Calibration of the $\text{Babar}$ CsI (Tl) Calorimeter

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Abstract. After nine years of operation, the $\text{Babar}$ experiment at the $e^+e^-$ $B$ factory PEP-II (Stanford Linear Accelerator Center) stopped data taking in April 2008. An important part of the experiment is the electromagnetic calorimeter which consists of 6580 CsI crystals doped with thallium and read out by Si-PIN photodiodes. The light yield of the CsI crystals is changing in time due to radiation exposure. In addition to the changing light yield, passive material in front of and between the crystals as well as signal thresholds during the reconstruction influence the reconstructed energies. This requires a time-dependent calibration of the calorimeter. The calibration issues are reviewed and the calibration results obtained from various data samples are presented.

1. Introduction

The photon energy calibration of the $\text{Babar}$ electromagnetic calorimeter (EMC) [1] is performed in three main steps. The first two, the calibration of the electronic readout chain and the charge-to-energy conversion at the single crystal level were discussed in the previous presentation [2].

This presentation describes a third calibration step applied at the cluster level. The limited shower containment due to the total CsI crystal length and the dead material in front of the calorimeter (0.3 to 0.7 radiation length ($X_0$)) and between the CsI crystals lead to an energy loss of the total cluster energy measurement. Moreover, the noise suppression and the energy deposited in crystals not associated with the clusters during the reconstruction process cause an additional reduction. Therefore, the measured cluster energy has to be calibrated to the true energy of the primary electron or photon which is performed by the cluster energy calibration.

2. Cluster energy calibration

2.1. Cluster energy calibration scheme

The cluster calibration requires processes which allow a calorimeter-independent energy determination of the calibration signature (mostly photons). Their predicted energy has to be compared to the measured energy in the calorimeter over a range from well below 100 MeV up to the highest energies. Since no single process covers the whole energy range, photons from $\pi^0$ decays ($\pi^0 \rightarrow \gamma\gamma$) produced in multi-hadron events are used in the low-energy regime ($70 \text{ MeV} < E_\gamma < 2 \text{ GeV}$). The high-energy regime ($400 \text{ MeV} < E_\gamma < 6 \text{ GeV}$) is covered by photons from radiative muon events ($e^+e^- \rightarrow \mu^+\mu^-\gamma$).

The calibration function

$$C = f(E_\gamma, \theta_\gamma)$$

(1)
depends on the energy $E_\gamma$ and the polar angle $\theta_\gamma$ of the photon. The emphasis of the calibration is to correct the measured cluster energies to the absolute energy scale and to describe the measured energy scale and their dependencies by the BABAR detector simulation based on GEANT4 [3].

Due to the poor statistical coverage of the full parameter space $(E_\gamma, \theta_\gamma)$, only the projections of the calibration function can be measured

$$C = g(E_\gamma) \cdot h(\theta_\gamma).$$

In a first step, the polar-angle-dependent part $h(\theta_\gamma)$ is determined using radiative muon events. After applying the polar-angle-dependent part $h(\theta_\gamma)$, the energy-dependent part $g(E_\gamma)$ is extracted from both the $\pi^0$ and the radiative muon sample over the full energy range.

### 2.2. Calibration with radiative muon data

Since the initial state parameters of the process $e^+e^- \rightarrow \mu^+\mu^-\gamma$ are known and the muon energies are measured in a calorimeter-independent way, the reaction is kinematically over-determined. Thus, the energy and the polar angle of the photon can be determined by a kinematic fit independent of any calorimetric measurement. The predicted photon energy $E^\gamma_{\text{true}}$ is compared to the photon energy measured in the EMC $E^\gamma_{\text{rec}}$ by considering the ratio distribution $E^\gamma_{\text{rec}}/E^\gamma_{\text{true}}$. The average values of the ratio distributions $\langle E^\gamma_{\text{rec}}/E^\gamma_{\text{true}} \rangle_{\text{fit}}$ are quantitatively evaluated by the peak position of a fit of a modified Log-normal distribution [4]. In the MC simulation, the cluster calibration function is extracted using the true photon energy $E^\gamma_{\text{true}}$ instead of the predicted one.

The asymmetric line shape of the photon response distribution $E^\gamma_{\text{rec}}$ causes systematic shifts of the ratio $E^\gamma_{\text{rec}}/E^\gamma_{\text{true}}$ and therefore the data-over-MC-simulation ratio has to be used to extract the calibration function.

The angular part $h(\theta_\gamma)$ of the calibration function is determined in the different areas of the $\theta$-modules (7 crystals each [2]) $\theta^k_i$. The following ratio yields the $\theta$-dependent calibration function for data:

$$h^{\text{data}}(\theta^k_i) = \frac{\langle E^\gamma_{\text{rec}}/E^\gamma_{\text{true}} \rangle_{\text{data}}(\theta^k_i)}{h^{\text{MC}}(\theta_\gamma) \cdot \langle E^\gamma_{\text{rec}}/E^\gamma_{\text{true}} \rangle_{\text{MC}}(\theta^k_i)}.$$  

The function is measured for three different ranges of the photon energy (I. 0.5–1.0 GeV, II. 1.0–2.0 GeV, III. 2.0 – 4.0 GeV) depending on the polar angle of the crystals ($\theta$ crystal index) and is shown for the data taking period 2006 in Figure 1. The full lines represent the parametrizations.

In order to determine the energy-dependent calibration function $g(E_\gamma)$ for simulated data, the $\theta$-dependent function $h(\theta_\gamma)$ is applied and $g_{\text{MC}}(E_\gamma)$ is obtained using the true photon energy.

**Figure 1.** $\theta$-dependent calibration in three energy ranges for $\mu\mu\gamma$ data of the data taking period 2006.

**Figure 2.** Energy-dependent calibration for $\pi^0$ and $\mu\mu\gamma$ data after applying the $\theta$-dependent part (data taking period 2006).
The calibration function for data is extracted from

\[ g_{\text{data}}(E_{\gamma}^i) = \frac{h_{\text{data}}(\theta_{\gamma}) \cdot (E_{\gamma}^i/E_{\text{fit}})_{\text{data}}(E_{\gamma}^i)}{g_{\text{MC}}(E_{\gamma}) \cdot h_{\text{MC}}(\theta_{\gamma}) \cdot (E_{\gamma}^i/E_{\text{fit}})_{\text{MC}}(E_{\gamma}^i)} . \]  

(4)

The red symbols in Figure 2 show the results obtained for the radiative muon data on a logarithmic \( E_{\gamma} \) scale.

2.3. Calibration with photons of \( \pi^0 \) decays

In order to measure \( g(E_{\gamma}^i) \) in the low-energy regime, \( \pi^0 \) decays with the two decay photons in the same energy range (symmetric \( \pi^0 \)'s) are selected. The distribution of the invariant mass \( m_{\gamma\gamma} \) of the \( \pi^0 \) candidates is shown as the blue distribution in Figure 3 for photons in the range 70 MeV < \( E_{\gamma 1} \), \( E_{\gamma 2} \) < 90 MeV. At low photon energies, peaking combinatorial background appears in the \( \pi^0 \) signal region. The combinatorial background contribution shown in Figure 3 (red histogram) is determined by combining photons from different events. Subtracting the background from the invariant mass distribution yields the \( \pi^0 \) signal distribution (Figure 4). The asymmetric line shape of the photon response causes the invariant mass \( m_{\gamma\gamma} \) of the \( \pi^0 \) candidates to be shifted by \( \Delta m = m(\pi^0) - m_{\gamma\gamma} \), even if the photon response is perfectly calibrated. \( \Delta m \) is a function of the photon energy resolution, the tail of the photon response function and the position resolution of the photons. To account for these effects, the calibration function \( g_{\text{data}}(E_{\gamma}) \) in the low-energy regime is determined as the ratio of the average invariant mass values obtained with calibrated photon energies in the MC simulation and uncalibrated energies in the data,

\[ g_{\text{data}}(E_{\gamma}^i) = \frac{C_{\text{MC}}(E_{\gamma}) \cdot \langle m_{\gamma\gamma} \rangle_{\text{MC}}(E_{\gamma}^i)}{h_{\text{data}}(\theta_{\gamma}) \cdot \langle m_{\gamma\gamma} \rangle_{\text{data}}(E_{\gamma}^i)} . \]  

(5)

The average values of the invariant mass distributions \( \langle m_{\gamma\gamma} \rangle \) are quantitatively evaluated by the determination of the peak position by a fit of a modified Log-normal distribution [4]. The blue symbols in Figure 2 show \( g_{\text{data}}(E_{\gamma}^i) \) on a logarithmic \( E_{\gamma} \) scale for the \( \pi^0 \) sample of the data taking period 2006. The full line represents the parametrization of the energy-dependent part of the photon calibration.

1 The \( \pi^0 \) mass distribution is a convolution of the two asymmetric photon response functions.
This scheme implies a perfect description of the data by the MC simulation. Any deviation causes systematic shifts in the invariant mass and therefore shifts of the calibration function. Using typical discrepancies between data and MC simulation, the systematic uncertainties are estimated to be about 0.3% in case of the $\pi^0$ sample. In case of the radiative muon sample, the systematic uncertainties decrease from 0.5% at the lowest energy value to 0.1% at the highest.

2.4. Cluster calibration results

The invariant mass ratio of data and simulation for the $\pi^0$ sample of the 2007 data taking period before (blue symbols) and after (red symbols) applying the calibration is shown in Figure 5. In case of the green symbols, the daughter photons of the $\pi^0$ decay originate from different energy ranges. Without cluster calibration, the deviations between data and MC simulations are as large as 1.5% and $(E_\gamma, \theta_\gamma)$-dependent. After applying the calibration, within the uncertainties the data are well described by the MC simulation and are independent of $E_\gamma$ and $\theta_\gamma$.

Figure 5. Invariant mass ratio of data and MC simulation for the $\pi^0$ sample of the 2007 data taking period.

Figure 6. $E_{\text{rec}}^\gamma / E_{\text{fit}}^\gamma$ data-MC-simulation ratio for the radiative muon sample of the 2006 data taking period.

MC-simulation ratio of the quantity $E_{\text{rec}}^\gamma / E_{\text{fit}}^\gamma$ for the radiative muon sample of the 2006 data taking period is shown in Figure 6. As in case of the $\pi^0$ sample, after applying the calibration, the data are well described within the estimated uncertainties from the data-MC-simulation agreement. No remaining dependencies on $E_\gamma$ and $\theta_\gamma$ are observed.

2.5. Validation of the cluster energy calibration

In the process $\Sigma \rightarrow \Lambda \gamma \rightarrow p\pi\gamma$ the photon energy is constrained and can be used to perform an independent test of the calibration at low photon energies ($50\text{MeV} < E_\gamma < 400\text{GeV}$). The photon energy is calculated using tracking and particle identification information

$$E_{\gamma}^{\text{calc}} = \frac{M_\Sigma^2 - M_\Lambda^2}{2(E_\Lambda - p_\Lambda \cos \theta_\Lambda \gamma)}$$

(6)
where \( M_X \) denotes the invariant mass, \( E \) the energy, \( p \) the momentum of the particles and \( \theta_{\Lambda \gamma} \), the opening angle between \( \Lambda \) and \( \gamma \). The ratio of the predicted to the measured photon energy in the projections of \( E_\gamma \) and \( \theta_\gamma \) is measured and is found to be consistent with 1 within the total uncertainties of about 1%.

In the high-energy regime, the photon energy scale can be probed by the process \( B^0 \rightarrow K^{*0, \gamma} \rightarrow K^+ \pi^- \gamma \). The photon energy in this process ranges from 1.5 GeV to 3.5 GeV. The difference between the reconstructed energy \( E_{\text{rec}}^{B^0} \) of the \( B^0 \) and the beam energy \( E^*_{\text{beam}} \) (both in the center of mass frame)

\[
\Delta E = E_{\text{rec}}^{B^0} - E^*_{\text{beam}}
\]

is determined with quantities measured by the tracking system, particle identification and the photon energy. The measurements yield \( \Delta E_{\text{data}} = (-8.7 \pm 2.3) \text{ MeV} \) for the data and \( \Delta E_{\text{MC}} = (-8.5 \pm 0.2) \text{ MeV} \) for the MC simulation. This translates to a deviation of the photon energy scale of \( (-0.35 \pm 0.09) \% \) for data.

3. Smearing of the photon response in MC data

The line shape of the photon response is not fully described by the MC simulation. As a consequence, it is difficult to model selection criteria and efficiencies in physics analyses. The main goal is the improvement of the MC simulation description by tuning the MC model to data. Because of the large amount of MC data already simulated, a simplified approach is to introduce an additional term to the simulated photon response. It reflects the difference between the measurement and the MC simulation. Data of the process \( e^+e^- \rightarrow \mu^+\mu^-\gamma \) allows to determine a smearing matrix (Students \( t \) distribution [5]) \( S_{ij} \) which connects the bin \( i \) of the distribution of the normalized photon response \( E_{\text{rec}}^{ij}/E_{\text{fit}}^{ij} \) in MC simulation with the bin \( j \) of the data distribution. The smearing matrix depends on the photon energy and the calorimeter area.

After applying the smearing procedure to the MC data, the measured photon line shape in data is very well modeled. As an independent test, the \( \Delta E \) distribution of \( B^0 \rightarrow K^{*0, \gamma} \rightarrow K^+ \pi^- \gamma \) processes is compared in data and MC simulation. The \( \Delta E \) line shape in data is very well described by the smeared MC simulation.

4. Monitoring of the EMC with muons

The signatures of minimum ionizing muons (from \( e^+e^- \rightarrow \mu^+\mu^- \)) measured in the EMC provide a stable signal in time with an energy loss in a CsI crystal of about 200 MeV depending on the muon energy. Selecting muons which fully pass one crystal and normalizing the muon signal by the crystal length allows to monitor the time stability of the crystal response. The average energy deposition of each crystal is determined as the peak position of a fit of a modified Log-normal distribution [4] to the muon signal.

The time stability over the full time of the \( B\bar{B} \) operation can be seen by building the average over \( \phi \) of the mean energy deposition of each crystal. The muon energy increases with decreasing \( \theta \) (in forward direction). Therefore, the relativistic rise of \( dE/dx \) [6] leads to an increase of the average muon response in forward direction. The time dependence is illustrated in Figure 7 for the barrel part of the calorimeter. The variation over the data taking period from 2001 to 2008 is about \( \pm 0.5 \% \).

The normalized muon response can be used to determine calibration factors for each crystal. The width of the measured cluster energy of the photons from radiative muons over the predicted photon energy \( E_{\text{rec}}^\gamma / E_{\text{fit}}^\gamma \) judges the improvement in the resolution. The crystal calibration system considers the non-homogeneous light yield over the crystal length by using low energy and high energy signals (see [2]). However, in case of a calibration with muons this effect is not included and therefore the energy resolution degrades.
5. Lateral non-uniformity correction

Between the CsI crystals, dead material cannot be avoided. As a result, a drop of the response $E_{\gamma}^{\text{rec}}/E_{\gamma}^{\text{fit}}$ at the crystal edges by about $2 - 3\%$ is observed (see Figure 8 red histogram). As in case of the cluster calibration, photons of the process $e^+e^- \rightarrow \mu^+\mu^-\gamma$ are used to obtain a correction function (lateral non-uniformity correction) depending on the impact position on the crystal surface. The correction function is determined in two dimensions and in five energy bins ($400 \text{ MeV} < E_{\gamma} < 8 \text{ GeV}$). Applying the lateral non-uniformity correction, the photon response is found to be independent of the impact position as shown in Figure 8 as green histogram. The energy resolution is measured to improve by about 10\%.

6. Association of EMC cluster and DIRC information

The dead material in front of the central part of the EMC varies between 0.3 and 0.6 $X_0$. The largest contribution is from the quartz bars of the $B\overline{B}$ particle identification system, an internally reflecting Cherenkov counter (DIRC) [1]. The fraction of photons with an electromagnetic shower starting in front of the EMC is about 8\%. These showers have a significant energy loss outside of the calorimeter. Therefore, the mean energy is smaller and a major contribution to the low-energy tail in the line shape of the photon response is observed. The additional fluctuations degrade the energy resolution. To study the calorimeter performance and the influence of resolution effects on data selection and efficiencies, it is of advantage to tag showers which started in front of the EMC. These early showers result in Cherenkov rings in the DIRC caused by the charged particles of the shower. Associating the Cherenkov rings and the EMC cluster allows for a selection of the early showering photons. In a sample of generic $B^0\overline{B}^0$ MC events, the fraction of true early showers in the number of reconstructed showers is 37\%. This number increases to 60\% for the $e^+e^- \rightarrow \mu^+\mu^-\gamma$ sample due to the smaller number of charged tracks. In data, 12\% of the $\pi^0$'s have at least one daughter photon with a selected early shower. The average of the invariant mass distribution of these reconstructed $\pi^0$'s is by about 1.5 MeV smaller than the invariant mass of $\pi^0$'s without early showering photon.

7. Reference list

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