Tracking and vertexing using the ATLAS detector

G. Gaycken on behalf of the ATLAS collaboration
"high" pileup event with 28 vertices, the typical run-2 event has \( \sim 15 \) vertices.
The ATLAS inner detector
2 T magnetic field, ID radius 1.1 m, coverage $|\eta| < 2.5$

Technologies:

TRT:
Xe (Ar) filled straw tubes ($\varnothing = 4$ mm), $\varnothing(30)$ crossed straws per track.

SCT:
Double sided strips 8 barrel layers, 9 disks, $80 \mu m \times \sim 6$ cm, 40 mrad stereo angle

Pixel:
3 layers, 3 disks, $50 \times 400 \mu m^2$

IBL:
1 barrel layer, $50 \times 250 \mu m^2$, radius 3.3 cm
Atlas ID track reconstruction:
Atlas ID track reconstruction:

Build Clusters
Atlas ID track reconstruction:

Build Clusters

Make track seeds
Atlas ID track reconstruction:

- Build Clusters
- Make track seeds
- Find tracks
Atlas ID track reconstruction:

1. Build Clusters
2. Make track seeds
3. Find tracks
4. Handle merged Pixel cluster (NN)
Atlas ID track reconstruction:

1. Build Clusters
2. Make track seeds
3. Find tracks
4. Handle merged Pixel cluster (NN)
5. Resolve ambiguities and fit track (GXF)
Atlas ID track reconstruction:

- Build Clusters
- Make track seeds
- Find tracks
- Handle merged Pixel cluster (NN)
- Resolve ambiguities and fit track (GXF)
- Extend to TRT
Alignment

- based on global $\chi^2$ minimisation of hit-to-track residuals,
- performed at different levels: sub-detector $\rightarrow$ layers $\rightarrow$ modules.
- Since run 2, alignment updates ($\sim$ every 10 min):

**IBL bowing correction**

**Pixel y-position**

\[ \Theta(100 \, \mu m) \]

\[ \Theta(5 \, \mu m) \]
Alignment stability

- Alignment monitored to fix emerging issues immediately, but also by fast reprocessing.
Weak modes

Global $\chi^2$ from hit-to-track residuals unaffected.
→ need external constraints:
  e.g. invariant mass in $Z \rightarrow \mu\mu$, or $J/\psi \rightarrow \mu\mu$
Radial distortions

For each radial expansion $\delta R$: track parameters exist which lead to identical residuals i.e. same sagitta $s$, same $z$ positions $\Delta z$

$$p'_T \simeq p_T (1 + 2 \delta R / R_0)$$

$$p'_z \simeq p_z (1 + \delta R / R_0)$$

→ Momentum scale not constrained by hit-to-track residuals.
Radial distortion

\[ \frac{\Delta p_T}{p_T} \approx 0.1\% \]

Measured radial distortion ~ stable throughout years (corresponds to distortion of ID radius of ~ 500µm).

**ATLAS Preliminary**

Data 2016 \( \sqrt{s} = 13 \) TeV \( L=33 \) fb\(^{-1} \)

\( |\eta_\mu| < 1.07 \)

\[ \epsilon = \frac{\delta R/R_0}{10^{-3}} \]

- \( \triangle Z \rightarrow \mu^+\mu^- \)
- \( \circ J/\psi \rightarrow \mu^+\mu^- \)
- \( \triangledown Y \rightarrow \mu^+\mu^- \)
Tracking efficiency

Average tracking efficiency

Average track multiplicity

- In run-2 tracks reconstructed with $p_T > 500$ MeV.
- Uncertainties evaluated for two working points:
  - Loose: larger efficiency.
  - Tight Primary: larger purity.
Tracking stability

In particular for track based luminosity measurements (Z-counting) stability crucial:

- event yield with di-muons in invariant mass window.

In 2017 track selection for Z-counting adjusted to improve stability wrt. $\langle \mu \rangle$:

**Average interaction / BX ($\langle \mu \rangle$)**

![Graph showing average interaction per BX over time](image)

**Efficiency vs $\langle \mu \rangle$**

- re-optimised track selection
- initial track selection
- MC
- Data
Tracking stability

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Efficiency vs $\langle \mu \rangle$  
Efficiency vs time

- re-optimised track selection
- initial track selection
- MC
- Data
IBL radiation damage

Radiation damage impacts charge collections → cluster size.

![Graph showing the relationship between delivered luminosity and cluster size](graph)

**ATLAS Preliminary**

Data 2016, $\sqrt{s} = 13$ TeV

IBL

Cluster size

$\langle dE/dx \rangle$

$\langle$cluster size $\phi\rangle$

$\langle$cluster size $z\rangle$

Delivered luminosity [fb$^{-1}$]

HV 80 V

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IBL Charge collection

Charge Collection Efficiency

Integrated Luminosity [fb⁻¹]

ATLAS Preliminary

IBL planar modules

Data 80 V

Standalone Simulation 80 V
IBL Charge collection

Charge Collection Efficiency vs. Integrated Luminosity [fb⁻¹]

ATLAS Preliminary
IBL planar modules

Data 80 V
Data 150 V
Standalone Simulation 80 V
Standalone Simulation 150 V
IBL radiation damage

Radiation damage impacts charge collections $\rightarrow$ cluster size.

![Graph showing the relationship between delivered luminosity and cluster size](image)

**ATLAS Preliminary**

Data 2016, $\sqrt{s} = 13$ TeV

Cluster size

$dE/dx$
IBL charge vs bias voltage

ToT [BC] vs Bias Voltage [V]

- **data - end 2017**
- **Standalone Simulation: $\phi=6 \times 10^{14} \text{n}_\text{eq}/\text{cm}^2$ (end 2017)**

**ATLAS**

Preliminary

IBL planar modules

**Bias Voltage [V]**
**IBL charge vs bias voltage**

![Graph showing ToT vs Bias Voltage for IBL planar modules, with data and simulation points, indicating ATLAS Preliminary results.](image-url)
tracks (ghost) associated to jets ($p_T > 20$ GeV) in di-jet events:

$d_0$ resolution

$z_0$ resolution

Impact parameter resolution very stable!
For pp collisions, primary vertices reconstructed with iterative vertex finder assigning tracks to individual vertex candidates.

Efficiency $\mathcal{O}(40\%)$: 90% acceptance, detector effects dominant at low $\mu$, vertex merging at high $\mu$.

Alternative methods being studied for run 3 and beyond.
Vertex multiplicity

2017

\[ \langle \mu \rangle_{\text{bunch}} = 43.3 \text{ with } \pm 4\% \text{ syst. on } \langle \mu \rangle_{\text{bunch}} \]
\[ \langle \mu \rangle_{\text{bunch}} = 28.2 \]

2018

\[ \langle \mu \rangle_{\text{bunch}} = 45.5 \]
\[ \langle \mu \rangle_{\text{bunch}} = 47.1 \]

- Stable performance over run 2 \( \mu \) range, but
- efficiency differs between fills by \( \mathcal{O}(\%) \).
Vertex multiplicity

2017

ATLAS Preliminary

\[ \langle \mu \rangle_{\text{bunch}} = 43.3 \text{ with } \pm 4\% \text{ syst. on } \langle \mu \rangle_{\text{bunch}} \]

\[ \langle \mu \rangle_{\text{bunch}} = 28.2 \]

2018

ATLAS Preliminary

data 2018, \( \sqrt{s} = 13 \text{ TeV} \)

- April \( \langle \mu \rangle = 45.5 \)
- June \( \langle \mu \rangle = 47.1 \)

Stable performance over run 2 \( \mu \) range, but

- efficiency differs between fills by \( O(\%) \).
Run 3 and beyond

- Few algorithmic changes planned for run 3:
  - better handling of merged SCT clusters,
  - possible switch to an alternative primary vertex finder,
  - tuning for tracks in high $p_T$ jets.
- but large efforts to modernise the software
  - transition from multi-processing to multi threading (event parallel to algorithm, sub-algorithm parallel),
  - staged migration to ACTS.
SCT merged clusters

Width of isolated SCT clusters in $\tau \rightarrow \pi\pi\pi$, $p_{T,\tau} > 400$ GeV

Single particle

More than one particle

unmerged all 3 $\pi$ produce SCT clusters on both sides, which are not connected.
SCT merged cluster

Cluster width to identify particle multiplicity:

**Width difference**

<table>
<thead>
<tr>
<th>Width difference</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
<td>400</td>
<td>300</td>
<td>200</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

- Observed width ($W_o$) - Calculated hit width ($W_{0.2}$)

**Performance of classification**

- Probability of correctly splitting merged hit
- Probability of splitting unmerged hit

**Computed hit width**

Computed from local track angle and Lorentz angle.

**ATLAS Simulation Preliminary**

Run 2, $\tau \rightarrow 3\pi^0\nu$, $|\eta|=0$

$P_{T,\tau} = 400-1000$ GeV

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SCT merged clusters

Efficiency

"Duplicate" tracks

Duplicate tracks  multiple reconstructed tracks associated to a single $\pi$.  

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A Common Tracking Software

- Toolbox for track reconstruction;
- modern, multi threading friendly code;
- detector and framework independent.
  → sharing of solutions across experiments.
- Most contributors from ATLAS (but should not stay like this)
  - Currently, solutions mostly based on ATLAS ideas.
  - In the future, all users will benefit from better algorithms.
- Plan to have fully migrated before run 4.

→ https://acts.web.cern.ch/AIDS.
Summary

- Stable performance through out run 2.
- Signs of radiation damage become visible, but mostly mitigated and no significant impact on physics performance yet.
- Alignment better and better understood.
- Considered algorithmic improvements for run 3:
  - improved handling of shared SCT clusters,
  - improved vertex finding better suited for high pileup.
Extra Material
Track selection

- **Loose:**
  - $|\eta| < 2.5,$
  - number of Silicon Hits $\geq 7,$
  - number of Shared Modules $\leq 1,$
  - number of Silicon Holes$^a \leq 2,$
  - number of Pixel Holes $\leq 1.$

- **Tight Primary:**
  - fulfills Loose requirements,
  - number of Silicon Hits $\geq 9$ and $\geq 11$ for $|\eta| > 1.65,$
  - at least 1 hit on first two pixel layers (if expected),
  - no pixel Holes.

$^a$Holes: locations between the inner and outermost hit of a track at which a hit is expected but non observed
Primary vertices

Multiplicity vs $\langle \mu \rangle$

Vertex z-position

ATLAS Preliminary
data 2018, $\sqrt{s} = 13$ TeV

$\mu_{\text{April}} = -6.213 \pm 0.002$
$\sigma_{\text{April}} = 36.936 \pm 0.001$

$\mu_{\text{June}} = -8.317 \pm 0.003$
$\sigma_{\text{June}} = 34.632 \pm 0.002$

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IBL Charge collection

Charge Collection Efficiency

ATLAS Preliminary
IBL planar modules

- Data 80 V
- Data 150 V
- Data 350 V
- Standalone Simulation 80 V
- Standalone Simulation 150 V
- Standalone Simulation 350 V

Integrated Luminosity [fb⁻¹]