Track and vertex reconstruction of the ATLAS Inner Detector in the high multiplicity LHC environment

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Abstract. With an average number of up to 30 pile-up interactions per bunch crossing in 2012 data, the ATLAS Inner Detector at the LHC is performing in an environment beyond its design specifications. This has a significant impact on event reconstruction such as additional demands on CPU time and disk space as well as an increased probability to reconstruct fake tracks. Therefore the track and vertex reconstruction performance has been optimised in several high pile-up scenarios (see [1]). Studies in data and simulation are presented which demonstrate that the performance of the Inner Detector track and vertex reconstruction is robust even in a high pile-up environment.

1. Introduction
The number of inelastic $pp$ interactions per bunch crossing can be described by a Poisson distribution. The mean number of inelastic $pp$ interactions per bunch crossing, $\mu$, is calculated using beam parameters by

$$\mu = \frac{L \sigma_{\text{inel}}}{n_{\text{bunch}} f_r}$$

(1)

where $L$ is the luminosity, $\sigma_{\text{inel}}$ the total inelastic cross-section, $n_{\text{bunch}}$ the number of bunches and $f_r$ the LHC revolution frequency. As $\mu$ varies between bunches the average over all analysed bunches is used in this note. The peak average number of interactions per bunch crossing for 2012 data-taking is shown in Fig. 1.

The ATLAS Inner Detector [2, 3] (see Fig. 2) consists of three subdetectors and covers a pseudorapidity range of $|\eta| < 2.5$: A silicon pixel detector with three barrel layers and three

![Figure 1. Maximum mean number of $pp$ interactions per beam crossing versus day. The plot shows the maximum of the average values for all bunch crossings in predefined time windows during stable beam [4].](image-url)
layers in each of the two end caps and a silicon microstrip detector (SCT) with four barrel layers and nine layers in each of the two end caps. In addition there is a transition radiation tracker (TRT), which consists of 73 barrel layers and 160 end-cap planes. While the high granularity silicon detectors operate with a read-out window of 25 ns, corresponding to the minimum LHC bunch spacing, the read-out window of the smaller granulated TRT is 75 ns, which makes it sensitive to out-of-time pile-up.

2. Track and Vertex Reconstruction
ATLAS track reconstruction [5] is based on several sequential algorithms, of which the studies in this note focus on the inside-out algorithm:
After forming spacepoints from clusters of neighbouring silicon measurements (hits) seeds are created of three spacepoints. From those seeds the track candidate is successively extrapolated to the next layer and its trajectory is refitted. Finally the track is extended into the TRT. Additionally an ambiguity solver scores tracks to resolve between track candidates and reject tracks which do not meet certain criteria. For instance track candidates with a transverse momentum of $p_T < 400$ MeV are rejected.

For the reconstruction of the interaction vertices [6], seeds are determined by finding the maximum in the binned longitudinal impact parameter distribution of the reconstructed tracks. The vertex position is determined around the seeds with an adaptive vertex fit [7], a robust $\chi^2$ based fit procedure which down-weights the contribution of outliers to the $\chi^2$ of the vertex. Incompatible tracks are used to seed new vertices. The vertex with the highest $\sum p_T^2$ is labelled as the primary vertex.

3. Studies in high Pile-up
Track reconstruction algorithms aim to efficiently reconstruct the trajectories of charged particles passing through the ATLAS Inner Detector, while minimising fakes. Fakes, i.e. reconstructed tracks which are purely combinatorial collections of hits, become an increasing problem with pile-up and are mainly attributed to problems of the pattern recognition with nearby hits of different particles. While the initial track reconstruction cuts were designed for a high track reconstruction efficiency for the measurement of charged particle multiplicity [8], different cuts have been studied and so-called robust cuts (see Table 1) have been found to give the best rejection of fake tracks and having only a moderate impact on the primary track reconstruction efficiency. Primary particles are defined as the first particles in the decay chain from the $pp$

![Figure 2. ATLAS Inner Detector [3].](image)

![Figure 3. Occupancy in the TRT versus Pixel for the $\mu = 15$ and the $\mu = 29$ fill [1].](image)
interaction with a mean lifetime greater than $3 \times 10^{-11}$ s. Subsequent particles are labelled as secondary.

**Table 1.** Track reconstruction cuts: the minimum required number of silicon hits on track (pixel and SCT) and the maximum number of allowed holes on track in the pixel. Holes are defined as missing hits on track fit traversing a sensitive detector layer.

| Si hits pixel holes | default | >= 7 | <= 2 |
|---------------------|---------|------|------|
| robust              | >= 9    | == 0 |

Three dedicated minimum-bias simulation samples were produced using Pythia 8 [9] with ATLAS minimum bias tune 4C [10], indicated with $\mu = 1$ for a single minimum bias interaction and $\mu = 11, \ldots, 41$ for samples overlaid with on average 10, $\ldots, 40$ additional minimum bias interactions respectively.

To determine the impact of pile-up in data, datasets extracted from special LHC fills taken at the end of 2011 have been studied. One dataset with an average of $\mu = 15$ and 50 ns bunch spacing with an integrated luminosity of $12.7 \mu b^{-1}$. Two datasets with an average of $\mu = 29$ and $\mu = 26$ having an integrated luminosity of $4.7 \mu b^{-1}$ and $482 \mu b^{-1}$ respectively have been extracted from a fill with only one bunch per beam. The dataset with $\mu = 32$ corresponds to an integrated luminosity of $12.8 \mu b^{-1}$ taken from a fill with $\sim 8 \mu s$ bunch spacing.

Figure 3 shows the pixel and the TRT occupancy for two fills with different amount of pile-up. Despite its position close to the interaction point but due to the high granularity of the pixel detector the occupancy reaches values up to 0.01%, while it goes up to 30% in the TRT. However, no significant saturation can be found demonstrating the excellent performance of the detectors. The higher occupancy in the TRT detector for the $\mu = 15$ fill is due to out-of-time pile-up.

**Track Reconstruction Efficiency**

Figure 4 shows the primary track reconstruction efficiency in dependence of $\eta$. It is defined as the fraction of true primary particles in the Inner Detector acceptance that are successfully matched to a reconstructed track. The efficiency is stable even with additional pile-up. However,
applying the robust selection decreases the efficiency by \( \sim 5\% \). The secondary efficiency drops by about 1-2\% [1].

Although a good rejection of fakes can be retrieved by imposing robust cuts they are not applied during track reconstruction, since the loss in the efficiencies has a significant impact on certain event topologies.

**Fake rate**

The non-primary fraction is defined as the fraction of reconstructed tracks which cannot be matched to a primary particle of all reconstructed tracks. Thus, the non-primary fraction is the sum of secondary interactions and fake tracks. The increase of fake tracks with pile-up is apparent in the dramatic increase of the non-primary fraction (Fig. 5). This is supported by the fact that the secondary efficiency has been found to be stable with increasing pile-up [1]. Imposing the robust track requirements keeps the non-primary rate at the same level for all studied pile-up scenarios, hence removing the additional fake tracks produced in the high pile-up environment.

Since the average number of particles per interaction is independent of pile-up the number of reconstructed tracks is expected to increase linearly with the number of interactions. For the default track reconstruction settings Fig. 6 shows a deviation from this behaviour for the \( \mu = 29 \) dataset which can be explained by the increase in the number of combinatorical fake tracks found in simulation. Applying the robust cuts eventually eliminates this fake contribution. This stability of robust tracks is seen in both, data and simulation.

**Track Quality**

The tails of the transverse impact parameter distribution at \( d_0 > 2 \text{ mm} \) are sensitive to secondary tracks. Its unchanged size with additional pile-up, which can be observed in Fig. 7, demonstrates that the secondary reconstruction efficiency is not affected by additional pile-up. This is in accordance with findings from simulation [1].

The number of hits on tracks is an important measure for the track quality. For the pixel and the SCT no effects have been found with additional pile-up. The first detector where effects are expected is the TRT. However, Fig. 8 shows that the track quality remains unaffected for high \( \mu \).

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**Figure 6.** Average number of tracks per event as a function of the number of vertices for the \( \mu = 26 \) dataset and simulation with default and robust cuts [1].

**Figure 7.** Transverse impact parameter distribution with respect to the primary vertex for \( \mu = 15, \mu = 29 \) and \( \mu = 32 \) [1].

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Figure 8. Number of TRT hits for tracks meeting the robust requirements for $\mu = 15$, $\mu = 29$ and $\mu = 32$. The distributions are normalised to the same number of reconstructed tracks [1].

**Vertex Reconstruction**

The number of interaction vertices is directly proportional to the number of pile-up interactions. At higher pile-up and consequently a higher vertex density deviations from a linear increase of the number of reconstructed vertices with $\mu$ are expected. This can be observed in Fig. 9 for simulation and data, indicating that the vertex reconstruction algorithm is fairly robust and well-modelled. More details can be found in [12] of these proceedings.

**Reconstruction Time**

Track reconstruction time rises rapidly with increasing multiplicity such that the Inner Detector reconstruction becomes the dominant component of the total reconstruction time. Therefore independent of the robust selection cuts requirements on the seed finding have been made to reject seeds which never became track candidates. This optimisation had a negligible impact on performance and reduced the reconstruction time by 30% (see Fig. 10).

Figure 9. Average number of vertices per event as a function of the average number of interactions per bunch crossing in 2011 data and simulation [11].

Figure 10. CPU reconstruction time per event for $\mu = 1, 11, 21, 31$. The seed finding is labeled 2011 for the old and 2012 for the new seed finding respectively [1].
4. Conclusion
A good performance of the Inner Detector track reconstruction has been demonstrated in data containing significant pile up. Robust track reconstruction cuts have been introduced to control the fake rate in high pile-up without changing the track quality. Still, the track reconstruction efficiency decreases by \( \sim 5\% \). The findings in simulation could be confirmed by studies in data.

In vertex reconstruction, which becomes increasingly important for measuring the amount of pile-up, an essential ingredient for many analyses, small effects could be observed in the high pile-up environment. However, this is expected and found to be well-modelled by simulation.

In summary the ATLAS Inner Detector track and vertex reconstruction is well-prepared for the ongoing 2012 run.

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