Boosting the discovery potential for the LHC Run 3
Improved Track Reconstruction for prompt and long-lived particles in ATLAS

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Introduction
The ATLAS Inner Detector

• Barrel:
  • TRT: Gaseous detector (straw tubes) → ~30 measurements/track
  • SCT: Silicon strip detectors → 8 measurements/track
  • Pixels and IBL: Silicon pixel detectors → 4 measurements/track

• End-caps on each side:
  • Pixels
  • SCT
  • TRT
**ATLAS Primary Tracking**

- Space Point & Drift Circle Formation
- Pixel & Strip Seed Finding
- Track Finding
- Ambiguity Resolution
- TRT Extended Track Refit

**ATLAS Back-Tracking**

- TRT Segment Finding in Calorimeter Regions of Interest
- Track Finding
- Ambiguity Resolution
- TRT Extended Track Refit
Changes with respect to Run 2 track reconstruction:

- Tighter cluster on track requirements ($7 \rightarrow 8$)
- Tighter impact parameter selection ($|d_0| < 10 \text{ mm} \rightarrow |d_0| < 5 \text{ mm}$)
- More selective backtracking
- Better seeding
- Confirmation space-point for falsely reconstructed track suppression
- New vertex finder (using ACTS implementation)
- Additional ‘long radius tracking’ pass in all events
Physics performance and software optimisation

**ATLAS Preliminary**
- Run 2 Data Reconstruction
- ATLAS Tracking CPU vs µ
  - LHC Fill 6291
  - Run 2 Reconstruction
  - Run 3 Reconstruction without LRT
  - Run 3 Reconstruction

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**Run 2 vs 3 data reconstruction**
- Speedup vs µ
  - LHC Fill 6291

**Ambiguity resolution**
- TRT
- Track finding
- Miscellaneous

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Physics performance and software optimisation

ATLAS Simulation Preliminary
charged particles from hard scatter

Reconstruction efficiency

Run 2 Reconstruction
Run 3 Reconstruction

Simulation Preliminary

ATLAS
MC

Number of reconstructed tracks

Dashed lines: Linear fit to $\mu \in (10..25)$

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Pixel cluster splitting

- Separation of track smaller than sensitive elements size
  → clusters shared between tracks
  → lower track reconstruction efficiency with standard algorithms
- Neural network based cluster splitting
  → determine: number of particles → hit positions → hit position uncertainties
- Different NNs for 1, 2, ≥ 3 particle hits:
  • Old: 1 NN for position, 2 NNs for uncertainties (local x & y) each
  • New: 1 mixture density network each
Pixel cluster splitting

**ATLAS** Simulation Preliminary

PYTHIA8 dijet, $1.8 < \pT < 2.5$ TeV
2-particle clusters local X direction

**ATLAS** Simulation Preliminary

PYTHIA8 dijet, $1.8 < \pT < 2.5$ TeV
3-particle clusters local X direction

**ATLAS** Simulation Preliminary

MDN 2D Gaussian Kernel
$\mu = 0.12 \mu m$, $rms = 12.7 \mu m$

**ATLAS** Simulation Preliminary

MDN 2D Gaussian Kernel
$\mu = 0.20 \mu m$, $rms = 17.3 \mu m$

**ATLAS** Simulation Preliminary

Position Network Regression NN
$\mu = 5.88 \mu m$, $rms = 16.9 \mu m$

**ATLAS** Simulation Preliminary

Position Network Regression NN
$\mu = 1.94 \mu m$, $rms = 23.5 \mu m$
Primary vertexing

Iterative Vertex Fitter (old)

- IVF
- Selected tracks
- Seed pool
- New vertex seed
- Add tracks to fit due to significance
- Fit single vertex
- Remove outliers
- Remove compatible tracks from seed pool

Adaptive Multi Vertex Finder/Fitter (new)

- AMVF
- Selected tracks
- Seed pool
- New vertex seed
- Add tracks to fit due to significance within wide z window
- Fit new vertex candidate along with any linked previously fit vertices (fit constrained to seed width)
- Remove outliers, compare against previously fit vertices
- Remove compatible tracks from seed pool
Primary vertexing

\[ \sqrt{s} = 13 \text{ TeV} \]

**ATLAS Simulation Preliminary**

Average number of reconstructed vertices

Number of pp interactions per bunch crossing

100% interaction reconstruction efficiency

Reconstruction acceptance

**AMVF, t\bar{t}**

**IVF, t\bar{t}**

**AMVF - MATCHED**

**AMVF - MERGED**

**AMVF - SPLIT**

**AMVF - FAKE**

ATLAS

Simulation Preliminary = 13 TeV
Primary vertexing

Athena → ACTS

**ATLAS** Simulation Preliminary

$\sqrt{s} = 13$ TeV, $t\bar{t}$, $(\mu) \in [40,60]$  

- **Athena AMVF Gaussian Seeder**
- **ACTS AMVF Gaussian Seeder**
- **ACTS AMVF Grid Seeder**

Avg. reconstruction times per event:
- Athena AMVF Gaussian Seeder: 260 ms
- ACTS AMVF Gaussian Seeder: 125 ms
- ACTS AMVF Grid Seeder: 89 ms

### Fraction of events

<table>
<thead>
<tr>
<th>$(z_{\text{reco}} - z_{\text{true}})$ [mm]</th>
<th>Athena AMVF</th>
<th>ACTS AMVF</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.1 to -0.05</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>-0.05 to 0</td>
<td>0.45</td>
<td>0.46</td>
</tr>
<tr>
<td>0 to 0.05</td>
<td>0.5</td>
<td>0.51</td>
</tr>
<tr>
<td>0.05 to 0.1</td>
<td>0.2</td>
<td>0.21</td>
</tr>
</tbody>
</table>

### Local pile-up density

<table>
<thead>
<tr>
<th>Local pile-up density [vertices/mm]</th>
<th>Athena AMVF</th>
<th>ACTS AMVF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 0.2</td>
<td>1.05</td>
<td>1.06</td>
</tr>
<tr>
<td>0.2 to 0.4</td>
<td>1.05</td>
<td>1.06</td>
</tr>
<tr>
<td>0.4 to 0.6</td>
<td>1.05</td>
<td>1.06</td>
</tr>
<tr>
<td>0.6 to 0.8</td>
<td>1.05</td>
<td>1.06</td>
</tr>
<tr>
<td>0.8 to 1.0</td>
<td>1.05</td>
<td>1.06</td>
</tr>
<tr>
<td>1.0 to 1.2</td>
<td>1.05</td>
<td>1.06</td>
</tr>
<tr>
<td>1.2 to 1.4</td>
<td>1.05</td>
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</tr>
<tr>
<td>1.6 to 1.8</td>
<td>1.05</td>
<td>1.06</td>
</tr>
<tr>
<td>1.8 to 2.0</td>
<td>1.05</td>
<td>1.06</td>
</tr>
</tbody>
</table>
Large radius tracking

- Additional tracking pass after standard tracking
- Same reconstruction strategy as primary tracking:
  - Maximum $|d_0| \to 300$ mm, $|z_0| \to 500$ mm
  - Old: optimised for high efficiency
    $\to$ large number of fakes
  - New: optimised for fake reduction
    $\to$ 10–15% reduction in efficiency, 95% reduction in fakes
  - Benchmark: signal models with secondary vertex topologies, $c\tau = 100$ mm:
    - Pair-produced neutral pseudo-scalar $a$ boson
      $\to$ hadronic displaced vertex
    - Heavy-neutral-lepton $\to$ di-lepton displaced vertex
Large radius tracking
Performance vs. production radius

**ATLAS** Simulation Preliminary \( \sqrt{s} = 13 \text{ TeV} \)

- VH, \( H \rightarrow aa \rightarrow b\bar{b}b\bar{b} \)
  - \( m_a = 55 \text{ GeV}, \ c_\tau_a = 100 \text{ mm} \)
- Standard Tracking
- Large Radius Tracking

- Technical Efficiency
- Production Radius [mm]

- W, \( W \rightarrow Nl, N \rightarrow llv \)
  - \( m_N = 15 \text{ GeV}, \ c_\tau_N = 100 \text{ mm} \)
- Combined

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Large radius tracking

Performance vs. impact parameter

**ATLAS** Simulation Preliminary $\sqrt{s} = 13$ TeV

*VH, $H\rightarrow aa\rightarrow b\bar{b}b\bar{b}$*

$m_a = 55$ GeV, $c\tau_a = 100$ mm

- **Combined**
- **Large Radius Tracking**
- **Standard Tracking**

*Technical Efficiency*

$|d_0|$ [mm] 0 50 100 150 200 250 300

$|d|$ 0 0.2 0.4 0.6 0.8 1 1.2 1.4

**ATLAS** Simulation Preliminary $\sqrt{s} = 13$ TeV

*W$\rightarrow$Nl, $N\rightarrow llv$*

$m_N = 15$ GeV, $c\tau_N = 100$ mm

- **Combined**
- **Large Radius Tracking**
- **Standard Tracking**

*Technical Efficiency*

$|d_0|$ [mm] 0 2 4 6 8 10

$|d|$ 0 0.2 0.4 0.6 0.8 1 1.2 1.4

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Large radius tracking

Performance

**ATLAS** Simulation Preliminary

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$VH, H \to aa \to b\bar{b}b\bar{b}$

$m_a = 55$ GeV, $c_{\tau a} = 100$ mm

- LLP Run 2 Reconstruction
- LLP Run 3 Reconstruction
- Non-LLP Run 2 Reconstruction
- Non-LLP Run 3 Reconstruction
- Active layers

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Conclusion

- Significant improvements over ATLAS Run 2 track reconstruction
- Factor 2–4 (pile-up dependent) reduction in processing time/event
- Retaining Run 2 reconstruction efficiency in standard tracking
- Additional ‘standard’ large radius tracking pass instead of special reconstruction for ∼ 10% raw data