Sensor shapes and weak modes of the ATLAS Inner Detector track-based alignment

Julian Wollrath
Physikalisches Institut
Albert-Ludwigs-Universität Freiburg

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Introduction
The ATLAS Detector

- General purpose experiment:
  - Inner tracking system
  - Calorimetry system: electromagnetic & hadronic
  - Muon system
- Run-2:
  - Data taken from 2015 until 2018
  - Proton-proton collisions at $\sqrt{s} = 13$ TeV
  - Recorded integrated luminosity: 147 fb$^{-1}$
Introduction
The ATLAS Inner Detector

- Barrel:
  - TRT: Gaseous detector (straw tubes)
    → $\sim 30$ measurements/track
  - SCT: Silicon strip detectors
    → 8 measurements/track
  - Pixels and IBL: Silicon pixel detectors
    → 4 measurements/track
- Endcaps on each side: Pixels, SCT and TRT
Track-based alignment

- Track-based alignment based on residual minimisation
- Alignment parameters are determined iteratively
- Constraints on track parameters and/or alignment corrections can be included

\[
\chi^2 = \sum_t \left[ r^\top(t, a) V^{-1} r(t, a) + R^\top(t) V_t^{-1} R(t) \right]
\]

Track parameter constraints

\[
+ R'^\top(a) V_a^{-1} R'(a)
\]

Alignment parameter and tolerances constraints

Track parameters:
\[ t = \{(d_0, z_0, \varphi_0, \vartheta, q/p), (\vartheta_{\text{scat}}, \ldots)\} \]

Alignment parameters:
\[ a = (T_x, T_y, T_z, R_x, R_y, R_z) \times N_{\text{struct}} \]
Precision mass measurements

- Scale calibrated with $Z \rightarrow \mu^+ \mu^-$
- EW fit sensitivity to new physics dominated by $m_W$
- $m_W = 80.370 \pm 7 \text{(stat.)} \pm 11 \text{(exp.syst.)} \pm 14 \text{(mod.syst.)} \text{ MeV}$ (at $\sqrt{s} = 7 \text{ GeV}$ with ATLAS)
- Calibration of muon momentum scale: large contribution to syst. uncertainty: $\sim 9 \text{ MeV}$

![Graph showing mass measurements](https://doi.org/10.1140/epjc/s10052-017-5475-4)
Radial distortions

- Weak modes:
  - geometrical distortions preserving the helicoidal path of tracks
  - real detector deformations or ill-defined alignment solutions
  - sagitta bias, $d_0$ bias, …
- Assess with reconstructing invariant masses of $Z \rightarrow \mu^+ \mu^-$
- Also possible: Use of other decays i.e. $J/\psi \rightarrow \mu^+ \mu^-$
- Layer inflation model for radial distortion: $p_T \sim qB \frac{R^2}{8s}$

\[
\tilde{p}_T = p_T (1 + \delta R / R_0)
\]
\[
\cot \tilde{\theta} = \cot \theta (1 + \delta R / R_0)^{-1}
\]
\[
\tilde{p}_z = p_z
\]
Radial distortions
Barrel region

\[ \delta m = \frac{m_{\text{fit}}}{m_{\text{MC}}} - \frac{m_{\text{MC}}}{m_{\text{MC}}} \]

peak of \( m_{\mu^+\mu^-} \) in data
peak of \( m_{\mu^+\mu^-} \) in MC

\[ \frac{\delta m(\phi)}{m_{\text{MC}}} = B + A \cos(N (\phi - \phi_0)) \]

\( B = (-0.80 \pm 0.01) \times 10^{-3} \)

\( A = (0.23 \pm 0.02) \times 10^{-3} \)

\( \phi_0 = (1.08 \pm 0.01) \text{ rad} \)

\( N = 2 \)

Data 2016 & 2017
\( \sqrt{s} = 13 \text{ TeV} \)
• SCT barrel deformation compatible with elliptical deformation
• Minor axis of deformation in horizontal plane
• Difference in minor and major axis length: $\sim 100 \, \mu m$
- Pixel module shape measured and corrected for
- IBL modules assumed to be flat
- 14 staves with 4 (3D) + 12 (planar) + 4 (3D) modules each
- Evaluate track-to-hit residuals for data from one LHC fill taken on 9th–10th Nov. 2017 with $\sim 9 \times 10^5$ IBL hits
- Modules: Pixels: shape corrected; IBL: assumed flat
- Align detector $\rightarrow$ mean residual per module $\sim 0\,\mu m$
- Detailed look into the modules:
IBL sensor shape extraction

- IBL modules assumed to be flat → this assumption is overly simple
- Extract sensor shape from $\sim 2 \times 10^9$ tracks from late 2017
- Split each sensor into $21 \times 21$ cells
- Local-$z$ from track-to-hit residual:
  $z' = x_{\text{residual}}' \cot \phi'$:
  → local-$z$ per cell: weighted mean
- Interpolate shape with Bernstein-Bézier function
Correcting for shape

- Feed shape parametrisation into track reconstruction
- Correct track incident position on module surface by local-z value:

\[ x_{\text{correction}} = -z(x, y) \frac{x_{\text{track}}}{z_{\text{track}}} , \quad y_{\text{correction}} = -z(x, y) \frac{y_{\text{track}}}{z_{\text{track}}} \]
Local-\(x\) and local-\(y\) residuals

Flat sensor assumption

Shape taken into account

Shape taken into account
Conclusion

- Radial distortions:
  - see SCT barrel distortion compatible with elliptical deformation
  - invariant mass reconstruction of $J/\psi \rightarrow \mu^+\mu^-$ and $Z \rightarrow \mu^+\mu^-$ points to presence of radial distortions
- IBL sensor shapes extracted from track-to-hit residuals:
  - deviation from flat sensor hypothesis mostly $\pm 20\,\mu\text{m}$ range
  - shape corrections remove most of structure in local-$x$ and local-$y$ residuals
  - this will improve IBL alignment and impact parameter resolution
Backup
Bernstein-Bézier representation of surfaces

- Bernstein basis polynomial:

\[ B_{i,n} = \binom{n}{i} t^i (1 - t)^{n-i}, \quad 0 \leq t \leq 1 \quad (i = 0, 1, \ldots, n) \]

- Surface:

\[ r(u, v) = \sum_{i=0}^{n} \sum_{j=0}^{m} B_{i,n}(u)B_{j,m}(v) \Psi_{i,j}, \quad 0 \leq u, v \leq 1 \]