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Physics and performance of the High Granularity Timing Detector

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The expected increase in particle flux in the high-luminosity phase of the LHC (HL-LHC), with an instantaneous luminosity that can reach $\mathcal{L} = 7.5 \times 10^{34}$ cm^{-2} s^{-1}, will have a significant impact on the pile-up with potentially 200 interactions per bunch crossing. The performances of electrons and photons, as well as those of jets and missing transverse energy, will be strongly degraded in the endcap and the forward regions of the detector, where the granularity of the electromagnetic calorimeter is coarser and the momentum resolution of the Inner Tracker (ITk) is poorer. In order to mitigate the pile-up contamination coming from this high luminosity, a High Granularity Timing Detector (HGTD) is proposed in front of the LAr endcap calorimeters, covering the pseudo-rapidity region between 2.4 and 4.0. The high granularity and the high-precision timing information will improve pile-up reduction. It will also improve the forward object reconstruction, and complement the performance of the updated ITk in the forward region of the ATLAS detector. This leads to an amelioration in the jet and lepton reconstruction performances. The ability of the HGTD detector to improve the pile-up jet rejection and the lepton isolation efficiency within the forward region, in addition to the physics and performance results, is presented.

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1. Introduction

In order to extend the discovery potential, both accelerator and experiments are planned to be upgraded, where the high-luminosity LHC detector (HL-LHC) will be able to reach an instantaneous luminosity up to $\mathcal{L} = 7.5 \times 10^{34}$ cm^{-2} s^{-1}, five times higher than its nominal value [1]. The large increase of the pile-up interactions is one of the main challenges for the high luminosity LHC, where the interaction region will extend to 50 mm (RMS) along the beam axis and will generate an average of 1.6 collisions/mm compared to the 0.24 collisions/mm reached in Run 2 (see figure 1). With this high pile-up environment, the tracking is challenging in the forward region, where the density of the charged particles produced in the primary interaction gets to its maximum. Therefore, the HGTD was designed to complement the information given by the upgraded tracking system (ITK) [3].

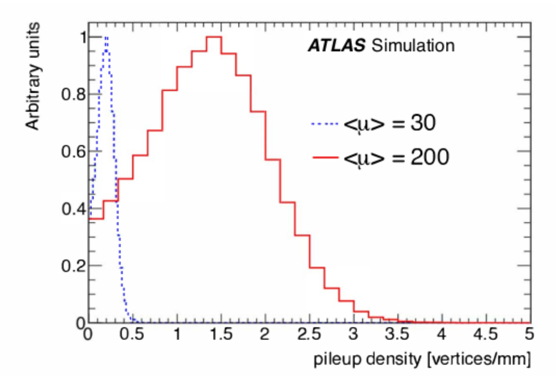
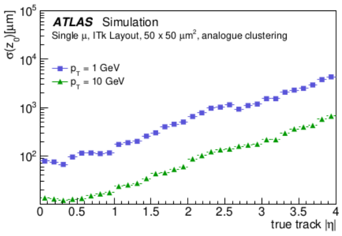


Figure 1: Local pile-up vertex density comparing two different values of $\langle\mu\rangle$: $\langle\mu\rangle = 30$ and $\langle\mu\rangle = 200$ [2].

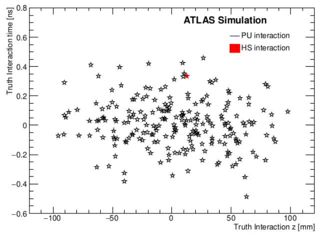
The main goal of the HGTD is to improve the forward object reconstruction with its high granularity and precise timing information that leads to distinguishing objects coming from the signal and the background. The precise association of tracks to primary vertices given by the HGTD is the key approach to reduce the effect of pile-up on the event reconstruction, and therefore improve the physics performance that can enhance the physics potential of the ATLAS detector.

2. HGTD Motivation

At an average pile-up density of 200 ($\langle\mu\rangle = 200$) in which multiple vertices are merged, the impact parameter resolution degrades dramatically in the end cap region. In this case, the longitudinal impact parameter resolution (σ_{z_0}) becomes poorer for track vertex association when η gets higher (see figure 2(a)). Adding additional timing information will improve the track vertex association. The HGTD detector was designed with this goal [2]. By combining both position and timing resolution information, it will be easier to distinguish the multiplicity of the reconstruction vertex created by the pile-up contamination, meaning that the interactions that are close in space would be separated in time. Figure 2(b) illustrates this effect, showing the distribution in time and space (in z) of the vertex region.



(a)



(b)

Figure 2: (a) Resolution of the longitudinal impact parameter, z_0, as a function of η for different p_T values for muons using ITK alone. (b) Visualisation of the discrimination between hard-scattering (red) and pile-up interaction (black) in z-t plane for $\langle\mu\rangle = 200$ [2].

3. HGTD Low Gain Avalanche Detector

The High Granularity Timing Detector (HGTD) will be inserted in the gap region between the endcap calorimeters and the barrel, where the granularity of the electromagnetic calorimeter is coarser and the momentum resolution of the Inner Tracker is poorer, at a distance of approximately ±3.5 mm from the nominal interaction position. This new detector will provide a highly precise time measurement for tracks with an optimal time resolution of 30 ps, in the pseudo-rapidity region from 2.4 to 4.0. The implementation of the HGTD requires thin radiation-resistant sensors with a high time resolution. A new sensor technology, called Low Gain Avalanche Detector (LGAD) [4] has been designed to meet these requirements. This type of sensor was first produced by the Centro Nacional de Microelectronica (CNM) of Barcelona and developed over the last five years in the RD50 collaboration.

LGADs are n-on-p silicon detectors with an additional p-type doped layer containing charge multiplication to achieve an internal gain. Figure 3 illustrates the principle of the LGAD technology, displaying how the high doped region caused a very high electric field region, where an avalanche of electrons will be created, causing an additional electron-hole pairs.

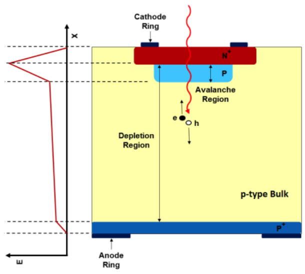


Figure 3: Cross section of an LGAD sensor [2].

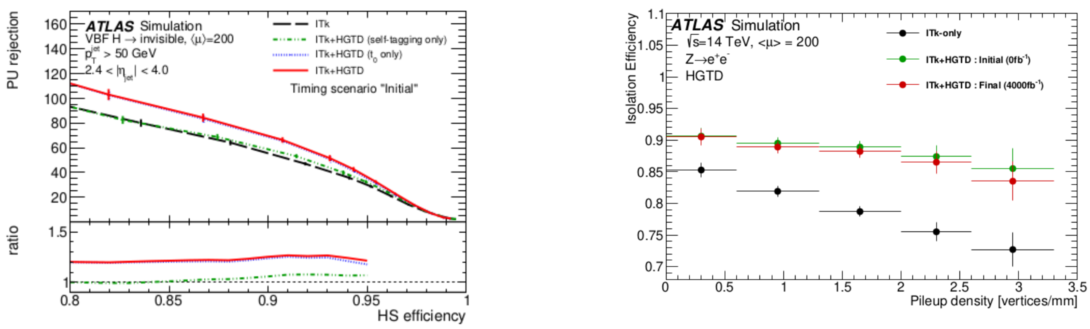
The development of LGAD sensors aims to optimize an excellent timing resolution between 35 and 70 ps per hit over their lifetime. This time resolution was determined by considering three major effects: time walk from amplitude variations, jitter caused by the electronic noise, and Landau fluctuation from non-uniform energy deposits.

4. HGTD Performance

The additional time information provided by the HGTD detector improves the reconstruction of different physics objects. This can be achieved by reducing the efficiency of the reconstruction of these objects by rejecting the pile-up contamination.

Two approaches are available to correctly associate tracks to the corresponding vertex. The first

and most powerful one is based on the determination of the hard-scatter time noted t_0 which will be used as a global reference to verify the time compatibility of tracks related to jets or to other physics objects in the event. However, this strategy is not possible for all the events. This is why a second technique named self-tagging, where the knowledge of t_0 is not required, is used. The main idea is to check the time consistency of tracks that correspond to the same object among themselves.
The key element to reject the pile-up in jets is the precise association of jets with tracks and primary vertices, using the powerful discriminant R_{p_T}. It is defined as the scalar sum of p_T for all tracks inside the jet cone originating from the hard-scatter vertex, divided by the fully calibrated jet p_T. Large values of this variable correspond to the hard-scatter jets and the small values to the pile-up ones. At high-level of pile-up and especially in the forward region, the discriminant power of this variable gets reduced. The addition of the timing information increases the separation power between hard-scattering and pile-up jets by summing only the tracks with times compatible with the time of the hard-scatter vertex at a level of 2σ. The use of the HGTD provides a significant improvement of about 20% in the pile-up jets suppression (see figure 4(a)).
In a further way, the HGTD can be used to improve the lepton isolation at the high level of pile-up. The lepton isolation is defined as the probability that no tracks with $p_T > 1$ GeV are reconstructed in $\Delta R < 0.2$ of the lepton track. By assigning a time to leptons, the out-of-time pile-up tracks within the isolation cone will be rejected in the forward region. Figure 4(b) illustrates the efficiency of the lepton isolation, considering electrons coming from Z boson decays. As seen in the figure 4(b), the electron isolation efficiency is improved by about 10% for a local pile-up density of the order of 1.6 vertices/mm. This confirms that the improvement is given by the HGTD and that the pile-up density dependence is lowered.



(a) (b)

Figure 4: (a) Pile-up jet rejection as a function of hard-scatter jet efficiency within $2.4 < \eta < 4.0$ region. (b) The efficiency for electrons to pass track-isolation criteria as a function of the local vertex density, for the ITk-only and ITk+HGTD scenarios [2].

5. Conclusion

The precise timing information provided by the HGTD detector will be a powerful new tool to mitigate the pile-up interactions in the forward region at High-Luminosity LHC. The HGTD offers a clear improvement for physics objects performance by complementing the performance of the upgraded ITK while reducing the efficiency of the reconstruction of these objects by correctly associating tracks to vertices which is the key element to minimizing pile-up contamination.

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