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Track reconstruction in high-multiplicity environments with the ATLAS Detector at the LHC

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During 2017, the Large Hadron Collider provided record-breaking integrated and instantaneous luminosities, resulting in huge amounts of data with the number of interactions per bunch crossing being significantly beyond design values. I discuss the track reconstruction performance with the ATLAS detector in high-multiplicity data. I also discuss the expected tracking performance in even higher multiplicity environments in future data-taking at the high-luminosity LHC.

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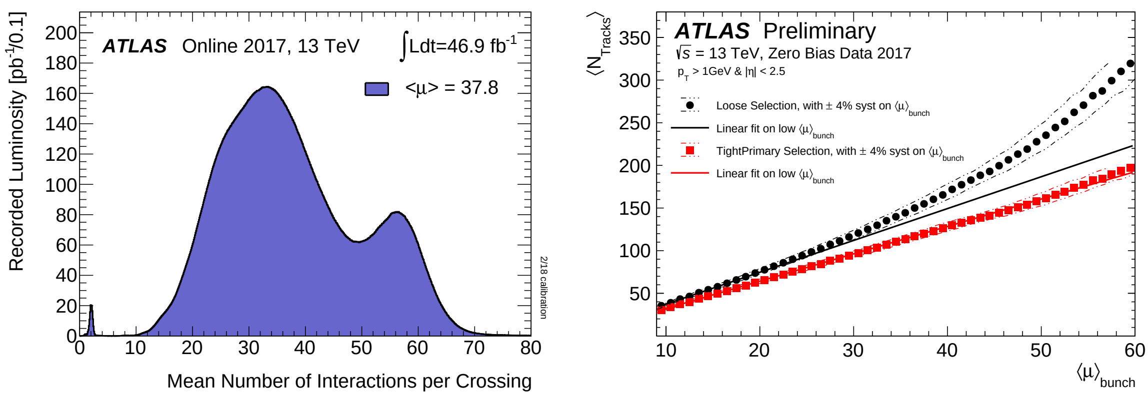
1. Introduction

During 2017, the Large Hadron Collider (LHC) provided record-breaking integrated and instantaneous luminosities, resulting in huge amounts of data with numbers of interactions per bunch crossing significantly beyond initial projections. I aim to answer the following questions. How does the ATLAS [1] Inner Detector track reconstruction perform in such high-multiplicity data? What are our plans for tracking at even higher numbers of interactions in future data-taking at the high-luminosity LHC (HL-LHC)? Which of the new tracking and vertexing algorithmic developments for the HL-LHC could be useful for the LHC data-taking in LHC Run 3, prior to the HL-LHC upgrade?

2. Tracking performance in 2017

The LHC design value of instantaneous luminosity was 10^{34} cm^{-2}s^{-1} and the corresponding average number of inelastic proton-proton (pp) interactions per bunch-crossings was $\mu = 19$ [2]. During 2017 the peak instantaneous luminosity delivered to ATLAS during stable beams was 2.09 10^{34} cm^{-2}s^{-1}. Figure 1a shows the luminosity-weighted distribution of the mean number of interactions per bunch crossing. The average number of inelastic interactions during 2017 data-taking was $\langle\mu\rangle = 37.8$.



(a) (b)

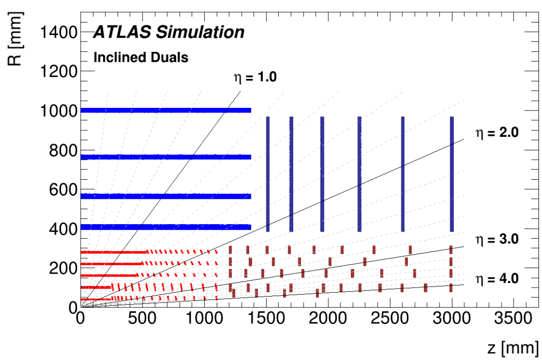
Figure 1: a) Luminosity-weighted distribution of the mean number of interactions per crossing for the 2017 pp collision data [3]. b) Average number of charged particle tracks that pass a preselection of $p_T > 1$ GeVand $|\eta| < 2.5$ reconstructed per event in the ATLAS Inner Detector as a function of $\langle\mu\rangle_{\text{bunch}}$ for the Loose and TightPrimary track selections. The solid line shows a linear fit to the data in the region $9 < \langle\mu\rangle_{\text{bunch}} < 16$. Source: [4].

At such high particle multiplicities it is challenging for the track reconstruction algorithms to efficiently identify the tracks from charged particles. High particle densities can result in mis-reconstructed tracks from random associations of genuine particle signals and (to smaller extent) noise hits. Figure 1b shows the number of charged particle tracks reconstructed per event in the ATLAS Inner Detector as a function of mean number of inelastic interactions per bunch crossing $\langle\mu\rangle_{\text{bunch}}$. The 2017 data events using the Loose and TightPrimary track selections defined in [5] are shown. Apart from the 2017 data, the linear fit to the data in the region $9 < \langle\mu\rangle_{\text{bunch}} < 16$ is shown and extended to higher $\langle\mu\rangle_{\text{bunch}}$ values. The number of genuine particle tracks is to first order proportional to $\langle\mu\rangle_{\text{bunch}}$. Deviation from the linearity would indicate the presence of mis-reconstructed tracks. As seen in Figure 1b, the Loose Selection shows good linearity up to values of $\langle\mu\rangle_{\text{bunch}} \sim 30$ and moderate deviations at higher $\langle\mu\rangle_{\text{bunch}}$ values. The TightPrimary track selections shows excellent linearity in the full $\langle\mu\rangle_{\text{bunch}}$ range. Besides track reconstruction also vertex reconstruction in 2017 data shows good linearity as a function of $\langle\mu\rangle_{\text{bunch}}$ and no notable degradation of vertex position resolution is observed in high-μ events [6].

Thus in spite of the challenging conditions during 2017 data-taking, the ATLAS tracking detector and track reconstruction continued to perform excellently. This is due to the number of detector upgrades the ATLAS collaboration made during the Long Shutdown (2013-2015) in anticipation of luminosities and $\langle\mu\rangle$ values beyond the LHC design values. Most notably, an additional high granularity layer has been added to the pixel detector at the radius of only R= 32.5 mm from the beam-line. This new Insertable B-Layer [7] preserves tracking performance at high μ, and notably improves track impact parameter resolution and vertexing performance.

3. High-Luminosity LHC & new Inner Tracker

The HL-LHC is a major upgrade of the LHC which will enable the LHC to collect up to about 4000 fb^{-1} of data in about a decade of data-taking. The data-taking will start following the Long Shutdown 3 (2023-2025). The ultimate design parameters could enable HL-LHC to operate at levelled peak luminosities up to $7.5 \cdot 10^{34}$ cm^{-2}s^{-1} and peak μ up to ~ 200 [8]. To cope with notably higher multiplicity, data read-out rates and to improve rejection of tracks from additional interactions, the current ATLAS tracking detector will be replaced with the new Inner Tracker (ITk). A candidate ITk layout is shown in Figure 2a. ITk will be an all-silicon detector with five pixel and four micro-strip detector layers in the barrel, accompanied by the end-ring and end-cap systems in the forward region [9]. ITk will enable track reconstruction for track $|\eta| < 4$, extending the range of the current Run 2 ATLAS tracker ($|\eta| < 2.5$).



(a)

Requirement	Pseudorapidity interval		
	$\lvert\eta\rvert < 2.0$	$2.0 < \lvert\eta\rvert < 2.6$	$2.6 < \lvert\eta\rvert < 4.0$
Pixel+Strip hits	≥ 9	≥ 8	≥ 7
Pixel hits	≥ 1	≥ 1	≥ 1
Holes	< 2	< 2	< 2
Double holes	≤ 1	≤ 1	≤ 1
Pixel holes	< 2	< 2	< 2
Strip holes	< 2	< 2	< 2
p_T [MeV]	> 900	> 400	> 400
$\lvert d_0\rvert$	≤ 2 mm	≤ 2 mm	≤ 10 mm
$\lvert z_0\rvert$	≤ 20 cm	≤ 20 cm	≤ 20 cm

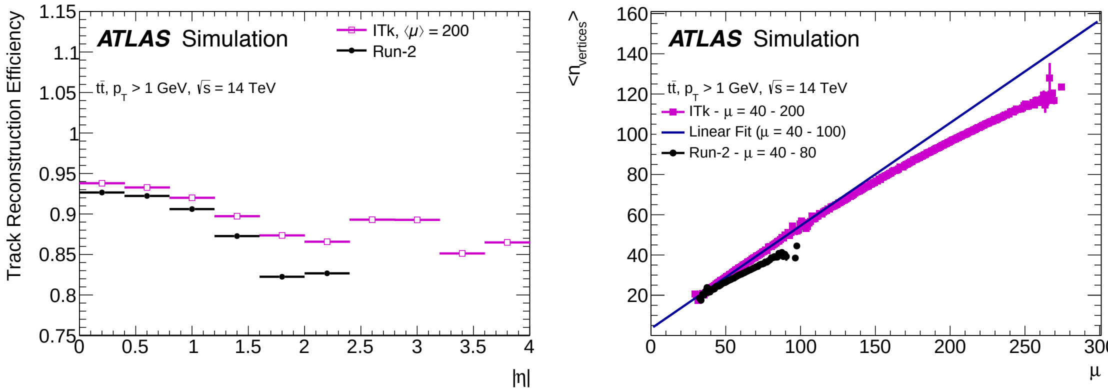
(b)

Figure 2: a) A candidate ITk layout. b) ITk track selection requirements. Source: [9].

4. ITk tracking and vertexing performance

The ITk should preserve and, if possible, exceed the physics performance of the current Run 2 detector, under the HL-LHC operational conditions. The track selection requirements for the ITk depend on the pseudorapidity [1] as shown in Table 2b. The following definitions are used in the table: hole is defined as a case when a track candidate crosses an active sensors but no hit is found. Double holes are holes in two consecutive active sensors. The d_0 and z_0 are the transverse and longitudinal track impact parameters, defined with respect to the mean position of the beam spot.

The tracking efficiency and the rate of mis-reconstructed tracks are key tracking performance metrics. The efficiency is defined as the fraction of prompt particles which are associated with tracks passing the track selection requirements. In Figure 3a the ITk track reconstruction is shown to have high efficiency, out-performing the Run 2 detector for $|\eta| < 2.5$ and retaining high efficiency also in the region of $2.5 < |\eta| < 4$. The rate of mis-reconstructed tracks is about an order of magnitude smaller in the ITk compared to the Run 2 detector. With the ITk both the track reconstruction efficiency and the rate of mis-reconstructed tracks are robust against the presence of additional interactions. As μ increases from 40 to 250 the efficiency and mis-reconstructed track rates are degraded by only about 1%. Besides efficiency and mis-reconstructed track rates the ITk track parameter resolutions were also shown to exceed or preserve the Run 2 detector ones [9].



(a) (b)

Figure 3: a) ITk Track reconstruction efficiency for $t\bar{t}$ events with an average of $\mu = 200$. Results with the current Run 2 detector are also shown. b) The average number of reconstructed primary vertices in $t\bar{t}$ events as a function of μ. The solid lines show a linear fit to the simulation in the region $40 < \mu < 100$, extrapolated to higher values. Results obtained Run 2 simulation sample and Run 2 primary vertex reconstruction code are also shown. Source: [9].

In the central region the ITk provides up to 13 (five pixel and $2 \cdot 4$ micro-strip) silicon hits and nine hits are required in order for tracks to pass the selection requirements. The Loose track selection used in Run 2 tracking requires seven silicon hits whereby the Run 2 tracker provides 12

[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 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, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

(four pixel and $2 \cdot 4$ micro-strip) hits. Thus, the ITk tracking performance indicates that tightening the silicon hit requirements in the Loose selection could reduce the dependence on $\langle\mu\rangle_{\text{bunch}}$ without notably compromising the efficiency. The $|\eta|$-dependent cuts might also benefit the Run 3 tracking at high $\langle\mu\rangle_{\text{bunch}}$.

The vertex reconstruction at ITk uses Adaptive Multi-Vertex Finding algorithm (AMVF) which fits multiple vertices simultaneously [10]. This differs from the Run 2 Iterative Vertex Finding (IVF) algorithm which fits one vertex at the time [11]. Figure 3b shows the average number of reconstructed primary vertices as a function of μ. The AMVF algorithm shows good linearity up to $\mu \sim 100$. In typical HL-LHC operating conditions the deviations from the linearity due to vertex merging are observed. The IVF algorithm also has good linearity, but has a lower vertex reconstruction efficiency compared to AMVF, as can be inferred from the steeper slope of the AMVF distribution. Thus, AMVF is a good candidate to improve rejection of events from additional interactions in high-μ events in Run 3.

5. Summary & Outlook

ATLAS track reconstruction continues to perform excellently at luminosities and μ values notably higher than the LHC designed values. As the instantaneous luminosities and pile-up rates keep increasing during 2018 and Run 3, tracking and vertexing can benefit from the ideas and algorithmic developments targeting the HL-LHC. Examples are pseudorapidity-dependent track selection cuts, tighter track selection requirements and AMVF vertexing.

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