The LHCb RICH detectors: operations and performance

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on behalf of the LHCb RICH group

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Outline

- Evolution of the LHCb RICH system for LHC Run 3
- Overview of operations
- Monitoring tools
- Detector calibrations
- Hadron identification performance

Introduction

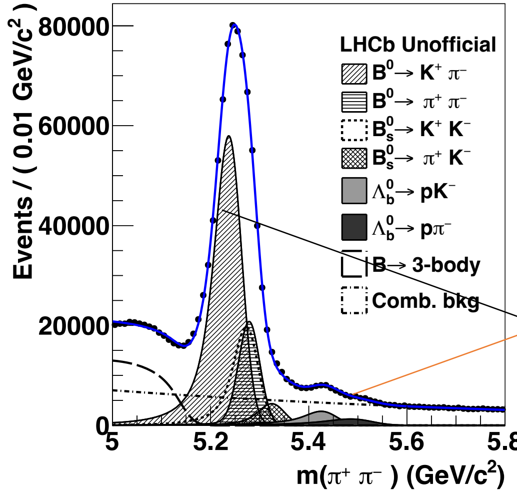
- Flavour physics measurements at LHCb require hadron identification in a **wide range of momenta between approximately 3 and 100 GeV**
  - Distinguish final states of otherwise identical topologies
  - Powerful combinatorial background rejection
  - Used in the second level of online selections

[EPJC 73 (2013) 2431](#)

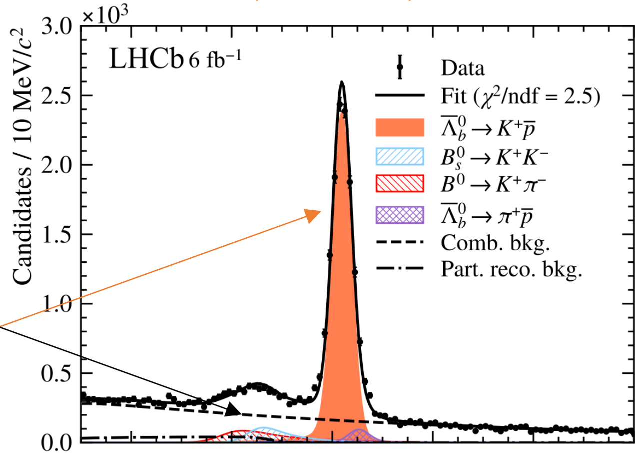
[JINST 17 (2022) 07, P07013](#)

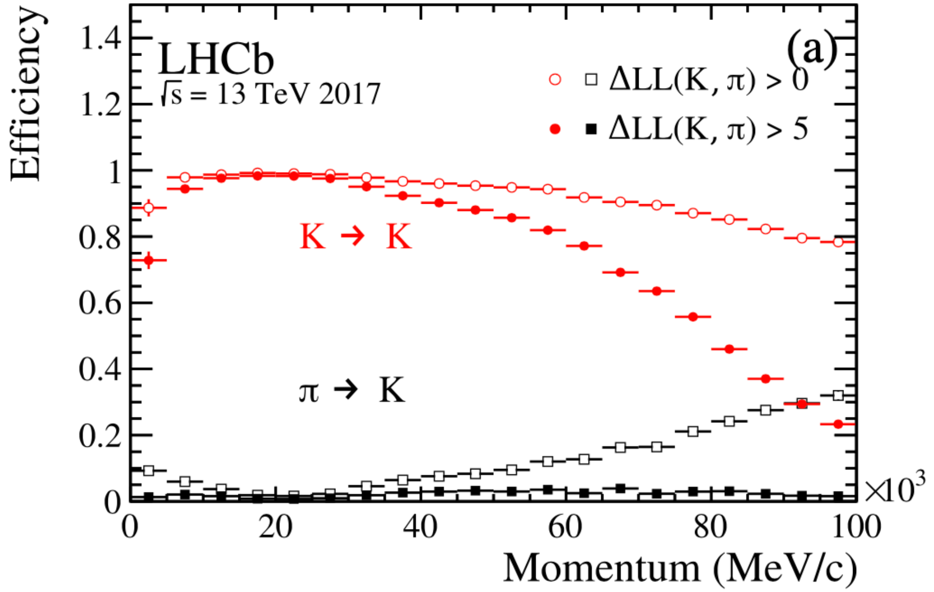
- Successful experience of a RICH system at a high-energy and high-intensity hadron collider demonstrated in Run 1 (2011-2012) and Run 2 (2015-2018)

$$\frac{N(\Lambda_b^0 \to pK^-)}{N(B^0 \to K^+\pi^-)} \sim 1/15$$



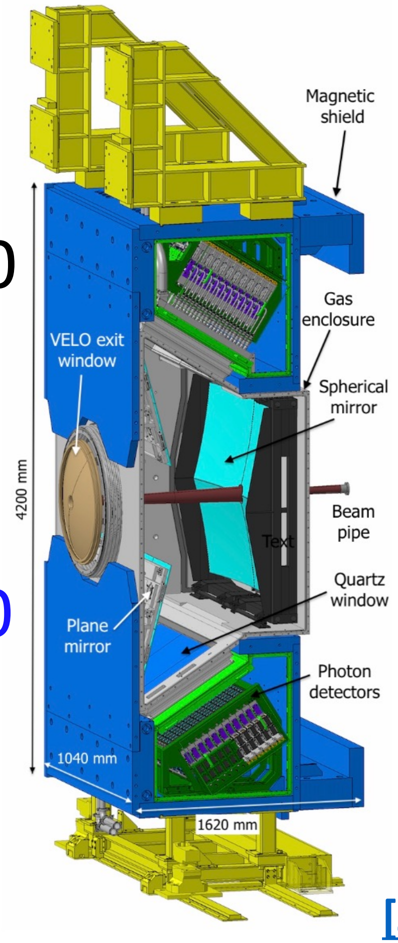
$$\frac{N(\Lambda_b^0 \to pK^-)}{N(B^0 \to K^+\pi^-)} \sim 100$$

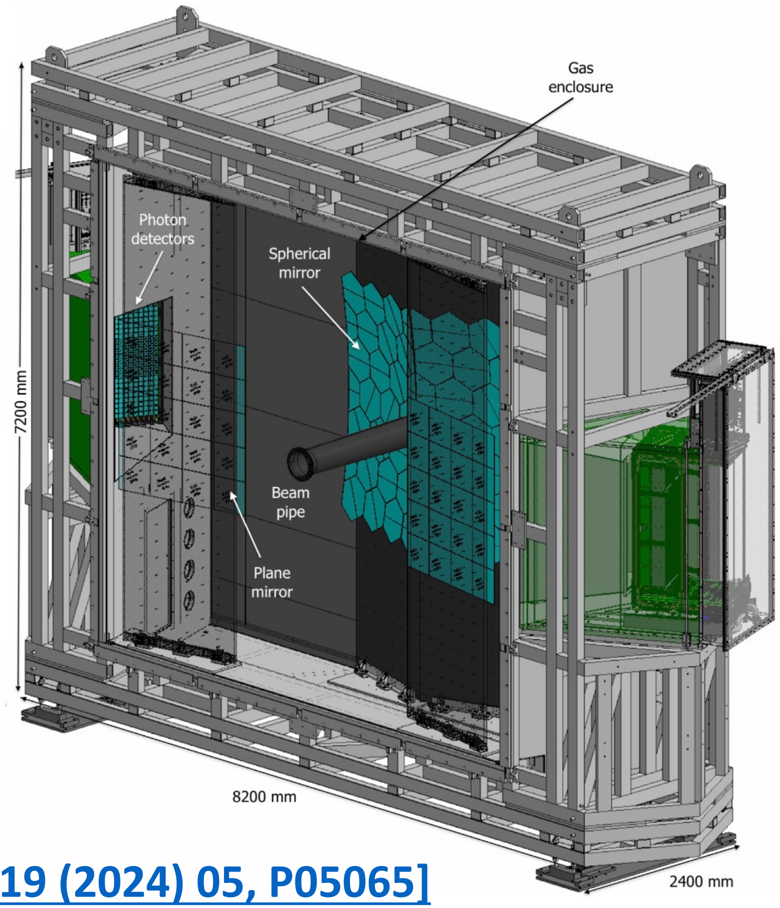




The LHCb RICH detectors in Run 3

- Run 3 RICH detectors designed to keep the same hadron identification performance of their predecessors at $L = 2 \cdot 10^{33} cm^{-2} s^{-1}$ (5x Run 1 and 2) with a continuous 40 MHz readout
- Same envelope, layout, radiators
- RICH1 with C_4F_{10} (n=1.0014 at λ=400 nm) to cover 3-40 GeV over 25-300 mrad
- RICH2 with CF_4 (n=1.0005 at λ=400 nm) to cover 15-100 GeV over 15-120 mrad
- **New RICH1 optics and mechanics**
- **New photon detection chain**

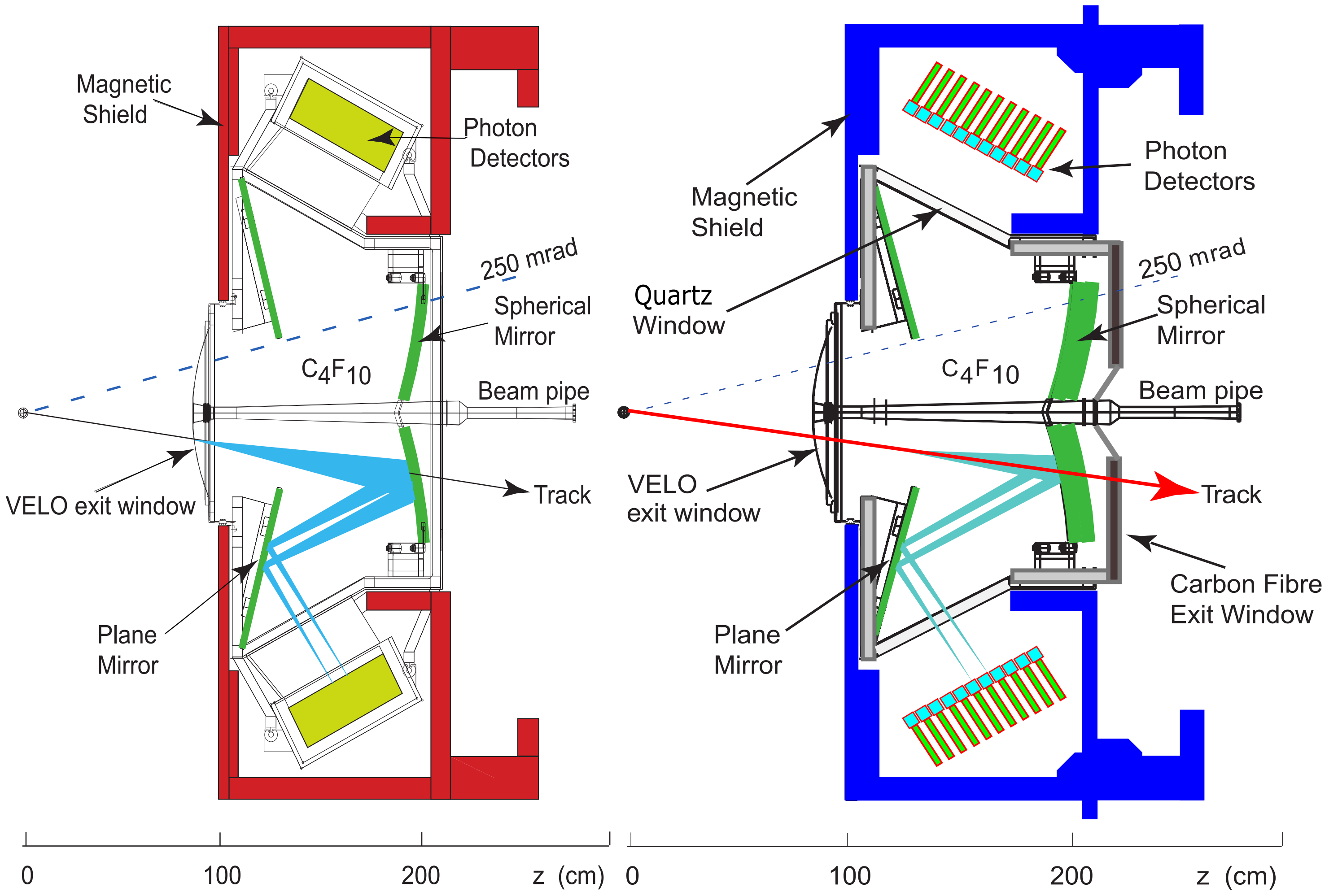




[JINST 19 (2024) 05, P05065]

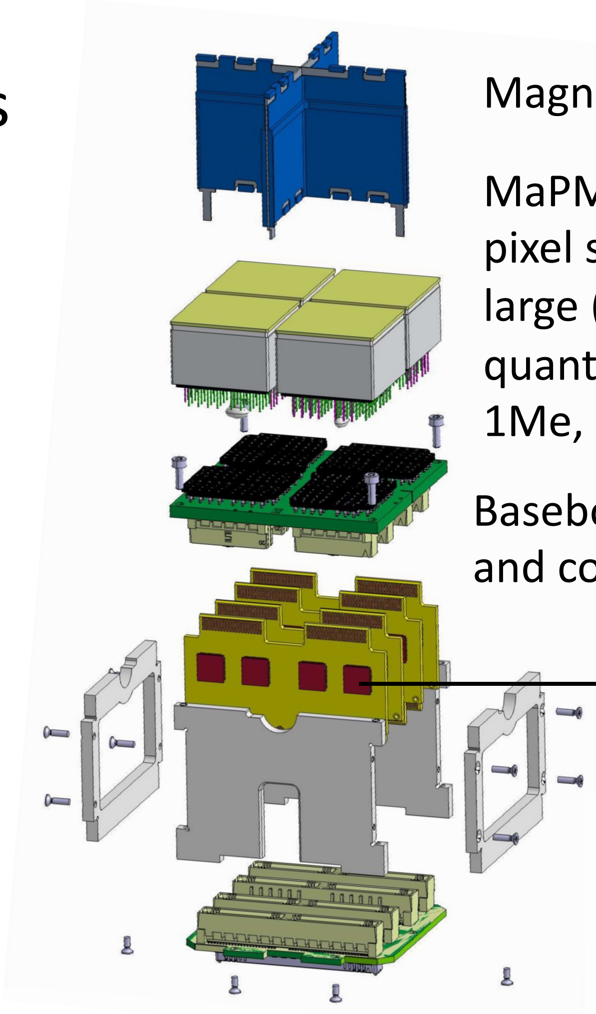
Evolution of the RICH1 system for Run 3

- Increase the radius of curvature of the carbon-fibre spherical mirrors by ~ $\sqrt{2}$, reduce the tilt of the optical elements and move the photon detector planes further outside the acceptance => **halve the peak photon hit density** and **improve single-photon resolution** (reduced pixel-size and emission-point errors)
- Extend the radiator volume by ~ 100 mm => **+15% Cherenkov photons**



Evolution of the photon detection chain for Run 3

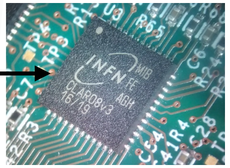
- Continuous readout at 40 MHz => replace HPDs with MaPMTs and new frontend electronics (**200k channels**)
- Improved matching of quantum efficiency of MaPMTs with radiators dispersion => **improve single photon resolution** (reduced chromatic error) and **increase detected Cherenkov photons per track**



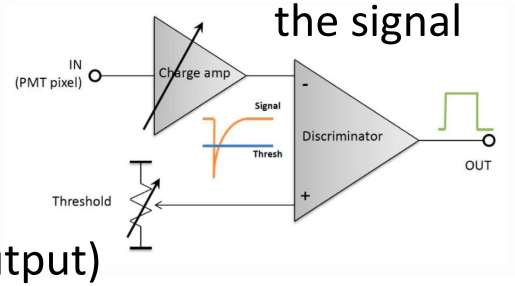
Magnetic shielding (RICH1)

MaPMTs: 2.8 x 2.8 mm^2 pixel size, 80% active area, large (**40% at 300 nm**) quantum efficiency, G > 1Me, DCR < 2.5 kHz/cm^2

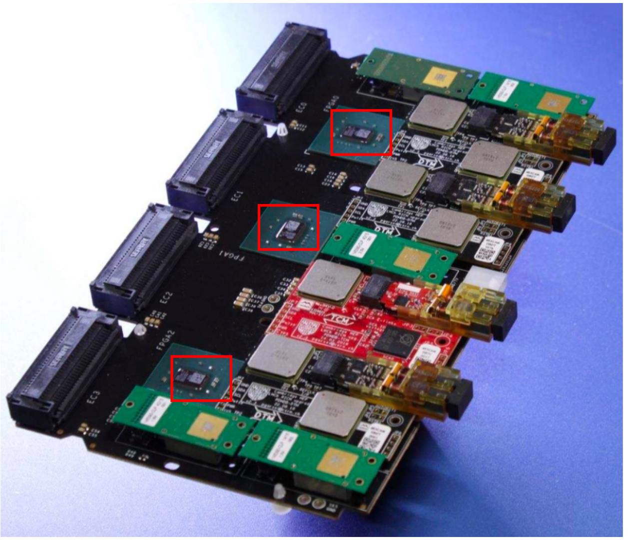
Baseboard (voltage divider and collect analog output)



CLARO ASIC to digitise the signal



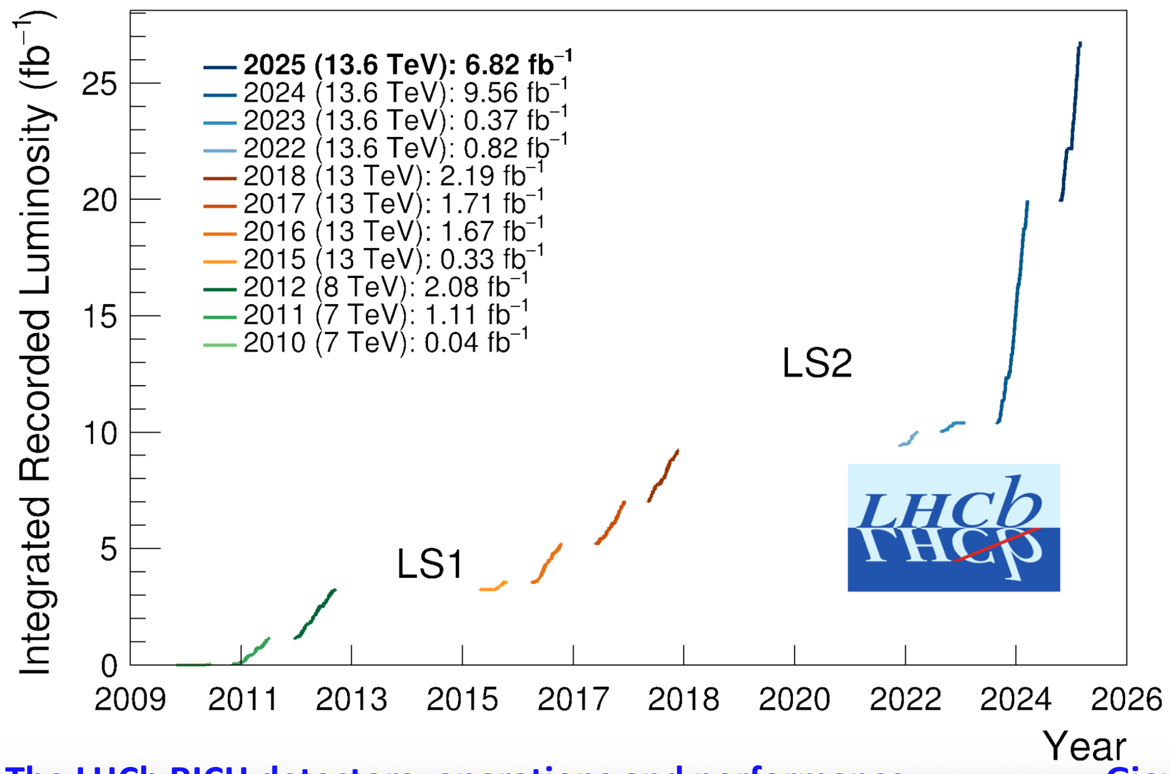
Backboard (deliver digital output)

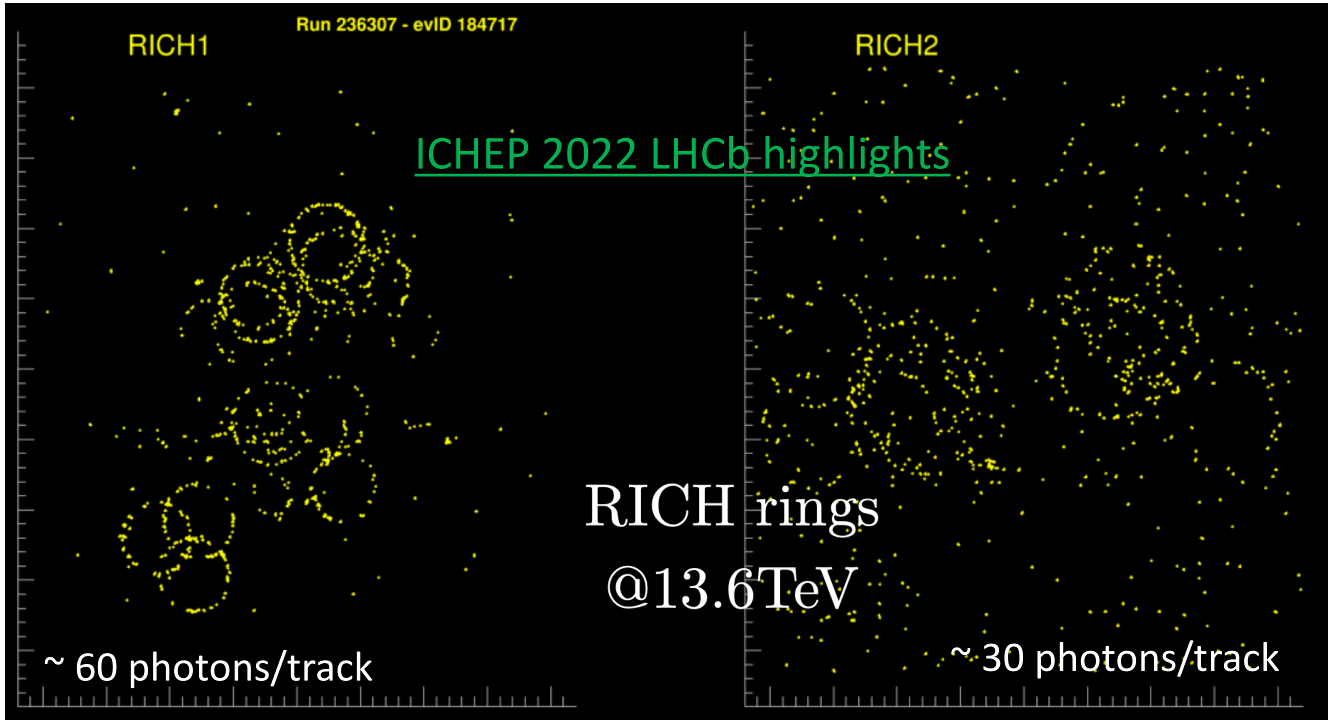


Flexible Kintex7 FPGA-based digital Board interfacing with LHCb backend boards using the GigaBit Transceiver protocol

Overview of Run 3 operations

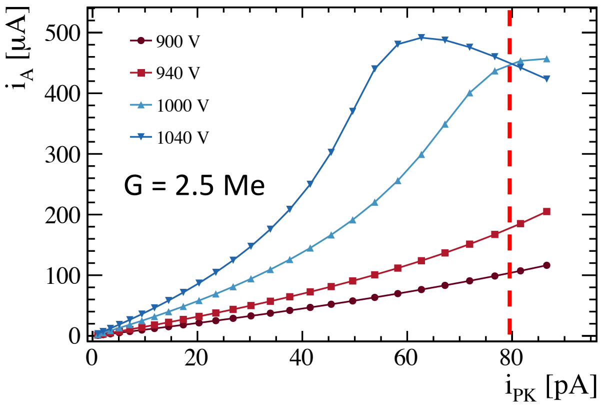
- Operational on-time since the start of Run 3 in 2022 thanks to an intense campaign of quality assurance and commissioning lasting 10 years
  - See Antonino Sergi's talk at RICH2022 for more details
- LHCb Upgrade I commissioning in 2022, followed by the LHC vacuum incident in the VELO volume in 2023 => 2024 has been the first physics production year

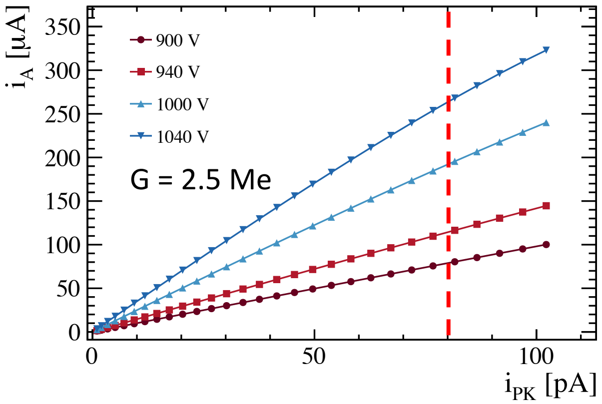


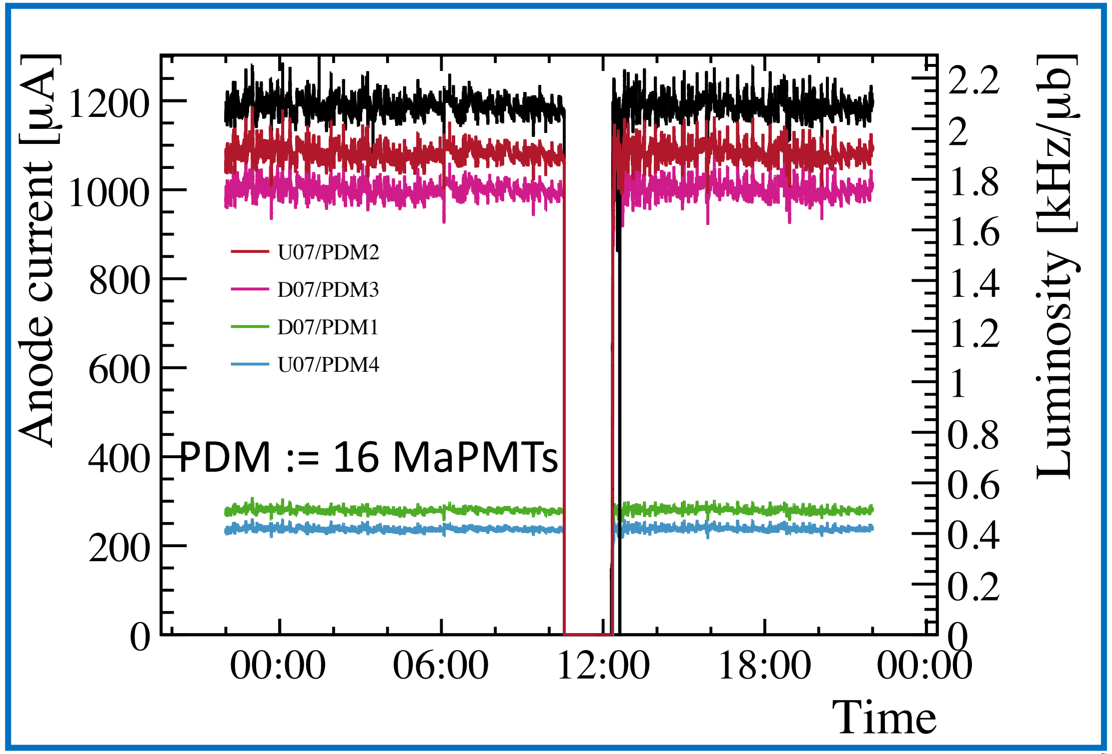


Operational tools

- Automated safety actions based on the monitoring of environmental parameters such as temperature and pressure of Novec cooling circuits
  - Backed-up by hardware interlocks in case of major network disruptions
- Custom high-voltage supply scheme implemented for MaPMTs to mitigate loss of gain linearity expected at the highest illumination rates
  - **Supply last dynode independently**
  - Allows direct monitoring of anode currents
    - maximum rating from HPK is 100 μA / MaPMT
    - signals proportional to instantaneous luminosity

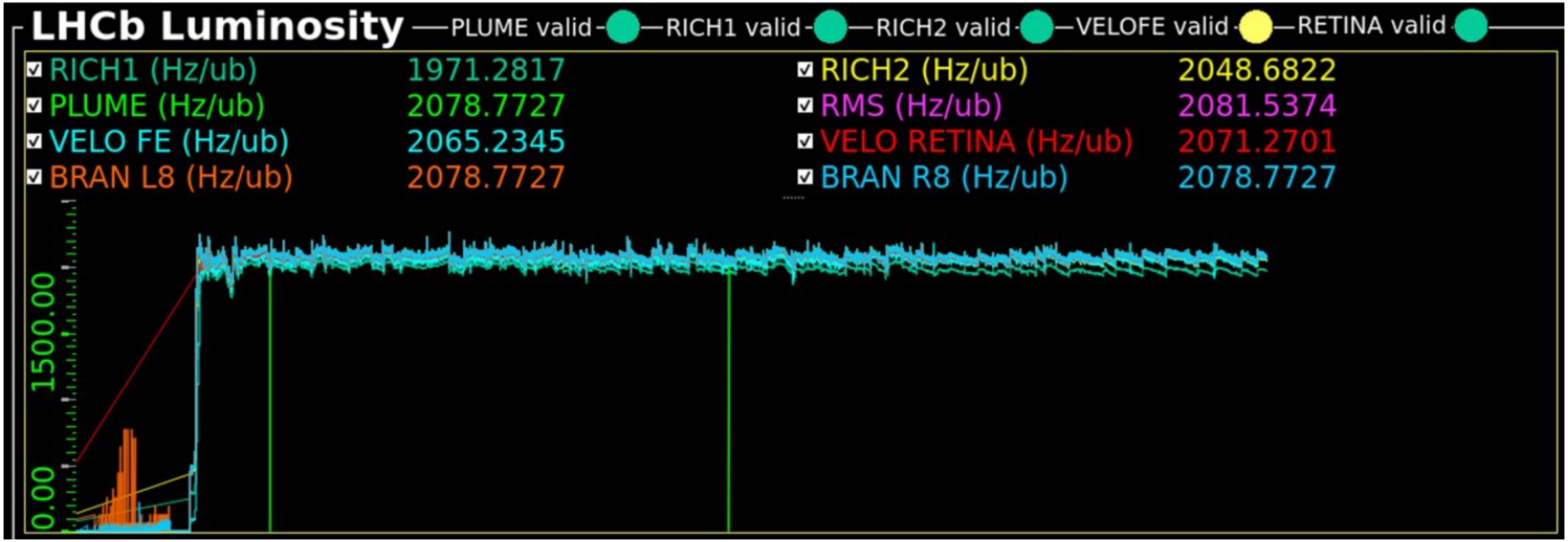






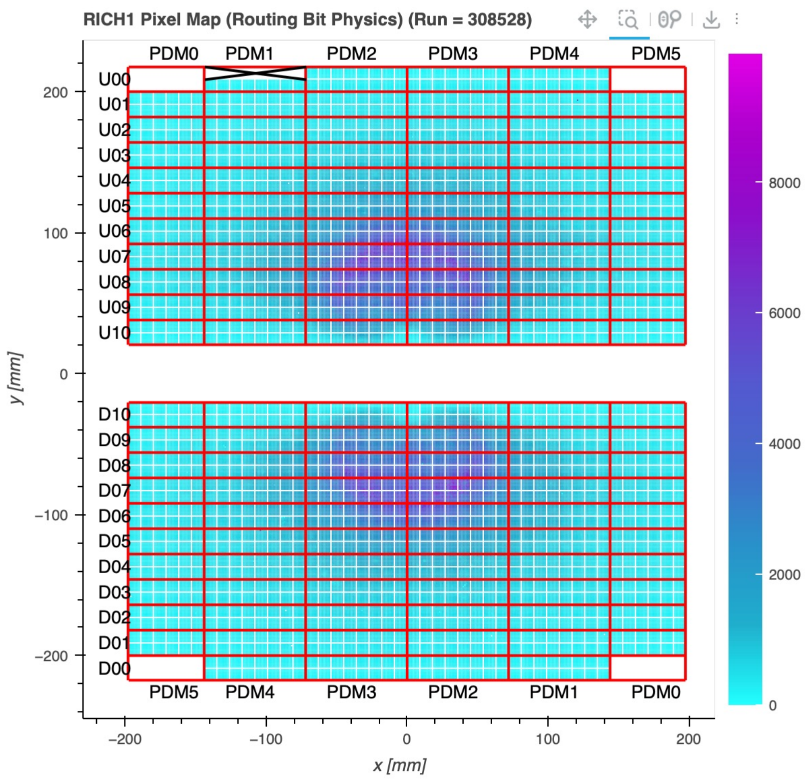
LHCb RICH system as luminometer

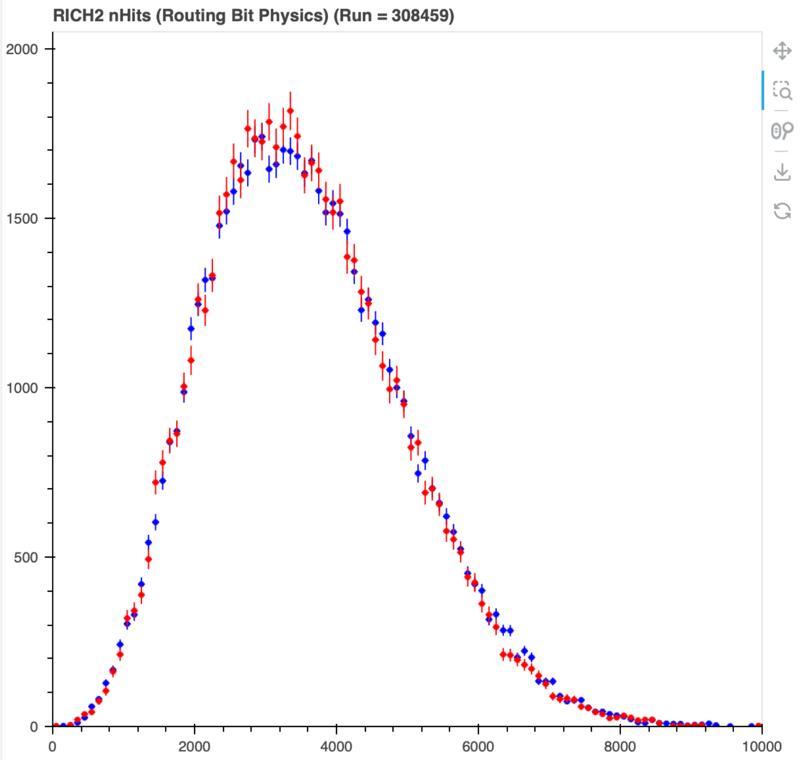
- New application of the LHCb RICH system [JINST 20 (2025) 08, P08001]
- Online luminosity determined from 90 (RICH1) and 144 (RICH2) counters
- RICH1 and RICH2 signals (**independent from the data-taking status**) sent to the LHC-OP team as backup to PLUME (main LHCb luminometer)

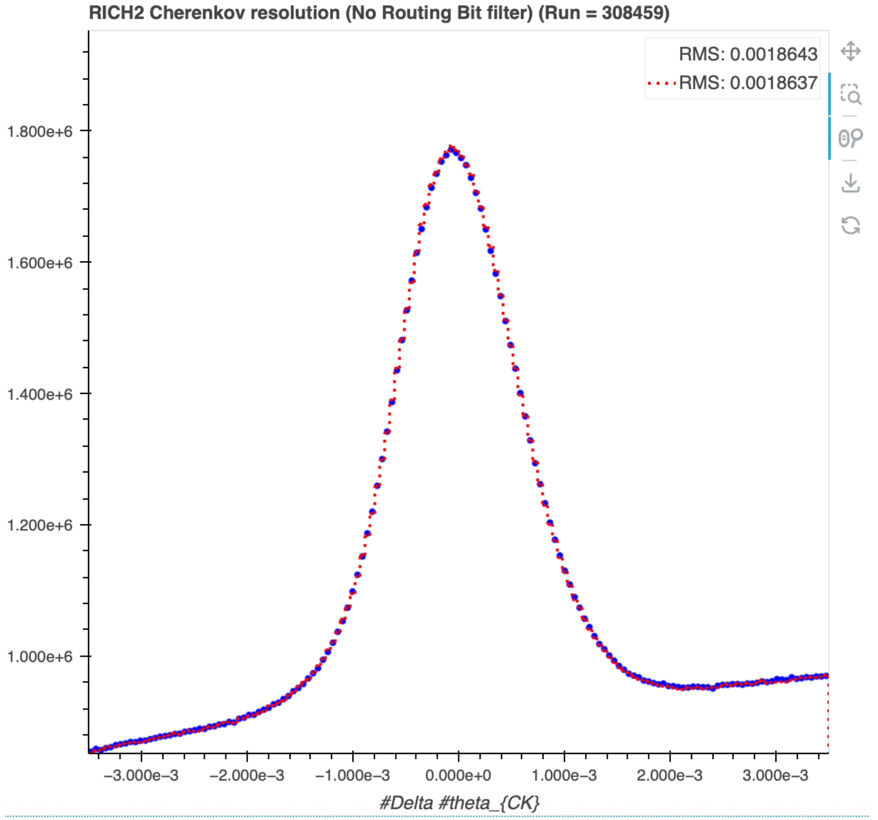


Operational tools

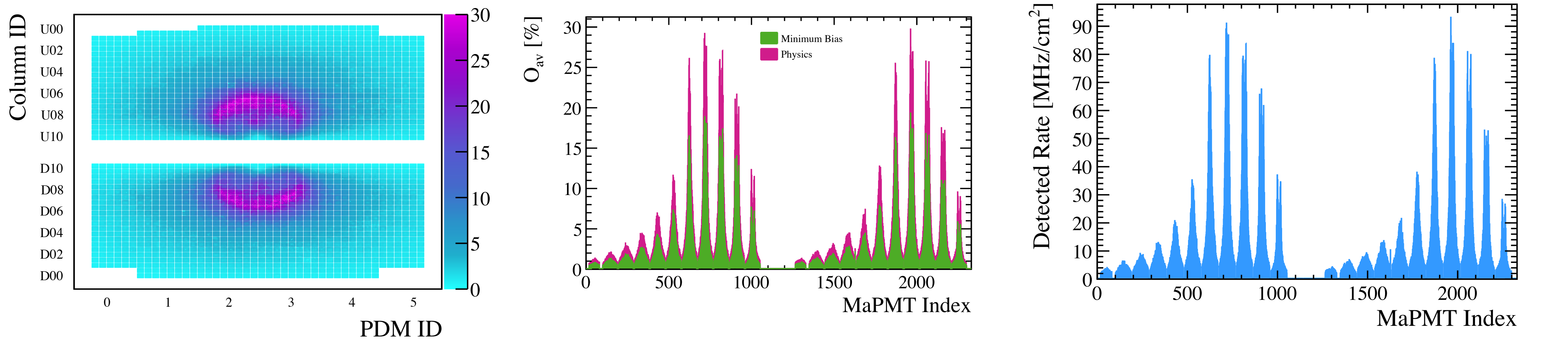
- Automated actions to recover from occasional (1 every 3 hours in the full detector) Single-Event Effects induced by radiation on the Kintex7 FPGAs: **no downtime and no effects on PID performance**
- Several online data-monitoring histograms available for data managers

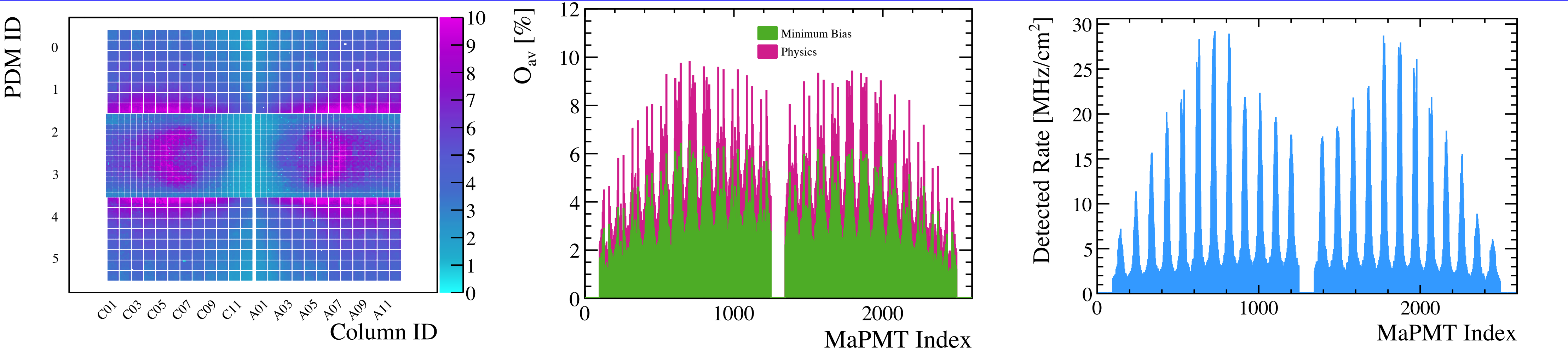






Online monitoring: occupancies and rates



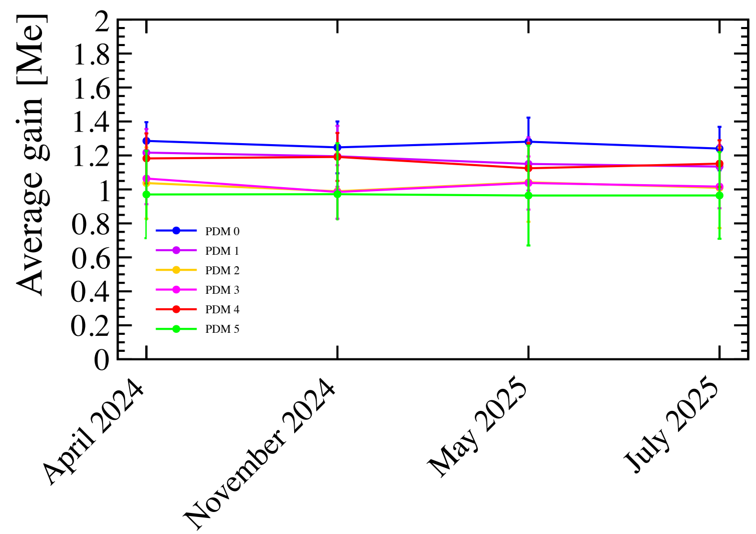


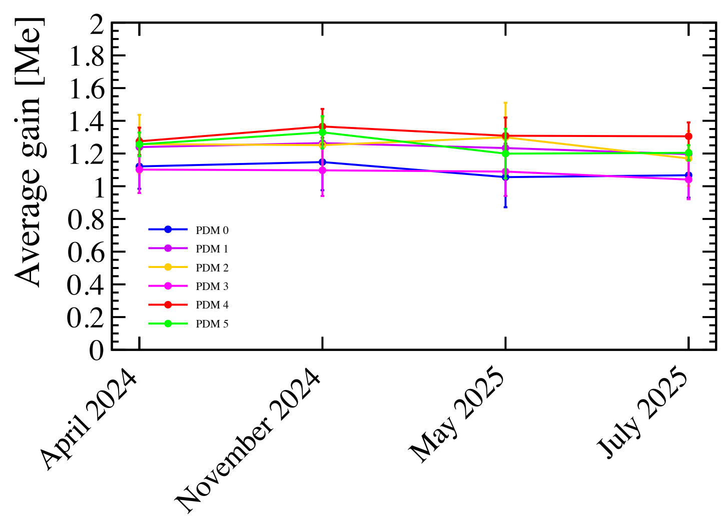
- Occupancies for RICH1 and RICH2 according to expectations: minimum bias occupancy at 40 MHz converted to detected rate densities

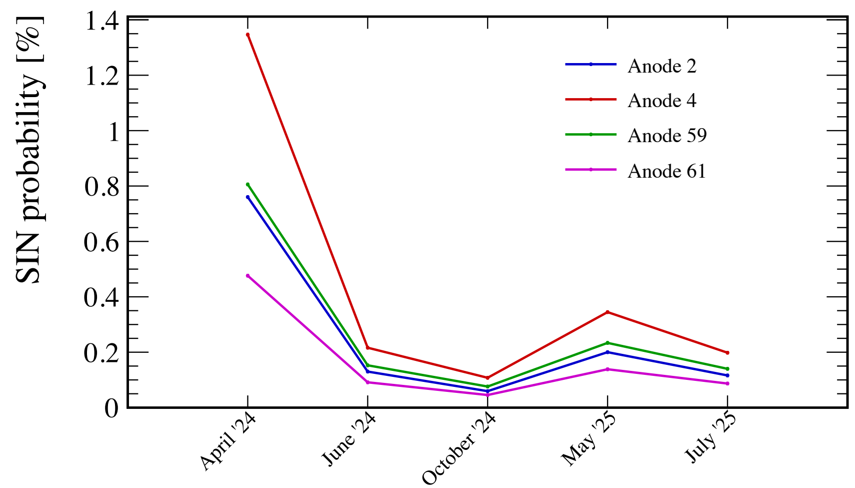
Monitoring: MaPMT gain and noise

- Dedicated runs during LHC intensity ramp-up periods used to monitor gain, check for ageing and assess the noise evolution of MaPMTs
- No significant ageing observed so far
- Dark counts below 1 kHz/cm^2
- Signal-induced noise: consistent and significant reduction after extensive periods of illumination, below 1% afterpulse-like probability for all pixels

[JINST 16 (2021) P11030]

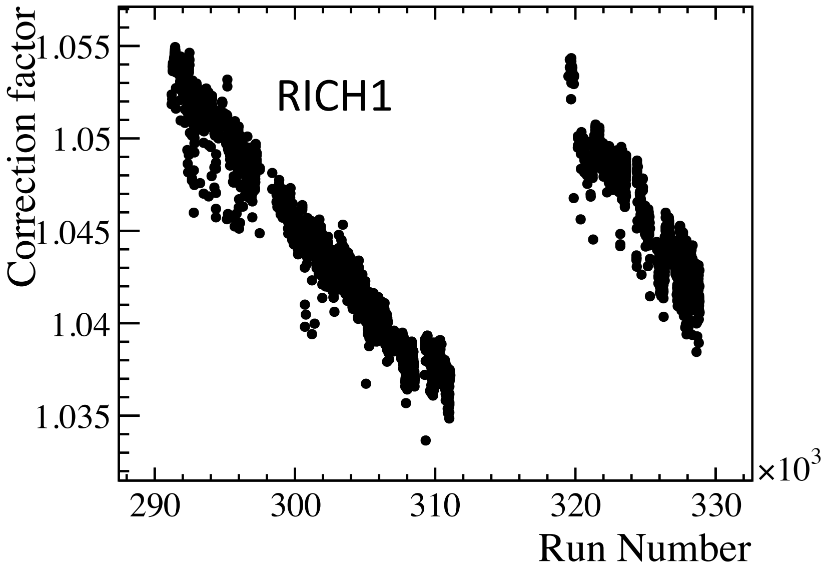


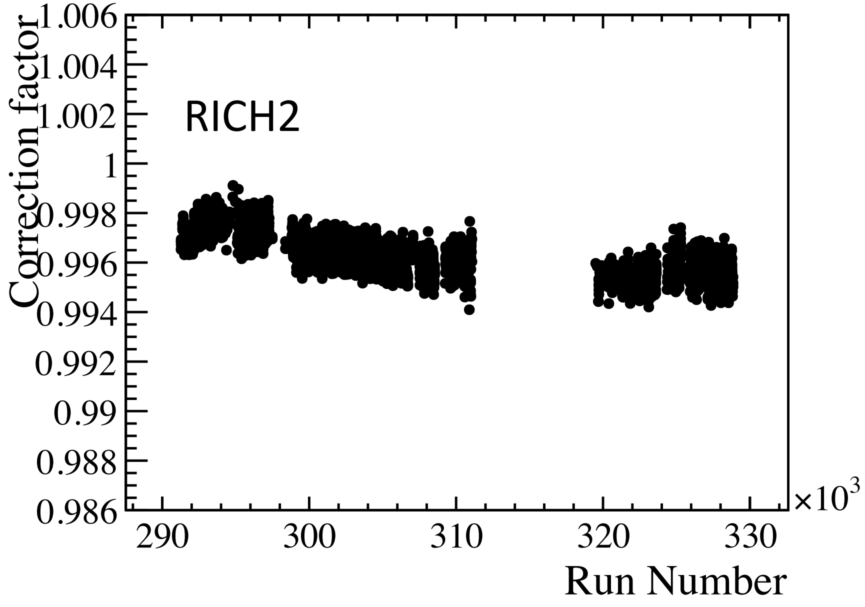




Online monitoring: refractive index

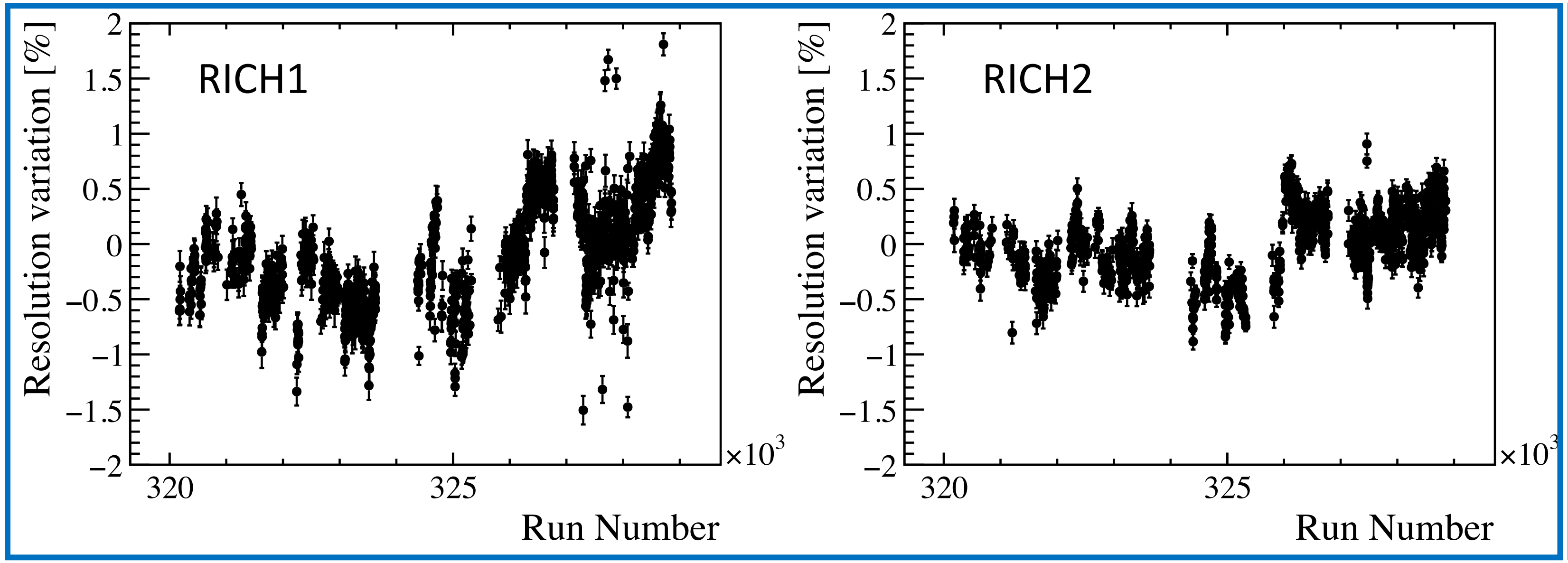
- Required to correct for environmental (temperature and pressure) and purity (small sub-percent/month air contamination in RICH1) changes of the radiators
  - Starting point determined from several temperature and pressure sensors placed inside the gas enclosure
- Reconstructed Cherenkov angle from high momentum tracks ($\cos\theta_c \sim 1/n$) to determine and calibrate the **refractive index per run** directly from data with an online data monitoring task

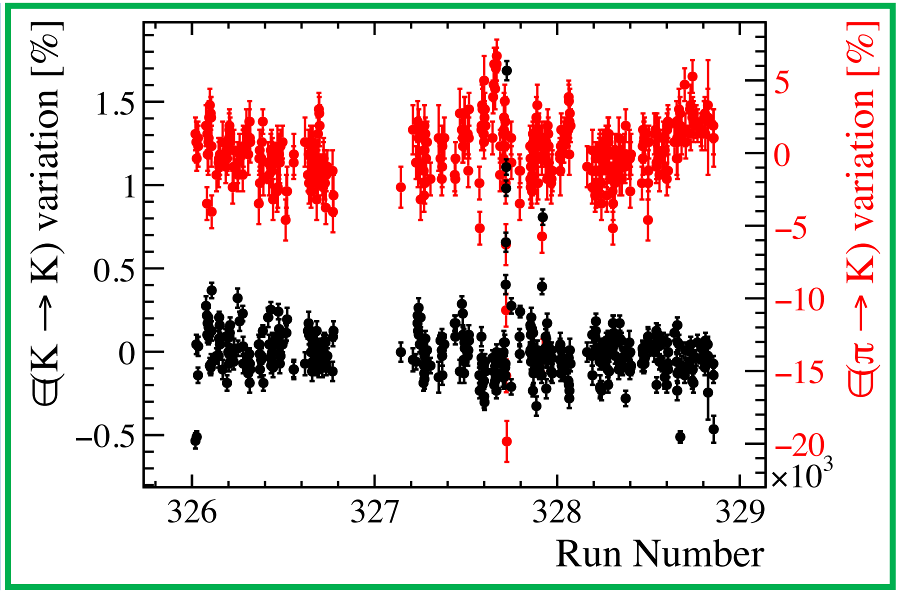




Online monitoring: resolution and PID trends

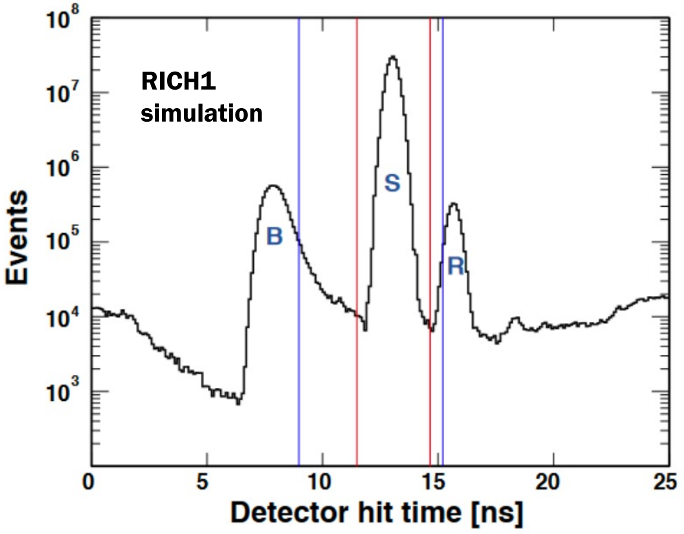
- Same tool for refractive index used to monitor the trend of the relative variation of single photon resolutions across time
- Deferred determination of the relative variation of PID performance after the completion of the processing of the second level of online selections (2-3 days after data-taking) to minimise latency of PID assessment and remove need for manual actions

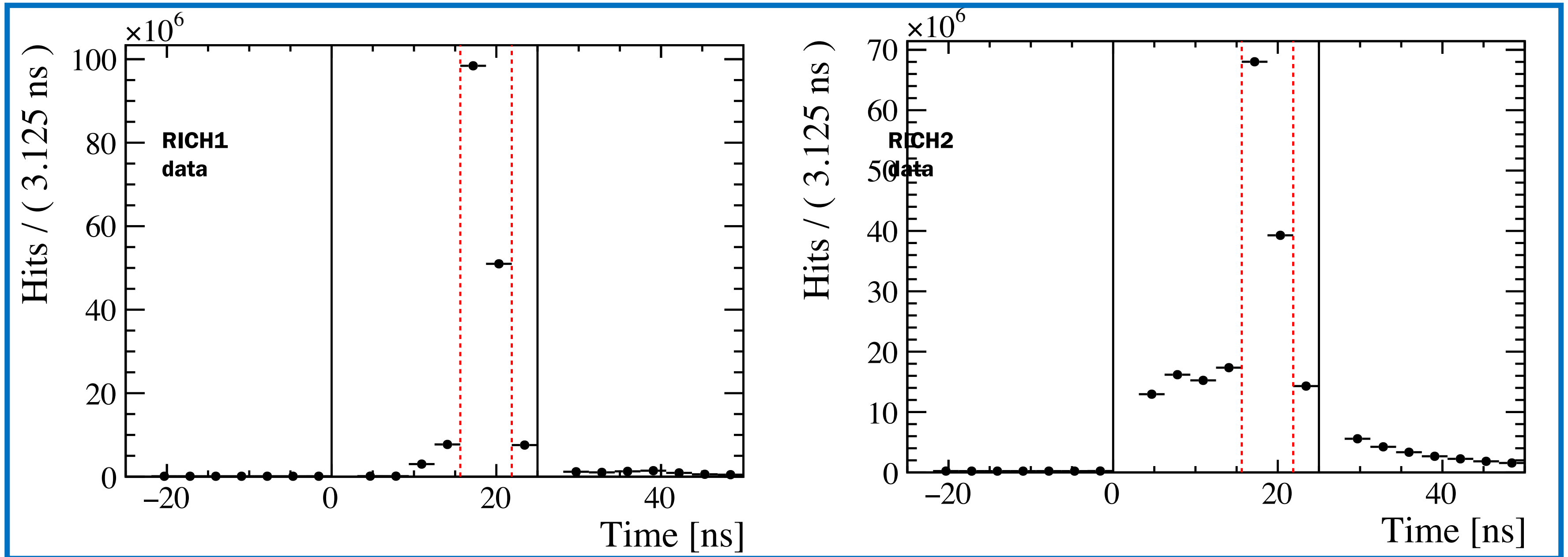




Calibrations: time alignment

- Matching of data from the ~ 2500 optical links with the LHC bunch crossing identifiers done by means of adjustable 25 ns delays in the backend boards
- Clock distribution system allows for signal latching at 360 MHz in firmware: demonstration of **3.125 ns gating** to reduce out of time backgrounds
  - Pave the way for new applications of the RICH system, see [Abhinaba Upadhyay talk]
- 6.25 ns time gating window deployed since 2022





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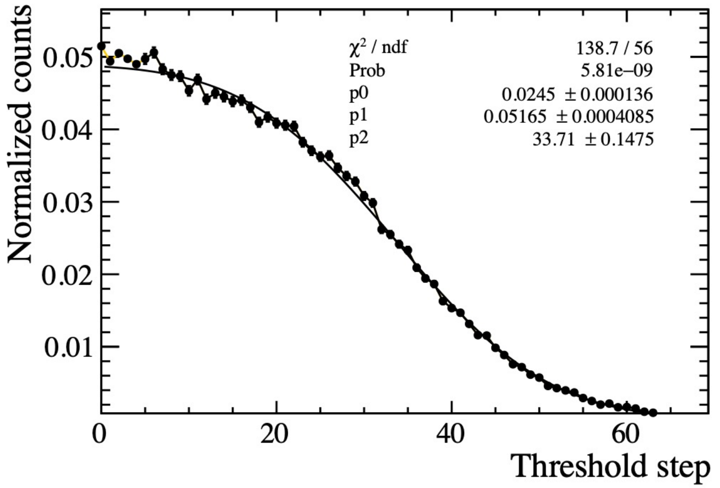
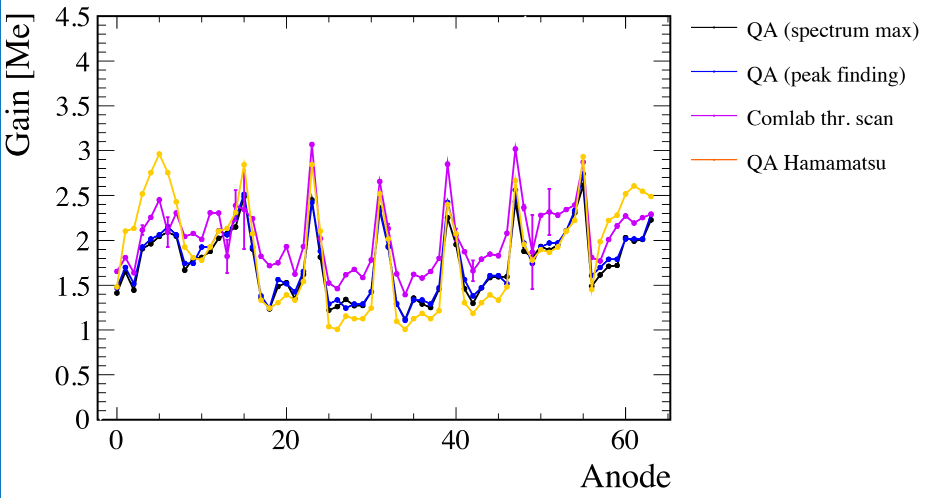
Calibrations: gain equalisation

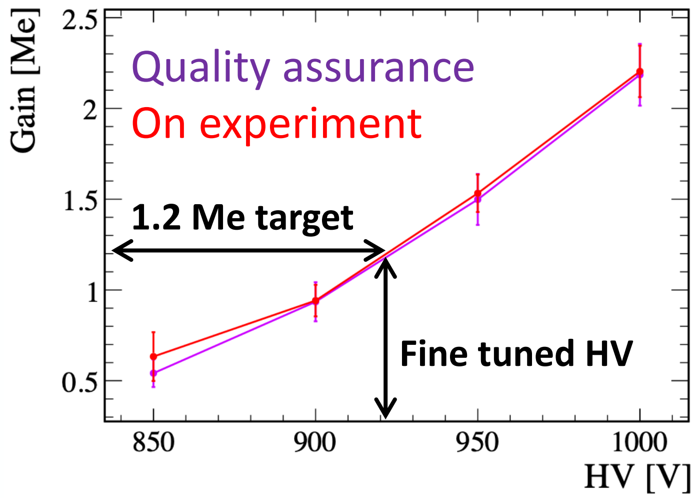
- Average gain of the 200k MaPMT channels through automated threshold scan procedures with beam
  - same procedure used to monitor and correct for ageing
  - excellent agreement between quality assurance and on experiment results
  - Average gains equalised to **1.2 Me** (frontend thresholds at 200 ke) by tuning the operating high-voltages



Single channel threshold scan



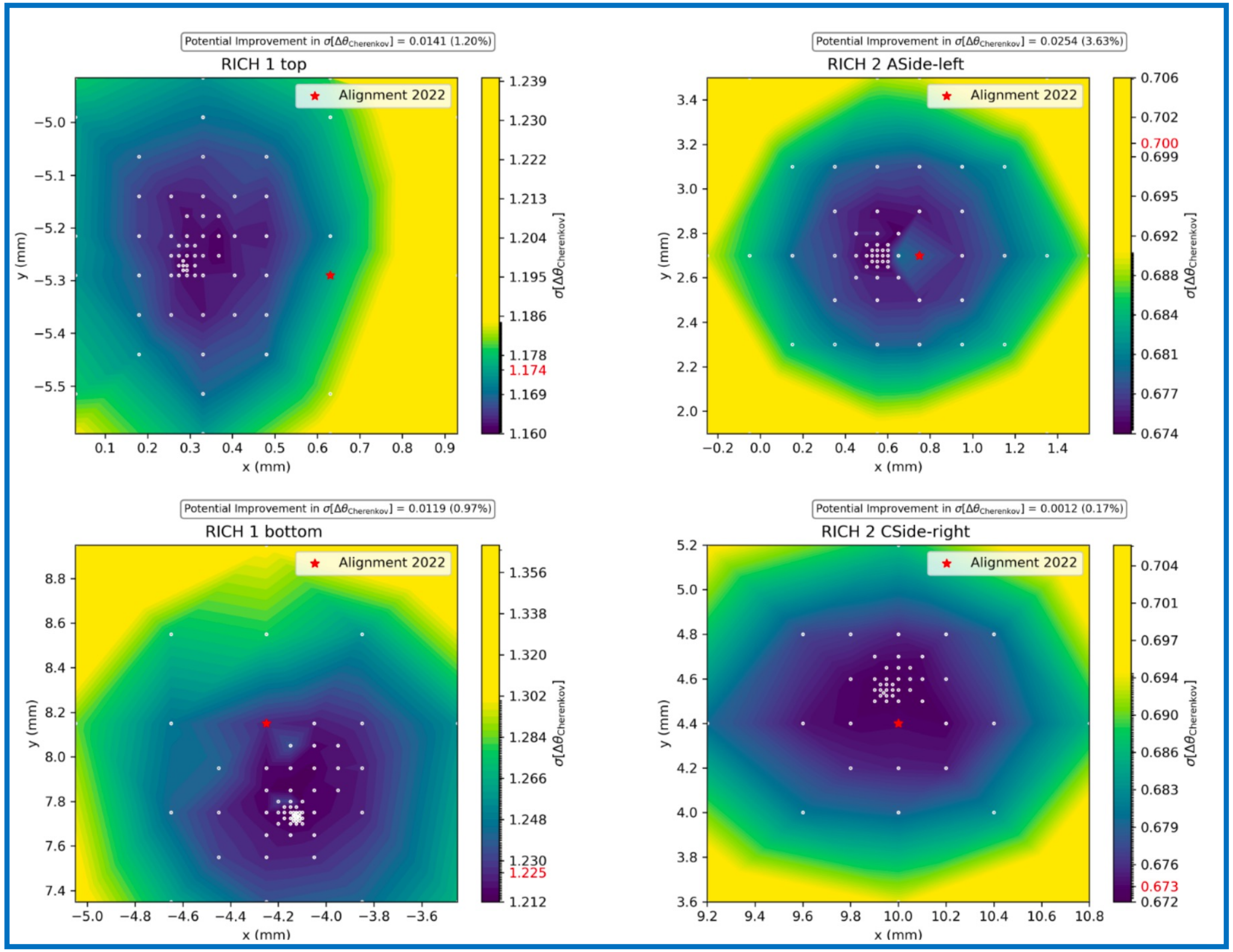
Results for the 64 anodes of one MaPMT



Results for one group of 16 MaPMTs

Calibrations: space alignment

- Single photon resolution also has a contribution from the spatial alignment of the optical system and from the relative alignment with the trackers
- Hardware alignment done during the installation
- Software alignment correcting for residual imperfections checked every LHC fill
  - Photon detector panels and mirrors alignment

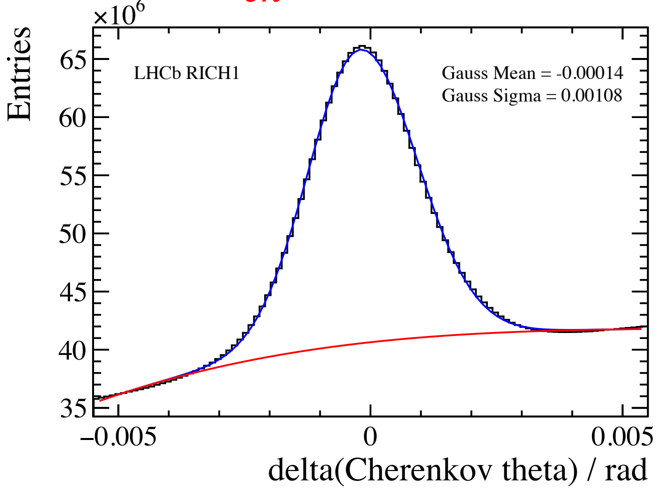


LHCb-FIGURE-2023-007

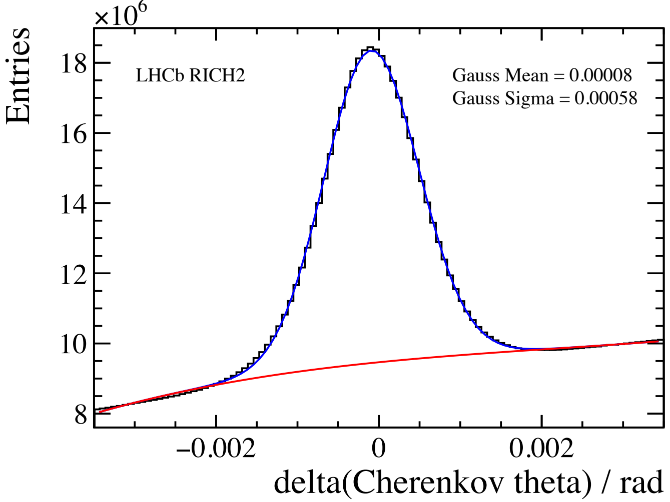
Calibrations: Single-photon resolution

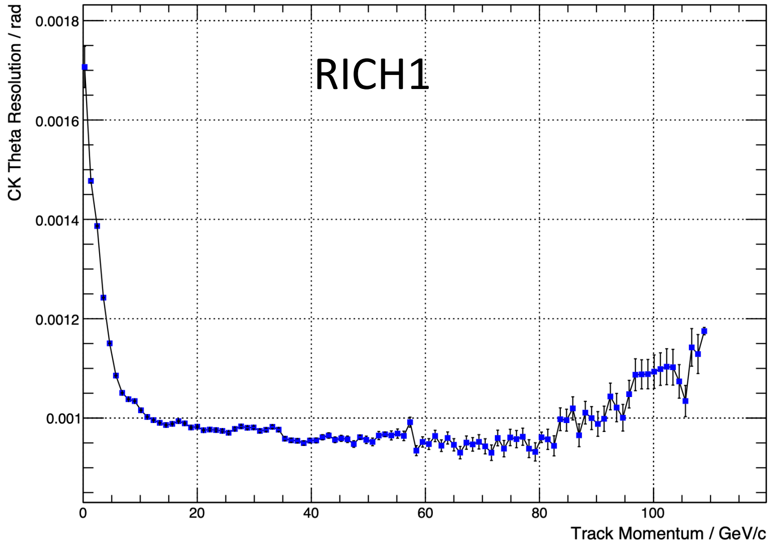
- Studied behaviour of single photon resolution as a function of track momenta
- Close to expectations moving to the direction of solving a long-standing discrepancy between data and MC for RICH1
- Propagated run-by-run to the PID reconstruction software

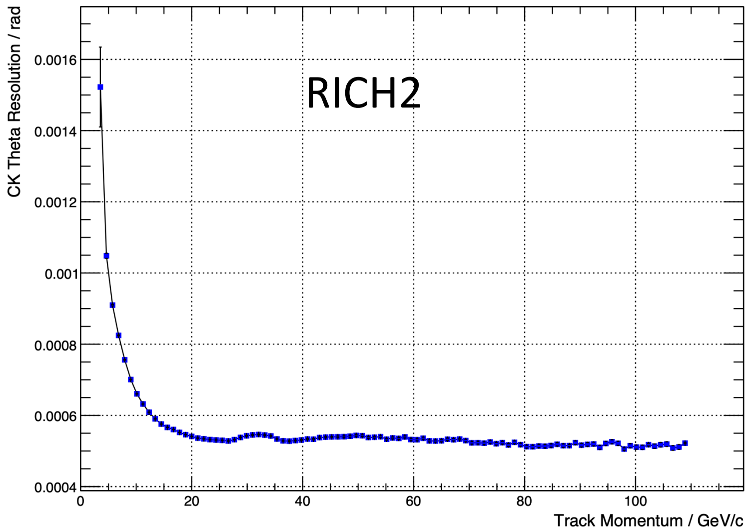
$\sigma_{ch} \sim 1.08\ mrad$



$\sigma_{ch} \sim 0.58\ mrad$

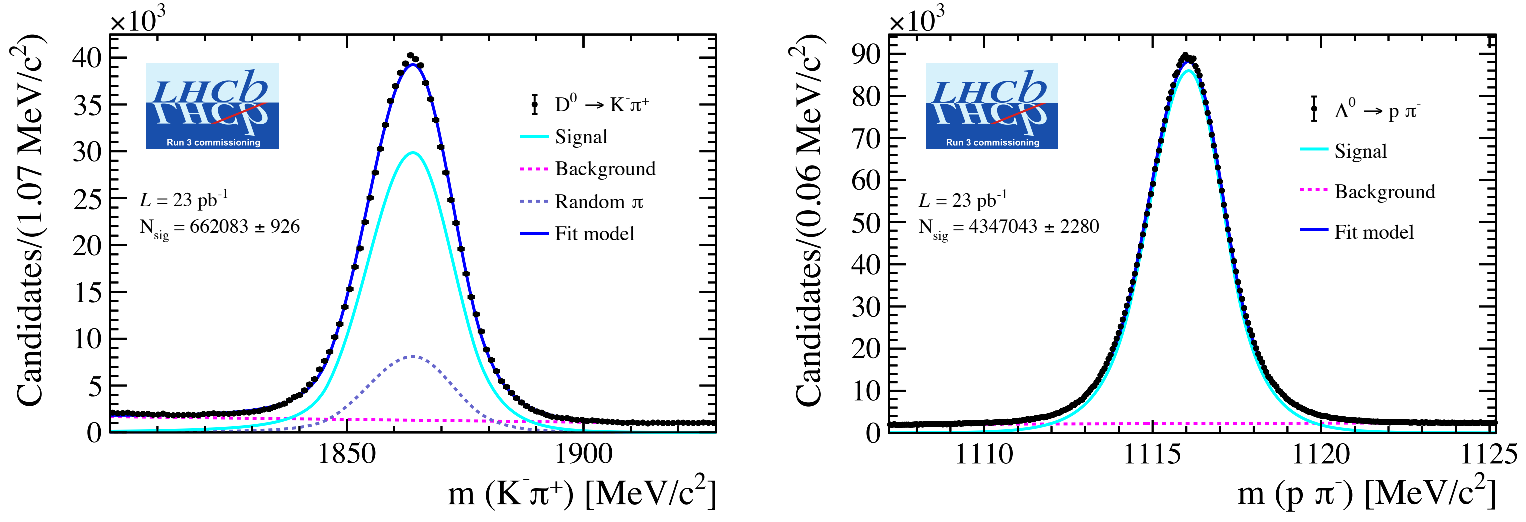


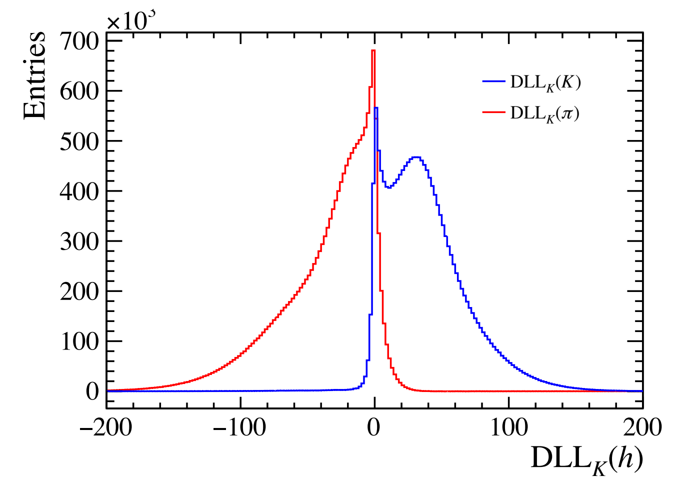




Hadron identification performance

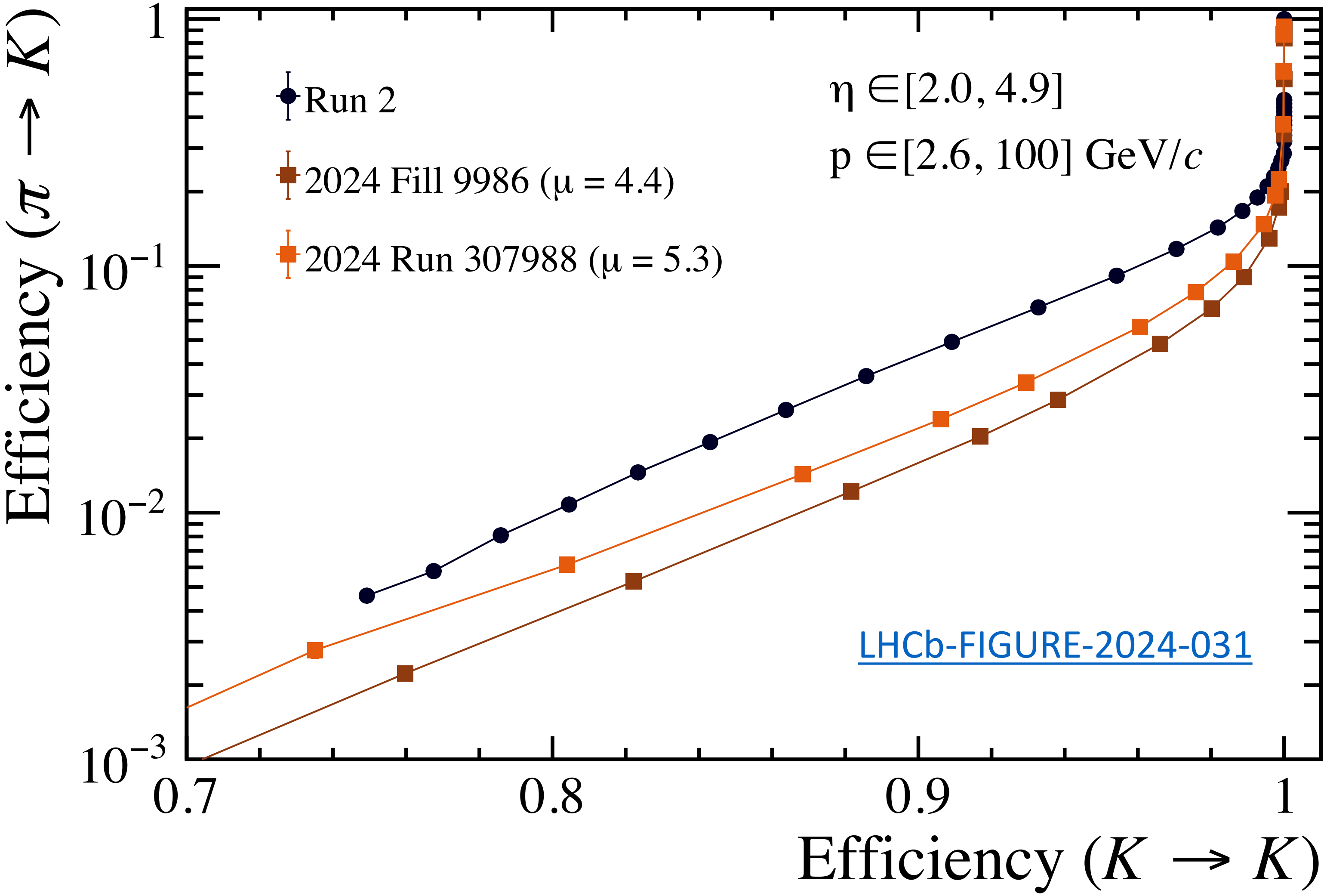
- RICH detectors single photon resolution, number of detected photons per track, operational stability and calibrations impact the hadron identification performance used in data analyses to select the signal of interest and reject backgrounds
- Performance determined through the studies of calibration samples selected by purely kinematic means: $D^{*+} \rightarrow D^0(\rightarrow \mathbf{K}^-\boldsymbol{\pi}^+)\pi^+$ and $\Lambda \rightarrow \mathbf{p}\pi^-$
- Cut on high-level variables defined as $DLLh = \ln(h)\,/\ln(\pi)$ in bins of momentum, angular acceptance and event multiplicity





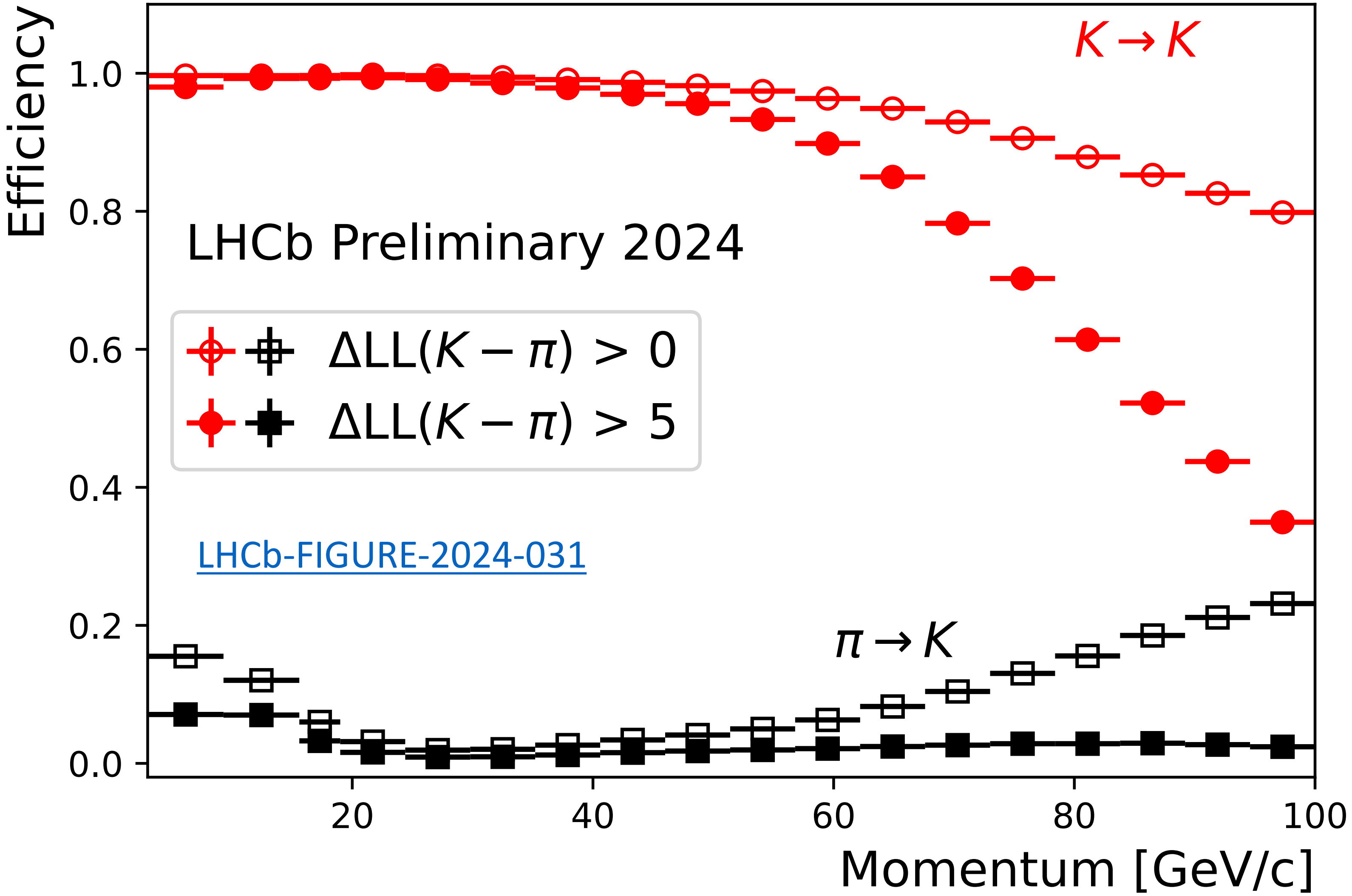
Hadron identification performance

- **Better performance than their predecessors** at 5x the instantaneous luminosity



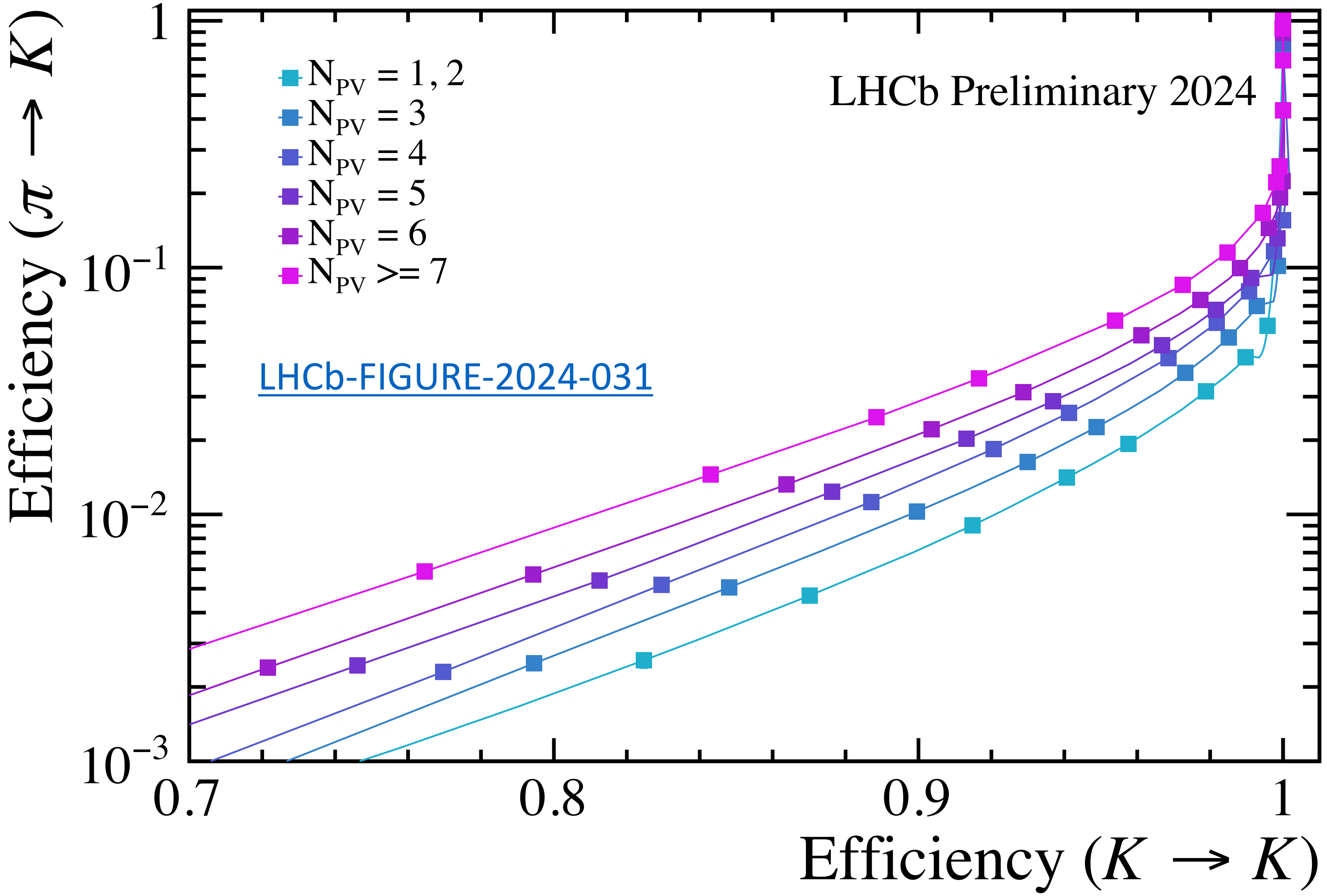
Hadron identification performance

- Performance studied in the **full range of momenta**

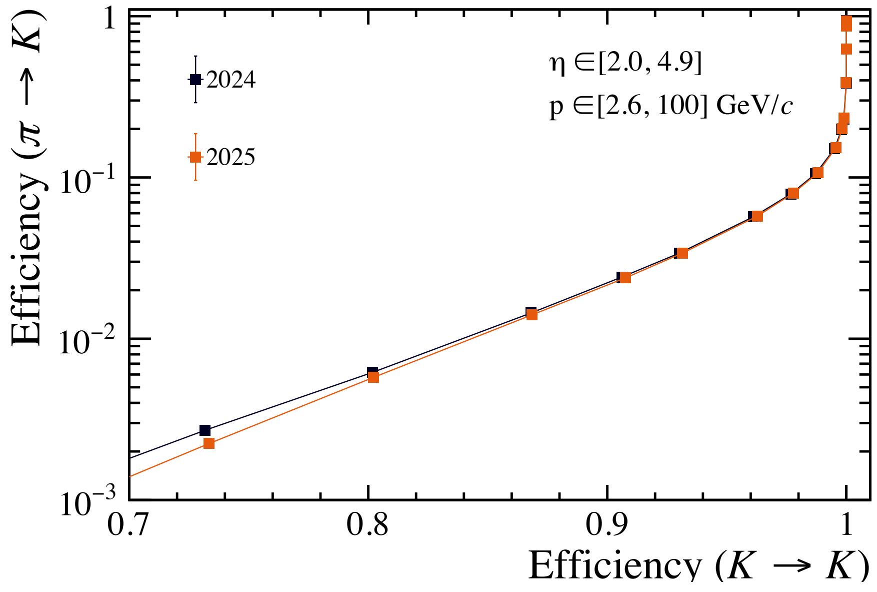


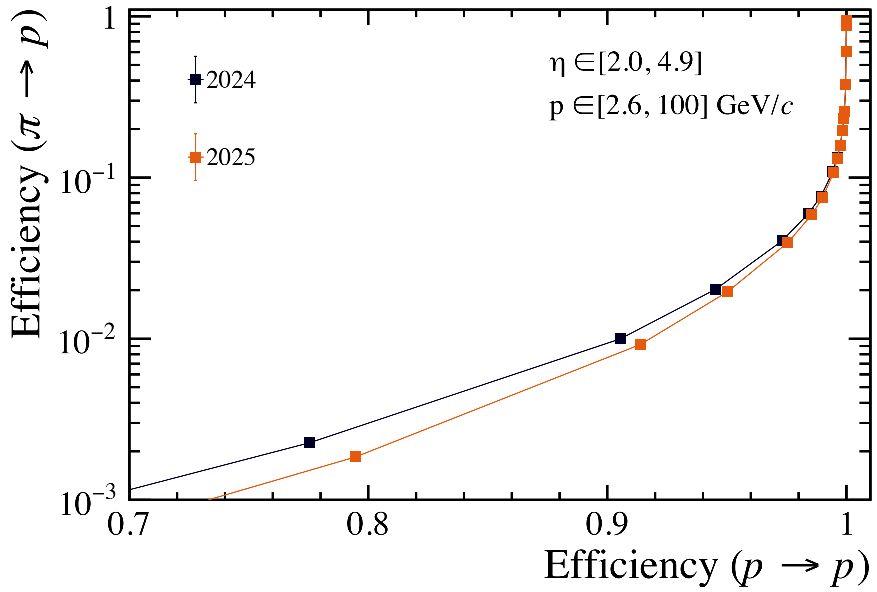
Hadron identification performance

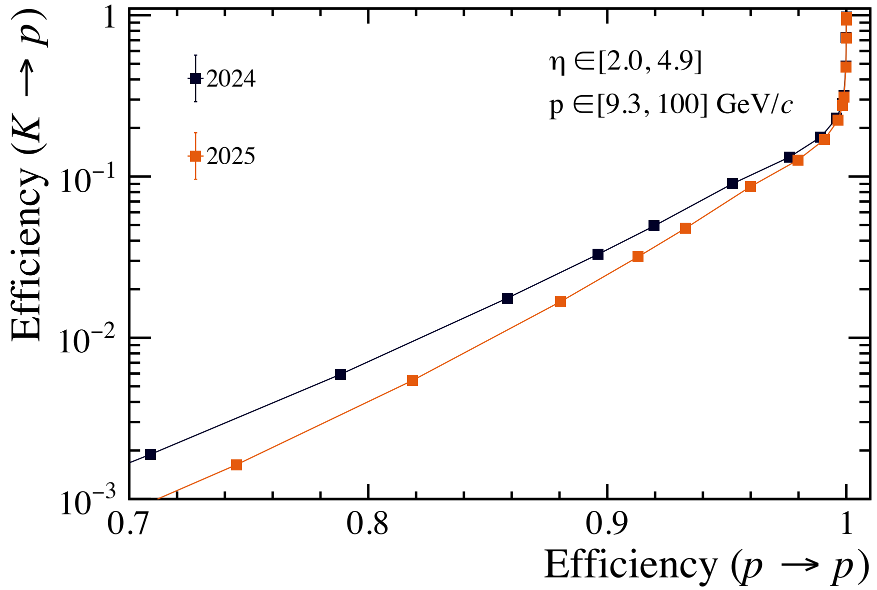
- Degradation for increasing multiplicity **according to expectations**



Stability of hadron identification performance





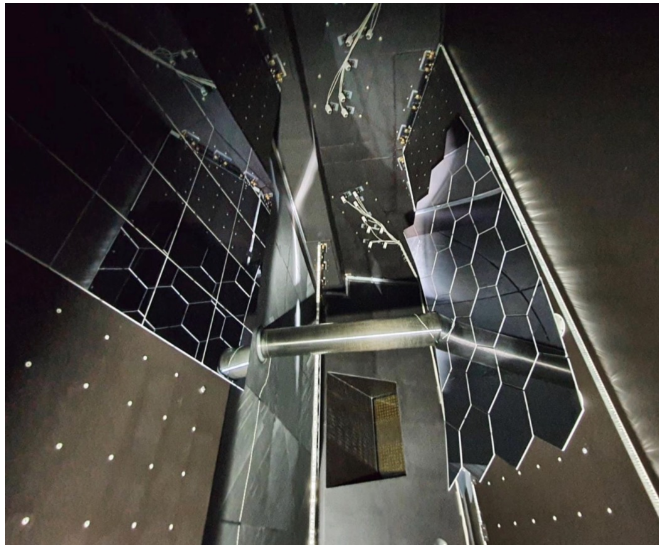


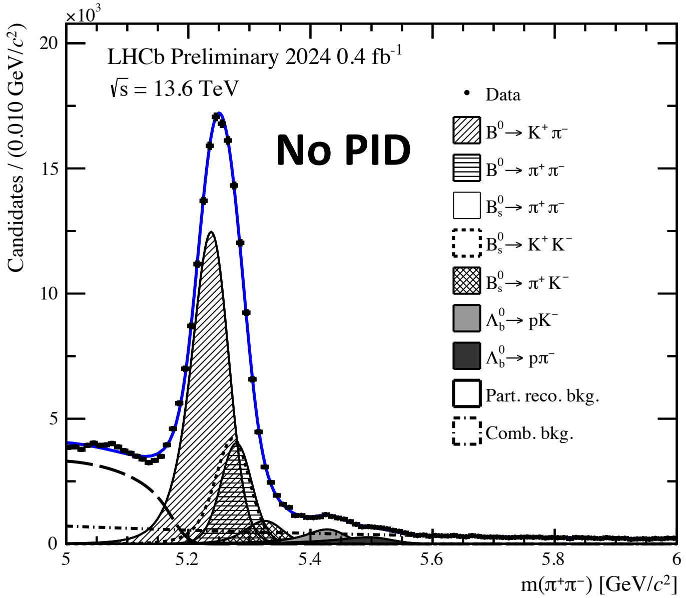
- 95% $K \to K$ ID for 4% $\pi \to K$ misID
- 95% $p \to p$ ID for 2% $\pi \to p$ misID
- 95% $p \to p$ ID for 6% $K \to p$ misID

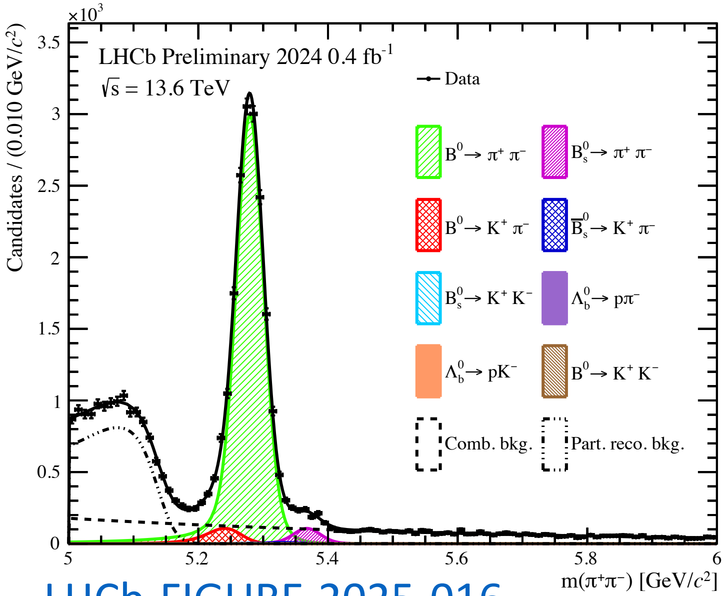
In the full range of momenta

Conclusions

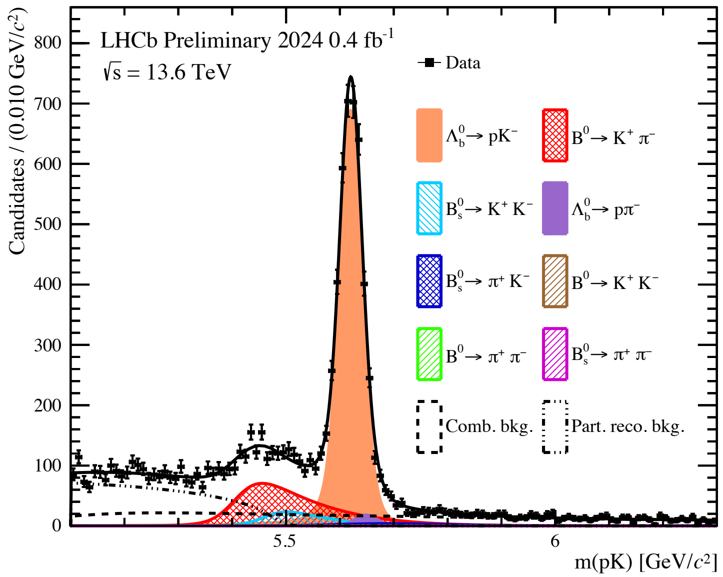
- LHCb RICH detectors operating with excellent data-taking and data-quality efficiencies
- Calibration and monitoring procedures well-established
- Unprecedented hadron identification performance provided by the RICH detectors paving the way for state-of-the-art measurements with Upgrade I LHCb







LHCb-FIGURE-2025-016



Extra Slides

How to get there

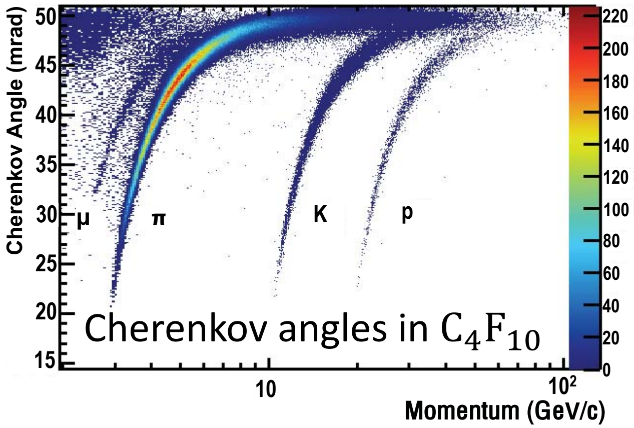
For a single track, mass hypothesis separated at

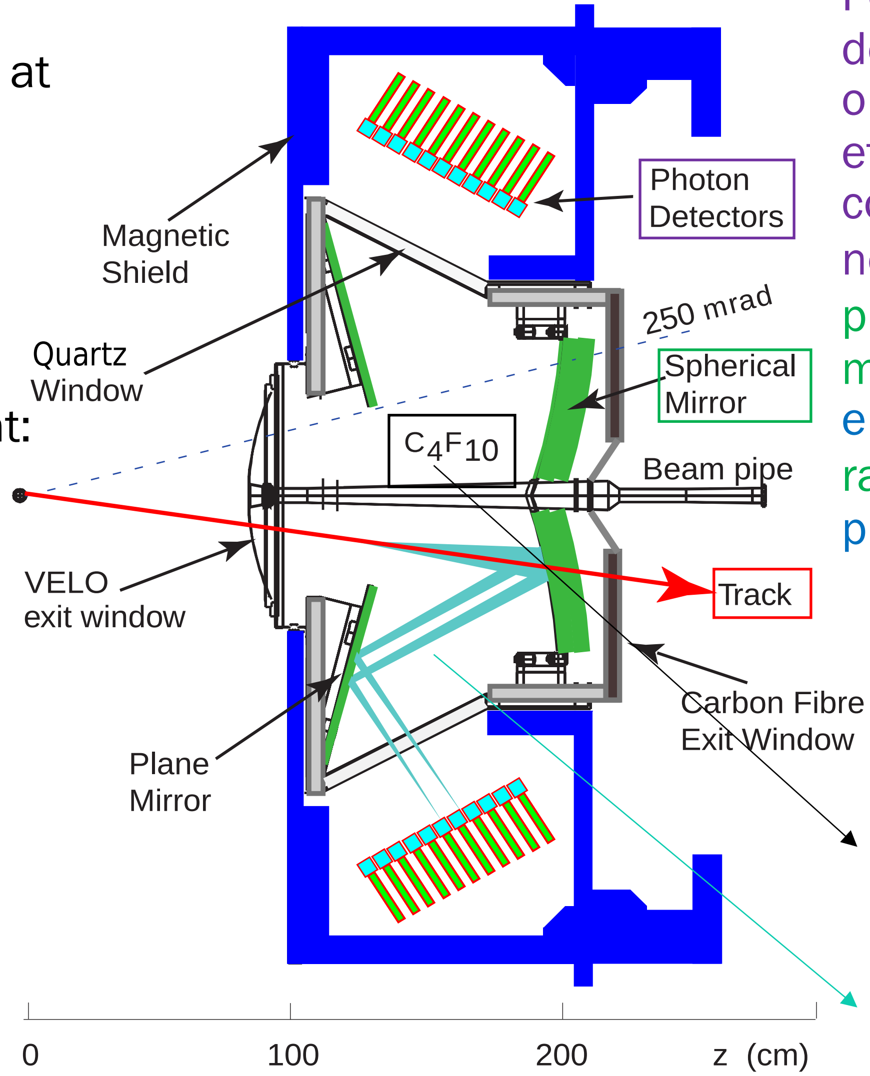
$$n_\sigma = \left|m_1^2 - m_2^2\right| / 2p^2 \Delta\theta_c \tan\theta_c$$

$$\Delta\theta_c = \sigma_c / \sqrt{N_{ph}} \oplus C_{trk}$$

Single photon resolution σ_c relevant at high momenta (and in busy events)

In practice ~ 100 tracks per inelastic pp event: effectively construct a global log-likelihood between measured hits and expected hit patterns from tracks: **robust reconstruction**





Position sensitive single photon detectors (and frontend electronics) outside the acceptance, quantum efficiency to reduce chromatic error contribution, low pixel size d_{px}, low noise

provide focussing with minimal material budget, tilt impacting the emission point error σ_{ep}, curvature radius impacting ring size and the pixel size error σ_{px}

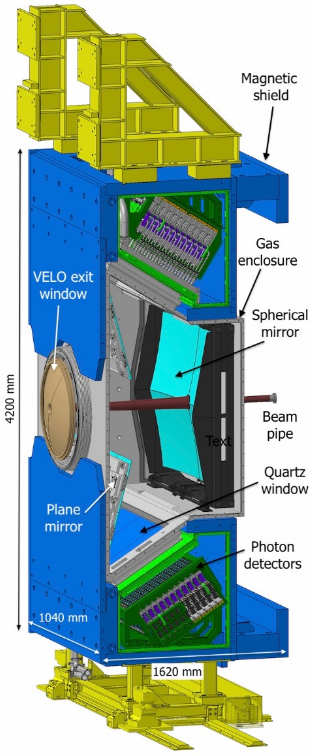
information from the tracking system: trajectory/curvature of track and momentum estimate

Radiator refractive index tuned to match momentum range, low dispersion to minimise chromatic error contribution

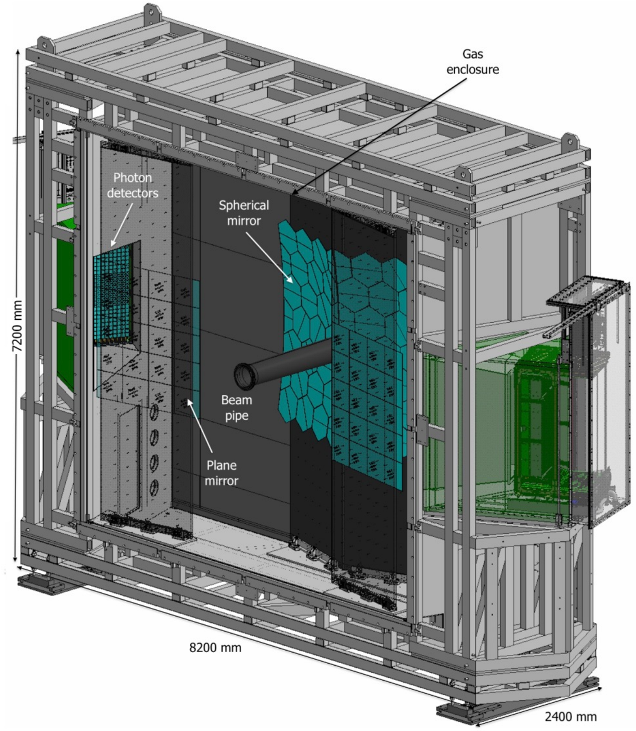
Large radiator volume to maximise track optical paths and therefore number of Cherenkov photons (N_{ph})

The LHCb RICH detectors and their upgrade

- Two RICH detectors
  - RICH1 with C_4F_{10} (n=1.0014 at λ=400 nm STP) to cover 3-40 GeV over 25-300 mrad
  - RICH2 with CF_4 (n=1.0005 at λ=400 nm STP) to cover 15-100 GeV over 15-120 mrad
- Boundary conditions for Run 3 LHCb: run at a five-fold increased instantaneous luminosity ($\boldsymbol{\mathcal{L} = 2 \cdot 10^{33} cm^{-2} s^{-1}}$), with a continuous **40 MHz readout rate** and keeping the **same subdetector envelopes**
  - Upgrade both RICH detectors to target the Run 1 and 2 excellent performances in a harsher environment
  - **New RICH1 optics and mechanics**
  - Replace Hybrid Photon Detectors with embedded 1 MHz readout electronics with **MaPMTs and new electronics in both RICH1 and RICH2**



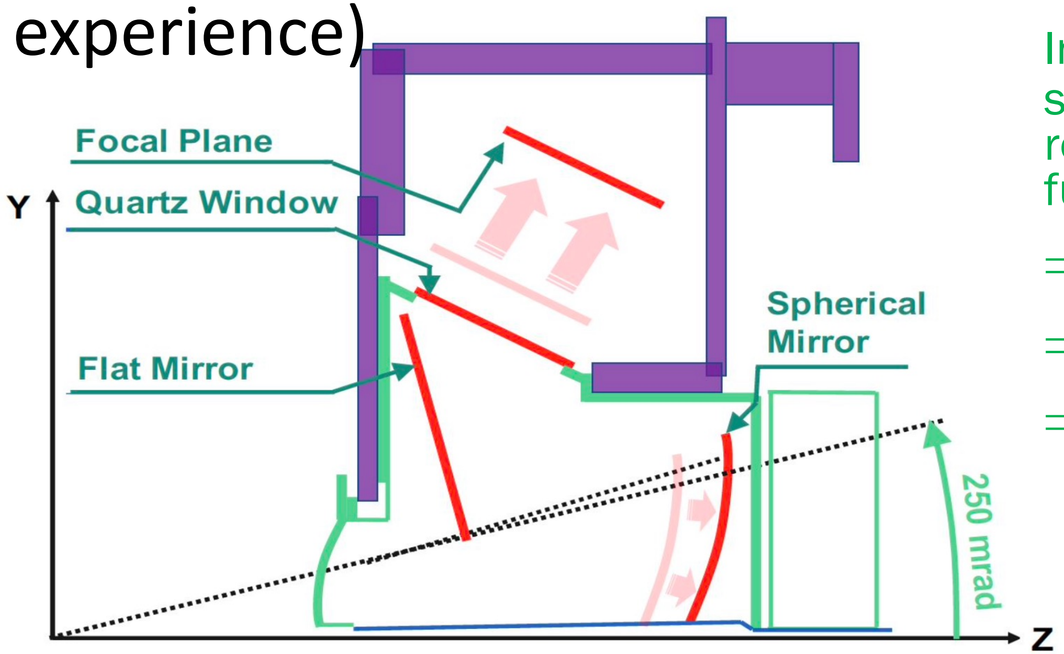
RICH1 (~ $4\ m^3$)



RICH2 (~ $140\ m^3$)

RICH1 optics and mechanics

- Re-design and re-build full RICH1 optics and mechanics to **keep peak occupancy under control (below 30% at 40 MHz)** for optimal photon hits/tracks association (based on Run 1 and 2 experience)

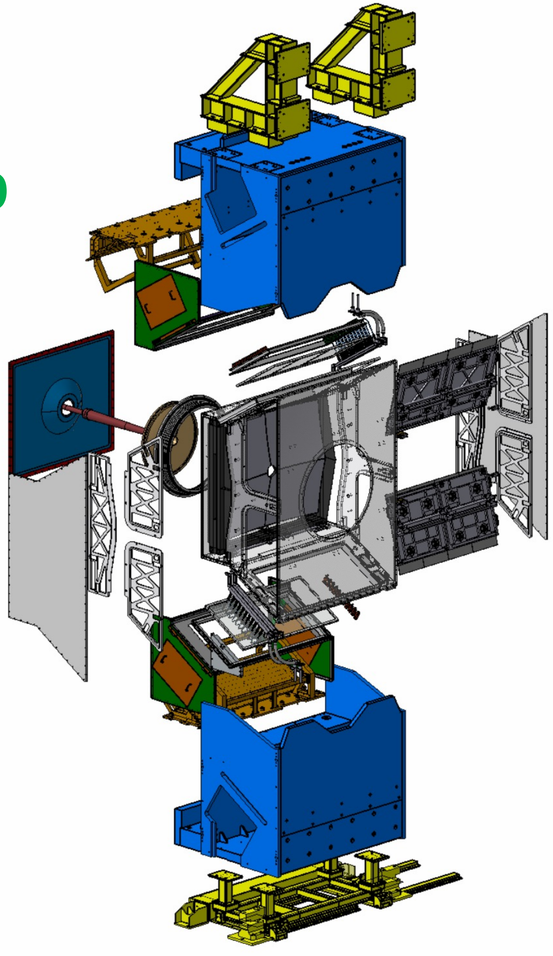


Increase radius of curvature R of spherical mirrors by a factor ~ √2, reduce tilt and move the focal plane further outside the acceptance

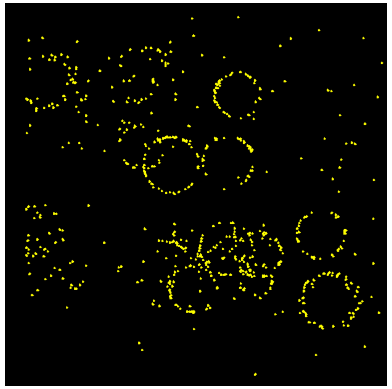
⇒**peak occupancy halved**

⇒**reduced** $\sigma_{px} = d_{px}/\sqrt{3}R$

⇒**reduced** σ_{ep}



Extend radiator volume in z by ~ 100 mm => +14% Cherenkov photons per track

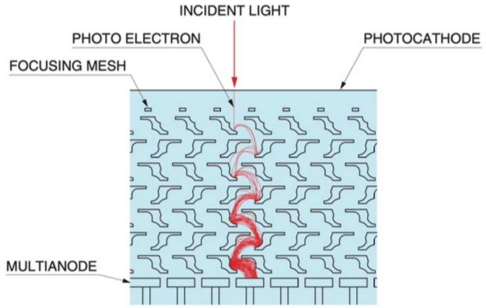


R = 3650 mm in RICH1 => "ring radii" (~ $\theta_c R/2$) for p=30 GeV would be

~ 9.6, 9.2 and 7.8 cm for pions, kaons and protons, respectively (but not exactly rings!)

Photon sensors

Hamamatsu MaPMTs with 8×8 pixels

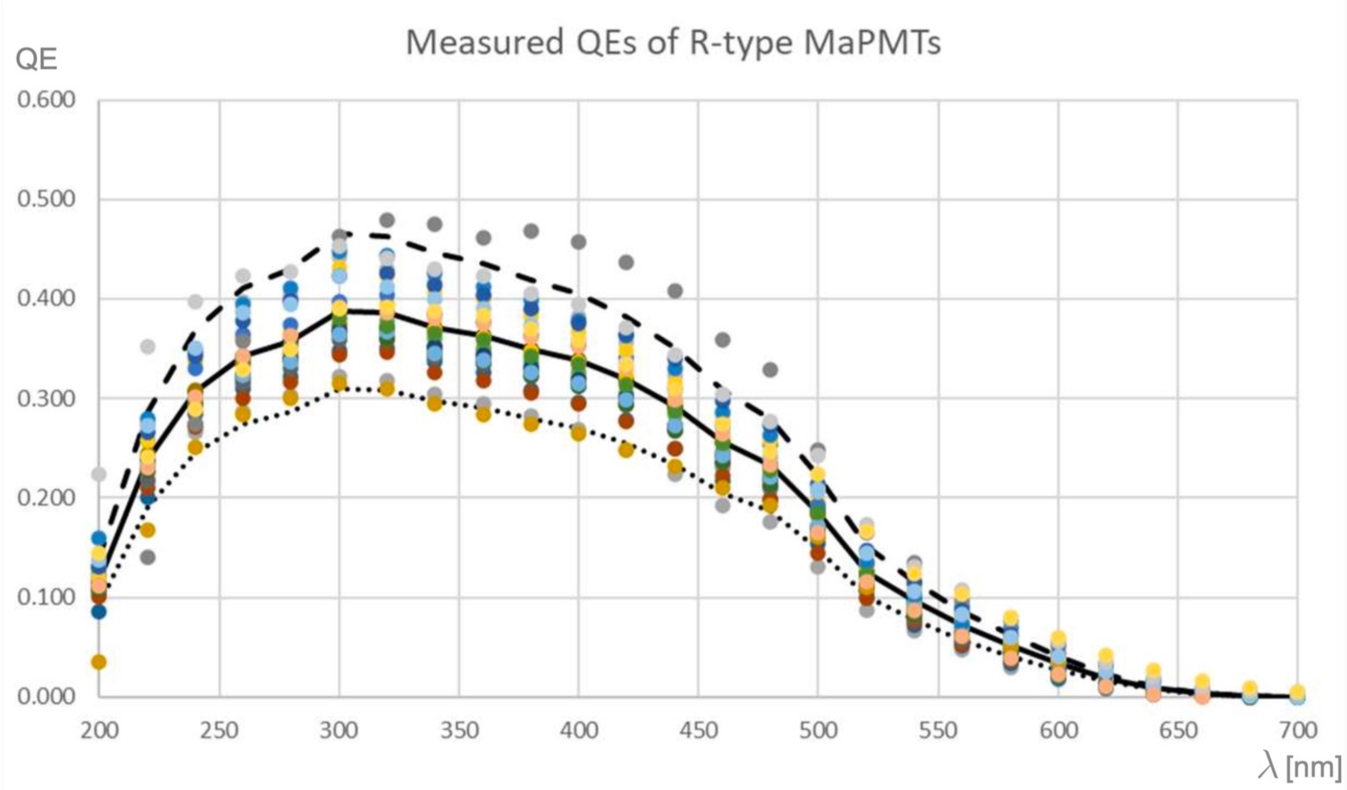


	R11265 (R13742)	R12699 (R13743)
size [mm^2]	26.2×26.2	52×52
pixel size [mm^2]	2.88×2.88	6×6
number of devices	2656	384
active area	77%	87%
average gain @ 1 kV	> 1 Me	
gain uniformity	1:4	1:3
peak/valley (P/V) ratio @ 1 kV	no more than 3 pixels with P/V< 1.3	
dark-count rate @ 1 kV	< 2.5 kHz/cm^2	
quantum efficiency	$> 30\%$ @ 300 nm	

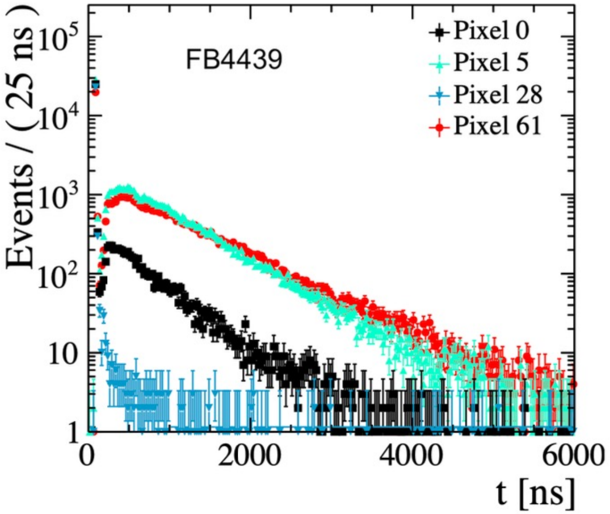
Special series R13742 and R13743 respecting these technical specifications

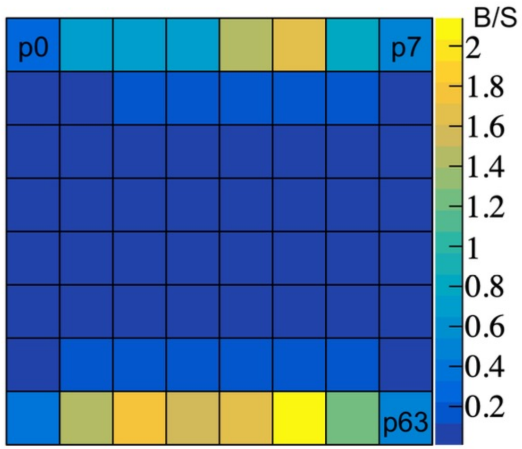
Quantum Efficiency

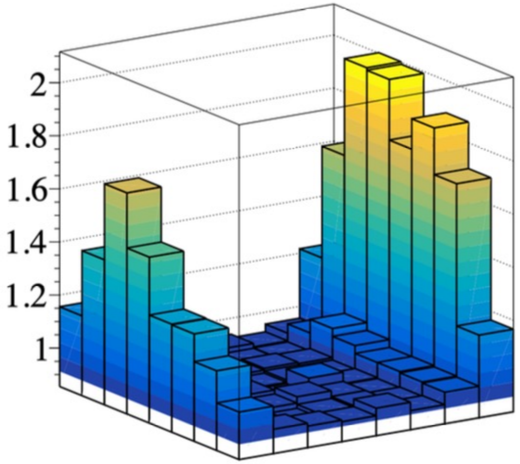
- quantum efficiency measured in a dedicated setup at CERN on a subsample of devices (technical specification from Hamamatsu on the Blue Sensitivity Index)
- UV-glass entrance window: sensitivity to single-photon between 200 and 600 nm
- **ultra bi-alkali photocathodes allow to reach an excellent quantum efficiency of 40% at 300 nm in average!**

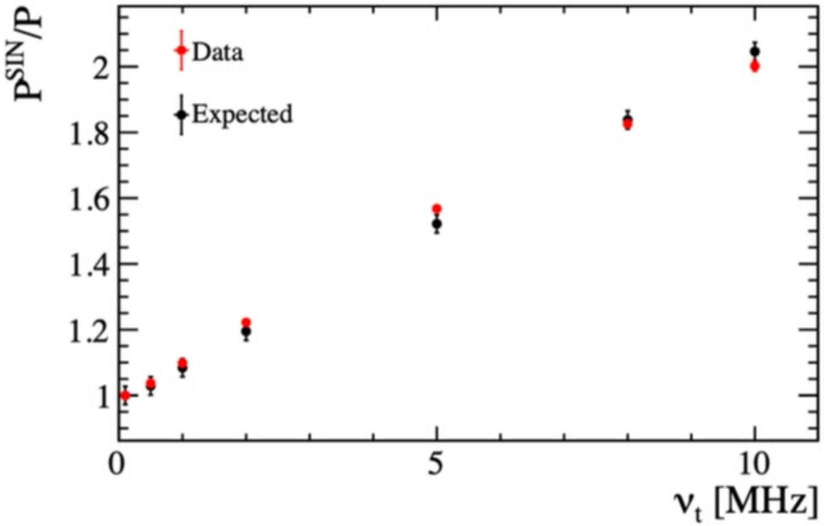


Signal-Induced Noise





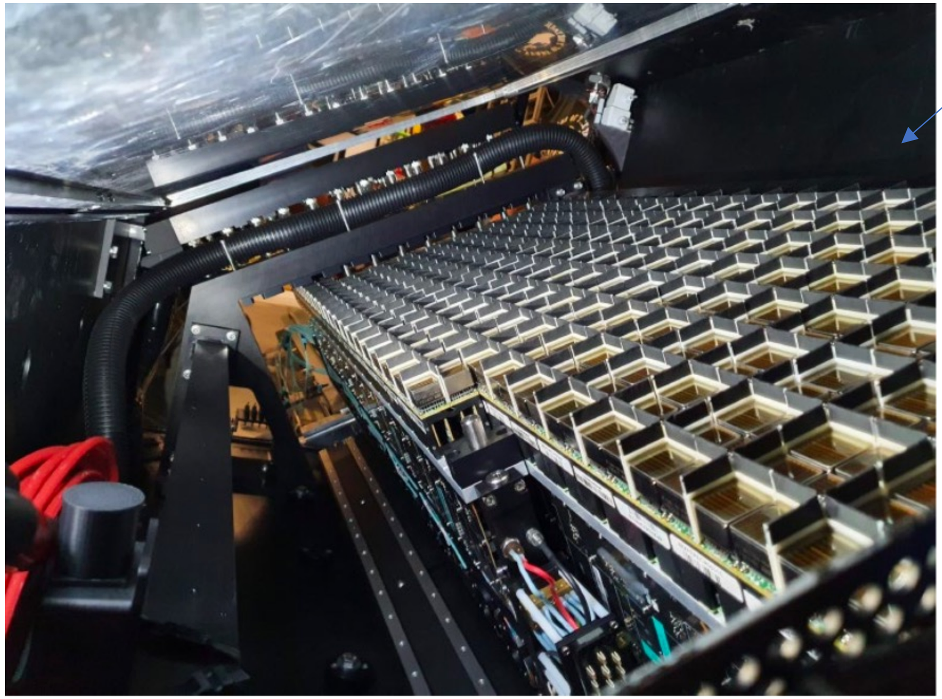




MaPMT	μ^0_{sin}	μ^5_{sin}	μ^{28}_{sin}	μ^{61}_{sin}
FB4439	0.2457 ± 0.0035	1.695 ± 0.013	0.0109 ± 0.0007	2.139 ± 0.018
FB2294	0.0745 ± 0.0012	0.3715 ± 0.0029	0.0076 ± 0.0004	0.491 ± 0.003
FB2312	0.132 ± 0.0017	0.747 ± 0.004	0.0081 ± 0.0004	2.231 ± 0.011
FB4500	0.266 ± 0.004	1.398 ± 0.012	0.0103 ± 0.0007	1.034 ± 0.010

Photon detection planes

- Cover an area of approximately $4\ \mathrm{m}^2$ with **detected rates** up to $\mathcal{O}(100\ \mathrm{MHz/cm}^2)$ in the high occupancy region down to $\mathcal{O}(5\ \mathrm{MHz/cm}^2)$ in the peripheral region
  - trade-off between performance and costs achieved by employing coarser granularity MaPMTs (6 x 6 mm^2 pixel size) in the outer region of RICH2



One side of RICH1 installed in the LHCb cavern

One side of RICH2 in the commissioning lab

Overview of Run 3 operations

- Contribution of the RICH detectors at the global inefficiency << 1% thanks to the advanced automation of the system
  - Stored 2024 LHCb luminosity: 9.56/fb
  - Only 18.8/pb lost because of the RICHes in 2024