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Geometric alignment of the SND detector

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Abstract. We present the design, implementation and validation of the software procedure used to perform geometric calibration of the electromagnetic calorimeter with respect to the tracking system of the SND detector (BINP, Novosibirsk). This procedure is based on the mathematical model describing the relative calorimeter position by means of a set of parameters. The parameter values are determined by minimizing a $\chi^2$ function using the difference between directions reconstructed in these two subdetectors for $e^+e^- \to e^+e^-$ data events.

1. Introduction

The SND detector \cite{1, 2, 3} is a nonmagnetic detector used at the $e^+e^-$ collider VEPP-2000 \cite{4} (BINP) for the hadronic cross-section measurement experiments in the center of mass energy range $0.3 \div 2.0$ GeV. The SND consists of several subsystems (Fig.1) including the spherical electromagnetic calorimeter (EMC), the cylindrical tracking system (TS), the threshold Cherenkov counters and the muon detector.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure1.png}
\caption{The SND scheme: 1 — vacuum pipe, 2 — tracking system (TS), 3 — threshold Cherenkov counter, 4–5 — electromagnetic calorimeter (NaI (Tl)) (EMC), 6 — iron absorber, 7–9 — muon detector, 10 — focusing solenoids, 11 — rails, 12 — wheels.}
\end{figure}

The EMC is composed of 1632 NaI(Tl) crystals arranged in 3 spherical layers. The EMC spherical shape covers polar angle range of $18^\circ - 162^\circ$ and provides uniform coverage of solid angle $0.95 \cdot 4\pi$. The EMC crystals are rigidly fixed to two supporting aluminum spheres: the first one is for the first two layers of crystals while the second one is for the third layer. The EMC is divided into 2 hemispheres which can be moved in the horizontal direction orthogonal...
to the detector axis using rails and wheels (Fig. 1: labels 11 and 12). It’s used to access the TS and the interior sphere of the SND.

The EMC and the TS provide main information for event reconstruction: the TS measures parameters of charge particle tracks \( (z_0; d_0; \varphi; \theta) \) while the EMC measures the energy and the angular position of the electromagnetic showers \( (\varphi_{EMC}; \theta_{EMC}) \). For the events occurred inside the SND to be effectively reconstructed it is important to know precise positions of the EMC sensitive crystals relative to the TS. However the data demonstrates difference between particle angles reconstructed with the TS and with the EMC. We attribute this difference to misalignment of the EMC relative to the TS. This misalignment can result in kinematic discrepancy inside the events containing both charged and neutral particles (like \( e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0 \)). That is why we perform the software alignment procedure that reveals the true EMC position relative to the TS. We utilize \( e^+e^- \) scattering events because electrons and positrons have reliable angle measurements in both the TS and the EMC.

2. Mathematical model

The right handed coordinate system fixed with the TS is used as the reference coordinate system. Its center is at the TS center, the Z axis is directed along the TS horizontal axis, the Y axis is directed vertically upwards and the X axis is directed towards the collider ring center. We consider the EMC halves as rigid bodies.

To describe the EMC position relative to the TS two sets of parameters are used. The first set describes the rotation and the shift of the EMC as a whole: \( \alpha \) is the angle of common EMC rotation around the TS Z axis \( (0^\circ < \alpha < 360^\circ) \); \( \beta_x \) and \( \beta_y \) describes the EMC tilt with respect to the TS Z axis; \( dx, dy, dz \) are the EMC shifts in corresponding directions relative to the TS. The second set of parameters describes rotations and shifts of the hemispheres relative to the EMC: \( \mu \) is the separation half-angle of the EMC hemispheres \( (0^\circ < \mu < 90^\circ) \); \( \tau \) is the separation direction angle from the vertical direction, \( (-180^\circ < \tau < 180^\circ) \); \( dx_{rel}, dy_{rel}, dz_{rel} \) are the hemisphere relative shifts; \( \beta_{rel} \) is the angle of the relative rotation around the X axis, \( (0^\circ < \beta_{rel} < 360^\circ) \).

Subtracting angles of an aligned EMC point from a misaligned EMC point we build the model functions which describe the difference between reconstructed angles for \( \sin(\varphi_{TS} - \varphi_{EMC}) \) and \( \theta_{TS} - \theta_{EMC} \). Here \( \varphi_{EMC}, \theta_{EMC} \) are azimuth and polar angles reconstructed in the EMC while \( \varphi_{TS} \) and \( \theta_{TS} \) represent the expectation for the EMC cluster direction from the TS track and determined as the polar coordinates of the point where the track crosses a sphere with the radius \( R \) given by: \( R = R_0 + X_0 \cdot (x_{max} - \frac{2x_{max}}{\sin \theta}) \). Here \( R_0 \) is the EMC inner radius, \( x_{max} = \log \frac{E_c}{E} - 0.5 \) is the maximum of the longitudinal electromagnetic shower distribution [5], \( x_{pre} \) is an estimation of the sensitive material thickness between the interaction point and the EMC, \( X_0 \) is the radiation length for NaI, \( E_c \) is its critical energy. Unfortunately, the maximum of the energy deposition in the EMC is located in the first two layers, making impossible to estimate the misalignment of the third layer.

To retrieve the parameter values a \( \chi^2 \) function is minimized. This function is constructed from the squared differences between the measured angle residuals and the expected ones, parametrized with the model functions, with the differences being scaled by a measurement error squared and summed over 160 spatial bins \( (16 \varphi_{EMC} \times 10^2 \theta_{EMC}) \). Each error includes both a statistical and systematic component. Systematic uncertainty is attributed to the non-uniformity in the EMC spatial reconstruction and shortcomings of the model. This is expected to be the same for polar and azimuth direction and estimated from the data to be \( \sim 0.2^\circ \). Minimization is performed using the TMinuit class from the ROOT framework [6]. Typical results of the function fit are illustrated in Fig. 2.
Figure 2. Results of the function fit for one energy point, $E_{beam} = 612.5$ MeV. Here $\varphi_{TS}, \theta_{TS}$ - are azimuth and polar TS angles, $\varphi_{EMC}, \theta_{EMC}$ are azimuth and polar EMC angles.

3. Calibration procedure and results
The geometric calibration procedure includes several steps starting from the $e^+e^- \rightarrow e^+e^-$ event selection (2 collinear tracks, energy between 0.8 and 1.1 of $E_{beam}$ for each particle).

The next step is to minimize the $\chi^2$ function using the 2D histogram constructed using the selected events. After that the values of the alignment parameters are stored in the conditions data base and can be applied during reconstruction and simulation.

The calibration algorithm was validated using MC simulation where the EMC is described misaligned according to the parameters. Comparison of this MC simulation with the data demonstrates a good agreement. (Fig.3).

The procedure described in this section was applied to $\sim$ 2000 runs, recorded in the data taking period of 2010-2011 years, with integrated luminosity integral $25.3 \, pb^{-1}$. Fig. 4 shows evolution of the parameter values during this period. The value of $\alpha$ was large but stable during this period while the value of $dx$ changed slightly several times due to disassembling and reassembling the detector. The rest of the parameters were quite small and stable.

Some results of the applied calibration for the $e^+e^- \rightarrow e^+e^-$ events and the $e^+e^- \rightarrow 2\gamma$ annihilation events are shown in Fig.5 and Fig.6.
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4. Conclusions

We have developed and implemented the geometric calibration procedure for the SND detector electromagnetic calorimeter. The algorithm is validated using MC simulation. It is shown that most of the alignment parameter values stay stable between disassembling and reassembling the detector.

The procedure allows us to reduce the polar and azimuth angles discrepancy between the TS and the EMC measurements. Azimuth angle common bias of $\sim 3^\circ$ and irregularity of $\sim 1^\circ$ are removed. We see improvement in the EMC angular resolution due to this correction by 15.6\% as well.

The results of geometric calibration are used in the actual experimental data analysis and more realistic MC simulation.

Acknowledgments

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Figure 5. Results of the geometric correction for $e^+e^- \rightarrow e^+e^-$ data, $E_{\text{beam}} = 612.5$ MeV: difference between angles reconstructed in the EMC and in the TS before (blue unfilled histograms) and after (red filled histograms) the correction. Here $\varphi, (\theta)$ - an azimuth (polar) TS angle, $\varphi_{\text{EMC}}, \theta_{\text{EMC},z}$ - a polar EMC angle with correction for the interaction point shift along the TS Z axis.

Figure 6. Results of the geometric correction for $e^+e^- \rightarrow 2\gamma$ data, $E_{\text{beam}} = 612.5$ MeV: difference between azimuth EMC angles reconstructed for two photons $(\varphi_{\text{EMC},1}\varphi_{\text{EMC},2})$ before (blue unfilled histogram) and after (red filled histogram).