Primary vertex reconstruction at the ATLAS experiment

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Abstract. These proceedings present the method and performance of primary vertex reconstruction at the ATLAS experiment during Runs 1 and 2 at the LHC. The studies presented focus on data taken during 2012 at a centre-of-mass energy of \( \sqrt{s} = 8 \) TeV, and during 2015-2016 at \( \sqrt{s} = 13 \) TeV. Some predictions toward future runs are also presented. The measurement of the position and size of the luminous region and its use as a constraint to improve the primary vertex resolution are discussed.

1. Introduction

This summary describes the performance of primary vertex reconstruction with the ATLAS detector, during Run 1 and 2 of the LHC from 2010 to 2016, reflecting data collected in proton–proton collisions with a centre-of-mass energy \( \sqrt{s} = 8 \) TeV and 13 TeV. Initial studies into vertex reconstruction performance at the High Luminosity LHC (HL-LHC) are also presented.

The ATLAS detector [1] is comprised of an inner detector (ID) surrounded by a thin superconducting solenoid, a calorimeter system and a muon spectrometer embedded in a toroidal magnetic field. The ID is the primary detector used for vertex reconstruction. The ID covers the pseudorapidity range \( |\eta| < 2.5 \).

Particle trajectories are identified using the combined information from the sub-detectors of the ID. In Run 1 the ID consisted of the innermost silicon pixel detector, the surrounding silicon microstrip semiconductor tracker (SCT), and the transition radiation tracker (TRT), made of...
straw tubes filled with a Xe-CO$_2$ gas mixture [2]. In Run 2 the insertable B-layer (IBL), made of silicon pixels, was added in the region closest to the beam pipe.

An aspect of primary vertex reconstruction requiring special attention is the superposition of multiple inelastic $pp$ interactions reconstructed as a single physics event with many primary vertices. These additional primary vertices, the dominant components of the total cross section, which are usually soft-QCD interactions, are referred to as pile-up. The average number of inelastic $pp$ interactions per bunch crossing under constant beam conditions is denoted as $\mu$. During the majority of Run 1, in 2012, and in Run 2 up until 2016, the average $\mu$ was between 20 and 25.

2. Description of Data
The studies shown in these proceeding use data taken with the ATLAS detector in Runs 1 and 2 and Monte Carlo simulation. The data was collected with a minimum-bias trigger, designed to record a random selection of bunch crossings, unbiased by any hard physics produced in the bunch crossing. In the context of vertex reconstruction, this data is similar to pile-up. Monte Carlo simulation is used to study both these minimum-bias samples and the hard-scatter physics processes $Z \rightarrow \mu\mu$ and $t\bar{t}$. The hard-scatter physics processes are generated with pile-up collisions overlaid, for $\mu$ from 0 to 40, and separately for $\mu$ from 190 to 210. Additionally, to study the collective effects of multiple primary vertices in a high pile-up environment without a hard-scatter interaction, MC simulation with no hard-scattering process but only pile-up was created for $\mu$ up to 72.

When comparing data with simulation in the presence of pile-up interactions, the average number of collisions per bunch crossing in simulation is re-weighted to match that measured in data. In order to obtain the same visible cross section for $pp$ interactions for the simulation and data, a $\mu$-rescaling is also applied before the re-weighting.

3. Primary vertex reconstruction
3.1. Track Selection
Primary vertex reconstruction uses a sub-set of all reconstructed tracks, selected with tight requirements to maintain a low rate of fake tracks (tracks which do not share a large proportion of hits with a true particle traversing the detector). Also, impact parameter requirements are applied to reduce contamination from tracks originating from secondary interactions. The general structure and performance of ATLAS track reconstruction is described in detail in Ref. [3]. The tracks are selected according to the following criteria:

- $p_T > 400$ MeV; $|d_0| < 4$ mm; $\sigma(d_0) < 5$ mm; $\sigma(z_0) < 10$ mm;
- SCT detector hits $\geq 4$; silicon (SCT or pixel) hits $\geq 9$; no pixel holes;
- if $|\eta| \geq 1.65$, silicon hits $\geq 11$; No more than one SCT hole (Run 2);
- IBL hits + B-layer (closest pixel layer) hits $\geq 1$ (Run 2);
- A maximum of 1 shared pixel hit or 2 shared SCT hits (Run 2).

Here the symbols $d_0$ and $z_0$ denote the transverse and longitudinal impact parameters of tracks with respect to the centre of the luminous region, and $\sigma(d_0)$ and $\sigma(z_0)$ denote the corresponding uncertainties. A hole represents a measurement on a detector surface that is expected, given the trajectory predictions, but not observed.

3.2. Primary vertex reconstruction
After a set of tracks satisfying the track selection criteria is defined, vertices are reconstructed in the following steps:
• A seed position for the first vertex is selected. The transverse position of the first seed is taken as the center of the beam spot. The $z$-coordinate of the seed is the mode of the $z$-coordinates of tracks at their respective points of closest approach to the reconstructed center of the beam spot.

• The tracks and the seed are used to estimate the best vertex position with a fit. The fit is an iterative annealing procedure, and in each iteration less compatible tracks are down-weighted and the vertex position is recomputed. In early iterations all tracks have similar weights; as the iterations progress the weights have a larger spread, until finally incompatible tracks (those with less good agreement in the fit) have small weights and therefore very little effect in the fit and compatible tracks have large weights and a strong influence on the fit. The distribution of weights for different iterations is shown in Fig. 1.

• After the vertex position is determined, tracks that are incompatible with the vertex are removed from it and allowed to be used in the determination of another vertex.

• The procedure is repeated with the remaining tracks in the event.

The reconstructed position and width of the beam spot can be used as an additional measurement during the during the primary vertex fit. Tracks outside the beam spot have low compatibility with the vertex fit and are thus removed in the iterative fitting procedure. This procedure is referred to as the beam-spot constraint. In the $z$-direction, the length of the luminous region has no significant impact on the resolution of primary vertices.

3.3. Beam-spot reconstruction and stability
The beam-spot reconstruction is based on an unbinned maximum-likelihood fit to the spatial distribution of primary vertices collected from many events. These primary vertices are reconstructed without beam-spot constraint from a representative subset of the data. The evolution of the beam-spot size as a function of time during a typical LHC fill is shown in Fig. 2. During 2016 the size of the beam spot was reduced to less than 10 $\mu$m in the transverse direction because of improvements in the LHC’s beam parameters.

4. Hard-scatter interaction vertices
4.1. Monte Carlo truth matching and classification of vertices
Using MC simulation, the effect of pile up on vertex reconstruction can be studied. A series of categories is defined based on whether the tracks used in hard-scatter vertex reconstruction originate from the hard scatter or from pile-up interactions.

For each vertex, the sum of the weights assigned to all contributing tracks is normalised to unity, and the fractional weights of individual tracks in each vertex are calculated. Vertices can then be put into one of the following exclusive categories:
Matched vertex: Tracks identified as coming from the same generated interaction contribute at least 70% of the total weight of tracks fitted to the reconstructed vertex.

Merged vertex: No single generated interaction contributes more than 70% of track weight to the reconstructed vertex. Two or more generated interactions contribute to the reconstructed vertex.

Split vertex: The generated interaction with the largest contribution to the reconstructed vertex is also the largest contributor to one or more other reconstructed vertices.

A reconstructed hard-scatter event can be classified based on one of the following definitions:

- Clean: Event contains one matched vertex corresponding to the hard-scatter interaction. The hard-scatter interaction does not contribute more than 50% of the total track weight to any other vertex.

- Low pile-up contamination: Event contains one and only one merged vertex where the hard-scatter interaction contributes more than 50% of the total track weight.

- High pile-up contamination: Event does not contain any vertex where the hard-scatter interaction contributes more than 50% of the total track weight, but does contain a merged vertex in which the hard-scatter interaction contributes 1%-50% of the total track weight.

- Split: Event contains at least two merged vertices in which the hard-scatter interaction contributes more than 50% of the total track weight.

4.2. Vertex reconstruction and selection efficiency for hard-scatter interactions

Assuming that the hard-scatter primary vertex produces reconstructed tracks, the efficiency of hard-scatter primary vertex reconstruction is predicted to be larger than 99%. Figure 3 shows the fraction of $Z \rightarrow \mu \mu$ vertices classified as having Low or High pile-up contamination, as a function of $\mu$. At $\mu = 40$, about 10% of $Z \rightarrow \mu \mu$ vertices have high pile-up contamination. The fraction of events containing split vertices remains negligible for all $\mu$.

This pile-up contamination lead to a degradation of position resolution. Figure 4 shows the distribution of residuals of the primary vertex position in a $Z \rightarrow \mu \mu$ sample for different classes. The residuals are calculated as the distance between the position of the hard-scatter primary vertex at generator level and its position obtained from the primary vertex reconstruction. The categories of clean reconstruction, low and high pile-up contamination show progressively degrading resolution. This effect is visibly largest for the $z$-coordinate, because the transverse coordinates are constrained by the beam-spot width.

In addition to the degradation of the spatial resolution, the presence of significant pile-up makes it more difficult to correctly identify the hard-scatter primary vertex among the many
vertices reconstructed

![Graph](image)

**Figure 3.** The fraction of hard-scatter primary vertices reconstructed with various levels of pile-up contamination, as a function of the average pile-up, $\mu$. The black circles show the fraction of vertices in events categorised as clean, and the blue and red circles show the fraction of vertices in events with low and high pile-up contamination respectively. The open crosses show the sum of the fractions of events that are clean and those with low pile-up contamination; the filled crosses show the sum from all categories and represent the overall efficiency.

![Graph](image)

**Figure 4.** The residual distributions in (a) $x$ and (b) $z$ coordinates for reconstructed primary vertices in a sample of simulated $Z \rightarrow \mu\mu$ events for the four classes of events defined in Section 4.1. The distributions are normalised to the same area.

pile-up vertices reconstructed in most bunch crossings. For most hard-scatter physics processes, it is effective to identify the hard-scatter primary vertex as the primary vertex with the highest sum of the squared transverse momenta of contributing tracks: $\Sigma p_T^2$. This criterion is based on the assumption that the charged particles produced in hard-scatter interactions have on average a harder transverse momentum spectrum than those produced in pile-up collisions.

The efficiency to reconstruct and then select the hard-scatter primary vertex is shown as a function of $\mu$ in Fig. 5 for different physics processes.

### 5. Performance in the high pile-up regime

Reconstruction of pile-up vertices was studied for $\mu$ up to 72. The efficiency of pile-up vertex reconstruction decreases with increasing pile-up. Effects related to the merging of adjacent primary vertices start to play a significant role as pile-up increases.

Figure 6 shows the average number of expected reconstructed primary vertices as a function of
μ, for the two main classes of vertices defined in Section 4, matched vertices and merged vertices. Vertices classified as “Split” are not shown because they represent a very small contribution of the total number of reconstructed pile-up vertices at μ = 70.

6. Efficiency of vertex reconstruction as a function of pile-up

The number of reconstructed vertices as a function of μ can be estimated with a model based on the reconstruction efficiency and the probability of vertex merging.

The parameterisation, as a function of μ, is as follows:

$$\langle n_{\text{Vertices}} \rangle = p_0 + \epsilon \mu - F(\epsilon \mu, p_{\text{merge}}),$$  \hspace{1cm} (1)

where $\epsilon$ is the efficiency of the vertex reconstruction algorithm before including vertex merging effects, and $p_0$ accounts for any small offset arising from non-collision background. The function $F(\epsilon \mu, p_{\text{merge}})$ represents the average number of vertices lost due to merging effects, taking into account the number of reconstructible vertices and the vertex merging probability, $p_{\text{merge}}$. This model is discussed in more detail in Ref. [4].

The distribution of $\Delta z$ between vertices measured in a low pile-up data sample is used to derive a two-vertex merging probability density function $p_{\text{merge}}(\Delta z)$. This function can then be combined with a given beam-spot shape to derive an analytical relationship between the number of reconstructible vertices per event, $\epsilon \mu$, and the average number of reconstructed vertices, $\langle n_{\text{Vertices}} \rangle$. Using this approach, the effect of different beam-spot sizes on the merging probability can also be evaluated. This is shown in Fig. 7(a). The dependence of vertex reconstruction efficiency on the density of interactions is evident in the difference between the orange and
Figure 7. Distribution of the average number of reconstructed vertices as a function of the number of interactions per bunch crossing, $\mu$. (a) MC simulation of minimum-bias events (triangles) and the analytical function in Eq. 1 fit to the simulation (solid orange line). The blue line shows the result with a different beamspot longitudinal profile (approximately flat, called Crab Kissing). The dashed curves show the average estimated number of vertices lost to merging. (b) Minimum-bias data (black points) from 2012. The line shows the result of Eq. 1 fit to simulation. The inner dark (blue) band shows the systematic uncertainty in the fit from the beam-spot length, while the outer light (green) band shows the total uncertainty in the fit. The panels at the bottom of the figures represent the ratios of data to the fit. (c) Minimum-bias data (black points) from 2016 and the result of a fit of Eq. 1 to simulation. The blue solid lines. The blue line shows the number of reconstructed vertices when the beamspot longitudinal profile is approximately flat (called Crab Kissing [5]). The dashed lines show the number of vertices lost when two or more vertices merge.

6.1. Comparison of data to simulation
Data are compared to Eq. 1 with the parameters $\epsilon$ and $p_{\text{merge}}$ fixed to the values from a fit to simulation, and with the small value of $p_0$ extracted from a fit to the data. The result is shown in Fig. 7(b) and (c) for 8 TeV data and 13 TeV respectively. The uncertainty bands in Fig. 7(b) and (c) show the beam-spot size uncertainty and the total uncertainty, which is computed by summing in quadrature the beam-spot size and the dominant $\mu$-rescaling uncertainty terms.

This comparison shows that the analytical description proposed to describe primary vertex reconstruction efficiency is valid: vertex merging is the effect that has the largest impact, and remaining effects related to the presence of fake and split vertices are negligible.
Figure 8. Distribution of the number of reconstructed vertices per event for (a) a sample of $\sqrt{s} = 8$ TeV minimum-bias data for the pile-up range $21 < \mu < 23$, and (b) a sample of $\sqrt{s} = 14$ TeV simulated $t\bar{t}$ events for the pile-up range $190 < \mu < 210$.

7. Looking ahead

Vertex reconstruction performance at very high pile was studied using simulation samples generated with average $\mu$ of 200. In these studies tracks out to $|\eta|$ of 2.5 were used. Potential extensions to the ATLAS ID are not taken advantage of. Figure 8 shows the number of reconstructed vertices for average $\mu$ of 22 and 200. In the $\mu = 200$ sample the beam spot is 12 $\mu$m in the transverse plane and 50 mm in the beam direction. In the high pile-up environment, vertex reconstruction is dominated by merging of nearby vertices, reducing the overall efficiency of reconstructing pile-up vertices.

Figure 9 extrapolates the CPU performance of the current algorithm to high pile-up conditions using simulated $t\bar{t}$ events at $\sqrt{s} = 14$ TeV. The fraction of the total computing time for vertex reconstruction which is devoted to selecting tracks compatible with a seed, and reassigning tracks to vertices post-fit, is much higher for the $\mu = 200$ sample, but the majority of the time is spent in the vertex fit for both pile-up cases.

Figure 9. Contributions of different steps of the vertex reconstruction to the total reconstruction time per event with an average number of pile-up interactions of either $\langle \mu \rangle = 0$ or 200. The error bands include statistical uncertainties only. The bottom table provides the relative increase in reconstruction time for each step of the algorithm.

8. References

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