Tracking performance with the HL-LHC ATLAS detector

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The High-Luminosity Large Hadron Collider (HL-LHC) aims to increase the LHC data-set by an order of magnitude in order to increase its potential for discoveries. The high pileup at the HL-LHC presents a highly challenging environment to particle detectors. To cope with this, the current Inner Detector of the ATLAS experiment will be replaced with a new all-silicon Inner Tracker (ITk). The expected tracking performance of the ITk is presented and impact of the tracking performance on vertex reconstruction, jet flavour tagging and pileup jet rejection is shown. These studies were performed for two possible options of the pixel sensor pitch.

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1. Introduction

In the middle of 2026 the start of the High-Luminosity LHC (HL-LHC) is planned. The HL-LHC represents a dramatic step in the LHC performance – it will operate at an instantaneous luminosity of up to 7.5×10^{34} cm^{-2}s^{-1}, delivering an integrated luminosity up to 4000 fb^{-1}. This environment implies a big change in experimental conditions – an average number of proton–proton collisions per bunch crossing, $\langle\mu\rangle$, up to 200 is expected. Extensive detector upgrades will enable the ATLAS experiment [1] to operate at HL-LHC. In particular the current Inner Detector will be replaced by the new Inner Tracker (ITk) during the Phase-II upgrade. One key figure of merit when designing the ITk is the tracking performance and its impact on the physics object reconstruction.

2. The ATLAS Inner Tracker

The ATLAS Inner Tracker is an all-silicon detector, consisting of a pixel subsystem (5 barrel layers + 2 sets of 5 endcap discs) and a strip subsystem (4 barrel layers + 2 sets of 6 endcap wheels). The Technical Design Reports for the pixel [2] and strip [3] subsystems describe the design of the ITk in detail (the design has been evolving [4] since the publication of the reports). The ITk has many advantages: the extended pseudorapidity[1] coverage up to 4, an excellent granularity due to a smaller pixel sensor size: 50×50 μm^2 or 25×100 μm^2 (the pixel pitch is under consideration [4]), a reduced amount of detector material traversed by particles and short time needed for the track reconstruction.

3. Tracking performance

3.1. Hermeticity

The ITk will provide an excellent hermeticity. The desired minimum 9 pixel and strip measurements on the track in the full detector acceptance will be ensured as it is shown in Figure 1 by using single muon events with the transverse momentum p_T = 1 GeV. The number of tracks with fewer hits will be very small and these tracks represent rare cases of particles passing through the gaps between strip or pixel modules.

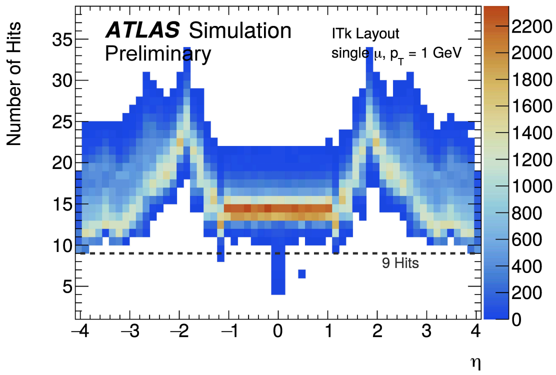
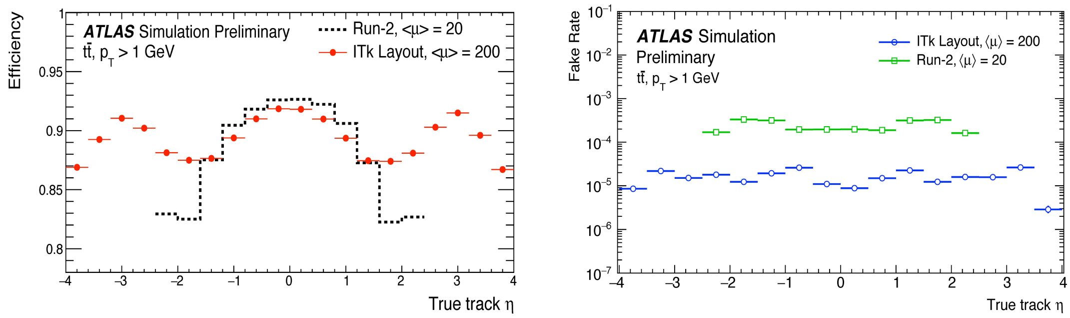


Figure 1: The number of pixel and strip measurements on track for single muon events with p_T = 1 GeV [4].

3.2. Reconstruction efficiency and fake tracks

The key observables for the tracking performance are: the reconstruction efficiency and the rate at which "fake" tracks are reconstructed. The reconstruction efficiency is defined as the fraction of prompt particles which are associated with tracks passing a track quality selection and

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) and the z-axis along 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. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$, θ is the polar angle.



(a) (b)

Figure 2: The track reconstruction efficiency **(a)** and fake rate **(b)**, for $t\bar{t}$ events with $\langle\mu\rangle = 200$ for the ITk and $\langle\mu\rangle = 20$ for Run-2 [4].

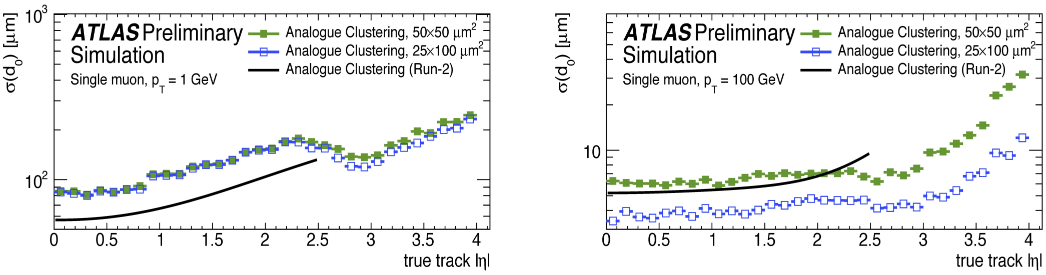
the fake rate is the fraction of tracks not corresponding to any prompt particle. Figure 2 presents the efficiency and fake rate for tracks from the hard-scatter (HS) interaction in $\langle\mu\rangle = 200$ $t\bar{t}$ events. The efficiency in the central region is expected to be comparable to the current Inner Detector result (Run-2), while for $|\eta| > 2$ the ITk will significantly improve the efficiency. The fake rate in the ITk is predicted to be very low due to the high number of silicon precision hits per track.

3.3. Track parameter resolution

The transverse (d_0) and longitudinal (z_0) impact parameter resolution, as well as the particle transverse momentum resolution determine the expected performance of the ITk in terms of physics object reconstruction such as *b*-tagging and lepton or jet reconstruction. The resolutions are presented in Figures 3 and 4 for single muon events with p_T = 1 or 100 GeV. For p_T = 1 GeV they are dominated by a multiple scattering but for p_T = 100 GeV intrinsic resolutions have the biggest impact.

Figure 3 shows the transverse impact parameter resolution. For p_T = 100 GeV the pixel pitch choice is important (Figure 3(b)). With a pixel pitch 50×50 μm^2 the resolution is expected to be comparable to Run-2 due to the 50×250 μm^2 size used in the Insertable B-Layer (IBL) [5] in the current ATLAS detector. A pitch of 25×100 μm^2 will visibly improve the resolution due to the improved intrinsic resolution of the ϕ coordinate of pixel sensors. For p_T = 1 GeV the ITk in the current layout [4] will not match the Run-2 result (Figure 3(a)) because the distance of the innermost pixel layer from the beam spot in the ITk (39 mm) is larger than in the IBL (33 mm) [5].

The longitudinal impact parameter resolution is expected to match the Run-2 result for low p_T, but for high p_T the ITk will dramatically improve the resolution for both pixel pitch options (Figure 4(a)) due to the larger longitudinal pixel size in the IBL.



(a) (b)

Figure 3: The resolution of transverse impact parameter for single muon events with p_T = 1 GeV **(a)** and p_T = 100 GeV **(b)** [4].

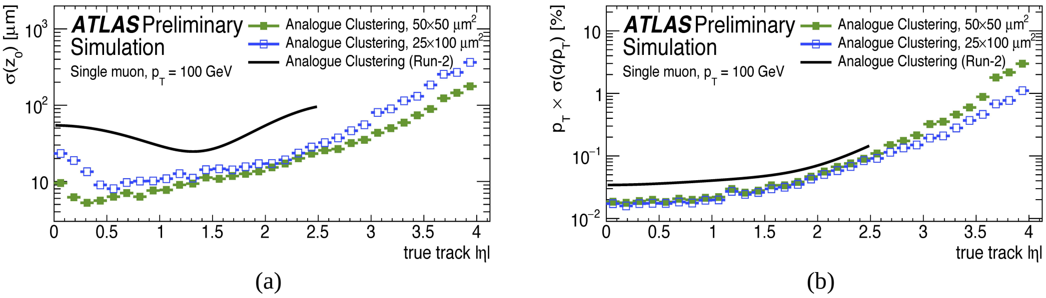


Figure 4: The longitudinal impact parameter resolution **(a)** and the transverse momentum resolution **(b)**, for single muon events with p_T = 100 GeV [4].

The transverse momentum resolution for the ITk is expected to improve Run-2 results for both p_T values and both pixel sizes due to the higher intrinsic resolution in the bending direction of the strip sensors used in the radial region where the current Inner Detector uses straw tubes. For $p_T = 100$ GeV the improvement will be greater and present in the full $|\eta|$ range of Run-2 (Figure 4(b)).

3.4. Vertexing

The reconstructed tracks are the input for the reconstruction of candidates for the interaction vertex. In the ITk the vertex reconstruction is performed by using the Adaptive Multi-Vertex Finder algorithm, which uses the same fitting technique as the Iterative Vertex Finder algorithm used during Run-2 [6], but it fits for several vertices simultaneously.

Figure 5(a) presents the vertex reconstruction efficiency for $\langle\mu\rangle$ = 200 events of Higgs boson produced via Vector Boson Fusion (VBF) and decaying invisibly via $H \to 4\nu$. The efficiency is defined as the expected fraction of events in which the vertex corresponding to the HS interaction is successfully reconstructed (ie. the vertex is within a 2 mm window around the generator-level HS vertex) as a function of the local pileup density. The efficiency in the ITk is expected to be greatly improved – for VBF $H \to 4\nu$ it will be close to 90% and slightly dependent on the pileup density.

Figure 5(b) shows the expected resolution in the z coordinate of successfully reconstructed vertex candidates for $\langle\mu\rangle$ = 200 $t\bar{t}$ events. The ITk will significantly improve the resolution compared to Run-2, both in magnitude and in robustness against pileup.

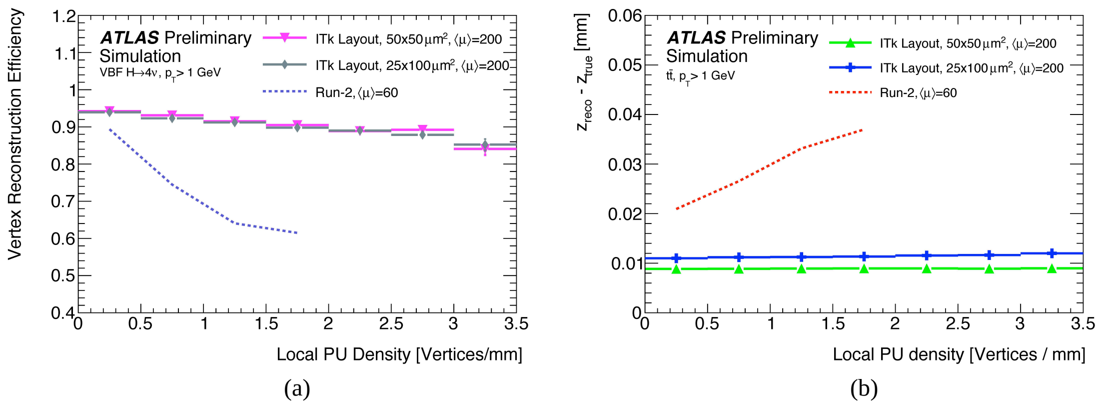
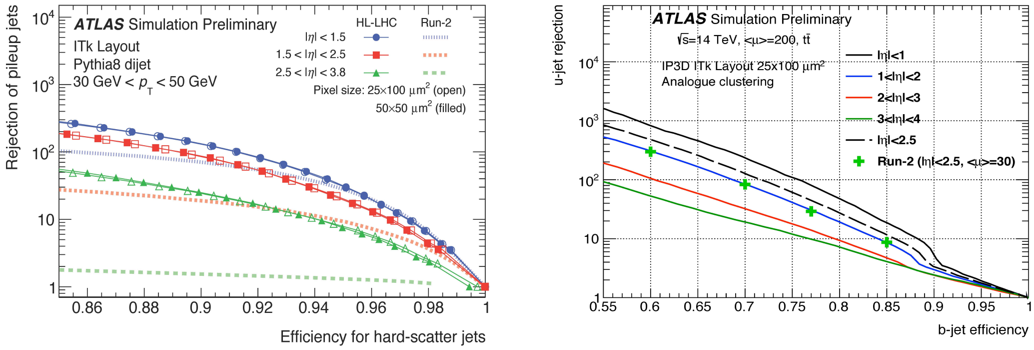


Figure 5: The vertex candidates reconstruction efficiency for VBF $H \to 4\nu$ events **(a)** and the resolution in the z coordinate of successfully reconstructed vertex candidates for $t\bar{t}$ events **(b)**, both at $\langle\mu\rangle$ = 200 for the ITk and $\langle\mu\rangle$ = 60 for Run-2, studied as a function of the pileup density [4].



(a) (b)

Figure 6: The rejection of jets from pileup events using the R_{pT} discriminant as a function of the efficiency for jets from the hard scatter vertex for di-jet events **(a)** and the rejection of light-flavour jets with the IP3D tagger as a function of the efficiency for retaining b-jets for $t\bar{t}$ events **(b)**, both at $\langle\mu\rangle = 200$ for the ITk and $\langle\mu\rangle \sim 30$ for Run-2 [4].

3.5. Pileup jet rejection and jet flavor tagging

The tracking information is used to discriminate between jets from pileup vertices and jets from the HS vertex. Figure 6(a) presents the predicted pileup jet rejection using the R_{pT} discriminant as a function of the efficiency for retaining jets from the HS vertex for $\langle\mu\rangle = 200$ di-jet events. The R_{pT} discriminant is defined as the scalar sum of the p_T of the tracks associated with the jet originating from the HS vertex, divided by the calibrated jet p_T [7]. In the central region the pileup jet rejection is expected to be relatively close to Run-2, but in the forward region the ITk will clearly improve the rejection (for $|\eta| > 2.5$ the Run-2 result is based on calorimeter-timing information).

Track impact parameters are used to separate heavy flavour jets originating from *b*- and *c*-quarks from jets originating from light quarks and gluons. Figure 6(b) shows the expected rejection of light-flavour jets with the IP3D tagger [8] as a function of the efficiency for retaining *b*-jets for $\langle\mu\rangle = 200\, t\bar{t}$ events. The ITk is expected to surpass light-flavour jet rejection for Run-2 and a 25×100 μm² pixel pitch can improve the rejection due to the improved resolution in the transverse impact parameter.

4. Conclusions

The tracking performance of the ITk for two options of the pixel sensor pitch: 50×50 μm² and 25×100 μm², in general is expected to improve over the Run-2 level. Predictions for the performance of vertex reconstruction, pileup jet rejection and jet flavor tagging are promising. These performances will retain or exceed the Run-2 level, with high robustness against pileup.

References

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