Energy loss correction for a crystal calorimeter*

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Abstract Material effect of inner-detectors on the performances of the BESIII Electromagnetic Calorimeter (EMC) is investigated. The BESIII Time-Of-Flight counters (TOF) have been utilized to improve the energy resolution and detection efficiency for photons after a careful energy calibration. A matching algorithm between TOF and EMC energy deposits is developed, and the effects of beam-related background are discussed. The energy resolution is improved and the photon detection efficiency can be increased by the combined measurement of EMC and TOF detectors.

Key words BESIII, calorimeter, material effect, calibration, resolution, efficiency

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1 Introduction

Beijing Spectrometer (BESIII)[1, 2] is a multi-purposed detector to be operated at the Beijing Electron Positron Collider (BEPCII) currently under a major upgrade for physics at tau-charm energy region.

The Electromagnetic Calorimeter (EMC), made of CsI(Tl) crystals, is one of the most important components of the BESIII detector. Its primary function is to measure photons with a high detection efficiency, good energy and position resolution. However its performance is affected by materials in front of it. In this paper, we present a study utilizing the energy deposit in the Time-Of-Flight counters (TOF) to improve the energy resolution and detection efficiency of the BESIII detector for photons.

2 Material effect

The layout of the BESIII detector is shown in Fig. 1. There are two sub-detectors in front of the EMC: the Drift Chamber (DC) and TOF, and a Be beam pipe around the interaction point. The inner

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and outer skins of DC are made of carbon fiber with a total thickness of 1.32 cm. A gas mixture of 60% He-40% propane with a long radiation length (∼550 m) is chosen as the working gas. TOF consists of two layers of BC408 scintillators, each with a thickness of 5 cm. All the materials in front of EMC and their radiation length are tabulated in Table 1. Clearly TOF takes up the most proportion of the radiation length.

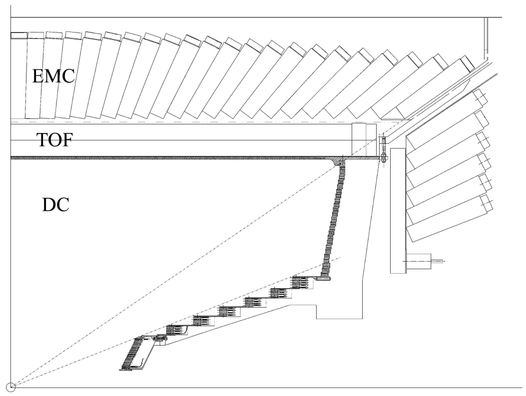

Fig. 1. Layout of the BESIII detector.

Table 1. Materials in front of EMC.

component	material	radiation length
beam pipe	0.14 cm beryllium	0.4%
DC	1.32 cm carbon fiber	6.0%
TOF	10 cm scintillator	23.5%

Material effects on the performance of EMC can be understood by the photon interactions with matter[3]: Compton scattering and pair production. Photons after the Compton scattering, whose fractional contribution to the total cross section decreases as the photon energy increases, may not be reconstructed in the proper direction. Its energy loss has a large fluctuations. In such a case, photon energy measured in EMC has a large uncertainty. Above 50 MeV, photon interaction is dominated by the pair production of electrons and positrons, which radiate photons again and subsequently form an electromagnetic shower. Such interactions, if they happen in front of EMC, will generate fluctuations of energy deposition, hence affect the energy resolution of EMC. Fig. 2 shows the energy deposit in TOF for 1 GeV photons from a Monte Carlo simulation using the Geant4 package[4]. It's a Landau like distribution with a long tail up to several hundreds of MeV.

Clearly the energy resolution of EMC is deteriorated due to material effects, which are mainly attributed to TOF. Fortunately, TOF is a sensitive detector by which the energy deposit of photons can be measured. It is expected that the combined measurement of TOF and EMC can significantly improve the photon energy resolution.

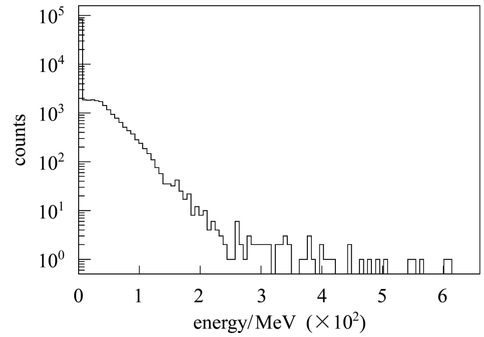

Fig. 2. Energy deposit in TOF for 1 GeV photons.

3 Calibration of TOF energy and hit position

In order to combine the energy measurement of TOF and EMC, the absolute energy calibration for TOF is required. Since the total collected charge of each scintillator depends not only on the deposited energy but also on the z-coordinate of hit position, the calibration should take this into account. Muon from the process $J/\psi \rightarrow \mu^+\mu^-$ is a very good candidate for the calibration during the data taking because its energy loss is a well defined quantity and the hit position can be determined by the drift chamber from track extrapolation[5].

Monte Carlo samples of $J/\psi \rightarrow \mu^+\mu^-$ are produced by the Geant4 based BESIII simulation package BOOST[6] with full geometry and material description. Secondary photons generated from the energy deposit in TOF scintillators are simulated, and the resulting photoelectron signals at each readout PMT are collected and transformed to ADC and TDC signals.

The energy deposit of a muon in TOF can be calculated as the differential energy loss ($\mathrm{d}E/\mathrm{d}x$) times the track length. The $\mathrm{d}E/\mathrm{d}x$ is obtained from the peak of the Landau distribution, about 1.78 MeV/cm. The hit position and the movement direction are from the track extrapolation based on the drift chamber information. Assuming a straight line of the muon track (reasonable for high momentum muons in a 1 T magnetic field), its length can be easily calculated based on the TOF geometry.

Since a photon leaves no signal in the drift chamber, its hit position can not be determined by the track extrapolation but rather, by the charge division or timing difference at two ends of the scintillator. Due to the non-linearity or saturation of the PMT and readout electronics, timing difference is a better method. Fig. 3(a) shows the hit position as a function of ΔT, the difference of measured TDC at each end of the scintillator. This function is obtained from muons and is considered to be the same for photons, because their interactions with the scintillator are both electromagnetic. It can be fitted with a linear function through the origin in ideal case. When the two TDCs of a scintillator bar are equal, the hit position is at $z=0$. The corresponding θ resolution as a function of the incident photon energy is shown in Fig. 3(b). It decreases with the increasing energy, and gets better than 25 mrad above 200 MeV.

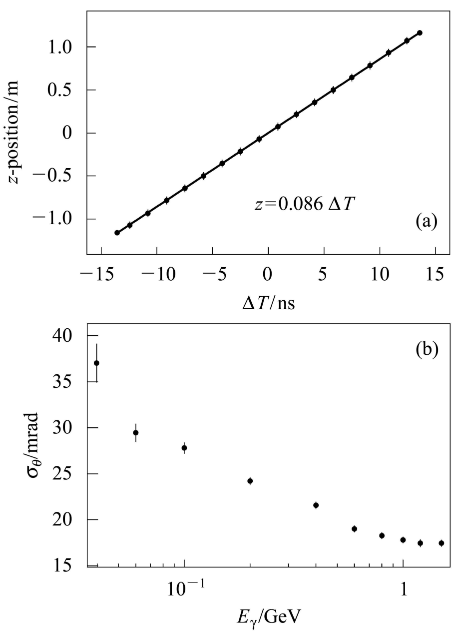

Fig. 3. (a) Hit position as a function of timing difference between the two ends of the scintillator, together with the fitted function. (b) The θ resolution as a function of the incident photon energy.

The energy deposit in TOF is a function of the hit position and the charge collected at each end of the scintillator bar, as shown in Fig. 4, where energy is the product of $\mathrm{d}E/\mathrm{d}x$ and track length as mentioned above. The charge collected at each end of the scintillator is denoted as ADC_0 and ADC_1, respectively, which can be fitted very well with an exponential function, except for a few points at the edge of scintillator. For example, the charge readout at $z=0$ for 1 MeV energy deposit is about 17 ADC counts.

The charge linearity of the TOF readout electronics is not perfect. A typical channel is measured as shown in Fig. 5(a). The readout ADC counts as a function of the input signal amplitude can be fit with a second order polynomial with a fitting error less than 2%. Since there are no data above 5 V up to now, this response curve is assumed to be flat after 5 V. The actual dynamic range is therefore from 0.2 V to 5 V, corresponding to an energy deposit of about 1.8 MeV to 45 MeV in TOF at $z=0$.

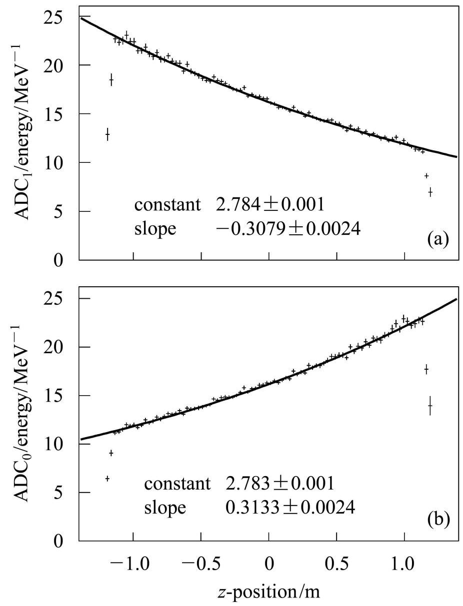

Fig. 4. Charge collected as a function of the hit position, (a) the west end and (b) the east end. The fitted functions are exponentials.

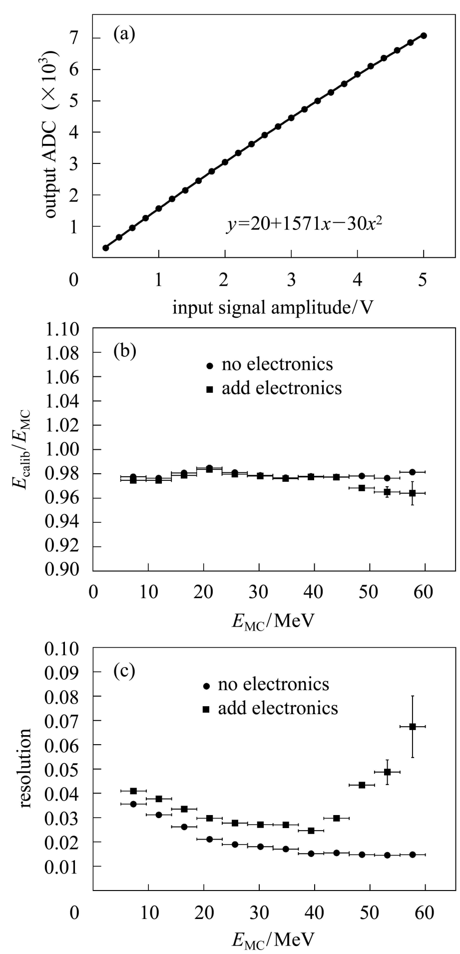

Fig. 5. (a) Linearity of the TOF readout electronics. The points are the measured data, and the curve is the fitted function. (b) Energy linearity. (c) Energy resolution as a function of energy deposit.

Once the hit position is obtained from TDC, energy deposit can be computed from the weighted average of two ADCs at both ends, taking into account the non-linearity and related errors. Fig. 5(b) and 5(c) show the linearity and energy resolution as a function of energy deposit in TOF, respectively. By taking into account the response of readout electronics from Fig. 5(a), the ratio of the "measured energy" after the calibration $E_{\rm calib}$ to the "true energy" from Monte Carlo $E_{\rm MC}$ deviates from unity at energies higher than 45 MeV, showing the effects of saturation. While such a ratio is a constant, showing no sign of saturation, if the response of readout electronics is not taken into account. The resolution as a function of energy deposit also shows a clear effect of saturation.

4 TOF and EMC match

In a physics event, there could be several secondary particles, together with electronic noise and beam-related backgrounds. Several scintillators may have signals at the same time, and many showers will be reconstructed in EMC. Therefore, a sophisticated matching algorithm is needed to reconstruct true particles.

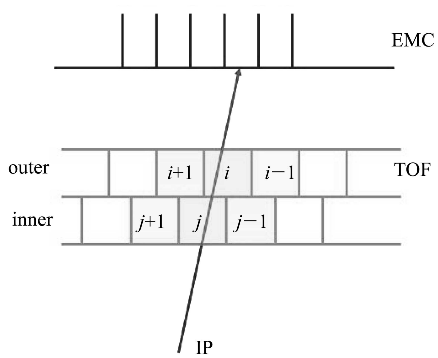

Fig. 6. TOF and EMC match in ϕ direction.

The matching algorithm takes into account both the θ and ϕ directions. There are 88 scintillator bars in each layer of TOF with the same shape arranged evenly along the ϕ direction, and 120 uniformly arranged EMC crystals behind them. A neutral track produced at the interaction point (IP) can pass through TOF and hit EMC, as shown in Fig. 6. The hit position of EMC can be retrieved from the EMC reconstruction, and the corresponding scintillators of each layer in TOF can be found according to its ϕ angle. Since the electromagnetic shower develops laterally, and may spread to several scintillators, the best approach for obtaining the best energy resolution could be to take three lateral bars(called tof2×3) instead of one lateral bar(called tof2×1). On the other hand, the electronics noise and backgrounds may deteriorate the resolution if too many bars are included into the sum. Hence the number of scintillators to be used relies on the noise level and calls for optimization from the experimental data.

After the corresponding scintillators in tof2×1 or tof2×3 are selected, their θ angles, namely the hit position can be calculated and compared with the θ angle given by the EMC shower. The distribution of $\Delta\theta$ ($\theta_{\rm TOF}-\theta_{\rm EMC}$) for 1 GeV photon is shown in Fig. 7. It can be fitted with a double-Gaussian function, and the weighted σ is about 22 mrad. The matching window is chosen as $|\Delta\theta| < 3\sigma$, and it is photon energy dependent.

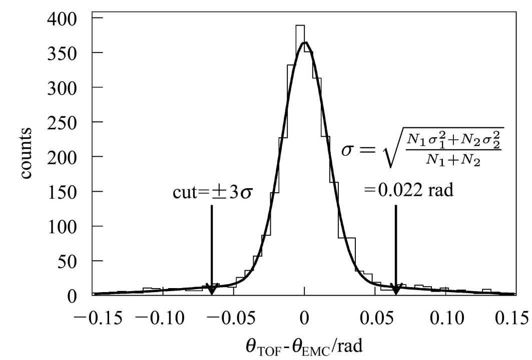

Fig. 7. TOF and EMC match in θ direction. The histogram is fitted with a double-Gaussian and the matching window is $|\Delta\theta| < 3\sigma$. N_i and σ_i (i=1,2) denote the area and standard deviation of ith Gaussian, respectively.

5 Performances study

5.1 Energy resolution and efficiency

Energy resolution and detection efficiency, as two of the most important quantities for EMC, are used to investigate the effect of TOF correction.

The distribution of the shower energy shows a non-Gaussian tail at the low energy side, shown in Fig. 8(a) and (b), caused mainly by the front, rear and side leakage of energy. It can be fitted with[7]

$$\frac{E_{\rm rec}}{E_{\rm init}} = N\exp\left(-\frac{1}{2\sigma_0^2}\ln^2\left(1-\frac{E_{\rm rec}-E_{\rm peak}}{\sigma_E}\eta\right)-\frac{\sigma_0^2}{2}\right), \tag{1}$$

in which $E_{\rm rec}$ is the reconstructed shower energy, $E_{\rm init}$ is the initial photon energy, $E_{\rm peak}$ is the most probable energy, η is a unsymmetric parameter, σ_E is the standard deviation, and N is the normalization factor. σ_0 is expressed with η:

$$\sigma_0 = \frac{2}{\xi}\sinh^{-1}\left(\frac{\eta\xi}{2}\right), \tag{2}$$

$$\xi = 2\sqrt{\ln(4)} \approx 2.355\,. \tag{3}$$

Energy resolution is defined as $\sigma_E/E_{\rm peak}$. The detection efficiency is defined as

$$\varepsilon = N_{\rm rec}/N_{\rm MC}\,, \tag{4}$$

where $N_{\rm MC}$ is the number of generated Monte Carlo events, and $N_{\rm rec}$ the number of reconstructed events which satisfies the following criteria for being good photons:

$$\begin{aligned} E_{\rm peak}-4\sigma_E < E_{\rm rec} < E_{\rm peak}+2\sigma_E, \\ |\theta_{\rm rec}-\theta_{\rm init}| < 3\sigma_\theta, \\ |\phi_{\rm rec}-\phi_{\rm init}| < 3\sigma_\phi. \end{aligned} \tag{5}$$

The statistical error of the detection efficiency is obtained as:

$$\sigma_\varepsilon = \sqrt{\varepsilon(1-\varepsilon)/N_{\rm MC}}\,. \tag{6}$$

Monte Carlo samples of single photons with energies up to 1.5 GeV with 0.5 MeV electronics noise per channel are generated to check the performance. At low photon energy of 0.1 GeV, the energy deposit in TOF is relatively large and a tail can be seen in the EMC reconstructed energy, as shown in Fig. 8(a). The label emc5×5 is a sum over 25 crystals around the hit position of EMC. The tail is clearly reduced by adding the matched TOF energy, tof2×3, hence the photon efficiency is improved. While at high photon energy of 1 GeV, the long tail is suppressed and the TOF correction can narrow the width which is deteriorated by the material effect, as shown in Fig. 8(b).

Figures 8(c) and (d) show the distribution of the energy resolution and detection efficiency for single photon as a function of incident photon energy, respectively. Here σ_E in Eq. (5) is chosen as the σ_E of emc5×5 matched with tof2×3. Because the material effect changes the shape of energy spectrum, the energy resolution deviates from the smooth function proportional to $1/\sqrt{E}$, starting from above 300 MeV, and the detection efficiency decreases rapidly at low energies, if TOF is not used. After the energy reconstructed in TOF is matched and added to EMC shower, the energy resolution shows a great improvement and the deviation almost disappears. For 1 GeV photon, the energy resolution is improved from 2.7% to 2.2% and 2.3%, for tof2×3 and tof2×1, respectively. The detection efficiency is increased by up to 10%.

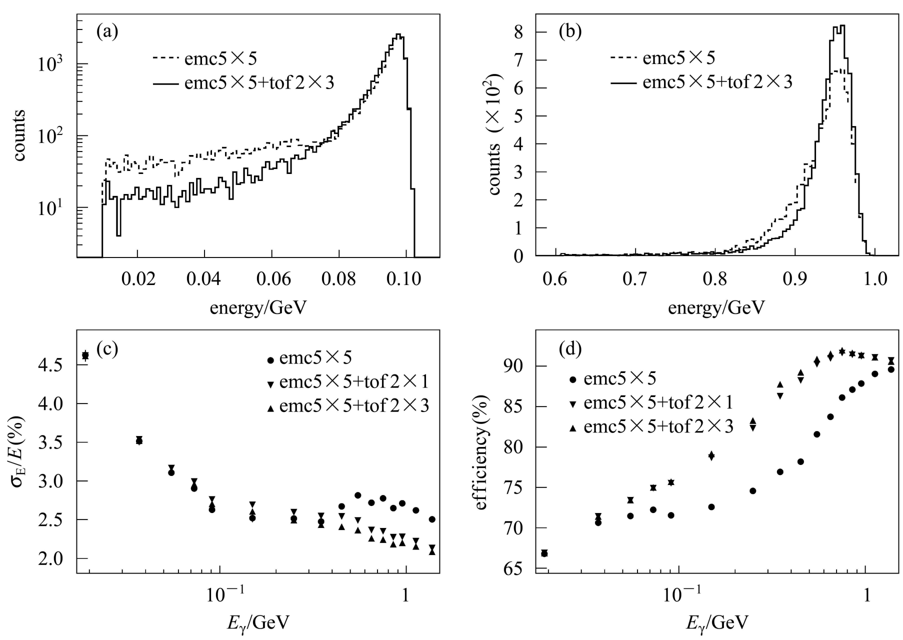

Fig. 8. Reconstructed energy distribution in EMC for (a) 0.1 GeV and (b) 1 GeV photons. The broken line is for EMC only, while the solid line with TOF correction. (c) and (d) the distribution of energy resolution and detection efficiency as a function of incident photon energy, respectively.

5.2 Study of scintillators which have signals at single end

In the above studies, only those scintillators in TOF which have signals at both ends are used, because the calibration of z-coordinate of the hit position need the time information of both ends. If the scintillators which have signal at single end are also considered, the resolution and efficiency might be improved further. In this case, the hit position of TOF is determined not by the time channel but by the EMC shower. And the energy deposit is calculated with the single charge channel. However, according to Monte Carlo simulation, the resolution and efficiency show no obvious improvement. The reason is that the single end signal is mainly caused by low energy deposit (less than 5 MeV) in TOF, which makes little contribution to the energy reconstruction, and it's difficult to be identified from noise. Therefore, the algorithm of energy reconstruction for single end scintillator is not used.

5.3 Effects of beam-related backgrounds

As mentioned in the previous section, the beam-related backgrounds may have an impact on the matching of EMC and TOF. These backgrounds are mainly caused by the lost beam-electrons through the beam-gas interactions[8] and the Touschek effect[9]. Monte Carlo samples of the beam-lost electrons are generated. From the simulation of the detector response, the average number of scintillators, which have signals caused by the backgrounds in a good event, is 0.05 with an average energy deposit of 11.2 MeV. Considering the matching window in both ϕ and θ directions, only 0.3% of these background signals will be matched with EMC, thus it is a negligible effect. To verify this conclusion, the background samples in TOF are mixed with single photon events. These new data are reconstructed with the above mentioned matching algorithm, and the EMC performance shows no noticeable deterioration at high energies. For low energy photons of 0.1 GeV, the resolution is worsened only by 0.01% even at 10 times more backgrounds than the currently estimated level. The efficiency is not changed either.

6 Conclusion

Calibration of the TOF energy and the hit position, as well as a matching algorithm of TOF and EMC has been developed. Based on a Monte Carlo simulation study, the energy resolution and detection efficiency for photons are improved with TOF correction. However, in current simulation, the interactions between low energy photons and scintillators are not described perfectly, and the transportation and gathering of secondary photons in scintillators are simulated with a simple model. On the other hand, the performances of TOF electronics are affected by the beam environment. Therefore, the results obtained now may be not exactly the same as in the real data. In that case, the comparison between data and Monte Carlo is essentially important, and the parameters and models used in simulation should be adjusted carefully according to experiment. That will help us comprehend the detector's behavior deeply and give best results.

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