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Enhancing Particle Reconstruction and Identification with the MIP Timing Detector at CMS

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The MIP Timing Detector that will be installed at the CMS experiment is a novel kind of detector which will assign times to charged particles with an unprecedented resolution of 30-60 ps. This will allow vertex reconstruction in 4D, an essential feature to perform pileup mitigation in the high vertex multiplicity environment which is going to characterize the High-Luminosity phase of the LHC. In this contribution, we explore the impact of the track path length resolution in the computation of the time-of-flight, which is a crucial factor that comes into play when computing precise time information at the vertex. In addition to that, a summary of the particle identification performance and its impact on the track time resolution will be reported. The results presented here provide the first estimate of the track path length resolution in CMS and demonstrate that its effect is subdominant when compared to the time resolution of the detector.

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1. Motivation

The Large Hadron Collider (LHC) will soon undergo its High-Luminosity (HL) upgrade. The accelerator will enter a long shutdown period during mid-2026, while the start of operations of the HL phase is scheduled to happen in 2030. During the shutdown time frame, the Compact Muon Solenoid (CMS) experiment will be updated in order to be ready for the data-taking at the HL-LHC, the new detector configuration is referred to as Phase-II of the experiment [1]. The upgrade of the collider will raise the center-of-mass energy to the value of $\sqrt{s} = 14\,\text{TeV}$ and will increase the instantaneous luminosity to $5 - 7.5 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$. The increase in luminosity of the HL-LHC will result in an increased number of mean collisions per bunch crossing, pileup (PU). The HL-LHC will deliver events to CMS with a mean PU from 140 to 200, substantially higher when compared to the current value of ~ 60 PU collisions per bunch-crossing. In order to tackle the challenge of the increase in PU, the CMS experiment is going to install a new subdetector: the MIP Timing Detector (MTD) [2], which consists of the Barrel Timing Layer (BTL, which covers pseudorapidity $|\eta| < 1.48$) and the Endcap Timing Layer (ETL, covering $1.6 < |\eta| < 3.0$). The precise timing information of 30-60 ps given by this detector can be exploited to reconstruct vertices not only in space but in time as well (4D vertexing), dramatically improving the experiment's capability of distinguishing them.

This contribution focuses on the estimate of the impact of the track path length reconstruction uncertainty on the overall uncertainty in the track time at the vertex. Moreover, the particle identification (PID) performance and its impact on the track time resolution will be discussed.

2. Track path length resolution estimate

In order to reconstruct primary vertices in 4D, it is necessary to start from the timing information given by MTD and to propagate that time to the point of closest approach (PCA) of each track to the beamline. The time at the PCA is computed in the following way:

$$t_{\text{PCA}}(hyp) = t_{\text{MTD}} - \text{TOF}(hyp), \tag{1}$$

where t_{MTD} is the time associated to the track, measured by the MTD and TOF is the time-of-flight, which depends on the specific mass hypothesis (hyp). The TOF is computed by summing the TOF contributions that are due to the propagation of the track between the n_{layers} different detector layers, in the following way:

$$\text{TOF}(hyp) = \sum_i \text{TOF}_i(hyp) = \sum_i \frac{\ell_i}{\beta_i(hyp)c}, \qquad i = 1, \ldots, n_{\text{layers}}. \tag{2}$$

ℓ_i here is the length estimated from the track helix parametrization between one layer and the next in the propagation, taking into account the magnetic field and the particle interactions with the detector material. The velocity β_i is estimated based on the momentum measurement carried out at each detector layer and assuming a specific mass. The mass hypotheses considered in the current reconstruction software consist in $hyp \in \{\pi^{\pm}, K^{\pm}, p/\bar{p}\}$: namely charged pion, kaon and (anti)proton hypotheses, respectively.

There are several factors that influence the uncertainty in the t_{PCA} value: the MTD time resolution,

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the correctness of the track-cluster association, the correctness of the mass assigned to the track and the uncertainty in the TOF. The focus of this discussion will be on the latter.
The uncertainty in the TOF has two contributions: one is due to the uncertainty in the velocity measurement β_i, which depends solely on the momentum uncertainty, this has been previously computed and implemented in the CMS reconstruction software [3]. This uncertainty is comparable to the MTD time resolution only for soft massive particles, such as kaons and protons below a few GeV of momentum. The other contribution is the uncertainty in the track path length estimation. Here, a preliminary study assessing the current resolution in the path length measurement is reported [4]. The adopted strategy consists in the usage of Monte-Carlo samples of muons generated with PU = 0 conditions. The estimated path length is computed through the sum of the single path length contributions PL = $\sum_i \ell_i$ shown in Eq. 2. This value is compared against the simulated "true" path length, which is obtained from the length travelled by the simulated track between the simulated vertex and the energy-weighted average position of the simulated hits in MTD, using the same algorithm of reconstruction for correctly associated hits. The results are reported in Fig. 1 for tracks going in the BTL and ETL regions. The muon sample was chosen to focus on the PL estimation resolution, to help factor out hadronic interactions or other physics phenomena that may happen in the inner part of the detector when considering other particles. The events have been

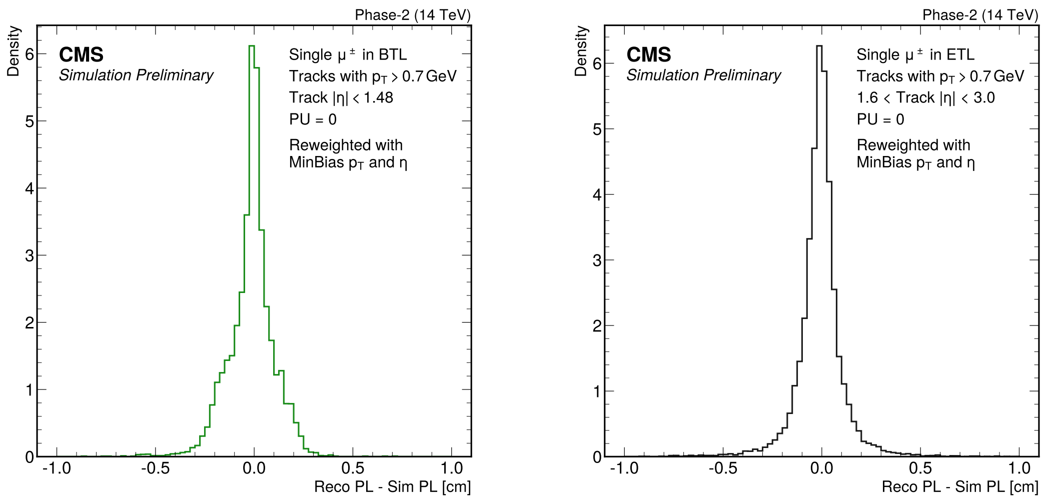

Figure 1: Residual between the reconstructed and simulated track path length (PL) for tracks that fall in the BTL (left) and ETL (right) regions. Considering single muon events with PU = 0. The counts are reweighted on the basis of the p_T and η spectrum of Minimum Bias. Considering both detectors, the spread of the distributions indicates a contribution of the PL resolution that is well below 10 ps [4].

reweighted using the p_T and η spectrum of Minimum Bias charged particles, considering events simulated at $\sqrt{s}$ = 14 TeV. In both the BTL and ETL cases, the PL resolution is of the order of few millimeters. The larger spread that can be seen in the BTL PL residuals can be attributed to the larger dimension of the detecting unit of that detector, which consists of a LYSO:Ce crystal bar with dimensions ~ 3.12 × 3.75 × 54.7 mm^3, in addition to the fact that a charged track can often leave a signature which consists of an extended cluster, composed by more than one LYSO:Ce crystal. On

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the other hand, clusters in ETL are mostly limited to a single Low Gain Avalanche Diode (LGAD) pixel, which has smaller dimensions: $\sim 1.3 \times 1.3 \times 0.05\ \mathrm{mm}^3$ (here the 0.05 mm refers to the active region of the sensor, which is embedded within a 0.3 mm thick silicon wafer). In both cases, the spread of these residuals leads to a resolution on the TOF due to the path length that is well below 10 ps. This can be compared with the expected time resolution of MTD, which will be in the order of 30-60 ps depending on the integrated dose level, therefore the resolution on the track path length appears to be a subdominant effect when compared with the MTD time resolution.

3. Particle Identification and track time resolution performance

Following the association of a time at the PCA to the tracks, it is possible to carry out vertex reconstruction. However, there is an ambiguity on the mass of each track and thus an ambiguity on the $t_{\mathrm{PCA}}(hyp)$ value, but the vertex time is needed in order to disambiguate the mass hypothesis. In order to solve this, an iterative approach is adopted: first, the vertices are determined in 3D exploiting the Deterministic Annealing (DA) algorithm [5] and a time is associated to them. This is done by considering all three mass hypotheses with appropriate prior probabilities and minimizing a specific cost function [6]. Afterwards, particle identification (PID) can be carried out by evaluating the compatibility between $t_{\mathrm{PCA}}(hyp)$ and the time of the vertex, by computing the following quantity for the different mass hypotheses:

$$\chi^2_{\mathrm{hyp}} = \frac{(z_{\mathrm{PCA}} - z_{\mathrm{vtx}})^2}{\sigma^2_{z_{\mathrm{vtx}}}} + \frac{(t_{\mathrm{PCA}}(hyp) - t_{\mathrm{vtx}})^2}{\sigma^2_{t_{\mathrm{vtx}}}}, \tag{3}$$

where $z_{\mathrm{vtx}}, \sigma_{z_{\mathrm{vtx}}}$ and $t_{\mathrm{vtx}}, \sigma_{t_{\mathrm{vtx}}}$ are the z and time coordinates of the vertex, with their respective uncertainties, and z_{PCA} is the z coordinate of the track at the PCA. The different χ^2_{hyp} are compared

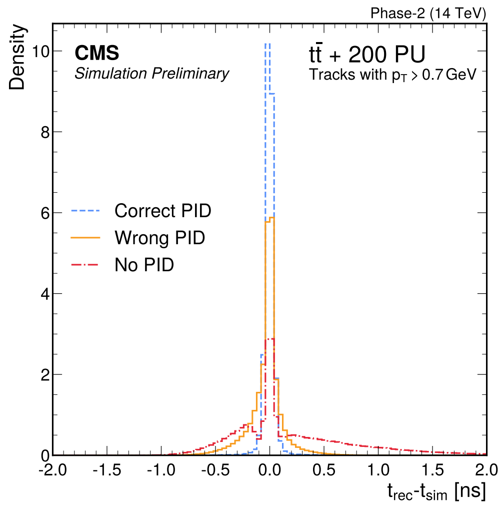

Figure 2: Track time residuals as a function of the PID assignment, considering the three hypotheses: $hyp \in \{\pi^\pm, K^\pm, p/\bar{p}\}$, in the case of a $t\bar{t}$ samples with PU = 200. Each distribution is normalized to the integral. Tracks on which the PID algorithm fails are treated as pions. The residual is computed between the reconstructed time at the PCA and the simulated vertex time [4].

and the track time can be reassigned on this basis. Afterwards, the vertices are re-reconstructed with a time-aware version of the DA algorithm. At this stage, PID can be carried out again considering the new 4D vertices. The final performance on PID, considering a $t\bar{t}$ sample with PU = 200, shows that the current reconstruction algorithm is able to assign the correct mass to charged tracks with $p_T > 0.7$ GeV approximately in 72% of cases, a wrong mass is assigned to $\sim$ 17% of tracks and the algorithm fails to identify the mass of $\sim$ 11% of tracks. How this affects the time resolution at the PCA is reported in Fig. 2, where the reconstructed track time at the PCA ($\mathrm{t_{rec}}$) is compared against the simulated vertex time ($\mathrm{t_{sim}}$). It can be seen that tracks with correct PID assignment have a peaked and narrow distribution around 0, while the distribution for tracks with wrong mass assignment displays larger tails reaching $\sim$ 100 ps, this is due to the error in the track time that is caused by the wrong mass assigned to the track. The PID algorithm can fail to assign a mass to the track. This happens if the vertex has no time associated to it, or has a too large time uncertainty —currently only tracks associated to vertices with time uncertainty below 25 ps are considered for PID— or if the time difference between track and vertex time is larger than $(t_{\mathrm{PCA}}(hyp) - t_{\mathrm{vtx}})^2/\sigma^2_{\mathrm{t,vtx}} > 5$ for every hypothesis considered. The tracks on which the PID algorithm fails (No PID) are treated as pions, they display a double-tailed distribution in Fig. 2, which is mainly due to wrong track-cluster associations. In the case of failure of mass assignment, the TOF uncertainty is inflated with an additional term $\sigma_{\mathrm{TOF,fail}} = \mathrm{TOF}(p/\bar{p}) - \mathrm{TOF}(\pi^{\pm})$ to account for the ambiguity on the mass.
The best PID performance is achieved in the range of around 1–4 GeV for $K^{\pm}$, and about 1–8 GeV for protons, reaching up to $80-90\%$ of mass assignment efficiency in the lower-momentum part of these momentum intervals.

4. Conclusions

The results shown in this contribution report for the first time an estimate of the track path length resolution for tracks reconstructed in CMS during Phase-II. This quantity will play an essential role in event reconstruction at CMS during the HL-LHC period, due to its usage in time propagation to the vertex, crucial for the 4D vertex reconstruction. The results reported here show that the resolution in the track path length determination is of the order of few millimeters, therefore the expected impact on the time resolution is expected to be well below 10 ps. In addition to that, this contribution reports an overview of the particle identification performance and how it affects the track time resolution. The cases of correct, wrong and missing mass assignment have been illustrated. Moreover, an estimate of the current reconstruction performance in the case of $t\bar{t}$ sample of simulated events with PU = 200 has been shown. The MIP Timing Detector is going to be installed in CMS during the forthcoming LHC shutdown period. Together with the other upgrades involving CMS, MTD is going to help the experiment probe the Standard Model, and what may be beyond it, exploiting the unprecedented energy and luminosity that will be delivered by the HL-LHC.

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