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The ATLAS inner detector trigger performance in Run 3

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The performance of the inner detector (ID) tracking trigger of the ATLAS experiment at the Large Hadron Collider (LHC) is presented, evaluated using early Run 3 data. Included are results from the evolved standard trigger track reconstruction, and from new unconventional tracking strategies used for the first time in the Run 3 trigger. The application of ID tracking in the Run 3 trigger is significantly expanded, in particular full-detector tracking is utilized for hadronic signatures such as jets and missing transverse energy triggers, for the first time. To meet computing resource limitations, new features have been developed. These include machine-learning additions for the track seeding, together with many additional improvements with respect to the trigger tracking used in LHC Run 2. As the world's highest-energy particle accelerator, the LHC provides a unique opportunity for directly searching for new physics beyond the Standard Model. Massive long-lived particles (LLPs), which are absent in the Standard Model are present in many well-motivated theories of beyond-the-Standard-Model physics. These new massive LLPs can decay into other particles far from the LHC interaction region, resulting in novel experimental signatures and so require new complex techniques for their identification. Prior to Run 3, the ATLAS trigger did not include dedicated tracking triggers for the explicit identification of massive LLPs decaying in the inner tracking detectors. To enhance the sensitivity of such searches, a series of new triggers were developed for the Run 3 data taking in 2022. These included various novel unconventional tracking signatures, such as those for displaced tracks, displaced jets, or short tracks which disappear within the ID tracking volume. With these developments, the high performance of the ID trigger remains essential for the ATLAS physics programme in Run 3, both for precision measurements of the Standard Model and now also searches for new physics beyond the Standard Model.

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1. Introduction

The trigger system [1] is an essential component of the ATLAS experiment [2, 3] at the Large Hadron Collider (LHC), as it decides which events are recorded for analysis. It has operated efficiently since the start of LHC Run 3 in 2022, at a centre-of-mass energy of up to $\sqrt{s} = 13.6$ TeV and up to a mean of 60 pile-up interactions per bunch crossing. Track reconstruction using hits from the inner detector (ID) is vital to the trigger performance. This document summarizes some of the many improvements that were made to handle the increased luminosity and pile-up in Run 3 with limited computing resources, the resulting ID trigger performance in proton-proton collisions in 2022, and some improvements under consideration for the remainder of Run 3. In addition, a number of new, unconventional tracking signatures are discussed.

2. The ATLAS inner detector and trigger system

The ATLAS ID provides charged-particle track reconstruction within the pseudorapidity range $|\eta| < 2.5$. It is immersed in a 2 T axial magnetic field and consists of a silicon pixel detector with four layers in the barrel region and three in each endcap, a silicon microstrip (SCT) detector with four layers in the barrel region and nine in each endcap, and a straw-tube transition radiation tracker (TRT) which provides around 30 additional hits per track.

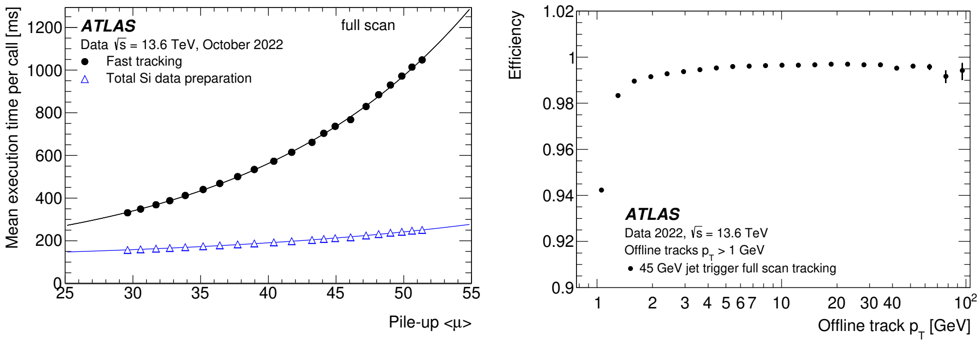
The ATLAS trigger system consists of a hardware first-level (L1) trigger and a software-based high-level trigger (HLT). The L1 trigger reduces the event rate from the bunch crossing rate of about 40 MHz to a maximum of 100 kHz and provides regions of interest (RoIs) based on energy deposits in the calorimeters and the muon spectrometer to the HLT. Track reconstruction from hits in the ID is run in the HLT. It is separated into three stages, each of which takes the tracks from the previous stage and can be used for event selection so that subsequent stages are run on fewer events, reducing the processing time. The stages are:

1. **Fast track finder (FTF)**: runs custom pattern recognition and a fast track fit using hits from the pixel and SCT layers. It is still typically the most time-consuming component due to the combinatorial nature of pattern recognition.
2. **Precision tracking**: refits FTF tracks using full offline track reconstruction, which reduces the number of fakes, and extends them to the TRT, which improves track momentum resolution.
3. **Gaussian sum filter (GSF)** [4]: takes account of bremsstrahlung in electron triggers. This was not used in the trigger before Run 3.

3. Full-detector tracking

A key development in Run 3 is running the fast tracking in the full ID (full scan) for triggers based on jets and missing transverse energy (E_{T}). This is useful for forming *particle-flow* (PFlow) objects [5] combining tracks with calorimeter topological clusters. PFlow objects can be used for jet finding with improved energy resolution at low transverse momenta (p_{T}) [6] and better separation of the hard-scatter interaction from pile-up. However, the full-scan tracking is extremely time-consuming, so optimizations had to be made to reduce the processing time while limiting reduction in efficiency. Seed making is one of the most time-consuming aspects of the tracking; it is reconfigured to use space-point triplets consisting of only pixel or only SCT hits, and machine learning techniques [7] are used for seed selection for pattern recognition. Track extrapolation into the SCT is performed with a reduced window to search for hits in the subsequent layers.

Even with these improvements, the full-scan tracking can take over a second per event, as shown in Figure 1(a), and takes up 26% of the total event processing time in the HLT. The full-scan tracking efficiency is approximately 98.5% relative to the offline reconstruction for events recorded with a 45 GeV jet trigger in 2022. The efficiency against offline track p_{T} is shown in Figure 1(b). It is only around 94% at 1 GeV, the threshold used in the pattern recognition, and reaches a plateau at approximately 5 GeV.



(a) **(b)**

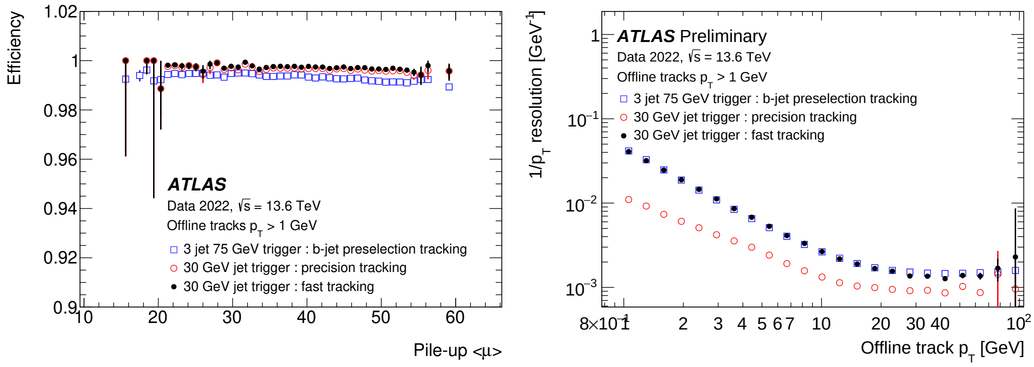
Figure 1: Performance of full-detector fast tracking in 2022 data: (a) mean execution times for the tracking and silicon data preparation in jet triggers as a function of the average pile-up, and (b) track finding efficiency with respect to offline tracks versus the offline track p_{T}, evaluated for the 45 GeV jet trigger. Only statistical uncertainties are shown. Solid lines are a guide to the eye [1].

Vertex finding in the trigger uses the same algorithm as offline [8], with tracks from the full-scan tracking. The vertex with the largest sum of p_{T}^2 of the associated tracks is chosen as the primary vertex. The efficiency for finding the offline primary vertex in the trigger is close to 100% for all z and pile-up multiplicities. The z resolution of the trigger primary vertex is between 40 and 50 µm over the full z range of $|z| < 150$ mm. The vertex finding only takes 14 ms on average at a pile-up of 52.

4. *b*-jet triggers

To reduce the rate of full-scan tracking, a preselection stage is used in b-jet triggers, where jets are constructed by topological clustering of calorimeter cells, and fast tracking is only run in RoIs within $|\Delta\eta| < 0.4$, $|\Delta\phi| < 0.4$ around the jet axes for all jets with $E_{\mathrm{T}} > 20$ GeV, and $|z| < 150$ mm. Events are then required to satisfy a loose b-tagging requirement of a fast b-tagging algorithm using these tracks as inputs [9]. Since 2023, primary vertex finding has been added to this preselection stage, as the execution time is insignificant compared to the tracking, and vertex information improves the b-tagging efficiency. For events passing the preselection, full-scan tracking and primary vertex finding are executed and used for PFlow jet reconstruction. Fast tracking, followed by precision tracking with TRT extension is then run in RoIs defined around the PFlow jets and using the primary vertex coordinates, for input to a final b-tagger.

The efficiency of the b-jet preselection tracking, and fast and precision tracking in the PFlow-jet RoIs is plotted against pile-up in Figure 2(a). The precision tracking efficiency is higher than 99% even at high pile-up and the tracking efficiency in the PFlow-jet RoIs is higher than in the preselection. Figure 2(b) shows that precision tracking significantly improves the p_T resolution. Figure 3(a) shows that preselection takes much less time than the full-scan tracking (Figure 1(a)).



(a) **(b)**

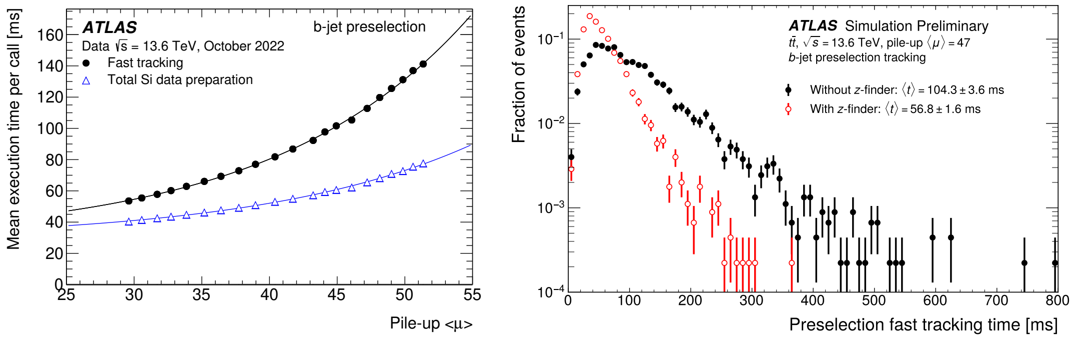
Figure 2: (a) The efficiency of the b-jet related tracking in the trigger with respect to offline as a function of the average pile-up [1]. (b) The p_T resolution of the b-jet related tracking [10]. Only statistical uncertainties are shown.

Work on further improvements is ongoing, including a new tagging algorithm based on a transformer neural network architecture, using primary vertex information in preselection, and the determination of primary vertex z-position prior to track reconstruction with the z-finder algorithm [11]. This allows restricting the preselection RoI in z, which reduces preselection tracking CPU cost by almost a factor of 2, as shown in Figure 3(b), with virtually no loss in trigger efficiency, and could become important at higher pile-up.

5. Unconventional tracking triggers

Many theories of physics beyond the Standard Model contain massive long-lived particles (LLPs) which would decay far from the primary interaction, within the ID. Dedicated triggers for LLPs have been developed for Run 3, including large radius tracking (LRT) triggers for displaced tracks and jets, and triggers for short tracks disappearing within the ID.

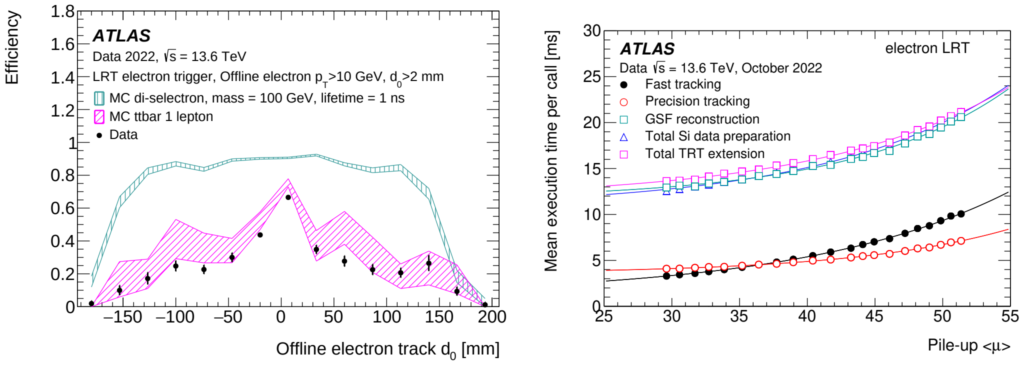
The LRT is configured to reconstruct tracks at large d_0 (more than a few millimetres), but originating before the first SCT layer, at a radius of approximately 300 mm. Only SCT hits are used for seeding, and the seeds not ordered by impact parameter. Tracking is expanded to cover $|z_0| < 500$ mm and $|d_0| < 300$ mm, with stricter track quality requirements, e.g. at least 8 hits per track. Electron and muon RoIs are expanded in η and ϕ. The size of the RoI in ϕ is a limiting factor in the tracking efficiency at large d_0, but a trade-off has to be made between tracking acceptance and computing cost. For full-scan LRT, the remaining hits after a standard tracking pass are used, tracking is restricted to $|d_0| > 2$ mm, tracks are not extended into the TRT, and track candidates are required to have $p_T > 1$ GeV.



(a) **(b)**

Figure 3: (a) Mean execution times for the b-jet preselection tracking and silicon data preparation in the ATLAS Run 3 trigger as a function of the average pile-up. Errors bars showing statistical uncertainties are smaller than the symbols used to plot the data. The solid lines are a guide to the eye [1]. (b) Time taken to run the fast track finder in the b-jet trigger preselection without (filled black circles) and with the z-finder (empty red circles) on a simulated $t\bar{t}$ event sample, measured on a 2.9 GHz Intel processor. The time with the z-finder includes the time taken to run both the z-finder and the track finding. The error bars show Poisson statistical uncertainties [12].

A plot of the LRT efficiency for electron displaced track triggers with respect to offline electrons is shown in Figure 4(a). The tracking efficiency in data is similar to that in $t\bar{t}$ Monte Carlo (MC) simulation, but much higher in simulations of LLPs that these triggers are targeting, especially at high d_0 and high pile-up. The data preparation, tracking and TRT track extension execution times for electron and muon LRT are plotted as a function of the mean pile-up in Figure 4(b). The data preparation steps take a few milliseconds longer than for standard tracking for electrons, and 1.5–3 times for muons, but fast tracking is faster (1.5–2 times for electrons and 2–3 times for muons).



(a) **(b)**

Figure 4: (a) The GSF tracking efficiency for the LRT electron trigger with respect to the merged standard and large radius offline electron track collections versus d_0 for data, semi-leptonic $t\bar{t}$ MC events, and simulated pair production of selectrons with a 1 ns lifetime and a mass of 100 GeV. Only statistical uncertainties are shown. (b) The mean silicon data preparation, tracking and TRT track extension execution times for electron LRT in the HLT as a function of the mean pile-up. Errors bars showing statistical uncertainties are smaller than the symbols used to plot the data. The solid lines are a guide to the eye [1].

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