Calibration of the ALICE PHOS calorimeter

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Abstract. The procedure for the energy calibration of the high granularity electromagnetic calorimeter PHOS of the ALICE experiment is presented. The methods used to perform the relative gain calibration, to estimate the geometrical alignment and the corresponding correction of the absolute energy scale, to calculate the non-linearity correction coefficients and finally, to calculate the time-dependent calibration corrections, are discussed and illustrated by the PHOS performance in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV. After applying all corrections, the widths of $\pi^0$ and $\eta$ meson peaks at $p_T > 1.7$ GeV/c $\sigma_{\pi^0} = 4.51 \pm 0.03$ MeV/$c^2$ and $\sigma_\eta = 15.3 \pm 1.0$ MeV/$c^2$, respectively, were achieved.

1. Introduction

The ALICE experiment [1] is one of the four major experiments at the Large Hadron Collider (LHC) at CERN. Its primary physics goal is the study of the properties of the hot and dense quark-gluon plasma created in ultrarelativistic heavy-ion collisions. One of ALICE’s electromagnetic calorimeters, the PHOton Spectrometer (PHOS) [2], is designed to measure spectra, collective flow and correlations of thermal and prompt direct photons, and of neutral mesons via decay into photon pairs. In this paper, the methods used for the calibration of the PHOS detector during the LHC data taking campaigns of 2009–2013 (Run 1) and 2015–2017 (Run 2) are described and results of the calibration are presented.

The PHOS is a single arm, high-resolution electromagnetic calorimeter which detects and identifies photons and electrons in the wide $p_T$ range from $\sim 100$ MeV/$c$ to $\sim 100$ GeV/$c$ at mid-rapidity and, additionally, provides a trigger in case of a large energy deposition. PHOS is subdivided into four independent units, named modules, positioned at the bottom of the ALICE detector at a radial distance of 460 cm from the interaction point to the front surface of crystals. It covers approximately a quarter of a unit in pseudo-rapidity, $|\eta| \leq 0.125$, and 70° in azimuthal angle. Its total active area is 6 m$^2$. Three PHOS modules are segmented into 3584 detection elements (cells) arranged in 56 rows of 64 elements each, while the fourth module has 56 rows of 32 elements. Each element is made of a $22 \times 22 \times 180$ mm$^3$ lead-tungstate crystal, PbWO$_4$, coupled to a $5 \times 5$ mm$^2$ Avalanche PhotoDiode (APD).

The light yield of PbWO$_4$ crystals is relatively low and strongly depends on the temperature (with coefficient $-2\%/{^\circ C}$). In order to increase it by about a factor 3 compared to normal conditions, the PHOS crystals are operated at a temperature of $-25^\circ C$. The energy resolution of a PHOS prototype was measured under these conditions in beam tests [3]. The temperature of PbWO$_4$ crystals is stabilized with a precision of 0.3°C. The monitoring system with LEDs and stable current generators allows every single channel to be monitored [4].
2. Calibration procedure

Photons and electrons hitting an electromagnetic calorimeter produce electromagnetic showers with transverse profile determined by the Molière radius characteristic of the material used for the calorimeter. When the transverse cell size of the calorimeter is comparable with the Molière radius, such as in the PHOS case, the electromagnetic shower is developed in several adjacent cells around the one containing the primary hit. The group of cells with common edges, containing the electromagnetic shower generated by a photon, is referred to as a cluster [5]. The amplitude of signals measured in the cells of the cluster is proportional to the deposited energy in the cells, up to the unknown calibration parameter. Relative energy calibration means equalization of the response of all channels to the same energy deposition.

2.1. Photodetector gain equalization

Each APD has its individual gain-voltage characteristic. The dependence of the APD gain on the bias voltage was measured using the PHOS LED monitoring system, whose programmable light output was tested to be very stable over several hours, a period of time longer than is necessary for the gain measurements. The APD gain is calculated as the ratio of the measured amplitude at a given voltage to a reference amplitude at 20 V where the dark current in the APD is negligible. The APD gain was set to 29 for all channels in order to provide the designed dynamic range. With this requirement, the bias voltage varies from 290 to 395 V.

The APD gains equalization is important in order to make the threshold of the trigger efficiency response curve as sharp as possible which ensures uniformity of trigger response in PHOS acceptance. It was performed once during PHOS commissioning in Run 1 and another time before the start of the Run 2 data taking period. The calibration needs to be further refined to take into account the different light yield of crystals. The spread of light yields is relatively small, about 12% [6], and the APD gain equalization can thus be considered as a first step towards the energy calibration based on ‘physics signals’ from collision events.

2.2. Calibration using the $\pi^0$ peak position

To find the calibration coefficients $\alpha_i$, the di-photon invariant mass distribution is constructed:

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma,1}E_{\gamma,2}(1 - \cos \theta_{12})},$$

where $E_{\gamma,i}$ is the energy of the reconstructed photon $i$, and $\theta_{12}$ is the opening angle between the two photons. One of two photons, e.g. $\gamma_1$, must hit the cell $i$ under consideration while the second one, $\gamma_2$, is any other photon in the event. The invariant mass distribution shows a peak corresponding to the $\pi^0$ meson at $m_i$ with some mass shift due to mis-calibration. The correction to the calibration coefficient, which relates the measured amplitude $A$ and corrected energy $E_{\text{corr}}$ as $E_{\text{corr}} = \alpha_i \cdot c_i \cdot A$, is defined by the following equation:

$$c_i = \left(\frac{m_{\pi^0}}{m_i}\right)^n,$$

where $m_{\pi^0}$ is the true $\pi^0$ mass. The procedure is then iteratively applied, with $\alpha_i$ being updated to $\alpha_{i+1} = \alpha_i \cdot c_i$ for each iteration, until no further improvement of a calibration is found.

From Eq. (1) and (2) one can expect that the best power is $n = 2$. However, with this choice one implicitly assumes that the influence of re-calibration of all other cells on average is negligible, which in reality is not the case. To illustrate this, the procedure is applied to a toy model implementing several values of $n$. The model assumes that the entire photon energy is deposited in one cell of a calorimeter. In the model, a calorimeter covers a pseudorapidity $|\eta| < 1$ and full azimuthal angle with a granularity of $100 \times 100$ cells in the $\phi$ and $\eta$ directions. Each
cell has an independent calibration coefficient which initially is randomly assigned according to a Gaussian distribution with mean 1 and a width of 20%.

The particle generator is tuned to produce neutral pions with a flat rapidity and azimuthal distribution and a realistic \( p_T \) spectrum as measured in pp collisions at \( \sqrt{s} = 7 \) TeV [7]. The generated \( \pi^0 \) mesons are forced to decay into photon pairs. Two values of calorimeter energy resolution are considered: resolution obtained in the PHOS beam tests, \((\sigma_E)\), and twice as large (\(2\sigma_E\)). A cut on the minimal reconstructed photon energy \( E_\gamma > E_\text{min} = 0.3 \) GeV is applied to ensure that energy distributions in the toy model and data are similar.

Figure 1 (left) shows the dependence of a residual de-calibration \( \alpha_c \), defined as the RMS of the difference between estimated and true calibration coefficients \( \alpha_i - \alpha_i^{\text{true}} \) for all cells of the toy simulation, versus iteration number. The final precision of the calibration depends on the accuracy of the reconstructed \( \pi^0 \) peak position, which in turn depends on the peak width (defined by the energy and position resolution) and the available statistics. In the model, the statistics of the simulated pions is defined by a requirement to have \(10^3\) reconstructed photons per cell after a \( p_T \) cut of \( 1.7 \) GeV/c on the reconstructed photon pairs, the same as in the calibration using real data. The value \( n \approx 2 \) is found to lead to some oscillations and poor convergence of the algorithm. For powers \( n < 2 \), the residual de-calibration saturates at values corresponding to the final precision of the calibration.

![Figure 1](image1.png)

**Figure 1.** Left: study using a toy Monte-Carlo simulation of the convergence of the iterative calibration procedure based on the equalization of the \( \pi^0 \) peak position. The residual de-calibration \( \sigma_c \) is shown as a function of the iteration number. Right: dependence of the \( \pi^0 \) peak width on the iteration number for photon pairs with \( p_T > 1.7 \) GeV/c in four PHOS modules in the real data analysis.

To find the optimal value of \( n \), \( \sigma_c \) is studied as a function of iteration number for several values of \( n \). For large values of \( n \), few iterations are needed to reach saturation. However, better accuracy is obtained for lower values of \( n \). Since an analysis with real data is very time-consuming we chose a value of \( n = 1.6 \), which provides the best accuracy after 2–3 iterations.

The procedure described above is used in the final step of the calibration of the PHOS detector. The calibration is performed using physics data from pp collisions at \( \sqrt{s} = 13 \) TeV recorded in 2017. The sample contains \(7.7 \cdot 10^8 \) minimum bias (MB) events and \( 5 \cdot 10^7 \) events recorded with the PHOS L0 trigger [8], corresponding to an integrated luminosity \( L_{\text{int}} = 12 \) nb\(^{-1}\) and \( 5.9 \) pb\(^{-1}\), respectively. Cuts on minimum number of cells in cluster, \( N_{\text{cells}} > 2 \), and minimum cluster energy, \( E_{\text{clus}} > E_{\text{min}} = 0.3 \) GeV, are applied to reject rare events induced by hadron interactions directly in the APD. Also a cut on the cluster dispersion is applied for selecting clusters corresponding to the electromagnetic shower transverse size [5]. A minimum pion transverse momentum cut \( p_T > 1.7 \) GeV/c is imposed to reduce the combinatorial background.
Figure 1 (right) shows that about 3 iterations are sufficient to reach an almost final calibration. This is in good agreement with the predictions of the toy Monte Carlo. The width of the peak in modules 2 and 3 is close to what is expected from Monte Carlo simulations by taking into account the PbWO$_4$ response and ideal calibration. In modules 1 and 4, the width is larger because of a batch of front-end electronics cards with somewhat higher noise characteristics.

3. Cross-checks and corrections

3.1. Energy non-linearity correction

There are several effects which may influence linearity of PHOS energy measurement: electronic noise, light attenuation in crystals, electronic thresholds, amplitude digitization and shower leakage. Correcting for this non-linearity is important in many aspects of physical analysis, for example to reduce the width of neutral meson peak width in wide $p_T$ bins etc. The non-linearity is corrected via recalculation of the cluster energy $E$ by the following simple parameterization:

$$E_{\text{corr}} = a + b\sqrt{E} + cE + dE^2,$$

(3)

where the two first parameters $a$ and $b$ are considered below as free parameters and the last two terms with $c = 1.05$ and $d = 2.49 \times 10^{-4}$ GeV$^{-1}$ are fixed corrections related to the shower leakage estimated through Monte-Carlo simulations [5]. Using real data, a set of invariant mass distributions was calculated, corrected for non-linearity with a given set of non-linearity parameters ($a$, $b$). Depending on the set of parameters ($a$, $b$), the peak position can increase or decrease with $p_T$. To find the best set of parameters, a fit of the peak $p_T$-dependence with a constant function is performed in the range $1 - 10$ GeV/$c$. The optimal value, obtained by minimizing $\chi^2$, is $(a = 0.03 \pm 0.01$ GeV, $b = 0.090 \pm 0.005$ GeV$^{1/2}$).

3.2. Calibration using identified electrons

For electrons, one can compare the energy measured in the calorimeter, $E$, with the momentum reconstructed in the tracking system, $p$. There are two advantages of this approach compared to the calibration using the $\pi^0$ mass peak: first, one considers single clusters and no iterative procedure is necessary; second, it does not depend on the exact position of the calorimeter and its geometrical mis-alignment, appearing in the calculation of the opening angle $\theta_{12}$ in Eq. (1), is not mixed with energy calibration. Drawbacks of this method are the limited number of reconstructed electrons and the strong sensitivity to the material budget in front of the calorimeter. We use this method as a cross-check for the calibration using the $\pi^0$ mass peak.

The same data sample is used for the calibration via electrons in real data as for the calibration using the $\pi^0$ mass peak. Charged tracks are reconstructed with the ALICE central tracking system [1]. Fitting the $E/p$ distributions, the electron peak position and the peak width are extracted as a function of cluster energy in two middle PHOS modules, see Fig. 2. To improve accuracy of the $E/p$ peak position extraction, the cut on cluster dispersion is applied and tracks identified as electrons using the specific ionization energy loss $dE/dx$ in the TPC [9] are selected. At high $p_T$, the mean is close to unity, but gradually decreases towards smaller $p_T$, reflecting an increased relative energy loss of lower energy electrons. The measured $E/p$ peak position and width are compared with the same quantities calculated with Monte Carlo simulations of pp collision with the PYTHIA event generator and the standard ALICE software framework.

3.3. Geometrical alignment

Two-photon invariant mass, defined in Eq. (1), can also be expressed as

$$m_{\gamma\gamma} = 2\sqrt{E_1E_2|\sin(\theta_{12}/2)|} \approx \sqrt{E_1E_2} \frac{L_{12}}{R},$$

(4)
Figure 2. Electron $E/p$ peak position (left) and widths (right) in data and MC.

where $L_{12}$ is the distance between clusters in a calorimeter and $R$ is the distance from the interaction point (IP) to the calorimeter. Uncertainties in the measurement of $R$ directly translate to uncertainties in the energy scale. The estimate of the PHOS alignment is performed by matching tracks reconstructed in the tracking system with clusters in PHOS. To study the alignment it is convenient to use the local coordinate system of PHOS module where $z$ is the coordinate along the beam and $x$ is the coordinate perpendicular to the beam.

One can express the difference between the $z$ coordinate of the reconstructed cluster position in the calorimeter, $z_{\text{PHOS}}$, and the point of the track extrapolated to the surface of the calorimeter, $z_{\text{track}}$, through the ratio of true ($R_{\text{true}}$) and expected ($R$) radial distances:

$$dz = z_{\text{PHOS}} - z_{\text{track}} = z_{\text{PHOS}} - R \tan \theta = z_{\text{PHOS}} \left(1 - \frac{R}{R_{\text{true}}} \right).$$

The depth of the maximal energy deposition of a shower is assumed to correspond to that of a photon and a correction is introduced to the cluster center of gravity so that $x$ and $z$ coordinates correspond to those of the photon crossed the front surface of PHOS [5]. Electron showers are very similar to the ones of photons but reach their maximum about one unit in radiation length $X_0$ earlier than photons. This effect corresponds to the slope $B_e = -0.19 \cdot 10^{-2}$ in the dependence of $\langle dz \rangle$ versus $z$ distribution. The extracted slope, $B_{\text{measured}} = -0.23 \cdot 10^{-2}$, is slightly larger than $B_e$. This corresponds to $\sim 4$ mm inward radial shift of the PHOS modules.

3.4. Run-by-run energy calibration

The long-term stability of amplitude measurements in the PHOS may be influenced by temperature dependent light yield of PbWO$_4$ crystals and APDs amplification, switching on and off front-end electronics cards and the crystal transparency dependence on the absorbed radiation dose. Run-wise calibration correction common for all channels in each PHOS module was implemented to account for all these effects. In order to estimate this correction, for each run the mean value of the $\pi^0$ mass peak, reconstructed only of photon pairs detected in same module, was extracted. In the calibration procedure the mean value of the peak position over the whole period is calculated and deviations with respect to this value are estimated. If the peak position in a module is known with uncertainty better than 1 MeV, all calibration coefficients in a module are corrected by the ratio $m_{\text{mean}}/m_{\text{run}}$, otherwise the mean value is used.

4. Results

The invariant mass spectrum of cluster pairs after applying all calibration corrections is shown in Fig. 3 in the region of $\pi^0$ (left) and $\eta$-meson (right) peaks. For the $\pi^0$ meson the di-
The photon invariant mass distribution is fitted with a sum of a Crystal Ball function [10] for the peak description and a polynomial of the second order for the combinatorial background. For the $\eta$ meson a sum of Gaussian and second order polynomial is used. Both the $\pi^0$ and $\eta$ meson peak positions are consistent with their PDG values $m_{\pi^0} = 134.98$ MeV/$c^2$ and $m_{\eta} = 547.9$ MeV/$c^2$ within statistical uncertainties. The widths of $\pi^0$ and $\eta$ meson peaks at $p_T > 1.7$ GeV/$c$, $\sigma_{\pi^0} = 4.51 \pm 0.03$ MeV/$c^2$ and $\sigma_{\eta} = 15.3 \pm 1.0$ MeV/$c^2$, respectively, were achieved.

**Figure 3.** Invariant mass distributions of cluster pairs for $p_T > 1.7$ GeV/$c$ in the $\pi^0$ (left) and $\eta$ (right) mass region after calibration with per-channel $\pi^0$ peak equalization.

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