Performance of ATLAS tracking

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on behalf of the ATLAS collaboration
Geography: Where are we?

Run 2:
- IBL close to the beam pipe

~6M Channels, 50x250µm pixels

SCT: 6M Channels, 80µm strips
Pixels: 80M Channels, 50x400µm pixel
TRT: 350k channels, r=2mm straws

The reality! (lots of material)
Tracking: How we do it (1)

Space Point Seeded Tracking Finding
- building triplets of space points
- resolve detector elements in a given road and start track candidate search
- dedicated road search for electrons allowing kinks due to energy loss

Track fitting:
- Global least square
- Kalman filter
=> Computationally intensive
Tracking: How we do it (2)
Sounds easy?

Showing both the challenge and necessity:

• Tracking in dense environments is hard
• Vertexing resolution is important

A reminder: Material!

\[ \mu = \text{pp interactions per event (pileup)} \]
Tracking aims

Reconstruction of track parameters: $d_0$, $z_0$, $\eta$, $\phi$, $q/p$

→ Detailed knowledge of:

➤ Material

➤ Alignment

➤ Detector efficiencies

➤ Detector resolution
Material

Beam pipe material is known accurately (~1%) Hadronic interactions are sensitive to interaction length Photon conversions are sensitive to $X_0$

Initial underestimate of IBL material has subsequently been corrected

Material uncertainties dominate systematic errors; typical uncertainty <5%
Material

Track extension efficiency method, potentially more sensitive at $\eta > 1.5$

SCT extension efficiency = \( \frac{\text{Number of Pixel track segments matched to a full track}}{\text{Total Number of Pixel track segments}} \)
Alignment

- Track-based alignment:
  Use track $X^2$ to estimate element positions (ok in Run 1)

- ‘Weak modes’: Geometrical distortions which leave the $X^2$ invariant. Additional information is used to reduce the effect: survey, beamspot constraint, kinematic constraints

- Run 2: IBL bowing and pixel vertical movement seen on ‘fast’ timescales. Automated alignment introduced; every 20min for first hour and very 100min thereafter.

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDTR-2016-005
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDTR-2016-009
Total ionisation dose effect and IBL distortion

Accumulation of ionising dose opened the leakage channels in the transistors of the IBL front-end electronics. Making the IBL power consumption unstable.

Thermal expansion mismatch inside the IBL stave is sensitive to the front-end power consumption change (local temp. change). Consequently, causing rapid change of IBL stave’s bowing distortion.

\[ \pi + \]
Detector efficiencies

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/SCT-2016-001

[Graph showing hit efficiencies for different regions (EndcapC, Barrel, EndcapA) with data from May 2016, \\(|\mathit{s}|=13\ \text{TeV})

(configuration=hit vetoed if there is a hit in preceding timebin)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2016-012

[Graph showing hit-on-track efficiency for 2016 data with two different thresholds (ToT>3 and ToT>5)]

(Pixel plot in preparation)
Detector resolutions

**Figure 7**: The TRT Barrel (left) and End-Cap (right) residual distribution for the 13 TeV collision data sample reconstructed with the June alignment (black) and March alignment (green) as well as observed in the perfectly aligned simulation (red). The distributions are integrated over all hits assigned to tracks in the respective TRT regions. The parameter $\mu$ represents the mean of the distributions. The distributions have been normalized to the same number of entries.

**Figure 8**: The IBL mean of the local x (left) and local y (right) residual distributions as a function of the global z position of the module observed with the 13 TeV collision data sample reconstructed with the June alignment (black) and March alignment (green) as well as observed in the perfectly aligned simulation (red). The pattern seen with the March alignment is consistent with an average stave bowing due to the different operational temperature. This was efficiently eliminated with a Level 3 realignment of the IBL in the June alignment campaign. It is worth noting that, in case of a pure bowing deformation, residual means at the stave extremities should be unaltered. The overall offset seen in the left plot of Fig. 8 indicates an additional Level 1 rotation of the IBL which could have occurred due to severe environmental cycles between the two data taking periods.

The overall improvement obtained with the collision data alignment can be summarized by the one-dimensional distributions of the mean residuals per IBL sensor. Fig. 9 shows the distributions for the two sensitive measurement directions. The achieved local alignment accuracy is at the level of one micron in the most sensitive direction (local x) and under three microns in the direction along the beam line.

**Table**: TRACK-HIT RESIDUAL

<table>
<thead>
<tr>
<th>Component</th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IBL</strong></td>
<td>$\sigma_x=13\mu$m</td>
<td>$\sigma_x=15\mu$m</td>
</tr>
<tr>
<td></td>
<td>$\sigma_y=87\mu$m</td>
<td>$\sigma_y=165\mu$m</td>
</tr>
<tr>
<td><strong>Pixel</strong></td>
<td>$\sigma_x=9\mu$m</td>
<td>$\sigma_x=15\mu$m</td>
</tr>
<tr>
<td></td>
<td>$\sigma_y=87\mu$m</td>
<td>$\sigma_y=165\mu$m</td>
</tr>
<tr>
<td><strong>SCT</strong></td>
<td>$\sigma=24\mu$m</td>
<td>$\sigma=30\mu$m</td>
</tr>
<tr>
<td><strong>TRT</strong></td>
<td>$\sigma=128\mu$m</td>
<td>$\sigma=124\mu$m</td>
</tr>
</tbody>
</table>
Track performance metrics

- Resolution metrics:
  - Sagittal bias (handle on rotational ‘weak mode’) Expressed as a $1/p$ bias, TeV$^{-1}$
  - $d_0$ and $z_0$ resolutions Impact parameters, expressed in μm

- Efficiency metrics
  - Efficiency/fake trade-off
Sagittal Bias

Charge-dependant; analysis uses neutral \( \rightarrow \) two-body decays which constrain the invariant mass. The calorimeter provides an additional energy measurement.

\[ p \rightarrow p(1 + q p_T \delta_{\text{sagitta}})^{-1} \]

"the distortion which creates a 10% momentum bias for a 10 GeV particle differs from the parabolic approximation by only 0.3 \( \mu \)m at the outer SCT radius"
$d_0$ and $z_0$ resolutions

Greatly improved between run-1 and run-2

:: IBL, Material reduction at pixel boundaries
Tracking efficiency

<table>
<thead>
<tr>
<th>Track Quality Selection</th>
<th>Loose</th>
<th>Tight Primary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$ Range</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$2.3 \leq</td>
<td>\eta</td>
<td>\leq 2.5$</td>
</tr>
<tr>
<td>Track Reconstruction Efficiency</td>
<td>91%</td>
<td>86%</td>
</tr>
<tr>
<td>$\text{Sys}_{+5%\text{Extra}}$</td>
<td>0.4%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\text{Sys}_{\text{PixServExtra}}$</td>
<td>—</td>
<td>2.0%</td>
</tr>
<tr>
<td>$\text{Sys}_{+30%,1\text{BLEExtra}}$</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Total Systematic Uncertainty</td>
<td>0.4%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

*Uncertainty dominated by the knowledge of material distribution*
Vertexing

Iterative approach:

- Track selection…
- …gives vertex ‘seeds’

- Seeds and the tracks are fitted iteratively, less compatible tracks are down-weighted and seeds refitted

- Tracks which are incompatible are removed and may be used in fitting additional vertices…

- …until no unassociated tracks are left or no additional vertex can be found
Vertex efficiency

Number of vertices should be proportional to $\mu$...

...but become merged when too close
Vertex resolution

Sim 2014: IBL effect

2015: Comparison of MC/data

Vertexing software: future?

(Simulation)

Track image is Fourier transformed, filtered and transformed back

Track seeds appear in one step

Good efficiency

Computationally expensive, but scales well
Large Radius Tracking

![Graph 1: ATLAS Preliminary Simulation $\sqrt{s} = 13$ TeV, R-hadrons](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDTR-2016-006/)

- Standard tracking
- Large radius tracking
- Standard + Large radius tracking

![Graph 2: ATLAS Preliminary Simulation $\sqrt{s} = 13$ TeV, $LLZ'$ to $\mu\mu$](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDTR-2016-006/)

- Standard tracking
- Large radius tracking
- Standard + Large radius tracking
Tracking in dense environments

Run 2: Increasingly high event rate
- Mitigated by high granularity IBL
- Neural Net introduced for pixel cluster disambiguation
- Using cluster charge, shape, layer correlation and incidence angle


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/PERF-2012-05/
Software Changes

Run1-Run2 Changes:

- 32→64 bit
- Compiler upgrade, C++ changes
- CLHEP→Eigen
- New (simplified) EDM
- Introduce ‘xAOD’

ACTS: ‘A Common Tracking Software’

http://acts.web.cern.ch
Looking to the future…

LHC / HL-LHC Plan

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4 - 5...</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>2012</td>
<td>2013</td>
<td>2014</td>
</tr>
<tr>
<td>7 TeV</td>
<td>8 TeV</td>
<td>13 TeV</td>
<td>14 TeV</td>
</tr>
</tbody>
</table>

**LHC**

- LS1: splice consolidation button collimators R2E project
- EYETS
- 30 fb⁻¹

**HL-LHC**

- 14 TeV
- 150 fb⁻¹

- LS3: HL-LHC installation
- 14 TeV
- 300 fb⁻¹

- ATLAS - CMS upgrade phase 1
- 2.5 x nominal luminosity
- 2019 - 2020

- ATLAS - CMS upgrade phase 2
- 2.5 x nominal luminosity
- 2024 - 2026

- 5 to 7 x nominal luminosity
- 2024 - 2026

- 3000 fb⁻¹

- Integrated luminosity
- 2028
Looking to the future...

**Run3:** Systemic changes affecting tracking

- Multiprocess → Multithreading (∴ memory/core)

1.25GB per worker in this example; but will be higher

**MP vs serial**

**FTK:** Tracking joins the trigger. Massively parallel processing enabling tracking to be done after L1, before L2, using existing IBL, pixel and SCT detectors.

**ITk:** at **HL-LHC (2024)**, we get a new tracker!
Concluding

- LHC delivering luminosity reliably
- Inner Detector has responded, delivering above design specifications
- IBL has proven its worth!
- Time dependent alignment, Neural Net clustering and other algorithmic improvements have been successfully introduced
- Preparation has already begun for Run 3 and beyond