First Alignment of the CMS Tracker and Implications for the First Collision Data

Andrei Gritsan
Johns Hopkins University
CMS Collaboration

July 17, 2009

Europhysics Conference on High Energy Physics
Krakow, Poland
Tracker in the CMS Detector

CMS Detector at LHC

CMS Tracker
1440 Si Pixel
15148 Si Strip modules

Large Hadron Collider, 27km
CMS Tracker Alignment Goal

• Alignment goal: **nail down** (few $\mu$m) all 16,588 modules ($\times$ 6 dof)

\[
\chi^2(p_{\text{modules}}, q_{\text{tracks}}) = \sum_{i=1}^{N_{\text{residuals}}} r_i^T V_i^{-1} r_i
\]

Andrei Gritsan, JHU III July 17, 2009
Statistical Methods in CMS Tracker Alignment

- **Global method** ("Millepede II")

  \[ \chi^2(p, q) = \sum_{j} \sum_{i} \frac{(y_{ji} - f_{ji}(p, q_j))^2}{\sigma_{ji}^2} = \sum_{ji} \frac{r_{ji}^2}{\sigma_{ji}^2} \]

<table>
<thead>
<tr>
<th>pros</th>
<th>module correlations included</th>
<th>less CPU with one or few iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>cons</td>
<td>helix trajectory model used</td>
<td>large matrix may limit N parameters</td>
</tr>
</tbody>
</table>

- **Local iterative method**

  \[ \chi^2_{\text{module}} = \sum_i r_i^T (p_m) V_i^{-1} r_i(p_m) + \sum_j r_{*j}^T (p_m) V_{*j}^{-1} r_{*j}(p_m) \]

  \[ \Delta p_m = \left[ \sum_i J_i^T V_i^{-1} J_i \right]^{-1} \left[ \sum_i J_i^T V_i^{-1} r_i \right] ; \quad J_i = \partial r_i / \partial p_m \]

<table>
<thead>
<tr>
<th>pros</th>
<th>full Kalman Filter track model</th>
<th>simple implementation, all dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>cons</td>
<td>ignore correlations in one iteration</td>
<td>large CPU with many iterations</td>
</tr>
</tbody>
</table>

Andrei Gritsan, JHU

IV

July 17, 2009
Tracker Alignment without Magnetic Field

- Partial tracker: summer 2007
- Full tracker: summer 2008

- \( \sim 50/80\mu m \) in TOB/TIB
- \( \sim 30-40\mu m \) in TOB/TIB

\[ \text{RMS (\mu m)} \]

- Data - no alignment
- Data - HIP alignment
- MC - ideal geometry
- MC - tuned misalignment (TIB = \( 80\mu m \), TOB = \( 50\mu m \))

\[ \text{Distribution of mean of residuals for TIB} \]
- Ideal (MC); RMS = \( 21\mu m \)
- Aligned (Data); RMS = \( 30\mu m \)
- Design (Data); RMS = \( 7.07\mu m \)

\[ \text{Distribution of mean of residuals for TOB} \]
- Ideal (MC); RMS = \( 25\mu m \)
- Aligned (Data); RMS = \( 47\mu m \)
- Design (Data); RMS = \( 161\mu m \)

\text{arXiv:0904.1220}
CMS Tracker Alignment with Magnetic Field

• Best data for alignment of CMS Tracker: fall 2008 ("CRAFT")

\[ \sim 4 \text{M cosmic tracks} \] for Tracker alignment

B-field = 3.8T \Rightarrow \text{account for multiple scattering track-by-track}

• Require good quality tracks and hits: \( p > 4 \text{ GeV}/c \)
  
  clean hits, outlier hit rejection, \( \chi^2 \) cut, min hits, 2D hits only \( \sim 4\% \) in Pixels
Alignment Strategy

- Multi-step approach by both algorithms to address CMS geometry:
  - large structure movement: coherent $v$ alignment of 1D modules
  - alignment of two sides of 2D strip modules (units): $u$, $w$, $\gamma$

- Combined method
  (1) run global method
  $\Rightarrow$ solve global correlations quickly
  (2) run local method
  $\Rightarrow$ solve locally to match track model in all degrees-of-freedom (dof)
Example: Pixel Residuals (local, global, combined)

- Residuals $\Leftarrow$ multiple scattering + hit errors + alignment errors
  (random) (random) (systematic)

$r_{\phi}$ pixel hit errors $\sim 19 \mu m$ here

Andrei Gritsan, JHU VIII July 17, 2009
Median of the Residuals

Pixel Barrel

Strip Barrel

Pixel Encap

Strip Endcap

note: vertical cosmics ⇒ lower statistics in endcaps

Andrei Gritsan, JHU  IX July 17, 2009
Cosmic Track Halves: Collision-like Tracks

- Tracker resolution with data (require Pixel hits, near collision point)
  - compare non-aligned data → aligned with data → "ideal" MC
  - significant effect of alignment
  - approaching ideal in momentum precision with this track sample

![Graph showing pairs of split tracks with statistical measures](image-url)

- Data combined method
- MC Ideal
- Data non aligned

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-3.431e-05</td>
</tr>
<tr>
<td>RMS</td>
<td>0.0008909</td>
</tr>
<tr>
<td>Mean</td>
<td>5.353e-05</td>
</tr>
<tr>
<td>RMS</td>
<td>0.0008435</td>
</tr>
<tr>
<td>Mean</td>
<td>0.0001168</td>
</tr>
<tr>
<td>RMS</td>
<td>0.002128</td>
</tr>
</tbody>
</table>

Andrei Gritsan, JHU  
July 17, 2009
Cosmic Track Halves: Four Other Parameters

- These four parameters ($d_{xy}$, $d_z$, $\phi$, $\theta$) dominated by Pixels
  - measuring vertex and track direction, note: all $p_T$-dependent

![Graphs showing distributions of $d_{xy}$, $d_z$, $\phi$, $\theta$.]
Monte Carlo Studies: Misalignments

• Comprehensive hierarchical model of CMS Tracker misalignment:
  – “hardware” only “SurveyLAS”
  – “Startup-2008” before collisions “SurveyLASCosmics” (based on 2008 info)
  – “10/pb”
  – “100/pb” (roughly data expected in 2009-2010 LHC run)
  – “ideal” best possible alignment

• Track efficiency stable with proper APE (Alignment Parameter Errors)
  – but fake rate goes up with misalignment

![Global Efficiency vs η](image1)

APE set to 0

![Fake rate vs η for ttbar events](image2)
Monte Carlo Studies: Misalignments

- Compare resolution in track parameters
  - compare "Startup-2008" → "100/pb" → "ideal"
  - for 100 GeV/c track \( \Delta \frac{p_T}{p_T} \sim 9.2\% \rightarrow 5.9\% \rightarrow 3.2\% \)
    \( \Delta (d_{xy}) \sim 106 \mu m \rightarrow 29 \mu m \rightarrow 20 \mu m \)

- New "Startup-2009" would be closer to "100/pb" already
  - benefit from cosmic commissioning run and analysis presented today
  - note: systematic effects not considered here

\[ \Delta(p_T)/p_T \]

\[ \Delta(d_{xy}) \]
Monte Carlo Studies: \( b \)-tagging

- Many **New Physics** models: \( t \rightarrow b \) displaced vertex (\( cT_b \approx 450 \, \mu m \))

- all \( b \)-tag alignment sensitive
- both positions and errors important
- approaching “ideal” at “100/pb”
Monte Carlo: Example of a Discovery Reach

- Reconstruct narrow $X \rightarrow ZZ \rightarrow 4\mu, 4e, \text{or } 2e2\mu$

  joint likelihood fit analysis as an example
test 5/fb at Higgs production rate

  "non-aligned" $\rightarrow$ "Startup-2009" $\rightarrow$ "ideal " $\Rightarrow$ makes big difference

  - $m_{ZZ}$ width $4.4 \rightarrow 3.5 \rightarrow 2.6$ GeV
  - significance $4.1 \rightarrow 4.5 \rightarrow 4.8 \sigma$

  \[
  \text{from } \sqrt{2 \ln \left( \frac{L_{s+b}}{L_b} \right)}
  \]

  \[
  \begin{array}{c|c|c}
  \text{Ideal} & \text{Mean} & 249.8 \\
  \text{RMS} & 2.645 \\
  \text{Mean} & 249.5 \\
  \text{RMS} & 3.493 \\
  \text{Mean} & 249.2 \\
  \text{RMS} & 4.391 \\
  \end{array}
  \]

  \[
  \begin{array}{c|c|c}
  \text{Non-Aligned} & \text{Mean} & 4.76 \\
  \text{RMS} & 1.116 \\
  \text{Mean} & 4.461 \\
  \text{RMS} & 1.054 \\
  \text{Mean} & 4.119 \\
  \text{RMS} & 1.04 \\
  \end{array}
  \]
Systematic Misalignments

- Systematic distortions of the Tracker
  - may be \( \chi^2 \) invariant
  - may introduce physics bias
    e.g. charge bias with layer rotation

\[ r \Delta \phi \text{ vs. } r \]
\[ r \Delta \phi \text{ vs. } z \]

(\( \Delta r, \Delta z, r \Delta \phi \)) vs. (\( r, z, \phi \))

← layer rotation
recovered in alignment

← twist and some others
harder with cosmics alone
Summary

- CMS Tracker alignment:
  - challenging task (16588 elements)
  - successful CMS run with cosmics
  - complementary statistical methods
    best combination of global & local
  - achieved local deviations as low as 3µm

- Implication for first physics
  - discovery reach sensitive to tracker alignment
    e.g. fake rate, b-tag, resonance resolution
  - performance is already ahead of expectation
  - systematic limitations with cosmics alone
    more to come from collisions