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The performance of the ATLAS Inner Detector tracking trigger in high pileup collisions at 13 TeV at the Large Hadron Collider (Run 2) and plans for Run 3

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The performance of the Inner Detector tracking trigger of the ATLAS experiment at the LHC is evaluated for the data-taking period of Run 2 (2015-2018). The Inner Detector tracking was used for the muon, electron, tau and b-jet triggers, and its high performance is essential for the ATLAS physics programme, including many precision measurements of the Standard Model and searches for new physics. The detailed efficiencies and resolutions of the trigger for a wide range of physics signatures are presented for the Run 2 data. In preparation for LHC Run 3, which started in the summer of 2022, the application of Inner Detector tracking in the trigger has been significantly expanded, in particular, full-detector tracking is now utilized for hadronic signatures such as jets and missing transverse energy triggers for the first time. To meet computing resource limitations various improvements, including machine-learning-based track seeding, have been developed.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

https://pos.sissa.it/

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1. Introduction

The ATLAS detector [1] at the LHC is a multi-purpose particle detector with a forward–backward symmetric cylindrical geometry and a near-4π coverage in solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, providing a 2T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner detector (ID) allows the precise reconstruction of charged-particle trajectories in the pseudorapidity range $|\eta| < 2.5$ and is comprised of three sub-systems: the high granularity silicon pixel detector (Pixel), the silicon microstrip tracker (SCT), and the transition radiation tracker (TRT). An additional layer of silicon pixels, the insertable B-layer [2, 3], was installed in preparation for Run 2.

The trigger system is an essential component of any collider experiment. At the LHC, the trigger has the crucial role of reducing the rate of accepted events from the 40 MHz bunch crossing rate to a value that is manageable for permanent storage ($\approx$ 1.2kHz). In order to find and save events needed for the ATLAS physics program, a two-level trigger system is used: a hardware, pipelined level-1 (L1) trigger running on a subset of the detector information from the calorimeters and the muon spectrometer, and the software-based High-Level Trigger (HLT), running a series of algorithms using tracking information from the inner detector to perform track reconstruction on a dedicated CPU farm. Reconstructed track segments in the muon spectrometer and high-energy clusters in the calorimeters are used at level-1 to define regions of interest (RoI) in the detector which are used for full, offline-like track reconstruction in the HLT. Tracking can be run over both RoIs or the entire inner detector (Full Scan).

The specific design and performance of the Run 2 ID Trigger is described in Ref. [4]. To briefly summarise the steps of the tracking algorithms in the trigger: starting with an RoI/Full Scan from L1, the data preparation step retrieves the hits from the SCT and pixel detectors and forms space-points. Track seeding and formation are then performed by the Fast Track Finder (FTF) which is optimised for tracking efficiency with respect to the offline tracking. The next step is an optional event selection filter; this uses information from the FTF to discard unwanted events, saving processing time in subsequent tracking algorithms. Seeded with the information from the FTF algorithm, the Precision Tracking stage then uses the offline track fit with the hits identified by the fast tracking stage, which is optimised for purity and resolution. Here the track candidates are extended to the TRT and duplicate track candidates are removed.

2. Run 2 Inner Detector Trigger

For Run 2, the LHC increased the centre-of-mass energy in *pp* collisions from 8 to 13 TeV, with a reduction of the nominal bunch spacing from 50 ns to 25 ns [5] and an increase in the beam intensity per bunch crossing. This increase led to higher track and hit multiplicities due to a significant increase in the mean number of interactions per bunch crossing (so-called 'pile-up', μ). The Run 1 trigger design included a 2-level HLT, with separate, dedicated farms for the fast reconstruction (L2) and precision tracking (Event Filter) stages. This configuration was too slow at higher pile-up multiplicities, so for Run 2 the farms were combined, removing the need for duplicate data preparation and pattern recognition steps. This new tracking strategy, alongside an extensive programme of software optimisation, resulted in an approximately three times faster processing time per event for Run 2 when compared to Run 1, shown on the left of Figure 1a.

A feature of Run 2 tracking was the introduction of *multistage tracking*. This refers to the process of passing an RoI through the same tracking-related algorithm with the second pass being constructed to overlap with, extend, or update the RoI of the first pass. Multistage tracking strategies were employed in both the hadronic tau trigger and the b-jet trigger for Run 2 to limit the tracking CPU usage in wider and overlapping RoIs. The result of using this new strategy in the tau trigger is the ability to use a larger RoI in eta and phi than possible in Run 1, whilst saving approximately 30% processing time overall in the Fast Tracking stage as shown by Figure 1b.

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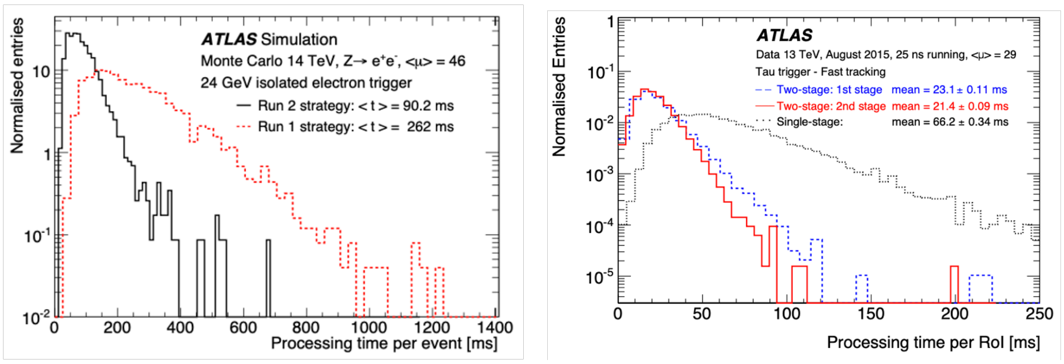
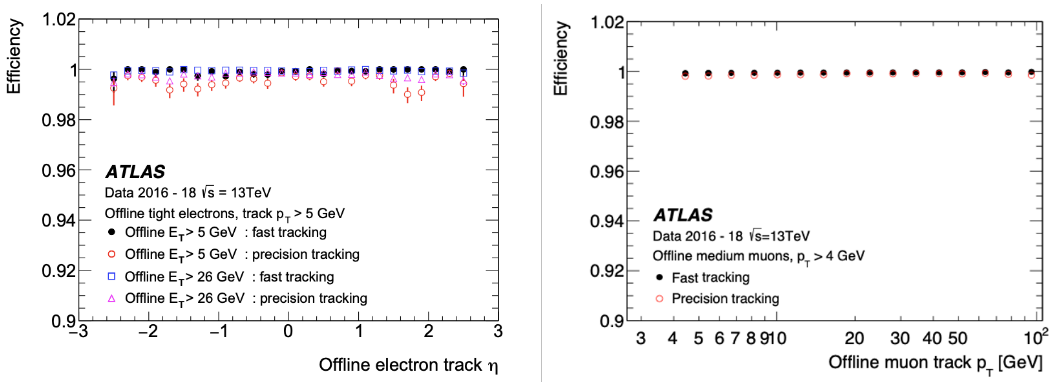


(a) (b)

Figure 1: Left, the total time required for the isolated 24 GeV electron trigger for simulated $Z \to e^+e^-$ events with the Run 1 and Run 2 strategies respectively. Right, the processing time per RoI for the fast track finder algorithm in ID tau trigger using single and multistage tracking strategies [4].

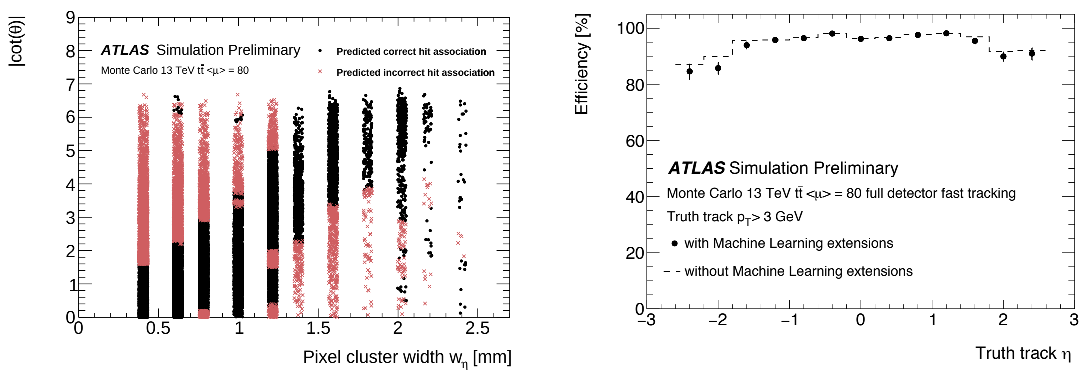


(a) (b)

Figure 2: The ID trigger tracking efficiency for (a) electrons selected by the 5 GeV and 26 GeV triggers as a function of offline electron track η, (b) muons selected by 4 GeV triggers as a function of offline muon p_{T} for both the fast and precision tracking algorithms [4].

The performance of the ID trigger tracking is evaluated by comparing tracks found by online trigger algorithms to tracks found by the full offline track reconstruction for each signature. To perform ID performance measurements, specific ID performance triggers were used; these triggers are similar to the standard triggers, however, they only select events using information from the calorimeters and the muon spectrometer, not the ID tracking. This allows for the unbiased estimation of the tracking performance in the ID trigger. Figures 2a and 2b demonstrate the high-level performance of the ID tracking during Run 2, achieving close to 100% efficiency and high resolution for a variety of electron and muon triggers across the range of transverse momentum (p_{T}) and all psuedorapidities (η) for both fast and precision tracking algorithms. The inefficiencies shown in Figure 2a between $1.4 < |\eta| < 1.8$ are due to the transition between the barrel and the end-cap modules, however, even here the efficiency with respect to offline reconstruction is greater than 99%.

In addition to the standard performance triggers, double-object performance triggers were also available in Run 2 that employ a tag and probe technique to select two lepton candidates consistent with the decay of a Z boson. The presence of a pure, fully selected tag lepton reduces the rate of events accepted by the trigger. The selection of probes without use of ID information, that, combined with the tag, reconstruct an invariant mass close to that of the Z boson greatly increases the purity of probe lepton candidates. This technique allows for an increase in the statistical precision with respect to the performance measurements using single



(a) **(b)**

Figure 3: Simulation of the predicted classification of doublet spacepoints in association with a truth track in the ATLAS pixel detector (a) and the corresponding efficiency with respect to the truth track η with and without the machine learning extensions (b) [6].

object triggers, allowing the determination of the efficiency towards much higher transverse momenta. It can be seen in Figure 2b that even for muon transverse momenta approaching 100 GeV, near-100% efficiencies are maintained.

3. Developments for Run 3

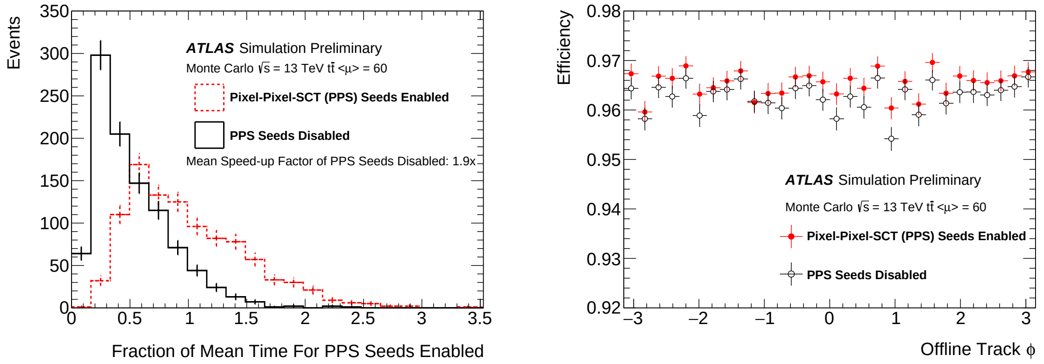
ATLAS plans to expand the use of Full Scan tracking for Run 3; specifically for all jet and Missing Transverse Energy (MET) triggers. This is naturally a computationally expensive process, so to make this feasible under Run 3 conditions, it was necessary to reduce the execution time of the tracking algorithms. This section will highlight a few of the developments in the trigger to achieve this technical challenge.

As pile-up increases, the number of hits in the detector at any given time greatly increases. This makes the process of combining hits into tracks (track seeding) drastically more time-consuming. The ability to reject bad seeds early on saves time during not only the track seeding stage but also computation time downstream in the subsequent tracking algorithms. Using machine learning to filter the clusters based on their inclination angle, θ, with respect to the z-axis, and their longitudinal width in η, w_η, it is possible to accurately predict whether a doublet of spacepoint hits will associate with the same Monte Carlo truth track [6]. The results of training this classifier are shown in Figure 3a.

By implementing the banding seen in Figure 3a as a look-up table for filtering the space-point doublets, the CPU processing time is reduced by a factor in the range of 1.6 - 2.3, depending on the level of pile-up. As more hits are rejected, it is inevitable that some of these will in fact be good hits. Consequently, the filter does come with the price of a small inefficiency of between 0.7 - 1.1%, as shown in Figure 3b, located predominately at larger $|\eta|$. The results shown in Figures 3a and 3b were obtained through detailed detector simulation of Monte Carlo 13 TeV $t\bar{t}$ data at mean pile-up, $<\mu>= 80$.

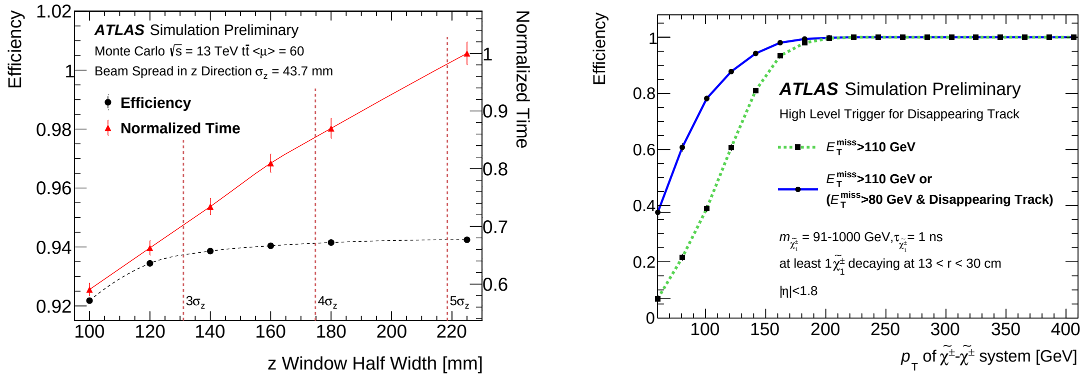
Triplets, combinations of doublets, are formed in the track seeding with a mix of Pixel hits and SCT hits; for example, a triplet with two Pixel hits and one SCT hit would make a PPS seed. The second upgrade targeting the track seeding stage reduces the processing time by disabling these PPS seeds [7].

Figure 4a demonstrates the reduction in CPU possible by disabling these PPS seeds and only using seeds constituting three Pixel (PPP) or three SCT (SSS) hits. Comparing the mean execution time from the normalised distributions corresponds to a reduction by a factor of 1.9 when the PPS seeds are disabled when compared to the case where they are enabled. As in the case of the machine learning-based filter, this reduction in computation time is only achievable at the cost of a further small reduction in the online track reconstruction efficiency with respect to offline reconstruction. Figure 4b illustrates this efficiency loss



(a) (b)

Figure 4: Comparison of the fast-track-finder algorithm running over the full detector for PPS seeds enabled/disabled for (a) event processing time normalised such that the PPS enabled distribution's mean is 1, and (b) per track efficiencies with respect to the offline tracks as a function of azimuthal angle, ϕ [7].



(a) (b)

Figure 5: (a) Per track reconstruction efficiency and the corresponding normalised processing time for a range of RoI z half-widths for the full detector fast tracking stage [7]. (b) Default Run 2 missing transverse energy trigger compared with the new disappearing track trigger for simulated Monte Carlo events with long-lived charginos [8].

as a function of azimuthal angle, ϕ, which is seen to be no larger than 1% across the full ϕ range. The results shown in Figures 4a and 4b were obtained through detailed detector simulation of the fast-track-finder algorithm over the full detector for Monte Carlo simulations of the $t\bar{t}$ process in 13 TeV collisions at an mean pile-up of $<\mu>= 60$.

Another Run 3 improvement with the objective of speeding-up processing time focuses on the RoI width along the beam-line (z-axis) [7]. Naturally, reducing the z half-width of the RoI reduces the processing time, however, this is constrained by the impact on the tracking efficiency in high pile-up environments. Figure 5a details how tracking efficiency changes with z half-width on the left axis and the corresponding processing time for that RoI z half-width on the right axis. Times normalised with respect to the processing time for a z half-width of 225 mm are shown. It can be seen that using a z half-width of at least three standard deviations of the beam spot (130mm) results in a CPU reduction of up to 30% whilst incurring a less than 1% inefficiency.

In addition to the developments and extensions for conventional tracking, for Run 3 ATLAS has introduced a number of entirely new unconventional tracking signatures for Run 3. This is with a view to increasing the selection efficiency for instance for long lived particles (LLP) that might decay some significant time after production, well inside the detector volume. Such particles may provide signatures for many new physics processes. Additional signatures may include displaced vertices, jets and leptons, and disappearing tracks in the detector. Previously, such searches had to rely on triggers only using the calorimeter or muon spectrometer. For Run 3, the new triggers target events with disappearing tracks and displaced leptons, significantly increasing the acceptance of the trigger to models with LLPs. Figure 5b exemplifies the effectiveness of one of these new triggers, showcasing the use of a lower threshold for missing transverse energy that would significantly increase acceptance for models with lower momentum. Displaced leptons will be directly targeted in the trigger for the first time using Large Radius Tracking (LRT), which is expected to drastically improve track reconstruction efficiency at large displacements from the beam line compared to the standard HLT tracking [9].

4. Outlook

The ID Trigger is a crucial element of the ATLAS trigger system and the tracking performance was excellent during LHC Run 2. Without the ID Trigger, it would not be possible to achieve the performance needed for the ATLAS physics programme. There have been significant developments to the trigger in preparation for Run 3. Large reductions made in the computation time of the various tracking algorithms have allowed for the use of Full Scan tracking during Run 3. New triggers utilising unconventional tracking can directly target physics models with long-lived particles, greatly improving the sensitivity of the trigger to new physics compared to Run 2.

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