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Performances of the LHCf Arm1 detector during $\sqrt{s}$=13.6 TeV p-p operation in 2022

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The LHCf experiment obtained the data in the operation with pp collisions at $\sqrt{s}$ = 13.6 TeV in 2022. The statistics is 10 times larger than that of the previous operation in 2015. This large statistics data allow us to measure the production of strange mesons like η and K^0, and it will improve hadronic interaction models commonly used for simulations of air showers produced by ultra-high energy cosmic rays. The energy scale is one of the most important parameters for analyses of differential production cross-section measurements with the LHCf detectors. This paper presents the stability of the energy scale of the Arm1 detector during the operation in 2022 by using the reconstructed invariant mass of the π^0 meson. As a result, we confirmed that the stability is about 1%.

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1. Introduction

The origin and acceleration mechanism of ultra-high energy cosmic-rays (UHECRs) are unknown. UHECRs are measured by the Telescope array (TA) experiment [1] and the Pierre Auger Observatory (PAO) [2] using surface detectors and fluorescence detectors covering a huge effective area. The mass composition of primary cosmic rays are estimated by comparing experimental data and Monte Carlo (MC) simulation. However, the prediction of X_{max} of air showers produced by primary cosmic rays depends on the hadronic interaction model, and the fact induces a large uncertainty of estimated mass composition of UHECR [3]. In addition, the numbers of observed muons by TA and PAO are 30% more than the prediction calculated with any hadronic interaction models [4]. These problems are due to a poor understanding of hadronic interactions. Hadronic interaction models are based on phenomenological models, and they need to be tuned using experimental data from accelerator experiments.

The LHC-forward (LHCf) experiment was designed to measure neutral particles, which are mainly photons [5] and neutrons [6], produced at a very forward region (pseudorapidity $\eta > 8.4$) of an interaction point of Large Hadron Collider (LHC) for improving the hadronic interaction models. LHCf had the operations with proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV in 2015, and $\sqrt{s} = 13.6$ TeV in 2022. The LHCf measured differential production cross-section of η mesons using the data obtained in 2015. However the precision of the measurement was limited due to poor statistics [7]. In the operation in 2022, thanks to upgrades of the trigger logic and data acquisition (DAQ) systems, we could obtain 10 times more statistics than that of the operation in 2015 [8].

In this paper, we discuss the energy scale stability of an LHCf detector during the operation in 2022. The stability of the energy scale has a significant impact on differential production cross-section results because the spectra of mesons measured by LHCf are very steep [5]. In the LHCf, π^0 candidate events can be used for investigating the stability of the energy scale.

2. LHCf Experiment

The LHCf experiment has two detectors, called Arm1 detector and Arm2 detector, which were installed 141 m apart on either side of the ATLAS interaction point called IP1. In this study, we focused on the Arm1 detector. The Arm1 detector consists of two calorimeter towers, called the large tower and the small tower, and their acceptance are 40 mm × 40 mm and 20 mm × 20 mm, respectively. Each tower has 16 sampling layers of Gd_2SiO_5 (GSO) plates, 4 position-sensitive layers of X-Y GSO bar hodoscopes, and tungsten plates (Fig.2). The thickness of the tower is 44 radiation lengths (X_0), and it is enough to contain electromagnetic showers induced by photons with TeV energies. The energy resolution for photons is 3%, and the position resolution is 0.2 mm.

Energies of incident photon are estimated from energy deposit in each sampling layer. The calibration of each layer has been performed using a electron beams with 200 GeV/c at Super Proton Synchrotron (SPS) in 2021. An energy estimator (E_{est}) was defined as the total of energy deposit (dE_i) from the second layer to the thirteenth layer after some corrections;

$$E_{est} = \sum_{i=2}^{13} dE_i \times Y_i(x, y) \times L_i(x, y) \times S_i \quad (1)$$

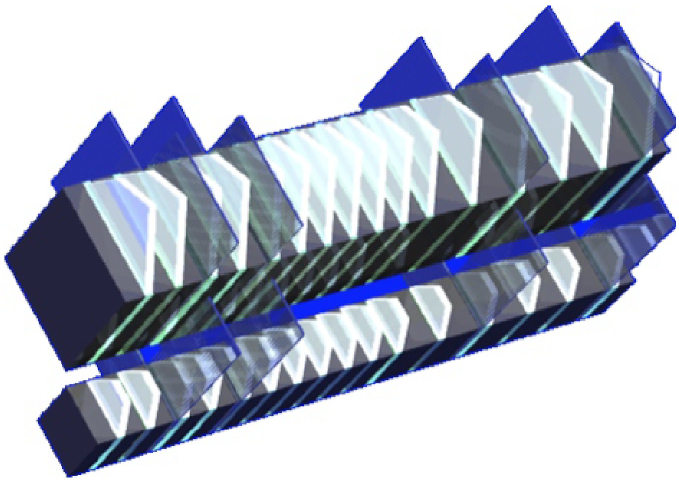

Figure 1: The schematic view of the LHCf Arm1 detector.

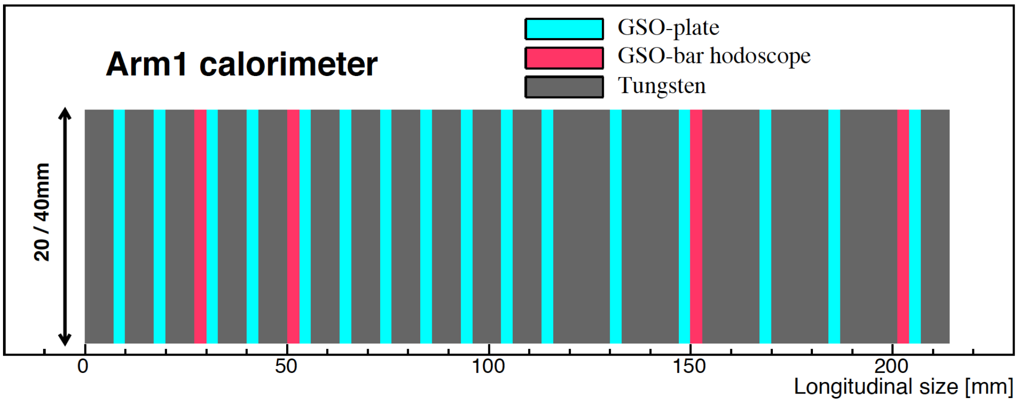

Figure 2: The longitudinal structure of the LHCf Arm1 detector.

where $Y_i(x, y)$ is a position-dependent correction factor of light collection efficiency for the i-th layer, $L_i(x, y)$ is a correction factor of shower leakage, and S_i is the correction factor corresponding to the different sampling step. Finally, the reconstructed energy (E_{rec}) is calculated as $E_{rec} = F(E_{est})$ where $F(E_{est})$ is a second polynominal function defined using a MC simulation.

3. The operation in 2022

The LHCf operation was conducted with pp collisions at $\sqrt{s}$ = 13.6 TeV from September 24 to 26. The bunch intensity was 1.35×10^{13}, and the luminosity was approximately 0.4 $\mu b/s$ at IP1. The most of recorded data was obtained in a very-long operation for about 72 hours, which was performed with switching the vertical position of the Arm1 detector between nominal and 5mm higher positions every 18 hours. The triggers were generated mainly from four trigger modes. One of them was designed to obtain π^0 enrich samples (π^0 trigger). The π^0 triggers were generated if electromagnetic shower with a certain energy are detected in both the two towers. The π^0 trigger rate was 320 Hz, and the recorded rate was approximately 160 Hz due to the readout efficiency of about 50% [8]. In total, 25M π^0-triggered events were obtained.

4. Analysis method

4.1 π^0 invariant mass reconstruction

At pp collisions, many π^0 are produced at IP1, and they are immediately decayed to photon pairs. The π^0 can be measured from two photons detected by the Arm1 detector. The invariant mass of a photon pair is reconstructed from the energies of photons measured by each calorimter tower E_{γ_1} and E_{γ_2}, and the opening angle of two photons θ as follows;

$$M_{\gamma\gamma} = \theta\sqrt{E_{\gamma_1} E_{\gamma_2}} \tag{2}$$

The opening angle θ was calculated from the incident positions of two photons a (Fig.3) on the Arm1 detector and the distance between the Arm1 detector and IP1 (141 m) as follows;

$$\theta = \frac{a}{141} \quad (a \ll 141) \tag{3}$$

In this analysis, we used pi^0 triggered events. The following four event selection were applied to the event sample to select photon candidate events; First, the events hitting near the edge of the calorimeters with less than 2 mm were not used because of poor resolution of both energy and position. Second, only events with reconstructed energies above 200 GeV are used. In these energies, the trigger efficiency for photons is 100%, and contamination of background from the secondary particles and the beam pipes is negligible. Third, a particle identification selection for photons was applied. The parameter of shower development depth L_{90}, which defined as the depth where 90% of the total shower particles contains, was required to be lower than 20 X_0. Last, only events in which only one particle hits each tower are used for better energy reconstruction performance.

Figure 4 shows the distribution of invariant mass reconstructed from photon pairs in the selected events from a sample corresponding to a 100 min operation in 2022 (about 3% of the total statistics). A distinct peak can be seen at 106.8 MeV, which should correspond to invariant mass of π^0 . The peak mass was -20.8% different from the π^0 mass of 135 MeV [9], and it should be due to the energy scale shift. We are investigating the big shift of 20%, which cannot be explained by the estimated calibration uncertainty of 3%.

4.2 Energy scale stability

Even the presence of energy scale shift, we checked the stability of the energy scale of the Arm1 detector during the whole operation period in 2022. The opening angle calculated from the distance between IP1 and the detector, and the distance between the photon hitting positions should be solid, and the stability of the π^0 mass peak position, therefore, corresponds to the stability of energy scale. The peak position was obtained by a Gaussian fitting of the reconstructed mass distribution around the peak.

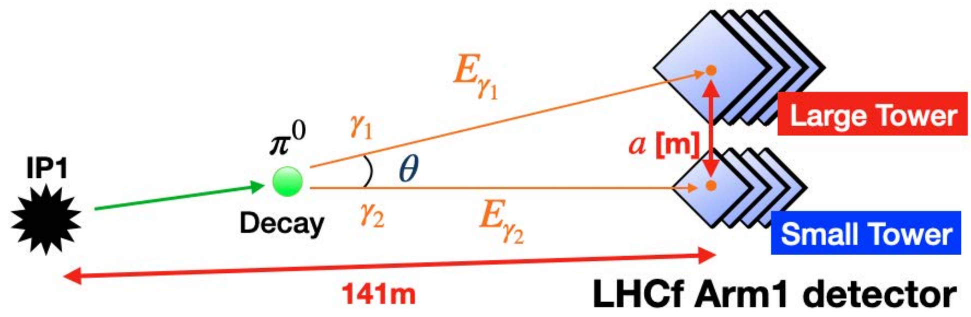

Figure 3: Measurement of π^0 by detecting the two photons inject into each tower of the Arm1 detector.

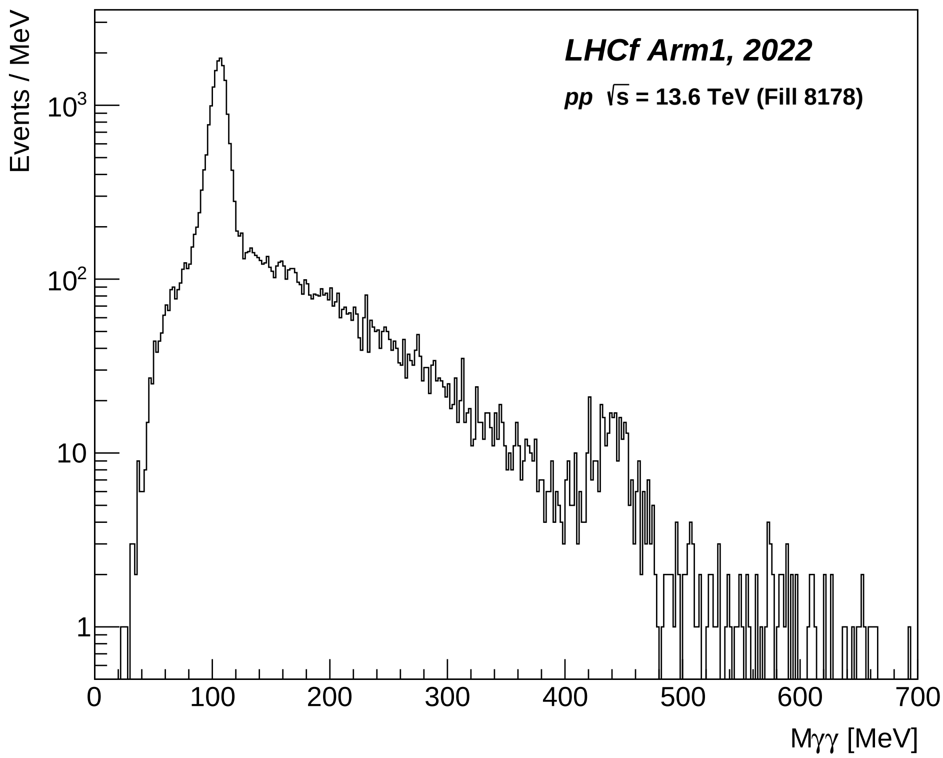

Figure 4: Invariant mass distribution reconstructed from photon pairs for the Arm1 detector by using selected events from a sample corresponding to a 100 mins operation in 2022.

5. Results

Figure 5 shows the stability of the energy scale during the operation in 2022. The horizontal axis is the time. The vertical axis is the obtained π^0 invariant mass normalized by the result for the first one hour. Each data point corresponds to the result for one hour. It was found that the data was decreased about 1% from the first to the last measurement. This energy scale change is lower than the systematic uncertainty of energy scale estimated for analyses with 2015 data (3.4%) [5].

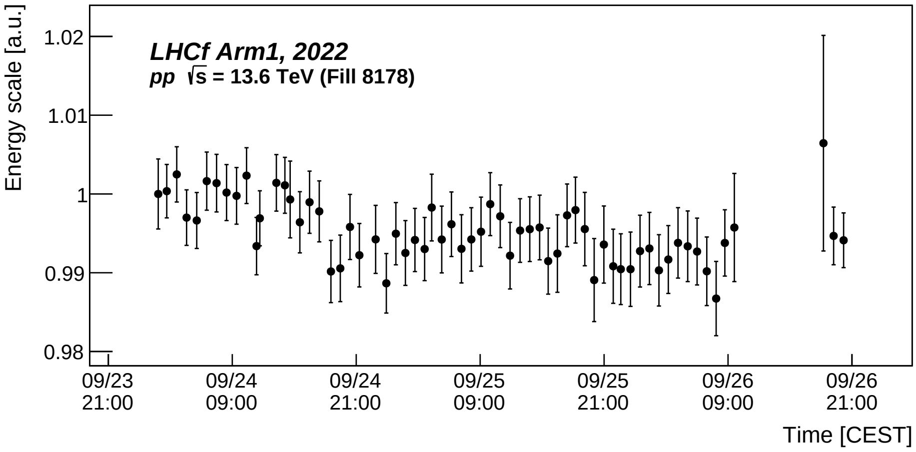

Figure 5: The stability of the energy scale for the Arm1 detector during the operation in 2022.

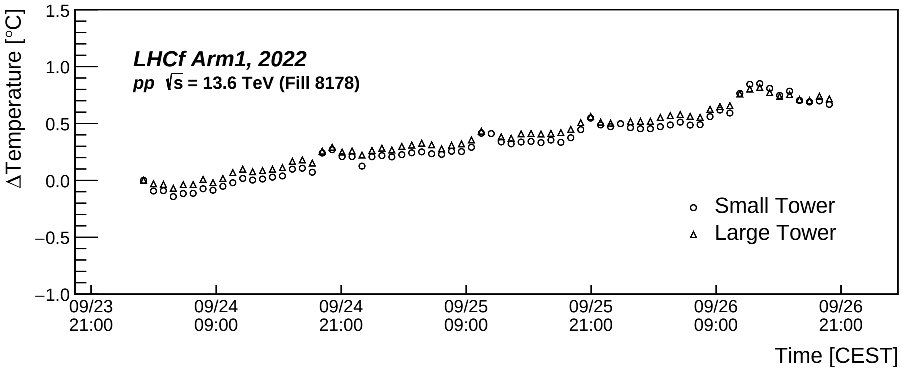

Figure 6: The temperature change of the fourth sampling layer in the Arm1 detector from when the measurement started during the operation in 2022.

The temperature change of the detector is one of the possible reasons for this change. The detector temperatures were monitored by platinum resistance thermometers scotched to PMT holders. The temperature dependence of the gain of PMT is -0.25 % / °C which was measured at a beam test in 2012 in both the two towers [10]. Figure 6 shows the stability of temperature measured by the thermometers of fourth sampling layers during the operation in 2022. The horizontal axis is the time, and the vertical axis is the relative temperature from the first data point. As a result, the temperature was increased by 0.8 °C in both the two towers through the operation. Therefore, the change of the energy scale coursed by the temperature change is estimated to be only -0.18%. Another possible reason is a radiation damage of scintillators, and its quantitative estimation is ongoing.

6. Summary

We investigated the stability of the energy scale for the Arm1 detector using the reconstructed π^0 mass distribution from 25M π^0 triggered events obtained during the operation in 2022. As a result, the stability of the energy scale is stable within 1%. The detector temperature was changed by 0.8 °C, and the contribution to the energy scale change is estimated to be -0.18%. Even sources of this change is not well understood yet, the energy scale can be calibrated using the result.

References

[1] R.Abbasi et al., "Highlights from the Telescope Array experiment" Pos(ICRC2021), 012 (2021).

[2] Pierre Auger Collaboration, "The Pierre Auger Cosmic Ray Observatory" Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Vol.798, doi:10.1016/j.nima.2015.06.058 (2015).

[3] S.Petrera et al, "Recent results from the Pierre Auger Observatory", EPJ Web of Conferences 208, 08001 (2019), doi:10.1051/epjconf/201920808001.

[4] A.Aab et al., "Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events", Phys. Rev. D 91, 032003 (2015), doi:10.1103/PhysRevD.91.032003.

[5] O.Adriani et al., the LHCf Collaboration, "Measurement of forward photon production cross-section in proton–proton collisions at with the LHCf detector", Phys. Lett. B doi:10.1016/j.physletb.2017.12.050 (2018).

[6] O.Adriani et al., the LHCf Collaboration, "Measurement of inclusive forward neutron production cross section in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the LHCf Arm2 detector", JHEP11(2018)073, doi:10.1007/JHEP11(2018)073.

[7] G.Piparo, "Measurement of the forward η meson production rate in p-p collisions at $\sqrt{s}$=13 TeV with the LHCf-Arm2 detector", https://cds.cern.ch/record/2857050 (2023).

[8] The LHCf Collaboration, "LHCf Technical Proposal for the LHC Run3", https://cds.cern.ch/record/2679323 (2019).

[9] R.L.Workmanetal et al, "Particle Data Group 2022", Prog. Theor. Exp. Phys. 2022,083C01(2022).

[10] E.Matsubayashi, "Correction for PMT temperature dependence of the LHCf calorimeters", http://cds.cern.ch/record/2158946 (2015).