ENHANCING PARTICLE RECONSTRUCTION AND IDENTIFICATION WITH THE MIP TIMING DETECTOR AT CMS

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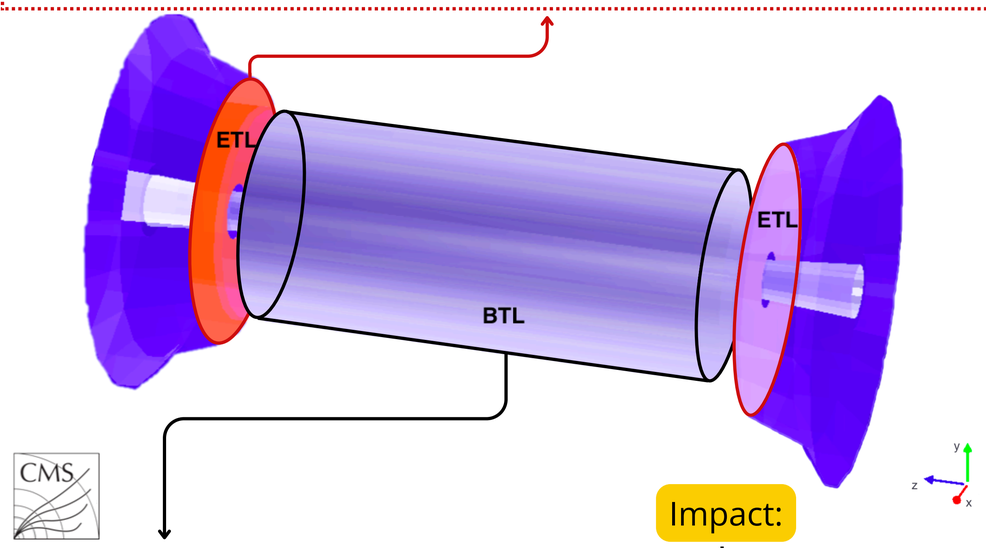
MTD: MIP Timing Detector [1]

MTD is a **timing detector** to be installed in CMS **for the HL-LHC era** (2030-2041).

Endcap Timing Layer (ETL):

- 1.6 < |η| < 3.0
- Two layers of Low Gain Avalanche Diodes, each pixel has dimensions ~ 1.3 × 1.3 × 0.050 mm^3
- Surface & position: 14 m^2, set between tracker and endcap calorimeter



Barrel Timing Layer (BTL):

- |η| < 1.48
- Made of ~ 3.12 × 3.75 × 54.7 mm^3 LYSO:Ce crystals + SiPM detectors
- Position & dimension: R ~115 cm, |z|< 2.6 m

Expected time resolution:

- **30-40 ps** at the beginning of HL-LHC
- **50-60 ps** at the end of HL-LHC

Impact:

- ***Pileup mitigation***: recovering current pileup rejection performance
- ***Beyond Standard Model searches***: extends physics reach, probing models with exotic time signatures

Vertex reconstruction and particle identification

Reconstructed tracks → vertices are reconstructed with Deterministic Annealing clustering algorithm (DA) [4,5] in an **iterative approach**.

DA → vertices in 3D, time computed with DA approach → Carry out particle identification & reassign track times → DA → vertices in 4D → Tracks with PID and time at PCA eventually reassigned

Particle identification (PID) is done by assessing **track time compatibility in space and time** with vertex (z_{vtx}, t_{vtx}):

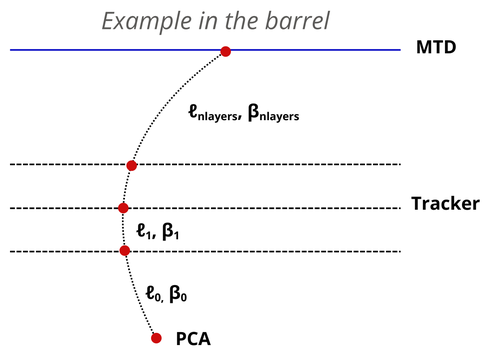
$$\chi^2_{hyp} = \frac{(z_{PCA} - z_{vtx})^2}{\sigma^2_{z_{vtx}}} + \frac{(t_{PCA}(hyp) - t_{vtx})^2}{\sigma^2_{t_{vtx}}}$$

If no match is found, track is assumed to be from a π± & TOF uncertainty is inflated.
Failure of mass assignment (No PID) → if vertex has **no time**, time **uncertainty > 25 ps**, or if: $\frac{(t_{PCA}(hyp) - t_{vtx})^2}{\sigma^2_{t_{vtx}}} > 5$

Track backpropagation

Tracks matched to MTD clusters (with time t_{MTD}) have **time at point of closest approach** (PCA) computed as:

$$t_{PCA}(hyp) = t_{MTD} - \mathrm{TOF}(hyp)$$

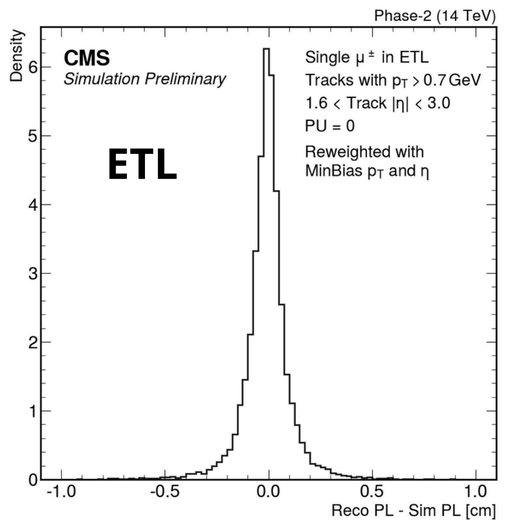


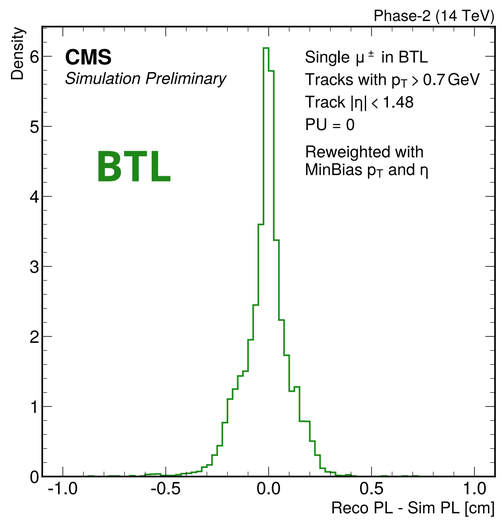
TOF → Time-of-Flight between PCA and MTD, **computed layer-by-layer**, for mass hypothesis *hyp* ($\pi^{\pm}$, $K^{\pm}$, *proton*):

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

Two sources of uncertainty on TOF:

- ***Velocity***: impactful for soft massive particles (e.g. protons) [2]
- ***Path length*** *(PL)*: small impact when compared to MTD time uncertainty [3] NEW





Few millimeters path length resolution ⟷ **Corresponding TOF resolution well below 10 ps →** ***Subdominant when compared to MTD uncertainty***

Different cluster structure between BTL & ETL. Clusters can span several crystals and reach **dimensions of centimeters in BTL**, while most clusters in ETL are **made up of one pixel**.

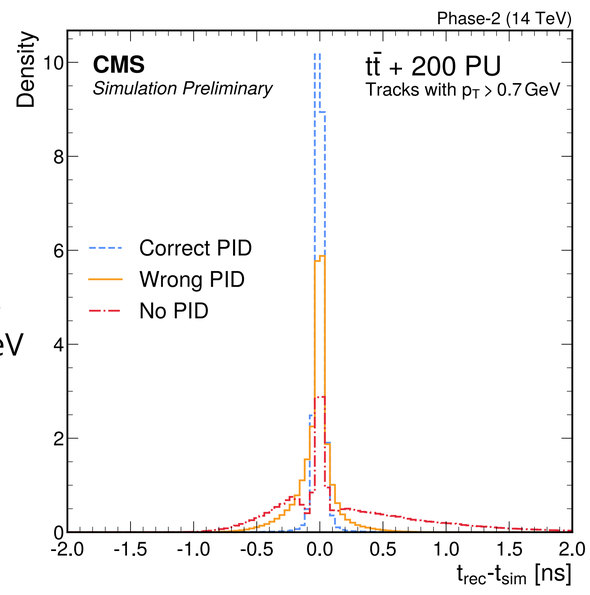
Time at point of closest approach and particle identification performance

PID assigned in last iteration, $t\bar{t}$ sample:

% of tracks	Correct	Wrong	No PID
	~72%	~17%	~11%

- Failure of PID can be due to **low multiplicity vertices** & **wrong track-MTD associations**, happens mainly at soft momenta ~ 0.7 - 2 GeV

Best mass assignment performance is in momentum range ~ 1 - 4 GeV for $K^{\pm}$ and ~ 1 - 8 GeV for protons



Conclusion & next steps

- Path length uncertainty contribution to TOF uncertainty → **well below MTD error**
- Assessment of current PID performance → **good discrimination at low momenta**
- Consider ways to improve PID efficiency
- Study other algorithms to carry out vertex reconstruction

References

- [1] CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*. CERN LHCC-2019-003.
- [2] CMS Collaboration, *Improved use of MTD time in vertex reconstruction.* CMS-DP-2024-048.
- [3] CMS Collaboration, *Track time uncertainties at the point of closest approach computed with MTD.* CMS-DP-2025-037.
- [4] CMS Collaboration, *Update of the vertex reconstruction using track time from MTD.* CMS-DP-2024-085.
- [5] K. Rose, *Deterministic Annealing for Clustering, Compression, Classification, Regression and related Optimisation Problems.* Proc. IEEE 86 (1998) 2210.