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

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The MIP Timing Detector (MTD) of the CMS experiment, currently under construction for the High Luminosity phase of LHC, emerges as a key player in the pursuit of unrivaled temporal precision in particle physics. The precise measurement of the time-of-arrival of charged particles provided by the MTD enables the implementation of a 4D vertex reconstruction and helps to discriminate interaction vertices within the same bunch crossing, aiming to recover the vertex cross-contamination levels of the current LHC conditions.

In this contribution, we explore the impact of the measured track momentum uncertainty in the time-of-flight determination and its use in the vertex reconstruction and mass hypothesis assignment, shedding light on its potential impact on event reconstruction and classification. The results presented in this abstract demonstrate the efficacy of the MTD in advancing our understanding of particle dynamics in CMS, opening new avenues for an effective usage of precision timing in pileup mitigation and as a tool to probe signatures of new physics with characteristic time structures.

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1. Motivation

During the High-Luminosity phase of the Large Hadron Collider, 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 $5 - 7.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This increase will result in a higher number of simultaneous collisions per bunch-crossing, or pileup (PU), ranging between 140 and 200, presenting a challenging environment for LHC experiments. To address this, the Compact Muon Solenoid (CMS) experiment [1] [2] will introduce a novel MIP Timing Detector (MTD) as part of its Phase-II upgrade [3]. MTD will allow for 4D vertex reconstruction by incorporating precise time measurements, helping to separate spatially overlapping vertices (expected longitudinal spread of $\sim 5\,\mathrm{cm}$) exploiting their temporal separation (spread of $\sim 200\,\mathrm{ps}$). With a track time resolution of 30–40 ps one can reduce the effective pileup back to current levels (approximately ~ 60) by reconstructing and thus distinguishing vertices that are close in time to the signal vertex.

This report outlines recent developments to the MTD software, namely inclusion of time-of-flight in track time uncertainty estimation and its impact on vertex reconstruction.

2. Vertex reconstruction

The first step in vertex reconstruction involves back-propagating the track time information measured by MTD to the beamline – where the vertices lie –, yielding the beamline time t_0, by computing their time of flight (TOF), given their trajectory length, momentum (p) and a mass hypothesis (hp). This process introduces an extra contribution to the total time uncertainty, whose impact must be properly evaluated to make sure vertex reconstruction quality is not compromised.

The uncertainty on time of flight derives from particle momentum uncertainty σ_p, estimated from track curvature, whose propagation to the time of flight yields $\sigma_{\mathrm{TOF}}(\mathrm{hp})$, evaluated for the three mass hypotheses $\mathrm{hp} = \{\pi, K, p\}$ representing the majority of charged particles produced in typical collision events. A comparison of the estimated MTD hit uncertainty σ_{MTD}, σ_{TOF} and total track time uncertainty $\sigma_{t_0}(\mathrm{hp}) = \sqrt{\sigma^2_{\mathrm{MTD}} + \sigma^2_{\mathrm{TOF}}(\mathrm{hp})}$ distributions is shown in Figure 1 as a function of track momentum. As expected, the contribution of σ_{TOF} becomes significant only for low momentum tracks ($p \lesssim 2\,\mathrm{GeV}$) and for heavier mass hypotheses (proton), for which $\sigma_{\mathrm{TOF}} \sim O(10\,\mathrm{ps})$ becomes comparable to σ_{MTD} and cannot be neglected.

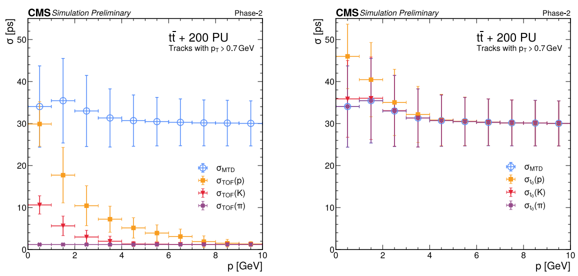

Figure 1: On the left, estimated MTD hit uncertainty σ_{MTD} (blue) compared to σ_{TOF} under the pion (purple), kaon (red) and proton (orange) hypotheses. On the right, σ_{MTD} is compared to total track time uncertainty σ_{t_0}. For each momentum bin, the mean value and standard deviation of the distribution is shown [4].

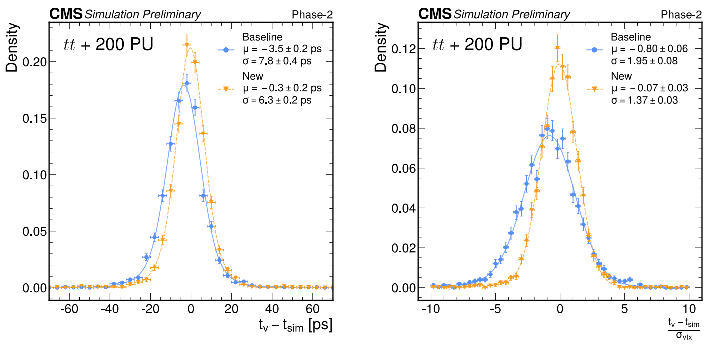

Figure 2: Signal vertex time resolution (left) and pull (right) distribution in a sample of $t\bar{t}$ events with $\overline{\text{PU}} = 200$, comparing the "Baseline" approach (vertex time as weighted t_0 mean) and the "New" one (vertex time from DA algorithm). Distributions are fit with a double Gaussian, displaying the parameters of the narrowest one [4].

The ensuing steps involve identifying the correct mass hypothesis for each particle, using the resulting track times and positions at the beamline to cluster tracks in vertex candidates, and finally fitting their 4D coordinates. For a given track, however, mass assignment is performed on the basis of the time compatibility of each hypothesis with its respective vertex; the circular dependence between the two tasks has hence required devising an iterative reconstruction algorithm [3]. The 4D reconstruction is performed by clustering tracks in the zt plane using a time-aware extension of the 3D clustering approach, with the final vertex time and uncertainty obtained from the weighted average of track times using only the most likely mass hypothesis for each track. The algorithm performance is assessed in terms of resolution and pull distributions, reported in Figure 2 ("Baseline"); the core of the resolution distribution is approximately 8 ps wide.

This is compared to an alternative algorithm ("New") in which the final weighted average is replaced by a deterministic annealing (DA) algorithm that assigns time to reconstructed vertices by minimizing an appropriately defined free energy function F that simultaneously considers all mass hypotheses for each track [4]. The new algorithm results in a slightly better vertex time resolution (approximately 6 ps) and a pull distribution with a width closer to the expected value of 1; however, it also reduces resolution bias (now compatible with 0) thanks to the mitigated impact of misidentified tracks due to the lack of hard mass assignments.

The impact of introducing σ_{TOF} on vertex reconstruction quality has been tested by checking for differences in vertex time resolution and pull distributions, showing no appreciable deviations and hence proving its introduction negligible.

References

[1] CMS Collaboration, *The CMS experiment at the CERN LHC*, JINST **3** (2008) S08004.

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[3] CMS Collaboration, *A MIP Timing Detector for the CMS Phase-II Upgrade*, CMS-TDR-020.

[4] CMS Collaboration, *Improved use of MTD time in vertex reconstruction*. CMS-DP-2024-048.