Energy correction for the BGO calorimeter of DAMPE using an electron beam*

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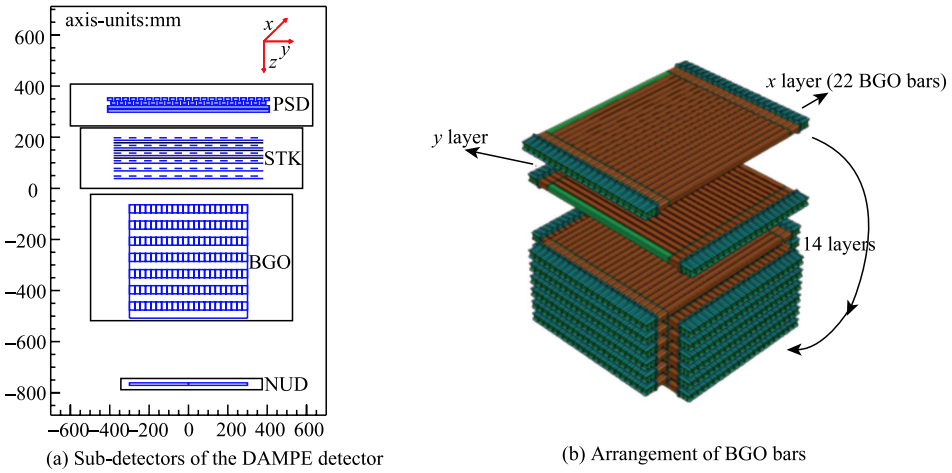
Abstract: The DArk Matter Particle Explorer is an orbital indirect dark matter search experiment which measures the spectra of photons, electrons and positrons originating from deep space. The electromagnetic calorimeter (ECAL), made of bismuth germinate (BGO), is one of the key sub-detectors of DAMPE, and is designed for energy measurement with a large dynamic range from 5 GeV to 10 TeV. In this paper, methods for energy correction are discussed, in order to reconstruct the primary energy of the incident electrons. Different methods are chosen for the appropriate energy ranges. The correction results of Geant4 simulation and beam test data (at CERN) are presented.

Keywords: dark matter, BGO ECAL, energy correction, beam test

PACS: 29.30.Dn, 29.40.Vj, 29.85.+c **DOI:** 10.1088/1674-1137/40/8/086202

1 Introduction

The DArk Matter Particle Explorer (DAMPE) is an indirect dark matter search mission launched at the end of 2015, which measures the spectra of photons, electrons and positrons within a large energy range (from 5 GeV to 10 TeV) with an energy resolution of 1.5% at 800 GeV in space. The DAMPE detector consists of four sub-detectors [1, 2]: the Plastic Scintillator Detector (PSD), the Silicon Tungsten Tracker (STK), the BGO ECAL and the Neutron Detector (NUD) (Fig.1(a)). The PSD provides cosmic ion discrimination and also identifies electrons from photons. The STK gives tracking



(a) Sub-detectors of the DAMPE detector (b) Arrangement of BGO bars

Fig. 1. Structure of the DAMPE detector and the BGO ECAL.

Received 9 November 2015, Revised 29 April 2016

∗ Supported by the Chinese 973 Program (2010CB833002), the Strategic Priority Research Program on Space Science of the Chinese Academy of Science (XDA04040202-4) and 100 Talents Program of CAS

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information and e/γ identification. The BGO ECAL is designed as a total absorption detector, measuring the energy deposition due to particle shower and imaging the shower development profile, thus providing a hadron background rejection. The NUD, at the bottom of the detector, improves the e/p identification capacity. The BGO ECAL is composed of 14 layers of BGO crystal bars interleaved crosswise in two dimensions, about 31 radiation lengths in total longitudinally. Each layer consists of 22 BGO bars (25 mm×25 mm×600 mm). Since there exist 2.5 mm gaps of dead material for support between bars of the same layer and 4 mm gaps between layers (Fig. 1(b)), the energy loss in the transverse gaps (between BGO bars) and in the longitudinal gaps (between layers) has to be dealt with in shower energy reconstruction.

2 Electron energy correction of the BGO ECAL

When an electromagnetic cluster in the BGO ECAL is defined, the energy contained in the cluster of calorimeter cells is less than the energy of the incidence electron. This is possibly due to energy losses in the dead material between bars of both the same layer and adjacent layers and also in front of the calorimeter. To recover the incidence energy from the measured energy, some correction methods were tested to find those that fit DAMPE best. The emphasis of this paper is on correcting the deposited energy of the beam test electrons below 300 GeV. We tried the last layer method and similar ones [3], and for <300 GeV, the electron shower is well contained by the 31 radiation-length calorimeter, although for a higher energy range around 800 GeV to 10 TeV, backward energy leakage correction would be necessary. The shower transverse profile method [4] would not yield satisfactory results because the granularity of the BGO array is not fine enough. Finally, two main methods, namely $S1/S3$ and F-Z (as described below), were chosen in different energy ranges. The data used for this work was obtained from a beam test experiment conducted in November 2014 at CERN, and Monte Carlo (MC) data of electrons from Geant4-based programs.

2.1 Description of methods

The BGO calorimeter, as mentioned above, contains dead material between crystal bars. For electrons passing through the calorimeter in different positions as shown in Fig. 2, the simulation data (Fig. 3) shows that energy deposits are quite different with electrons injecting positions. In Fig. 2, arrow 1 represents electrons hitting the BGO bars (corresponding to the red peak with least energy loss and number 1 in Fig. 3); arrow 2 stands for electrons hitting the gaps of dead material in the x-dimension and crystals in the y-dimension (corresponding to the wide green peak with medium energy loss and number 2 in Fig. 3); arrow 3 means electrons hitting the gaps of dead material in the y-dimension and crystals in the x-dimension (corresponding to the wide light blue peak with medium energy loss and number 3 in Fig. 3); arrow 4 represents electrons hitting the gaps of dead material both in the x-dimension and y-dimension (corresponding to the wide spread spectrum with most energy loss and number 4 in Fig. 3).

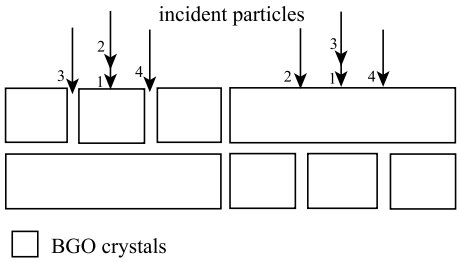

Fig. 2. (color online) Possible incidence electron positions. Left is dimension x, and right is dimension y.

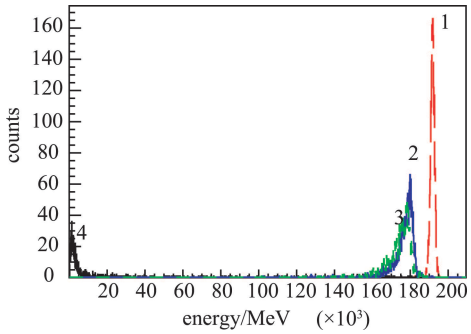

Fig. 3. (color online) The distribution of energy deposit of 200 GeV electron beam source with a spot size of a few centimeters (MC data). The red peak numbered 1 stands for electrons hitting the BGO bars, the green peak numbered 2 for electrons hitting the gaps in the x-dimension, the light blue peak numbered 3 for electrons hitting the gaps in the y-dimension, and the dark blue peak numbered 4 for the electrons hitting the gaps in both x-dimension and y-dimension.

2.1.1 $S1/S3$ method

The $S1/S3$ method [5, 6] takes into consideration small dead material between neighboring cells, especially cells of the same layer. For layer i, the maximum energy deposited in a bar is $s1[i]$, and the energy deposited in this bar and in its two adjacent bars is $s3[i]$, then the $S1/S3$ ratio x is defined as

$$x=\frac{S1}{S3}=\frac{\sum\limits_{i}s1[i]}{\sum\limits_{i}s3[i]}. \quad (1)$$

Parameter F is defined as the ratio of the energy given by the calorimeter against the incident energy. The effect of dead material between cells appears to be related to the ratio x. Using 5 GeV simulated electrons with Gaussian intensity beam spot of a diameter of 4 cm, perpendicularly injected to the ECAL, the relation between the ratio x and $F(x)$, the fraction of measured to incidence energy is evaluated event-by-event. The distribution of $F(x)$ versus x from a 50000-event sample is displayed in Fig. 4 (blue triangle). The empirical Equation (2) with a constant term and a linear term is used to fit the Monte Carlo data with parameters F_0, x_0, k and x_1.

$$F(x)=\begin{cases}F_0 & x<x_0\\ k(x-x_0)+F_0 & x_0\leqslant x<x_1\end{cases}. \tag{2}$$

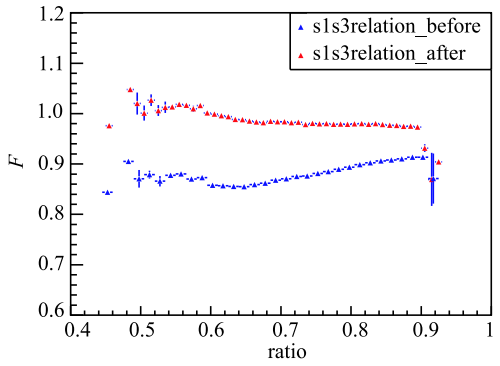

Fig. 4. (color online) $S1/S3$ ratio x-energy fraction F relation before and after correction of 5 GeV simulated electrons.

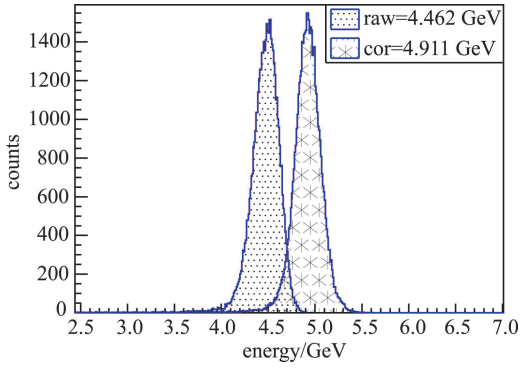

Fig. 5. Energy distribution before and after $S1/S3$ correction of simulated 5 GeV electrons; "raw" indicates raw data energy and "cor" corrected energy.

With the optimized parameters, the incident energy can be restored, $E_i = E_{\rm raw}/F(x)$ event by event. The red triangle in Fig. 4 shows the distribution of corrected $F(x)$ versus x. The features of the fit parameters will be discussed in the following sections. As shown in Fig. 4, the F value after correction is much closer to 1.0, while before correction it could vary from 0.84 to about 0.92. The effect of the $S1/S3$ correction method for 5 GeV electrons is displayed in Fig. 5. It can be seen that the mean of the energy distribution before the correction is around 4.5 GeV while after $S1/S3$ correction it becomes closer to the incident 5 GeV.

2.1.2 F-Z method

The F-Z method [7] is used to recover energy loss in both gaps between BGO bars of the same layer and gaps between the layers. The F-Z method uses the parameter F defined as mentioned above in 2.1.1, and Z is defined as the shower development longitudinal barycenter of the incident electrons (defined in Equation (3)). Z_i is defined as the longitudinal position of the i-th layer center.

$$Z=\frac{\sum\limits_i E_i Z_i}{E_{\rm tot}} \tag{3}$$

E_i is defined as the energy deposit in layer i. The Z value is measured by the radiation length of the BGO crystal. The F-Z relation of the 50 GeV electrons obtained from Geant4-based simulation is shown in Fig. 6.

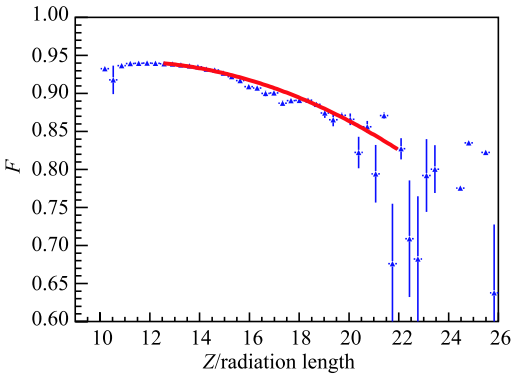

Fig. 6. (color online) F-Z relation of 50 GeV electron simulation data.

The F-Z relation indicates that with the Z value getting larger, the ratio of energy measured by the BGO calorimeter against the incident energy of electrons would become smaller. The larger Z value means the electron goes through more BGO crystal layers, which could cause more energy loss in gaps between the layers. The F-Z relation is fitted by a quadratic function (Equation (4)) (The fitting curve is shown as the red line in Fig. 6).

$$F(z)=p_0+p_1 z+p_2 z^2 \tag{4}$$

2.2 Choice of methods

The most suitable method for a given energy range is chosen according to its energy correction performance. The $S1/S3$ method is not applied to higher energies because, for example, as shown in Fig. 7, the fit function

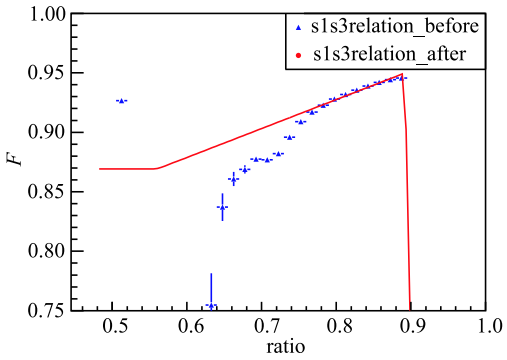

Fig. 7. (color online) $S1/S3$ ratio x-energy fraction F relation of 50 GeV electrons (MC data, red line from fit function Eq. (2)).

can-not describe the relation well, because the $S1/S3$ method does not account for gaps between layers properly. The ratio-F relation for 50 GeV electrons is more curved than linear, so the fit function used for the $S1/S3$ correction would no longer be suitable. Therefore, for energies above 35 GeV, the $S1/S3$ correction method is replaced by the F-Z method. The F-Z method is able to cover the energy range of 35 GeV to 300 GeV. The parameters used here and in the following energy corrections are obtained from the beam test data and are studied for both methods.

2.3 Study of energy dependence of the fit parameters

2.3.1 $S1/S3$ method parameter-energy relation

To study the energy dependence of the fit parameters, MC data samples with various electron energy ranges from 3 GeV to 300 GeV were produced and reconstructed. Plots like Fig. 4 and Fig. 6 were obtained and parameter fits are made with Eq. (2) and Eq. (4), respectively. As shown in Fig. 8, the fit parameters in Equation (2) of the $S1/S3$ method do not fluctuate much with regard to energy changes. As mentioned in Section 2.2, the $S1/S3$ method can-not be applied to higher energy so the energy range in Fig. 8 is 3 GeV to 35 GeV. All the parameter-energy relations shown in Fig. 8, Fig. 9, Fig. 10 and Fig. 11 are fitted with constant functions. This result indicates that it is sufficient to use the same set of parameters for different energy points within the energy range of 3 GeV to 20 GeV for beam test data.

2.3.2 F-Z method parameter-energy relation

MC data samples of 35 GeV to 300 GeV are used to study the energy dependence of the parameters in Eq. (4). Figure 9 shows there is no significant energy dependence of the fit parameters in Eq. (4). According to Fig. 9, it is viable to use the same set of parameters throughout the energy range of 50 GeV to 300 GeV for beam test data.

2.4 Parameter-incidence angle relation

The beam test experiment also uses electrons above 50 GeV with different incidence angles ranging from 0° to 30°, and studies have been carried out with Geant4-based simulation to investigate the relation between incidence angles and fit parameters, which can be seen in Fig. 10 (50 GeV simulated electrons). Within polar angles from 0° to 30°, the fit parameters do not vary significantly with incident angle changes. From beam test data, there exists no transverse energy leakage caused by incidence angles.

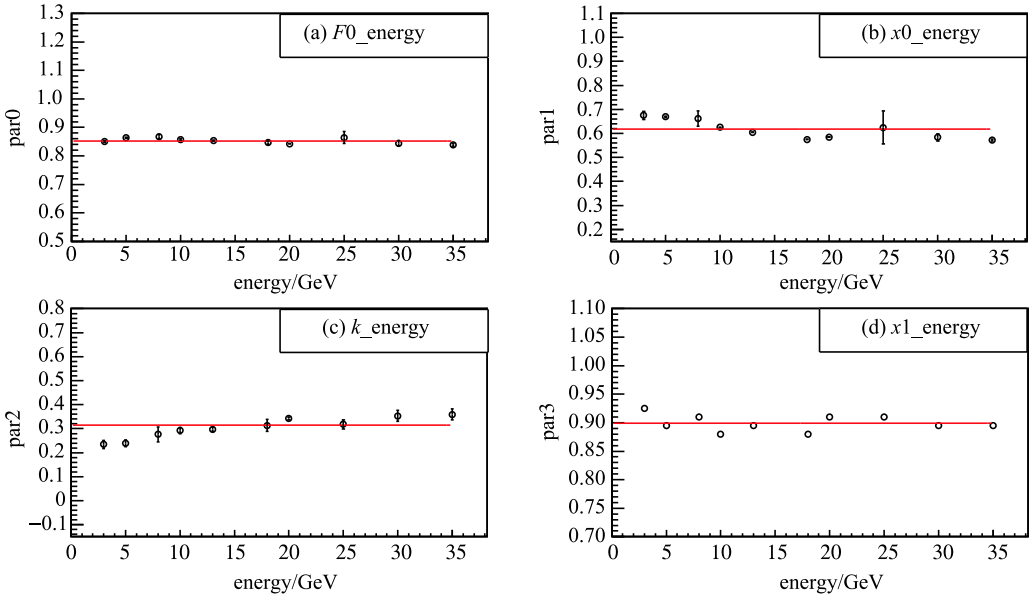

Fig. 8. Parameter-energy relation of $S1/S3$ method.

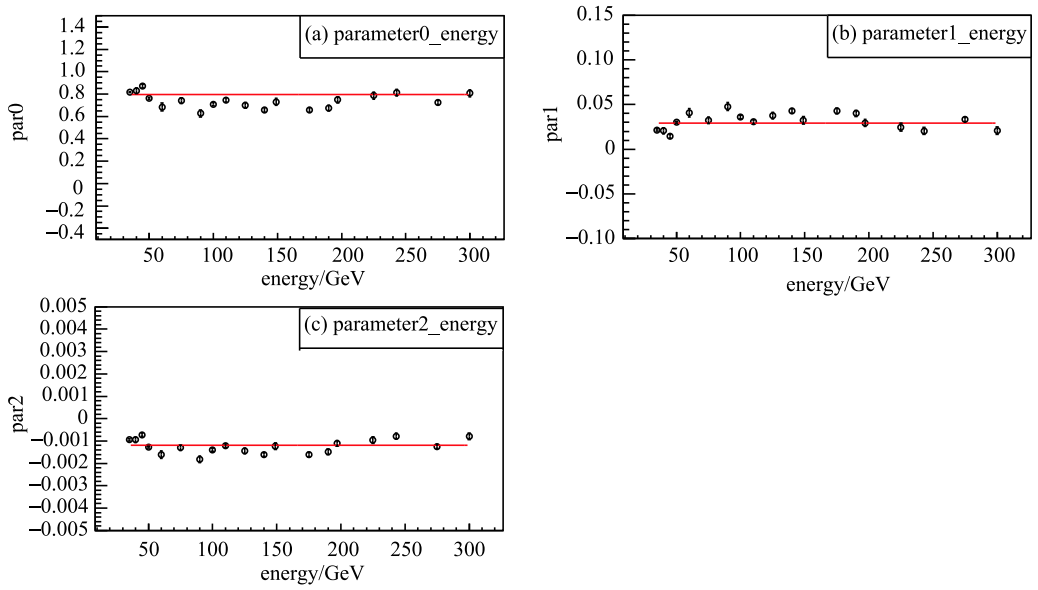

Fig. 9. Parameter-energy relation of the F-Z method. Electrons with incidence angle of 0°.

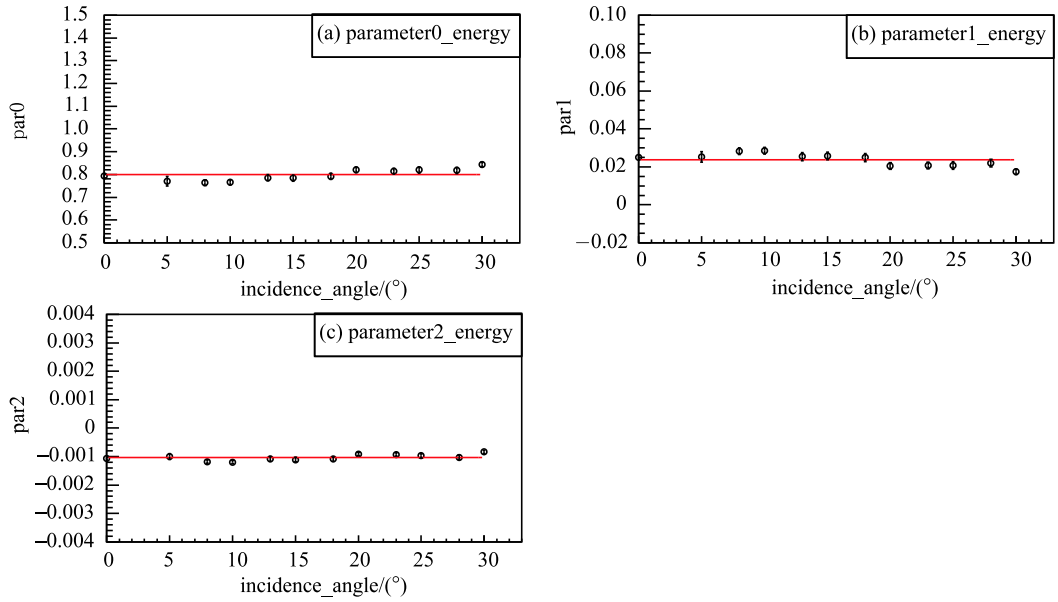

Fig. 10. Parameter-incidence angle relation of 50 GeV simulated electrons.

To study the influence of electron energy on fit parameters at a given incidence angle, more simulations were conducted. No evidence indicates that variation of fitting parameters of electrons with incidence angles is energy-dependent for electron energy above 50 GeV (as shown in Fig. 11).

3 Correction results of beam test data

The energy correction results for the electron beam test data using the $S1/S3$ method at 5 GeV (Fig. 12(a)) and results using F-Z method 100 GeV(b) are shown in Fig. 12 as examples. Figure 13 shows the energy correction results for beam test data with F-Z method at incidence angles of 5°(a) and 30°(b). Table 1 lists the fractions of the reconstructed energies and the energy resolutions before and after correction. The reconstructed energies and the energy resolutions before and after correction are displayed in Fig. 14.

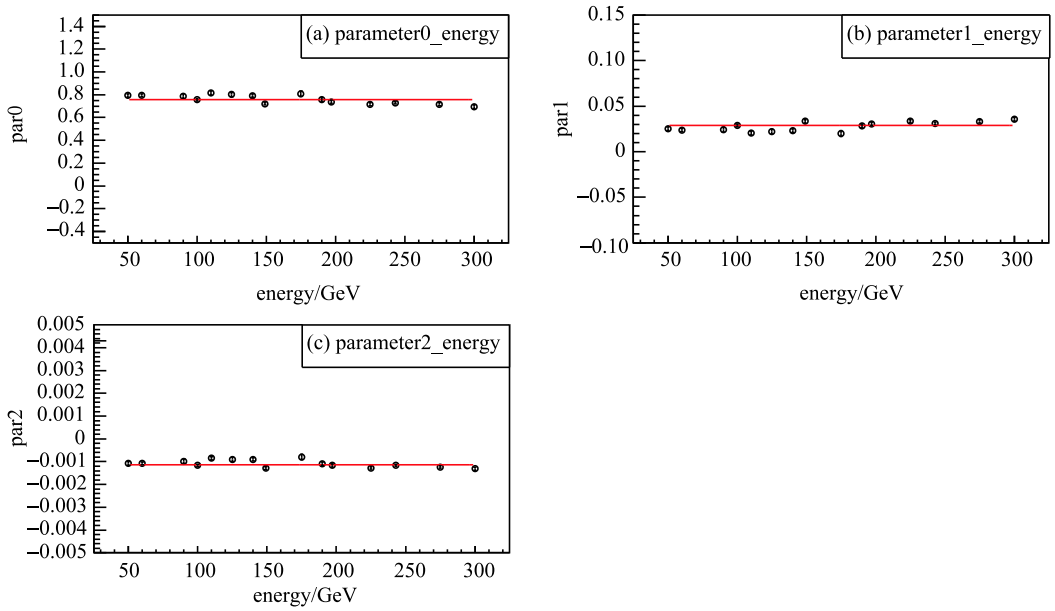

Fig. 11. Parameter-energy relation of simulated electrons with incidence angle of 15°.

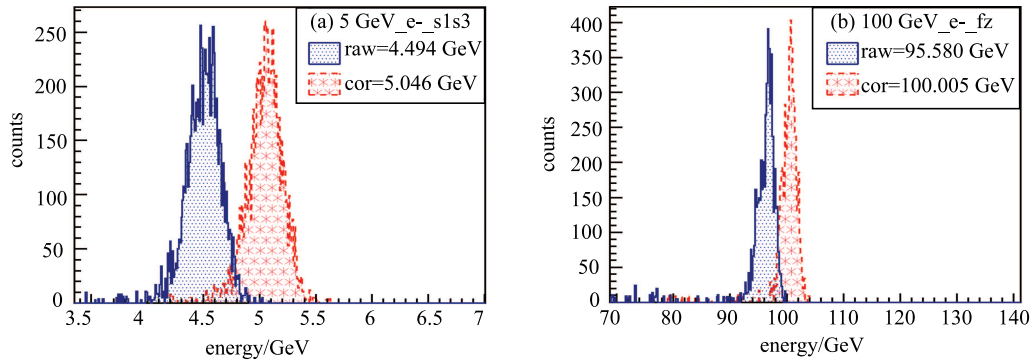

Fig. 12. Beam test electrons energy distribution before and after correction; "raw" indicates mean energy for raw data and "cor" mean energy after correction.

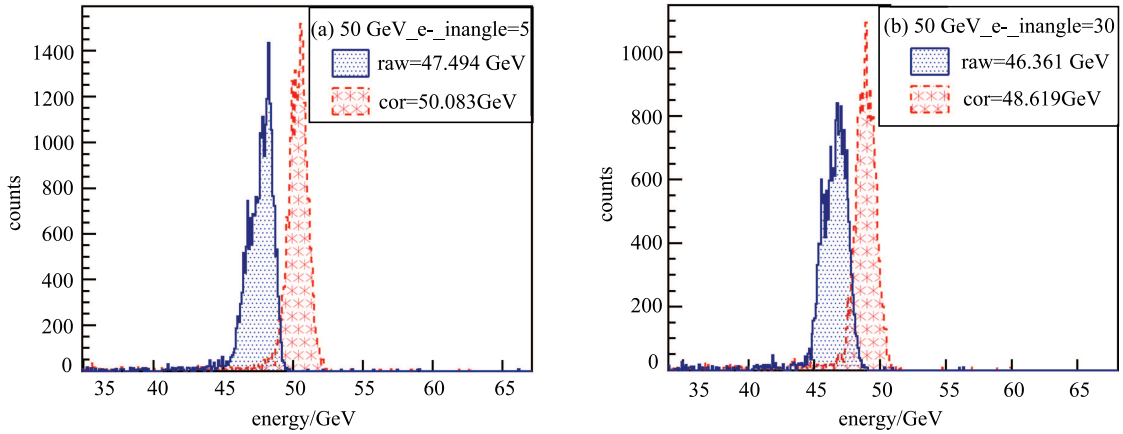

Fig. 13. Energy distribution of beam test data 50 GeV electrons with incidence angles of 5° and 30° as examples before and after correction

Table 1. Energy ratio and energy resolution before and after correction

inenergy/GeV	raw/GeV	corrected/GeV	raw ratio /%	corrected ratio /%	raw resolution /%	corrected resolution/%
3	2.643	2.951	88.1	98.4	4.26	3.64
4	3.568	3.973	89.2	99.33	3.38	3.13
5	4.503	5.009	90.06	100.18	2.96	2.64
50	47.57	49.64	95.14	99.28	1.72	1.5
100	96.42	100.5	96.42	100.5	1.36	1.14
149	142.5	148.3	95.64	99.5	1.41	1.29
197	189.2	197	96.04	100	1.05	1.09
243	235	244.7	96.71	100.6	1.00	0.99

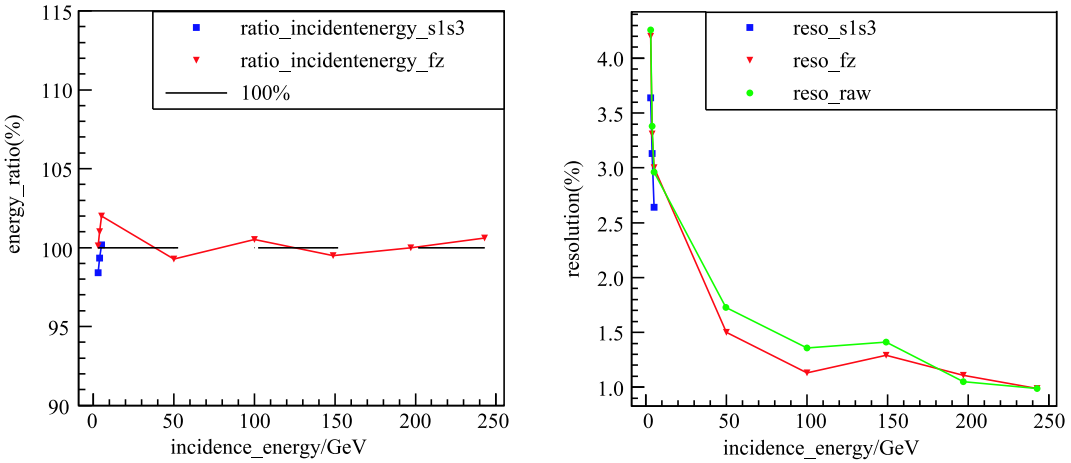

Fig. 14. Energy reconstructed versus incidence energy and energy resolution versus incidence energy. "Energy_ratio" is defined as the ratio of corrected energy against incidence energy.

4 Conclusion

Two correction methods are applied to the data samples for both the simulation and beam test with electron energies from 3 to 243 GeV, restoring the measured energies to the incidence energies very well. The $S1/S3$ method is used for the energy range of 3 GeV to 35 GeV and the F-Z method is used for energy range of 35 GeV up to 300 GeV. The systematic precisions of energy measurement have been improved. The energy resolutions are a little better after correction. The corrected energy resolution is below 4% for electrons under 10 GeV and about 1% for electrons above 100 GeV.

We would like to thank our DAMPE colleagues from the University of Geneva, the University of Lecce, and the University of Bari, and the CERN test beam team.

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