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THE DESIGN AND PERFORMANCE OF THE ATLAS INNER DETECTOR TRIGGER FOR RUN 2

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The design and performance of the ATLAS Inner Detector (ID) trigger algorithms running online on the High Level Trigger (HLT) computing cluster with the early LHC Run 2 data are discussed. During the LHC shutdown from 2013 to 2015, the HLT farm was redesigned to run in a single HLT stage, rather than in two stages (Level 2 and Event Filter) as was used in Run 1. This allowed for a redesign of the HLT ID tracking algorithm, which aims to satisfy the challenging demands of the higher collision energy of the LHC in Run 2 and is essential for tracking of different charged particles in the ATLAS detector. The detailed performance of the tracking algorithms with the initial Run 2 data is discussed for electrons, muons and other charged particles. Comparison with the Run 1 strategy is made and demonstrates the superior performance of the strategy adopted for Run 2.

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INTRODUCTION

The ATLAS detector is one of the general-purpose detectors located at the Large Hadron Collider (LHC) [1, 2]. It consists of an inner tracking detector, called the Inner Detector (ID), a calorimeter system including electromagnetic and hadronic calorimeters, and a muon spectrometer. The ID, as one of the major components of the ATLAS detector, provides vital information for the tracking and identification of charged particles. It is composed of three sub-detectors: two silicon detectors, which are the Pixel and the Semiconductor Tracker (SCT), and a Transition Radiation Tracker (TRT). The Pixel is a 3-layer system at both the barrel and the end-cap of the detector, with the inner most layer separated by only 50.5 mm from the beamline. The SCT has 4 double-layered strip detectors in the barrel region and 9 in the end-cap. The TRT contains 320,000 straw tubes and optimally can provide 36 hits for one single-particle track.

From 2013 to 2015, the LHC was shut down and went through a series of upgrades. The key parameters of the LHC at the end of Run 1 and Run 2 are listed in Table 1. The increased centre-of-mass energy of the proton–proton collisions allows for probing the physics at a higher energy regime. A significantly higher luminosity is foreseen, which primarily comes from the reduced colliding proton bunch interval and the increased additional proton–proton interactions per bunch crossing, $\langle\mu\rangle$, also referred to as pile-up. This however produces a more complex tracking environment.

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Table 1. **Comparison of the LHC parameters at the end of Run 1 and Run 2**

Centre-of-mass energy, TeV	8	13
Bunch interval, ns	50	25
Instantaneous luminosity, $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$	$8 \cdot 10^{33}$	$2 \cdot 10^{34}$
$\langle \mu \rangle$	~ 21	~ 50

In order to meet the challenges due to the higher event rate and the more complicated tracking environment, the ATLAS detector was upgraded during the shutdown. Particularly for the ID, various upgrades have been developed and implemented. The major upgrades are listed below:

• A newly inserted layer of pixel detectors, the Insertable B-Layer (IBL) [3], which is 33.25 mm away from the beamline and is expected to largely improve the tracking resolution.

• Upgraded trigger hardware and the corresponding firmware.

• The redesigned trigger software operated with the higher input rate and pile-up in Run 2 with a faster decision-making and reasonable tracking performance.

1. THE ATLAS TRIGGER SYSTEM

In Run 1, the ATLAS experiment had a 3-level trigger system [4]. Level 1 (L1) is purely hardware and firmware based. It collects information in the calorimeters and muon spectrometer with no information from the ID and defines geometrical Regions of Interest (RoI) in the detector, where potentially interesting physics objects are located. RoIs are fed to the High Level Trigger (HLT) [5], which consisted of two levels of software triggers, Level 2 (L2) and the Event Filter (EF). The parameters of the trigger system in Run 1 are listed in Table 2, including the highest input and output rates reached during Run 1 and the average decision time for each trigger level. The final trigger output rate reached 1 kHz, with an average rate of 350 Hz.

In Run 2, L2 and EF are merged into one stage to run on a single PC node. This allows for a simplified data flow in-between different trigger levels and removal of duplicated algorithms at L2 and EF. Both L1 and HLT were upgraded to deal with the higher input rate and the denser tracking environment. The design parameters for L1 and HLT after the upgrade are shown in Table 3. L1 is expected to run under a doubled input rate at 40 MHz,

Table 2. **The parameters of the ATLAS trigger system in Run 1**

Parameter	L1	L2	EF
Peak input rate, MHz	20	65	6.5
Peak output rate, kHz	65	6.5	1
Decision time	$< 2.5\ \mu$s	~ 75 ms	~ 1 s

Table 3. **The parameters of the ATLAS trigger system in Run 2 [7]**

Parameter	L1	HLT
Input rate, MHz	40	100
Output rate, kHz	100	1
Decision time	$< 2.5\ \mu$s	~ 200 ms

with an increased output rate of 100 kHz. The average output rate of the HLT is expected to reach 1 kHz. Additionally, a hardware-based ID track processor, the Fast TracKer (FTK) [6], is under development. It is designed to find tracks using fast custom hardware and provide tracking information to the HLT for each L1 accepted event. The current plan is to install the FTK in the barrel region in early 2016 and the forward region later in 2016.

2. REDESIGNED HLT ID TRACKING ALGORITHM

The HLT tracking in general runs in 2 stages: a fast tracking stage and a precision tracking stage. In Run 1, L2 ran as the fast tracking stage producing fast but low quality tracks; EF as the precision tracking stage, which did the full reconstruction and fitting of candidate tracks. Since L2 and EF ran on different CPU farms, the data preparation and track seeding had to be done separately for L2 and EF [8].

The merged HLT allowed for the redesign of the ID tracking algorithm. A Fast Track Finder (FTF) is developed as the new fast tracking algorithm. The precision tracking stage, similar to that in Run 1, is developed based on offline track reconstruction software, but optimised for speed. The merged HLT allows a common storage and data preparation for FTF and precision tracking. In addition, the precision tracking now is seeded directly by FTF, with initial track candidates produced by FTF passed directly on to the precision tracking stage. This removes duplicated algorithms in the two stages of tracking, especially the pattern recognition algorithm in the track seeding, which produces initial tracks from single hits in the detector and is one of the most time-consuming algorithms. In Run 1, this used to be executed both in L2 and EF due to limited sharing of information between the two stages. The removal of the duplication introduces a dramatic improvement in the algorithm speed [9]. Additionally, FTF can be used alone to create vertices useful for selections of b-jets and taus.

The overall improvement due to the implementation of the redesigned ID tracking algorithm is shown in Fig. 1, in which the total processing time for each event in a 24 GeV isolated electron trigger is compared between the Run 1 and Run 2 strategies. The average processing time for the Run 1 strategy is 262 ms, whereas for Run 2 it is only 90 ms.

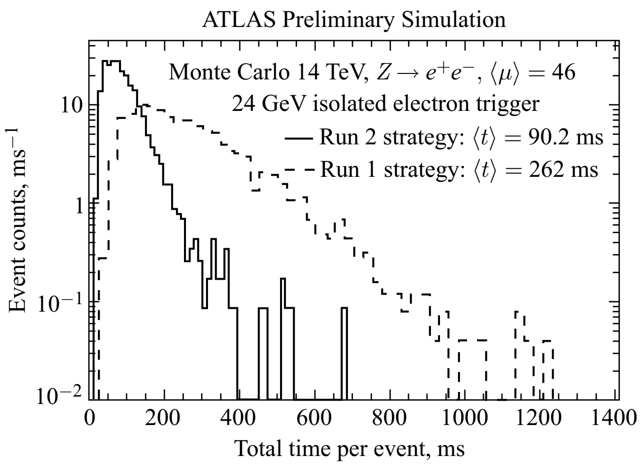

Fig. 1. Improvement from the redesigned ID tracking algorithm in Run 2 [10]

3. PROFILING AND OPTIMISATION

Since the Run 2 strategy is constructed from Run 1 algorithms, studies have been done to improve the speed and memory usage of Run 1 algorithms. Hotspots in the algorithms are identified by profiling and hence are optimised. There are other improvements coming from software upgrades, including update of the compiler to GCC4.8, migration from 32-bit to 64-bit architecture and the upgrade of the linear algebra library from CLHEP [11] to Eigen [12]. Improvements from these optimisations are illustrated in Fig. 2. The execution time is shown for each call of the tested algorithms running on simulated data. These include the collection of all Pattern Recognition algorithms (Fig. 2, *a*) and Ambiguity Solver (Fig. 2, *b*). The comparison is between algorithms deployed in Run 1 (built in 2013) and their extensions with the changes mentioned above (built in 2014). As can be seen from the figures, the average execution time is reduced dramatically by the optimisations. The plot on the left demonstrates the pure technical improvement from the profiling and optimisation. The algorithm runs three times faster than before the optimisation. The plot on the right shows an improvement of a factor of 10, which comes from the combination of the technical optimisation and the redesigned algorithm [9, 13].

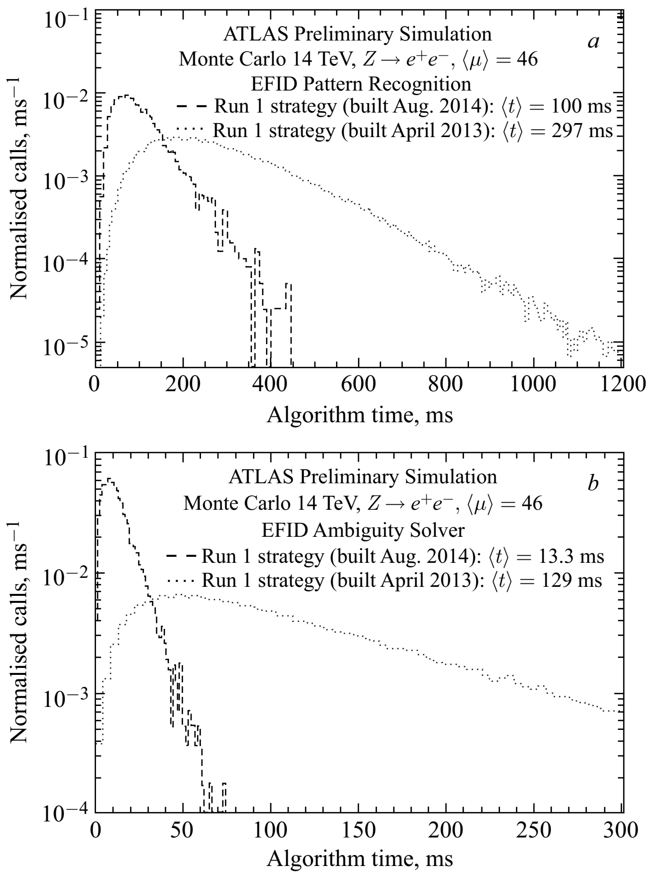

Fig. 2. Improvement in algorithm timing from profiling and optimisation [10]

4. RUN 2 HLT TRACKING PERFORMANCE

The performance of the redesigned ID tracking algorithm is discussed in this section. The studies are performed using 13 TeV data collected in June and July 2015. Dedicated performance triggers are used in order to select unbiased event samples, where no ID track requirement is imposed on events.

Figure 3 shows the tracking performance in minimum bias trigger, which selects sample of events with a minimal requirement and runs over all ID tracks. The track finding efficiency is shown as a function of offline track (*a*) p_T and (*b*) d_0, where p_T is the momentum in the transverse plane with respect to the beamline and d_0, the transverse impact parameter, is defined as the closest approach from the track to the beamline in the transverse plane. The efficiency is measured with respect to offline tracks, which are tracks found by offline track reconstruction software. As can be seen from the plots, the redesigned ID tracking algorithm achieves close to 100% efficiency. Fig. 3, c shows the $\Delta\eta$ distribution of the online tracks found by the minimum bias trigger with respect to offline tracks, where η is the pseudorapidity[1]. The narrow width of the distribution of approximately 0.01 represents a good η resolution.

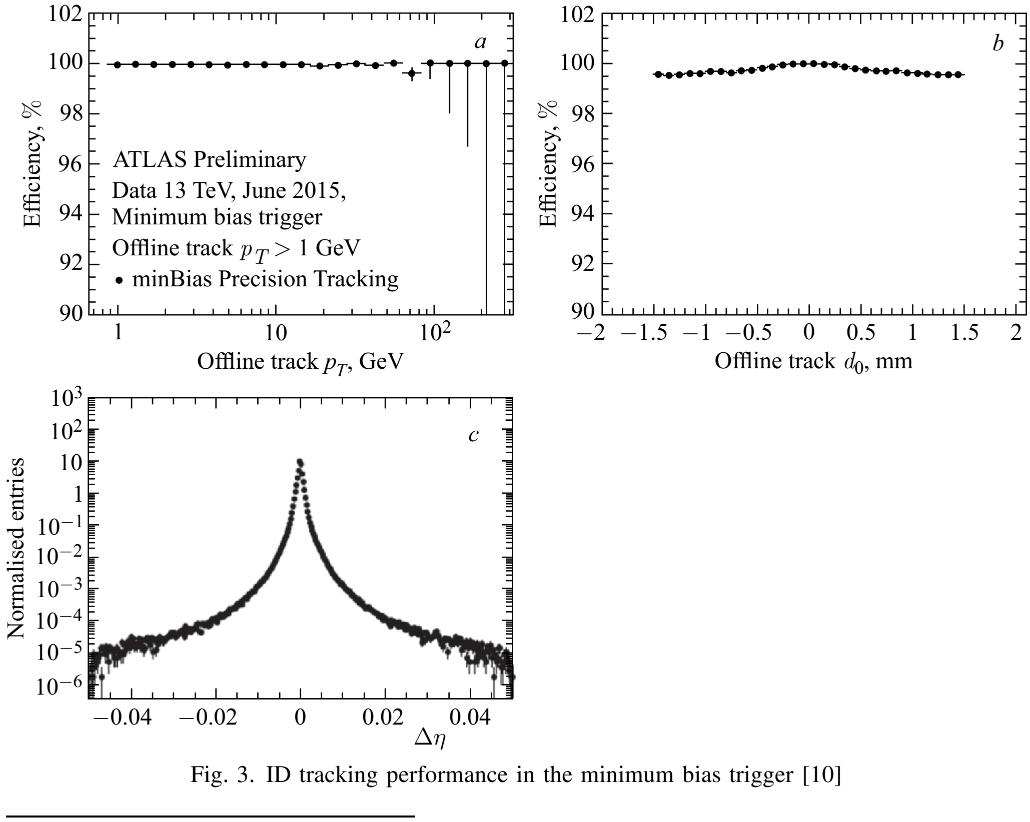

Fig. 3. ID tracking performance in the minimum bias trigger [10]

[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z axis coinciding with the axis of the beam pipe. The x axis points from the IP to the centre of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta \equiv -\ln[\tan(\theta/2)]$.

The tracking performance in the muon and electron triggers is shown in Fig. 4, where the muon trigger is shown on the left column for offline tracks with $p_T > 10$ GeV, the electron trigger is shown on the right for offline tracks with $p_T > 20$ GeV. FTF and precision tracking are tested separately, where FTF is shown in red and precision tracking in black. The plots, from top to bottom, show the tracking efficiency as a function of offline track p_T and η, and the distribution of $\Delta(1/p_T)$ calculated with respect to offline tracks, where $\Delta(1/p_T)$ represents the accuracy on the measurement of track curvature, which is used to calculate

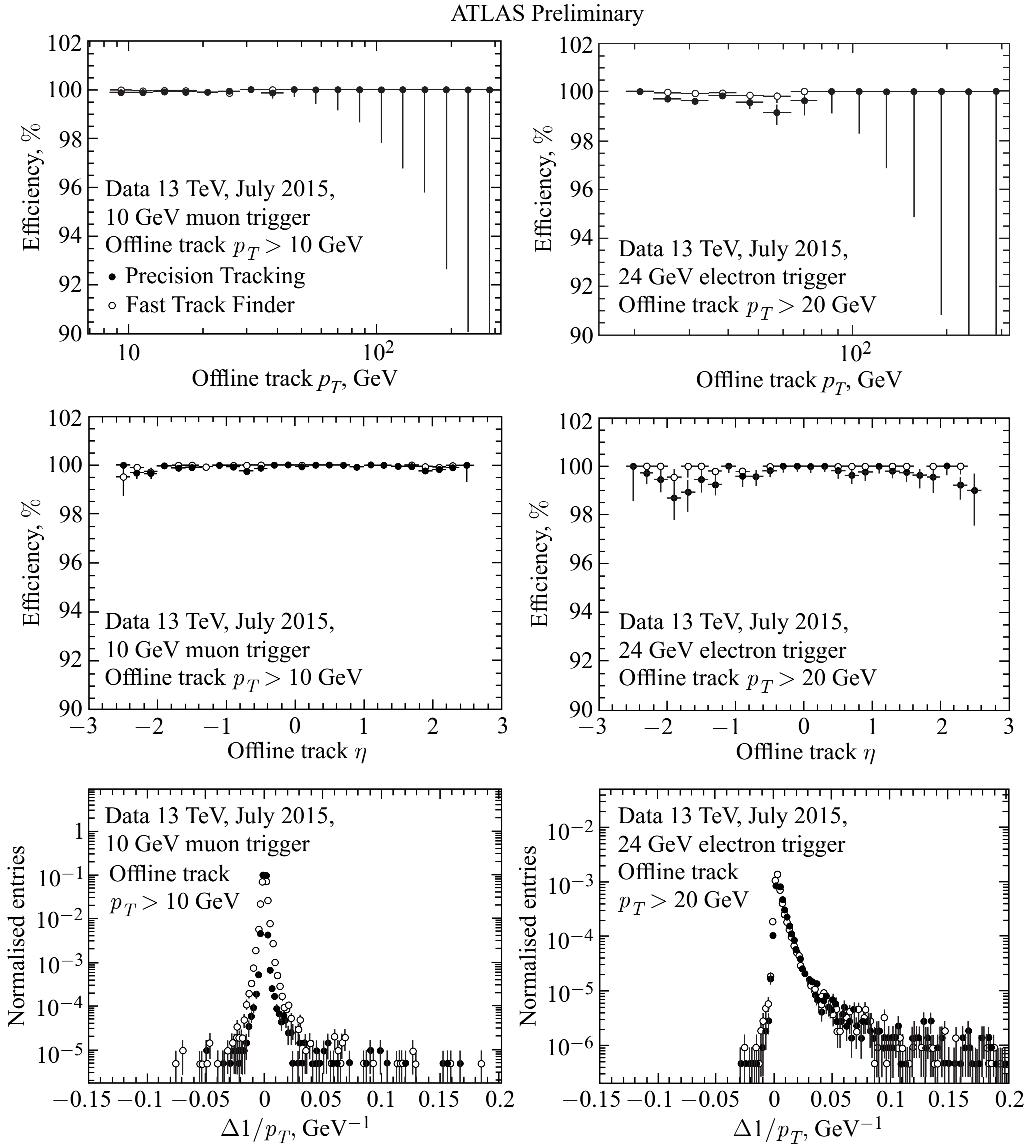

Fig. 4. ID tracking performance in the muon (left) and electron (right) triggers [10]

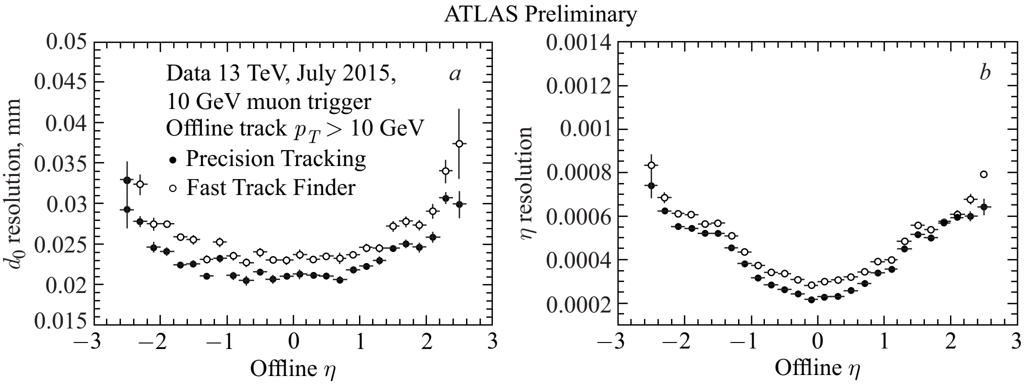

Fig. 5. ID tracking resolution in d_0 (*a*) and η (*b*) in muon trigger [10]

the momentum of the track. A very high efficiency can be seen in both electron and muon trigger. The narrow width of the $\Delta(1/p_T)$ distribution represents a very good resolution in track curvature. The relatively lower efficiency and longer tail of the $\Delta(1/p_T)$ distribution in electron trigger is due to electron bremsstrahlung.

Figure 5 shows the d_0 (*a*) and η (*b*) resolution in the muon trigger as a function of offline track η. Both precision tracking and FTF have an excellent overall resolution, where the d_0 resolution is better than 0.03 mm and the η resolution is better than 10^{-3}. As expected, the precision tracking has a better resolution than FTF. Lower resolution is observed in the high-η region, which is due to the detector geometry.

CONCLUSIONS

In conclusion, HLT in Run 2 has been merged into a single stage, allowing for a redesigned ID tracking algorithm. A dramatic speed improvement is achieved due to the merged data preparation and track seeding in the single-stage HLT. Other improvements in timing have been achieved by profiling and optimisation in the algorithms. In total, the ID tracking has gained a reduction of a factor of three in the average processing time for each event, operated at a significantly higher input rate. Despite the timing improvement, an excellent tracking performance is preserved, including close to 100% tracking efficiency and a good tracking resolution.

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