ATLAS Track and Vertex Reconstruction for Run-3 and High-Luminosity LHC

by Markus Elsing on behalf of the ATLAS Collaboration
Experience from Run-2 and Outlook

- **current ATLAS Inner Detector**
  - 4 Pixel layers, 4 double sided Strips, Transition Radiation Tracker
  - was upgraded in Long Shutdown-1 with 4th Pixel layer (IBL)
  - designed for excellent performance at pile-up of 23
  - during Run-2 operated routinely at pile-up well above 35

- preserving performance is a challenge!
  - tracking and vertexing needs to be robust against pile-up
  - CPU required for reconstruction increases rapidly with pile-up!

- **large radius tracking**
  - searches for long-lived particles!
  - significant CPU for additional tracking pass
  - not possible in Tier-0 during Run-2
  - required dedicated stream, processed on the Grid

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ATLAS Preliminary Run 2 data reconstruction Run 6291

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<th>Runtime (a.u.)</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
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<td>95</td>
<td></td>
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- **unconventional tracking topologies**
  - displaced multi-track vertices in ID + MET, jets, leptons
  - disappearing tracks
  - non-prompt photons
  - displaced leptons, lepton jets, or lepton pairs
  - emerging jets
  - trackless jets with low EMfrac
  - displaced multi-track vertices in Muon Spectrometer

- **Ambiguity resolution**
  - Track finder
  - Miscellaneous

Credit: Heather Russell
Outlook to Run-3 and HL-LHC

- **Run-3 expected av. pile-up is ~50**
  - double total integrated luminosity until 2025
  - end-of-lifetime of current Inner Detector

- **goal of LH-LHC is to collect 4 ab^{-1}**
  - average pile-up will rise to 140 to 200!
  - radiation levels and data rates unprecedented
  - ATLAS Inner Tracker (ITk) upgrade (all silicon)

- **a challenge !**
  - require excellent tracking performance, despite harsh pile-up environment
  - CPU for reconstruction and disk space needs will exceed computing budget extrapolations
  - computing technology becoming heterogenous, with many core CPUs and accelerators (GPU, FPGA)

- **tracking developments for Run-3 are also a preparation towards HL-LHC**
Run-2(3) Tracking and Vertexing Chain

pre-processing
- Pixel+SCT clustering
- TRT drift circle formation
- space points formation
Run-2(3) Tracking and Vertexing Chain

- **pre-processing**
  - Pixel+SCT clustering
  - TRT drift circle formation
  - space points formation

- **combinatorial track finder**
  - iterative:
    1. Pixel seeds
    2. Pixel+SCT seeds
    3. SCT seeds
  - restricted to roads
  - Brem.recovery in EM Regions-of-Interest

- **ambiguity solution**
  - runs hole search
  - scores tracks according to quality
  - NN cluster splitting in jets
  - precise least square fit with Brem.recovery
  - final selection cuts

- **extension into TRT**
  - progressive finder
  - refit of track with Brem.
  - scoring and selection cuts
Run-2(3) Tracking and Vertexing Chain

**Pre-processing**
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**Combinatorial Track Finder**
- Iterative:
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**Ambiguity Solution**
- Precise fit and selection
- TRT seeded tracks

**TRT Seeded Finder**
- From TRT into SCT+Pixels
- Combinatorial finder

**TRT Segment Finder**
- In EM Regions-of-Interest
- On remaining drift circles
- Uses Hough transform

**Extension into TRT**
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- Runs hole search
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**Tracklet Finder**
- Muon candidates \(|\eta| > 2.5\)
- Short tracks

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Run-2(3) Tracking and Vertexing Chain

vertexing
- primary vertexing
- conversion and V0 search

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**Ambiguity Solution**
- precise fit and selection
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**TRT Seeded Finder**
- from TRT into SCT+Pixels
- combinatorial finder

**Large Radius Tracking (LRT)**
- as a additional iteration
  - combinatorial track finder, ambiguity solution, extension, secondary vertexing
  - different track selection strategy adopted to event topology

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Optimisation of Run-3 Tracking Software

- intensive development programme
  - software technology changed to multi-threading
  - optimisation of primary tracking:
    - stricter cuts: at least 8 hits and $|d_0| < 5$ mm
    - Back-Tracking and TRT optimised and seeded using EM calorimeter deposits with $E_T > 6$ GeV
    - seeding and pattern recognition tuning: stricter cuts, narrower roads, seed confirmation
    - novel primary vertex finder (first time using ACTS*)
  - apply optimisations also to Large Radius Tracking (LRT)

- $\times 4$ speedup for tracking at 90 pile-up
  - include faster LRT in Tier-0 reconstruction (all events)
    - huge simplification in computing model and reduction in storage
    - exiting prospects for searches!
  - Run-3 reconstruction overall $\times 2$ faster and improved selection reduces event size by 25%

* I'll come to ACTS later
Optimisation of Run-3 Tracking Software

- **effect on tracking performance**
  - CPU improvements largely due to early rejection of fakes and secondaries
  - Efficiency loss varies from 1% (4%) at high-(low-)p_T
    - N(hit) ≥ 8 for Run-3, compared to N(hit)≥7 for Run-2
  - Much more linear increase in number of tracks vs pile-up indicates improved pile-up robustness

- **primary tracking + LRT still >50% CPU**
New Run-3 Primary Vertex Reconstruction

- **change in vertex finding algorithm:**
  - Run-2: Iterative Primary Vertex Finder (IVF)
  - Run-3: Adaptive Multi-Vertex Finder (AMVF)

- **AMVF reconstruction strategy:**
  - novel gaussian track density vertex seed finder
  - tracks are associated to vertex candidates with weights according to their distance
  - vertex candidates share tracks and are fitted simultaneously

- **much improved pile-up performance:**
  - improved separation of nearby vertices along z
  - better efficiency for $t\bar{t}$ and VBF $H \rightarrow 4\nu$
  - 20% (10%) better resolution for $t\bar{t}$ (VBF $H \rightarrow 4\nu$)

- **AMVF implemented in ACTS* framework**
  - modern software yields 40% speedup in CPU!

* I'll come to ACTS later

Markus Elsing
The ATLAS HL-LHC Tracker (ITk) Upgrade

ATLAS Simulation Preliminary

ITk Layout: 23-00-03

η = 1.0

η = 2.0

η = 3.0

η = 4.0

Strip barrel

outer Pixel barrel

inner Pixels

Strip end-caps

outer Pixel end-caps
The ATLAS HL-LHC Tracker (ITk) Upgrade

- designed for fast precision tracking
  - 5 Pixel layers, 4 Strip layers (double-sided)
    - extends $|\eta|$ coverage from 2.5 to 4.0
    - improved granularity and hit redundancy
    - aims to minimise material in active tracking region
  - 5 layer ITk Pixel Detector with ring design:
    - efficient standalone seed finding in Pixels at all $\eta$
  - flexible Pixel ring placement:
    - keeps hit coverage constant in forward region
    - avoid large gaps between adjacent rings

- default ITk track reconstruction:
  - no TRT, hence simplified tracking chain
  - seed finding only in Pixels or in Strips, followed by track finder and ambiguity solution
  - significant speed-up of reconstruction at 200 pile-up, with excellent performance
ITk Tracking Performance (Default Tracking)

- high-purity track selection
  - raise N(hit) cut from 7 (Run-2) to 9 to further reduce fakes
- excellent tracking efficiency and fakes
  - pion efficiency limited by hadronic interactions in detector ITk material
  - excellent linearity in number of tracks vs pile-up, up to the highest pile-up

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ATLAS Simulation Preliminary
ITk layout: 23-00-03
\( p_T > 1 \text{ GeV} \)

- Run 2 \( |\eta| < 2.4, \langle \mu \rangle = 38 \)
- ITk \( |\eta| < 2.4, \langle \mu \rangle = 200 \)
- ITk \( |\eta| < 4.0, \langle \mu \rangle = 200 \)

Efficiency vs Number of tracks vs pile-up

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Efficiency vs Truth \( \eta \)

- \( p_T = 10 \text{ GeV} \)
- Single \( \mu \)
- Single \( e \)
- Single \( \pi \)

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Efficiency vs Truth \( \eta \)

- Run-2, \( \langle \mu \rangle = 38 \)
- ITk, \( \langle \mu \rangle = 200 \)

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Tracking efficiency (hadrons)

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ATL-PHYS-PUB-2021-024
**ITk Tracking Performance (Default Tracking)**

- **much better impact parameter resolution**
  - in particular at high-\(p_T\) (less affected by multiple scattering)
  - Pixel pitch: 25x100 \(\mu\text{m}^2\) (layer-0 barrel), 50x50 \(\mu\text{m}^2\) (elsewhere)

- **results in improved performance for physics**
  - primary vertex reconstruction
  - b-tagging
  - pile-up jet rejection
  - ...

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**ATLAS Simulation Preliminary**
\(\sqrt{s} = 14\text{ TeV}, \langle p_T \rangle > 1 \text{ GeV}\)
ITk layout: 23-00-03

Primary vertex reconstruction*
- AMVF
- IVF

* Run-2 reference is still IVF, ITk uses AMVF with an alternative vertex seed finder
Fast ITk Track Reconstruction Prototype

- **fast ITK tracking strategy**
  - drop Strip seeding iteration, rely on 5 layer Pixel seeding (!)
  - drop Ambiguity Solution, move functionality to Track Finding:
    - use Kalman Filter as final fit
    - precise cluster corrections
    - material model (approximate)
    - final track selection
    - duplicate removal (approximate)

- **excellent CPU results (8x faster)**
  - at cost of some performance
  - CPU for tracking not dominating in event reconstruction anymore
  - QCD generators and Geant4 dominate in total ATLAS CPU budget for HL-LHC (!)

- **new detector**
  - optimise tracking
  - require new detector

**CPU needs**
- ID Run-2 Reconstruction
- Default ITk Reconstruction
- Fast Track Reconstruction (ITk)

**ATLAS Simulation Preliminary**
- ITk Layout, tt events
- CPU needs

**Run-2**
- ATk
- ITk
- FullSim

**EvGen**

**ATLAS Preliminary**

2020 Computing Model - CPU: 2030: Conservative R&D

**Markus Elsing**

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**Notes:**

- CPU needs
- New detector
- ITk Layout, tt events
- Fast Track Reconstruction (ITk)
- Optimization of tracking
- Event reconstruction
- Material model
- Final track selection
- CPU results (8x faster)
- QCD generators and Geant4 dominate

**Graphs and Data:**

- CPU budget breakdown
- Simulation types
- Fast Track Reconstruction
- ITk Layout
- Run-2

**Markus Elsing**

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Performance of Fast ITk Reconstruction

● prototype yields excellent results, despite approximations to achieve CPU savings
  ➡ some efficiency loss in barrel, transition and forward region
  ➡ no large rate of additional (fake) tracks
  ➡ resolutions mostly as default reconstruction, with some exceptions due to approximations in Kalman Filter

● performance of fast ITk reconstruction already satisfies trigger requirements
  ➡ relevant for Event Filter reconstruction, possible alternative to hardware based tracking at Point-1
ACTS Tracking Software Project

- **ACTS (A Common Tracking Software)**
  - Open source project, initially started by ATLAS in view of HL-LHC
  - Number of experiments contributing and used as platform for R&D
    - sPHENIX, Belle-II, FASER, LHCb, CEPC, FCC, ...
    - Tracking Machine Learning (TrackingML) challenge
    - Open Data Detector (ODD) allows for generic tracking R&D

- **Tracking suite for ATLAS Phase-2 software**
  - Designed ground-up for multi-threading
  - Modern data model and code design
  - Support for heterogeneous architectures (CPU, GPU, ...)
  - Run-3 primary vertexing first deployment of ACTS code

- **Much improved technical performance (CPU)**
  - Use fast ACTS (Combinatorial) Kalman Filter to implement a fast ITk reconstruction without approximations
  - Goal is to fully recover physics performance without losing excellent CPU results of current prototype
Summary and Conclusions

● tracking and vertexing software is well prepared for Run-3
  ➔ based on Run-2 experience, significant improvements have been implemented
    • technical migration to multi-threading
    • reconstruction time reduced by more than a factor ×2
    • large radius tracking will be integrated into prompt reconstruction at Tier-0
    • new Adaptive Multi Vertex Finder deployed (ACTS based)

● tracking software preparation for HL-LHC is advancing well
  ➔ the ITk upgrade, together with optimised tracking software, will allow to improve on Run-2(3) tracking performance, even in presence of 200 pile-up
  ➔ fully functional fast ITk reconstruction cuts down CPU time for tracking by factor ×8, a game-changer for ATLAS Phase-2 offline computing and for trigger processing
  ➔ ATLAS is investing strongly into the ACTS open source tracking software project to modernise its tracking software for the HL-LHC