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Big Data and Quantum Computing

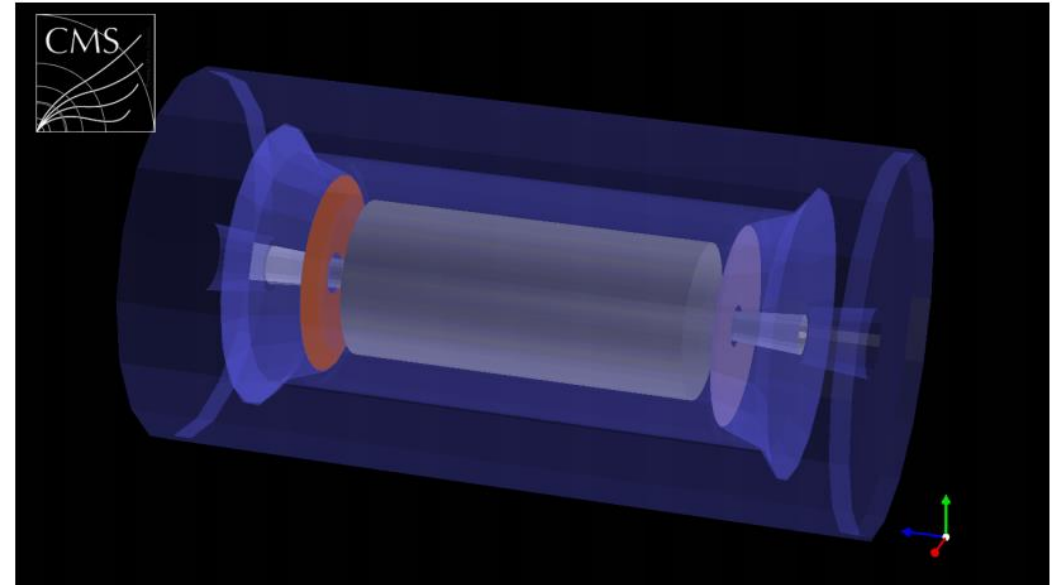
Optimal use of timing measurement in vertex reconstruction at CMS

Ksenia de Leo for the CMS Collaboration
INFN Trieste

ICSC Spoke 2, Catania, 11 December 2024

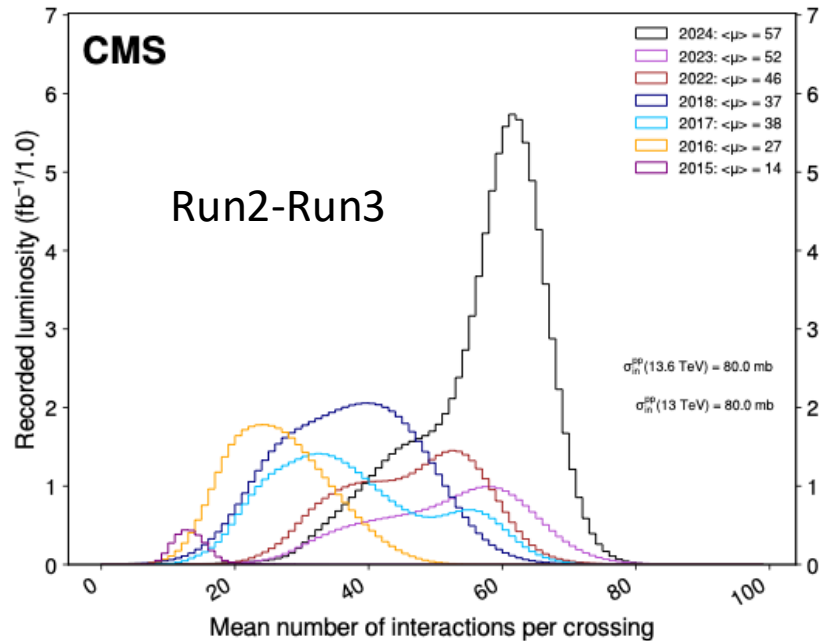
Outline

- HL-LHC
- Mip Timing Detector
- 4D vertex reconstruction
- Update of the 4D algorithm
- Performace study of:
 - vertex time resolution
 - reconstruction efficiency
 - pileup rejection

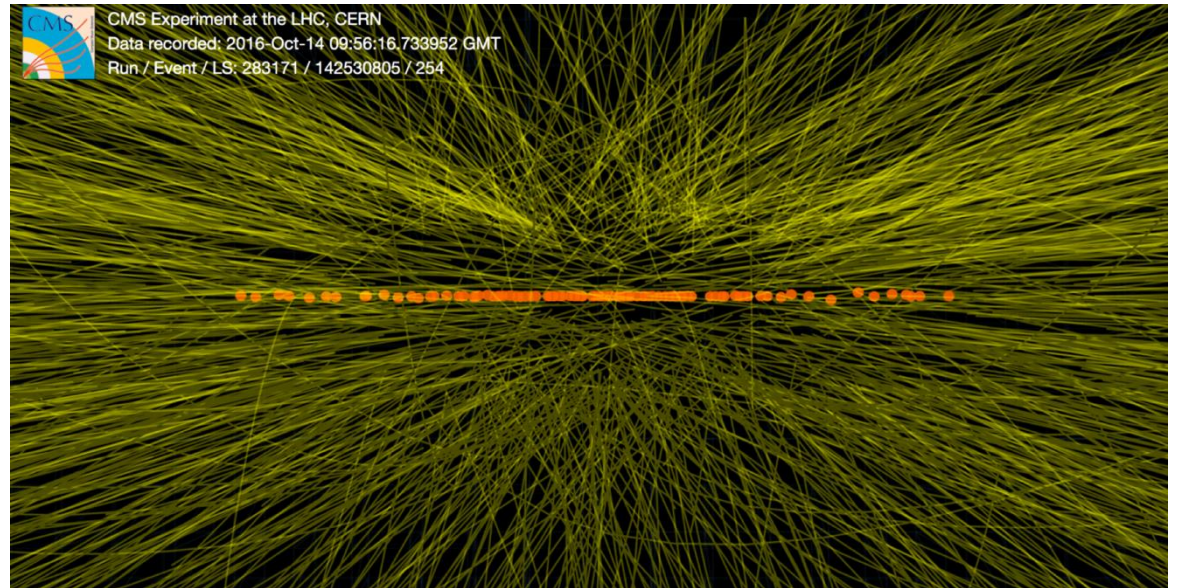


HL-LHC

- **High-luminosity** LHC era (HL-LHC) starting in ~2030 → precise measurements of the Standard Model and searches for new physics
- Higher instantaneous luminosity → **higher** number of **pileup** (PU) interactions $\langle \text{PU} \rangle = 140-200$
- Crucial to isolate **interaction of interest** and mitigate **effects of PU** on object reconstruction
- How? **Track-vertex association**



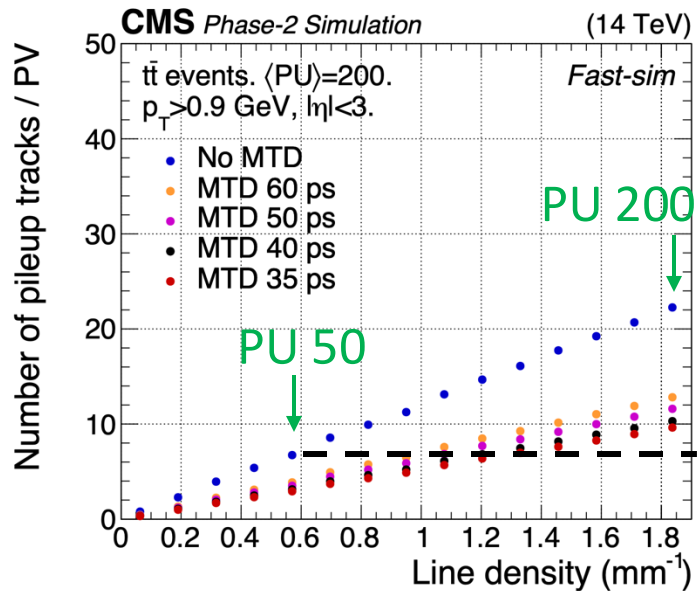
[CMS Luminosity - Public Results](#)



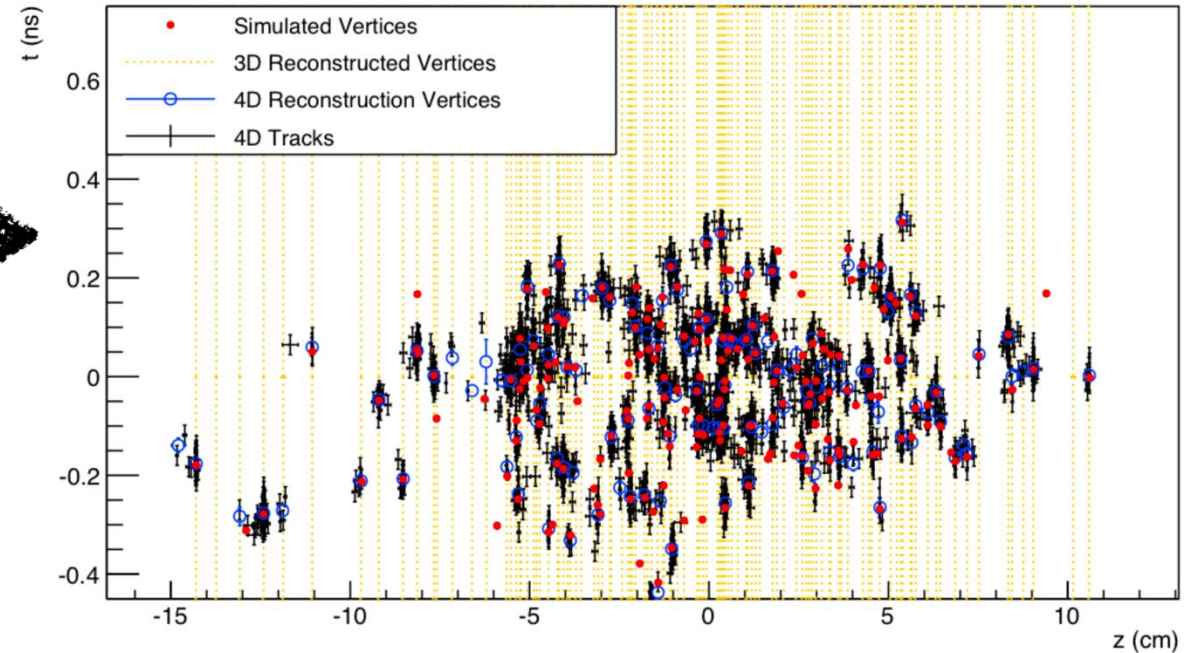
~130 pp collisions - recorded by CMS in 2016 during a high PU run

Precision timing at CMS in HL-LHC

- Use timing information to **separate vertices** that **overlap in space**
- Modern detector technologies allow **~30 ps time resolution** → smaller than the pp collision spread in time of 180-200 ps (longitudinal spread around 5 cm)
- Possible effective separation!



[CMS MTD Technical Design Report](#)



[CMS MTD Technical Design Report](#)

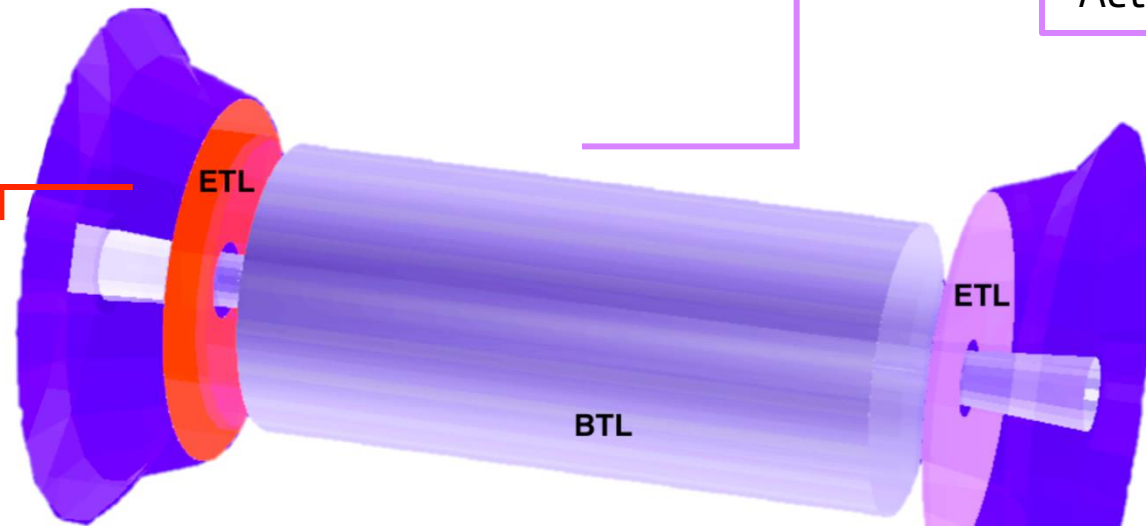
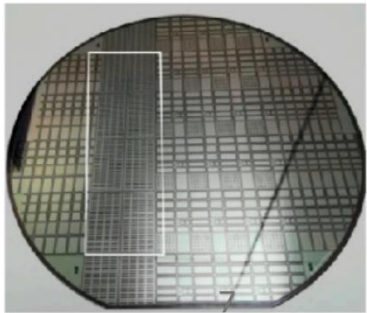
From 3D to 4D vertex reconstruction
 → effective PU as in Phase-1

Mip Timing Detector

- Mip Timing Detector (MTD) [[CMS MTD Technical Design Report](#)] to measure time of charged particles
- Placed between tracker and calorimeter
- Almost hermetic coverage with $|\eta| < 3$

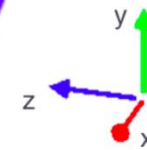
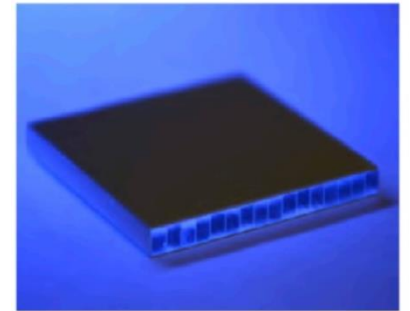
Endcap Timing Layer (ETL)

- LGADs
- $1.6 < |\eta| < 3$
- Active area $\sim 14 \text{ m}^2$



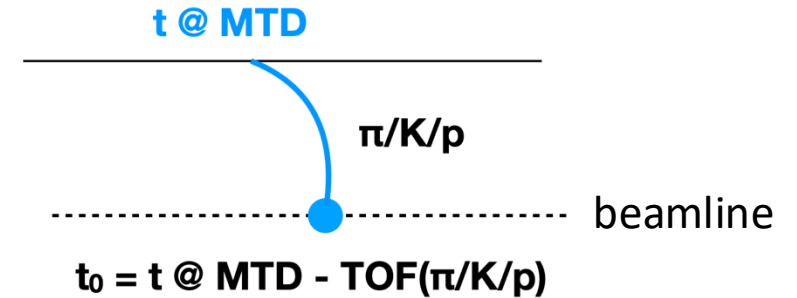
Barrel Timing Layer (BTL)

- LYSO bars + 2 SiPM/bar
- $|\eta| < 1.45$, $p_T > 0.7 \text{ GeV}$
- Active area $\sim 38 \text{ m}^2$

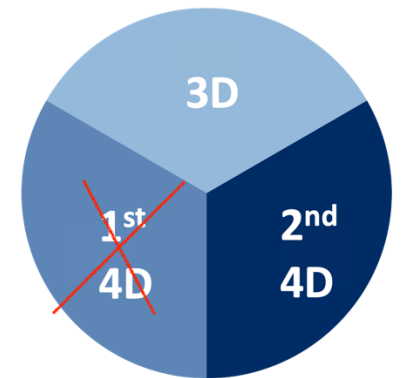


4D vertex reconstruction in a nutshell

- **4D vertex reconstruction** and particle identification (**PID**) go hand by hand
- So far **2 steps** of vertex reconstruction in **legacy 4D** algorithm:
 - 1st iteration:
 1. reconstruct vertices using π *hypothesis* - with inflated uncertainty $\Delta(\text{TOF}_p - \text{TOF}_\pi)$
 2. calculate vertex time
 3. perform PID
 - 2nd iteration:
 1. reconstruct vertices using *updated track times* - remove inflated uncertainty
 2. calculate vertex time
 3. perform PID
- The **updated 4D** algorithm replaces the first iteration with the 3D vertices:
 - Possible thanks to time computation available for 3D vertices as well
- Possible to **reduce** the vertex reconstruction **CPU time** of 30% without loss in performance



RecoVertex
~ 10% of RECO time



Vertex time computation

- In **legacy 4D**: compute time using only the mass hypothesis assigned after PID with a simple **weighted average**

$$t_{\text{vtx}} = \frac{\sum_i \frac{1}{\sigma_{t,i}^2} \cdot t_i}{\sum_i \frac{1}{\sigma_{t,i}^2}}$$

t_i = track time
 $\sigma_{t,i}$ = track time uncertainty

- **New**: time computed with a **deterministic annealing (DA) time algorithm** using all 3 mass hypothesis, minimizing the cost function:

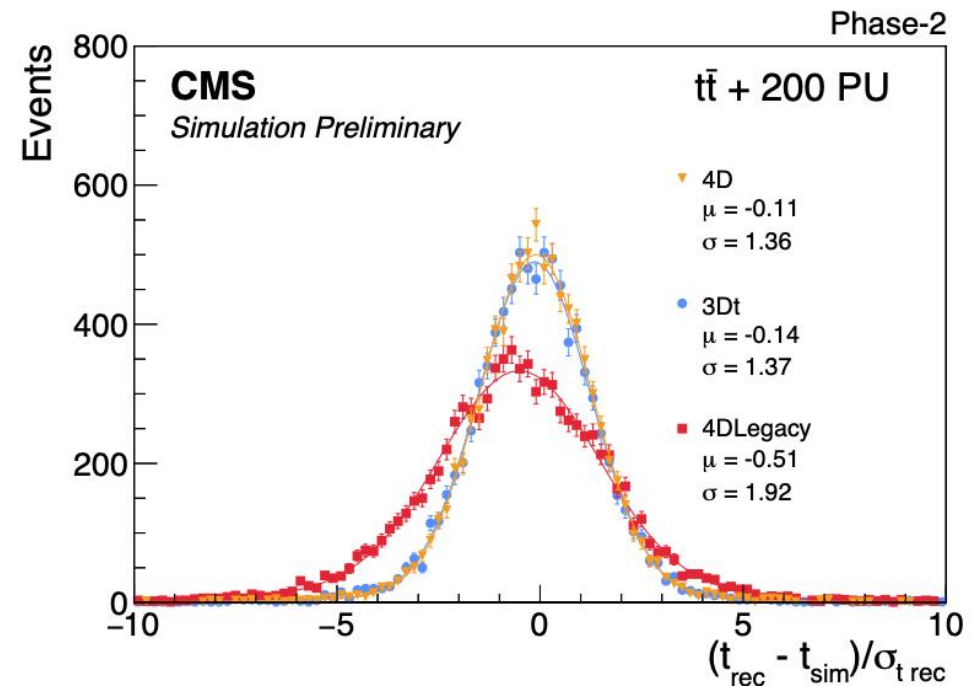
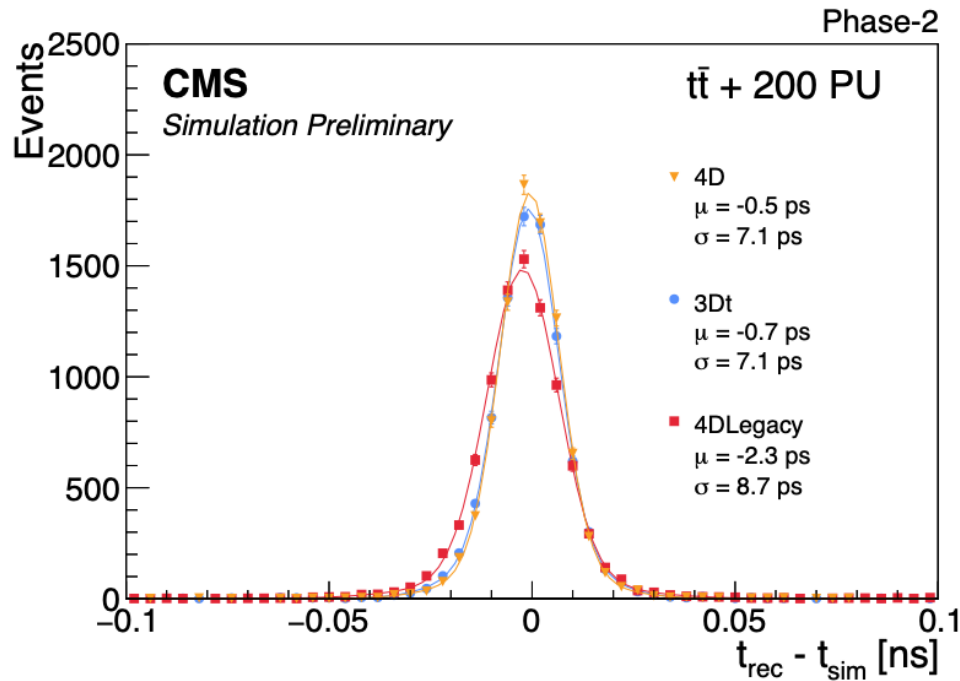
$$F = -T \sum_{\text{tracks},i} w_{0,i} \log \left(Z_0 + \alpha_{\pi} e^{-\frac{(t_i(\pi) - t_v)^2}{2T\sigma_{t,i}^2(\pi)}} + \alpha_K e^{-\frac{(t_i(K) - t_v)^2}{2T\sigma_{t,i}^2(K)}} + \alpha_p e^{-\frac{(t_i(p) - t_v)^2}{2T\sigma_{t,i}^2(p)}} \right)$$

$w_{0,i}$ = track weight from adaptive vertex fit
 $t_i(\pi, K, p)$ = track time for π, K, p
 $\sigma_{t,i}(\pi, K, p)$ = track time uncertainty for π, K, p
 $\alpha_{\pi, K, p}$ = a priori probability for π, K, p (0.7,0.2,0.1)

- This algorithm can be applied to a reconstructed vertex regardless of the use of time in its clustering and fitting:
 - **3Dt** vertex with the DA time calculation
 - **updated 4D** with the DA time calculation in 2nd step

Signal vertex time

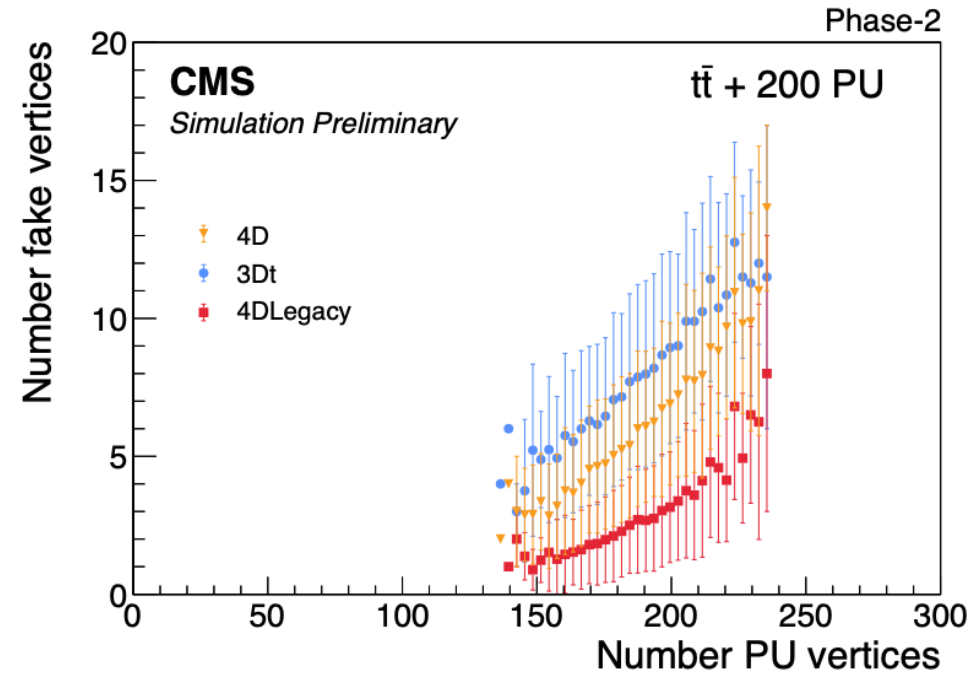
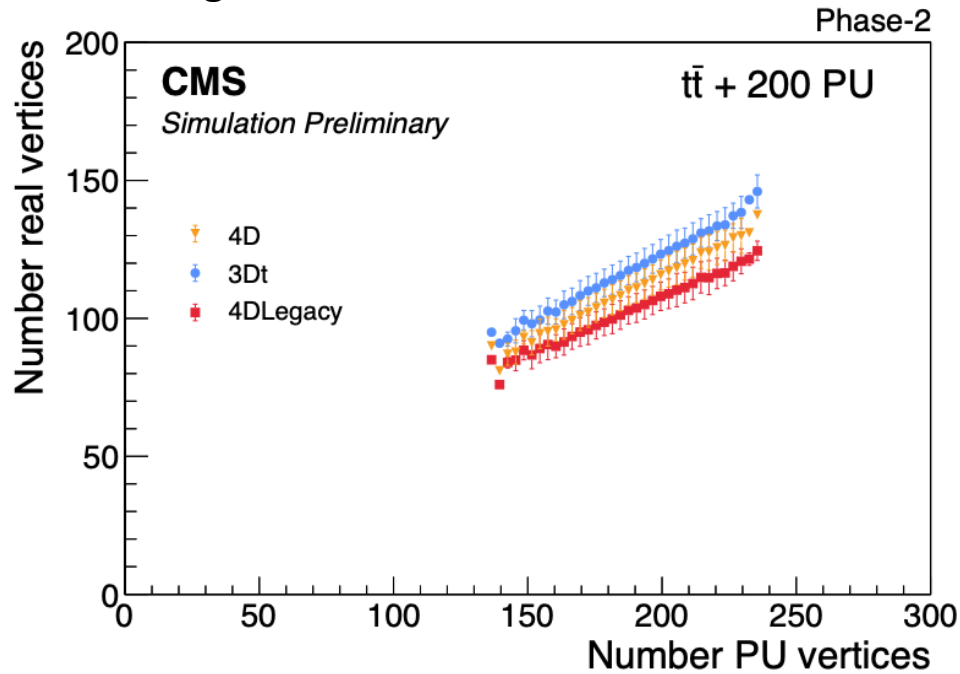
- The vertex **time resolution** and **pull** for signal vertices, the distributions are fitted with a double Gaussian: the parameters shown refer to the narrowest one
- The updated **4D** and **3Dt** algorithms show an **improvement** in time **resolution** and **pull** wrt the **legacy 4D** algorithm
- The negative **bias** in **legacy 4D**, due to possible misassignment to K/p hypothesis, is **reduced** in the **3Dt** and updated **4D** thanks to time computation always accounting for all mass hypotheses



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Number of vertices

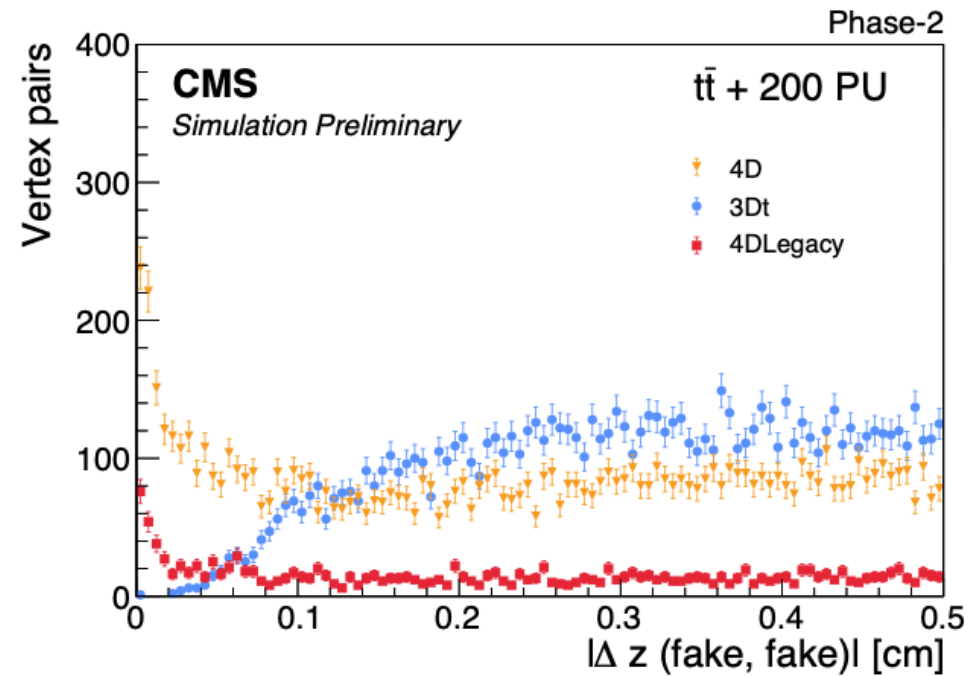
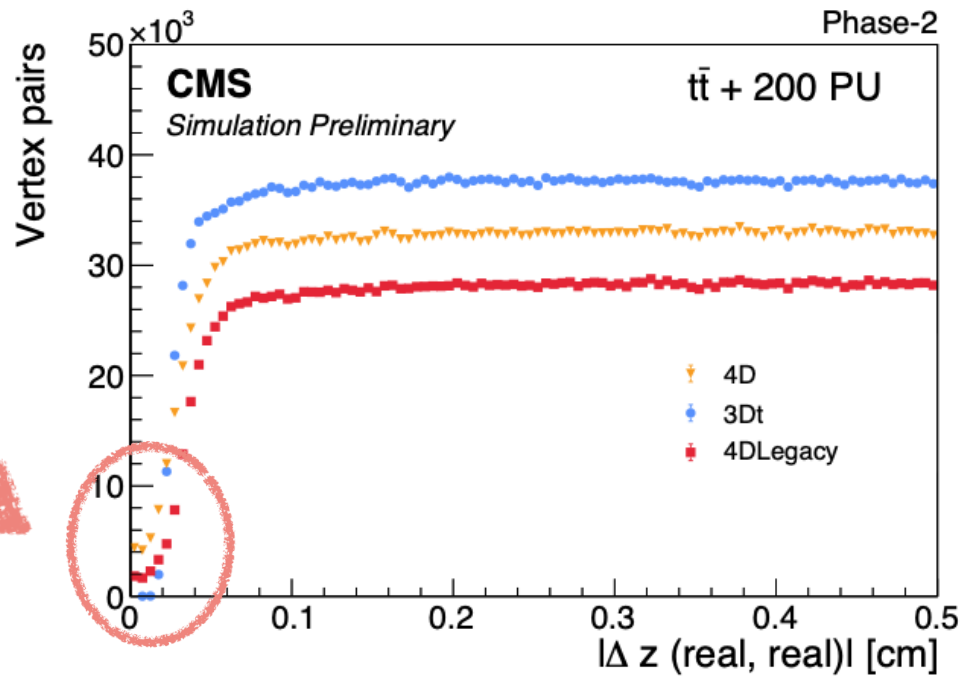
- The number of reconstructed vertices as a function of the number of PU vertices for **real** and **fake** vertices
- Classification based on **matching to MC truth** - both true tracks and vertices (details in [backup](#))
- The **3Dt** reconstructs more real vertices, but also more fakes
- The updated **4D** algorithm shows a **higher number of vertices** than the legacy, with a performance in between the **4D legacy** and the **3Dt** algorithms



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Distance in z

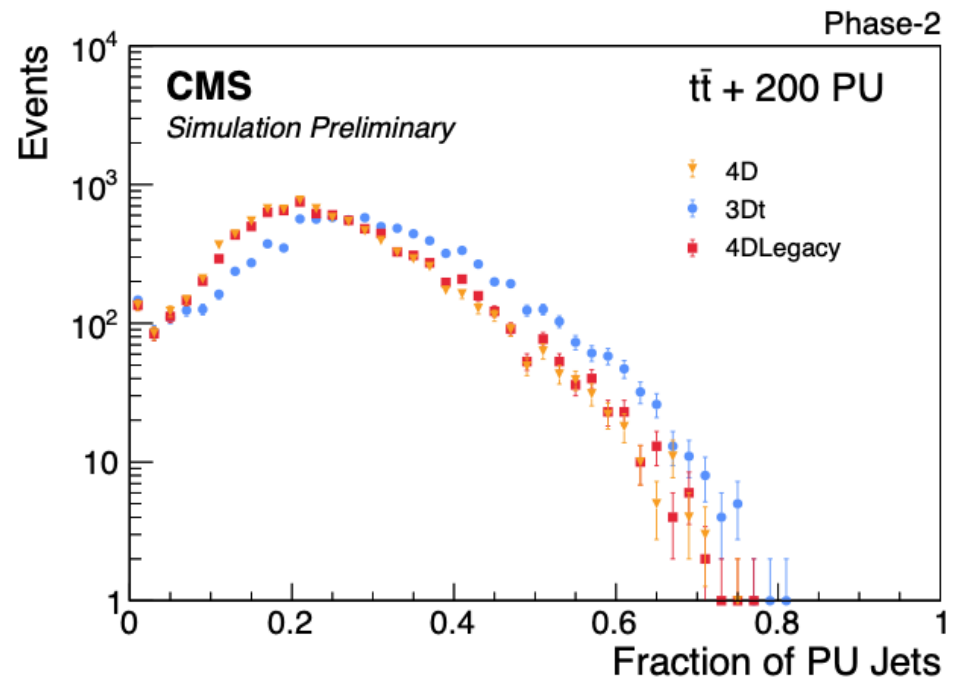
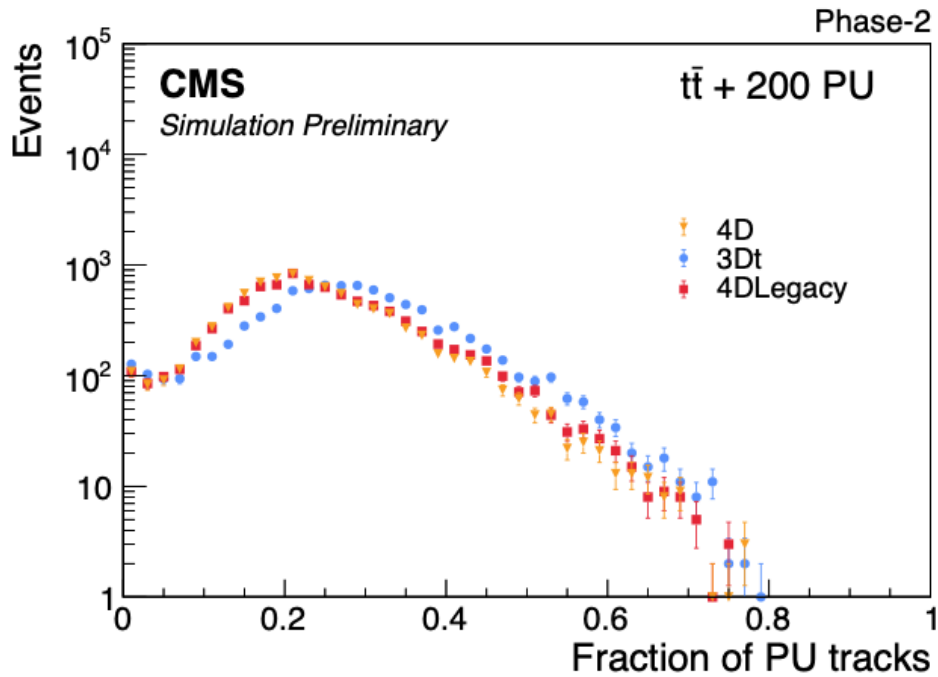
- Distance between pairs of reco vertices: the updated **4D** algorithm shows more real-real vertex pairs close in z than **legacy 4D**, but also more fakes
- The **3Dt** algorithm is not designed to reconstruct vertices with separation less than ~ 0.3 mm
- The **improvement** in the new algorithm is visible especially for **real vertex pairs with Δz close to 0**
- Advantage in the use of **timing**: vertices that overlap in space can be separated in time



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Pileup contamination for the leading vertex

- Compare vertex algorithms in terms of **PU rejection**
- **Tracks** associated to a reco vertex are classified based on MC truth matching as: fake, from primary vertex, from secondary vertex or PU tracks
- **Jet observables**: cluster jets from charged tracks from same reco vertex, with/without PU tracks
- A **reduction** in the **PU contamination** of ~10/15% can be seen in the **4D algorithms** with respect to the **3Dt** one



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Conclusions

- The timing information of **MTD** is important to **mitigate** the effects of **PU** in HL-LHC
- A set of tools has been developed for evaluating the performance of different vertex reconstruction algorithms in terms of:
 - Vertex **time resolution**
 - Number of reconstructed **true** and **fake** vertices
 - **PU rejection**
- They serve as benchmark for future developments and exploration of new techniques
- The optimization of the **4D** vertex reconstruction is presented
- The results highlight the advantage in the use of **timing**:
 - **vertices overlapping in space can be separated in time improving PU rejection**



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BACKUP

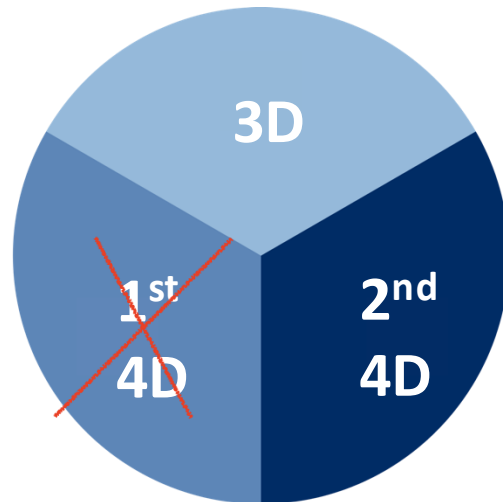
References

- [1] CMS Collaboration, "A MIP Timing Detector for the CMS Phase-2 Upgrade", technical report, CERN, Geneva, 2019.
- [2] CMS Collaboration, "Update of the vertex reconstruction using track time from MTD", CMS DP-2024-085 (2024).

The updated 4D algorithm

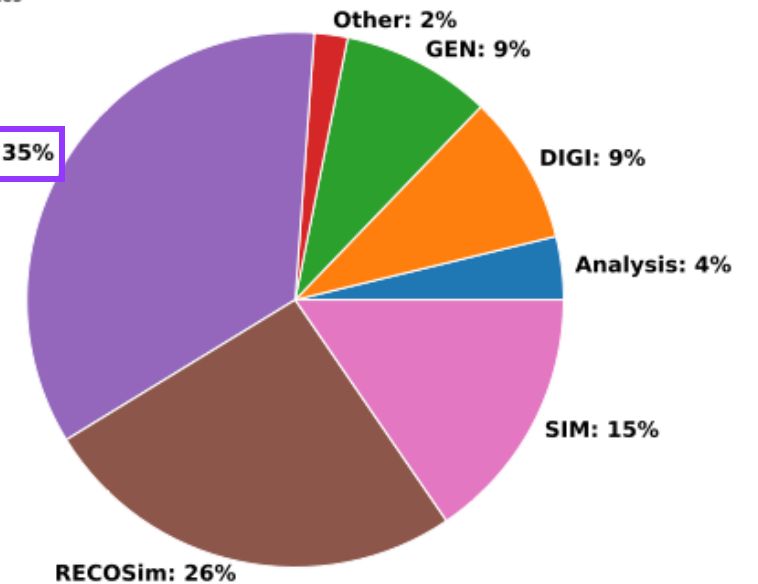
- The **updated 4D** algorithm [[CMS-DP/2024-085](#)] replaces the 1st step of **legacy 4D** with 3D vertices:
 - Possible thanks to **time** computation available for 3D vertices as well (**3Dt**)
 - **Reduce** the vertex reconstruction **CPU-time** by 30% without loss in performance
- The **time computation algorithm** is updated
 - **Improved** vertex time resolution, pull and bias

RecoVertex ~10%
of RECO time



Each vertex reco step
~same CPU-time
→ also with new time computation

CMS Public
Total CPU HL-LHC (2031/No R&D Improvements) fractions
2022 Estimates



HL-LHC projections
[CMS Offline and Computing - Public Results](#)

Vertex association to MC truth

To evaluate the performance of the vertex reconstruction, an algorithm has been developed to **match reconstructed vertices to MC truth**, based on the common origin of tracks in the reconstructed and simulated vertices. The reconstructed tracks are matched to the true simulated charged particles, and the simulated vertices from which they originate define the set of true primary vertices in the event. The matching algorithm is based on the sum of weights:

$$W_{os} = \frac{w_{trk}}{\sigma_{z,trk}^2} \frac{1}{\text{erf}(\sigma_t/\sigma_T)}$$

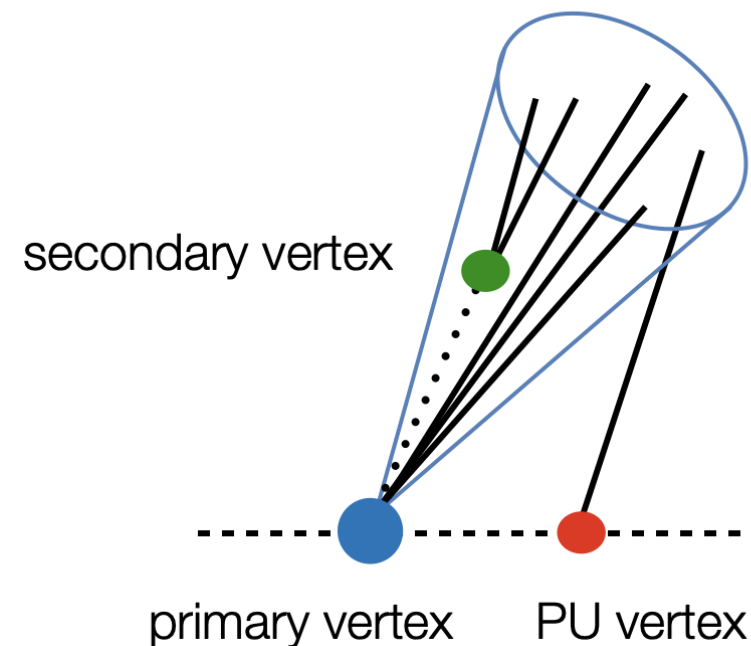
where w_{trk} is the weight assigned by the adaptive vertex fit, $\sigma_{z,trk}$ the track resolution, σ_t the track time uncertainty and σ_T the time width of the beamspot. The time dependent part is present only for tracks with time information.

A **one-to-one matching** is performed: for a given reconstructed vertex, the dominating simulated vertex is the one with largest sum of W_{os} . Whenever possible, the dominating simulated vertex is matched to the reconstructed one. If a simulated vertex dominates more than one reconstructed vertex, the match is made between that simulated vertex and the reconstructed one that receives the largest weight among the dominated reconstructed vertices. The algorithm proceeds in an iterative manner for all the reconstructed vertices. Depending on the outcome of the algorithm, vertices are classified as:

- **real**: a good matching is found within the maximum allowed number of iterations (set to 8),
- **fake**: no matching can be found, meaning that there is no simulated vertex dominating the reconstructed vertex that does not dominate other vertices more.

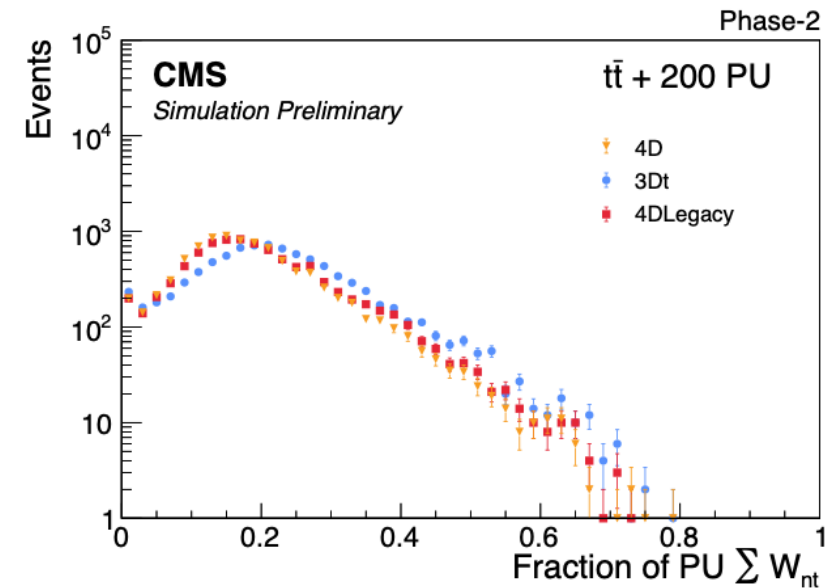
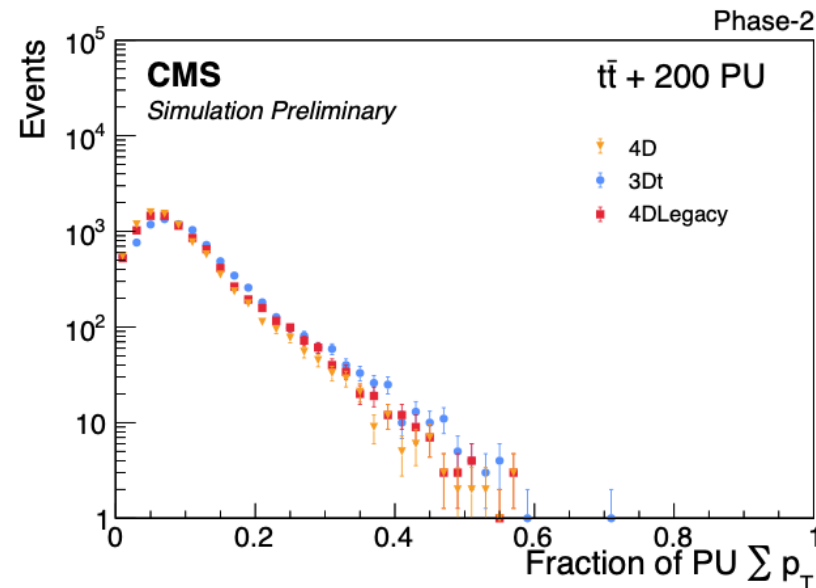
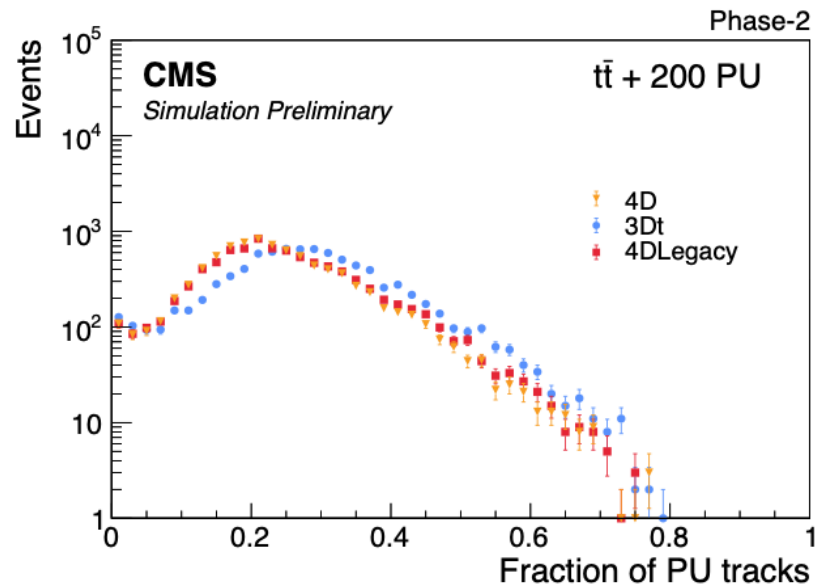
Pileup contamination

- Compare vertex algorithms in terms of **PU rejection**:
 - crucial for object reconstruction in HL-LHC
 - primary goal of MTD
- Monitor **track-based** and **jet-based** observables
- **Tracks** associated to a reconstructed vertex are classified based on MC truth matching as:
 - Track from primary vertex
 - Track from secondary vertex
 - PU track
 - Fake track, not matched to any true particle
- **Jets** are built by clustering reconstructed charged tracks originating from the same vertex
- The relative **contribution of PU** to jet-based quantities is estimated by clustering jets without the PU tracks and recomputing the observables



Pileup contamination – track observables

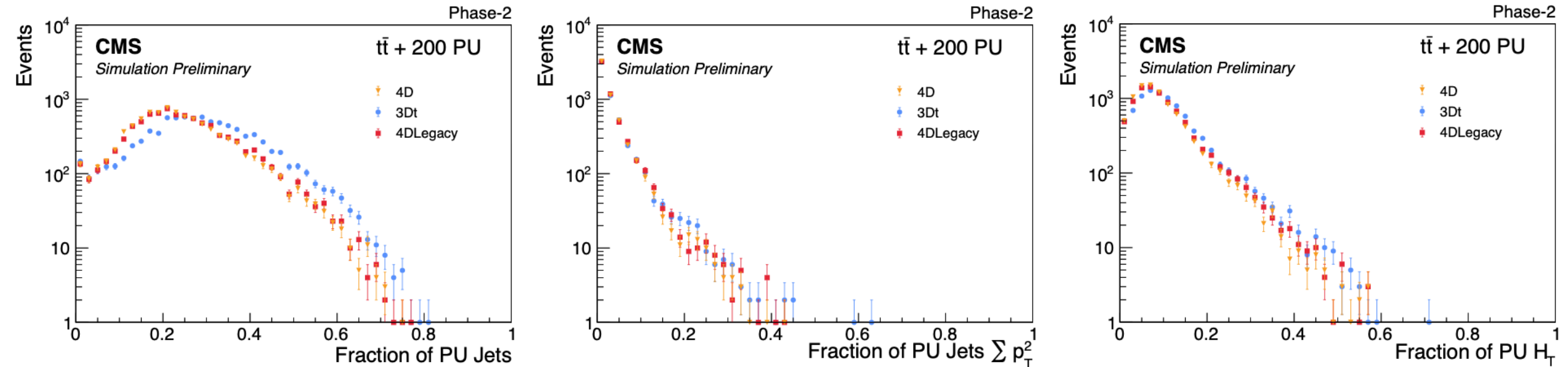
- Impact of PU on track multiplicity, sum of track p_T and $\sum_{trk} W_{nt}^{trk} = \sum_{trk} w_{trk} \times \min(p_{T,trk}, 1)$, the sum of weights of tracks, where low momentum tracks are downgraded, an auxiliary weight in the matching algorithm
- A **PU reduction** of ~10/15% can be seen in the **4D algorithms** with respect to the **3Dt** one



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Pileup contamination – jet observables

- Impact of PU on jet multiplicity, sum of p_T^2 of jets and H_T , the sum of the transverse energy of jets
- A **PU reduction** of ~10/15% can be seen in the **4D algorithms** with respect to the **3Dt** one in some variables, while the sum of jet p_T^2 , used in the jet sorting, is insensitive to the vertex reconstruction algorithm



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