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Physics opportunities with a MIP Timing Detector in CMS for HL-LHC

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Within the upgrade program of the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) for the High-Luminosity phase data taking (HL-LHC), the installation of a new timing layer to measure the time of minimum ionizing particles (MIPs) with a time resolution of 30-40 ps is planned. The time information of the tracks from this new MIP Timing Detector (MTD) will improve the rejection of spurious tracks and vertices arising from the expected harsh pile-up conditions from machine operation. At the same time this detector will provide particle identification capabilities based on the time-of-flight, and will bring unique physics opportunities for interesting signatures such as those including long-lived particles. An overview of these possibilities is given, using the state of the art of the simulation and reconstruction of the MTD detector.

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1. Introduction

A Mip Timing Detector (MTD) was proposed as a new sub-detector for the upgrade of CMS in view of the HL-LHC, with the purpose of measuring the time of arrival of charged particles in front of the calorimetric system with a precision of about 30-40 ps. The potential impact of such a detector on the CMS physics program during the HL-LHC data taking was discussed in the Technical Design Report (TDR) of the detector [1].

After the TDR release, new performance projections were produced exploring different timing resolution scenarios [2]. We studied the effects of a deteriorated MTD barrel (BTL) resolution to an extreme scenario including module degradation and a safety margin on the radiation field uncertainty. Furthermore the possibility to extend the physics case for MTD in different areas, for instance exploiting particle identification (PID) capabilities in B physics, was investigated.

2. Update of performance of Double Higgs cross section measurement

Concerning the study of double Higgs bosons (HH) production, the MTD TDR presented projections of the expected significance of the SM HH signal in three scenarios: no MTD, MTD with 35 ps average resolution, and MTD with 50 ps average resolution [1]. In this section, we estimate the individual contributions of BTL and ETL, the endcap sections of the MTD, to the expected Standard Model (SM) HH significance in each TDR scenario as well as an additional scenario in which average BTL resolution is 70 ps and average ETL resolution is 35 ps.

Table 1 shows the projected expected significance for the SM HH signal when exploiting the timing information provided by MTD in b-tagging and particle isolation. The BTL- and ETL-only projections are derived from the TDR projections assuming expected significance scales linearly with the increase in signal efficiency provided by each subdetector. Results are reported for 3000 fb^{-1} and derived under the assumption that an HH signal exists with the strength and properties predicted by the SM. As shown in Table 1, exploiting MTD timing information meaningfully improves the expected SM HH signal significance in all three MTD performance scenarios.

3. Update of performance of Long Lived Particles searches

The MTD provides new, powerful information in searches for long-lived particles (LLPs). In this document we integrate the LLPs projections presented in the MTD TDR [1], by exploring different MTD timing resolution scenarios.

3.1 Final states with delayed photons

In the GMSB benchmark scenario [3] used as the reference for this topology, the lightest neutralino $\tilde{\chi}_1^0$ is the next-to-lightest supersymmetric particle. It can be long-lived and decay to a photon and a gravitino ($\tilde{G}$), which is the lightest supersymmetric particle. We aim here to provide a precise estimation of the photon time-of-flight resolution (σ_{TOF}) and test different BTL timing resolution scenarios. We assume that t_{TOF} is given by the difference between the time of arrival of the photon on ECAL (t_{ECAL}) and the time of the primary vertex (t_{vtx}). Therefore the overall timing resolution on t_{TOF} is given by $\sigma_{TOF} = \sqrt{\sigma_{vtx}^2 + \sigma_{ECAL}^2}$. While σ_{ECAL} can be assumed to

35 ps BTL, 35 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.38	1.52	1.60
$bb\gamma\gamma$	1.70	1.75	1.85	1.90
Combined	2.31	2.40	2.57	2.66

50 ps BTL, 50 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.36	1.44	1.50
$bb\gamma\gamma$	1.70	1.72	1.78	1.80
Combined	2.31	2.37	2.47	2.53

70 ps BTL, 35 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.92	0.94
$bb\tau\tau$	1.30	1.38	1.36	1.44
$bb\gamma\gamma$	1.70	1.75	1.76	1.81
Combined	2.31	2.40	2.41	2.51

Table 1: Projections for the HH signal significance in units of σ when exploiting the timing information provided by MTD in b-tagging and particle isolation. Projections are presented for three decay channels and their combination for three MTD performance scenarios.

be of the order of 30 ps [4], we estimate here precisely σ_{vtx} starting from a realistic estimate of the number of tracks in the event associated to the primary vertex. By counting how many tracks end up in the BTL (N_{BTL}) and in the ETL (N_{ETL}) and by associating to each of them individually the corresponding timing resolution ($\sigma_{BTL/ETL}$) we can estimate:

$$\sigma_{vtx} = \sqrt{\frac{1}{N_{BTL}/\sigma^2_{BTL} + N_{ETL}/\sigma^2_{ETL}}} \tag{1}$$

Assuming two extreme BTL resolution scenarios (30 and 70 ps) we re-run the TDR timing-based analysis. As expected for this specific benchmark analysis a possible worsening of the BTL timing resolution does not affect the overall analysis sensitivity. This is due to the fact that the σ_{TOF} of the photon is dominated by the ECAL timing resolution. It is true however that the presence of the MTD is crucial in this context to estimate precisely the time of the primary vertex, thanks to the large multiplicity of tracks produced in the interaction.

3.2 Heavy Stable Charged Particles

Heavy Stable Charged Particle (HSCP) in the form of a stau ($\tilde{\tau}$) are LLPs with a very large lifetime crossing the full detector predicted by GMSB models. It is possible to explore this topology through the measurement the particle velocity, β, using the path length and the time difference between the primary vertex and the particle hits in the MTD. This quantity can be used to discriminate between signal and background SM processes, mostly leptons from Drell-Yan (DY) production, and the resolution in the time measurement is the main factor distorting the measurement. Assuming two extreme scenarios of the BTL and ETL timing resolutions, we produce the $1/\beta$ distributions for HSCP signal and DY background as shown in Figure 1 (left) for a reference HSCP mass of 432 GeV. Figure 1 (right) shows the corresponding receiver operating characteristic (ROC) curves associated to the best and worst scenarios obtained by applying a variable cut on $1/\beta$ providing the given signal/background efficiency. A selection corresponding to more than five times the $1/\beta$ RMS observed for background events for the best (worst) scenario is applied in order to reasonably assume 0 background events passing this selection. Imposing the same five-sigma criteria with the resolution provided by the best scenario, increases the signal acceptance up to 23%.

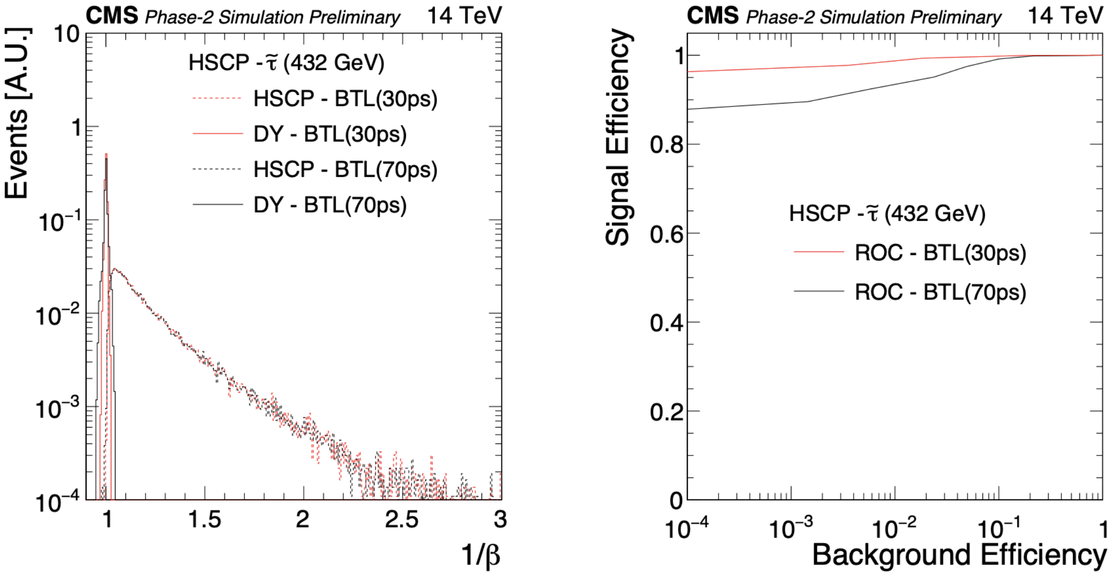

Figure 1: Distribution of $1/\beta$ for DY+Jets events with and without the MTD and signal events (left). ROC curve associated to the $1/\beta$ for the best and worst scenarios. (right).

4. Particle identification and its use in B physics

The PID based on the 4D primary vertex (PV) reconstruction algorithm is based on the space-time compatibility between the track back-propagated to the point of closest approach (PCA) and the 4D vertex to which the track may be associated, asking for a weight of the track in the vertex fit greater than 0.5, and looking for vertices with a vertex time uncertainty not exceeding 25 ps. The compatibility is expressed in terms of:

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

requiring a maximal distance from the PCA along the z coordinate $(z_{PCA} - z_{PV})$ of 1 mm, and that the significance $(t_{PCA,hyp} - t_{PV})/\sigma_{t_{MTD}}$ for a given mass hypothesis hyp does not exceed 5.

Here t_{PCA} and σ_{MTD} are the time back-extrapolated to the PCA and the corresponding estimated uncertainty on the time measured in MTD for the track. The χ^2_{hyp}, computed for $t_{PCA,hyp}$ corresponding to different mass hypotheses, is then used to define hypothesis probabilities $e^{-\chi^2_{hyp}}$, which are normalized to the sum of probabilities for the π/K/p hypotheses. These probabilities may be used to define a particle identification.

4.1 Performance of PID from 4D vertex reconstruction

The performance of the 4D-vertex-based PID, is studied on a sample of $t\bar{t}$ events with a Poisson average pileup $\langle N_{PU} \rangle = 200$. Reconstructed charged tracks are requested to be associated to the leading primary vertex of the event with a weight in its fit larger than 0.5 and to have an MTD time correctly measured. Tracks are considered if they are matched to a simulated charged particle, and the leading primary vertex must correspond to the true simulated signal vertex of the event. In this way the possible performance deterioration due to the incorrect identification of the leading event vertex is factorized from the genuine MTD performances.

The sample of selected tracks with MTD time associated is divided according to the type of associated simulated primary particle MC_{truth}, pion, kaon or proton, and the PID efficiency matrix is computed as a function of the track momentum p and angular region. Also tracks without a positive PID are considered collectively in a single category. The PID efficiency is defined as:

$$\epsilon(\pi/K/p/no_{PID})_{MC_{truth}} = \frac{N(\pi/K/p/no_{PID})_{MC_{truth}}}{N_{MC_{truth}}} \tag{3}$$

where $N_{MC_{truth}}$ is the number of selected tracks matched to a generated particle of type $MC_{truth} = \pi/K/p$ and $N(\pi/K/p/no_{PID})_{MC_{truth}}$ is the number of these tracks that have been identified by the algorithm as respectively pions, kaons, protons, or that have not got a positive identification. The results are shown for example for true kaons in Fig. 2. The impact of the time resolution on the PID performance has been studied using a simplified model based on the DELPHES program [5]. Figure 3 contains a summary of the results obtained for different time resolution scenarios using DELPHES. The range of momentum with a purity higher than 70% is shown for different species and time resolution scenarios. The PID efficiency is indicated by the colors in the bars.

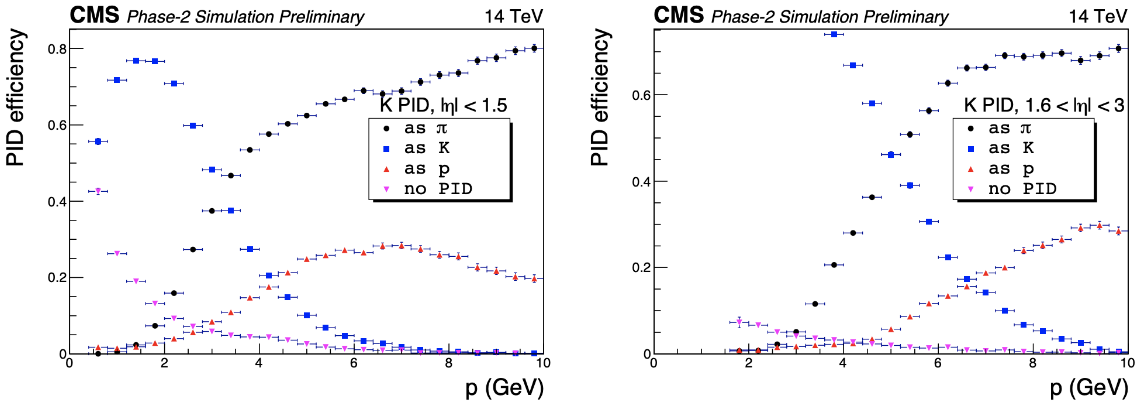

Figure 2: PID efficiency for simulated kaons associated to a selected track.

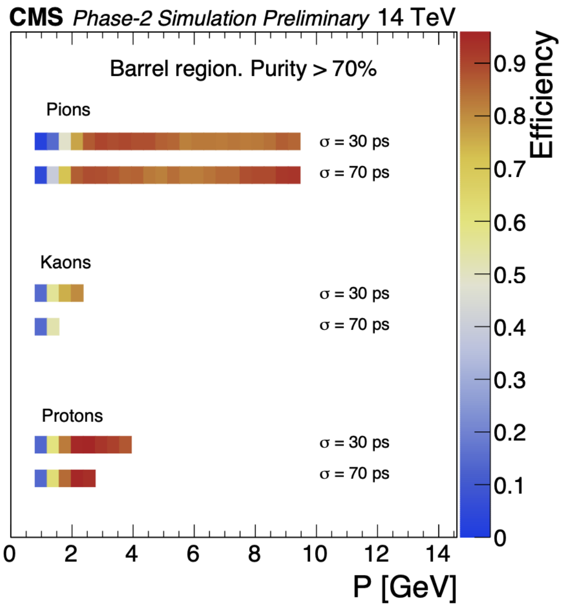

Figure 3: Momentum range with a purity higher than 70% for different species and BTL time resolution scenarios. Tracks are from simulated top-antitop events with an average of pileup events $\langle N_{PU} \rangle = 200$.

PID timing can be exploited in Heavy Ion Physics, as shown in the MTD TDR [1], but is also useful in B physics [2]. The measurement of the CP violation in the decay $B_s \rightarrow J/\Psi\phi(1020)$ is considered as a test case. The B meson flavour at production time can be "tagged" by exploiting the charge correlation between the s-quark sign and the charge of a soft kaon from the primary decay vertex from which the B meson is coming (same-side tagging). The PID from the MTD, when integrated in the Phase-2 extrapolation of this analysis, shows a significant improvement of the tagging performances, up to 25% with respect to the case where no tagging is applied.

References

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