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The performance of the new LHCf detector for hadronic showers

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The Large Hadron Collider forward (LHCf) experiment is designed to understand the hadronic interaction between cosmic rays and the atmosphere. We have measured neutral particles, photons and neutrons, in very forward region of $\sqrt{s} = 13$ TeV proton-proton collision at CERN-LHC. Before this operation, the LHCf detectors were updated in 2014 by replacing the plastic scintillators with GSO scintillators to improve radiation-hardness. In this paper, we present the performance of the one of the new LHCf detectors for hadronic showers evaluated by a beam test at CERN–SPS and MC simulations. The energy resolution and position resolution are found to be 42 % and 0.9 mm, respectively, at the center of the detector for a 350 GeV proton beam. We confirmed the new detector performance is consistent with the performance of the old detector used in the 2010 operation as expected.

KEYWORDS: UHECRs, the Large Hadron Collider, Very-forward neutron production

1. Introduction

Forward particle production in the hadronic interactions is one of the crucial points to understand the development of cosmic rays air showers. The Large Hadron Collider forward (LHCf) experiment is designed to understand the hadronic interaction between cosmic-ray and atmosphere [1]. It measures neutral particles, mainly photons and neutrons, emitted in very forward region of the LHC. The measurement of neutron production in hadronic interaction enables us to know inelasticity.

The LHCf experiment has measured forward particles in proton–proton collisions at $\sqrt{s} =$ 900 GeV, 2.76 TeV, 7 TeV and 13 TeV. Before the measurement in $\sqrt{s} = 13$ TeV proton–proton collision, we upgraded the detectors to improve the radiation resistance. Due to the upgrade, we confirmed the performance of the LHCf detectors using accelerator beams and Monte Carlo simulations. We already completed the performance study for electro-magnetic showers [2]. In this paper, we report the performance of the LHCf detectors for hadronic showers.

2. The LHCf detectors

The LHCf experiment has two independent detectors named "Arm1" and "Arm2". In this paper, we show the results of the Arm1 detector. The LHCf Arm1 detector is made of two calorimeter towers. The transverse dimensions of the calorimeter towers are 20 mm × 20 mm and 40 mm × 40 mm. Both calorimeters are composed of 16 layers of sampling scintillation panels interleaved with tungsten plates and position sensitive detectors. Position sensitive detectors are made of four pairs of X–Y position layers. Each layer consists of a bundle of Gd_2SiO_5(GSO) scintillator bars with 1 mm × 1 mm cross section [3].

3. The SPS beam test

The performance of the new calorimeters for hadronic showers was studied in 2015 by using 250 to 350 GeV proton beams at the CERN–SPS H4 beam line. Beam was injected to the LHCf detector after passing through the trigger scintillators and the ADAMO silicon strip trackers [4]. MC simulations were also performed to compare with the results of the beam tests. For the MC simulations, we used the COSMOS(v.7.645) and EPICS(v.9.165) packages [5]. We selected DPMJET3.0-4 as hadronic interaction model to simulate the detector response.

4. Analysis and results

4.1 Position reconstruction and resolution

The transverse hit positions were measured by four pairs of X–Y position layers. First, we chose a layer which is the nearest to the shower maximum. Then, we fitted the lateral distributions by,

$$f(x) = \frac{A_1}{\pi}\left[\frac{\gamma_1}{(x - X_{ARM1})^2 + \gamma_1}\right] + \frac{A_2}{\pi}\left[\frac{\gamma_2}{(x - X_{ARM1})^2 + \gamma_2}\right] \tag{1}$$

where $A_{1,2}$ are size parameters, $\gamma_{1,2}$ are width parameters. The first and second terms characterized with the suffixes 1 and 2 describe the sharp and broad components of the lateral distribution. X_{ARM1} is the peak position of the distribution in the Arm1 position detector.

The performance of the position reconstruction is estimated by comparing the hit positions determined by the LHCf position detector and by the ADAMO tracker. Figure 1 shows the distribution of residuals of the LHCf detected position from the ADAMO detected position for 350 GeV proton incident. The position resolution is defined as the Full Width at Half Maximum of the distribution. Finally, the position resolutions are 1.2 mm, 1.0 mm and 0.9 mm for 250 GeV, 300 GeV and 350 GeV proton beams, respectively. This result is consistent with the position resolutions of the old detecter.

4.2 Energy reconstruction and resolution

Because of the limitation of the detector size, a fraction of shower particles leaks out from the detectors. Also, the light collection efficiency depends on the beam incident position. To correct these effects, we computed correction factors. In the simulation, we included the light collection maps [2] and injected 1 TeV neutron beam to whole the detector. The shower leakage correction factor by,

$$f(x, y) = \frac{\langle S'(x, y)\rangle}{\langle S'_{center}\rangle} \tag{2}$$

where S' means the sum of the particle energy deposition at the scintillator layers. '(x,y) 'and 'center ' mean the incident position and the detector center, respectively. Figure 2 shows the shower collection rate as a function of the detector position for the Arm1 20mm calorimeter.

We also computed the energy conversion coefficient using the same simulation setup as the one used to determine the shower collection rates. Figure 3 shows the energy response function for the Arm1 small calorimeter obtained by MC simulation. We fitted this relation using linear function and obtained a function,

$$E = 88.9S + 10.7[GeV] \tag{3}$$

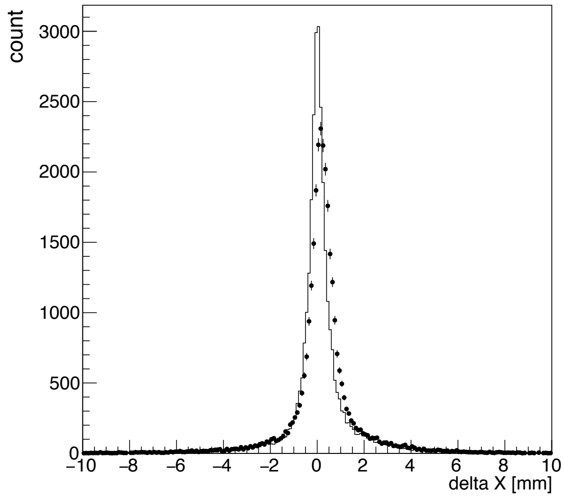

Fig. 1. The difference between the GSO-bar detected position and "true" hit position measured by the ADAMO tracker in the case of a 350 GeV proton beam for Arm1 small tower. The black points correspond to the experimental data and the histogram corresponds to the MC simulation.

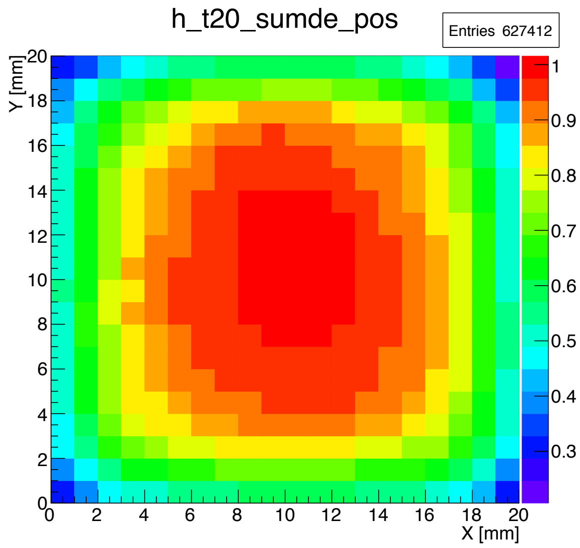

Fig. 2. The position dependence of fraction of energy deposit. The X and Y axes show the incident position.The color shows the shower collection normalized to the value at the center.

Here S means the energy deposit in the detector after shower leakage correction using Formula 2 and E means reconstructed particle energy.

Figure 4 shows the reconstructed energy distribution for the 350 GeV proton beam. We estimated energy resolution as standard deviation / mean of the distribution. The energy resolution was 41.7 % at 350 GeV and was found to be almost independent from beam energies. Also we found that the MC simulation results are consistent with the experimental data.

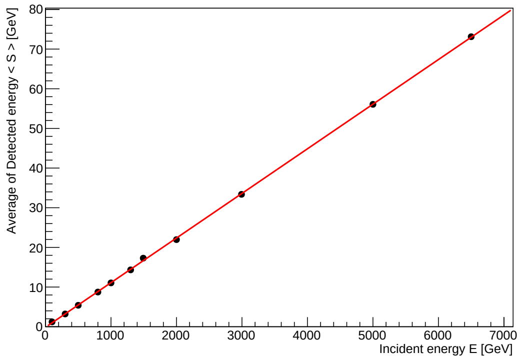

Fig. 3. The energy response function for the Arm1 small calorimeter obtained by MC simulation with DPMJET3.0-4.

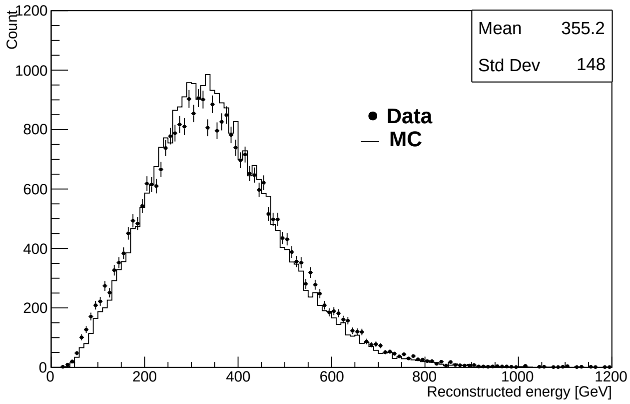

Fig. 4. The reconstructed energy distribution in the case of the 350 GeV proton beam. The black points show the experimental data and the histogram shows the MC simulation.

5. Summary

The performance of the new LHCf detectors were studied by using 250 – 350 GeV proton test beams and MC simulations. We determined the position by fitting the lateral shower distributions and found that the position resolution was 0.9 – 1.2 mm. We found the energy resolution was about 42 %. These results are consistent with the performance of the old detectors.

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