Track Based Software Alignment of the Mu3e Pixel Detector Using the General Triplet Track Fit

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Introduction

The Mu3e experiment [1], currently under commissioning at the Paul Scherrer Institute (PSI) in Switzerland, aims to search for the charged lepton flavor-violating (CLFV) decay $\mu^+ \to e^+e^+e^-$ with an ultimate sensitivity corresponding to one signal decay in 10^{16} muon decays.

Achieving this sensitivity requires strong background suppression. Since the three signal particles originate from a common decay vertex, accurate vertex reconstruction with a spatial resolution below 200 µm is required to distinguish signal decays from backgrounds such as Michel decays, $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, Bhabha scattering, and radiative muon decays. In addition, the signal is characterized by an invariant mass equal to the muon mass and a total momentum of zero in the muon rest frame. A momentum resolution below 0.5 MeV is therefore crucial for the Mu3e experiment.

To meet the required resolution, the Mu3e detector uses highly granular pixel sensors with a spatial resolution of approximately 23 µm and ultra-light detector layers corresponding to about 0.11% x/X_0 per layer, thereby minimizing the effects of multiple Coulomb scattering. The detector is cooled using gaseous helium to reduce the amount of material inside the active detector volume. This lightweight structure and changing operating conditions can lead to mechanical shifts and misalignments in the detector making precise alignment of all detector components crucial in achieving precise event selection from a high-rate data stream of approximately 100 Gbit/s for the Mu3e experiment [1].
In addition to mechanical alignment during detector construction and optical measurements during installation (metrology-based alignment), track-based software alignment provides a complementary approach by using reconstructed tracks to determine and correct misaligned detector components. The method uses the General Triplet Track Fit (GTTF) [2] - a non-iterative, triplet-based track fit - that simultaneously determines track and alignment parameters while incorporating hit uncertainties and multiple scattering effects. Its design is highly parallelizable and scalable, making it particularly well-suited for online alignment tasks leveraging hardware accelerators such as FPGAs or GPUs.

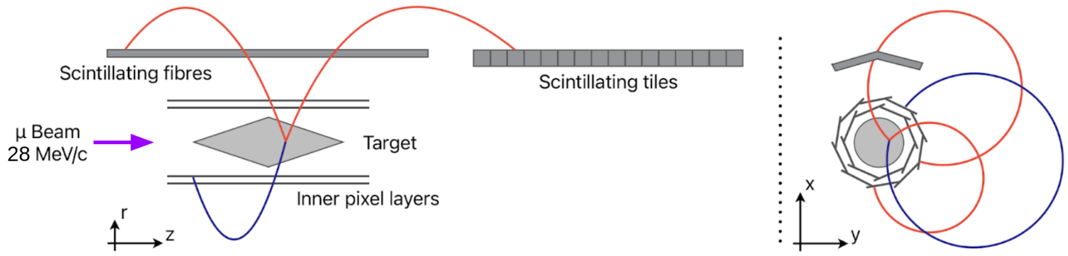

Figure 1: Schematic of the minimal detector configuration used in June 2025. Three particle tracks are shown, two positron tracks (red) and one electron track (blue) originating from the target, which is surrounded by two full inner pixel layers. In addition, one scintillating fiber module was installed. Shallow particles also reach three out of the 14 installed scintillating tile modules. Figure adapted from [1].

Results

The alignment method is applied to data taken during a commissioning run in June 2025 using a minimal detector configuration, shown in Figure 1. The configuration consisted of two inner pixel layers. Consequently, the reconstructed tracks contain two hits from the outgoing trajectory and two hits from the recurling ingoing trajectory, resulting in the minimum of four hits required for track reconstruction. This requirement limits the geometrical acceptance of the detector. For the alignment procedure, only tracks with a reconstructed momentum above 40 MeV/c were considered. The GTTF provides both the reconstructed track parameters and a measure of the fit quality. The resulting reduced χ^2, normalized by the number of degrees of freedom, is shown in Figure 2. For a correctly modeled fit, the expected value of the reduced χ^2 is approximately one. For tracks reconstructed using the unaligned and metrology-aligned geometries, the reduced χ^2 has a most probable value of approximately 3.5, indicating a significant discrepancy between the measured hits and the fitted track model. In contrast, the track-based alignment improves the fit quality. The comparison also indicates that aligning composite detector structures, such as ladders and layers, can be more important for the track reconstruction than applying sensor-to-sensor corrections based solely on metrology measurements. A residual discrepancy remains, however, and is currently under investigation. One possible source is energy loss, which is not yet included in the current implementation of the fit.

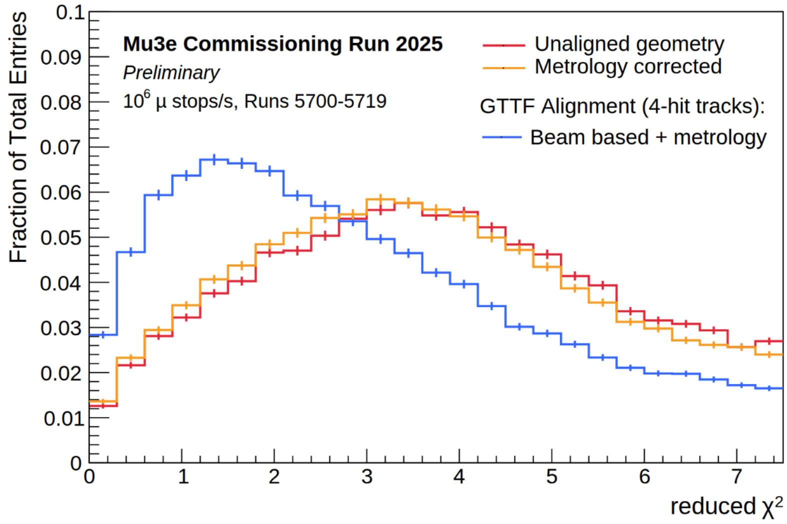

Figure 2: Reduced χ^2 distributions of reconstructed tracks using GTTF for three detector alignments. The red, orange, and blue histograms correspond to the unaligned, metrology-aligned, and track-based aligned geometries, respectively. The corrections for track-based alignment are obtained from four-hit tracks reconstructed with the metrology alignment. All histograms are normalized to unit area; error bars indicate statistical uncertainties.

Outlook

The General Triplet Track Fit (GTTF) provides a promising approach for track-based alignment without requiring an external track fit or iterative alignment procedure. The results indicate that global ladder and layer alignment has a larger impact on track reconstruction than sensor-level alignment. Its high degree of parallelizability makes the GTTF particularly attractive for online alignment of the Mu3e detector. Future studies will investigate the applicability and performance of the method using data from increasingly complete detector configurations and will address remaining discrepancies, including the impact of energy loss.

References

[1] Mu3e Collaboration. Technical design of the phase i mu3e experiment. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 1014:165679, 2021.

[2] A. Schöning. A general track fit based on triplets. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 1075:170391, 2025.