ATLAS Tracking and Vertexing Performance

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On behalf of the ATLAS Collaboration
The ATLAS Inner Detector

Within a 2T B-Field

<table>
<thead>
<tr>
<th></th>
<th>Pixel</th>
<th>SCT</th>
<th>TRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Silicon pixels</td>
<td>Silicon strips</td>
<td>Drift tubes</td>
</tr>
<tr>
<td>Resolution</td>
<td>$10,\mu m (R_\phi)$, $115,\mu m (Z)$</td>
<td>$17,\mu m (R_\phi)$, $580,\mu m (Z)$</td>
<td>$130,\mu m (R_\phi)$</td>
</tr>
<tr>
<td>Number of Layers</td>
<td>3 Barrel, 2x3 Endcap</td>
<td>4 Barrel, 2x9 Endcap</td>
<td>3 Barrel, 2x40 Endcap</td>
</tr>
<tr>
<td>Number of Modules</td>
<td>1744</td>
<td>4088</td>
<td>176</td>
</tr>
</tbody>
</table>
Expected Performance

- Table below gives expected resolutions from simulation.
- Multiple scattering means that track parameter resolutions are dependent on $p_T$.

\[
\sigma_X(p_T) = \sigma_X(\infty) \left(1 + \frac{p_X}{p_T}\right)
\]

**Barrel Slice**

| Track parameter                              | $0.25 < |\eta| < 0.50$ | $1.50 < |\eta| < 1.75$ |
|---------------------------------------------|-------------------------|------------------------|
| Inverse transverse momentum ($q/p_T$)       | 0.34 TeV$^{-1}$         | 0.41 TeV$^{-1}$        |
| Azimuthal angle ($\phi$)                    | 70 $\mu$rad             | 92 $\mu$rad            |
| Polar angle ($\cot \theta$)                | $0.7 \times 10^{-3}$     | $1.2 \times 10^{-3}$   |
| Transverse impact parameter ($d_0$)         | 10 $\mu$m               | 12 $\mu$m              |
| Longitudinal impact parameter ($z_0 \times \sin \theta$) | 91 $\mu$m     | 71 $\mu$m              |

**Endcap Slice**

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- How do we achieve this performance?
  - At high $p_T$:
    - ID Alignment: Determining the position/orientation of the ID modules.
    - Understanding the $b$-field mapping of the detector (already mapped to very high $\sim 0.4$ mT precision)
  - At low $p_T$:
    - Understanding the material distribution.
ID Alignment

- Alignment is crucial for resolutions (at high $p_T$) and momentum scale:
  - Require alignment to $\sim 10\mu$m precision in measurement plane.
- Alignment has been substantially improved using 900 GeV collisions data!
- Estimated residual misalignments $\sim 17\mu$m (Pixel barrel) $\sim 25\mu$m (SCT barrel).
Material Description

- Understanding the ID material distribution is crucial for low $p_T$ tracking:
  - To understand the contribution of multiple scattering (resolutions).
  - To correctly compensate for ionisation losses in the track fit ($p_T$ scale).

Data-MC comparison of rate of secondary hadronic interaction vertices as a function of radius in barrel.

Data-MC comparison of rate of photon conversions in barrel as a function of radius in the barrel.

Direct probes of material map show that it is generally very good – discrepancy in Pixel support structure already understood.
$K^0_s \rightarrow \pi^+\pi^-$ Reconstruction

- $K_s$ reconstruction probes quality of low $p_T$ track reconstruction (< 1 GeV):
  - Mainly sensitive to material description
- Fitted mass and width compatible with MC simulation (and PDG mass):
  - Validation of track momentum scale at low $p_T$

PDG mass = 497.614 ± 0.024 MeV

Both tracks $|\eta| < 1.2$
Barrel

Data: $\mu = 497.427\pm0.006$ (stat.)  $\sigma = 5.60$
MC: $\mu = 497.329\pm0.006$ (stat.)  $\sigma = 5.42$

Both tracks $|\eta| > 1.2$
Endcaps

Data: $\mu = 497.797\pm0.016$ (stat.)  $\sigma = 10.45$
MC: $\mu = 497.868\pm0.016$ (stat.)  $\sigma = 10.14$
Probing Material Map with $K^0_S$

- Incorrect material budget will bias track momenta and hence $K_S \rightarrow \pi^+\pi^-$ reconstructed mass.
- Compare reconstructed $K_S$ mass over a large rapidity range with special MC minbias simulation samples with additional material.
- No evidence for additional material in the barrel.
- Evidence for ~10% material uncertainty in endcaps.

![Graph showing fitted mass ratio of $K^0_S$ over various rapidity ranges with data and MC simulations.](image-url)
Reconstruction of Cascade Decays

- All measured resonance masses in agreement with PDG values.
- All measured resonance widths in agreement with simulation expectations.
Muons identified from combined ID and muon spectrometer track, but $m_{\mu\mu}$ formed from ID-tracks only.

- No deviation larger than $0.2 \pm 0.1\%$ in mean of reconstructed mass vs PDG.
  - Validation of momentum scale for average muon $p_T \sim 4$ GeV.
- Across all rapidity ranges width of signal peak in agreement with MC simulation.

J/ψ→μμ Reconstruction

\[
\int \sqrt{s} = 7 \text{ TeV} \\
L \, dt = 78 \text{ nb}^{-1}
\]

- $N_{J/\psi} = 5350 \pm 90$
- $m_{J/\psi} = 3.095 \pm 0.001$ GeV
- $\sigma_m = 71 \pm 1$ MeV

PDG value

\[
\begin{array}{c|c|c}
\hline
\eta(J/\psi) & m_{J/\psi} & \sigma_m \\
\hline
-3 & 3.095 & 71 \\
-2 & 3.095 & 71 \\
-1 & 3.095 & 71 \\
0 & 3.095 & 71 \\
1 & 3.095 & 71 \\
2 & 3.095 & 71 \\
3 & 3.095 & 71 \\
\hline
\end{array}
\]

\[
\begin{array}{c|c|c}
\hline
\eta(J/\psi) & \sigma_m & \\
\hline
-3 & 0.04 & \\
-2 & 0.04 & \\
-1 & 0.04 & \\
0 & 0.04 & \\
1 & 0.04 & \\
2 & 0.04 & \\
3 & 0.04 & \\
\hline
\end{array}
\]
• Tracking efficiencies are thus far determined from MC simulation.
• Main systematic is from uncertainty in material budget.
• We can do this since (after much work) the simulation models the tracks seen in data extremely well:
• Iterative vertex finding algorithm:
  – Uses all tracks not significantly different from beamspot with $p_T > 100$ MeV and minimum number of hits in silicon detectors.
  – Fits these to a single vertex, with progressive downweighting of outlier tracks.
  – Tracks incompatible with vertex are used to seed a new one.
  – Repeats until no tracks left or no new seed created.
• In case of multiple vertices – primary vertex chosen as that with highest $\sum p_T^2$

- Primary vertex reconstruction efficiency as a function of number of tracks.
- Turn on due to looser definition of tracks in the analysis.
- Vertex efficiency is 100% provided there are enough tracks of reasonable quality.
Data-driven single-vertex resolution determination:
- Split single vertices randomly into two and refit independently.
- Width of the resultant vertex separation distribution gives intrinsic resolution.

Resolution dependent on number and $p_T$ of tracks used to fit vertex:
- Can look significantly better for high $p_T$ analyses.

Primary Vertex Resolution

- $x$-y resolution $\sim 30\mu m$
- $z$ resolution $\sim 50\mu m$ for $N_{trks} = 70$
Impact Parameter Resolution

- B-tagging relies on successful identification of tracks/vertices displaced from the primary interaction:
  - Understanding of transverse impact parameter ($d_0$) resolution is crucial.

Width of $d_0$ distribution is a convolution of $d_0$ resolution $\sigma_{d_0,\text{trk}}$ and primary vtx resolution $\sigma_{d_0,\text{PV}}$

$$R_{\text{meas}}(d_0) = \int \exp \left[ -\frac{1}{2} \frac{d_0^2}{\sigma_{d_0,\text{trk}}^2 + \sigma_{d_0,\text{PV}}^2} \right] P(\sigma_{d_0,\text{PV}}) d\sigma_{d_0,\text{PV}}$$

- Iterative procedure is applied to deconvolve $\sigma_{d_0,\text{trk}}$ from $\sigma_{d_0,\text{PV}}$.
- Good agreement with MC at low $p_T$.
- Deviations at high $p_T$ potentially due to residual misalignment.
Summary & Conclusions

• Detailed comparisons between track reconstruction in data and simulation demonstrate that tracking at ATLAS is already very well understood.
• “Successful” reconstruction of low mass resonances demonstrates the accuracy of the momentum determination at low $p_T$
  – The material description is already very good and can be improved further.
  – Work ongoing to assess the reconstruction of higher mass resonances such as $Z$ bosons (more sensitive to alignment and B-field mapping).
• Primary vertex reconstruction is working well and data-driven methods can be used to determine the vertex resolution and efficiency.
• Data-driven determination of impact parameter resolutions and comparison to simulation demonstrates that this is also generally well understood – rapid commissioning of $b$-taggers should be possible.
Backup Slides
Track-Based Alignment Algorithms

6 DoF

\[ \vec{r}_i \equiv \hat{m}_i - \hat{e}_i(\pi, a) \]

\[ \chi^2 = \sum_{\text{tracks}} \vec{r}^T V^{-1} \vec{r} \]

- Use module residual distributions to determine alignment constants \( a \).
- **Global \( \chi^2 \) Algorithm** (Pixel & SCT):
  - full minimisation of \( \chi^2 \) w.r.t track parameters \( \pi \) and \( a \).
  - Requires 6N x 6N matrix inversion (N=5832)! Numerically challenging!
  - Iterative procedure needed.
  - Baseline algorithm for Si alignment.