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Studies of seeding algorithms in future particle collider experiments

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1 Introduction

The High Luminosity Large Hadron Collider (HL-LHC), is preparing for a substantial increase in its luminosity. The objective is to accumulate a integrated luminosity of between 3000 and 4000 fb^{-1} during the operational phase. This comes with a unique set of engineering and computational challenges as the experiment is set to operate with an increased average of simultaneous collisions occurring during each bunch crossing (*pile-up*) from $\langle \mu \rangle = 60$ to $\langle \mu \rangle = 200$. This complicates the ability to effectively identify individual particle tracks within the detector. To address these challenges, the experiments at the HL-LHC will undergo significant upgrades to several sub-detectors. For the ATLAS Experiment, one of the two large multi-purpose experiments at the LHC, these upgrades include the implementation of a fully silicon inner tracker detector[1][2] (ITk) as opposed to the current implementation of both silicon and transition radiation technologies, and the introduction of a High-Granularity Timing Detector[3] (HGTD) in the forward region $|\eta| \in [2.4, 4]$[1]. These enhancements, are part of the ATLAS experiment's efforts to mitigate the effects of the increased pile-up. Computational demand increases with the scheduled upgrades, due to the increased complexity of reconstructing particle tracks in a high luminosity environment. Overlapping tracks and duplicate tracks are more common with increased pile-up, making background rejection challenging. Reconstruction of tracks is already a large contributor to the total CPU consumption in event reconstruction, with expected increments in HL-LHC. The motivation for more efficient tracking algorithms is clear, and a significant improvement in CPU performance is required to maintain operating the experiment with an expected five-fold increase in total CPU consumption by 2032[4]. Due to the high radiation dose in proximity of the interaction point, the two innermost pixel layers of the ITk will have to be replaced after a certain number of years of data taking. Studies are ongoing in ATLAS [5] to bring in technological innovation and fully exploit the potential of HL-LHC by including 4-dimensional (4D) tracking detectors in the ATLAS barrel region as a replacement of the innermost ITk pixel layers. 4D trackers are devices capable of simultaneously measuring spatial and temporal coordinates with extremely good resolution (O(m) and O(few tens of ps)) and represent the next avenue for charged-particle tracking. If installed in the ATLAS barrel region, it would allow to obtain hermetic coverage with timing information and to maximise the investment on the HGTD by overcoming the limitations due to its acceptance restricted to the forward region. Pile-up interactions do not occur in the same place and at the same time as the signal candidate (hard-scatter), but our current detectors rely only on spatial information to discriminate among them, leaving unresolved a temporal degeneracy. Thus, assigning also a high-precision time stamp to particle tracks is a ground-breaking feature in the rejection of pile-up. While the preliminary investigation in Ref. [5] focuses on the impact that timing information has on high level objects such as vertices and jet flavour tagging, in this study we focus on studying how track timing information can be used in

[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 $\eta = -\ln\tan(\theta/2)$.

seeding algorithms both in ATLAS and in experiments at future particle colliders. The addition of the temporal coordinate in the detector holds the potential to allow for vast improvements in CPU timing.

1.1 Tracking algorithms: Seeding

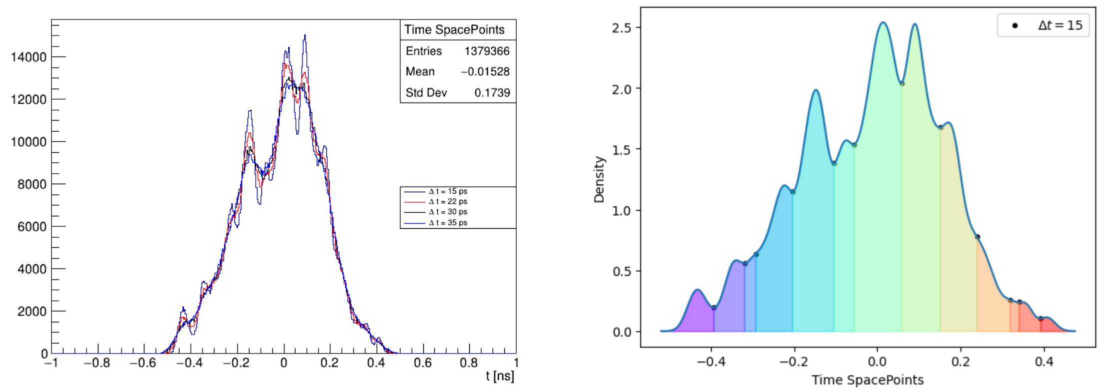
When charged particles move through the layers of the detector, they leave a trail of hits as they interact with the sensitive materials of the sensors. To gather information about the charged particles involved in the experiment, we reconstruct their trajectories by combining information from the sensors that they passed through using a Combinatorial Kalman Filter (CKF) algorithm. The presence of the magnetic field allows for the determination of the momentum of the charged particles, from the reconstructed curvature of the track. These reconstructed trajectories of charged particles serve as the starting point for other objects reconstruction algorithms in the event reconstruction process, such as electrons, muons or jets, before the event analysis is done.
The first step in track reconstruction consists of forming clusters of hits in space in the pixel and strip detectors. These clusters are the Space-Points (SPs) which are used for the seed formation. The formation of seeds starts by finding a triplet of SPs that are in different layers of either the pixel detector or the strip detector. The search for candidate SPs is performed per (ϕ,z) bin of the detector. The middle SP is taken, then the top and bottom SP are searched in neighbouring bins on bottom and top layers. Finally, the triplets of SPs are fit under helical path hypothesis to extract the track parameters that serve as starting point for the CKF reconstruction algorithm.

2 ATLAS, ITk beyond RUN 4

The harsh radiation environment damages the silicon detector layers, requiring the replacement of the innermost ITk layers midway through Run 4. This poses the opportunity to introduce in the second innermost layer new ultra-fast timing pixel sensors which could provide a high precision time of arrival measurement, unlocking 4D tracking capabilities of the ITk detector. For the studies presented in this document, we assumed that time measurements of the time of arrival of particles on sensors are available at hit-level.

To substantially enhance the seeding algorithm, it is necessary for a minimum of two layers to contain time information. This is because having only one layer with time information leaves the SPs with no reference point for comparing their time coordinates. However, by studying the time information in just one layer we can already determine what the single hit time resolution has to be in order to effectively distinguish hits coming from different collisions. Intuitively, the comparison of the time of arrival between two layers would improve efficiency and reconstruction time of the tracking as the number of seed candidates drastically drops due to the differentiation based on time difference between the SPs. However, the resolution of these time measurements play a significant role. With a pileup of $\langle\mu\rangle = 200$ and $\sigma = 180$ ps spread, collisions occur every $\mathcal{O}(1)$ ps. To put this in perspective, the anticipated time resolution of the HGTD is 30 ps at the beginning of operation degrading to 50 ps at the end of the operation of HL-LHC.

Similar resolution scenarios are being investigated in these studies for 4D tracking seeding. Additionally, the added dimension introduces a new kind of complexity, as there are numerous ways the current algorithm can be modified to implement the time information to ultimately distinguish the particle tracks. Taken together, the time resolution and the integration of the time information present a significant challenge for the future of the ATLAS experiment.



(a) (b)

Figure 1: (Left) Simulation of time at SpacePoints for one $\langle\mu\rangle = 200$ PU event for different values of time resolution in the detector. (Right) Clustering of time in the second layer of ITk with temporal resolution $\sigma = 15$ ps at $\langle\mu\rangle = 200$ PU. The SPs are clustered by calculating the minima of the Gaussian Kernel-Density Estimate of the time information. Each local minimum indicates the bin edge of the time cluster.

To study the time information in events in the ITk's second layer, we simulated $t\bar{t}$ collisions in the ITK geometry using Athena, the ATLAS software infrastructure. The centre of mass energy for the collisions was $\sqrt{s} = 14$TeV with emulated 200 PU by combining 200 single hard scatter events together with a Gaussian spread in time that has a standard deviation of $\sigma = 180$ps.
The resolution effect of the silicon time detector was then simulated by smearing the SPs individually with a Gaussian distribution with varying spread. In Figure 1a the resulting distribution of time for the SPs is displayed for various resolutions. This shows clearly why it is important to obtain a very high timing resolution for the silicon detectors, as it allows to better distinguish what SPs belong to which collision. The highest track-timing resolution that has been looked at for the ITk beyond run 4 after the replacement of the innermost layers, is $\sigma = 30$ ps, for which the details in the SP time resolution are minimal. In order to make any distinctions between the collisions solely on the information in the SPs, a higher time resolution would be required to have any sizeable improvements in track seeding algorithms.
By forming clusters in time, the seeding algorithms can leverage the time information and only seed in the neighbouring time clusters of a SP, similarly how it does for the spatial plane (ϕ, z) bin in the SP doublet search. A straightforward way to make time clusters is to distinguish the peaks in the time distribution. This strategy is employed

for a simulation with a time resolution of $\sigma = 15ps$, and displayed in Figure 1b, by estimating the distribution with a Gaussian Kernel-Density-Estimate. The local minima indicate the distinction between two neighbouring clusters in time. Using this approach, we identified approximately $\mathcal{O}(10)$ clusters which can roughly indicate SPs coming from the different collisions. However, conducting further analysis of the seeding algorithm and the implementation of the time cluster strategy were deferred to future investigations. This decision was influenced by technical challenges encountered with the Athena software, particularly related to issues with PU events. Therefore, I shifted the focus of the studies towards future particle collider experiments, aiming to offer a broader perspective on the application of seeding algorithms that incorporate temporal data.

3 Future Particle Collider Experiments

Detectors at future particle collider experiments that incorporate temporal information hold great potential for various types of colliders. In proton-proton hadron colliders like the LHC, mitigating the effects of pile-up, is crucial. For upcoming colliders like the Future Circular Collider (FCC)[12], which operates at $\mathcal{O}(1000)$ pile-up levels, timing information at each detector layer is essential. It allows for the association of hits that align in time, thereby dramatically reducing complexity. Achieving extreme timing resolutions in the range of 5-10 picoseconds per track is essential to effectively manage pile-up and prevent the merging of unrelated vertices[8].
Electron-positron colliders, like the International Linear Collider (ILC)[6], aim for high-precision measurements. Achieving this requires minimal passive material in detectors. Timing resolutions at the picosecond level are necessary, to enable TOF calculations, enhancing particle identification, especially for low-momentum particles.
Muon colliders face a unique challenge due to the decay of muons within collision beams, generating a beam-induced background (BIB). Precise hit timing reduces BIB by isolating hits consistent with collision time. Correlating timing data across detector layers helps identify hits from the same particle. A $20-30$ ps timing resolution is sufficient to effectively manage BIB, enhancing the potential of muon collider experiments.
Future particle colliders can be studied by simulating particle collisions in the Open Data Detector (ODD)[10], a general purpose particle detector that is implemented in the A Common Tracking Software[9] (ACTS) library. The ACTS library will also be used by the ATLAS experiment during HL-LHC, therefore any finding from this study could also be adapted to ATLAS. The layout of the ODD is visualized in Figure 2 with a red box indicating the three innermost pixel layers of the barrel region that we focus this study on. This framework allows the accurate simulation of particle collision events in a future hadron collider with a choice for the set of parameters, specifically the PU and the temporal measurement resolution.

4 Metrics

When evaluating the performance of a seeding algorithm, several key metrics are typically used to assess its effectiveness. Two critical metrics in this context are efficiency and

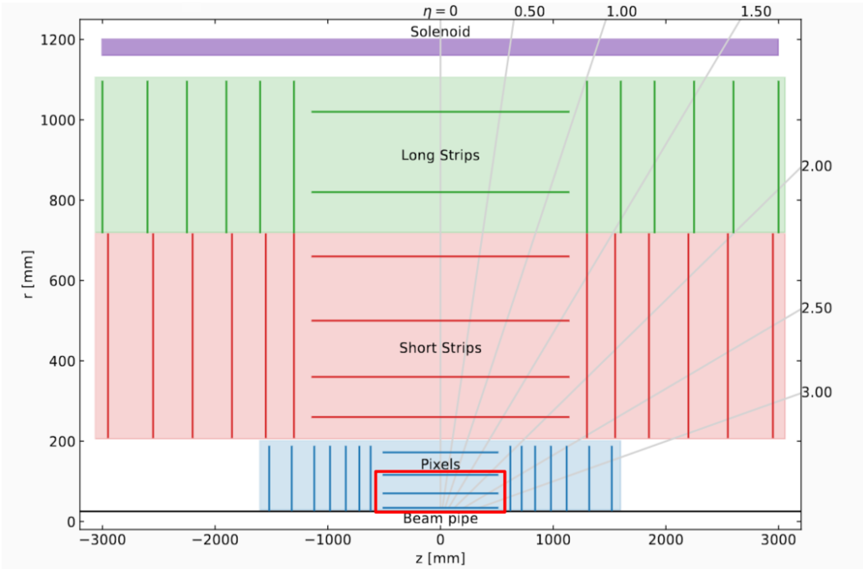


Figure 2: Open Data Detector Layout[10]. Red box indicates the three innermost pixel layers of interest for this study.

fake rate. These metrics are defined by the number of particles that are matched by the seeding algorithm and for which the correct tracks are reconstructed, these we call matched particles. Contrary there are also unmatched seeds, the number of seeds that do not match any particles and therefore are noise in the seeding algorithm. The efficiency and fake rate are defined as:

$$\text{Efficiency} = \frac{\#\text{ matched particles}}{\#\text{ total particles}} \tag{1}$$

$$\text{Fake Rate} = \frac{\#\text{ unmatched seeds}}{\#\text{ total seeds}} \tag{2}$$

The efficiency gives an indication on how good the algorithm is at reconstructing the tracks of the particles in the simulation. Lower efficiency resembles a loss of particles that could potentially be used for further analysis. In return the fake rate quantifies how often the algorithm mistakenly selects low-quality or irrelevant candidates as potential seeds. Lower fake rate implies that the algorithm is sufficient in filtering out tracks that are not linked to particles, ensuring that the chosen seeds are valuable.
Regarding resource management, two additional metrics are of significance: the total number of seeds and the algorithm's CPU Time. The total number of seeds represents the pool of candidates for the track reconstruction algorithm. Lower counts of seeds directly lowers the use of computational resources, as fewer tracks are reconstructed. However, it should be balanced with efficiency to ensure that the reduction in candidates does not compromise the quality of selected seeds. The total measurement of computational resources consumed by the algorithm is reflected in the CPU time to perform the seeding task. In the context of future particle particle collider experiments, the CPU time plays a vital role as the integrated luminosity will increase to 4000 fb^{-1} for the HL-LHC, the

computational resource will be one of the major bottlenecks in the reconstruction process. By keeping the computational demands low, the resources for data processing and, consequently, for data analysis are kept within manageable bounds for the experiment.

4.1 Methods

In this work we focus on the study of track reconstruction for the three innermost layers of the ODD Pixel barrel region. In the seeding stage of the track reconstruction, the candidate SPs for the seed are searched per (ϕ, z) bin of the detector. The central SP is selected from the (ϕ, z) bin, and then the top and bottom SP are identified in neighboring bins on the respective top and bottom layers of the detector. This determination is made based on geometrical assumptions relative to the interaction point. One of the requirements is based on compatibility cuts between SP-doublets to check the r-distance and curvature to be compatible with a track, check if the origin along z-axis is within collision region, and more. The strategy implemented to introduce the time information in the algorithm, is to add an additional time compatibility cut for the SP-doublet check. After TOF correction the time between the SPs is assured to be between two or three $\sigma = 30ps$ time resolution of the silicon detector, during this process. This assures that the SPs that are too far separated in time can not form a seed as the two events are likely to not be related to each other. The impact of the introduced algorithm is studied based on its performance on the aforementioned metrics.

4.1.1 Simulated Data

To study seeding algorithms for future particle colliders, we conducted a simulation study for the ODD detector[10] using the ACTS [9] library. The simulated data consisted of a total of 1k $t\bar{t}$ events with $\langle \eta \rangle = 200$ at a centre-of-mass energy of $\sqrt{s} = 14$TeV for the first three innermost pixel layers of the ODD geometry. Due to the simulated pileup, the bunch crossing have a standard deviation of $\Delta t = 180$ps. The sample was generated using Pythia8[7] with the particle propagation simulated using Fatras[11].
The time information is propagated from the truth particles to the hits in the detector. Reconstructed particle hit times are emulated by a Gaussian smearing of the truth particle time for the resolution value of $\sigma = 30$ ps. The resulting time information is visualized in Figure 3, with the reconstructed time and TOF corrected time. The TOF correction is assuming the particles move at the speed of light and subtracting the distance traveled from the time of arrival. The time of flight corrected time is given by:

$$t_{TOFcorr} = t_{rec} - \frac{1}{c}\sqrt{x^2 + y^2 + z^2}, \tag{3}$$

where x, y, z are the spatial coordinates of the SPs and t_rec is the reconstructed time of the SPs.

4.1.2 Result

In Figure 4 the performance of the seeding algorithm is summarized in four metrics, number of total seeds, efficiency, fake rate and CPU time. The large reduction in CPU time

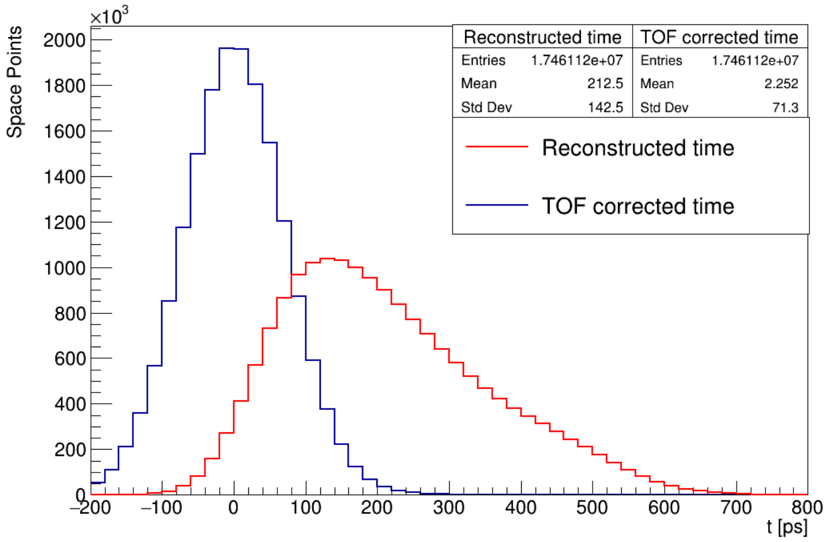


Figure 3: Reconstructed time of the Space Points in ODD detector barrel region and the corresponding TOF corrected time of the Space Points for a total of 1000 events. Simulation data of $t\bar{t}$ collision at $\sqrt{s} = 14\text{TeV}$ with pileup of $\langle\mu\rangle = 200$. The time resolution of the silicon is simulated with $\sigma = 30$ ps.

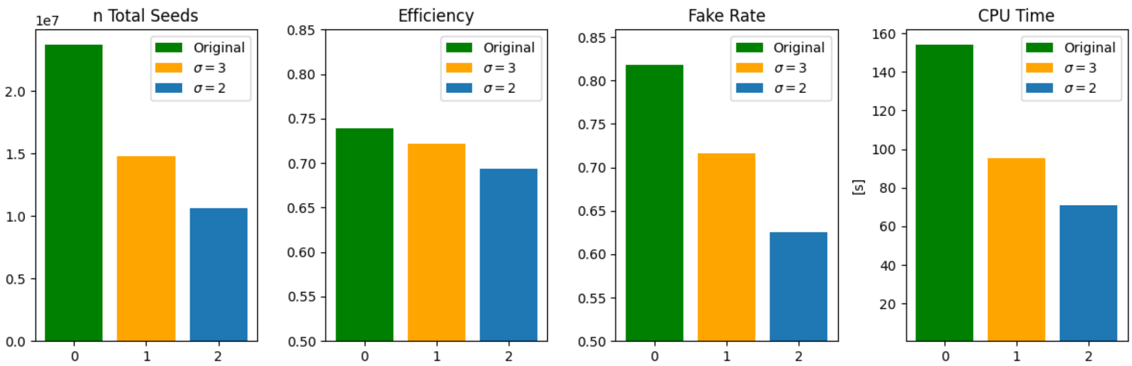


Figure 4: Seeding Algorithm performance metrics. Comparison of the number of total seeds, efficiency, fake rate and CPU time for the original algorithm and the algorithm with time information implemented with two or three sigma acceptance range.

is reflected in the number of total seeds being much lower for the implemented algorithm compared to the original, but the efficiency and fake rate allow for a broader view. The efficiency shows a slight reduction with the proposed seeding algorithm compared to the original, indicating a loss of information on particles in the detector. However, most of the seeds that are being lost by the introduction of time information, are fake seeds, since the reduction in fake rate is much larger than the reduction of efficiency. Reducing the number of fake seeds in the experiment ultimately reduces the amount of fake tracks that are reconstructed, saving computational resources and also disk space for the further analysis phase.

To provide a deeper understanding of the seeding algorithm's performance and its cor-

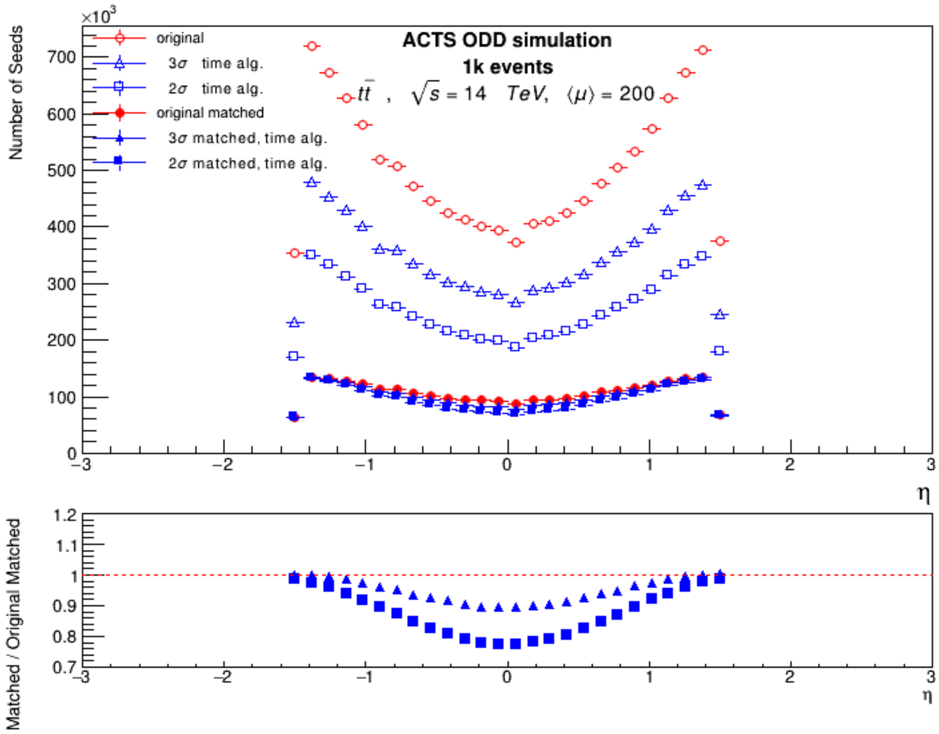


Figure 5: Number of seeds vs η. Ratio plot indicating the number of matched seeds of the algorithm including time information compared to the original algorithm. The seeds that match with a truth particle of the simulation are marked as matched.

relation with the detector's geometry, the variation in the number of seeds as a function of η is illustrated in Figure 5. The introduction of the time information decreased the total amount of seeds produced significantly, with only a slight reduction in the number of seeds that match a truth particle. In the ratio plot it becomes evident that for smaller values of $|\eta|$ the number of matched seeds decreases in the seed formation. This is related to the imperfect TOF correction which has a larger error for shorter distances between SPs.

5 Take away message

In future particle collider experiments, the availability of temporal information from sensors within particle detectors opens up the possibility of distinguishing particle tracks based on the time they pass through detector layers. This study focused on the ODD, implemented in ACTS, to evaluate seeding algorithms with time information in future particle collider experiments. Evaluating the performance of the seeding algorithms yielded promising results in terms of reducing CPU usage and Fake Rate. This reduction is crucial, especially at the HL-LHC, where efficient management of computational resources is essential for successful data analysis. The Seeding algorithm is not optimized for the ODD geometry, and in order to achieve comparable efficiency as in the ITk of ATLAS, the seeding algorithm will have to be tuned accordingly. This study serves as a starting point for future studies in the temporal seeding domain for future particle colliders highlighting the opportunity that presents itself with temporal information in a particle detector.

6 appendices

6.1 Time information argument

Here is the argument for a L layer detector with time information. Explain situation; the detector has $L = 6$ layers total, with $\sum_{l=1}^{L+1} n_l = N$ total space points. To make a possible seed, three space points that are in neighbouring layers are required. The total amount of combinations is therefore:

$$\#\text{ Seeds} = \sum_{l=1}^{L-1} n_l \sum_{l=2}^{L} n_l \sum_{l=3}^{L+1} n_l. \tag{4}$$

Introduce time clusters in the first two layers, such that only seeds can be formed from space points that are in the same time cluster.

$$\#\text{ Seeds} = n_3 \sum_{k=0}^{K} \delta_{1,k}\delta_{2,k} + \sum_{l=1}^{L-1} n_l \sum_{l=2}^{L} n_l \sum_{l=3}^{L+1} n_l, \tag{5}$$

where $\sum_{k=0}^{K} \delta_{l,k} = n_l$ is the amount of hits in cluster k for layer l. This results in,

$$n_3 \sum_{k=0}^{K} \delta_{1,k}\delta_{2,k} < n3 \sum_{k=0}^{K} \delta_{1,k} \sum_{k=0}^{K} \delta_{2,k}, \tag{6}$$

reducing the amount of computations. For the case with time information in all the layers this reduces to:

$$\#\text{ Seeds} = \sum_{i=0}^{L-1} \sum_{k=0}^{K} \delta_{l,k}\delta_{l+1,k}\delta_{l+2,k}. \tag{7}$$

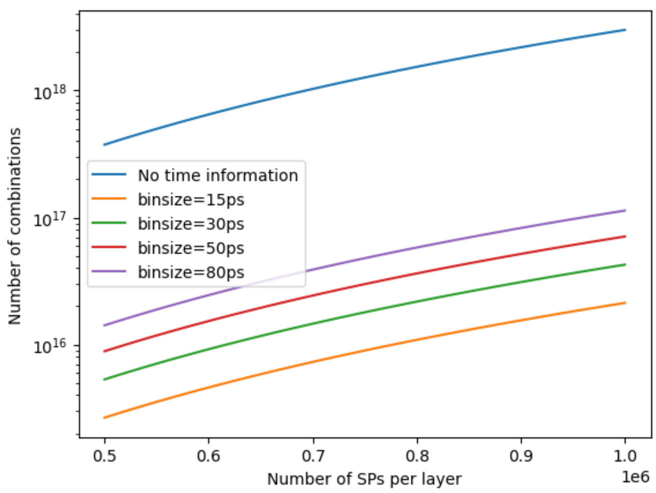


Figure 6: Numerical calculation of the number of combinations for the number of SPs per layer with the implementation of the time information.

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