Commissioning the ATLAS Inner Detector Trigger

Mark Sutton on behalf of the ATLAS Collaboration

The University of Sheffield, Department of Physics and Astronomy, The Hicks Building, Hounsfield Road, Sheffield S3 4RJ, Great Britain

E-mail: sutt@cern.ch

Abstract. The ATLAS experiment [1] is one of two general-purpose experiments at the Large Hadron Collider (LHC). It has a three-level trigger, designed to reduce the 40 MHz bunch-crossing rate to about 200Hz for recording. Online track reconstruction, an essential ingredient to achieve this design goal, is performed at the software-based second (Level 2) and third (Event Filter, EF) levels, running on farms of commercial PCs. The Level 2 trigger, designed to provide about a 50-fold reduction in the event rate with an average execution time of about 40 ms, uses custom fast tracking algorithms, doing complementary pattern recognition on data either from the silicon detectors or from the transition-radiation tracker. The EF uses offline software components and has been designed to give about a further 10-fold rate reduction with an average execution time of about 4 s. We report on the commissioning of the tracking algorithms and their performance with cosmic-ray data collected recently in the first combined running with the whole detector fully assembled. We describe customizations to the algorithms to have close to 100% efficiency for cosmic tracks that are used for the alignment of the trackers, since they are normally tuned for tracks originating from around the beampipe.

1. Introduction

The large event rate of the Large Hadron Collider (LHC) makes the online selection of interesting physics events an essential and challenging requirement to achieve the physics goals of the LHC. The 40 MHz bunch crossing rate of the LHC means that to reduce the output rate of the ATLAS high level trigger to the 200 Hz that can be written and stored offline a rejection factor of more than ve orders of magnitude is required. For the LHC design luminosity, up to around 25 *pp* interactions per bunch crossing may be expected. This means that interesting physics events will usually be overlaid by some number of uninteresting, pileup interactions from which they must be disentangled. For the silicon tracking detectors near the beam line, where occupancy is highest these pileup interactions complicate the pattern recognition since hits from the overlying pileup interactions increase the probability of incorrectly assigning hits from pileup tracks to tracks from the interactions of most interest. In addition, the data volume, readout and the reconstruction latency are all increased. Therefore it is important that the trigger algorithms are both fast and robust enough to ensure that rare and interesting events are not lost.

The LHC is expected to commence luminosity operation later in 2009 and it is important that the online Inner Detector tracking algorithms are operating well far inadvance of the first collisions. To this end a detailed program of commissioning the algorithms is underway. The early stages of this program have relied on tuning and development of the algorithms' performance in terms of efficiency, resolution and timing using Monte Carlo data from the simulated detector. With the complete detector now operational, a new phase of operation
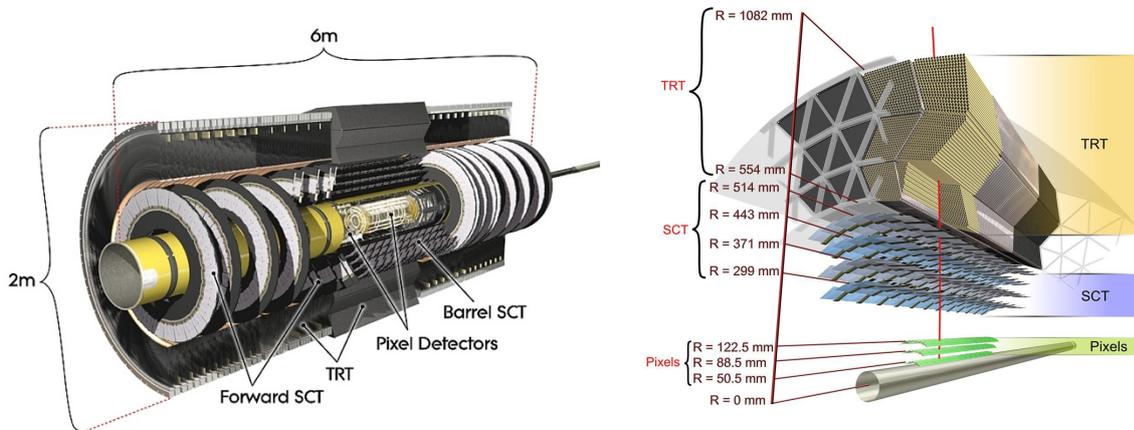
Figure 1. The Inner Detector. The left figure shows a diagram of the complete Inner Detector, with the Pixel detector nearest the beampipe, surrounded by the Semiconductor Tracker and the Transition Radiation Tracker. The barrel, and endcap (wheel) structure can be clearly seen. The right figure shows a close up of a sector from the barrel, showing the structure of the Pixel and SCT ladders and the layout of the TRT straws.

has begun with the using data from the actual detector to understand the performance of the detector and the online and offline reconstruction algorithms.

1.1. The Inner Detector

The ATLAS Inner Detector can be seen in Figure 1 and consists of three subsystems. Nearest the beamline is the Pixel detector, consisting of 1744 silicon pixel detectors with readout pixels of size 50×400 μm arranged in three layers in the barrel, three endcap wheels in the forward (positive z) and three in the rear (negative z) direction[1] The Semicondictor Tracker (SCT) at a larger radius than the pixel detector consists of 8176 silicon strip detectors with 80 μm readout pitch, with wafers arranged back to back to provide a small 40 mrad stereo angle. The SCT consists of four barrel layers, and 9 wheels each in the forward and rear directions. The outermost of the Inner detector subsystems is the Transition Radiation Tracker (TRT) which consists of 2 mm radius straw drift tubes containing a Xenon (70%)-CO_2(27%)-O_2(3%) gas mix, arranged as two barrel sections with straws parallel to the beamline direction in the barrel sections and forward and rear endcaps with straws arranged radially. The Inner Detector is enclosed in a superconducting 2 T solenoid for providing track transverse momentum discrimination.

1.2. The ATLAS trigger and DAQ systems

To achieve the high level of event rejection, the ATLAS trigger [2] has been designed as a three level trigger system. The first level (LVL1) trigger is a hardware pipelined trigger using custom electronics with reduced granularity information, predominantly from the calorimeter and the muon systems. This is clocked at the bunch crossing rate and delivers a decision after a fixed latency of 2.5 μs. During LVL1 processing regions of interest (RoIs) are indentified in the detector that contain features of interest that merit additional reconstruction. On a LVL1 accept the data are read out into custom Readout Buffers (ROBs) where they are stored for

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[1] In the right-handed ATLAS frame, z lies along the beam direction with r being the radius transverse to the beamline, y upwards and the positive x axis pointing towards the centre of the LHC machine.
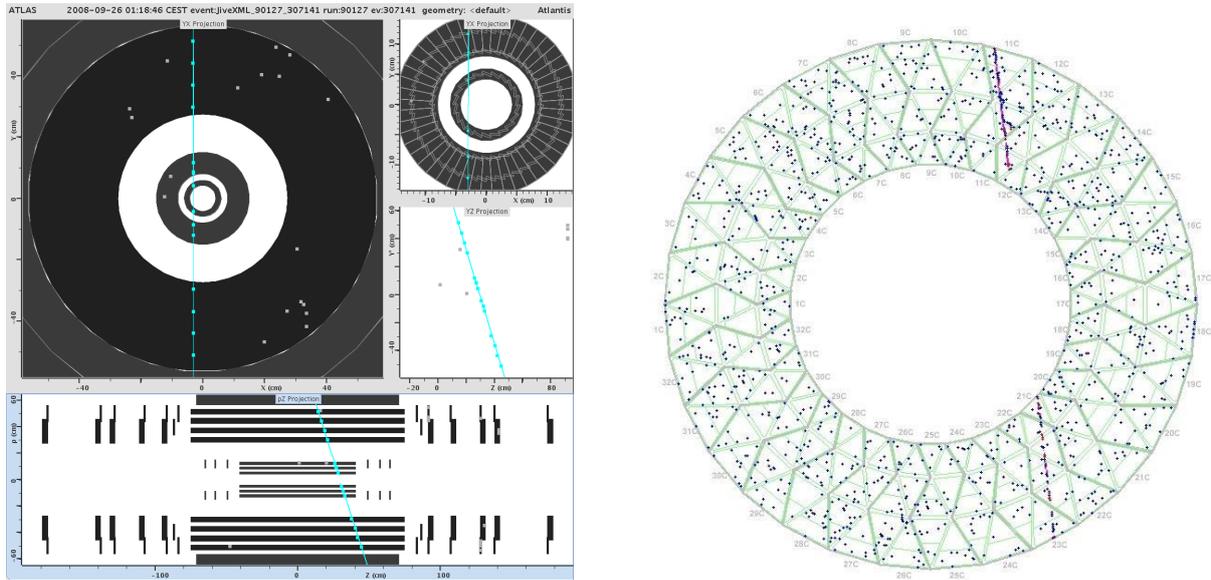
Figure 2. On the left, a typical cosmic ray muon event reconstructed in the Pixel detector and SCT showing the two Level 2 tracks which can be seen clearly in the close up of the Pixel detector in the top right of the figure. The right figure shows a typical cosmic event reconstructed in the TRT. The SCT and Pixel detector are not show.

access by the level 2 (Level 2) system - the first stage in the ATLAS High Level Trigger (HLT). The ATLAS HLT consists of two farms of fast commodity CPU's. The farms currently consists of 850 nodes, each consisting of 2 quad core CPU's running Linux and is divided into 2 sub farms, one for the Level 2 trigger and one for the third level Event Filter (EF). During the Level 2 processing the algorithms have access to the detector data with the full spacial granularity, but only for that data within the identifed LVL1 region of interest. This approach reduces the data volume and processing required at Level 2. The maximum Level 2 input rate is around 75 kHz and the maximum output rate is around 3 kHz. In addition, the Level 2 process is the first stage of the trigger that has access to the detailed Inner Detector data. On a Level 2 accept, the full event is constructed by the Event Builder which passes the data onto the third level Event Filter (EF). This is also a CPU farm, but running seeded versions of the offline reconstruction algorithms with access to the complete detector data and the full alignment and calibration. At Level 2 it is possible to combine tracking information from the Inner Detector with calorimeter or muon system data to enable improved particle reconstruction, essential for the identification of signatures which may signal new or rare physics, e.g. high transverse energy electrons, photons and muons or final states containing b-quarks.

2. Commissioning

In order to understand the operation of the trigger algorithms with real data from the real detector before collisions it is important to commission the trigger system as fully as possible before the first luminosity data. Details of the commissioning of the HLT and its other subsystems can be found elsewhere in these proceedings [3, 4].

A number of ATLAS Technical runs where Monte Carlo data are injected into the DAQ system have been used to help commission aspects of the the HLT such as the event distribution, streaming and monitoring. To evaluate the algorithms performance with real data from the complete detector, incorporating features such as misaligment and dead or noisy channels, data
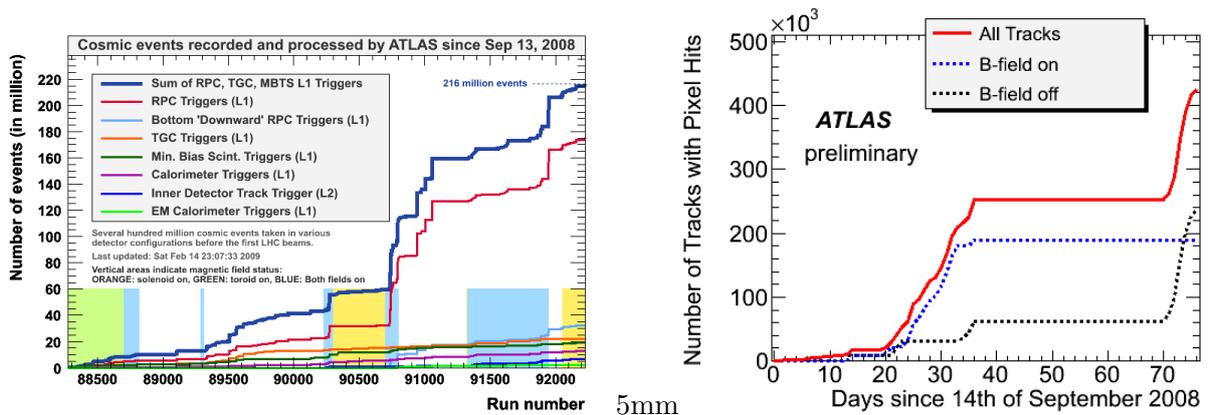
Figure 3. The integrated number of tracks collected during the combined cosmic commissioning run at the end of 2008.

collected from cosmic ray muons can be used. This allows detectors to be timed-in, and allows studies of the realistic data preparation and noise occupancy.

Although a great deal can be done using cosmic ray muons, these have a different event topology from tracks originating from collisions. Results from single beams operation are also extremely useful for commissioning, however the LHC accident in autumn 2008 meant in total only $\mathcal{O}(1000)$ events were passed to the HLT during the LHC single beam operation which is not enough for detailed commissioning studies. From September to December in 2008 ATLAS undertook a dedicated combined cosmic run with the full detector triggering on cosmic ray muons with no beams in the machine. Results from this commissioning data taking period will be presented in this article.

Figure 2 shows typical cosmic ray muon events illustrating the usual top-to-bottom topology, where the muon tracks themselves can have a large impact parameter, d_0, with respect to the beamline. In addition, since the tracks travel from the top of the detector to the bottom, the hits in the top half of the detector will arrive earlier with respect to those from the bottom half. In a collision, the hits nearest the beamline will arrive before those at larger radius.

For tracks arising from collisions this d_0 will typically be of the order of a few hundred microns, and so the trigger algorithms are optimised to give a high efficiency for tracks traveling outwards from the vicinity of the beamline. In the trigger the cosmic tracks will therefore be reconstructed as two tracks - one in the upper and one in the lower halves of the detector.

2.1. Cosmic trigger selection
To study the algorithm performance in terms of efficiencies unbiased or orthogonal triggers are required. For alignment studies, trigger bias is not a as important as maximising the number of useful tracks and the illuminations of the detector elements. For the LVL1 trigger the principle subsystem that generates the LVL1 trigger accept is the muon subsystem. A sample of accepted events from this LVL1 trigger are accepted with a passthough trigger, without requiring a subsequent HLT verification, but with a large prescale factor to reduce the high rate. This gives us an unbiased trigger for efficiency studies, but with a lower rate for events where a muon traverses the Inner Detector. For efficient event collection of tracks with an Inner Detector track for alignment studies, there is also a LVL1 "Fast-OR" from the TRT which uses a coincidences of hits in the TRT from the detector front end electronics but does not perform detailed reconstruction of the hits. In addition, events where any of the Level 2 algorithms reconstruct a track are saved in the Inner Detector cosmic stream. The Event Filter the algorithms were running in evaluation mode to study the performance, although the results
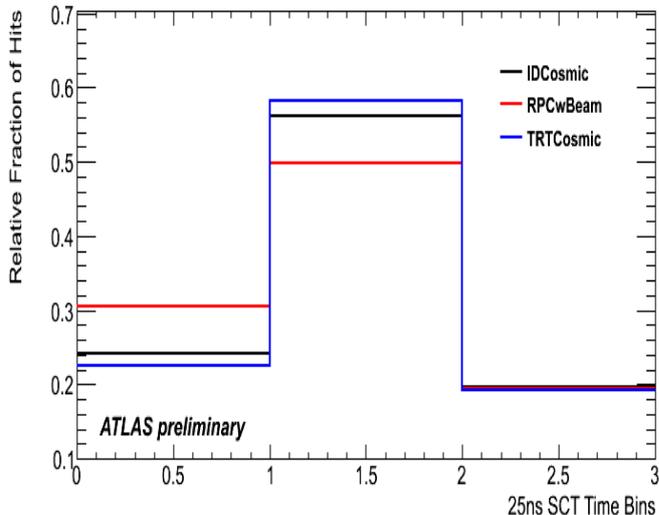
Figure 4. The timing of the SCT. The timing is chosen so that the readout over three successive bunch crossings maximises the hit arrival in the central bin.

were not used for event selection.

The integrated number of events collected in the cosmic run collected since the start of the run in September 2008 until November 2008 is shown in Figure 3 illustrating more than 216 million events collected, with over 400 thousand collected with hits in the pixel detector, divided equally between tracks with and without the solenoid operational. When the run finished in December over 300 million events had been written to tape.

For data collected without the soleniodal magnetic field, the track pointing is more precise, but there is no information on the track momentum so that the effects of multiple scattering cannot be very well taken into account. Since it is not envisioned that ATLAS will collect collision data with no magnetic field, only results from the algorithms with the magnetic field on are reported here.

3. The Inner Detector Trigger
In the HLT there are several tracking algorithms that can be used for the cosmic running. The Event Filter, runs a version of the tracking very close to that of the full, offline reconstruction. During the cosmic run the EF algorithm was deployed for the last few weeks of the data taking, and was running in observational mode only. Studies to evaluate the performance of the EF tracking are still ongoing, so this article will concentrate on studies using the Level 2 algorithms. For the cosmic running there three algorithms are available at Level 2:

- The TRT segment finder is a special algorithm specifically designed for cosmics and uses only hits from the TRT. It is a wrapped version of the offline tracking which limits itself to a vertical slice through the detector.

- SiTrack [5] is a silicon hit based algorithm that looks for seed pairs of hits of hits in the inner layers consistent with a beamline constraint and uses fast lookup tables to identify hits consistent with these tracks in outer layers. Groups of hits consistent with single tracks are merged and duplicate and outlying hits are removed and the remaining hits passed to the track fitter.

- IDScan [6] is also a silicon hit based algorithm, although by identifying the most probable z position of the vertex of any interaction identifying clusters of hits in $\eta - \phi$ space is possible as hits consistent with track candidates. Following this, groups of hits from these clusters that are also consistent in $1/p_T - \phi$ space are passed to the track fitter.
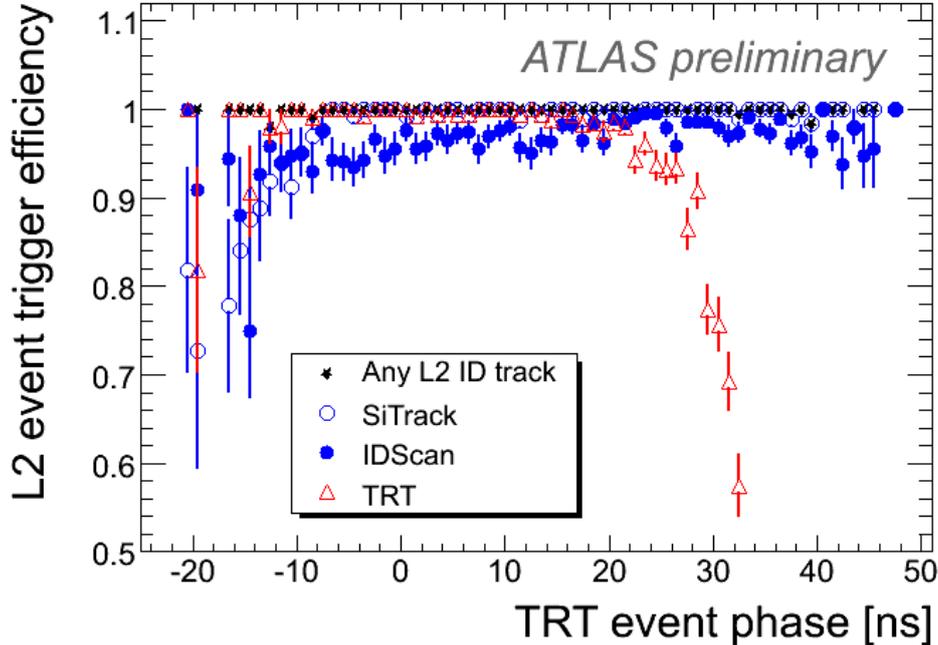
Figure 5. The Level 2 event finding efficiency for good offline tracks versus the TRT event phase.

Following the pattern recognition stages of SiTrack and IDScan, both algorithms then use a common Kalman filter track fit [7] for fast track reconstruction. Tracks can be extrapolated into the TRT [8] to provide improved p_T resolution and particle identification. Both the silicon algorithms are designed and optimised for the collision geometry for tracks with a small impact parameter with respect to the beamline.

Since the cosmics do not typically originate from the beamline, to deal with the large impact parameter both IDScan and SiTrack can use an additional pre-processing stage, specifically for reconstruction of cosmic tracks in the barrel region. First pairs of hits on opposite sides of the silicon detectors, are used to define the outer limits of a cigar shaped road between them. Hits in the inner layers consistent with this road in both $r - \phi$ and $z - r$ are identified and a 3-d linear track is fitted to calculate the impact parameter. The spacepoints are then shifted in x consistent with this impact parameter so that the hits themselves are presented to the algorithms as if they originate from a track from the origin in the $r - \phi$ plane. This enables the study the algorithm performance with minimal additional modifications with respect to the collision algorithms.

Besides the spacepoint shifting algorithm SiTrack can operate in a mode where the beamline constraint of the original spacepoint seeds is relaxed so that seed pairs can come from anywhere in the detector. In this way SiTrack can run without the need for the spacepoint shifting pre-processing stage but in a mode less similar to that used for collisions. The actual efficiency for the shift code is very high for high momentum tracks, but not so high for low momentum tracks.

4. Performance

One issue that is very important for early running is to correctly time in the detectors such that the pipelines are synchronised with the bunch crossing. For data taking with cosmic ray muons, this is more complicated, since the cosmic ray muons themselves can arrive at any time and so are not synchronised with the bunch crossing clock. As a result, more loose timing requirements
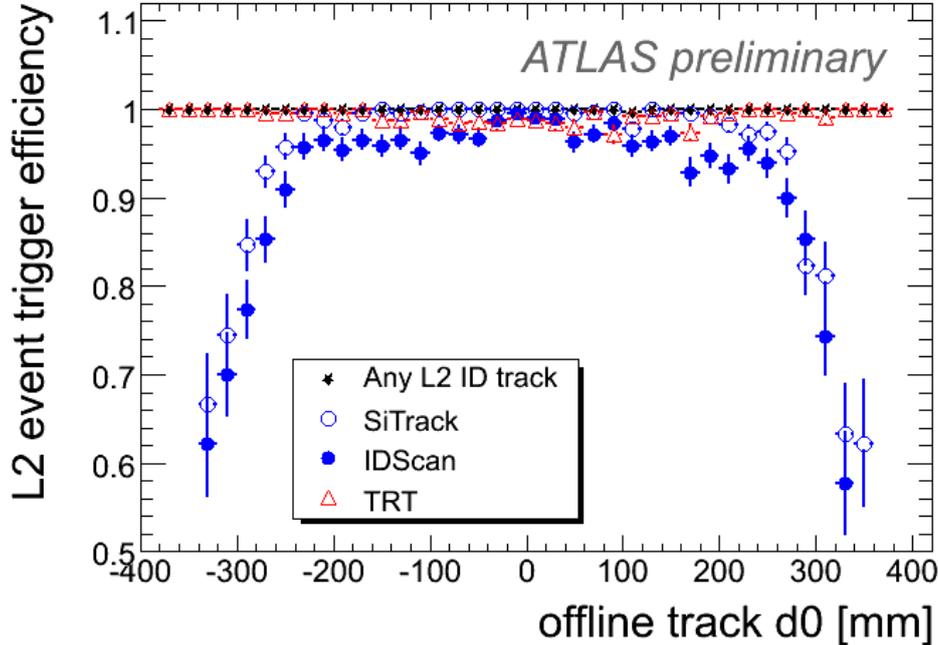
Figure 6. The level 2 event finding efficiency for good offline tracks versus the offline reconstructed track d_0.

must be made. For the cosmic running, and the Pixel detector reads out 8 successive bunch crossings, whereas the SCT reads out three. Figure 4 shows the relative fraction of hits from cosmic ray muon events in each of the three successive bunch crossings for the SCT where the timing of the SCT readout has been adjusted to obtain the maximum hit efficiency for the central bunch crossing interval.

Since the TRT consists of many straw drift tubes, the maximum drift time of around 50 ns for a straw has to be taken into account. During offline reconstruction, the time of the track in relation to the bunch crossing, known as the event phase, is calculated for the hits in the TRT. During readout, to take account of this maximum drift time the TRT reads out in a 75 ns time window from the nominal bunch crossing time to allow hits in the 25 ns bunch crossing interval to be read out.

Hits a long distance from the sense wires with long drift times arrive in the window if the event is very soon after the bunch crossing, as would be the case for collisions, but for events where the cosmic track arrives late in the bunch interval, the long drift time means that hits can arrive outside the 75 ns window which can lead to a loss of efficiency for the track finding. This can be clearly seen in Figure 5 which shows the efficiency for finding an event with a good offline reconstructed track with at least 3 hits in both the upper and lower halves of the silicon detectors, versus this event phase for all three Level 2 tracking algorithms, clearly showing the loss of efficiency for late tracks where the event phase is larger than around 25 ns. Both silicon algorithms are to a greater or lesser extent unaffected by the timing, since they read out multiple bunch crossings.

Figure 6 shows the event finding efficiency for reconstructing an event with a good cosmic track reconstructed with the offline algorithm and containing at least 3 silicon hits in both the upper and lower halves of the detector and with an event phase within the range -10 to 25 ns as a function of the offline track impact parameter.

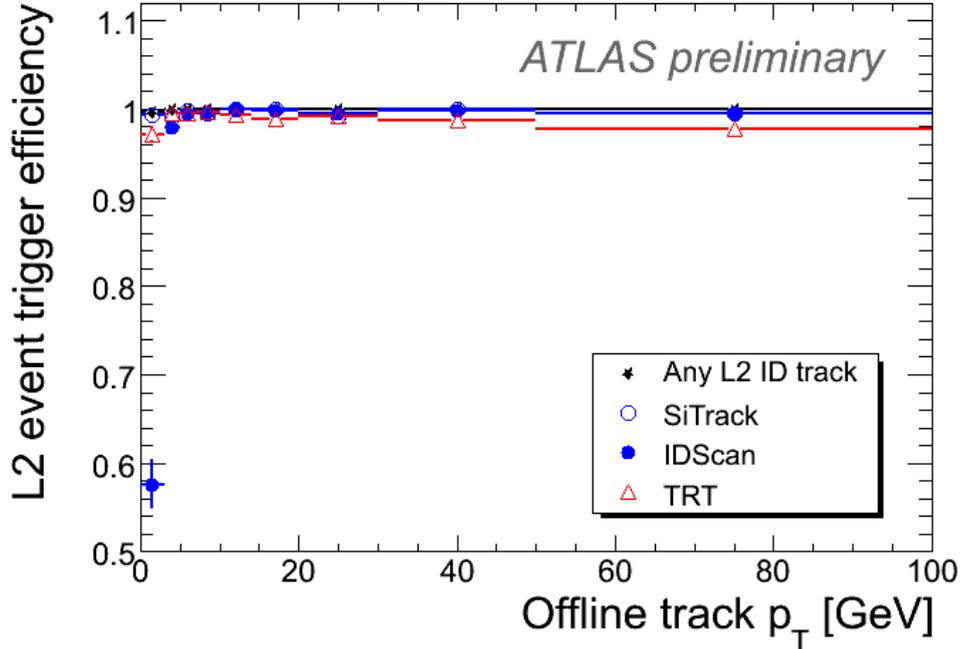For the TRT Segment finder, because of the larger size of the detector the efficiency is

Figure 7. The level 2 event finding efficiency for good offline tracks versus the offline reconstructed track p_T. The lower efficiency for IDScan in the lowest p_T bin is due to the inefficiency of the cosmic reconstruction spacepoint shifting algorithm in this range.

quite flat as a function of d0 and extends to quite a large impact parameter. For the silicon algorithms, SiTrack and IDScan, the efficiency starts to fall for impact parameters greater than about 250 mm corresponding to the region where there are no hits in the pixel detector and hits start to be lost from the inner layers of the SCT. The IDScan efficiency is slightly lower for IDScan than for SiTrack which can be understood by considering the efficiency as a function of the p_T of the offline reconstructed track shown in Figure 7.

For offline reconstructed tracks with high p_T the efficiencies for both SiTrack and IDScan are approximately the same, but at low p_T, the efficiency for IDScan is significantly lower than either of the two other algorithms.

For this study, SiTrack was running in the mode where it used unshifted spacepoints and with the relaxed beamline constraint. The loss of efficiency for IDScan is due to the spacepoint shifter which is only used for reconstructing cosmic tracks. Since it fits a straight track to calculate the impact parameter, this can be inaccurate at low p_T if the tracks have significant curvature. At higher p_T, when the tracks are straighter, the spacepoint shifting works well and this loss of efficiency does not occur so that the efficiency for both silicon based algorithms is comparable. Studies on collision Monte Carlo shows that the intrinsic efficiency of IDScan for low p_T tracks originating near the beamline, using no spacepoint point shift is comparable to that for SiTrack.

The combined efficiency for all three algorithms is better than 99% for all cosmics passing through the Inner Detector barrel volume and approaches 100% for high p_T.

5. Detector alignmnet
The large efficiency for reconstructing Inner Detector tracks from the Inner Detector Cosmic stream provides a large sample for alignment studies for the Inner Detector. This is useful for the trigger since it will improve the reconstructed track resolutions and enable higher precision calculation of track parameters for the determination of track impact parameter for selection of
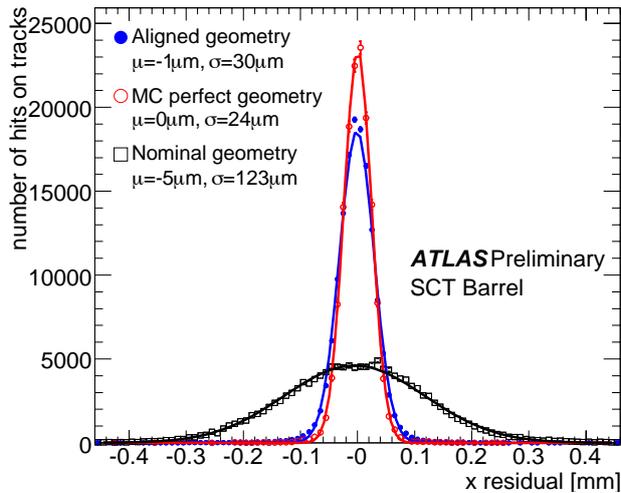
Figure 8. The $r - \phi$ residuals of SCT hits from offline reconstructed cosmic tracks showing the improvement of the residuals after the alignment procedure.

heavy flavour decays and tagging of b-jets.

Figure 8 shows the hit residuals along the wafer local x $(r-\phi)$ direction for the SCT hits from offline reconstructed cosmic tracks. This clearly shows the improvement of the residuals for the nominal reconstruction from around 120 μm before the alignment procedure, to the improved value of around 24 μm, comparable to that for the perfectly aligned detector simulated in the Monte Carlo of around 16 μm. The $r - \phi$ residuals for the Pixel detector shows a similar improvement since the Pixel and SCT $r - \phi$ pitches are similar at 50 μm and 80 μm respectively. Since the cosmics tracks essentially all lie in the vertical plane, the alignment of modules in the horizontal plane or in the endcap is not so precise.

6. Conclusions

The ATLAS Inner Detector Trigger is an essential feature of the ATLAS trigger to realise the physics goals of the LHC program. The Inner Detector Trigger has been routinely operated during the combined cosmic commissioning run collecting more than 300 million cosmic tracks, with more than 400 thousand with hits in the pixel detector allowing detailed performance studies of the algorithms themselves and providing high quality tracks for use in the detector alignment and further offline studies.

Both the Level 2 and Event Filter algorithms have been successfully deployed online and the Inner Detector Trigger commissioning program is already very advanced. The Inner Detector Trigger will be ready to meet the challenge of the first LHC collisions in the ATLAS detector expected for later in 2009.

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