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Performance evaluation of LHCf-ATLAS ZDC joint measurement using proton beam

LHCf Collaboration
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Abstract. Measurements of forward neutrons in pp collisions will allow us to investigate π-p cross-section via one-pion exchange process, which are important for air shower development. However, the precision of these measurements is limited by the energy resolution of the LHCf detectors. To improve it, a joint measurement with the ATLAS ZDC was planned. In 2021, a beam test was conducted to evaluate the performance of the joint measurement of the LHCf-Arm1 and ZDC detectors using proton beams of 350 GeV at SPS. Combining the LHCf data with the ZDC data, we confirmed that the energy resolution improved from about 40% to 21.4%.

1 Introduction

The muon excess and model discrepancy of mass composition of ultra-high energy cosmic rays are mainly caused by a poor understanding of high-energy hadronic interaction [1]. Especially for high energies, π interactions are hardly understood. To study the hadronic interaction and to contribute to improving the models, LHC-forward (LHCf) experiment [2] measures neutral particles emitted to the very forward region of pp collision at the Large Hadron Collider (LHC). If LHCf detects the neutron energy properly, we can tag the one pion exchange events [3]. From the one pion exchange, we will be able to measure total cross-section and multiplicity of π-p interactions using a joint operation data of LHCf and ATLAS. For these reasons, the LHCf experiment is expected to contribute more to model improvement due to the improved energy resolution for neutrons. Energy resolution for neutrons will be improved by combining energies deposited in LHCf with that in the ATLAS Zero Degree Calorimeter (ZDC), located immediately downstream of the LHCf detector.

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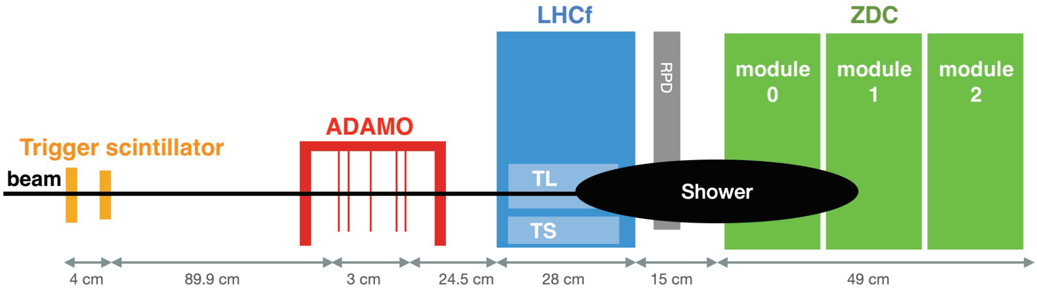

Figure 1. Experimental setup of the beam test. Beams were injected from the left-hand side, and they passed through trigger scintillators, ADAMO, LHCf, and ZDC in that order.

2 LHCf experiment and Arm1 detector

LHCf detectors are located 140 m apart on either side of the ATLAS Interaction point (IP1). One is called Arm1 and the other Arm2. We measure photons, π^0s, and neutrons. Arm1 detector consists of two sampling calorimeter towers, the Large Tower (TL) and the Small Tower (TS). Each tower has a sandwich structure of 16 layers of GSO plates, 4 layers of GSO-bar XY hodoscopes, and 16 layers of tungsten plates. The total length is $44X_0$[1] and $1.6\lambda_I$[2]. The energy resolution for neutrons is ~40%. The position resolution is better than 1 mm for neutrons [5].

3 Strategy of the operation in 2022

The LHCf had an LHC operation with proton-proton collisions at $\sqrt{s}$ = 13.6 TeV during the low-luminosity special run period scheduled for September 2022. To improve the energy resolution for neutrons, LHCf performs a joint operation with ZDC detector. Three hadronic modules of the ZDC detector [6], called as ZDC-HAD, were installed behind the LHCf detector. Each module consists of tungsten layers and fused-silica fiber layers, and produced Cherenkov lights in the fibers were read by a PMT. The interaction length of the ZDC-HAD modules is $3.4\lambda_I$, and the total interaction length of LHCf and ZDC-HAD detectors is $5.0\lambda_I$. Therefore, most of the hadron shower can be contained and the energy resolution is expected to be improved.

4 Beam test at SPS in 2021

4.1 Experimental setup

We conducted a beam test at the H4 beam line of SPS at CERN from 24th to 28th September 2021 to verify the performance of the joint measurement and to calibrate the energy. A set of trigger scintillators and a silicon tracker (ADAMO) were installed in front of the LHCf and ZDC detectors as shown in Fig. 1. ADAMO is a silicon strip detector, and it precisely determines the position of incident particles. Proton beams with 350 GeV/c were injected to the detectors with changing the position of detectors. In total, 860 k events were collected.

[1] X_0 is the radiation length.
[2] λ_I is the interaction length. For reference, $1\lambda_I$ of tungsten is 191.9 g/cm^{-2} [4].

4.2 Analysis

4.2.1 Event quality cut and incident position cut

Events with only one track observed in ADAMO were selected to remove the events affected by pile-up and with showering in materials of the beam line. By projecting the track at ADAMO to the LHCf detector, the incident positions of the beam particles were determined. Moreover, a cut to select event with beam position in a 8 mm squared area in the center of the TL was applied.

4.2.2 Energy Reconstruction

Total energy deposit in LHCf and ZDC detector was used as the energy estimator of the hadronic showers. The energy deposit in the LHCf-Arm1 detector, E_{LHCf}, was calculated from the summation of energy deposit in 16 scintillator layers after pedestal subtraction and gain calibration. The energy deposit of ZDC, E_{ZDC}, was obtained as a simple summation of pedestal-subtracted ADC counts from three ZDC modules because of non-availability of gain parameters in this moment. Leaked shower particles from the LHCf detector were measured in the ZDC detector. So, we were able to see the anti-correlation between LHCf energy deposit and ZDC energy deposit (Fig. 2). Considering the difference of the energy scale between E_{LHCf} and E_{ZDC}, the total energy deposit of the two detector, $E_{\mathrm{LHCf+ZDC}}$, was defined using the function;

$$E_{\mathrm{LHCf+ZDC}} = E_{\mathrm{LHCf}} + a \times E_{\mathrm{ZDC}} \tag{1}$$

where a is a energy scale factor, which was obtained by fitting the correlation plot of Fig. 2 with a linear function. The value of α is ~ 0.0089 ± 0.0006.

4.3 Result

Figure 3 shows the distribution of obtained $E_{\mathrm{LHCf+ZDC}}$ in the selected events. The $E_{\mathrm{LHCf+ZDC}}$ values were scaled as the mean value of the distribution to 350 GeV, and it is called 'corrected energy'. The corrected energy distribution from only the LHCf-measured energies was shown for the comparison. The energy resolution was estimated from the fitting result of the distribution by a gaussian function from 200 GeV to 500 GeV. The obtained energy resolution for LHCf + ZDC was 21.4%, which is considerably better than the 46% achieved by LHCf alone.

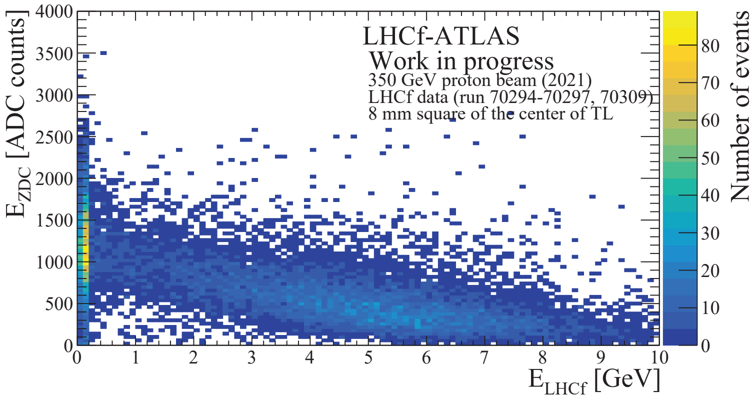

Figure 2. Correlation of the energy deposit in LHCf and the ZDC. The horizontal axis shows the total of LHCf energy deposit [GeV]. The vertical axis shows the summation of three ZDC modules' ADC counts.

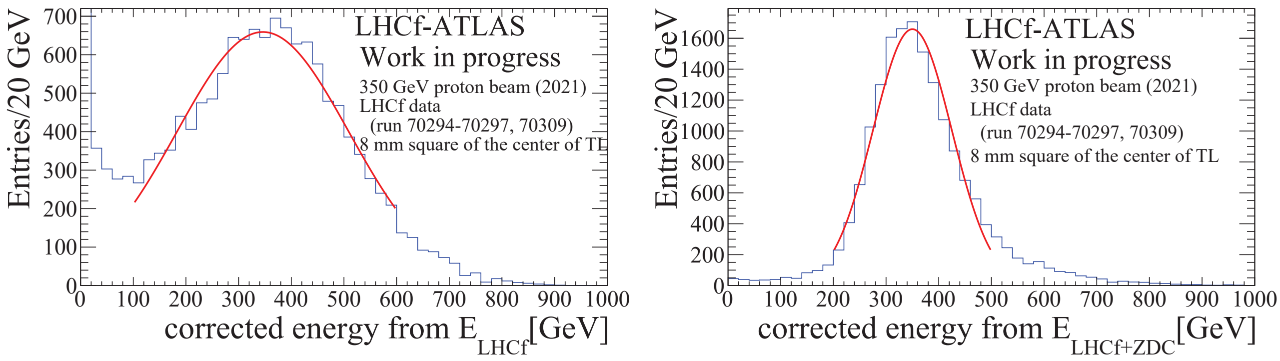

Figure 3. The distributions of 'corrected energies'. The red curves show Gaussian fits to the data. (left) Corrected energy from total energy deposit of LHCf only. (right) Corrected energy estimated from the summation of total energies in LHCf and ZDC. $a \sim 0.0089 \pm 0.0006$ was used as the scale factor of Eq.(1).

5 Summary

By analyzing data taken with 350 GeV proton beams at the SPS H4 beam line, we characterized the energy resolution resulting from joint operations of the LHCf and ATLAS ZDC detectors. The resolution was measured to be 21.4%. This value represents a strong improvement compared to the 46% resolution achieved by LHCf alone. The combined method will be applied to the data obtained with proton-proton collisions at $\sqrt{s}$ = 13.6 TeV at LHC in September 2022 for studying the π-p interactions.

Finally, we would like to thank the staff of the SPS and the North area test beam facility for making this beam test possible.

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