Fast tracking in hadron collider experiments

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Abstract. We present two algorithms that, when used sequentially, can reduce the combinatorics before any track reconstruction in the high occupancy tracking environments of future hadron collider experiments. The first algorithm finds the z-position of the primary physics interaction; the second selects groups of hits consistent with tracks coming from this z-position, rejecting most pile-up/noise/ghost hits. We demonstrate with examples of simulated events from ATLAS at the LHC that the algorithms are flexible, robust and efficient and at the same time fast enough to be used at the second level trigger for filtering the data before applying any tracking algorithms.

INTRODUCTION

Triggering is one of the greatest challenges at hadron collider experiments and will be even more so in the future. For example, at the LHC beams will be colliding every 25 ns and the time available for second level trigger algorithms will be about 10 ms. To make things worse, the pp (or $p\bar{p}$) interaction leading to the interesting physics process (referred to as *the physics interaction or physics event* hereafter) will be accompanied by several minimum bias interactions (referred to as *the pile-up interactions or pile-up events* hereafter) occurring simultaneously ($\sim$5 at the Tevatron Run-IIb, $\sim$20 at the LHC design luminosity). This adds significantly to the complexity of the events.

The consequences are particularly severe for the tracking algorithms. A typical ATLAS event at the LHC design luminosity contains about 30000 silicon spacepoints[1]. This high hit occupancy (especially in the inner detector layers) leads to long execution times (due to combinatorics) and has a cost in performance (due to hit misassociation).

An approach to reduce combinatorics and hence execution time has been to apply the tracking algorithms in so-called Regions of Interest (RoI), which are rectangular slices in (η,ϕ) but opening up in z towards the beam line to account for the uncertainty on the z-position of the physics interaction (an example of an RoI in ATLAS is shown in Fig. 1b,c). The position of the RoI is determined by the first level trigger information from the outer detectors (calorimeters and/or muon chambers). The size depends on the type of RoI; for example, isolated electron or muon RoI are narrow, while jet RoI are wider. Restricting to RoI is natural at the trigger level and leads to some reduction of combinatorics. However, the problem of combinatorics is still present due to the need to extend the RoI in z towards the beam line, where the hit occupancy is the highest.

In this report, we are proposing a new approach, which makes use of the differences between the physics and the pile-up events in order to clean up the spacepoints before applying any tracking algorithms. There are two important differences to exploit: (a) there is a significant spread in z of the various interactions (at the LHC $\sigma_z = 6$ cm) and (b) the physics event has on average higher transverse momentum than the pile-up.

The new approach proceeds in two steps. First, the z position of the physics interaction is determined. Then, hits are rejected if they are not consistent with a track coming from the above z position. The remaining ones are grouped into track candidates.

The algorithms implementing the above ideas are described below. They are applied to example cases from ATLAS at the LHC design luminosity. These include RoI from isolated $p_T = 40\,\mathrm{GeV}/c$ electrons, from thin QCD jets (which are the major background to electron first level triggers) and from WH events with $m_H = 100\,\mathrm{GeV}/c^2$ and $H \rightarrow b\bar{b}$ (denoted WH(100) hereafter). The size of the first two types of RoI is ($\Delta\eta = 0.2$, $\Delta\phi = 0.2$, $\Delta z = 22.4$ cm) while the WH(100) RoI are wider ($\Delta\eta = 1.0$, $\Delta\phi = 1.0$, $\Delta z = 30$ cm). The execution time of the algorithms was measured on a 600 MHz Pentium-III processor.

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[1] Hits and spacepoints have identical meaning throughout this report

THE Z-FINDER

The general principle of the algorithm is summarised in the following steps:

- The RoI is divided into many small bins in ϕ.
- In a given ϕ bin, each pair of hits from different layers is used to calculate a z by linear extrapolation to the beam line (this assumes a solenoidal magnetic field, where the helix trajectories of charged tracks are straight lines in the ρ-z projection).
- A one-dimensional histogram is filled with the z calculated for each hit pair.
- The z position of the physics event is taken to be the one corresponding to the z-histogram bin with the maximum number of entries.

An example of a z-histogram from an electron RoI in ATLAS is shown in Fig. 1a.

The key point of the algorithm is the division of the RoI in small ϕ bins. This has a double significance: (a) it gives naturally more weight to high p_T tracks and therefore to the physics event as opposed to the pile-up events and (b) it reduces drastically the combinatorics, hence minimising the quadratic time behaviour of the algorithm. This is easier to understand with an example: depending on the size of the ϕ bins, the hits of high p_T tracks will be contained in one ϕ bin. Assuming that there are seven hits per track, one such high p_T track will give $7 \times 6/2 = 21$ hit pairs and therefore entries in the z-histogram. In other words, by design, there are more entries from high p_T tracks in the z-histogram, than from low p_T tracks, the hits of which fall into several ϕ bins. In order to avoid loss of efficiency due to binning effects (tracks on the boundary of bins would give fewer hit pairs) hits from a given ϕ bin are also paired with those from the two neighbouring bins.

The ϕ bin size is a parameter that can be adjusted. Its optimal value depends on the type of the RoI. In RoI from isolated electrons or muons high p_T, the ϕ binning should be as fine as possible (0.2° in the ATLAS examples below), since this minimises the number of random hit pairs. In jet RoI, it has to be wider since there are more tracks with moderate p_T (0.4° in the ATLAS WH(100) example).

The bin size of the z-histogram should also be kept small in order to minimise potential random fluctuations. The optimal bin size is similar to the expected resolution on the z position of the physics event.

The efficiency of the algorithm on electron RoI in ATLAS is

$$\varepsilon = 97.5 \pm 0.4\,\%,$$

independent of η. Most of the loss is due to detector inefficiencies and hard bremsstrahlung radiation, which reduces significantly the p_T of the track. The z position is determined with a resolution of $\sim 180 \pm 5\,\mu$m, with no tails. Similar results are achieved with WH(100) jet RoI.

The execution time as a function of the number of hits (N_h) for electron and thin QCD jet RoI is $t = 35 + 1.24 \times N_h + 0.0004 \times N_h^2$ (in μs). It can be seen that the coefficient of the quadratic term is very small; as mentioned before, this is due to the fine binning in ϕ. The average execution time for QCD jet RoI ($\langle N_h \rangle \sim 250$), which constitute the vast majority of first level trigger electron RoI, is

$$\langle t \rangle = 370\,\mu s.$$

Apart from the ϕ and z bin sizes, adjustable parameters are also the first and last detector layers to be used. This makes the algorithm flexible to use in physics cases as different as single isolated high p_T track RoI and jet RoI like in the ATLAS examples. Since the electron RoI contain only one (high p_T) track giving the z position information it is necessary to use hits from all layers in order to benefit from the combinatorics, whereas WH(100) RoI contain many tracks of moderate p_T and therefore using only the first three detector layers suffices.

The flexibility of the algorithm ensures its robustness to changes in the detector or background conditions. For instance, a study of the ATLAS electron RoI without using the hits at the first pixel layer showed that the performance of the algorithm degrades very slightly (efficiency $\sim 95\,\%$, z-resolution $\sim 300\,\mu$m).

THE HIT FILTER

The hit filtering algorithm is based on the fact that all hits of a track of sufficiently high p_T are contained in a small solid angle in (η, ϕ) that starts from the track's initial z position, in contrast to hits from tracks originating from different z positions. The principle of the algorithm can be described in the following steps:

- Given the z-position of the physics event, a 2D-histogram in (η, ϕ) is constructed.
- In each (η, ϕ) bin, the number N_L of different detector layers containing hits is counted. If N_L is above a given threshold all the hits in this bin are accepted, otherwise they are rejected.
- Hits from neighbouring bins are clustered into groups (this is done to eliminate binning effects). Very often, a group contains the hits of just one track.

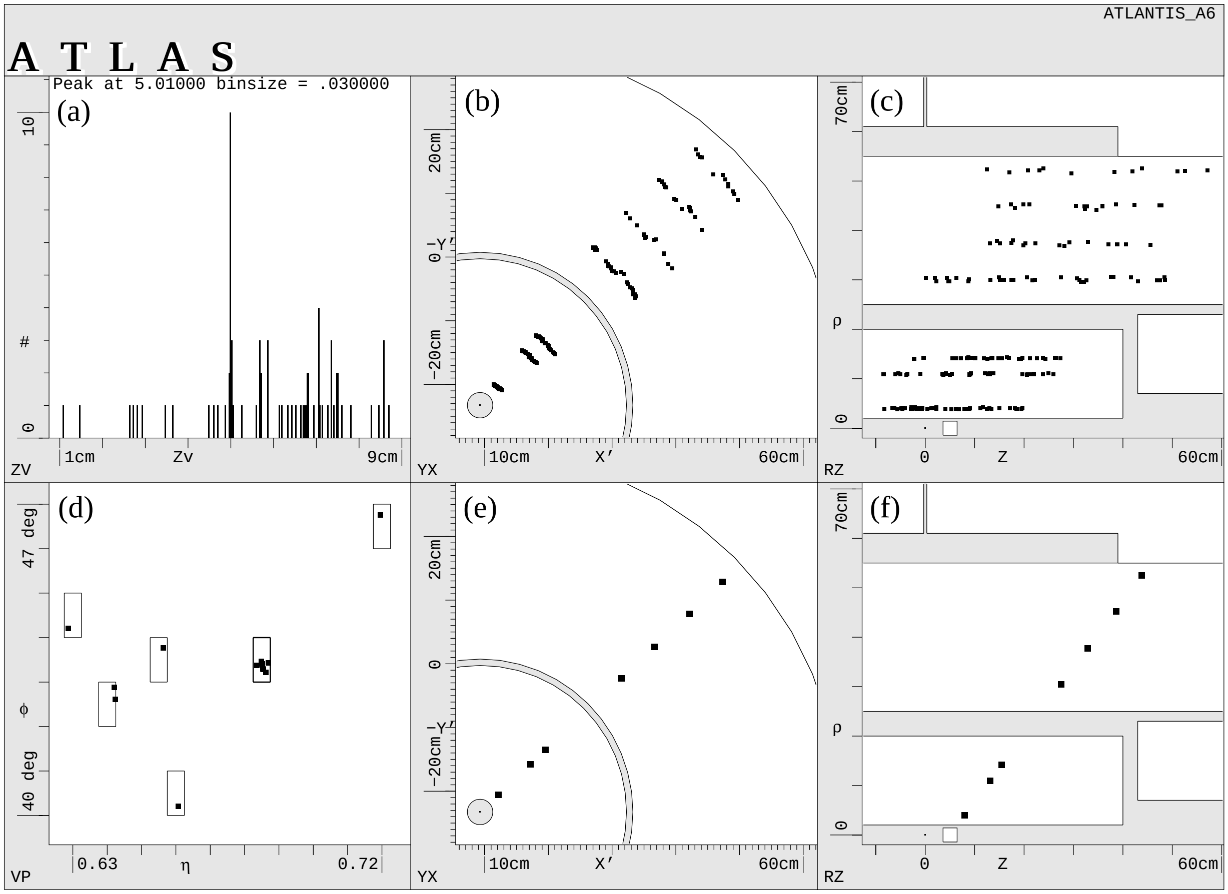

FIGURE 1. From an electron RoI: (a) the z-histogram (shown only around the initial z-position of the electron; the rest is flat), (b,c) x-y and ρ-z views of the RoI before hit filtering, (d) the part of the 2D-histogram in (η, ϕ) containing electron (only bins containing hits are drawn; the hits from the electron are all concentrated in one bin) and (e,f) x-y and ρ-z views of the RoI after filtering.

The size of the bins in η and ϕ can be adjusted according to the physics case. The size in η depends on the detector resolution in the z coordinate and the resolution on the reconstructed z position of the physics event. The size in ϕ determines a p_T cut-off, below which a track spans into many bins in ϕ and thus the algorithm starts to become inefficient. In ATLAS, for an η bin size of 0.004 and a ϕ bin size of 2°, the algorithm is essentially 100 % efficient for tracks with $p_T > 2\,\mathrm{GeV}/c$, which is a cut-off commonly used for triggering.

The time behaviour of the algorithm is linear. In ATLAS, $t = 2.5 \times N_h$ (in μs). This leads to an average time of

$$\langle t \rangle = 630\,\mu s$$

for QCD jet RoI.

About 95 % of the hits are rejected by the filter. Thus, the subsequent track reconstruction can be very fast, especially since it can be restricted to the individual groups of hits. An example of applying these algorithms on an electron RoI in ATLAS is shown in Fig. 1.

CONCLUSIONS

Improving the speed of tracking algorithms is extremely important for future hadron collider experiments, where the presence of many pile-up interactions simultaneously recorded with the interesting physics event leads to a very high hit occupancy in the tracking detectors.

We propose to concentrate on the physics interaction early at the trigger level, by first finding its z position and then selecting only groups of hits that are compatible with having been produced by tracks originating from that z position. We have described two algorithms following this scheme. In examples from ATLAS, the algorithms have been shown to be both very fast and efficient. They are also general enough to be applicable to other hadron collider experiments, in a wide range of physics cases (such as single isolated tracks or jets). Finally, the algorithms are flexible and hence can be adapted easily to different detector or background conditions, a characteristic that makes them suitable to be used at triggering.