Track reconstruction with the ATLAS experiment

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Certain sketches courtesy of A. Salzburger
LHC ring at CERN: 27 km circumference

So far:
- 0.9 / 2.8 / 5 / 7 / 8 / 13 TeV proton–proton collisions
- 2.8 / 5 TeV Pb–Pb collisions
- 5 TeV p–Pb collisions

SPS ring: 7 km circumference
Big Physics Questions for the LHC

• Why do particles have mass?
  • Possible answer: The Higgs boson

• Why is gravity so weak?
  • Possible answers: supersymmetric particles, extra dimensions

• What is dark matter?
  • Possible answer: the lightest supersymmetric particle

• The unexpected …
• Run-1 was the first of four expected runs for the LHC
• It was certainly very exciting, but it's still very early days for the LHC
• In Run-2, has 2x the energy (8→13 TeV) and expect ~4x the luminosity (25-100 fb⁻¹), e.g. 10x more Higgs bosons
  • Much more physics to come!
The Tracking Challenge

Up to ~5k charged particles per event
Need to reconstruct every one efficiently, precisely and quickly
The Tracking Challenge

- Typically ~15 particles per proton-proton collision at 13 TeV
- Not only one isolated interesting collision
  - high luminosity = high pile-up

\[ \langle \mu \rangle = \frac{L \cdot \sigma_{\text{inel}}}{N_{\text{bunch}} \cdot f_{\text{LHC}}} \]

|\begin{tabular}{|c|c|c|}
\hline
 & Run-1 & Run-2 & Run-3 \\
\hline
\mu & 21 & 40 & 150-200? \\
\hline
Tracks & ~280 & ~600 & ~7-10k \\
\hline
\end{tabular}|
17 reconstructed vertices
The Tracking Challenge (II)

- Need to reconstruct all those particles **efficiently** (typically >99% for non-interacting particles) and with a **low fake rate** (typically <<1%)
- CPU time scales in \( \sim \)quadrature with number of tracks or \( \mu \)
- Very challenging to obtain good performance within computing resources
  - Re-optimisation during LS1 to reduce CPU by factor of 4

Figure 3: Time per event as measured in seconds to reconstruct data events triggered by the presence of jets, missing transverse energy or tau-leptons, as a function of the number of primary vertices and the software release. The data was collected at the end of 2012 at the conclusion of LHC run-1.
Not just about charged particles

• Track reconstruction is not just about reconstructing charged particles
• Tracks are used in almost every element of reconstruction
  • Leptons
  • Primary vertices
  • Pileup removal for jets and missing energy
• Jet flavour tagging

Vertex reconstruction  Pile up removal  Jet flavour tagging
The ATLAS Detector
The ATLAS Inner Detector

- New innermost pixel layer
- 50 x 400 μm silicon pixels
- 80 μm stereo strips
- straw tubes
- 50 x 400 μm silicon pixels
- New innermost pixel layer
<table>
<thead>
<tr>
<th></th>
<th>Pixel</th>
<th>SCT</th>
<th>TRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read-out units</td>
<td>~92M</td>
<td>6.3M</td>
<td>250k</td>
</tr>
<tr>
<td>Size</td>
<td>50 x 400 (250) μm</td>
<td>80 μm pitch</td>
<td>4mm</td>
</tr>
<tr>
<td>Read-out</td>
<td>Charge</td>
<td>Digital</td>
<td>Digital +transition radiation</td>
</tr>
<tr>
<td>Layers</td>
<td>4 B, 3x2 EC</td>
<td>4 B, 9x2 EC</td>
<td>73 B, 160 EC</td>
</tr>
<tr>
<td>Hits</td>
<td>4</td>
<td>8</td>
<td>30</td>
</tr>
</tbody>
</table>
The Insertable B-layer (IBL)

IBL Insertion

<table>
<thead>
<tr>
<th></th>
<th>IBL</th>
<th>Pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius [mm]</td>
<td>33</td>
<td>51</td>
</tr>
<tr>
<td>Pitch [μm]</td>
<td>50x250</td>
<td>50x400</td>
</tr>
</tbody>
</table>

“Old” pixel detector

Pixel Test Stand
### Comparison: LHC Tracking detectors

<table>
<thead>
<tr>
<th></th>
<th>ALICE</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>R inner</td>
<td>3.9 cm</td>
<td>3.3 cm</td>
<td>4.4 cm</td>
</tr>
<tr>
<td>R outer</td>
<td>3.7 m</td>
<td>1.1 m</td>
<td>1.1 m</td>
</tr>
<tr>
<td>Length</td>
<td>5 m</td>
<td>5.4 m</td>
<td>5.8 m</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>\text{ range}$</td>
<td>0.9</td>
</tr>
<tr>
<td>B field</td>
<td>0.5 T</td>
<td>2 T</td>
<td>4 T</td>
</tr>
<tr>
<td>Total $X_0$ near $\eta=0$</td>
<td>0.08 (ITS) + 0.035 (TPC) + 0.234 (TRD)</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Power</td>
<td>6 kW (ITS)</td>
<td>70 kW</td>
<td>60 kW</td>
</tr>
<tr>
<td>$r_\phi$ resolution near outer radius</td>
<td>$\sim 800 \mu m$ TPC $\sim 500 \mu m$ TRD</td>
<td>130 $\mu m$ per TRT straw</td>
<td>35 $\mu m$ per strip layer</td>
</tr>
<tr>
<td>$p_T$ resolution at 1GeV and at 100 GeV</td>
<td>0.7% 3% (in pp)</td>
<td>1.3% 3.8%</td>
<td>0.7% 1.5%</td>
</tr>
</tbody>
</table>
Track Reconstruction

*From detector information to reconstructed charged particles*
Particles in a magnetic field

- Magnetic field bends charged particles to measure their momenta
  - in a perfect homogenous field: circle in transverse direction
  - helical track in a solenoidal field
  - transverse & longitudinal components are independent
- ATLAS field is far from homogenous
- Solve equations numerically!

\[
\frac{d^2 \mathbf{r}}{ds^2} = \frac{q}{p} \left[ \frac{d\mathbf{r}}{ds} \times \mathbf{B}(\mathbf{r}) \right]
\]

\[
\frac{d^2 x}{dz^2} = \frac{q}{p} R \left[ \frac{dx}{dz} \frac{dy}{dz} B_x - \left( 1 + \left( \frac{dx}{dz} \right)^2 \right) B_y + \frac{dy}{dz} B_z \right]
\]

\[
\frac{d^2 y}{dz^2} = \frac{q}{p} R \left[ \left( 1 + \left( \frac{dy}{dz} \right)^2 \right) B_x - \frac{dx}{dz} \frac{dy}{dz} B_y - \frac{dx}{dz} B_z \right]
\]

\[
R = \frac{ds}{dz} = \sqrt{1 + \left( \frac{dx}{dz} \right)^2 + \left( \frac{dy}{dz} \right)^2}
\]
## Particle interactions with matter

Measure particles via interactions with active and passive detector material

<table>
<thead>
<tr>
<th>Type</th>
<th>Particles</th>
<th>Fund. parameter</th>
<th>Characteristics</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Multiple Scattering</strong></td>
<td>all charged particles</td>
<td>radiation length $X_0$</td>
<td>almost gaussian average effect 0 depends $\sim 1/p$</td>
<td>deflects particles, increases measurement uncertainty</td>
</tr>
<tr>
<td><strong>Ionisation loss</strong></td>
<td>all charged particles</td>
<td>effective density $A/Z \times \rho$</td>
<td>small effect in tracker, small dependence on $p$</td>
<td>increases momentum uncertainty</td>
</tr>
<tr>
<td><strong>Bremsstrahlung</strong></td>
<td>all charged particles, dominant for e</td>
<td>radiation length $X_0$</td>
<td>highly non-gaussian, depends $\sim 1/m^2$</td>
<td>introduces measurement bias</td>
</tr>
<tr>
<td><strong>Hadronic Int.</strong></td>
<td>all hadronic particles</td>
<td>nuclear interaction length $\Lambda_0$</td>
<td>destroys particle, rather constant effect in $p$</td>
<td>main source of track reconstruction inefficiency</td>
</tr>
</tbody>
</table>
Track Parametrisation

- A trajectory of a charged particle in a magnetic field requires **five track parameters** \( q \)

\[
q = (d_0, z_0, \phi, \theta, q/p)
\]

- Uncertainties encoded in a covariance matrix

\[
C = \begin{pmatrix}
\sigma^2(d_0) & \text{cov}(d_0, z_0) & \text{cov}(d_0, \phi) & \text{cov}(d_0, \theta) & \text{cov}(d_0, q/p) \\
\cdot & \sigma^2(z_0) & \text{cov}(z_0, \phi) & \text{cov}(z_0, \theta) & \text{cov}(z_0, q/p) \\
\cdot & \cdot & \sigma^2(\phi) & \text{cov}(\phi, \theta) & \text{cov}(\phi, q/p) \\
\cdot & \cdot & \cdot & \sigma^2(\theta) & \text{cov}(\theta, q/p) \\
\cdot & \cdot & \cdot & \cdot & \sigma^2(q/p)
\end{pmatrix}
\]

- Right handed coordinate system
- Azimuthal angle, \( \phi \), measured in transverse plane in \([-\pi, +\pi]\)
- Polar angle, \( \theta \) measured from z axis in \([0, \pi]\)
- Pseudorapidity, \( \eta = -\ln (\tan \theta/2) \)
Track Reconstruction

Transition Radiation Tracker

Silicon Detectors

Nominal Interaction Point

Space point formation

Seed finding

Track finding

Ambiguity Solving

TRT Extension
Space point formation

• Create space points from detector information
  • 3D locations
• Adjacent silicon cells form a cluster*

Stereo angle to improve precision of strip system

*We actually do something smarter, but I’ll come back to this later
Seeding and Track Finding

• Seeds are combinations of three space points
• Filtered to reduce duplicates
• Extend seed following most likely path: reject unlikely candidates as early as possible
• Multiple paths if possible, apply Kalman filter
• Typically 20k seeds → 2k track candidates → 1k tracks
Ambiguity Solving

• Strategy: Obtain high efficiency by applying loose requirements during reconstruction and find the best candidates by ambiguity solving

• Precise least-square fit to estimate track parameters

• Select best silicon-only tracks using a scoring function
  • hit content
  • holes
  • shared hits
  • fit quality

![Graph showing track score vs. transverse momentum](image1)

![Graph showing number of track candidates vs. eta](image2)

ATLAS Preliminary
\( \sqrt{s} = 7 \text{ TeV} \)
\( p_T > 500 \text{ MeV} \)
TRT Extension

- Final step is to extend silicon tracks into the TRT
- Increased track length improves momentum measurement
- Typically ~90% efficiency within TRT acceptance
- Track fit to estimate the final track parameters
Track Reconstruction

**Inside-out**
- Space point formation
- Seed finding
- Track candidates (Combinatorial Kalman Filter)
- Ambiguity Solving
- TRT Extension

**Outside-in**
- TRT Segment Finder
- Track candidates (Combinatorial Kalman Filter)
- Ambiguity Solving

**Special Algorithms**
- Pixel Tracklets
- Large impact parameter tracks
- Electron tracking
Tracking Performance
Track reconstruction efficiency

\[
\text{Track Reconstruction Efficiency} \approx 91\% \quad \text{at } |\eta| = 0
\]

no drop in efficiency with pile up
Inner Detector Material

Dominant component in the uncertainty on the tracking efficiency is material: detailed studies of the ID material

Three complimentary methods to x-ray the detector
Material mapping with interactions

- x-ray the material in the detector by reconstructing position of interactions
- Photon conversions: proportional to $\lambda_0$
- Hadronic interactions: proportional to $X_0$, high resolution
- Used during run-1 to obtain 5-15% uncertainty on material budget
Run-2 Material Results

**Hadronic Interactions**

- **ATLAS** Preliminary
- $\sqrt{s} = 13$ TeV
- $|\eta| < 2.4$
- Data 2015

**Conversions**

- **ATLAS** Preliminary
- $\sqrt{s} = 13$ TeV, $|\eta| < 2.4$
- Data 2015
- Pythia8 Simulation (Updated Geometry)
- Pythia8 Simulation (Default Geometry)

**SCT Extension**

- **ATLAS** Preliminary
- $\sqrt{s} = 13$ TeV
- Data 2015
- Pythia8 Simulation (Updated Geometry)
- EPOS Simulation (Updated Geometry)
Fake rate

- Fake rate negligible < 0.1% at $\mu = 0$
- Fake rate increases with pile up
- Can be controlled with tighter cuts (and slight efficiency loss)
- Estimate fake rate in data from non-linearity in tracks vs $\mu$
  - +5% for $\mu = 25$
  - ~50% data/MC agreement
Track Parameter Resolution

\[(d_0, z_0, \theta, \phi, q/p)\]

- Momentum resolution from known resonances, e.g. J/ψ, K_{s}_0
- Impact parameter resolution from prompt tracks

\[\text{Candidates} / 2 \text{ MeV} \]
\[\text{Candidates} / \text{20 GeV} \]

**Multiple scattering**

**Intrinsic resolution**
alignment

\[\begin{array}{c}
\text{Data 2012, } \sqrt{s} = 8 \text{ TeV} \\
\text{Data 2015, } \sqrt{s} = 13 \text{ TeV}
\end{array} \]
Alignment

- Determine positions of active detector elements using tracks
- Minimise $\chi^2$ of track residuals
  \[ \chi^2 = \sum_{\text{hits}} \left( \frac{m_i - h_i(\vec{\alpha})}{\sigma_i} \right)^2 \]
- Iterative procedures moving from large structures (e.g. barrel) to smaller structures (e.g. modules)
- Additional constraints, e.g. resonances to control weak modes
• During commissioning, IBL staves found to bow depending on temperature: 10μm/K

\[ f(z) = B - M \left( \frac{z^2 - z_0^2}{z^2} \right) \]
• During commissioning, IBL staves found to bow depending on temperature: 10µm/K

• At higher beam intensity, increasing leakage currents developed in IBL modules, inducing temperature variations

• Huge effort to develop time-dependent alignment
IBL Alignment

- During commissioning, IBL staves found to bow depending on temperature: 10μm/K
- At higher beam intensity, increasing leakage currents developed in IBL modules, inducing temperature variations
- Huge effort to develop time-dependent alignment
  - No significant impact on physics performance
Tracks in jets I

- In the IBL TDR, tracking improved, but b-tagging degraded, particularly at high $p_T$ (up to 3.5x)

- Largely due to merged clusters from collimated tracks in high $p_T$ jet cores
  - Accentuated with the IBL due to smaller radius

- Introduced neural networks to use 2D cluster charge distribution to identify and split merged clusters
  - Split 70% of 2-particle clusters, 10% of 1-particle clusters
  - Improved single particle resolution, e.g. for $\delta$-rays

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![Diagram showing improved resolution and b-tagging](image-url)
Tracks in jets II

- Track reconstruction updated to further exploit NN clustering for Run-2
- **Defer** NN clustering to later in track reconstruction (ambiguity solving)
  - Combine with **track information** to improve performance
- **Correlate** the NN information between layers
- Improved **track reconstruction efficiency** in the core of jets
- **Measured performance** of NN clustering in **data**
From Tracking to Physics

Selected Examples
Vertex Reconstruction

Identify location and position of proton-proton interactions

100% efficiency for \( \geq 4 \) tracks

Typical resolution: 10-40\( \mu \text{m} \) (x,y), 30-50 \( \mu \text{m} \) (z)

pile up \( \rightarrow \) merging impacts the efficiency
• ~2/3 of the energy in a jet is carried by charged particles
• Tracks are used extensively to identify jets from pile up interactions and to correct for the impact of pile up jets
  • Jet Vertex Tagger (JVT): ~90% efficiency, ~1% fake rate
• Tracks used to mitigate the impact of pile up on missing energy
Tracking and flavour tagging

- Tracks are used in flavour tagging to identify and measure the location of displaced vertices from heavy-flavour decays
- Large improvement for run-2
  - Mostly from improvement in track parameter resolution from IBL
Electron reconstruction for $H \rightarrow ZZ$

- Track reconstruction adapted to account for electron energy loss

- Pattern Recognition Changes
  - Track candidates can “lose” energy (up to 30%) when looking for hits on the next layer

- Ambiguity Resolution and TRT extension
  - Rejected track candidates are refitted with electron hypothesis

- Electron efficiency gain for $H \rightarrow 4e$: ~ 8% average up to 15% at $p_T \sim 7$ GeV

- +60% acceptance x efficiency gain for $H \rightarrow 4e$
Charged particle multiplicity

- The charged particle multiplicity is typically the first measurement at a hadron collider
- Poorly understood theoretically: parameters need tuning
- Improve modelling of pile up
- Dominated by the uncertainty on the track reconstruction efficiency
Minimum Bias Results

- Good prediction of total multiplicity
- Reasonable agreement from Pythia and EPOS
  - Difficulties in phase space extrema
Track jets in boosted topologies

- Searches for high mass objects use large radius jets to maintain acceptance at low dR
- Early Run-2 search for $X \rightarrow ZH(bb)$
- Large R jet ($R = 1.0$) used to search for the Higgs candidate, need track jets for b-tagging
- No excess observed, set limits on $Z'$ mass
- More data needed to be sensitive to $A \rightarrow ZH$
In anomaly-mediated supersymmetry breaking (AMSB) models, lightest chargino is nearly mass-degenerate with the lightest neutralino.

- Decays to neutralino and a soft pions
- Lifetime is long enough to produce a track with no hits in the outer regions
- Custom track reconstruction algorithm developed for short tracks

SUSY: Disappearing tracks

\[ m_\chi \sim \begin{cases} 100 & \text{ns} \\ 150 & \text{ns} \\ 200 & \text{ns} \\ 250 & \text{ns} \\ 300 & \text{ns} \\ 350 & \text{ns} \\ 400 & \text{ns} \\ 450 & \text{ns} \\ 500 & \text{ns} \\ 550 & \text{ns} \\ 600 & \text{ns} \end{cases} \]
The Future: HL-LHC
Tracking for High Pileup

Markus Elsing

Seminar at University Wuppertal, July 3rd, 2014

ATLAS HL-LHC event in new tracker

- overview
- processor landscape
- ARMs to GPGPUs
- i/o
- goldilocks no more
- golden rules
- tools for the future
- projects and ideas for tracking

Typical HL-LHC event
Potential Performance

- Tracking results from the recent scoping exercise
- Compared the performance of three candidate layouts with different costs
- ~90% efficiency and << 1% fake rate with the reference layout
  - Despite pile up of ~200!
- Very promising despite untuned layouts and tracking
ITK Layout Concepts

Extended

Inclined
Conclusion

• Track reconstruction at the LHC is a challenging task
  • Requires extremely high performance and efficient resource usage
  • Sophisticated algorithms have been developed to meet the demands of the LHC environment
• Tracks are used in almost every aspect of reconstruction and directly or indirectly in almost every physics analysis
• Innovation in the tracking domain can have a direct impact on physics analyses
• HL-LHC will provide new challenges and a fascinating playground for developing further tracking algorithms
Back up