Towards a precise measurement of particle time-of-flight with the new MIP Timing Detector with the CMS experiment

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Summary. — The design and primary use cases of the novel MIP Timing Detector (MTD), introduced by the CMS experiment for its High-Luminosity Large Hadron Collider (HL-LHC) Phase-II upgrade, are here described. The strategy for its application to 4D vertex reconstruction is outlined, with a focus on the latest developments in uncertainty estimation. The introduction of a new source of uncertainty on track times, namely particle time of flight uncertainty, is discussed, along with its estimation strategy and comparison to MTD uncertainty. This additional contribution is non-negligible for low-momentum heavy particles, such as protons with $p \lesssim 2\,\mathrm{GeV}$; however, impact on final vertex performance has been found to be minimal.

1. – Introduction

During the High-Luminosity phase of the Large Hadron Collider (HL-LHC), currently scheduled to start in 2029 and marking the start of Phase-II of the LHC physics programme, the accelerator will collide protons at a record center-of-mass energy of $\sqrt{s} = 14\,\mathrm{TeV}$ and an unprecedented instantaneous luminosity of 5×10^{34}–$7.5 \times 10^{34}\,\mathrm{cm}^{-1}\,\mathrm{s}^{-1}$. This increase will result in a higher number of simultaneous collisions per bunch-crossing, known as pileup (PU), ranging between 140 and 200. This presents a challenging environment for LHC experiments compared to the one they were originally designed for, both in terms of detector operation and event reconstruction. As part of its Phase-II upgrade, the Compact Muon Solenoid (CMS) experiment is hence planning to introduce a novel MIP Timing Detector (MTD) designed to mitigate the increase in pileup by reconstructing vertices in 4D by integrating time information [1]. The key concept is that, for each bunch crossing, space-overlapping vertices (which could be previously told apart up to vertex line densities of $1\,\mathrm{mm}^{-1}$ by exploiting the excellent CMS tracker resolution) can still be time-separated and thus discriminated given a sufficiently high time resolution. Indeed, given the expected spread of interaction vertices of approximately 5 cm along the beamline direction and 200 ps in time, as depicted in Figure 1, with a track time resolution of 30–40 ps one can reduce the effective pileup back to current levels

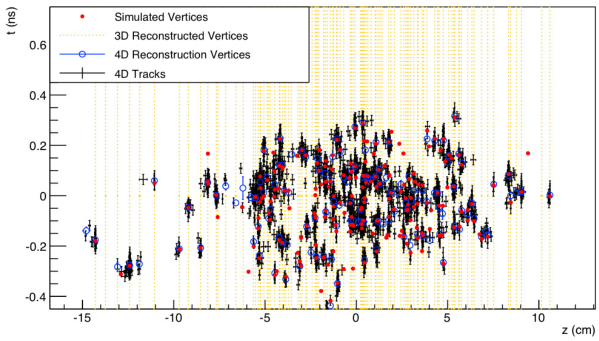

Fig. 1.: Simulated and reconstructed vertices in a bunch crossing with 200 pileup interactions assuming an MTD resolution of $\sim 30\,\mathrm{ps}$. Simulated vertices are reported as red dots; 3D-reconstructed vertices are drawn as vertical yellow lines, while 4D-reconstructed tracks and vertices are drawn as black crosses and blue open circles.

(approximately ~ 60) by reconstructing and thus distinguishing vertices that are close in time to the signal vertex.

Improved pileup mitigation bears significant physics potential. The reconstruction quality of several quantities employed by a large fraction of physics analyses at CMS will benefit from the additional timing information, including but not limited to particle isolation, b-tagging efficiency and missing transverse energy resolution. Moreover, the physics reach of the experiment will also be enhanced in entirely new directions. For instance, MTD will provide CMS with enhanced Particle Identification (PID) capabilities, enabling innovative searches for Heavy Stable Charged Particles (HSCP) through direct velocity (β) measurements. Indeed, as most Standard Model (SM) particles at LHC are produced with a velocity $\beta \sim 1$, MTD provides sensitivity to the discovery of exotic massive particles that are produced at appreciably lower velocities. The difference in the distribution of $1/\beta$ between typical SM particles produced in collisions and a benchmark HSCP model with a heavy stau $\tilde{\tau}$ at a mass of $m = 432\,\mathrm{GeV}$ is shown in Figure 2; by selecting signal events by placing a cut on $1/\beta$, the introduction of MTD can achieve an increase in signal acceptance of approximately a factor 4.

In this report, we will document some of the latest developments to the MTD reconstruction software, aimed at improving vertex reconstruction quality. The focus will be on the improved estimation of track time uncertainty through time-of-flight uncertainty, and how this can impact later stages of reconstruction.

2. – The MIP Timing Detector

Detectors included in the CMS High-Luminosity upgrade are meant to operate efficiently through the entirety of Phase-II up to at least $3\,\mathrm{ab}^{-1}$ of integrated luminosity. The MTD design was hence guided by mechanical constraints, performance and radiation tolerance, leading to a final plan consisting of a thin layer between the experiment's tracker and calorimeters, divided into a barrel (covering the pseudorapidity region $|\eta| < 1.5$) section, denoted Barrel Timing Layer (BTL), and two endcap sections, the Endcap Timing Layer (ETL), covering up to $|\eta| = 3.0$, as depicted in Figure 3. Different technologies

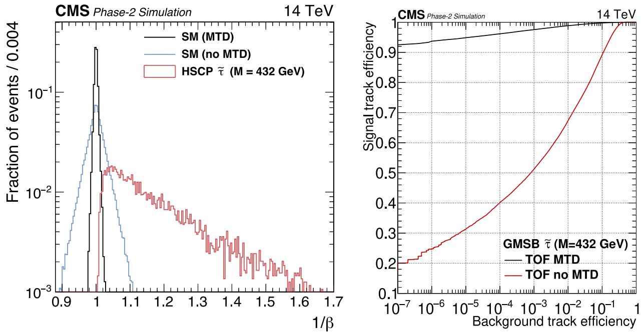

Fig. 2.: Distribution of $1/\beta$ for DY+Jets events with and without the MTD and signal events (left) and ROC curve associated to the $1/\beta$ selection (right).

have been employed for the two components to accommodate the differing environments: indeed, the outer radius of the ETL receives about the same dose as the highest $|\eta|$ part of the BTL, but its inner radius receives nearly a factor of 30 more due to its proximity to the beamline. Given these constraints, the technology chosen for the BTL is a crystal scintillator read out by SiPMs (Silicon Photomultipliers), pixelated avalanche photodiodes operating in Geiger breakdown mode. For the ETL, optimal performance is achieved by using LGADs (Low Gain Avalanche Detectors), which are silicon sensors with an internal gain between 10 and 30. Both detectors are capable of providing a resolution on the particle time of arrival of approximately 30–40 ps.

3. – Vertex reconstruction

Once the information on MTD hit times is acquired and properly matched to charged tracks – detected by the tracker as a sequence of ionization deposits – according to space and time compatibility criteria, it must be then combined to reconstruct vertices.

3·1. *Track backpropagation.* – To reconstruct vertices, track times must be backpropagated from the MTD layer to the point of closest approach to the beamline – where the vertices lie – by computing their time of flight (TOF). This requires making a

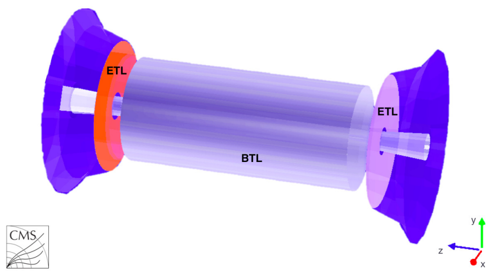

Fig. 3.: Schematic view of the GEANT geometry of the timing layers, including a barrel layer (grey cylinder), at the interface between the tracker and the ECAL, and two silicon endcap (orange and light violet discs) timing layers in front of the endcap calorimeter.

mass assignment for the track, however, as its velocity depends on both its momentum and mass. Under a given mass hypothesis (hp), and assuming constant momentum (i.e. neglecting energy losses), TOF is given by:

$$\text{TOF(hp)} = \frac{\ell}{\beta_{\text{hp}} c} = \frac{\ell}{c} \times \frac{\sqrt{p^2 + m_{\text{hp}}^2 c^2}}{p} \tag{1}$$

Knowing the particle time of arrival at MTD t_{MTD} with uncertainty σ_{MTD}, we can obtain the time at the beamline t_0 as:

$$t_0(\text{hp}) = t_{\text{MTD}} - \text{TOF(hp)} \tag{2}$$

It is important to keep all uncertainty contributions under control to ensure total time uncertainty respects the 30–40 ps requirement and vertex reconstruction quality is not compromised, affecting pileup rejection capabilities. Therefore, the contribution to uncertainty from time of flight must be properly evaluated.

Particle momentum is estimated from track curvature, measured by the tracker with uncertainty σ_p. To get the estimated uncertainty on the time of flight, we can hence propagate σ_p to Equation 1, obtaining:

$$\sigma_{\text{TOF}}(\text{hp}) = \sigma_p \cdot \left| \frac{\partial \text{TOF(hp)}}{\partial p} \right| = \sigma_p \cdot \frac{\ell}{c} \frac{m^2 c^2}{p^2 \sqrt{p^2 + m_{\text{hp}}^2 c^2}} \tag{3}$$

This contribution must be evaluated for the three mass hypotheses considered for vertex reconstruction, namely the pion, kaon, and proton hypotheses, chosen because they represent the majority of charged particles produced in typical collision events. σ_{TOF} has been also studied as a function of particle momentum to reflect the dependence reported in Equation 3. A comparison of the σ_{MTD} and σ_{TOF} distributions is shown in Figure 4 [2], as well as the distribution of total track time uncertainty σ_{t_0} obtained as:

$$\sigma_{t_0}(\text{hp}) = \sqrt{\sigma_{\text{MTD}}^2 + \sigma_{\text{TOF}}^2(\text{hp})} \tag{4}$$

As expected from the dependence of $\sigma_{\text{TOF}}(\text{hp})$ on particle mass and momentum, the contribution of σ_{TOF} is only significant for low momentum tracks ($p \lesssim 2\,\text{GeV}$) and for heavier mass hypotheses (proton). Under these conditions, $\sigma_{\text{TOF}} \sim \mathcal{O}(10\,\text{ps})$ becomes comparable to σ_{MTD}, and cannot be neglected. This can potentially impact all reconstruction steps involving σ_{t_0}, such as vertex reconstruction, as will be treated in the following.

3˙2. *Particle identification.* – Identifying which is the correct mass hypothesis for each particle is one of the key ingredients to accurate vertex reconstruction. Mass assignment is performed based on the compatibility of each hypothesis with the assigned vertex as estimated by the χ^2 value:

$$\chi^2(\text{hp}) = \frac{(z_0 - z_v)^2}{\sigma_{z_0}^2} + \frac{(t_0(\text{hp}) - t_v)^2}{\sigma_{t_0}^2(\text{hp})} \tag{5}$$

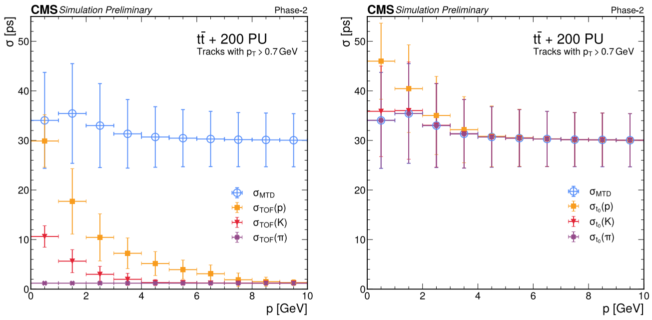

Fig. 4.: On the left, estimated MTD hit uncertainty σ_{MTD} (blue) compared to σ_{TOF} under the pion (purple), kaon (red) and proton (orange) hypotheses. On the right, σ_{MTD} is compared to the total track time uncertainty σ_{t_0} as obtained from Equation 4. For each momentum bin, the mean value and standard deviation of the distribution is shown.

It is thus evident that this task is intrinsically interconnected with vertex reconstruction. As will be illustrated in the ensuing section, this circular dependence has been overcome through an iterative approach to vertex reconstruction.

3˙3. *Vertex reconstruction algorithm.* – Given the collection of track times and positions at the beamline, tracks can be clustered to form candidate vertices, which are then fit to extract their 4D coordinates. The currently implemented algorithm comprises two steps:

1. Vertex candidates are clustered in the zt plane (4D clustering) using a time-aware extension of the 3D clustering approach assuming the pion hypothesis for all tracks, inflating track time uncertainty by the maximum error due to misidentification, i.e. $\sigma_{t_0} = \sqrt{\sigma^2_{\mathrm{MTD}} + \Delta\mathrm{TOF}^2}$ with $\Delta\mathrm{TOF} = \mathrm{TOF}(\pi) - \mathrm{TOF}(p)$. A first estimation of vertex times is then obtained as the weighted average of track times. On the basis of this preliminary vertex time estimation, the first round of particle identification is performed; for successfully identified tracks the mass assignment ambiguity is removed from the uncertainty and, if necessary, time at the beamline is appropriately recomputed.

2. Tracks undergo 4D clustering once again using the revised mass hypotheses and uncertainties for tracks. The final vertex time, obtained as the weighted average of track times based on the updated mass assignments, is finally employed in the second and last round of particle identification.

The performance of this algorithm can be characterized by examining the resolution distribution reported in Figure 5; the core of the resolution distribution is approximately 10 ps wide.

Finally, the impact of introducing σ_{TOF} on vertex reconstruction quality has been tested by checking for differences in vertex time resolution and pull distributions. No appreciable deviation was observed, leading to the conclusion that incorporating time of flight uncertainty bears a negligible impact on vertex reconstruction performance due to the overall small number of low-momentum proton tracks.

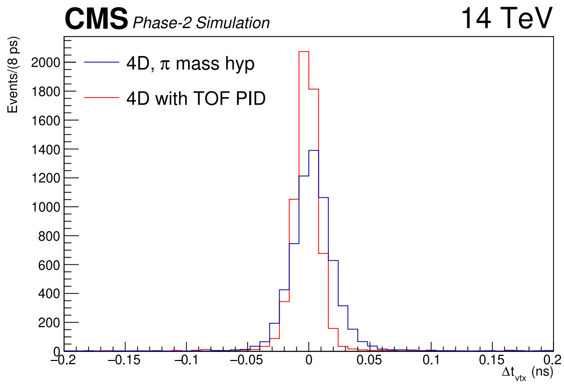

Fig. 5.: Signal vertex time resolution in a sample of $t\bar{t}$ events with an average pileup of 200 after the first (blue) and second (red) reconstruction step as described in Section **3**˙3; the core of the latter distribution corresponds to a resolution of 10 ps.

4. – Conclusions

The strategy for using MTD for 4D vertex reconstruction, aimed at reducing the impact of the increased pileup during Phase-II of the LHC, has been outlined. Recent developments have been highlighted, particularly the improved estimation of track time uncertainty through the inclusion of time of flight uncertainty. σ_{TOF} has been shown to be of $\mathcal{O}(10\,\mathrm{ps})$, and hence comparable to σ_{MTD}, for low-momentum ($p \lesssim 2\,\mathrm{GeV}$) heavy particles, such as protons; nonetheless, its impact on subsequent reconstruction steps, such as vertex reconstruction performance, has been estimated to be negligible. Recent improvements to the vertex time fit algorithm have been also illustrated, resulting in an improved resolution bias and width.

REFERENCES

[1] CMS Collab., CMS-TDR-020, *A MIP Timing Detector for the CMS Phase-II Upgrade*
[2] CMS Collab., CMS-DP-2024/048, *Improved use of MTD time in vertex reconstruction*;