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Expected tracking performance of the ATLAS Phase-II Inner Tracker Upgrade

Thomas Strebler[a,*] **for the ATLAS collaboration**

[a] *CPPM,*
Aix-Marseille Université, CNRS/IN2P3, Marseille, France

E-mail: thomas.strebler@cern.ch

The upgrade to the High-Luminosity LHC (HL-LHC), with its increase to 140-200 proton-proton collisions per bunch crossing, poses formidable challenges for track reconstruction. The Inner Tracker (ITk) is a silicon-only replacement of the current ATLAS tracking system as part of its Phase-II upgrade, designed to meet the challenges and continue to deliver high-performance track reconstruction. This contribution gives an overview of the expected performance of tracking and its impact on higher level objects. The ITk most recent layout optimisation and developments, and their impact on tracking performance, will also be reviewed.

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

*Speaker

https://pos.sissa.it/

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1. The ATLAS Phase-II Inner Tracker upgrade

The High-Luminosity LHC (HL-LHC) is expected to operate from 2029, with an instantaneous luminosity up to 7.5 $\text{cm}^{-2}\text{s}^{-1}$ and an average number of inelastic proton collisions per bunch crossing ($\langle\mu\rangle$) up to 200, compared to a peak luminosity around 2.0 $\text{cm}^{-2}\text{s}^{-1}$ and $\langle\mu\rangle$ up to 55 for Run 3. Those data-taking conditions will present unprecedented challenges for the tracking detector of the ATLAS experiment, induced by the increased level of radiation and higher detector occupancy. In order to guarantee tracking performance at least equivalent to what is currently achieved with the Run 3 detector, a new all-silicon Inner Tracker (ITk) [1, 2] illustrated in Fig. 1 will replace the current Inner Detector (ID) [3]. The layout of the ITk detector, made of the inner Pixel and outer Strip detector, is presented in Fig. 2. The Pixel detector consists of five flat barrel layers and multiple inclined or vertical ring-shaped end-cap disks, extending the coverage up to $|\eta| = 4.0$. The Strip Detector has four strip double-module layers in the barrel region and six end-cap disks, covering the pseudorapidity range up to $|\eta| < 2.7$. The increased ITk tracking coverage in the forward region with respect to the ID is an opportunity to improve the object reconstruction acceptance and pileup suppression, which will be one of the main challenges for object reconstruction at HL-LHC.

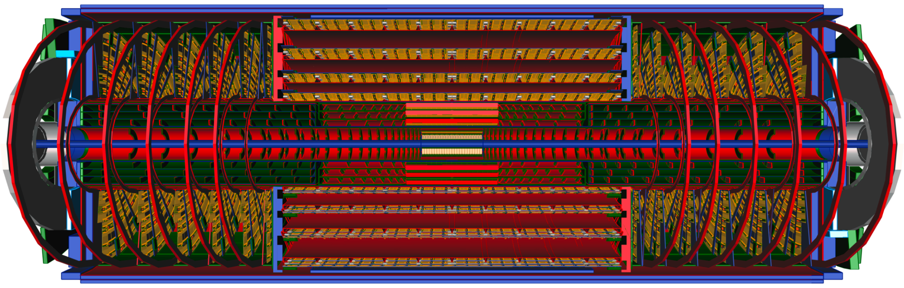


Figure 1: Display of the ITk detector. [4]

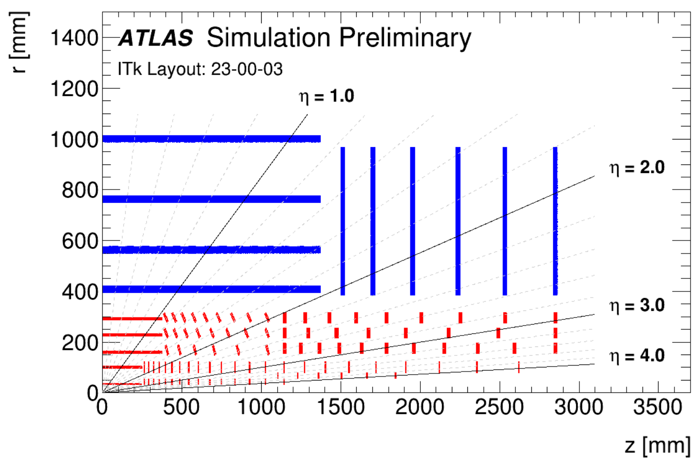


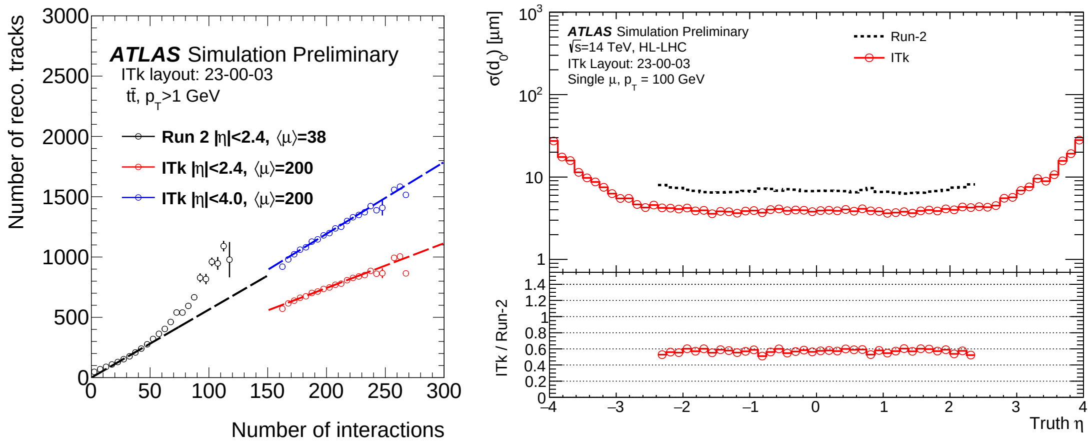
Figure 2: A schematic depiction of the most recent ITk layout. The active elements of the strip detector are shown in blue, and those of the pixel detector are shown in red. [4]

Since the ITk Pixel Technical Design Report [2], the layout of the detector has known several evolutions described in [4, 5]. With its most recent layout, following a thorough technical review, the radius of the barrel section of the innermost pixel layer has in particular been reduced from 39 down to 34 mm, motivated by the expected improvement in tracking performance. The use of a smaller pixel pitch of 25×100 or 50×50 μm^2 with respect to the ID is also playing a key role in mitigating the higher particle density expected with the larger pileup and to improve the track impact parameter resolutions. Recent studies have examined the impact on tracking performance of a staged installation of the ITk Pixel detector [8], in particular focused on an option where the outermost pixel layer would be installed after Run 4, to allow for some contingency in the tight Long Shutdown 3 schedule. This has been the opportunity to confirm that the five-layer design of the ITk Pixel detector guarantees a much better robustness against detector defects, while at the same time offering the possibility to reduce the CPU consumption required for track reconstruction, through the use of selections applied early in the algorithms, which will be a critical element both for offline and trigger reconstruction.

2. Expected tracking performance

Thanks to the optimal exploitation of the ITk layout, excellent tracking performance is expected at $\langle\mu\rangle = 200$ in spite of the high density of pileup particles. The tracking efficiency in the central region in particular is expected to be compatible within 5% with the one achieved with the ID, while reaching a similar level in the newly accessible forward region. One of the main challenges for tracking reconstruction in a $\langle\mu\rangle = 200$ environment is to keep under control the amount of "fake" tracks, reconstructed from combinations of hits originating from different particles. Thanks to the combination of an optimised seeding strategy and of hit requirements directly benefiting from the optimal detector layout, a negligible fake rate can be achieved with ITk, as illustrated in Fig. 3a, where a linear dependence is observed for the number of reconstructed tracks as a function of the number of pileup interactions, unlike with the Run-2 reconstruction which was associated with a larger fake rate. The improvement achieved in the transverse impact parameter (d_0) resolution is highlighted in Fig. 3b and directly connected with the smaller pixel pitch available with ITk. The transverse momentum resolution for high-p_T charged particles is also improved owing to the better silicon strip sensor resolution in the bending direction, compared to the current Transition Radiation Tracker detector.

While primary track reconstruction is optimised for charged particles produced in the primary interaction or from secondary vertices with limited displacements (from τ lepton or B hadron decays), dedicated tracking algorithms are also used to reconstruct particles associated with a larger displacement. Those are typically designed to run after the primary track reconstruction, using as inputs the silicon hits not yet used for the reconstruction of primary tracks. A dedicated reconstruction pass, seeded by clusters in the electromagnetic calorimeter, is for instance used for photons converting into an electron-positron pair after a material interaction, while the Large Radius Tracking (LRT) reconstruction aims at reconstructing the decay products of long-lived particles predicted in some Beyond-the-Standard-Model scenarios. The performance of those algorithms re-optimised for ITk is illustrated in Fig. 4, with a good reconstruction efficiency achieved up to the first ITk strip layer at a radius of 400 mm. The LRT reconstruction can in particular be tuned



(a) **(b)**

Figure 3: (a) Number of reconstructed tracks per event with p_{T}>1 GeV for $t\bar{t}$ events at $\langle\mu\rangle = 200$ with ITk compared with the Run 2 detector at $\langle\mu\rangle = 38$. The dashed lines illustrate the results of linear fit performed over the limited range corresponding to 160-200 (0-40) interactions for ITk (the Run 2 detector) to illustrate the pileup dependence of this quantity. (b) Transverse impact parameter (d_0) resolution as a function of η for 100 GeV muons without pileup, compared between the Run 2 detector and the updated ITk layout. [4]

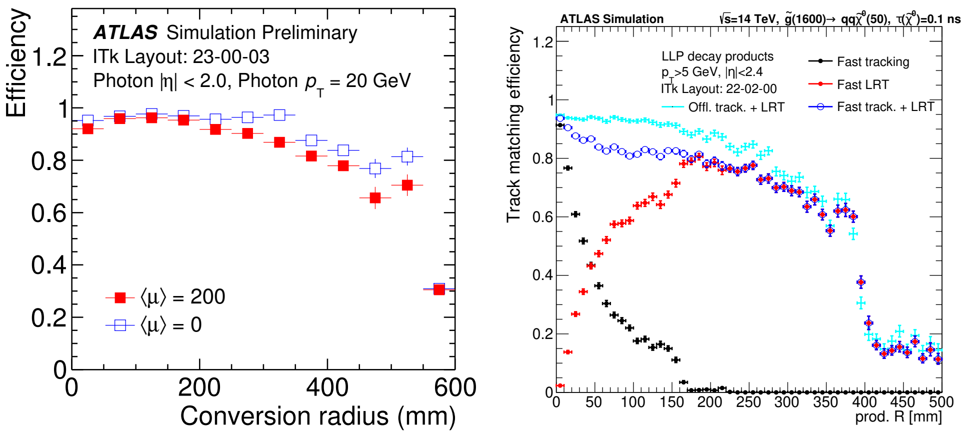
to run in a full software-based prototype of the track reconstruction at trigger level (fast LRT) [6] compatible with the timing requirements of trigger algorithms, while maintaining a very good trigger acceptance.

3. Expected performance for high-level object reconstruction

In order to mitigate the expected increase in local pileup density around the hard-scatter primary vertex, a new Adaptive Multi-Vertex Fitter and Finder (AMVF) reconstruction algorithm has been commissioned for the Run 3 reconstruction already [7]. Its improved robustness against pileup has been confirmed also with ITk in $\langle\mu\rangle = 200$ conditions, as shown in Fig. 5a. The improvement achieved in the longitudinal position resolution of the primary vertex has a direct impact on the performance of jet-tagging algorithms, as in the case of b-tagging. Pileup jet rejection algorithms will also benefit from an improved rejection, illustrated in Fig. 5b, which will be instrumental in the high pileup environment of HL-LHC. The extended $|\eta|$ coverage gives also the opportunity to improve their performance by more than one order of magnitude in the forward region with respect to Run 2, since the current ATLAS detector can only rely on calorimeter timing information in that case.

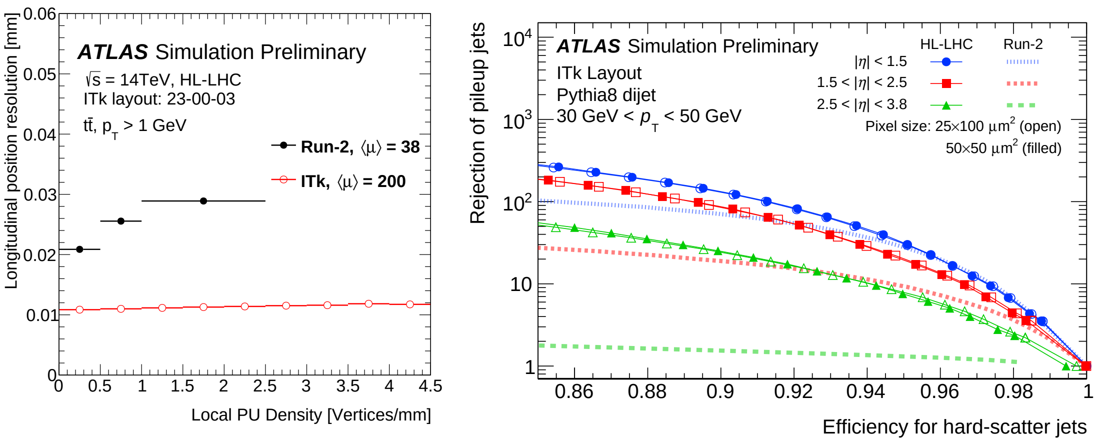
4. Software developments

In view of Run 4 data-taking, the tracking reconstruction software will undergo a major transition, moving from a custom ATLAS implementation to the use the external detector-generic ACTS software library [9]. This evolution will have a major impact, not only on the ITk track reconstruction but on many reconstruction algorithms relying on tracking algorithms, such as



(a) (b)

Figure 4: (a) Reconstruction efficiency for converted photons with p_T= 20 GeV as a function of their conversion radius, with and without pileup [4]. (b) Track reconstruction efficiency as a function of the production radius the fast LRT reconstruction. The efficiency is estimated for long-lived neutralino decay products with p_T> 5 GeV and $|\eta|$ < 2.4. The efficiency for the primary fast tracking trigger reconstruction (black) is compared with the standalone trigger fast LRT reconstruction (red), the combined trigger primary fast tracking and LRT (dark blue) and the combined offline primary fast tracking and LRT (cyan). [6]



(a) (b)

Figure 5: (a) Longitudinal position resolution of the reconstructed primary vertex, evaluated in $t\bar{t}$ events with $\langle\mu\rangle$ = 200, obtained with the updated ITk layout and the AMVF algorithm. For comparison, the performance obtained with the Run 2 Inner Detector with the IVF algorithm and an average pileup of 38 is also shown. [4] (b) Pileup jet rejection as a function of the hard-scatter jet efficiency for jet with 30 < p_T < 50 GeV using the R_{pT} pileup jet discriminant. Results for di-jet events with $\langle\mu\rangle$ = 200 are compared to the Run-2 performance. [5]

electron, Particle-Flow, secondary vertex and muon reconstruction. A major benefit is expected thanks to the optimal and efficient code design available in this external library, which will provide an improved maintainability and will be instrumental to fulfill the Run 4 computing requirements. The migration to this library will also offer a better modularity in order to study alternative implementations of some parts of the tracking reconstruction chain, in particular based on machine-learning algorithms such as Graph Neural Networks.

5. Conclusion

The ITk detector will face unprecedented challenges for tracking reconstruction, related in particular to the sizable increase in detector occupancy due to larger pileup. Despite this, excellent tracking performance is expected, both for particles produced in the primary interaction or from displaced vertices, directly benefiting from the optimized ITk detector layout and years of experience in tracking reconstruction with the current ATLAS detector. A major evolution for the tracking reconstruction software is also expected over the next years through migration to the ACTS software suite, which will improve the maintainability and the technical performance of the software to a level compatible with the Run 4 computing requirements. All of this will then directly benefit high-level algorithms used for object reconstruction and identification and ultimately the sensitivity of physics analyses to be carried with the datasets collected at the HL-LHC.

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