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Precision timing with the CMS MIP timing detector

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The Compact Muon Solenoid detector at the CERN Large Hadron Collider is undergoing an extensive Phase II upgrade program to prepare for the challenging conditions of the High-Luminosity LHC. In particular, a new timing layer with hermetic coverage up to a pseudo-rapidity of $|\eta|$=3 will measure minimum ionizing particles with a time resolution of 30 ps. This MIP Timing Detector will consist of a central barrel region based on LYSO:Ce crystals read out with SiPMs and two end-caps instrumented with radiation-tolerant Low Gain Avalanche Detectors. The precision time information from the MTD will reduce the effects of the high levels of pile-up 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, a timing resolution of 30-40 ps is expected to improve the effective luminosity by about 25% through gains in b-tagging and isolation efficiency. We present motivations for precision timing at the HL-LHC and overview the MTD design, while also highlighting specific physics studies benefiting from the improved timing information.

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1. Introduction

The High Luminosity Large Hadron Collider (HL-LHC) [1] will reach instantaneous luminosities in excess of 10 ^{35} cm^{2}s^{-1} imposing very challenging conditions to the physics program in terms of overlapping spurious collisions (pile-up) and hit occupancy. This can be seen in figure 1 (left) where the vertex density with respect to the longitudinal coordinate for the LHC and for the HL-LHC under two realistic scenarios with 140 and 200 pile-up collisions is shown. This increase of the particle multiplicity in every bunch crossing presents several challenges to the reconstruction algorithms of the HL-LHC detectors. One of the available handles to mitigate this effect consists in the use of the particle time information to discriminate among vertices since at the HL-LHC they are distributed along the time coordinate. Figure 1 (right) shows the distribution of vertices on the Z-Time plane with a time spread of about 180 ps. By measuring the production time of charged particles, the time associated to the vertices can be estimated and used to mitigate the pile-up, helping the reconstruction of physics objects such as jets, leptons, etc. In addition to this, the time information brings unique physics potential by using time-of-flight tagging in different physics flavours. For all these reasons the Compact Muon Solenoid (CMS) experiment [2] is planning to inclue a MIP Timing Detector (MTD) for operation at the HL-LHC.

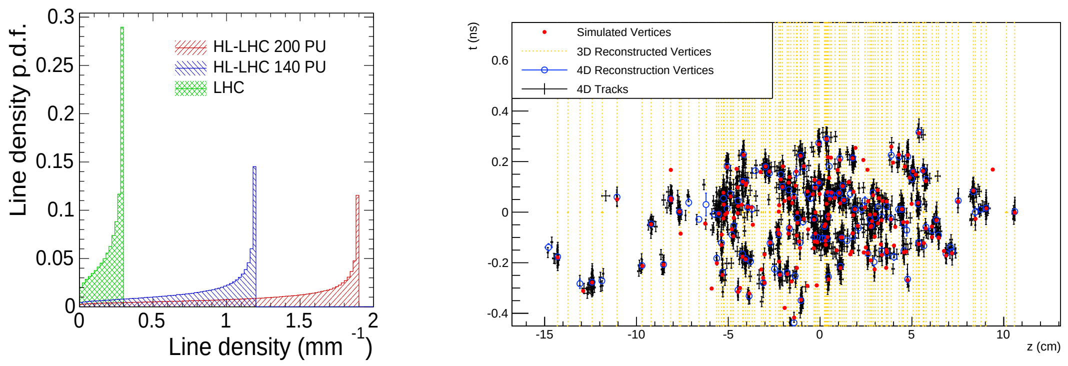

Figure 1: Distribution of the density of vertices per unit length (left) and expected distribution of vertices in the z-t plane at the HL-LHC.

2. The MTD design

The CMS MTD consists of two parts: the Barrel Timing Layer (BTL) and the Endcap Timing Layer (ETL). Both components will be installed right after the CMS tracker. The BTL will cover the central region up to a pseudorapidity of 1.45 while the ETL will cover the two forward regions up to a pseudorapitidy of 2.9 as sketched in Figure 2.

The BTL uses scintillation technology based on LYSO crystals [3] because of their excellent radiation tolerance and their fast rise and decay times. The crystals have a bar shape with 3x3 mm^2 section and 57 mm length and have silicon photomultipliers (SiPM) at the two ends. The longitudinal axis of the crystal bars is oriented along the ϕ direction within CMS. Crystals are grouped in modules of 1x16 covering a rectangular area of about 60x52 mm^2. Such modules are arranged in

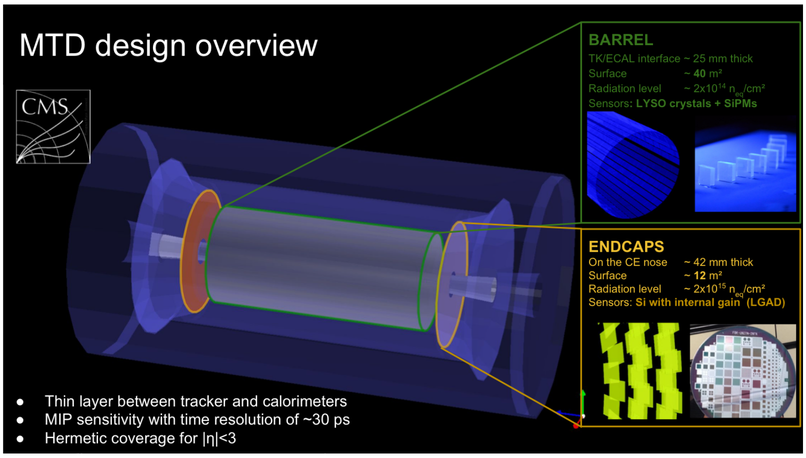

Figure 2: Diagram showing the MTD design with details about the technologies being used in both the BTL and ETL.

a matrix of 3x8 to constitute one readout unit. Six of such units are used to fill a tray and a total of 72 trays allows to cover the total surface of the detector. The time response and resolution of the LYSO crystals have been studied in test beams. Figure 3 (left) shows the timing resolution as a function of the longitudinal coordinate of the crystal for the SiPM located at the two extremes of the crystal and the average. A nice uniformity and an overall resolution better than 30 ps is observed.

The ETL uses silicon sensors based on Low Gain Avalanche Diodes (LGADs) [4]. These diodes contain a highly doped p+ region just below the n- implants increasing the electric field and providing an excellent time resolution while having an excellent radiation tolerance for the large fluences in the endcap (< 2x10^{15} neq/cm^2). The size of the pixels is 3x3 mm^2 to keep the capacitance low. In order to optimize the numbers of sensors per production wafer the pixel are organized in small sensors of 21x42 mm^2 area. The time resolution and hit effiency of the pixels have been studied in test beams showing a great performance. Figure 3 (right) shows the hit efficiency of an array of 4x4 pixels with an overall efficiency greater than 99%.

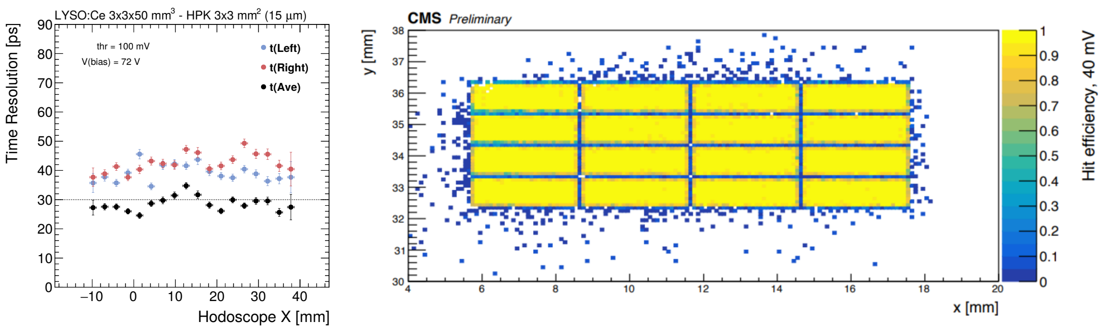

Figure 3: Time resolution as a function of the longitudinal coordinate of the crystal (left) and hit efficiency for an array of 4x4 LGAD pixels (right).

3. Physics object performance

The inclusion of timing information in the reconstruction algorithms improves the performance and mitigates the effect of pile-up by reducing the number of spurious tracks belonging to vertices displaced in time with respect to the primary vertex. This has a strong impact on the number of fake jets, the b-tagging algorithms, the isolation of leptons, and the resolution of the missing transverse momentum. Figure 4 (left) shows the ROC curve associated to the CMS b-tagging identification algorithm for three different cases: no pile-up and no MTD, a pile-up of 200 and no MTD, and a pile-up of 200 and the MTD. The performance of the algorithm is severely degraded because of the effect of the pile-up, however the inclusion of the timing information helps reducing the effect. Figure 4 (right) shows the resolution of the missing transverse momentum with and without using the timing information as a function of the density of vertices. An improvement of about 15% is observed for the expected density at the HL-LHC.

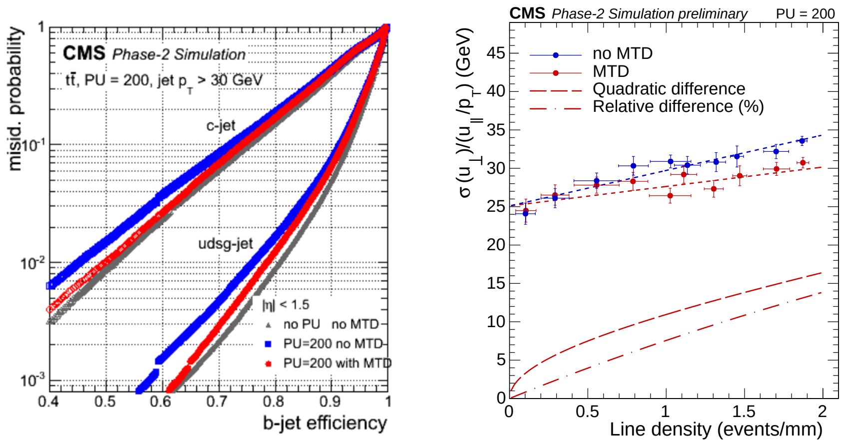

Figure 4: B-tagging efficiency as a function of the missidentification probability for the b-tagging algorithms with and without the MTD (left) and resolution of the transverse missing momentum with and without the MTD (right).

4. Impact on Physics analysis and new physics potential

The improvement of the physics objects performance has a strong impact on the physics analysis. In order the assess this potential, the search for double Higgs (HH) at the HL-LHC is used. The HH search targets a final state in which one of the Higgs bosons decays into a pair of bottom quark-antiquarks while the other decayins into a bottom quark-antiquark, a pair of photons, a pair of tau leptons, a pair of Z bosons decaying to charged leptons, or a pair of W bosons decaying also to leptons. Since this analysis covers almost all the possible final states, the improvements brought by the MTD, affecting all the different objects can be studied fully. An example of the improvements observed in this analysis can be seen in Figure 5 where the pseudorapidity acceptance is shown for the HH to four bottom quarks and for the HH to two bottom quarks and two photons. In both cases an acceptance improvement is observed in the range 14-17% for an MTD composed only of the BTL and in the range 18-22% for both the BTL and the ETL.

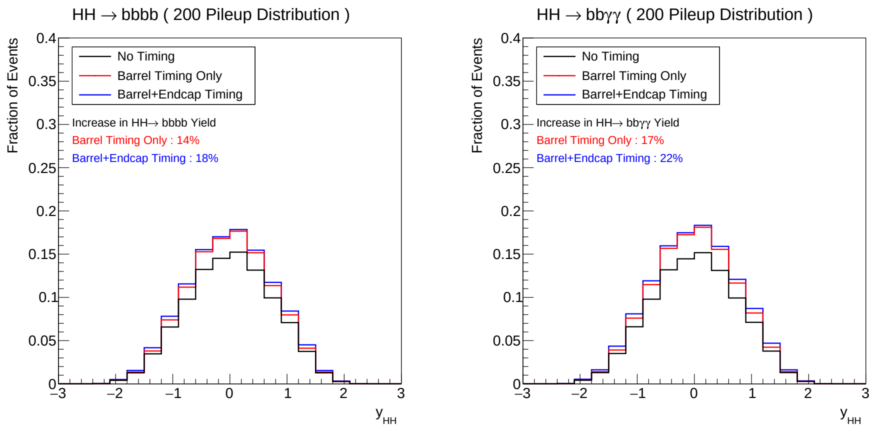

Figure 5: Yields as a function of the Higgs rapidity for the HH→bbbb (left) and HH→bb$\gamma\gamma$ final states (right).

The MTD will also bring unique physics potential to the CMS physics program. This is important for new physics models involving long-lived particles (LLP) not decaying at the center of the detector. This kind of particles are difficult to be reconstructed because of small number of hits they leave in the detector. One of the handles used in the past is the fact that they are displaced with respect to the PV. However this is not only true in the spatial coordinates but also in the time coordinate. The timing information of the tracks can be used to discriminate those displaced in time with respect to the PV. Figure 6 (left) shows one example in a search for a Heavy Stable Charged Particle (HSCP) at the CMS experiment. The HSCP particle, in this case a Supersymmetric stau, is produced and moves slowly through the whole CMS detector. The velocity of the stau is highly discriminant since it moves much slower than most of the SM particles being produced at the vertex. The blue distribution shows the velocity for background particles measured using the energy loss, while the black distribution shows the velocity for background particles using the MTD information. The velocity resolution is much better using the MTD and gives place to a large acceptance improvement in the analysis.

The use of the timing information will also allow to measure the properties of the LLP in some Beyond Standard Model (BSM) models. Figure 6 (right) considers a Gauge Mediated Symmetry Breaking (GMSB) SUSY model in which a pair of top squarks are produced decaying into a pair of long-lived neutralino and a pair of top quarks. The long-lived neutralino decays finally into a gravitino and a Z boson decaying into a pair of charged leptons. The velocity of the long-lived neutralino can be estimated by using the distance and time delay between the primary and the dilepton vertex. Once the velocity is known, the decay of the neutralino can be solved in its own system of reference in which the momentum of the gravitino equals the momentum of the leptons. Under these conditions and assuming the mass of the gravitino is known, the mass of the neutralino can be reconstructed as shown in Figure 6 (right).

5. Conclusions

The CMS upgrade program includes a MIP Timing Detector providing a 30-40 ps time resolu-

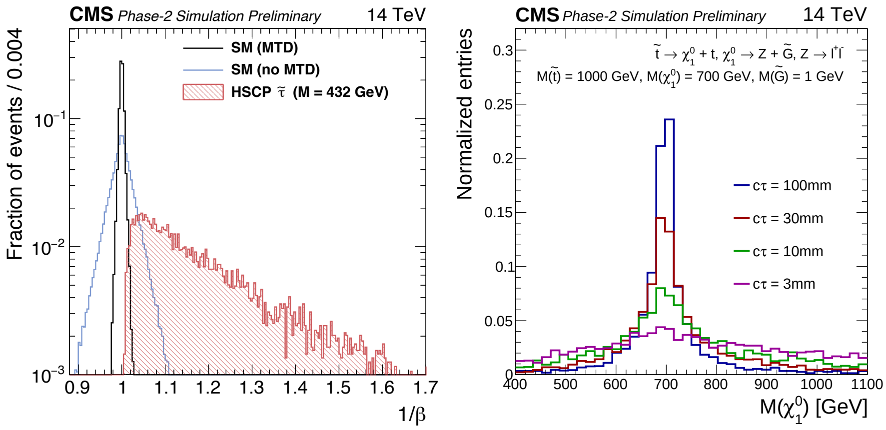

Figure 6: Distribution of the inverse of the particle velocity for the HSCP signal, the background, and the background estimated with the MTD (left), and neutralino mass estimated using the timing information for a SUSY GMSB model with different lifetimes (right).

tion. This detector will be composed of two parts: the Barrel Timing Layer based on LYSO crystals and the Endcap Timing Layer based on silicon sensors (LGADs). The inclusion of timing information is expected to have a strong impact in the mitigation of the harsh pile-up conditions at the HL-LHC. By associating a time stamp to the tracks, the number of spurious tracks not compatible in time with the primary vertex will be reduced improving the physics object performance for jet reconstruction, b-tagging algorithms, lepton isolation, transverse missing momentum resolution, etc. These improvements will translate into a sensitivity increase for important analyses such as the double Higgs search, and will also bring unique physics potential for complicated topologies such as those involving the production of long-lived particles.

References

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