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

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Abstract

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). A new timing detector in CMS will measure minimum ionizing particles (MIPs) with a time resolution of 30-40 ps for MIP signals at a rate of 2.5 Mhit/s per channel at the beginning of HL-LHC operation. 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, bringing new capabilities to the CMS detector. The barrel timing layer (BTL) of the MTD will use sensors that are based on LYSO Ce scintillation crystals coupled to SiPMs with TOFHIR ASICs for the front-end readout. In this talk we will present motivations for precision timing at the HL-LHC and an overview of the MTD BTL design, including ongoing R and D studies targeting enhanced timing performance and radiation tolerance.

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

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The Compact Muon Solenoid detector at the CERN LHC is undergoing an extensive Phase II upgrade program to prepare for the challenging conditions of the High-Luminosity LHC. A new timing detector, MTD, will measure minimum ionizing particles with a time resolution of 30-40 ps at a rate of 2.5 Mhit/s per channel at the beginning of the operations. The precision time information from this detector will reduce the effects of the high levels of pileup, bringing new capabilities to the CMS detector. The barrel timing layer will use sensors that are based on LYSO:Ce scintillating crystals coupled to SiPMs with TOFHIR ASICs for the front-end readout. We will present motivations for precision timing at the High-Luminosity LHC and an overview of the MTD barrel design, including ongoing R&D studies targeting enhanced timing performance and radiation tolerance.

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*Speaker

1. Introduction

The High Luminosity Phase of the LHC program is expected to start in the second half of this decade, based on a major improvement of the accelerator to increase the instantaneous luminosity by a factor of 10. To cope with the raised pile-up, the CMS collaboration has implemented an upgrade program based on higher detector granularity to reduce occupancy, improved trigger capabilities and bandwidth, and use of timing information, to correctly assign charged tracks and neutrals to the primary collision. The latter upgrade foresees the use of timing from the calorimeters and the installation of specialised layers dedicated to minimum ionizing particles.

The minimum ionizing particle (MIP) Timing Detector (MTD) of CMS consists of a single timing layer equipping both barrel and end-cap regions. Radiation tolerance, integration issues and schedule constraints, as well as cost considerations, have led to the choice of Lutetium Yttrium Orthosilicate crystal bars doped with Cerium (LYSO:Ce) crystals read out by silicon photomultipliers (SiPMs) for the barrel and Low-Gain Avalanche Diodes (LGADs) for the end-caps [1].

The basic sensor of the barrel sector is a $3 \times 3 \times 57$ mm^3 LYSO bar. The scintillation light is measured with a pair of SiPMs, one at each end of the crystal bar. This choice allows for the minimization of the SiPM active area and the power budget, the optimization of the resolution, with a $\sqrt{2}$ improvement, and the determination of track position with a resolution of the order of a millimeter. To minimize the radial size and reduce the impact on full CMS detector design the volume of the tracker support tube is used (Fig. 1). The crystals, aligned in the ϕ direction, are organized in 72 trays. SiPMs are read out by an ad-hoc ASIC (TOFHiR) for analog processing and digitization, exploiting the noise cancellation using a baseline restoration algorithm.

A recent evaluation of SiPM prototypes irradiated up to 1 MeV-neutron equivalent fluences of 3x10^{14} neq/cm^2 has shown dark current levels about 50% higher than what initially foreseen in the TDR [1], requiring further actions to mitigate the performance loss. To reduce the impact of the SiPMs dark count rate, induced by the large radiation budgets of HL-LHC, there exist two possible handles: lower the operation temperature and implement a systematic thermal annealing of the SiPMs. The addition of thermoelectric coolers (TEC), mounted on the SiPM package has the potential on the one hand to reduce the operation temperature, from -35°C to -45°C, and on the other hand to locally increase the temperature when the beam is off, during LHC shutdowns or technical stops. Given the high TECs power efficiency, the additional power required to operate

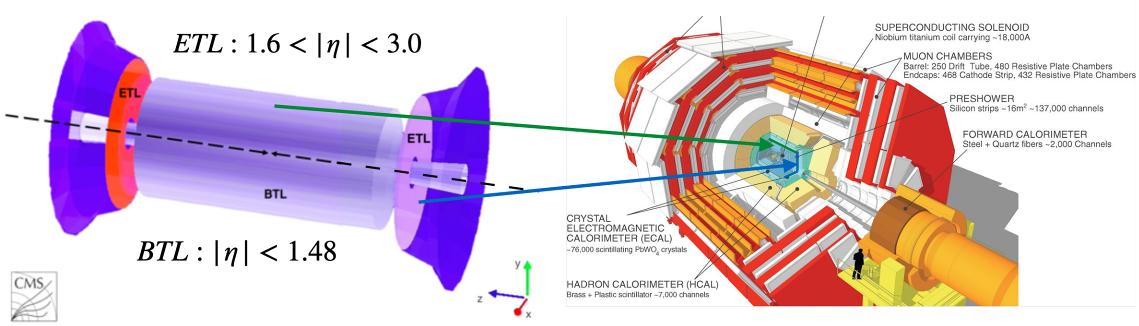

Figure 1: CMS Timing Layer layout and position in the CMS detector.

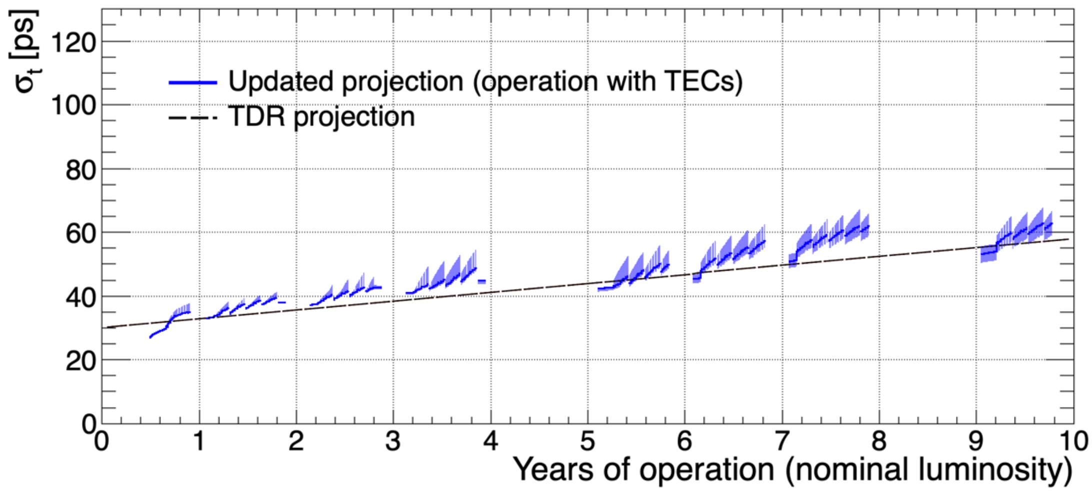

Figure 2: Expected time resolution of barrel MTD as a function of time at HL-LHC as originally estimated in the TDR [1] and with the updated evaluation of SiPM dark current and the addition of TECs.

the TECs will be compensated by the SiPM dark current reduction. The original projection of the behavior of the time resolution as a function of time of operations can be recovered, mitigating the impact of the dark current increase, as shown in Fig. 2.

2. Test beam results

The most important figure of merit of the performance of the MTD is the time resolution and must be evaluated very carefully. A 120 GeV proton beam at the Fermilab Test Beam Facility has been used to measure the time resolution of unirradiated sensors. The layout of the test beam consisted of a scintillation counter for trigger purposes, a silicon tracker telescope, and a Photek 240 Micro Channel Plate-PMT (MCP-PMT) to measure a reference time (Fig. 3). Crystals and SiPMs were located inside a dark box with temperature maintained at 25 ± 1°C. Two different types of SiPMs were tested: from Hamamatsu with an active area of 3×3 mm^2 and from Fondazione Bruno Kessler with an active area of 5×5 mm^2. The box could be rotated with respect to the direction of beam, thus allowing the study of the response produced by tracks which are not orthogonal to the crystal, as for low momentum tracks and for crystals positioned at large pseudorapidities in CMS.

The time resolution is obtained with two different methods: by comparing the time measured with the BTL sensor (LYSO+SiPM) under study to the one measured by the MCP-PMT and by studying the difference between the times of arrival measured at the two bar ends. Results show that time resolution improves with the increase in light output and is dominated by stochastic fluctuations, scaling, at first approximation, with the inverse of the square root of the signal amplitude (see left plot in Fig. 4). No degradation of the performance is observed by varying the MIP angle of incidence and results demonstrate the benefit of the enhanced light output related to the increased slant thickness. The time and energy response look uniform along the bar; when there is energy sharing between adjacent bars the degradation is negligible if the inter-crystal gap is sufficiently small (< 200 μm).

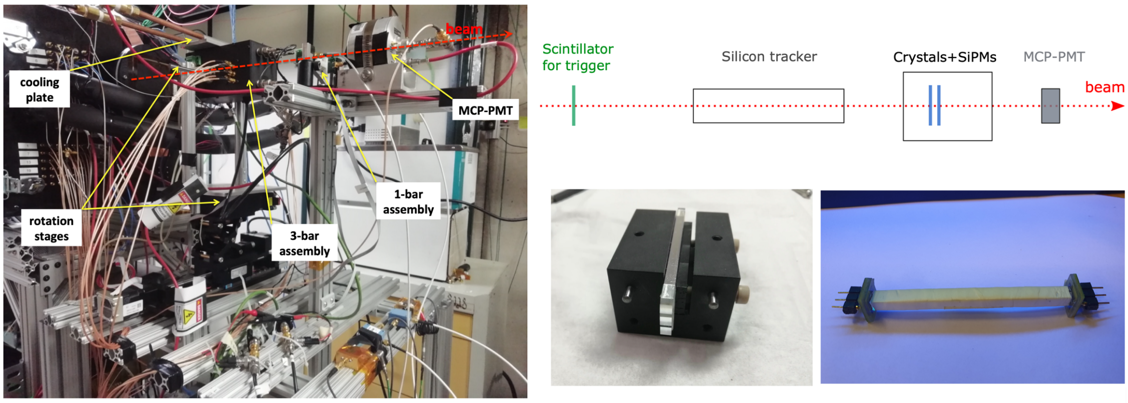

Figure 3: Left: experimental setup on the beam line and of the mechanical support for the rotation of the box housing the crystal bars. Top right: Sketch of the beam line: scintillator (trigger), silicon tracker (MIP position in the transverse plane), crystal+SiPMs test setups under study and MCP-PMT (reference time). Bottom right: three-bar assembly and single wrapped bar glued to SiPMs.

A normal incidence of a MIP on a 3 mm thick bar corresponds to a 2.6 MeV energy deposition. The resulting resolution of about 28-30 ps (right plot of Fig. 4) can be extrapolated to about 22 ps for the 4.2 MeV energy deposition expected in the BTL final design. After including the other contributions from clock, digitization, electronics and noise, the time resolution corresponds to about 30 ps, which is the expected performance at the beginning of the operations.

The position of the MIP track along the bar can be also determined by exploiting the time difference at the two bar ends. A resolution of few millimetres is obtained. In the orthogonal direction, for tracks crossing adjacent bars, the track impact position is obtained from the amplitude-weighted average of the position of the bars. A precision below 1 mm is achieved for all angles of incidence that were tested.

3. Physics performance

The time measurement of MIPs provides further tools to discriminate among the many vertices belonging to the same bunch crossing. With a time-aware extension (4D) of the vertex reconstruction, a timing resolution of 30 ps, about one sixth of the time spread of the LHC luminous region, should recover a track purity of vertices similar to present LHC conditions.

Higgs boson physics will greatly benefit from the increased luminosity provided by HL-LHC [3], since more and more precise measurements of the Higgs couplings will be crucial to verify in depth the validity of the Standard Model. The measurement of the boson trilinear self-coupling is one of the most ambitious goals of the HL-LHC physics program. A very promising way to directly access this coupling is through the study of the very rare Higgs pair production. The most sensitive channels are $H \to bb\gamma\gamma$ and $H \to bb\tau\tau$. The improvements introduced by MTD in reconstruction objects, like lepton and photon isolation, b tagging, jet and missing E_T, provide a ~12% increase in statistical significance, which is equivalent to a luminosity increase of ~25% [1].

Improved timing measurements can also significantly increase the discovery potential of new physics. In scenarios predicting long-lived neutralinos the improvement in the determination of

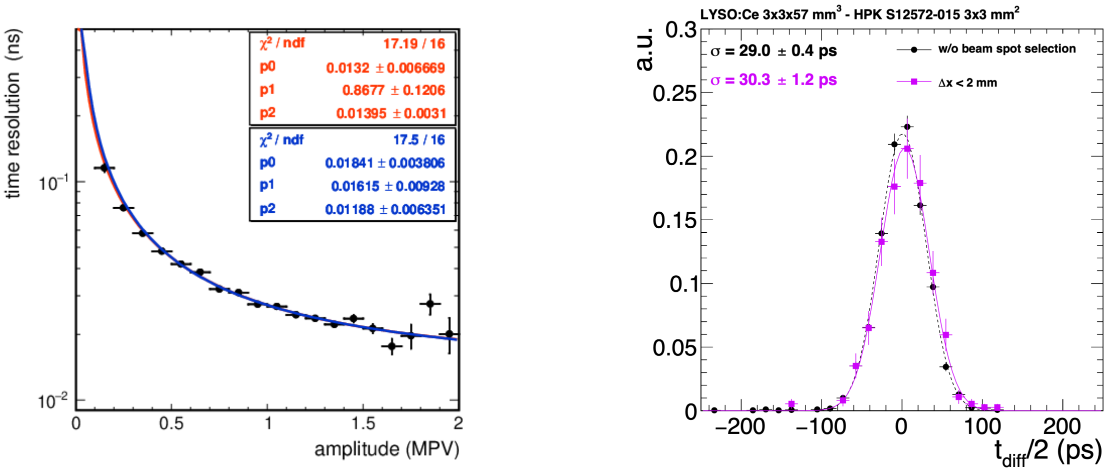

Figure 4: Time resolution for a 3×3×57 mm3 LYSO:Ce bar coupled to Hamamatsu SiPMs. Right: as a function of the amplitude of the signal. Left: inclusive, also for tracks with impact point in a 2 mm wide spot at 1 cm from the bar end.

the time of the vertex extends the sensitivity to larger neutralino masses. For heavy stable charged particles the additional time measurement of the track provided by MTD improves the determination of the β of the new particle, thus extending the phase-space region of the search [1].

4. Conclusions

The CMS MIP timing detector exploits the timing of charged tracks to mitigate impact of pile-up at HL-LHC conditions. The Barrel sector of the detector is made of scintillating LYSO crystal bars coupled with SiPMs. R&D campaigns are being carried out, to demonstrate that the performance is achievable with the chosen technologies.

The results achieved with a 120 GeV proton beam at Fermilab indicate that this sensor design with double-end readout is suitable for the measurement of the arrival time of minimum ionizing particles with a resolution of about 30 ps, at the beginning of HL-LHC. With the addition of thermoelectric coolers the effect of the SiPM dark current will be mitigated and the resolution will increase to only 60 ps at the end of operations. With such a performance, MTD will significantly improve the discovery potential of double Higgs and lond-lived particles searches.

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