Track Reconstruction in the ATLAS Detector: Combinatorial Kalman Filter and Run 3 Performance

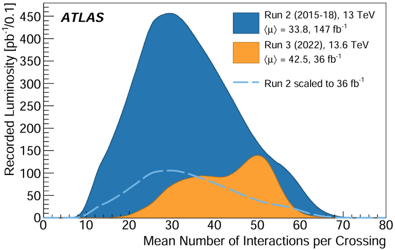
Group 8

May 28, 2026

Outlook

Motivation

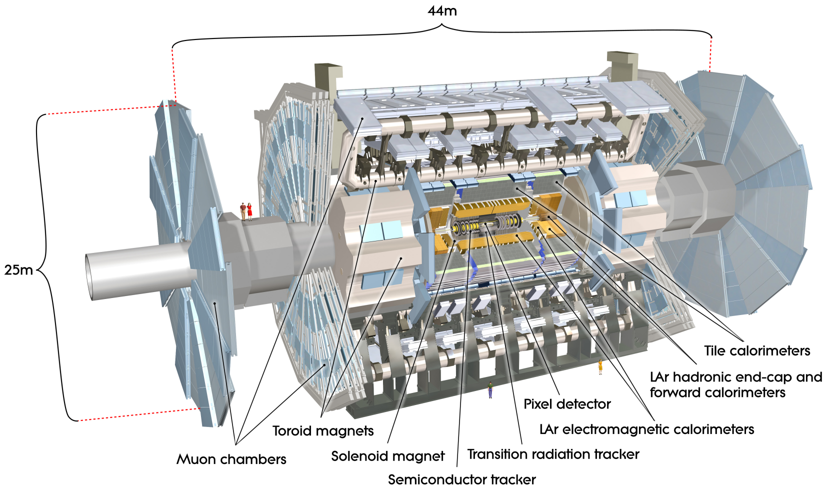
- With the increasing luminosities at the LHC Run 3 and HL-LHC, the requirements of a faster and more robust track reconstruction become critical.
- During LHC Run 3, events with an average of 50 or more simultaneous *pp* interactions per bunch crossing (pile-up) represents a challenging task for the ATLAS experiment's reconstruction software due to the combinatorial complexity. [2]
- To address this, the ATLAS collaboration introduced major software improvements. By re-tuning and re-optimizing every step of the inner detector track reconstruction, the processing time was reduced to **twice as fast** as the previous version without significant loss in efficiency, and the rate of combinatorial fake tracks was reduced by **more than a factor two**. [2]



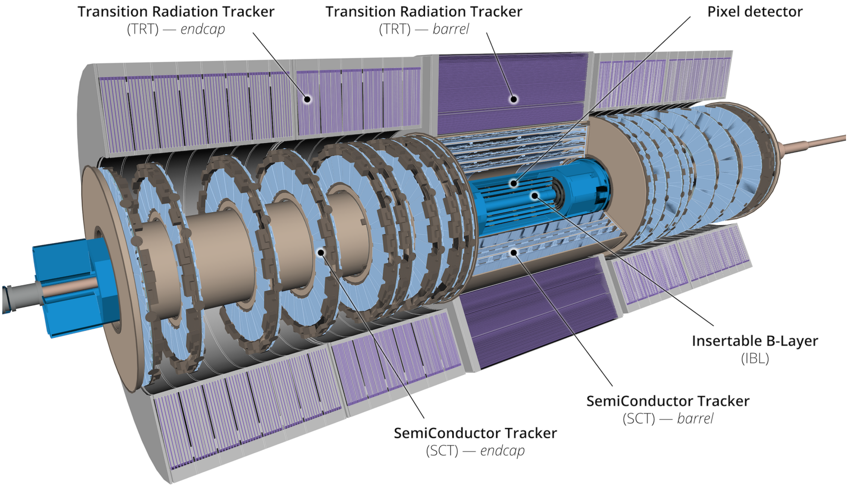
The Next Frontier: The High-Luminosity LHC (HL-LHC)

- Looking ahead, the HL-LHC will push instantaneous luminosity even further, increasing the number of simultaneous proton-proton interactions per bunch crossing to **up to 200**. [1]
- This ultra-dense environment will far exceed the capabilities of the current ATLAS Inner Detector (ID).
- As a solution:
  - A new all-silicon **Inner Tracker (ITk)** will replace the current ID. It is designed to maintain high tracking performance and meet the challenges of unprecedented radiation levels and occupancy. [1]
  - Add the **High Granularity Timing Detector (HGTD)** to distinguish pileup vertices in time
  - Explore **ML-based track reconstruction** (GNN, Transformer) for GPU acceleration
  - The CKF may remain as the baseline algorithm, but it will be heavily optimized and may run on GPUs in the future.

The ATLAS Detector

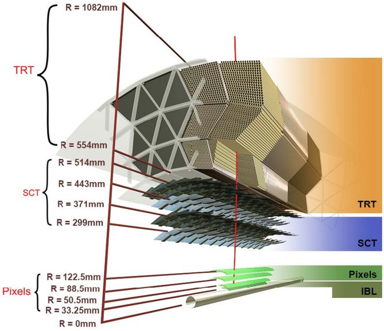


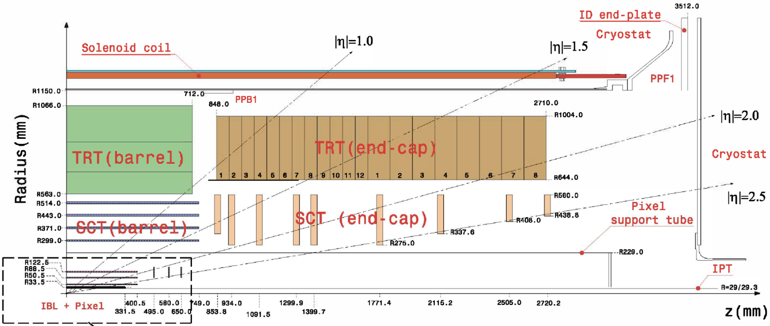
The Inner Detector

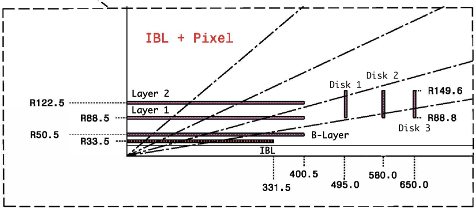


The Inner Detector (ID) is the primary tracking device for measuring the paths of all charged particles in ATLAS [3, 4]. The ID system is immersed in a $2T$ axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$. It is composed of three sub-detectors (from inside to outside): [**article1**]

1. High-granularity silicon Pixel Detector: Covers the vertex region and typically provides **four** measurements per track, the first hit normally being in the Insertable B-Layer (IBL).
2. Semiconductor Tracker (SCT): A silicon microstrip tracker that usually provides **eight** measurements per track.
3. Transition Radiation Tracker (TRT): Comprises several layers of gas-filled straw tubes interleaved with transition radiation material, giving ~ 36 hits. The TRT provides electron identification capability through the detection of transition radiation X-ray photons.



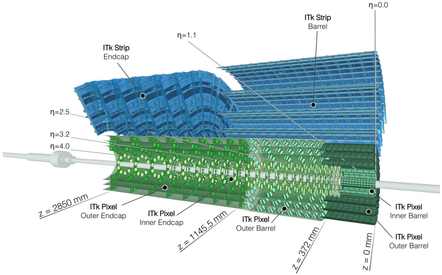


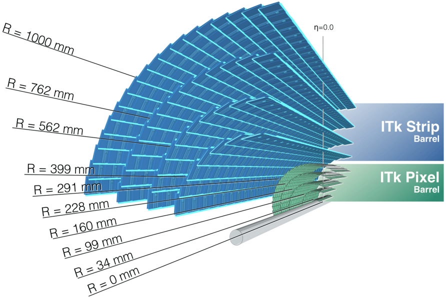


Detector envelopes (mm)

IBL	31<R<40
Pixel	42.5<R<242
SCT barrel	255<R<549
SCT end-cap	251<R<610
TRT barrel	554<R<1082
TRT end-cap	617<R<1106

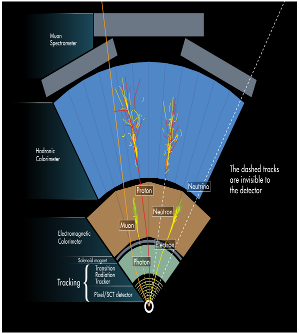
- Will be installed as a part of its Phase-II detector upgrade program in preparation for HL-LHC data-taking.





Object Reconstruction

- A reconstructed track and a cluster in one of the two calorimeters that matches the track energy and direction indicates the kind of charged particle that made the track ($e^{\pm}$, long-living charged hadrons like protons).
- A cluster without an associated track indicates a neutral particle (photon, long-living neutral hadrons like pions and neutrons)
- Muons have minimal interaction with the calorimeters, but do leave a track in both the ID and Muon Spectrometer (MS) system.
- Particle that escape the detector entirely, such as neutrinos or some BSM particles, could be seen as imbalance in the transverse momentum refereed to as Missing Transverse Energy (MET).



Combinatorial Kalman Filter (CKF) vs Standard KF

Limitation of the Standard Kalman Filter

The standard Kalman Filter (KF) is optimal for sequential estimation **but** it picks only the *closest* hit at each step. In high pileup environments, the closest hit is often the *wrong* hit.

Key Difference

The CKF generates **multiple candidate tracks** for each starting seed by branching at every detector layer.

Feature	**Standard KF**	**CKF**
Hit selection	Single closest hit	All hits within 3σ road
Candidate tracks	One path	Many parallel candidates
Decision type	Greedy / local	Combinatorial search
Best for	Low occupancy	High multiplicity

CKF

The CKF is the **primary tracking algorithm** used in ATLAS for both Run 2 and Run 3.

The Five-Step Track Reconstruction Chain

1. **Clustering**: Raw detector signals $\rightarrow$ 3D space points.
2. **Seed finding**: Triplet of hits (typically from pixel layers) $\rightarrow$ initial track candidate (curvature, direction).
3. **Track finding** (CKF): Extend seeds outward, branching at each layer.
4. **Ambiguity solving**: Remove duplicate / fake tracks via a score-based selection.
5. **Track fitting**: Final Kalman filter + smoother for optimal parameter estimation.

Why this order?

Each step reduces the combinatorial complexity before passing to the next. Seeds drastically cut down the number of starting points; CKF keeps possibilities open; ambiguity solving cleans the result.

Step 2 – Seed Finding

What is a seed?

A combination of **three space points** (usually from three pixel layers) plus a fast circle fit to estimate p_T and direction.

The pointing requirement

Tracks from the primary vertex have small impact parameter d_0 (distance of closest approach to the beam line). ATLAS imposes strict pointing cuts – tracks must point back to the interaction region.

Example

If seeds are of poor quality, the CKF will undergo *combinatorial explosion*. Therefore, high-quality seeding is crucial.

Step 3 – CKF Algorithm Details

Track parameter state vector (5 parameters)

$$\vec{p} = (d_0,\ z_0,\ \phi,\ \theta,\ q/p)$$

- d_0: signed impact parameter (perigee)
- z_0: z-coordinate at closest approach
- ϕ: azimuthal angle
- θ: polar angle
- q/p: charge over momentum

Prediction and Filtering (for each candidate hit)

Prediction:

$$\tilde{q}_{k|k-1} = F_{k|k-1}\tilde{q}_{k-1} + d_k, \qquad C_{k|k-1} = F_{k|k-1}C_{k-1}F^T_{k|k-1} + Q_k$$

Filter update:

$$\tilde{q}_k = \tilde{q}_{k|k-1} + K_k[m_k - H_k\tilde{q}_{k|k-1}]$$
$$K_k = C_{k|k-1}H_k^T(V_k + H_kC_{k|k-1}H_k^T)^{-1}$$

Step 4 – Ambiguity Solving

Why is it necessary?

CKF produces many overlapping candidate tracks that share hits. We must select the **best set of non-overlapping tracks** that explain the event.

ATLAS ambiguity solver (greedy)

1. Score each track: score $= f(\chi^2/\text{ndof}, \text{ number of hits}, \text{ shared hit penalties})$
2. Sort candidates by score (best first)
3. Accept the highest-scoring track
4. Remove all hits assigned to that track
5. Repeat until no tracks remain

Remark

This is a **local optimization** – very fast, though not guaranteed globally optimal.

New in Run 3: Large-Radius Tracking (LRT)

Motivation

Long-lived particles (LLPs) decay far from the interaction point. Traditional tracking imposes $d_0 \approx 0$, so LLP decay products were rejected [5].

What LRT does

- Loosens the pointing requirement (allows larger d_0)
- Uses hits not assigned to primary tracks
- In Run 2: LRT caused many fake tracks $\rightarrow$ run only on subsets
- In Run 3: **LRT runs in all events**, greatly expanding LLP search phase space

Remark

LRT increases CPU consumption by $\sim 10-20\%$ when run for all events, but the physics gain is substantial.

Expected Performance

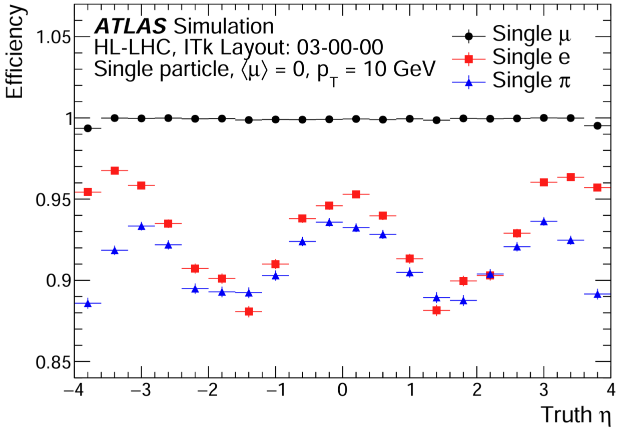
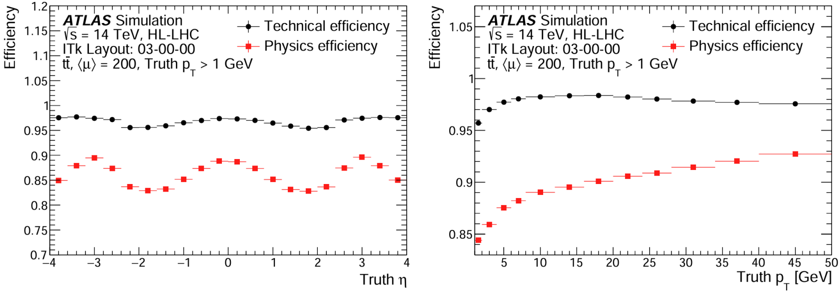


Figure 14: Expected physics tracking efficiency for single muons, electrons and pions with p_{T} = 10 GeV without pile-up.



(a) (b)

Figure 16: Comparison between the expected technical and physics tracking efficiencies as a function of (a) η and (b) p_{T} in $t\bar{t}$ events at $\langle\mu\rangle = 200$ for hard-scatter particles with $p_{\mathrm{T}} > 1$ GeV with the ITk detector.

Expected Performance

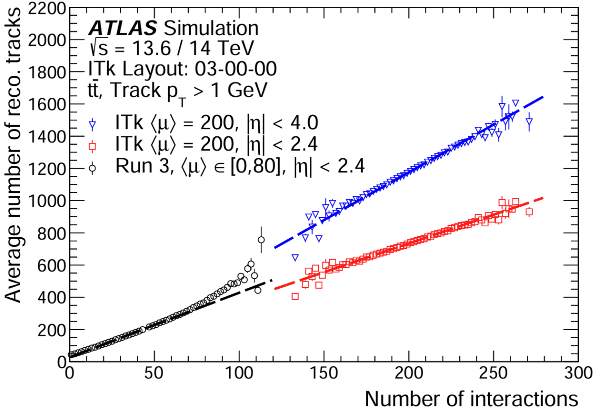


Figure 20: Number of reconstructed tracks per event with $p_T > 1$ GeV as a function of the number of interactions for $t\bar{t}$ events at $\langle\mu\rangle = 200$ with the ITk detector compared with the Run 3 detector, in conditions with a uniform $\langle\mu\rangle$ distribution between 0 and 80. The dashed lines illustrate the results of linear fits performed over the limited range corresponding to $\langle\mu\rangle$ between 120 and 280 for the ITk and between 20 and 60 (extrapolated to 0–120) for the Run 3 detector to illustrate the pile-up dependence of this quantity.

Summary

Run 3 Achievements

- Track reconstruction **twice as fast** as previous version
- Fake track rate reduced by $>$ **factor 2**
- Large-Radius Tracking (LRT) now runs in **all events**, enabling long-lived particle searches

Challenges Ahead – HL-LHC

- Pile-up up to $\langle \mu \rangle = 200$ far exceeds current ID capabilities
- New **all-silicon ITk** + **HGTD** will maintain performance
- CKF remains baseline, but may be GPU-accelerated

Example

Key Takeaway The Combinatorial Kalman Filter is the heart of ATLAS tracking. Through continuous optimisation, it has delivered dramatic speed gains in Run 3, and with the ITk upgrade, it will power ATLAS through the HL-LHC era.

References

[1] G. Aad et al. "Expected tracking performance of the ATLAS Inner Tracker at the High-Luminosity LHC". In: *Journal of Instrumentation* 20.02 (Feb. 2025), P02018. ISSN: 1748-0221. DOI: 10.1088/1748-0221/20/02/p02018.

[2] G. Aad et al. "Software Performance of the ATLAS Track Reconstruction for LHC Run 3". In: *Computing and Software for Big Science* 8.1 (Apr. 2024). ISSN: 2510-2044. DOI: 10.1007/s41781-023-00111-y.

[3] G. Aad et al. "The ATLAS Experiment at the CERN Large Hadron Collider". In: *Journal of Instrumentation* 3.08 (Aug. 2008), S08003. DOI: 10.1088/1748-0221/3/08/S08003.

[4] G. Aad et al. "The ATLAS experiment at the CERN Large Hadron Collider: a description of the detector configuration for Run 3". In: *Journal of Instrumentation* 19.05 (Mar. 2024), P05063. DOI: 10.1088/1748-0221/19/05/P05063.

[5] ATLAS Collaboration. "Performance of the reconstruction of large impact parameter tracks in the inner detector of ATLAS". In: *Eur. Phys. J. C* 83 (2023), p. 1081. DOI: 10.1140/epjc/s10052-023-12024-6. arXiv: 2304.12867 [hep-ex].


thank you