Absolute photon energy calibration for the BESIII EMC*

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Abstract The absolute energy calibration with photons from π^0's for the BESIII EMC is discussed. Using 3 million hadronic events, the preliminary results are presented. Precision of about 1% in the photon energy measurement is obtained from crossing check using photons in $\psi(2S)\rightarrow\gamma\chi_{c1,2}(1P)$.

Key words electromagnetic calorimeter; absolute energy calibration; π^0 decay.

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1 Introduction

BEPCII/BESIII [1] is the major upgrade of BEPC/BESII [2], and BESIII is designed to study hadron spectroscopy and τ-charm physics [3]. The cylindrical BESIII is inside a superconducting solenoid magnet with a 1.0 T magnetic field and consists of a helium-gas based drift chamber (MDC), a Time-of-Flight (TOF) system, an CsI(Tl) Electro-Magnetic Calorimeter (EMC) and a RPC-based muon chamber (MUC) . The detector has a total acceptance of 93% of 4π. The expected charged particle momentum resolution and photon energy resolution are 0.5% and 2.5% at 1 GeV respectively. The energy resolution for photons at BESIII is much better than that of BESII [2] and comparable to CLEO [4] and Crystal Ball [5]. Precise measurements photon of energies enable BESIII experiments to study physics involving photons, π^0 and η with high accuracy. The detector simulation software BOOST [6] is based on GEANT4. All of the work is done in the BESIII Offline Software System (BOSS) [7].

The off-line calibration of the BESIII EMC goes through two steps. The first is the calibration by Bhabha events which determines the gain factor for each crystal that converts ADC counts to the deposited energy expected by simulation. However, due to the material in front of the EMC and the transverse and longitudinal shower energy leakage, the reconstructed energy during this step is usually not equal to the incident energy. Therefore, the second step, absolute energy calibration, is needed to determine the absolute energy scale which corrects deposit shower energies ($E_{\rm shower}$) to their incident energies ($E_{\rm true}$). The main idea of absolute energy calibration is to use known information related to the energy of photons to calculate the correction factor. In a Monte Carlo (MC) simulation, absolute energy calibration can be easily done since we know the true energies of incident photons. For real data, special physics processes are chosen to correct the scale of photon energy. In

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this paper, we present a method to do the absolute energy correction using π^0.

2 Calibration method

In the energy region of BEPC II, energies of photons produced via π^0 decay distribute over a large range (0.04–1.6GeV). Calibration of the the absolute photon energy with these photons has statistical advantages and does not depend on other detectors, such as MDC and TOF.

2.1 Asymmetric distribution of photon energy and π^0 invariant mass

Because of the energy leakage out of crystals and interaction in the material in front of the EMC, the line shape of photon energy deposits does not follow a Gaussian distribution. Fig. 1(a) shows the distribution of photon energies in the $e^+e^- \to \gamma\gamma$ process at $\sqrt{s} = 3.686$ GeV in real data. We parameterize the asymmetric distribution of photon energies by a Novosibirsk function [8]:

$$f_{\rm Nov}(m) = A\exp\left(\frac{-\ln^2\left(1+t\dfrac{\sinh(t\sqrt{\ln 4})}{t\sqrt{\ln 4}}\dfrac{m-m_0}{\sigma}\right)}{2t^2}-\frac{t^2}{2}\right), \tag{1}$$

where A is the normalization constant, $\sigma(>0)$ is the resolution, m_0 is the mean value and $t(<0)$ parameterizes the tail. This function can be seen as a Gaussian distribution with an asymmetric tail.

In the $\pi^0 \to \gamma\gamma$ process, the invariant mass of π^0 can be calculated by the following equation:

$$m^{\rm exp}_{\gamma\gamma} = \sqrt{2E_{\rm low}E_{\rm high}(1-\cos\theta_{\gamma\gamma})}, \tag{2}$$

where $E_{\rm low}$ and $E_{\rm high}$ are energies of the low and high momentum photons from π^0 decay, $\theta_{\gamma\gamma}$ is the angle between them. If either photon from π^0 decay loses part of its energy, the reconstructed mass of π^0 will be lower than its nominal value. As shown in Fig. 1(b), the line shape of the invariant mass of Monte Carlo π^0 with momentum 0–1.5 GeV/c can also be parameterized by a Novosibirsk function.

2.2 Determination of the correction factors

The correction factor $E_{\rm shower}/E_{\rm true}$ can be determined by adjusting the invariant mass of photon pairs to π^0's nominal mass, where $E_{\rm shower}$ is the deposit shower energy in a 5×5 crystal cluster and $E_{\rm true}$ is the true energy of the incident photon. To extract correction factors, the reconstructed photons in the energy range 0.04–1.6 GeV are grouped according to their energies into 7 bins (0.04–0.08 GeV, 0.08–0.135 GeV, 0.135–0.22 GeV, 0.22–0.36 GeV, 0.36–0.6 GeV, 0.6–1.0 GeV and 1.0–1.6 GeV). Thus for each π^0 daughter photon pair ($E_{\rm low}$ and $E_{\rm high}$), one photon has an energy in the i-th bin and the second one has an energy in the j-th bin. Then invariant masses of photon

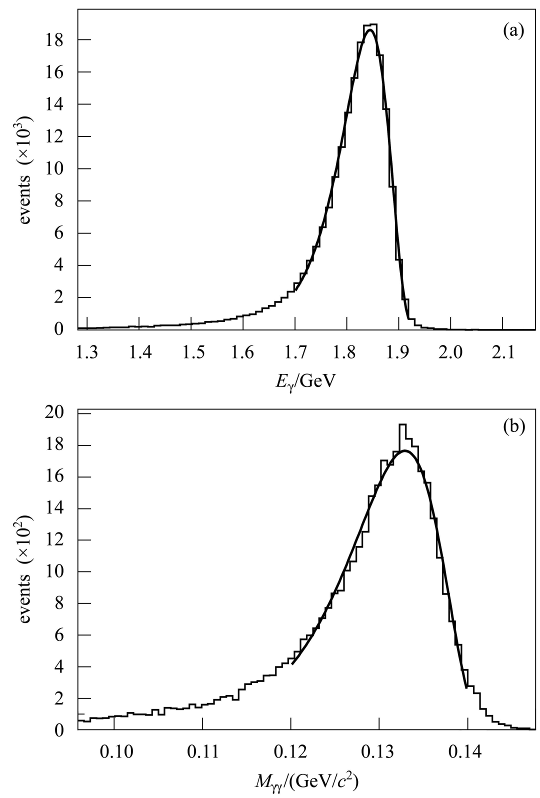

Fig. 1. (a) Distribution of γ energies in the $e^+e^- \to \gamma\gamma$ process at $\sqrt{s} = 3.686$ GeV. (b) Invariant mass of Monte Carlo π^0 with momentum 0–1.5 GeV/c.

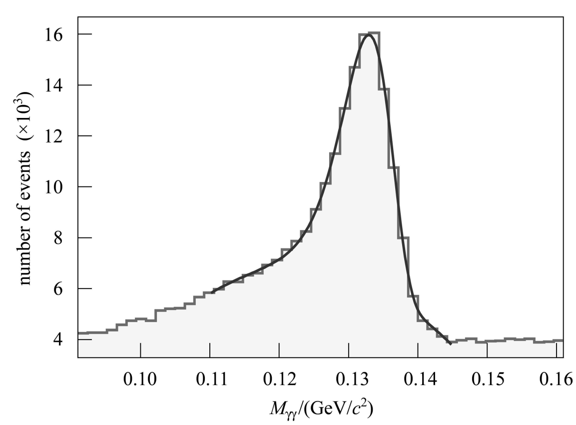

Fig. 2. Distribution of the invariant mass of photon pairs for $E_{\rm low}$ from 0.08 GeV to 0.135 GeV, $E_{\rm high}$ from 0.135 GeV to 0.22 GeV.

pairs are obtained for these energy bin combinations. Fig. 2 shows an example of the π^0 mass distribution of the invariant mass of photon pairs for E_{low} from 0.08 GeV to 0.135 GeV and E_{high} from 0.135 GeV to 0.22 GeV. Then π^0 mass distribution in Fig. 2 is fitted with a Novosibirsk function plus a 2nd order polynomial background term.

The correction factor in the i-th energy bin is written in the form of an exponent: $E_{\mathrm{shower}}/E_{\mathrm{true}} = \exp(\alpha_i)$. Thus in the i-th E_{low} bin and the j-th E_{high} bin, the corrected π^0 mass can be expressed in the following form:

$$\begin{aligned}
&m_{\gamma\gamma}^{\mathrm{cor}} = \\
&\sqrt{2E_{\mathrm{low}}\exp(-\alpha_i)E_{\mathrm{high}}\exp(-\alpha_j)(1-\cos\theta_{\gamma\gamma})} = \\
&\sqrt{2E_{\mathrm{low}}E_{\mathrm{high}}(1-\cos\theta_{\gamma\gamma})}\cdot\exp(-\alpha_i/2-\alpha_j/2) = \\
&m_{\gamma\gamma}^{\mathrm{raw}}\cdot\exp(-\alpha_i/2-\alpha_j/2),
\end{aligned} \tag{3}$$

where $m_{\gamma\gamma}^{\mathrm{raw}}$ is the invariant mass of the photon pair calculated with the uncorrected shower energy. Then the wanted shift (logarithmical) of π^0 mass to MC expected value in the i-th and j-th bin (for an explanation see Eq. (13)) can be written as:

$$C_{ij} = \alpha_i/2+\alpha_j/2\pm\sigma_{ij}\,, \tag{4}$$

where C_{ij} is the logarithmical mass shift, and σ_{ij} is its statistical error.

Define a χ^2 function:

$$\chi^2 = \sum_i\sum_j \frac{(\alpha_i/2+\alpha_j/2-C_{ij})^2}{\sigma_{ij}^2}\,. \tag{5}$$

Minimizing it yields:

$$\sum_i\sum_j \frac{\alpha_i/2+\alpha_j/2-C_{ij}}{\sigma_{ij}^2}(\delta_{ik}+\delta_{jk}) = 0, \quad k=1,2,...,n,\ \text{here } n=7, \tag{6}$$

where

$$\delta_{jk} = \begin{cases} 1, & \text{if } j{=}k \\ 0, & \text{if } j{\neq}k. \end{cases} \tag{7}$$

In matrix form it can be written as:

$$\sum_{m=1}^{n} A_{mk}\alpha_m = B_k, k=1,2,...,7\,, \tag{8}$$

where

$$A_{mk} = \sum_i\sum_j \frac{(\delta_{im}+\delta_{jm})(\delta_{ik}+\delta_{jk})}{2\sigma_{ij}^2}, \tag{9}$$

$$B_k = \sum_i\sum_j \frac{(\delta_{ik}+\delta_{jk})C_{ij}}{\sigma_{ij}^2}. \tag{10}$$

The correction factors α_i and their statistical errors can be derived as:

$$\alpha_k = \sum_{i=1}^{n} A_{ki}^{-1}B_i, \tag{11}$$

$$\Delta\alpha_k = \sqrt{2A_{kk}^{-1}}. \tag{12}$$

Due to the asymmetric shape of deposited photon energies, the peak value of the photon pair invariant mass distribution does not equal the π^0 nominal mass (0.135 GeV/c^2) even after shifting the photon energy peak to its true value [9, 10]. For this reason, the expected π^0 mass for each energy bin combination is not simply equal to its nominal mass but needs to be obtained by MC simulation. The needed shift C_{ij} is determined by:

$$C_{ij} = \ln m_{\gamma\gamma}^{\mathrm{data}} - \ln m_{\gamma\gamma}^{\mathrm{exp}}, \tag{13}$$

where $m_{\gamma\gamma}^{\mathrm{exp}}$ and $m_{\gamma\gamma}^{\mathrm{data}}$ are π^0 masses for Monte Carlo simulation and data. The errors of $\ln m_{\gamma\gamma}^{\mathrm{exp}}$ and $\ln m_{\gamma\gamma}^{\mathrm{data}}$ are $\sigma_{ij}(\ln m_{\gamma\gamma}^{\mathrm{exp}})$ and $\sigma_{ij}(\ln m_{\gamma\gamma}^{\mathrm{data}})$. Then the error of C_{ij} can be evaluated:

$$\sigma_{ij}^2(C_{ij}) = \sigma_{ij}^2(\ln m_{\gamma\gamma}^{\mathrm{data}}) + \sigma_{ij}^2(\ln m_{\gamma\gamma}^{\mathrm{exp}}). \tag{14}$$

3 Pre-calibration

In order to simulate the π^0 mass shift and eliminate the geometry dependence of photon energies, pre-calibration is done before π^0 calibration: MC simulated single photons in the energy range 0.03–2 GeV and cosine polar angle range −0.93–0.93 are generated and fitted using a Novosibirsk function to extract the peaks of the distribution. Correction factors are determined by shifting these peaks to their true energies. Fig. 3 shows the comparison of shower energies before and after MC single photon correction using 100 k $e^+e^- \to \gamma\gamma$ events at E = 1.843 GeV in real data.

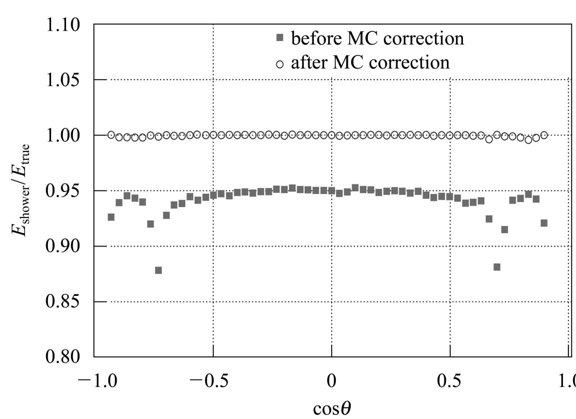

Fig. 3. Comparison of shower energies before and after MC single photon correction using $e^+e^- \to \gamma\gamma$ events at E = 1.843 GeV in real data.

To obtain the expected value of reconstructed π^0 mass in Monte Carlo, 10M inclusive $\psi(2S)$ data are generated. In this MC sample, the known decay modes of $\psi(2S)$ are generated with EvtGen [11] according to PDG [12], and the remaining unknown decays are generated with the Lundcharm generator [11]. The resulting invariant masses of π^0 from inclusive $\psi(2S)$ decays in Monte Carlo and real data are presented in Fig. 4. The π^0 mass is lower in real data compared with Monte Carlo because of the non-linear energy response, which is to be dealt with using π^0 calibration.

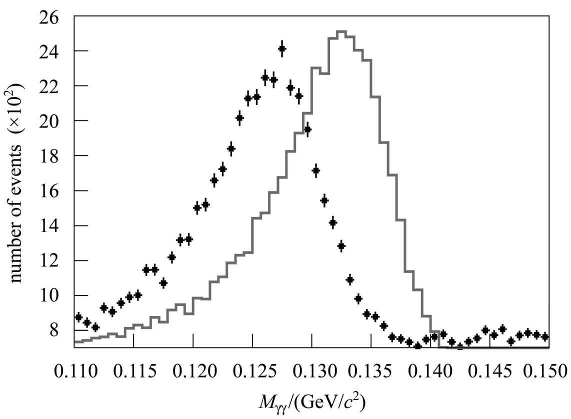

Fig. 4. Distribution of invariant mass of π^0 in inclusive $\psi(2S)$ decays in real data (points with error bars) and Monte Carlo (histogram).

4 π^0 calibration

After the MC single photon correction, the π^0 calibration is performed with real data. To reject the Bhabha, di-photon and beam gas background, the π^0 sample is obtained from pre-selected events.

4.1 Hadron event selection

The selections of hadron events are based on selections of good charged and neutral tracks. For a good charged track candidate, it is required to be produced in the interaction region with $R_{xy} < 1$cm and $R_z < 5$cm, where R_{xy} and R_z are the closest distances from the beam line to the reconstructed track in the x-y plane and the z direction respectively; the Time-of-Flight measurement is required to be consistent with the hadron (π/K/p) hypothesis; the fired layers of this track in the muon counter must be less than 6. A neutral cluster is identified as a good photon if the following requirements are satisfied: the energy deposit in the EMC is greater than 0.04 GeV; the angle between the neutral track and its nearest charged track is greater than 20° to reduce the backgrounds from the split-off showers; 450 ns $< t_{\rm EMC} <$ 1350 ns, where $t_{\rm EMC}$ is the time information of the EMC, to veto beam gas related backgrounds. The numbers of selected good charged and neutral tracks are $N_{\rm ch}$ and N_γ.

An event will be classified as a hadron event if the following requirements are satisfied: at least two charged tracks with at least one good track; $N_{\rm ch} + N_\gamma \geqslant 3$ to suppress the QED process and cosmic ray backgrounds; the total energy deposit in the EMC must be greater than $0.2 \times E_{\rm beam}$; the energy asymmetry in the EMC is less than 0.95, where the energy asymmetry is defined as the ratio of the vector sum to the scalar sum of deposited energy in the EMC, to reduce most of the beam gas background; the acoplanner angle must be greater than 10° for two-prong events to veto lepton pair events.

4.2 Calibration results

About 3 million hadronic events were selected from BESIII data taken in Oct. 2008. The geometry ($\cos\theta$) dependent energy correction factors are applied to all good photon candidates. Neutral pions are reconstructed through $\pi^0 \to \gamma\gamma$, where the two photons are required to be from the barrel part of the EMC and the angles between these two photons are required to be greater than 10° to reduce the effect of overlapping showers.

About 3.8 million $\gamma\gamma$ pairs are selected according to the above criteria. Fig. 5 shows the photon energy distribution ($E_{\rm low}$ and $E_{\rm high}$) of these $\gamma\gamma$ pairs. Fig. 6 shows the invariant masses of photon pairs for all energy bin combinations. For the ij-th energy bin combination, $E_{\rm low}$ is in the i-th bin and $E_{\rm high}$ is in the j-th bin. When i=1 and j=1, signals of π^0 are difficult to obtain due to the background from

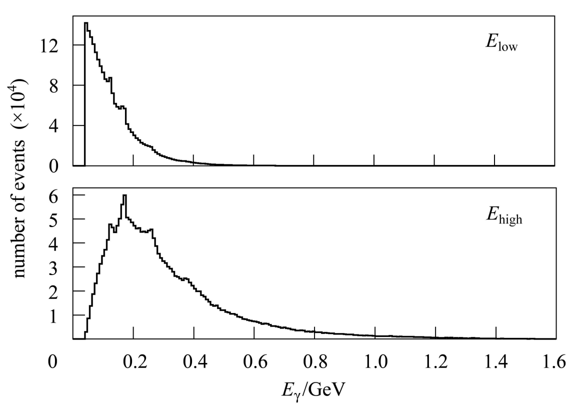

Fig. 5. Photon energy distribution of $\gamma\gamma$ pairs.

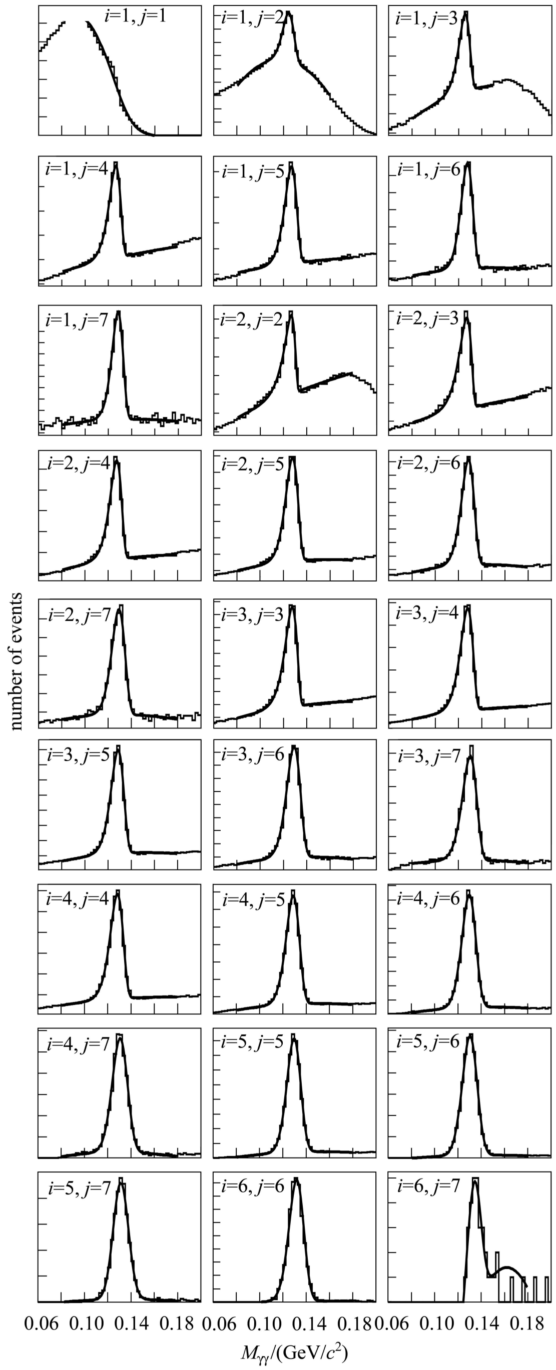

Fig. 6. The invariant mass of $\gamma\gamma$ for different energy bin combinations (ij). Both of the photons are required to be in the barrel.

random combination of low-energy photons. When i=6, j=7 and i=7, j=7, the statistics is not enough to do a reliable fit. These energy bin combinations are removed when calculating the correction factors. The histogram of invariant mass for each energy bin combination is fitted with a Novosibirsk function plus a 2nd order polynomial background term. All parameters of the Novosibirsk function and the 2nd order polynomial are allowed to float. The peak value and its fit error of the Novosibirsk function is extracted as the π^0 mass and its error for the ij-th bin combination. Applying the method in Section 3, the correction factors for each energy bin are calculated with them. Fig. 7 shows the photon energy correction factors as a function of $\ln E$, the logarithm scale of photon energies. This correction factor at $E = 1.843$ GeV ($\ln E/1$ GeV=0.611) is obtained using $e^+e^- \rightarrow \gamma\gamma$ events (see Section 3) and others are obtained from π^0 calibration. This calibration function can be parameterized by a 3rd polynomial:

$$E_{\text{shower}}/E_{\text{true}} = a_0 + a_1 \ln E_{\text{shower}} + a_2 \ln^2 E_{\text{shower}}. \quad (15)$$

To estimate the errors from binning, the energy value to be fitted in each bin is varied from the center of the bin to the weighted center of the energy distribution in this bin. Table 1 lists the coefficients and their errors.

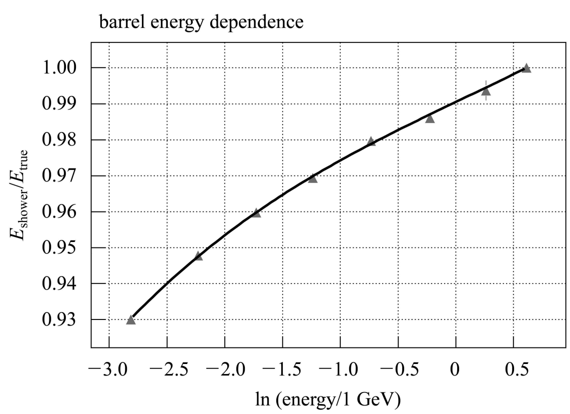

Fig. 7. Photon energy correction factors versus $\ln E$ obtained from π^0 calibration.

Table 1. Coefficients of the calibration function.

Coeff.	value	Stat. error	error from binning
a_0	0.9905	0.0004	0.0004
a_1	0.01537	0.0003	0.0004
a_2	−0.0002	0.0007	0.0005
a_3	0.0007	0.0002	0.0002

5 Performance check

Physics processes are used to check the performance of the absolute photon energy calibration. The transition photon energies of $\psi(2S) \rightarrow \gamma\chi_{cJ}(1P)$ are precisely known. The $\gamma\gamma\mu^+\mu^-$ events via subsequent decay $\psi(2S) \rightarrow \gamma\chi_{c1,2}(1P)$, $\chi_{c1,2}(1P) \rightarrow \gamma J/\psi$, $J/\psi \rightarrow \mu\mu$ can provide ideal photon tags for the validation of the photon energy calibration in the low energy region.

Events with 2 good charged tracks with a total charge of zero are required. Momenta of charged tracks are required to be greater than 1.2 GeV/c and less than 1.8 GeV/c. To reject electrons, each charged track should satisfy $E/p < 0.6$. The invariant mass of the two charged tracks with the muon hypothesis is required to be in the the mass range of J/ψ (3.0–3.2 GeV).

The number of good photons is required to be 2 or 3. The most energetic photon $\gamma_{\rm high}$ from $\chi_{\rm cJ}(1P)$ decay must have an energy greater than 0.3 GeV. The photon from $\psi(2S) \to \gamma\chi_{\rm c1,2}(1P)$ is selected by requiring that the angle ($\mathrm{d}\theta_{\rm recoil}$) between the photon candidate and the recoiling momentum of $\gamma_{\rm high}$ plus the two charged tracks is less than 20°. If there is more than one photon which satisfies the requirements, the photon with the smallest $\mathrm{d}\theta_{\rm recoil}$ is selected. Each shower is corrected with the factors obtained from π^0 calibration.

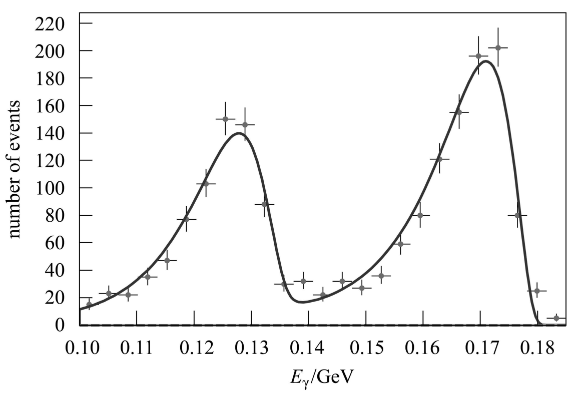

Fig. 8. Photon energy in $\psi(2S)\to\gamma\chi_{\rm c1,2}(1P)$ with π^0 calibration.

About 2k photons pass the cuts and the spectrum is shown in Fig. 8. Transition photons in $\psi(2S) \to \gamma\chi_{\rm c1}(1P)$ and $\psi(2S) \to \gamma\chi_{\rm c2}(1P)$ are included in the spectrum with little background. Their signal shape is parameterized by a convolution of a Breit-Wigner and a Novosibirsk function in the fit of the spectrum and the background is neglected. The natural widths of the $\chi_{\rm c1,2}(1P)$ are fixed to their world average values [12]. As shown in Fig. 8, the points with error bars represent the data and the solid line represents the fit. The fitted photon line energies with statistical errors are 171.26±0.17 MeV and 127.43±0.26 MeV respectively. By comparing discrepancies between the fitted values and PDG values 171.16 MeV and 127.60 MeV, the difference is determined to be 0.1%. The geometry ($\cos\theta$) dependence after the π^0 calibration obtained from $\psi(2S) \to \gamma\chi_{\rm c1}(1P)$ in real data suggests an uncertainty of maximum 1% in energy measurement, as shown in Fig. 9. The geometry dependence of the photon energy scale can be further corrected with real data after more data have been taken.

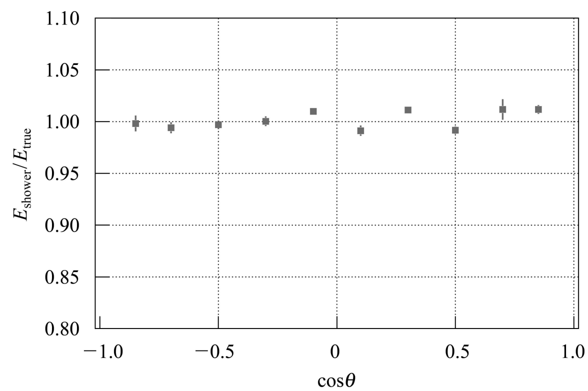

Fig. 9. Geometry dependence of the γ energy scale after π^0 calibration obtained from analyzing $\psi(2S) \to \gamma\chi_{\rm c1}(1P)$.

6 Summary

Absolute energy calibration with a π^0 sample has been done with data taken at BESIII. In the barrel part of the EMC, the calibration result is very good in the measurements of transit photon energies of $\psi(2S) \to \gamma\chi_{\rm c1,2}(1P)$. Due to the high noise level, in endcap detectors, the π^0 calibration cannot provide a stable result even with one photon in the barrel and another one in endcaps. We expect to use the QED process $\mathrm{e^+e^-} \to \gamma\mathrm{e^+e^-}$ to rescale the correction factors in the high energy range.

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