The LHCb RICH Upgrade: Operations and Performance

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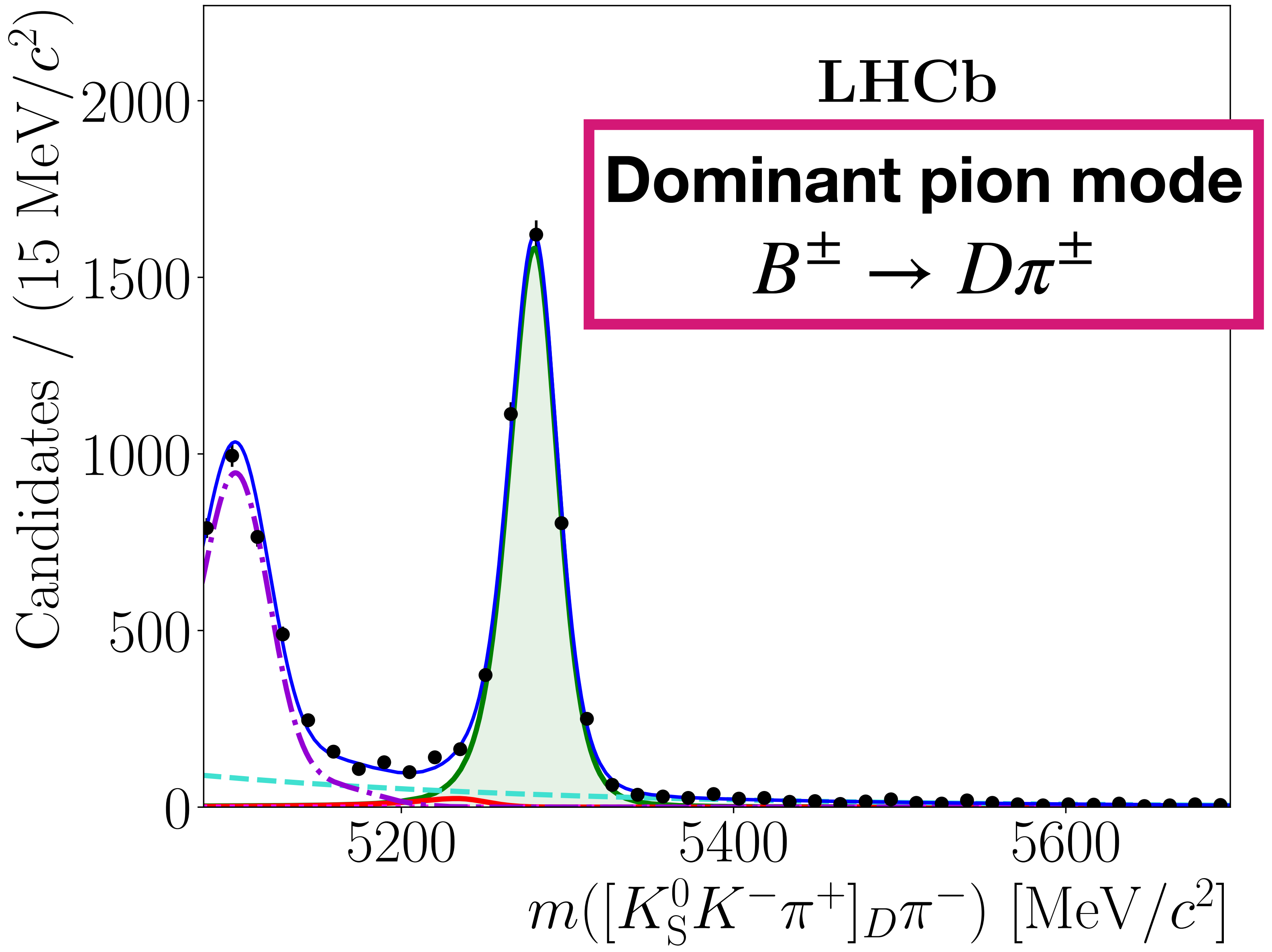
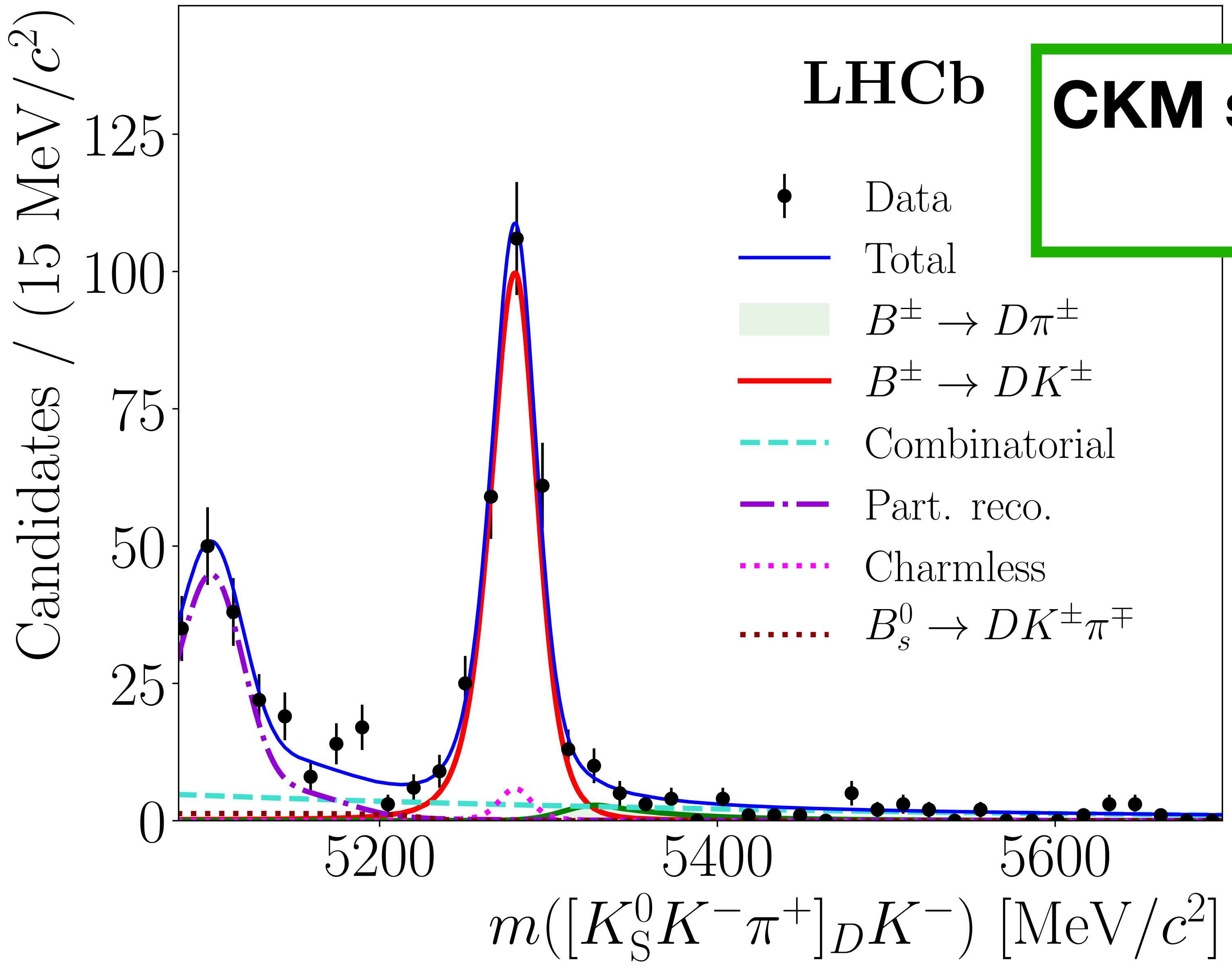
Charged Hadron identification with the LHCb RICH sub-detectors

- Charged hadron identification (PID) is a crucial component of the LHCb experiment, in particular for flavor physics studies.
- The RICH sub-detectors provide such essential PID capabilities in a wide momentum range ~[3,100] GeV/c, allowing to discriminate decays that have the same topology.
  - This is fundamental to **suppress leading order decay modes** and **efficiently select Cabibbo suppressed decays** to perform rare decay and CP violation studies
- Efficient combinatorial background rejection used by all LHCb analyses.
- More details on Giovanni's talk





CKM suppressed kaon mode
$B^{\pm} \to DK^{\pm}$

Dominant pion mode suppressed to negligible levels while retaining 70% of kaon candidates

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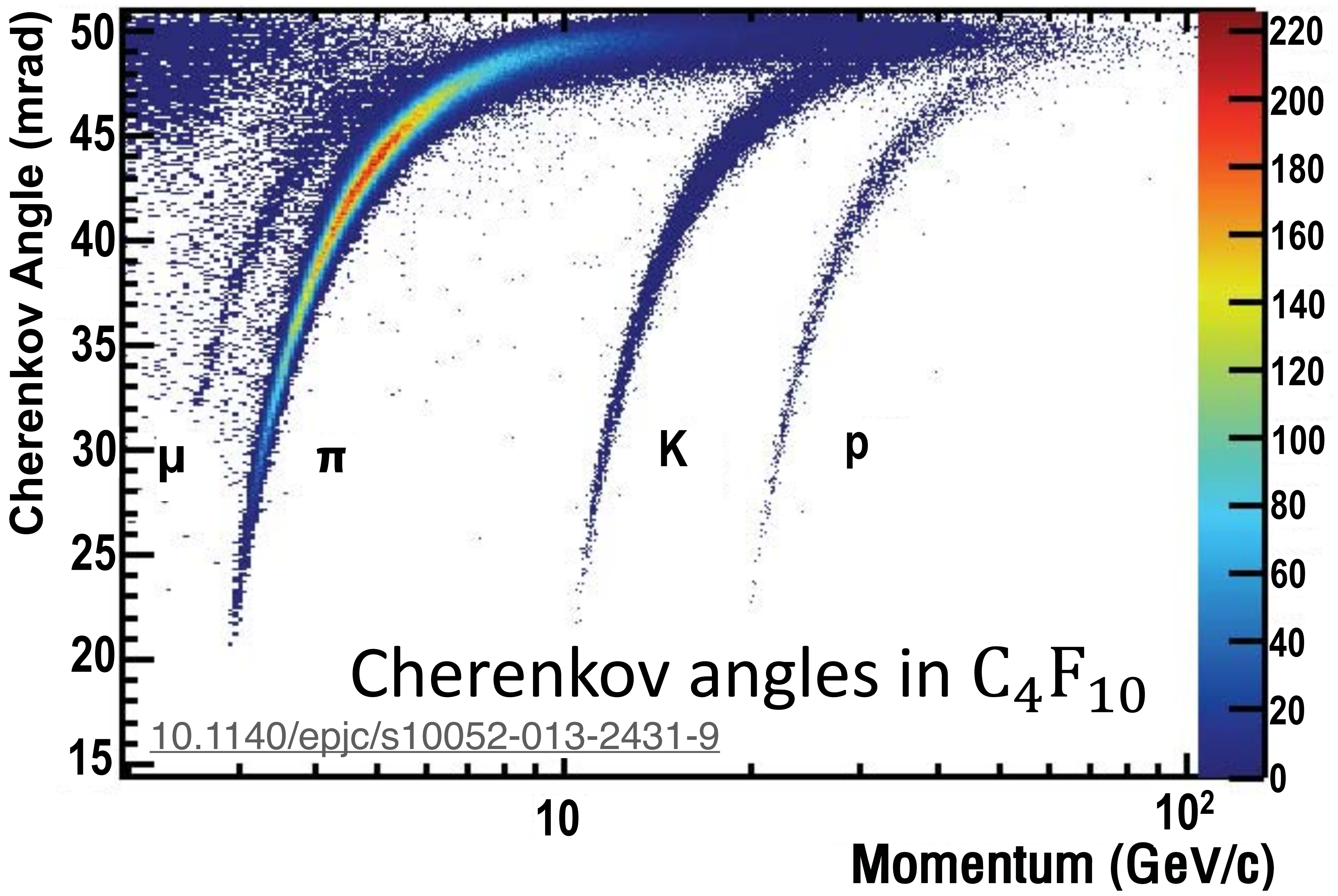
RICH detectors performance

- For a single track, two mass hypotheses (e.g. π and K) can be separated using the measured Cherenkov angle by estimating the number of standard deviations n_σ that separates them:

$$n_\sigma = \frac{\Delta\theta_c}{\Delta\theta_{c,res}} = \frac{|m_K^2 - m_\pi^2|}{2p^2 \Delta\theta_{c,res} tan(\theta_c)}$$

where $$\Delta\theta_{c,res} = \frac{\sigma_c}{\sqrt{N_{ph}}} + C_{tracking,alignment,..}$$



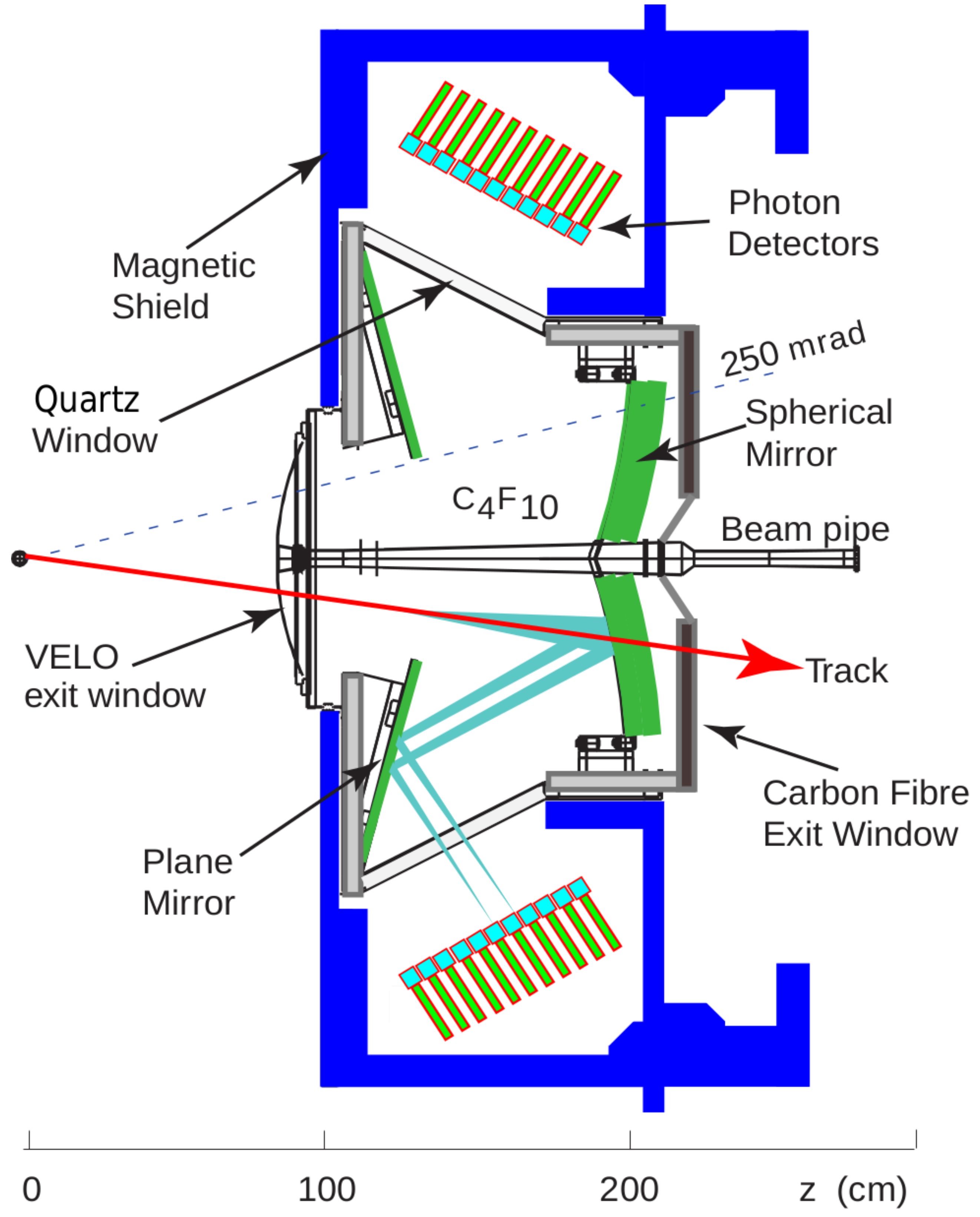
- The RICH detectors performance is intrinsically driven by:
  - Cherenkov angle resolution σ_c:
    - Emission point error
    - Pixel size error
    - Chromatic uncertainty
- Detected Cherenkov photon per track N_{ph}
- Contribution from tracking system (to estimate p and tracks trajectories)

The LHCb RICH Upgrade: present and past detectors

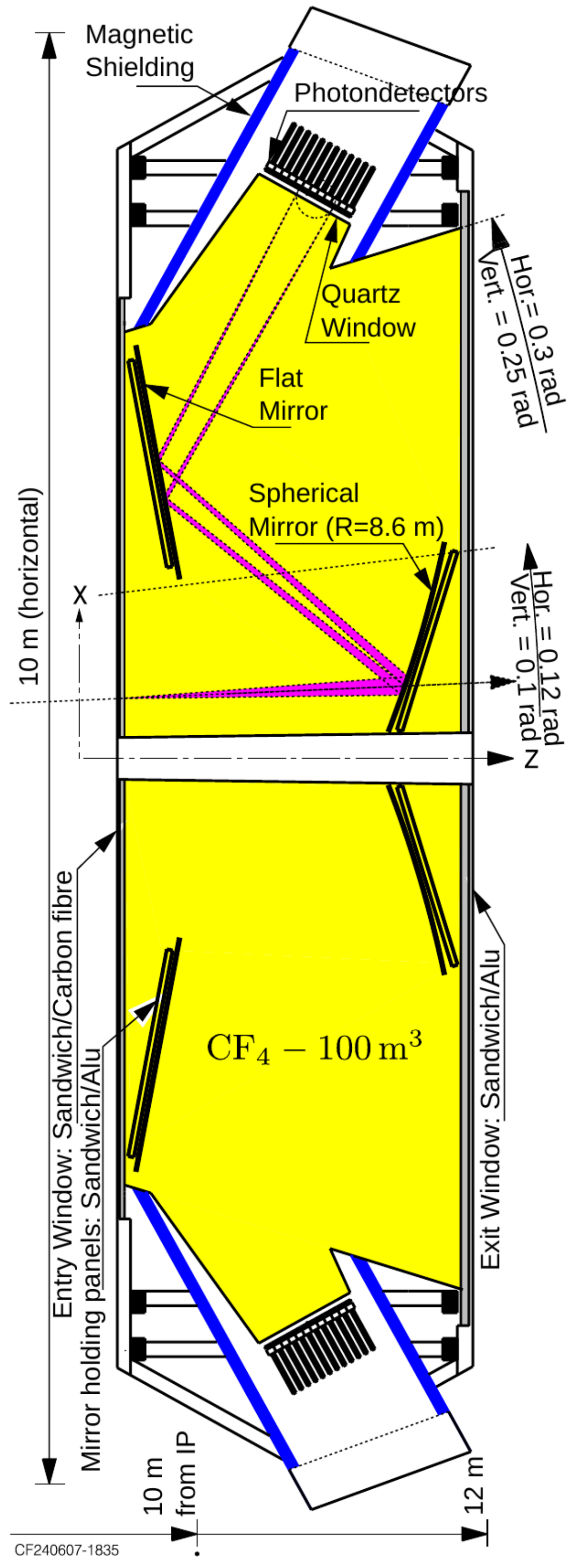
- There are two RICH detectors, both composed by a gas enclosure containing the radiator and an optical system composed by spherical and flat mirrors.

- The optoelectronic chain is composed by position sensitive sensors with the relative electronics, placed outside the LHCb detector acceptance.

RICH1
[3,40] GeV/c over 25-300 mrad



RICH2
[15,100] GeV/c over 15-120 mrad



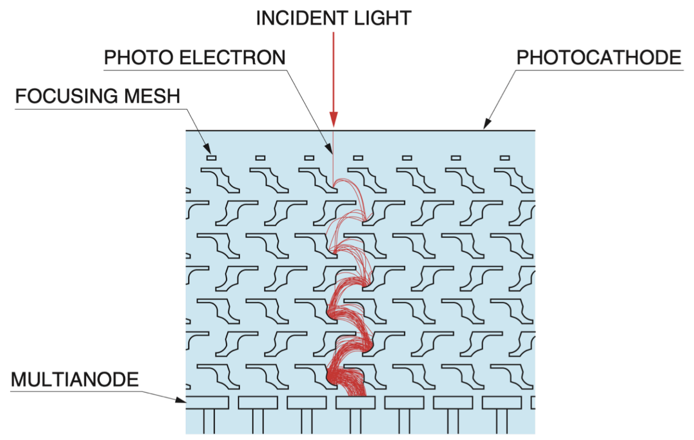
RICH during LHC Run 1-2	RICH Upgrade (LHC Run 3)
Hybrid Photon Detectors (HPDs) 1MHz readout front-end encapsulated with the HPDs	Multi-Anode Photomultipliers (MAPMTs) New Front-End (FE) Electronics, featuring the CLARO8 ASIC New DAQ system New optical system for RICH1

The LHCb RICH Upgrade

- After Run 1/2, LHCb experiment's precision on key flavor physics observables were still statistically limited.
  - Main limitation with the upgraded luminosity: maximum allowed output rate of the first trigger stage (L0), implemented in hardware.
  - Optimal strategy: implementation of a full-software trigger that discriminates signal channels based on complete event reconstruction.

New trigger strategy, higher luminosity alongside a full revision of the software and data processing

- Active area of the order of 80% and spatial granularity O(10 mm^2)
- appropriate gain and quantum efficiency
  - Gain higher than 10^6 e^-
  - Quantum efficiency of the order of 40% at 300 nm thanks to the ultra bi-alkali photocathodes
- low dark count rate (O(kHz/cm^2))



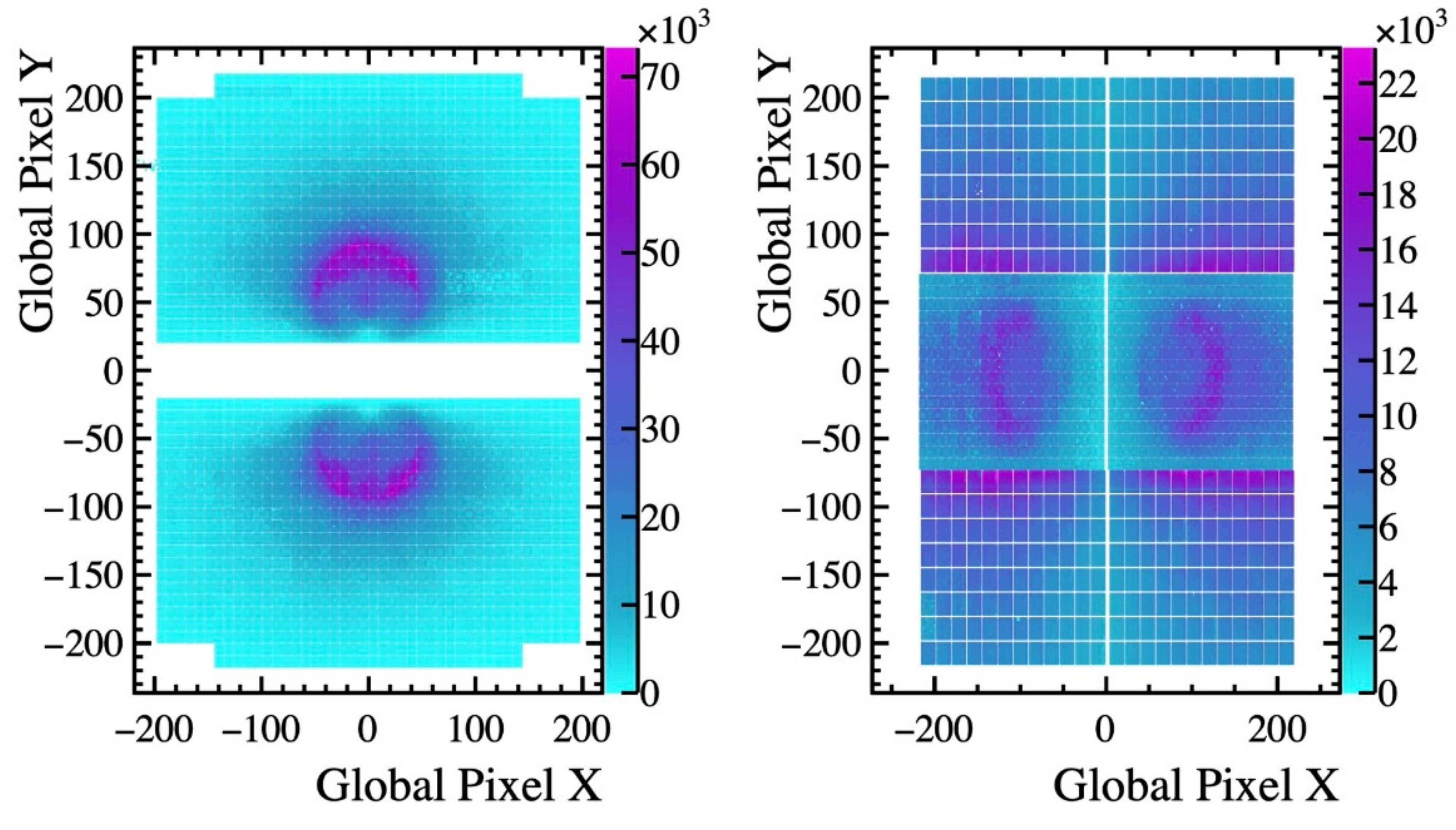
Single-photon detection at the 40 MHz LHC bunch crossing rate achieved with CLARO asic

To magnify the ring and spread photons over a larger area
- Peak occupancy under 30% in order to maintain the PID performance

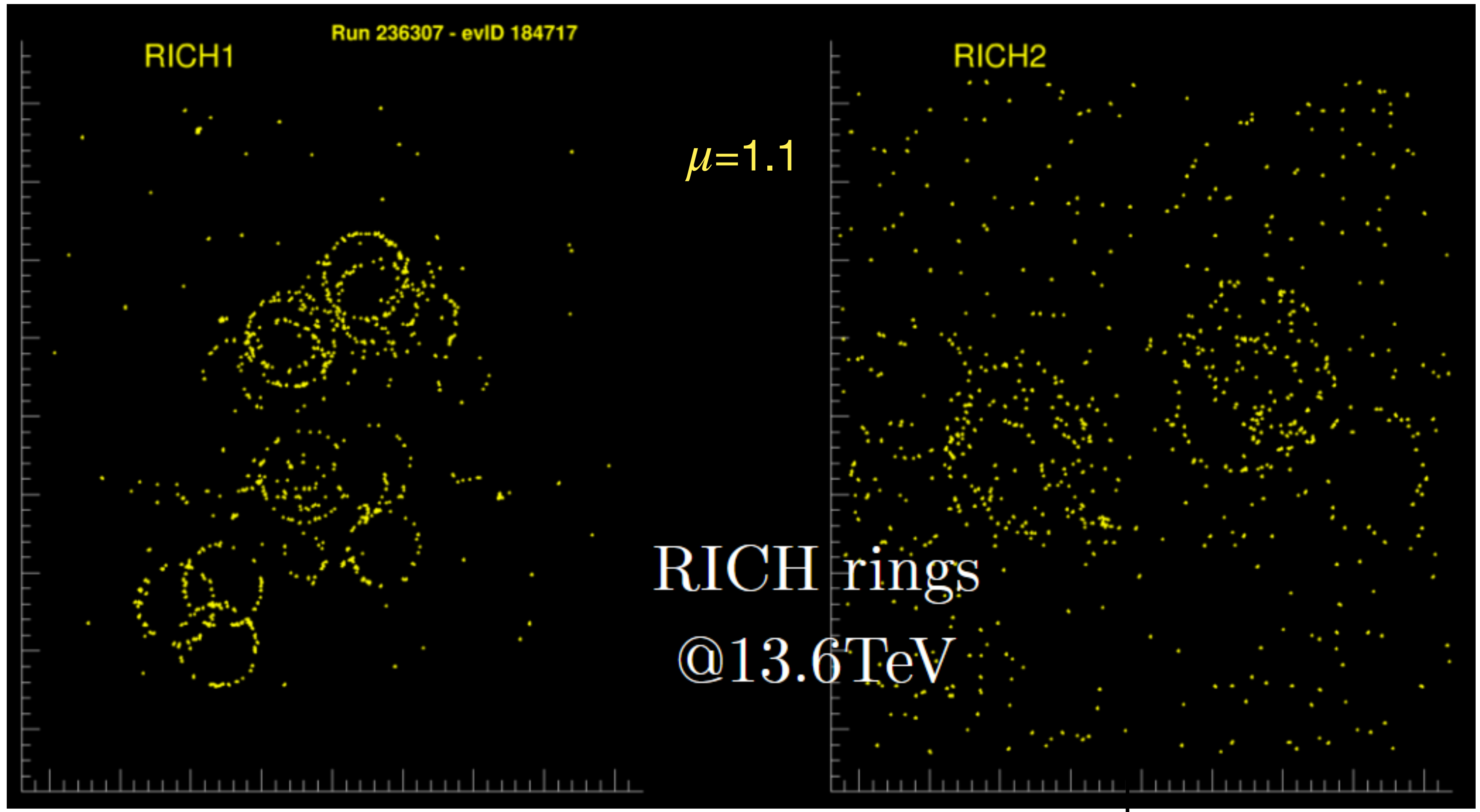
RICH Upgrade (LHC Run 3)
Multi-Anode Photomultipliers (MAPMTs) New Front-End (FE) Electronics, featuring the CLARO8 ASIC New DAQ system New optical system for RICH1

Upgraded RICH detectors

RICH detectors have been fully operational since the start of Run 3

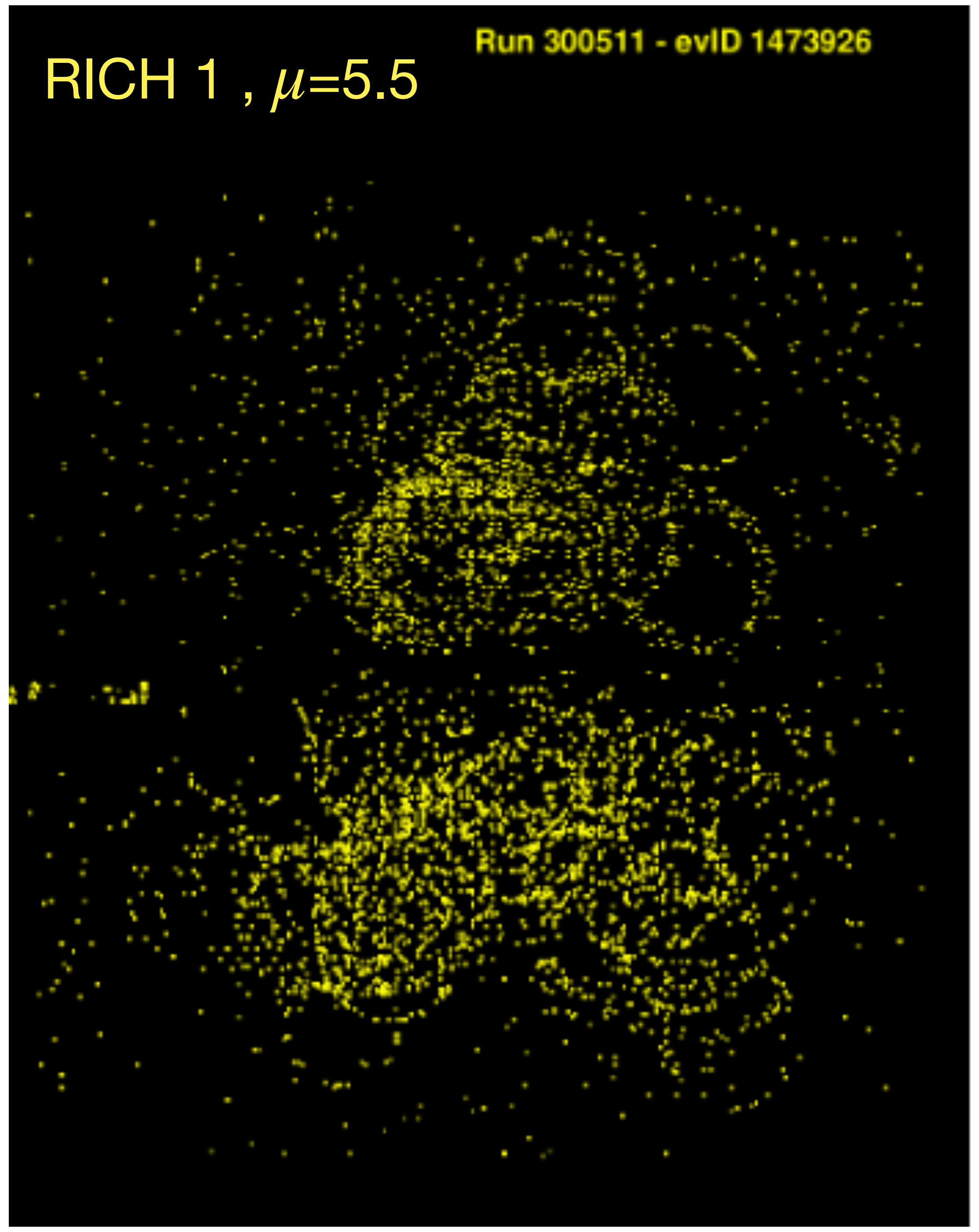


Cumulative hitmaps



ICHEP 2022:

LHCb highlights



Single event display at nominal pileup

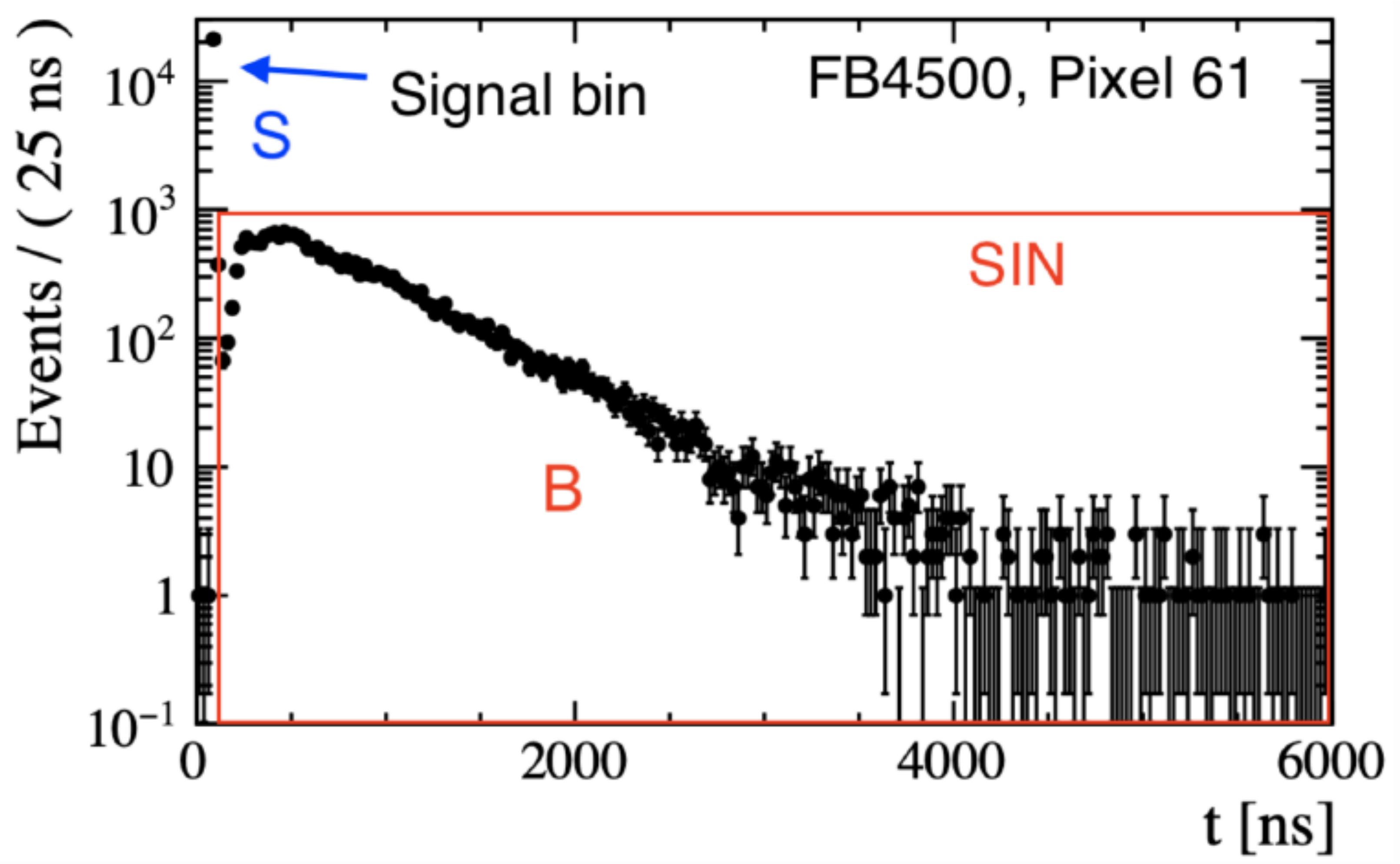
Calibration and monitoring of the photo-detection chain

- Several calibration procedures have been followed in order to ensure the best detector performance:

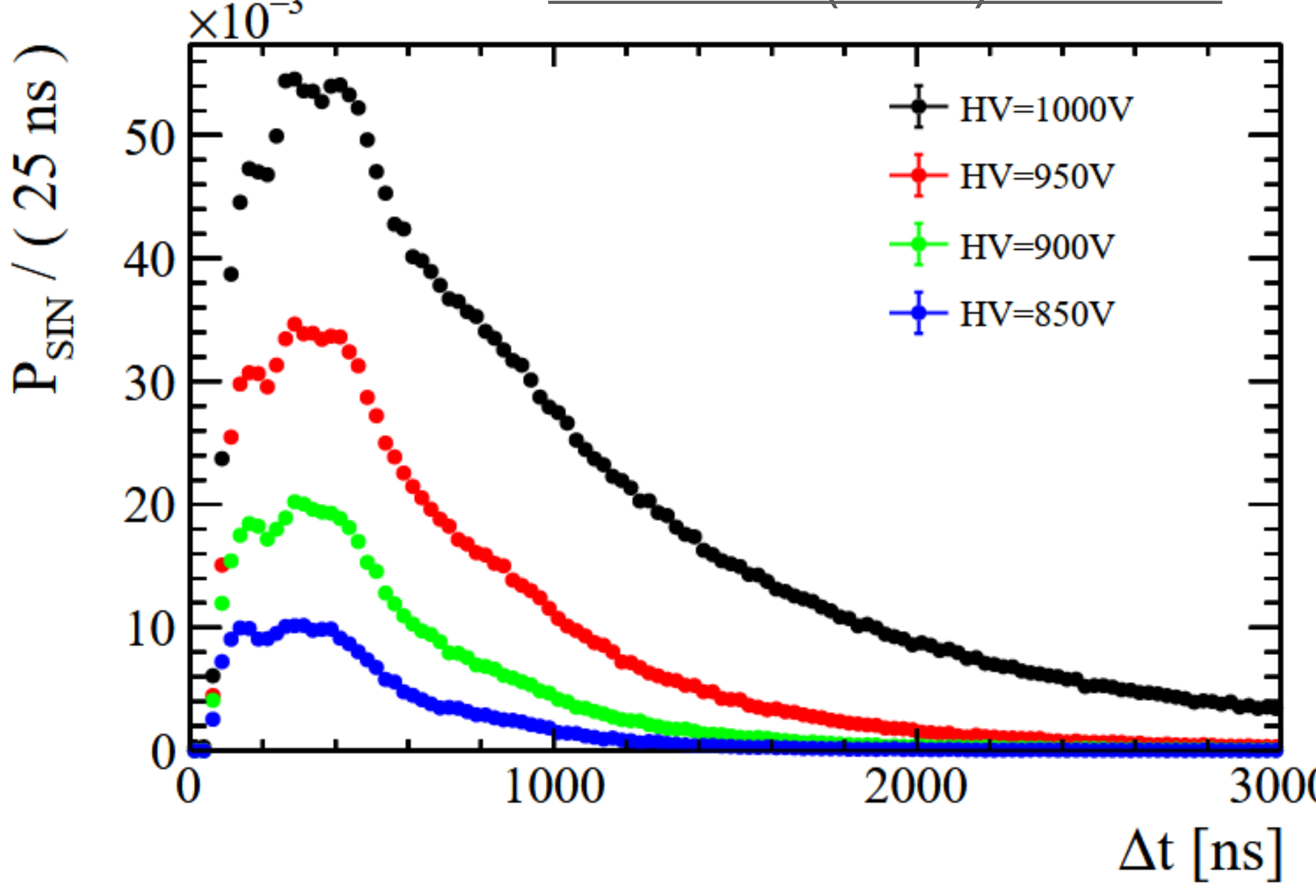
  - **Background studies:**
    - Signal Induced Noise: noise present only in correlation with signal and located in specific areas of the MaPMT

  - **Luminosity estimation:** obtained monitoring the calibrated measurement of the power supply currents
    - Last dynode of the MaPMTs supplied independently to preserve gain linearity at high rates up to 100 MHz/cm^2

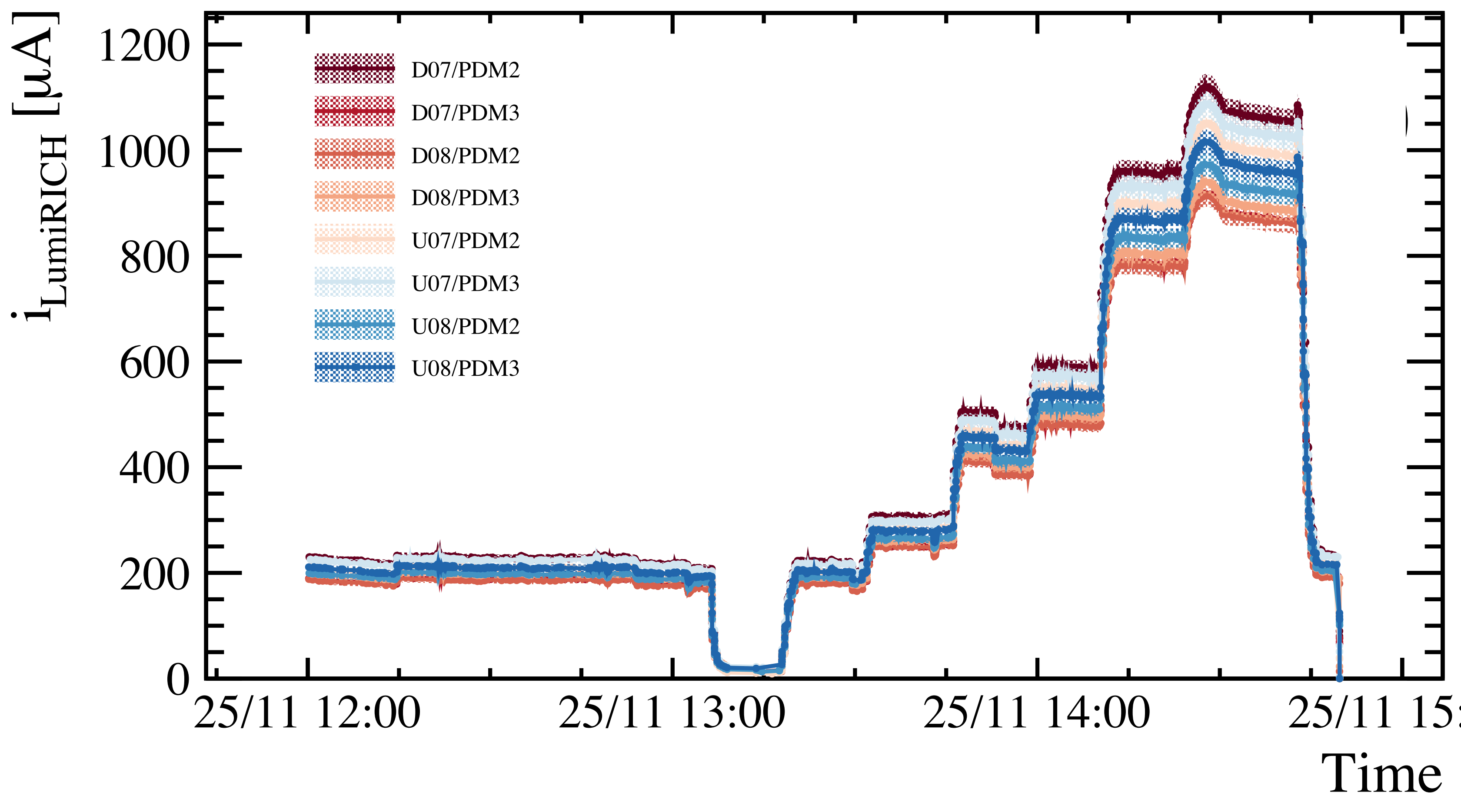
  - **Gain monitoring** via threshold scans



JINST 16 (2021) P11030



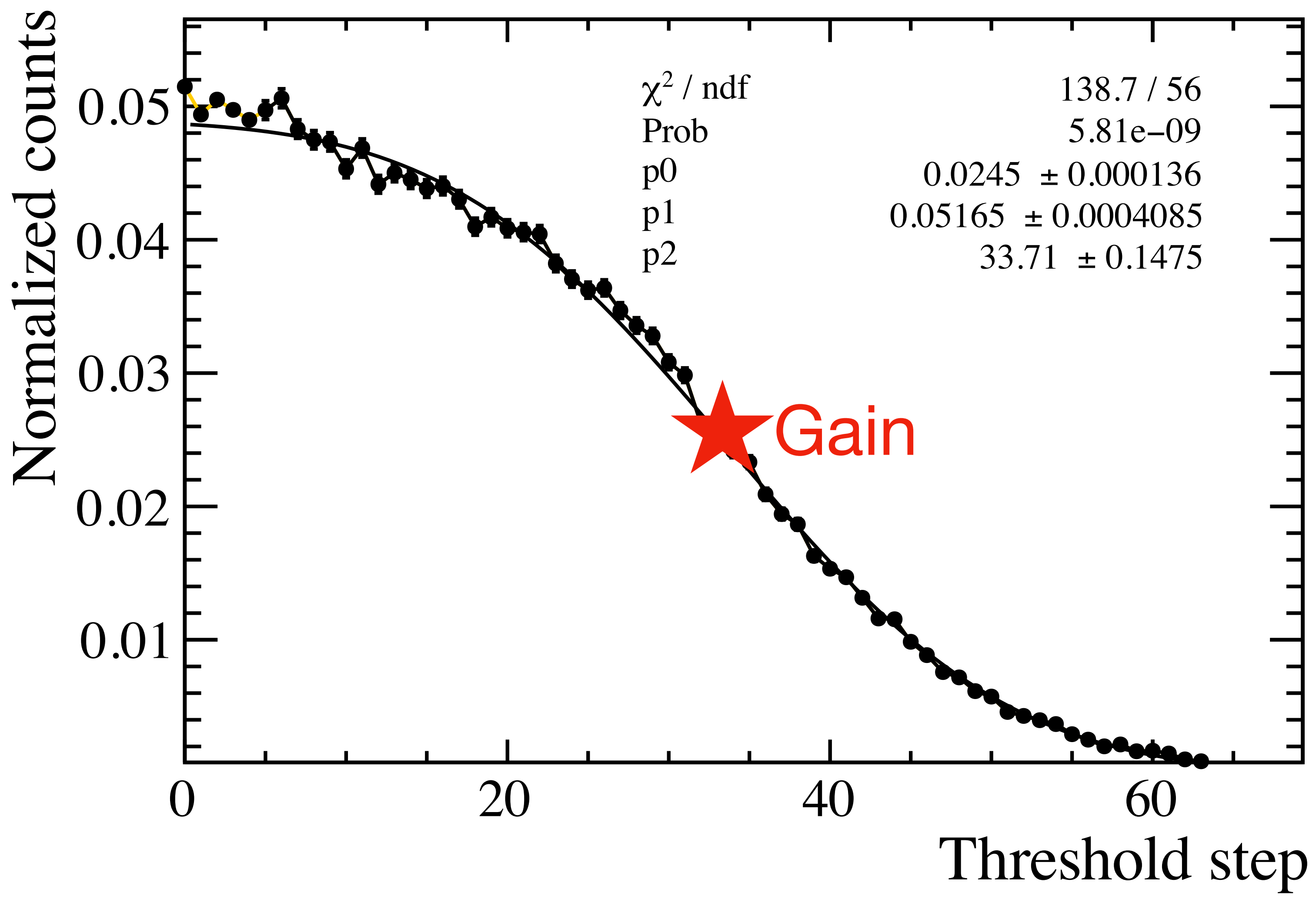
arXiv:2503.05273

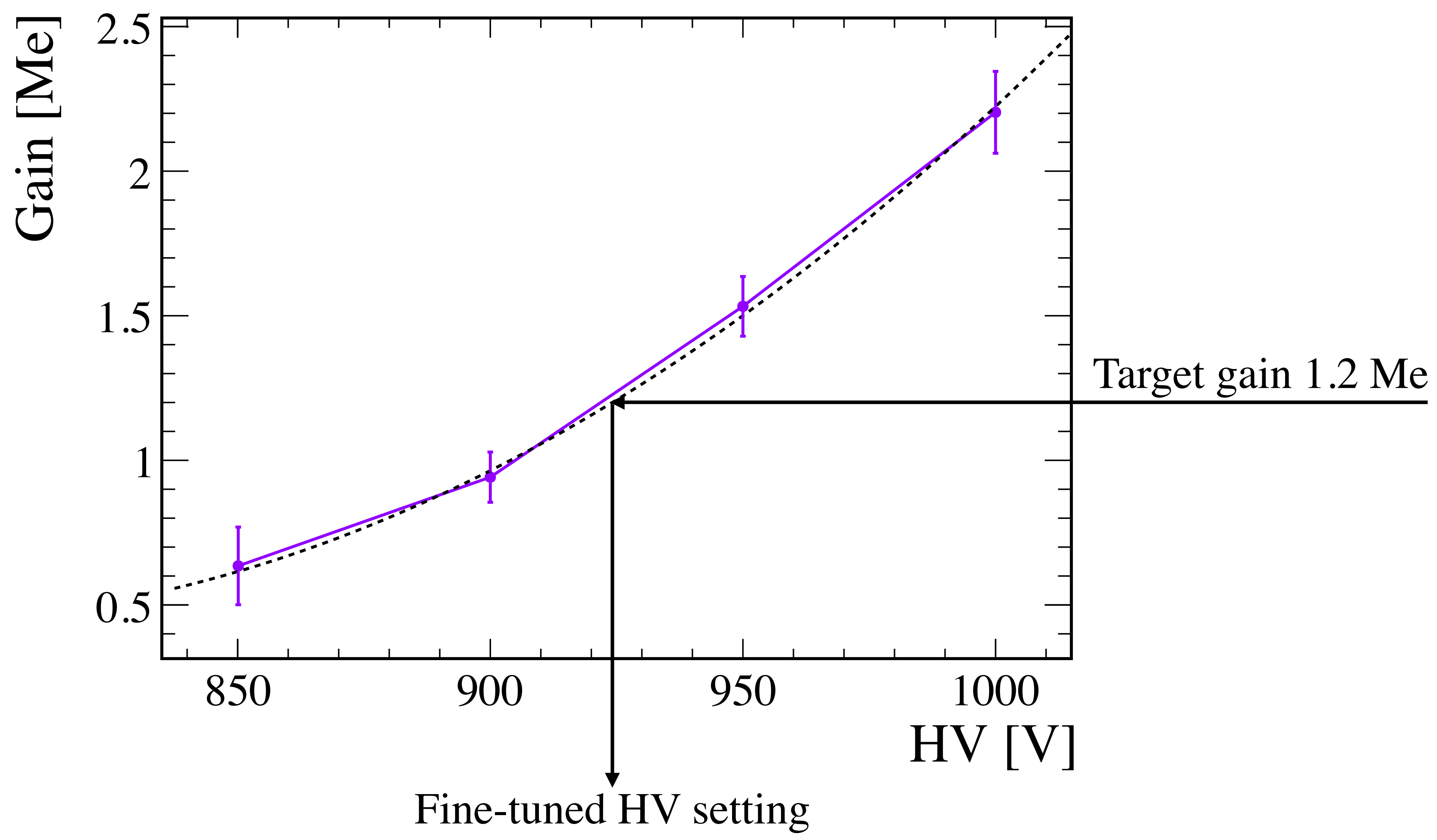


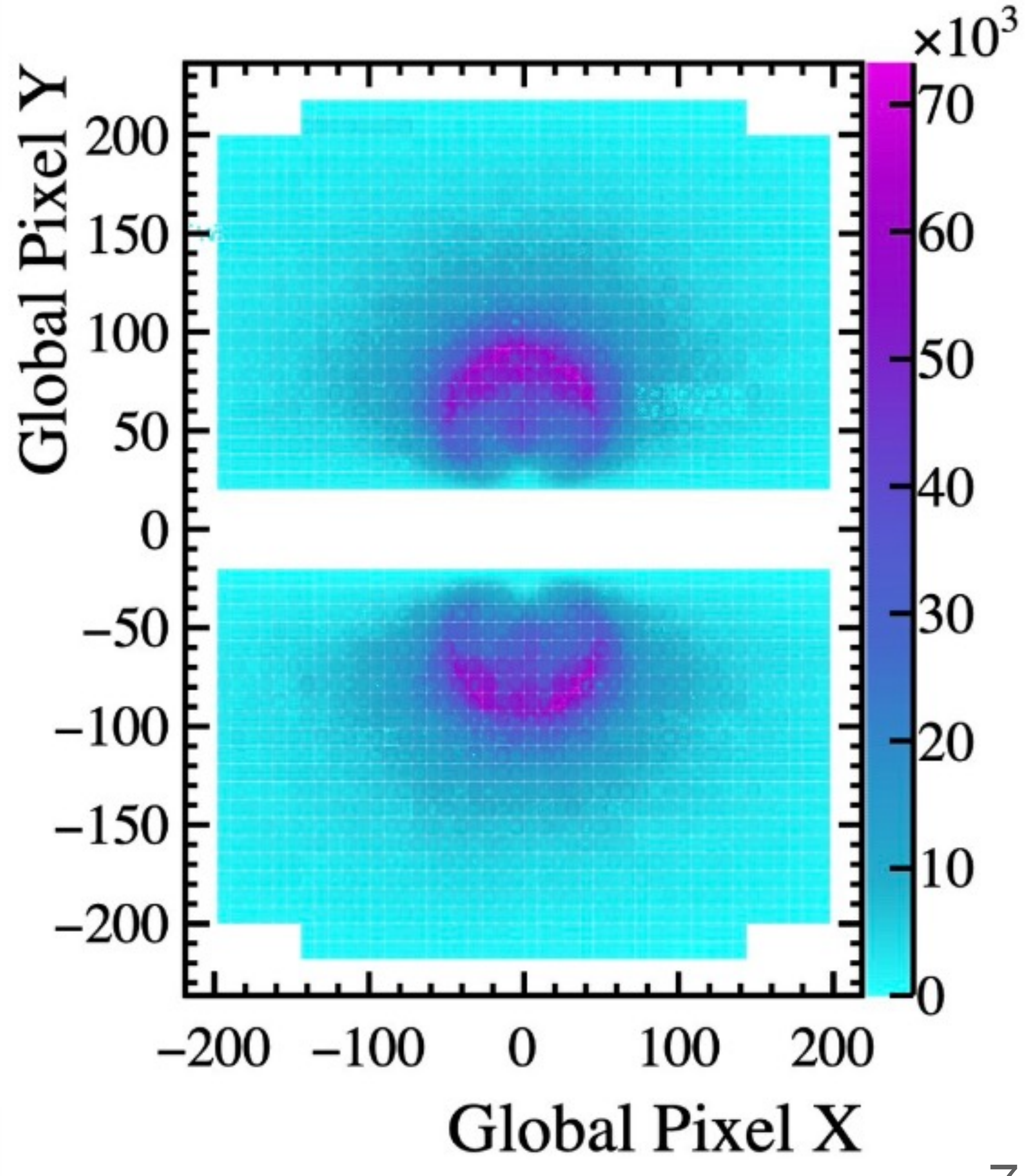
Gain equalisation

- Gain of 200k MAPMTs channels have been extracted:
  - analysis of the integrated charge spectrum acquired with the threshold scan datasets

- The dependance of gain on the HV setting has been studied:
  - possibility to choose a target gain and fine tune the HV settings to make the sensors response uniform across the photo-detection planes
  - margin to adjust HV setting in order to avoid future ageing







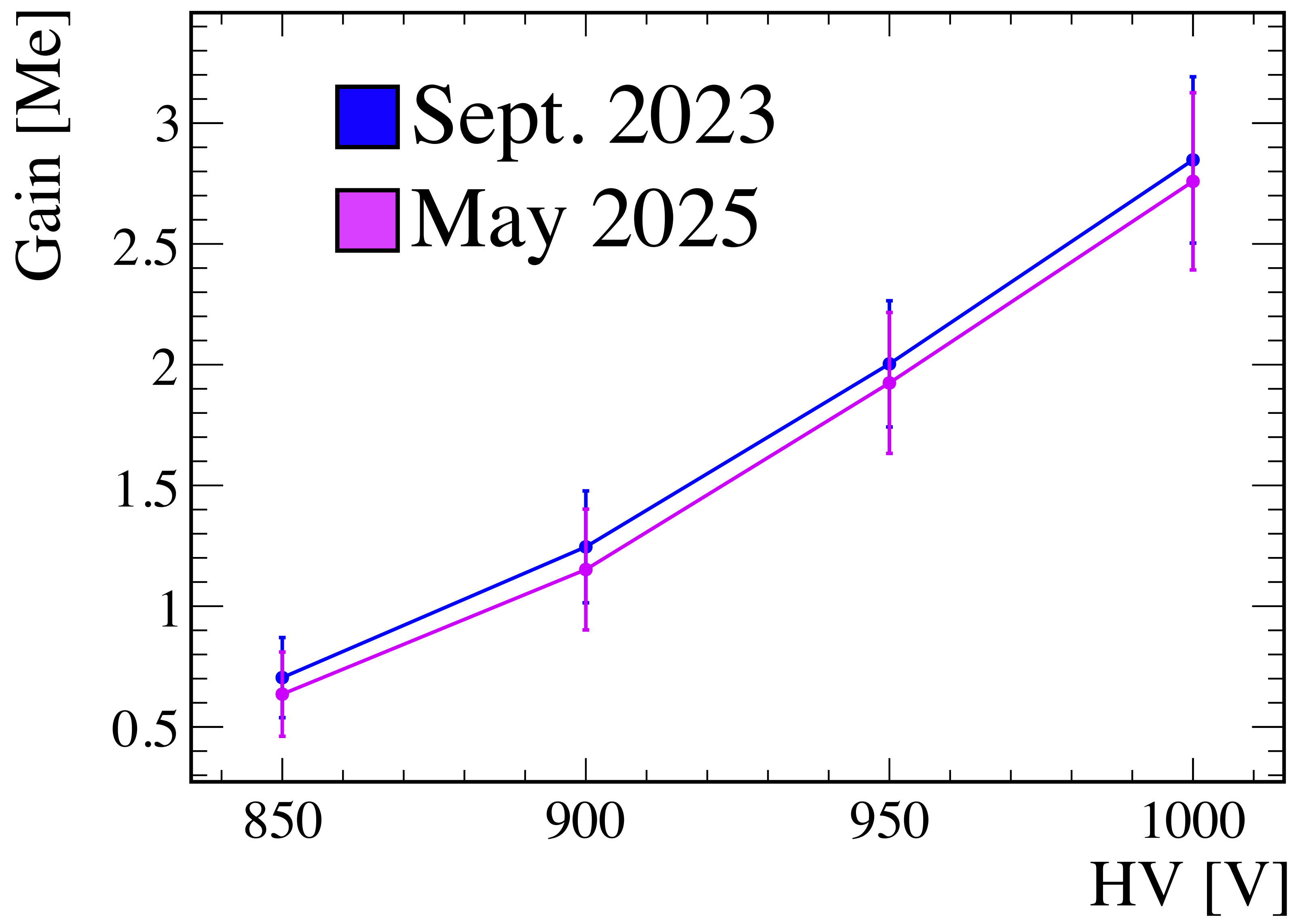
MAPMTs ageing monitoring

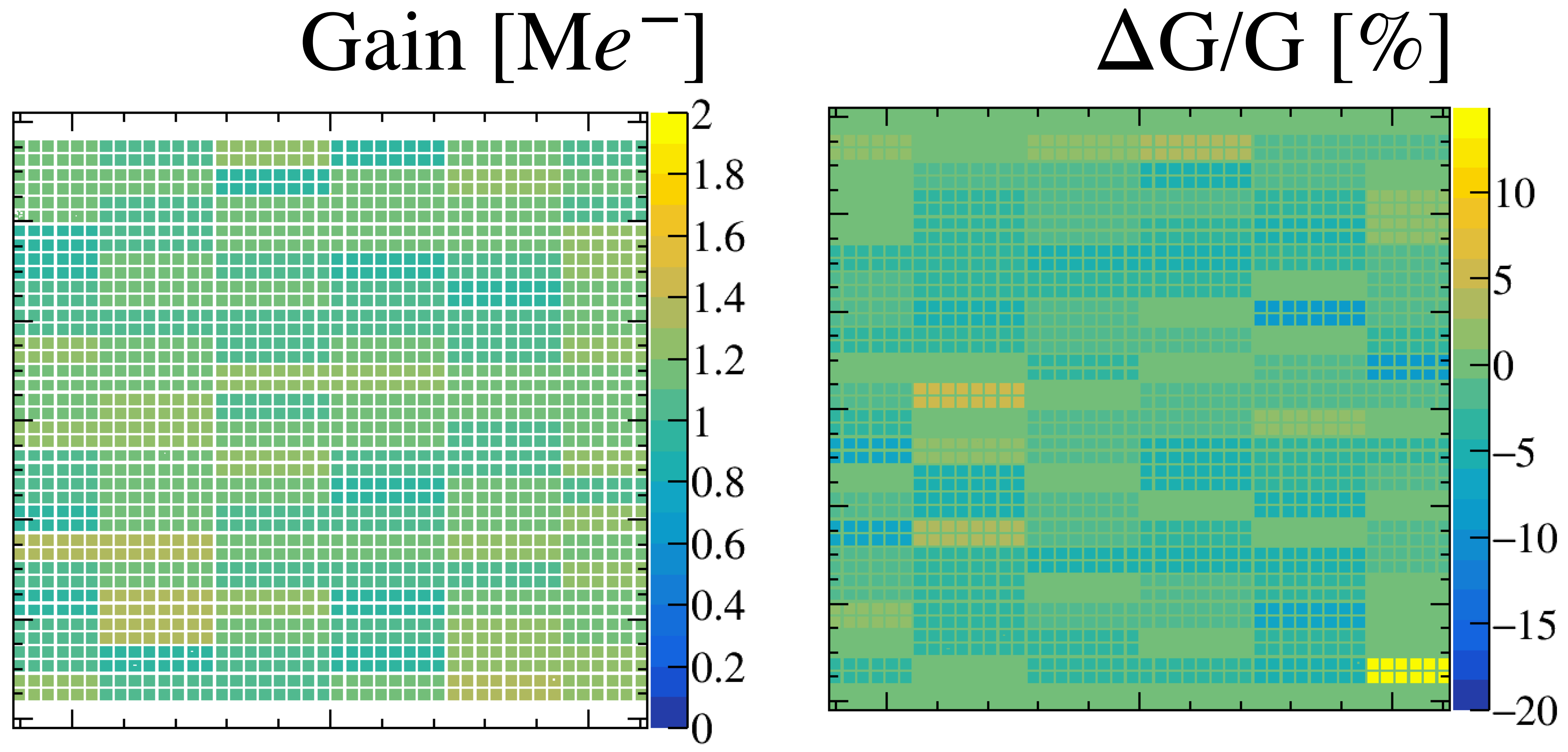
Ageing on the MAPMTs is expected at two levels:

- ageing of the photocathode, causing loss of quantum efficiency.
- ageing of the multiplication chain, causing a loss of gain
  - Gain monitoring is thus needed to check on the ageing of the photo-sensors
  - Threshold scan datasets have been acquired several time across the LHC Run 3 data taking year.

The gain dependence on HV has been measured recently and compared to the same value at the end of 2023:

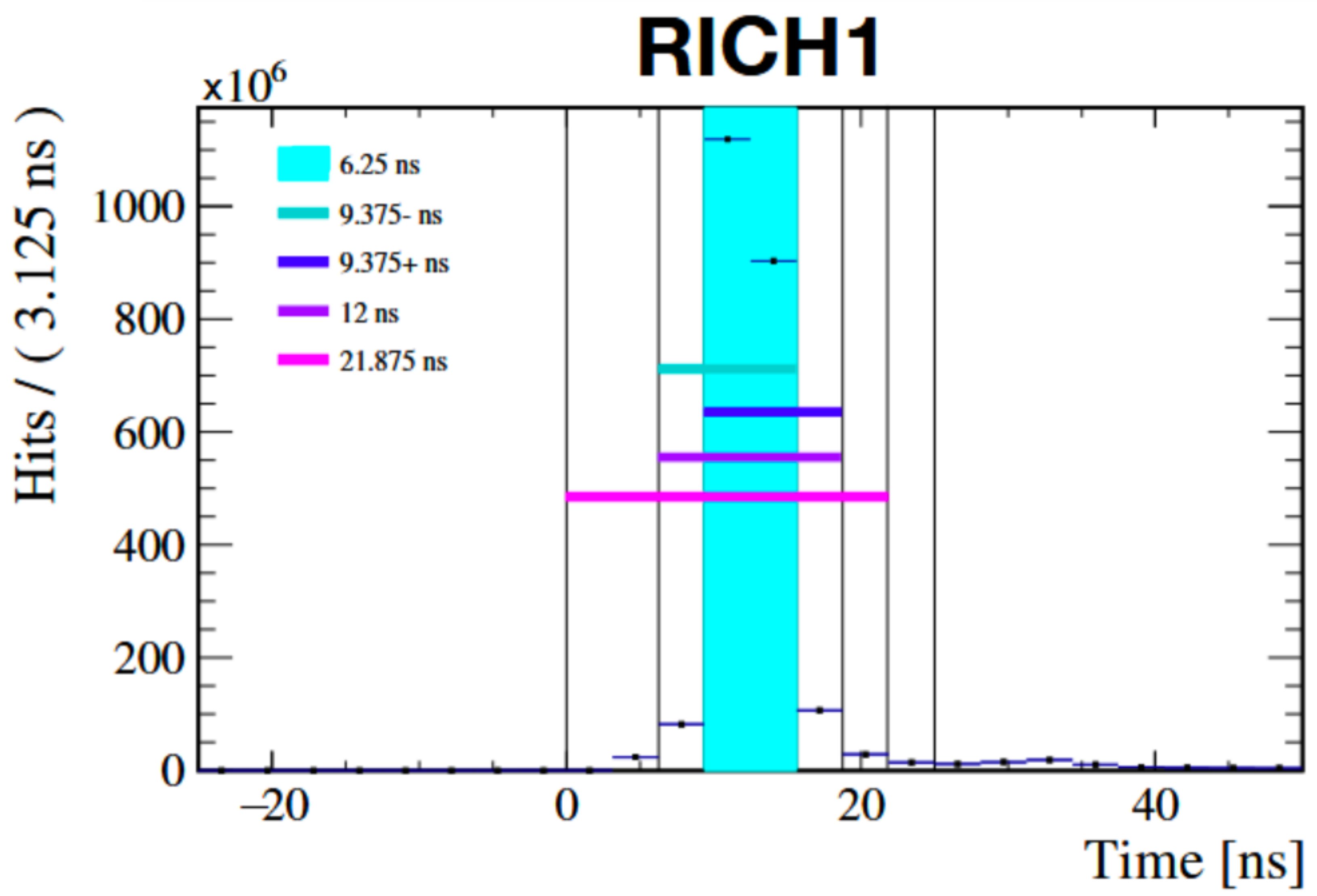
- A decrease of gain of ~5% is observed
- Such variations are well within the relative uncertainties as expected

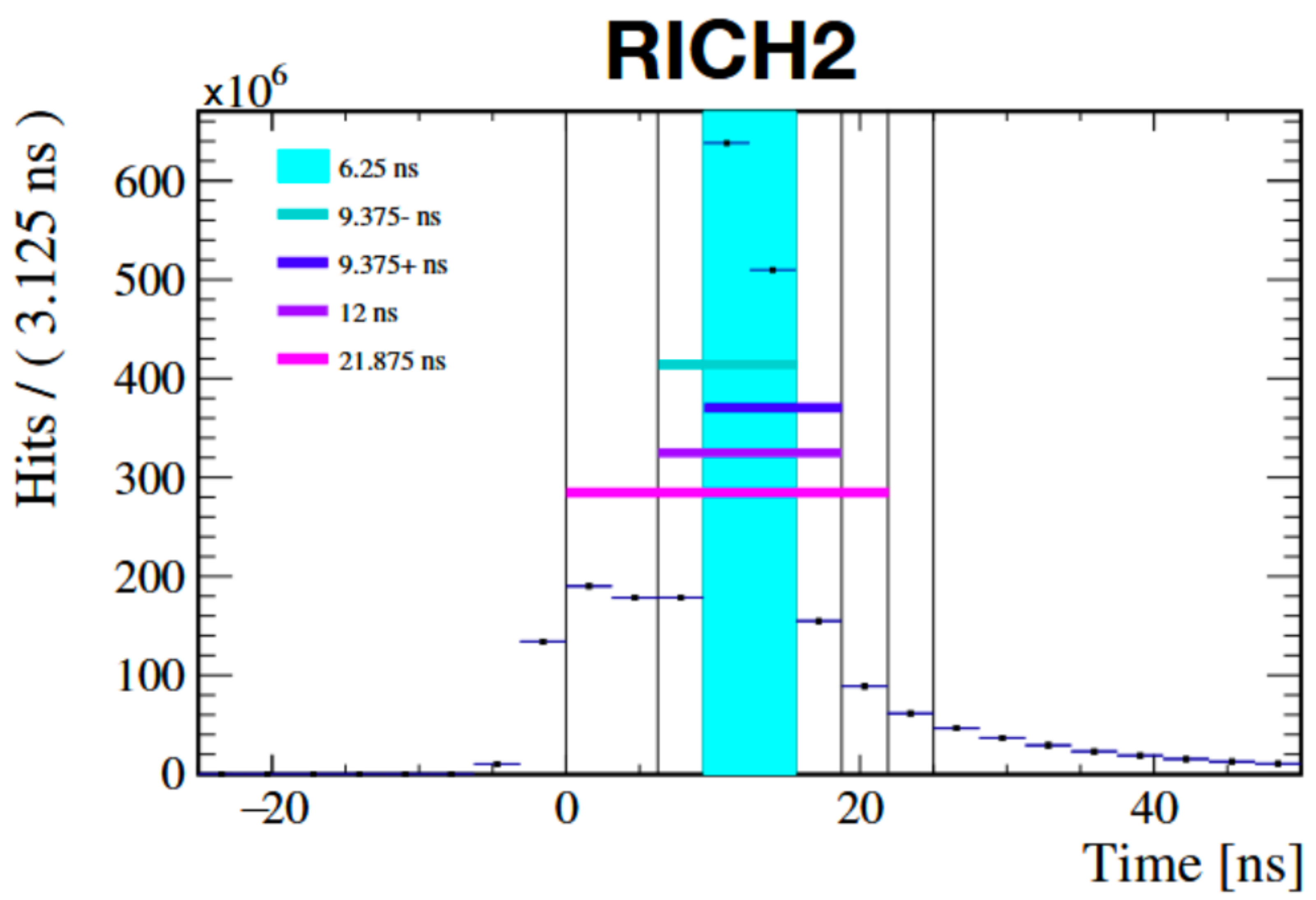




Time alignment

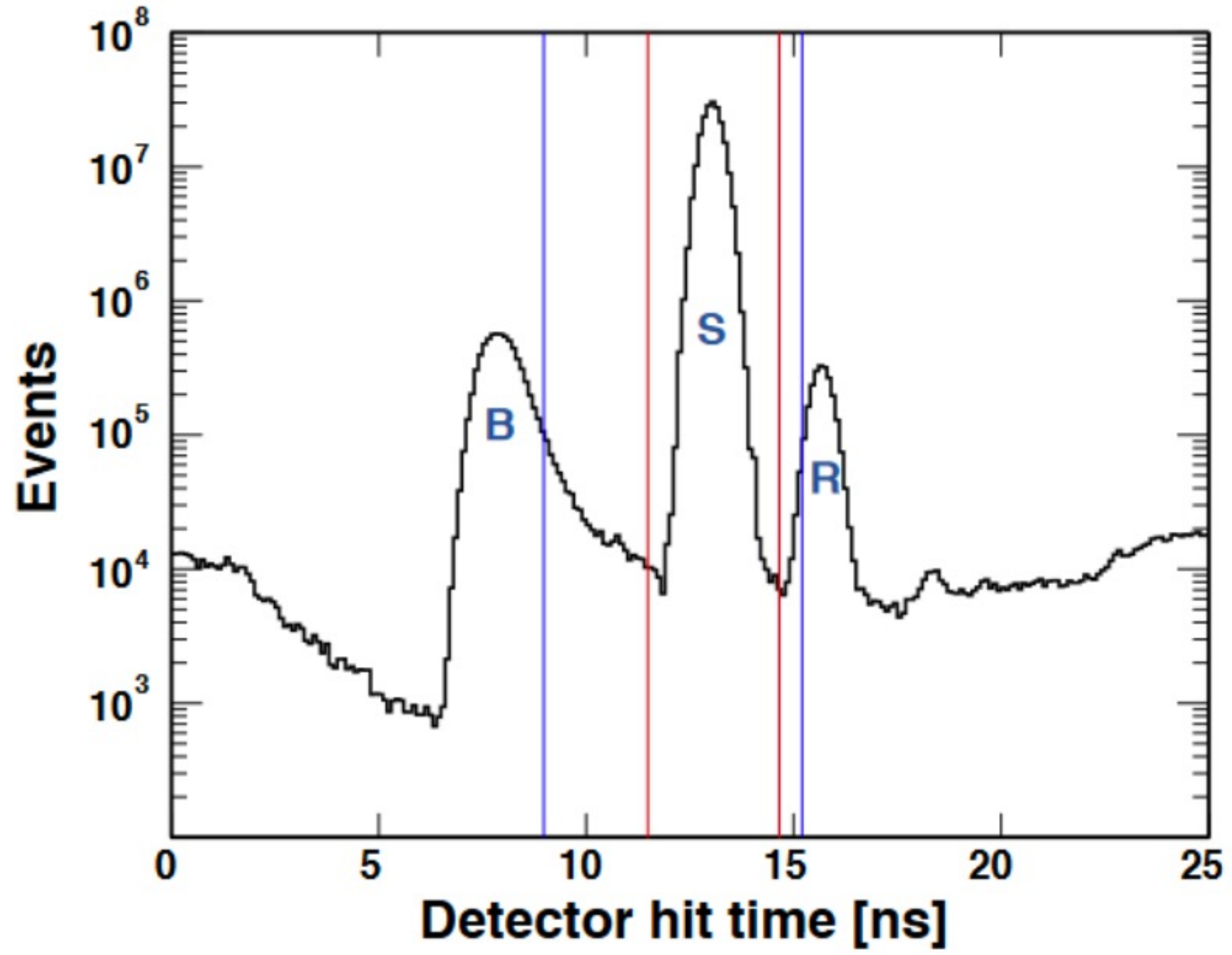
- The RICH sub detectors time alignment is performed in two steps:
  - Coarse time alignment: in the 25 ns of the bunch crossing ID
  - Fine time alignment:
    - apply a signal latching scheme based on gating in few ns to maximize detection efficiency while reducing out-of-time background
    - Identify the rising edge of the digitized signal (minimum gating is 3.125 ns)





- Optimal configuration to enhance photon detection reducing the background at the minimum: 6.25 ns gating window

From simulation:



B: photons hitting directly the photo-sensors

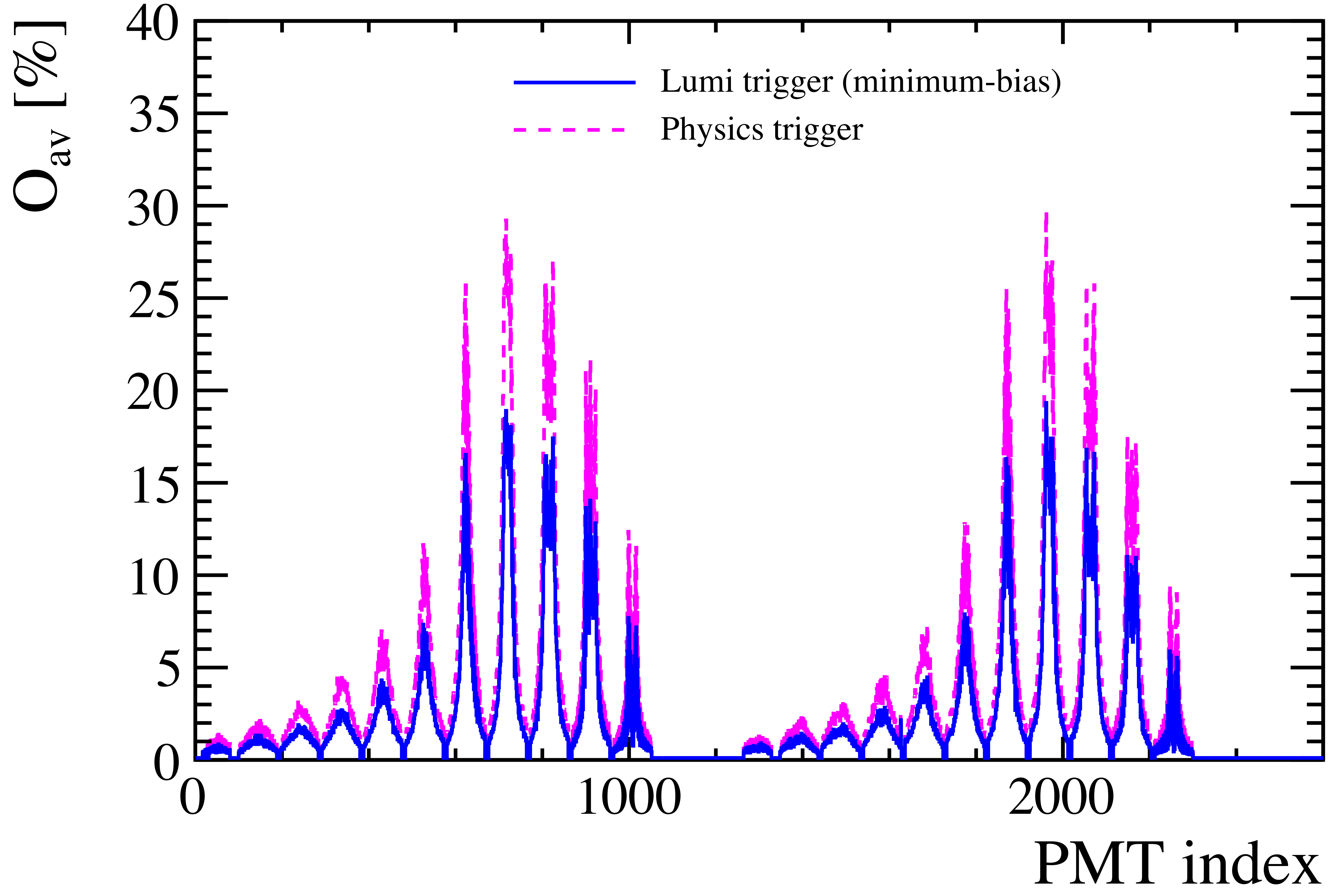
S: Cherenkov signal

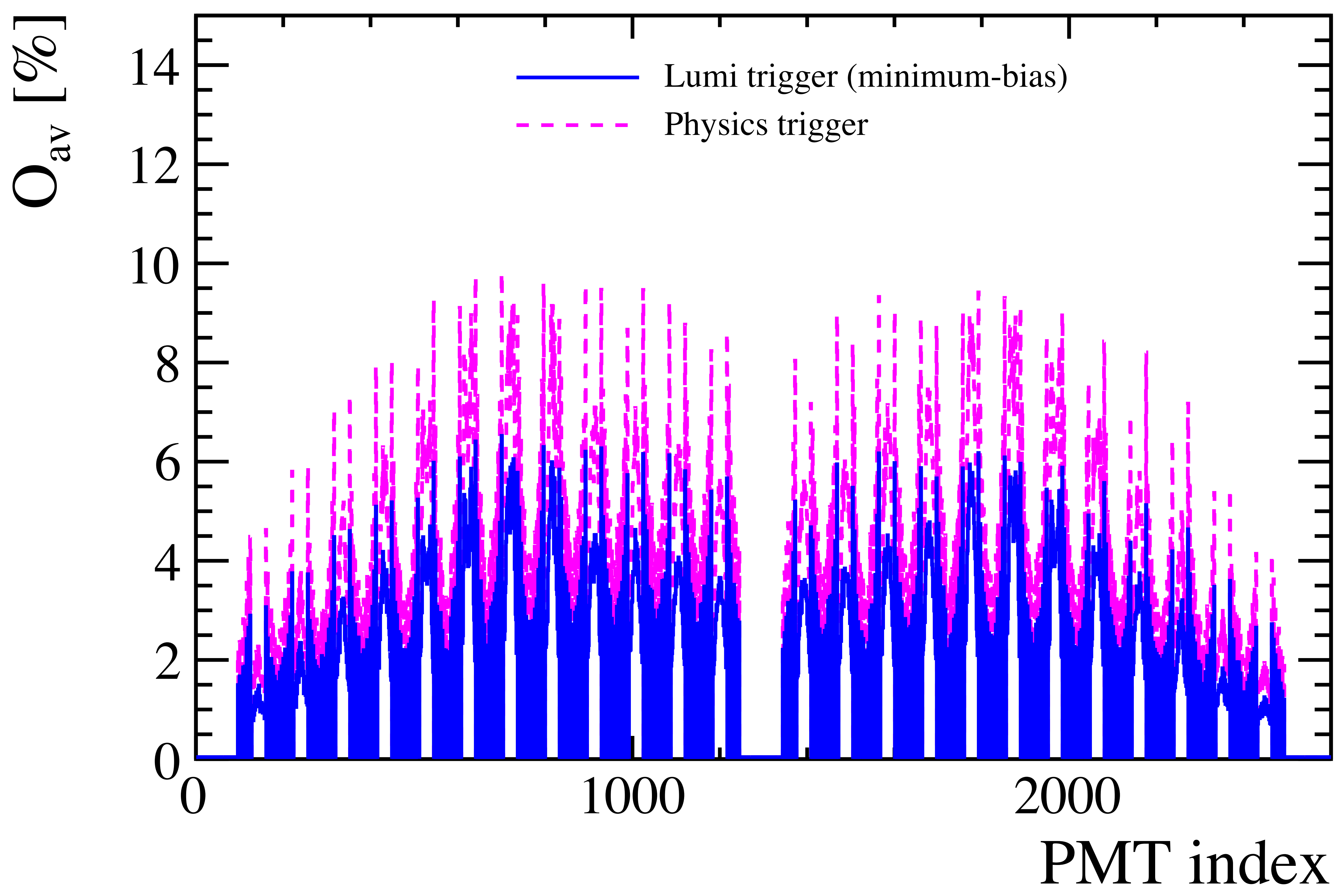
R: photons that have been reflected multiple times by the optical system

Occupancy in real data

- To achieve the desired performance, the detector was designed to work up to 30% occupancy
  - In real data: peak occupancy around 30% per physics event at nominal pile-up (5.5) as by design

arXiv:2503.05273

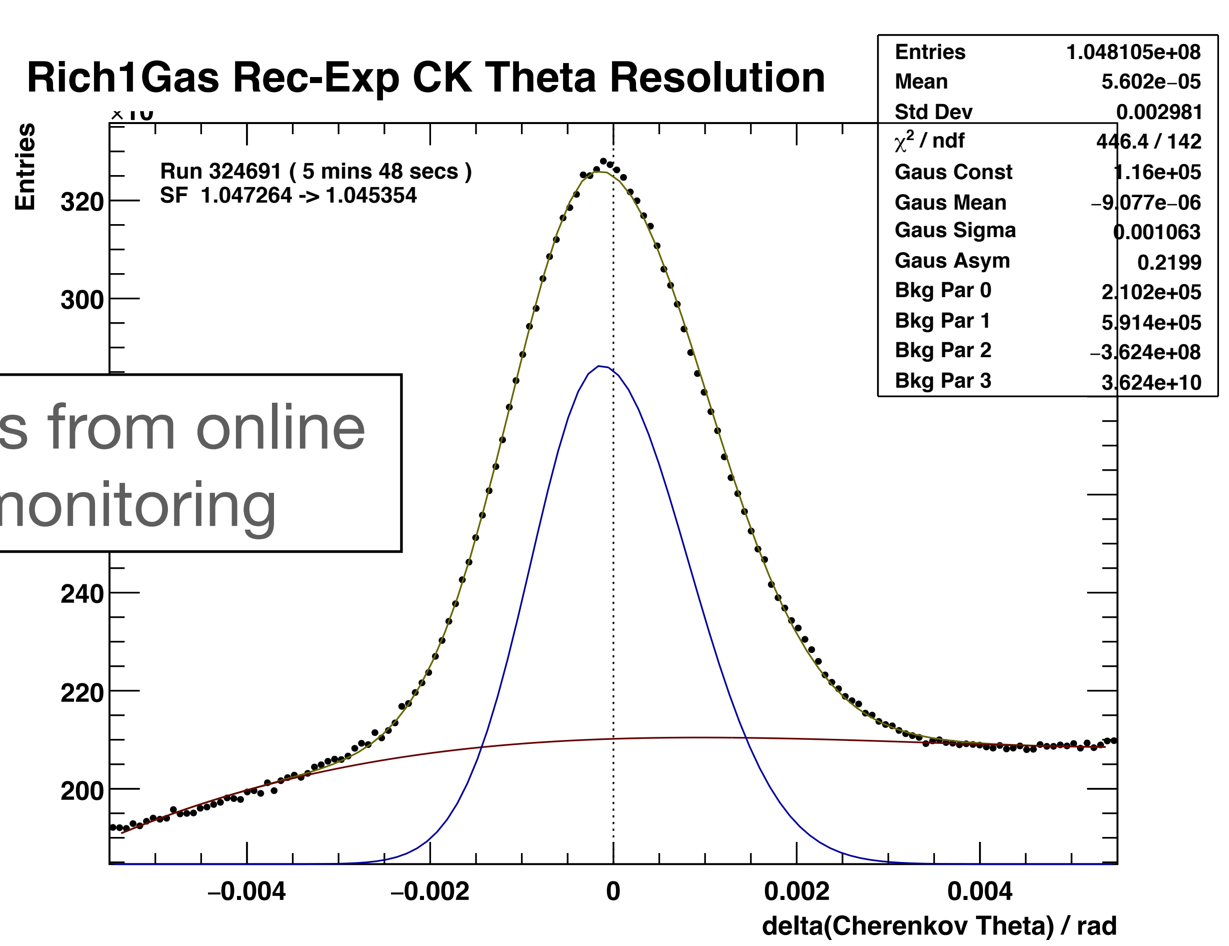


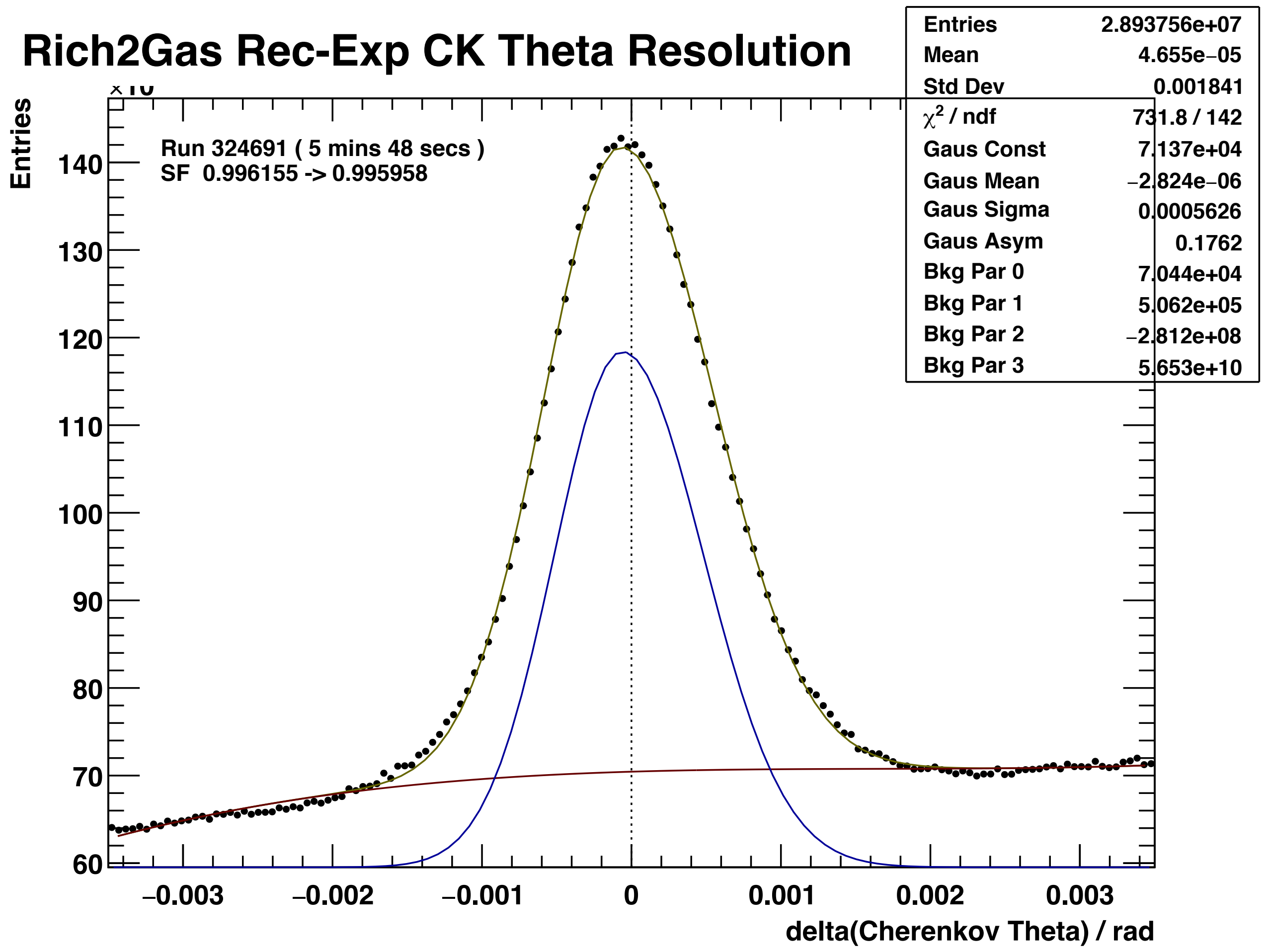


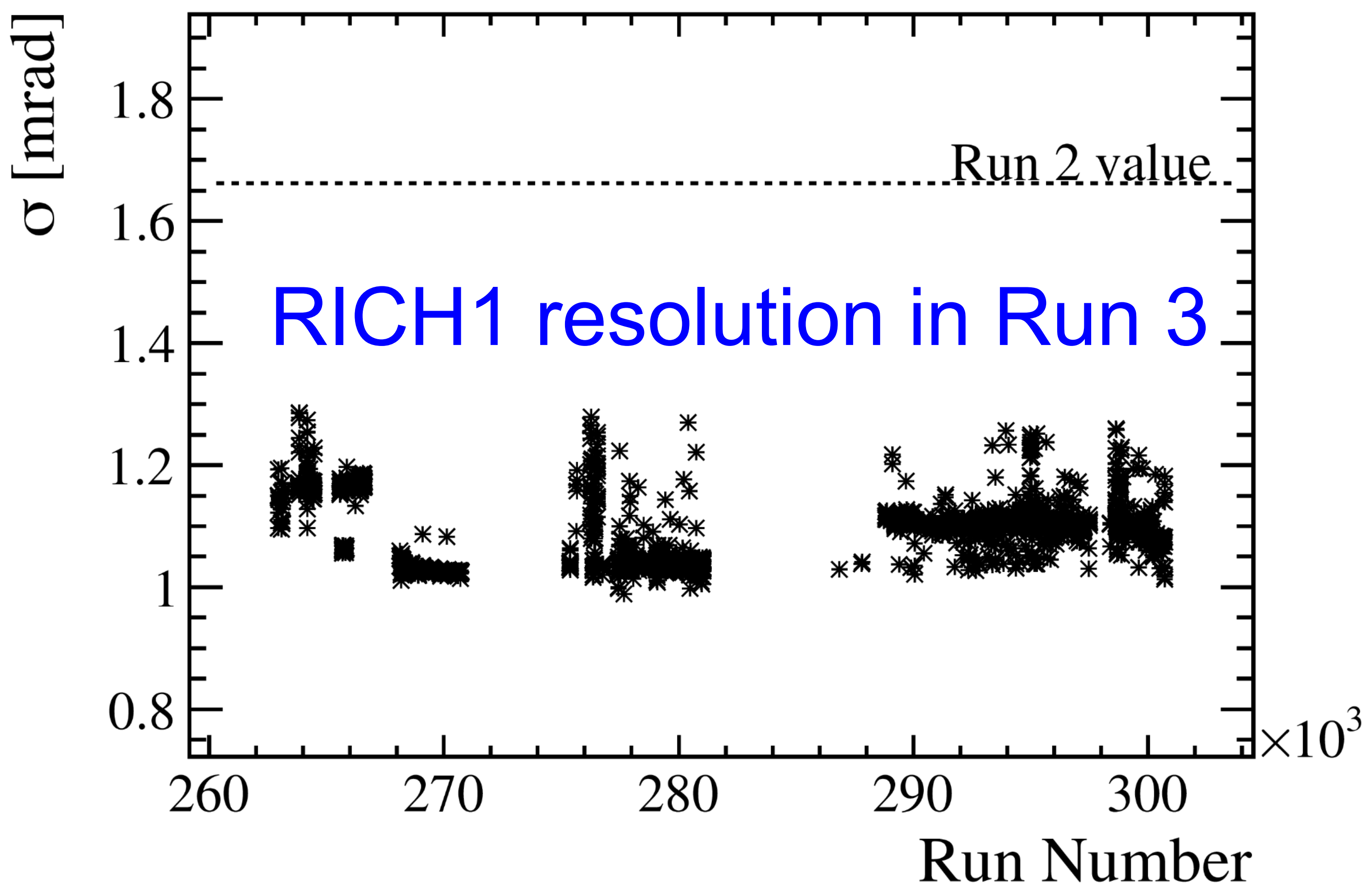
Cherenkov angle resolution and online monitoring

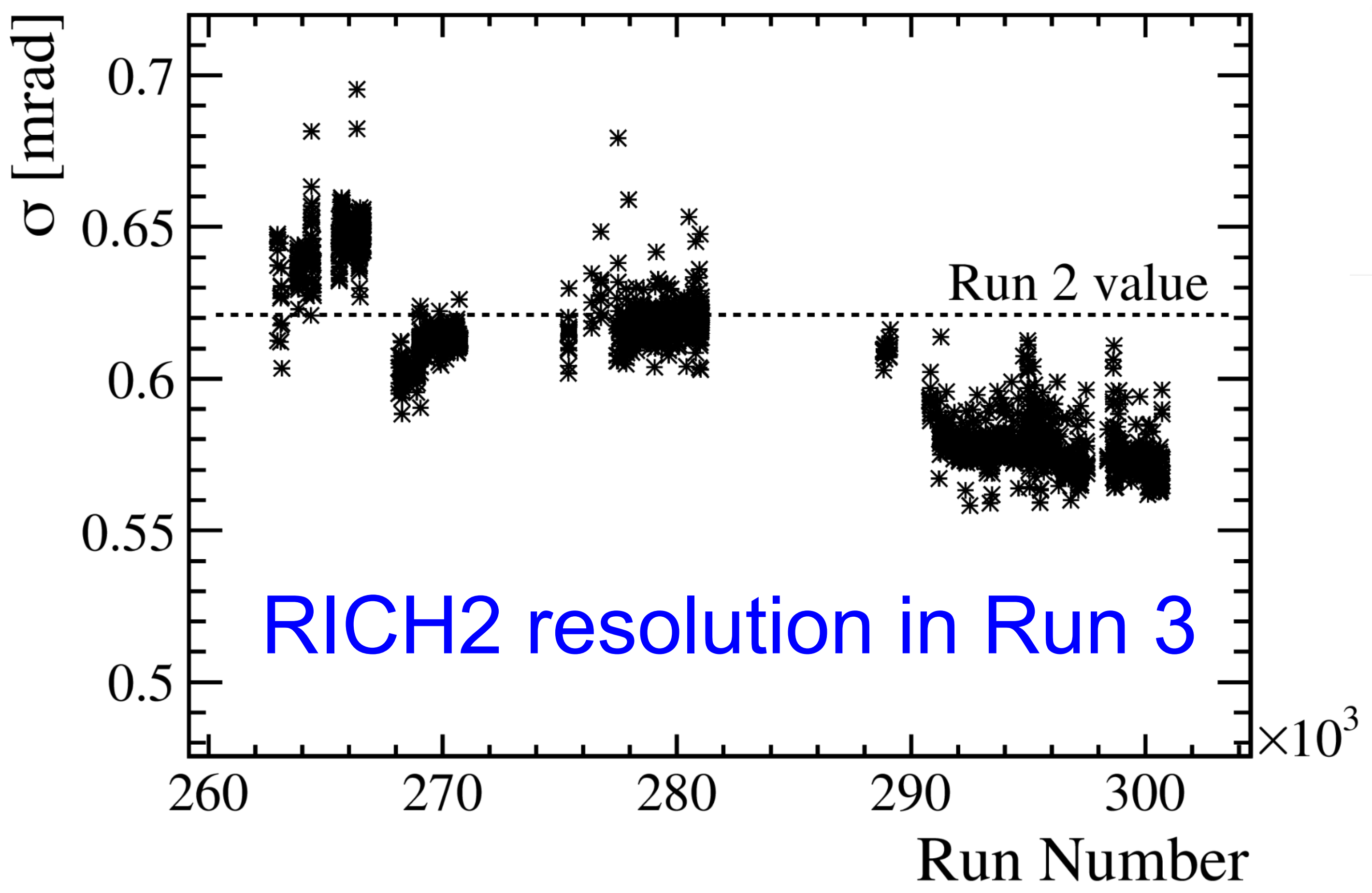
- Single photon Cherenkov angle resolution is one of the main figure of merit to evaluate the RICH performance:
  - It is reconstructed via an online monitoring task selecting high momentum tracks
  - It allows to perform refractive index calibrations as well ($\cos\theta_c \sim 1/n$)
  - It is dependent on the software spatial alignment (mirrors and panels)

Plots from online monitoring



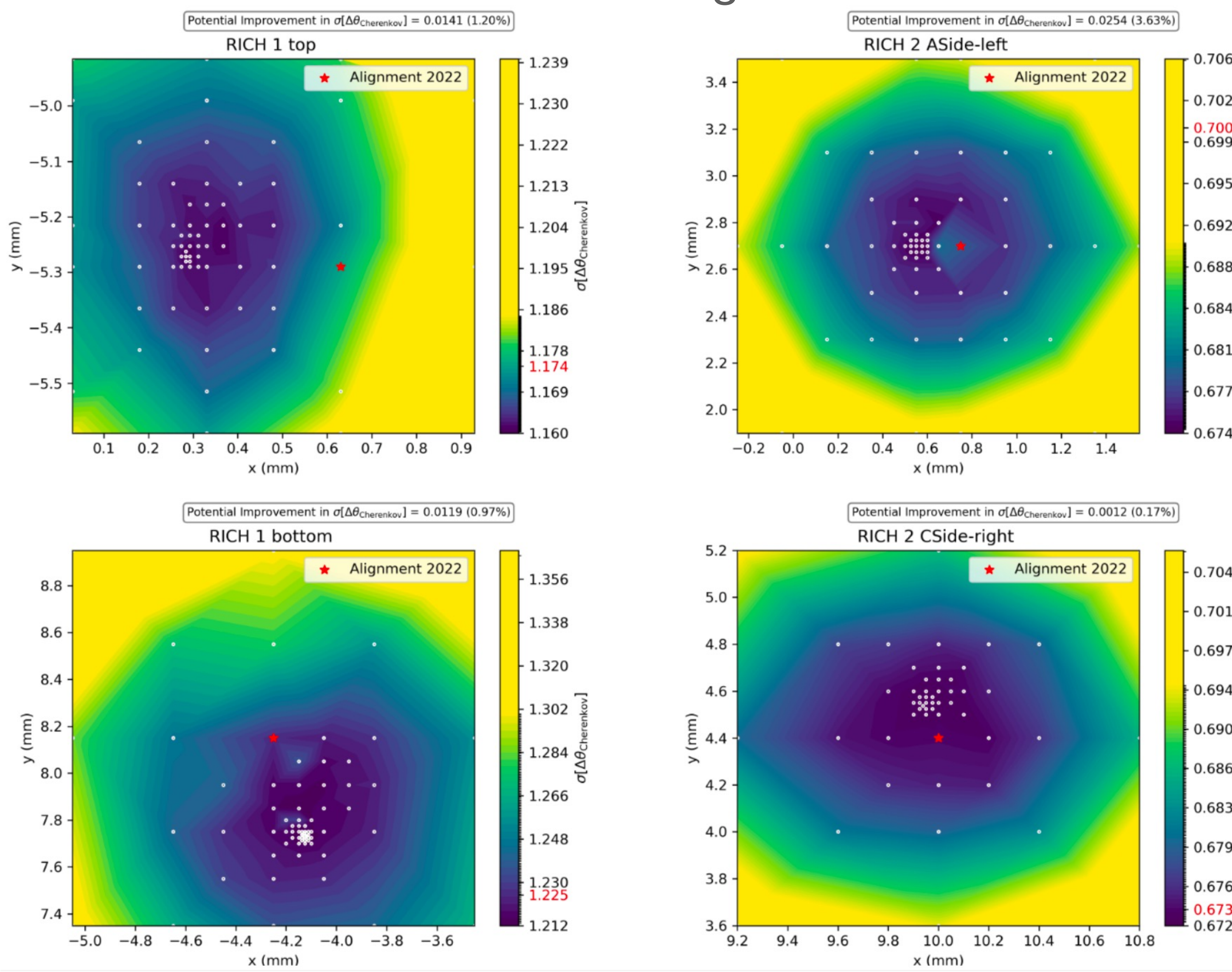






- The online monitoring provides estimation for:
  - Single Photon Cherenkov angle resolution
  - post-reconstruction photon yield per track
  - Experiment control system variables

Panels alignment

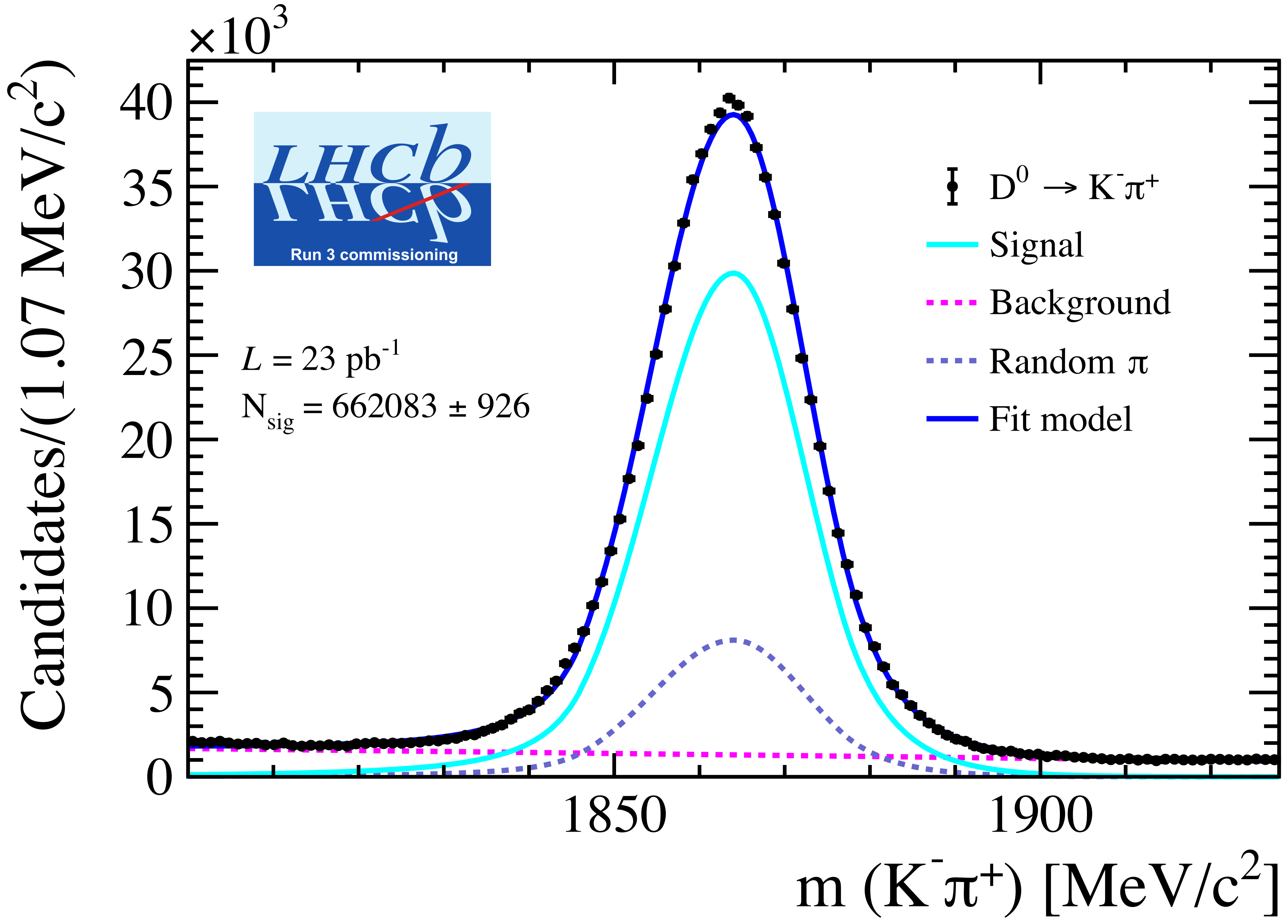


PID performance: calibration samples

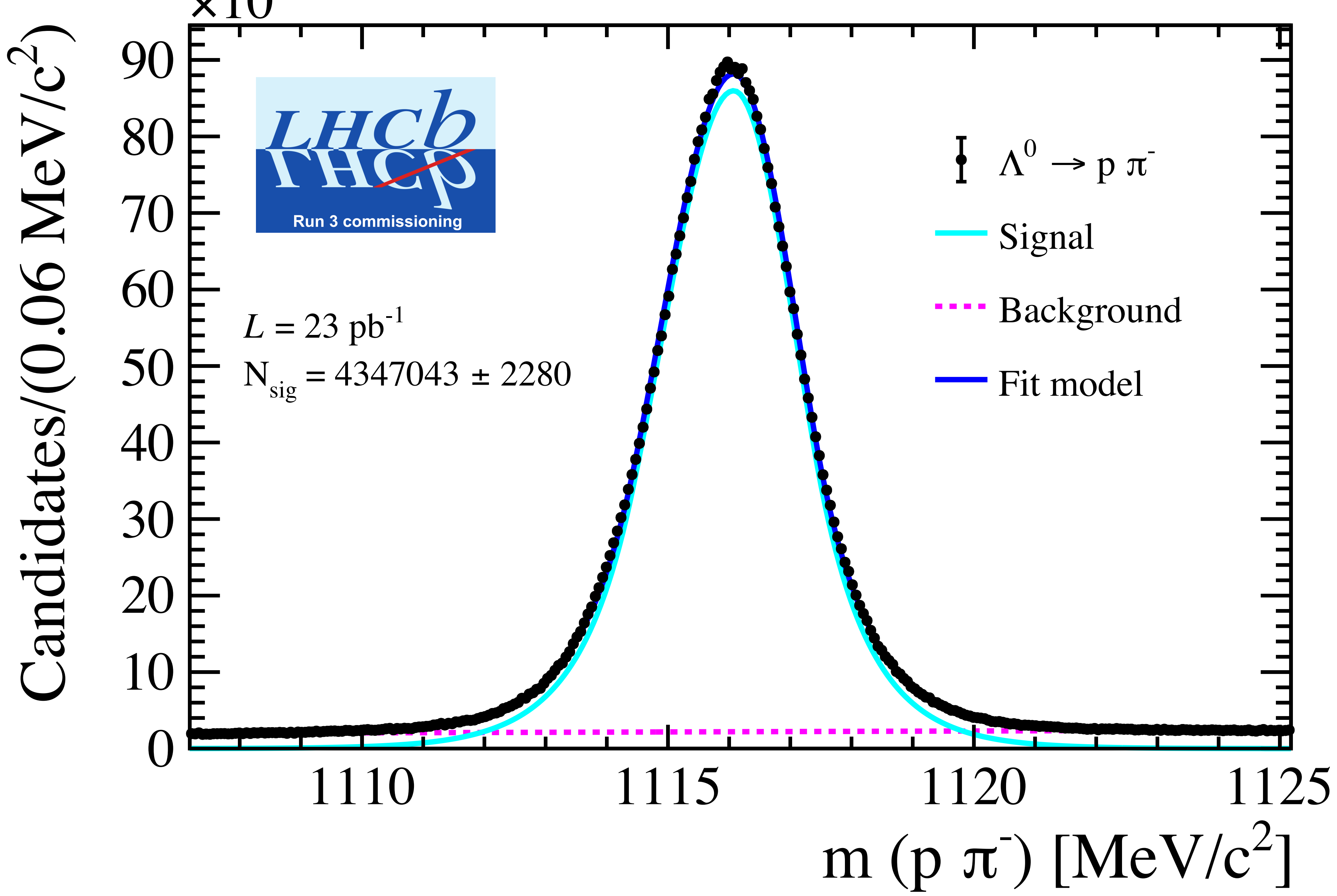
- PID performance of the RICH detectors depends on the single photon resolution, number of detected photons per track, operational stability and calibrations.

- Calibration samples are exploited to assess the PID performance estimating the efficiency and mis-ID efficiency by varying the PID cut on high level variables:
  - $D^{*+} \to D^0(\to K^- \pi^+)\pi_s^+$ for pions and kaons discrimination
  - $\Lambda^0 \to p\pi^-$ for pions and protons discrimination

- Selection on such samples is based on kinematics requirements only.



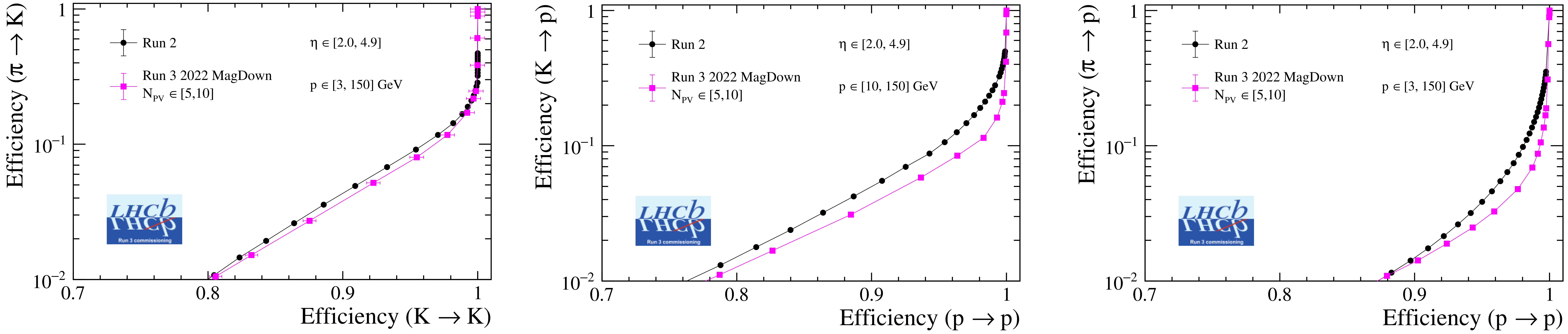
LHCb-FIGURE-2023-019



PID performance: Run 2 vs Run 3

- The PID performance has been fully characterized in bin of momentum, pseudorapidity of the tracks and occupancy.
- In particular, comparing high-pile up events in Run 3 (pile-up ∼5.5) with Run 2 values (pile-up ∼1), it possible to observe that the excellent PID performance of Run 2 is retained and outperformed.

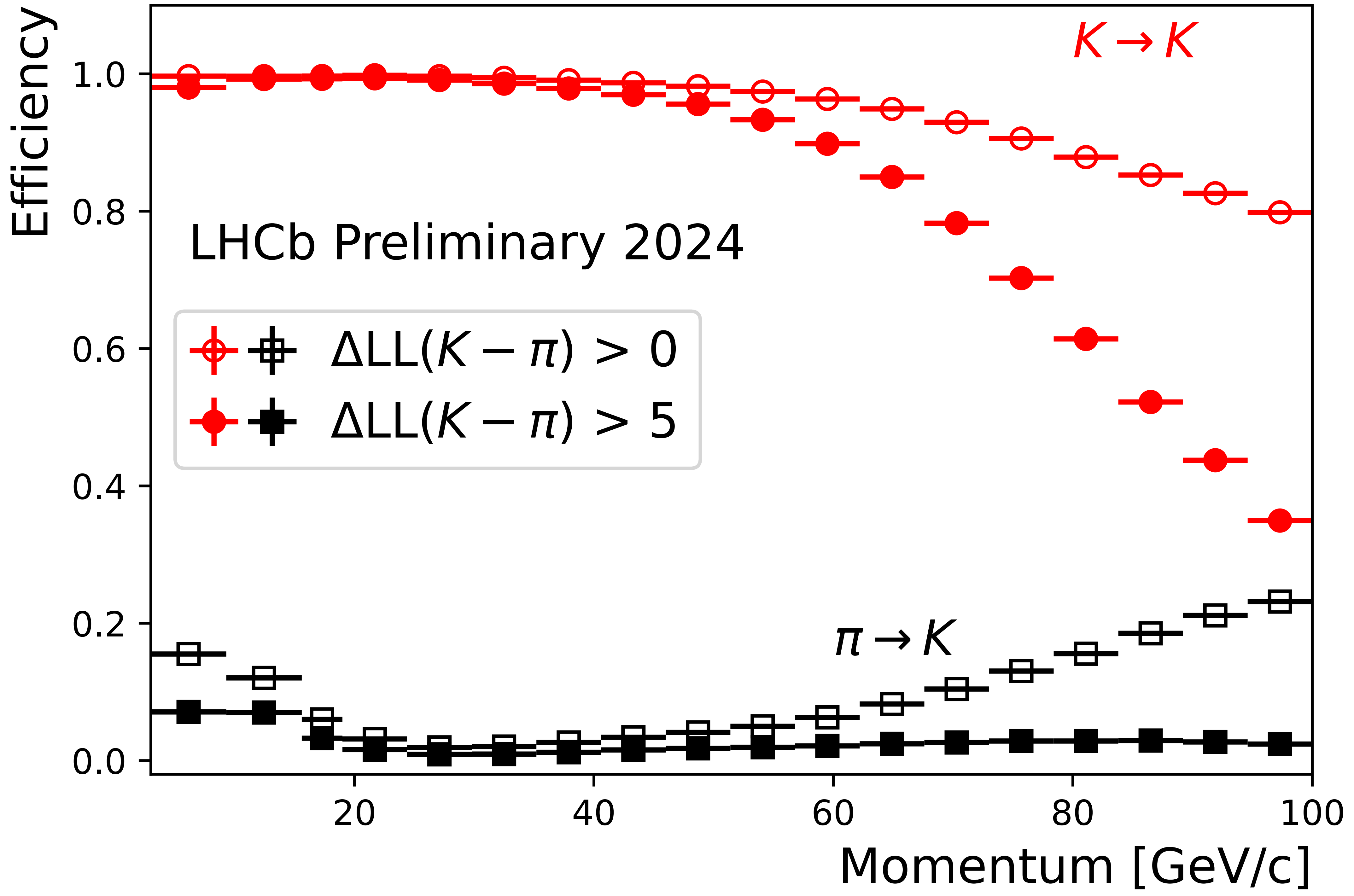
LHCb-FIGURE-2023-019

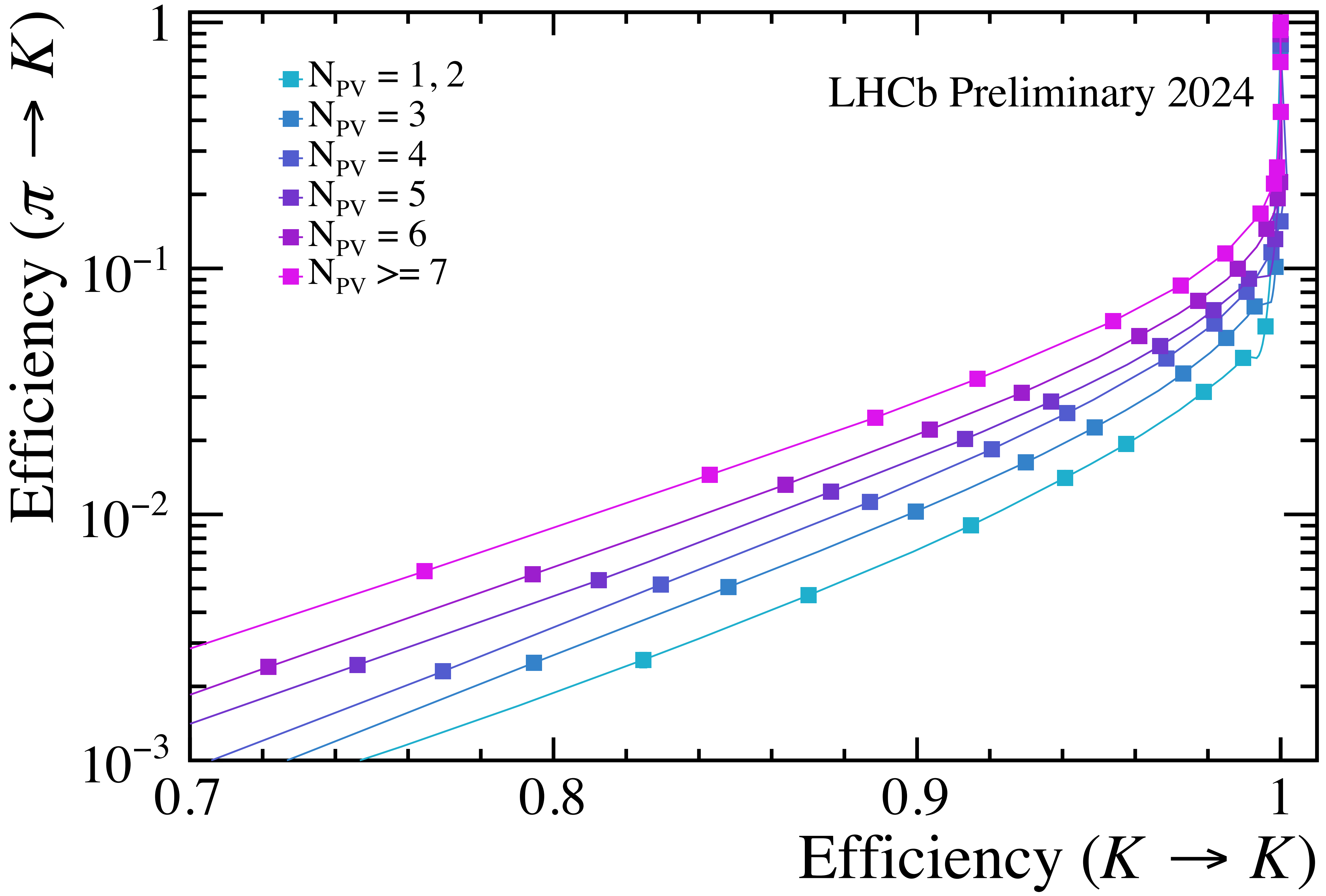


PID performance with 2024 data

- PID efficiency and misidentification rate as a function of the momentum:
  - Loose PID selection: high signal efficiency
  - Tight PID selection: high background rejection

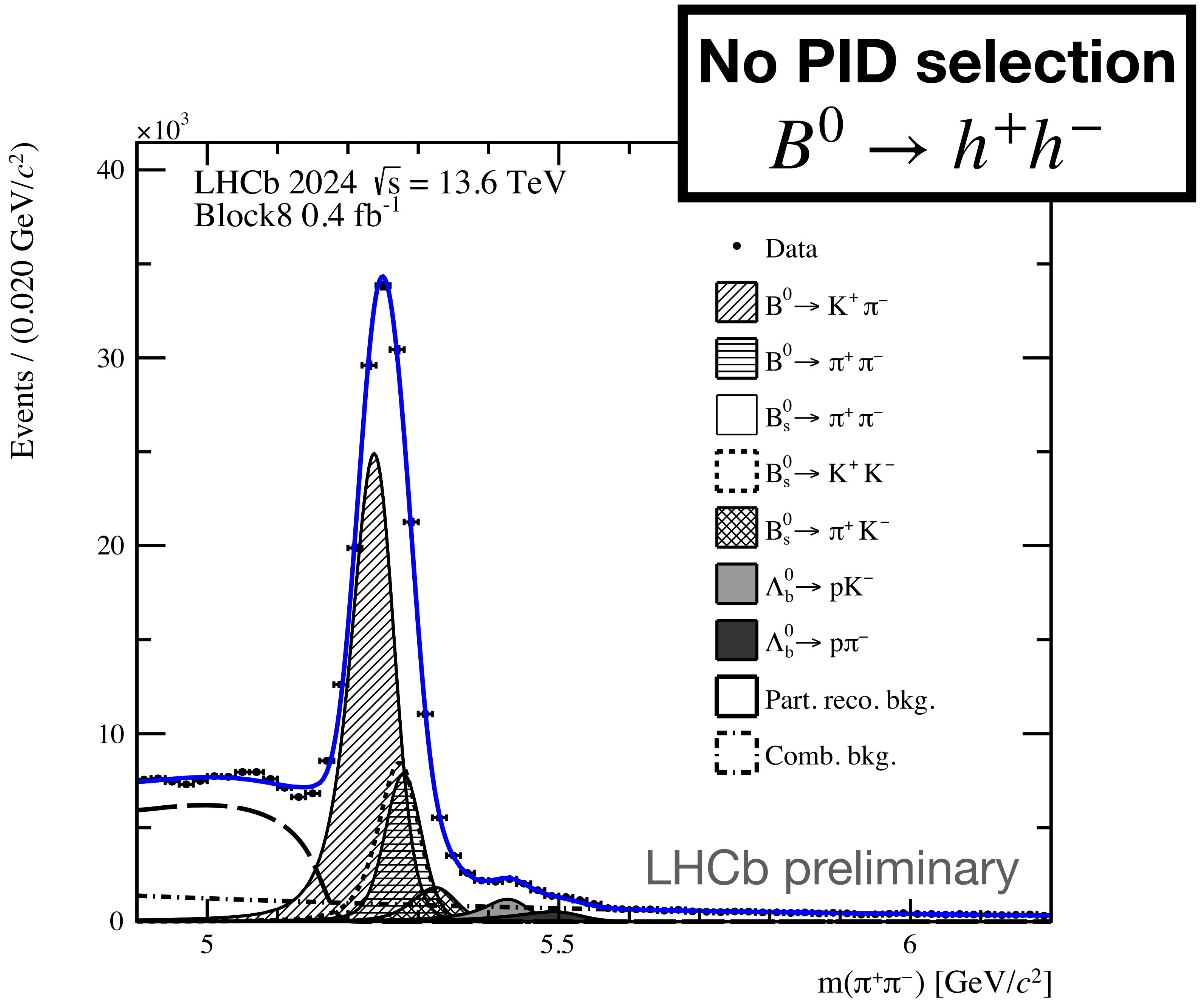
- Dependence on the number of primary vertices per event N_{PV} :
  - lower N_{PV} values imply a better PID performance

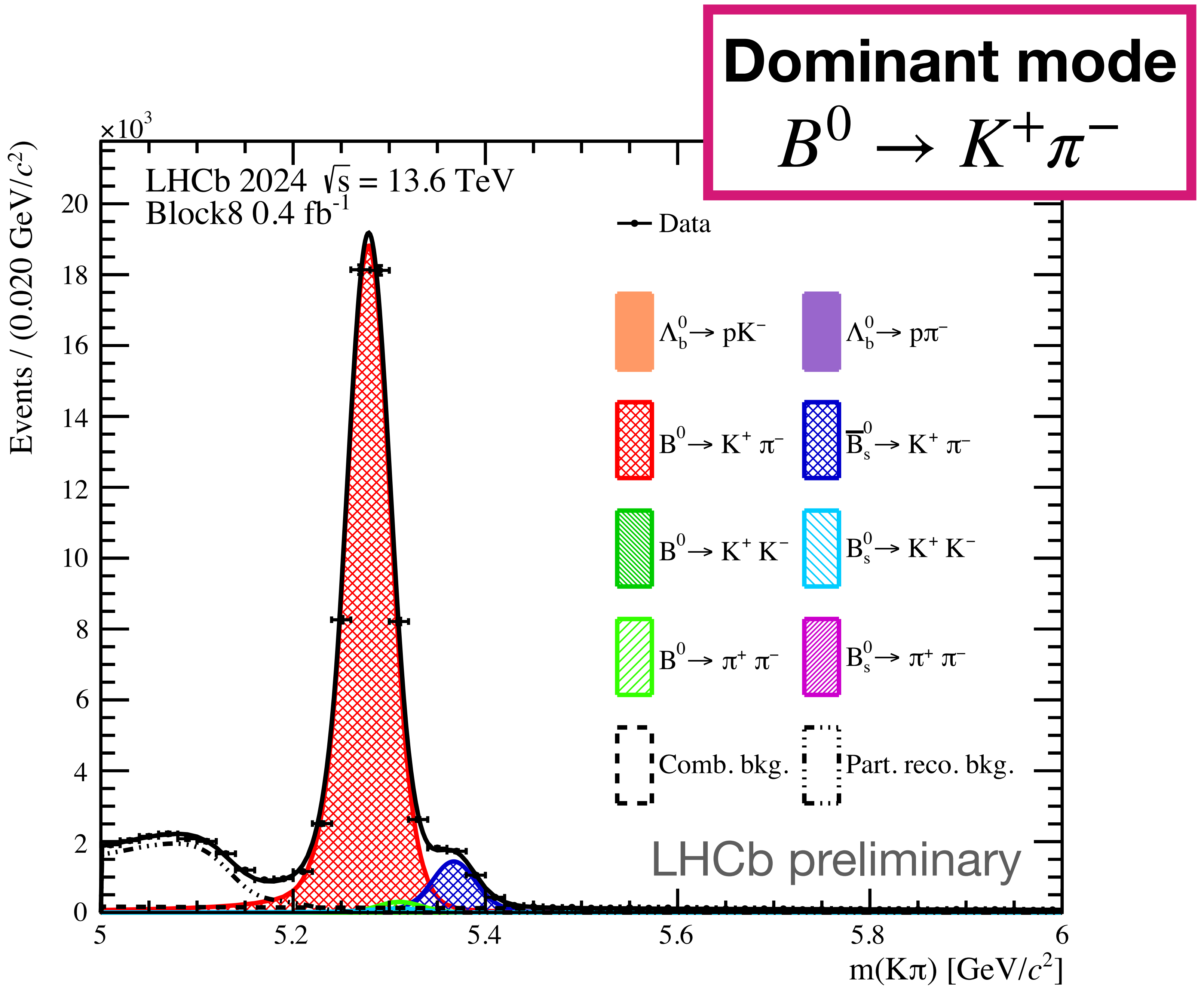


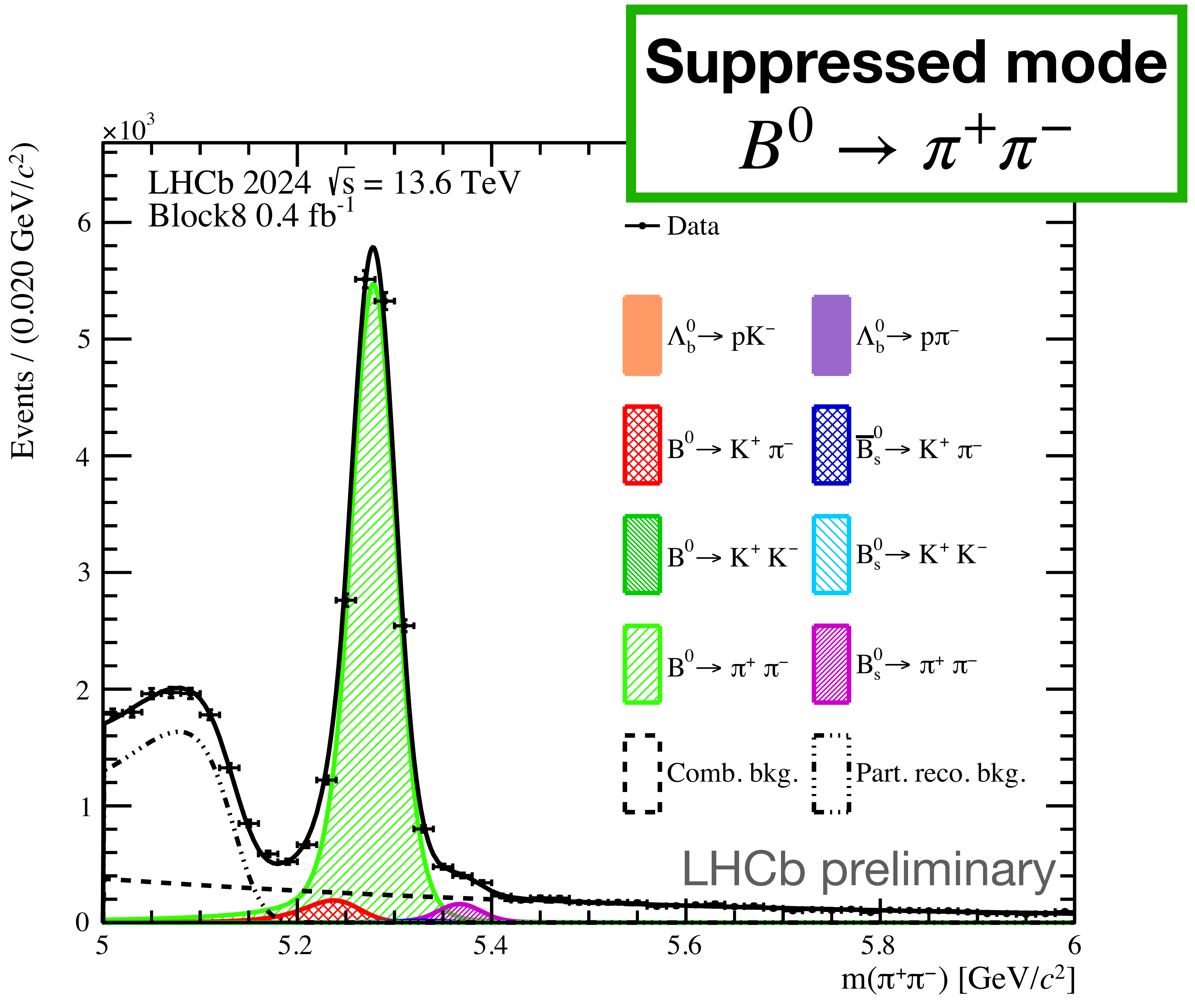


PID selection on Run 3 data

- The effect of the PID selection from the upgraded RICH sub-detectors can be observed in this example from the Run 3 LHCb analysis regarding the $B^0 \to h^+h^-$ decays:







Conclusions

- The LHCb detectors have been operating smoothly since the start of Run 3.
- Accurate calibration procedures allow to fully exploit the detectors potential.
- The PID performance outperformed the one available during Run 1 and Run 2:
    - Unmatched PID discrimination power for the LHCb analysis

Back-up slides

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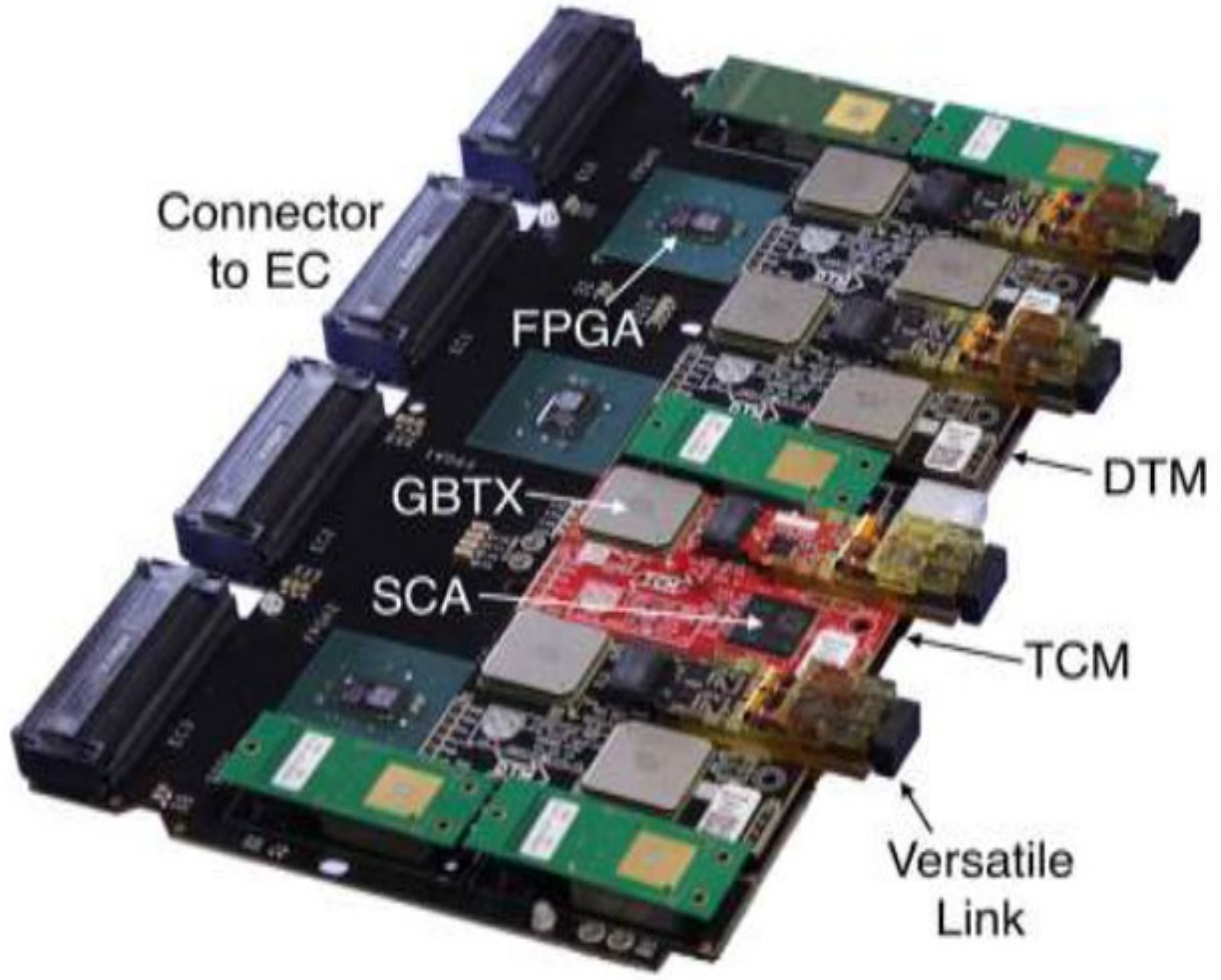
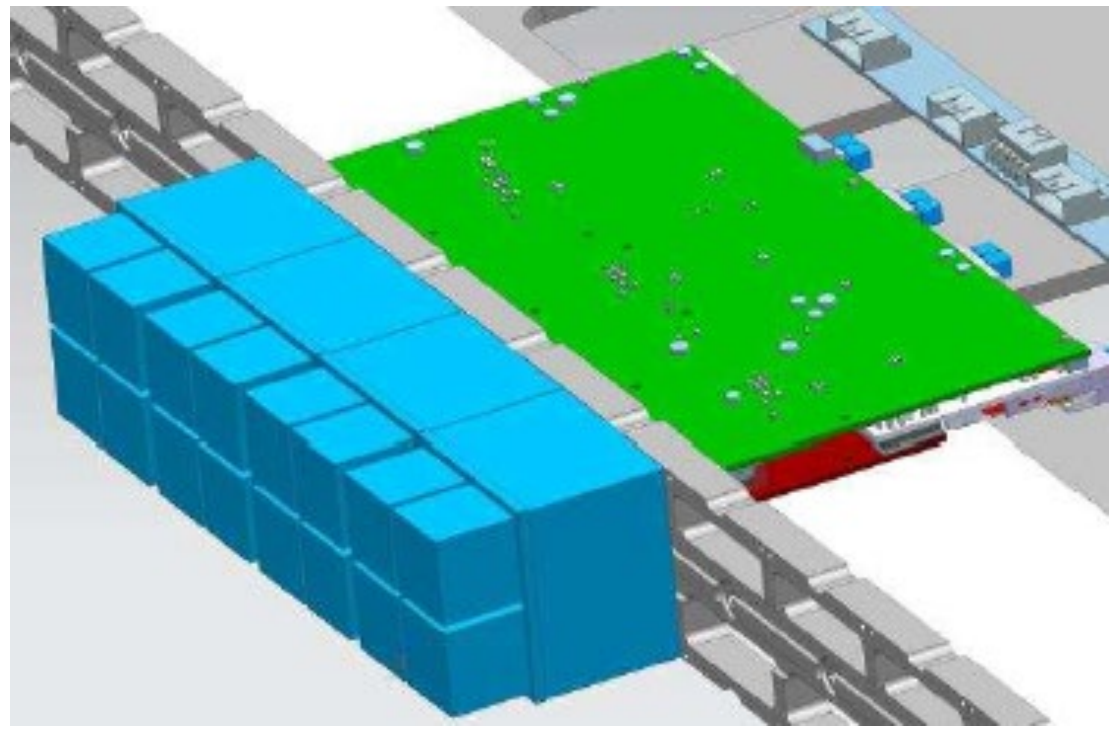
The Photon Detection Module

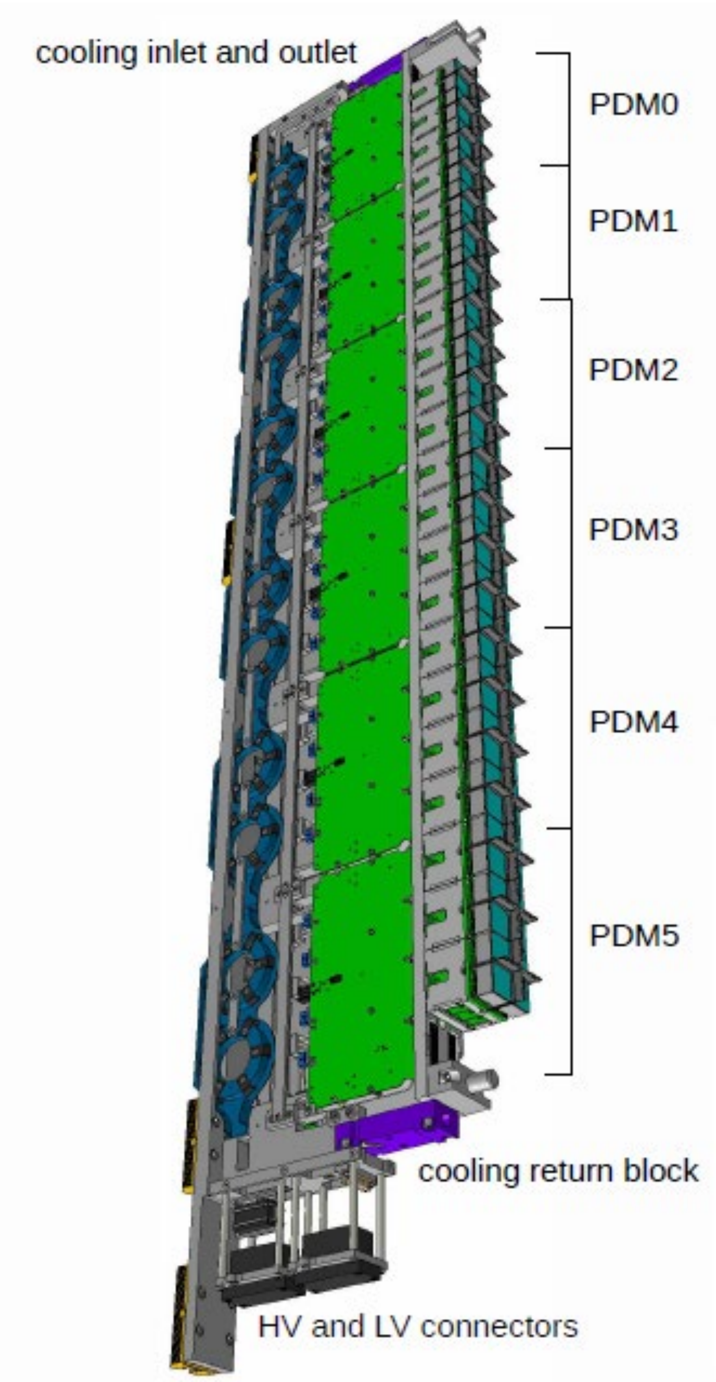
- Front-end digital board:
  - Capture CLARO outputs
  - Synchronize to LHC clock
  - Data algorithm, format, transmission

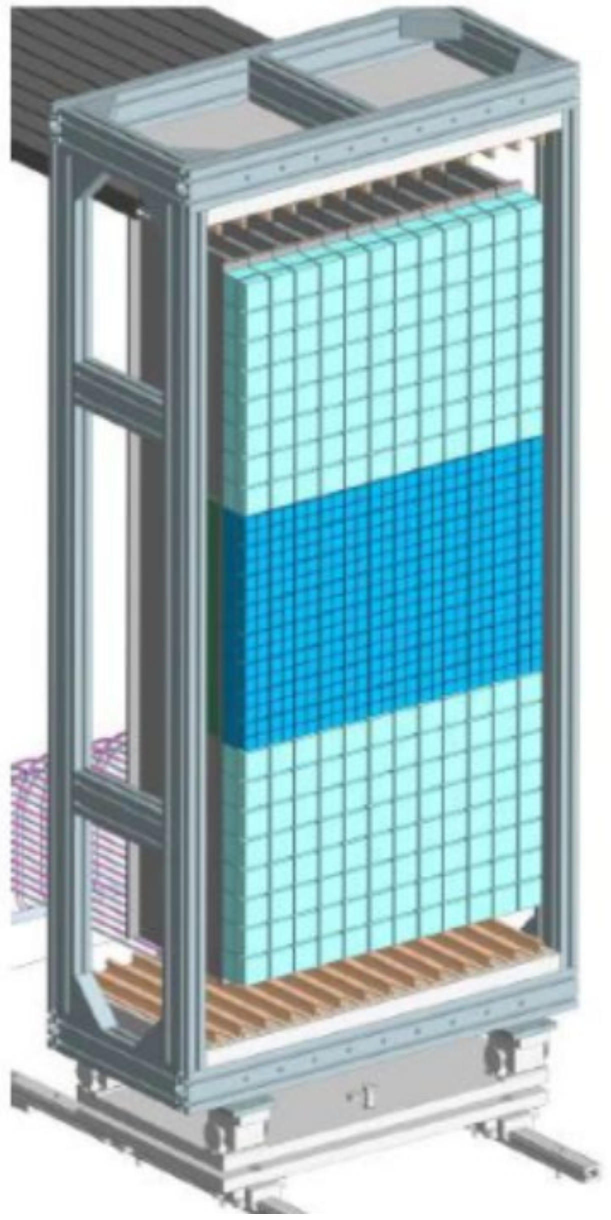




- PDMDB: motherboard with FPGAs and power distribution
  - Plugins for control and data transmission, DTM and TCM

- Elementary Cells + PDMDB form the logical unit called Photon Detector Module (PDM)
  - Share common LV and HV distribution





RICH reconstruction

RICH detector hits:
- Event decoding
- Photon hits

Tracks:
- Track radiator trajectories
- Ray traced Cherenkov cones
- Expected Cherenkov angles
- Expected Cherenkov resolutions

Cherenkov photon candidates:
- Reconstruction from photon hits and tracks
- Predicted likelihood distribution for each pixel

PID likelihood minimization:
- Computes likelihood values for each track and hypothesis
- Results of PID quoted as $DLL(h-\pi) = \Delta logL(h-\pi)$ with $h \in [\pi, K, p]$, assuming π as baseline hypothesis