# Study of BESIII electromagnetic calorimeter performance with radiative lepton pair events (postprint)

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## Abstract

We study the photon detection efficiency and position resolution of the electromagnetic calorimeter (EMC) of the BESIII detector. The control samples of the initial-state-radiation (ISR) process of e+e−→ + − at J/ and (3770) resonances are used for the calibration of the photon cluster shapes and photon detection efficiency study. The photon detection efficiency is defined as the fraction of predicted photon, determined by performing a kinematic fit with the four momenta of two charged tracks only, matched with the actual photons in the EMC. The spatial resolution of the EMC is studied in polar ( ) and azimuthal ( ) angle directions in a cylindrical coordinate system centered at the interaction point, with z-axis along the beam direction.

## Full Text

## Preamble

### Study of BESIII Electromagnetic Calorimeter Performance with Radiative Lepton Pair Events

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**Abstract:** We study the photon detection efficiency and position resolution of the electromagnetic calorimeter (EMC) of the BESIII detector. Control samples from the initial-state-radiation (ISR) process $e^+e^- \to \gamma\mu^+\mu^-$ at the $J/\psi$ and

$\psi(3770)$ resonances are used for calibrating photon cluster shapes and investigating photon detection efficiency. The photon detection efficiency is defined as the fraction of predicted photons—determined by performing a kinematic fit using only the four-momenta of the two charged tracks—that are successfully matched with actual photons in the EMC. The spatial resolution of the EMC is studied in both polar ($\theta$) and azimuthal ($\phi$) directions in a cylindrical coordinate system centered at the interaction point, with the $z$-axis aligned along the beam direction.

**Keywords:** Photon detection efficiency, Electromagnetic calorimeter, Spatial resolution, BESIII experiment

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## Introduction

The BESIII experiment is a high-intensity electron-positron collider located at the Institute of High Energy Physics in Beijing, China [**?**]. It has collected large datasets at various center-of-mass energies between 2.0–4.6 GeV, including the $J/\psi$ and $\psi(3770)$ resonances, to study hadron spectroscopy and search for new physics phenomena in the tau-charm region. Other low-lying charmonium states can be produced via radiative photon emission from high-energy resonances, such as $J/\psi \to \gamma\eta_c$ decays. The masses and widths of measured charmonium states are limited by the resolution of photon energy and position measurements when determined from the recoil mass of the photon. BESIII employs a CsI(Tl)-based electromagnetic calorimeter (EMC) to measure electromagnetic showers from electrons and photons with excellent energy and angular resolutions [**?**]. The energy (position) resolution of the BESIII EMC is $2.5\%/\sqrt{E(\mathrm{GeV})}$ $(6\,\mathrm{mm}/\sqrt{E(\mathrm{GeV})})$.

Incident particles interact with EMC detector materials, lose energy, and generate electromagnetic showers [**?**]. Typical electromagnetic showers spread across many adjacent crystals, forming clusters of connected energy deposits. The EMC distinguishes charged from neutral particles: energy deposits associated with charged tracks should have a corresponding track, while neutral particles produce only energy deposits. Photons produce very short and compact cluster shapes, whereas hadrons and other particles generate broad, scattered cluster shapes. Pattern recognition algorithms analyze shower shapes to differentiate real photons from fake ones [**?**]. The energy of showering particles in the EMC is defined as the energy deposited in $3 \times 3$ or $5 \times 5$ crystal arrays [**?**].

A primary task of the BESIII EMC is measuring the energy and position of electrons, photons, and neutral particles with excellent resolution. Any bias in shower position measurement could cause systematic shifts in kinematic variables—for example, the four-momenta of neutral pions—thus degrading the EMC position resolution and introducing bias in physical parameter measurements. Therefore, possible biases must be carefully studied and corrected. The position resolution of the EMC also depends on crystal performance [**?**].

This paper describes our study of photon detection efficiency and position resolution of the BESIII EMC using radiative muon pair events. We detail the procedure for calibrating photon cluster shapes to separate real photons from fake ones. The position resolution is defined as the separation in polar ($\theta$) and azimuthal ($\phi$) angles between reconstructed and expected positions of charged tracks on the front face of EMC crystals.

## 2 BESIII Detector

The BESIII spectrometer is a multi-purpose detector designed to simultaneously measure many properties of particles produced in $e^+e^-$ collisions near the tau-charm region, as described in detail in [**?**]. It provides 93% geometric acceptance of $4\pi$ and consists of four detector subsystems. Charged particle momenta are measured in a 43-layer helium-based main drift chamber (40% He, 60% $C_3H_8$) operating in a 1.0 T solenoidal magnetic field. A scintillator-based time-of-flight system (TOF) with one barrel and two endcaps, along with energy loss ($dE/dx$) measurements in the tracking system, are used for charged particle identification. Photon and electron energies are measured by the EMC, while muons are identified using a muon chamber (MuC) containing nine (eight) layers of resistive plate chambers interleaved with steel in the barrel (endcap) region.

## 2.1 BESIII Electromagnetic Calorimeter

The BESIII EMC contains 6,240 CsI(Tl) crystals arranged in barrel and endcap regions [**?**]. Each crystal is 28 cm long (15.1 radiation lengths $X_0$). The barrel region contains 5,280 crystals divided into 44 rings (denoted by $\theta_{\text{index}}$), with 120 crystals per ring. All crystals are tilted by 1.5 degrees in $\phi$ and 1.5-3.0 degrees in $\theta$ (±5 cm away from the interaction point along the beam direction) to prevent photons from escaping through gaps between crystals. Each endcap region contains six rings with 96, 96, 80, 80, 64, and 64 crystals respectively. The endcaps use 33 different crystal sizes, including 192 irregular pentagonal crystals among the 960 total endcap crystals.

## 3 Data and Monte Carlo Simulation

We study EMC performance using 2.93 $\text{fb}^{-1}$ (0.08 $\text{fb}^{-1}$) of data collected at the $\psi(3770)$ ($J/\psi$) resonance during 2009-2011 [**?**]. Equivalent samples of generic $J/\psi$ and $\psi(3770)$ decays simulated with the EvtGen package [**?**] are used for background studies. Bhabha scattering and diphoton events are generated with BABAYAGA [**?**], while the PHOKHARA package [**?**] simulates initial-state-radiation (ISR) channels: $e^+e^- \to \gamma\mu^+\mu^-$, $e^+e^- \to \gamma\pi^+\pi^-$, and $e^+e^- \to \gamma\pi^+\pi^-\pi^0$. Detector response and time-dependent reconstruction efficiencies are determined from GEANT4-based Monte Carlo simulation [**?**] and included in the simulated events.

## 4 Study of EMC Performance with Radiative Muon Pair Events

We use control samples from the ISR process $e^+e^- \to \gamma\mu^+\mu^-$ at $J/\psi$ and $\psi(3770)$ resonances to study energy and position resolutions and photon detection efficiency. Events are reconstructed with two oppositely charged tracks required to have their points of closest approach to the beamline within ±10.0 cm in the beam direction ($V_z$) and ±1.0 cm in the plane perpendicular to the beam ($V_{x,y}$). The tracks must also fall within the detector acceptance region [**?**]. To enhance muon purity, we require penetration depth in the MuC greater than 35 cm [**?**]. A kinematic fit is performed using the two charged tracks with the constraint that the missing track mass must be zero, requiring $\chi^2 < 25$. Since muon and pion masses are very similar, radiative pion pair events are also considered signal. At this stage, background contributions are less than 1%. Photon estimates from the kinematic fit are used to compute EMC energy and position resolutions and photon detection efficiency.

Figure 1 [Figure 1: see original paper] shows the energy and cosine of polar angle distributions for predicted photons in both $J/\psi$ and $\psi(3770)$ datasets. A peak around 0.6 GeV appears in the $\psi(3770)$ energy distribution due to ISR production of the $J/\psi$ resonance. The Monte Carlo simulation describes the data well.

### 4.1 Calibration of Photon Cluster Shape

Shower processes in the EMC must be well-characterized for particle identification and reconstruction. Several variables have been developed to study shower shapes, including second moment and lateral moment (LAT) [**?**]. These quantify the transverse shower shape and separate electromagnetic from hadronic showers, as EM showers deposit large energy fractions in one or two crystals while hadronic showers are more diffuse.

The second moment is defined as $\sum_i E_i r_i^2 / \sum_i E_i$, where $E_i$ is the energy deposited in the $i$th crystal and $r_i$ is the radial distance from the cluster center. The LAT [**?**] is defined as:

$$\mathrm{LAT} = \frac{\sum_{i=3} E_i r_i^2}{\sum_{i=3} E_i r_i^2 + E_1 r^2 + E_2 r^2}$$

where $r$ is the average distance between crystals (5 cm).

We calibrate LAT and second moment distributions by adjusting the EMC incoherent noise (EINC) value [**?**]. A clean sample of radiative muon pair events is used. Figure 2 [Figure 2: see original paper] shows a clear discrepancy between data and old MC simulated with the previously used EINC value of 0.20 MeV, with data shifted to higher lateral and second moments. This discrepancy is resolved in new MC simulated with EINC = 0.27 MeV, which describes the data well.

We study EINC effects on energy and position resolutions—computed from differences in energy and angular distributions between predicted and reconstructed photons—at various predicted photon energies ($E_{\text{pred}}$) using both old (EINC = 0.20 MeV) and new (EINC = 0.27 MeV) MC. Figure 3 [Figure 3: see original paper] shows that energy resolution in the new MC is slightly worse than in the old MC but much closer to real data. However, increased EINC and kinematic fit effects are negligible in angular distributions. Spatial resolutions are multiplied by $l$ and $r$ for $\theta$ and $\phi$ directions respectively to express them in cm, where $l$ is the path length from the interaction point to the EMC cluster centroid and $r$ is the EMC inner radius. Position resolution in old MC is compatible with new MC. Polar angle resolution appears worse than expected due to dependence on $V_z$ resolution, which is much larger than $V_x$ and $V_y$ resolutions. Azimuthal angle resolution, depending on $V_x$ and $V_y$, appears compatible with expectations in the high-energy region. Energy and position resolutions from MC-truth agree well with data and MC values in the high-energy region.

### 4.2 Photon Detection Efficiency

We compute photon detection efficiency as the fraction of predicted photons matched with actual EMC photons using the clean radiative muon pair sample. If a predicted photon matches an actual photon, the $\theta_{\gamma,\gamma_{\text{pred}}}$ and $E_\gamma/E_{\text{pred}}$ distributions should peak at 0 radian and 1 respectively, where $\theta_{\gamma,\gamma_{\text{pred}}}$ is the angle between predicted and reconstructed photons and $E_\gamma/E_{\text{pred}}$ is the energy ratio (Figure 4 [Figure 4: see original paper]). Regions with $\theta_{\gamma,\gamma_{\text{pred}}} < 0.5$ radian and $E_\gamma/E_{\text{pred}} \in [0.15, 1.4]$ define the photon detection region. Figure 5 [Figure 5: see original paper] shows photon detection efficiency as a function of energy and cosine of polar angle for data and MC. Systematic uncertainty due to photon reconstruction, defined as the relative efficiency difference between data and MC, is observed at the 1% level (Figure 6 [Figure 6: see original paper]).

## 5 Shower Position Reconstruction

Incident particles create electromagnetic showers inside the calorimeter that develop laterally and longitudinally across several connected crystals as the particles lose energy. The continuous connected region of crystals with energy deposits forms a cluster. Each shower is identified by a seed—the local energy maximum among neighbors. A center-of-gravity (CG) method calculates the impact coordinate $x_c$ of showering particles on the EMC front face [**?**, **?**]. Mathematically, the CG is defined as:

$$x_c = \frac{\sum_i W_i(E_i)x_i}{\sum_i W_i(E_i)}$$

where $W_i(E_i)$ is the energy weighting function and $x_i$ is the coordinate of the $i$th crystal center in the cluster on the EMC front face. The sum includes all crystals in the cluster.

The simplified "linear weighting function" is defined as $W_i(E_i) = E_i$. The "logarithmic weighting function" reduces weight for the most energetic crystals and enhances low-energy contributions:

$$W_{\log}(E_i) = \mathrm{Max}\{0, a_0 + \ln(E_i) - \ln(E_{\mathrm{tot}})\}$$

where $E_{\mathrm{tot}}$ is the total deposited energy and $a_0 = 4.0$ is a cutoff parameter ensuring positive arguments and removing very low-energy crystals. BESIII uses both methods for shower position measurement [**?**].

### 5.1 Position Resolution

We study EMC position resolution using a radiative Bhabha sample at the $J/\psi$ resonance by examining $\delta\theta$ and $\delta\phi$ distributions—defined as separations in $(\theta, \phi)$ between reconstructed and expected track positions on the EMC front face. These angular distributions are converted to cm units via $\Delta\theta = \delta\theta \times l$ and $\Delta\phi = \delta\phi \times r$. Figure 7 [Figure 7: see original paper] shows $\Delta\theta$ and $\Delta\phi$ resolution versus electron momentum. The $\Delta\phi$ resolution degrades slightly at low momentum due to magnetic field effects. The EMC position resolution for $e^{\pm}$ appears compatible with expectations, whereas in Figure 3 the resolution seemed degraded due to poorer event vertex resolution.

Simulated single electron and photon events help understand discrepancies between photon and charged track position resolutions. Expected track positions are computed using either MC-truth information at the EMC crystal front face or extrapolated tracks from the MDC. Figure 8 [Figure 8: see original paper] shows EMC position resolution in $\theta$ and $\phi$ for electrons and photons. The $\theta$ resolution computed using MDC-extrapolated tracks appears worse due to large extrapolation uncertainties. Position resolutions for charged and neutral tracks are identical and compatible with expectations in single electron/photon control samples. The EMC intrinsic resolutions from photons and electrons are consistent, with resolution determined by EMC geometry.

## 6 Summary and Conclusion

We have calibrated photon cluster shapes and computed photon detection efficiency of the BESIII detector using a clean control sample of radiative muon pair events. Systematic uncertainty due to photon reconstruction, defined as the relative efficiency difference between data and MC, is observed at the 1% level. EMC position resolution has been studied independently in polar and azimuthal angles using a radiative Bhabha sample. The position resolution is compatible with expected values for both charged and neutral tracks.

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