Primary vertex time reconstruction using the LHCb RICH detectors

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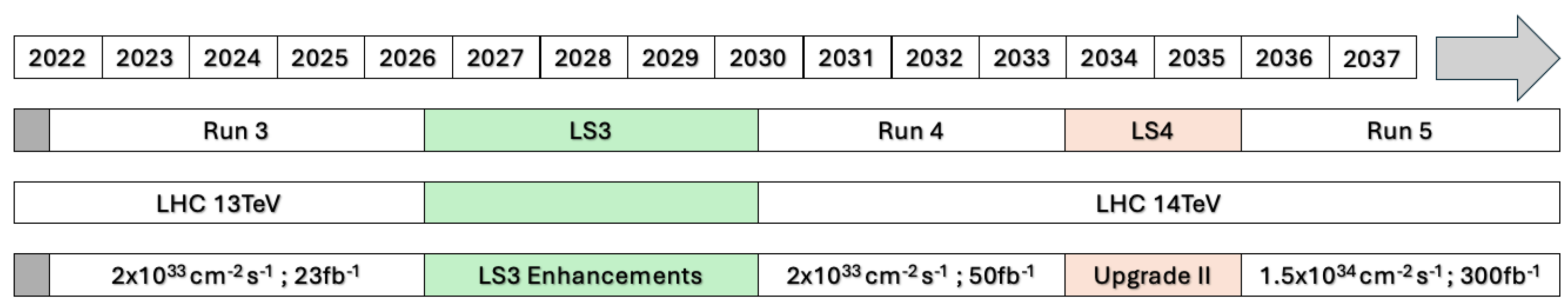
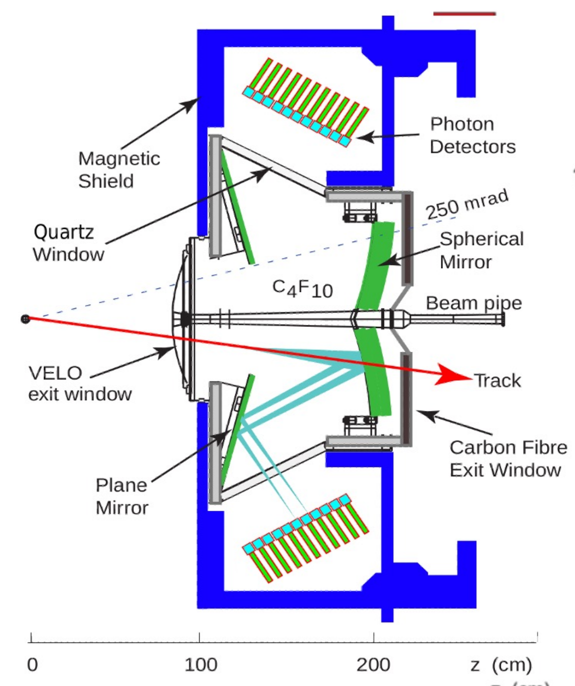
1. Introduction and motivation

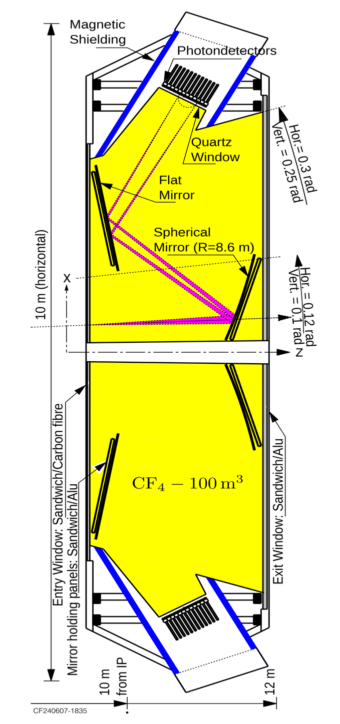
During LHC High-Luminosity phase, the LHCb RICH detector will face challenges due to increased particle multiplicity and pile-up of hits in the photon detector. Introducing sub-100 ps time information is crucial to maintaining excellent particle-identification (PID) performance. The LHCb RICH collaboration will introduce timing during the LS3 Enhancements [1], using a new front-end electronics readout chain based on the FastRICH ASIC [2], capable of timestamping photon detector hits with ~25ps time bins.

- Improved PID performance during Run 4.
- New fast-timing perspective to LHCb including a primary vertex (PV) time estimate during Run 4.
- Introduction of technologies for high-luminosity operation ahead of Upgrade II.
  - New photodetectors for the RICHs.
  - PV time from tracking.





RICH 1

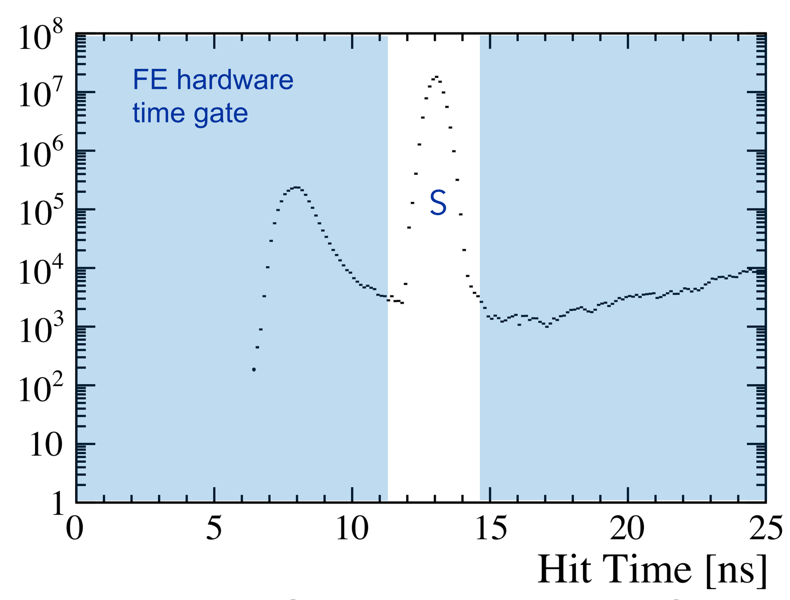


RICH 2

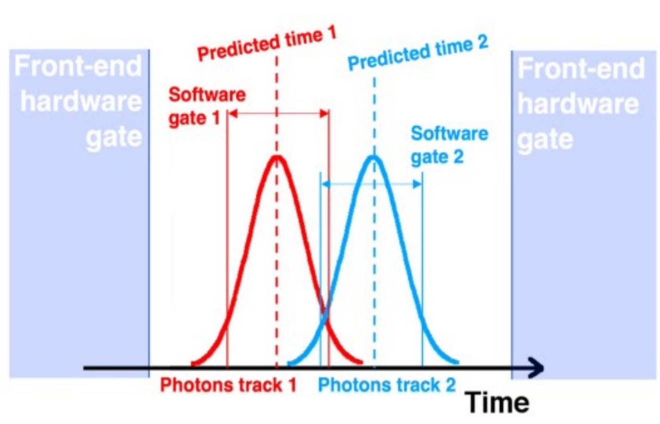
2. The time information in the RICH detectors

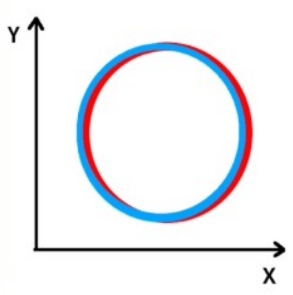
Cherenkov photons from a given track arrive almost simultaneously to the photodetector plane. However, photon time-of-arrival ('S') for multiple bunch crossings is spread across a few nanoseconds, mainly due to the PV time spread.

Without event reconstruction, the best time-based filtering is a nanosecond-scale time shutter around the expected RICH detector hit time.



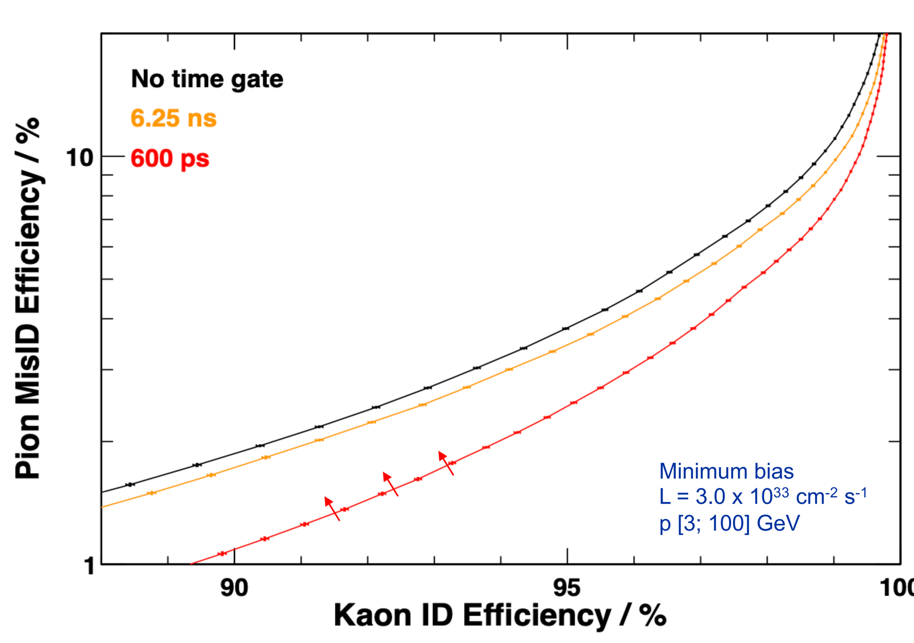
Using the RICH reconstruction, for a given PV time, the photon hit time can be predicted with sub-10 ps precision. [3]





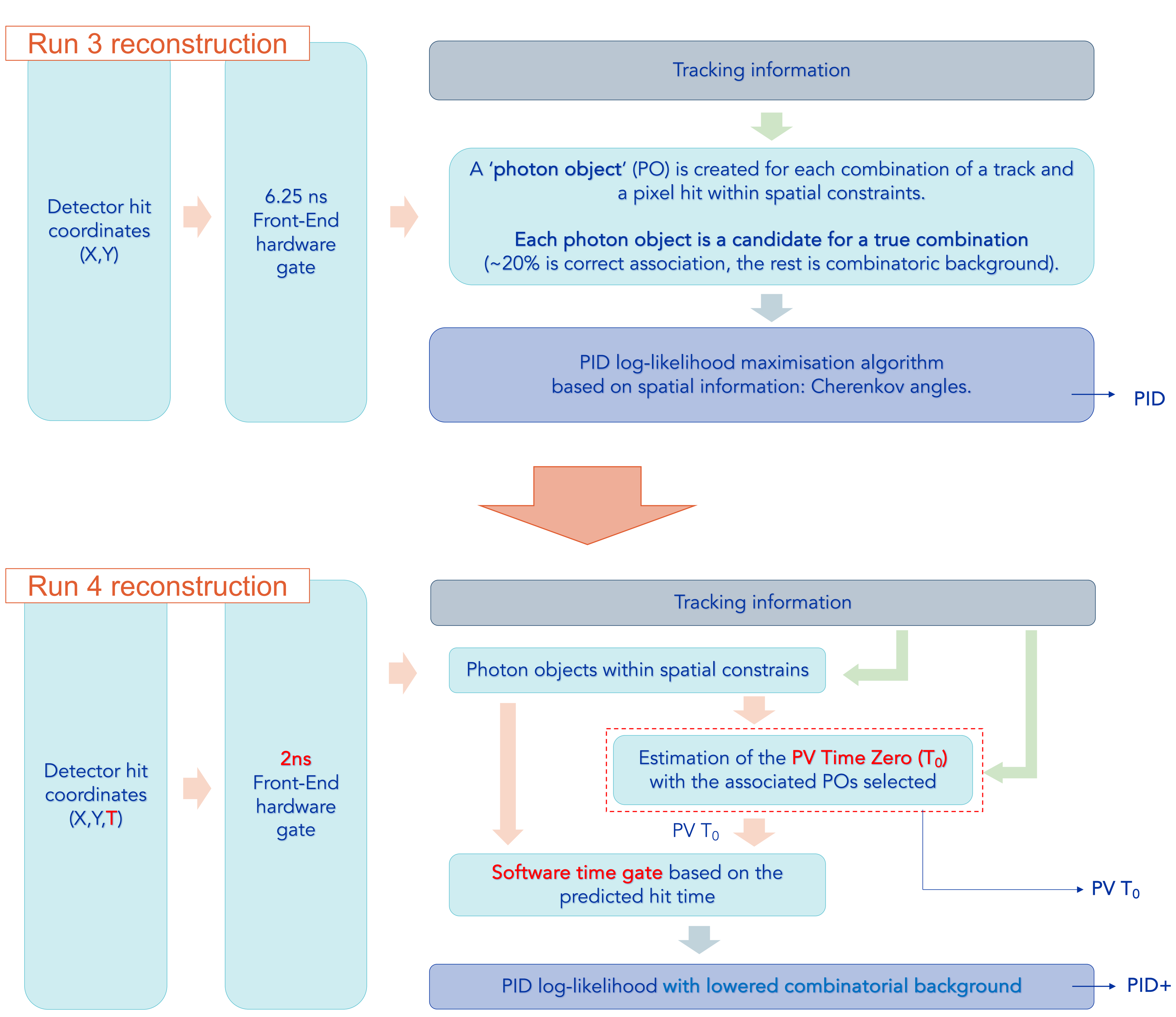
A software time gate can be applied around the predicted time to reduce the combinatorial background and improve the PID performance.

The software gate width depends on the photodetector time resolution (optimal value ~ $\pm 2\sigma_{det}$) and the precision of the PV time estimate.



The plot compares the simulated performance of Run 3 and Run 4, assuming a MAPMT time resolution of 150 ps and an exact PV time. [1][4] Uncertainty in the PV time will propagate to the predicted photon time and may require a wider software time gate to be chosen.

3. Introducing the software time gate in the RICH reconstruction

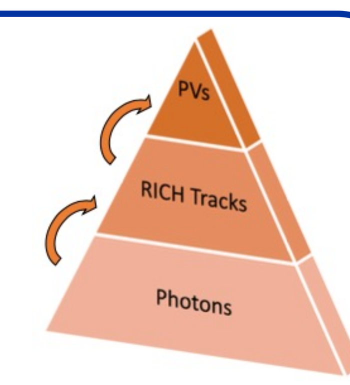


4. PV time estimation using RICH time information

$$RICH\ PV\ T_0 = \langle\ t_{hit} - t_{track,out} - t_{track,in} - t_{phot} + t_{spread}\ \rangle$$

N POs -> PVs

$t_{track,out}$: Track path to RICH entry point; $t_{track,in}$: Track path inside the RICH radiator; t_{phot}: Photon path inside RICH; t_{spread}: Sensor and FE electronics spread

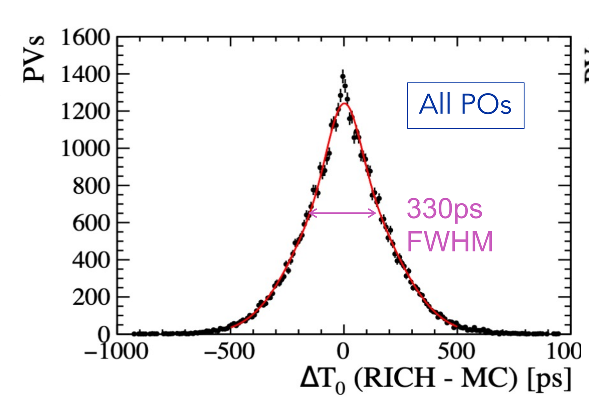


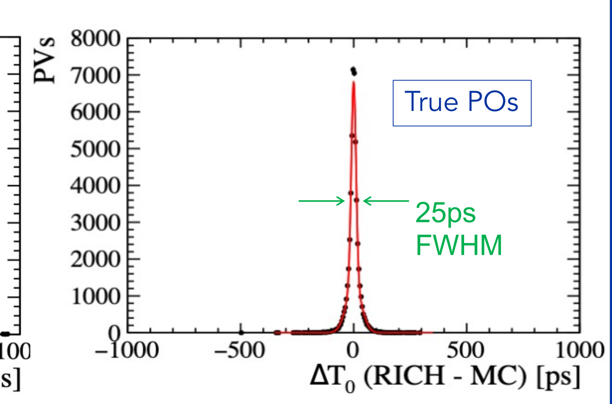
It is crucial to correctly select the true candidates associated with the PV to ensure the best PV time estimate.

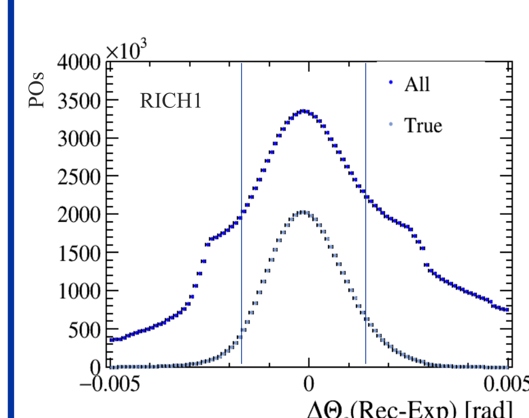
$$\textbf{Purity} = \frac{\text{True candidates}}{\text{All reconstructed photon objects}}$$

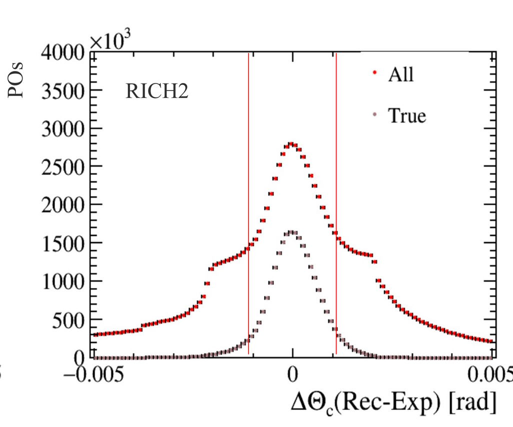
Selecting only true POs would result in a very accurate PV time estimate.

Several POs and track qualities have been investigated to increase the purity of the POs.





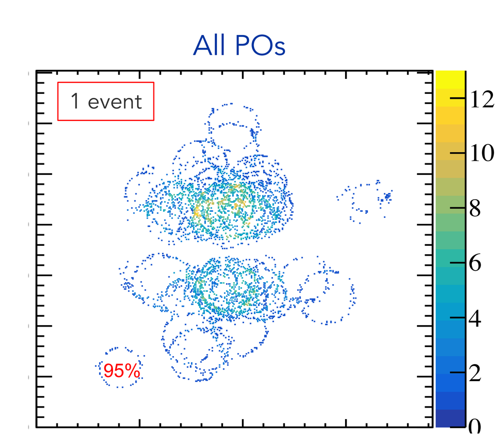


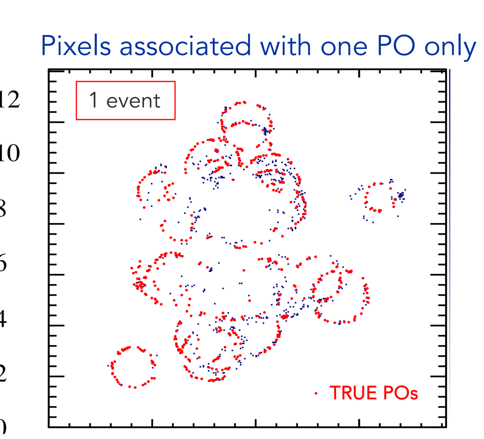


1. Cut on the Cherenkov angle resolution:

$$\Delta\theta_c = \theta_{rec.} - \theta_{exp.\ (pion)}$$

The optimal values found for the cut are 1.75 and 1.25 mrad for RICH1 and RICH2, respectively.





2. Selecting POs uniquely associated to a pixel.

These are photon hits that form only one candidate. The cut is heavy on the number of POs, but it does not affect the number of PVs reconstructed.

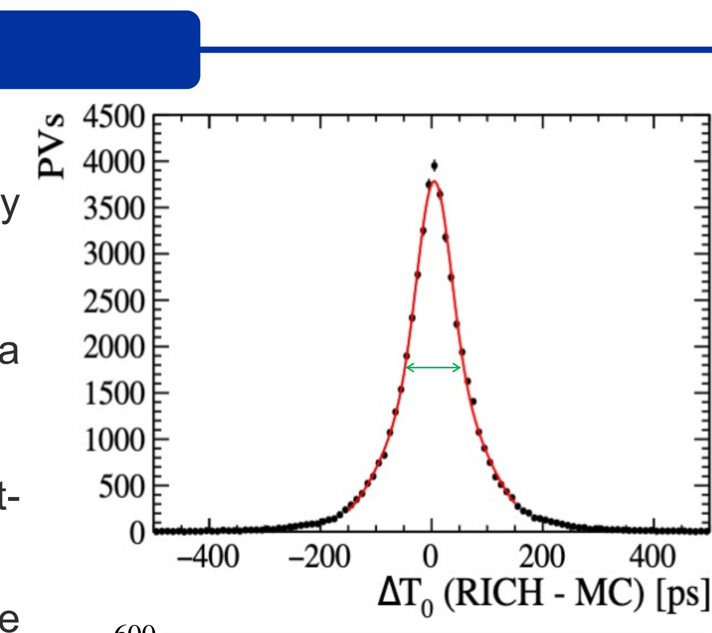
5. Results

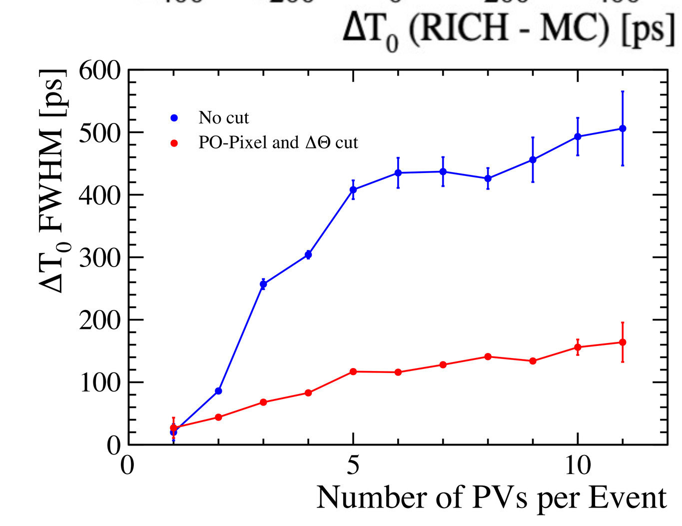
The two proposed cuts show an average purity increase of ~30%, with less than 1% of PVs lost.

Applying the two proposed cuts results in a resolution of **97ps FWHM**.

Further studies are ongoing, focusing on event-specific selections rather than global cuts.

- Impact of the number of PVs in the event on the PV time resolution.
- Algorithm to identify isolated tracks, which make the best contribution to the estimated PV time. Subsequently, the hits associated to that PV can be removed to reduce background for the other PVs.
  - Isolated-rings finder algorithm.
  - Machine-Learning model.





6. Summary and outlook

- The study shows how the time information can be integrated in the RICH detector and used to estimate the PV T_0, with a particular focus on the PO properties that can be exploited to improve the resolution.
- A sub-100 ps resolution (FWHM) has been achieved for ~99% of the PVs.
- Ongoing studies aim to further improve the PV time resolution with the goal of enhancing the PID performance of the RICH detector during Run 4.

KEY REFERENCES

[1] *LHCb Particle Identification Enhancement Technical Design Report*, CERN-LHCC-2023-005, LHCB-TDC-024.
[2] *The FastRICH ASIC for the LHCb RICH enhancements*, F. Keizer, Nuclear Instruments and Methods in Physics Research (https://doi.org/10.1016/j.nima.2024.169664)
[3] *Sub-nanosecond Cherenkov photon detection for LHCb particle identification in high-occupancy conditions and semiconductor tracking for muon scattering tomography*, F. Keizer (Doctoral Thesis).
[4] *Proposal for LHCb RICH detector enhancements during LHC Long Shutdown 3*, CERN-LHCb-PUB-2021-014