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Precision Timing with the CMS MTD Barrel Timing Layer for HL-LHC

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Summary. — The Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider (LHC) is undergoing an extensive Phase-2 upgrade program to prepare for the challenging conditions of the High-Luminosity LHC (HL-LHC). A new timing detector in CMS will measure minimum ionizing particles (MIPs) with a time resolution of 30–40 ps. The precision time information from this MIP Timing Detector (MTD) will reduce the effects of the high levels of pileup expected at the HL-LHC, enhancing and expanding the physics reach of the CMS detector. The central Barrel Timing Layer (BTL) will be based on LYSO:Ce crystals read out with silicon photomultipliers (SiPMs). The BTL will use elongated crystal bars, with double-sided readout (a SiPM on each end of the crystal), in order to maximize detector performance within the constraints of space, cost, and channel count. An overview of the MTD BTL design, highlighting some of the physics analyses impacted by the MTD is presented. Extensive R&D studies carried out to optimize the BTL design are summarized, with particular emphasis on the test beam results in which the goal of 30 ps timing resolution has been achieved.

1. – The CMS Phase-2 upgrade for HL-LHC

The LHC is approaching the HL-LHC era [1], in which the instantaneous luminosity of the collider will increase by a factor between three and five with respect to current operating values. The increase in the amount of data is a breach towards unobserved phenomena but represents also a major challenge for the detectors. The CMS experiment Phase2 upgrade aims at preserving the experiment current performance, in terms of background rejection and particle identification, in the more challenging HL-LHC frame. The main challenges for the detectors are represented by radiation damage and an increase in the number of concurrent pp interactions per beam crossing, which is defined as pileup (PU). The average PU will go from 30–40 units, which is the current value at LHC, to 140–200 units at HL-LHC.

2. – Time: A new reconstruction dimension

The CMS experiment uses the Particle Flow (PF) algorithm [2] as its main tool for pileup mitigation. The PF efficiency is significantly degraded with a vertex overlap along the beam axis higher than 1 vertex/mm. Figure 1 shows the distribution on the z coordinate (x-axis) and time (y-axis) for 200 simulated vertexes. The typical RMSs for a bunch crossing recorded at CMS are ∼5 cm along the z-axis and 180–200 ps in time.

The power of a space-time reconstruction lies in the fact that vertexes overlapping in space are not necessarily overlapped in the time domain. The number of effective PU vertices is therefore reduced to only the ones with compatible time measurements. The effective pileup expected with different resolutions for the time of flight of the particles is in table I. A time resolution of about 60 ps would warrant a three-fold reduction in the effective PU, while a resolution of 30 ps would result in an effective PU comparable to the current PU values.

3. – The MIP Timing Detector

The Mip Timing Detector (MTD) [3] is dedicated to timing measurements for Minimum Ionizing Particles (MIP). It comprises a barrel and two end-cap sections, exploiting different technologies for the active detectors to optimize the performance *versus* the radiation level, service, and cost constraints. The MTD barrel section (Barrel Timing Layer, BTL) will cover the region at pseudorapidity $|\eta| < 1.5$. It will be formed by sensors of LYSO:Ce crystal bars with a 57×3.12 mm^2 front face and an average thickness of 3 mm, coupled at the two smaller ends with 3×3 mm^2 Silicon PhotoMultipliers (SiPMs). This sensor design was finalized through a thorough test beam campaign in 2017 and 2018. In the next section, studies carried out to characterize the timing performance of BTL sensor prototypes are presented, together with the September 2018 test beam measurements, which provided time resolution results compatible with the MTD target $\sigma_t = 30$ ps

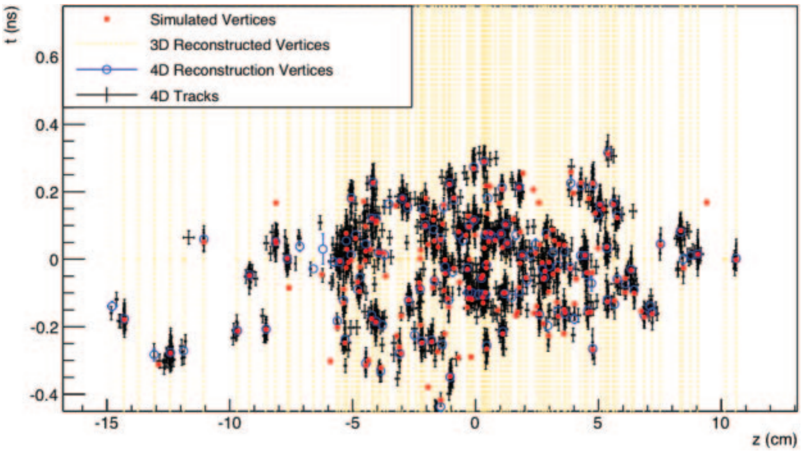

Fig. 1. – Simulated collision vertexes at 200 pileup, with a 5 cm RMS along the beam axis. Simulated vertexes are in red; the yellow lines indicate the z coordinates coming from reconstruction in 3D, with visible vertexes merging; blue dots are the 4D reconstructed vertexes [3].

TABLE I. – *Effective pileup values for different MTD time resolution below 60 ps, considering a full coverage detector with 100% efficiency.*

σ^t_{MTD} (ps)	Effective PU
none	200
60	70
45	50
30	33

4. – Studies on the timing performance of BTL sensor prototypes and test beam results

When a charged particle crosses a BTL LYSO:Ce crystal, it excites the crystal structure along the particle path. A fraction of the photons emitted in the ensuing scintillation process propagates through the crystal to the SiPMs. The photoelectrons from the photon conversions are amplified within the SiPM, with a gain of $\mathcal{O}(10^5)$. The amplified

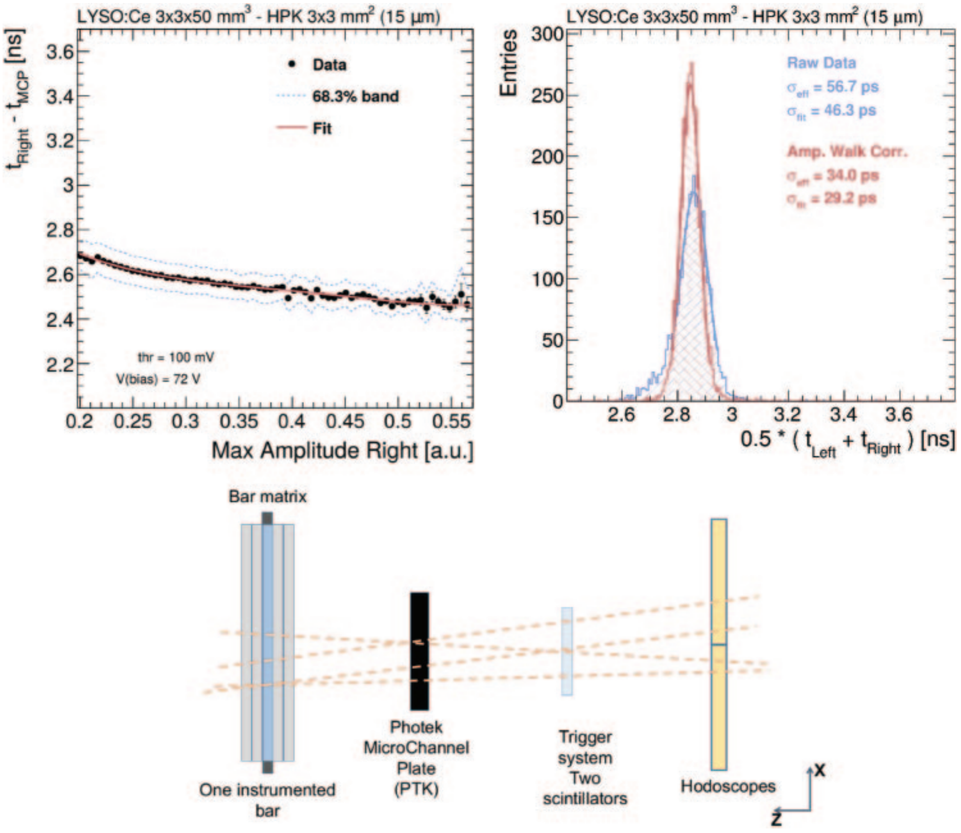

Fig. 2. – Top left: time measurements at one end of the BTL sensor as a function of the signal amplitude; the red line is a polynomial fit. Top right: distributions of the BTL sensor's time measurement before (blue) and after (red) AW correction. Bottom: experimental setup for the H4 September 2018 beam test.

signal, appropriately shaped, is used to extract the time of the particle crossing. The double-ended readout provides two independent measurements. The average of the two measurements is independent of the charged particle impact point and provides a $\sqrt{2}$ gain in the time resolution with respect to the single readout resolution. The time information is extracted using a leading edge discrimination technique with fixed threshold. The interval between the actual start of the signal and the threshold time is usually referred to as amplitude walk (AW), or time walk, and contributes with an additional spread to the time resolution that should be corrected.

In September 2018, a beam test for the MTD took place at the CERN H4 facility, in the SPS North Area. Results of the analysis of the beam test led to estimates of the BTL nominal time and spatial resolutions. Several bars of LYSO crystals, read out by HPK SiPMs with 15 μm cells, were tested. The beam test setup, shown in the bottom panel of fig. 2, comprised, upstream to the crystal bar, two hodoscopes used for tracking information ($\sigma \sim \mathcal{O}(1\ \mathrm{mm})$), a trigger system formed by two scintillators, and a Photek micro-channel plate detector (MCP), providing the reference time of passage of the particles through the apparatus with high resolution ($\sigma_t = 19$ ps). A beam of pions with $E_\pi = 80$ GeV was used for this beam test.

Data were collected for different sensor configurations and several SiPMs working points. The analysis steps and the results are summarized in the top panel of fig. 2, for one of these configurations. The panel on the left-hand side shows the time measurement at one end of the crystal, as a function of the signal amplitude. All of the measurements are relative to the external time reference (t_{MCP}), provided by the MCP. An empirical AW correction is extracted, from the dependence of the time measurement on the amplitude. The distributions of the mean time before and after the AW correction are shown on the right-hand panel of fig. 2. The time resolution improves from 46 to less than 30 ps.

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