Alignment and Measurement of the Magnetic Field for the Muon Counter at BESIII (Postprint)

Authors: Q. Gao, J. Z. Zhang, C. H. Li

Date: 2016-09-01T00:00:00+00:00

Abstract

Based on cosmic ray events taken without magnetic field during summer shutdown, we compare the coordinates of hits in muon counter with the expected interaction point of extrapolated tracks from the inner tracking system. By minimizing the difference, we align the muon counter with the inner tracking system. The muon counter is operating in magnetic return yoke and the magnetic field has never been measured before. The strength of the magnetic field of the muon counter is measured for the first time with $+$ and $-$ separately. After the alignment and magnetic field measurement, the offsets of hit-position for $+$ and $-$ are diminished. The alignment and magnetic field measurement are adopted in the latest BESIII offline software system. This makes physics analysis involving muon counter information more reliable.

Full Text

Preamble

The alignment and measurement of the magnetic field for muon counter at BESIII

Q. Gao[1], J. Z. Zhang[1], and C. H. Li[1]
[1]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049

Abstract

Based on cosmic-ray events taken without magnetic field during the summer shutdown, we compare the coordinates of hits in the muon counter with the expected interaction points of extrapolated tracks from the inner tracking system. By minimizing the difference, we align the muon counter with the inner tracking system.

The muon counter operates within the magnetic return yoke, and its magnetic field had never been measured before. The magnetic field strength is measured for the first time separately for μ^+ and μ^-. After alignment and magnetic field measurement, the hit-position offsets for μ^+ and μ^- are diminished. These alignment and magnetic field measurements have been adopted in the latest BESIII offline software system, making physics analyses involving muon counter information more reliable.

PACS numbers: 13.66.Jn, 13.85.Tp

INTRODUCTION

The BESIII detector (detailed in Ref. [1]) is a general-purpose magnetic spectrometer operating at the Beijing electron-positron collider II (BEPCII) [2] for measuring inclusive final states from electron-positron collisions and studying the properties of final-state particles and interaction dynamics.

The muon counter (MUC) is the outermost sub-detector of BESIII with a solid-angle coverage of $\Delta\Omega/4\pi = 0.89$. It plays a crucial role in separating muons from other charged particles, particularly pions. The minimum momentum for charged tracks to reach the MUC is approximately 0.4 GeV/c due to interactions with inner sub-detectors. The MUC is designed to provide a position resolution of 2 mm with a detection efficiency of 95% and a noise level below 0.4 Hz/cm^2.

When a particle passes through the MUC, the readout strip, made of resistive plate chambers (RPC), fires and provides spatial coordinates. The coordinates of each readout strip are assigned according to the design; however, deviations may exist between the actual position and the design due to imperfect installation or strip distortion over time. These factors necessitate alignment. For this purpose, we compare the positions of fired strips in the MUC with the expected interaction points (IP) of tracks extrapolated from the inner tracker (MDC). The MUC is placed in the magnetic flux return yoke, and the magnetic field is calculated based on the field in the inner detector (MDC) and electromagnetic laws using the ANSYS package. A direct measurement of the field is therefore desirable.

In this paper, we introduce a method to align the MUC with the inner tracking system, similar to that in Ref. [5]. We also measure the magnetic field in the MUC separately for μ^+ and μ^-. In the BESIII Offline Software System (BOSS) [6], the MUC geometry information is described by the file "muc.gdml" , which will be updated based on the alignment results.

II. THE MUON COUNTER AND ALIGNMENT METHOD

The MUC consists of three parts: a barrel and two endcaps. Each part comprises resistive plate chambers (RPCs) sandwiched between iron absorbers. The barrel is octagonal in shape and consists of eight segments, each containing nine layers.

A layer within a segment is referred to as a box. Each endcap comprises four segments with eight layers. There are 136 boxes in total. Box IDs (boxid) are numbered as [0,31] for the east endcap, [32,103] for the barrel, and [104,135] for the west endcap. The relative coordinates of strips within a box remain fixed regardless of the box' s position, so alignment of the MUC can be performed at the box level. The iron absorber thicknesses increase outward: 3 cm, 3 cm, 3 cm, 4 cm, 4 cm, 8 cm, 8 cm, 8 cm, and 15 cm. In the barrel, strips in odd RPC layers are oriented azimuthally and provide the z-coordinate, while those in even layers are oriented along the z-axis and provide the $r - \phi$ coordinate. In the endcaps, odd layers read out the x-coordinate and even layers the y-coordinate.

In the absence of a magnetic field, we assume charged particles maintain their original direction, with energy loss due only to ionization dE/dx, while neglecting muon decay and multiple scattering. We select muons from cosmic-ray events and compare their expected positions with the measured positions. The expected position is defined as the intersection of the muon track with each MUC layer, where the track is extrapolated from the inner tracker (MDC) to the RPC using GEANT4 [3]. The measured position is the coordinate of the fired strip. For a well-aligned detector, these two positions should coincide. The difference between them, defined as the residual ($R = V_{\text{expect}} - V_{\text{obs}}$), arises from misalignment between the MUC and the inner tracking system.

The residual distribution for strips in each box follows a Gaussian distribution, whose mean represents the coordinate deviation from the assigned position. The sigma of the Gaussian represents the uncertainty in the expected position due to multiple scattering in the material before the MUC.

Charged particles bend in a magnetic field, with opposite charges deflecting in opposite directions. Any overestimation or underestimation of the field strength will cause deviations between the actual particle trajectory and the expected one. The sign of the deviation from the expected position is opposite for μ^+ and μ^-. We use di-muon events, $e^+e^- \to \mu^+\mu^-$, to estimate the field strength. By measuring the residuals for μ^+ and μ^- separately, we can assess the accuracy of the field.

III. ALIGNMENT

A. Barrel

A sample of 2.1 million cosmic-ray events taken with the magnetic field turned off is used to align the MUC barrel with the inner tracker. During this data-taking period, the MUC endcaps were not installed, so only the barrel could be aligned using this sample. When muons from cosmic-ray events pass through the detector, they leave straight tracks from the outermost MUC layer to the detector center and exit through the opposite side. To utilize tracks extrapolated from the MDC, we select cosmic-ray events where the muon passes through the MDC. Each such event is reconstructed as two tracks originating from the detector center. The time difference between the two tracks in the TOF detector peaks around 6 ns.

The selection criteria are as follows: only barrel tracks with polar angle $|\cos\theta| < 0.8$ are accepted. Candidate events must contain two charged tracks that are back-to-back: the total momentum in the z-direction must satisfy $p_z^{\rm tot} < 0.5$ GeV/c, and the azimuthal and polar angles must satisfy $|\phi_1 - \phi_2 - \pi| < 0.6$ and $|\theta_1 + \theta_2 - \pi| < 0.7$. The TOF timing information must satisfy $t_1 \in [-5, 1.9]$ ns and $|\delta t| = |t_1 - t_2| > 5$ ns, where t_1 and t_2 are the timing measurements for the two charged tracks.

After applying these selection criteria, we obtain a sample of 2.1 million muon candidates with the magnetic field turned off. By plotting the hit residuals for each box for the selected candidates and fitting the distributions, we obtain the average residual for every barrel box, as shown in Fig. 1 [Figure 1: see original paper] (red dots for boxid from 32 to 103). The residuals are clearly non-zero for most boxes. We correct the coordinates of each box by adding the residual to the initial coordinate. We then use another 2.1 million cosmic-ray events with the magnetic field turned off to verify the alignment effectiveness. Figure 1 [Figure 1: see original paper] (blue stars for boxid from 32 to 103) shows the residuals after alignment, which are significantly reduced.

B. Endcaps

To align the two endcaps, we use a di-muon sample ($e^+e^- \to \mu^+\mu^-$) of 0.66 million events selected from data taken at 3.686 GeV with the standard BESIII magnetic field turned on. Cosmic-ray events are not used for endcap alignment due to their low counting rate. Since the magnetic field bends μ^+ and μ^- in opposite directions, residuals caused by an incorrect magnetic field cancel when summing μ^+ and μ^-; the remaining average residual indicates detector misalignment.

To select di-muon candidates, charged tracks must originate from the interaction point (IP) with $V_{xy} = \sqrt{V_x^2 + V_y^2} < 1$ cm and $|V_z| < 10$ cm, where V_x, V_y, and V_z are the coordinates of the point of closest approach to the run-dependent IP. Only endcap tracks are accepted, requiring the polar angles of the two charged tracks to satisfy $0.8 < |\cos\theta_{1,2}| < 0.93$. The momentum ($p$) of each track must exceed 1.7 GeV/c. The ratio of energy deposition (E) in the EMC to momentum must satisfy $0.06 < E/p < 0.2$ to suppress electron/positron backgrounds. Candidate events must contain two oppositely charged tracks that are back-to-back: $p_x^{\rm tot} < 0.1$ GeV/c, $p_y^{\rm tot} < 0.1$ GeV/c, $p_z^{\rm tot} < 0.1$ GeV/c, $|\phi_1 - \phi_2 - \pi| < 0.4$, and $|\theta_1 + \theta_2 - \pi| < 0.05$, where $\phi_{1,2}$ and $\theta_{1,2}$ are the azimuthal and polar angles of the two tracks. The TOF timing must satisfy $|\delta t| = |t_1 - t_2| < 4$ ns to suppress cosmic-ray events.

After applying these selection criteria, we obtain a di-muon sample of 0.66 million candidates. Using the same method as for the barrel, we obtain the hit residuals for each endcap box, as shown in Fig. 1 [Figure 1: see original paper] (red dots for boxid in the range [0, 31] [104, 135]). The residuals are clearly non-zero for most boxes. The coordinates of each box are corrected using the same method as for the barrel. We use another 0.64 million di-muon events from 3.686 GeV data to verify the alignment. Figure 1 [Figure 1: see original paper] (blue stars for boxid in the range [0, 31] [104, 135]) shows the residuals after alignment, which are much closer to zero.

IV. MAGNETIC FIELD MEASUREMENT

Before measuring the magnetic field, we find that the z-direction residuals for μ^+ and μ^- after alignment show little difference, indicating that the $r-\phi$ component of the magnetic field is well simulated by ANSYS. Therefore, we focus only on measuring the z-direction magnetic field in the barrel. Using the $r-\phi$ direction residuals for μ^+ and μ^- separately, we can measure the magnetic field. The correct field strength is obtained by multiplying the current value (from ANSYS calculations) by a factor determined by minimizing the residuals for μ^+ and μ^-. The current magnetic field is parameterized by $8 \times 9 = 72$ values (8 segments × 9 layers).

Figure 2 [Figure 2: see original paper] (left) illustrates the accumulation of residuals. Only even layers are shown because odd layers provide z-direction information. Here L_0, L_2, and L_4 denote layers 0, 2, and 4, respectively; $h_2 = 14$ cm is the distance from L_0 to L_2, and $h_4 = 15$ cm is the distance from L_2 to L_4; R_0, R_2, and R_4 are the residuals in layers L_0, L_2, and L_4, respectively. R_0 primarily arises from statistical uncertainties in the alignment of layer 0. R_2 contains contributions from R_0 and from $\Delta R_2 = R_2 - R_0$ due to magnetic field inaccuracies in L_0. The residual R_4 has three contributions: the first is R_0. The second part comes from magnetic field inaccuracies in L_0. Assuming the residual increases linearly as the particle propagates forward, this contribution is $\frac{h_2+h_4}{h_2} \times \Delta R_2$. The third part is the pure contribution from magnetic field inaccuracies in the preceding layer: $\Delta R_4 = R_4 - R_0 - \frac{h_2+h_4}{h_2} \times \Delta R_2$.

ΔR_2 and ΔR_4 are used to calculate the magnetic field in L_0 and L_2. Similarly, we obtain ΔR_6 and ΔR_8. By varying the MUC magnetic field (multiplying by a factor) and reconstructing the data again, we obtain new residuals. We repeat this procedure several times using test factors $\{0, 0.3, 0.5, 0.6, 0.8, 1\}$. Taking ΔR_4 as an example, Fig. 2 [Figure 2: see original paper] (right) shows a scatter plot of the factor versus ΔR_4 for one segment. We fit this relationship with a straight line to determine the factor at which $\Delta R_4 = 0$. Using the same method, we obtain the factors for other boxes. For the outermost layer 8, a factor of 1 is used since we lack sufficient information to measure its magnetic field. Assuming the magnetic field changes linearly, odd layers are assigned the average of their two neighboring layers. The measured factors for each box are listed in Table I [TABLE:I].

The factors for L_0 are near zero and sometimes negative because the L_0 RPC is located between the superconducting solenoid and the iron absorber. The magnetic field in the L_0 RPC is approximately 10^{-4} T, much weaker than that in the iron absorber. ANSYS cannot accurately describe such weak magnetic fields, so the small correction factors for L_0 are acceptable. The larger factors in outer layers indicate that the magnetic field decreases more slowly than predicted by ANSYS.

With the updated magnetic field, we reconstruct the data again. The residuals for μ^+ and μ^- in selected di-muon events are significantly reduced, as shown in Fig. 3 [Figure 3: see original paper].

V. VALIDATION OF THE ALIGNMENT AND MAGNETIC FIELD MEASUREMENT WITH $\gamma_{\mathbf{ISR}}\mu^+\mu^-$

To validate the alignment and magnetic field measurement, we use 0.2 million $\gamma_{\text{ISR}}\mu^+\mu^-$ events from J/ψ data. The residuals for μ^+ and μ^- before alignment and magnetic field measurement are shown in Fig. 4 [Figure 4: see original paper] (left). The charged track selection is the same as for di-muon events, with the additional requirement $E/p \in (0.1, 0.4)$. Candidates must have at least one photon with energy greater than 40 MeV. A four-constraint (4C) kinematic fit of the two tracks and photon candidate to the initial J/ψ four-momentum is performed, requiring $\chi^2_{4C} < 15$. The higher-momentum track must have a depth greater than 41 cm and fire more than 4 layers. The momentum of each track is required to be in the range $(1, 1.5)$ GeV/c to reject events from $J/\psi \to \mu^+\mu^-$, which typically have momentum around 1.55 GeV/c. The residuals for μ^+ and μ^- before alignment deviate from zero and increase for outer layers. After alignment and magnetic field updating, the new residuals for μ^+ and μ^-, shown in Fig. 4 [Figure 4: see original paper] (right), are centered around zero.

VI. CONCLUSION

Based on cosmic-ray events taken with the magnetic field turned off and di-muon events selected from 3.686 GeV data with the field turned on, we have aligned the MUC with the inner tracking system. Using the di-muon events, we have also measured the magnetic field in the MUC. After alignment and magnetic field updating, the position offsets for μ^+ and μ^- are significantly reduced. This work makes physics analyses involving MUC information more reliable.

Acknowledgments

This work is supported by the National Key Basic Research Program of China under Contract No. 2015CB856701; the National Natural Science Foundation of China (NSFC) under Contract Nos. Y61137005C.

References

[1] M. Ablikim et al. [BESIII Collaboration], Nucl. Instrum. Meth. A 614, 345 (2010).

[2] J. Z. Bai et al. [BESIII Collaboration], Nucl. Instrum. Meth. A 344, 319 (1994).

[3] S. Agostinelli et al. [GEANT4 Collaboration], Nucl. Instrum. Meth. A 506, 250 (2003).

[4] Y. T. Liang et al. Chin. Phys. C 33, 562-566 (2009).

[5] Z. Wang et al. HEP & NP 27(8), 716-721 (2003)(in Chinese).

[6] W. D. Li, H. M. Liu et al. Proceeding of CHEP06, Mumbai 2006.

[7] G. Balossini, C. M. Carloni Calame, G. Montagna, O. Nicrosini and F. Piccinini, Nucl. Phys. B 758, 227 (2006).

Note: Figure translations are in progress. See original paper for figures.