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

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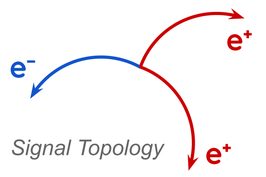
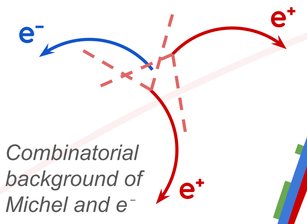
The Mu3e Experiment

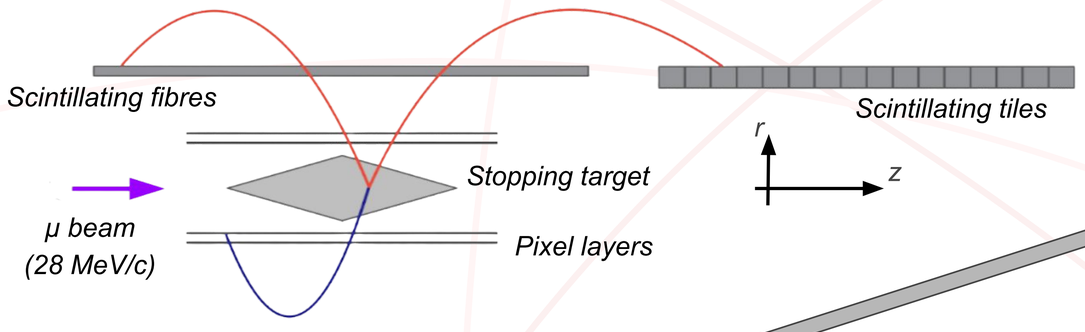
- aims to observe the **charged lepton flavor violating** (cLFV) decay $\mu^+ \to e^+e^-e^+$ with an ultimate sensitivity of 1 in 10^{16} μ decays [1]
- utilizes a **highly granular** (σ(x) ~ 25 μm) and **ultra light** pixel detector (0.1% X_0 / layer) requiring accurate alignment of all components



Signal Topology



Combinatorial background of Michel and e⁻

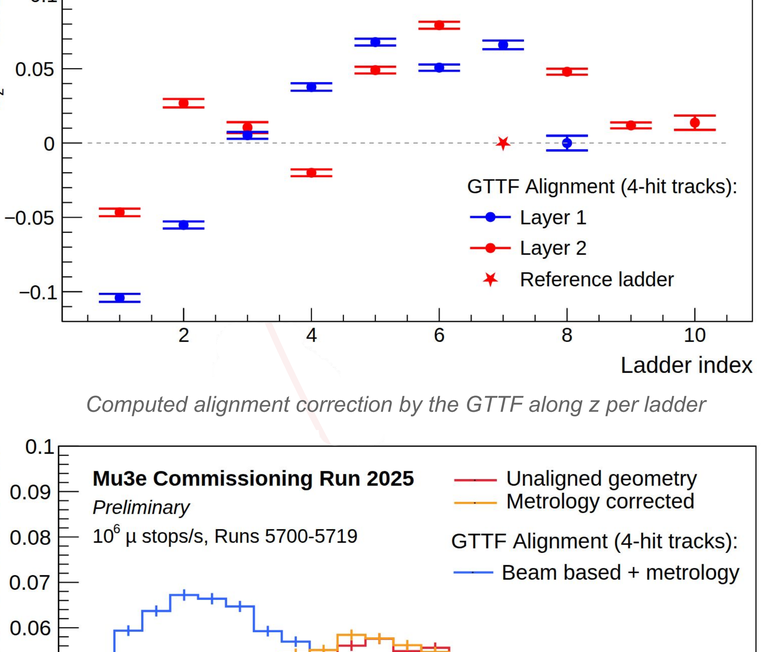


Minimal detector configuration - Commissioning Run 2025

The **General Triplet Track Fit** is a new method for track based alignment, by fitting track and alignment parameters **simultaneously** while including MS and hit uncertainties

2025 Data

- 1 week of stable data taking
- 108 pixels were installed (2 layers with 8 and 10 ladders respectively)
- in total 30 sensors had **mechanical damage or were lost** before/during operation
- additionally, some of the sensors showed **inefficiencies** and **missing links**



Vertex detector hit maps of layer 1 and layer 2

Results

Computed alignment correction by the GTTF along z per ladder

Reduced χ² of tracks reconstructed using different alignments

- alignment parameters are fitted *once* by GTTF
  - using only 4-hit tracks with a $\chi^2_{dof} < 15$ and $|p| > 40$ MeV
  - reference: ladder 7, layer 2
  - six alignment parameters per layer & ladder (*α, β, γ, rφ, z, r*) → 120x120 matrix
- the effect of **ladder & layer alignment** on the reconstruction is more significant than sensor level alignment **(metrology)**

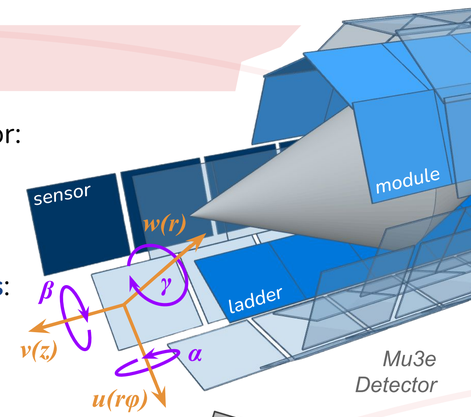
Misalignment

Main sources of misalignment in the Mu3e detector:

- limited construction precision : $\sigma_z^{pix} \approx 100\,\mu m$ [2]
- effects of thermal expansion : $\sigma_z^{pix} \approx 100\,\mu m$ [2]

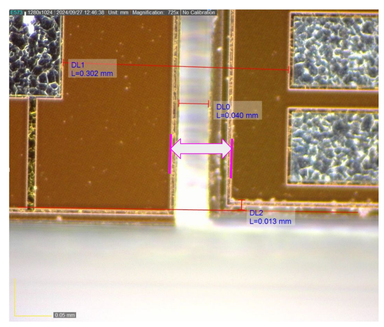
Misalignment modes of layers, **modules**, **ladders**, **pixels**:

- ***rotations (α,β,γ)*** and ***translations (u,v,w)***
- deformations, e.g. stretching, torsion and bowing



Alignment Strategies

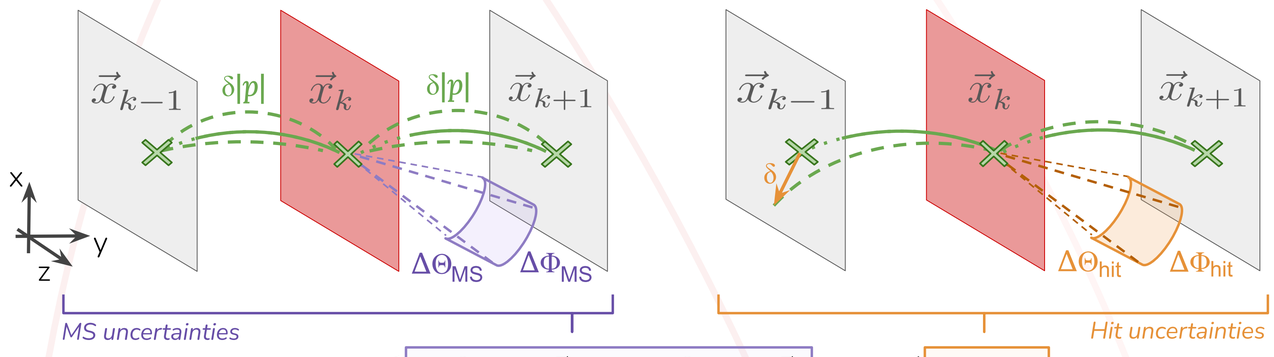
1. **Mechanical alignment**
   - performed during ladder assembly
2. **Optical alignment**
   - uses high resolution metrology data (post construction)
3. **Track based alignment**
   - uses tracks from Michel positrons ($\mu^+ \to e^+\nu_e\nu_\mu$)
   - fits the track and alignment parameters through minimization of a χ^2 function



High resolution image of the sensor positioning on an assembled ladder

General Triplet Track Fit

The General Triplet Track Fit (GTTF) [3] is a fully ***analytical track fit*** based on hit triplets and divided into three steps: the ***Triplet Parametrization***, an optional ***Triplet Fit*** and the ***Global Triplet Track Fit***. The momentum p ($\propto 1/\kappa$) is obtained by minimizing the residuals δ and the MS angles $\Delta\Psi = (\Delta\Theta, \Delta\Phi)$



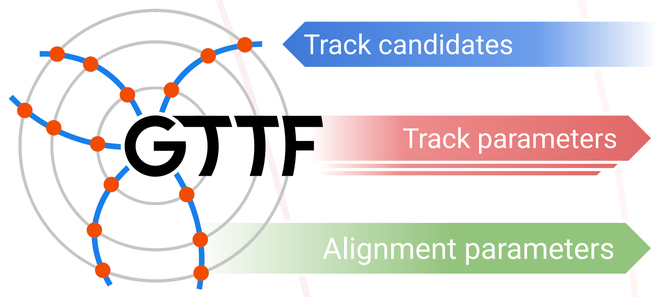
$$\chi^2 = \sum_{j=0}^{n_{\text{scat}}-1} \frac{\Delta\Theta^2_{\text{MS},j}(p,\vec{\delta})}{\sigma^2_{\Theta_{\text{MS},j}}} + \frac{\Delta\Phi^2_{\text{MS},j}(p,\vec{\delta})}{\sigma^2_{\Phi_{\text{MS},j}}} + \sum_{k=0}^{n_{\text{hit}}-1} \vec{\delta}_k^t V_k^{-1} \vec{\delta}_k$$

The ***non-iterative and modular form*** of GTTF makes it ***highly parallelizable***. Furthermore, the **track dependent χ^2** function can be extended by track independent **alignment parameters $\mathfrak{a}$**

- The χ^2 function becomes the **sum of many** individual track χ^2 functions

$$\chi^2_{tot} = \sum_{i=1}^{N} \chi^2_i(\boldsymbol{\kappa}_{i,3D}, \vec{\boldsymbol{\delta}}_i, \mathfrak{a})$$

- simultaneous computation of alignment and track parameters



Outlook

- ***General Triplet Track Fit*** provides a robust and scalable solution for determining hundreds of alignment parameters at once
- high parallelizability makes GTTF well-suited for online alignment
- GTTF can be used for **track based alignment** of the Mu3e detector ensuring its optimal performance

References

[1] K. Arndt et al., *Technical design of the phase I Mu3e experiment*, Nucl. Instr. Meth. A 1014 (2021)

[2] U. Hartenstein, *Track Based Alignment for the Mu3e Pixel Detector*, PhD thesis (2019)

[3] A. Schöning, *A General Track Fit based on Triplets*, Nucl. Instr. Meth. A 1075 (2025)

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