Primary vertex time reconstruction using LHCb RICH detectors

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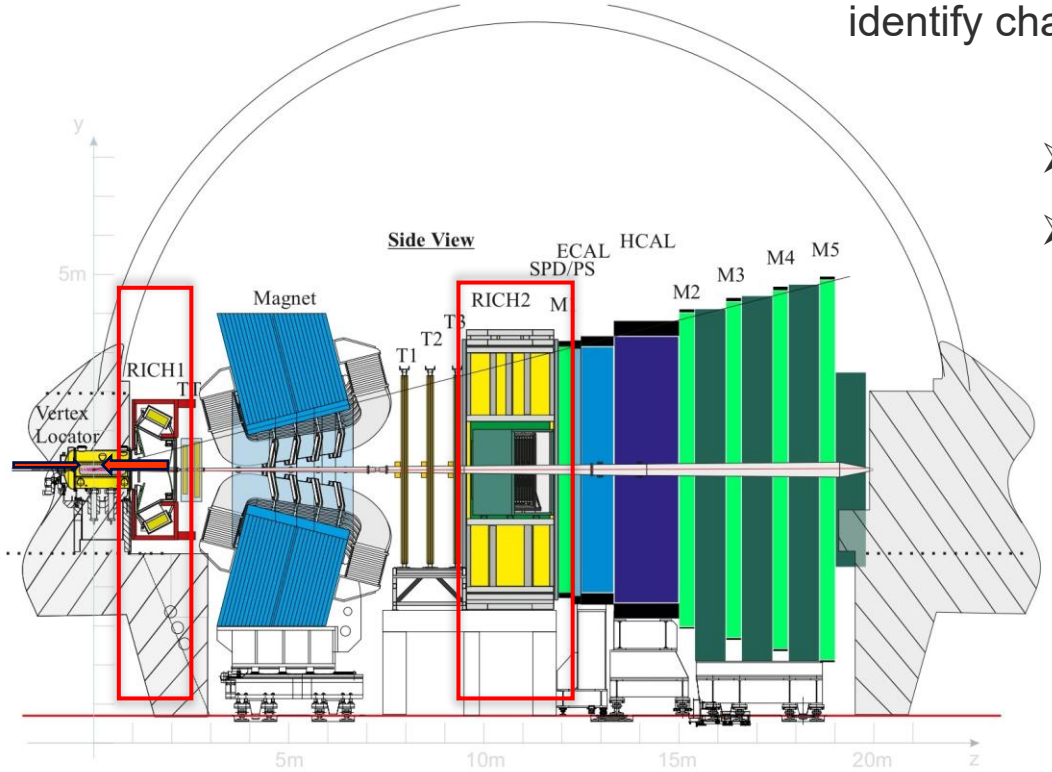
16th September 2025, RICH 2025 Workshop

LHCb RICH in Run 3



Lateral view of the LHCb experiment

The Ring-Imaging Cherenkov (RICH) detectors at LHCb are used to identify charged hadrons

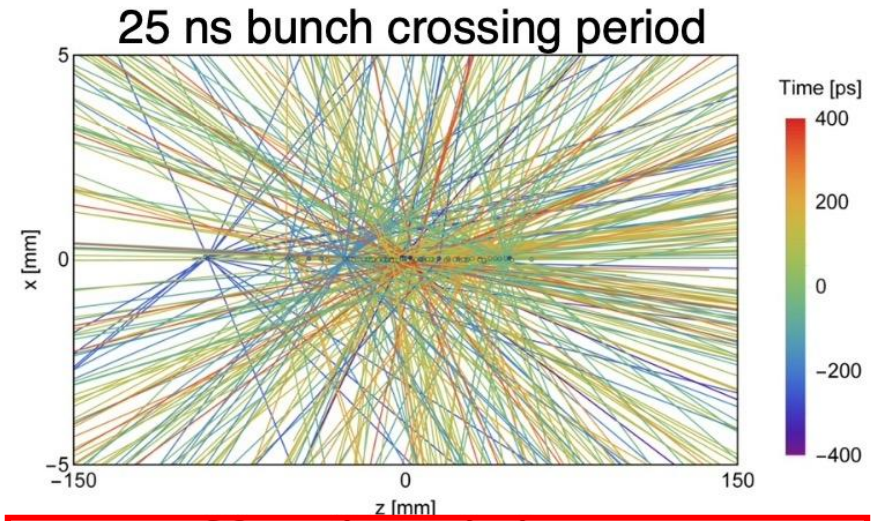
- RICH 1 is positioned upstream of the LHCb magnet
- RICH 2 located downstream of the magnet

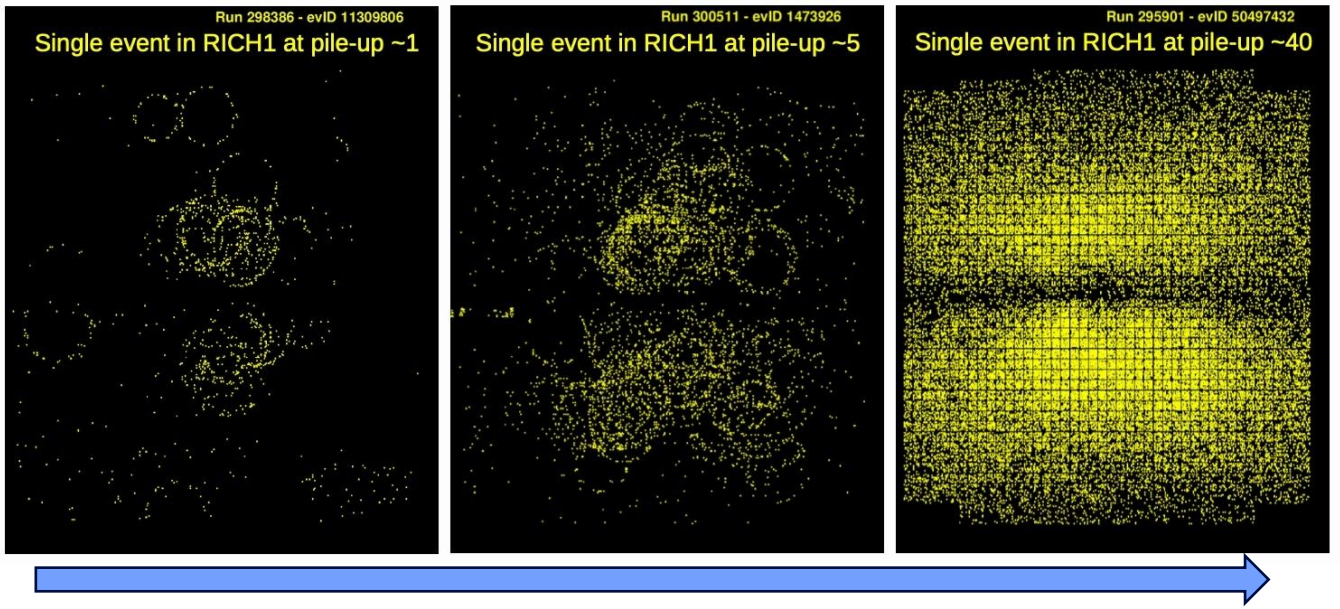
PREVIOUSLY

Giovanni's talk: "The LHCb RICH detectors: operations and performance"

The Cherenkov light emitted by the tracks in the radiators is guided by a mirror system to the photodetector planes

Luminosity challenge in RICH



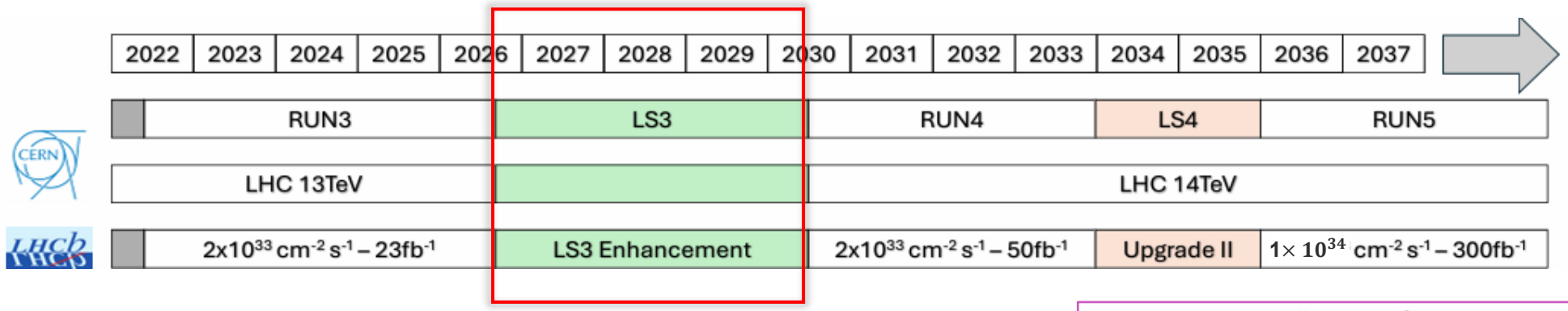


- With pileup the photodetector occupancy increases
- **As the LHC is moving towards higher luminosity era**
  - Higher detector occupancies

UPCOMING Claudio's talk: "The Upgrade II of the LHCb RICH system"

- Fast-timing is a crucial gateway to reduce pile-up to ensure particle identification (**PID**) performance of RICH detectors in Run 5

LS3 enhancements



PREVIOUSLY Vlad's poster: "The LS3 Enhancement of the RICH detectors"

- LHCb Run 3 will continue till mid 2026 at an instantaneous luminosity of $\mathbf{2}\times \mathbf{10}^{\mathbf{33}}\ \boldsymbol{cm}^{-\mathbf{2}}\ \boldsymbol{s}^{-\mathbf{1}}$

- **LS3 enhancements of LHCb-RICH** would enable
  - Novel fast-timing front end (**FE**) electronics (**FastRICH**) : reduced pileup with timing

PREVIOUSLY Floris' poster: "The FastRICH ASIC for next-generation RICH detectors"

  - Better PID performance in Run 4
  - Prepare for higher luminosity phase of LHC (2035 onwards at **7.5x Run 3 luminosity**)

Introducing timing information in LHCb RICH

The **LHCb tracker** will have timing information **only from Run 5** !

- With the **FastRICH ASIC** is capable of timestamping **photon hits at 25 ps**

  https://doi.org/10.1016/j.nima.2023.168475 10.1088/1748-0221/19/04/C04030

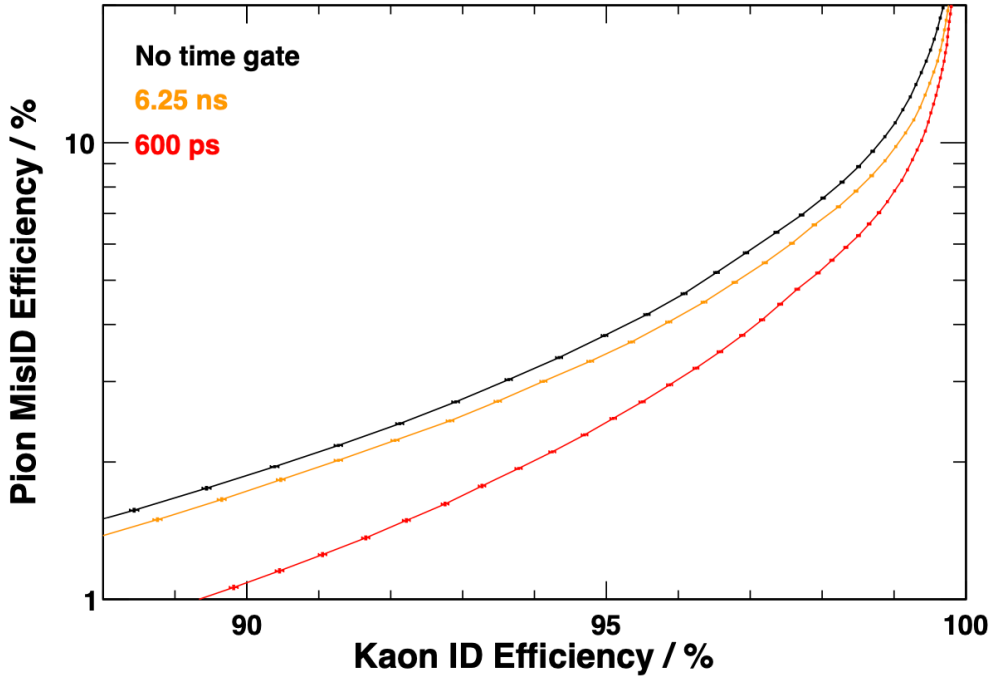
- So, in Run 4 only possible source to enable timing is from RICH standalone

- With this the LHCb RICH would function as a 4D detector:

  Spatial + timing information

"Shorter the time gate better the PID":

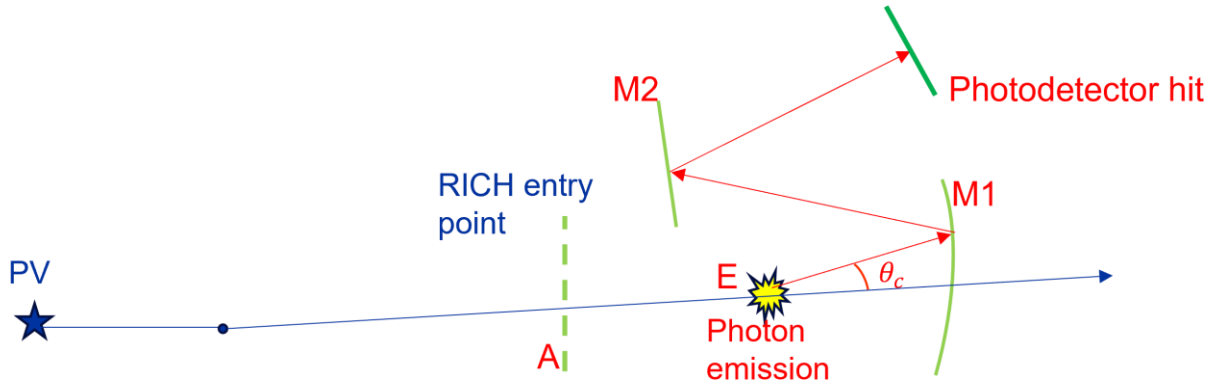
- Simulation shows that a fine software time gate can unleash better PID performance



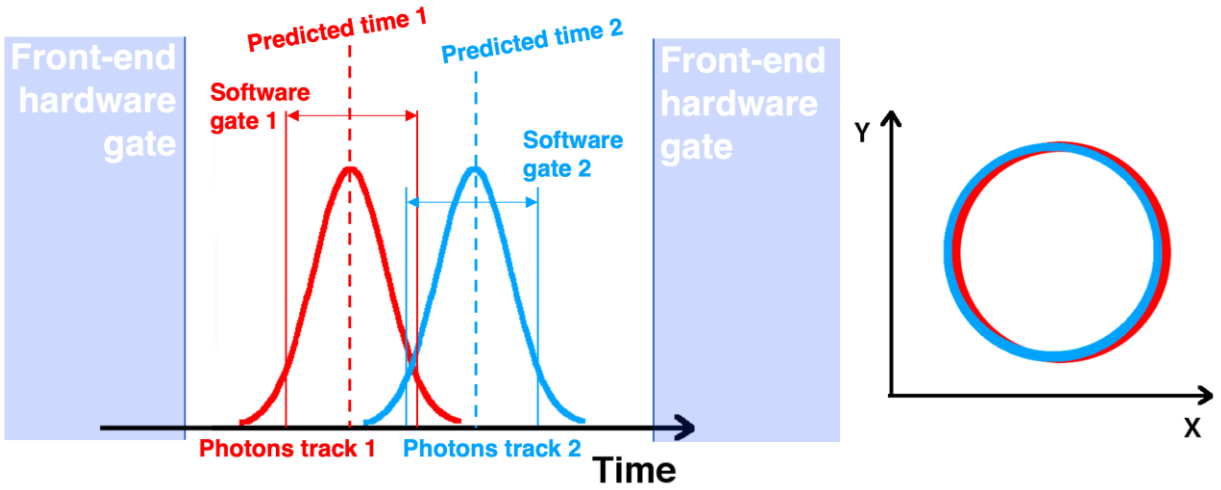
Photon timing techniques

Using RICH reconstruction for a given PV time

- The Cherenkov photon time-of-arrival (ToA) can be predicted, using reconstructed track and photon path, to **~ 10 ps**



With this approach, for the 1st time in LHCb we will have timing

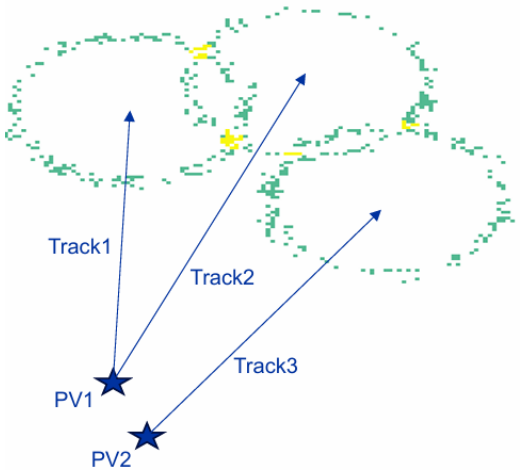


10.1088/1742-6596/2374/1/012074

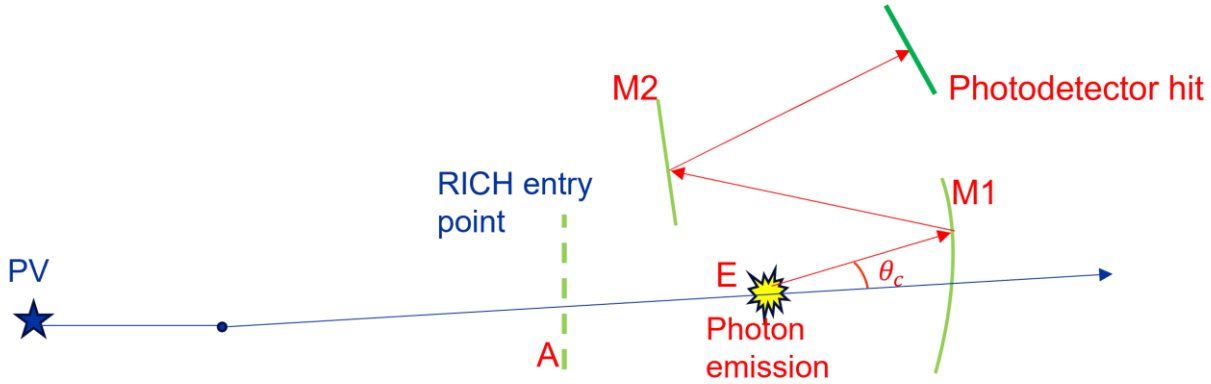
Software time gate around the predicted hit time, registers only hits within this window for PID

- gate width depends on: photo sensor time spread (~150 ps), Primary Vertex time (PVt_0) spread
- However, there is a wide spread in this $\boldsymbol{PVt_0}$

PVt_0 estimation : RICH standalone



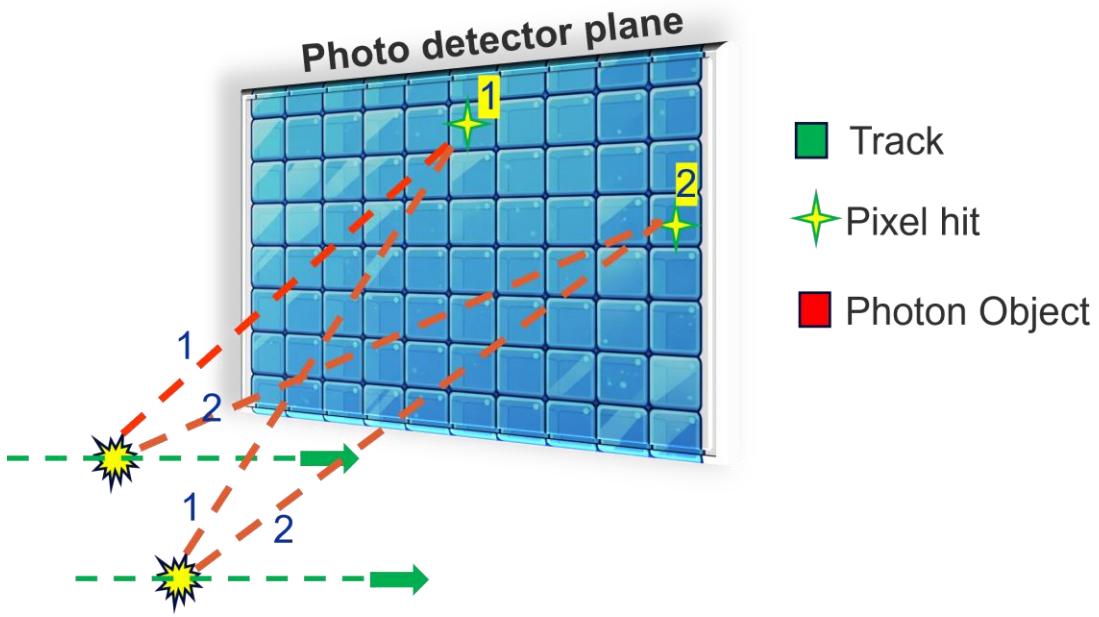
$$\text{RICH } PVt_0 = \left\langle t_{\text{hit}} - \underbrace{\frac{|r_A|}{c}\sqrt{1+\left(\frac{mc}{p}\right)^2}}_{\text{track path to entry point}} - \underbrace{\frac{d_{A,E}}{c}\, n\cos\theta_c}_{\text{track path inside the radiator}} - \underbrace{\left[d_{E,M1} + d_{M1,M2} + d_{M2,\text{ hit}}\right]\frac{n}{c}}_{\text{Photon path inside RICH}} + \underbrace{t_{\text{spread}}}_{\text{Sensor \& FE spread}} \right\rangle$$

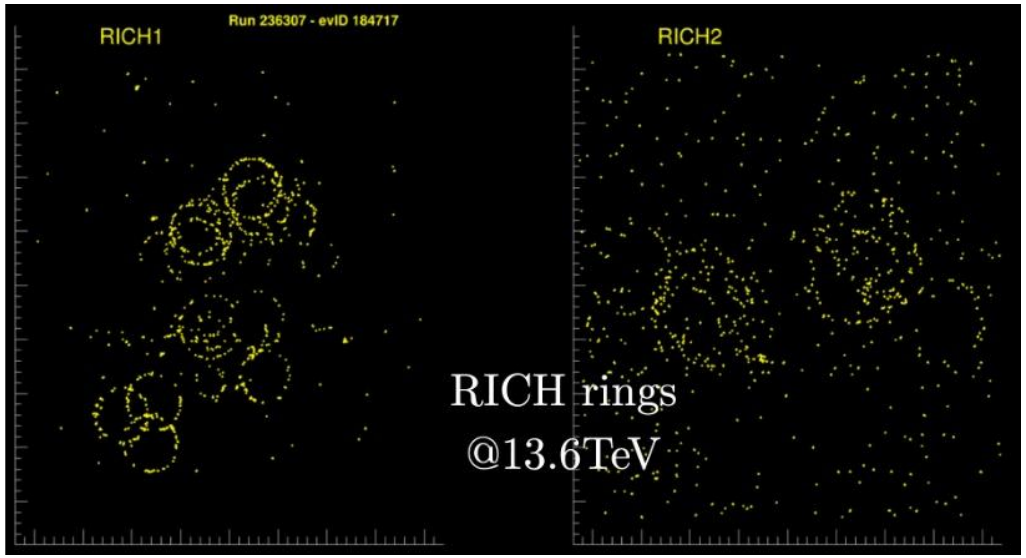


PVt_0 of a PV = **average** of PVt_0 computed over **Photon objects**

Understanding Photon Objects

- For each combination of a track and a pixel hit a **Photon Object (PO)** is created





- Single event hitmap, reveals the extent of combinatorics in PO associations

- Only **~20% of POs form correct association**

Run3 Reconstruction

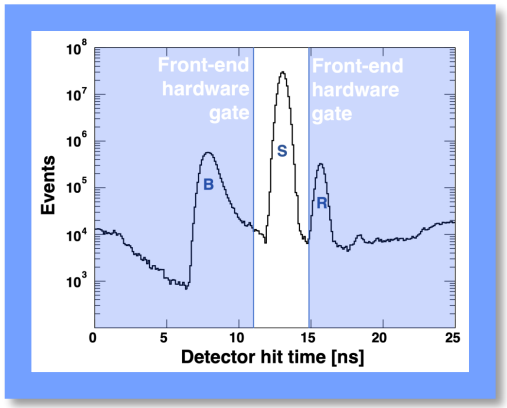
Photo detector hit Coordinates (X,Y)

Hardware Time Gate (**6.25 ns**)

Tracking Information

For each combination of a track and a pixel hit a **Photon Object (PO)** is created, within spatial constraints

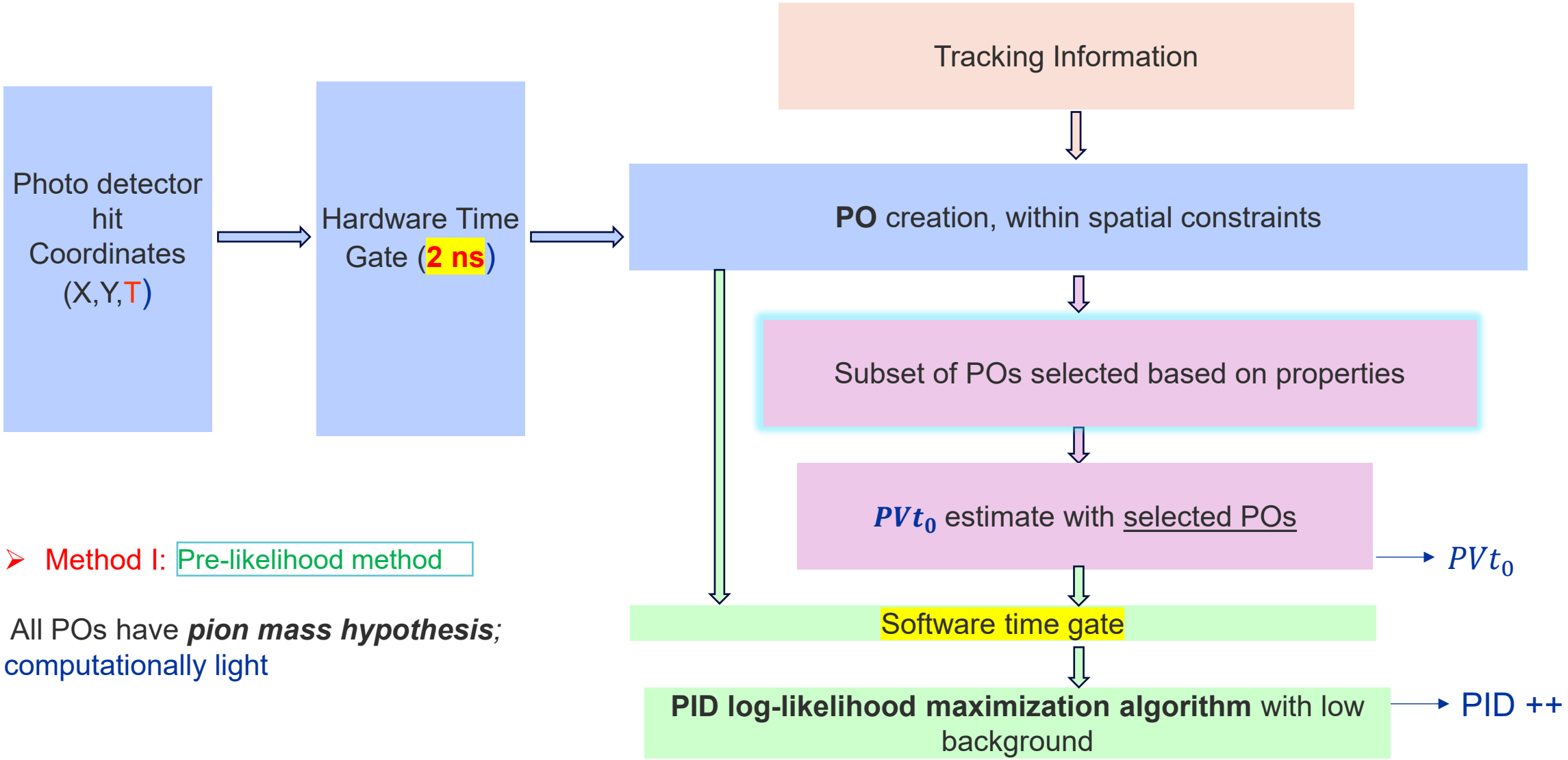
PID log-likelihood maximization algorithm: establishes **best mass hypothesis** of tracks → PID



Hardware gate on the FE electronics, rejects out of time photon signals

- **All tracks** are apriori presumed to be **pions by** PID log-likelihood maximization algorithm
- PO selection stage : to enable a subset of **good PO candidates**

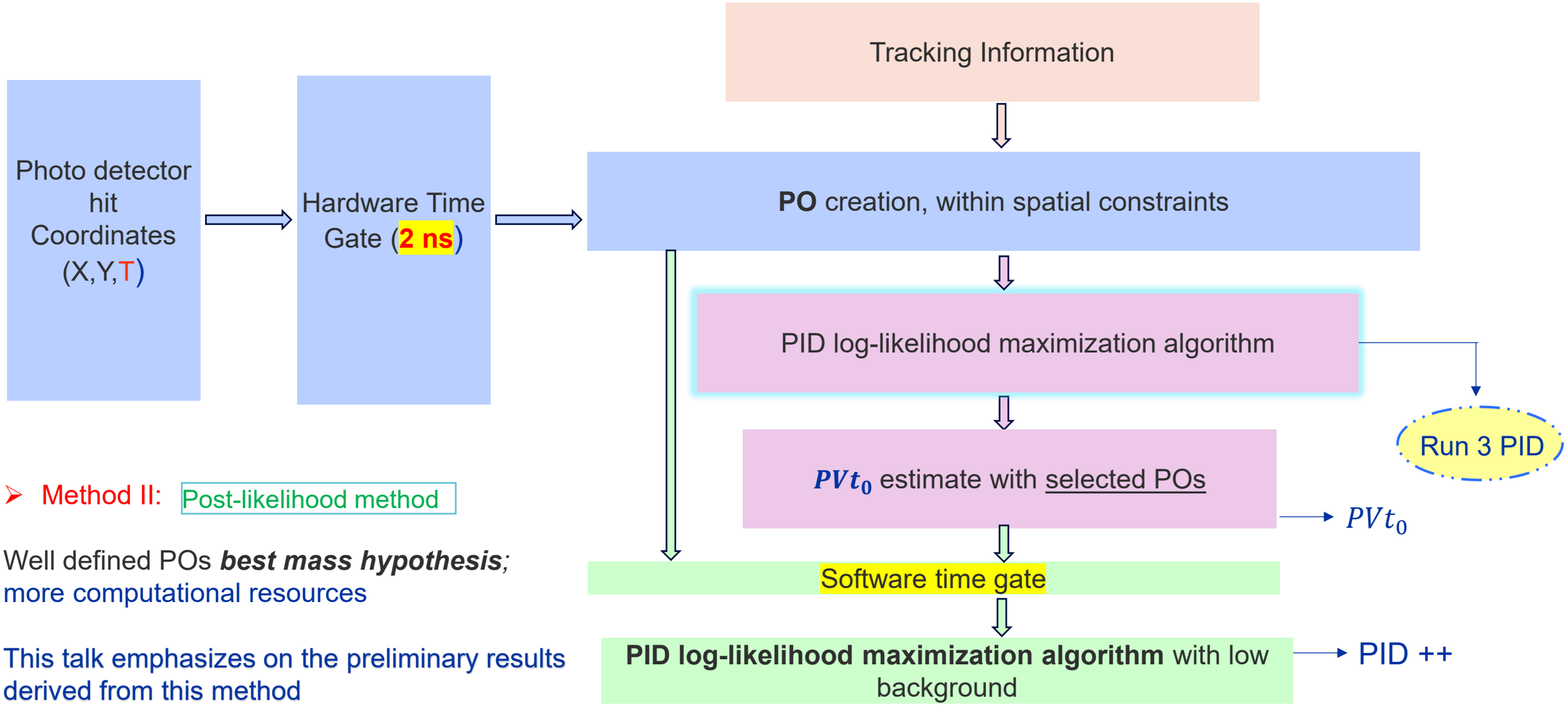
PVt_0 reconstruction pathway : for Run 4



- Method I: Pre-likelihood method

All POs have ***pion mass hypothesis***; computationally light

PVt_0 reconstruction pathway : for Run 4



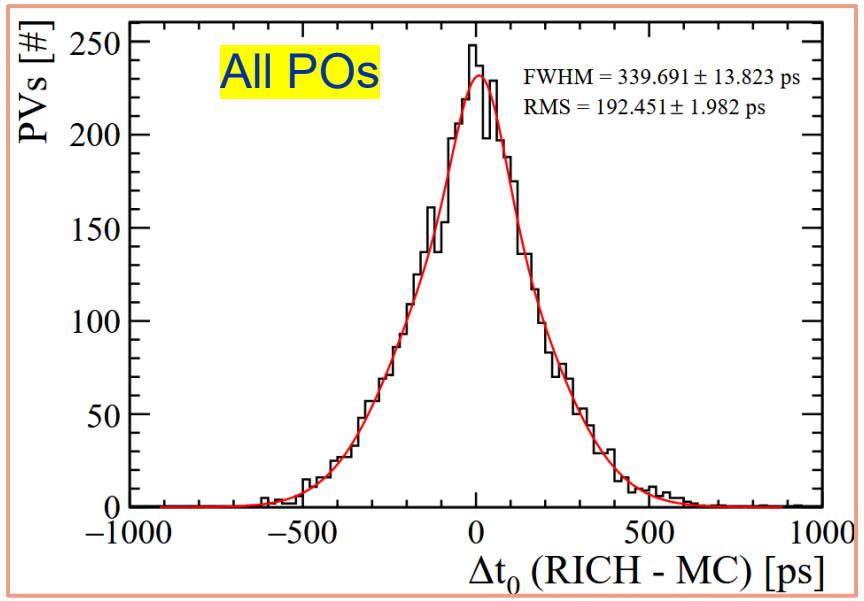
- Method II: Post-likelihood method

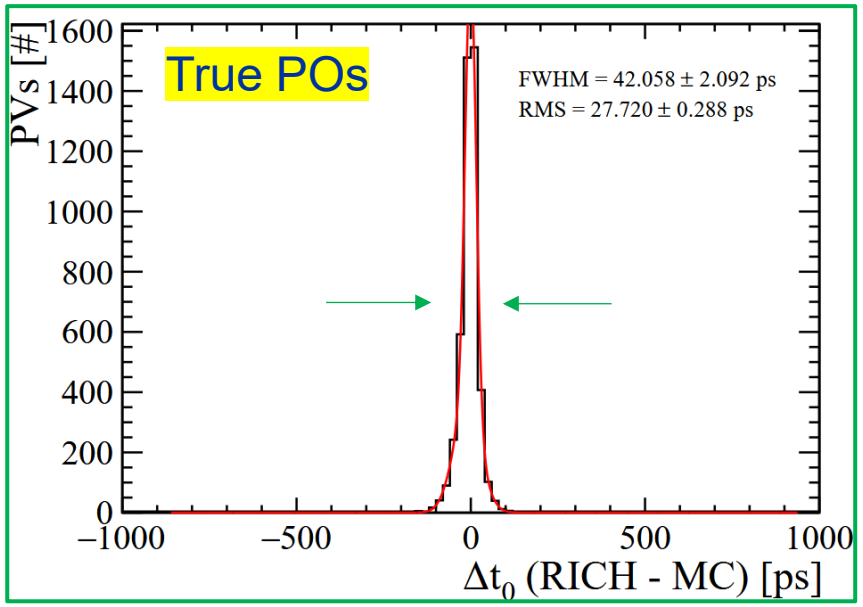
Well defined POs ***best mass hypothesis***; more computational resources

This talk emphasizes on the preliminary results derived from this method

PVt_0 resolution

All plots are fitted to a **Double Gaussian function**: FWHM of Δt_0 = RICH PVt_0 – MC PVt_0 is presented





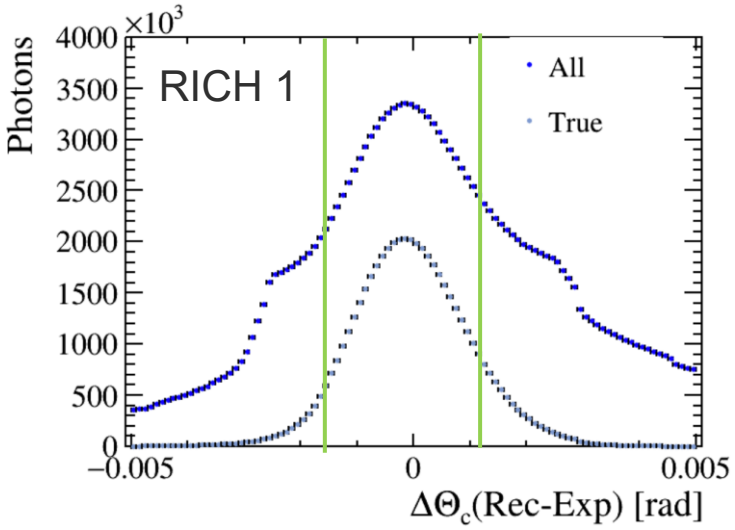
- With **All POs** ~ 339 ps
- With **True POs** ~ 42 ps

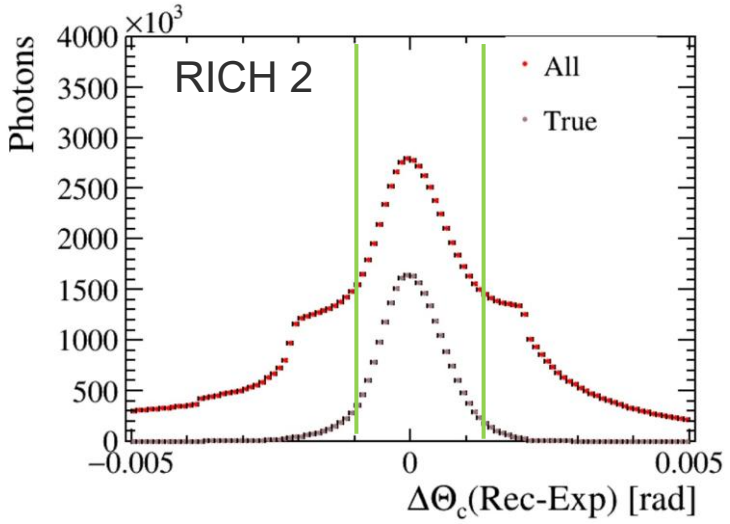
Purity of PO samples used to reconstruct PV plays a significant role in PVt_0 resolution

Photon Object properties

A PO intrinsically defines **signal amplitude (SA) :**Probability of a photon hit in a pixel, originated from a track with a given mass hypothesis

The probability distribution of Cherenkov angle resolution for photon signals from tracks (certain mass hypothesis)





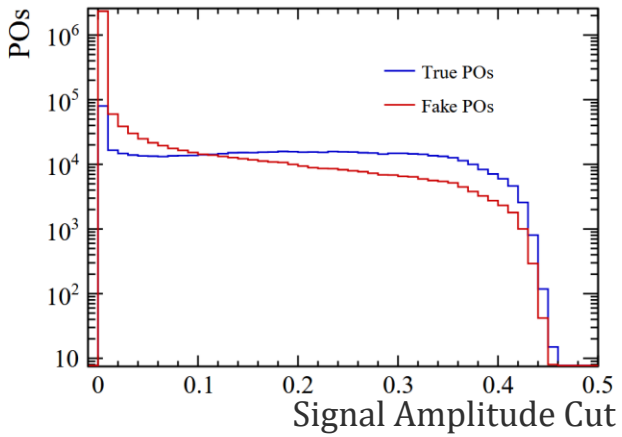
- $\Delta\theta_c = \theta_{rec.} - \theta_{exp.\ (pion)}$

From pixel hits — From tracks

- Fake POs towards the tail

MC insights: motivates to study of **SA** distribution of **true POs vs fake POs**

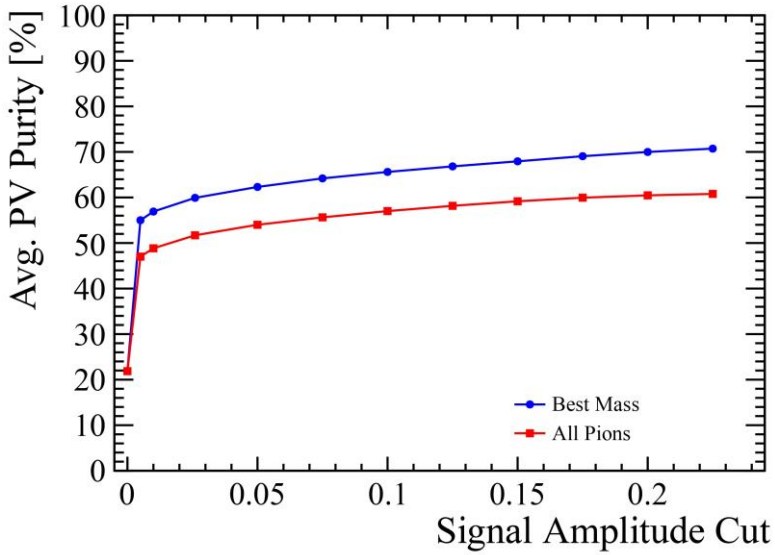
- At lower SA values (<0.05), POs mostly populated by fake candidates
- Exploiting cuts on SA of POs with best mass hypothesis



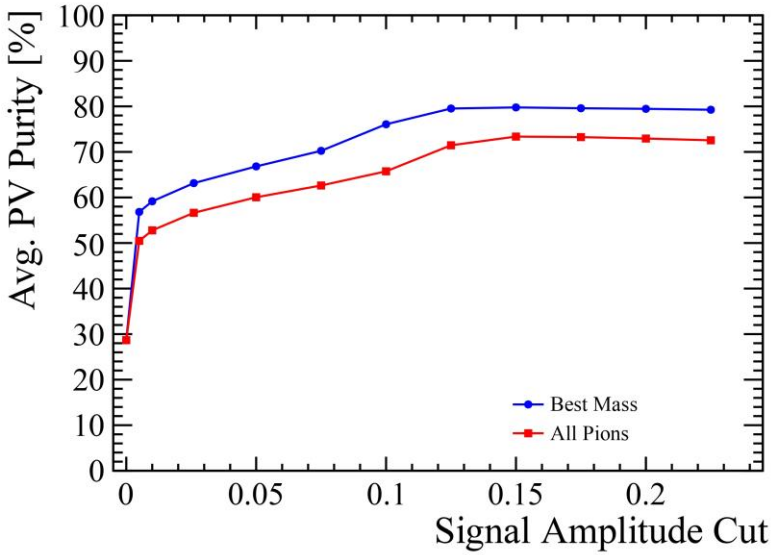
PV purity studies: SA cuts

$$\text{PV purity} = \frac{\textit{True POs associated to a PV}}{\textit{All reconstructed POs associated to a PV}}$$

RICH 1

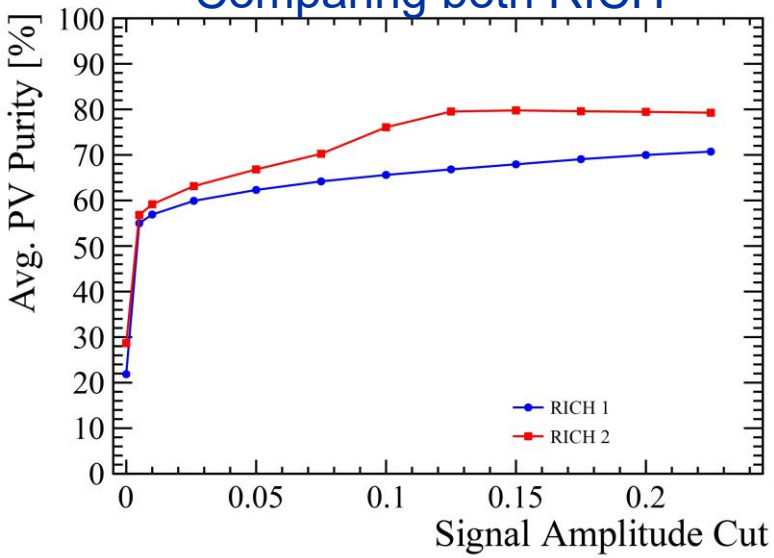


RICH 2



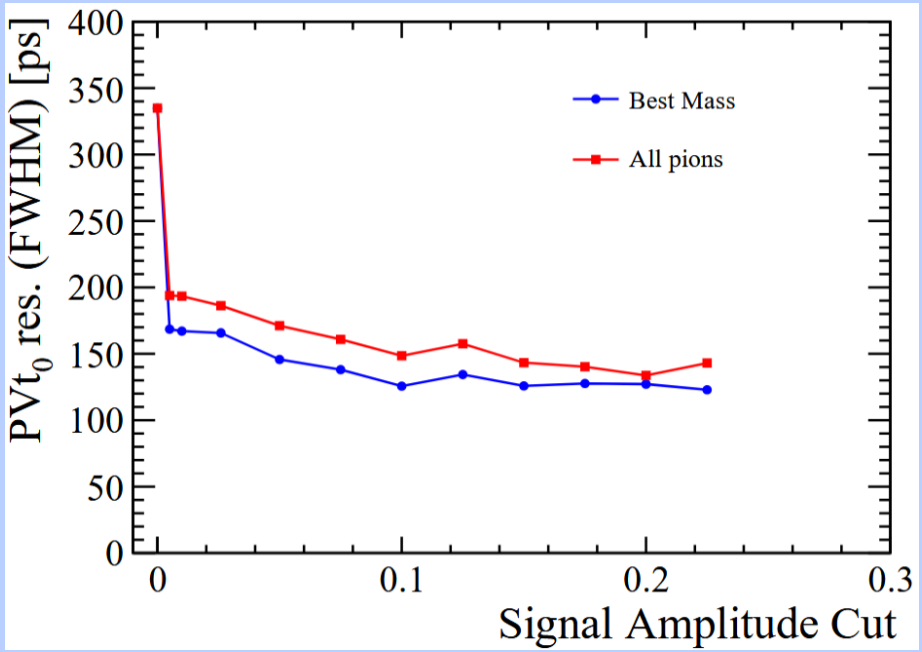
- ~10% gain in PV purity with ***best mass hypothesis***

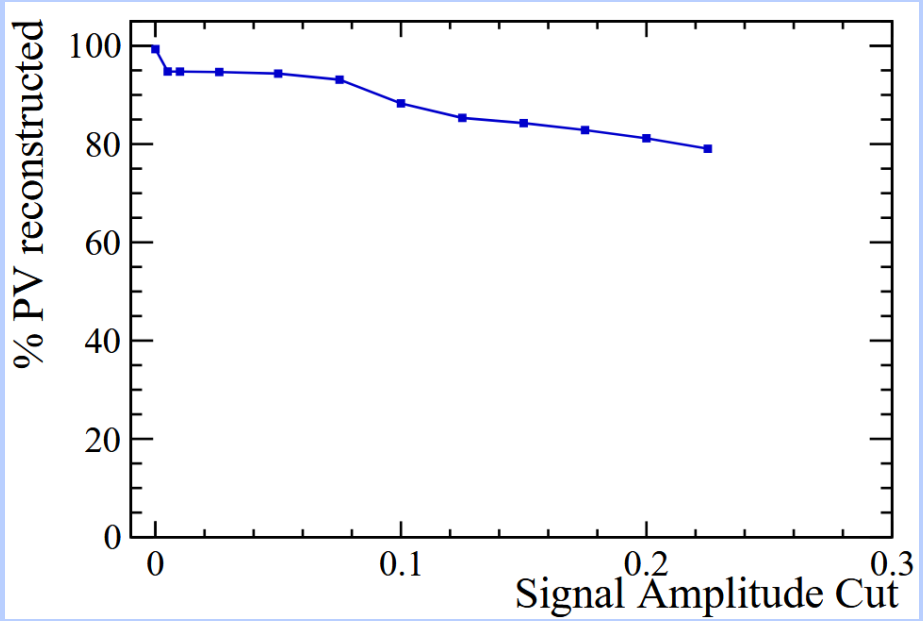
Comparing both RICH



- Rich 2 demonstrates **better performance** in constituting PV purity
  - Low combinatoric background

PVt_0 resolution with SA cuts only



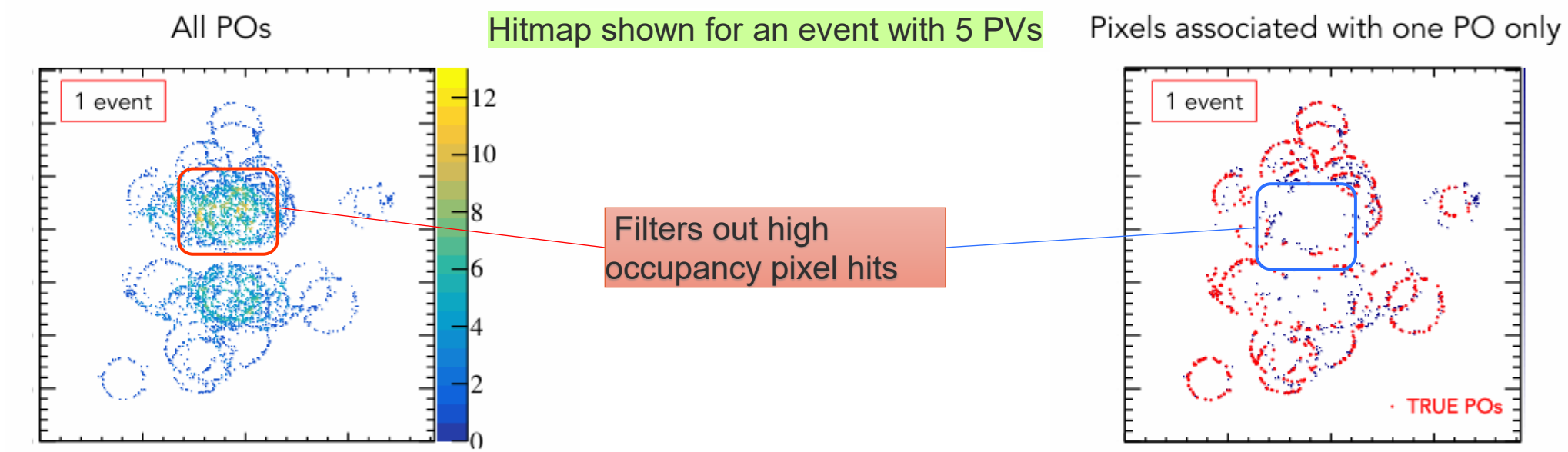


Using both RICH 1 & 2

- PVt_0 res. of **best mass vs pion mass**: is compared
- At **SA cut > 0.05**, FWHM of PVt_0 resolution with ***best mass hypothesis*** is **145 ps with 94% PVs reconstructed**
- **~15% enhanced** PVt_0 resolution compared to that of ***pion mass hypothesis*** (Δt_0 ~ 171 ps)

Selection of Pixels with 1 Photon Object only

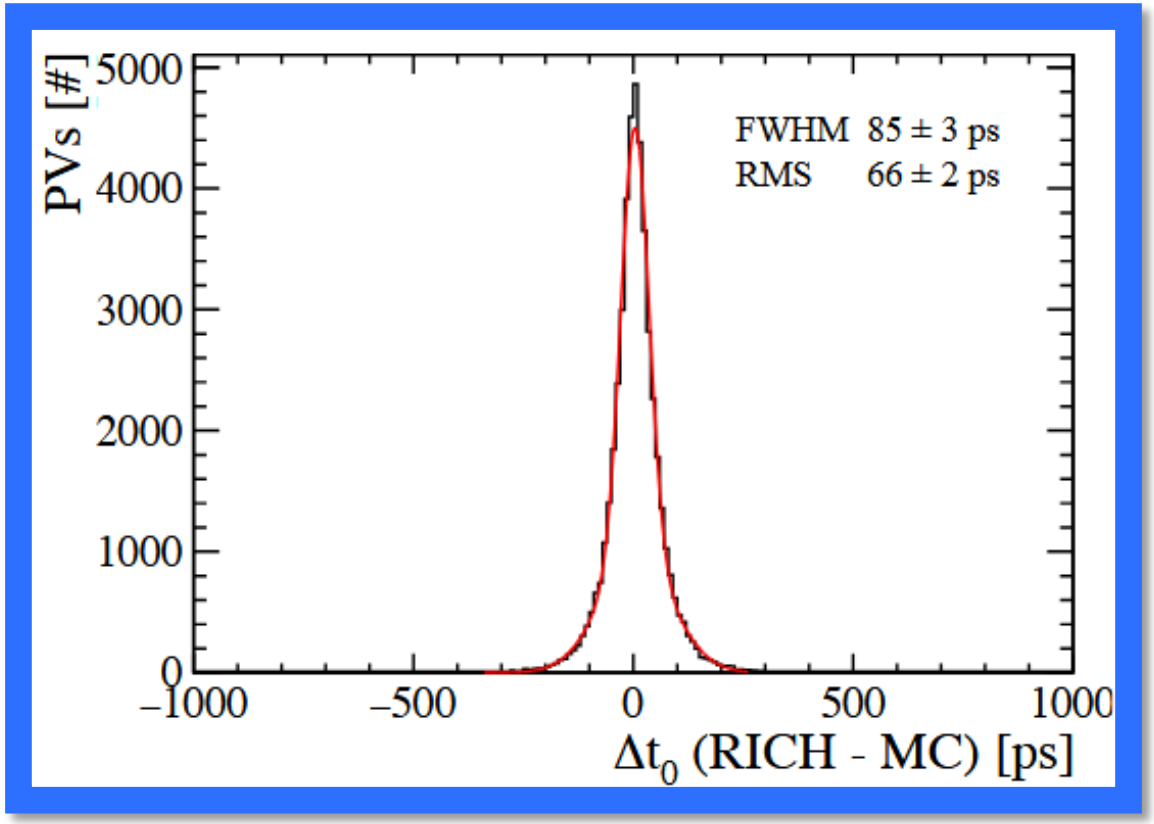
- Selection of **pixels associated to one PO only**



Studies with this pixel selection in the Pre-likelihood method, reveals:

- Significant drop down in combinatorics (only ~10% of POs make through)
- Reportedly, **~30% rise** in purity of PO samples used to reconstruct PVt_0

PVt_0 resolution with pixel-based selection



PVt_0 resolution post:

- Signal Amplitude Cut on POs
- Cut on pixels with more than 1 POs

- To inspect the enhancement in PVt_0 resolution from selection of pixels with 1PO, in the pre-likelihood treatment of POs
- using **both RICH at SA cut> 0.05**: appreciably fine PVt_0 resolution observed at **85 ps**, with 94% PVs reconstructed

Deems promising to investigate the PVt_0 estimation from POs with **Post-likelihood method,** using this geometric selection

Conclusive remarks

- In LS3, timing information can be made available from **LHCb-RICH standalone**
- Novel PVt_0 estimation algorithm to introduce a picosecond-scale software time gate in Run 4 RICH reconstruction
- To improve PVt_0 resolution, usage of a 2nd PID log-likelihood maximization algorithm
- A geometric cut on pixels with 1PO looks promising and is to be further explored in the context of PO with best mass tracks (**Post-likelihood method**)

Thanks !

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