

# Simulation and reconstruction of the BESIII EMC

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**Abstract.** The simulation and reconstruction software of the BES III Electromagnetic Calorimeter (EMC), are developed based on the object-oriented language C++, in the framework of Gaudi[1]. Performance of EMC are studied with data and compared with Monte Carlo samples.

## 1. Introduction

The Beijing Spectrometer (BES) III [2][3] is a multi-purpose detector operated at the Beijing electron-positron collider (BEPC) II for physics at tau-charm energy region.

The BES III detector consists of four sub-detectors: the Drift Chamber (DC), Time-Of-Fight counters(TOF), the Electromagnetic Calorimeter (EMC), and Muon Counters(MUC). EMC is used to measure energies and positions of electrons and photons with high detection efficiency and good resolutions. The simulation software of EMC shall implement detector simulation and digitization, and reconstruction software shall process the raw data, correct all possible bias and reconstruct the energy and position of incident particle.

This paper introduces the design and the implementation of the EMC simulation and reconstruction software package, developed in the framework of BES III Offline Software System(BOSS)[4]. The configuration of the EMC is described firstly, followed by the discussion of basic simulation and reconstruction algorithms. The performance of EMC and comparison between data and simulation is shown at the end.

## 2. Construction of the BES III EMC

The BESIII electromagnetic calorimeter, made of CsI(Tl) crystals, is composed of one barrel and two endcaps. The barrel has an inner radius of 94 cm and a total of 44 rings of crystals along the z direction, each with 120 crystals. It covers the polar angle of  $146.5^\circ - 33.5^\circ$  ( $|\cos\theta| = 0.83$ ). The endcaps with inner radius of 50cm are placed at 138.5 cm from the collision point, each consists of 6 rings and is split into two half circles. It covers the polar angle of  $32.5^\circ - 21.3^\circ$  ( $|\cos\theta| = 0.93$ ). Hence the total acceptance of the barrel and endcaps is 93% of  $4\pi$ , and The whole calorimeter has 6272 CsI(Tl) crystals with a total weight of about 24 tons. Each crystal has a length of 28 cm, a cross section of about  $5.2\text{ cm} \times 5.2\text{ cm}$  in front face and  $6.4\text{ cm} \times 6.4\text{ cm}$  in rear face. All crystals pointing to a position off from the interaction point by a few centimeters with a tilt angle of  $1^\circ - 3^\circ$ .

### 3. EMC Simulation

Simulation package is based on GEANT4, which contains the description of detector, physics list, tracking and digitization.

#### 3.1. Detector geometry and materials definition

The barrel crystal is described by GEANT4's G4Trap volumn. While endcap crystal is not regular and can't be reproduced by any volumn in GEANT4 directly. Instead, we introduce a new volumn called G4IrregBox[5], which describes a general hexahedron and takes the coordinates of its 8 vertices as input parameters. Besides crystals, other materials like casing, photodiode, pre-amplifier box, cable, water pipe and support system are also included in detector description.

#### 3.2. Physics list

A standard electro-magnetic interaction is provided by GEANT4 and used here for simulation. For hadronic interactions, several models have been tried and compared with BESIII data[6]. QGSP\_BERT\_HP gives best agreement between data and Monte Carlo.

#### 3.3. Tracking and hits

The tracking of particles through the EMC is essentially done according to the GEANT4 standard. When a particle traverses a sensitive volume (a crystal or photodiode), the hit information, such as the particle position, energy deposit, etc., are saved for the digitization procedure which is discussed in the next section.

#### 3.4. Digitization

The core component of digitization is the simulation of readout electronics. The response function of electronics can be calculated by forming an expression for the various components in the Laplace domain. The exponential decay constant is  $1 \mu\text{s}$  for Thallium doped CsI, which gives a  $1/(s+a)$  term in the Laplace domain, where  $a$  is the reciprocal of the decay time constant. The preamplifier is assumed to have an infinite time constant, giving a  $1/s$  term. The differentiation stage of shaping circuitry gives a  $s/(s+b)$  term ( $b = 1/CR$ ) and the integration parts gives a  $1/(s+c)^3$  contribution ( $c = 1/RC$ ). Then the final expression is the product of above terms:

$$\frac{1}{s+a} \times \frac{1}{s} \times \frac{s}{s+b} \times \frac{1}{(s+c)^3}. \quad (1)$$

Since the time constant of differentiation and integration are  $1 \mu\text{s}$ , the response function in time domain, i.e. waveform, is given by Inverse Laplace Transform:

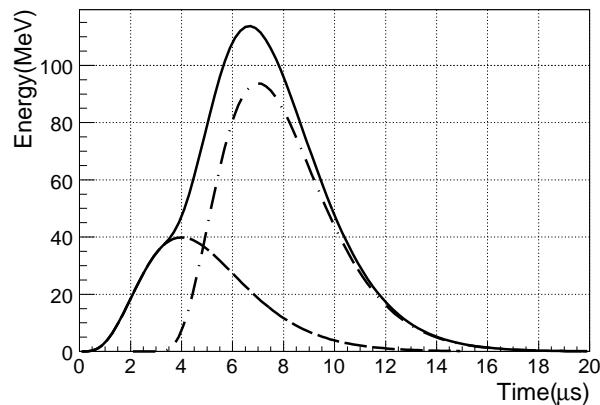
$$h(t) = \frac{1}{24} t^4 e^{-t/\tau}, \quad (2)$$

in which  $\tau=1 \mu\text{s}$ .

Based on the calibration constants, the waveform is easily scaled so the peak value equals energy deposit, i.e., energy sum of all hits in this crystal. Then this waveform is sampled at 50ns time interval starting with  $1.5\mu\text{s}$  ahead of the peak, and lasts  $3\mu\text{s}$ , i.e., 60 sampling points. The maximum amplitude of these sampling points is recorded as energy and the index of the maximum point is recorded as time.

#### 3.5. Noise simulation

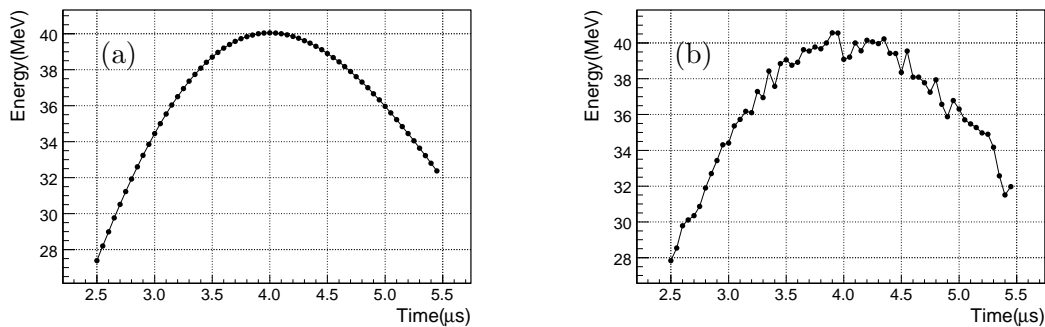
Beam related backgrounds are obtained from random trigger in real data, which contains energy and time information of each crystal caused by backgrounds. Each MC event is mixed with one of the background event which is randomly picked up from random trigger sample. If a crystal



**Figure 1.** Sum of waveforms. — Sum of waveforms, — · — signal, — — — background

has signal either from simulation or background, it will be kept. Otherwise the two signals in the same crystal will be added together by constructing two waveforms according to their energies and times, as shown in Fig.1. Obviously, the energy of mixed waveform is less than the sum of MC and background energies, and the time is between them.

Electronics noise is usually Gaussian distribution. A random noise is generated for each sampling point according to the measured noise and added with it. Fig.2 (a) shows ideal sampled waveform with 40 MeV energy and 4  $\mu$ s time. While in Fig.2 (b), 0.5 MeV noise is added and the energy and time are both deviated.



**Figure 2.** Sampled waveform (a) before and (b) after adding electronics noise.

#### 4. EMC Reconstruction

When a photon or an electron hit the EMC, it interacts with CsI(Tl) crystals. The photon transforms to  $e^+e^-$  through gamma conversion, and  $e^+$  or  $e^-$  releases photons through bremsstrahlung. These interactions continue alternately and form an electromagnetic shower. The shower develops laterally and longitudinally, losing energy in several connected crystals. The reconstruction algorithm searches these related crystals, adds their energy together, and calculates the hit position.

#### 4.1. Clustering

The primary task of the reconstruction software of a crystal calorimeter is to identify connected regions, called clusters. There are several ways to define them for different arrangement of crystals. At BES III, the definition of a cluster is a contiguous group of crystals above a certain threshold. Its finding algorithm is to recursively search for a list of neighboring crystals above a certain energy threshold, and add them into a list. Crystals in the list are retrieved and its neighboring crystals are searched for again. This process is continued until no neighboring crystals are found. All the crystals in the list form a cluster. The same procedure is implemented for crystals not in the list, until no more clusters are found.

#### 4.2. Cluster splitting

A cluster can be the result of energies deposited by one or more particles, corresponding to one or more showers. Each shower is recognized by a seed, which is the local maxima of energy deposit among its neighbors. If a cluster contains only one seed, only one shower, i.e., one particle is produced. If more seeds are found, for example, in a cluster caused by high momentum  $\pi^0$ , the cluster can be split to several showers. Every crystal in this multi-shower cluster will be assigned a weight from each seed, and contributes a corresponding shared energy to each shower.

#### 4.3. Shower energy

Energy is one of the most important quantities for physics analysis. Although the sum over of all crystals in a shower seems to deliver the best energy resolution, the electronics noise and backgrounds may be included in the sum, hence deteriorate the resolution. Some of the common practices to avoid this problem is to define the shower energy as  $E3 \times 3$  or  $E5 \times 5$ , a sum of 9 crystals or 25 crystals around the seed.

The distribution of the shower energy shows a non-Gaussian tail at the lower energy side, shown in Fig.3 and Fig.4, caused mainly by the front, rear and side leakage of energy. The energy loss in the Time-Of-Flight counters can be reconstructed and matched with EMC shower which is discussed in Ref.[9]. The energy peak then is corrected to expectation with  $\pi^0$  samples or photon samples from BESIII data, discussed in Ref.[10].

#### 4.4. Shower position

There are many different methods to obtain the shower position. The most simple and fast one is the weighted mean, as written in the following:

$$x_c = \frac{\sum_i W_i(E_i) x_i}{\sum_i W_i(E_i)}. \quad (3)$$

The weight,  $W_i(E_i)$ , is a function of energy deposited in the  $i$ th crystal, and  $x_i$  the coordinate of the crystal center at the front face. In Ref.[11] several weighting functions are carefully discussed. Two of them are listed here:

$$W_i^{(linear)}(E_i) = E_i, \quad (4)$$

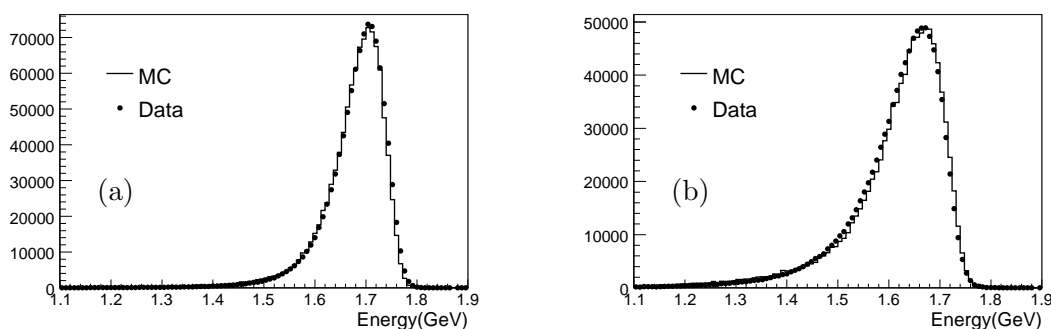
$$W_i^{(log)}(E_i) = \text{Max}\{0, a_0 + \ln(E_i) - \ln(E_{total})\}. \quad (5)$$

They are called linear weighting function and logarithmic weighting function, respectively. Both of them need corrections because of the complexity of the EMC geometry. Bhabha event is chosen for this purpose, and the real hit position is supplied by the track extrapolation[12] from the drift chamber information.

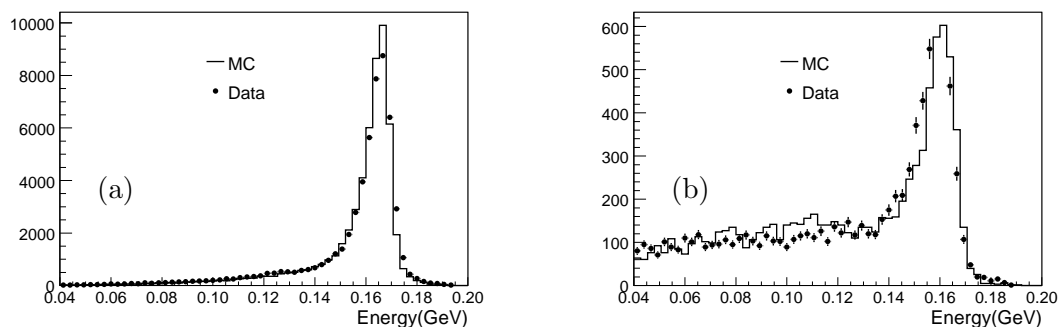
## 5. Performance study

In this section, data with centre of mass system energy 3.686 GeV is taken from March, 2009 to April, 2009, and data at 3.097 GeV energy point is taken in June, 2009.

Fig.3 shows reconstructed energy spectrum ( $E5 \times 5$ ) of electrons and positrons from  $e^+e^- \rightarrow e^+e^-$  (bhabha events) at 3.686 GeV in barrel and endcap, respectively, which presents good agreement between data and simulation for high energy showers. Energy resolution in endcap is much more worse than in barrel because there are more dead materials in front of endcap than barrel. For low energy showers, they are also consistent, as shown in Fig.4, in which photons are generated in  $\psi' \rightarrow \gamma\chi_{c1}$ . A long tail is shown at the low energy side also because of the material effect in front of EMC.



**Figure 3.** Energy spectrum of bhabha events in (a)barrel and (b)endcap

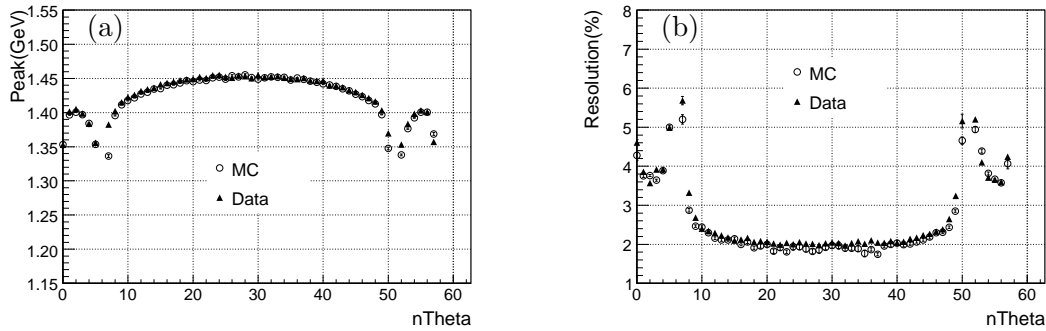


**Figure 4.** Energy spectrum of photon from  $\psi' \rightarrow \gamma\chi_{c1}$  in (a)barrel and (b)endcap

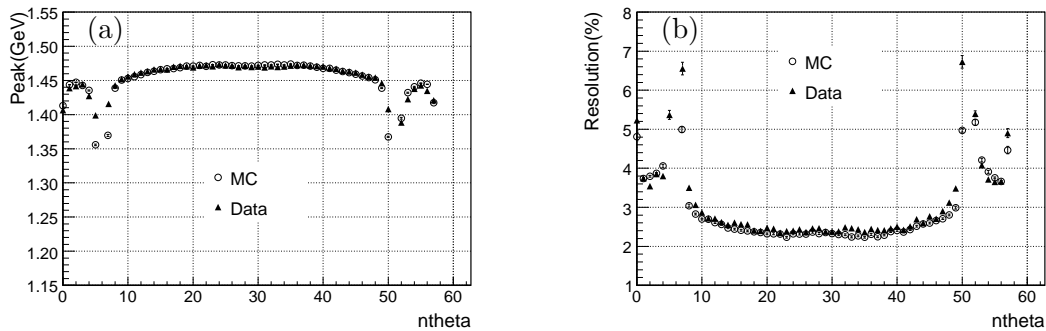
Fig.5 shows the average energy peak and energy resolution of electrons and positrons from  $e^+e^- \rightarrow e^+e^-$  at 3.097 GeV as a function of crystal id in  $\theta$  direction. Energy resolution is 2.3% in barrel and 4.1% in endcap for both data and simulation. While for photons from  $e^+e^- \rightarrow \gamma\gamma$  (diphoton events) at 3.097 GeV, energy resolution is 2.7% in barrel and 4.2% in endcap, showing worse than bhabha events. The reason is photons interact with the materials in front of EMC by the production of electrons and positrons which introduce large fluctuation of energy loss, and make energy resolution worse. However, data and simulation show good agreement.

## 6. Conclusion

The simulation and reconstruction software packages for the BES III EMC have been developed and work normally during data taken. The performances are studied with data and basically



**Figure 5.** (a)Energy peak and (b)energy resolution of bhabha events



**Figure 6.** (a)Energy peak and (b)energy resolution of diphoton events

consistent with simulation.

## References

- [1] Barrand, G. et al., A software architecture and framework for building HEP data processing applications, *Comput. Phys. Commun.*, 140: 45-55, 2001
- [2] Y.F. Wang, The construction of the BESIII detector *Int. J. Mod. Phys. A* 21(2006)5371.
- [3] BESIII Collaboration, *Nucl. Instr. Meth. A* Volume 614, Issue 3, 11 March 2010, Pages 345-399
- [4] Weidong Li, Huaimin Liu et al., The Offline Software for the BESIII Experiment, February 2006, Mumbai, India.
- [5] <http://hypernews.slac.stanford.edu/HyperNews/geant4/get/geometry/305.html>
- [6] G.F.Cao et al. *NIMA*, Volume 606, Issue 3, 21 July 2009
- [7] D.Antreasyan, "An algorithm for tagging photon and merged  $\pi$  showers in the crystal ball", *Crystal Ball note* 321, 1983
- [8] R. Seitz, SLAC-BABAR-NOTE-294
- [9] M.He, et al. *Chinese Physics C (HEP & NP)*, 2008, 32(04): 269-274
- [10] J.M.Bian, et al. *Chinese Physics C (HEP & NP)*, 2010 34(01): 7277
- [11] B.B.Brabson et al., *Nucl. Instr. Meth.*, A332(1993), 419
- [12] Liangliang, Wang et al., *HEP&NP*