INFN FERRARA
Istituto Nazionale di Fisica Nucleare
Sezione di Ferrara

LHCb

First results on the performance of the upgraded LHCb RICH detectors

16th Pisa Meeting on Advanced Detectors

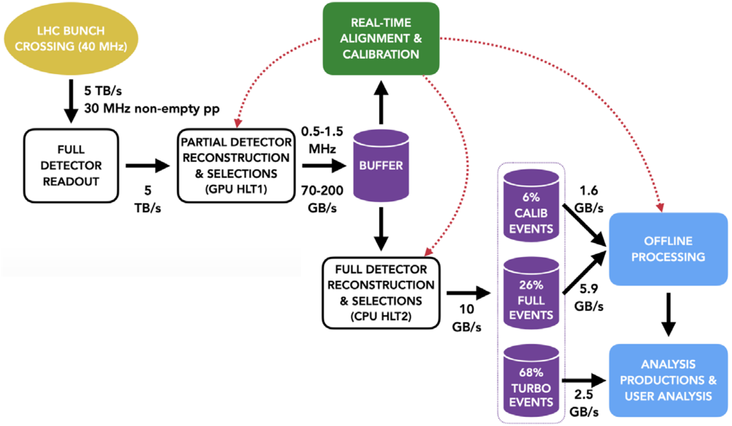
Edoardo Franzoso
on behalf of the LHCb RICH Group

Outline

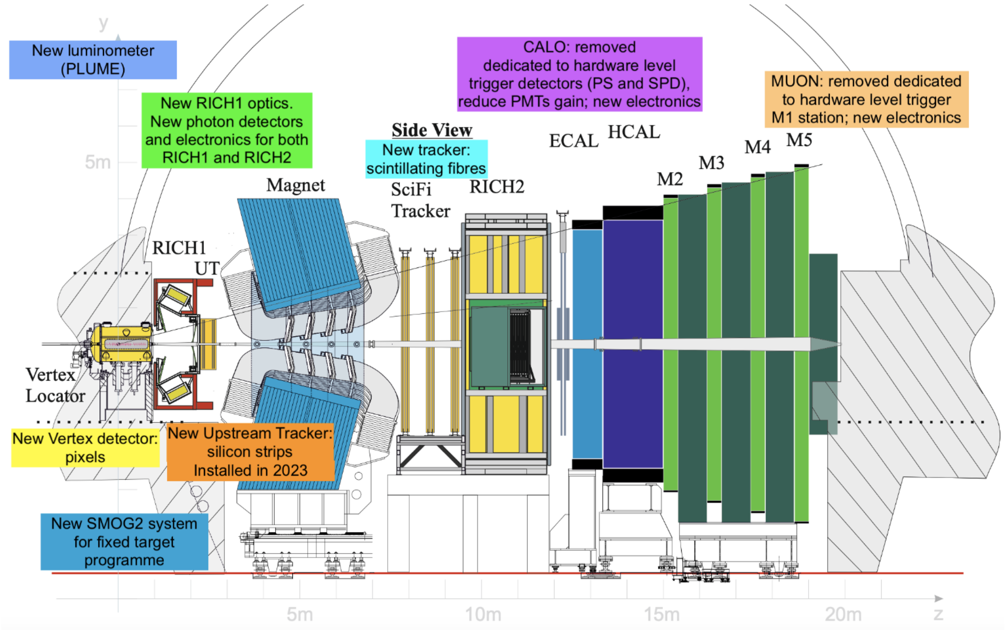
- **Overview of the LHCb Upgrade**
- **The Particle Identification in LHCb**
- **The RICH system Upgrade**
- **Detector tuning and optimization**
- **Performance evaluation**
- **Performance Online Monitoring**
- **Conclusions**

Overview of the LHCb Upgrade

- **Five-fold increase in the instantaneous luminosity** and pile-up
- **Removal of the hardware level trigger**
  - Increase in hadrons selection efficiency by factor ~2
- **Readout** of all subsystems **at 40 MHz**
  - **full-software trigger** architecture
  - First=level Trigger reconstruction on GPUs



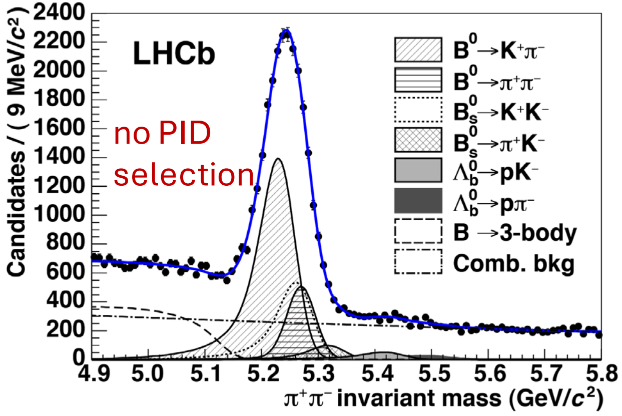
$$L_{\text{inst}} = 2 - 4 \cdot 10^{32} \rightarrow 2 \cdot 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$$

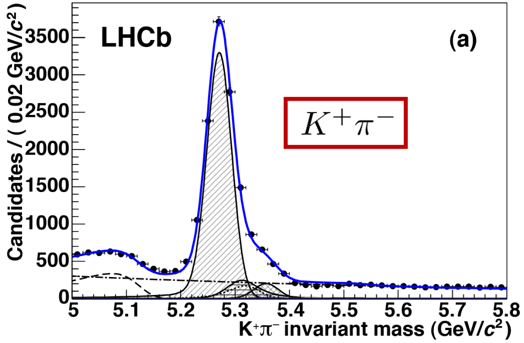


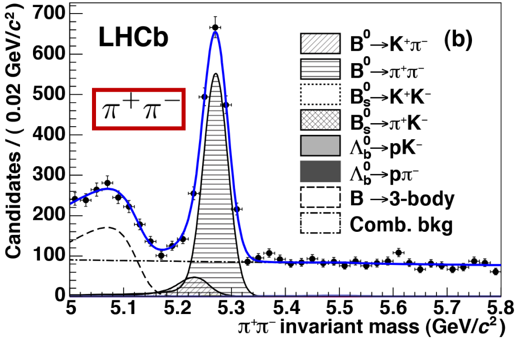
Charged Hadron Particle Identification (PID)

Hadron identification is a key ingredient in b-physics & hadron spectroscopy

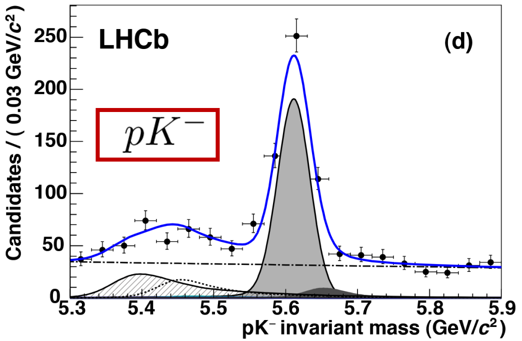
- **PID information for a charged track** is encoded in a DLL variable
  - **Log likelihood difference between a particle hypothesis and the baseline hypothesis (pion)**
- Combinatorial **background reduction**
- **Distinguishing** between **final states with the same topology**

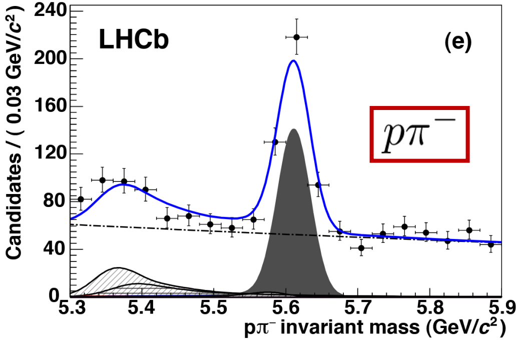


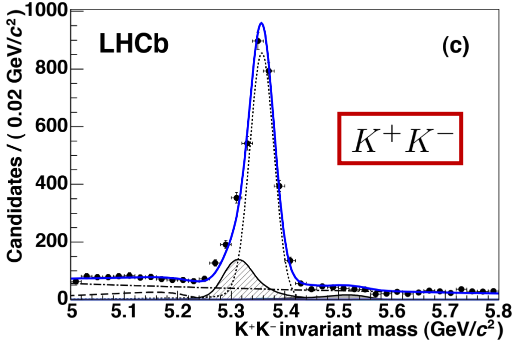




[LHCb, JHEP 10 (2012) 37]







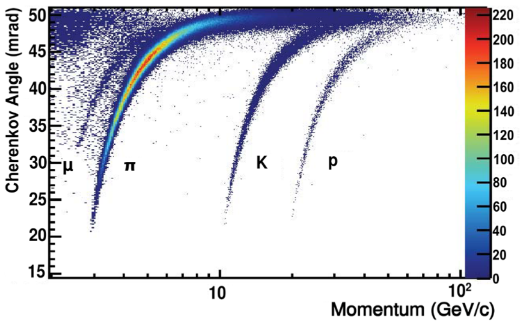
Evaluation of the RICH performance

Main figure of merit to assess the detector performance is the **Cherenkov angle resolution per single photon** → $\boldsymbol{\sigma_C}$

$$\Delta\beta/\beta = \Delta\theta_C \tan\theta_C, \text{ where } \Delta\theta_C = \sigma_c/\sqrt{N_{ph}} + C_{\text{tracking,alignment}}, \ldots$$

Uncertainty contributions

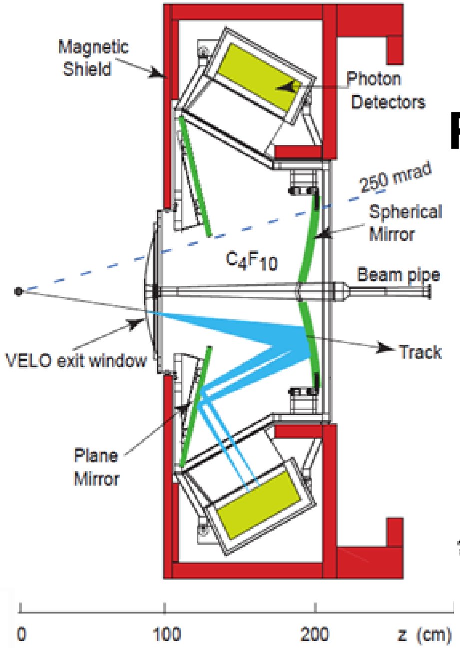
- **emission point error** due to the unknown emission point of the Cherenkov light
  - reduced by **optimizing the optics** of the mirror system to focus the Cherenkov light
- **pixel size error** : choose photon detectors with optimal spatial granularity
- **chromatic error** due to the radiator dispersion
  - different Cherenkov angles from the same track
  - Avoid large variations of the refractive index with the Cherenkov photons energy



- **Maximize photon yield (N_{ph})** per track
- **Minimize background counts**

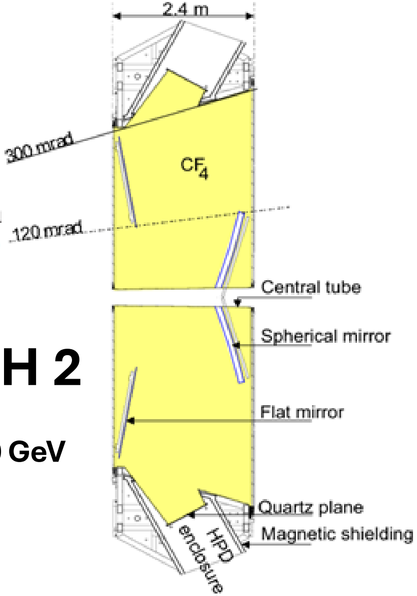
The RICH Detector System (2008-2018)

- **Radiator** contained in **gas enclosure**
- Optical system composed by **spherical and flat mirrors**
- Opto-electronics chain
    - **position sensitive photon detectors**
        - **Hybrid Photon Detectors (HPDs)** with encapsulate 1MHz readout front-end
    - **electronics outside the acceptance**



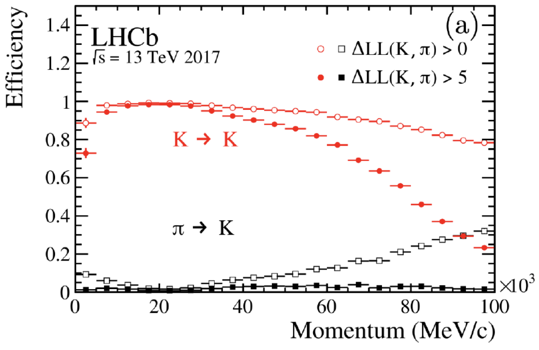
RICH 1

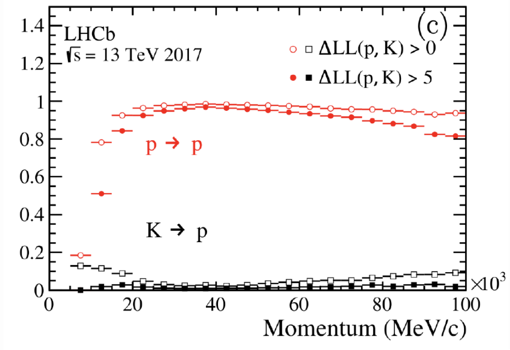
- Upstream
- $\boldsymbol{P} \in [\mathbf{2}-\mathbf{60}]\ \boldsymbol{GeV/c}$
- $n\ =\ 1.0014$



RICH 2

- Downstream
- ***P* coverage up to 100 GeV**
- $n\ =\ 1.0005$



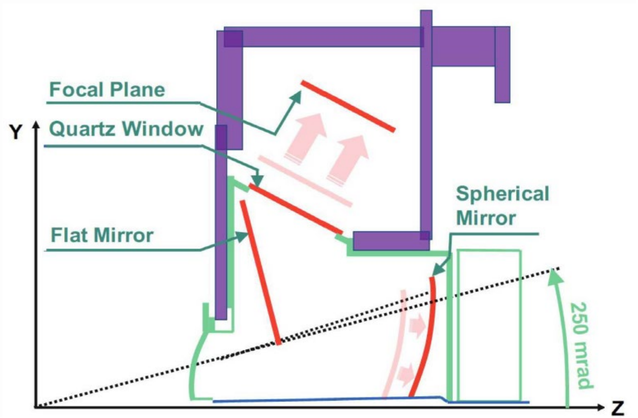


RICH System Upgrade

Poster by Federica Borgato
Upgrade of the LHCb RICH detectors
and characterisation of the new opto-electronics chain

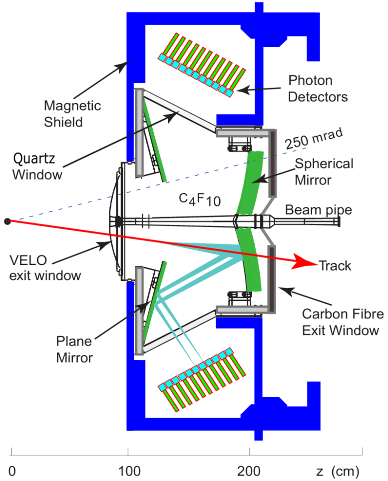
Optics & mechanics

- **Peak occupancy under 30%** → mantain PID performance
- **Redesigned RICH 1 optics** to magnify the ring and spread photons over a larger area
- **New mechanical support** for upgraded opto-electronics chain



Opto-electronics chain

- **New Front-End (FE) Electronics and DAQ system** to deal with 40 MHz readout rate
  - **CLARO8 ASIC** [M. Baszczyk et al 2017 JINST 12 P08019]
  - **FPGA-based Digital Board**
  - GigaBit Transceiver chip for data transmission
- HPDs replaced by Multianode Photomultiplier Tubes **(MaPMTs)**

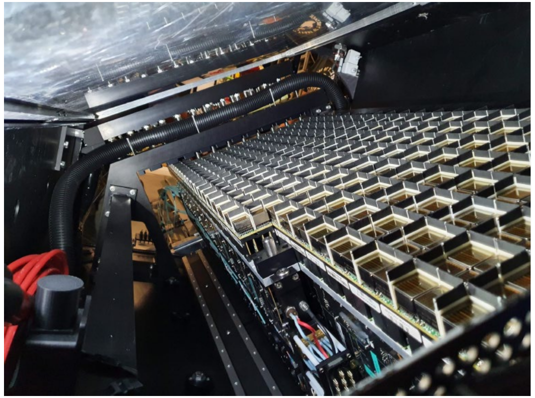


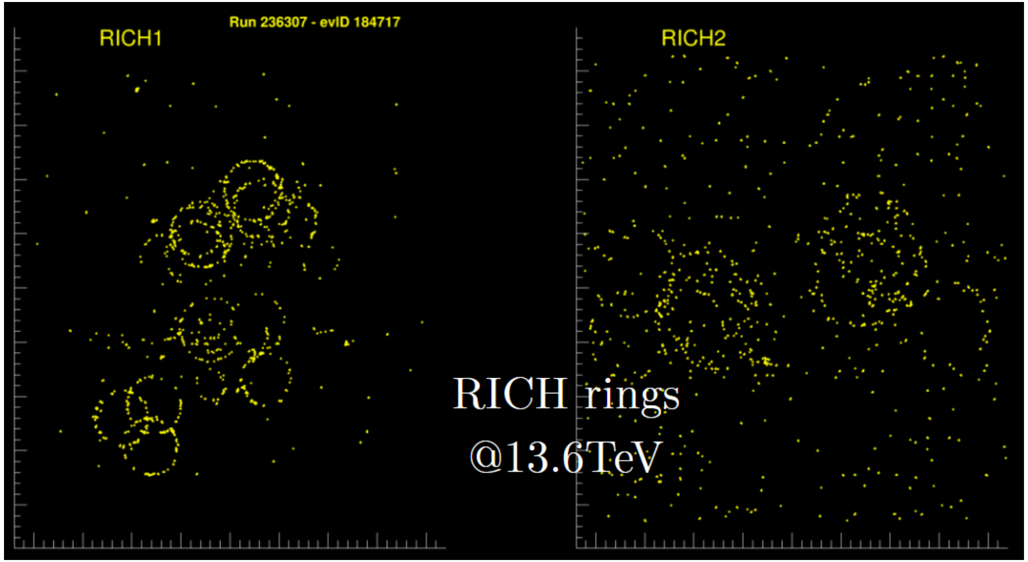
RICH System in Run 3

The RICH detector system is working successfully during LHCb Run3

- November 2021 → operating RICH 2 during LHC pilot beam
- May 2022 → first high energy beam on 5 July
- Collecting data efficiently since

One side of **RICH 1** in LHCb cavern



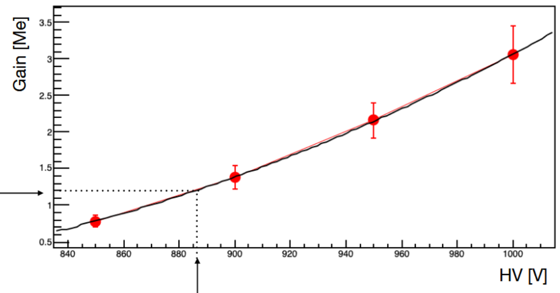


One side of **RICH 2** in Meyrin

Working point evaluation and Optimization

Threshold scans

- MaPMTs – CLARO chip **calibration**
- **HV tuning**
- **Ageing**



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Upgrade of the LHCb RICH detectors
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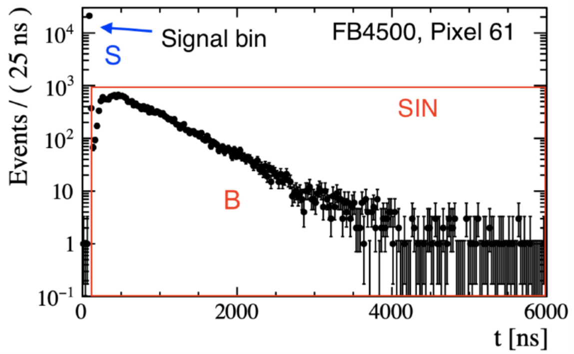
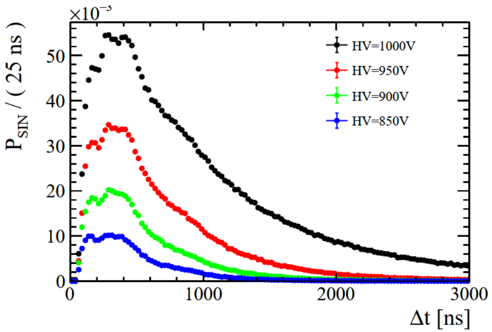




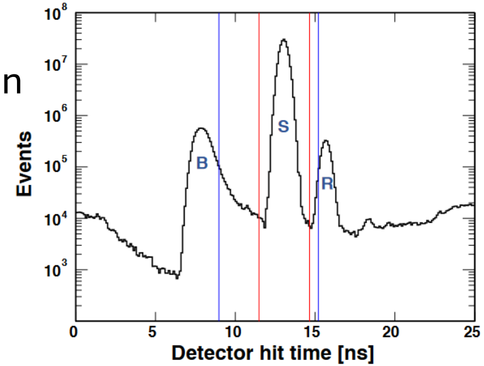
JINST 16 (2021) P11030

Background Studies

- **Signal Induced Noise**
  - **noise** present only **in correlation with signal** and located in specific areas of the MaPMT
- **Gain-noise optimization**

Time Alignment

Rich1
Simulation

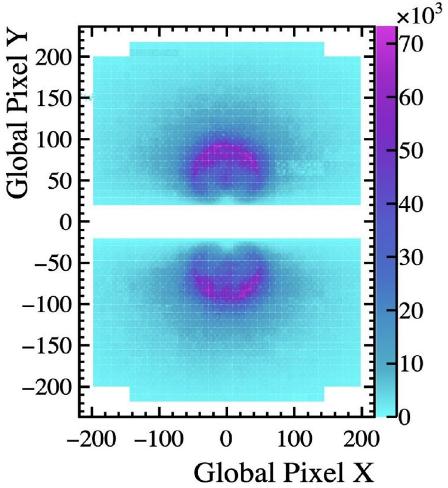


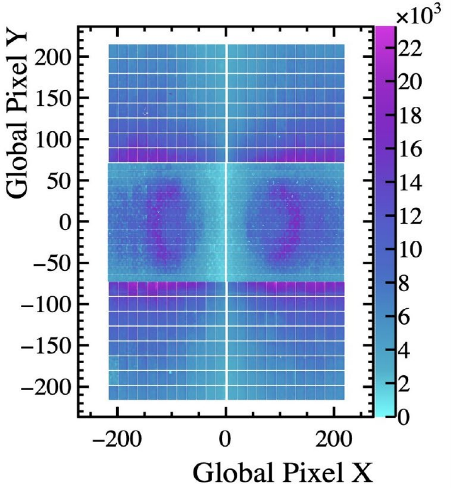
- **Coarse time alignment** in the 25 ns of the bunch crossing ID
- **Fine time alignment**
  - Apply a **signal latching scheme** based on gating in few ns to **maximize detection efficiency** while **reducing out-of-time background**

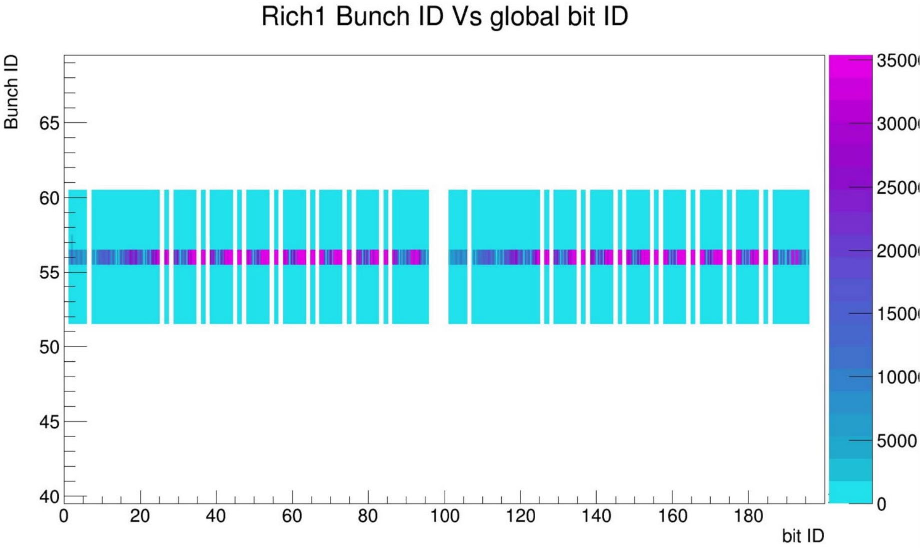
- Identify **the rising edge of the digitized signal** (minimum gating is 3.125 ns)
- In practice more than one minislot (3.125 ns) is required → Claro chip time resolution of ~ 3 - 4 ns is the bottleneck

RICH time aligned

- The time alignment procedure can be performed as a routine operation
- **Fine time alignment within 6.25 ns achieved**
- RICH detectors able to operate at 40 MHz, as by LHCb Upgrade design, and with further background suppression

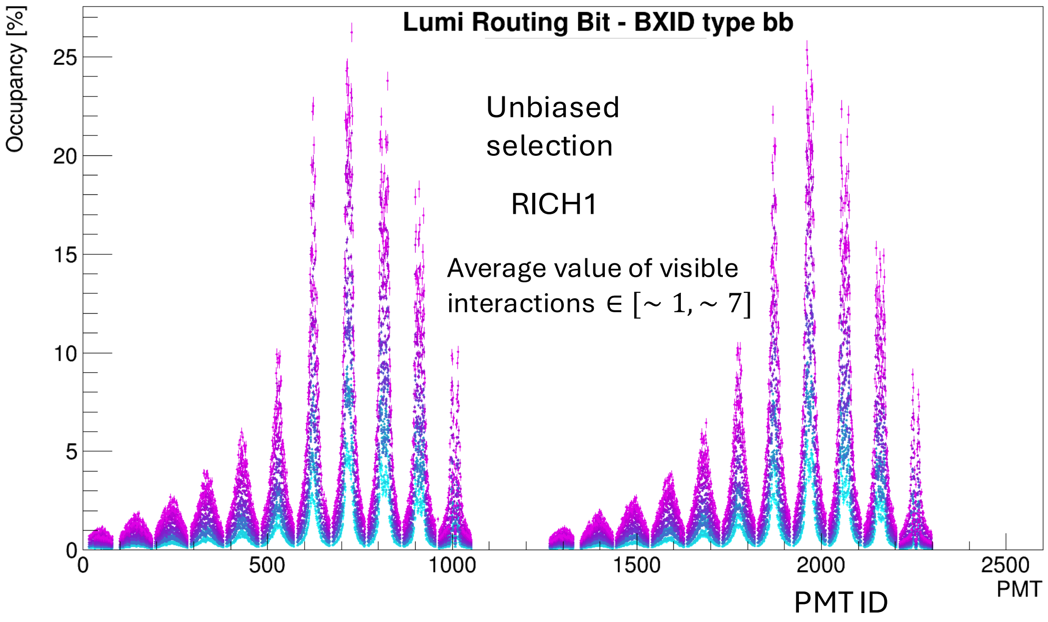


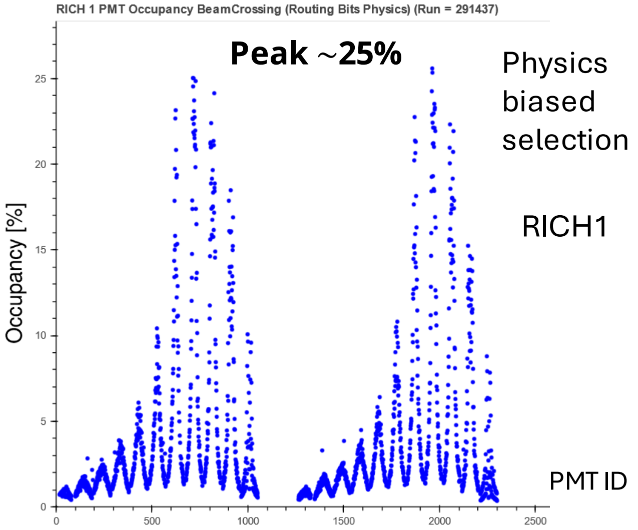


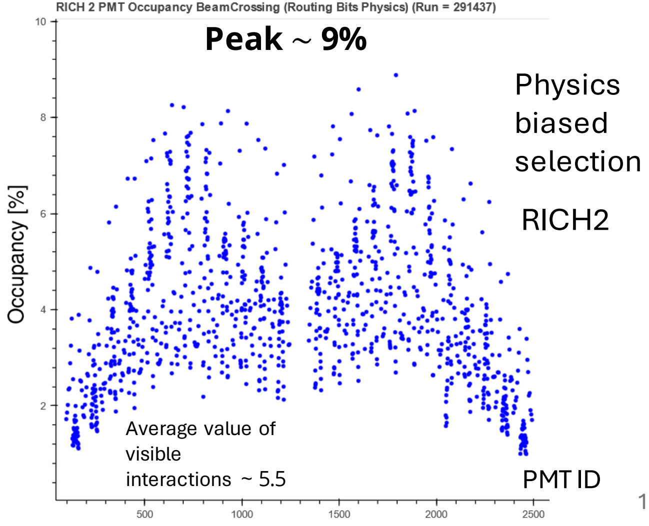


Occupancy in real data

- Occupancy in data at design pile-up
- Values below 30% as required to guarantee the excellent PID performance

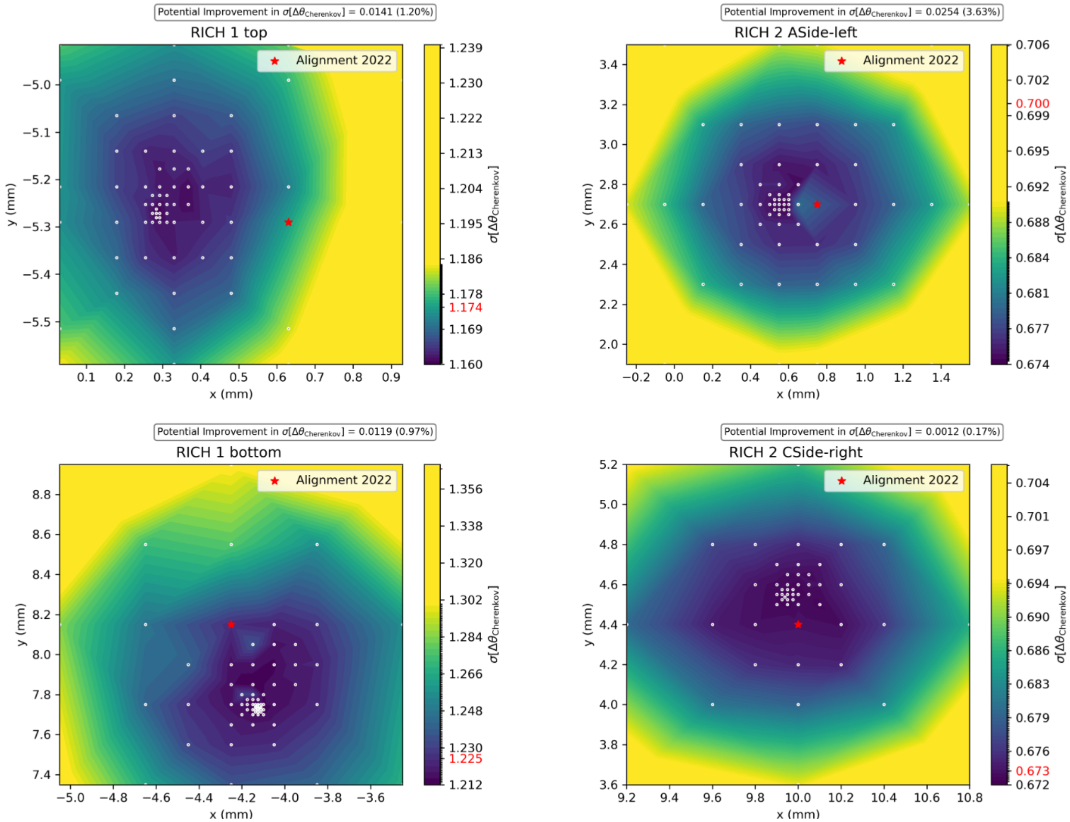




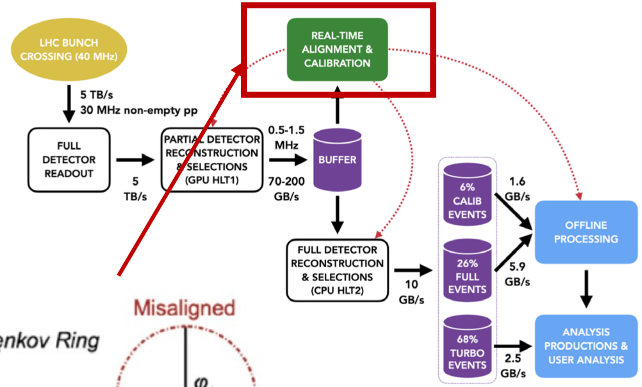


Panel Alignment

- Translating/rotating panels
- Small movements in X-Y of the panels to minimize the Cherenkov angle resolution



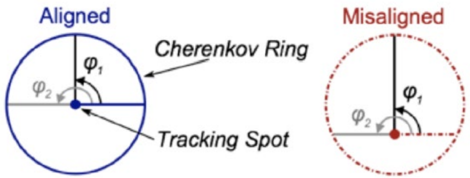
Mirror Alignment



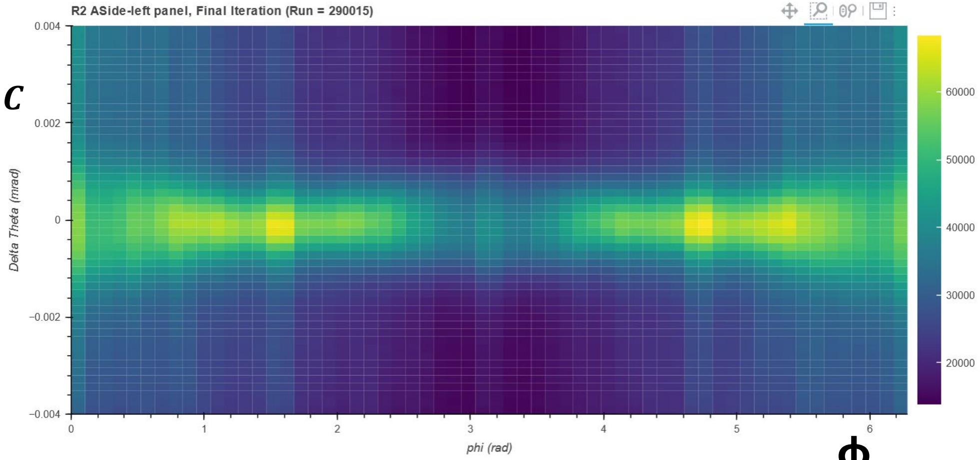
RICH mirror alignment is performed in a **real-time** task

- Look at the difference of each detected photon's reconstructed Cherenkov angle and its expected Cherenkov angle in bins of the azimuthal angle

- **Fit the $\Delta\theta_C$ distribution and correct for deviations** of its mean value from zero **in each ϕ bin**



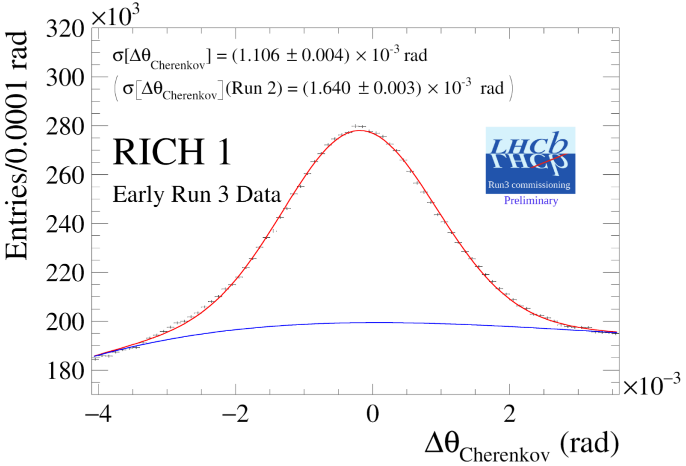
$\Delta\theta_C$

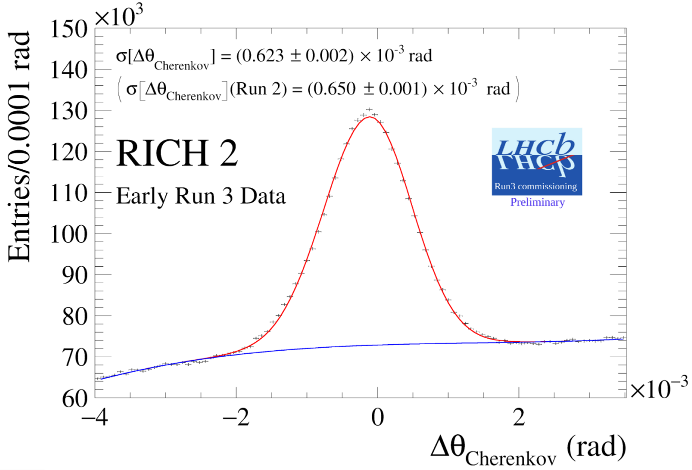


ϕ

Single Photon Cherenkov angle resolution

- One of the main figure of merit to **evaluate the performance**, it requires:
  - **High momentum tracks** reconstructed → dependence on tracking quality
  - Software **spatial alignment** → mirrors and panels





Radiator	C_4F_{10}		CF_4	
Detector version	RICH1 HPD (data)	RICH1 MaPMT (MC)	RICH2 HPD (data)	RICH2 MaPMT (MC)
Photon yield	30	60	18	30
Single photon errors [mrad]				
Chromatic	0.84	0.52	0.48	0.34
Pixel	0.99	0.50	0.35	0.22
Emission point	0.61	0.36	0.32	0.32
Overall	1.66	0.81	0.62	0.52

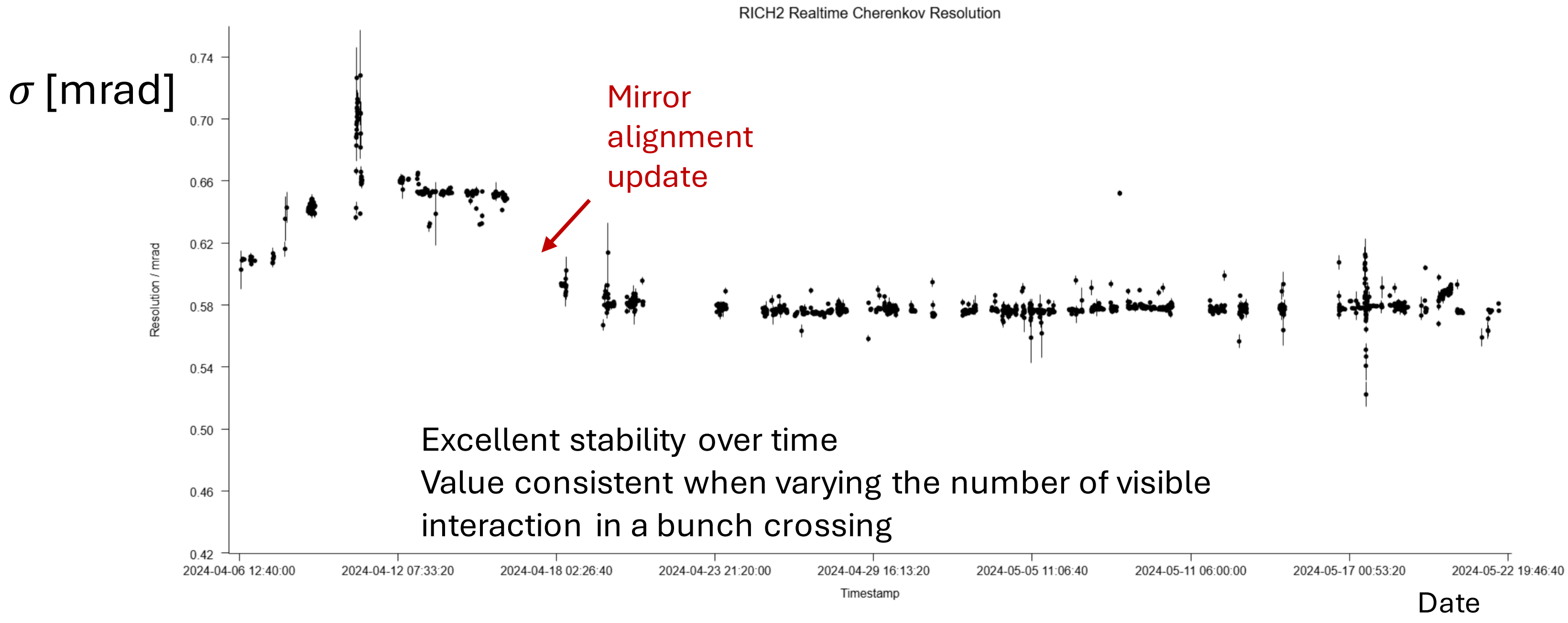
Clear performance **improvement** with respect Run 2 RICH system and **approaching the expected performance**

Online Monitoring

- Implemented **online monitoring of figure-of-merit variables**
- **Real-time feedback** of the performance of the detector
- Useful to **promptly detect issues** and **optimize data-taking**

We have independent variables available to understand the activity of the detector:

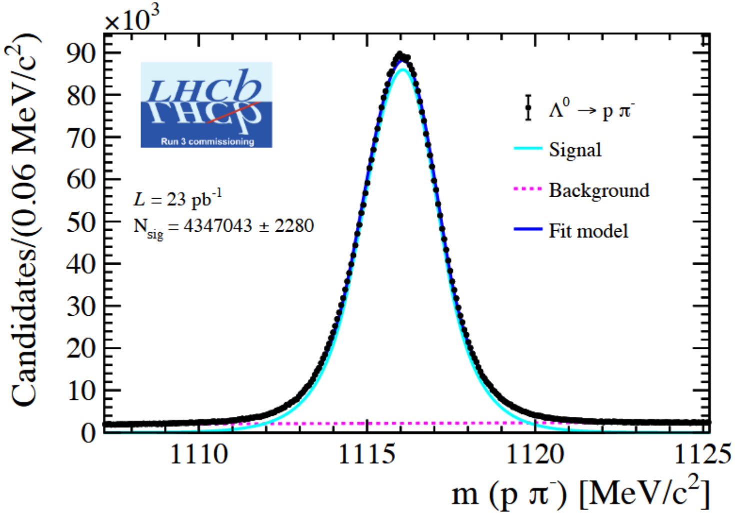
- **Single Photon Cherenkov angle resolution**
- post-reconstruction **photon yield per track**
- **Experiment control system variables** independent from the DAQ



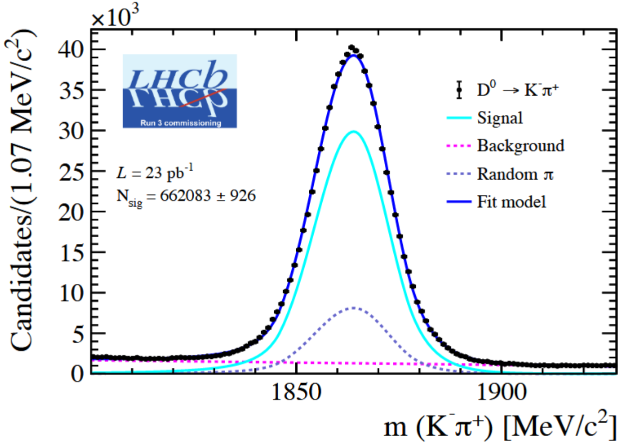
PID efficiency

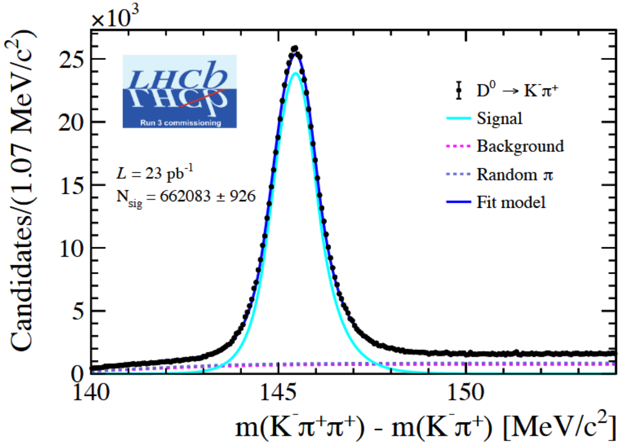
- Charged hadron separation performance is studied looking at **pure samples of pion, kaons and protons** from **control samples**
- Selection based on kinematic requirements only

$$\Lambda^0 \to p\pi^-$$



$$D^{*+} \to D^0 (\to K^- \pi^+) \pi_S^+$$

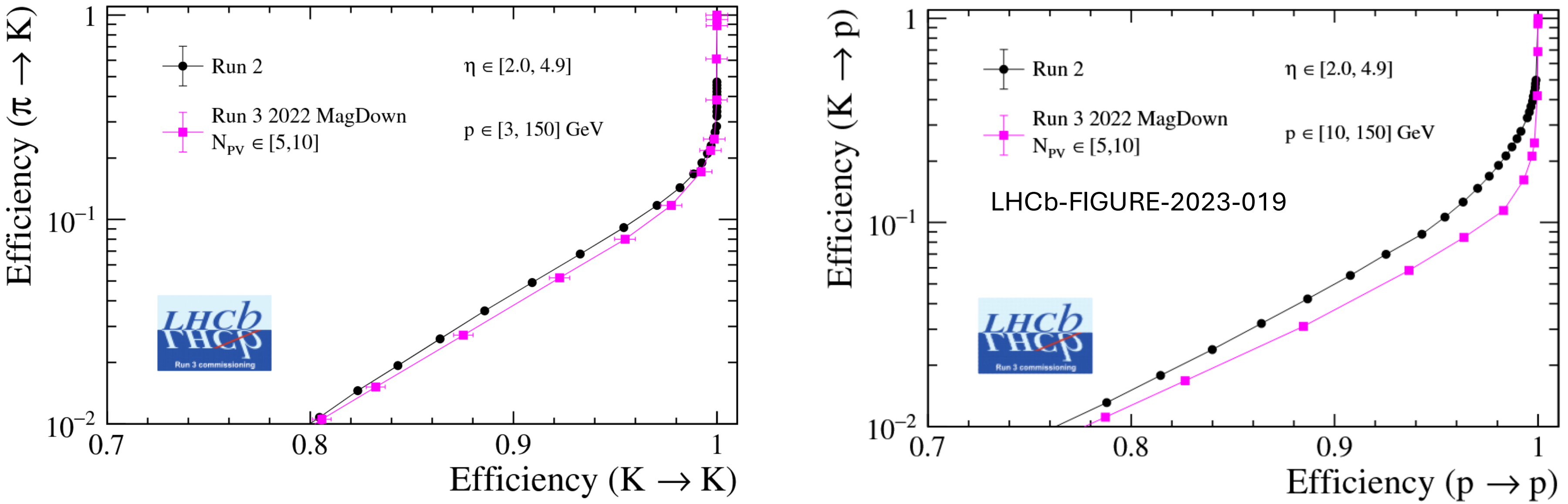




PID efficiency

Tag-and-probe method

- Look at **efficiency** and **mis-ID efficiency** by varying the PID cut
- Compare high-pile up events in Run 3 with Run 2 values (pile-up ~ 1)
- **Design goal** → retain excellent PID performance of Run 2

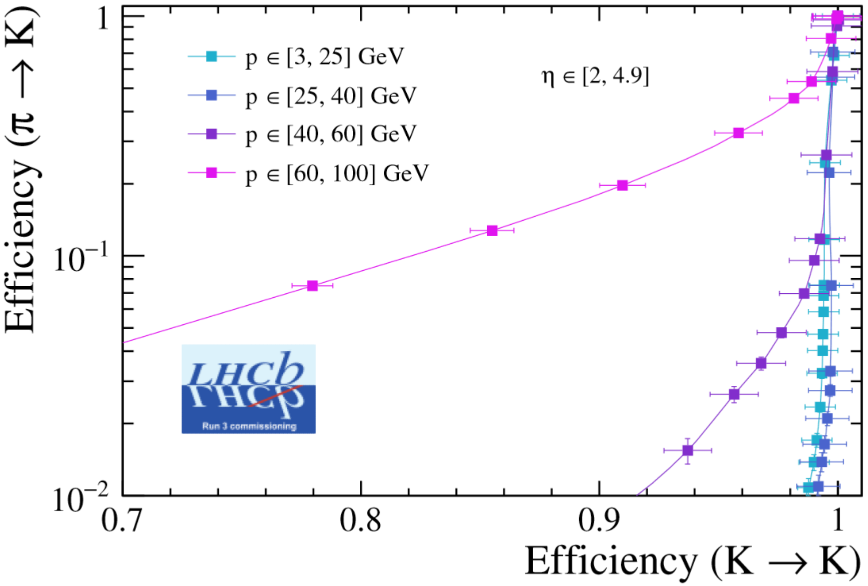


PID efficiency

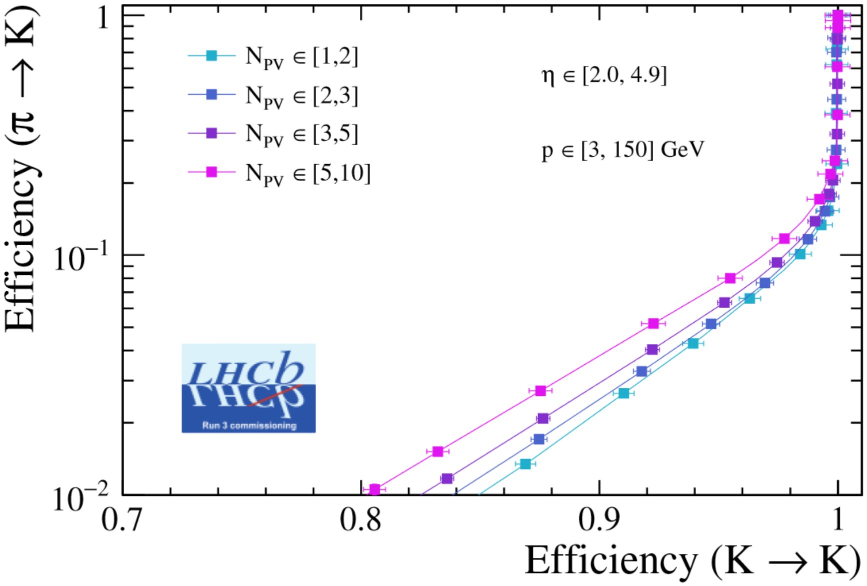
Fully **characterize the PID performance** in bin of momentum, pseudorapidity of the tracks and occupancy of the events

Similar studies as a function of the gating are foreseen

Momentum



Number of primary vertices



Conclusions

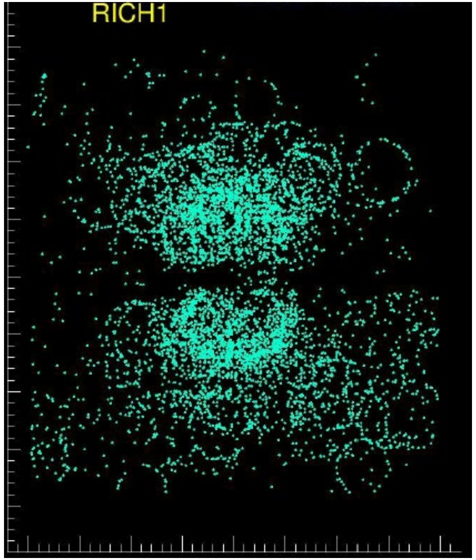
- The **LHCb RICH system is a unique PID system**: PID over **unprecedented large momentum range** with **extremely challenging peak occupancy**

- First years of data-taking during Run 3 show an **excellent PID performance**, better than the precedent RICH detector system
    - Steadily approaching to the designed values of Cherenkov angle resolution

- **The RICH system collected data efficiently since 2022**

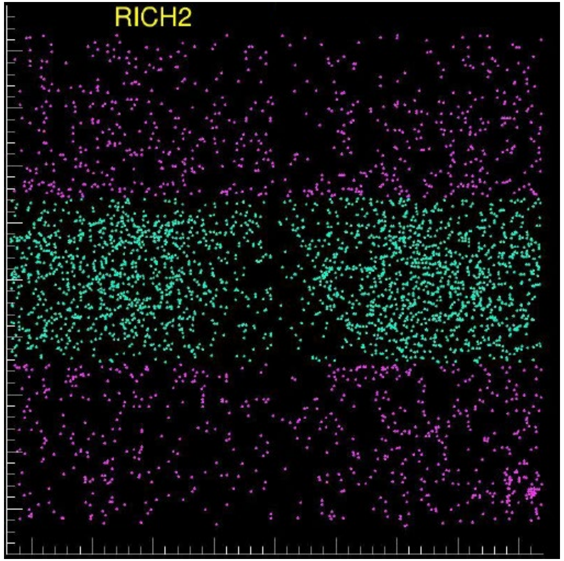
- **Very promising performance** anticipates exciting results from LHCb Physics programme in RUN3

5720 hits in RICH1



High multiplicity event Display

3733 hits in RICH2



Spares

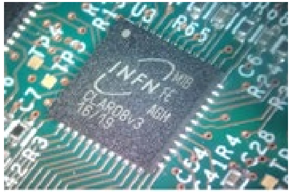
New Photomultipliers and Readout

To achieve the required readout rate, a new electronic (CLARO chip) has been developed and coupled with Multi-Anode PhotoMultiplier Tubes (MaPMTs), instead of the Hybrid Photon Detectors used for previous LHC runs

MaPMTs

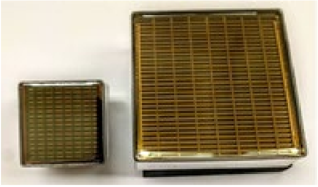
- R-type (1'') and H-type(2'')
- **64 pixels** each
- **High quantum efficiency** (QE) super-bialkali photocathode
  - lower chromatic error
- Gain $\sim 2 \cdot 10^6$ at $1\ kV$ with 1:3 pixel gain spread for a single MaPMT
- Dark count rate (DCR) $< 1\ kHz$ for each pixel

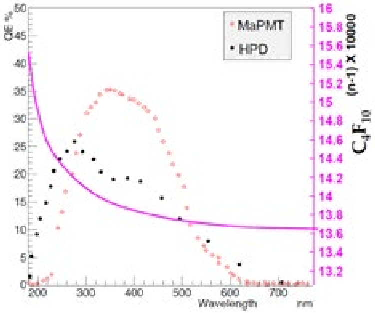
CLARO ASIC



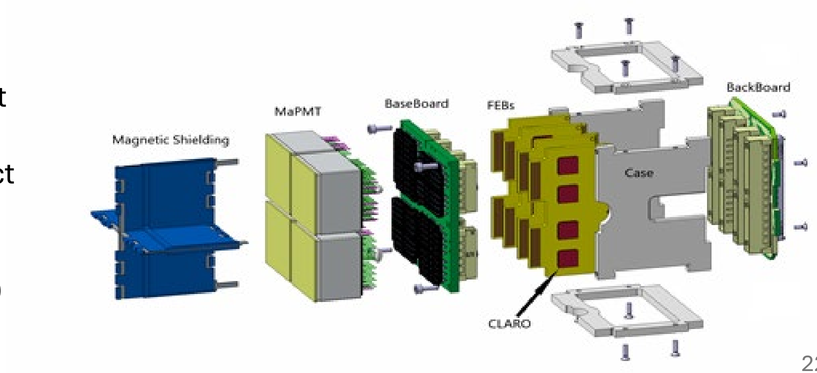
8 channel amplifier/discriminator

- 0.35 μm AMS CMOS technology
- Recovery time < 25 ns
- Adjustable threshold and attenuation for each channel
- Triple modular redundancy protection
- Radiation- hard by design





MaPMTs and readout electronics are coupled in a compact and fully functional unit called Elementary Cell (EC)



The Photon Detector Module

Front-end digital board:

- capture CLARO outputs
- synchronize to LHC clock
- data algorithm, format and transmission

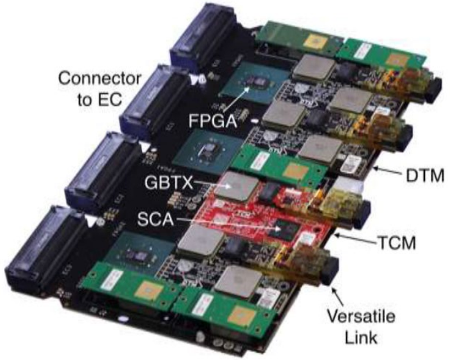
PDMDB: motherboard with FPGAs and power distribution

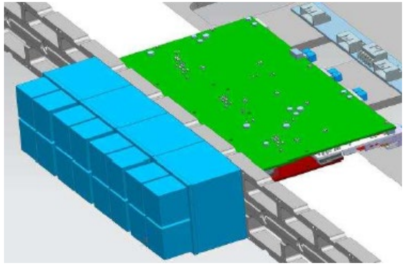
- plugins for controls and data transmission, DTM and TCM

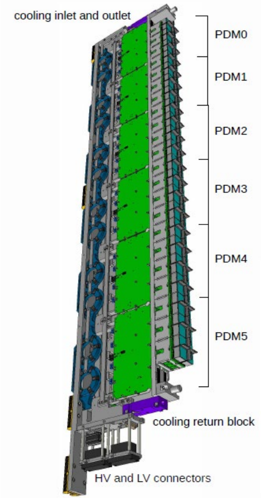
EC+PDMDB form the logical unit called the **Photon Detector Module (PDM)**

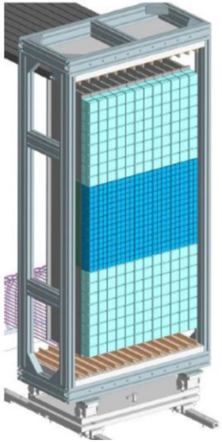
- share **common LV and HV distribution**

Modular design to facilitate maintenance



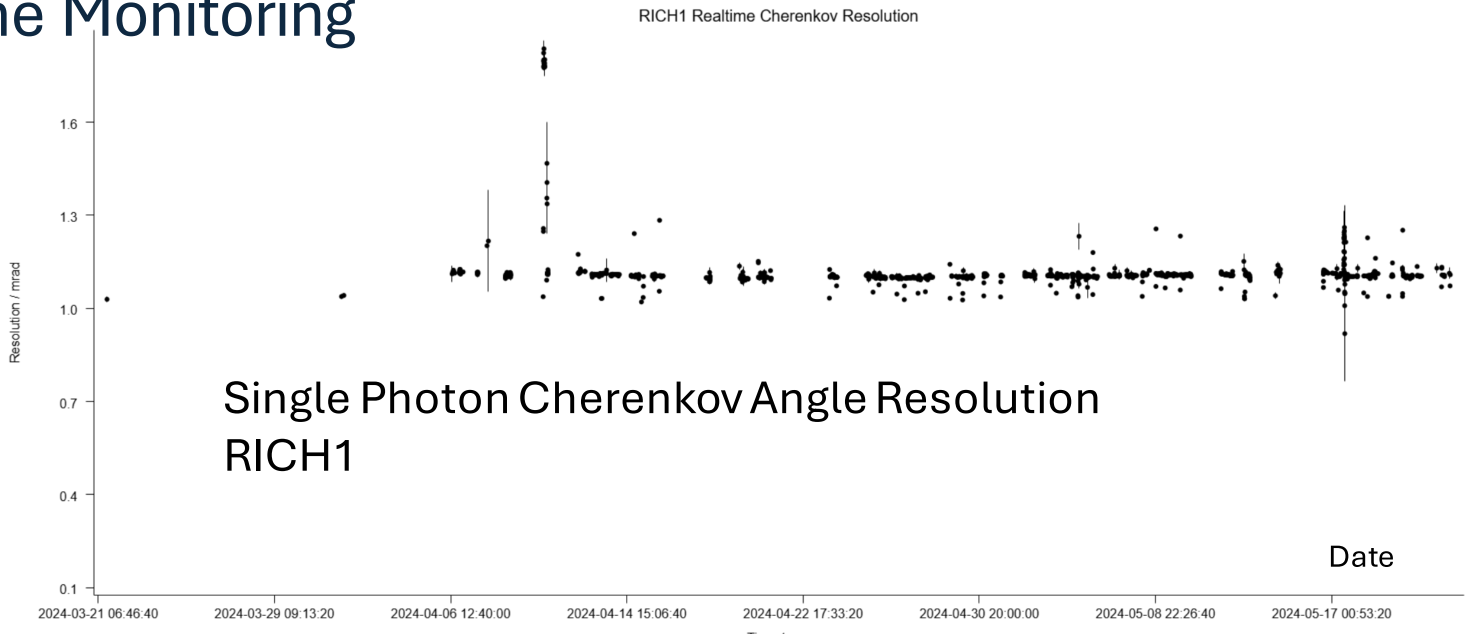


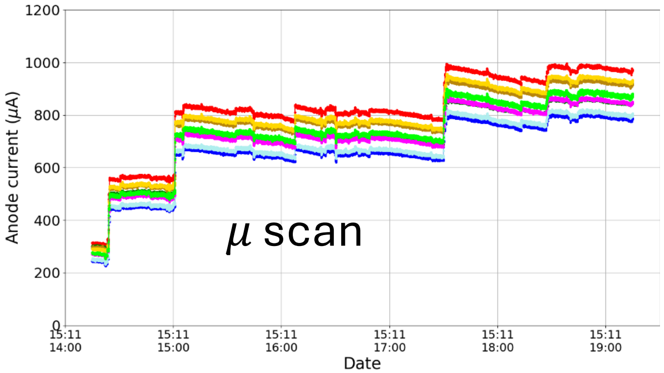




Novec circulated at 16∘C ensures MaPMT temperature at 25∘C

Online Monitoring





- MaPMTs operated by powering the last dynode to preserve the gain linearity
- **Anode currents scale linearly** with the activity seen by the detector, hence **with luminosity**
  - employed as alternative **online luminosity counters**
  - Independent from DAQ status

RICH Reconstruction

RICH Detector Hits
- Event decoding
- Photon hits

Reconstructed Tracks
- Trajectory inside radiator
- Expected Cherenkov photon yields
- Quartic equation to propagate inside the mirrors

Global likelihood algorithm
- Probability of signal hit in a pixel given set of particle mass-hypotheses for each track
- Find set of mass-hypotheses that maximize that likelihood

PID classifiers
- After minimization, evaluate the change in loglikelihood for each track under another mass hypothesis
- Obtain a $DLL(h-\pi) = \Delta logL(h-\pi)$ with $h \in [K,p]$ and assuming π as the baseline hypothesis