The LHCb RICH Upgrade: operations and performance

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Outline

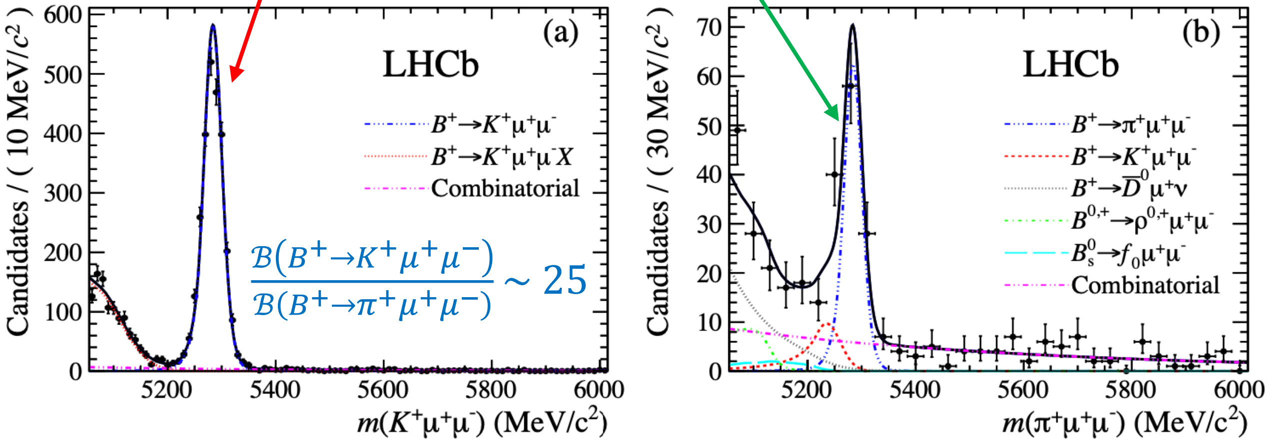
The Ring Imaging Cherenkov (RICH) detectors provide charged hadron identification to the LHCb experiment

- Impact of hadron identification on LHCb physics
- Calibration and operations
- Performance figures of merit with early data

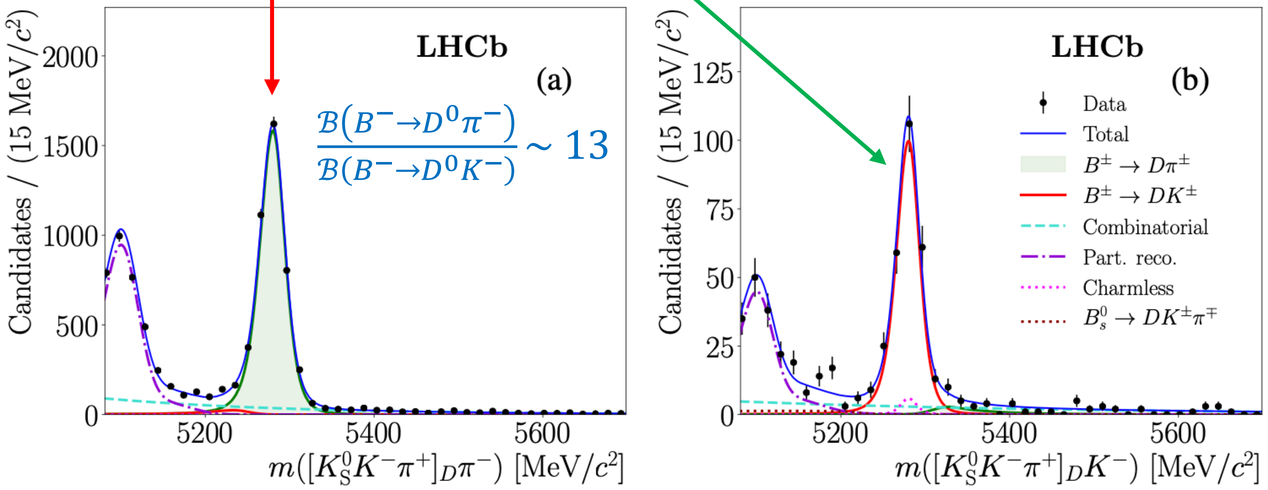
Impact of hadron identification

- Charged hadrons (pions, kaons and protons) identification in a **wide range of momenta between approximately 3 and 100 GeV** (up to ~ 150 GeV for protons)
- Important to distinguish final states of otherwise identical topology: suppress leading order decay modes and efficiently select Cabibbo suppressed decays to perform rare decay and CP violation studies
- Powerful combinatorial background rejection (large majority of tracks produced at the LHC are pions) used by all LHCb analyses

Dominant kaon mode suppressed by factor 80 while retaining 82% of pion candidates



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



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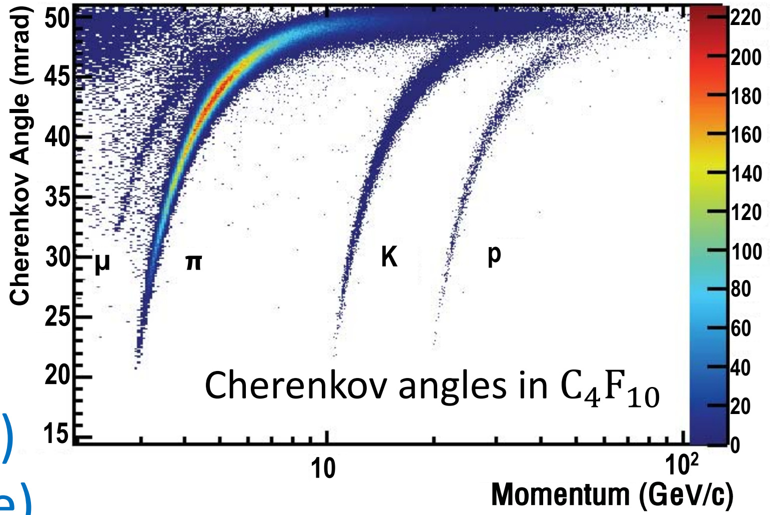
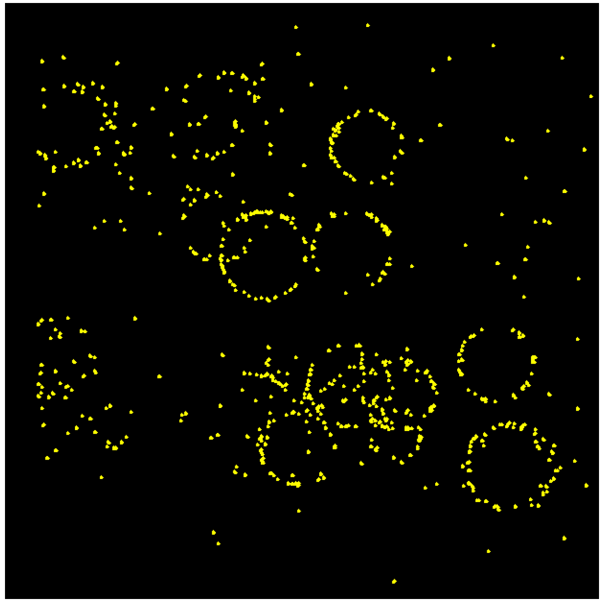
RICH detectors performance

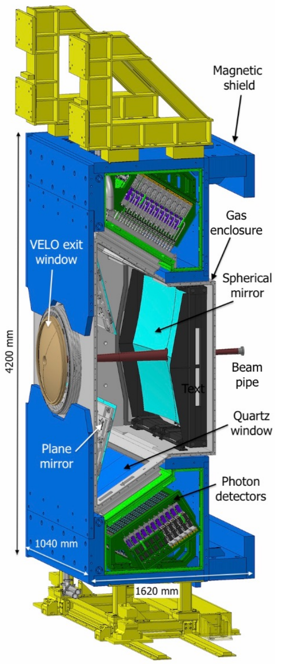
- Mass hypotheses separated at $n_\sigma = \left|m_1^2 - m_2^2\right| / 2p^2 \Delta\theta_c \tan\theta_c$ for a single track
  - $\Delta\theta_c = \sigma_c / \sqrt{N_{ph}} \oplus C_{trk}$
- RICH detectors performance intrinsically driven by
  - Cherenkov angle resolution σ_c
    - Emission point error (focussing optics and spherical mirror tilt)
    - Pixel size error (spherical mirror curvature radius and pixel size)
    - Chromatic uncertainty (radiator dispersion ⊗ quantum efficiency curve)
  - Detected Cherenkov photons per track N_{ph} (and low noise)
- Contribution from tracking system for trajectory of tracks and momentum estimate
- In practice ~ 100 tracks per inelastic pp event: effectively construct a global log-likelihood between measured hits and expected hit patterns from tracks with different mass hypotheses: **robust reconstruction**

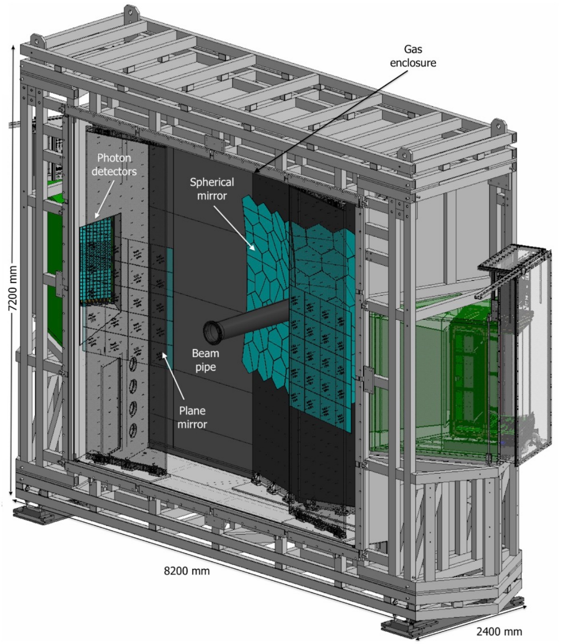


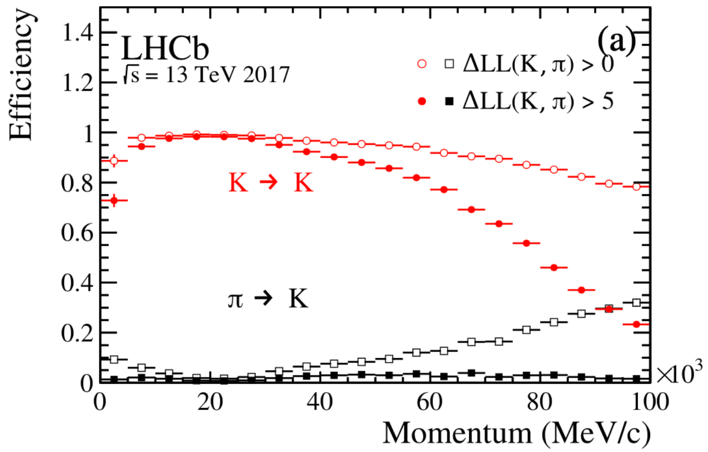


The LHCb RICH detectors

- 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 ($\boldsymbol{\mathcal{L} = 2 \cdot 10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1}}$), 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**

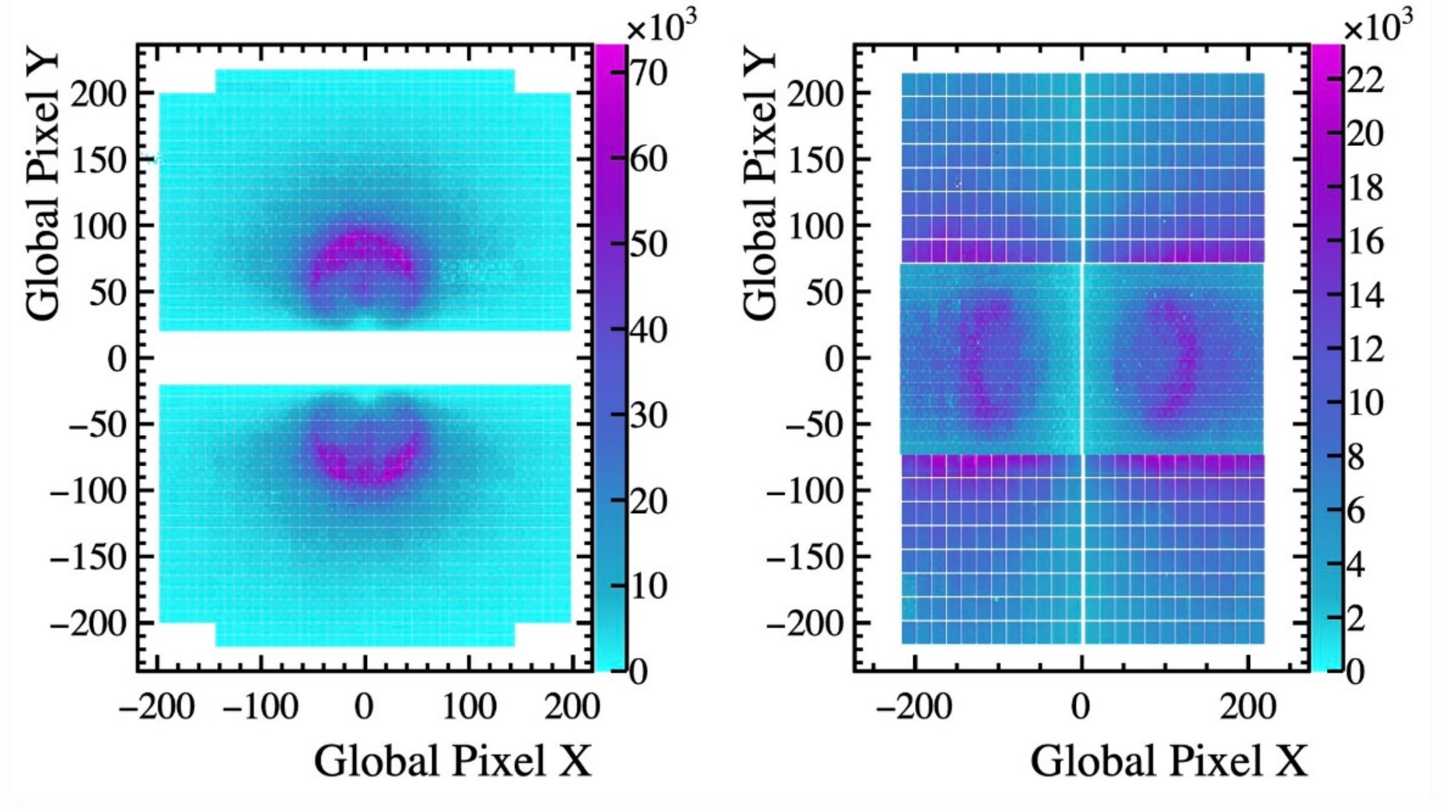




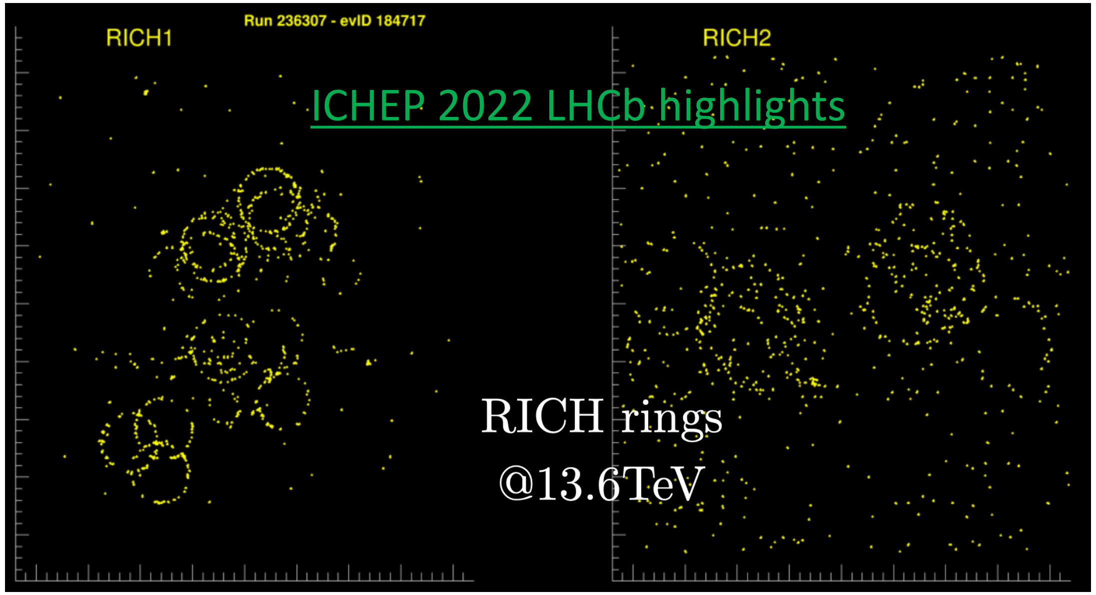


Upgraded RICH detectors start-up

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



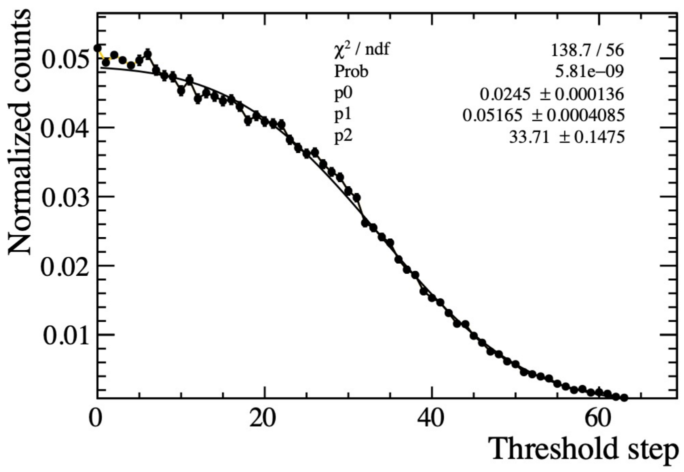
Cumulative hitmaps



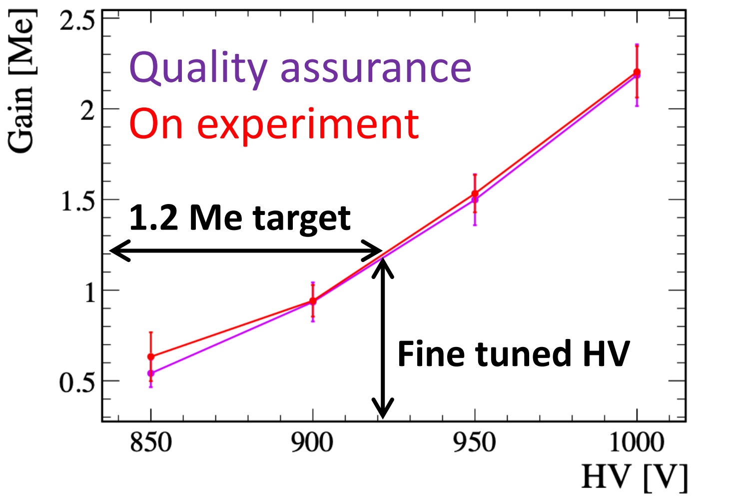
Single event display

Photon detection chain calibration and operations

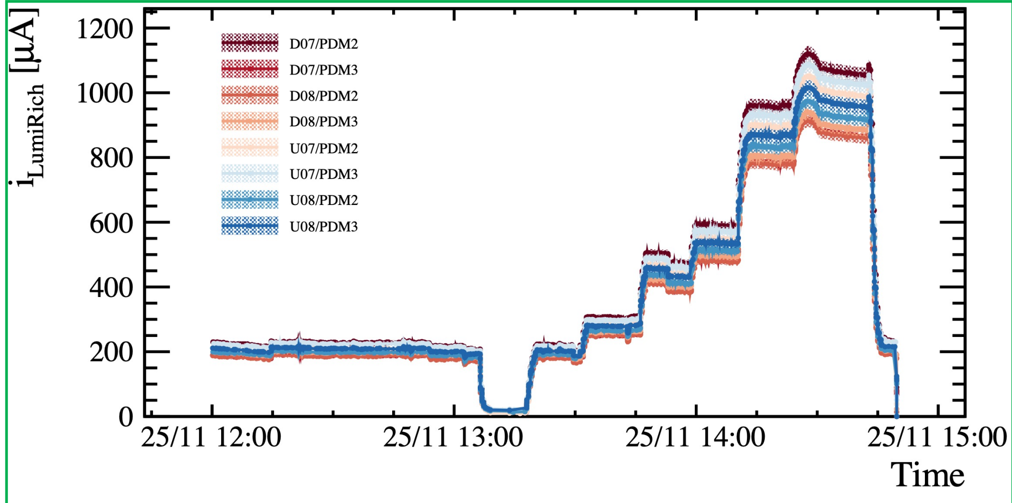
- **Tuning of operational and calibration tools to achieve the best performance**
- Average gain of the 200k MaPMT channels measured and equalised to 1.2 Me by tuning the operating high-voltages through automated threshold scan procedures with beam
    - excellent agreement between quality assurance and on experiment results
    - same procedure used to monitor and correct for ageing
    - frontend thresholds set to 200 ke
- Last dynode of the MaPMTs supplied independently to preserve gain linearity at high rates up to 100 MHz/cm^2
    - Provide online luminosity through the calibrated measurement of the power supply currents



Single channel threshold scan

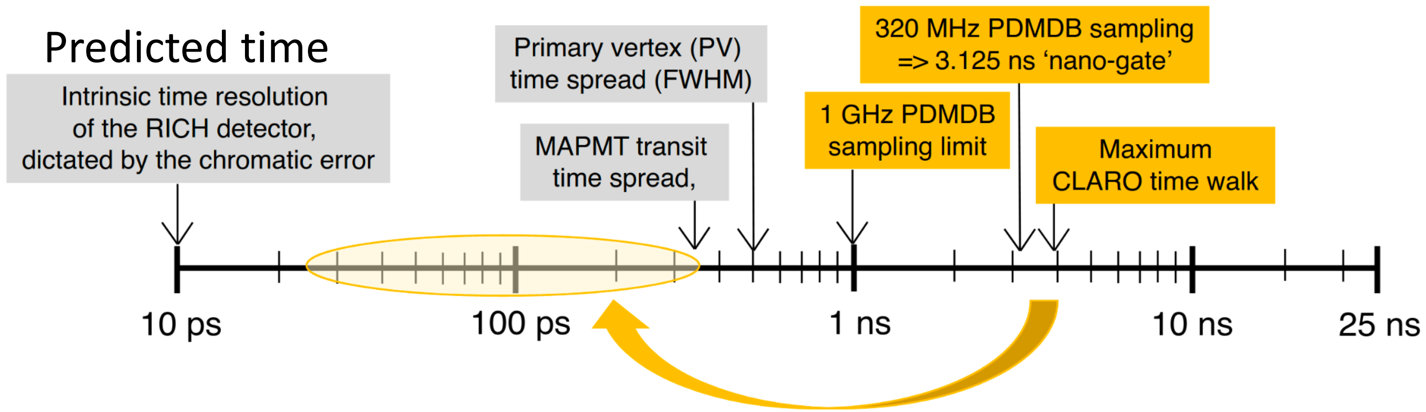


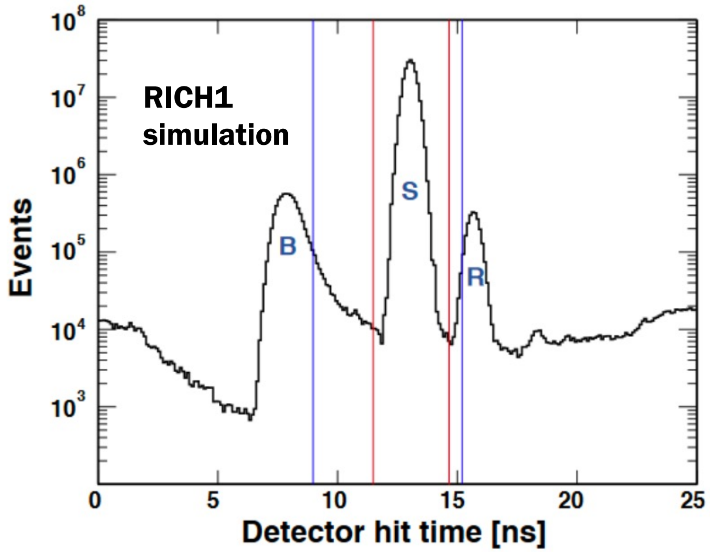
Results for one group of 16 MaPMTs

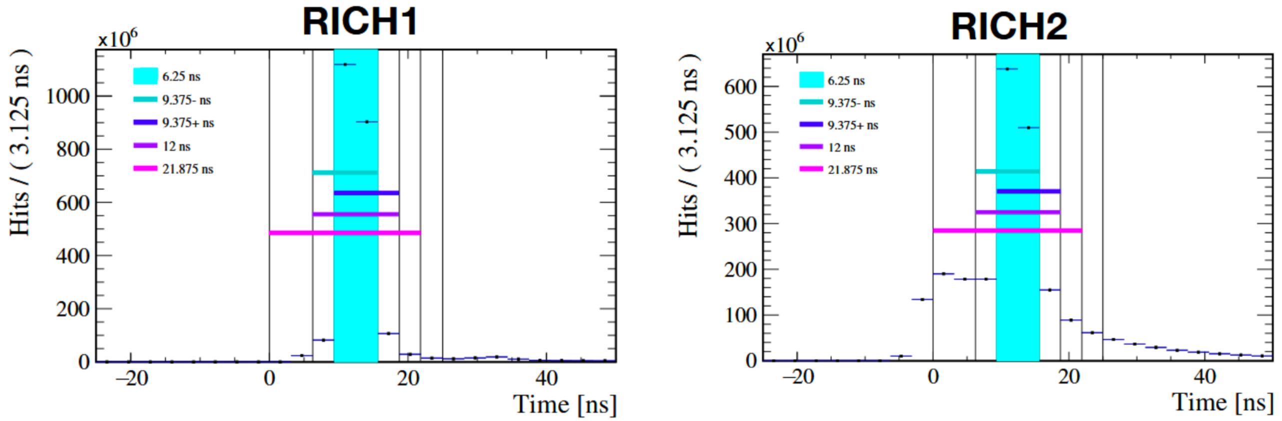


Time alignment

- Prompt emission of Cherenkov radiation and focussing optics suggestive of a fine time gating to reduce out of time backgrounds



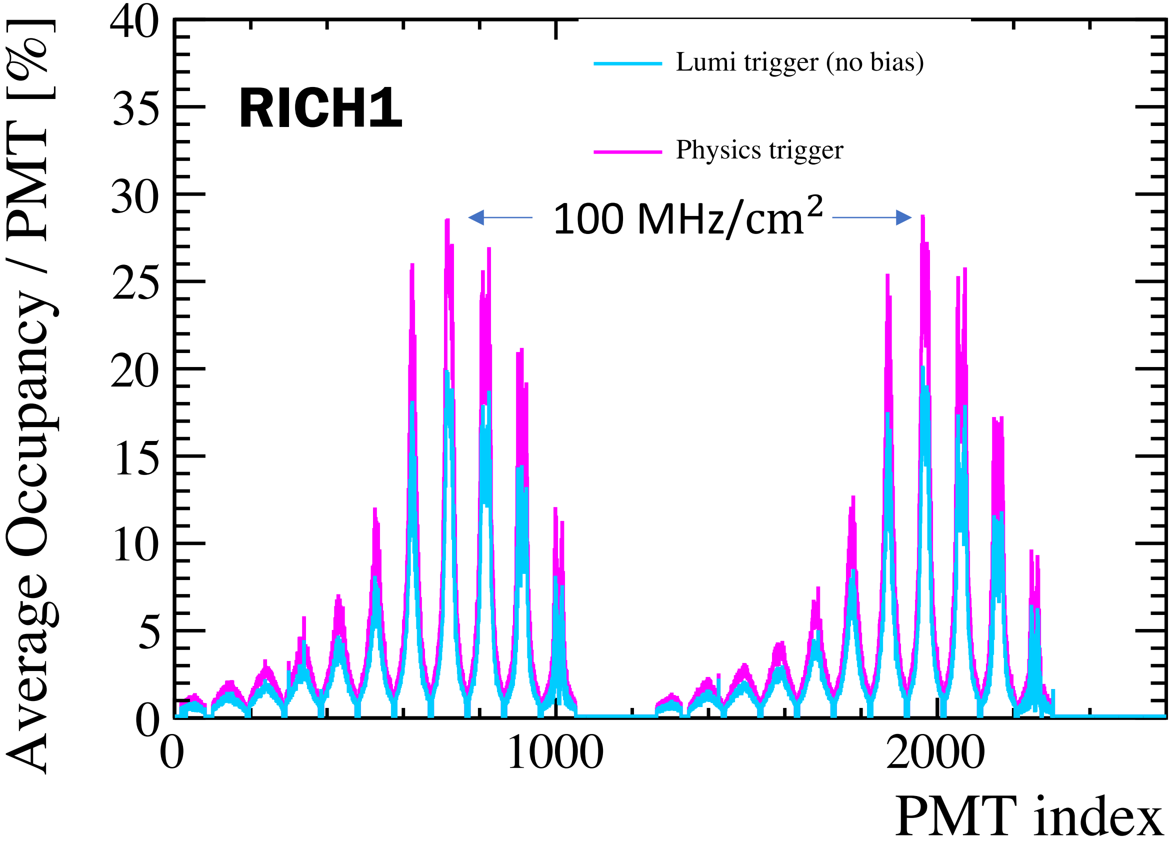


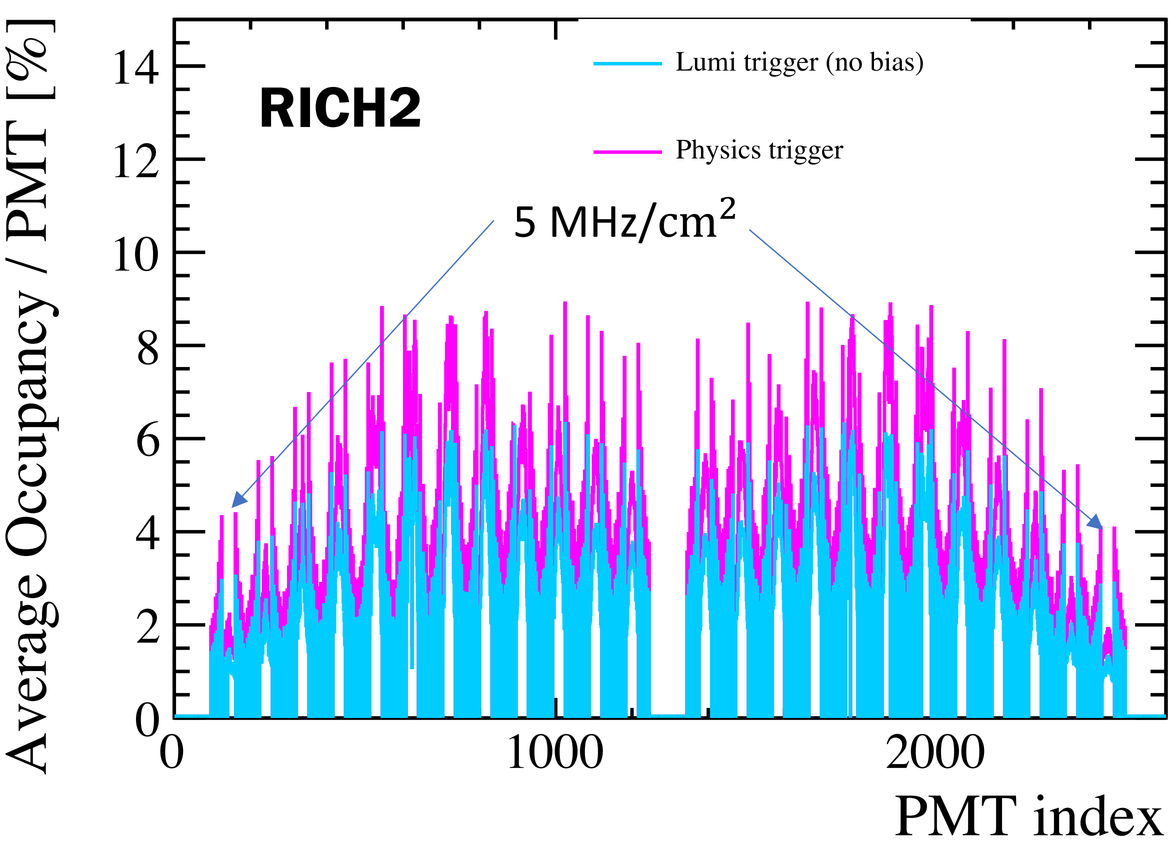


Best trade-off between photon detection efficiency and background rejection found for a 6.25 ns time gating window: deployed since end of 2022

- B: background due to particles travelling directly to the photon detection plane
- S: Cherenkov signal
- R: background due to multiple reflections of Cherenkov photons in the optical system
- + incoherent background due to instrumental internal noise/scintillation photons in the radiators

Occupancy at Run 3 average pile-up in 2024

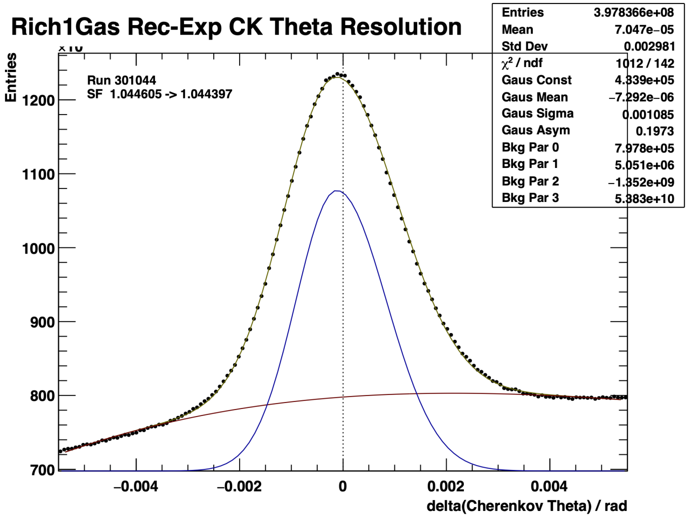


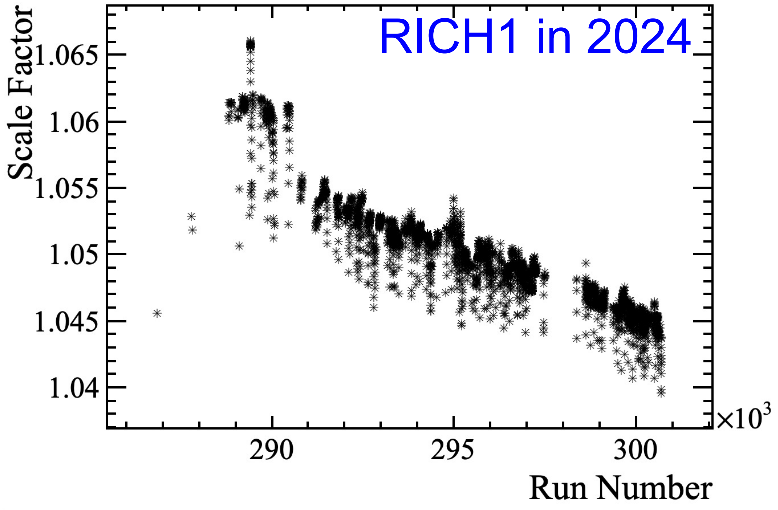


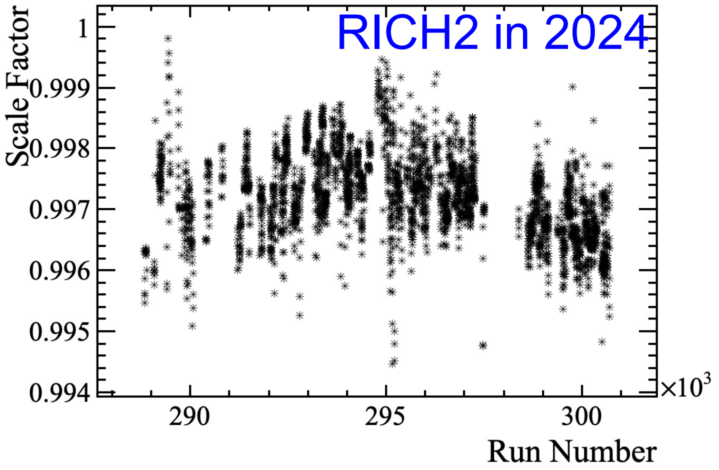
- No bias occupancy relevant operationally (e.g. MaPMT anode currents)
- Physics-biased occupancy relevant for performance
- **Peak occupancy around 30% (at 40 MHz) at nominal pile-up (5.5) as by design**

Online refractive index calibration

- Refractive index calibration required to correct for environmental (temperature and pressure) and purity (small sub-percent/month air contamination) changes of the radiators
  - Starting point determined from several temperature and pressure sensors placed into the gas enclosure
- Reconstructed Cherenkov angle from high momentum tracks ($\cos\theta_c \sim 1/n$) to determine the refractive index scale factors per run directly from data with an online data monitoring task
  - **Same task used to monitor online the single photon resolution trends**

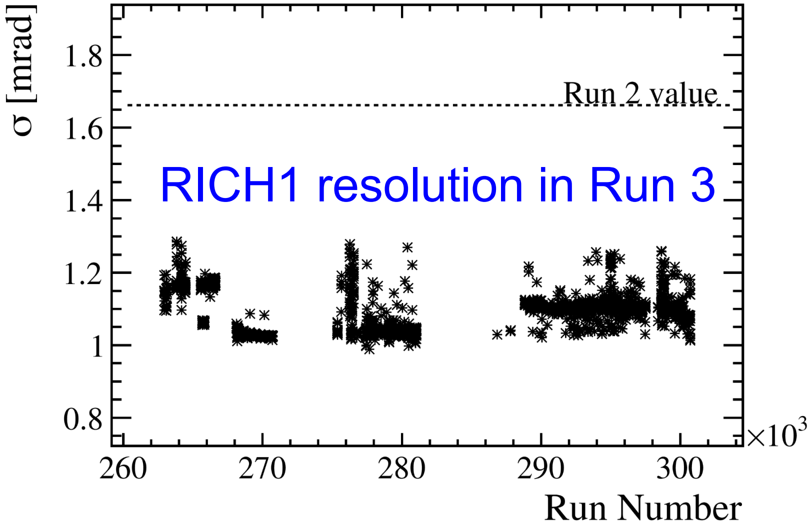


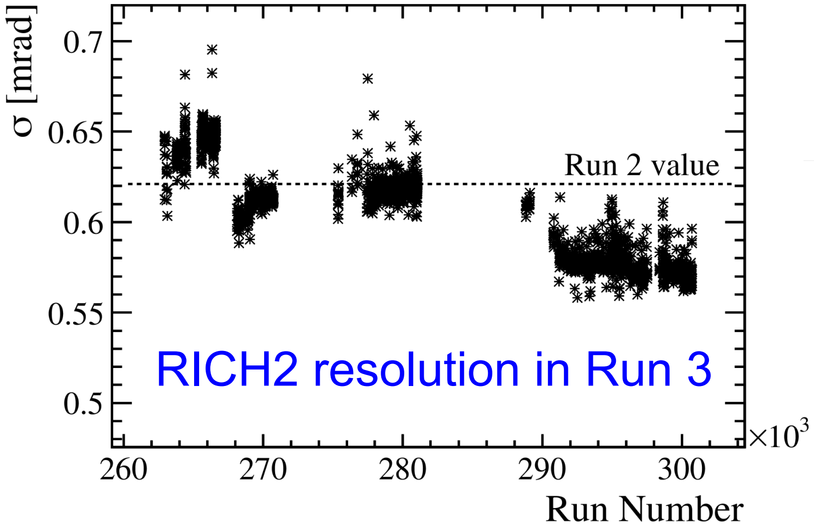


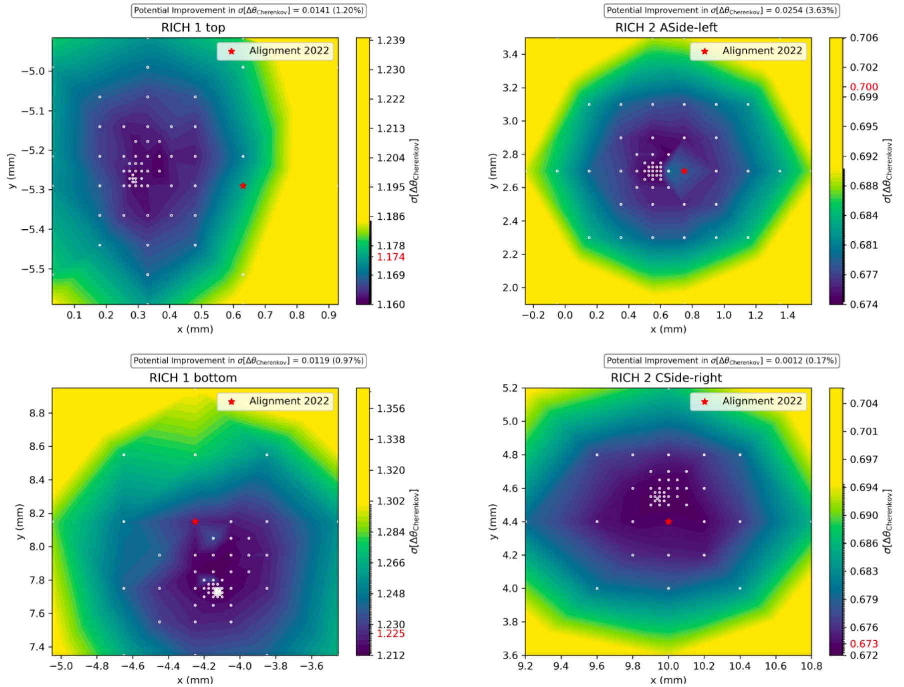


Alignment and Cherenkov angle resolution

- 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
  - photon detectors panel alignment done a few times per year to find the absolute minimum
  - Fine tuning corrections with mirrors alignment per run



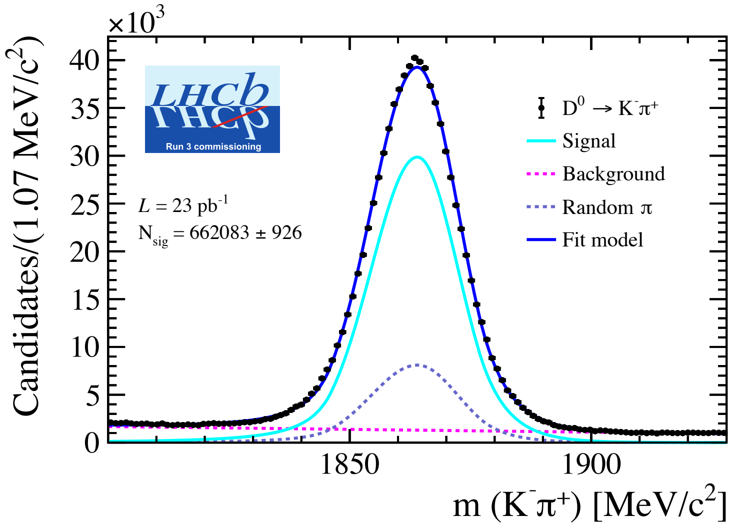


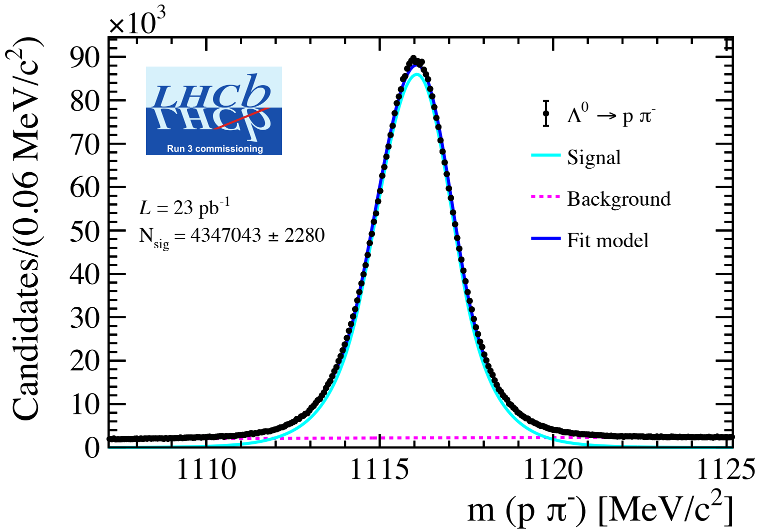


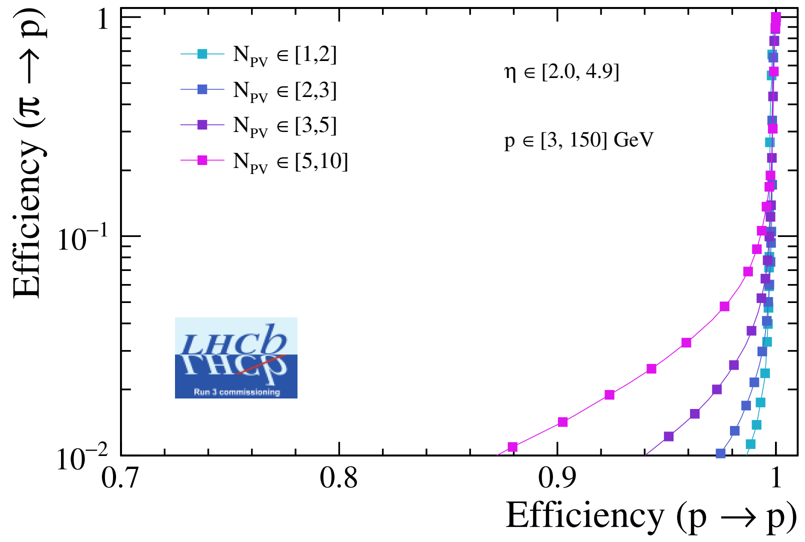
LHCb-FIGURE-2023-007

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: $D^{*+} \to D^0(\to \mathbf{K}^-\boldsymbol{\pi}^+)\pi^+$ and $\Lambda \to \mathbf{p}\pi^-$
- Cut on high level variables defined as $DLLh = \ln(h)\,/\ln(\pi)$ in bins of momentum, angular acceptance and event multiplicity

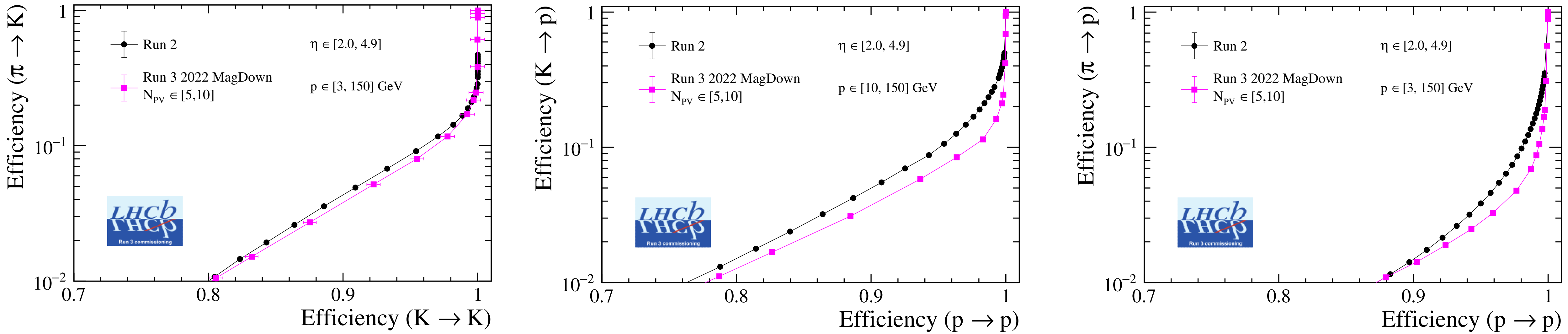






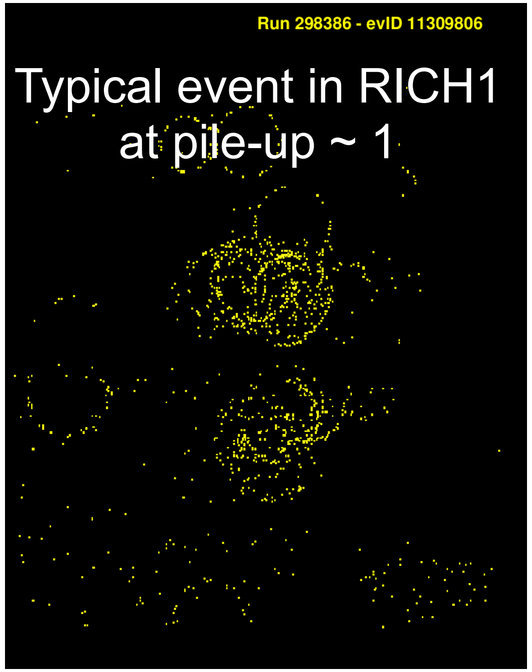
Hadron identification performance vs Run 2

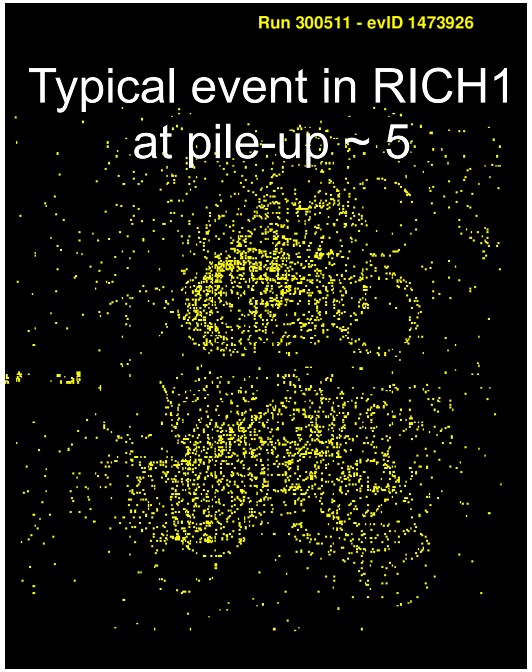
- Preliminary performance evaluated with data collected at the end of 2022
  - 2023 performance even better but biased by VELO open conditions (effectively select low occupancy regions) LHCb-FIGURE-2023-023
- Comparison between Run 2 performance curves and Run 3 curves in events with number of reconstructed primary vertices between 5 and 10
- Demonstrates that already with the preliminary calibrations performed in 2022 the upgraded RICH detectors will outperform the previous versions at the average pile-up value of Run 3 LHCb-FIGURE-2023-019



Conclusions

- The LHCb RICH detectors operate smoothly since the start of Run 3 and they already outperformed their former Run 1 and 2 versions in a more challenging environment with a five-fold increase in the average pile-up per event
- The ongoing global optimisation of the LHCb experiment is expected to further improve the charged hadron identification performance in Run 3 providing an unprecedented discrimination power to the LHCb analyses





Extra Slides

How to get there

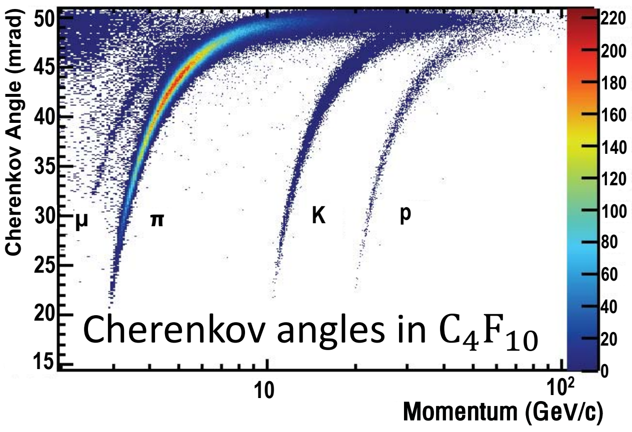
For a single track, mass hypothesis separated at

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

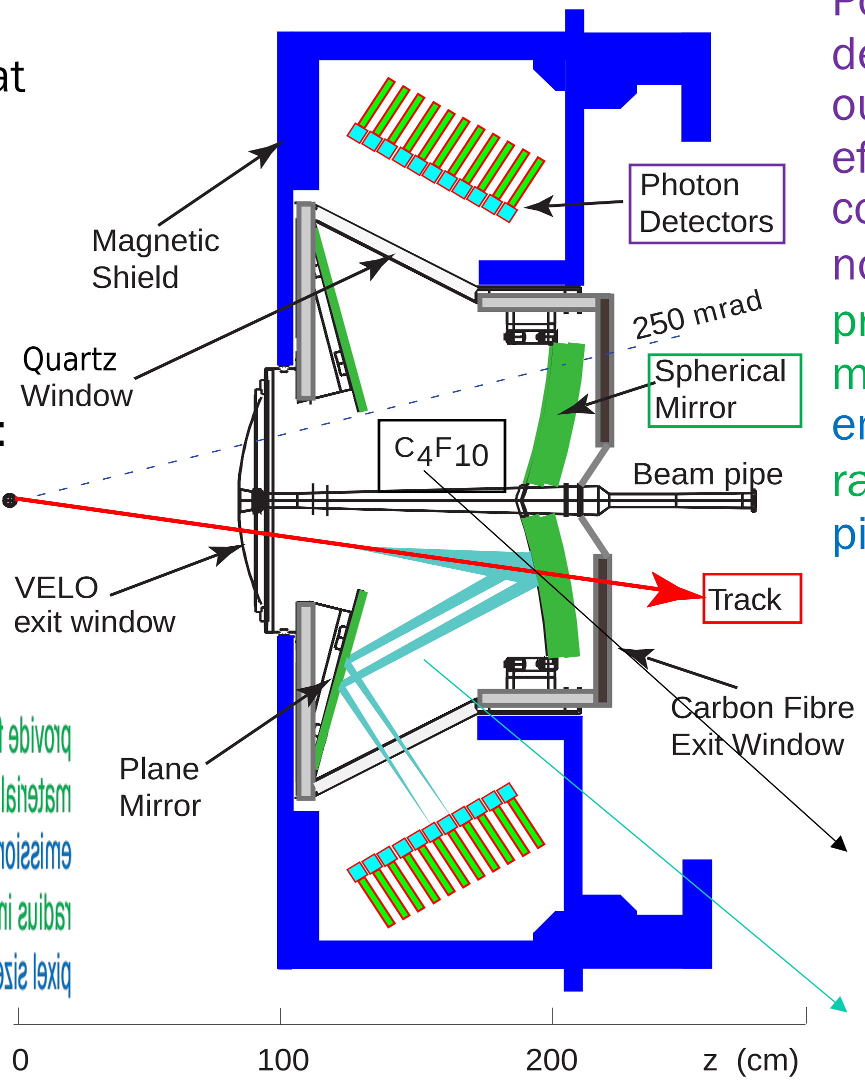
$$\Delta\theta_c = \sigma_c / \sqrt{N_{ph}} \oplus C_{trk}$$

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**



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}



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}

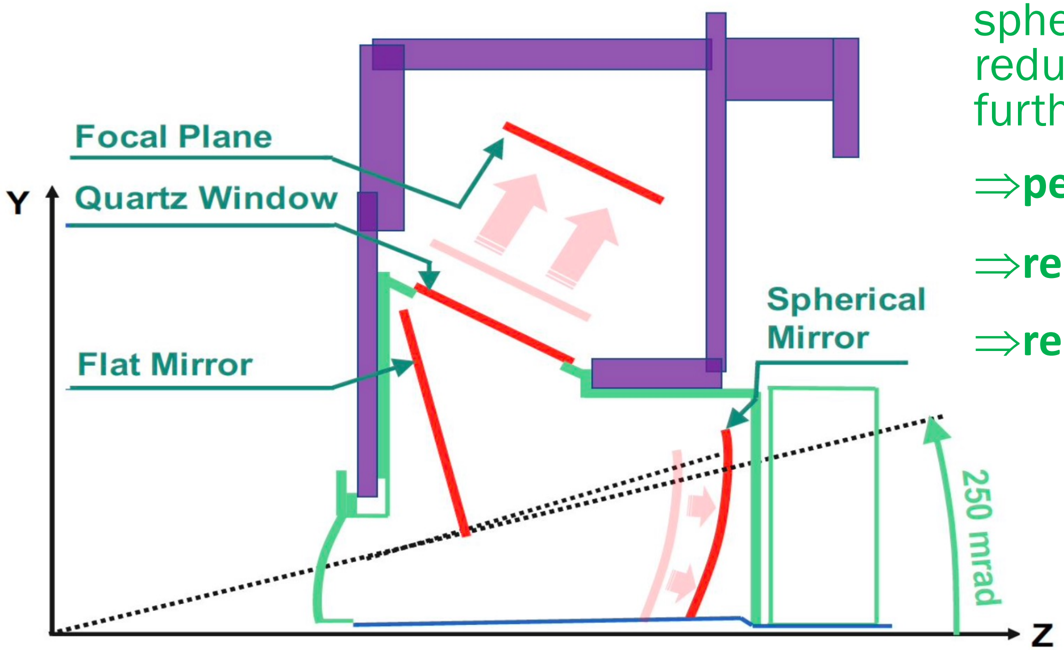
information from the tracking system: trajectory of track and momentum estimate

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})

RICH upgrade in a nutshell: RICH1 mechanics

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

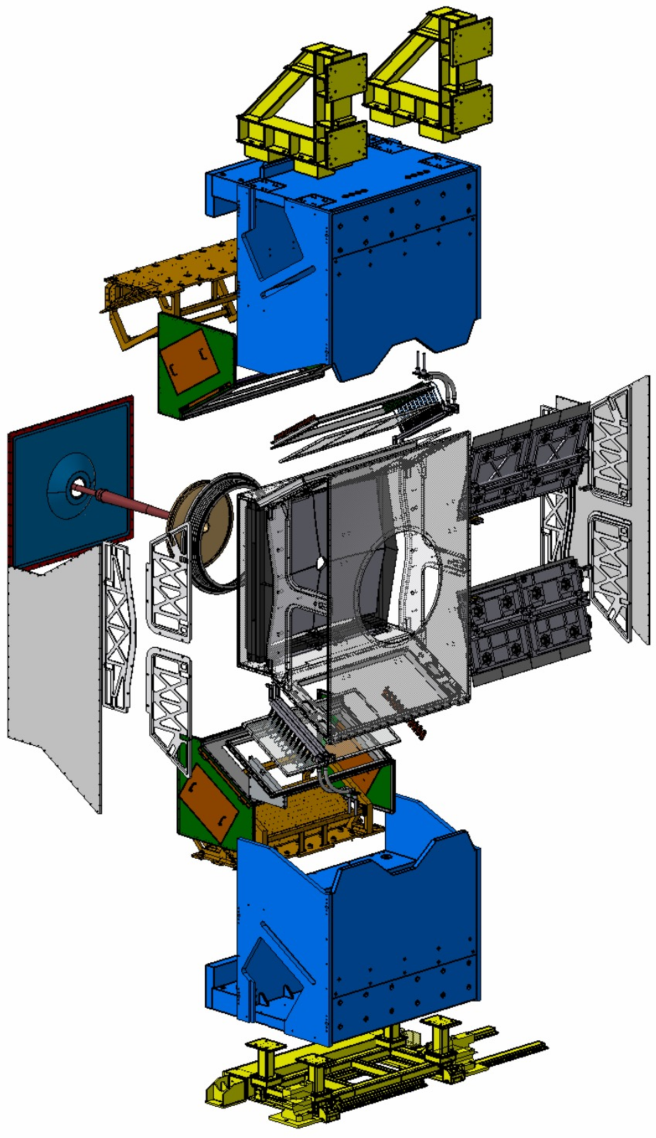


Increase radius of curvature R of spherical mirrors by a factor ~ √2, reduce tilt and move the focal plane further outside the acceptance

⇒**peak occupancy halved**

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

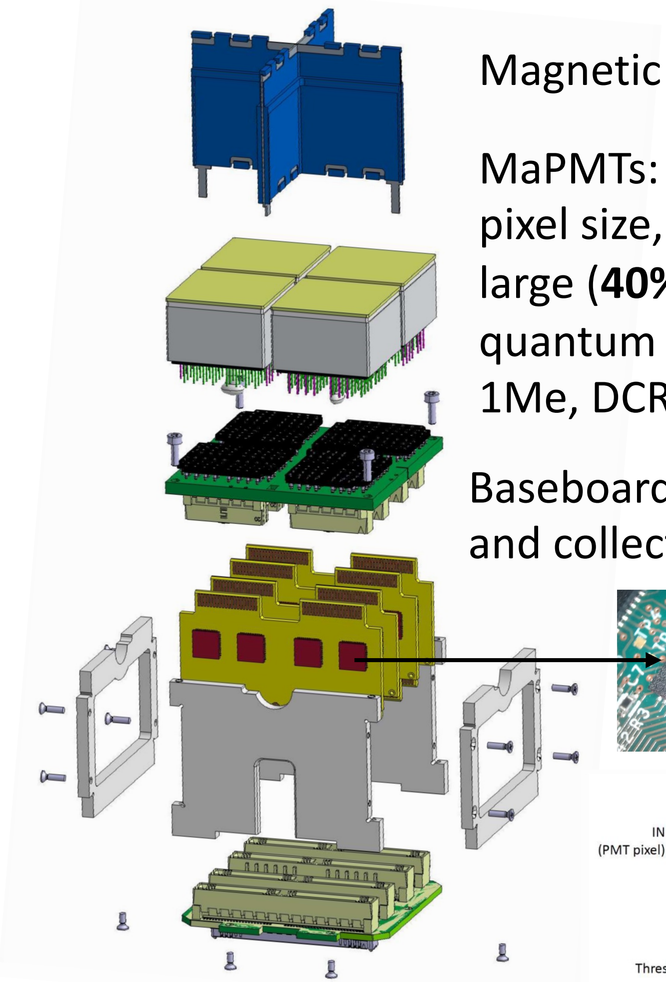
⇒**reduced** σ_{ep}



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

RICH upgrade in a nutshell: photon detection chain

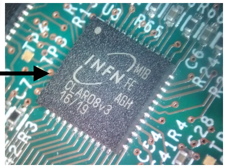
- Replace HPDs with commercial 64 channels Multi-anode photomultipliers Tubes (MaPMTs) and brand new frontend electronics



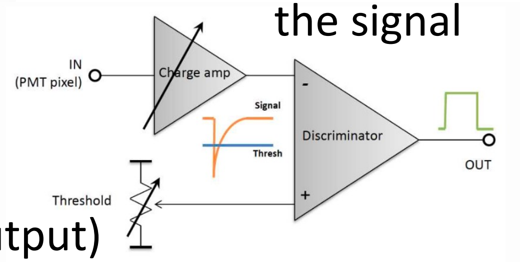
Magnetic shielding (RICH1)

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 $\mathrm{kHz/cm}^2$

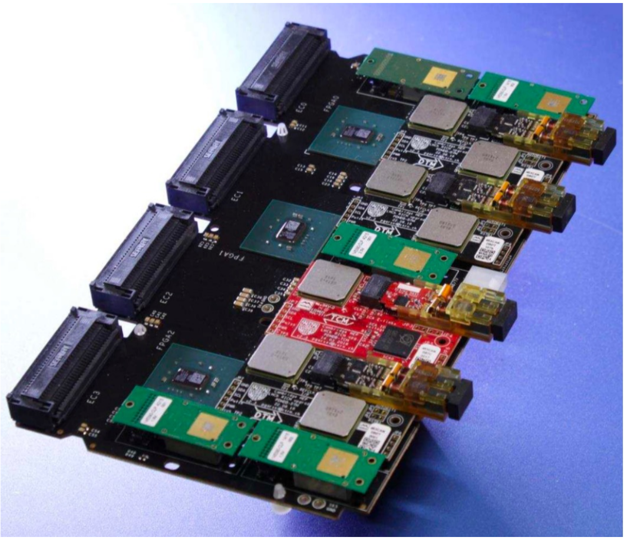
Baseboard (voltage divider and collect analog output)



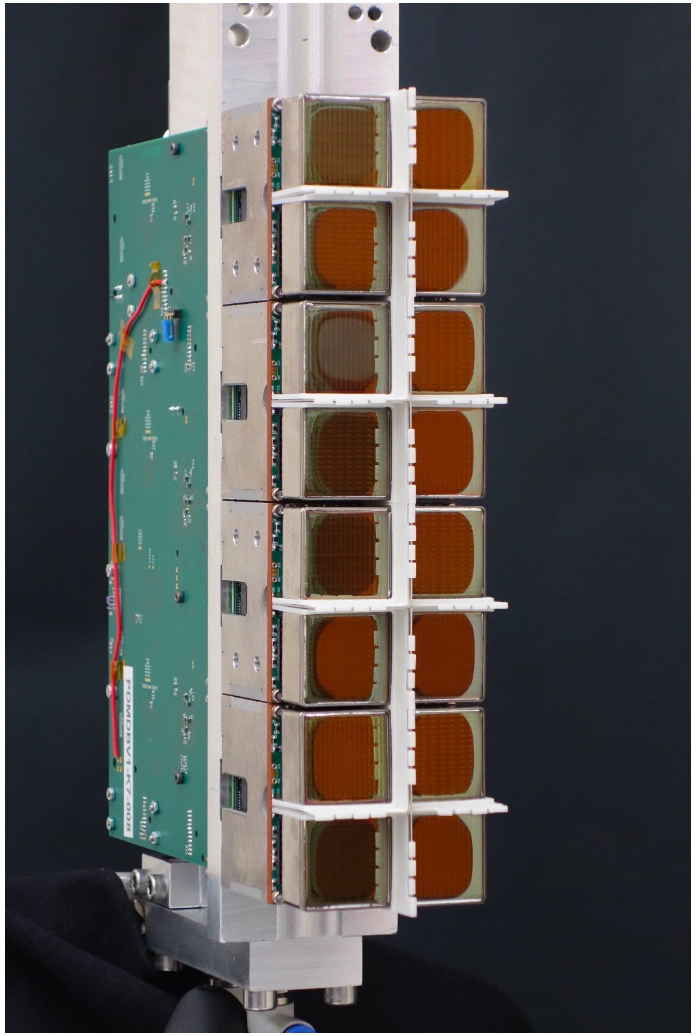
CLARO ASIC to digitise the signal



Backboard (deliver digital output)

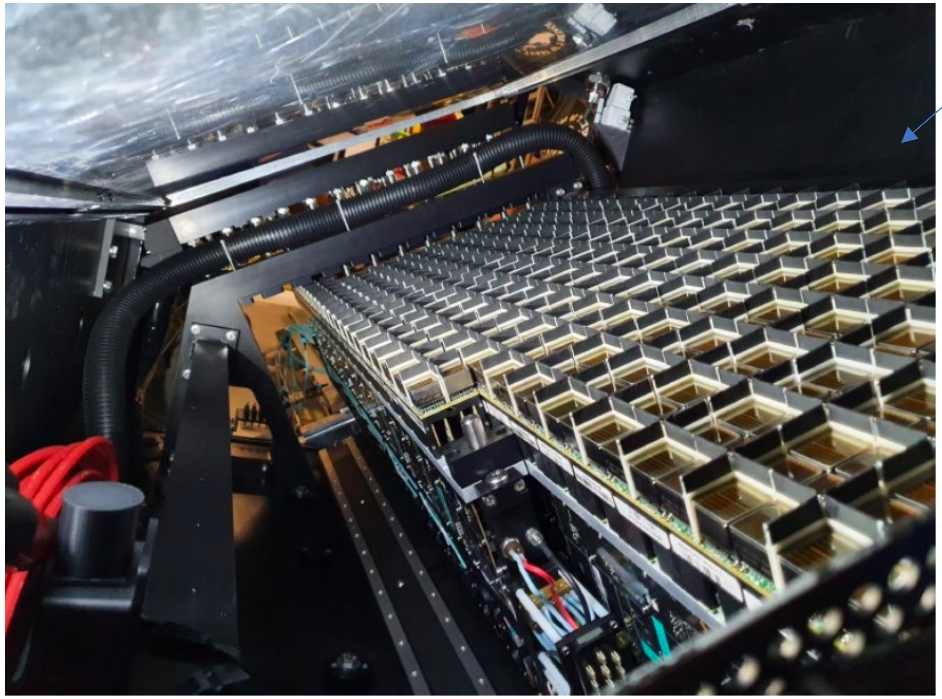


Flexible FPGA-based digital Board interfacing with LHCb backend boards using the GigaBit Transceiver protocol



RICH upgrade photon detection planes

- Cover a large area of approximately $4\ \mathrm{m}^2$ with detection 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