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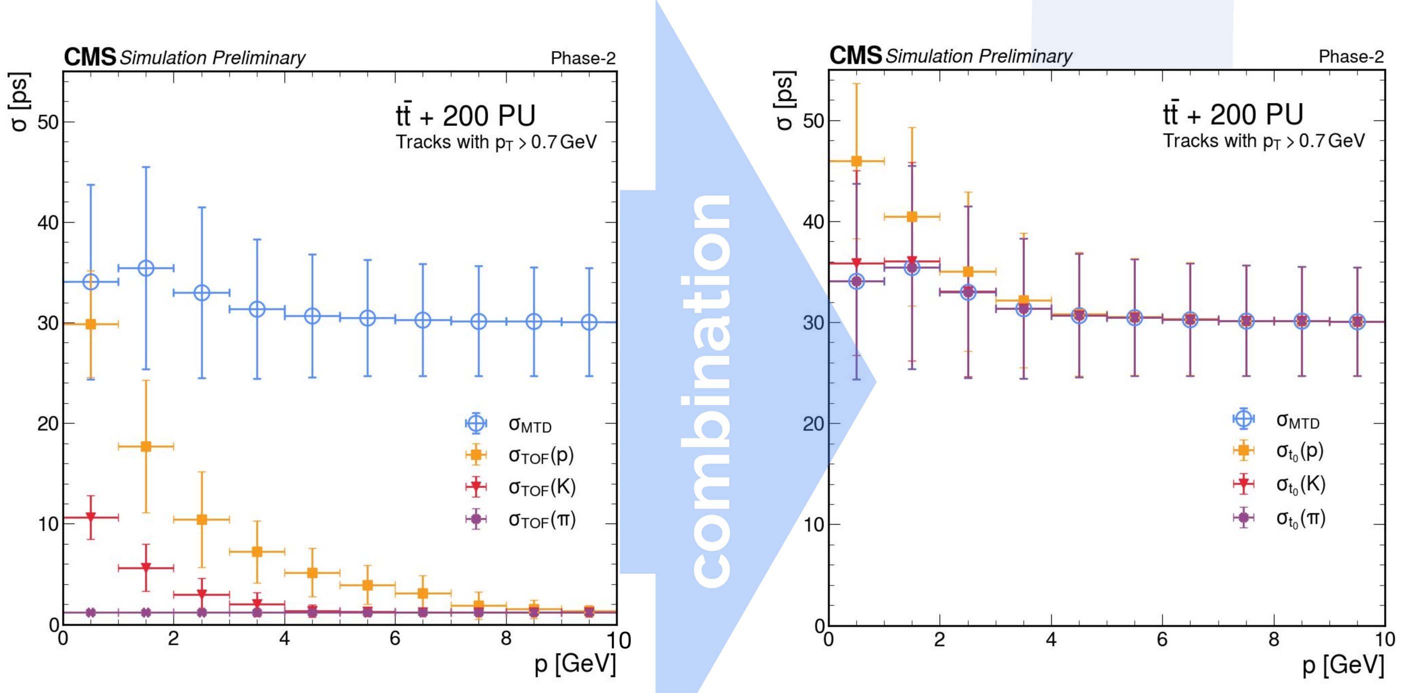
Track backpropagation

- MTD measures **time of arrival** of charged particles with a precision of σ_{MTD} **~ 30-40 ps**.
- Given its momentum, the track is **backpropagated** to the **beamline** by computing **time of flight** (TOF) under a **given mass hypothesis**:

$$t_0(\pi, K, p) = t_{\mathrm{MTD}} - \mathrm{TOF}(\pi, K, p)$$

- This introduces additional **mass-dependent** source of uncertainty σ_{TOF}:

$$\sigma_{t_0}(\pi, K, p) = \sqrt{\sigma^2_{\mathrm{MTD}} + \sigma^2_{\mathrm{TOF}}(\pi, K, p)}$$



! σ_{TOF} ~ $\mathcal{O}$ **(10 ps)** comparable to $\sigma(t_{MTD})$ for **heavy**, **low momentum** particles (protons with p < 2 GeV).

Vertex reconstruction

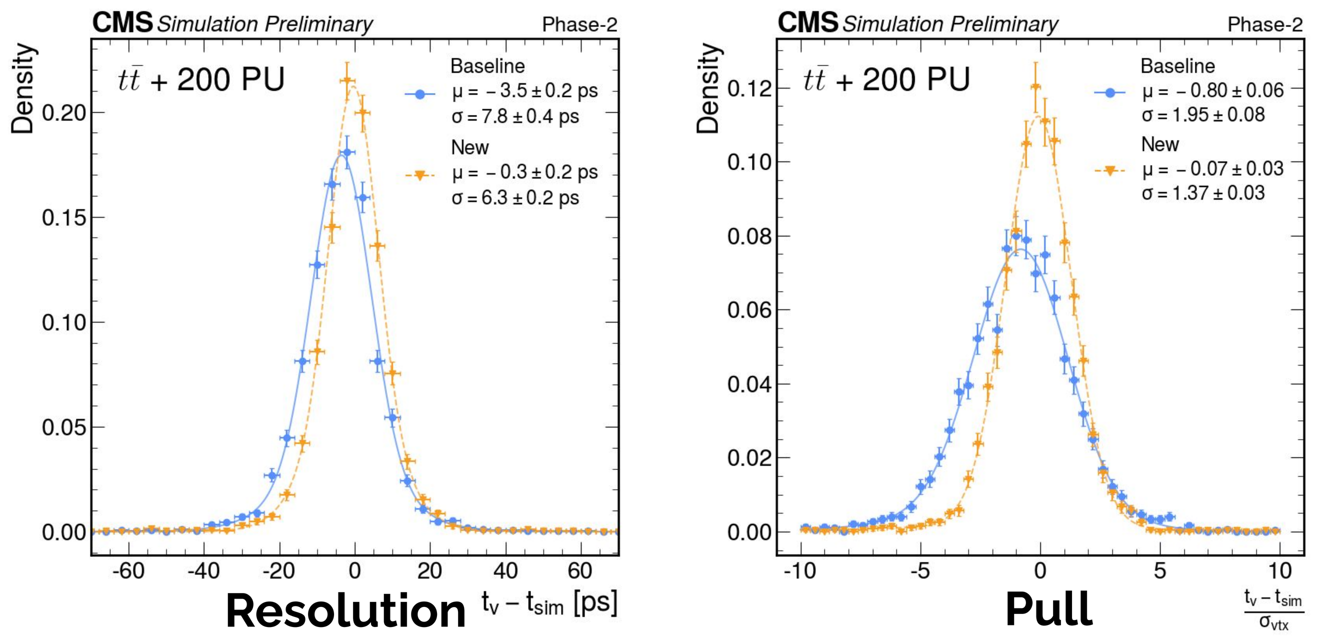
- Tracks are **clustered** to construct **vertices** given **beamline times** and **positions**.
- **However, how do we deal with track mass assignment?**
  - **Baseline**: take the *most likely* hypothesis; compute t_v as weighted average:

$$t_v = \frac{\sum_{\mathrm{tracks},i} w_i\, t_{0,i}(\pi, K, p)}{\sum_{\mathrm{tracks},i} w_i} \quad \text{with } w_i = \frac{1}{\sigma^2_{t_0,i}(\pi, K, p)}$$

  - **New**: consider *all* mass hypotheses weighted by compatibility with candidate vertex); t_v from **deterministic annealing** on appropriate cost function, hence, at last iteration n:

$$t_v = \frac{\sum_{\mathrm{tracks},i} \sum_{\mathrm{hp}} w_i(\mathrm{hp})\, t_{0,i}(\mathrm{hp})}{\sum_i \sum_{\mathrm{hp}} w_i(\mathrm{hp})} \quad \text{with } w_i(\mathrm{hp}) = \frac{\overbrace{\alpha_{\mathrm{hp}}}^{\text{prior probability}} \exp\left(-\chi^2_{i,\mathrm{hp}}\right)}{\underbrace{Z}_{\text{normalization}}} \times w_i^{\mathrm{3D}} \times \frac{1}{\sigma^2_{t_0,i}(\mathrm{hp})}$$

$$\chi^2_{i,\mathrm{hp}} = \frac{(t_{0,i}(\mathrm{hp}) - t_v^{(n-1)})^2}{\sigma^2_{t_0,i}(\mathrm{hp})}$$

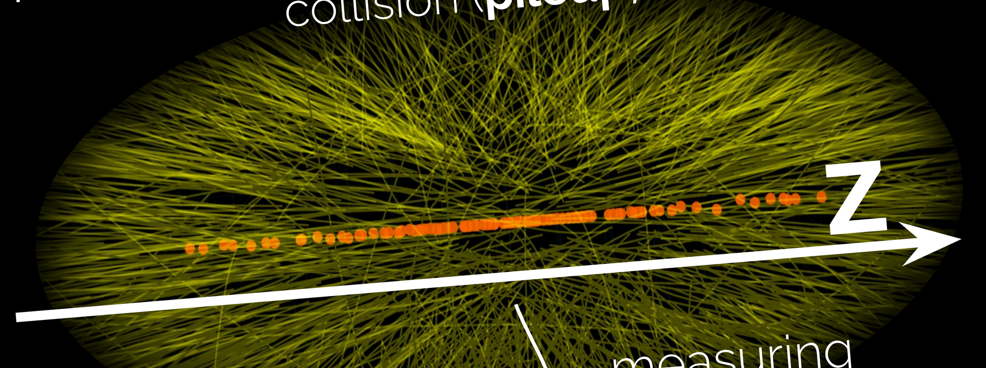


! New vertex time algorithm improves both **resolution** (now about **6 ps**) and **bias** (now compatible with 0), as well as reducing pull width.

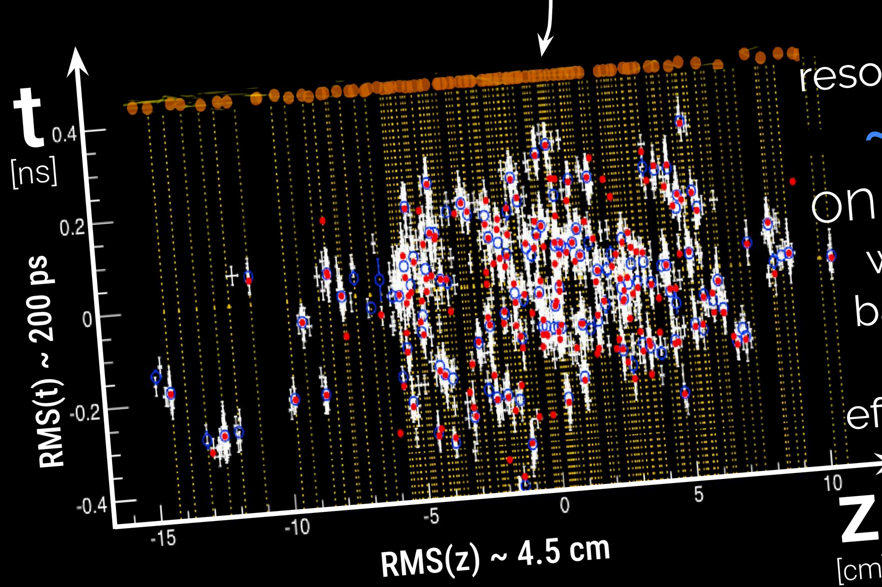
References: [1] CMS-TDR-020, "A MIP Timing Detector for the CMS Phase-2 Upgrade"; [2] CMS-DP-2022-025, "Update of the MTD physics case"; [3] CMS-DP-2024/048, "Improved use of MTD time in vertex reconstruction"

TOWARDS A **PRECISE** MEASUREMENT OF PARTICLES **TIME-OF-FLIGHT** WITH THE

During the High-Luminosity phase of LHC, we expect approximately **200 simultaneous interactions** per collision (**pileup, PU**)

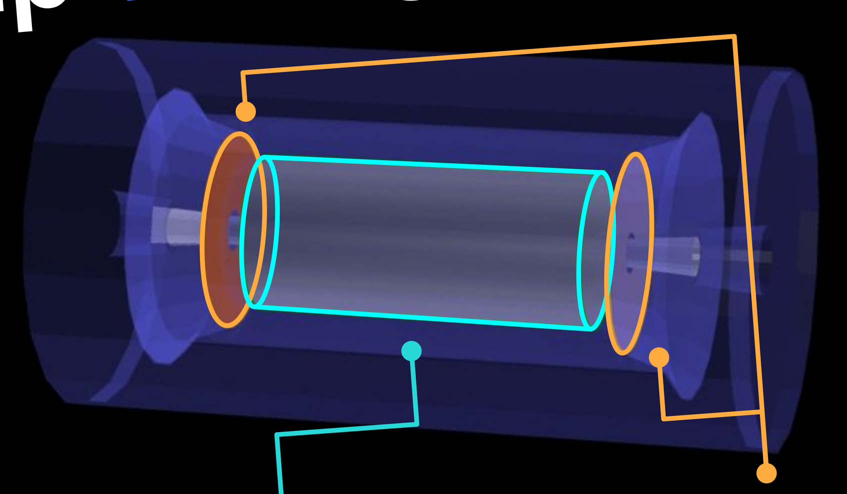


measuring **vertex time**



With a resolution of **~30 ps** on **tracks** we can go back to the current effective PU level

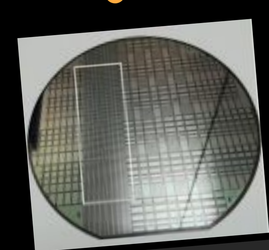
Mip Timing Detector



Barrel Timing Layer

LYSO crystals + SiPM

Endcap Timing Layer



Low Gain Avalanche Photodiodes

The CMS experiment will introduce the new MTD detector between the tracker and the electromagnetic calorimeter, measuring the **time of arrival of charged particles** with the required accuracy.

NEW **MIP TIMING DETECTOR** FOR THE **CMS** EXPERIMENT

PID is used for...

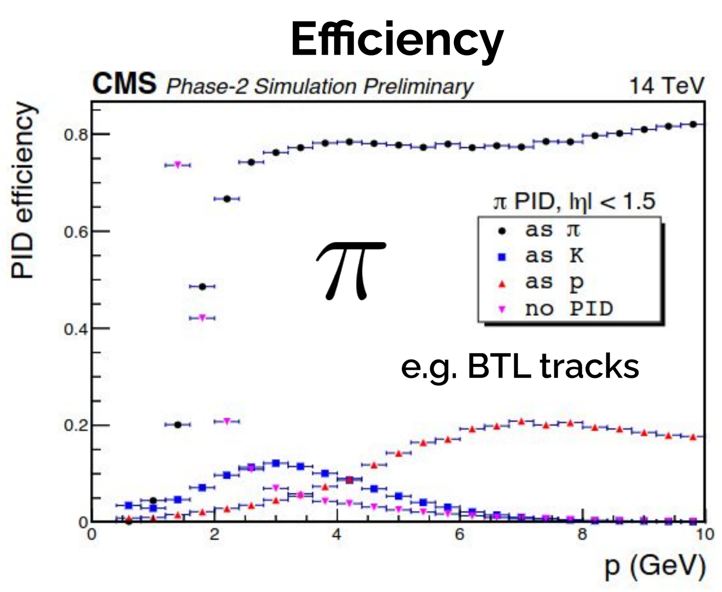
Time is used for...

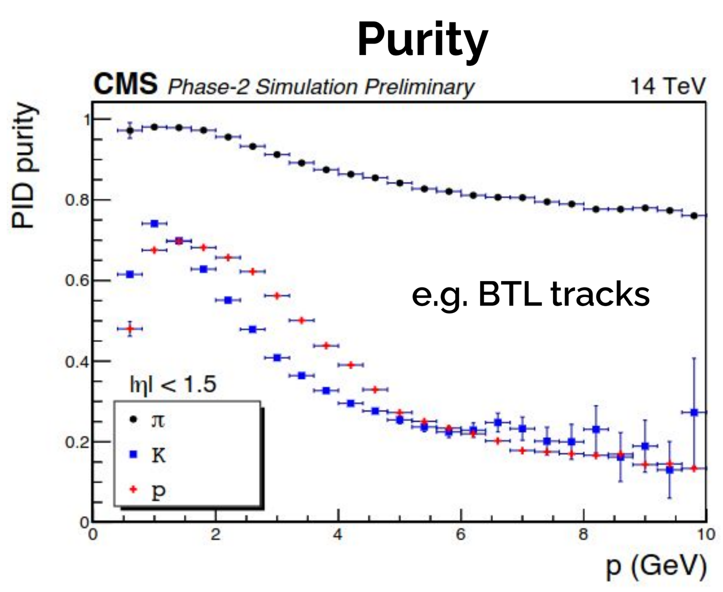
Food for thought

Current PID based on χ^2 **cuts**: many **possible developments**!

Particle identification (PID)

For each track, mass assignment done based on best **space-time compatibility** with the assigned **vertex time** evaluating χ^2 for **pion**, **kaon** and **proton** hypotheses:





! **Particle identification** is **iteratively connected** to **vertex reconstruction**; with this procedure, we can reach up to **80% efficiency** and **purity** on **pions, kaons and protons**, depending on momentum.

💡 Use variables from other detectors (e.g. particle **dE/dx** information from tracker)

💡 Pursue alternative **modern computational techniques** – possible synergy with time usage in vertex reconstruction

Physics case : Heavy Stable Charged Particle (HSCP) search

MTD can directly measure **particle velocity** β. Standard Model particles are typically produced with $\beta \sim 1$; we are thus sensitive to exotic massive particles, which could be detectably slower.

x4 **signal acceptance** in a **HSCP stau** benchmark model with M = 432 GeV!