EPJ Web of Conferences **283**, 05002 (2023) https://doi.org/10.1051/epjconf/202328305002
UHECR 2022

Status of the LHCf experiment

Ken Ohashi[1,*], *Oscar* Adriani[2,3], *Eugenio* Berti[2], *Pietro* Betti[2,3], *Lorenzo* Bonechi[2], *Massimo* Bongi[2,3], *Raffaello* D'Alessandro[2,3], *Sebastiano* Detti[2], *Maurice* Haguenauer[4], *Yoshitaka* Itow[1,5], *Katsuaki* Kasahara[6], *Yuga* Kitagami[1], *Moe* Kondo[1], *Yutaka* Matsubara[1], *Hiroaki* Menjo[1], *Yasushi* Muraki[1], *Paolo* Papini[2], *Giuseppe* Piparo[7,8,9], *Sergio* Ricciarini[2,10], *Takashi* Sako[11], *Nobuyuki* Sakurai[12], *Monica* Scaringella[2], *Yuki* Shimizu[13], *Tadashi* Tamura[13], *Alessio* Tiberio[2,3], *Shoji* Torii[14], *Alessia* Tricomi[7,8,9], *William C.* Turner[15], and *Kenji* Yoshida[6]

[1]Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan
[2]INFN Section of Florence, Florence, Italy
[3]University of Florence, Florence, Italy
[4]Ecole-Polytechnique, Palaiseau, France
[5]Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya, Japan
[6]Faculty of System Engineering, Shibaura Institute of Technology, Japan
[7]INFN Section of Catania, Italy
[8]University of Catania, Catania, Italy
[9]Centro Siciliano di Fisica Nucleare e di Struttura della Materia, CSFNSM, Catania, Italy
[10]IFAC-CNR, Florence, Italy
[11]ICRR, University of Tokyo, Kashiwa, Japan
[12]Tokushima University, Tokushima, Japan
[13]Kanagawa University, Kanagawa, Japan
[14]RISE, Waseda University, Shinjuku, Tokyo, Japan
[15]LBNL, Berkeley, California, USA

Abstract. A precise understanding of hadronic interactions is essential to interpreting the mass composition of ultra-high energy cosmic rays from the results of air shower experiments. The Large Hadron Collier forward (LHCf) experiment aims to measure forward neutral particles for validation of hadronic interaction models adopted in air shower simulations. We already published the production cross sections of forward photons and neutrons for proton-proton collisions at $\sqrt{s}$ = 13 TeV. Recently, we showed a preliminary result of the energy spectrum of forward η mesons for proton-proton collisions at $\sqrt{s}$ = 13 TeV. Moreover, in September 2022, we had another data-taking for proton-proton collisions at $\sqrt{s}$ =13.6 TeV. In data taking, we planned to obtain a number of π^0 and η candidates ten times larger for precise measurements and to perform the joint operation with ATLAS Roman pots and zero-degree calorimeters. Thanks to the joint operation with the ATLAS Roman pots, we can measure diffractive mass and neutral particles from diffractive dissociation simultaneously. Furthermore, energy resolution for neutrons is expected to be improved from 40% to 20% by combining the LHCf and the ATLAS zero-degree calorimeters. In this work, we report the status and prospects of the LHCf experiment.

1 Introduction

The origin of the ultra-high energy cosmic rays is unknown. The acceleration at the source and the propagation from the origin to Earth depends on the charge of these cosmic rays and therefore on the composition of these cosmic rays. These cosmic rays have been measured by air shower experiments such as the Pierre Auger Observatory [1] and the Telescope Array experiment [2]. The depth of maximum of the air shower development, X_{max}, and the number of muons on the ground were widely adopted for the mass-sensitive observables. The interpretation of the composition has been performed by comparing the measurements of these observables and their predictions by Monte Carlo simulation. However, predictions for both X_{max} and the number of muons show a large uncertainty due to the hadronic interaction models. Large uncertainty makes the interpretation challenging. In particular, the number of muons measured by the experiments was much larger than expected by the simulations [3]. This problem is known as the muon deficit problem. The ratio of pions to kaons in particle production of each hadronic interaction can be a source of the muon deficit problem [4]. Thus, the production of strange mesons is important. Furthermore, the large uncertainty in pion-nucleus collisions affects both X_{max} and muon components in air showers.

The Large Hadron Collider forward (LHCf) experiment measures forward neutral particle productions at the Large Hadron Collider (LHC). It shares the interaction point with the A Toroidal LHC Apparatus (ATLAS) experiment; thus, a common analysis using the LHCf de-

*e-mail: ohashi.ken@isee.nagoya-u.ac.jp

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

tectors and the ATLAS detectors can be performed. We completed the data taking of proton-proton collisions at $\sqrt{s} = 0.9, 2.76, 7,$ and 13 TeV and proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ and 8 TeV. Photons, π^0, and neutrons in the forward regions were measured. For proton-proton collisions with $\sqrt{s} = 13$ TeV, for example, measurements of forward photons [5] and neutrons [6] were published and the preliminary result for π^0 was shown [7]. Moreover, forward photons produced in diffractive dissociation were analyzed by the common analysis of the ATLAS and LHCf experiments [8]. However, several measurements are still missing: measurements of forward strange mesons, measurements of high-energy pion-proton collisions using the one-pion exchange process in the proton-proton collisions, and measurements of proton-light nucleus collisions.

Recently, we focused on the analysis of forward η mesons using data taken in 2015 and on the new data-taking in 2022. In this work, we present a preliminary result for the forward η mesons, the status of the common analysis, and the data-taking successfully completed in September 2022.

2 Status of the analysis of proton-proton collisions of $\sqrt{s} = 13$ TeV

2.1 Preliminary result of forward η meson

The η meson is one of the mesons that consists of strange and other quarks. It decays into two photons with a branching ratio of 39.14% [9]. We can reconstruct the meson from the two photons measured by the LHCf-Arm2 detector. The preliminary result of the η meson was shown in [10] and the final result is in preparation.

The analysis was performed using data taken between June 12th and 13th, 2015 (LHC Fill 3855), a special low luminosity run with $\beta^* = 19$ m. The half crossing angle was 145 μrad. Two data sets were used for the analysis; one is the data taken from 22:30 June 12th to 1:30 June 13th (CEST). The other is the data taken from 1:40 to 12:10 on June 13th. The collisions per bunch crossing ranged from 0.007 to 0.012 for the first data set and from 0.03 to 0.04 for the second data set. The integrated luminosity was 0.194 nb^{-1} and 1.9378 nb^{-1} for the first and second data sets, respectively.

The energy and positions were reconstructed from the energy deposit in each layer and measured by silicon microstrip layers. Several event selection criteria were applied to select events with photon-like signals in the both calorimeter towers of the LHCf-Arm2 detector. Events with a hit in 2mm from the calorimeter edge or with a reconstructed energy less than 200 GeV were removed. Photon-like events were selected using the longitudinal development of signals in the calorimeter. The depth $L_{90\%}$ that 90% of energy deposit was observed in a calorimeter tower was calculated and adopted as a parameter of the longitudinal development. An electromagnetic shower induced by a photon shows a larger energy deposit in the first several layers of the calorimeter tower, thus we can select photons by selecting events with small $L_{90\%}$. Events with more than one particle hit in a calorimeter tower were removed.

The invariant mass of two photons was reconstructed from the energy and positions of two photons by assuming a decay at the interaction point. Using the opening angle of two photons, θ, the invariant mass is calculated as follows;

$$M_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\theta)}, \qquad (1)$$

where E_1 and E_2 are the energy of two photons. We found that the mass of π^0 was shifted by -2.57 ± 0.04%. Thus the mass was artificially shifted the energy of single photons by -2.65% to correct the position of the π^0 mass peak to the reference value. The left plot of Fig. 1[10] shows the invariant mass distributions around the mass of the η meson. The distributions were fitted by an asymmetric Gaussian function and the third-order Chebyshev polynomial function for signals and backgrounds, respectively. The region within 3σ from the peak was considered as signal region, and the region from 4σ to 7σ from the peak was considered as background region. The energy spectrum of the backgrounds was estimated by scaling the spectrum of the events in the background regions and then we subtracted them from the events in the signal regions.

Correction factors were applied to the signal distributions; acceptance and selection efficiency was corrected using MC simulations. The branching ratio was corrected by the constant value. The inefficiency due to multi-hit rejections was corrected using the fraction of multi-hit events in each bin. Systematic uncertainties due to energy scale, beam center stability, particle identification, background subtraction, luminosity, and correction factors were considered. The right plot of Fig. 1[10] shows the preliminary result of the production cross sections of η for $P_{\mathrm{T}} < 1.10$ GeV. The black points are the results of the LHCf-Arm2 detector. Predictions by hadronic interaction models are shown by the solid color lines. QGSJET II-04 shows the best agreements among the models.

2.2 ATLAS-LHCf common analysis

After the preliminary result in [8], the common analysis of the ATLAS and LHCf collaborations is focusing on two directions: the energy spectrum of photons from single diffractive dissociation and the correlation between forward hadrons and the number of particles in central regions for the modeling of the multi-parton interaction. The latter was proposed in Ref. [11]. We are preparing the final result for the former and finalizing the analysis for the latter.

3 Data-taking of proton-proton collisions at $\sqrt{s} = 13.6$ TeV

3.1 Upgrades from the last data-taking and the common data-taking with ATLAS detectors

Several upgrades were applied for new data-taking in 2022. One is the upgrade to the LHCf-Arm2 detector. The other is the common data-taking with ATLAS detectors.

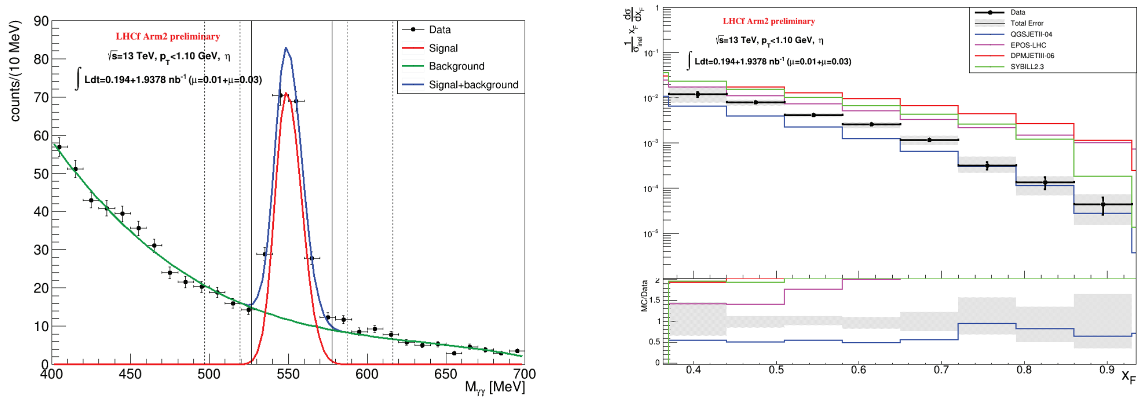

Figure 1. (left) Invariant mass distribution reconstructed from two photons [10]. (right) Production cross-sections of η meson [10].

The former one is the upgrade of read-out of the silicon microstrip layers of the LHCf-Arm2 detector. It allows us to improve read-out time and therefore the trigger rate. The latter one is the common data-taking with Zero degree calorimeters (ZDC) and Roman pots detectors of the ATLAS experiment. Figure 2 shows a schematic view of the common data-taking. Three modules of the ATLAS-ZDC detector were installed behind each LHCf detector. The thickness of the LHCf detectors to hadrons is 1.6 interaction length, therefore, not enough to measure hadrons precisely. By installing ATLAS-ZDC detectors, we can improve the energy resolutions for hadrons from 40% to approximately 20% [13]. Moreover, the common data-taking with the Roman pots detectors and the LHCf detectors allows us to measure both protons and particles in the dissociation system in single diffractive dissociation.

3.2 Physics targets

We have four main physics targets; a) precise measurements of π^0, η, and K^0 mesons, b) the measurements of pion-proton collisions using the one-pion exchange process, c) measurements of diffractive dissociation using the LHCf detectors and the Roman-pot detectors, d) measurements of Δ^+.

a Precise measurements of the π^0, η, and K^0 mesons

Measurements of π^0 and η mesons were performed using the data taken in 2015, while statistics of these mesons were limited. In particular, η meson candidates were approximately 1500 events and not enough to analyze p_{T} dependencies. Thanks to the upgrade in the read-out of the LHCf-Arm2 detector, we can measure ten times larger statistics of π^0 and η candidates than the previous data-taking. Moreover, we expect a few hundred K_s^0 candidates.

b The measurements of pion-proton collisions using the one-pion exchange process

Measurements of the one-pion exchange process in proton-proton collisions allow us to measure cross sections and particle productions in high-energy pion-proton collisions [14]. For measurements of the one-pion exchange process, we need to precisely measure the energy and positions of each neutron. By combining the ATLAS-ZDC and LHCf detectors, we can measure neutrons with good precisions: approximately 20% energy resolutions and better than 0.3 mm for position resolutions. By combining information from the ATLAS inner detector, we can reject contributions from the other processes and measure the one-pion exchange process [15].

c Measurements of diffractive dissociation using the LHCf detectors and the Roman-pot detectors

In the single diffractive dissociation, one proton is produced and particles are produced in the forward regions on the opposite side to the proton. The proton and the particles on the opposite side can be measured by the ATLAS Roman pots detectors and the LHCf detector, respectively. In this way, we can measure the diffractive mass and particles produced in dissociation simultaneously. It helps us to understand particle productions in diffractive dissociation.

d Measurements of Δ^+

By measuring a proton and a π^0 produced on the same side, we can measure Δ^+ produced in the forward regions if exists. The predictions of forward Δ^+ vary among hadronic interaction models, thus we can constrain predictions of hadronic interaction models.

3.3 Data-taking

The data-taking was successfully operated from 23rd to 26th September 2022. It was a special low-luminosity run with $\beta^* = 19$ m and the number of collisions per bunch crossing $\mu \sim 0.04$. Figure 3 shows the statics over time. We had approximately 48 hours of data-taking during this operation. We performed the data-taking with two detector positions to increase the detector coverage; the beam center position and the 5 mm higher position. The total statistics taken during this operation is approximately 300 million events.

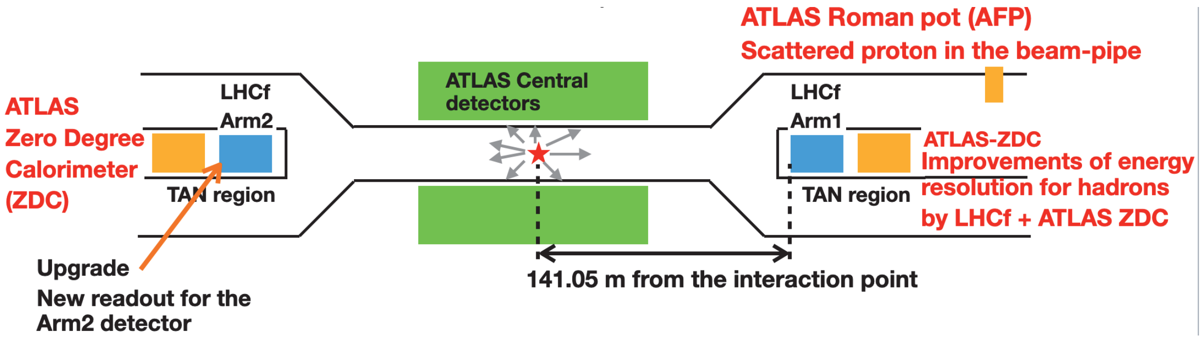

Figure 2. A schematic view of detector configurations of the data-taking in Sept. 2022.

The two-photon invariant mass distribution was calculated using the quarter data set of the LHCf-Arm2 beam-center position. Events with a photon in each calorimeter tower were selected. Figure 4 shows the preliminary two-photon invariant mass distributions. We found two peaks corresponding to π^0 and η mesons. Although a quarter of the one data set was analyzed, we have large statistics for π^0 and η candidates. The position of the peak is lower than expected. The detector is needed to be calibrated. We had a beam test of detectors a the Super Proton Synchrotron in October 2022 and will calibrate the energy scale later.

4 Summary

The LHCf experiment measures forward neutral particles to improve hadronic interaction models. Recently, we showed the preliminary result of forward η meson productions in proton-proton collisions at $\sqrt{s}$ = 13 TeV. QGSJET II-04 shows the best agreements among models. Moreover, we successfully completed the data-taking of proton-proton collisions at $\sqrt{s}$ = 13.6 TeV in September 2022. We took the larger number of π^0 and η candidates. It was confirmed using the invariant mass distributions of two photons. We found the shift of the peak position corresponding to π^0 and η mesons. Thus, we will perform the detector calibration using the test-beam data taken at the Super Proton Synchrotron in October 2022. In parallel, we will finalize the analysis of data taken in 2015 and start the analysis of data taken in 2022.

References

[1] A. Aab et al., The Pierre Auger Cosmic Ray Observatory, Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 798, 172 (2015), doi:10.1016/j.nima.2015.06.058, 1502.01323.

[2] R. Abbasi et al., Highlights from the Telescope Array experiment, In Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021), vol. 395, p. 012, doi:10.22323/1.395.0012 (2021).

[3] L. Cazon et al., "Working Group Report on the Combined Analysis of Muon Density Measurements from Eight Air Shower Experiments", In Proceedings of 36th International Cosmic Ray Conference — PoS(ICRC2019), vol. 358, p. 012, doi:10.22323/1.358.0214 (2021).

[4] J. Albrecht, L. Cazon, H. Dembinski et al., The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider, Astrophys.Space Sci. 367 (2022) 3, 27

[5] O. Adriani et al., the LHCf Collaboration, Phys. Lett. B 780 (2018) 233–239.

[6] O. Adriani et al., the LHCf Collaboration, JHEP07(2020)016.

[7] A. Tiberio et al., PoS (ICRC2021) 386, https://pos.sissa.it/395/386/.

[8] The ATLAS and LHCf Collaborations, ATLAS-CONF-2017-075, https://cds.cern.ch/record/2291387.

[9] P.D.G., R. Workman, V. Burkert, V. Crede, E. Klempt, U. Thoma, L. Tiator, K. Agashe, G. Aielli, B. Allanach, et al., Review of particle physics, Progress of theoretical and experimental physics 2022, 083C01 (2022).

[10] G. Piparo et al., To be published in the Proceedings of The Tenth Annual Conference on Large Hadron Collider Physics PoS(LHCP2022). The paper with the final result is in preparation.

[11] S. Ostapchenko, M. Bleicher, T. Pierog, and K. Werner, Phys. Rev. D 94 (2016) 114026.968 https://link.aps.org/doi/10.1103/PhysRevD.94.114026.

[12] LHCf Collaboration, "LHCf—Technical Proposal for the LHC Run 3." https://cds.cern.ch/record/2679323.

[13] M. Kondo et al., in this proceedings

[14] V.A. Petrov et al., Eur. Phys. J. C (2010) 65: 637—647.

[15] K. Ohashi et al., PoS (ICRC2021) 190, https://pos.sissa.it/395/190/.

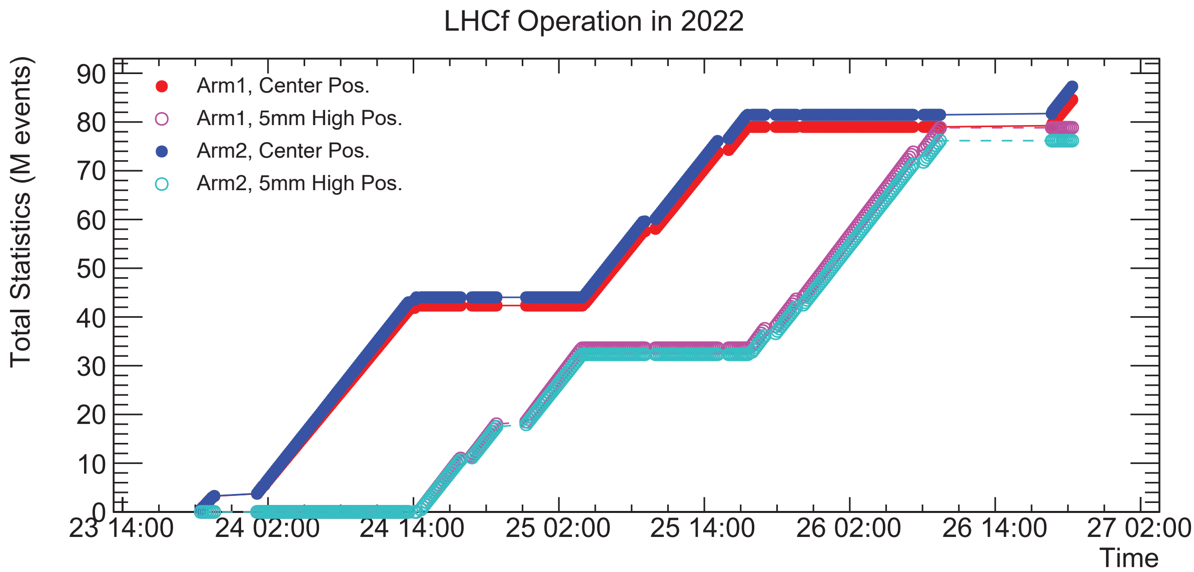

Figure 3. Total statistics in the data-taking.

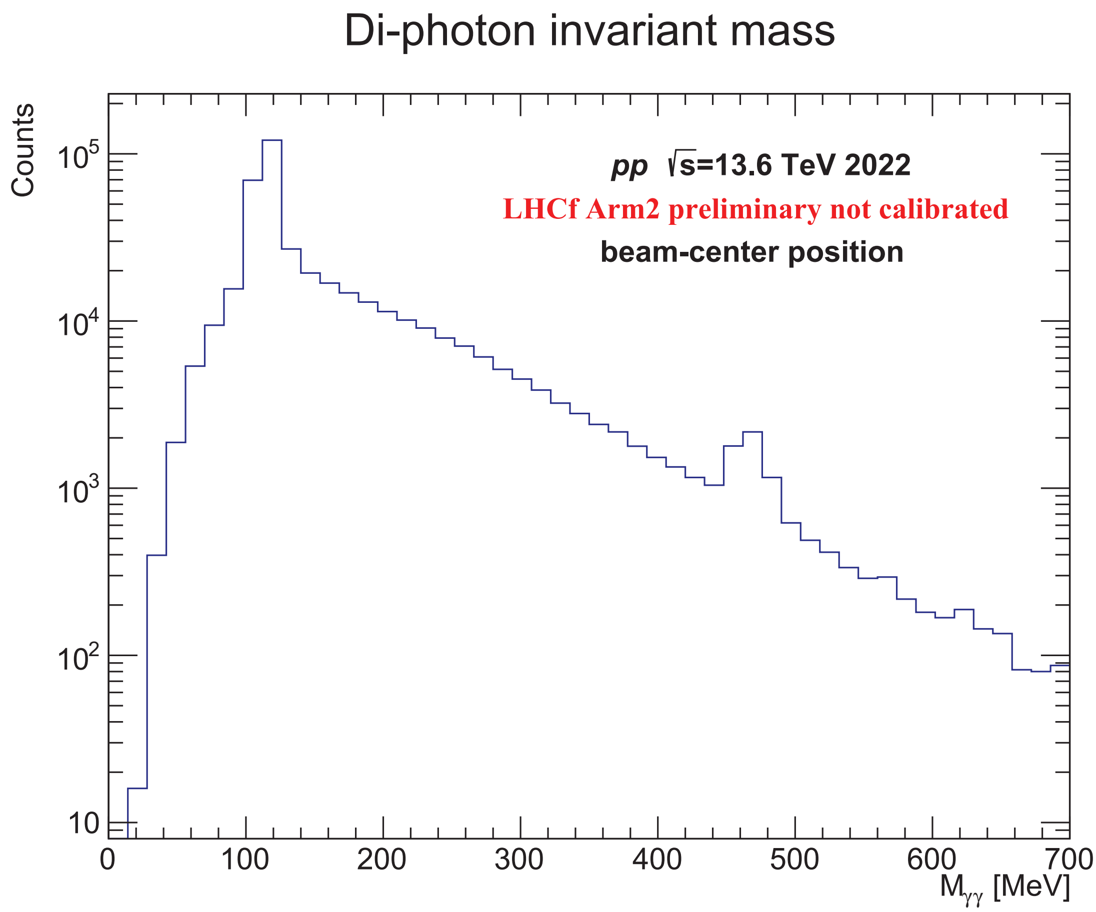

Figure 4. Preliminary invariant mass distribution reconstructed from the two photons for the LHCf-Arm2 detector. A quarter of the total statistics for the beam-center positions were analyzed.