interaction models used in air-shower simulations have been already improved, and better understanding of air-shower development phenomena was achieved. However, even after such improvement, some open questions arising from observations of UHECRs by the Pierre Auger and Telescope array experiments like the muon excess issue remain [1, 2].

The LHC forward (LHCf) experiment was designed to measure the production spectrum of neutral particles, photons, π^0's and neutrons, in the zero-degree region of LHC collisions. Most of the high energy particles are generated in the region, and these particle spectrum is one of the most important parameters in the hadronic interaction for understanding the air-shower development precisely. The LHCf had several operations with pp or pPb collisions at several collisions energies. In this presentation, we focus on the recent published result of very forward neutron energy spectra at pp, $\sqrt{s}$ = 13 TeV [3], and a preliminary result of π^0 spectrum measurement at pp, $\sqrt{s}$ = 13 TeV. The other results published in the past are found in [4, 5, 6, 7, 8]. In the later part, we also mention about on-going analyses and future operation plans.

2. The LHCf experiment

The LHCf have two sampling and positioning calorimeter detectors, called Arm1 and Arm2, which are installed at +/- 140 m from the LHC interaction point 1 (IP1) where the ATLAS detector is installed. Each detector is inserted into a narrow gap between two beam pipes connecting the LHC arc, and these detectors can access the zero-degree line of collisions with no material in the line expect a beam pipe wall with approximately one-radiation length thickness. Each detector consists of two independent calorimeter towers with the cross-sections facing IP1 of $20 \times 20\,\mathrm{mm}^2$ and $40 \times 40\,\mathrm{mm}^2$ in Arm1, and $25 \times 25\,\mathrm{mm}^2$ and $32 \times 32\,\mathrm{mm}^2$ in Arm2. Each tower is composed of tungsten plates, 16 scintillator layers for shower sampling, and 4 position sensitive layers. Figure 1 shows the schematic view of the LHCf detector location and the Arm1 detector. The energy resolutions for photons and neutrons are $< 5\%$ and 40%, respectively. More detailed performance of the detectors are found in [9, 10, 11].

The data used for the analyses described in the next section was obtained in an operation performed in June 2015 with pp collisions at the collision energy of $\sqrt{s}$ = 13 TeV. The operation period corresponds to one of the low-luminosity LHC runs. We obtained two data sets with slightly different beam luminosity and trigger condition of the LHCf data taking system. The first one is obtained under the very low-luminosity of $(3-5) \times 10^{28}$ cm^{2}s^{-1} with a simple trigger condition for detecting any showers developed in any calorimeter towers. In the second one, the luminosity

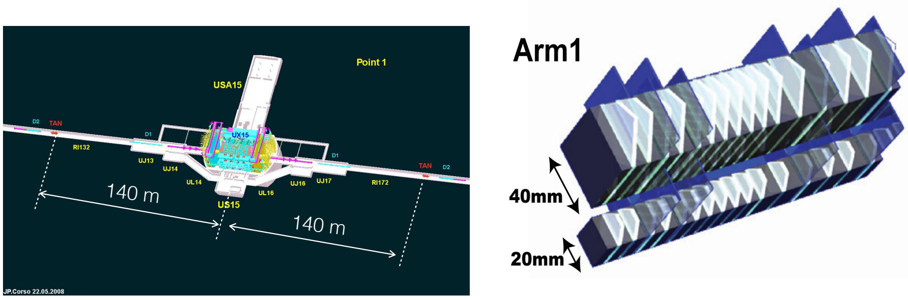

Figure 1: Caption

slightly increased to $(10-16)\times10^{28}$ cm^{2}s^{-1}, and a dedicated trigger mode for π^0 detection, requiring simultaneous detection of electromagnetic showers in both the towers, was activated with suppressing the trigger rate of the single shower triggers. The first data set is used for the neutron analysis, and both the first and second data sets are used for the π^0 analysis.

3. Recent results

3.1 Neutron measurement at pp, $\sqrt{s}$ = 13 TeV

Forward neutron measurement can address the inelasticity parameter of collisions, which is one of the important parameters to understand the air shower development phenomena. The inelasticity, k, is defined as the fraction of energy used for secondary particle productions, and it is calculated as $k = 1-E_{\mathrm{leading}}/E_0$, where E_0 is the primary particle energy and E_{leading} is the energy of the leading baryon in the collision products. Very energetic neutrons emitted in the zero-degree region can be leading baryons of pp collisions. The neutron measurement of LHCf has been published with pp, $\sqrt{s}$ = 7 TeV data in the past [8]. We extended this analysis to the data obtained by the Arm2 detector with pp collisions at $\sqrt{s}$ = 13 TeV.

Neutral hadrons, dominantly neutrons, hitting a LHCf calorimeter induce hadronic showers in the calorimeter, and they are developed relatively deeper and longitudinally longer than electromagnetic showers induced by photons. Parameterizing longitudinal shower shapes measured by the sampling layers, neutral hadron events are well discriminated from the photon events. After the event selection and some corrections, we performed an unfolding of the obtained spectrum to convoluted our measurement from the detector performance with 40% energy resolution. For details of the analysis, refer [3].

Figure 2 shows the measured neutron energy spectra in the three pseudo-rapidity regions, $\eta >$ 10.76, $8.99 < \eta < 9.22$, and $8.81 < \eta < 8.99$. For $\eta > 10.76$ including zero-degree of collisions, clearly a peak structure in the data spectrum is seen around 5 TeV, while the models predict lower flux than the data and no such peak structure in these spectra. Our data at pp, $\sqrt{s}$ = 7 TeV indicates similar one, however, it was not clear due to a large systematic uncertainty. Thanks to careful studies and improvement of the spectrum unfolding method, the peak structure was confirmed, while the unfolding is still one of the dominant sources of systematic uncertainties. For the other pseudorapidity ranges, the data points locate in the middle of the model predictions. SIBYLL 2.3 and EPOS-LHC show overall good agreement with the data.

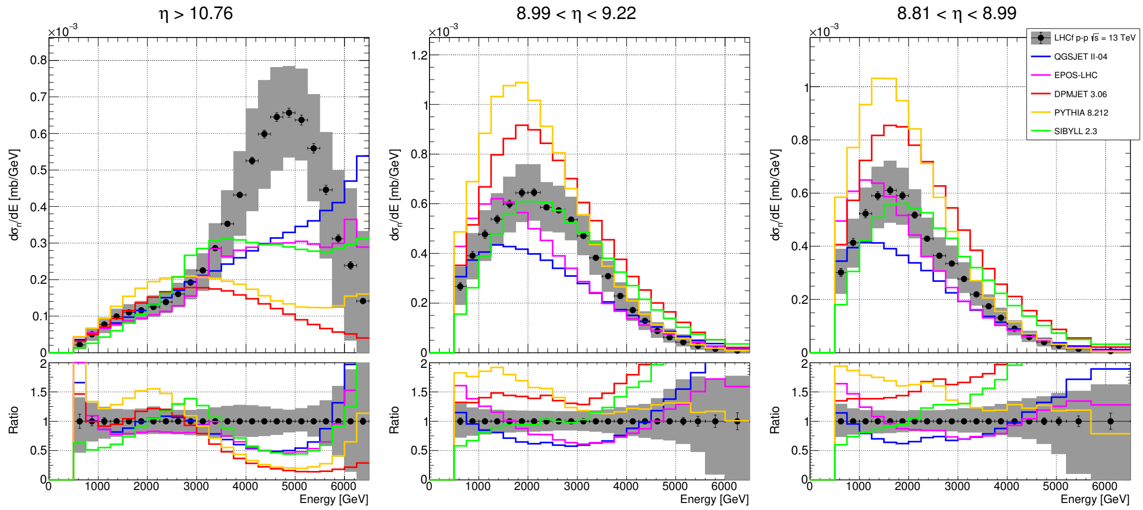

Figure 2: Neutron energy spectrum measured by the LHCf-Arm2 detector at pp, $\sqrt{s}$ = 13 TeV [3]. The black points represent the experimental data with the statistical error bars. The gray hatched areas represent the quadratic summation of statistic and systematic errors. The coloured histograms shows the model predictions. The upper panels shows the energy spectrum as $d\sigma_{\mathrm{n}}/dE$ and the bottom ones shows the ratios of the model to the data.

3.2 Neutral pion measurement at pp, $\sqrt{s}$ = 13 TeV

The measurement of forward π^0 production spectrum is one of the main target of the LHCf experiment. Photons produced from π^0 decays are a main source of electromagnetic cascades in cosmic-ray induced air showers, and the absolute flux and the energy spectrum shape of π^0's affect air-shower development. Our π^0 results at pp, $\sqrt{s}$ = 2.76 TeV and 7 TeV have been published [7]. In this presentation, we apply the analysis method well-established in the past analysis to the data taken by the LHCf-Arm1 detector at pp, $\sqrt{s}$ = 13 TeV.

The π^0 measurement is performed by detecting photon pairs produced from π^0 decays ($\pi^0 \rightarrow 2\gamma$: BR 98.8%) in both or one of the calorimeter towers simultaneously. π^0 kinematic quantities, energy, transverse momentum p_T, and mass, can be reconstructed from the measured energies and impact positions of the photons. We categorise the events into three types of events, π^0 Type 1, Type 2-TS and Type 2-TL, according to which calorimeter tower the photon pair hit. In Type 1, photon pairs are detected by both the towers (one photon in each tower), and in Type 2-TS (TL), they are detected by the smaller (larger) tower. Figure 3 shows the geometrical acceptance of π^0 detection by the Arm1 detector. Only Type 1 can address π^0's with the energies below 1 TeV, while Type 2 have a good acceptance in the high energy and p_T region of π^0's. Thanks to the approximately two times higher collision energy, the p_T coverage is two times wider than that at $\sqrt{s}$ = 7 TeV.

The distributions of reconstructed invariant mass of the detected photon pairs are shown in Fig. 4. Clear peaks corresponding to the π^0 mass are found in the all event types, and the signal window of the analysis are defined as the dashed vertical lines in Fig. 4 placing $\pm 3\sigma$ from the peak value. The contamination of background events into the signal window, which are mostly combinatorial events of two photons originating different π^0's, is estimated by using the events in

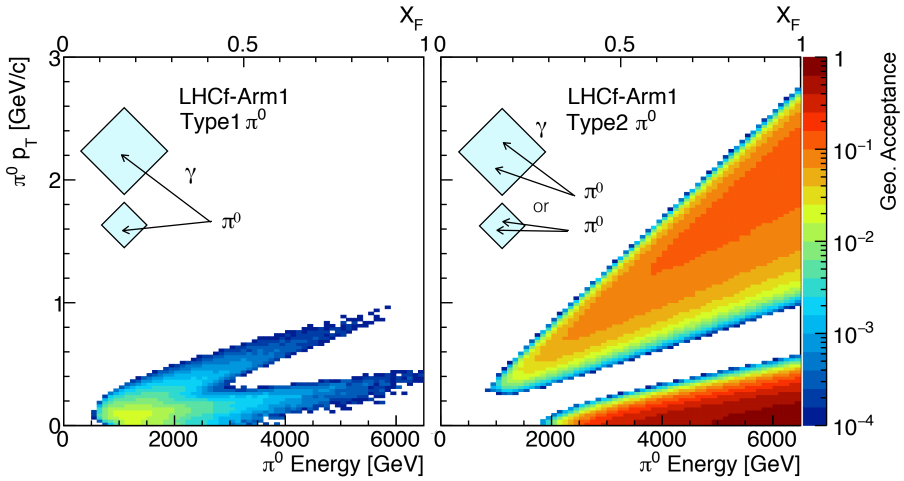

Figure 3: Geometrical acceptance of π^0 detection by the LHCf-Arm1 detector assuming as the energy threshold of photon detection is 200 GeV. The left and right panels show for Type 1 and Type 2 π^0 events, respectively.

the $\pm 6\sigma$ region except the signal region.

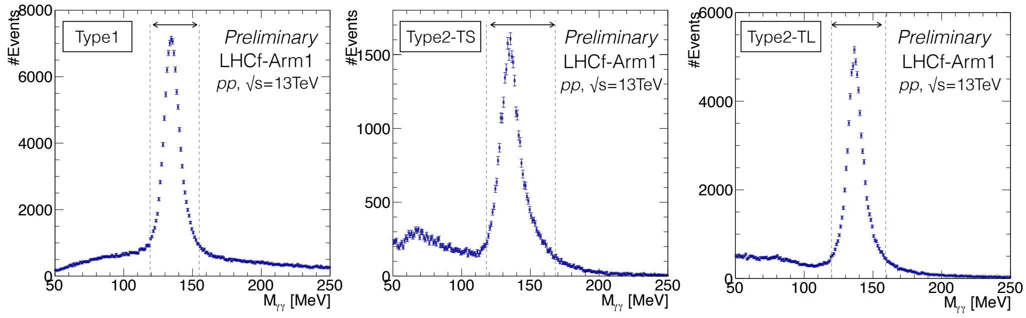

Figure 4: Reconstructed mass distribution from two photons events. The dashed lines and the arrow in each panel indicate the signal window used in this analysis.

Figure 5 shows a preliminary result of measured p_T spectra in each X_F[1] bin. The hatched areas indicate systematic uncertainties of the data points, which are estimated considering 3% energy scale error, the background estimation error, and uncertainties of simulation-driven correction factors. The data points of three event types smoothly connect, and many data points exceeding $p_T of 1$ GeV are obtained. The p_T regions with no data points will be covered by the data obtained by the Arm2 detector, and the data obtained when the detector was moved up by 5 mm.

4. Future prospects

4.1 On-going analyses

In addition to the π^0 analysis, two data analyses of the LHCf-ATLAS joint operation and the RHICf experiment are on-going in parallel.

[1]Feynman X, X_F is defined as $E_{\pi^0}/E_{\rm beam}$, where E_{π^0} is the π^0 energy and $E_{\rm beam}$ is the beam energy, 6.5 TeV.

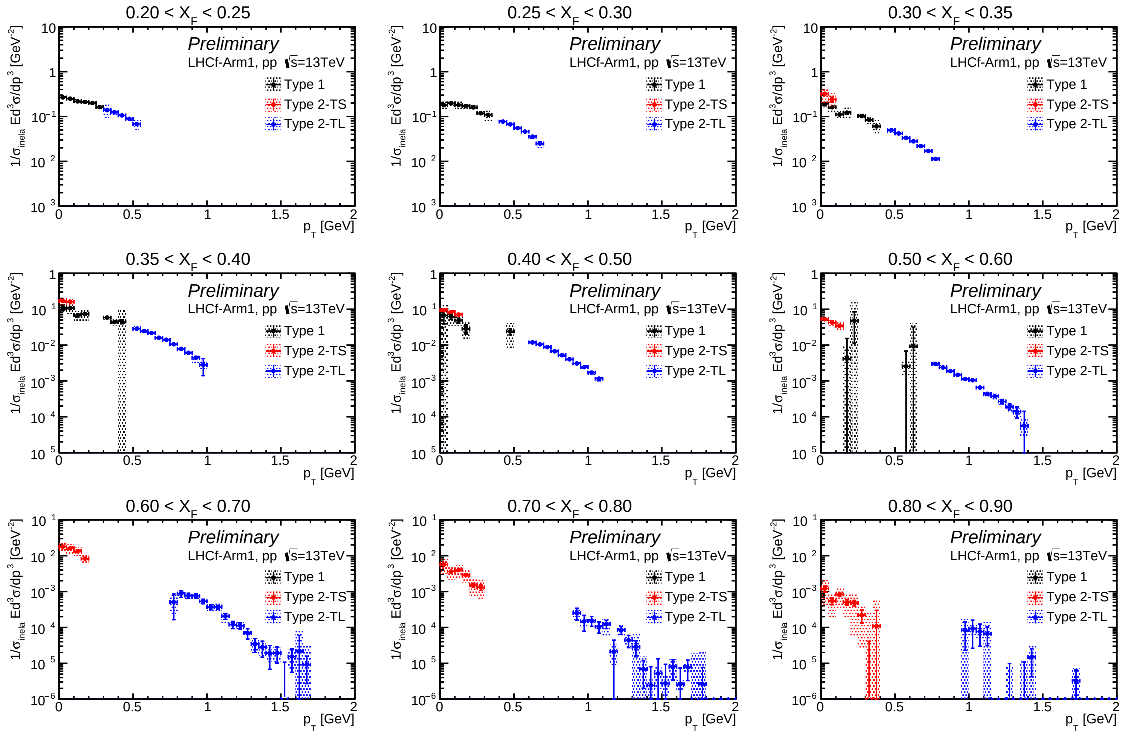

Figure 5: The π^0 production cross-section as functions of p_T and X_F of π^0's, measured by the LHCf-Arm1 detector at pp, $\sqrt{s} = 13$TeV. The error bars and hatched areas indicate statistical and systematic uncertainties, respectively.

The LHCf and ATLAS common data taking has been performed in the past operations by sending LHCf final trigger signals to the ATLAS data taking system. Combining the LHCf measurement with event-by-event central activities measured by the ATLAS detector, more detailed studies about the forward particle production mechanism can be performed. For example, the events at low-mass diffractive collisions were clearly distinguished by simply requiring no charged-particle tracks measured by the ATLAS vertex detector covering the pseudorapidity range $|\eta| < 2.5$ [12]. Such correlation studies between the forward and central particle production are on-going, and we can verify of the different phenomenological approaches implemented in the hadronic interaction models.

The RHIC forward (RHICf) experiment is a similar experiment performed at the Relativistic Heavy Ion Collider (RHIC) at BNL in USA. One of the main purposes is to measure the production spectrum of forward neutral particles at pp, $\sqrt{s}$ = 510 GeV and to test the collision energy dependency of them by comparing with the LHCf data. The operation was successfully completed in June 2017. The detector, which is the LHCf Arm1 detector shipped from CERN to BNL, was installed at 18 m from an RHIC interaction point, and covered the pseudorapidity range $\eta > 6$ including the zero-degree of collisions. The current analysis status is presented in [13].

4.2 Operations during LHC-Run 3

The LHCf plans two new operations in the LHC-Run 3 period, 2021-2023. The first one is an additional operation with pp collisions at $\sqrt{s}$ = 14 TeV (or 13 TeV). This is mainly for dramatically increasing statistics of high energy π^0 events and common events with ATLAS. Increasing the beam luminosity during the operation, in a one-day operation we can record 10 times more statistics of π^0 events than that in the 2015 operation. The operation is scheduled for 2021.

The second operation is with proton and Oxygen collisions. This is an ideal condition to study cosmic-ray interactions in the atmosphere, and it will be the first time to have proton and light ion collisions in the particle colliders. The proton-ion interaction can differ in many important aspects with respect to the more simple case of pp interactions. The difference, so called nuclear effect, can be addressed by the past measurements at pPb collisions, however, Pb is too heavy to study the effect for Nitrogen and Oxygen. In addition, the measurement at pO is experimentally preferable in order to suppress the background from Ultra-Peripheral Collisions (UPCs). UPC is an interaction between a proton and the electromagnetic field of an ion. In the measurement at pPb, UPC contribute approximately 50% and 90% of LHCf detected π^0 and neutron events, respectively. The cross-section of UPCs is propositional to the square of the atomic number, and the background from UPCs becomes a negligible level at pO collisions. The schedule of pO collisions in LHC is under discussion. The most likely period of the run is in 2023.

To achieve these goals, we are upgrading the readout electronics of the silicon detectors used in the Arm2 detector as position sensitive layers, which is a bottleneck of the data taking speed in the current system. Replacing the data transfer method between the electronics and a front-end computer from via a VME bus to a TCP/IP connection, the readout speed will become 10 times faster than that of the current system. The data taking rate of the whole system is expected to be improved from 500 Hz to, at least, 1 kHz. Additionally, a new trigger logic for effectively detecting high-energy electromagnetic shower events including Type 2 π^0 events will be introduced. This was originally designed for the RHICf experiment, and worked successfully [13]. The details of these upgrade and operation plan for LHC-Run 3 operations are described in a LHCf technical report [14].

5. Summary

We measured the neutron and π^0 spectrum by using data obtained in pp collisions at the collision energy of $\sqrt{s}$ = 13 TeV by the LHCf Arm2 and Arm1 detectors, respectively. On the measured neutron energy spectrum in $\eta > 10.74$, a clear peak structure was found around 5 TeV. Any models do not reproduce such structure, and all models predict lower flux than the data. In $8.99 < \eta < 9.22$, and $8.81 < \eta < 8.99$, we found that SIBYLL 2.3 and EPOS-LHC show overall good agreement with the experimental data. Analysing the three types of π^0 events, we obtained the spectrum in a wide p_T range exceeding 1 GeV. The analysis will be updated including other data sets to cover the whole p_T range.

We are now doing analyses of data already obtained at ATLAS-LHCf common operation and the RHICf experiment. They allow us to study detailed properties of forward hadron production in hadronic interactions. In addition to them, preparation for future operations planed for 2021 and 2023 with pp and proton-Oxygen collisions is on-going.

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