Track-based Alignment of the CMS Muon System

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Muon System (Endcap)
Event example: $h \rightarrow ZZ^* \rightarrow 4 \mu$
Motivation

Alignment of the Muon System geometry directly impacts the reconstruction of physics resonances decaying into high transverse momentum muon pairs.
Detector Apparatus

- **250 Drift Tube (DT) Chambers** (Barrel Region)
- **540 Cathode Strip Chambers (CSC)** (Endcap Region)
- Resistive Parallel Plate Chambers (RPC) used mostly for triggering

Sources of misalignment

- Magnetic stresses
- Gravitational stresses
- CMS maintenance and upgrades (taking apart the detector)

Our task is to align both regions for DT’s and CSC’s
Muon System Geometry

The DT’s and CSC’s are the geometric primitives that we want to align.

Each has its own system of local coordinates that we align along six degrees of freedom (DOF); $\delta x$, $\delta y$, $\delta z$, $\delta \phi_x$, $\delta \phi_y$, $\delta \phi_z$.
The Track-Based Alignment Procedure

Definitions

- **Residuals**: Displacement of the muon hit in the Muon System from the expected hit position.

- **Alignables**: The misalignment measured from a best-fit over the 6 DOF $\delta x$, $\delta y$, $\delta z$, $\delta \phi_x$, $\delta \phi_y$, and $\delta \phi_z$.

Track-based Alignment

We compare measured particle tracks to theoretical tracks in a reference geometry to calculate residuals, then perform a multidimensional best-fit on the alignables to produce an aligned geometry.

**Inputs**: Reference geometry, detector configuration, & data.

**Select** high-quality muons from data

**Propagate** expected muon positions by extrapolating from hits in the tracker

**Compute** track residuals

Multidimensional Fit of misalignment

**Validate** the Alignment: $Z > \mu\mu$ Reconstruction

**Output**: New Geometry
Alignment Procedure: Computing Residuals

Example: Residual Hypotheses with 3 DOF
We speculate on all the possibilities of geometry misalignment (here in 3 DOF, $\delta x$, $\delta y$, $\delta z$) and then add them all up to form the residual hypothesis ($\Delta x_0$, $\Delta y_0$).

Residual Hypothesis:

$$
\begin{align*}
\Delta x_0 &= S_x - \frac{dx}{dz} \delta z \\
\Delta y_0 &= S_y - \frac{dy}{dz} \delta z
\end{align*}
$$

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Alignment Procedure: 6-dimensional fit

\[
\begin{array}{c}
\Delta^k_0 = M^{kl} a^l \\
\end{array}
\]

<table>
<thead>
<tr>
<th>DT Chamber Alignment Matrix (Barrel)</th>
<th>CSC Alignment Matrix (Endcap)</th>
</tr>
</thead>
</table>
| \[
\begin{bmatrix}
\Delta x_0 \\
\Delta y_0 \\
\Delta \frac{dx}{dz} \\
\Delta \frac{dy}{dz}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & -\frac{dx}{dz} & -\frac{dy}{dz} \\
0 & 1 & -\frac{dy}{dz} & -\frac{dy}{dz} \\
0 & 0 & -\frac{dx}{dz} & -\frac{dy}{dz} \\
0 & 0 & -1 & -\frac{dy}{dz}
\end{bmatrix}
\begin{bmatrix}
\delta x \\
\delta y \\
\delta \phi_x \\
\delta \phi_y
\end{bmatrix}
\]
| \[
\begin{bmatrix}
\Delta(R\phi)_0 \\
\Delta y_0 \\
\Delta \frac{d(R\phi)}{dz} \\
\Delta \frac{dy}{dz}
\end{bmatrix} =
\begin{bmatrix}
1 & -\frac{x}{R} + 3\left(\frac{x}{R}\right)^2 & -\frac{dx}{dz} & -\frac{dy}{dz} \\
0 & 1 & -\frac{dy}{dz} & -\frac{dy}{dz} \\
0 & 0 & -1 & -\frac{dy}{dz}
\end{bmatrix}
\begin{bmatrix}
\delta x \\
\delta y \\
\delta \phi_x \\
\delta \phi_y
\end{bmatrix}
\]

Minimize the global fit function \( F(\vec{a}) \) along the 6 alignable DOF \( a \):

\[
F(\vec{a}) = \sum_{\text{residuals}} \sum_{\text{tracks}} \frac{w_i^k}{2\sigma^2} \left[ \Delta^k_i - (\Delta^k_i)_0(\vec{a}) \right]^2 + w_i^k \left( \text{Normalizing Factors} \right)
\]

- \( w_i^k \): Weights
- \( \Delta_i \): Observed Residual
- \( (\Delta_i)_0(\vec{a}) \): Hypothesized Residual
- \( \Delta_i \): Nuisance Parameter
Alignment Procedure: Results

The mean and RMS tell us the average misalignment and variance over all chambers in w.r.t. reference geometry.

These tools let us diagnose problems down to the chamber level before moving to validation.

Muon Alignment using 2017 Data
DT Geometry displacements in x, y, z, $\phi_x$, $\phi_y$, $\phi_z$

Wheel 0 (length x200, angle x200)
M(Z) is reconstructed using a muon pair

- 1 “global” muon = using hits in both tracker and the muon system
- 1 “standalone” muon = using only muon system hits

M(Z) plotted as a function of the kinematics of the standalone muon reveals geometry-dependent performance.

- **Red** = old geometry
- **Green** = new geometry

Dimuon mass and width binned by pseudorapidity ($\eta$) shows good improvement in the Z reconstruction for high-$\eta$ after alignment.
Validating the Alignment

Also, we routinely check for performance drops in the reconstruction using new muon data, e.g. M(Z) binned by standalone muon transverse momentum.

Time to rerun alignment!
Conclusion

Track-based muon alignment can align the Muon System geometry within 100 micron precision.

Alignment is crucial for maintaining muon kinematic resolution, and we validate each newly aligned geometry.

We have made substantial improvements to the alignment algorithm in recent years, and muon alignment is currently stable.

Future plans: Maintain codebase and continue to improve upon the alignment algorithm.
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Reference

Alignment of the CMS Muon System with Cosmic-Ray and Beam-Halo Muons