Absolute energy calibration and the use of timing information of the BESIII EMC

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Abstract. We introduce the absolute energy calibration of the electromagnetic calorimeter at BESIII. The precision after calibration is about 0.5% and the resolution difference between data and the simulation is about 5%. We also present a method to veto beam-gas background using the timing information of the EMC, which is crucial for physics analyses involving low energy photons at BESIII.

1. Introduction
Beijing Electron Positron Collider II and Beijing Spectrometer III (BEPCII/BESIII)[1] is a major upgrade of BEPC/BESII[2]. BESIII is designed to study τ-charm physics[3]. The BESIII detector is equipped with a CsI(Tl) crystal electro-magnetic calorimeter (EMC) which provides much improved energy measurement. The design energy resolution of BESIII EMC is 2.5% at 1GeV, which is about 10 times better than BESII. In this talk, we present an introduction to the absolute energy calibration, as well as the performance after calibration. As BESIII works in a relatively low energy region with high luminosity, the beam-gas background is a major consideration for physics involving low-energy photons, such as radiative charmonium transitions and reconstruction of low momentum π0s. We also present a method of using timing information of EMC to reject beam-gas background at BESIII.

2. BESIII electro-magnetic calorimeter (EMC)
The electromagnetic calorimeter is designed to precisely measure the energies of photons above 20 MeV and to provide trigger signals. It has a good e/π discrimination capability for momenta higher than 200 MeV/c. The structure of EMC is described in Ref [1], it consists of 6,240 large CsI(Tl) crystals located outside of the TOF counters and inside the coil of the solenoid. Its performance is greatly enhanced compared to the sampling EM calorimeter of BES/BESII which was made from streamer tubes sandwiched in between lead plates. The inner radius of the BESIII EMC is 94 cm. The length of the crystals is 28 cm or 15 radiation lengths (X0) with a front face of 5.2 cm × 5.2 cm. The depth and segmentation of the EMC are chosen to optimize the detector performance and to control the cost of the detector. The total weight of the crystals is approximately 24 tons. The design energy resolution of EM showers is σ = 2.5% and the position resolution is σ = 0.6 cm E (E in GeV) at 1 GeV. The angular coverage of the barrel EMC is 144.7° < θ < 33.5° (|cos(θ)| < 0.83). The two end caps cover 21.3° < θ < 34.5° and 145.4° < θ < 158.7° (0.85 < |cos(θ)| < 0.95). Performance checks using radiative Bhabha...
and Bhabha events indicate the precision of the energy measurement is better than 0.5% and the relative resolution reaches the design value of 2.5%.

3. Absolute energy calibration

The off-line calibration at BESIII goes through two steps. The first one is the calibration with Bhabha events which determines the gain factor for each crystal that converts ADC counts to deposited energy. 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 deposited shower energies ($E_{\text{shower}}$) to incident energies ($E_{\text{true}}$). The main idea of the absolute energy calibration is to use photons of known energy to calculate the correction factor.

3.1. MC calibration

To calibrate the reconstructed shower energy in the MC simulation, single photon samples with known energies and directions were generated. These samples are subjected to the reconstruction process. Then the ratios of the peak value of the reconstructed energy to the value of the true energy for each energy-position (polar angle) combination are extracted as the correction factors in MC and stored in a 2-D table. When applying the correction, factors are obtained from the 2-D table via interpolation. The MC correction can improve the precision of the energy reconstruction in MC to better than 0.1%. The geometry-depended energy leakage can also be corrected in this process and the remaining discrepancy as a function of energy will be further corrected using a data-driven method.

3.2. DATA calibration

$\pi^0 \rightarrow \gamma \gamma$ and $e^+e^- \rightarrow \gamma \gamma$ events are used to perform the absolute energy calibration in the data. 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. We parameterize the asymmetric distribution of photon energies by a Novosibirsk function:

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

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 $\pi^0 \rightarrow \gamma \gamma$ process, the invariant mass of the $\pi^0$ can be calculated as follows:

$$m_{\gamma\gamma}^{\exp} = \sqrt{2E_{\text{low}}E_{\text{high}}(1 - \cos\theta_{\gamma\gamma})},$$

where $E_{\text{low}}$ and $E_{\text{high}}$ are the energies of the low and high momentum photon from the $\pi^0$ decay and $\theta_{\gamma\gamma}$ is the angle between them. If either photon from the $\pi^0$ decay loses a part of its energy, the reconstructed mass of the $\pi^0$ will be lower than its nominal value. The line shape of the invariant mass of the $\pi^0$ can also be parameterized by a Novosibirsk function.

The correction factor $E_{\text{shower}}/E_{\text{true}}$ is determined by adjusting the invariant mass of photon pairs to the nominal $\pi^0$ mass, where $E_{\text{shower}}$ is the deposited shower energy in a $5 \times 5$ crystal cluster and $E_{\text{true}}$ is the true energy of the incident photon. To extract correction factors, the reconstructed photons are grouped according to their energies. Thus for each $\pi^0$ daughter photon pair ($E_{\text{low}}$ and $E_{\text{high}}$), 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 pairs in the data are obtained and fit for these
energy bin combinations. Each spectra is fitted with a Novosibirsk function plus a 2nd order polynomial background term.

Due to the asymmetric shape of the deposited photon energies, the peak value of the photon pairs invariant mass distribution is not equal to the π⁰ nominal mass (0.135 GeV/c²) even after shifting the photon energy peak to its true value [4][5]. For this reason, the expected π⁰ mass for each energy bin combination is not simply equal to the nominal mass but needs to be obtained by MC simulation. The needed shift $C_{ij}$ is determined by:

$$ C_{ij} = \ln m_{\gamma\gamma}^{\text{data}} - \ln m_{\gamma\gamma}^{\text{exp}}, $$

where $m_{\gamma\gamma}^{\text{exp}}$ and $m_{\gamma\gamma}^{\text{data}}$ are π⁰ masses for Monte Carlo simulation and data. The errors of $\ln m_{\gamma\gamma}^{\text{exp}}$ and $\ln m_{\gamma\gamma}^{\text{data}}$ are $\sigma_{ij}(\ln m_{\gamma\gamma}^{\text{exp}})$ and $\sigma_{ij}(\ln m_{\gamma\gamma}^{\text{data}})$. Then the error of $C_{ij}$ can be evaluated:

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

With about 10 M events in the 106 M $\psi'$ data events collected by BESIII, we performed the absolute energy calibration. The correction factor at $E=1.843\text{GeV}$ ($\ln E/1\text{GeV}=0.611$) is obtained using $e^+e^-\rightarrow \gamma\gamma$ events and the others are obtained from $\pi^0$ calibration. A 3rd order polynomial is fit to the factors as the calibration function.

### 3.3. Performance

Radiative photon in $\psi(2S)\rightarrow \gamma\chi_{cJ}(1P)$ and radiative Bhabha events, as well as $\pi^0$'s in the $\psi'\rightarrow \pi^0\pi^0 J/\psi$ process are used to check the performance of the absolute photon energy calibration. As shown in Fig. 1 and 2, the difference between the data and MC is found to be 0.5% in energy scale, 5% in resolution.

![Figure 1](image_url)

**Figure 1.** Comparisons between MC (lines) and data (dots): (a) energy distribution of the radiative photon in $\psi'\rightarrow \gamma\chi_{c1}\rightarrow \gamma J/\psi, J/\psi \rightarrow l^+l^-$; (b) energy distribution of the radiative photon in $\psi'\rightarrow \gamma\chi_{c2}\rightarrow \gamma J/\psi, J/\psi \rightarrow l^+l^-; (c)$ invariant mass distribution of $\pi^0$ in $\psi'\rightarrow \pi^0\pi^0 J/\psi, J/\psi \rightarrow l^+l^-$.  

### 4. Using of EMC timing information at BESIII

Physics analyses at BESIII which involve low energy photons such as $\psi'\rightarrow \pi^0 h_c$ ($p(\pi^0) = 84\text{MeV}$), $\psi'\rightarrow \gamma\eta_c$ ($E_\gamma = 47\text{MeV}$) require good photon identification in the low energy region. However, as the luminosity is much higher than at previous experiments, BESIII suffers from much higher beam-gas background. This is a substantial problem when the photon energy is less than 200 MeV. Because the time distribution of physics photons is Gaussian-like while beam-gas background photons are randomly distributed, a peaking time of the energy deposit in the EMC is reconstructed with a precision of 50 ns to discriminate them.
Figure 2. Peaks of the ratio of measured to expected energies ($E_{\text{measure}}/E_{\text{exp}}$) vs. the measured energy of the photon: (a) Comparison of the data (circle) and MC simulation (dot); (b) The difference between the data and MC simulation.

4.1. Timing information in a crystal
The BESIII-CsI(Tl) Calorimeter has 6240 detection units. Each unit consists of a CsI(Tl) crystal and two photodiodes. The main purpose of the read-out electronics of the detection unit is to measure the energy, timing information and to provide a fast energy trigger. Signals from the two photodiodes are amplified by two charge sensitive preamplifiers independently. These signals are summed and coupled to the main amplifier circuit. Then the combined signal is subject to three parallel 10 bit FADC channels with different full scale ranges corresponding to about 0−78, 78−625 and 625−2500 MeV. These FADCs, which are capable of operating at 20.8 MHz with 15 bit equivalent resolution, are realized by three 10 bit FADC channels with three different gains: $\times 0.5$, $\times 2$ and $\times 16$. The data from FADCs are sent to a digital pipeline and the peak finding circuit scans the peak of the signal waveform within 3 $\mu$s after the L1 trigger arrives. The step length of the scanning is 50 ns. The peak value is compared with the threshold stored in the threshold register, and signals smaller than the threshold are discarded. The amplitude of the peak is stored as the read-out energy information and the timing step number of the peak is stored as the time information. The precision of the time information is equal to the scanning step length, 50 ns. For the same trigger type (L1 time), a hit of a physics photon will be a bump in the 3-$\mu$s time scanning window while hits caused by beam-gas background are distributed randomly. The time resolution is determined by the fluctuation of the peaking time of crystals and uncertainty of the trigger time. Fig. 3 shows the crystal time information of physics photons with the same trigger time in the three energy (FADC) regions. The time resolutions are about 150 ns.

Figure 3. Time information of a crystal in different energy region in the data: (a) 0−78 MeV (b) 78−625 MeV (c) 625−2500 MeV.
4.2. Time information in a shower

The time information of the seed crystal in a shower will be reconstructed as the EMC time information of this shower. This raw EMC time is shifted by the trigger type and affected by the resolution of the trigger time. We use EMC time minus event start time in a event to cancel these effects. The subtracted EMC time is used to distinguish physic photon and beam-gas background. Using $\psi' \rightarrow \pi^0\pi^0J/\psi, J/\psi \rightarrow e^+e^-, \mu^+\mu^-$ events, we obtain the the EMC shower time before subtract event start time, event start times for different triggers and the subtracted EMC time used for physics analysis, as shown in Fig.4. From the third column of Fig.4 we find that the subtracted shower time information has little effect arising from the trigger.

![EMC TDC time (before subtract event start time)](image1)

Good photons

![Event start time](image2)

EMC time used for physics analysis

Event TDC time − event start time

Fake photons

Figure 4. Time information of EMC shower.

4.3. Use of EMC timing information

The cut imposed on the shower time is set to 0−14 (× 50 ns) because this value is safe enough to retain signal and veto beam-gas background (veto ratio 70%), as shown in Fig.5. The miscombination background of low-energy $\pi^0$ can also be significantly suppressed by this technique, as shown in Fig. 6. With the help of the time information, we have performed the inclusive analysis of $\psi' \rightarrow \pi^0h_c$ [6] which includes a very low momentum $\pi^0$ ($p(\pi^0)$ 84MeV). Timing information from the EMC is also playing an important role in background rejection in analyses of exclusive decays of $\psi' \rightarrow \pi^0h_c$ and $\psi' \rightarrow \gamma\eta_c(2S)$ ($E_\gamma=47$ MeV), which are ongoing at BESIII.

![Histogram: bkg γ without time cut](image3)

Barrel

Histogram: bkg γ with time cut
Blue: bkg γ with time cut
Ratio of bkg veto ~70%

![Histogram: bkg γ without time cut](image4)

EndCap

Histogram: bkg γ with time cut
Blue: bkg γ with time cut
Ratio of bkg veto ~70%

Figure 5. Performance of using time information to reject background for photon.
5. Summary
In summary, the absolute energy calibration of the EMC works well at BESIII and the precision of the energy measurement reaches 0.5%. Energy scales and lineshapes of photons and $\pi^0$'s have good DATA/MC agreements after calibration. Timing information is very useful as a beam-gas background veto at BESIII.

References
[1] M. Ablikim, et al. "Design and construction of the BESIII detector", arXiv:0911.4960, accepted by Nucl. Instrum. Meth. A
[2] J. Z. Bai et al. (BES Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 458, 627 (2001); 344, 319 (1994).
[3] "Physics at BESIII", Edited by K. T. Chao and Y. F. Wang, Int. J. Mod. Phys. A 24, No.1(2009) supp.
[4] A. Bukin and H. Marsiske, BaBar Note 433(1996).
[5] S. Li & B. Heltsley, CBX 02-17.
[6] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 104, 132002 (2010)