Advanced algorithms for 4D vertex reconstruction with the MIP Timing Detector at the HL-LHC in CMS

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Summary. — The High-Luminosity phase of the Large Hadron Collider (HL-LHC) will pose significant challenges to primary vertex reconstruction, which is crucial for many physics analyses, due to the substantial increase of pileup in collisions. To mitigate this effect, the upgraded CMS experiment will include the MIP Timing Detector (MTD) to measure the time of arrival of charged particles with a time resolution of 30-60 picoseconds. This work presents recent advancements in 4D vertex reconstruction algorithms, aiming to disentangle vertices within the dense HL-LHC environment by incorporating the track time information provided by the MTD. The performance of novel techniques, developed beyond initial studies performed at the time of the detector proposal, is evaluated by comparing vertex reconstruction efficiency, time resolution, and pileup rejection against existing methods. The beneficial impact of timing on vertex reconstruction, based on a detailed simulation and reconstruction software chain, is demonstrated.

1. – Introduction

The Large Hadron Collider (LHC) at CERN, after a five-year running period of proton collisions at a center-of-mass energy of 13.6 TeV (Run-3), is scheduled for Long Shutdown 3, to enable upgrades intended to increase the instantaneous luminosity by at least a factor of 5 above the LHC's design value. This will allow collecting unprecedented amount of data to perform precise measurements of the parameters of the Standard Model, and to improve the sensitivity of the search for physics beyond the Standard Model. The LHC is expected to resume operation in 2030, starting the High-Luminosity era.
Hard interactions of interest to CMS are accompanied, in the current Run-3 of the LHC, by an average of 60 additional collisions, known as pileup (PU), happening simultaneously in the same bunch crossing; on the other hand, the mean number of PU interactions for the HL-LHC is expected to be about 140-200. Due to the increased number of PU collisions, the identification and the reconstruction of the hard interaction can degrade; hence, to perform any physics analysis, it will be crucial to mitigate the effects of pileup on the object reconstruction.

The CMS experiment will undergo a major renovation for the HL-LHC, the Phase-2 upgrade, to maintain the current performance in terms of efficiency, resolution, and background rejection for all final state particles and physics observables used in data analyses. In this context, CMS will be instrumented with a new sub-detector to measure precisely the production time of minimum ionizing particles (MIPs): the MIP Timing Detector [1]. The 30-40 ps resolution in timing information for MIPs at the beginning of HL-LHC will degrade, due to radiation damage, to 50-60 ps at the end of data taking, for the barrel part. MTD will bring to CMS the capability to separate vertices overlapping in space but separated in time, thanks to a 4D vertex reconstruction, enabled by including the track time coordinate in the vertex reconstruction algorithm. It exploits the fact that individual collisions within the same bunch crossing are distributed over time with an RMS of about 190-200 ps, corresponding to approximately 5 cm spread along the beam direction, because of the longitudinal extent of the beams. Therefore, a time resolution of 30-60 ps is much smaller than the beam spot temporal spread and allows assigning tracks to the correct interaction vertices. Figure 1 visually demonstrates the potential of a space-time vertex reconstruction.
This work presents the vertex reconstruction algorithm with timing, labeled as "4DLegacy", and compares its performance to the latest optimized algorithm, labeled as "4D", as well as to the 3D vertex reconstruction (with time computed using the tracks contributing to this vertex), labeled as "3Dt", in terms of efficiency, time resolution, and PU rejection. All the studies are done on a Phase-2 simulated $t\bar{t}$ sample with PU 200.

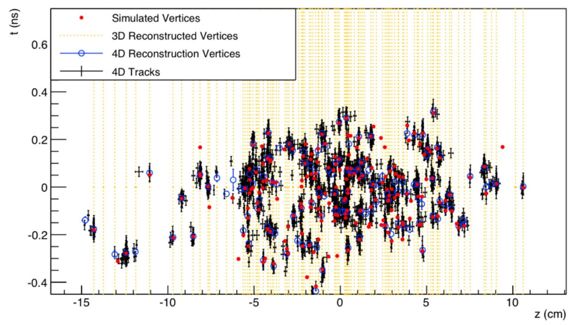

Fig. 1. – Comparison between 3D (vertical yellow lines) and 4D (blue open circles) reconstructed vertices in a bunch crossing with PU 200 [1]. Simulated vertices are marked by red dots. The black crosses represent tracks reconstructed including time information. The horizontal axis is the z-position along the beamline, while the vertical axis is the time.

2. – Vertex Reconstruction algorithms

The 3D vertex reconstruction is the current method employed by CMS and consists of a deterministic annealing (DA) algorithm for track clustering and an adaptive vertex fitter to compute the best estimate of vertex parameters [2]. Track clustering with DA is performed by finding the vertex position z_k^V through the minimization of the analogue of the free energy in statistical mechanics:

$$F = -T \sum_{trks,i} p_i \log \sum_{vertices,k} \rho_k e^{-\frac{1}{T}\frac{(z_i^T - z_k^V)^2}{\sigma_i^{z\,2}}}, \tag{1}$$

where "temperature" T is an optimization parameter of the algorithm, z_i^T is the z-coordinate of the points of closest approach (PCA) of the tracks to the center of the beam spot, $\sigma_i^{z^2}$ their associated uncertainties, and p_i and ρ_k are weights, respectively for tracks and vertices. The candidate vertices containing at least two tracks are then fitted using an adaptive vertex fitter.
The legacy 4D algorithm reconstructs vertices by clustering tracks with an extension of the DA in the spatial coordinate z along the beamline and in the track time, extrapolated back to the PCA to the beamline. It involves two iterations of vertex reconstruction, each consisting of 4D vertex clustering, vertex fit and time computation.
In the first iteration, when the particles' mass is a-priori unknown, the pion hypothesis (the most probable) is assumed for all tracks to calculate their time t_0 at the beam line:

$$t_0 = t_{MTD} - TOF_\pi, \tag{2}$$

where t_{MTD} is the time measured at the MTD surface and TOF_π is the time-of-flight in the pion hypothesis (computed based on the path length and particle velocity). To account for such assumption, the uncertainty on t_0 is inflated by adding in quadrature the difference in the TOF between the pion and proton hypotheses:

$$\sigma_0^2 = \sigma_{MTD}^2 + \sigma_{TOF}^2 + \Delta^2(TOF_p - TOF_\pi), \tag{3}$$

with σ_{MTD} being the MTD time uncertainty and σ_{TOF} the uncertainty on the TOF, that derives from momentum uncertainty and is estimated for each particle hypothesis (pion, kaon, proton). Once the vertex time is available, it is possible to perform the particle identification using the particles' TOF.
In the second iteration of the 4D vertex reconstruction, track time information is updated according to the new mass hypothesis assignment, the inflated uncertainties are removed, the vertices are re-clustered and the vertex time and particle identification are computed again. The vertex time is calculated simply as a weighted average:

$$t_v = \frac{\sum_{trks,i} w_i t_{0,i}}{\sum_{trks,i} w_i}, \tag{4}$$

where $w_i = \sigma_{t_{0,i}}^{-2}$, assuming a fixed mass hypothesis. The legacy 4D reconstruction, nevertheless, is not well optimized: CPU consumption is high; in the first iteration, the inflated uncertainty dominates over MTD uncertainty at low momenta and makes the benefits of time use limited; efficiency and purity are lower than in 3D reconstruction.
Due to the mentioned limitations, an optimized 4D algorithm was developed to improve both computational and physics performance [3]. A new vertex time computation has been included, which relies on a dedicated DA algorithm [4]. The vertex time is computed using all the mass hypotheses, by the minimization of the cost function:

$$F = -T \sum_{trks,i} w_{0,i} \log(Z_0 + \alpha_\pi e^{-\frac{(t_{0,i}(\pi)-t_v)^2}{2T\sigma^2_{t_{0,i}}(\pi)}} + \alpha_K e^{-\frac{(t_{0,i}(K)-t_v)^2}{2T\sigma^2_{t_{0,i}}(K)}} + \alpha_p e^{-\frac{(t_{0,i}(p)-t_v)^2}{2T\sigma^2_{t_{0,i}}(p)}}), \tag{5}$$

where $w_{0,i}$ is the i-th track weight, $t_{0,i}(\pi, K, p)$ the track times, $\sigma_{t_{0,i}}(\pi, K, p)$ their respective uncertainties, T the DA initial temperature and $Z_0 = e^{-\frac{1}{2}3^2}$ is the outlier-rejection constant (to downweight tracks for which none of the hypotheses provides an agreement better than $3\sigma_{t_{0,i}}T$ with the vertex time). The a-priori particle probability terms $\alpha_\pi/\alpha_K/\alpha_p$ are set to 0.7/0.2/0.1, respectively, as expected from hadronization models. This new time computation can be applied to a reconstructed vertex regardless of the use of time in its clustering, in particular on the standard 3D vertices (3Dt). The availability of a vertex time for 3D vertices allows the replacement of the first iteration of the 4D reconstruction with a 3D reconstruction with time. This allows the reduction of the vertex reconstruction CPU-time by $\sim 30\%$, without loss in physics performance. The new time computation is applied on the second iteration of the updated 4D vertex reconstruction as well, improving the time resolution.

3. – Performance studies

To evaluate the performance of vertex reconstruction and to compare the updated 4D, the legacy 4D, and the 3Dt algorithms, a matching was developed between reconstructed vertices and MC truth, based on the common origin of tracks in reconstructed and simulated vertices. The reconstructed vertices are divided into the real and fake categories, depending on whether or not they are matched to a simulated vertex. A simulated $t\bar{t}$ sample with PU of 200 was used to perform the studies.
Figure 2 shows the distribution of the differences between the reconstructed and simulated vertex time for signal vertices matched to simulated ones, and of their pulls. The 3Dt and 4D algorithms improve the time resolution and pull over the legacy 4D; in particular, the negative bias in legacy 4D vertex reconstruction is reduced in the 3Dt and 4D algorithms, thanks to the use of all mass hypotheses in the time computation.

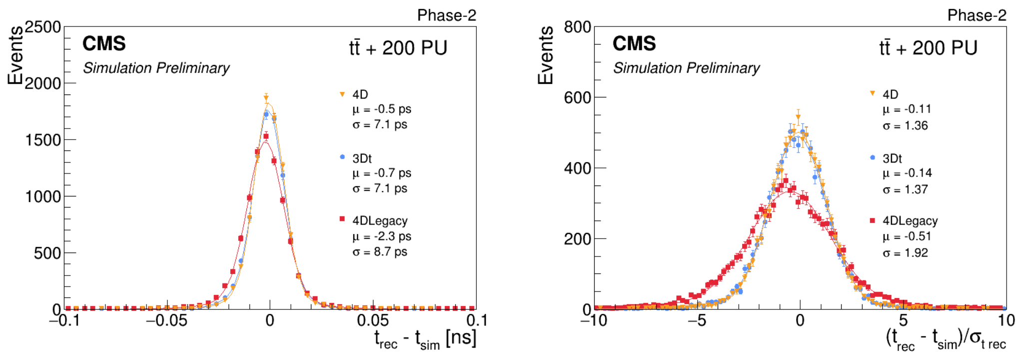

Fig. 2. – Time resolution (left) and pull (right) for signal vertices, matched to simulated vertices, in a $t\bar{t}$ sample with an average PU of 200, for 4D Legacy (red square), 4D (orange triangle) and 3Dt (blue circle) algorithms [3]. Distributions are fitted with a double Gaussian, the parameters of the narrowest one are shown.

In fig.3, the number of reconstructed vertices as a function of the number of PU vertices, divided for real and false vertices, is illustrated. The 4D algorithm shows intermediate performance between the legacy 4D algorithm and the 3Dt one, the latter in particular reconstructing more real vertices compared to the other algorithms, but also more fakes.
The distance Δz between pairs of real or fake reconstructed vertices is presented in fig.4. The updated 4D algorithm shows more true vertex pairs close to each other in z than

the legacy 4D, but also more fakes. The 3Dt algorithm, instead, can not reconstruct vertices with separation less than ~ 0.3 mm by design. The improvement given by the new algorithm is most visible for pairs of real vertices with Δz close to 0: the clear advantage given by the use of timing is the ability to separate in time spatially overlapping vertices. Figure 5 shows the impact of pileup on track multiplicity and jet-based observables for the leading vertex, which is identified as the reconstructed vertex with the largest value of summed physics-object p_T^2. Reconstructed charged tracks originating from the same vertex are clustered into jets with the fastjet package, using the anti-kT algorithm with distance parameter 0.4 [5]; 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. The contribution of pileup is about $10-15\%$ lower in legacy 4D and 4D vertices than in 3Dt, on the other hand, the sum of jet p_T^2 is less sensitive to the vertex reconstruction algorithm.

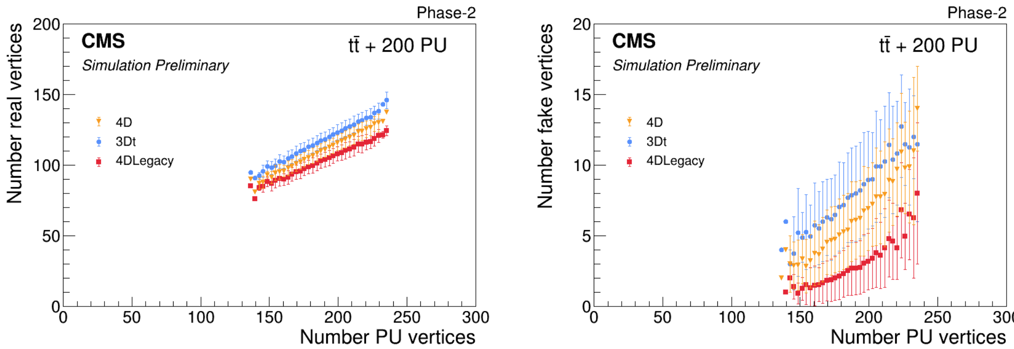

Fig. 3. – The number of reconstructed primary vertices, categorized as real (left) and fake (right), as a function of the number of simulated PU vertices, in a $t\bar{t}$ sample with an average PU of 200, for 4D Legacy (red square), 4D (orange triangle) and 3Dt (blue circle) algorithms [3]. The error bars represent the RMS of the distributions.

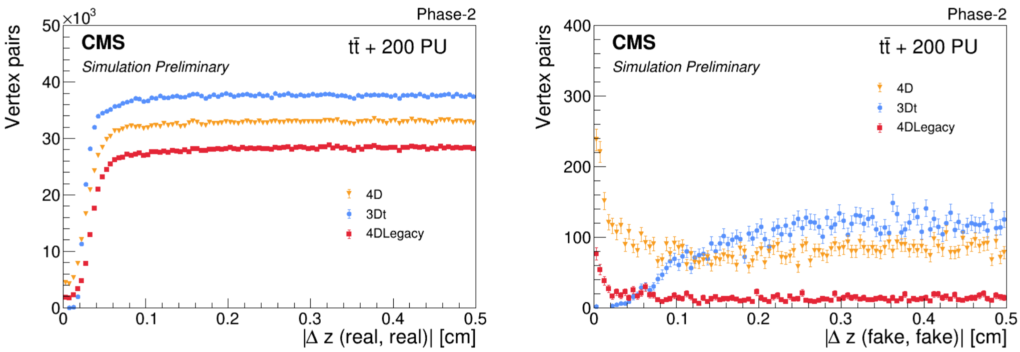

Fig. 4. – The distance in z between all pairs of reconstructed vertices, distinguished by real-real (left) and fake-fake (right), in a $t\bar{t}$ sample with an average PU of 200, for 4D Legacy (red square), 4D (orange triangle) and 3Dt (blue circle) algorithms [3].

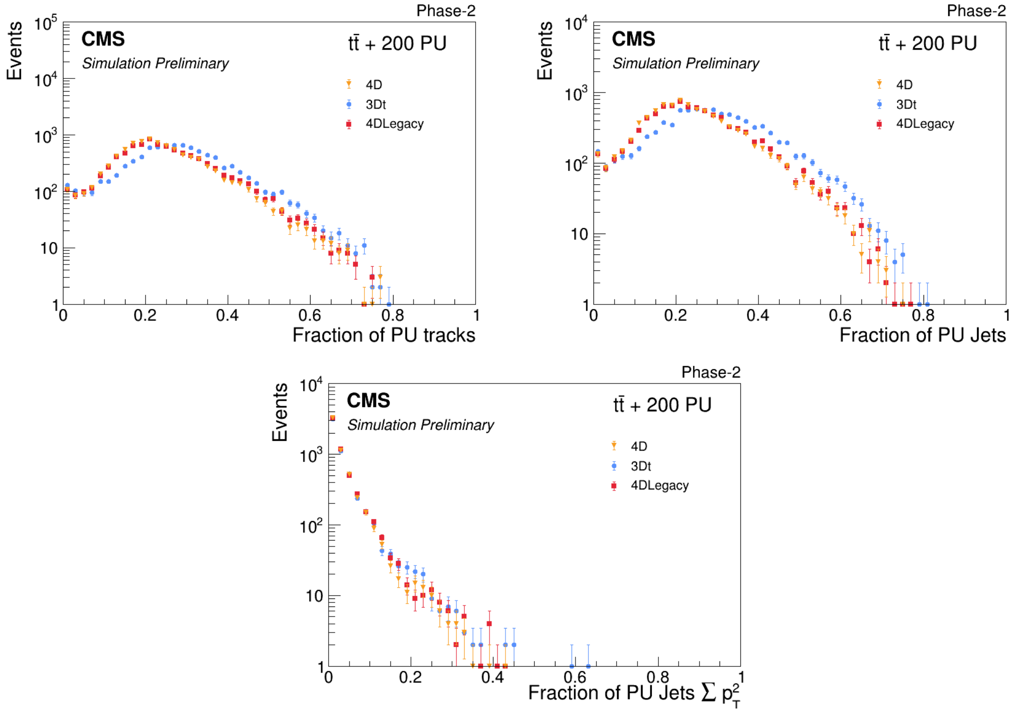

Fig. 5. – Relative contribution of pileup to track multiplicity (top left), jet multiplicity (top right) and $\sum_{jet} p_{T,jet}^2$ (bottom), in a $t\bar{t}$ sample with an average PU of 200, for 4D Legacy (red square), 4D (orange triangle) and 3Dt (blue circle) algorithms [3].

4. – Conclusions

This work presented the optimization of 4D vertex reconstruction, leveraging timing information from the MTD, a new CMS sub-detector for the HL-LHC. In particular, it was shown that using a Deterministic Annealing approach to compute the vertex time instead of a weighted average of the track times improves the resolution for signal vertices, and that the use of time information will allow the separation of vertices that overlap in space, but can be separated in time, improving the PU rejection.

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