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THE DESIGN AND PERFORMANCE OF THE ATLAS INNER DETECTOR TRIGGER IN HIGH PILEUP COLLISIONS AT 13 TEV AT THE LARGE HADRON COLLIDER

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The design and performance of the ATLAS Inner Detector (ID) trigger algorithms running online on the high level trigger (HLT) processor farm for 13 TeV LHC collision data with high pileup are discussed. The HLT ID tracking is a vital component in all physics signatures in the ATLAS Trigger for the precise selection of the rare or interesting events necessary for physics analysis without overwhelming the offline data storage in terms of both size and rate. To cope with the high expected interaction rates in the 13 TeV LHC collisions the ID trigger was redesigned during the 2013-15 long shutdown. The performance of the ID Trigger in the 2016 data from 13 TeV LHC collisions has been excellent and exceeded expectations as the interaction multiplicity increased throughout the year. The detailed efficiencies and resolutions of the trigger in a wide range of physics signatures are presented, to demonstrate how the trigger responded well under the extreme pileup conditions. The performance of the ID Trigger algorithms in the first data from the even higher interaction multiplicity collisions from 2017 are presented, and illustrates how the ID tracking continues to enable the ATLAS physics program currently, and will continue to do so in the future.

Keywords: trigger, track, HLT, tracking, vertex, vertexing, run 2, lhc, atlas, two-stage, roi, super-roi, pileup, performance, 2017, muon, jet, b-jet, efficiency, resolution, pixel, silicon, strip

1. The ATLAS Inner Detector and Inner Detector trigger system

The ATLAS detector is the largest of the four main experiments placed at interaction points around the ring of the Large Hadron Collider (LHC). ATLAS is a general-purpose cylindrical detector formed of a number of sub-detectors, each designed to measure different signatures of particles produced from LHC collisions [1].

The ATLAS Inner Detector (ID) is the sub-detector dedicated to measuring the paths charged particles take, known as tracks, as well as the positions charged particles originate from, known as vertices. The ID is formed of three sub-systems, which are each arranged in barrel or endcap configurations, depending on whether they are placed in the barrel or endcap regions of ATLAS. The first sub-system is the pixel detector, formed of layers of silicon pixel modules. Three layers of pixel modules are included in the barrel and endcap regions, with a fourth layer known as the Insertable B Layer (IBL) included closest to the LHC beamline in the barrel region. The IBL was added for LHC Run 2, and provides improved impact parameter resolution, which also results in improved identification of hadrons containing *b* quarks. Beyond the pixel detector is the Semiconducting Tracker (SCT), which is formed of four barrel and nine endcap layers of stereo-doublet silicon microstrip modules. Beyond the SCT is the Transition Radiation Tracker (TRT), which is formed of many gaseous straw tubes, and provides on average 36 hits per track. The TRT can also provide additional particle identification information.

The ID trigger is the part of the ATLAS High Level Trigger (HLT) system which performs fast online track and vertex reconstruction, using measurements from the ID. The HLT itself is a software-based trigger system which uses information from a hardware-based Level 1 (L1) trigger, which has run prior to the HLT, and measurements from all ATLAS sub-detectors to select collision events of interest. The HLT reduces the number of events to process and save to disk from a peak input rate of 100 kHz to an output rate of approximately 1 kHz.

The ID trigger is an essential part of this rate reduction for nearly all physics signatures. The tracks and vertices provided by the ID trigger allow the HLT to reconstruct physics-objects such as muons and hadronic jets with enough spatial precision to make effective HLT trigger decisions. This use of tracks and vertices becomes more important as the number of interactions per bunch crossing, known as pileup, increases; however, this increase in pileup also makes track and vertex reconstruction more difficult. In addition, track and vertex reconstruction are highly CPU intensive, which could produce a bottleneck within the HLT due to having to wait for track and vertex collections to be produced before running event reconstruction. This could result in "deadtime" in the HLT, where the processing rate is slower than the input rate, resulting in no computing resources being available during data taking.

The ID Trigger employs various methods to maintain accurate track and vertex reconstruction while keeping runtimes down. Firstly, tracking is split between two stages: the Fast Track Finder (FTF) which performs fast pattern recognition on hit clusters in the ID to produce an initial track collection; this is followed by precision tracking (PT) which takes the tracks found by the FTF and their hit clusters and improves the track quality while applying tighter requirements and handling hits shared between multiple tracks. The performance of both of these stages is comparable to the full offline track reconstruction algorithms. The second method used by the ID trigger is performing tracking and vertexing in reduced detector volumes known as Regions of Interest (RoIs). These RoIs are positioned based on information from the L1 trigger, and are sized according to the physics signature of interest. These RoI volumes reduce the amount of detector measurements that must be processed in each event. The third approach used by the ID trigger is employing multi-stage RoI methods which use multiple RoIs to further reduce the detector volume to be processed, and can further tailor RoI sizes to specific tasks within the ID trigger. This also allows reconstruction to be performed iteratively.

2. Multi-stage RoI methods

Two-stage tracking uses two RoIs in sequence, which allows reduced RoI volumes compared to using a single RoI. In this method, an initial first-stage RoI is defined which is long along the beamline, but narrow in phi and pseudorapidity[1]. The FTF is run in this first-stage RoI to produce an initial track collection; from this, a track or vertex of interest can be determined. A second-stage RoI can then be positioned centred on this track or vertex of interest. This second-stage RoI is much shorter along the beamline, but wider in phi and pseudorapidity. The FTF is then run again in the second-stage RoI, followed by the precision tracking to produce the final track collection. A cartoon comparing the sizes of the RoIs used in the two-stage tracking method to the standard one-stage method is shown in Figure .

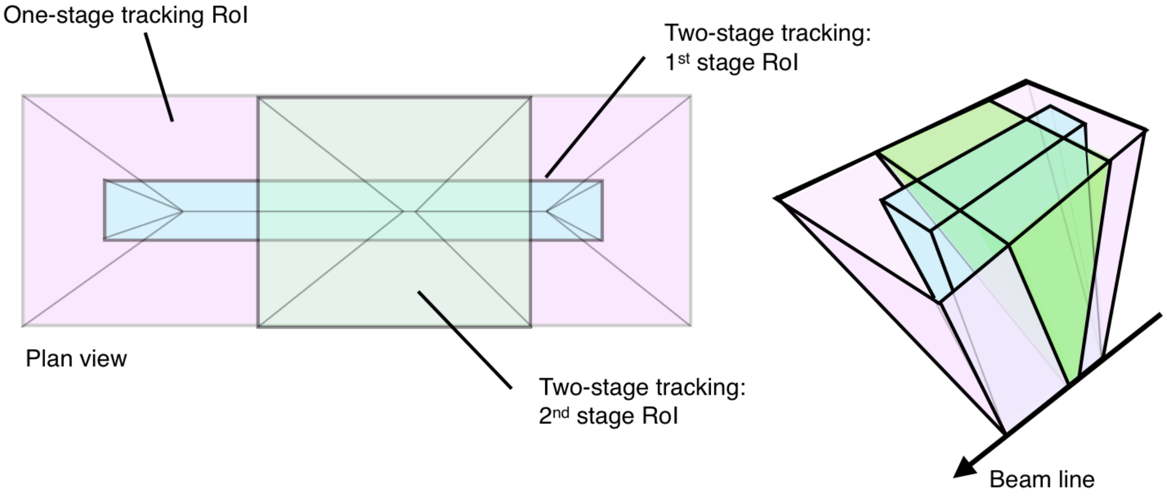

Figure 1. Illustration of RoIs from the one-stage tracking (pink) and two-stage tracking (blue - first stage, green - second stage) [2]

It can be seen that the total volume of the first- and second-stage RoIs of the two-stage tracking is less than the volume of the RoI used in the one-stage tracking. Two-stage tracking is employed in triggers for hadronic jets and hadronically decaying tau leptons. In these events, the position of interest along the beamline is not known from L1 trigger information; two-stage tracking allows this to be determined from the first-stage track collection. It has been seen from 2015 data that two-stage tracking results in a runtime improvement per-RoI compared to the one-stage method of approximately 20 ms for the FTF[2] on average, and approximately 7 ms for the PT on average.

Super RoIs combine multiple individual RoIs into a single geometric region, which avoids processing RoIs with overlapping volumes. This avoids processing the same tracks in multiple RoIs, which reduces processing time, and avoids double counting of tracks which can bias vertex reconstruction. In this method, multiple RoIs are defined which are long along the beamline, but narrow in phi and pseudorapidity, where the phi and pseudorapidity directions of each RoI are determined by information from the L1 trigger. These RoIs are then combined into the single super RoI volume. Tracking and vertexing can then be run in the super RoI. An example cartoon comparing multiple RoIs to a single super RoI is shown in Figure ; the overlapping regions can be seen in Figure a).

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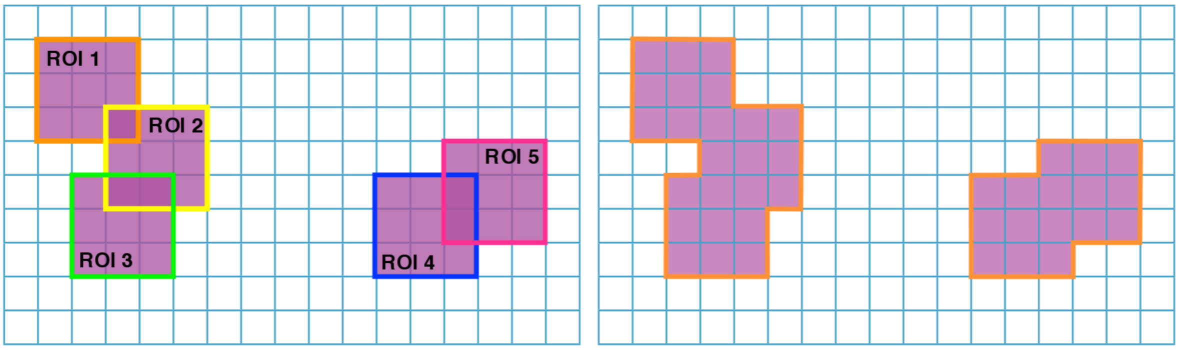
[1] Pseudorapidity is defined as $\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$, where θ is the angle from the beamline

[2] Comparing the FTF runtime for the single one-stage RoI to the sum of the FTF runtimes for the two two-stage RoIs



(a) Standard ROI approach

(b) Super-ROI approach

Figure 2. Illustration of a) multiple RoIs used in the standard RoI approach, b) single combined region used in the super RoI approach. The regions are defined in the phi-pseudorapidity plane

Triggers for hadronic jets containing *b* quarks, labelled as jet triggers in the performance plots in Section 3, employ both two-stage tracking and super RoI methods. In *b*-jet triggers, the individual RoIs that combine to form the super RoI use the phi and pseudorapidity of jets passing the L1 trigger requirements. Primary vertex reconstruction is run in the super RoI, and second-stage RoIs for each jet can be positioned around this primary vertex. The FTF and PT are run in the second-stage RoIs, followed by secondary vertex reconstruction needed for tagging hadrons containing *b* quarks.

3. Performance in 2017 data

During 2017, the LHC has been colliding protons at unprecedented scales as part of Run 2, with a collision energy of 13 TeV and instantaneous collision luminosity up to a peak of $20.5 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Due to these high rate conditions the collision pileup has also reached previously unseen values, with a peak average pileup of 78.1.

Performance of the ID trigger tracking has been evaluated in a subset of 2017 13 TeV data, showing the behaviour of the ID trigger in the strenuous conditions of Run 2. Performance is evaluated using triggers which do not use tracks in their decision making to avoid biasing the evaluation, but are otherwise identical to triggers used for physics data taking. Performance is defined relative to tracks found by the full offline tracking algorithms; efficiency is defined as the fraction of offline tracks found by the ID trigger tracking, and resolution is defined as the difference in track quantities between the offline track and corresponding ID trigger track.

For the performance evaluation of muon triggers, offline tracks matched to offline-reconstructed muons passing a medium quality requirement [3] are used. For the performance evaluation of jet triggers, all offline tracks within the trigger RoIs are used. Basic quality criteria on the number of track hits are also applied to offline tracks in both muon and jet trigger performance evaluations.

Figure shows the tracking efficiency in muon triggers as a function of average pileup. It is seen that the efficiency is greater than 99% across the full range of average pileup. In general, the ID trigger has been optimised to be robust up to a pileup of 80, and could maintain performance beyond this.

Figure and Figure show the tracking efficiency in muon triggers as a function of offline muon pseudorapidity and transverse momentum. It is seen that the efficiency is greater than 99% across the full range of both pseudorapidity and transverse momentum.

Figure and Figure respectively show the transverse impact parameter[3] resolution and spatial resolution along the beamline for muon triggers, as a function of offline muon transverse momentum. It is seen that the resolutions are in general excellent, going down to approximately 10 μm for transverse impact parameter and approximately 50 μm for position along the beamline resolution. It is seen that the PT improves track resolution compared to tracks from the FTF.

Figure shows the tracking efficiency in a jet trigger as a function of average pileup. Similar to muon triggers, the efficiency shows little dependence on pileup.

Figure and Figure show the tracking efficiency in a jet trigger as a function of offline track pseudorapidity and offline track transverse momentum. The efficiency is greater than 98% for central pseudorapidity, and is greater than 98% over most of the range of transverse momentum.

Figure and Figure respectively show the transverse impact parameter resolution and spatial resolution along the beamline for a jet trigger, as a function of offline track pseudorapidity. Good resolution performance is seen, going down to approximately 20 μm for transverse impact parameter and approximately 30 μm for position along the beamline resolution. The resolutions degrade as a function of pseudorapidity due to tracks passing through more detector material, resulting in increased multiple scattering.

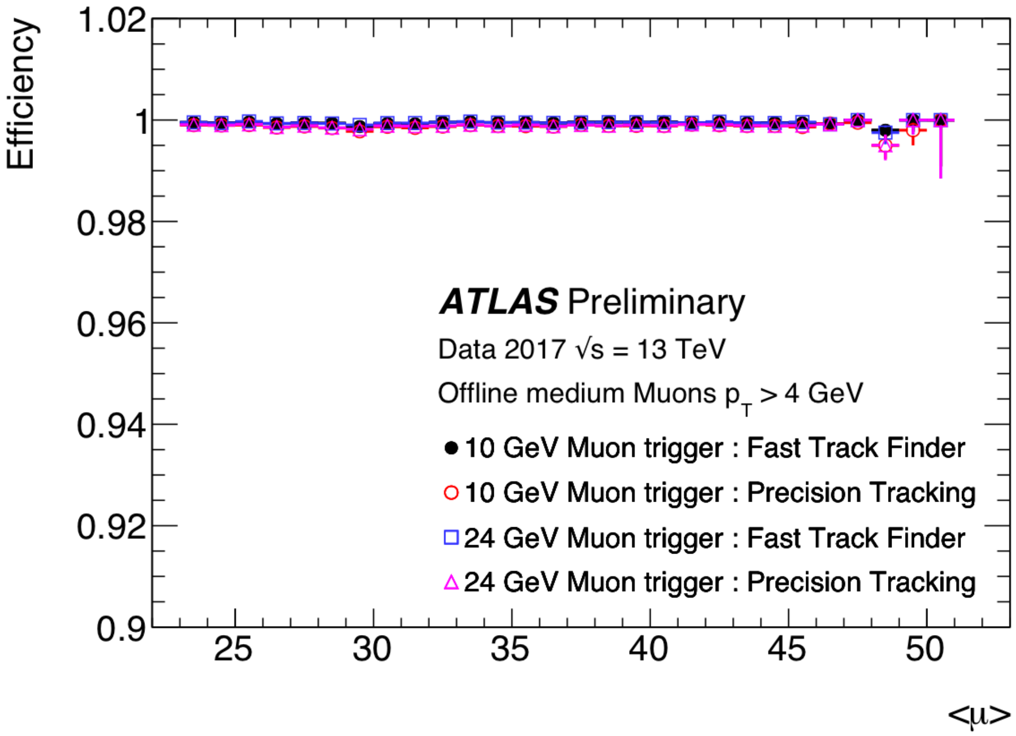


Figure 3. Track finding efficiency in muon triggers as a function of mean number of interactions per bunch crossing [2]

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[3] Transverse impact parameter is defined as the distance of closest approach to the beamline, in the plane transverse to the beamline

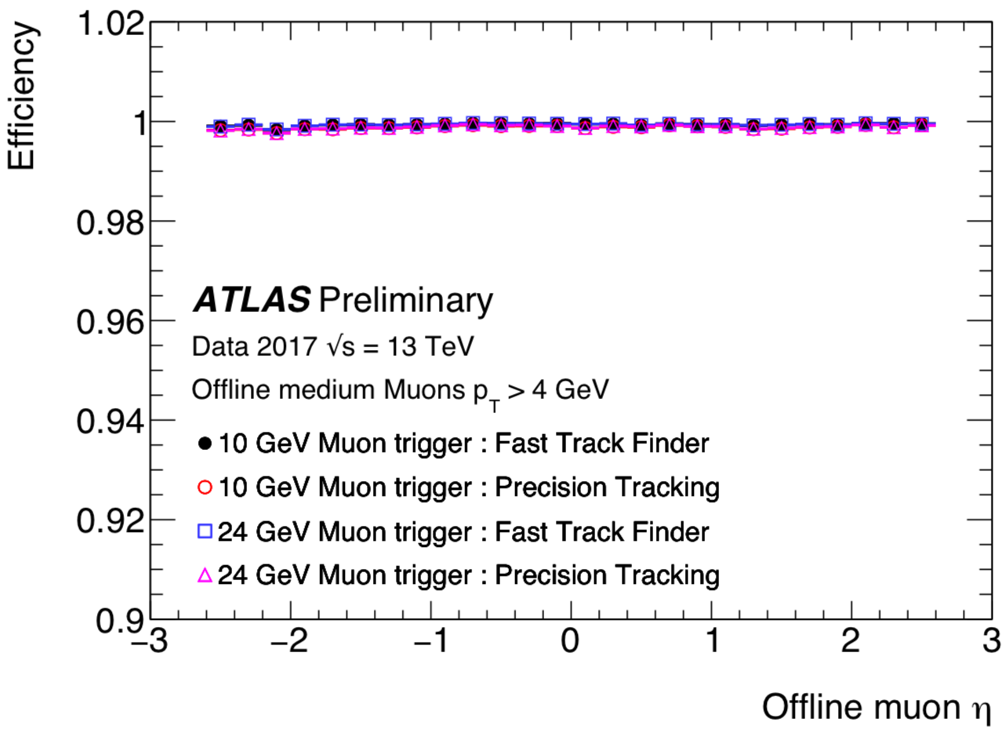

Figure 4. Track finding efficiency in muon triggers as a function of offline muon pseudorapidity [2]

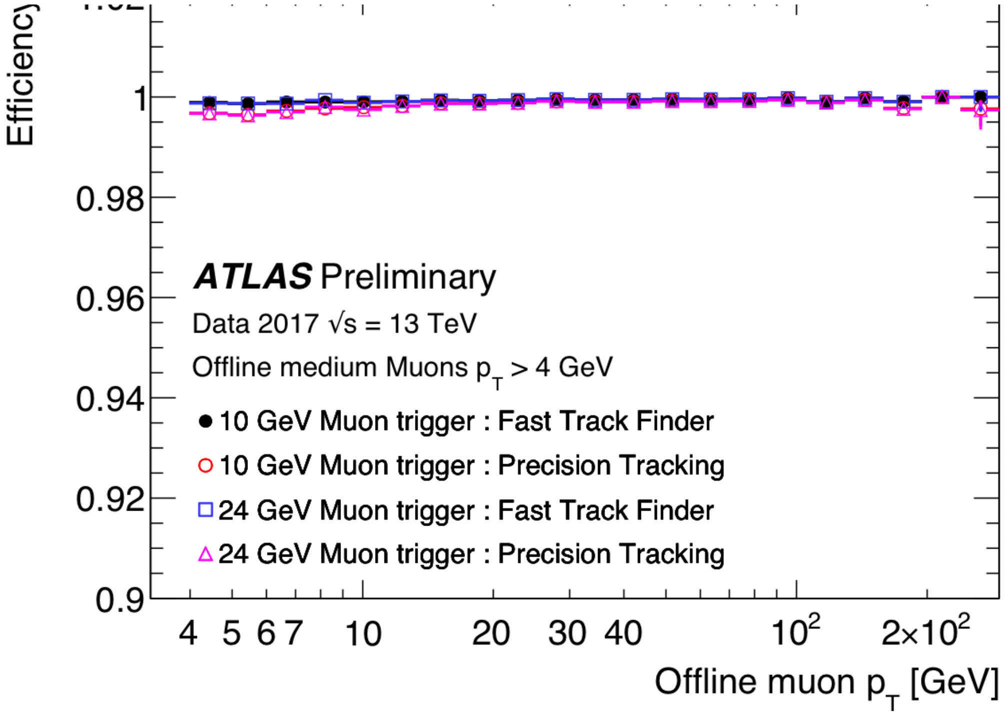

Figure 5. Track finding efficiency in muon triggers as a function of offline muon transverse momentum [2]

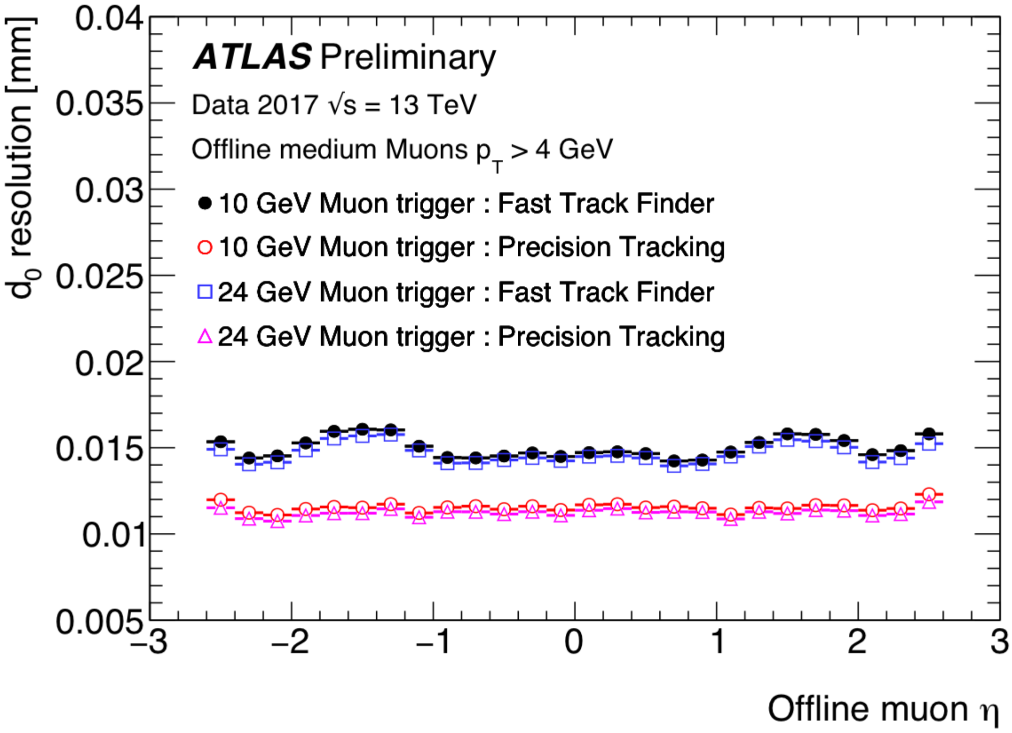

Figure 6. Track transverse impact parameter resolution in muon triggers as a function of offline muon transverse momentum [2]

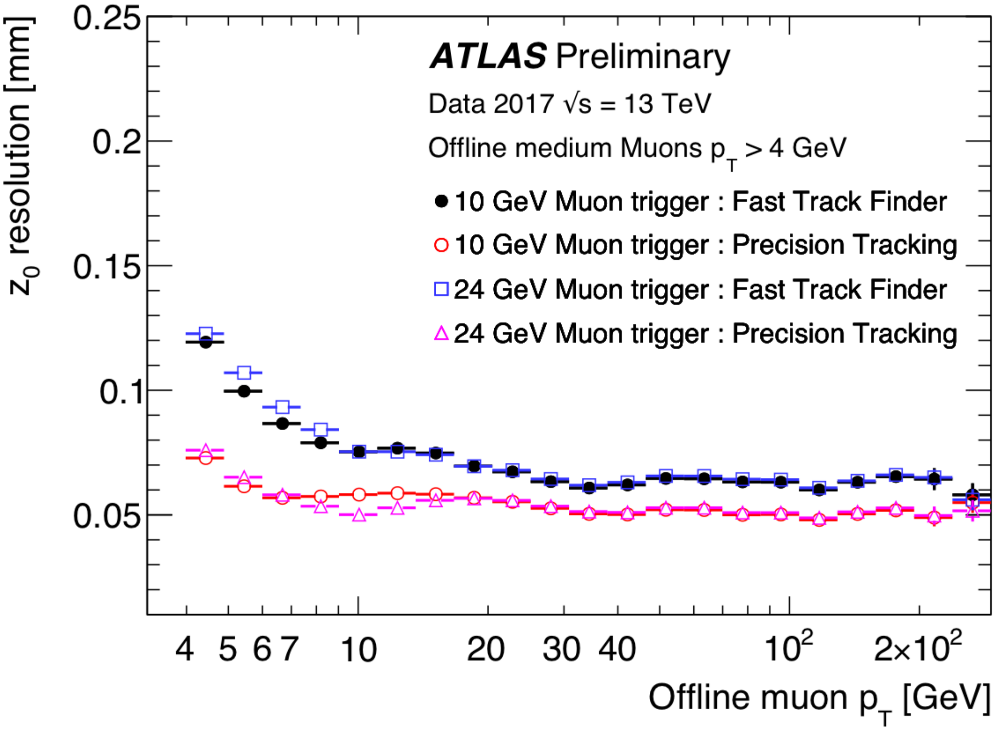

Figure 7. Track spatial resolution along the beamline in muon triggers as a function of offline muon transverse momentum [2]

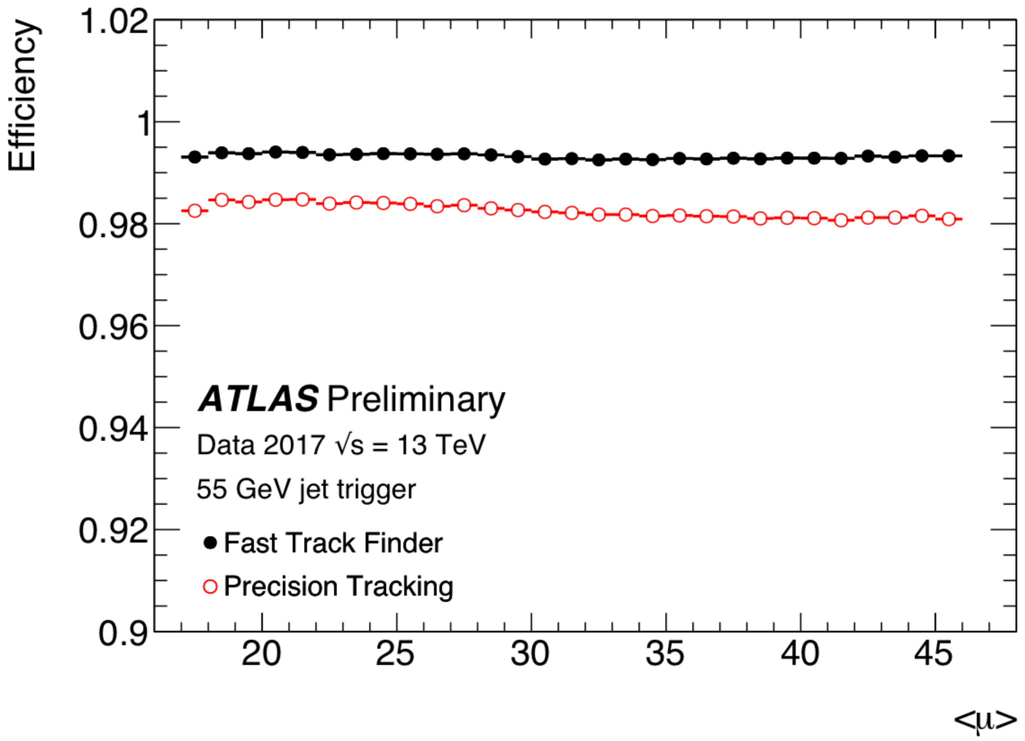

Figure 8. Track finding efficiency in a jet trigger as a function of mean number of interactions per bunch crossing [2]

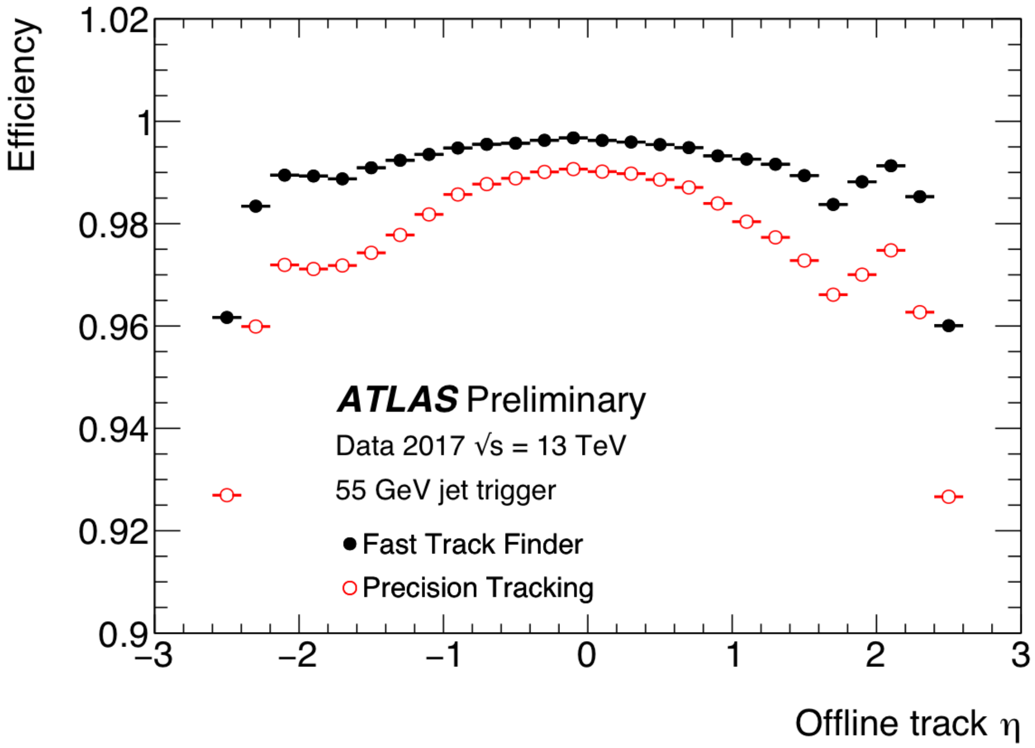

Figure 9. Track finding efficiency in a jet trigger as a function of offline track pseudorapidity [2]

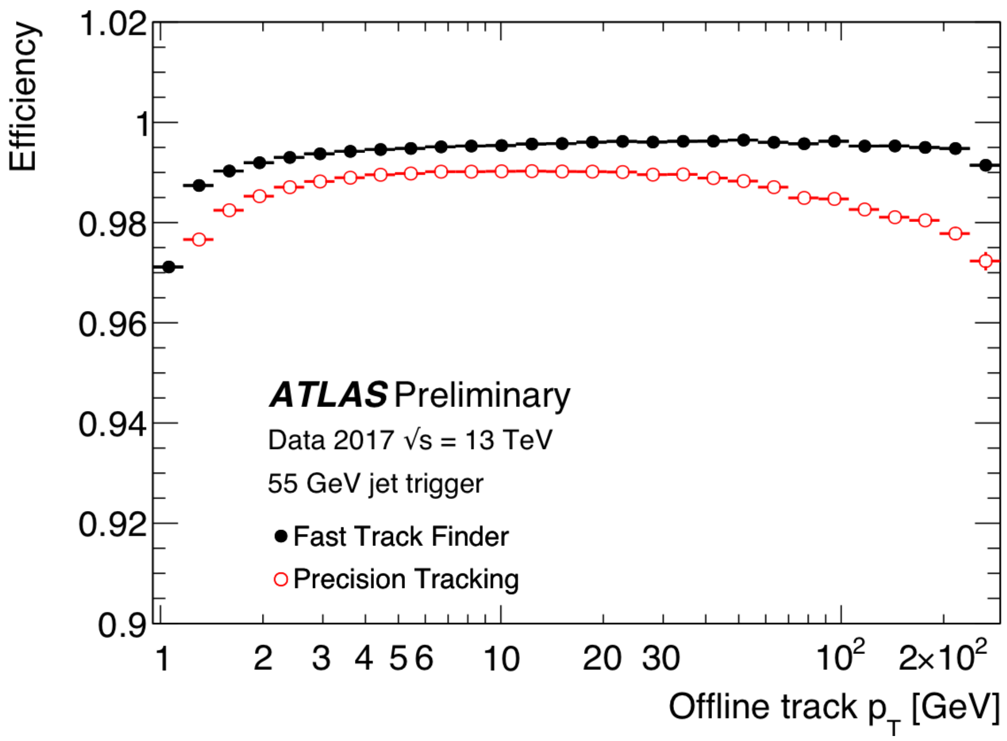

Figure 10. Track finding efficiency in a jet trigger as a function of offline track transverse momentum [2]

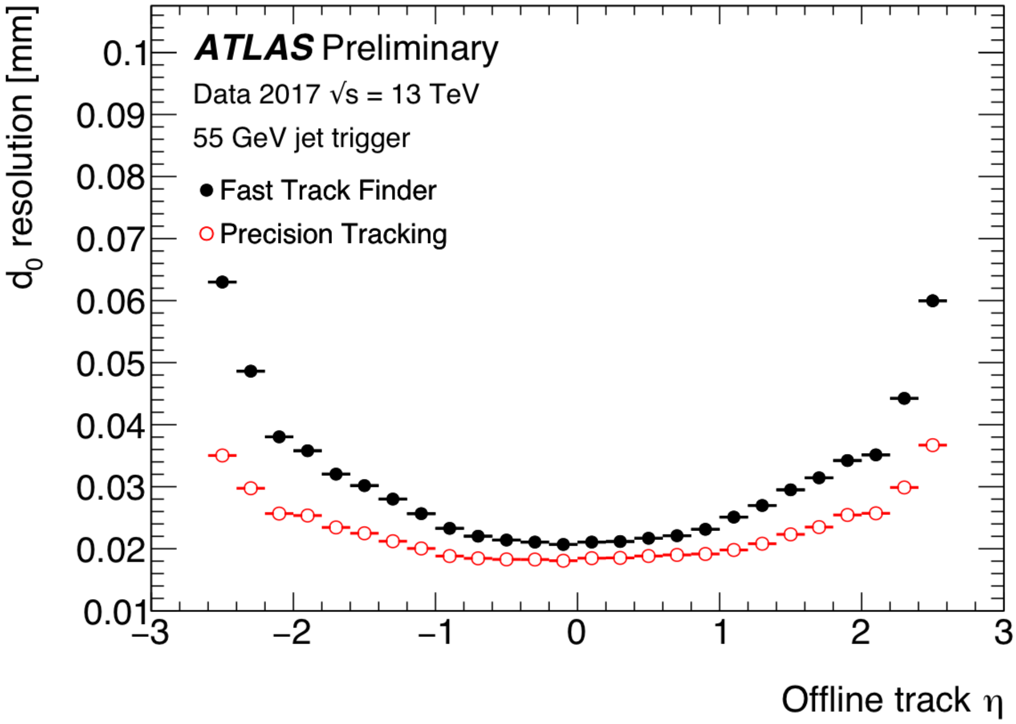

Figure 11. Track transverse impact parameter resolution in a jet trigger as a function of offline track pseudorapidity [2]

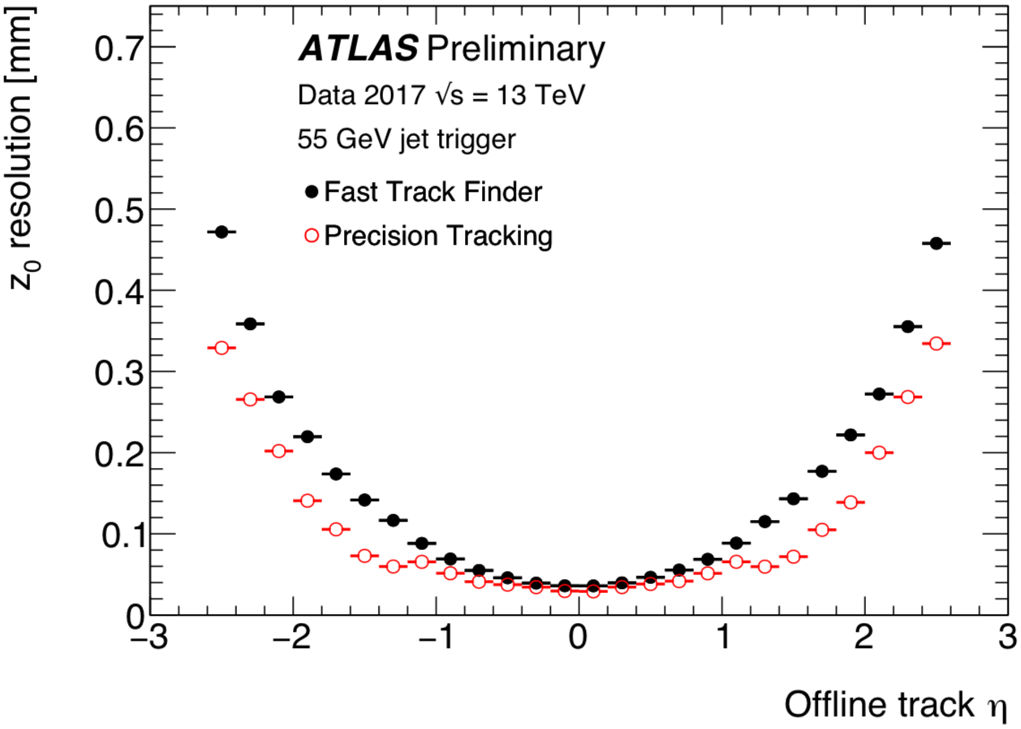

Figure 12. Track spatial resolution along the beamline in a jet trigger as a function of offline track pseudorapidity [2]

4. Conclusion

The ID trigger is a vital component of the ATLAS trigger system, and the high trigger efficiencies and necessary rate reduction would not be possible without it. During the strenuous conditions of LHC Run 2, the ID trigger has employed multi-stage RoI methods to mitigate the high collision rate and pileup: two-stage tracking allows further reduction in detector volumes processed by the ID trigger, while super RoIs avoid multiple processing and double counting of tracks.

The performance of the ID trigger in 2017 data taking is seen to be excellent, showing high track finding efficiencies and accurate spatial resolutions. In addition, track finding efficiency is seen to be insensitive to the high pileup conditions of LHC Run 2. The ID trigger is expected to continue providing excellent performance as LHC Run 2 continues.

References

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[3] The ATLAS Collaboration. Muon reconstruction performance of the ATLAS detector in proton-proton collision data at √s = 13 TeV. Eur. Phys. J. C76 (2016) no.5, 292.