Impact of tracker layout on track reconstruction with high pileup

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Abstract. High luminosity operation of the LHC is expected to deliver proton-proton collisions to experiments with an average number of proton-proton interactions reaching 200 in every bunch crossing. Reconstruction of charged particle tracks with current algorithms, in this environment, dominates reconstruction time and is increasingly computationally challenging. We discuss the importance of taking computing costs into account as a critical part of future tracker designs in HEP as well as the importance of algorithms used.

1. Introduction

The Large Hadron Collider (LHC) operating at CERN is the primary facility for experimental high energy physics at the energy frontier since 2009. It is expected to dominate the field for the next two decades or so \cite{1}. General purpose collider detectors ATLAS and CMS are used to collect proton-proton collision data from the LHC and are expected to continue their operation on this time scale. The ATLAS and CMS collaborations operating these detectors have been analyzing collected data for a variety of physics processes and publish results in about a hundred publications each year. Among the most known results is the discovery of the Higgs boson in 2012. Computing resources needed to process, store, and analyze the data towards the publications play a large role in the experiment ecosystem and carry a significant fraction of the total operating budget.

The LHC has reached its nominal design luminosity in 2016 and operates at a proton beam energy of 6.5 TeV since 2015. It is expected to reach its nominal design beam energy of 7 TeV as early as 2018, towards the end of the Run 2 period. Multiple proton-proton interactions can occur per bunch crossing (pileup). Towards the end of 2016 the colliding beams had routinely reached an average number of pileup interactions of about 50. The ATLAS and CMS detector data logging rate was about one kHz in each experiment. This data is processed offline first by event reconstruction algorithms, which deliver physics objects suitable for analyses or further post-processing. Among the algorithms, charged particle tracking takes more than a half of the total event reconstruction time. In order to process data at this rate and cope with the high pileup conditions the experiments have already made major updates to the offline reconstruction algorithms in preparations for Run 2 with significant algorithmic and physics selection optimizations, most notably for needs of the charged particle tracking \cite{2,3}.
In the coming years the instantaneous luminosity at the LHC is expected to increase, with the largest increase coming after the transition to the high-luminosity LHC (HL-LHC) [1]. During the HL-LHC operation the ATLAS and CMS experiments are expected to collect collision data with a mean number of pileup interactions reaching 200 and log the data for offline processing at a rate in the range of 5 to 7 kHz. In order to cope with the increased number of pileup interactions the experiments are planning upgrades of major detector components [4–7].

A combination of the increased number of pileup interactions and the logged data rate will increase computing needs for the offline reconstruction. While the reconstructed output size on disk per event increases roughly proportionally with the number of pileup interactions, the reconstruction time grows as a higher power of this rate. The CPU needs can then become the dominant fraction in the total spending on computing. As an example, estimates done by CMS [5] suggest that there can be about a factor of ten shortage of CPU power needed to reconstruct all events with the current software under the assumption of a flat spending profile and expected future technology cost gains. In this scenario the estimated computing cost to run track reconstruction over a decade or so of the HL-LHC operations can exceed the costs of the upgrade tracker detector construction. For this scenario to still be viable under the flat spending profile on computing, significant changes in algorithms used for tracking will need to happen, possibly at a cost to physics by reducing the phase space of reconstructed tracks. While the detector design is not yet final, further reduction in the total cost may be achieved with detector design changes that aid the reconstruction algorithms.

We consider two ingredients for the possible future charged particle tracking evolution towards the HL-LHC conditions: a tracking algorithm faster than the current conventional Kalman filter (KF) based tracking and a tracker layout design with pairs of sensitive layers placed closer than the current conventional tracker design of ATLAS or CMS with evenly-spaced layers. The analysis of the impact of the tracker layout is done in a simplified detector layout simulation corresponding to the HL-LHC conditions. Track building steps are tuned to have the same efficiency in all of the considered layout scenarios. To quantify the impact of the tracker layout change, we use a difference in the number of purely combinatorial track candidates reconstructed during the track building steps. A reduction of the combinatorial component corresponds to savings in the computing needs to run the track reconstruction.

2. Conventional tracking and alternatives

Three major steps can be identified for the track reconstruction: the track seeding, the track building or pattern recognition, and the track fitting. The track seeding aims to identify a possible starting point for the pattern recognition based on a small number of tracker hits and possible additional constraints for the proton-proton interaction origin. The charged particle track reconstruction in the ATLAS and CMS software relies on a Kalman filter based approach [2,3,8]. The KF technique is applied to both the pattern recognition and the track fitting. This is the conventional tracking approach.

The KF-based pattern recognition is outlined in a sketch in figure 1 (a). The initial seed state is propagated to the neighboring tracker detector layer. For every hit consistent with the propagated state a full track state update with the hit measurement is made. Ambiguities are treated as alternative track candidates, including those made by keeping the original candidate without a hit added on the layer. Uncertainties associated with material effects are accumulated as well. The procedure continues for every candidate until the last tracker layer, with some candidates terminated earlier based on a threshold on the number of layers without actual measurements. Every propagation and update includes manipulation of the full five-parameter track state and its covariance matrix. At the end, the candidates are ranked and the best one is selected. Application of the KF technique at this step allows for mathematically most optimal accounting of the measurement uncertainties as well as the material effects.
After the pattern recognition, hits associated with the selected track candidate are used in the final track fit. Typically this Kalman fit is done in the forward and backward direction with the final track state estimate coming from a combination of the two (smoothing). Apart from the possible further cleaning and selection, a large fraction of the candidates passing the final track fit become the reconstructed tracks provided for physics analyses.

In the pattern recognition the fraction of layers with ambiguities grows with increasing pileup multiplicities and the task becomes combinatorially complex. The number of candidates from combinatorial sources can become much larger than the number of final tracks. The computational cost of running the full KF-based pattern recognition can become prohibitive. A faster alternative can be considered to address this issue. Compared to the pattern recognition step, the final track fitting step has essentially no combinatorial growth with a number of pileup interactions. The KF-based fitting remains feasible with increasing pileup multiplicities.

The following aspects are important in a choice of a faster alternative to the KF-based pattern recognition: a reduction of high precision math operations for practical reasons and a maximization of locality of computations to specific detector regions. The latter is important to maximize utility of an implementation in a parallel computing environment, which is the driving technology trend with GPU, MIC, or similar architectures. The KF pattern recognition which proceeds sequentially hit by hit with possible branching on each layer is hard to parallelize effectively [9]. An algorithm that reconstructs separate parts of the track independently would allow for high degree of parallelization.

![Figure 1. Track building steps using a Kalman filter based tracking (a). Segment building and linking steps (b).](image)

**Figure 1.** Track building steps using a Kalman filter based tracking (a). Segment building and linking steps (b).

### 3. Segment linking as a fast tracking alternative

The segment linking algorithm outlined in figure 1 (b) is an example of a fast tracking algorithm, which can replace the seeding and the pattern recognition steps of the conventional KF-tracking. The implementation presented here is the most appropriate for track reconstruction in a uniform axial magnetic field in a tracker geometry with concentric measurement layers. The implementation is inspired by the segment linking algorithm used by the CDF collaboration [10].
For the study presented here we consider an implementation corresponding to the central (barrel) region which is applicable to either the ATLAS or CMS trackers.

The main steps of the algorithm are the segment building, the actual segment linking (a combination of segment pairs to make tracklets), and the tracklet merging. The segment building provides track line segments using measurements in two or more layers, which are separated well enough to provide high precision direction measurement. The segment linking step selects segments consistent with a helix of a track trajectory. The consistency with a helix is checked in both the $rz$ projection, where the trajectory is approximately a line, and in the $r\phi$ projection, where the trajectory is approximately a circle. In the $r\phi$ projection a pair of segments is finally selected if the two segment directions are consistent with two chords on a circle passing through the segment end points, as shown in figure 1 (b). The tracklet merging step creates track candidates by simply combining tracklets with shared segments.

The first two steps of the segment linking algorithm are implemented with rather simple math and logic. Segments are constructed with an assumption of a particle originating close to the proton-proton collision luminous region and having a momentum above a given threshold. This limits the possible phase space of considered segments. The segment pairs are linked into tracklets with matching requirements taking into account the segment position and direction resolution, material effects, and a possible range of curvatures of the trajectory. The selections are adjusted to maintain high efficiency above a $p_T$ threshold, which was set at 1 GeV for this study. Estimates of the impact of the tracker layout on this algorithm were done using tracklets. The computational resource waste for the tracklet merging and further steps completing the full tracking are expected to be driven by the fraction of the combinatorial component at the output of the segment linking.

4. Layer grouping setup
The tracker hit distribution on individual layers becomes rather uniform at high pileup multiplicities. Hits from particles with various momenta coming from separate proton-proton collisions dominate surrounding hit population for a given reconstructed charged particle track. The computing budget of an inclusive tracking algorithm is spent mostly on reconstruction of tracks from pileup interactions rather than on tracking of interesting signal interactions, as e.g. high momentum hadronic jet production. The segment building step, which is the least constrained part of the segment linking algorithm, has a large combinatorial component coming from surrounding hits originated from the pileup interactions. It is clear, as illustrated in figure 2, that the smaller the distance between the measurement layers, the smaller is the chance to build a segment from unrelated hits. This suggests that the combinatorial component in the segment linking will be reduced if the layers are grouped. This works, as shown below, as long as the segment direction precision remains high.

We implemented a simplified tracker simulation with realistic hit placement, including resolution and material effects corresponding to the CMS upgrade tracker [5]. A simulation of top quark-antiquark pair production in proton-proton collisions at a center of mass energy of 14 TeV with an average number of pileup interactions of 140 is used to study the impact of the tracker layout. The modified tracker layout is simulated by relatively short propagation of charged particles from their simulated positions on the nearest layers of the reference geometry to the reference radii of layers in the target simulated tracker layout. To illustrate effects of the distance between layer pairs, we consider the layer separations of 16 cm and 2 cm. Layer outlines for the two alternative layouts are shown in figure 3. The larger value corresponds to the equidistant layout roughly matching the layer positions for the reference geometry. The smaller value of 2 cm is selected as a somewhat extreme case from the engineering design perspective,

1 In the case of the CMS tracker a pair of doublet layers can be used.
Figure 2. The segment building and linking in presence of combinatorial background hits from pileup interactions for the equidistant layout (a) and for the grouped layout (b). The segment building window, highlighted by the dotted lines, is determined by the target high segment building efficiency and is expected to be roughly the same in both cases. More combinatorial background hits are picked up in the equidistant layout and lead to more background segments. While it still corresponds to a high enough precision of the reconstructed segment direction.

Figure 3. Simulated hit positions for the equidistant layout (in the $xy$ and $rz$ view (a)) and for the grouped layout (in the $xy$ and $rz$ view (b)). Only the displayed barrel region is used in this study.

5. Results
The estimate of the computing resource wasted is done using the $\Delta \beta$ matching variable distribution defined in figure 1 (b) and computed at the final step of the segment linking. Distributions of the $\Delta \beta$ for samples corresponding to the two tracker layouts are shown in figure 4. There are two components in the distribution of $\Delta \beta$: the narrow peak and the broad component under the peak. The narrow peak comes from track segment pairs that both belong to the same track. The broad component is from the combinatorial combinations of various sources: segments built from hits that do not belong to the same particle and segment pairs combined from different particles. The final selection of the tracklets from pairs of compatible segments is the requirement on $\Delta \beta$ value to be in the peak region as denoted with the gray band.

The combinatorial component dominates the population of selected tracklets in the equidistant tracker layout case, compared to about a factor of nine smaller contribution for the grouped layout. The efficiency to reconstruct tracklets for a simulated particle is essentially
Figure 4. Distributions of the $\Delta \beta$ in the equidistant (a) and grouped (b) layout scenarios for segment pairs passing all requirements except for the last one applied on the value of $\Delta \beta$. Entries in the peak above the combinatorial background correspond to segment pairs coming from the same track. The shaded region near the peak corresponds roughly to the final selection of the segment linking. There is a factor of about nine reduction in the combinatorial background in the grouped layout compared to the equidistant case.

6. Summary

The results of this study show that a grouped tracker layer layout can significantly reduce the cost of computing needed to reconstruct charged particle tracks compared to the conventional layout with roughly equidistant layer separation, similar to that currently planned for ATLAS and CMS detector upgrades. The tracker layout with the grouped layer separation of 2 cm is shown to reduce the combinatorial component of tracking by a factor of nine compared to the equidistant layout. Considering comparable cost of the upgrade tracker construction and the projected cost of running track reconstruction during the period of the HL-LHC, there is an opportunity to reduce the total cost of the experiment.

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