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Abstract

The MIP Timing Detector (MTD) is a novel component of the CMS experiment, currently under construction as part of the upgrade program to prepare for the High Luminosity era of the LHC (HL-LHC). The MTD will provide precise time information for charged particles and will play an important role in the mitigation of the high pileup expected in HL-LHC. The timing will be used to disentangle vertices that cannot be distinguished spatially, thus reducing the vertex cross-contamination and the effects of pileup on the physics observables used for any data analysis. This contribution presents the recent developments in the vertex reconstruction with the use of timing, and introduces a new set of tools useful to evaluate the performance of different reconstruction algorithms, which can serve as a benchmark for future developments in the field.

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Optimal use of timing measurement in vertex reconstruction at CMS

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Abstract. The MIP Timing Detector (MTD) is a novel component of the CMS experiment, currently under construction as part of the upgrade program to prepare for the High Luminosity era of the LHC (HL-LHC). The MTD will provide precise time information for charged particles and will play an important role in the mitigation of the high pileup expected in HL-LHC. The timing will be used to disentangle vertices that cannot be distinguished spatially, thus reducing the vertex cross-contamination and the effects of pileup on the physics observables used for any data analysis. This contribution presents the recent developments in the vertex reconstruction with the use of timing, and introduces a new set of tools useful to evaluate the performance of different reconstruction algorithms, which can serve as a benchmark for future developments in the field.

1 Introduction

The Large Hadron Collider (LHC) at CERN will enter a High-Luminosity era (HL-LHC), expected to begin in 2030, with the aim to collect $\sim$ 3 ab^{-1} of data to perform extremely precise measurements of the parameters of the Standard Model as well as searches for new physics. The instantaneous luminosity will be at least a factor of 5 higher than the initial design luminosity and it will come at the cost of an increase in the number of proton-proton (pp) interactions happening simultaneously, known as pileup (PU). The expected mean number of PU interactions will be 140-200, much higher compared to the value of around 60 currently present in Run 3 of the LHC. To perform any physics analysis, it will be crucial to isolate the interaction of interest among all the PU interactions and to mitigate the effects of PU on the object reconstruction. The CMS experiment will undergo an extensive upgrade program, the Phase 2 upgrade, to prepare for HL-LHC. In this context, a new sub-system will be added with the goal to measure the time of minimum ionizing particles (MIPs): the MIP Timing Detector (MTD) [1], with a precision of 30 – 40 ps. Such time resolution will be much smaller than the pp collision spread in time of $\mathcal{O}(200)$ ps, corresponding to a longitudinal spread of around 5 cm. The reconstruction of vertices with the inclusion of the track time coordinate (4D reconstruction) will allow to separate vertices that overlap in space but are separated in

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time, bringing the effective PU contamination back to Run 3 levels, where the tools for PU mitigation have been proven to work well.

In the following, the 4D vertex reconstruction algorithm will be presented, together with the latest improvements. The performance of the optimized algorithm will be compared to the previous version as well as to the 3D vertex algorithm, in terms of vertex time resolution, reconstruction efficiency and PU rejection.

2 Vertex reconstruction

The 4D vertex reconstruction algorithm as described in the MTD Technical Design Report (TDR) [1], labelled *legacy 4D*, is briefly recalled here. The algorithm consists of three main steps: the track clustering, the vertex fit and the vertex time computation. The vertex clustering relies on the track time, extrapolated to the point of closest approach (PCA) to the beamline, together with the spatial coordinates to reconstruct vertices. The track time at the PCA t_i is obtained starting from the time measured at the MTD surface t_{MTD}:

$$t_i = t_{\mathrm{MTD}} - \mathrm{TOF}(\pi), \tag{1}$$

where TOF(π) is the time-of-flight in the pion hypothesis, an initial assumption needed as the mass of the particles is a-priori unknown. To account for this approximation, an inflated uncertainty, given by the difference in the TOF between the pion and proton hypotheses, is added to the total time uncertainty:

$$\sigma(t_i) = \sigma(t_{\mathrm{MTD}}) \oplus \sigma(t_{\mathrm{TOF}}) \oplus \Delta(\mathrm{TOF}(p) - \mathrm{TOF}(\pi)), \tag{2}$$

where $\sigma(t_{\mathrm{MTD}})$ is the MTD time uncertainty and $\sigma(t_{\mathrm{TOF}})$ is the uncertainty on the TOF, that comes from the momentum uncertainty and is estimated for each particle hypotheses (pion, kaon, proton). The contribution of the TOF uncertainty has been studied and proven to have a negligible impact [2].

The vertex reconstruction follows an iterative procedure, by calculating the vertex time and then assigning the correct particle hypothesis using the constraint that the tracks originating from the same vertex have the same time at the beamline. The vertex time t_{vtx} is computed with a simple weighted average of the track times:

$$t_{\mathrm{vtx}} = \frac{\sum_i \sigma(t_i)^{-2} t_i}{\sum_i \sigma(t_i)^{-2}}. \tag{3}$$

With the updated track times, and removing the inflated uncertainties, the vertices are clustered a second time and the vertex time and particle identification are computed again.

Such algorithm is not the optimal one for different reasons. From the computational point of view, it is CPU-time consuming, considering that it is executed together with the standard 3D algorithm and that the first iteration of the 4D algorithm uses an inflated uncertainty, that dominates over the MTD uncertainty for low momentum particles, thus making a very limited use of the time information. Moreover, the 4D algorithm compared to the 3D one shows worse vertex reconstruction efficiency and purity. The aforementioned limitations of the legacy 4D vertex reconstruction algorithm have led to the optimization presented in the following, which improves the algorithm both from the computational point of view as well as in terms of physics performance [3].

A new vertex time computation has been included, which relies on a time-aware Deterministic Annealing (DA) algorithm [2, 4], that can be applied to a reconstructed vertex regardless of the use of time in its clustering. The algorithm computes the vertex time using all the mass hypotheses and minimizing the following cost function:

$$F = -T \sum_{\text{tracks},i} w_{0,i} \log\left(Z_0 + \alpha_\pi e^{-\frac{(t_i(\pi)-t_{\text{vtx}})^2}{2T\sigma(t_i)^2}} + \alpha_K e^{-\frac{(t_i(K)-t_{\text{vtx}})^2}{2T\sigma(t_i)^2}} + \alpha_p e^{-\frac{(t_i(p)-t_{\text{vtx}})^2}{2T\sigma(t_i)^2}}\right), \tag{4}$$

where $w_{0,i}$ is the track weight from the adaptive vertex fit, $t_i(\pi/K/p)$ is the track time at the PCA for the different mass hypotheses, $\sigma(t_i)$ is the corresponding track time uncertainty and T is the DA initial temperature. The term $Z_0 = e^{-\frac{1}{2}3^2}$ is the outlier-rejection constant, that enables the downweighting of tracks for which none of the hypotheses provides an agreement better than $3\sigma(t_i)T$ with the vertex time. The terms $\alpha_\pi/\alpha_K/\alpha_p$ are a-priori particle probabilities and they are set to 0.7/0.2/0.1, respectively, as expected from the particle multiplicity. The new time computation is applied on the standard 3D vertices, referred to as 3Dt in the following. The availability of a vertex time for 3Dt vertices allows the removal of the first iteration of the 4D reconstruction. In this way, it is possible to reduce the vertex reconstruction CPU-time by $\sim$ 30% without loss in performance. Moreover, the new time computation is applied on 4D vertices as well, improving the time resolution.

3 Vertex association to MC truth

To evaluate the performance of the vertex reconstruction algorithms, a matching between reconstructed and simulated vertices is made, based on the common origin of tracks. The matching is performed with an algorithm that first matches the reconstructed tracks to the true simulated particles. The simulated vertices from which the matched simulated particles originate are used to define the set of true primary vertices. The following weight is defined for each track, *weight-over-sigma* $W_{\text{os},i}$:

$$W_{\text{os},i} = \frac{w_{0,i}}{\sigma^2_{z,i}} \frac{1}{\text{erf}(\sigma(t_i)/\sigma_T)}, \tag{5}$$

where $\sigma_{z,i}$ is the track resolution along the nominal beam axis (z) and σ_T the time width of the beamspot. The time-dependent part is defined only for tracks with time information and it is set to 1 otherwise. A one-to-one matching is performed between the reconstructed and simulated vertices based on their respective sums of W_{os} weights. For each reconstructed vertex, the dominating simulated vertex is identified as the one with the highest sum of W_{os}. Whenever possible, the dominating simulated vertex is matched to the corresponding reconstructed vertex. If a simulated vertex dominates multiple reconstructed vertices, the match is assigned to the the reconstructed vertex that receives the highest weight. The algorithm proceeds in an iterative manner for all the reconstructed vertices, classifying them as either real or fake. A reconstructed vertex is classified as real if a suitable match is found within a maximum of 8 iterations. If no matching is found, meaning that no simulated vertex dominates the reconstructed vertex exclusively, it is classified as fake.

4 Results

A comparison of the performance of the updated 4D, the legacy 4D and the 3Dt algorithms is presented. The studies are performed on a simulated $t\bar{t}$ sample with PU of 200.

The vertex time resolution and pull are shown in Fig. 1 for signal vertices. The time resolution is defined as the difference between the reconstructed vertex time and the simulated vertex time. The pull is defined as the resolution divided by the reconstructed vertex time uncertainty. The distributions are fitted with a double Gaussian function and the parameters of the narrowest one are shown. The updated 4D and 3Dt algorithms show an improvement in the time resolution and pull with respect to the legacy 4D algorithm. In particular, the legacy 4D presents a negative bias, which is caused by an overestimation of the track mass and is reduced in the 4D and 3Dt algorithms thanks to the use of all mass hypotheses in the time computation. In Fig. 2 the number of reconstructed vertices is shown as a function of the number of PU vertices. The reconstructed vertices are divided in the real and fake categories, based on the matching to MC truth. The reconstructed vertices pass the selection on the number of degrees of freedom $n_{dof} > 4$. In general, the 3Dt algorithm reconstructs more real vertices compared to the other algorithms, but also more fakes. The updated 4D algorithm shows a higher number of real vertices than the legacy 4D but also a higher number of fakes, with a performance that lies in between the 4D legacy and the 3Dt algorithms.

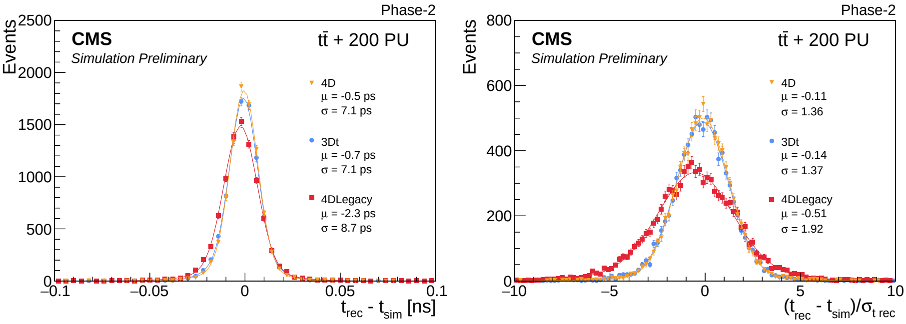

Figure 1. The vertex time resolution (left) and pull (right) for signal vertices matched to simulated vertices, for the updated 4D (orange triangles), the 3Dt (blue circles) and the 4DLegacy (red squares) vertex reconstruction algorithms. Figure from [3].

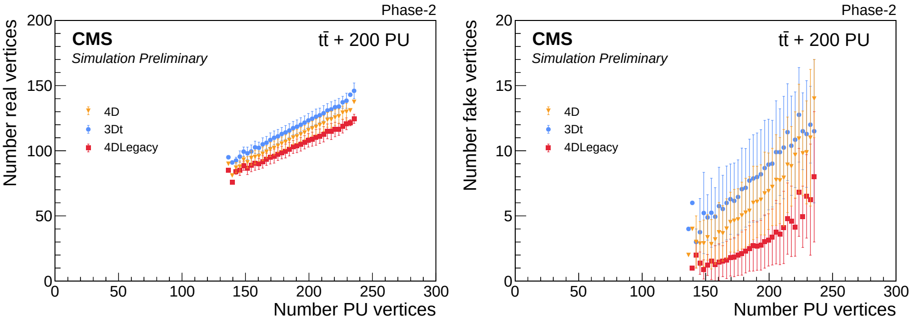

Figure 2. The number of reconstructed primary vertices as a function of the number of simulated PU vertices is shown for the updated 4D (orange triangles), the 3Dt (blue circles) and the 4DLegacy (red squares) vertex reconstruction algorithms. The reconstructed vertices, that pass the selection $n_{dof} > 4$, are categorized as real (left) and fake (right) vertices. The error bars indicate the RMS of the distributions. Figure from [3].

The distance in z (Δz) between all possible pairs of reconstructed vertices is presented in Fig. 3, for pairs of real or fake vertices. The 3Dt algorithm can not reconstruct vertices with separation less than ~ 0.3 mm by design. The updated 4D algorithm shows more real-real vertex pairs close in z than 4D legacy, but it also shows more fake vertices. The improvement in the new algorithm is noticeable especially for real vertex pairs with Δz close to 0, which is a clear example of the advantage in the use of timing: the reconstruction of vertices that overlap in space but can be separated in time. Finally, the PU contamination in vertices is studied. In particular, it is interesting to evaluate the cross-contamination for the leading vertex (LV), which is identified as the reconstructed vertex with the largest value of summed physics-object p_T^2. Track-based as well as jet-based observables are monitored, to provide a comparison between vertex algorithms in terms of PU rejection. The tracks that belong to a given reconstructed vertex can be classified based on the matching to the MC truth in the following categories:

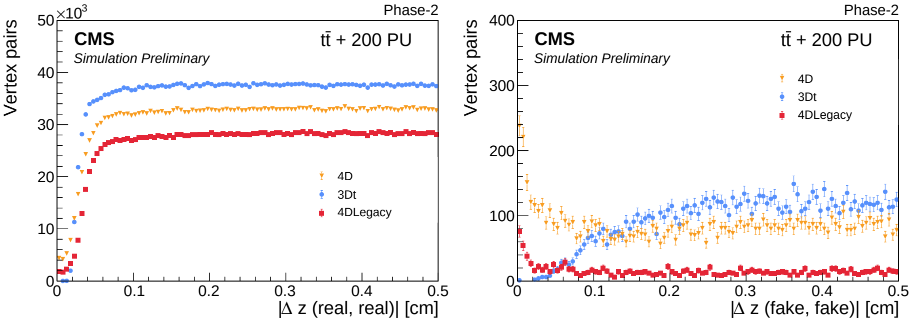

Figure 3. The distance in z (Δz) between all pairs of reconstructed vertices is shown for the updated 4D (orange triangles), the 3Dt (blue circles) and the 4DLegacy (red squares) vertex reconstruction algorithms. The Δz is presented for real-real (left) and fake-fake (right) vertex pairs. Figure from [3].

- track associated to the primary vertex,
- track associated to a secondary vertex,
- PU track,
- fake track, i.e. a reconstructed track not matched to any true particle.

Jets are constructed with a simplified approach by clustering the reconstructed charged tracks originating from the same vertex. The relative contribution of PU to jet-based observables is estimated by clustering jets without PU tracks, recomputing the observables, subtracting them from those computed using all charged tracks and normalizing to the version with all tracks. In Fig. 4 the relative contribution of PU to the track multiplicity (top left), the jet multiplicity (top right) and the $\sum_{jet} p_{T,jet}^2$ (bottom) is shown. The latter is similar to the variable used for vertex sorting in CMS. In general, a PU reduction of about $10 - 15\%$ can be seen in the updated 4D and 4D Legacy algorithms with respect to the 3Dt one. However, the $\sum_{jet} p_{T,jet}^2$ of jets is relatively insensitive to the choice of the vertex reconstruction algorithm.

5 Conclusions

The timing information provided by MTD will play an important role in reducing the effects of PU in HL-LHC. In particular, the 4D vertex reconstruction will allow the separation of vertices that overlap in space, but can be separated in time, improving the PU rejection. In this contribution, the latest improvements in the 4D vertex reconstruction algorithm are presented and the performance is compared to the legacy version of the algorithm and the

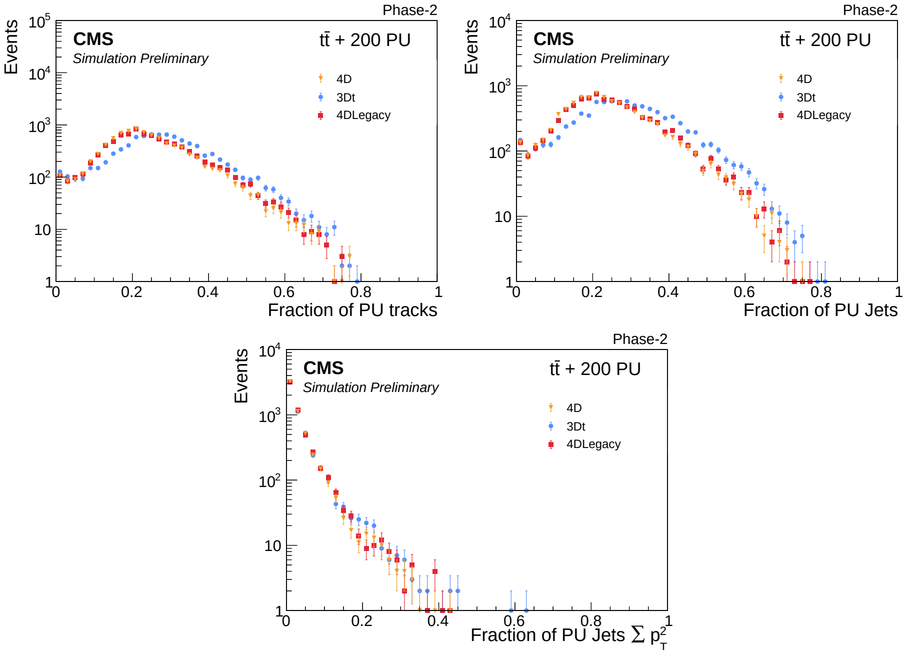

Figure 4. The relative contribution of PU to track multiplicity (top left), jet multiplicity (top right) and $\sum_{jet} p^2_{T,jet}$ (bottom) for the LV of the event, for the updated 4D (orange triangles), the 3Dt (blue circles) and the 4DLegacy (red squares) vertex reconstruction algorithms. Figure from [3].

standard 3D vertices. The tools designed to study the various algorithms in terms of vertex time resolution, number of reconstructed vertices, and PU rejection, are useful as reference for future developments in vertex reconstruction.

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