The CMS detector

SUPERCONDUCTING COIL

IRON YOKE

MUON BARREL

Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)

Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

TRACKER
Silicon Microstrips
Pixels

Total weight: 12,500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 Tesla
External muon devices

- Drift tubes (barrel)
- Cathode strip chambers (endcaps)
- Resistive plate chambers (trigger + redundancy)
Introduction

Inner tracking devices

- 207 m² of Si sensors
- 10.6 million strips
- 65.9 million pixels

**Strips**
- pitch 80 – 200 $\mu$m
- resolution 20 – 80 $\mu$m

**Pixels**
- size $100(r\phi) \times 150(z) \, \mu m^2$
- resolution 10 – 15 $\mu$m
Tracker reconstruction

1. Trajectory seeding
   - Seeded from hits in 2 pixel detector layers
   - Can use primary vertex constraint
     - Alternative (pixel-less) seeding under study

2. Trajectory building (pattern recognition)
   - Kalman filter inside-out, layer to layer
   - Includes energy loss and multiple scattering
   - All (best) candidates grown up to outermost layer

3. Trajectory cleaning
   - Remove mutually exclusive candidates (ambiguities)
   - Resolved based on shared hits

4. Track fitting and smoothing
   - Do Kalman fit of all hits for each candidate, inside-out (fitter)
   - Redo fit in opposite direction, starting with fitter state (smoother)

Muon devices reconstruction: cf. Martijn Mulders’ talk.
Tracker performance

1. \( \mu \) reconstruction efficiency
2. \( \pi \) reconstruction efficiency
3. transverse impact parameter resolution
4. transverse momentum resolution

F. Ronga (CERN-PH-CMG)
Assessing the impact of misalignment

Ideal detector geometry misaligned according to two “scenarios”:

1. “First data” scenario
   - Situation at LHC start-up (first few 100 pb$^{-1}$);
   - information from construction data, laser;
   - track-based alignment in Pixel detector.

2. “Long term” scenario
   - Situation after a few fb$^{-1}$;
   - alignment at sensor level $\sim 20 \mu m$

<table>
<thead>
<tr>
<th>Scenrio</th>
<th>Pixel</th>
<th>Inner Barrel</th>
<th>Silicon Strip</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Barrel</td>
<td>Outer Barrel</td>
<td>Inner Disk</td>
</tr>
<tr>
<td><strong>First Data Taking Scenario</strong></td>
<td>13</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Modules</td>
<td>5</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Ladders/Rods/Rings/Petals</td>
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<td>200</td>
<td>300</td>
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**Long Term Scenario**

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Alignment uncertainties in $\mu m$ for the two scenarios (tracker).
Impact of misalignment on track reconstruction

Global efficiency and transverse momentum resolution vs $\eta$ for perfect alignment and the various scenarios.

Taking into account alignment uncertainty improves tracking efficiency.
Alignment strategy

**Requirement:** better than intrinsic resolution

- Tracker: determine 100k parameters at a precision $\sim 10\mu m$
- Muons: 5k parameters at a precision of $100 - 500\mu m$

**Concept in numbers**

<table>
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<tr>
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<th>Muon [$\mu m$]</th>
<th>Tracker [\mu m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>$O$(mm)</td>
<td>100 – 500</td>
</tr>
<tr>
<td>Optical alignment</td>
<td>$\lesssim 100$</td>
<td>$&lt; 100$</td>
</tr>
<tr>
<td>Track-based</td>
<td>$\sim 100$ (or less)</td>
<td>$\sim 10$</td>
</tr>
</tbody>
</table>

**Remarks**

- Tracker: optical alignment ensures pattern recognition, track-based for final alignment (essential for pixels).
- Muons: optical alignment provides operational level, track-based alignment as cross-check and completion.
Construction knowledge

Inputs
• Robots for module production
• Coordinate measurement machines
• Photogrammetry

Provides
• initial position corrections;
• alignment position error.

Muon chamber X measurements

Tracker residuals
without and with survey info.
Optical alignment overview

Components

- Internal muon alignment
  - barrel
  - endcap
- Internal tracker alignment
- Muon w.r.t. tracker (Link system)

Specifications

- Tracker structures $\sim 10\mu m$
- Muon chambers at $\sim 100\mu m$
- Muon vs tracker $\sim 100\mu m$
Optical alignment concept

**Barrel muon**
- Monitor all chambers;
- complex triangulation.

**Endcap muon**
- Monitor selected chambers (23% of all chambers)

**Tracker (laser beams)**
- TEC w.r.t. TOB;
- TEC w.r.t. TIB.

⇒ Beams treated like tracks
Track-based alignment overview

- Novel techniques developed to cope with large number of parameters
- Three different algorithms implemented:
  - HIP algorithm (iterative method)
  - Kalman filter algorithm (extension of track fitter)
  - Millipede-II (full matrix calculation)
- Use of several data samples:
  - Muons from $Z \rightarrow \mu \mu$, $W \rightarrow \mu \nu$
  - Cosmic muons
  - Beam halo muons
  - Muons from $J/\psi$ and inclusive $B$ decays
  - High $p_t$ hadrons from QCD events (pixel)
- Combine with optical and survey data
- Take benefit mass and vertex constraints, overlap regions

More details in the **LHC Alignment Workshop** (CERN, September 2006)
Track-based alignment study [tracker I]

**HIP algorithm example**
- First data scenario
- Pixel barrel modules
- 200k $Z \rightarrow \mu\mu$
- 10 iterations
- RMS $\sim 7\mu m$ in $x,y$
- RMS $\sim 23\mu m$ in $z$
Track-based alignment study [tracker II]

**Kalman filter**
- 35k single $\mu$ $p_t = 100$ GeV/c
- TIB layers 1–4 alignment
  → RMS $\sim 21\mu$m

**MillePede II**
- TIB + TOB alignment
- 12015 alignment parameters
- MillePede I: 13h
  MillePede II: 32s (!)

Residuals in $r\phi$ before and after
(RMS $\sim 4.8\mu$m)

Residuals in local $x$ vs. number of processed tracks
Track-based alignment study [muon]

- 790 chambers ➞ ∼5000 parameters
- Large amount of material
  - Chambers considered as rigid body
  - Two methods:
    - tracks extrapolated from tracker
    - standalone muon tracks

Alignment of barrel chambers with standalone muon tracks from $W \rightarrow \mu\nu$ corresponding to 50h at $10^{34}$
Summary & Outlook

- Alignment of tracking devices in CMS is a challenge!
- Information from several sources (construction, optics, tracks) → provide starting point and/or redundancy
- Complex track-based alignment algorithms developed
  - use various data samples
  - exploit physical/geometrical constraints
  - use/combine with other sources
- Ongoing analysis of test beam and cosmic data → valuable experience gained!
- Proceeding well towards first physics data!