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Simulation and Software Integration of the CMS MIP Timing Detector for High-Luminosity LHC

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Abstract. The Compact Muon Solenoid detector at the Large Hadron Collider is undertaking an upgrade program in order to face the harsh conditions foreseen by the High-Luminosity era. This program comprises the installation of a new timing detector whose aim is to measure the time of MIPs, the minimum ionizing particles, with a resolution of around 30-40 ps. The time information provided by this new MIP Timing Detector will improve the rejection of spurious tracks and vertices, will enable particle identification based on the time of flight, and will bring unique physics opportunities for interesting signatures such as those including long-lived particles. All these capabilities require a full software infrastructure to simulate the timing detector and its digitization process, for locally reconstructing the time information associated with tracks, propagating it to the beam line, and contributing to the vertex building. In this paper, the main characteristics of this infrastructure and its integration into the offline software chain are discussed.

1. Introduction

After the three-year running period at 13-14 TeV (Run-3) started in 2022, the Large Hadron Collider (LHC) will go through a long shutdown of approximately 2.5 years, needed to upgrade the optics in the interaction region, with the aim of producing smaller and brighter beams. The LHC is expected to resume operation around 2026 [1], entering the so-called LHC High-Luminosity (LHC-HL) era or Phase-2 of LHC operations. The introduced upgrades will enable the accelerator to deliver a potential luminosity of 2×10^{35} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{1}$ at the beginning of each fill [2], although the nominal scenario foresees a nominal luminosity of around 5.0×10^{34} $\mathrm{cm}^{2} \cdot \mathrm{s}^{1}$, in order to limit the number of "pile-up" (PU) interactions occurring at each bunch crossing to around 140 (it was about 40 for the LHC Run-2). An ultimate scenario with a luminosity of 7.5×10^{34} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{1}$ is also considered, that will provide 30% more integrated luminosity at the cost of producing 200 PU collisions per beam crossing. The MIP timing detector (MTD) is a new detector capable of measuring the production time of the charged minimum ionizing particles (MIP) that will be installed in the Compact Muon Solenoid (CMS) experiment with the aim of disentangle this amount of PU interaction while maintaining good resolution and reconstruction efficiency for the physics objects. The MTD exploits the fact that the individual interactions are not exactly simultaneous, but they are distributed over time with a root mean square of 180–200 ps, due to the longitudinal extent of the beams. By associating tracks from a vertex to hits and their corresponding times in the MTD, the time at which the collision vertex occurred can be reconstructed, and the timing information can be used as an additional coordinate to discriminate between vertices (see Fig. 1).

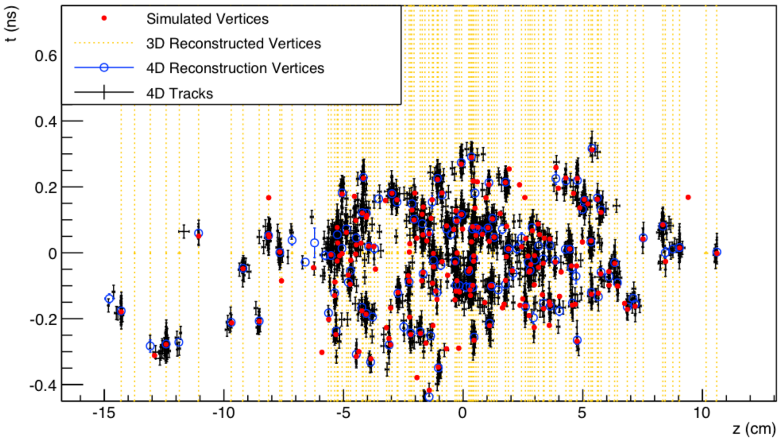

Figure 1. Simulated and reconstructed vertices in a 200 PU event, assuming a MIP timing detector covering the CMS barrel and endcaps [1]. The z-position and the time of the vertices are displayed on the x-axis and the y-axis, respectively.

2. Overview of the MIP timing detector design

The MTD is divided into two sections, following the layout of the CMS detector: the Barrel Timing Layer (BTL), covering $|\eta| < 1.5$, and the Endcap Timing Layer (ETL), covering $1.6 < |\eta| < 3.0$ (Fig. 2). The BTL and ETL will be implemented with, respectively, lutetium-yttrium orthosilicate doped with cerium (LYSO:Ce) crystal scintillators with silicon photomultipliers and low gain avalanche detectors silicon sensors. The MTD will be installed in the space between the tracker and the Electromagnetic Calorimeter (ECAL) [1].

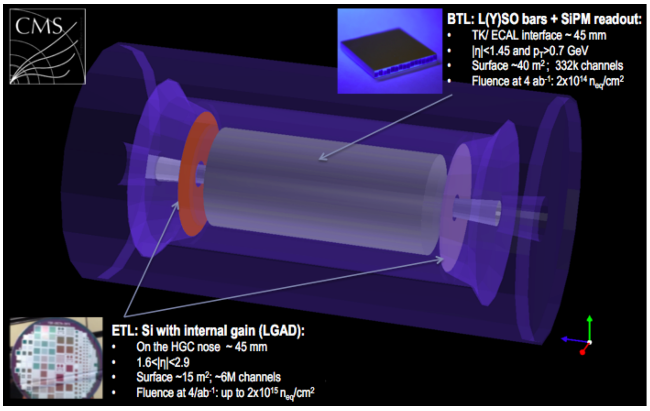

Figure 2. A schematic view of the GEANT4 [3] geometry of the timing layers implemented in CMSSW [4] for simulation studies, comprising a LYSO barrel (grey cylinder), at the interface between the tracker and the ECAL, and two silicon endcap (orange and light violet discs) timing layers in front of the endcap calorimeter [1].

3. Simulation and reconstruction

The event reconstruction studies are based on a complete GEANT4 simulation of the MTD detector, together with a modeling of the readout electronic response. The time and position of the particles crossing the MTD are reconstructed from the energy deposited in the active detector elements. A simple topological clustering is performed to associate adjacent MTD hits above the readout threshold. The time associated with a cluster is obtained from the average of single-hits time measurements, while the position is estimated using the cluster's barycenter, weighted by the single-hit energy.

3.1. MTD and track reconstruction

The tracks that have been reconstructed using the pixel detector and the strip tracker, are extrapolated to the MTD surface and matched with compatible clusters. The track is then refitted, taking the MTD cluster position as an additional spatial measurement, and the total path length p_{track} is computed, propagating the new track from the point of closest approach to the beam line, to the MTD front surface. In Fig. 3, the difference between the time of the refitted track and the simulation truth is shown, using pions generated in simulated top quark-antiquark ($t\bar{t}$) events at 14 TeV. The extracted track time resolution is around 33 ps. The efficiency for matching a reconstructed track to an MTD cluster as a function of the transverse momentum p_t is shown in Fig. 4 for single muons, with 200 PU events and without PU, and for single pion events in the acceptance region of the MTD ($\eta < 3$). The efficiency is above 90% for muons, lowered to about 80% for pions due to nuclear interactions in the tracker volume.

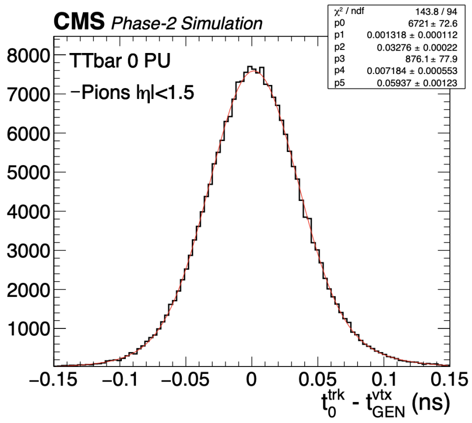

Figure 3. Distribution of the difference between the reconstructed time and the simulated time of a track at the vertex, for pions in simulated $t\bar{t}$ events at 14 TeV in the BTL acceptance region [1].

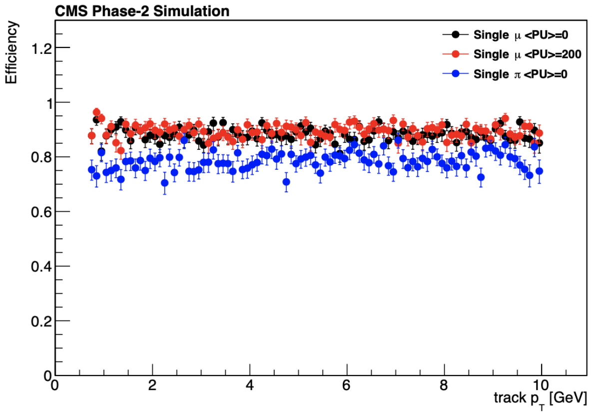

Figure 4. Cluster-track association's efficiency as a function of transverse momentum. Muons for events without PU (black) and with an average of 200 PU events (red) are compared to pions (blue) [1].

3.2. MTD and vertex reconstruction

The usual deterministic annealing vertex reconstruction algorithm adopted by CMS is extended to be time measurement-aware in order to produce the so-called 4D vertices, i.e. vertices that are reconstructed in time and space position. The pion mass hypothesis is used to compute the time of each track at the beam line, $t_{track} = t_{MTD} - p_{track}/\beta_{\pi}$, where t_{MTD} is the time of the cluster associated to the track. The uncertainty assigned to this measurement is inflated by adding in quadrature the difference in time of flight between the pion and the proton mass hypothesis. The compatibility of the tracks with reconstructed vertices is then tested, under pion vs kaon vs proton mass hypotheses, and times and uncertainties are reassigned according to the correct one. With these updated information, the 4D vertex reconstruction runs a second time, providing the vertex time with an uncertainty of about 10 ps (Fig.5).

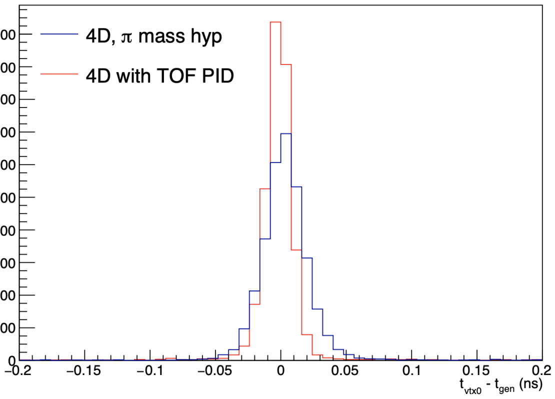

Figure 5. Distribution of the difference between the reconstructed and simulated time of the primary vertex in $t\bar{t}$ events at 200 PU, when the vertex is reconstructed using the pion mass hypothesis (blue), and with the corrected particle mass hypothesis (red) [1].

4. Impact on the physics of CMS

Considering an average MTD resolution per track of about 40-50 ps, the timing upgrade is expected to have a significant impact on the physics of CMS:

- Rejection of tracks from PU will be improved, by associating MTD tracks with the hard primary vertex (Fig. 6).
- Particle identification will be improved by using time of flight, very useful to boost performances of several heavy-ion studies.
- Timing information can be used to discriminate the primary vertex from long-lived particles' decay vertices.

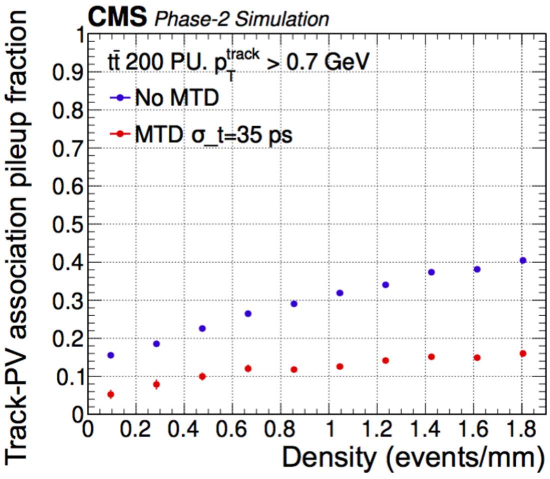

Figure 6. Fraction of PU tracks incorrectly associated with the hard primary vertex in $t\bar{t}$ events as a function of the PU density, for the 3D (blue) vertex reconstruction and the 4D (red) reconstruction including the MTD time information.

References

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