# Primary vertex timing reconstruction with the LHCb Ring Imaging Cherenkov detectors

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# Towards a time resolved LHCb

Colliders like the LHC are advancing toward **extremely high instantaneous luminosity.**

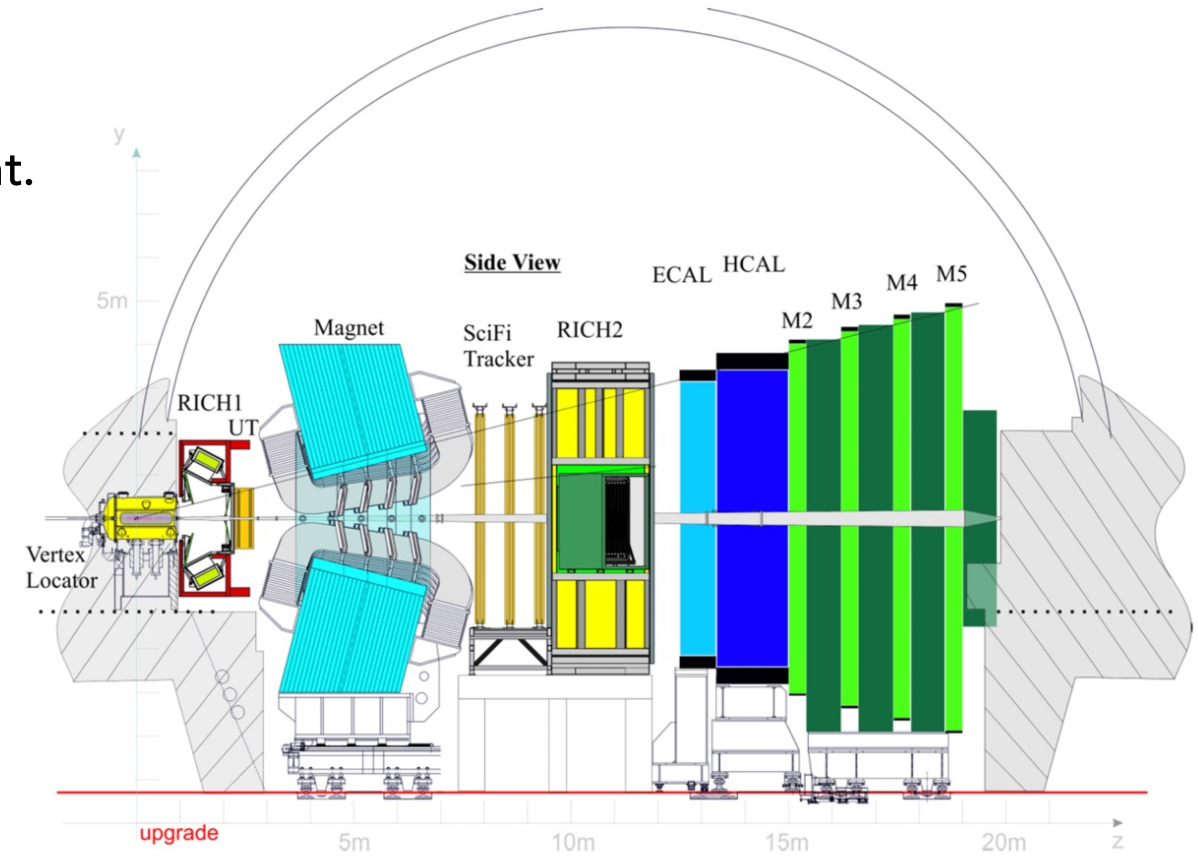
- ➢ Increased particle multiplicity.
- ➢ Higher detectors occupancy.

**Timing** is becoming a crucial asset for **LHCb experiment.**

- ➢ Many sub-detectors will introduce fast-timing information during Upgrade II (2034 - ).

In this context, this talk will illustrate the integration of timing information into the LHCb RICH detector reconstruction, focusing on the Primary Vertex (PV) time estimation.

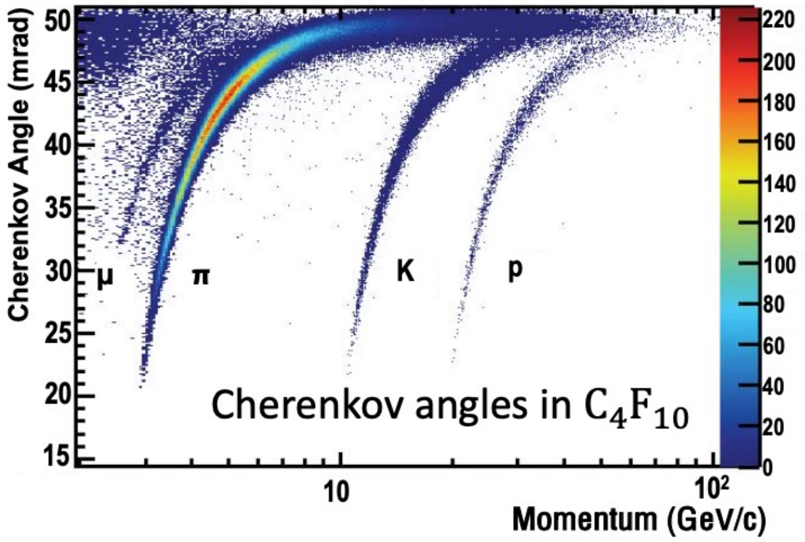
RICH reconstruction in the LHCb High-Level-Trigger 2.
(see Alessandro's talk).

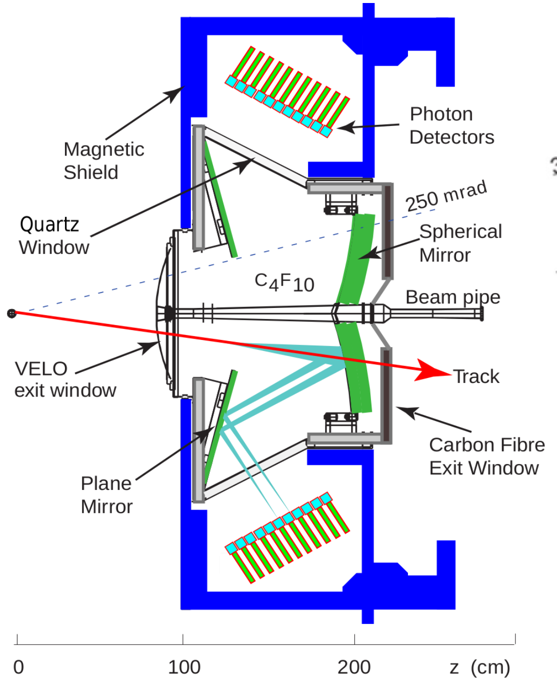


# The LHCb RICH detectors

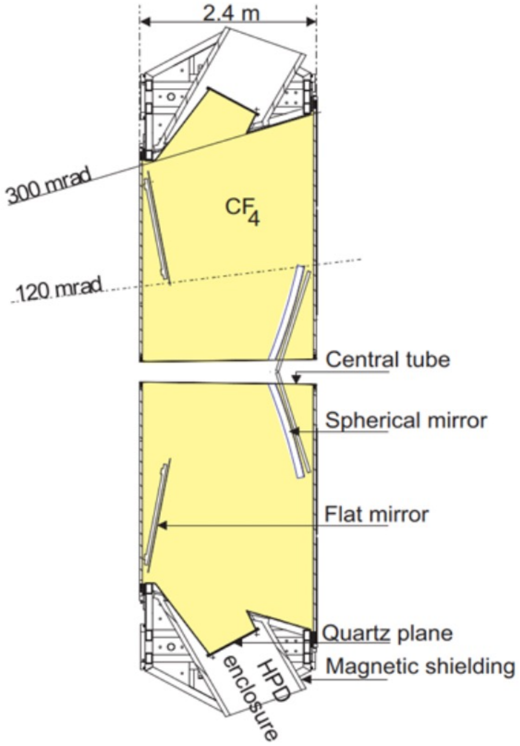
The **Ring Imaging Cherenkov (RICH) detectors at LHCb** provide **charged hadron identification** (momentum from 2 to 100 GeV/c).

The **Cherenkov light** emitted by the particles in the radiators is directed by an **optical system** toward the **photodetector planes.**

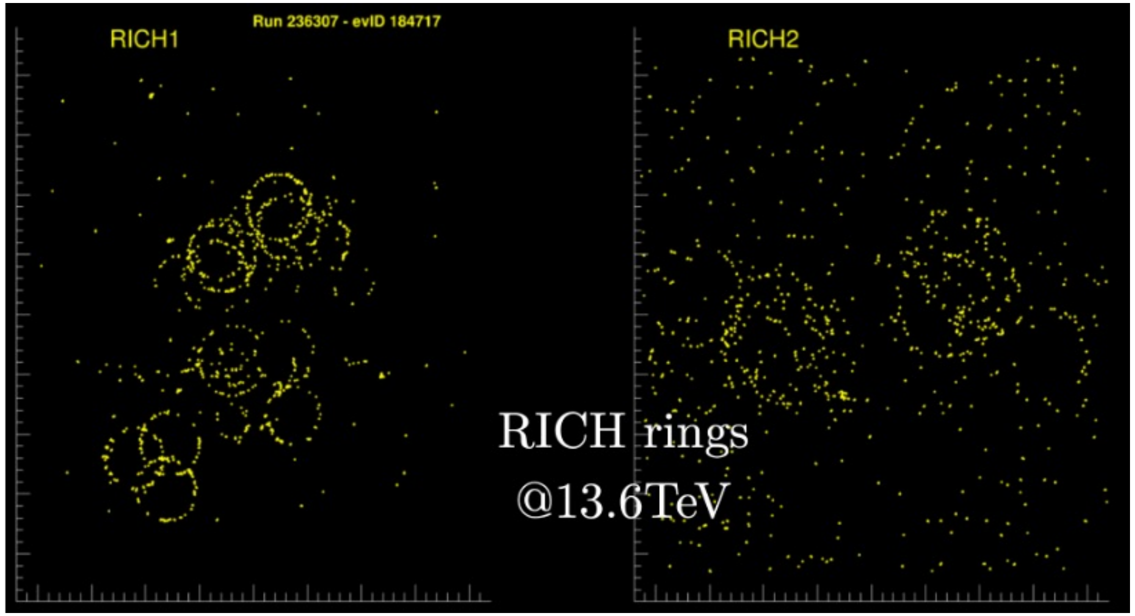



RICH 1




RICH 2




Single event display

# The LHCb RICH detectors – Long Shutdown 3 Enhancement

The RICH collaboration will anticipate the **introduction of timing** through an **enhancement program** during the LS3. The program includes the integration **of new front-end readout electronics**: the **FastRICH ASIC** capable of timestamping photon detector hits with ~**25 ps time bins**.

- Improved **PID performance** during Run4.
- Provide a **new fast-timing perspective** to LHCb including a **primary vertex (PV)** time estimate.
- Introduce technologies for high luminosity operation ahead of Upgrade II, when:
  - New photodetectors for the RICHs.
  - PV time from tracking.

| 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| RUN3 | LS3 | RUN4 | LS4 | RUN5 |
| LHC 13TeV | | LHC 14TeV | | |
| $2x10^{33}\ cm^{-2}\ s^{-1}$ – $23fb^{-1}$ | LS3 Enhancement | $2x10^{33}\ cm^{-2}\ s^{-1}$ – $50fb^{-1}$ | Upgrade II | $2x10^{33}\ cm^{-2}\ s^{-1}$ – $300fb^{-1}$ |

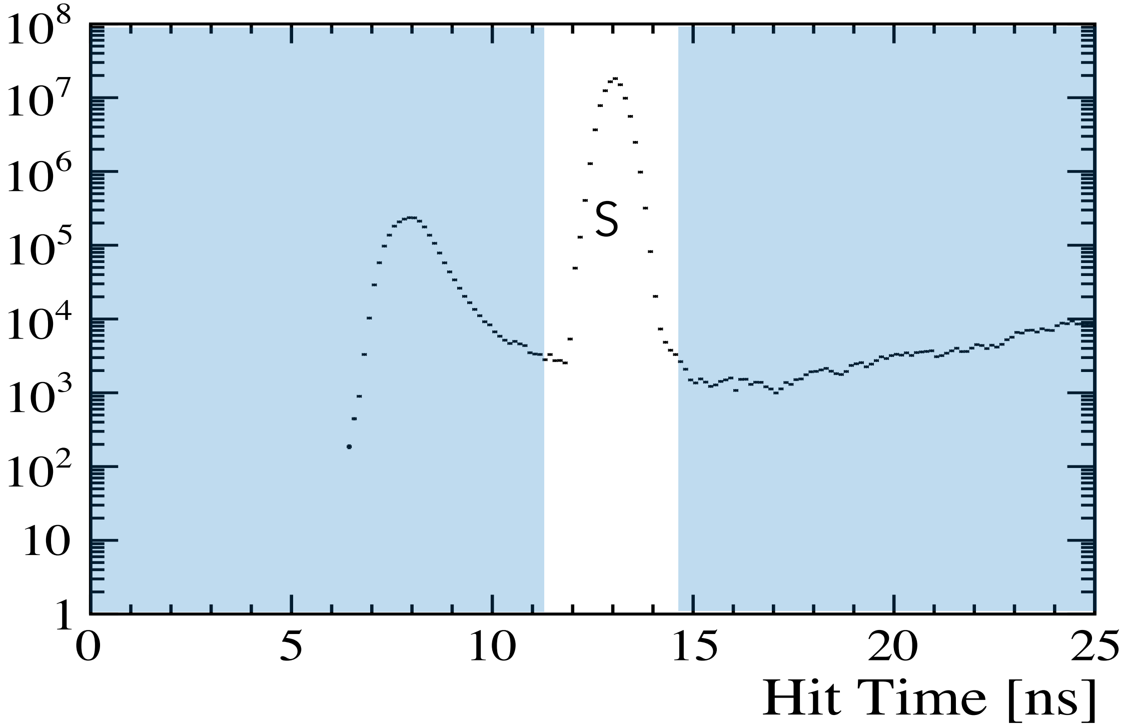
# Photon **time-of-arrival distribution** and **hardware time gate**

**Cherenkov photons** from a given track arrive almost **simultaneously**.

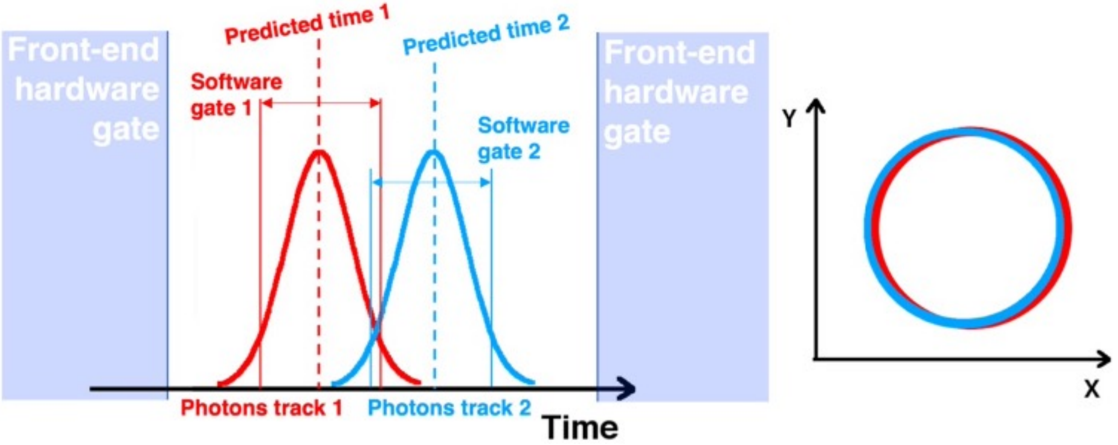
However, photon time-of-arrival ('S') of several bunch crossings is spread across a few nanoseconds.

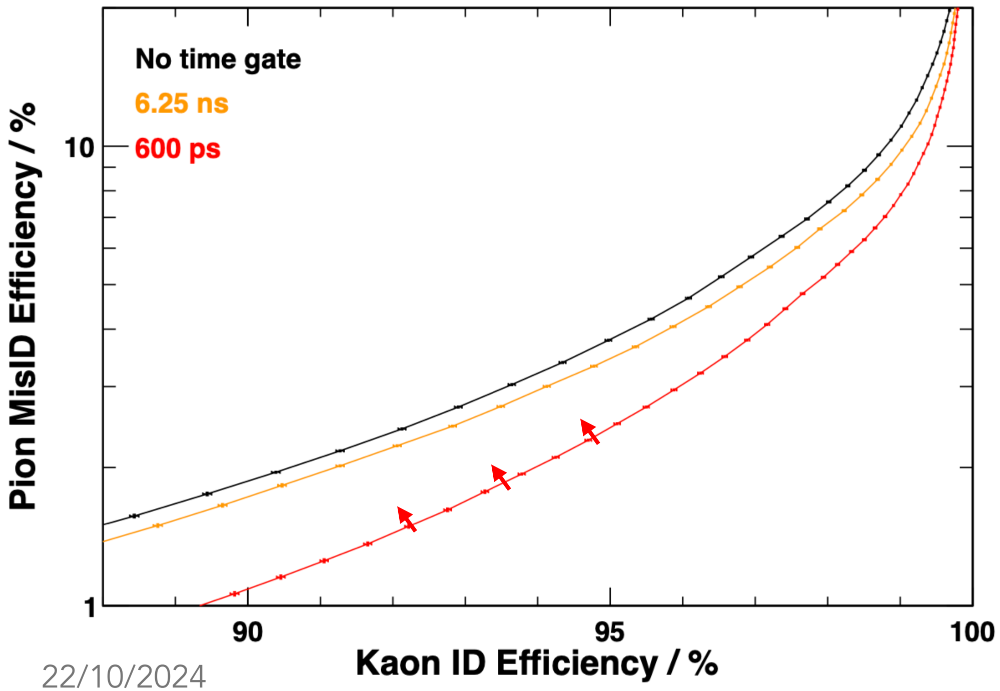
- **Primary vertex (PV) time spread.**
- Different track paths through the detectors.

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



# Photon **time-of-arrival distribution** and **time gates** in the reconstruction software




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

**Software time gate** around the predicted time:

- ➢ reduced combinatoric background,
- ➢ improved the PID performance.

The software time gate width depends on:

- ➢ **Sensor time spread** (optimal gate width = $\pm 2\sigma_{sensor}$ ).
  In RUN4, MAPMT spread ~ 150ps.
- ➢ **PV time estimate resolution**.
  In RUN4, estimated with RICH info only.
  After Upgrade II, from tracking.

# RUN3 RICH reconstruction

Detector hit coordinates (X,Y)

6.25 ns Front-End hardware gate

Tracking information

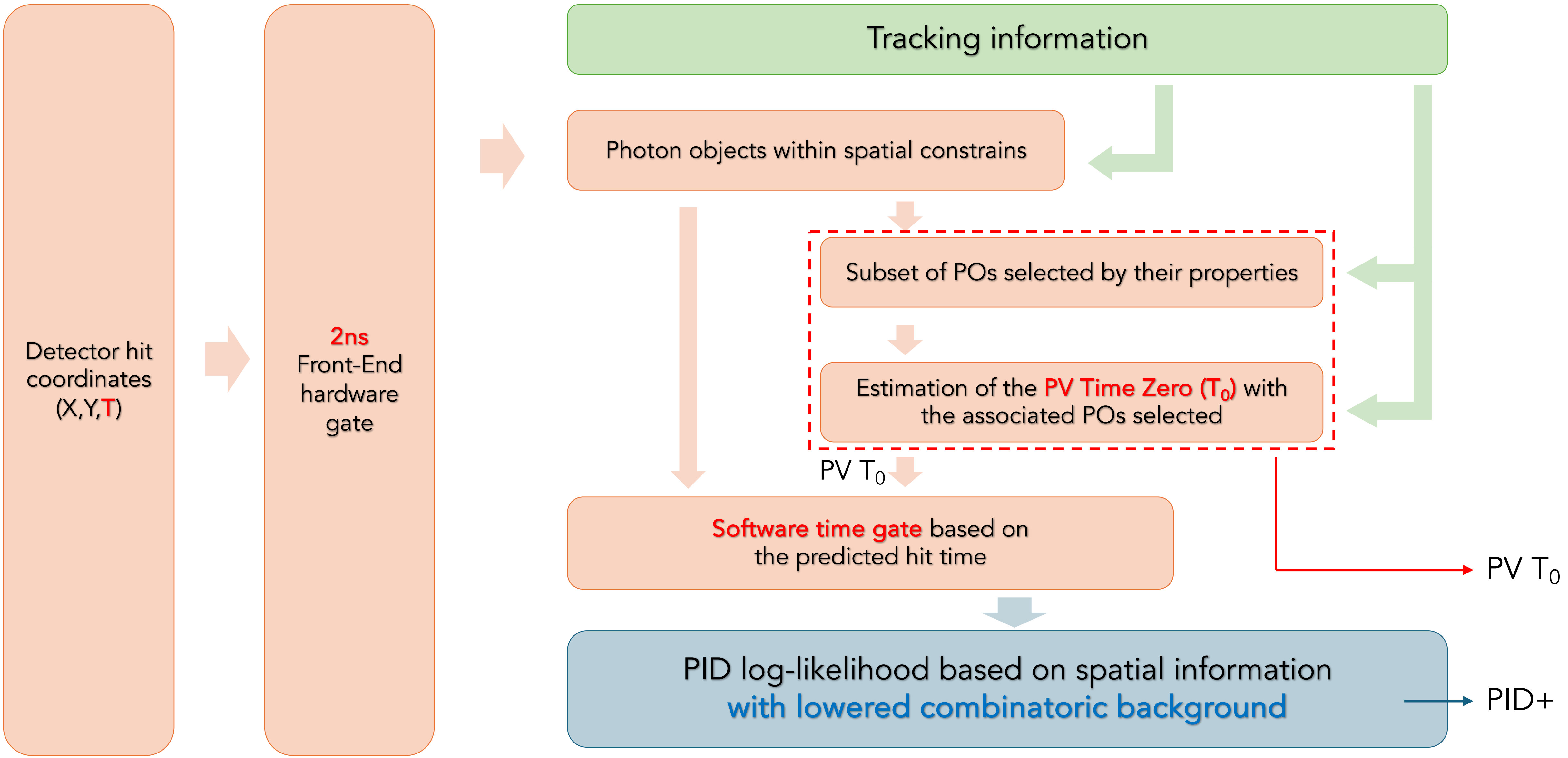
A **'photon object'** (PO) is created for each combination of a track and a pixel hit within spatial constraints.

**Each photon object is a candidate for a true combination**
(~20% is correct association, the rest is combinatoric background).

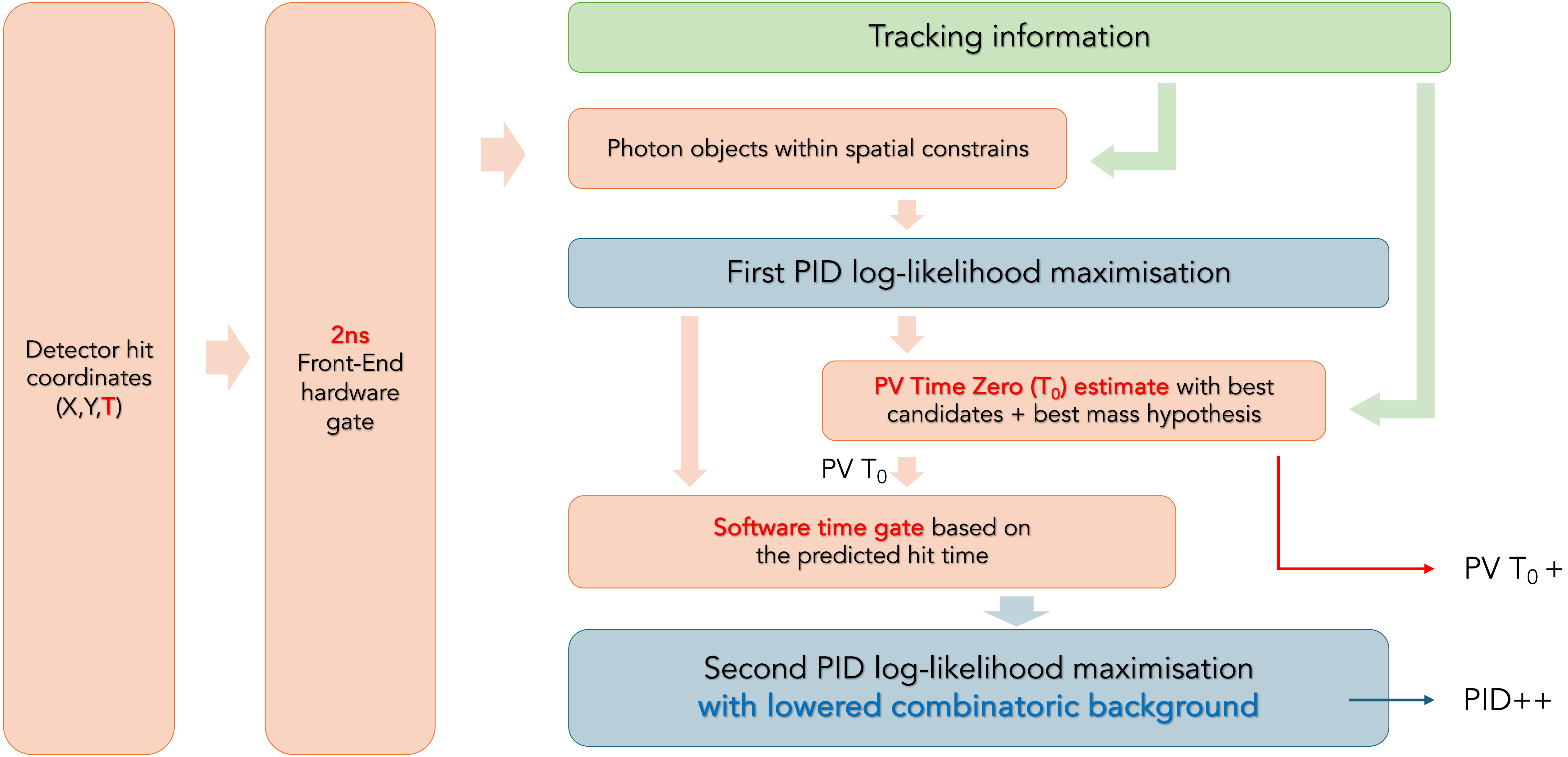
PID log-likelihood maximisation algorithm based on spatial information: Cherenkov angles.

→ PID

# Introduction of software time gate in the RICH reconstruction (RUN4)



# Introduction of software time gate in the RICH reconstruction (RUN4)



# RICH PV $T_0$ calculation and photon-objects-to-PV association

RICH PV $T_0$ obtained by **averaging the PV $T_0$ calculated for all the POs associated** with the PV.

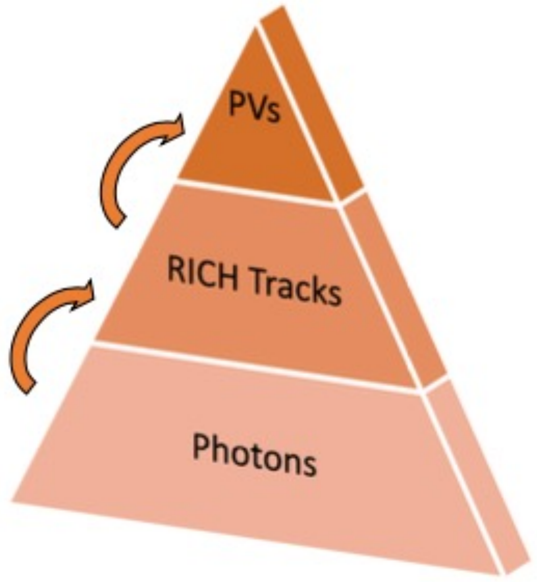
$$RICH\ PV\ T_0 = \left\langle \; t_{hit} - \underbrace{\frac{|r_A|}{c}\sqrt{1+\left(\frac{mc}{p}\right)^2}}_{\text{Track path to entry point}} - \underbrace{\frac{d_{A,E}}{c}\, n\cos\theta_c}_{\text{Track path inside the radiator}} - \underbrace{\left[d_{E,M1} + d_{M1,M2} + d_{M2,hit}\right]\frac{n}{c}}_{\text{Photon path inside the RICH}} + \underbrace{t_{spread}}_{\text{Sensor and FE spread}} \right\rangle_{\text{N POs -> PVs}}$$

Tracks → PVs
Optimised tracking which does not introduce inefficiencies.

Photons → Tracks
Correct relationship between photon hit and tracks affected by significant **combinatoric background**.

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

Several photon object (POs) and track qualities have been investigated to increase the **purity** of the POs.



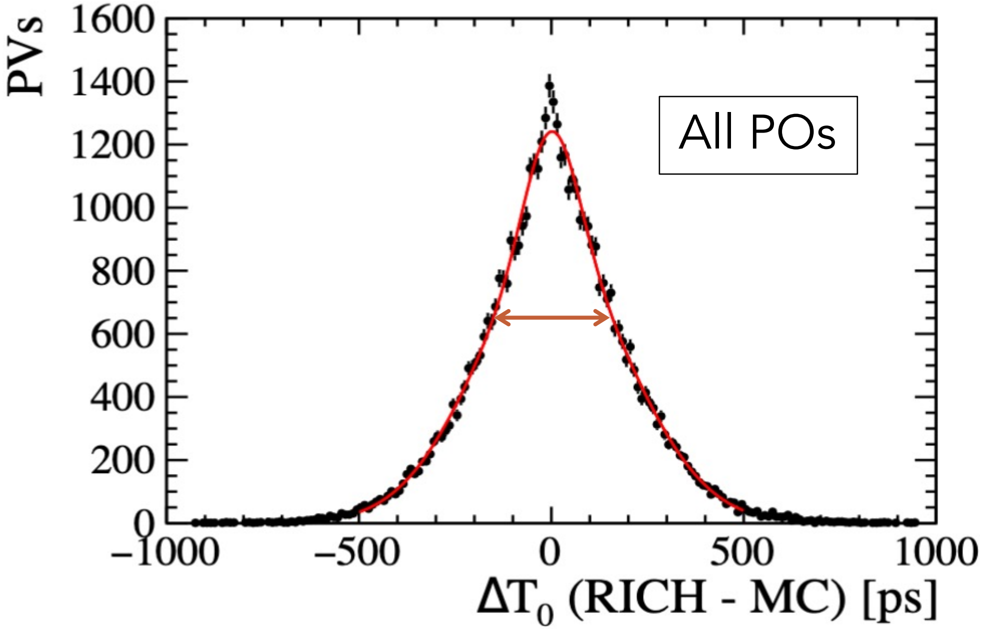
# PV $T_0$ resolution and POs purity impact on it

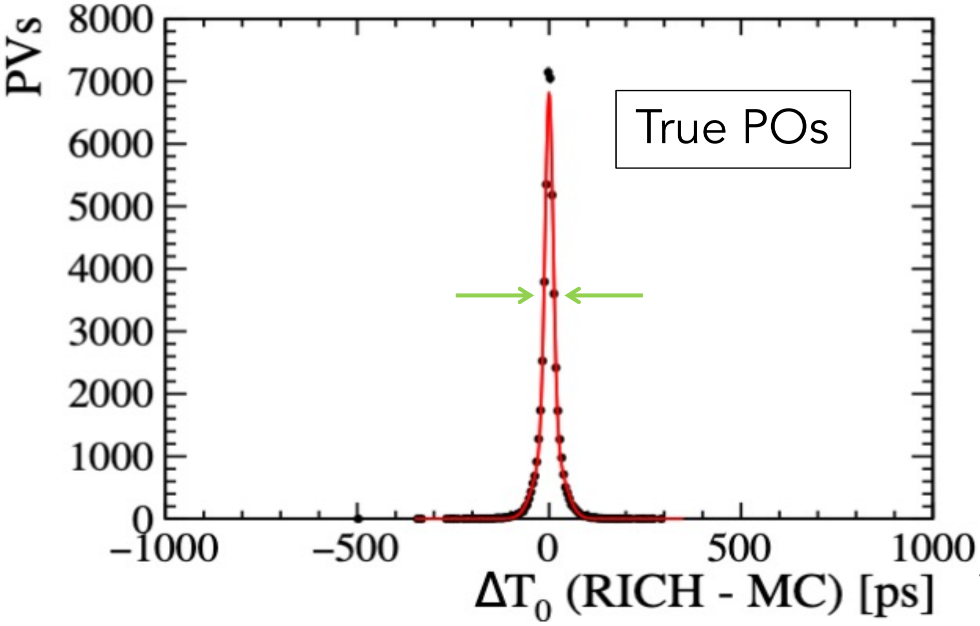
Resolution expressed as FWHM of the double gaussian fit.

With all the candidate POs -> 330ps.

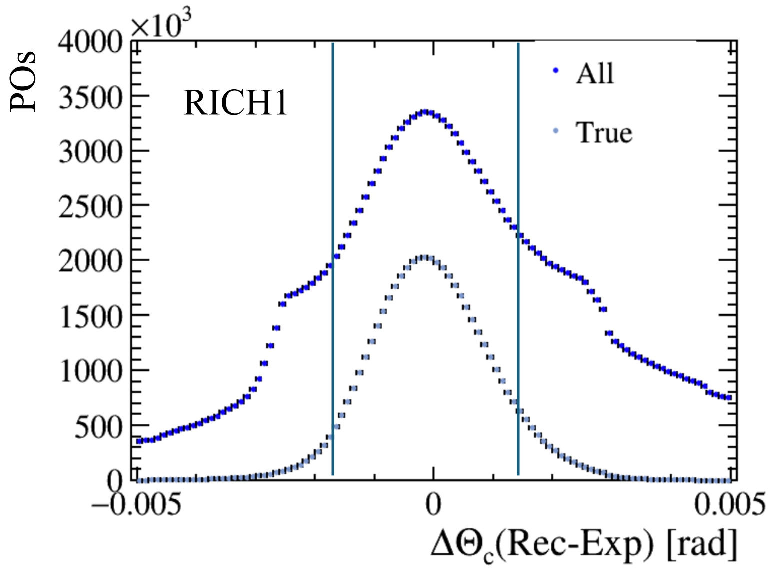
With true candidate POs -> 25ps.

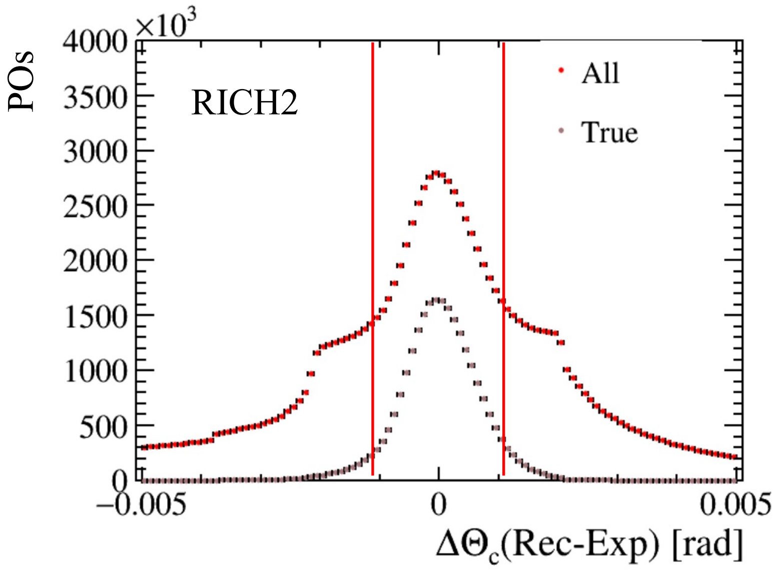
Focus on POs properties to improve the purity of the candidates.



# Cherenkov angle resolution ( $\Delta\theta$ )



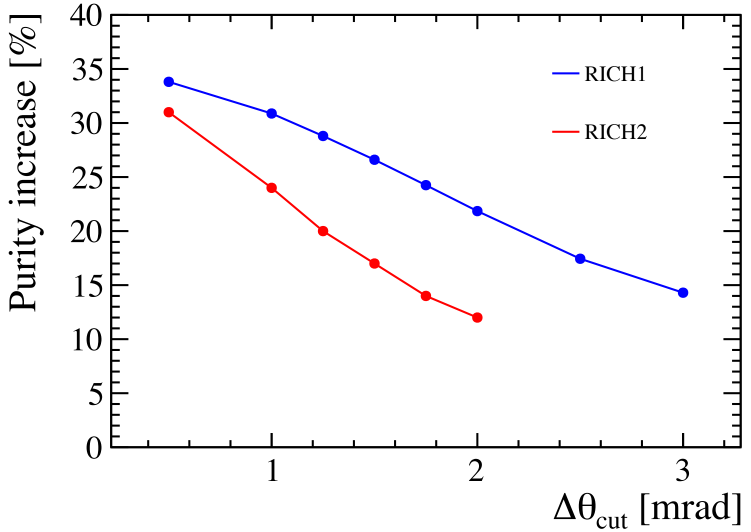



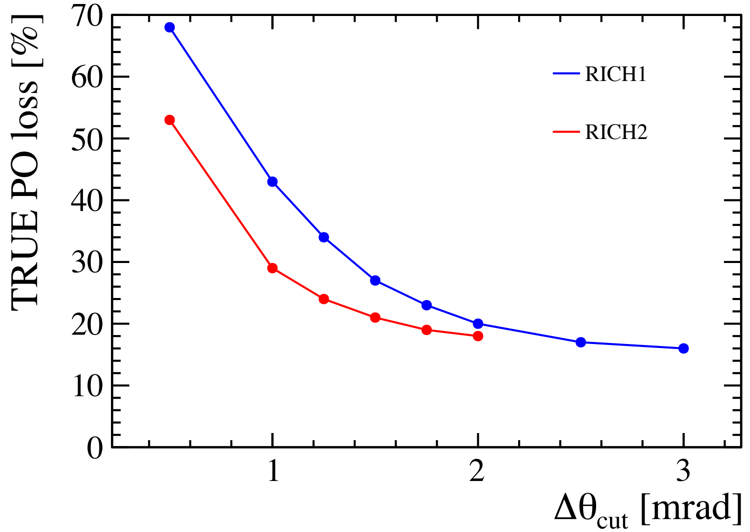

$\Delta\theta_c = \theta_{rec.} - \theta_{exp.\ (pion)}$

Tails mostly populated by fake candidates.

Optimal $\Delta\theta_c$ cuts are:

- 1.75 mrad for RICH1.
- 1.25 mrad for RICH2.



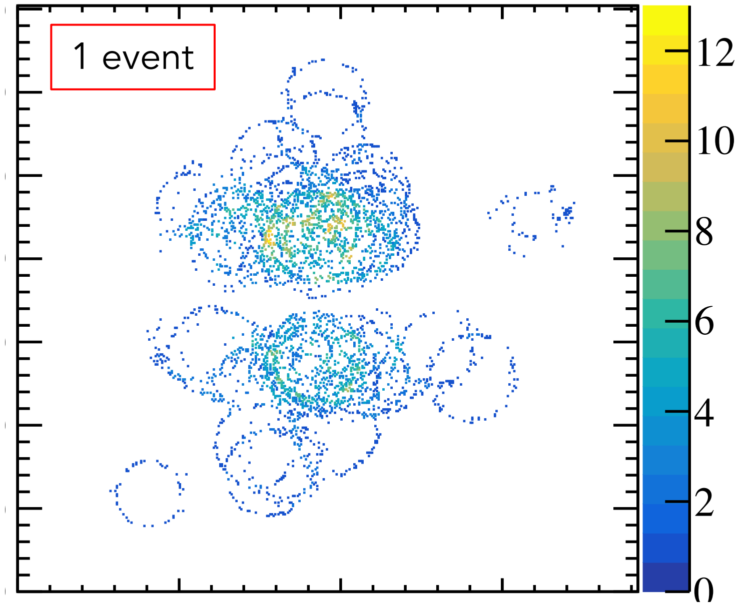



# Selection of pixels associated with one photon objects only (RICH1)

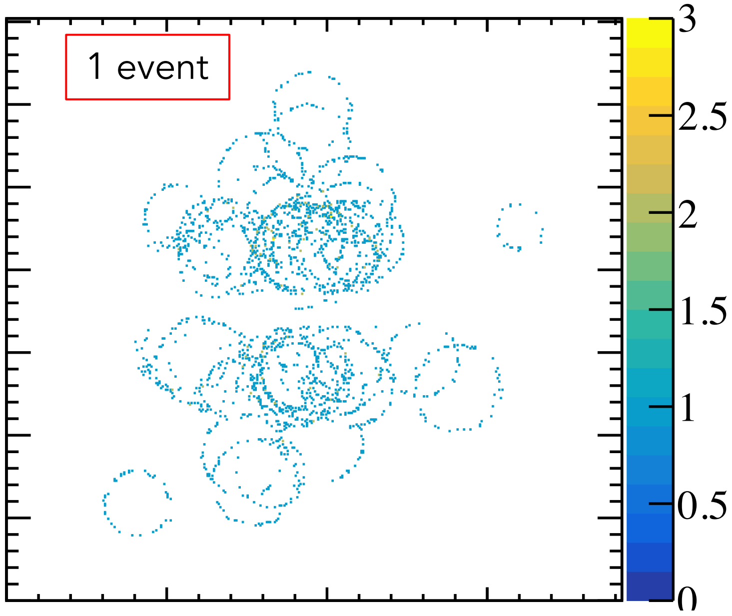
Only **10%** of the candidates passes this selection. High occupancy region strongly affected.

Nevertheless, $T_0$ **reconstructed for >99% of the PVs** and average **purity increase of ~30%**.

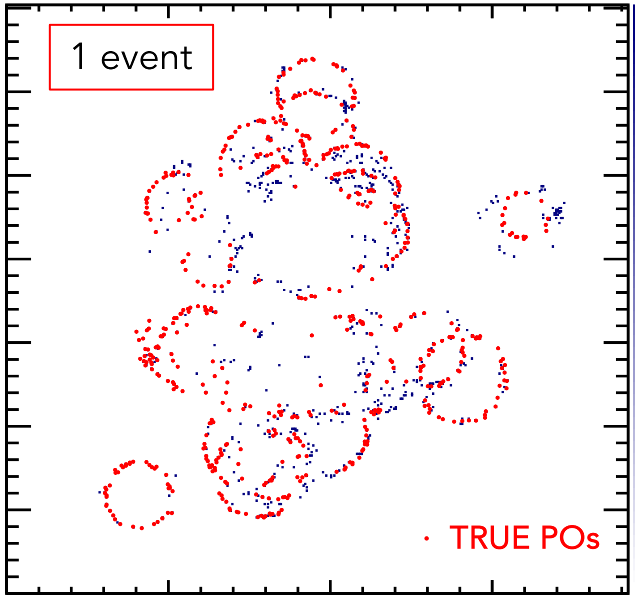
All POs




True POs



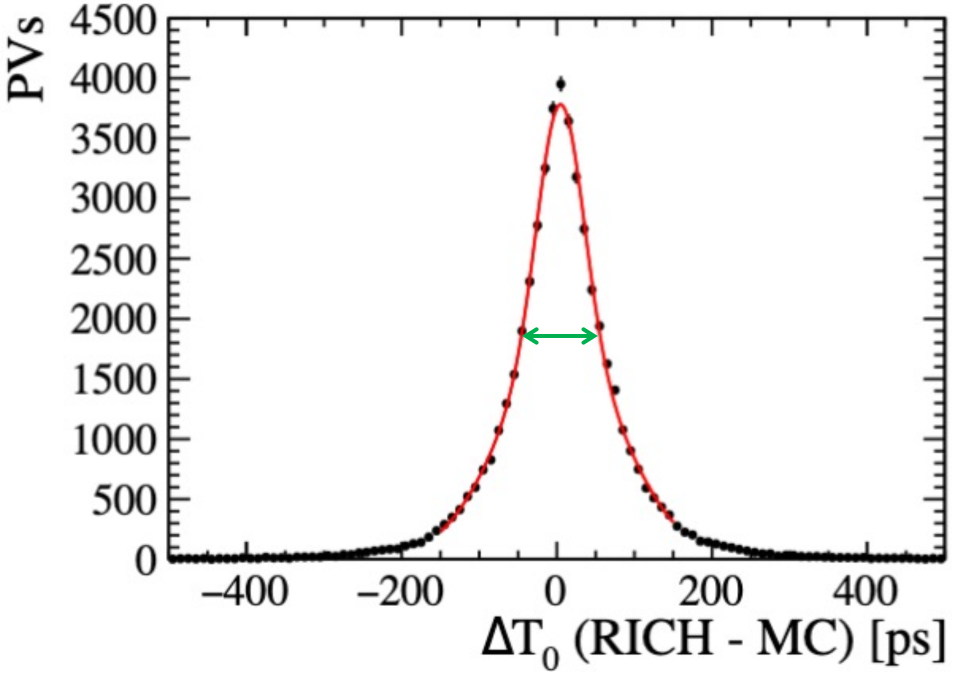

Pixels associated with one PO only

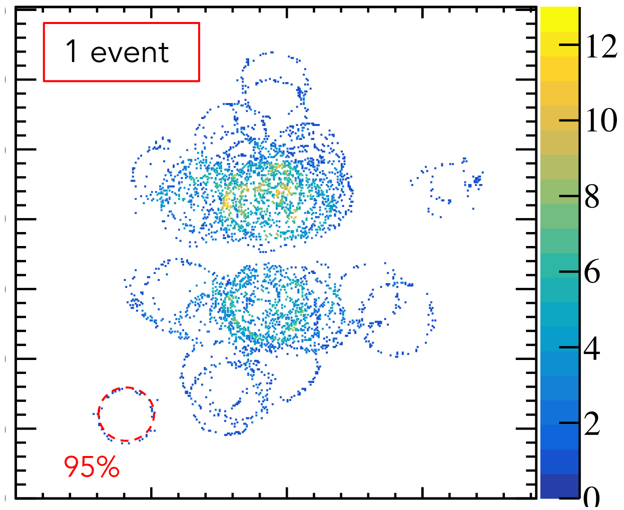


# PV $\Delta T_0$ resolution applying the 2 proposed cuts

The PV $T_0$ has been reconstructed for **98.7% of the PVs**.

The FWHM of the double gaussian fit is 97ps.



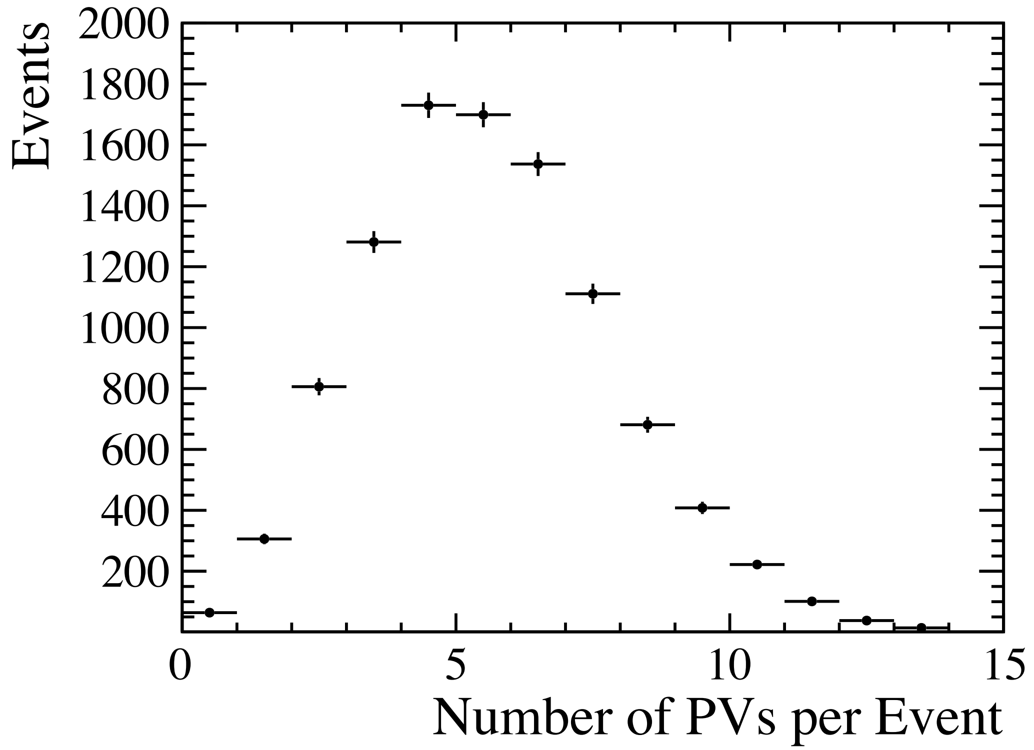



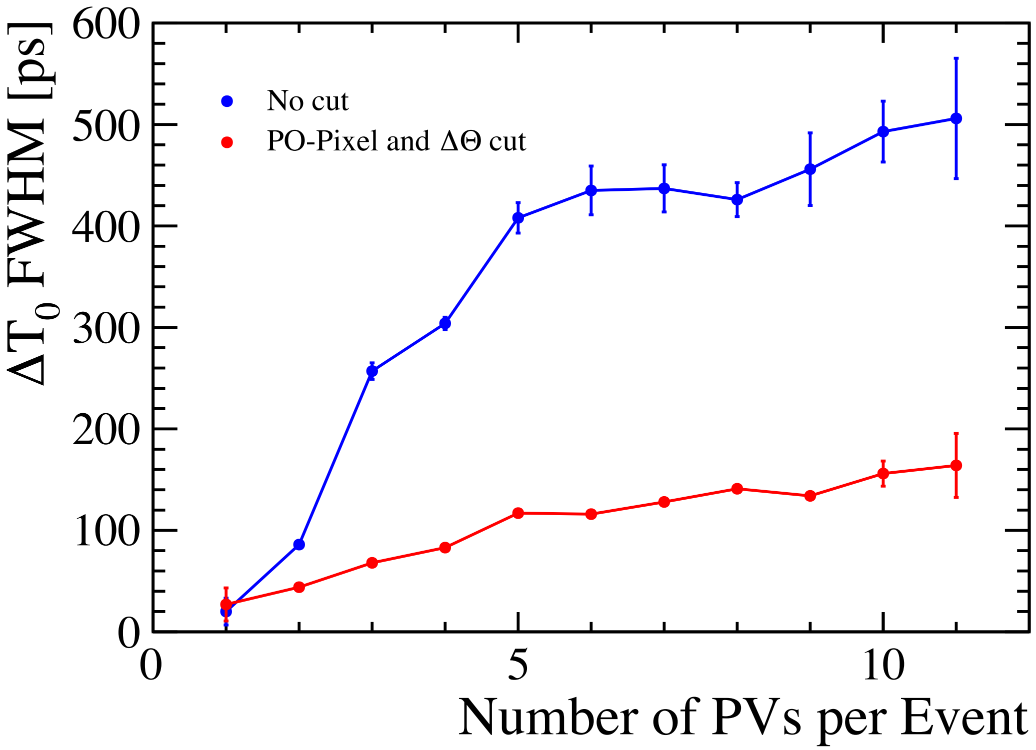

Further studies are ongoing on the PVs populating the tails.

Event-specific selections rather than global cuts:

- isolated tracks;
- number of PVs in the event.

# Impact of the number of PVs in the event on the $T_0$ resolution



# Conclusions

The study demonstrates the capability of estimating the PV $T_0$ using the RICH reconstruction information only.

Resolution of the PV $T_0$ estimate of 97ps (FWHM) for ~99% of the PVs.

Studies are ongoing to further improve the estimate resolution and to best integrate the algorithm in the reconstruction chain.

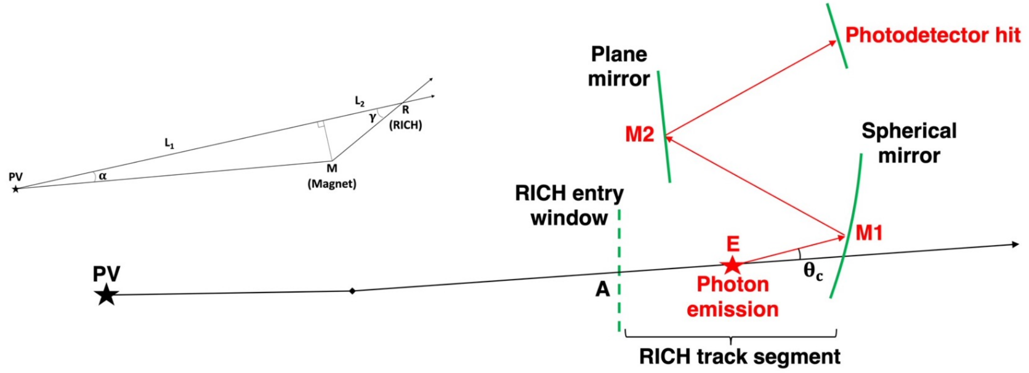
# BACKUP SLIDES

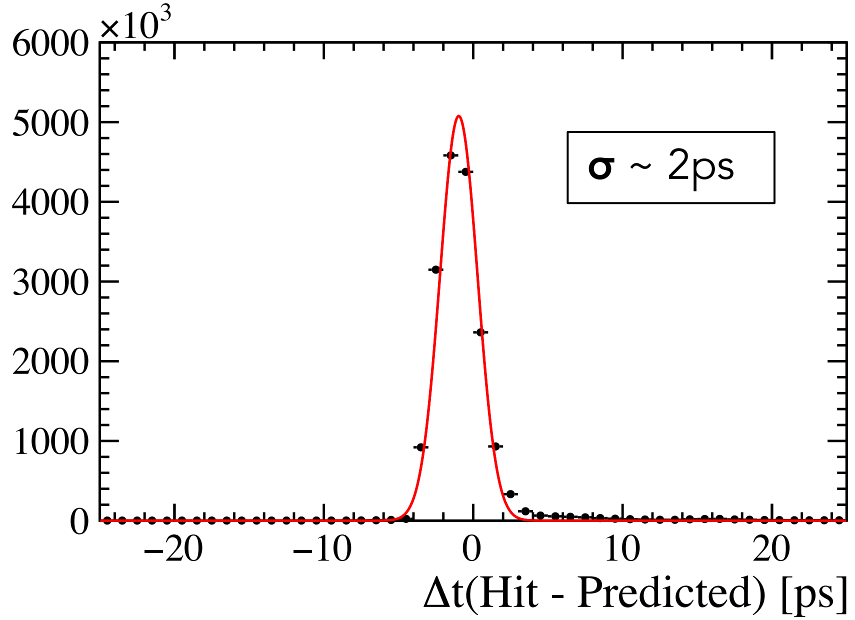
# Prediction of the photon hit time

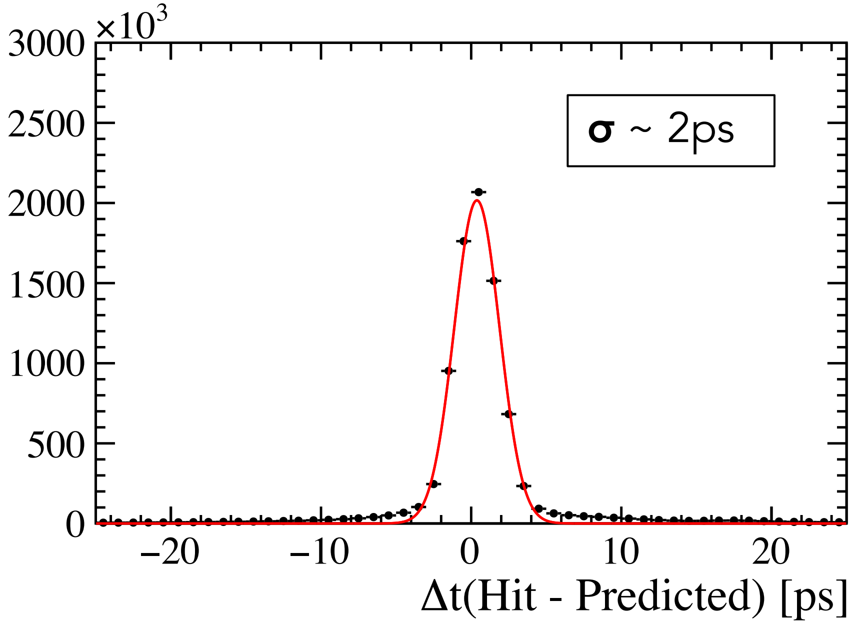
$$t_{hit|rec.} = t_{PV} + \frac{|r_A - r_{PV}|}{c}\sqrt{1+\left(\frac{mc}{p}\right)^2} + \frac{d_{A,E}}{c}\, n\, \cos\theta_c + \left[d_{E,M1} + d_{M1,M2} + d_{M2,hit}\right]\frac{n}{c}$$

Where for RICH 2, to account for curvature of low momentum tracks:

$$(r_A - r_{pv})' = (r_A - r_{pv})\left(1 + \frac{s}{2}\left(\frac{z_R}{z_M} - 1\right)\left(\frac{dx}{dz}\Big|_R - \frac{x}{z}\Big|_R\right)^2\right)$$

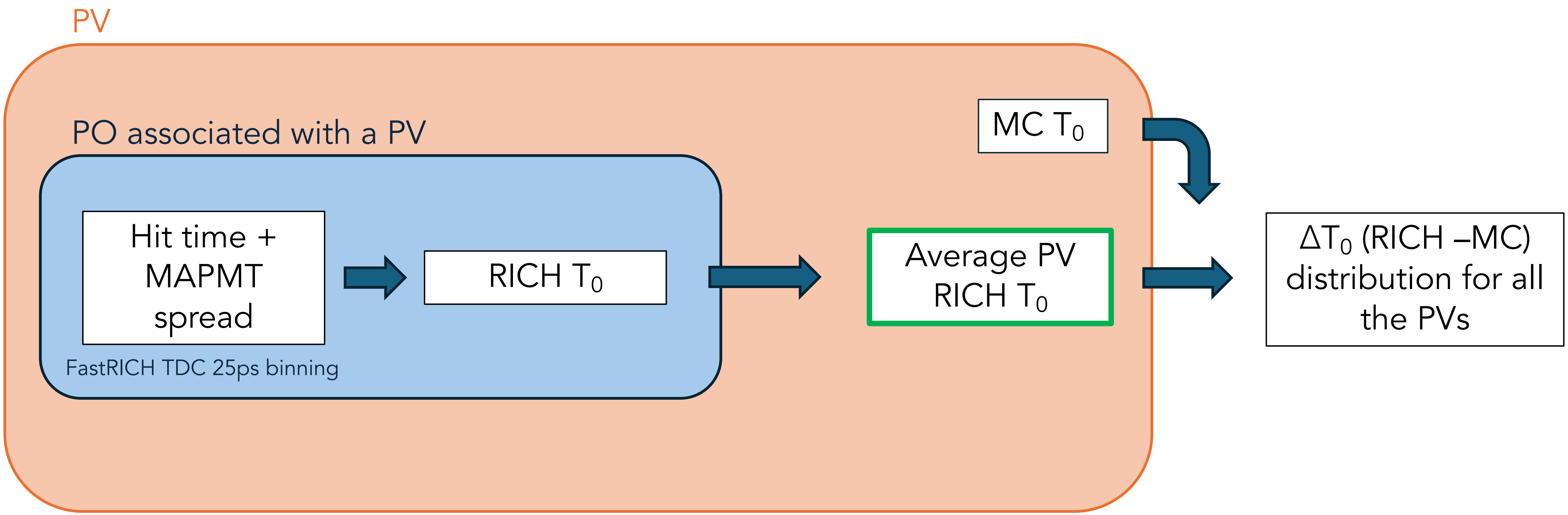


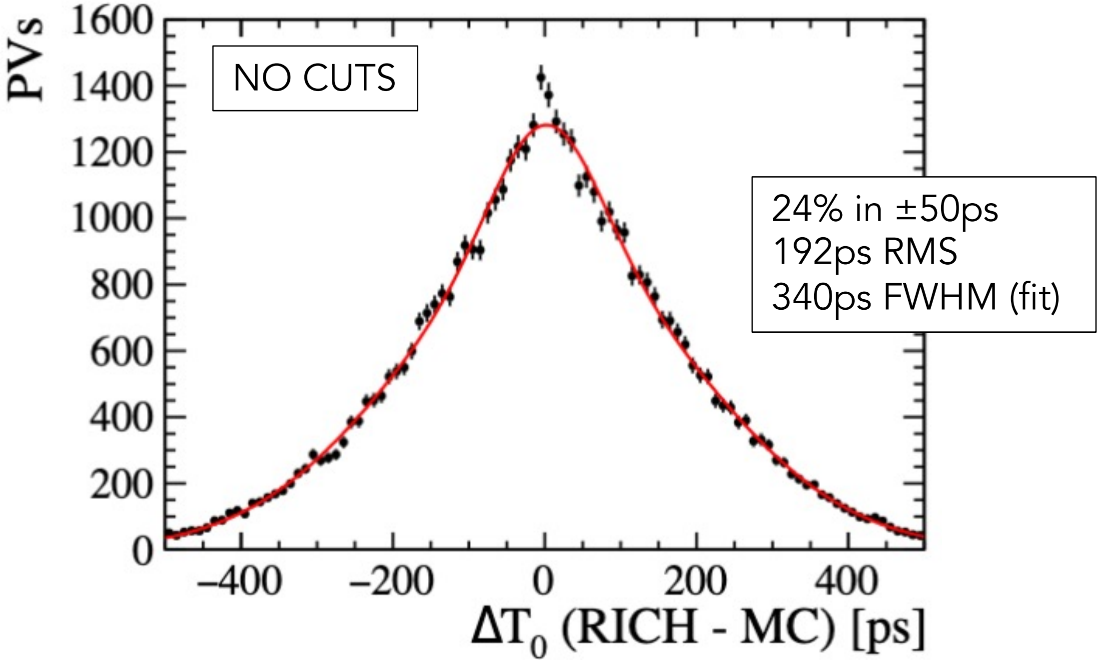



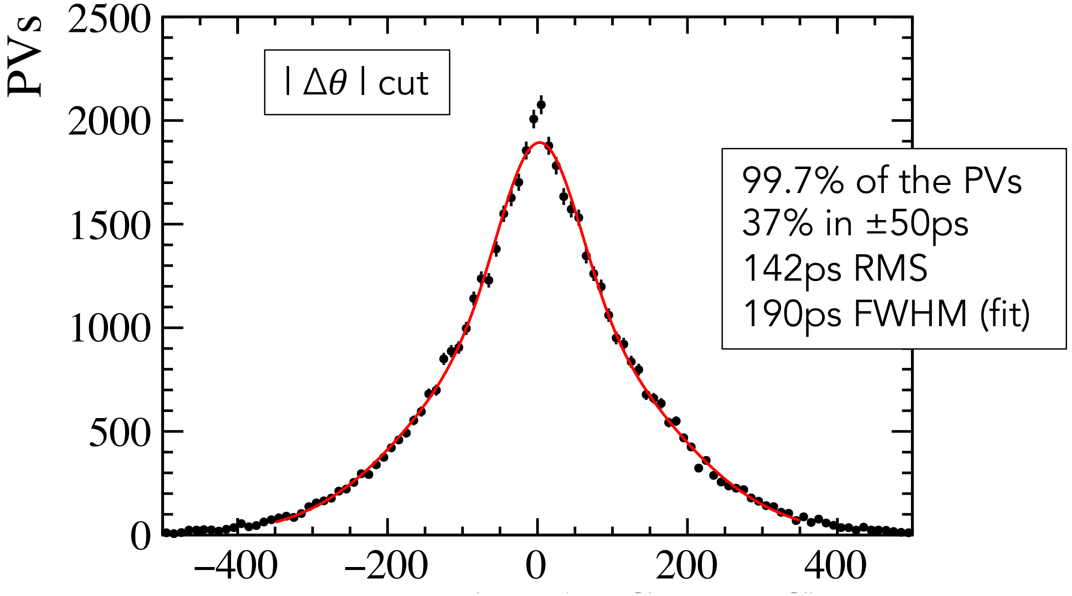
# Primary Vertex $T_0$ estimation with RICH information only

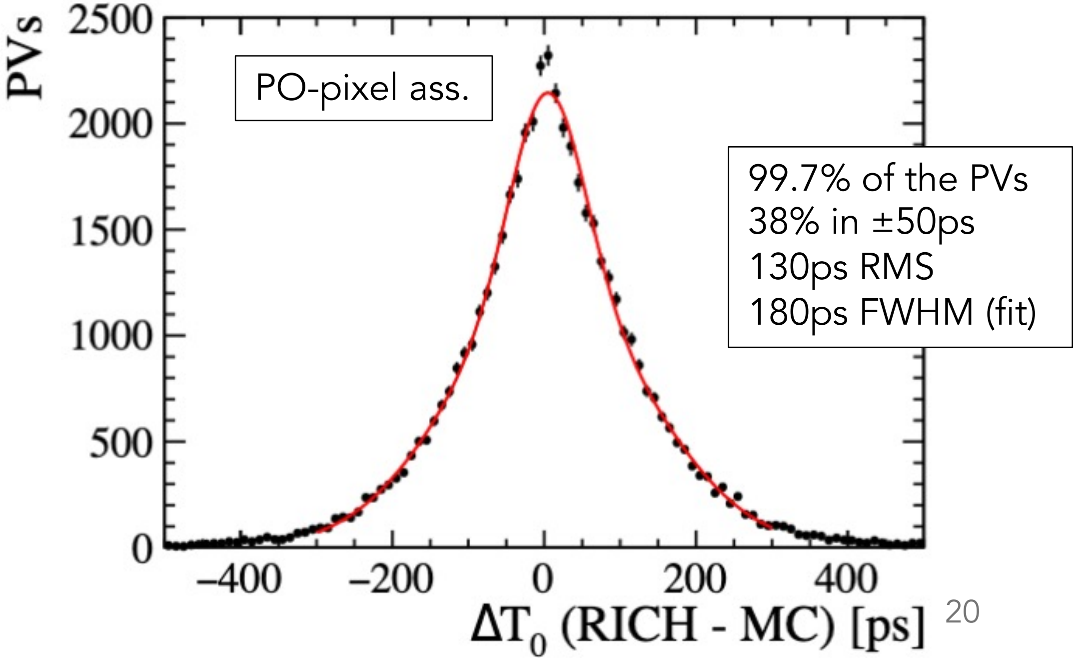
$$RICH\ PV\ T_0 = \left\langle t_{hit} - \frac{|r_A|}{c}\sqrt{1+\left(\frac{mc}{p}\right)^2} - \frac{d_{A,E}}{c}\, n\cos\theta_c - \left[d_{E,M1} + d_{M1,M2} + d_{M2,hit}\right]\frac{n}{c} + t_{spread} \right\rangle_{\text{N POs -> PVs}}$$



# 10k events – PV $T_0$ resolution applying the proposed cuts




Both the cuts improve the $\Delta T_0$ distribution going from an RMS of 200ps to <150ps. Moreover, the number of PVs in the ±50ps increases by >10%.

Nevertheless, this resolution is not enough to benefit from the software gate in terms of detector performance.

# Selection of pixels associated with one photon objects only (RICH1) + $\Delta\theta$ cut

The $\Delta\theta$ distribution after the PO-pixel association selection still presents tails, mostly populated by fake POs.

The **combination of the two cuts**, might lead to a purer sample of POs for the PV $T_0$ estimation.

Pixels associated with one PO only