

Precision Timing with the CMS MIP Timing Detector

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The Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider (LHC) is undergoing an extensive Phase II upgrade program to prepare for the challenging conditions of the High-Luminosity LHC (HL-LHC). In particular, a new timing layer will measure minimum ionizing particles (MIPs) with a time resolution of ~ 30 ps and hermetic coverage up to a pseudorapidity of $|\eta| = 3$. This MIP Timing Detector (MTD) will consist of a central barrel region based on LYSO:Ce crystals read out with silicon photomultipliers and two endcaps instrumented with radiation-tolerant low-gain avalanche diodes. The precision time information from the MTD will reduce the effects of the high levels of pileup expected at the HL-LHC and will bring new and unique capabilities to the CMS detector. The time information assigned to each track will enable the use of 4D reconstruction algorithms and will further discriminate interaction vertices within the same bunch crossing to recover the track purity of vertices in current LHC conditions. For instance, in the analysis of di-Higgs boson production decaying to heavy flavor and two photons, 30 ps timing resolution is expected to improve the effective luminosity by 22% through gains in b-tagging and photon isolation efficiency. We present motivations for precision timing at the HL-LHC and the ongoing MTD R&D targeting enhanced timing performance and radiation tolerance, including test beam results.

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1. Introduction: the need for precision timing at HL-LHC

In the high luminosity phase of LHC (HL-LHC) [1], expected to start in 2026, the accelerator will operate at a stable luminosity of $L = 5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with 140 simultaneous interactions per bunch crossing (pileup), with an ultimate scenario given by $L = 7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and 200 pileup events. These operating conditions correspond to an increase of a factor of about 4–5, compared to current LHC. The interactions will occur within an RMS spread of approximately 5 cm in space along the beam axis and 200 ps in time. The resulting line density of vertices, peaking at 1.3 and 1.9 mm^{-1} for 140 and 200 pileup events, respectively, will cause the spatial overlap of tracks and energy deposits from different interactions. Pileup mitigation, which in CMS rely upon global event description through particle-flow algorithms [4] and particle-vertex association, will become progressively ineffective in the transition from 140 to 200 pileup events, hence the degradation in the reconstruction of the physics objects coming from the interaction of interest, impacting many key physics measurements.

In this scenario, a timing measurement capability of all charged particles is a powerful tool for pileup mitigation, as spatially overlapped vertices can be resolved in the time domain. With a $\sim 30 \text{ ps}$ precision on the timing measurement, the effective multiplicity of pileup events would be reduced to levels comparable to current LHC, as shown in figure 1.

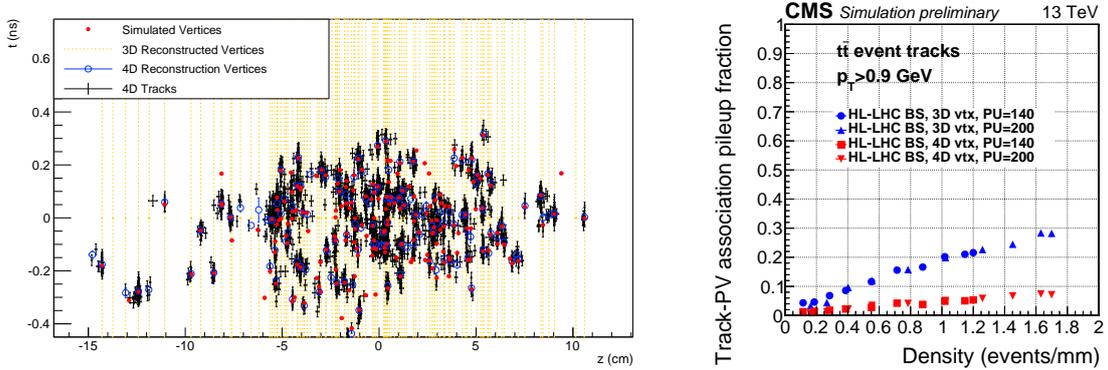


Figure 1: Left: simulated and 4D-reconstructed vertices in a 200 pileup event assuming a timing measurement with 30 ps resolution is available for all charged particles. The vertical lines indicate 3D-reconstructed vertices, with instances of vertex merging visible throughout the event display. Right: rate of tracks from pileup vertices incorrectly associated with the hard interaction vertex, normalized to the total number of tracks in the vertex. The rate of incorrect association with timing (red markers) and for a vertex line density of 1.9 mm^{-1} (i.e. pileup 200) is the same of the no-timing case (blue markers) for a 0.3 mm^{-1} vertex density (i.e. pileup 40, current LHC).

Therefore, in addition to the already foreseen Phase II detector upgrades [2, 3], the CMS Collaboration has proposed a new detector for the measurement of charged particle timing with $\sim 30 \text{ ps}$ resolution. The description of the proposed detector is in section 2, while the impact of precision timing on the CMS physics programs is detailed in section 3.

2. The MIP timing detector

The CMS Collaboration has proposed a new, dedicated detector for precision timing of minimum ionizing particles (MIPs) in addition to the additional timing capabilities of the Phase II-upgraded calorimeters. The MIP Timing Detector (MTD) aims at $\sim 100\%$ efficiency and 30–40 ps resolution on charged tracks. The integration with the existing CMS detectors and planned upgrades imposes that the detector be installed between the tracker and the calorimeters, covering a pseudorapidity range up to $|\eta| = 3.0$. The design of the detector was mainly driven by the requirement of covering a large area with a cost-effective technology, capable of sustaining the radiation levels expected by the end of HL-LHC, with marginal impact both on the tracker performance and integration schedule and the calorimeter performance.

For the barrel region of CMS, the design of the tracker support structure will be adapted and instrumented with a standalone timing layer with $\sim 1\text{ cm}^3$ granularity, based on lutetium-yttrium orthosilicate crystals (LYSO) activated with cerium read out with silicon photomultipliers (SiPM). Both LYSO scintillators and SiPMs are mature technologies with well-established industrialized production chains, which will allow the integration of the barrel MTD detector in CMS by the beginning of 2023, as required by the tracker installation schedule.

In the forward region, planar silicon devices with internal gain will be used, since the technology selected for the barrel cannot be extended to the endcap, due to radiation tolerance limitations. The chosen sensors are $\sim 2\text{ mm}^2$ pixels made by low-gain avalanche diodes (LGADs [5, 6]), which are being considered for the timing detector of the ATLAS experiment [7] too. The assembly and installation of the endcap discs can extend until the end of the LHC shutdown, thus providing additional time to complete the R&D plan.

3. The impact of precision timing on the CMS physics program at the HL-LHC

The CMS physics program at the HL-LHC will comprise a wide range of measurements, aimed at an in-depth characterization of the discovered Higgs boson through precise measurements of its couplings and the direct search of new phenomena beyond the standard model (BSM). Time-space reconstruction capabilities offered by the MTD have dramatic impact on several observables, effectively extending the acceptance of many key analyses. In particular, the rejection of tracks from pileup vertices based on their incompatibility with the hard scatter time can: improve the vertex identification; reduce the rate of pileup jets, with clear benefits for analysis relying on jet multiplicity event categorization, central or forward jet vetoes, or forward jet tagging; improve the resolution and reduce high mass tails of missing transverse momentum, which translates into lower (reducible) background levels for many BSM searches; improve the performance of b-tagging algorithms in high pileup conditions; remove pileup contamination in isolation cones of leptons and photons, thus allowing a higher identification efficiency for isolated objects. Moreover, the time information offers novel perspectives in searches for neutral long lived particles (LLPs), postulated in many BSM theories. The space-time information associated to the displaced decay vertex will enable a resonance reconstruction of the LLP, thus boosting the sensitivity of such searches.

A synopsis of all expected performance gains is presented in Table 3, where detector requirements are mapped into analysis and physics impacts.

signal	MTD improvement	analysis impact	physics impact
H \rightarrow $\gamma\gamma$ H \rightarrow 4ℓ	lepton isolation vertex identification	+25% statistical precision on cross sections	Higgs boson couplings
VBF H \rightarrow $\tau\tau$	isolation VBF jet tagging p_T^{miss} resolution	+30% statistical precision on cross sections	Higgs boson couplings
HH	isolation b tagging	+20% in signal yield	consolidate searches
EWK SUSY	p_T^{miss}	+40% reducible background reduction	+150 GeV mass reach
LLP	β_{LLP} from timing of displaced vertices	peaking mass reconstruction	unique discovery potential

Table 1: Representative channels for Higgs boson measurements and BSM searches used to map specific improvements thanks to the MTD into the relative performance gain at the analysis level (analysis impact) and in the measured physical quantity (physics impact).

4. Summary

The addition of a detector capable of efficiently and precisely measuring the time of charged particles will significantly mitigate the effect of pileup on all object-level observables at the HL-LHC. This mitigation yields significant improvements to many physics analyses – including Higgs, BSM, LLPs, and di-Higgs physics – by increasing signal efficiencies or reducing the width of residual distributions for discriminating variables. The proposed MTD is composed of two subsystems based on different sensor technologies: LYSO crystals and SiPMs for the barrel region and LGAD sensors for the endcap region. The technology choices were driven by performance, radiation, mechanics and schedule requirements and constraints. Both sensor technologies are mature and proven to achieve a 30–50 ps time resolution throughout the entire HL-LHC run.

References

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