The LHCb RICH detectors upgrade: from prototyping to operations

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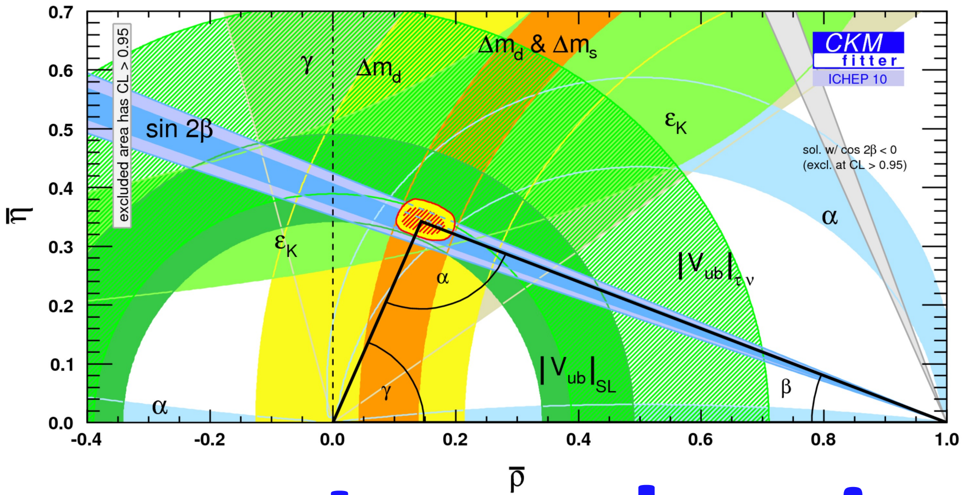
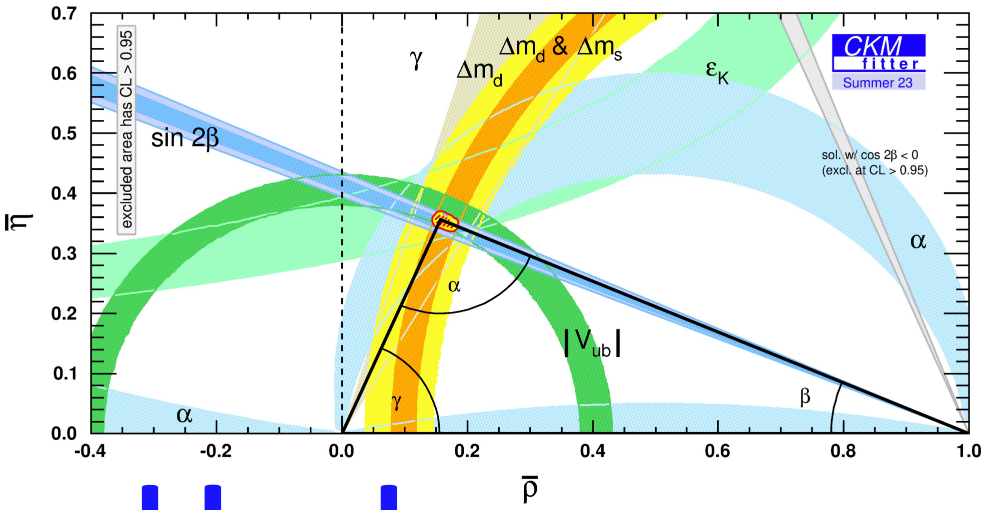
Outline

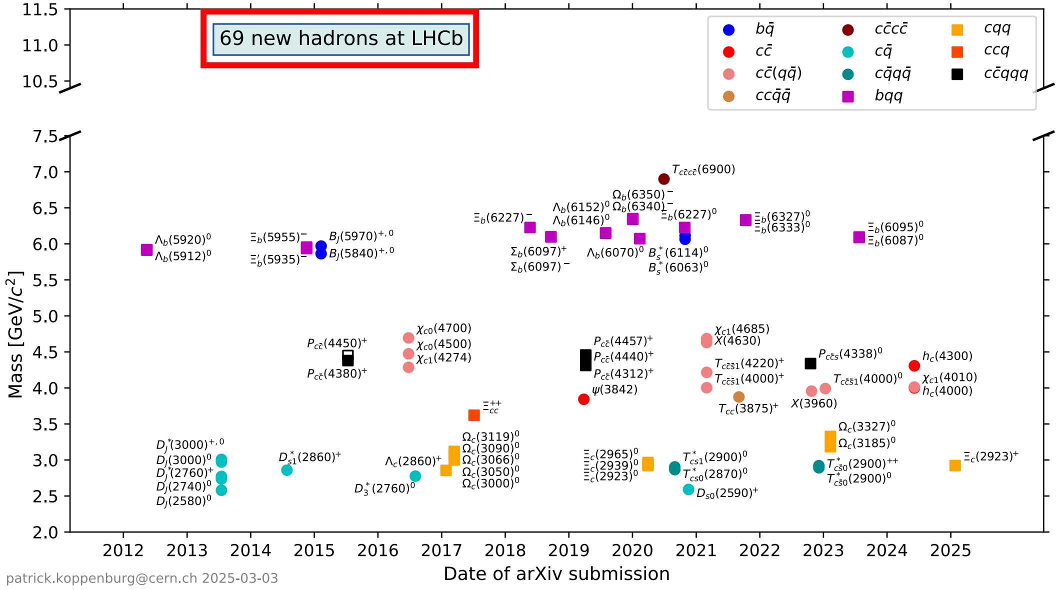
The Ring Imaging Cherenkov (RICH) detectors provide charged hadron identification to the LHCb experiment at CERN

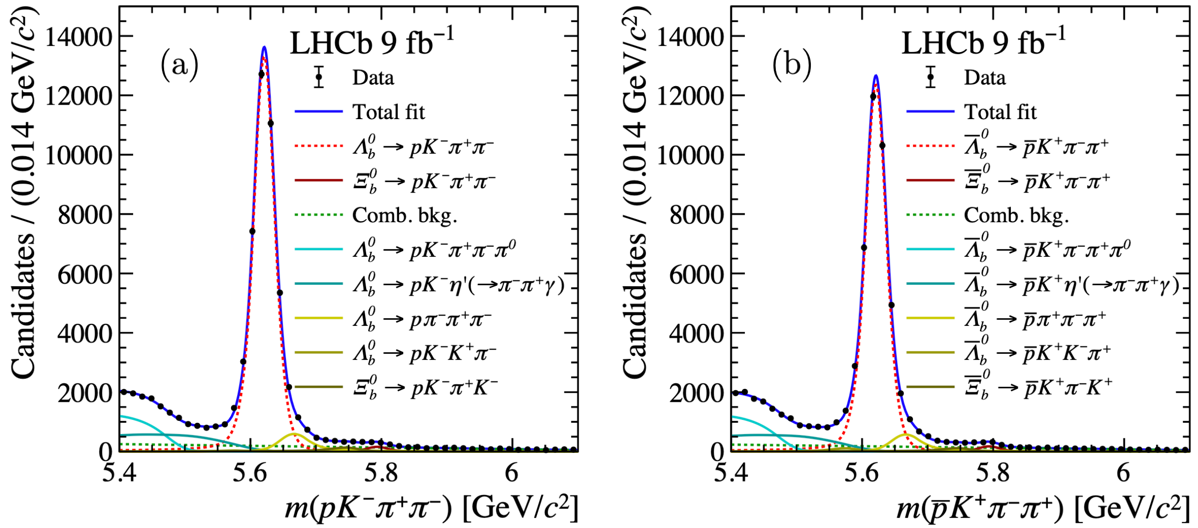
- Introduction to LHCb and impact of hadron identification on physics
- The LHCb RICH detectors and their upgrade
  - Photon detection chain prototyping and quality assurance
  - Optics and mechanics
- Commissioning and installation
- Operations and performance





Introduction to LHCb and hadron identification

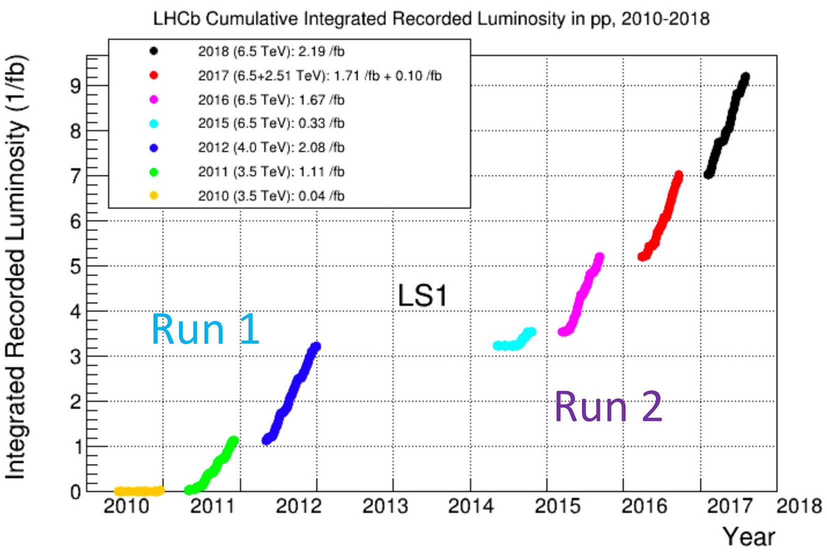


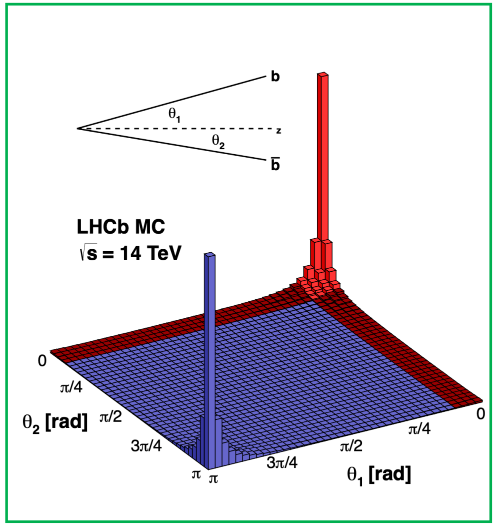


LHCb phase 1 (2010-2018)

2008 JINST 3 S08005

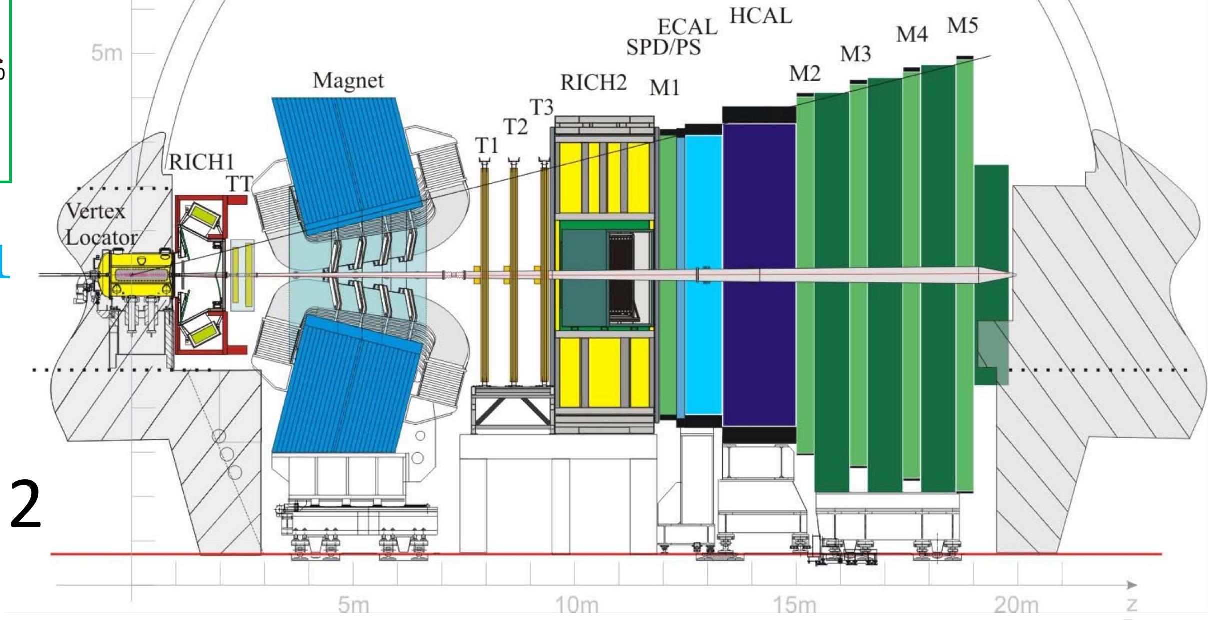
- Designed to perform indirect searches for new physics through **precision studies of b- and c-hadron decays**





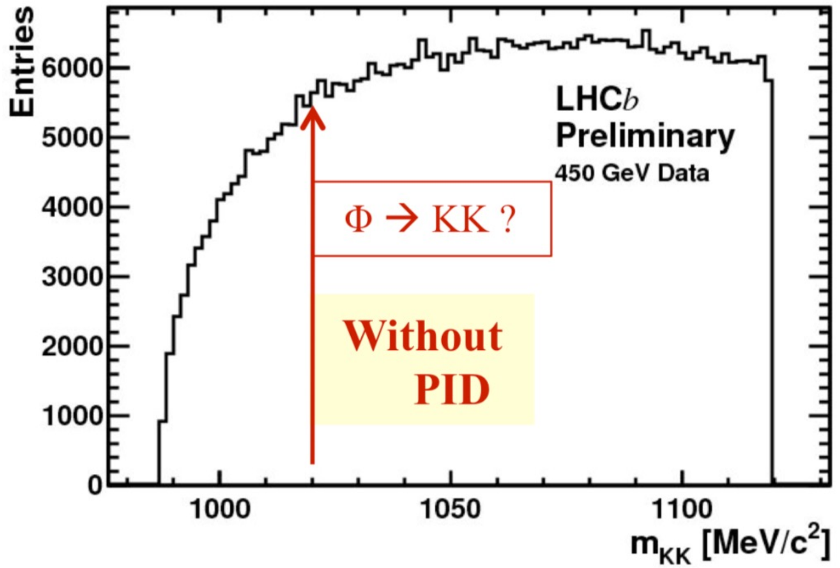
- Run 1, $\sqrt{s}$ = 7-8 TeV, $\mathcal{L} = 2 \cdot 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Run 2, $\sqrt{s}$= 13 TeV, $\mathcal{L} = 4 \cdot 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\sim 10^{12}$/ 10^{13} b-/c-hadrons in Run 1 + Run 2

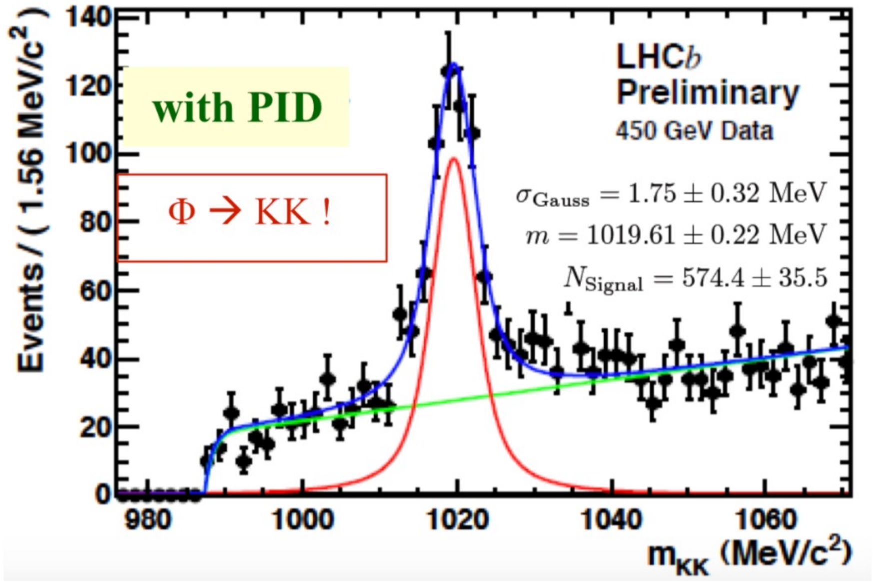
- Precise vertexing (σ_t ~ 45 fs)
- Excellent momentum resolution (σ_p/p ~ 0.5% -> 1% at 200 GeV)
- 90% trigger efficiency on muons
- Excellent hadron identification



Hadron identification with RICH detectors

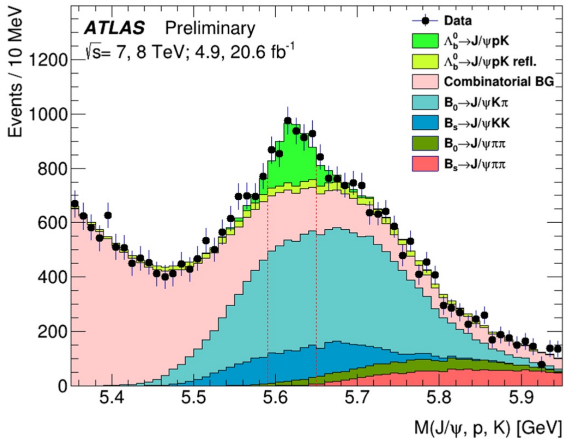
- Hundreds of photons and charged pions are produced in a hard pp interaction at the LHC inside the LHCb acceptance
- Use the properties of Cherenkov radiation to assign a mass hypotheses to charged particles in a **wide range of momenta up to 100 GeV**
  - reject combinatorial background due to random charged pions
  - distinguish final states of otherwise identical topology: : suppress leading order decay modes and efficiently select Cabibbo suppressed decays to improve the precision of rare decay and CP violation studies



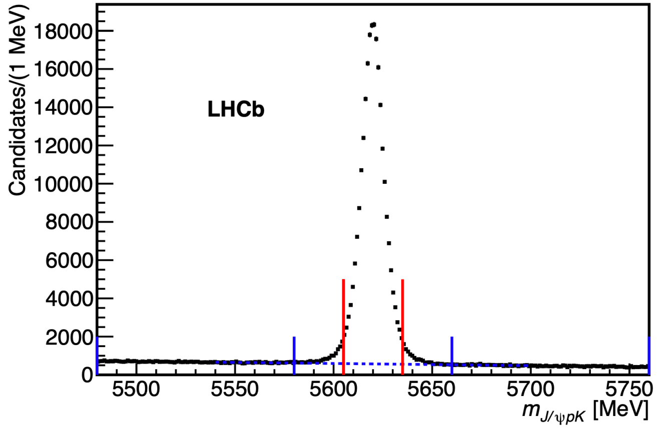


Impact of hadron identification on LHCb physics

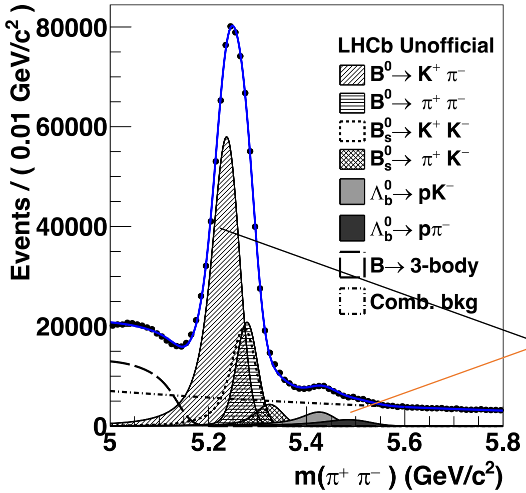
Without hadron ID



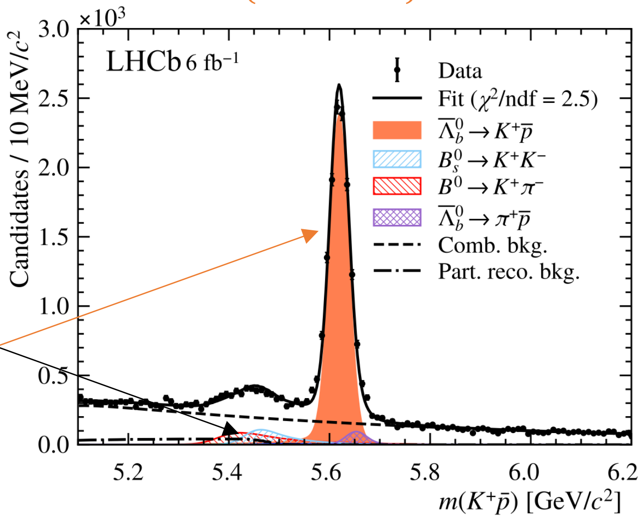
With hadron ID



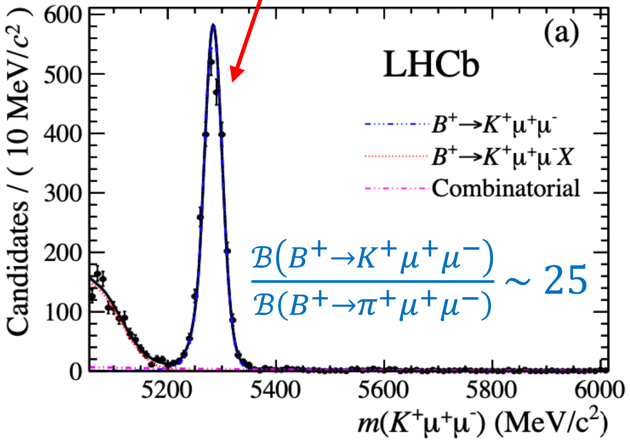
$$\frac{N(\Lambda_b^0 \to pK^-)}{N(B^0 \to K^+\pi^-)} \sim 1/15$$



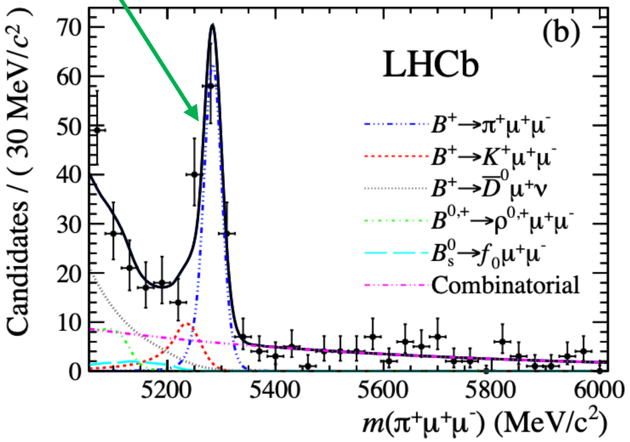
$$\frac{N(\Lambda_b^0 \to pK^-)}{N(B^0 \to K^+\pi^-)} \sim 100$$



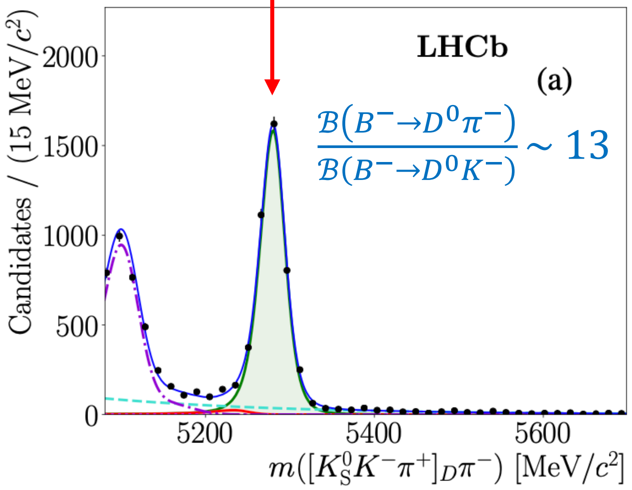
Dominant kaon mode suppressed by factor 80 while retaining 80% of pion candidates



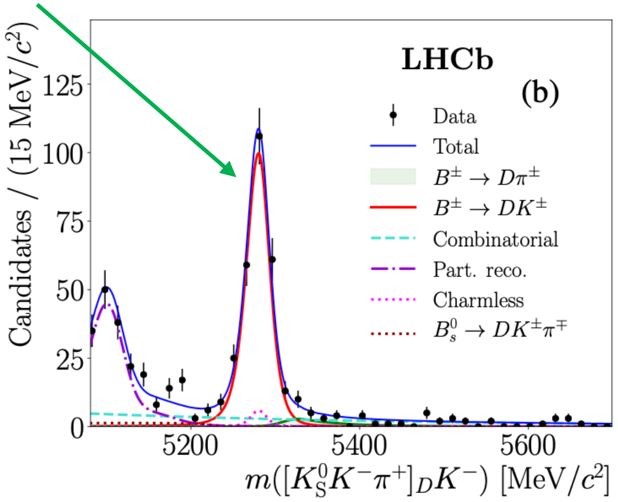
$$\frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)} \sim 25$$



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

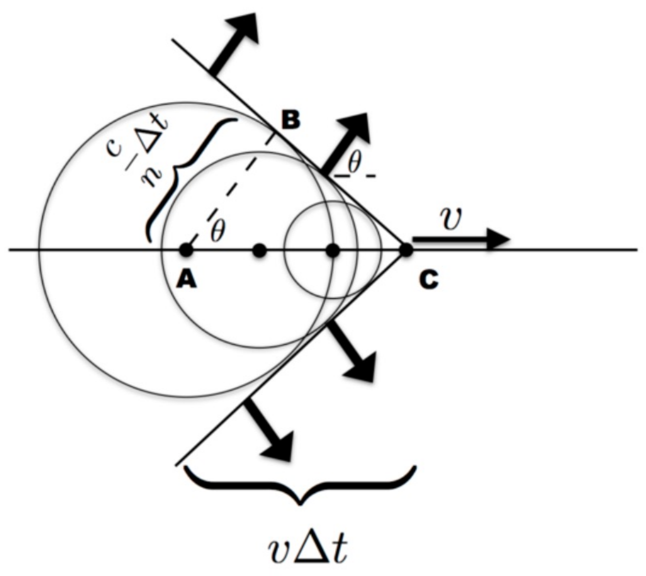


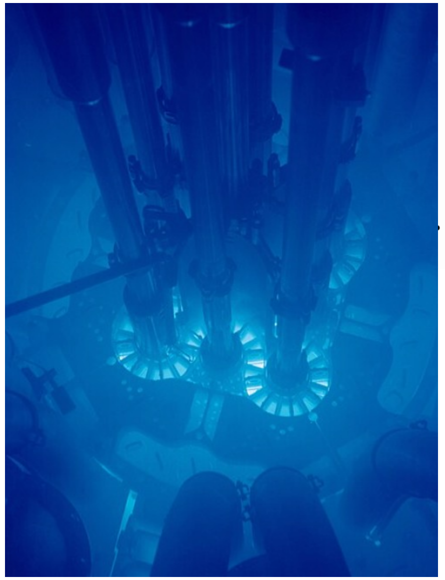
$$\frac{\mathcal{B}(B^- \to D^0\pi^-)}{\mathcal{B}(B^- \to D^0K^-)} \sim 13$$

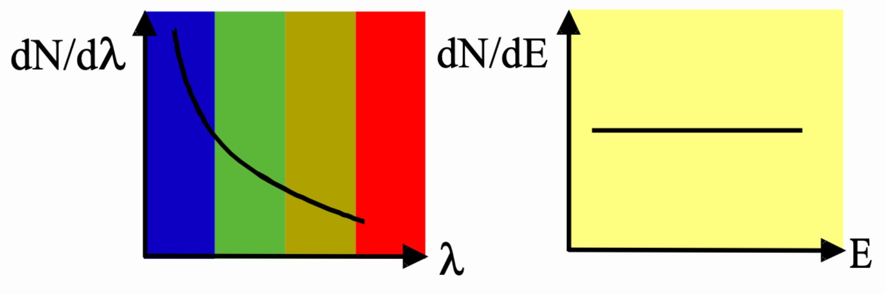


Cherenkov radiation

- Photons radiated by a material of refractive index n when a charged particle travels with a velocity $v = \beta c$ **larger than the phase speed of light c/n**
  - Energy **threshold**
  - coherent and **polarised** wavefront with **direction $\cos\theta_c = 1/\beta n$** (cone of light with axis given by the charged particle trajectory)
  - spectral dependence of the radiation for a path L of the charged track in the medium given by the Frank and Tamm equation $\mathrm{dN/dE} \sim 370\ L\ [\mathrm{cm}] \sin^2\theta_c\ \mathrm{eV}^{-1}$



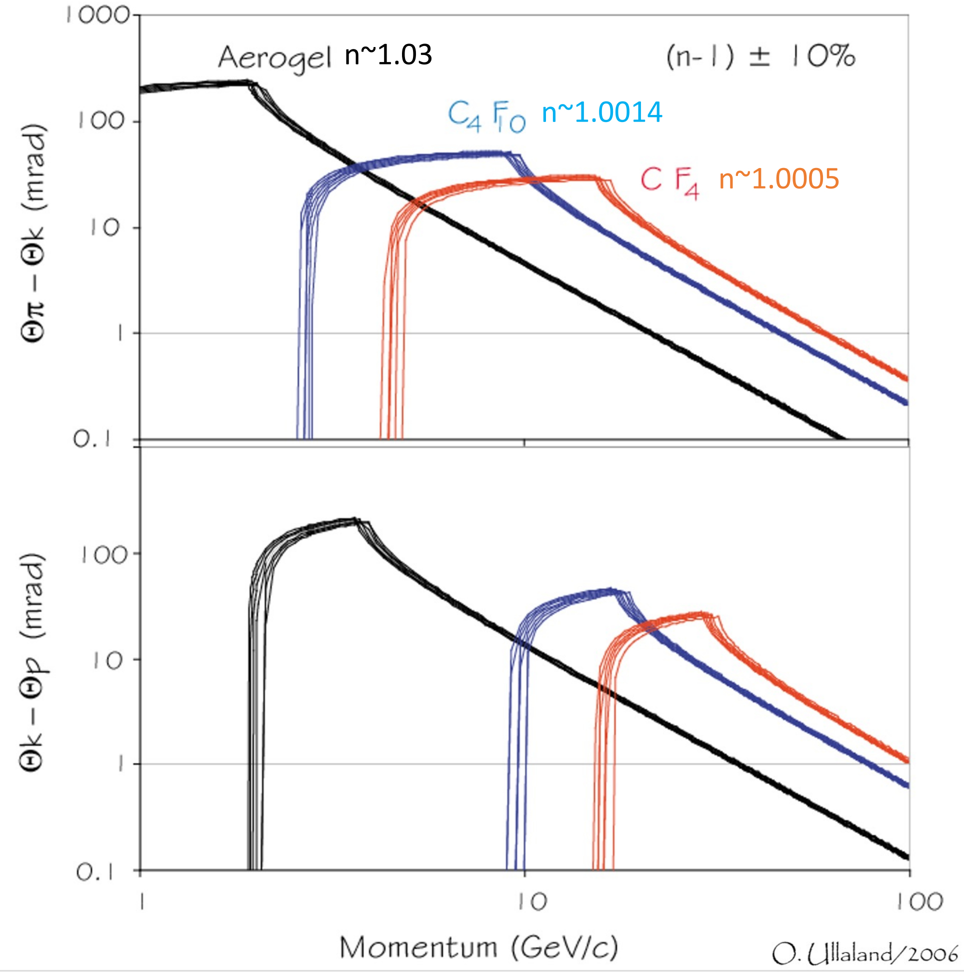




~ 500 photons are emitted by an electron in 1 cm of water (n=1.33) => **Cherenkov light is feeble!**

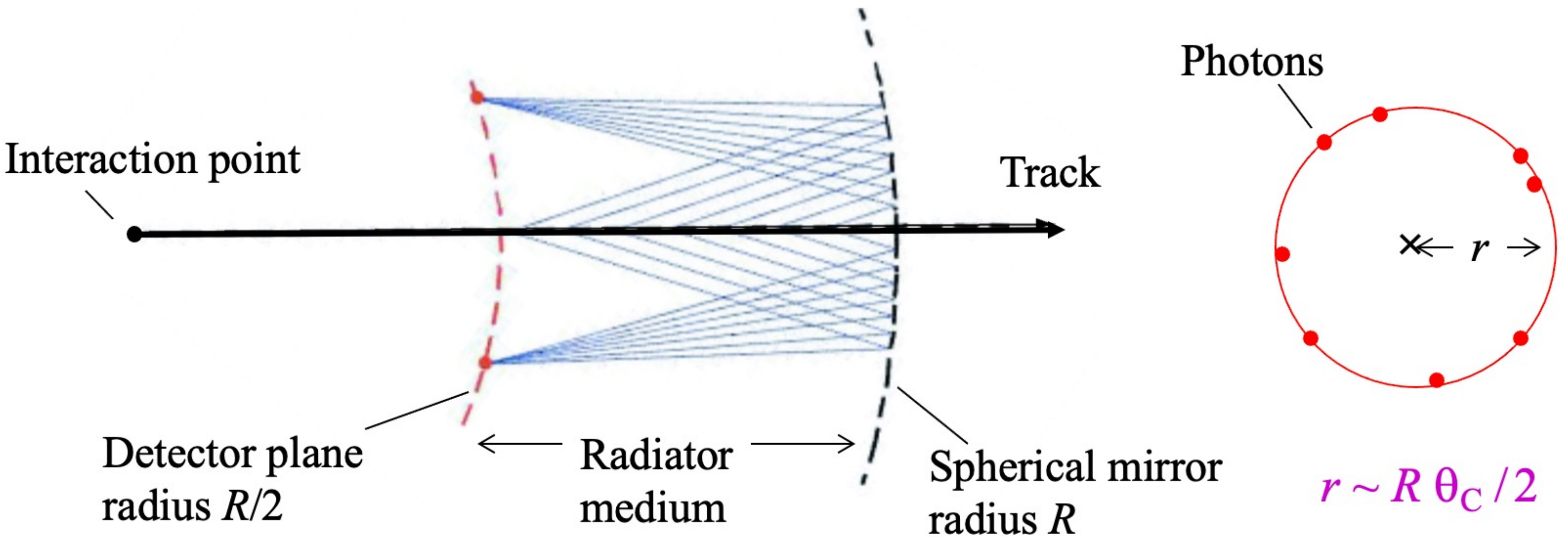
Cherenkov radiation for particle identification (PID)

- $m = p/\beta\gamma = p\sqrt{n^2 \cos^2 \theta_c - 1}$
- PID can be done measuring the Cherenkov angle θ_c when the momentum p is determined by the tracking system
- n is known by the choice of the radiator, determined according to the range of momentum that needs to be covered
- Mass discrimination in a wide momentum range is best reached if $n \gtrsim 1$ (e.g. fluorocarbon gases)



Ring imaging

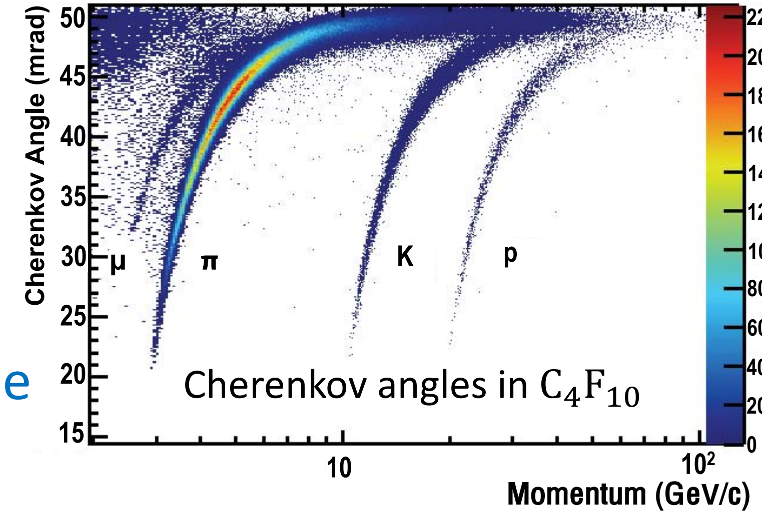
NIM 142 (1977) 377

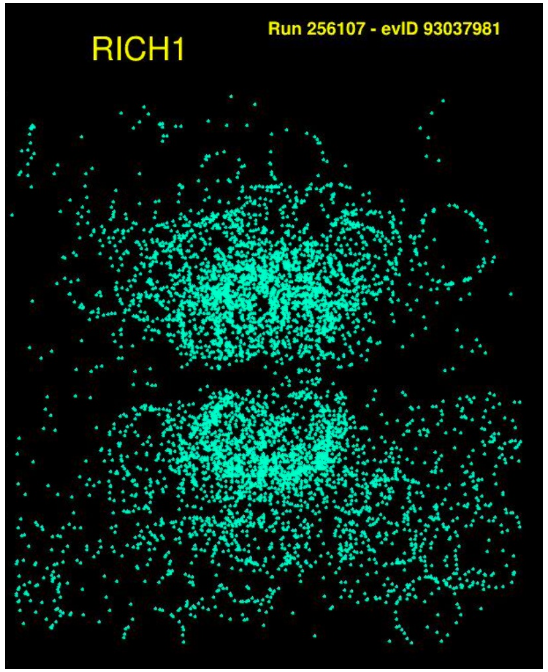


- Magnify the Cherenkov angle through a spherical mirror and measure the radius on a photon detection plane
- In practice tilted spherical mirror + flat mirror to reflect the image outside of the acceptance to not interfere with tracking/calorimetry systems and to reduce backgrounds
- Cherenkov emission + focussing optics => simultaneous time of arrival of all photons (neglecting optical aberrations and chromatic dispersion)

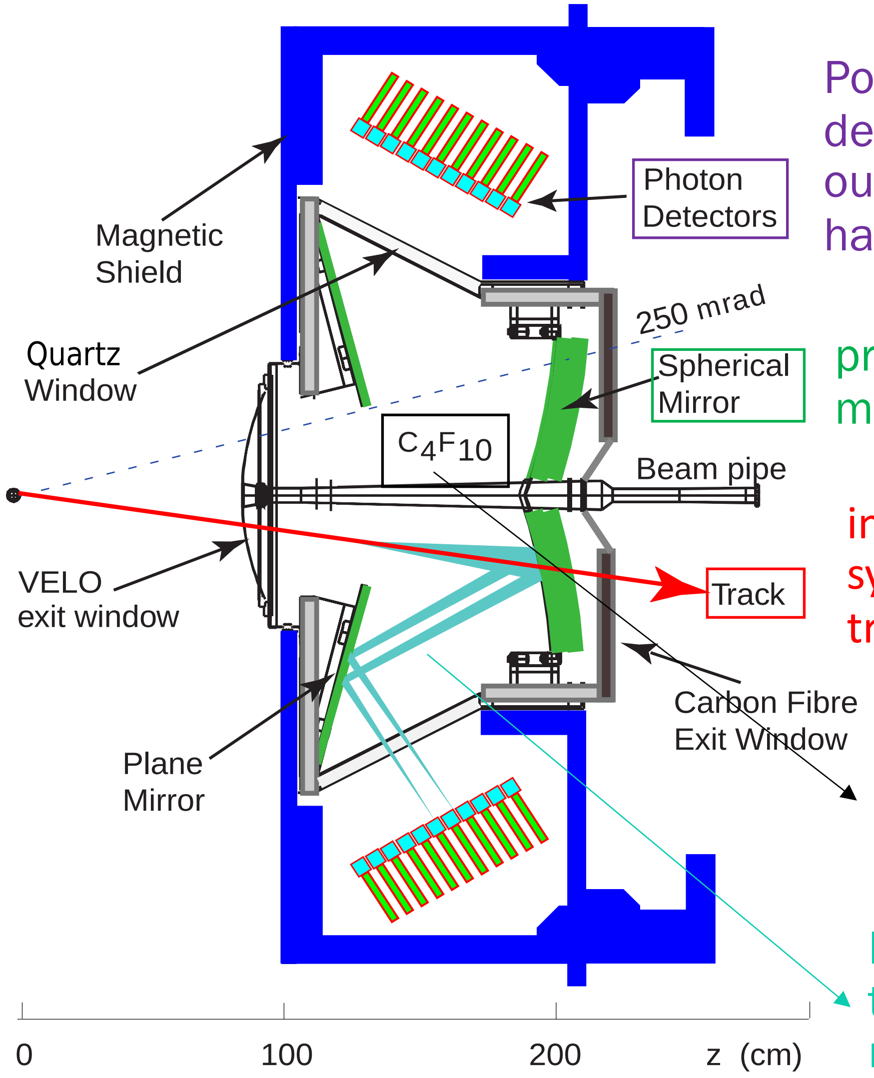
Requirements for RICH detectors

- Mass separation 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 due to the unknown emission points of the detected photons
    - Pixel size error due to the finite granularity of the photon detectors
    - Chromatic error due to the radiator dispersion and unknown photon energies
  - Detected Cherenkov photons per track N_{ph}
- Contribution from tracking system
- ~ 100 tracks per hard pp event in LHCb => build a global log-likelihood between measured hits and expected hit patterns from tracks (no direct association of hits with track)





How to get there



Position sensitive single-photon detectors and frontend electronics outside the acceptance, radiation hardness

provide focussing with minimal material budget

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

Radiator refractive index tuned to match momentum range

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

Minimise σ_c:

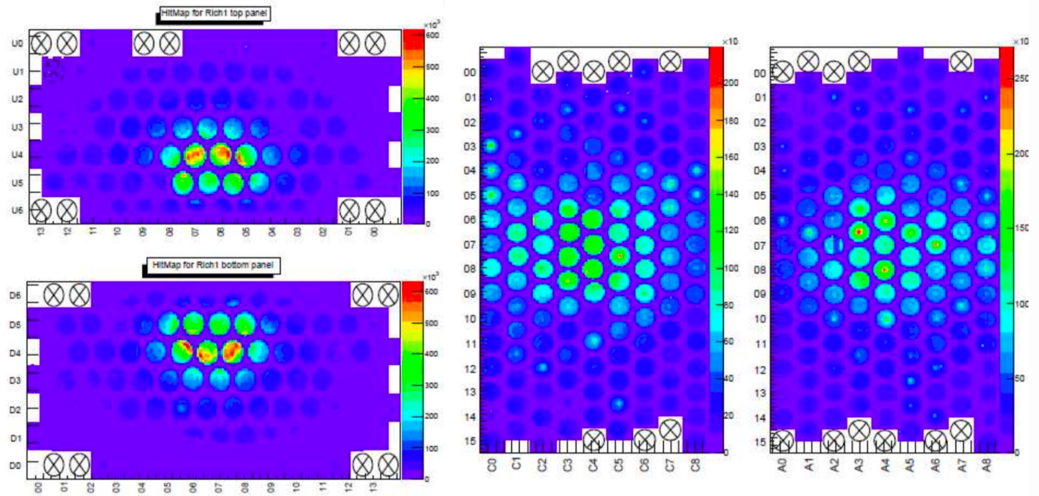
- Chromatic error: radiator dispersion $\otimes R_{mirrors} \otimes T_{quartz} \otimes$ photon detectors Quantum Efficiency (QE)
- Emission point error: optical aberrations, tilt of spherical mirrors
- Pixel size error: granularity of photon detectors, radius of curvature of spherical mirrors ($\sigma_{px} = d_{px}/\sqrt{3}R$)

Minimise C_{trk}

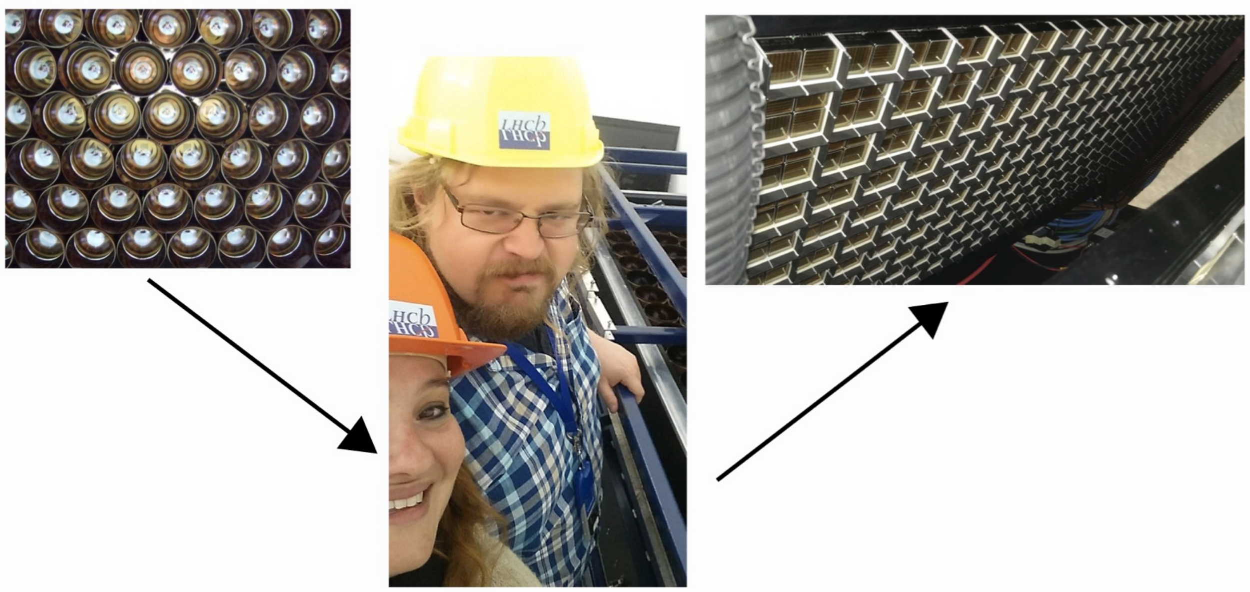
- Experiment optimisation: hit resolution, B-field knowledge, material budget

Maximise N_{ph}:

- photon detection: active area, gain, low electronics and sensors noise, large QE
- photon production: large gas volumes

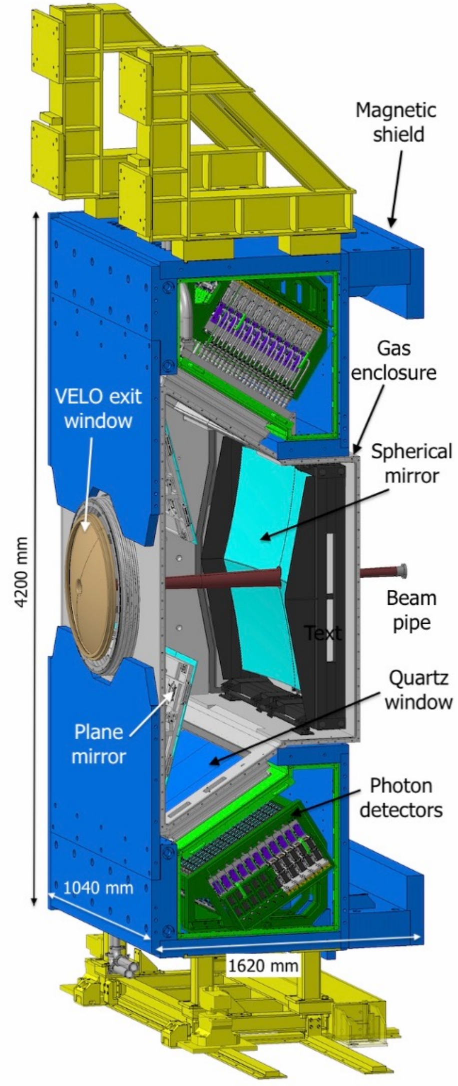


The LHCb RICH detectors and their upgrade

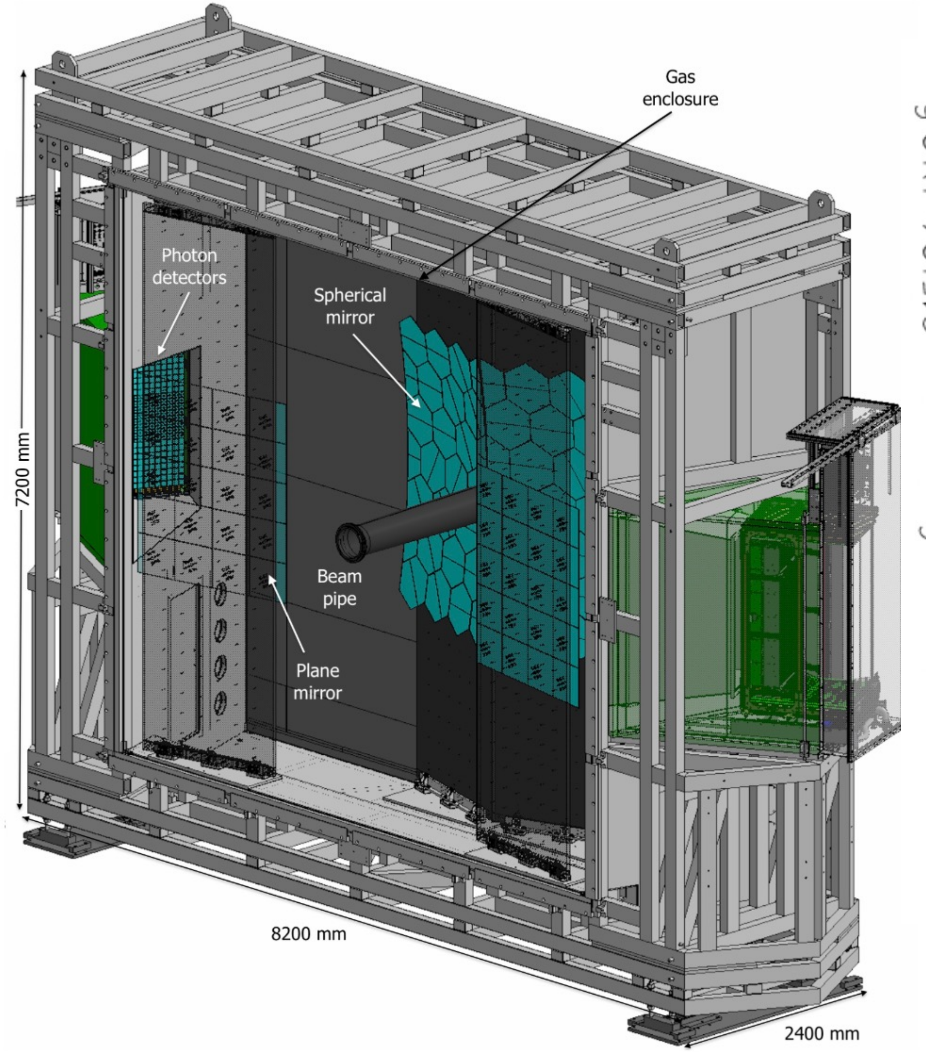


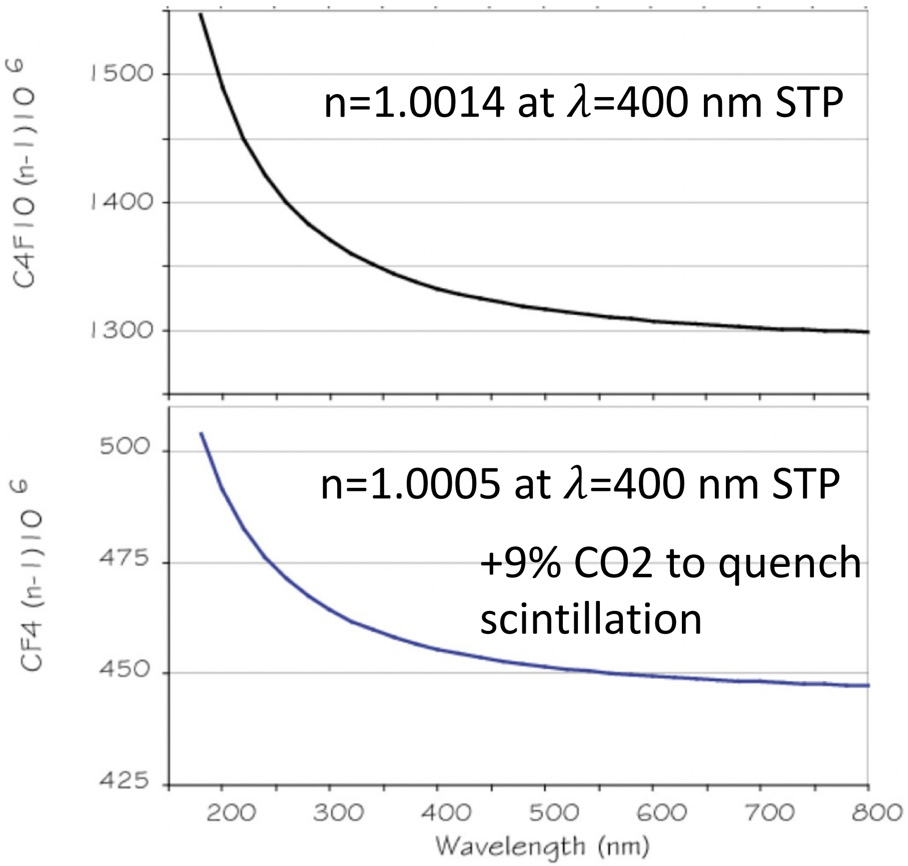
The LHCb RICH detectors

RICH1, ~ $4\ \mathrm{m}^3$, upstream, 8% X0
3-40 GeV over 25-300 mrad



RICH2, ~ $100\ \mathrm{m}^3$, downstream, 15% X0
15-100 GeV over 15-120 mrad





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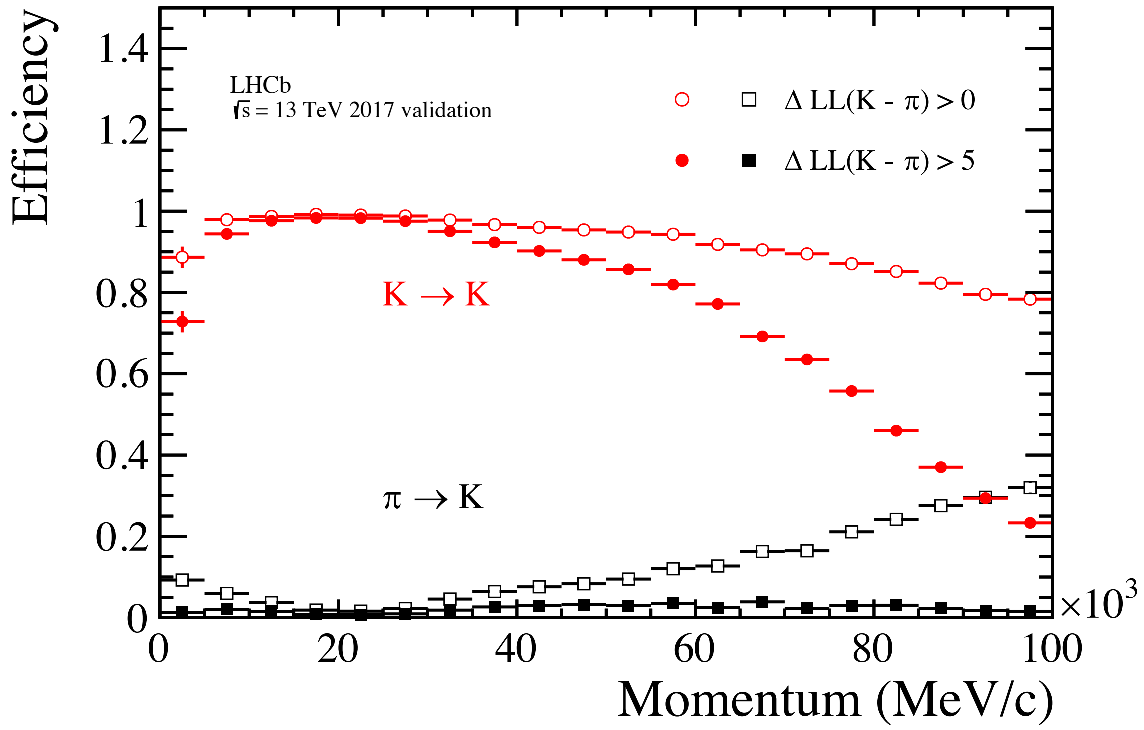
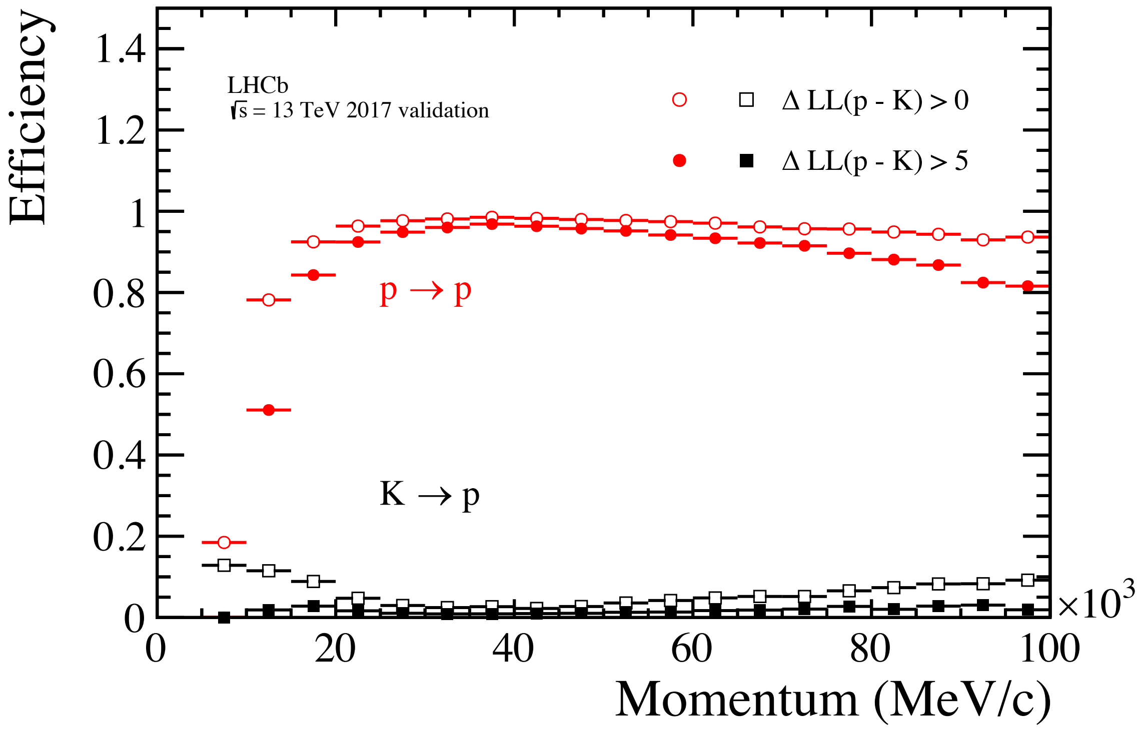
Phase-1 LHCb RICH detectors performance

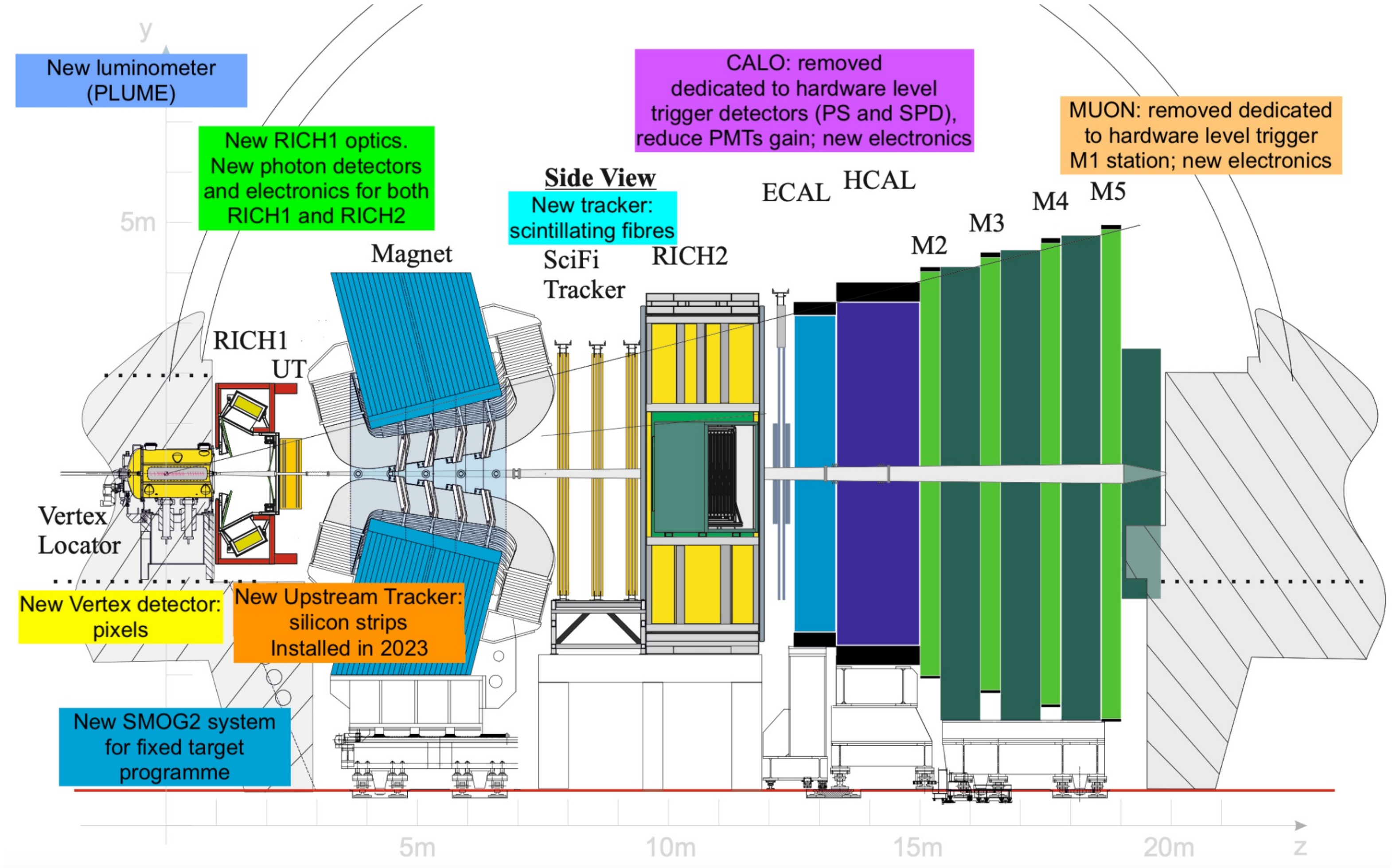
- The first generation of the LHCb RICH detectors operated in Run 1 and 2 with an excellent performance
- RICH1: $\sigma_c = 1.662 \pm 0.023$ mrad, $N_{ph} = 30 \pm 2$
- RICH2: $\sigma_c = 0.621 \pm 0.012$ mrad, $N_{ph} = 18.5 \pm 1.2$

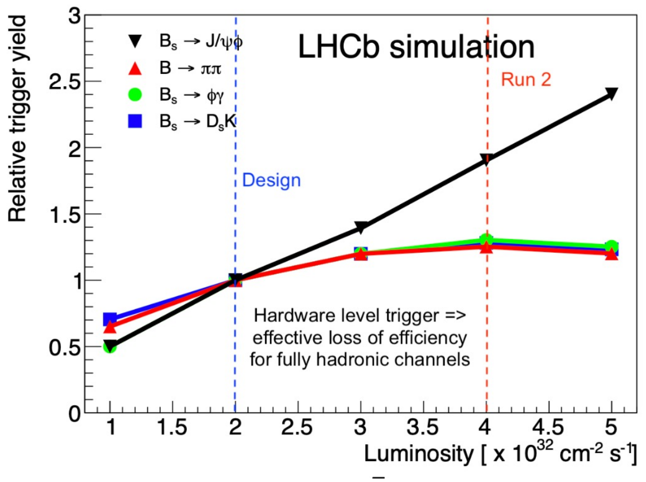
JINST 17 (2022) 07, P07013





LHCb upgrade: a new experiment



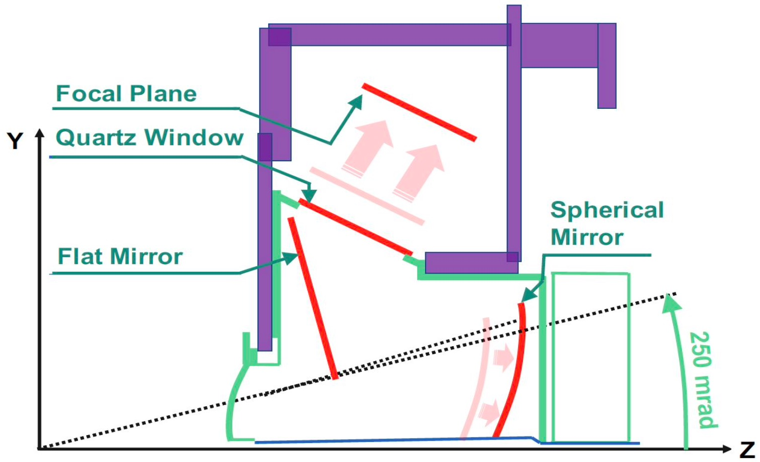


- 5x instantaneous luminosity
- $\mathcal{L} = 2 \cdot 10^{33}\text{cm}^{-2}\text{s}^{-1}$
- Removal of hardware level trigger
- **2.5 TB/s input bandwidth to a full software writing fully reconstructed objects at 10 GB/s to storage**

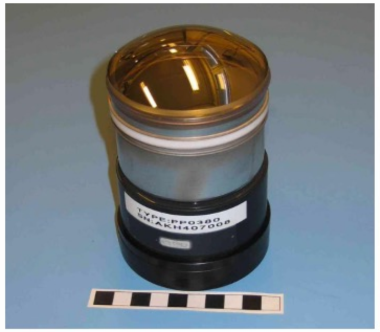
300 kHz $b\bar{b}$ and 5 MHz $c\bar{c}$ produced in the LHCb acceptance

LHCb RICH detectors upgrade concepts

- Boundary conditions for Run 3 LHCb: run with higher occupancy, using a continuous **40 MHz readout rate,** and keeping the **same subdetector envelopes**
- **New RICH1 optics and mechanics**



- Replace Hybrid Photon Detectors with embedded 1 MHz readout electronics with **new photon sensors and frontend electronics in both RICH1 and RICH2**
  - **New mechanical supports**



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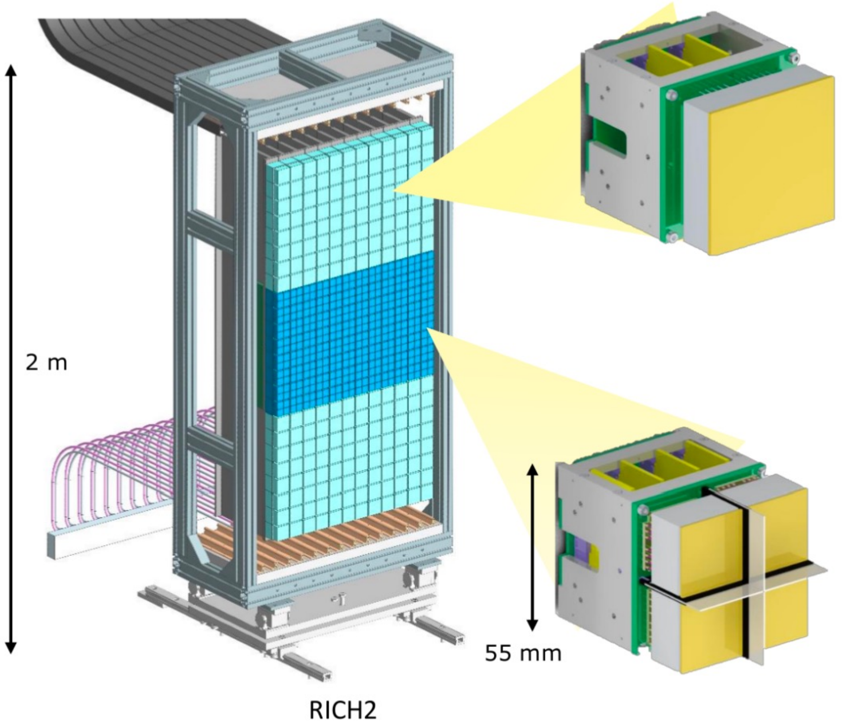
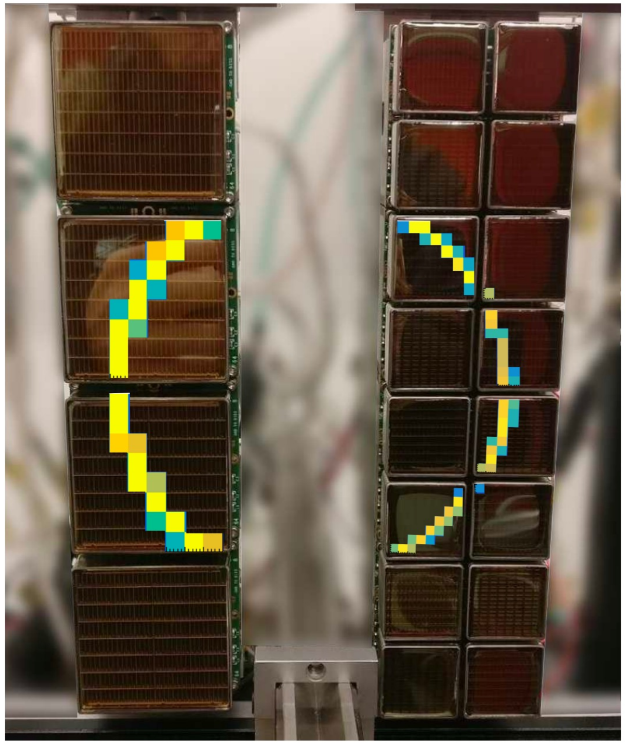
- **New digital electronics** for data transmission at 40 MHz using the GigaBit Transceiver (GBT) protocol

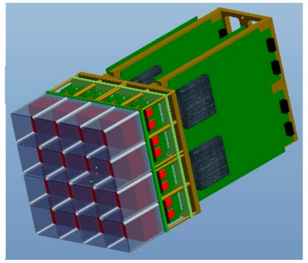




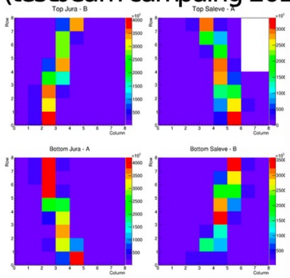
Photon detection chain prototyping and quality assurance

Timeline

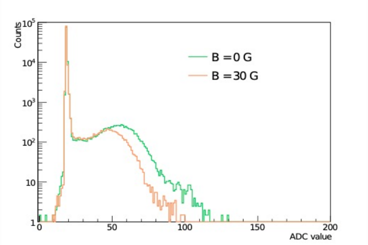
end of 2013: Technical Design Report
proposal of MaPMT module
HPD with external readout (backup)



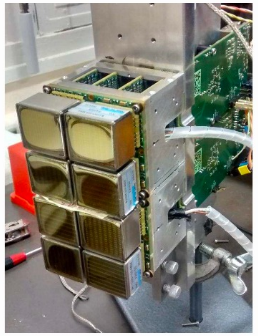
end of 2014: first concept of
Elementary Cell tested
on beam (testbeam campaing 2014-2018)



2015: full characterisation of R11265
contract with Hamamatsu:
3100 1in 450 2in



2015-2016: Elementary Cell validated
as basic unit of optoelectronics chain
Claro chip validate, Production Readiness Review

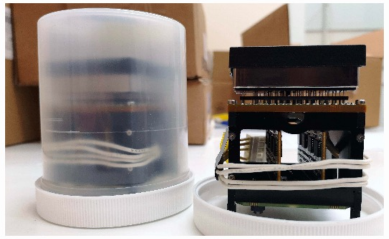


Photon Detector Quality Assurance
2016-2018
to qualify ~3500 units

2018: production of electronics componets
started, Quality Assurance
of ASIC and electronics

2018: installation of a Photon Detector Module
inside RICH2 and operation with LHCb
collisions during 2018 data taking

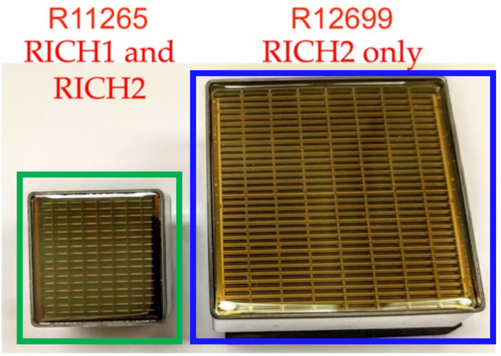
2019:Elementary Cells
QUality Assurance programme
started

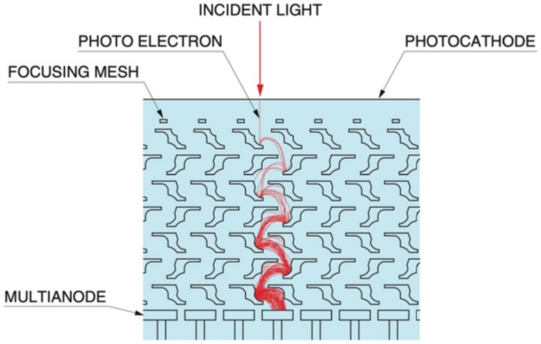


2019: column assembly and commissioning
started --> road towards installation

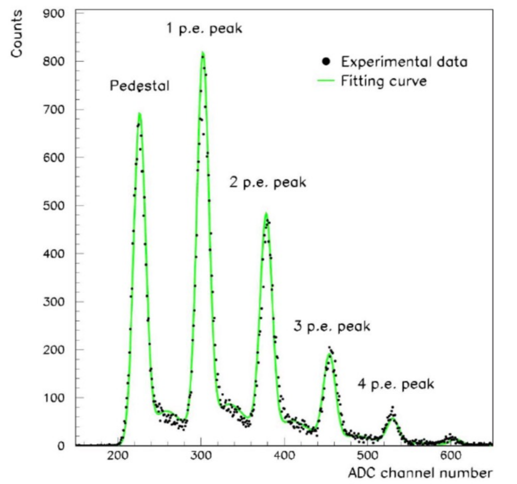
Multi-anode Photo-Multiplier Tubes (MaPMTs)

- Hamamatsu MaPMTs with 8 x 8 pixels to cope with **illumination rates up to 1 MHz/mm^2**
  - Pixel size: $3x3\ \mathrm{mm}^2$ for RICH1 and central region of RICH2, $6x6\ \mathrm{mm}^2$ in peripheral region of RICH2
  - Maximise N_{ph}: $\mathcal{O}(80\%)$ active area, gain > 10^6 and $\lesssim$ 10 Hz/mm^2 dark counts rate at 1 kV, quantum efficiency > 30% at 300 nm

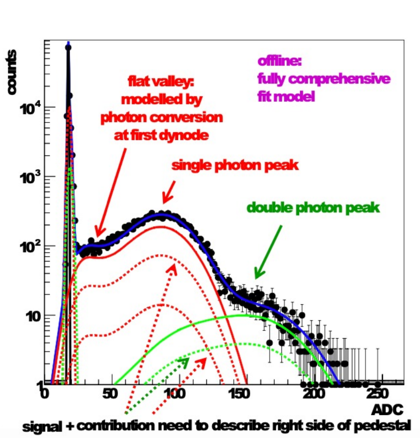




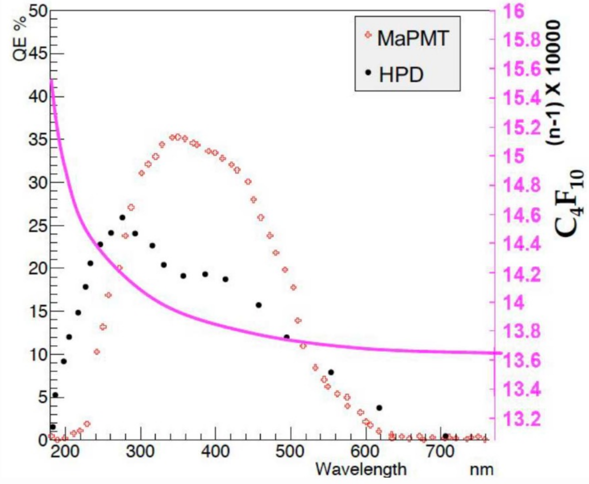
typical single photon spectrum (HPDs)



typical single photon spectrum (MaPMTs)

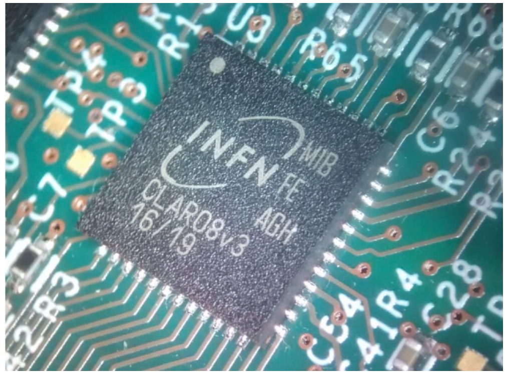


typical QEs and C_4F_{10} refractive index

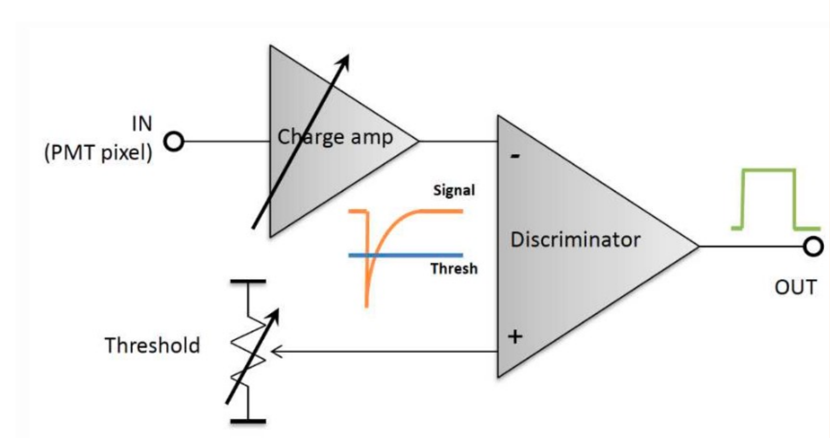


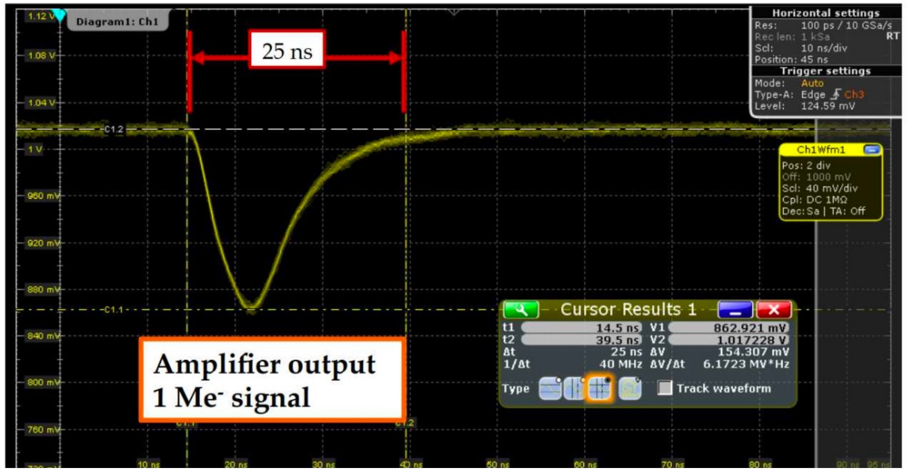
- Signal/Noise separation more critical than in HPDs: characterisation and study of performance key to correct operations
- Improve σ_c: green-shifted quantum efficiency with respect to HPDs

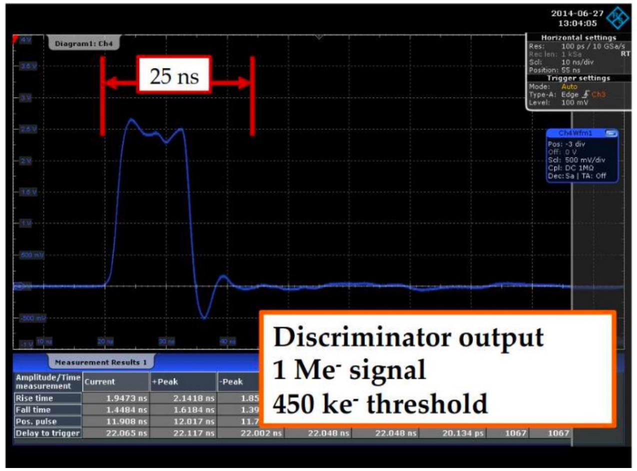
CLARO ASIC



- 8-channel amplifier+discriminator ASIC (**Ferrara**, Kracow, Milano Bicocca)
- Designed and optimised for single-photon counting coupled to MaPMTs
- 0.35 μm CMOS technology from AMS
- 40 MHz operations (recovery time < 25 ns)
- Low-power consumption (~ 1 mW/channel)
- Adjustable threshold and gain (6+2 bits) to compensate for MaPMT gain variation
- Binary readout
- Radiation-hard by design cells and triple-module-redundancy (TMR) protecting 128 bits configuration register







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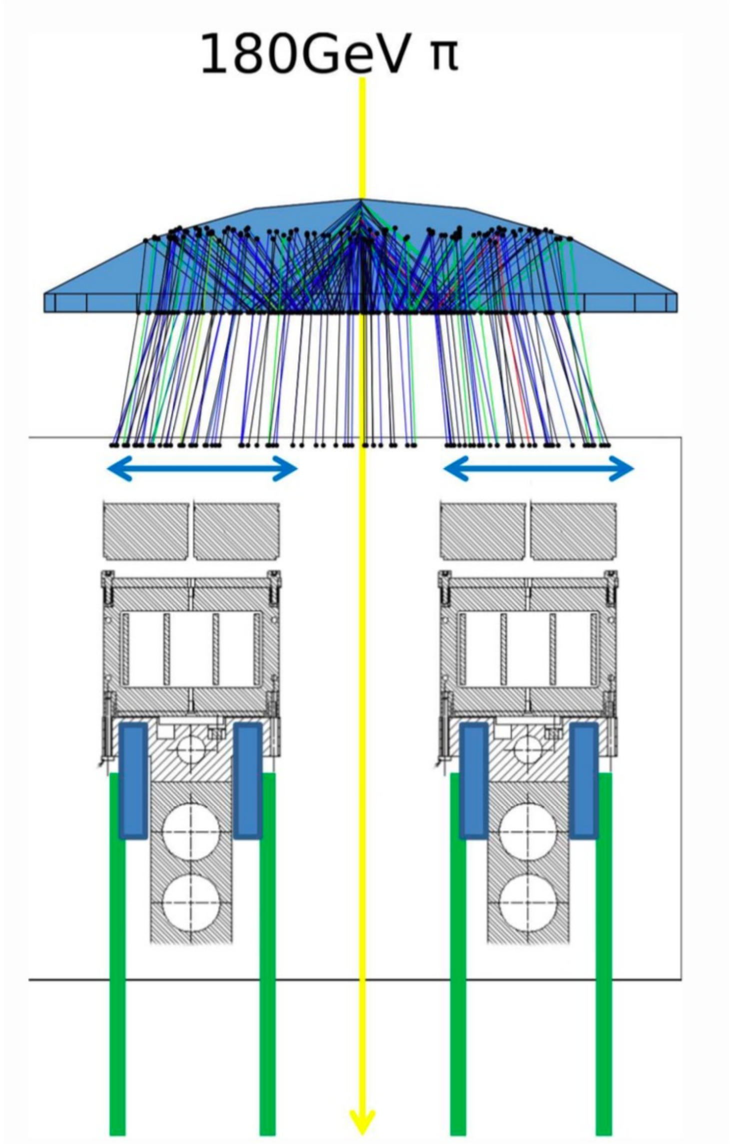
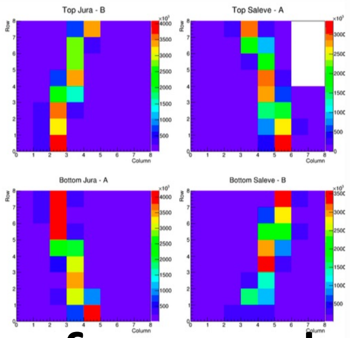
Testbeam campaigns



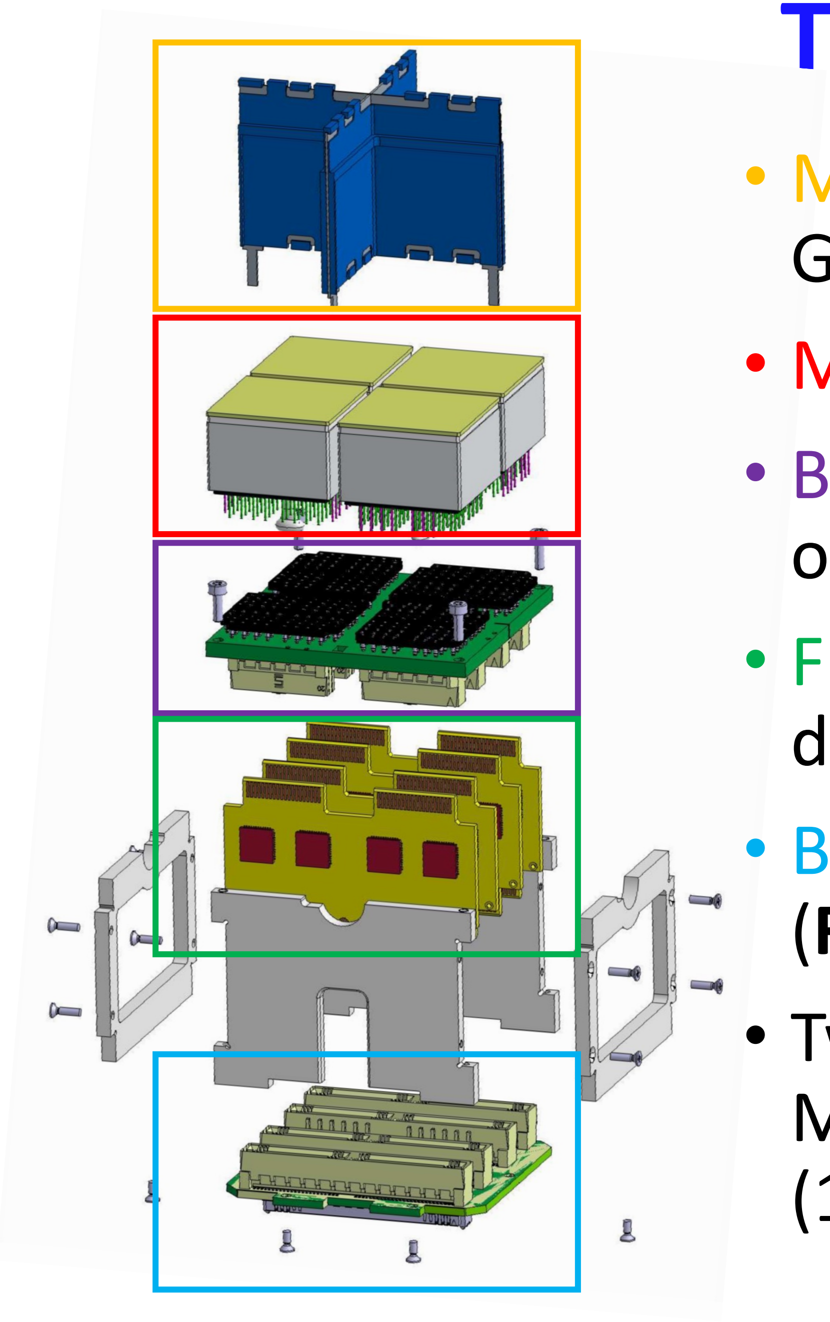
- First tests on a particle beam (mainly 180 GeV pions) in 2014 in the North Area of the Prevessin site at CERN
- Plano-convex lens used as radiator and focussing object: operability and photon-yield determination one of the main objectives of testbeams



	Data		Simulation		Analytical estimate
	mean	RMS	mean	RMS	mean
Total	13.4	3.8	13.1	2.9	-
PMT A	3.6	1.7	3.1	1.5	3.8
PMT B	3.3	1.6	3.1	1.5	4.1
PMT C	4.4	1.9	3.3	1.5	3.9
PMT D	4.2	1.8	3.3	1.5	4.1

- Validation of opto-electronics chain prototypes prior to production, inputs for modifications and design of modular unit: the elementary cell
- Continue testbeam campaigns up to 2018

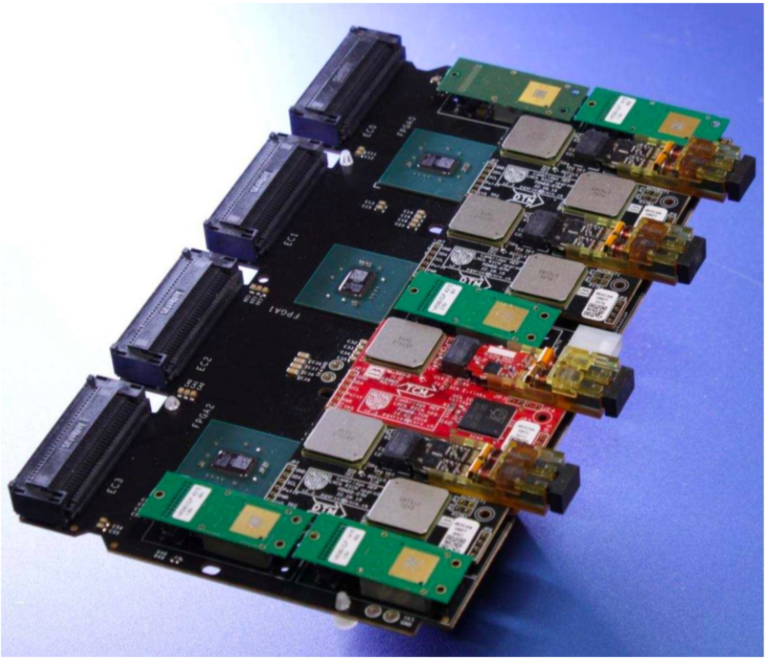
The Elementary Cell



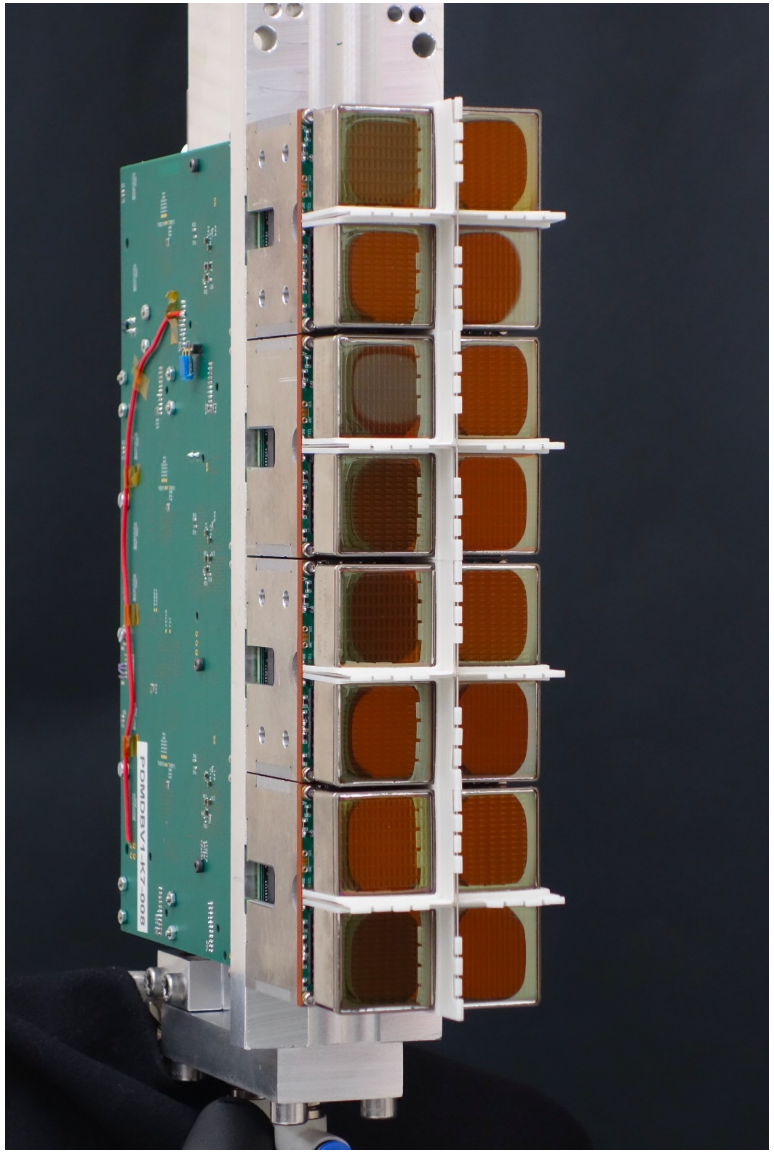
- Magnetic shield used in RICH1 (magnetic field of < 30 G): maintain photon counting efficiency in edge pixels
- MaPMTs
- Baseboard: host voltage divider, routing of analog output (Genova)
- Frontend board (FEB): host CLARO ASIC, routing of digitised signal (**Ferrara**)
- Backboard: routing of digitised output to the readout (**Ferrara**)
- Two types of Elementary Cells: EC-R (4 R11265 MaPMTs) in RICH1 and central part of RICH2, and EC-H (1 R12699 MaPMT) in peripheral region of RICH2

Photon Detector Module

- Flexible FPGA-based digital board (**PDMDB**): pack CLARO outputs, synchronise to LHC clock, transmit data to the LHCb common readout boards (Cambridge)
- Two flavours: one PDMDB-R serving 4 half EC-R, one PDMDB-H serving 4 EC-H

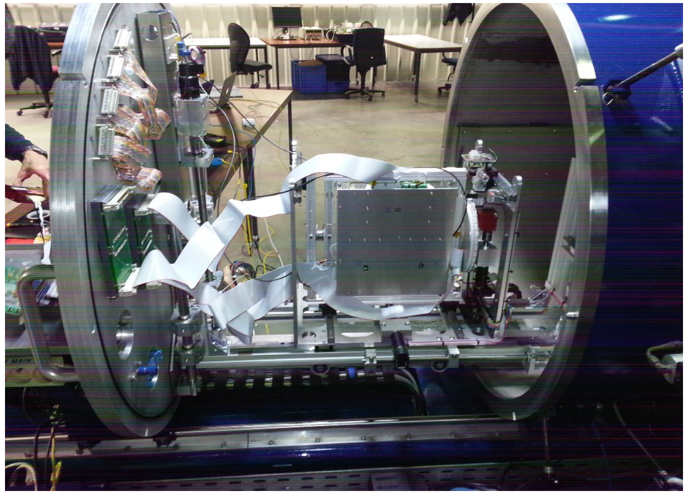


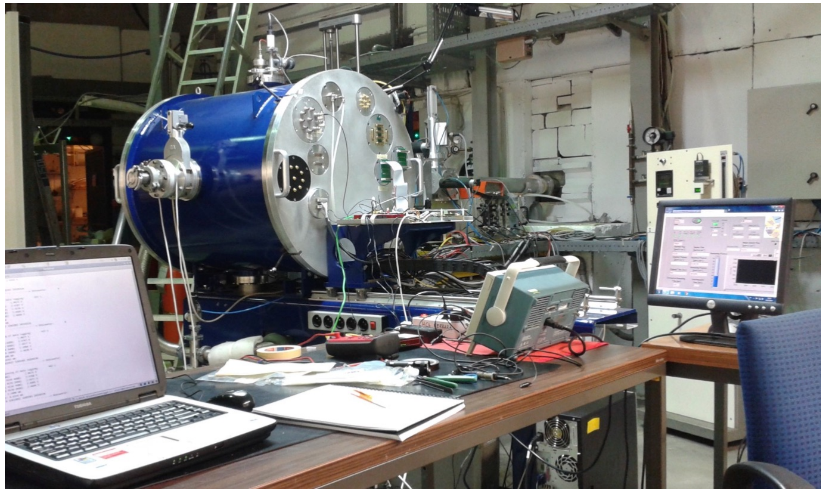
- ECs + PDMDB form an independent unit called **Photon Detector Module** (PDM) sharing common LV and HV distribution

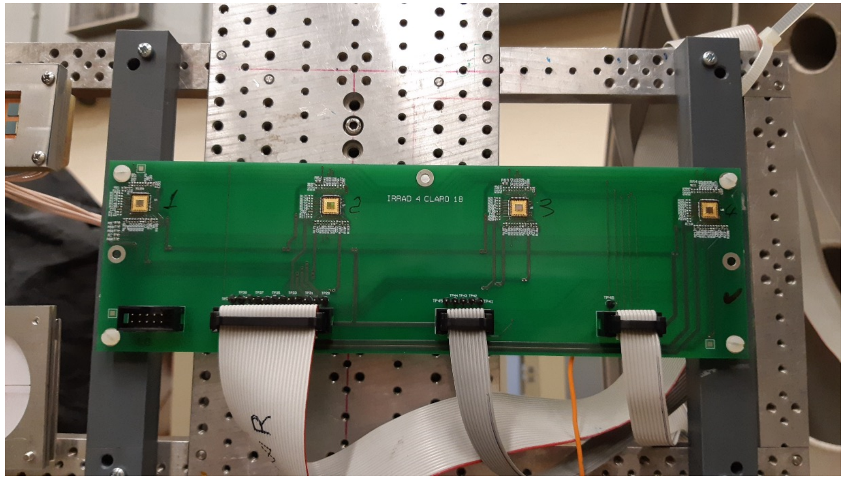


Irradiation campaigns

- Radiation levels: 200 krad Total Ionising Dose, $3 \cdot 10^{12}$ 1 MeV n_{eq}/cm^2 fluence
- Irradiation campaigns on MaPMTs and frontend electronics (**Ferrara**)
  - Selection of MaPMT window (UV glass vs borosilicate), inputs to modifications of existing prototypes (e.g. TMR protection added in CLARO configuration register)
- Irradiation campaigns on PDMDBs (Bucharest)
  - Assess impact of radiation on Kintex-7 FPGAs, incorporate protections in firmwares and auto-reconfigurations in control software

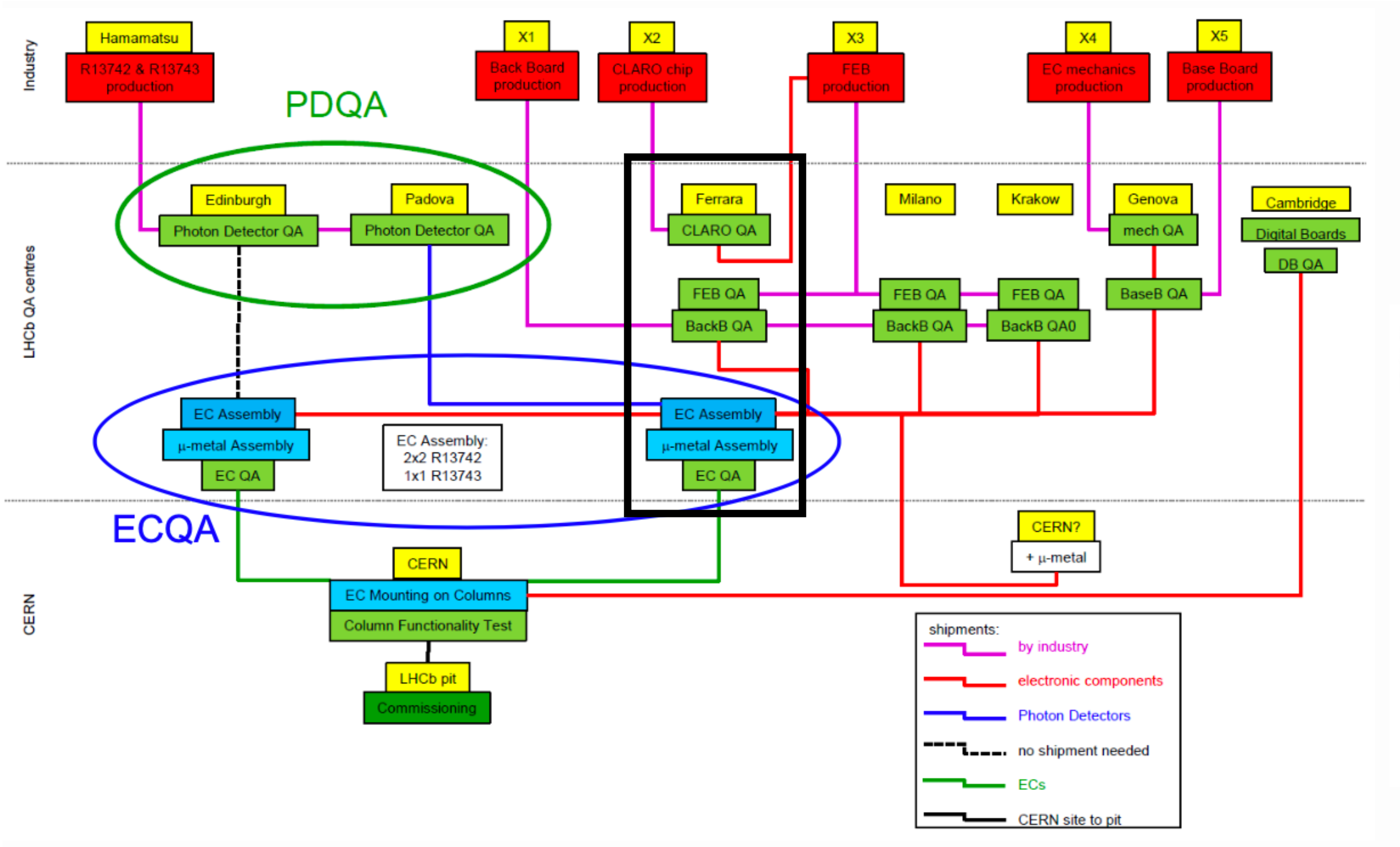






Quality assurance programmes

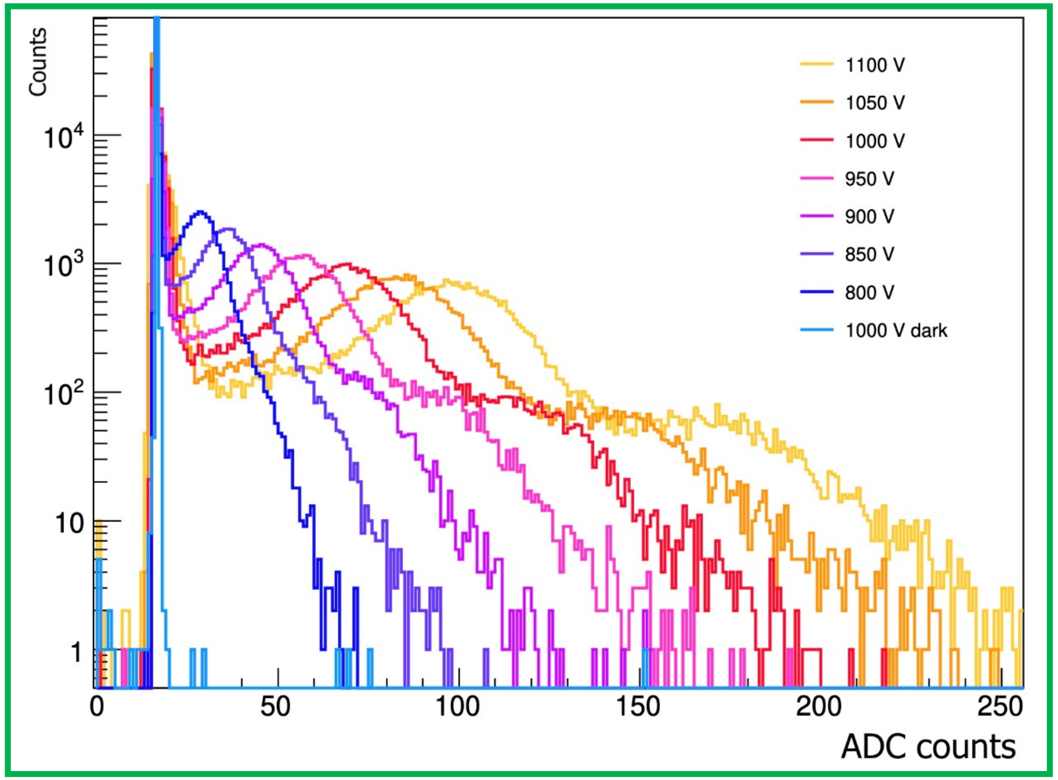
- Distributed programme of production of components, quality assurance (QA) campaigns across Europe, first calibrations, to converge for final assembling and commissioning at CERN



INFN

Photon detectors quality assurance

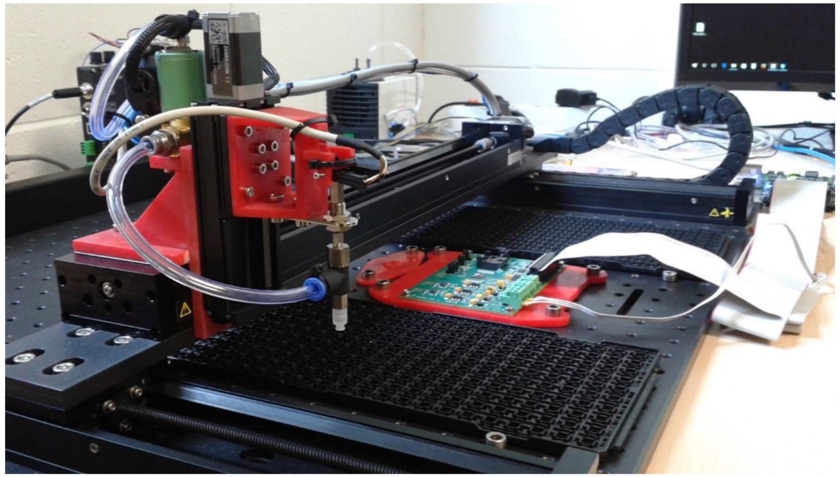
- Verify minimal contractual specifications for **3500 units** (Edinburgh, Padova)
- Gain per pixel determined at 1000 V -> 800 V in 50 V steps
- 1.5 M spectra fitted and data stored in a dedicated database
- Low rejection rate: 2.1% R13742 and 8.2% R13743

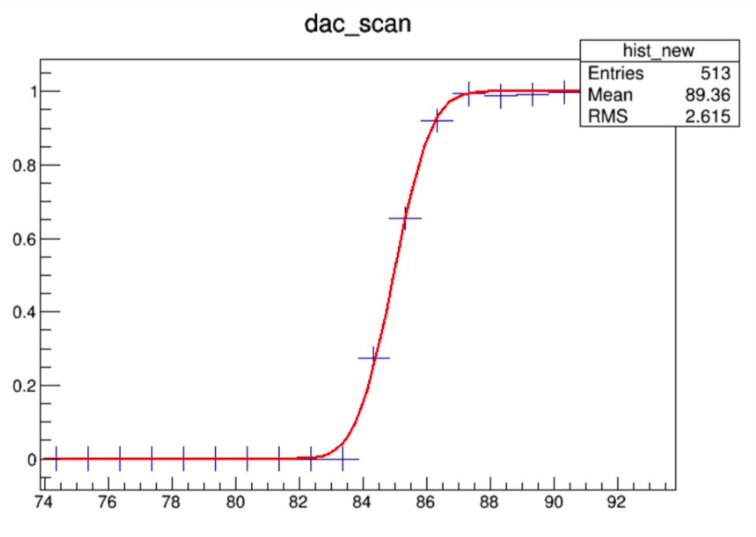


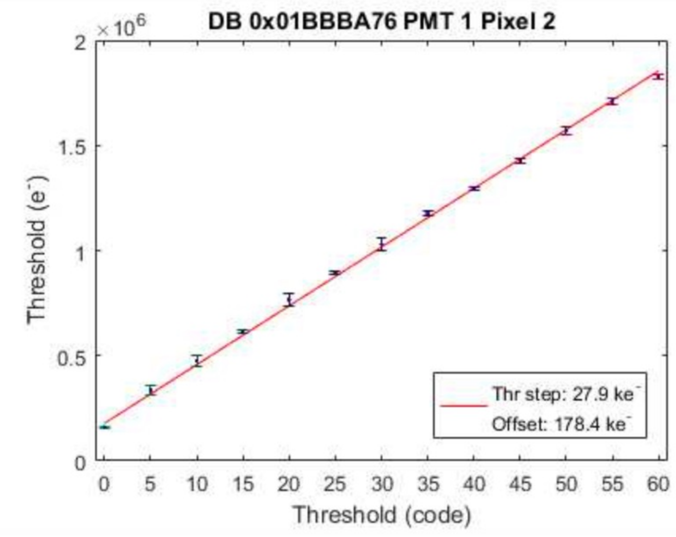
	R11265 (R13742)	R12699 (R13743)
size [mm^2]	26.2×26.2	52×52
pixel size [mm^2]	2.88×2.88	6×6
number of devices	2656	384
active area	77%	87%
average gain @ 1 kV	> 1 Me	
gain uniformity	1:4	1:3
peak/valley (P/V) ratio @ 1 kV	no more than 3 pixels with P/V< 1.3	
dark-count rate @ 1 kV	< 2.5 kHz/cm^2	
quantum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

CLARO, FEB and Backboard quality assurance

- Quality assurance for 4100 FEBs, 35k CLARO, 1250 Backboards + spares (**Ferrara**)

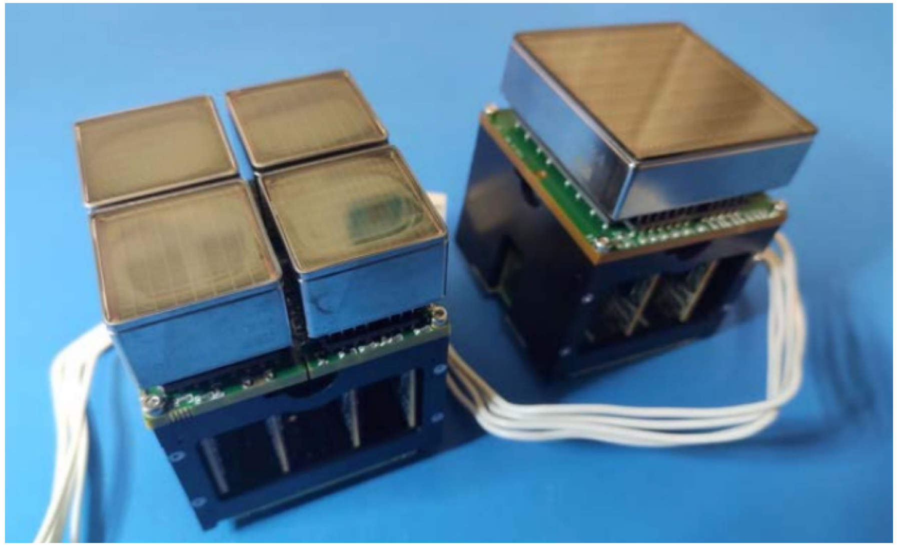


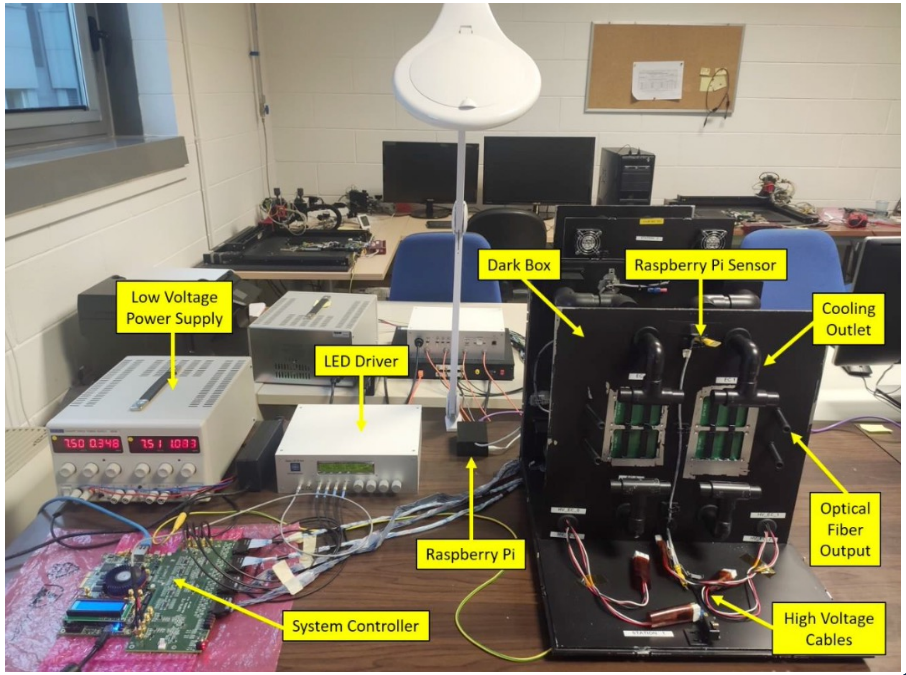




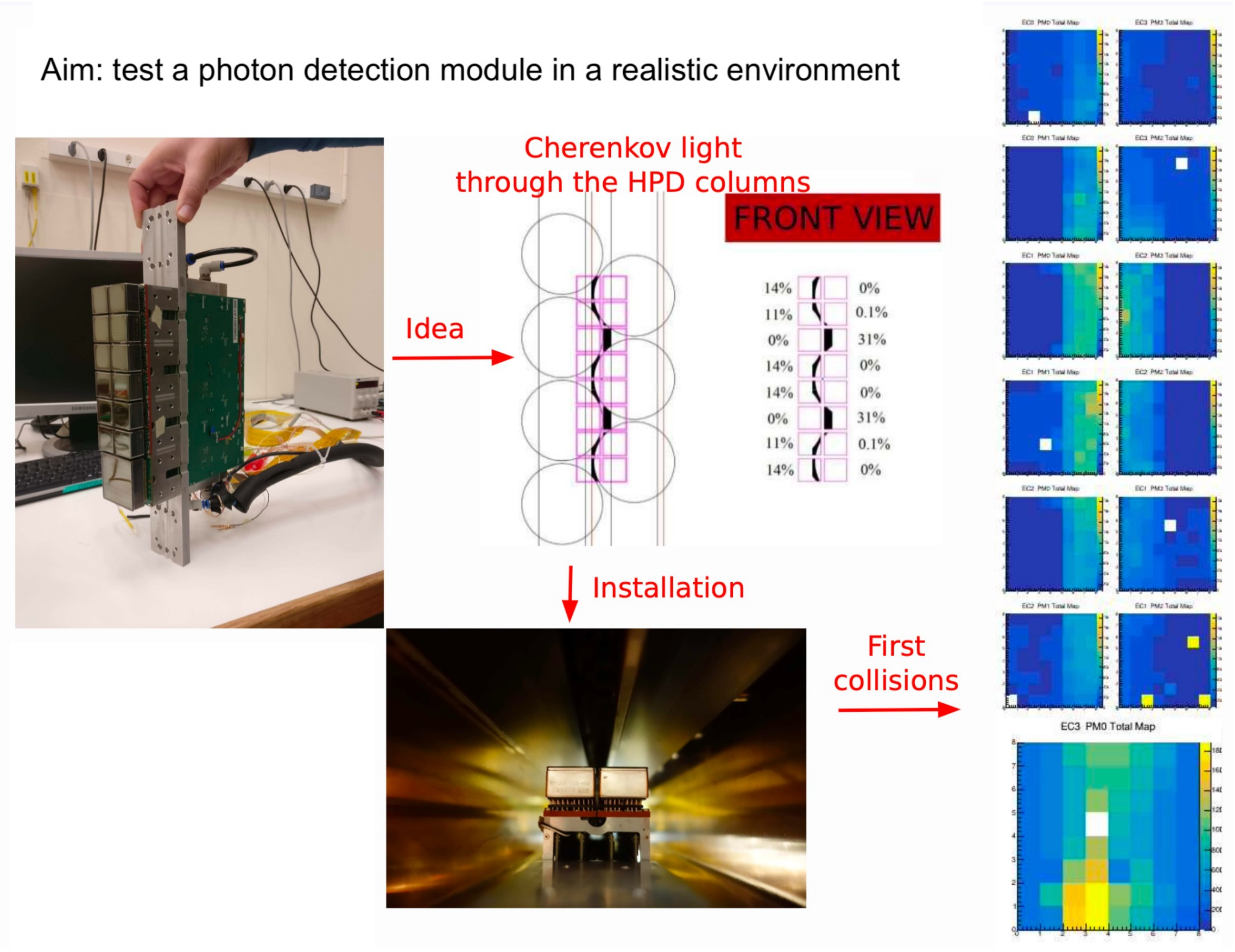
Elementary Cell quality assurance

- 1-inch MaPMTs grouped by gain and assembled in **800 EC-R**
- 2-inch MaPMTs assembled on **450 EC-H**
- One EC unit completed by Baseboard, FEBs and Backboard
- Verify basic functionality, calibration of CLARO channels, characterisation of MaPMTs at different HV values (Edinburgh, **Ferrara**)
- QA programme tuned to fully characterise an unexpected source of noise inside MaPMTs observed while operating a module in the LHCb experiment in 2018

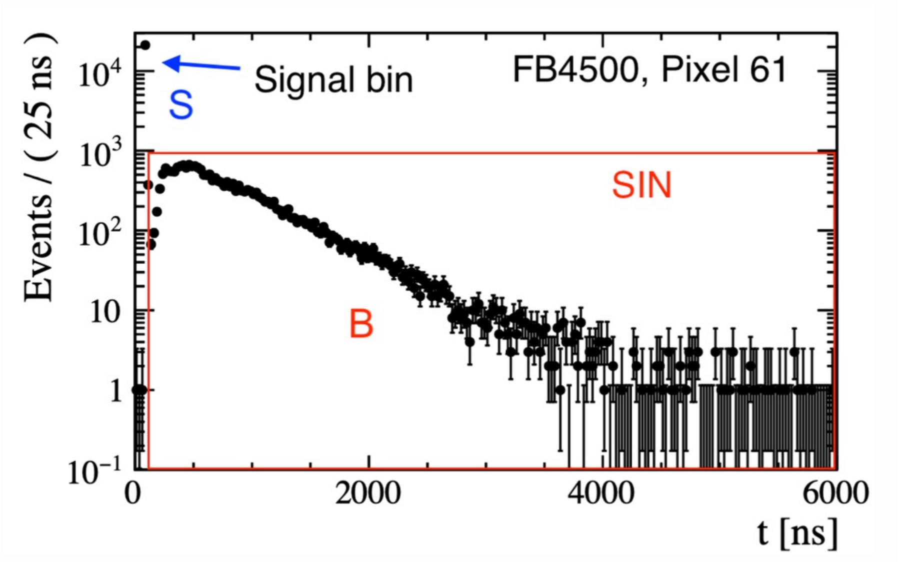




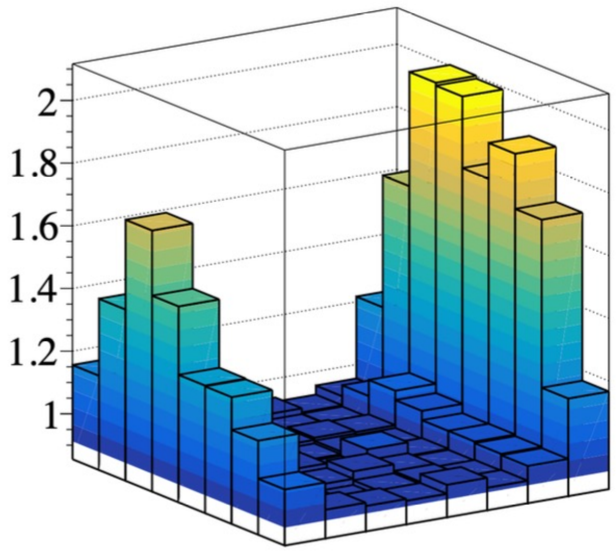
Operations of a module inside LHCb in 2018



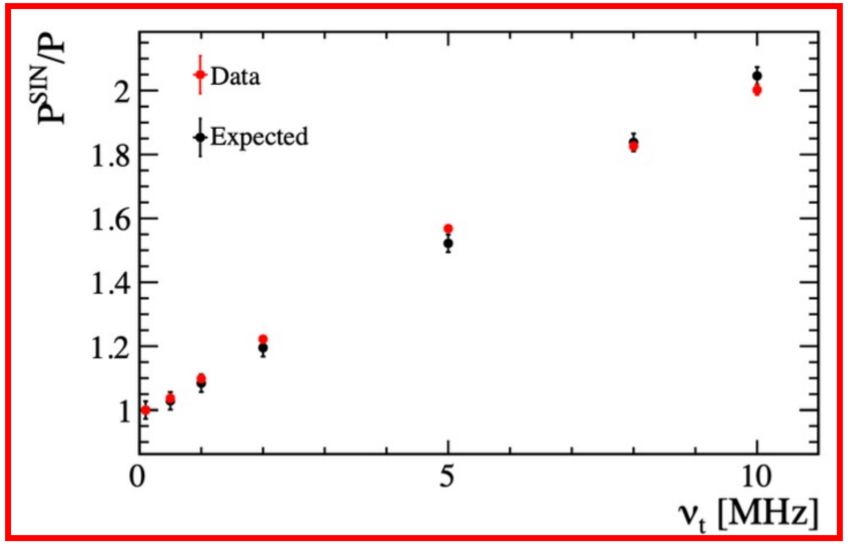
- Detection of out-of-time hits lasting up to few μs, confirmed with laboratory tests
- Located in specific border pixels with absolute values varying unit by unit

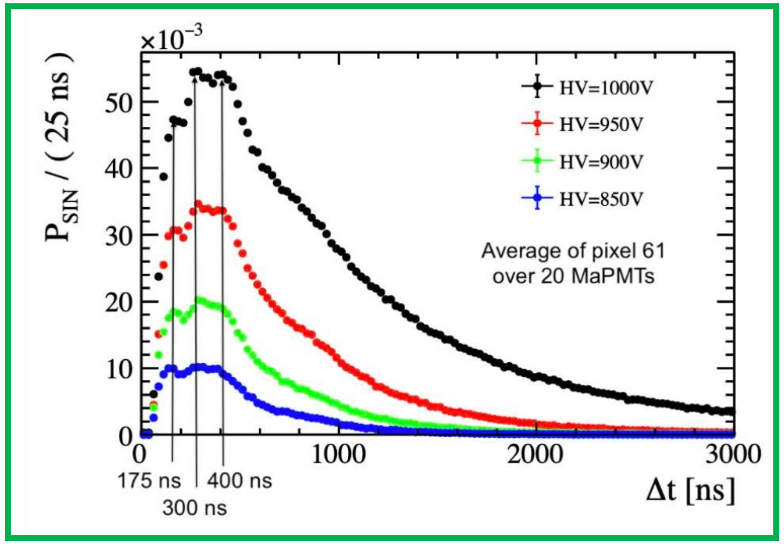


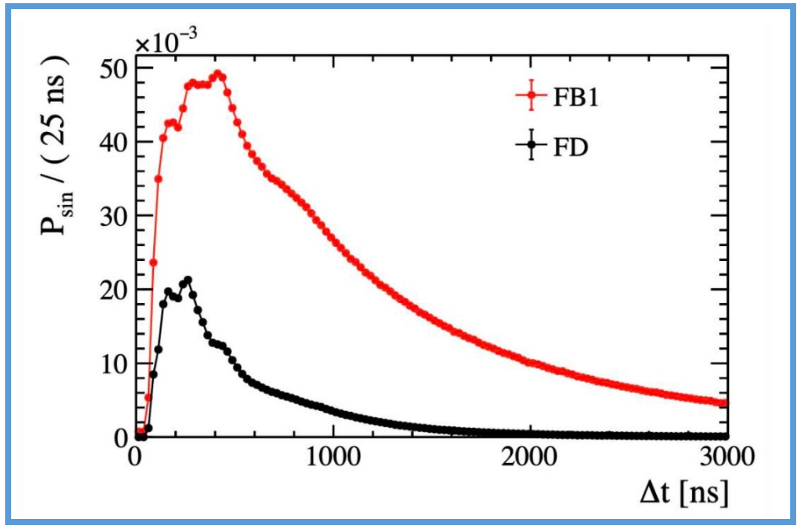
Signal-Induced Noise (SIN)



- Signal correlated => sizeable pile-up expected in high occupancy channels
- Strong dependence on the applied HV
- Fully characterised thanks to the ECQA programme: mechanism consistent with internal light emission and fluorescence decay [JINST 16 (2021) P11030]
- Mechanical fix introduced by Hamamatsu in a new sub-set of units



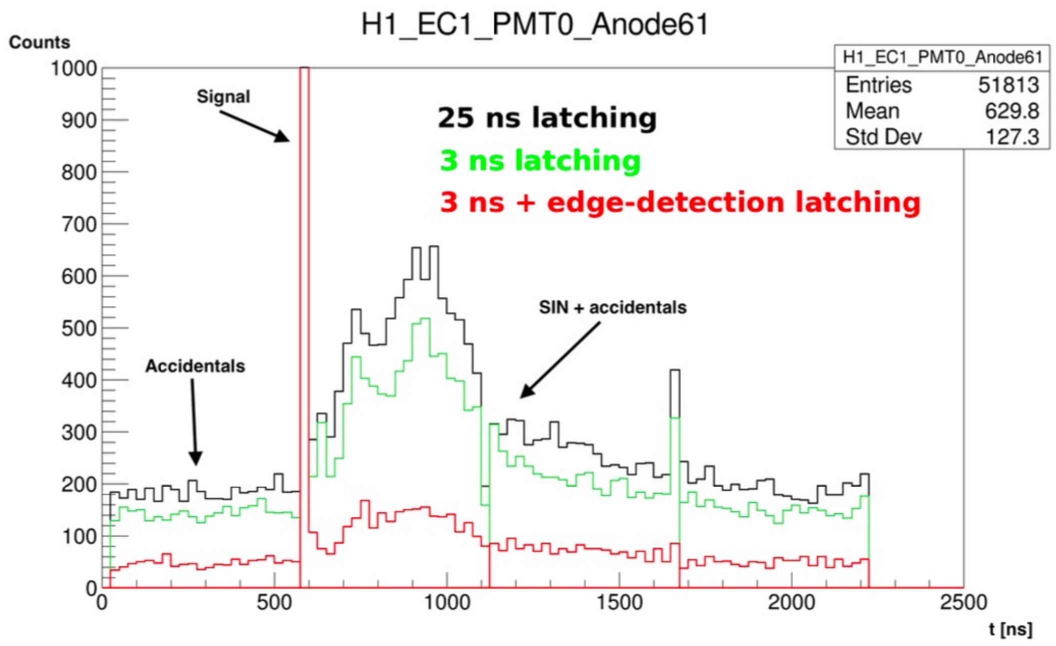


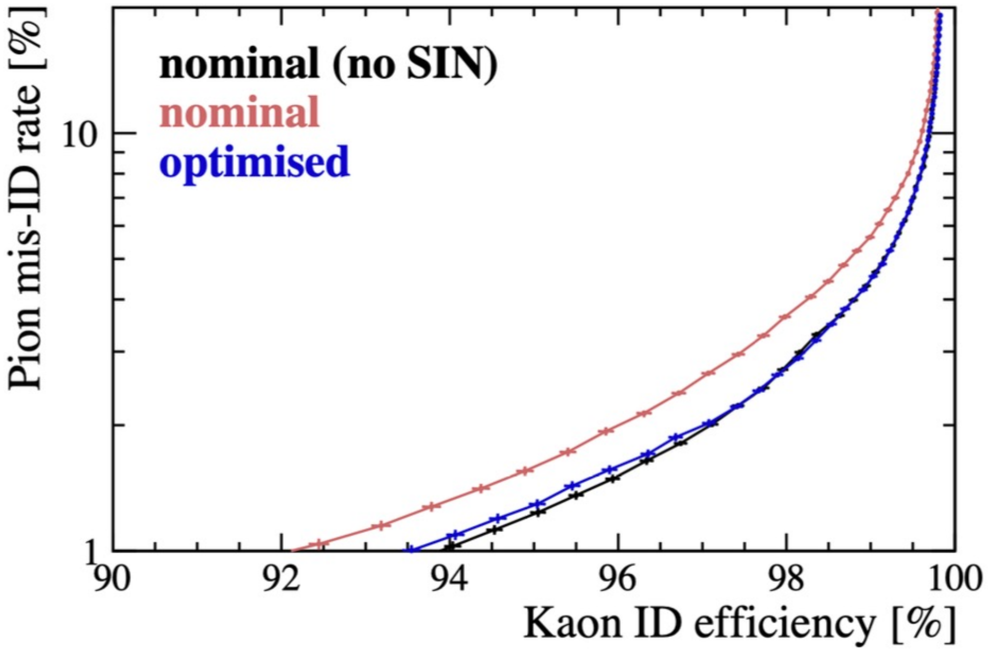


INFN

Implementation of timing

- An additional way to mitigate SIN (and in general non-Cherenkov signals) is the introduction of timing capabilities in the frontend electronics
- Implemented in last testbeam in 2018
- Simulations confirmed the recovery of the PID performance after the application of mitigation strategies (HV tuning, selection of new SIN-suppressed MaPMTs for the high occupancy regions, timing)

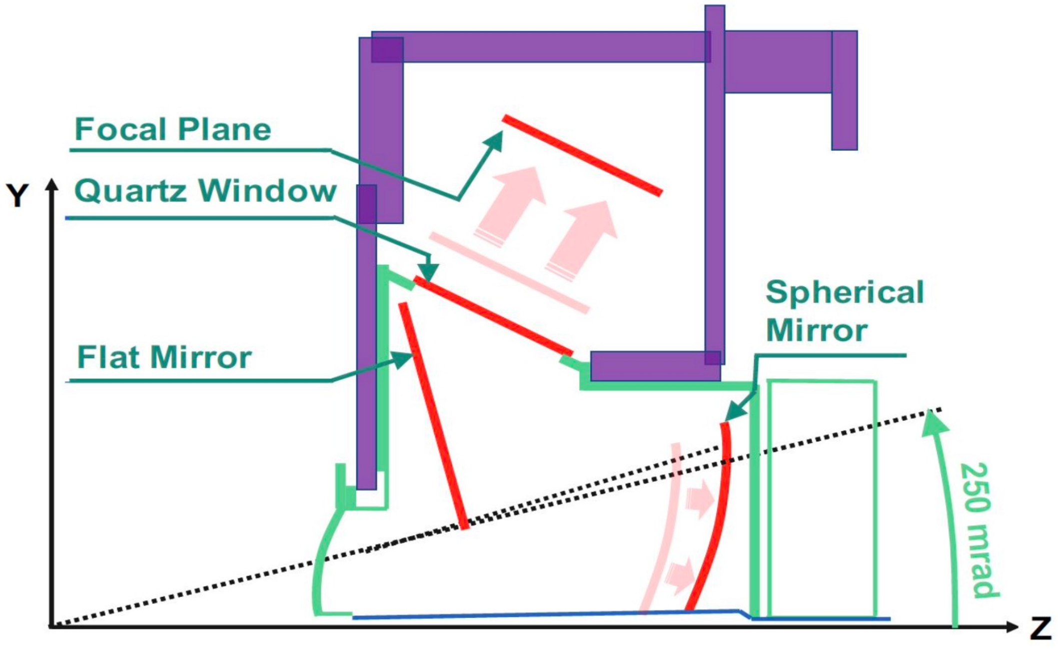




Optics and mechanics

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 pattern recognition (based on Run 1 and 2 experience)

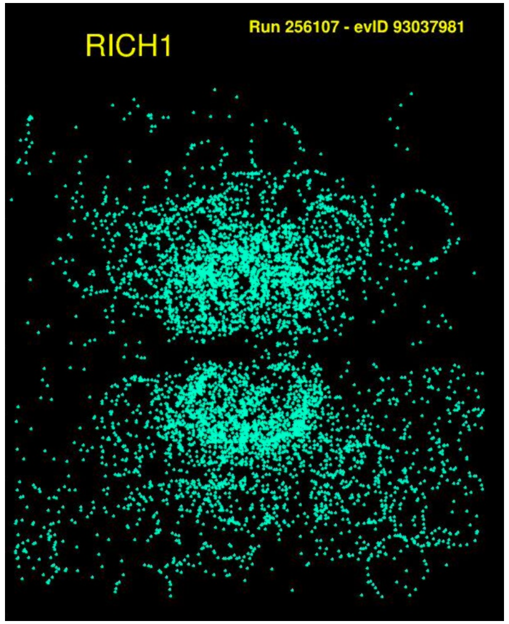


Increase radius of curvature R of spherical mirrors by a factor ~ √2, reduce tilt and move the focal plane further outside the acceptance

⇒**peak occupancy halved**

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

⇒**reduced** σ_{ep}



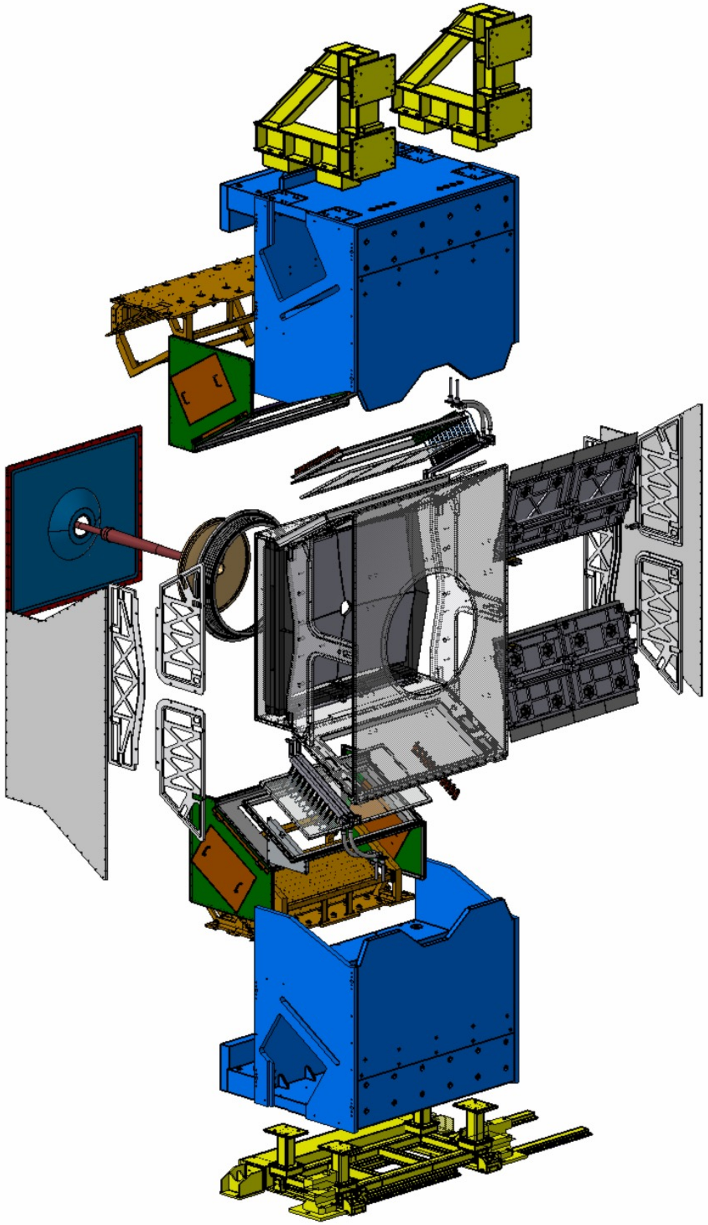
Extend radiator volume in z by ~ 100 mm => +14% Cherenkov photons per track

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

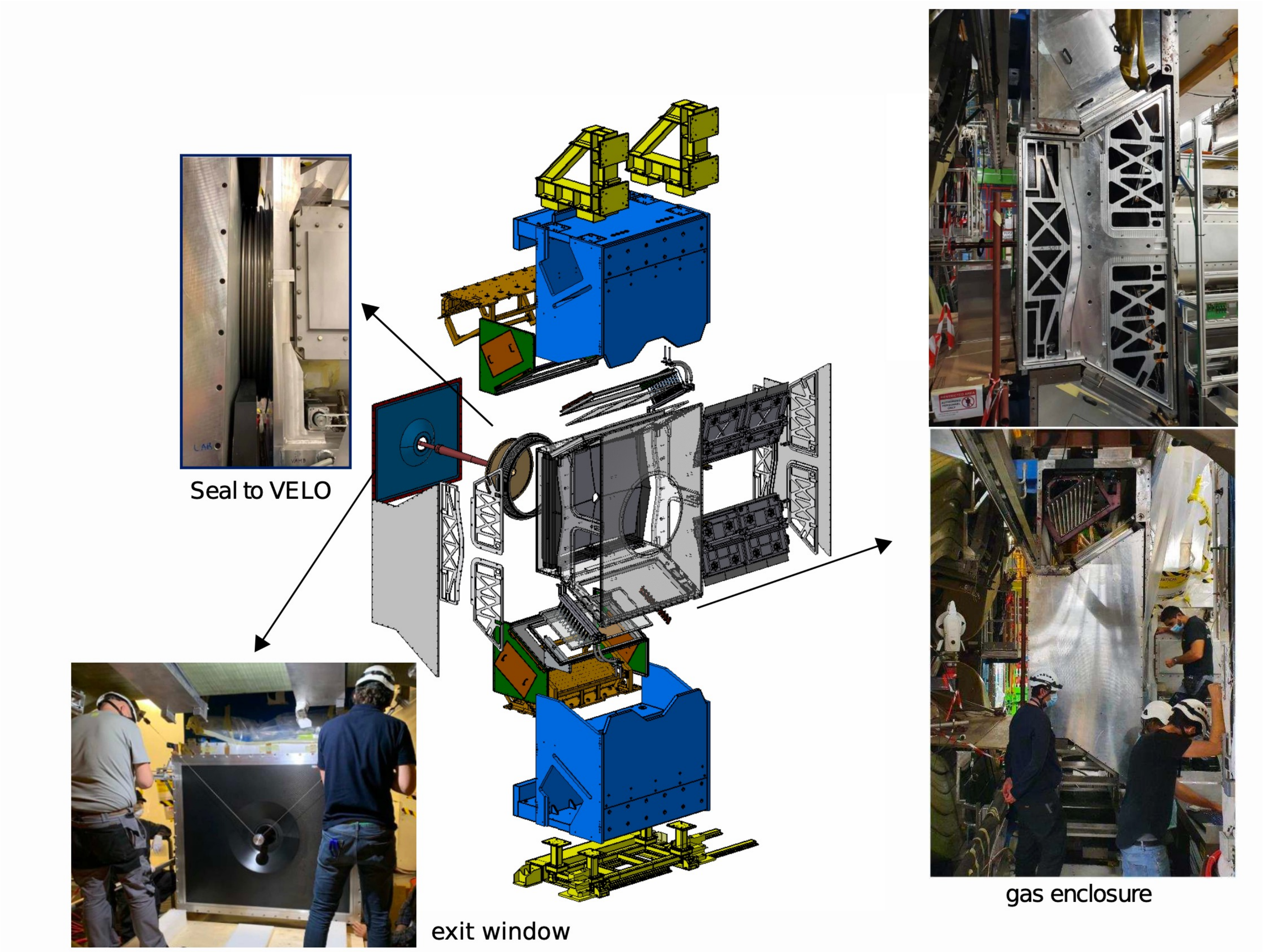
~ 9.6, 9.2 and 7.8 cm for pions, kaons and protons, respectively (but not exactly rings!)

A brand new RICH1

- New and larger gas enclosure (Oxford)
- New quartz windows separating the gas enclosure from the MaPMT enclosure above and below the beam-pipe (Oxford, CERN)
- RICH1 seal to VELO on the upstream side
- New carbon fibre exit window sealing the gas enclosure downstream (RAL)
- New 16 glass flat mirrors (Bristol, CERN)
- New 4 sherical carbon-fibre mirrors (Bristol, CERN)
- New MaPMT enclosure equipped to host opto-electronics chain mounted on columns (Imperial, Oxford)
- New tooling for installation and maintenance
- Material budget ~ halved: 4.8% X0
- **RICH1 mechanics installed between 2020 and 2021**

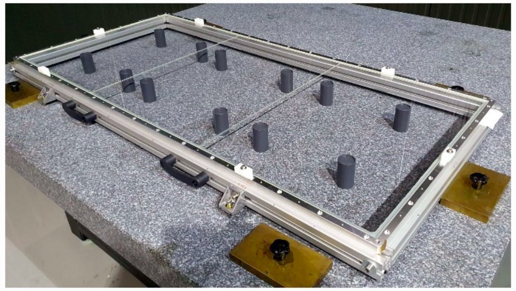


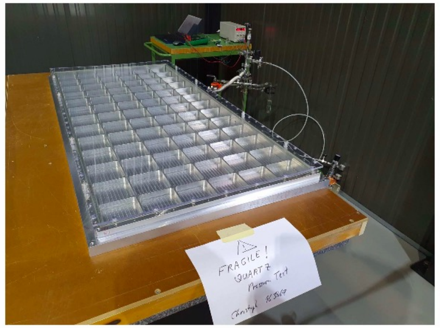
RICH1 mechanics installation

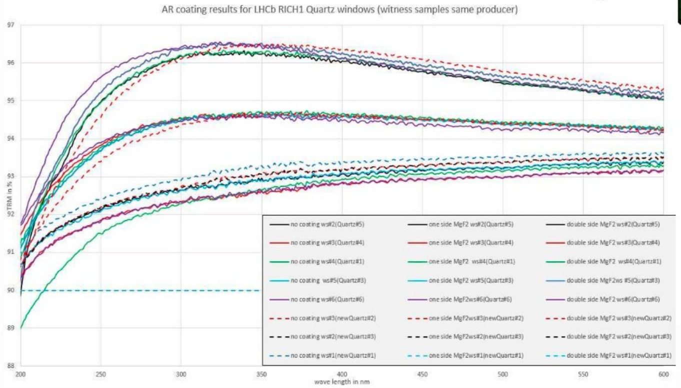


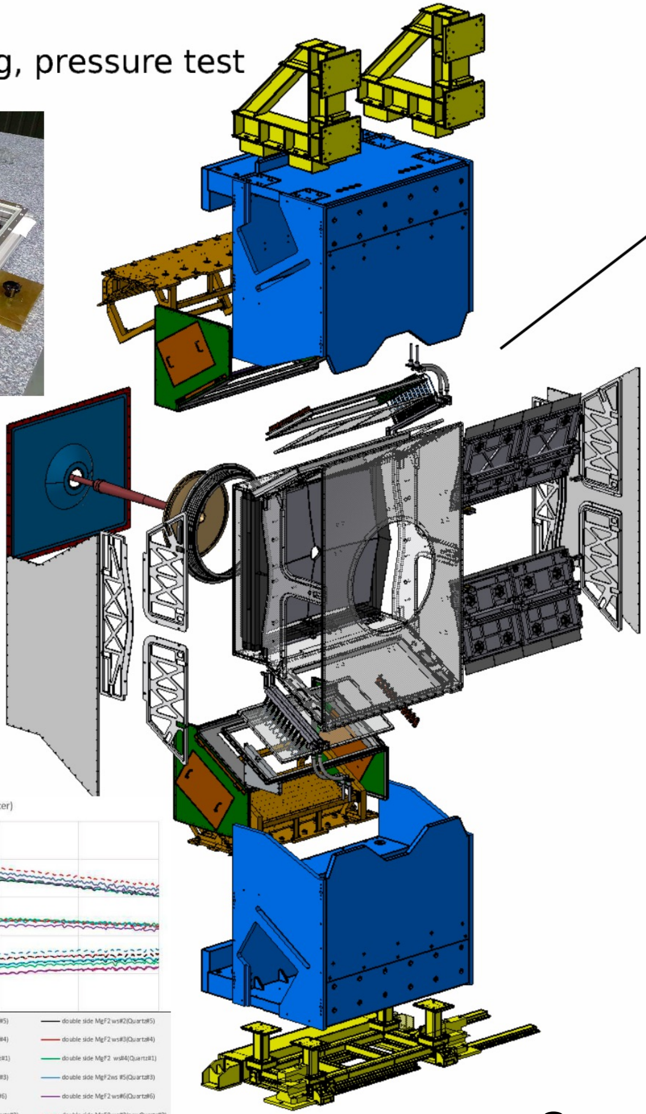
RICH1 mechanics installation

quartz window: coating, gluing, pressure test







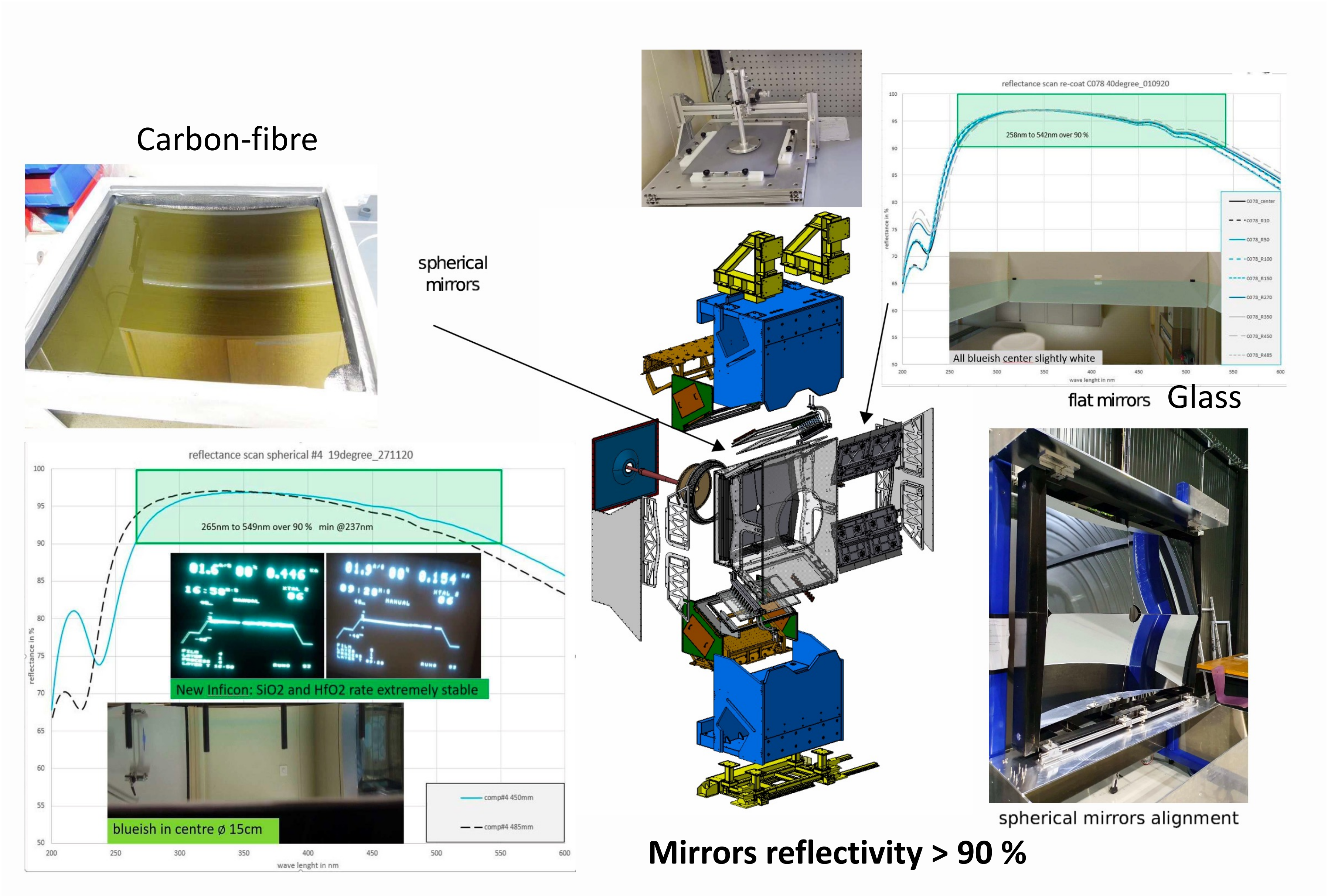


quartz window (up)

quartz window (down)

Quartz transmittivity > 90 %

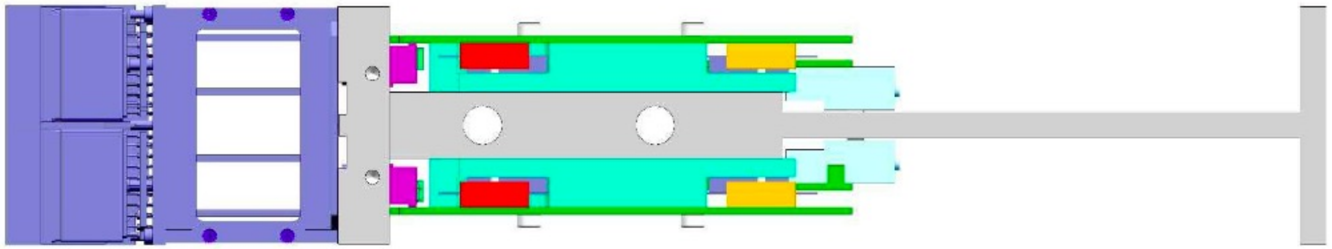
RICH1 mechanics installation

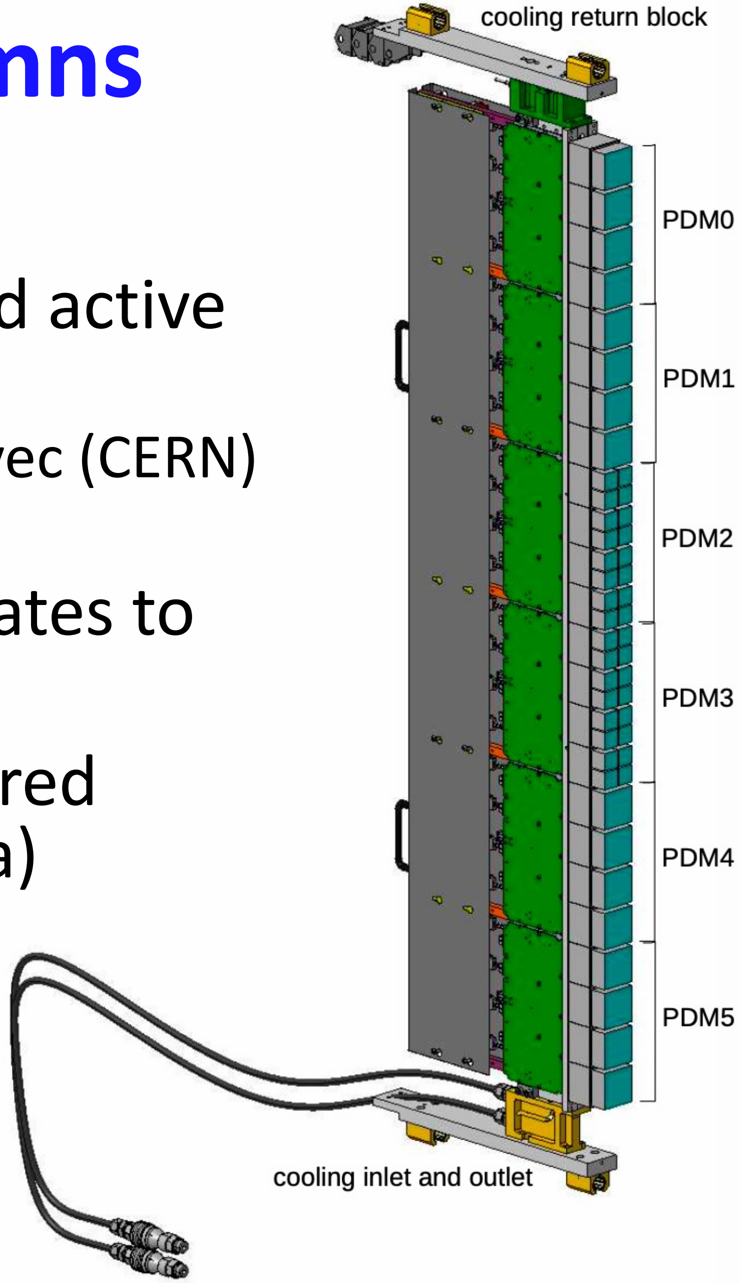


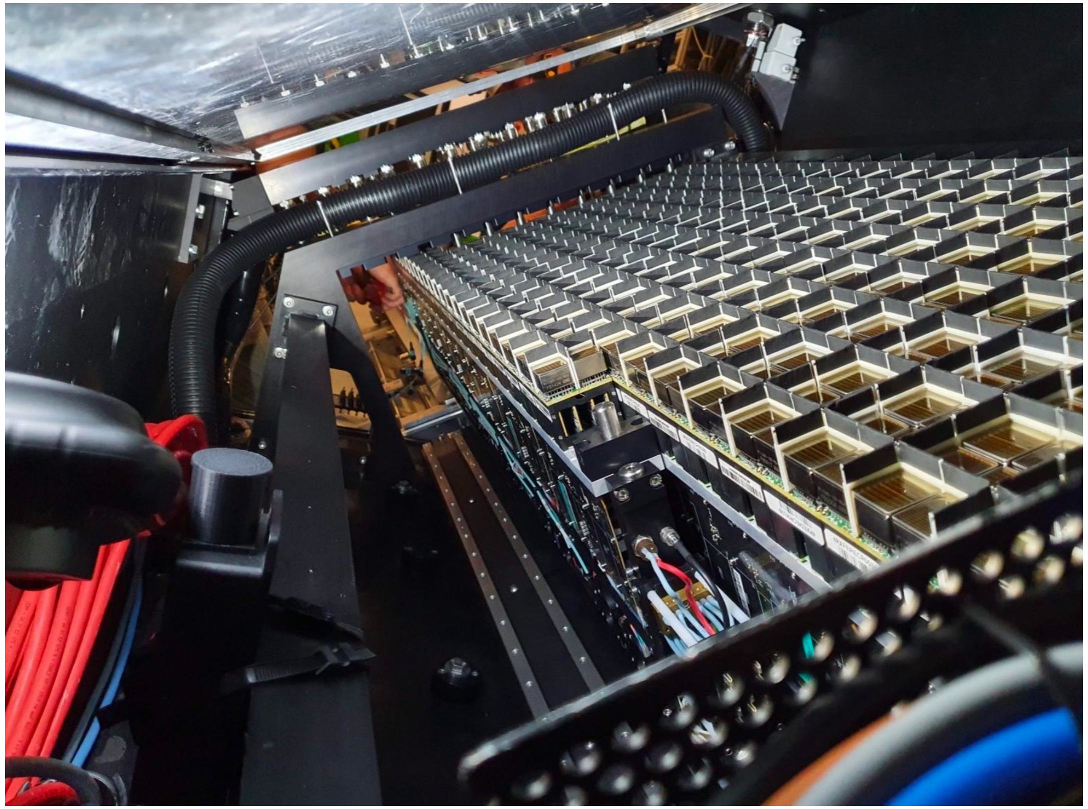
Mirrors reflectivity > 90 %

RICH mechanics: columns

- Mechanical support to host sensors and services
- T-shaped aluminium bar: 1.6 m support structure and active cooling element (Padova)
  - 6 mm ducts deep-drilled along T-bars for cooling with Novec (CERN) to keep MaPMT temperature < 25 °C
- PDMDB equipped with thermal pads and levelling plates to maximise coupling with the T-bar (CERN)
- T-bar design common to RICH1 and RICH2, with tailored designed of harnesses and services (Imperial, Padova)







Commissioning and installation

Columns assembling, commissioning and installation

test column assembled in June 2019
some EC from ECQA, some at CERN
prototype cabling

a long summer spent debugging
the column and developing software

experts debugging the commissioning
setup with the first test column

mechanics assembly
with final
production components
in parallell

preparation of components to be installed
on columns in September 2019

start of columns production
in Autumn 2019

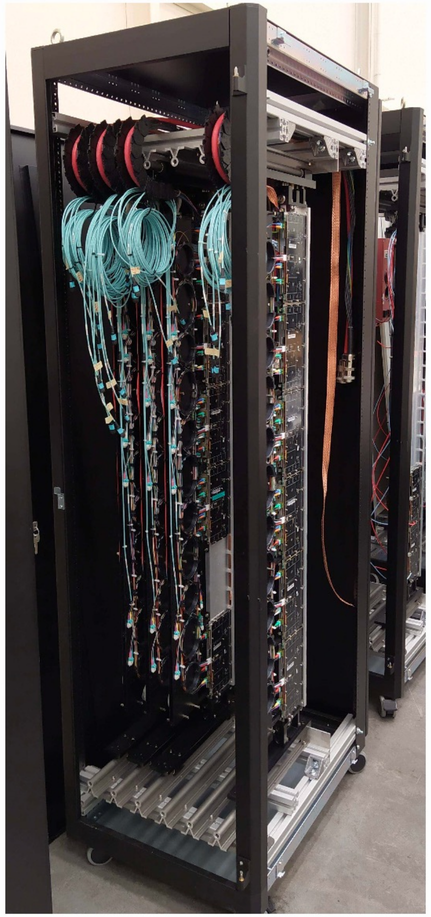
RICH2 columns assembling

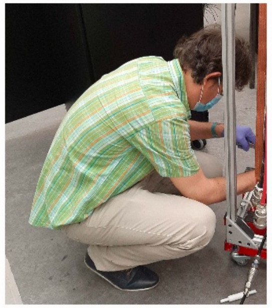
- Cabling started in October 2019, assembly completed in December 2019

Covid times: RICH2 as pilot project at CERN

RICH2 columns commissioning

Assembled columns in ComLab
select next column to test from cabinets





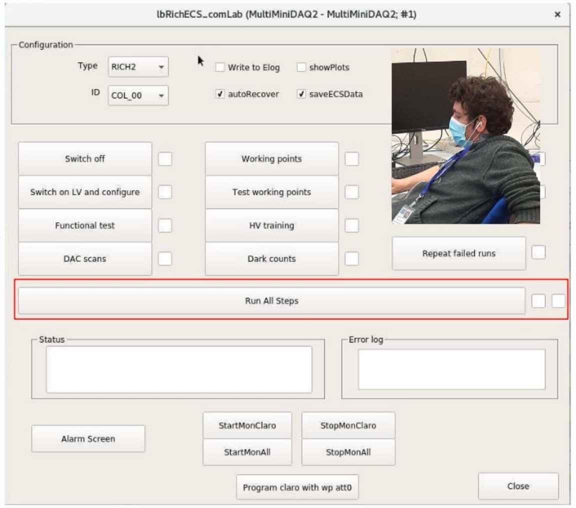
Check cooling
tightness

Elementary Cells
mounted on column

Column installed in SSB

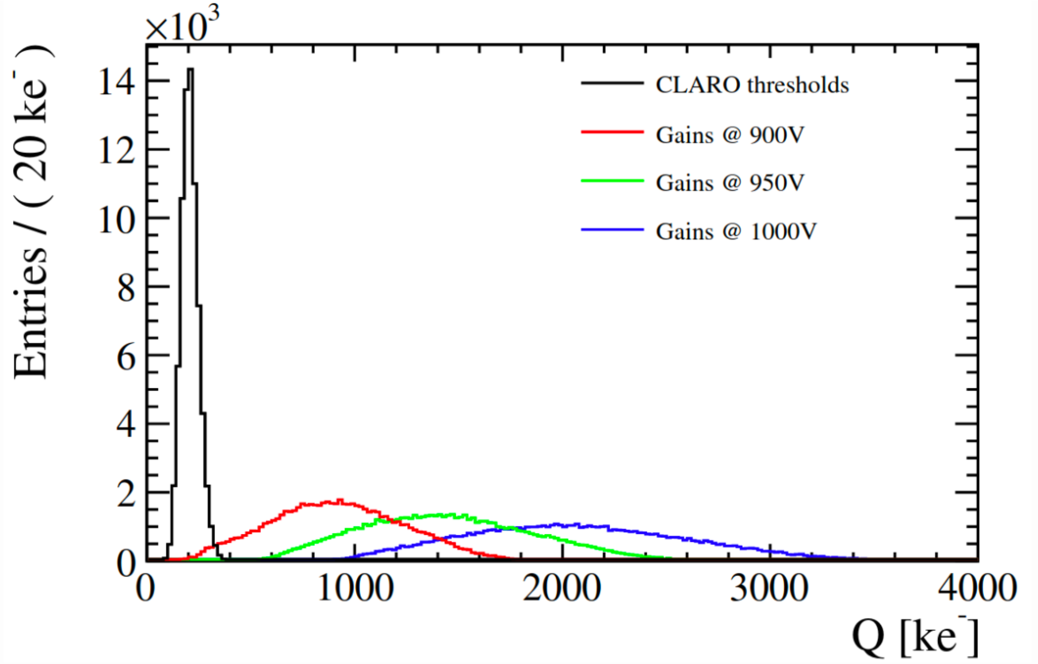
Start of commissioning protocol::

1) connectivity tests
2) automated test protocol



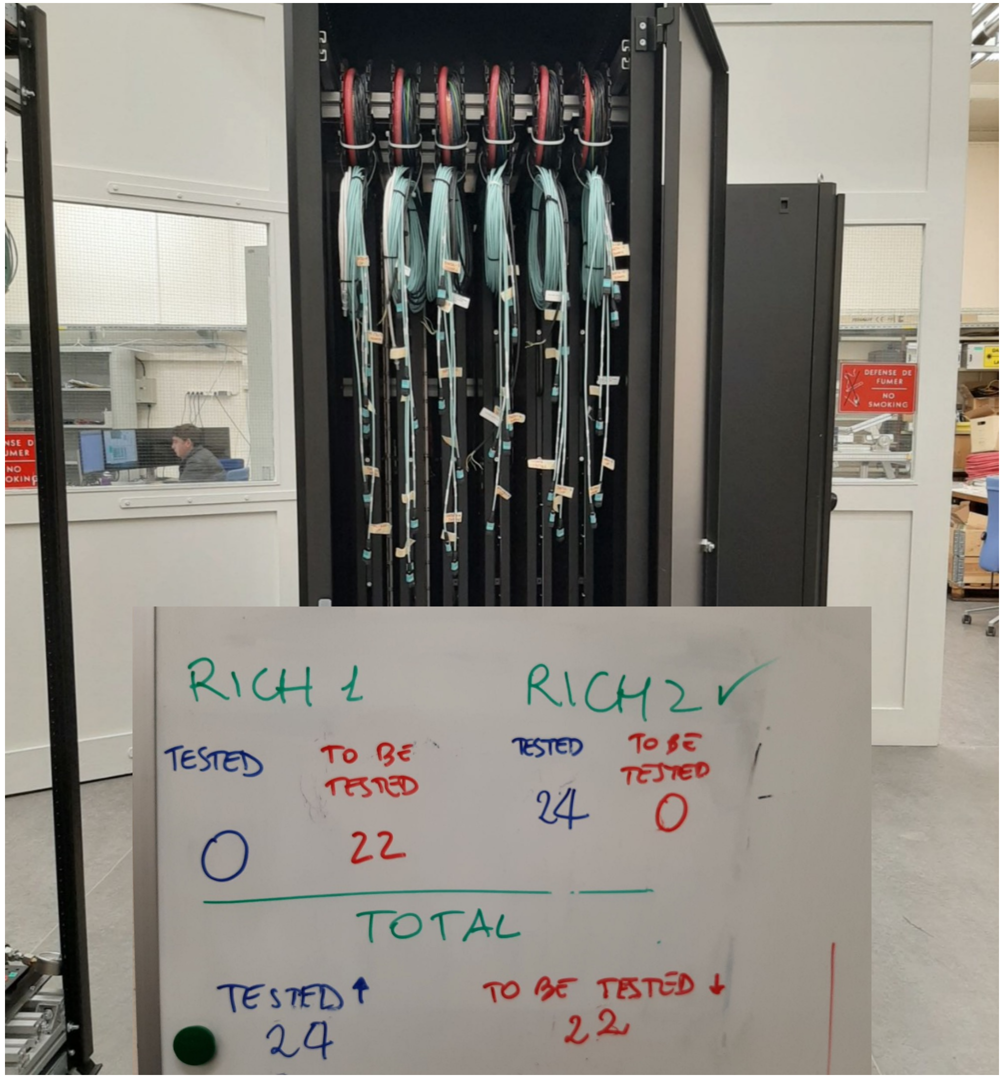
Columns commissioning protocol

- **Conceived to fully validate hardware and to gather operational parameters for the 200k channels composing the RICH detectors**
  - Initial functionality checks (LV, HV, channels connectivity, temperature sensors)
  - 15 test-pulse injection scans
    - re-calibrate CLARO thresholds and gains in the final assembly
    - Determination of working points to be used on-experiment
  - HV training (8 hours) for dark counts assessment
  - 20 threshold scans to measure gain of each MaPMT pixel at different HV values
  - 15 runs at different HV values and offsets in time to re-characterise SIN at different HV values



- **Fully automated** thanks to robust firmware and controls following the concept of reproducibility, redundancy and anticipation

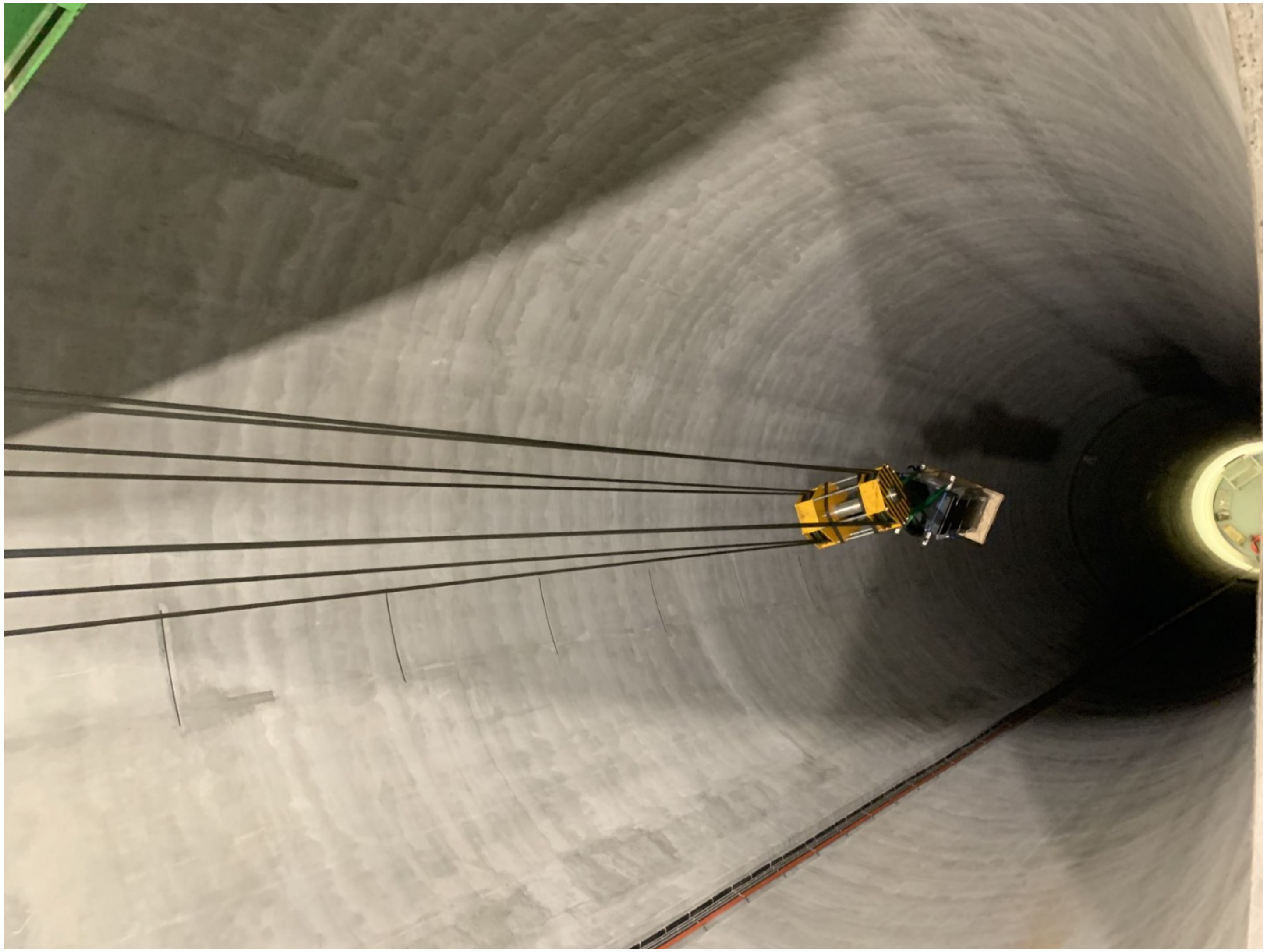
RICH2 columns ready for installation



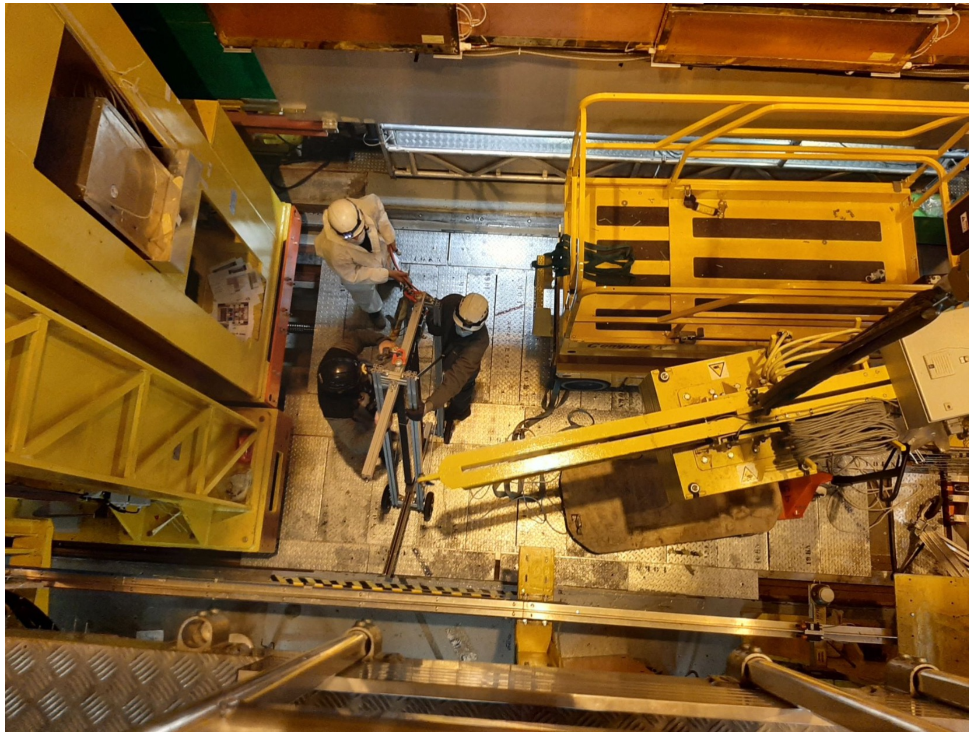
- **RICH2 columns commissioning completed in July 2020**

RICH2 ready for installation

RICH2 installation

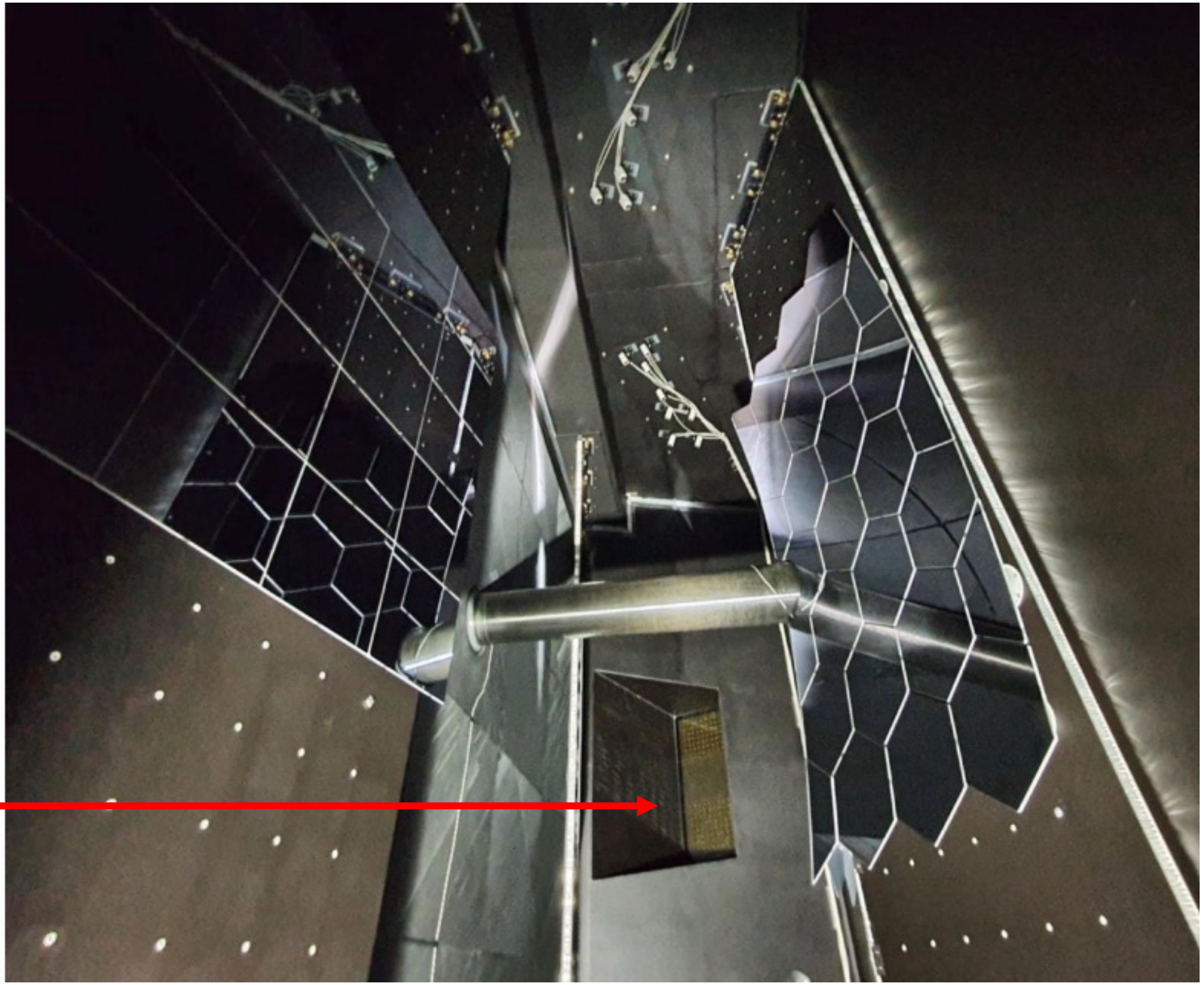


RICH2 installation



RICH2 installed

- **Installation, including services, completed between February and April 2021 (first new detector installed in LHCb)**

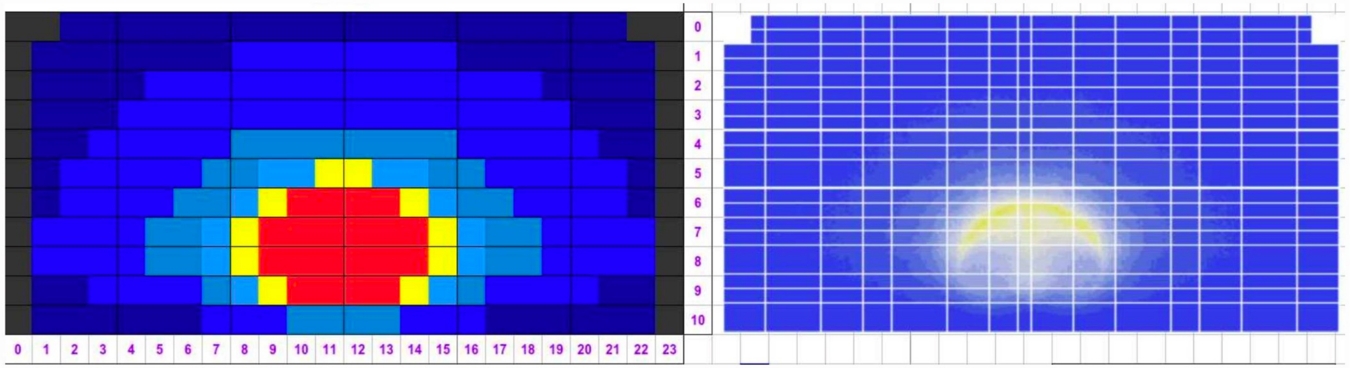


RICH1 columns assembling and commissioning

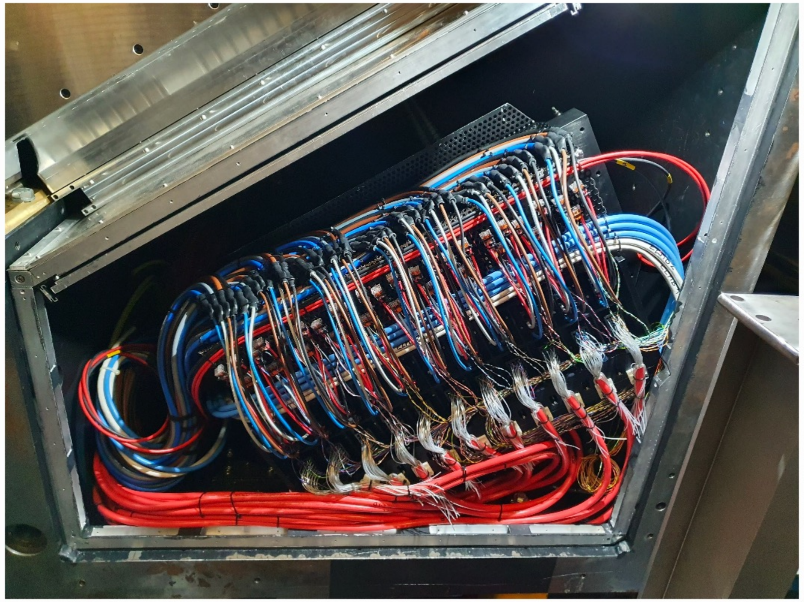
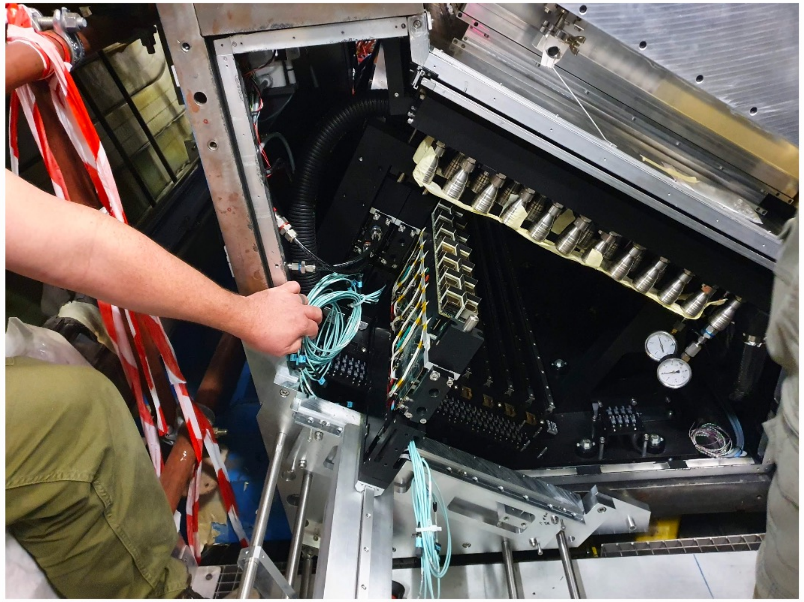
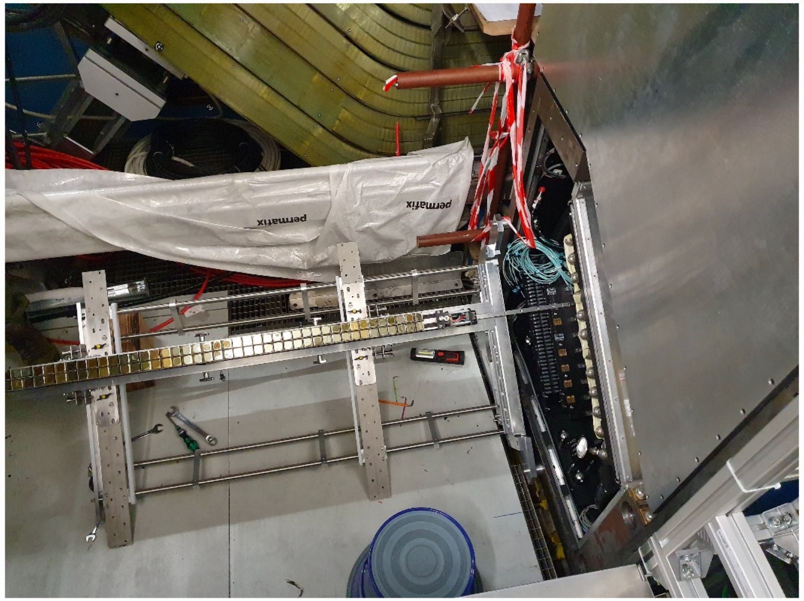
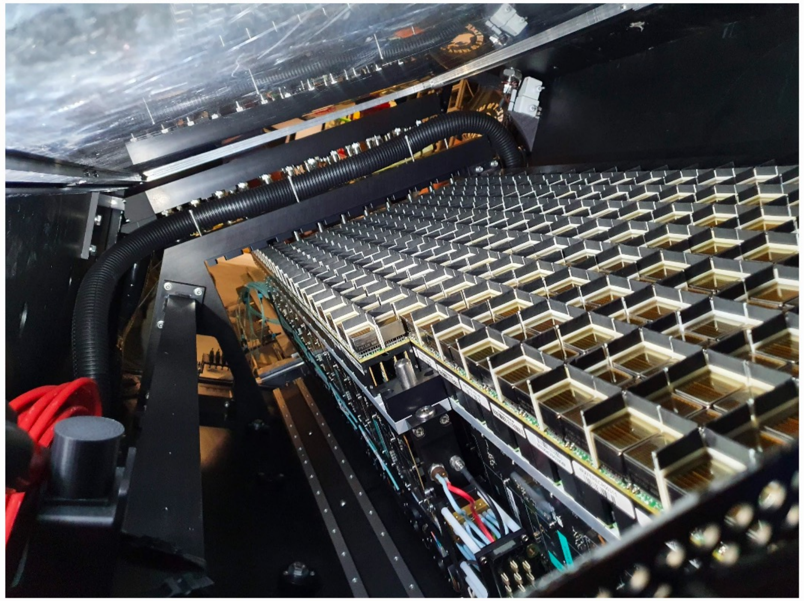
- Different modularity requiring different tooling and adaptations to the columns commissioning protocol
- Particular care on MaPMT SIN aspects
- Parallel to RICH2 works on-experiment
- Commissioning started in November 2020 and completed in November 2021

RICH1 sensors grouping

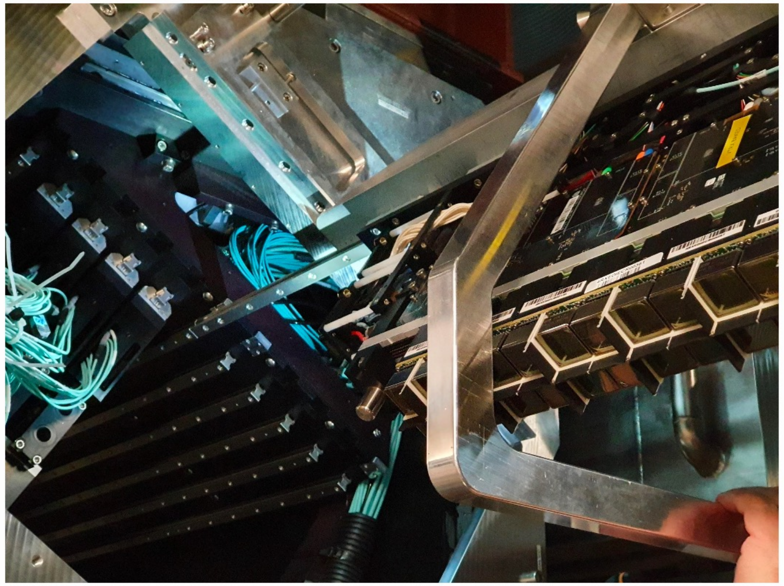
- SIN critical in high-occupancy regions of RICH1 (pile-up)
- Dedicated EC re-shuffling procedure of MaPMTs across ECs to match units with similar gain and low SIN
  - HV shared by 16 MaPMTs => 2D grouping combining PDQA and ECQA results
  - Plan possible thanks to a dedicated database storing all the QA information

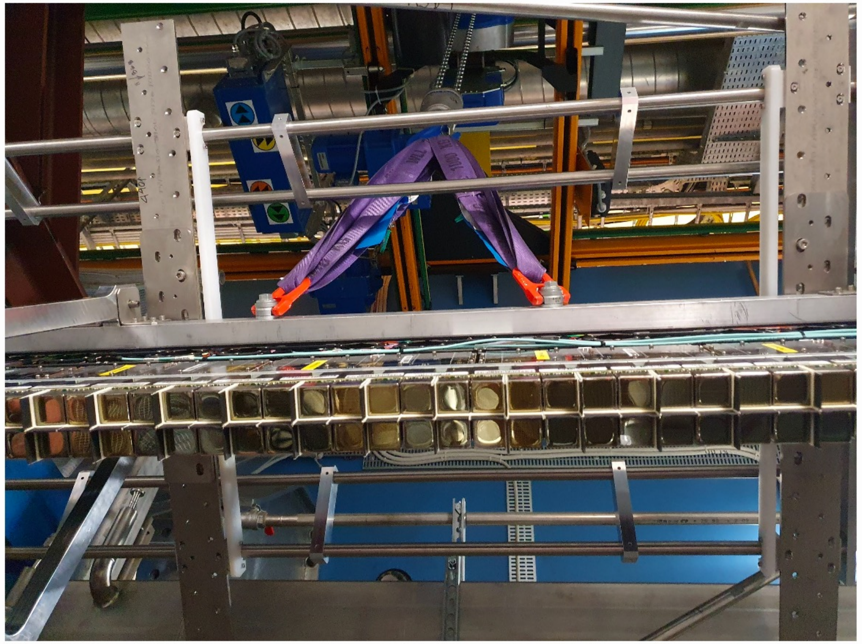


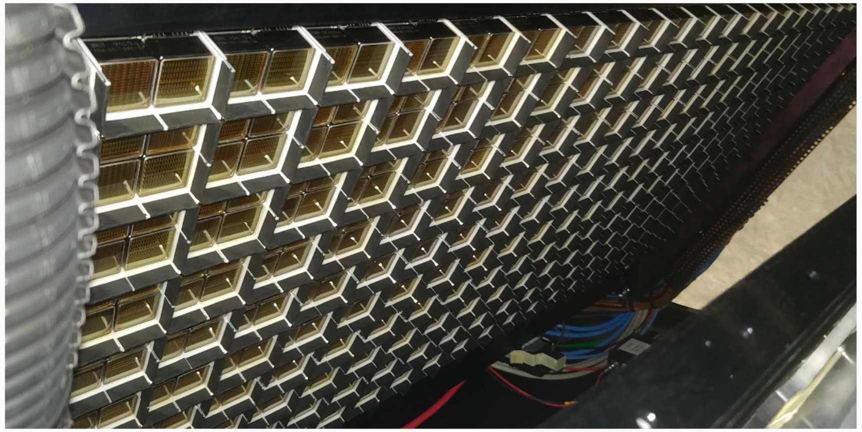
RICH1 columns installation

RICH1 columns installation

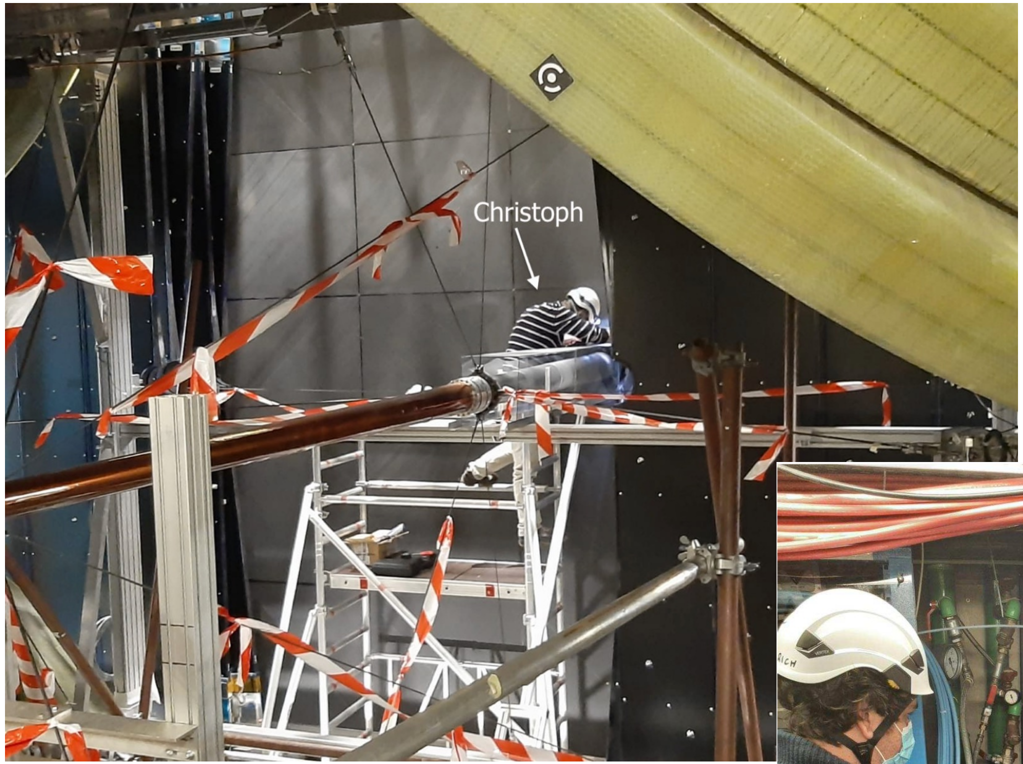


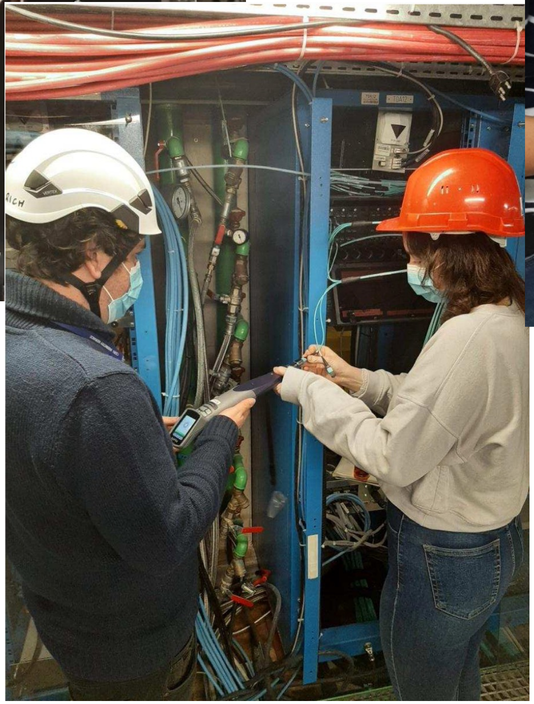


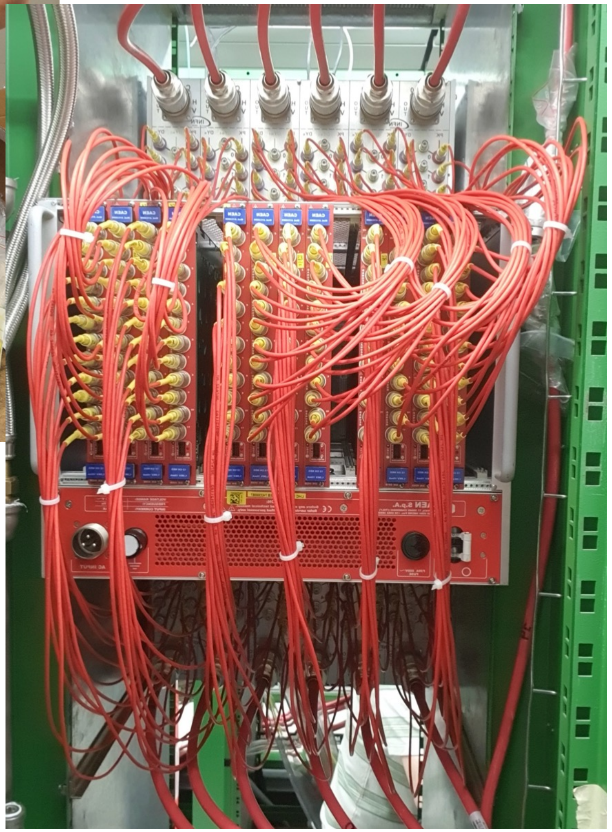


- **Installation completed in January 2022**

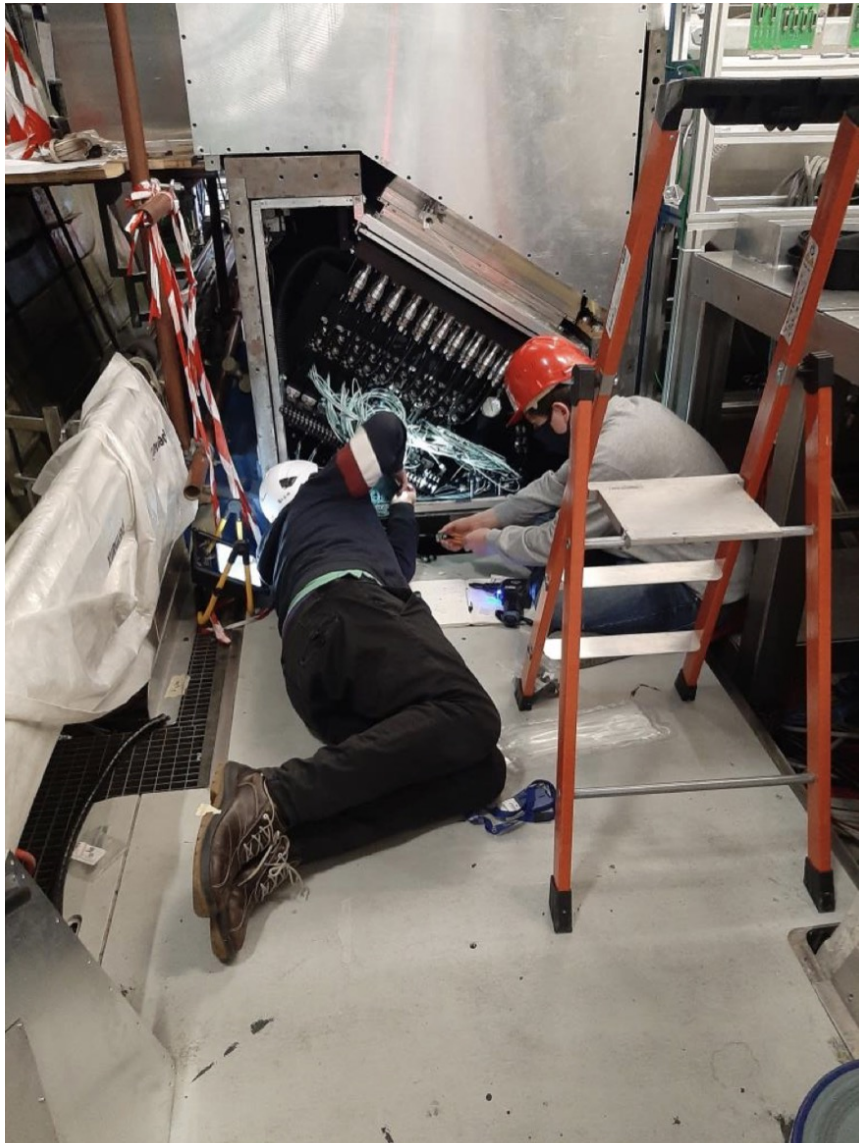
Services and cabling



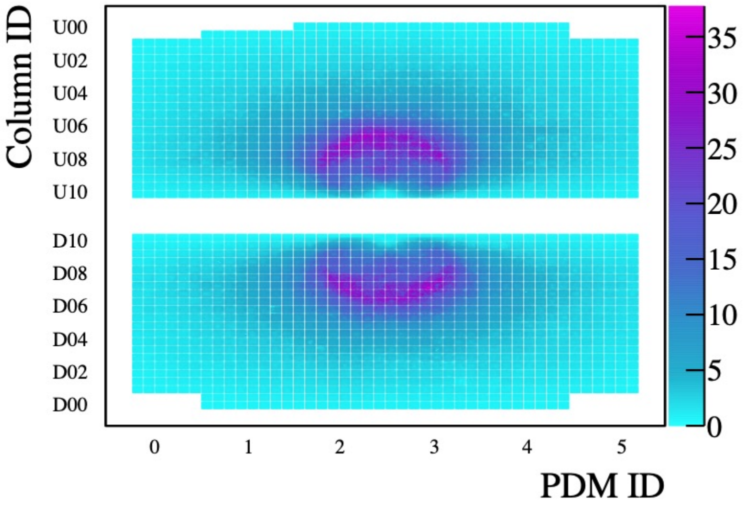


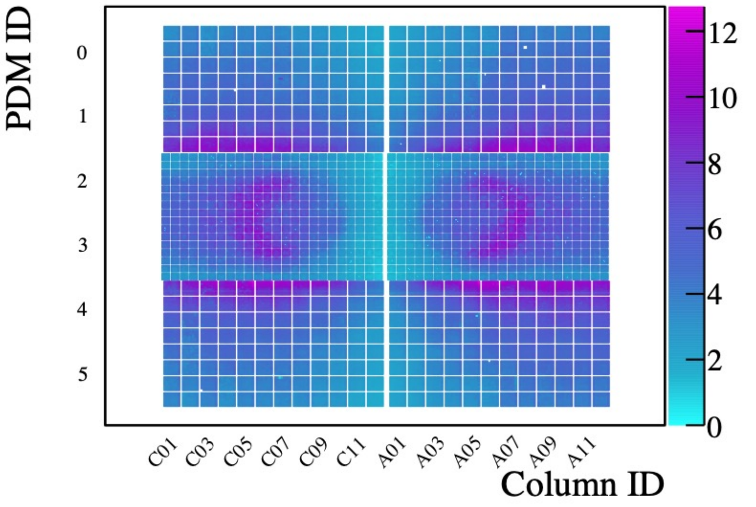


IG versus reality

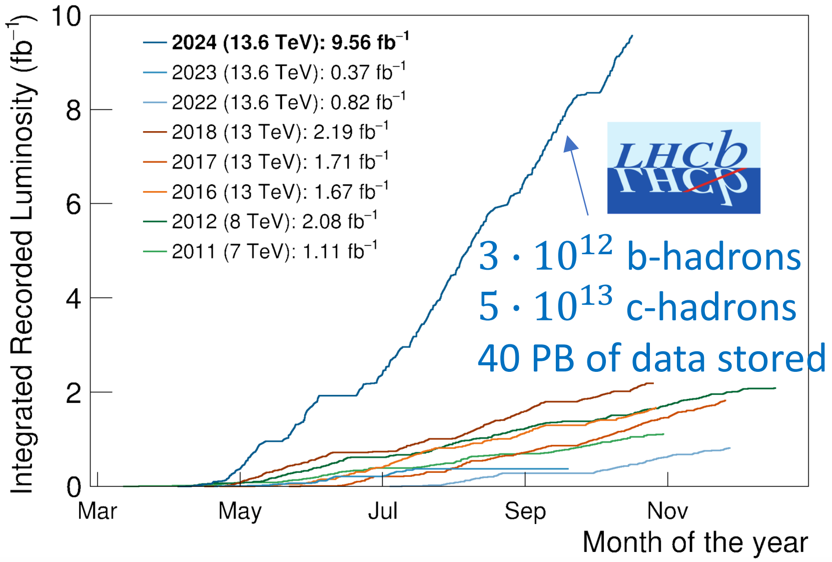


RICH1 installed





Operations and performance



LHC pilot beam

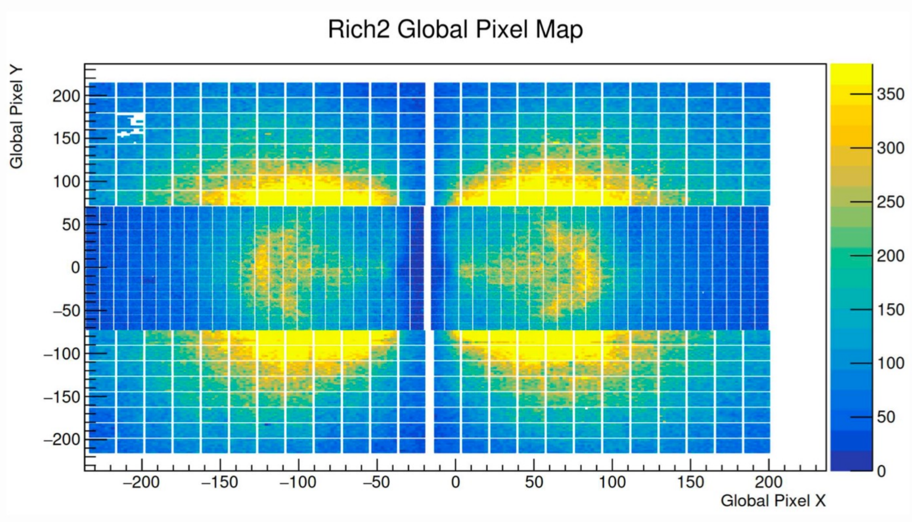
- First test with beam performed on RICH2 during pilot beam provided by the LHC at 450 GeV in October 2021 (restart after Long Shutdown 2): collisions quickly detected

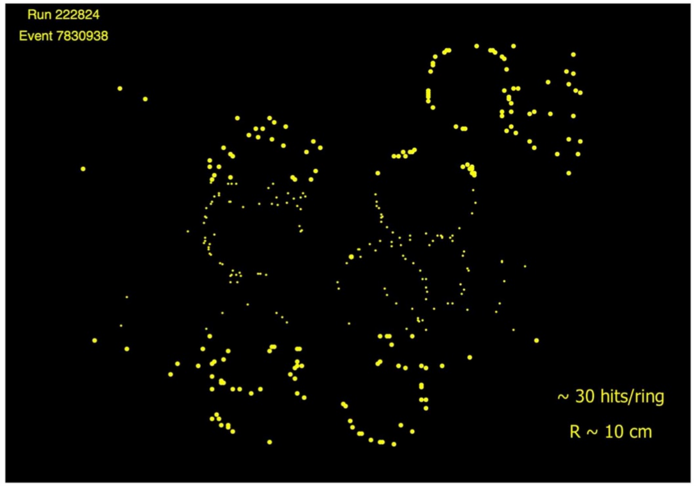
- Not shown in this picture: LHCb spokesperson orbiting around the control room in a desperate search for good news

LHC pilot beam

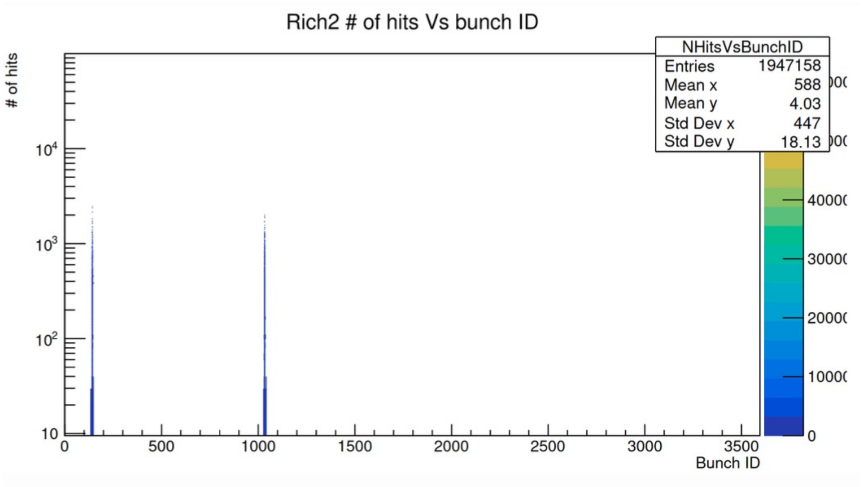
- Successful test of working points determined during commissioning
- First synchronisation with LHC clock and inter-channel time alignment
- First tuning of the HV
- Number of photons per ring (and rings size) consistent with expectations

[CERN EP-news]

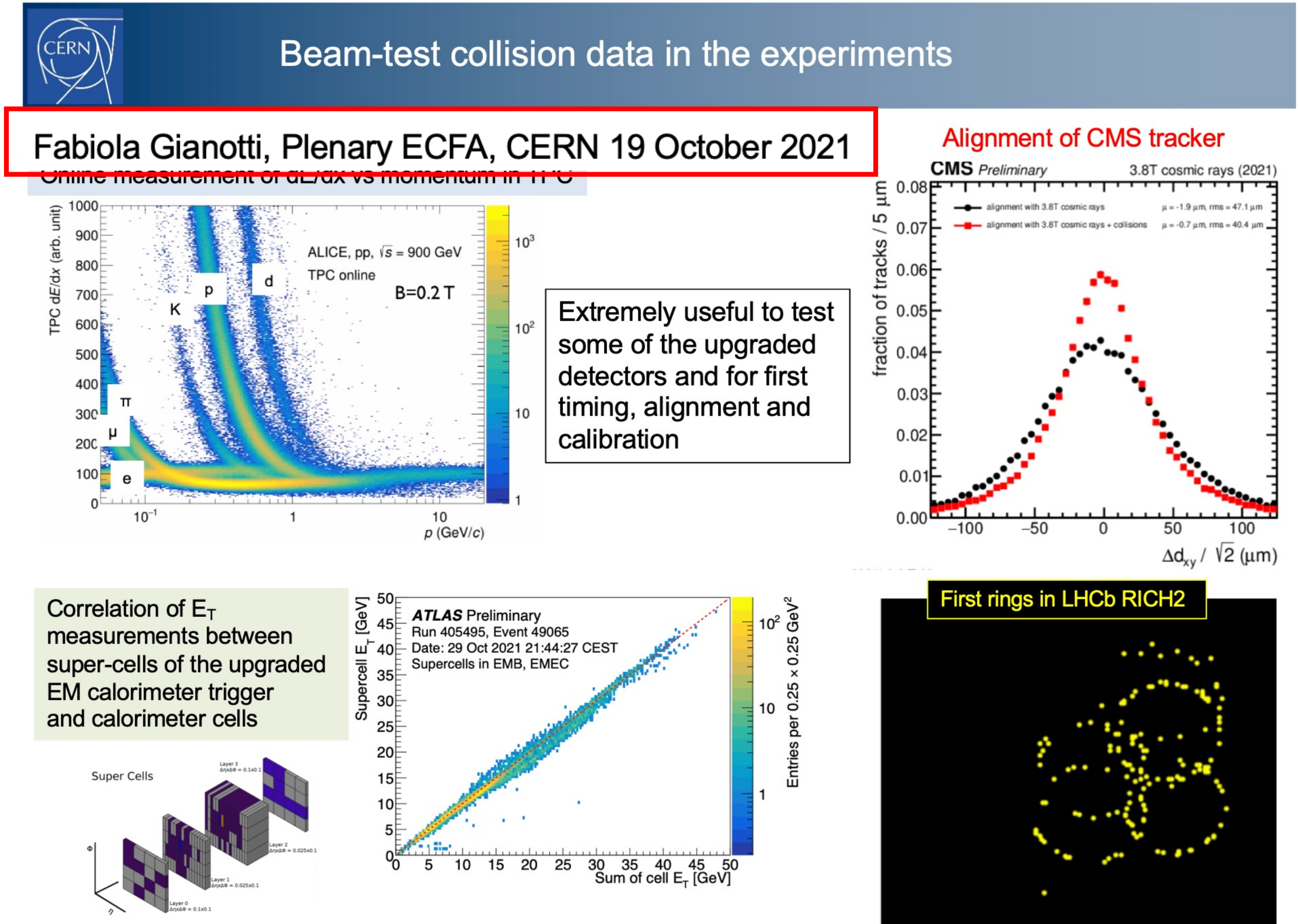




Rich2 # of hits Vs bunch ID



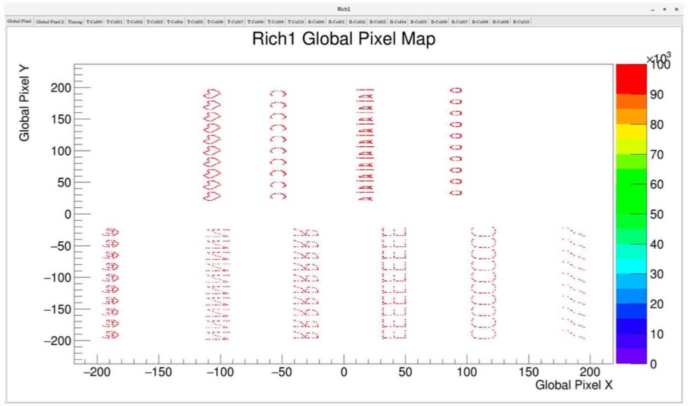
VIP citations

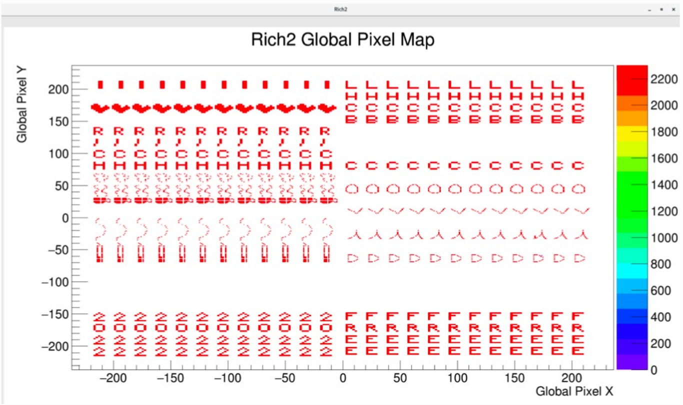


ECFA talk Nov. 2021

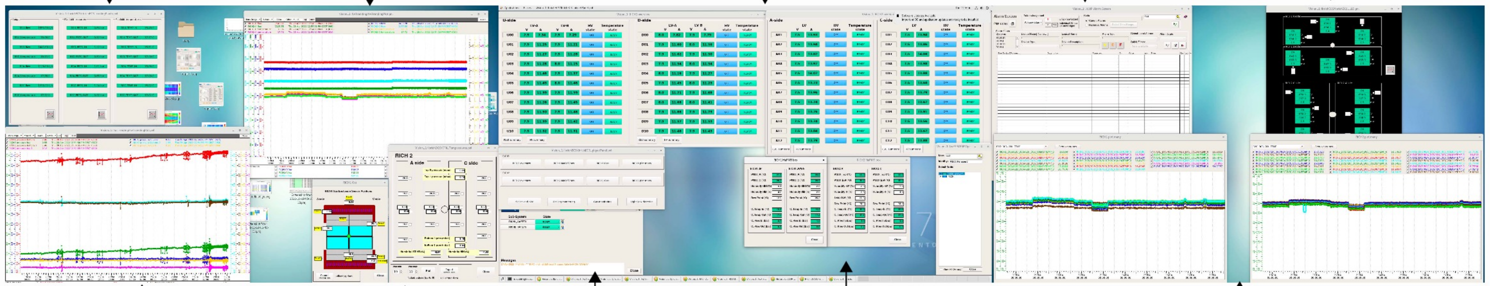
Detectors validation before collisions

mapping validation injecting pattern in FE

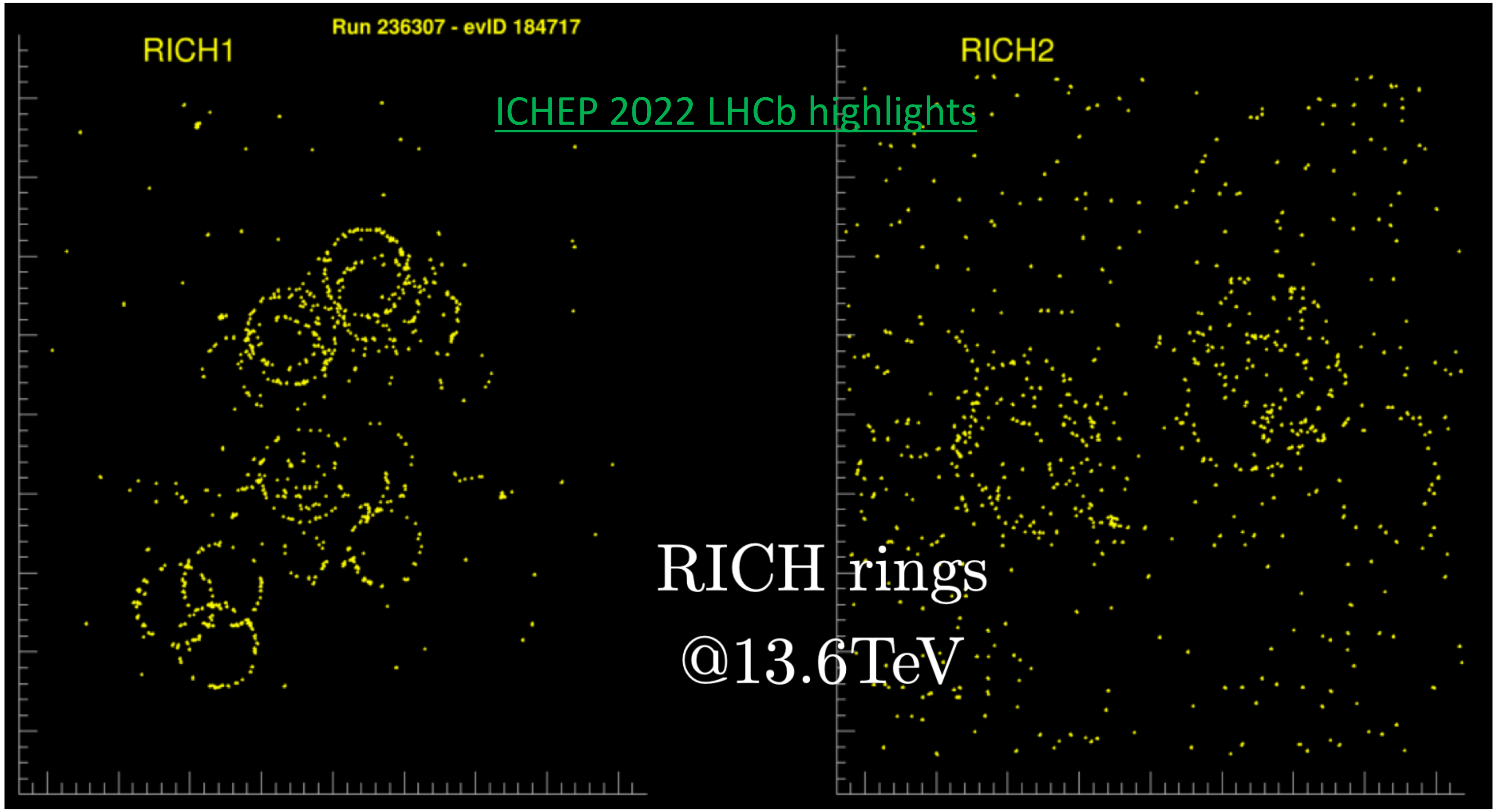




advanced monitoring facility for detector safety and operations



First high energy beams of Run 3

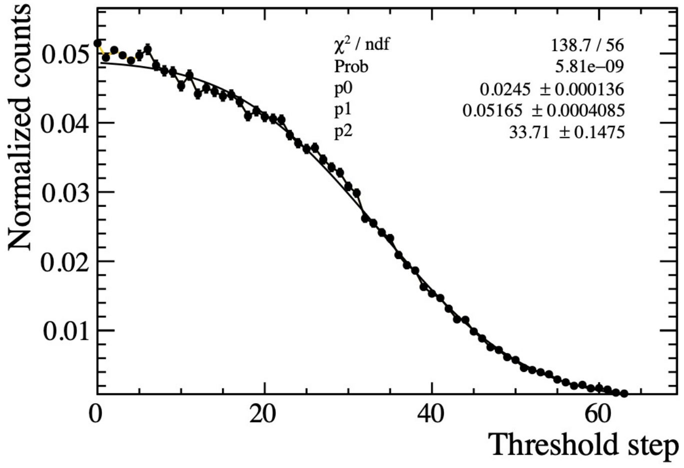


ICHEP 2022 LHCb highlights

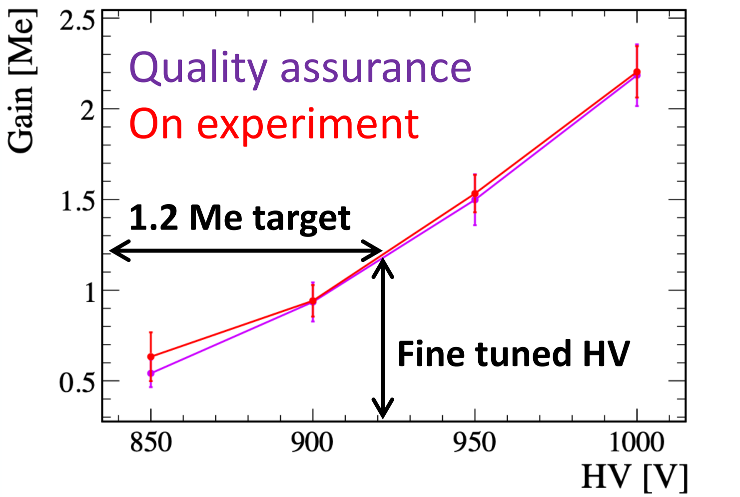
5th July 2022, CERN media event

Photon detection chain calibration and operations

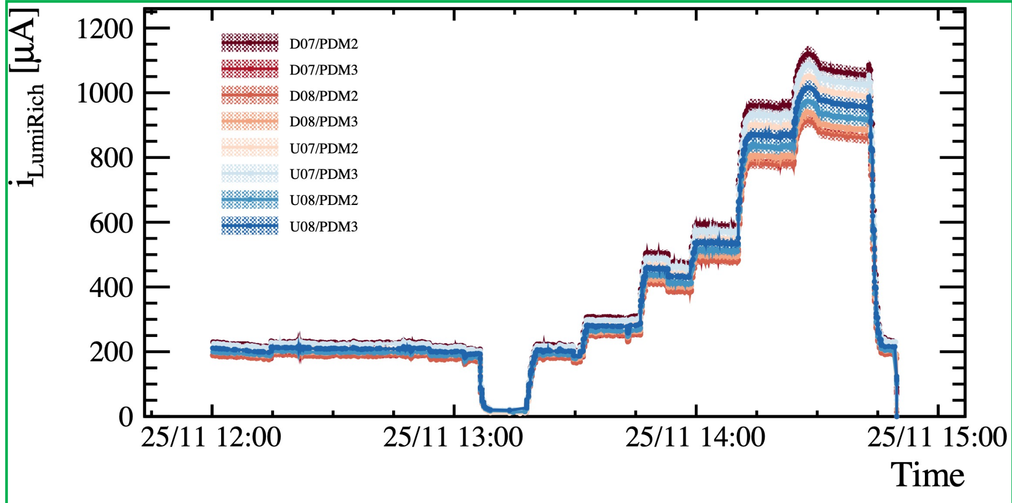
- **Tuning of operational and calibration tools to achieve the best performance**
- Average gain of the 200k MaPMT channels measured and equalised to 1.2 Me by tuning the operating high-voltages (**frontend thresholds set to 200 ke)**
  - automated threshold scan procedures with beam
  - excellent agreement between quality assurance and on experiment results
  - same procedure used to monitor and correct for ageing
- Last dynode of the MaPMTs supplied independently to preserve gain linearity at high rates up to 100 MHz/cm^2 [arXiv:2503.05273]
  - Provide online luminosity through the calibrated measurement of the power supply currents



Single channel threshold scan

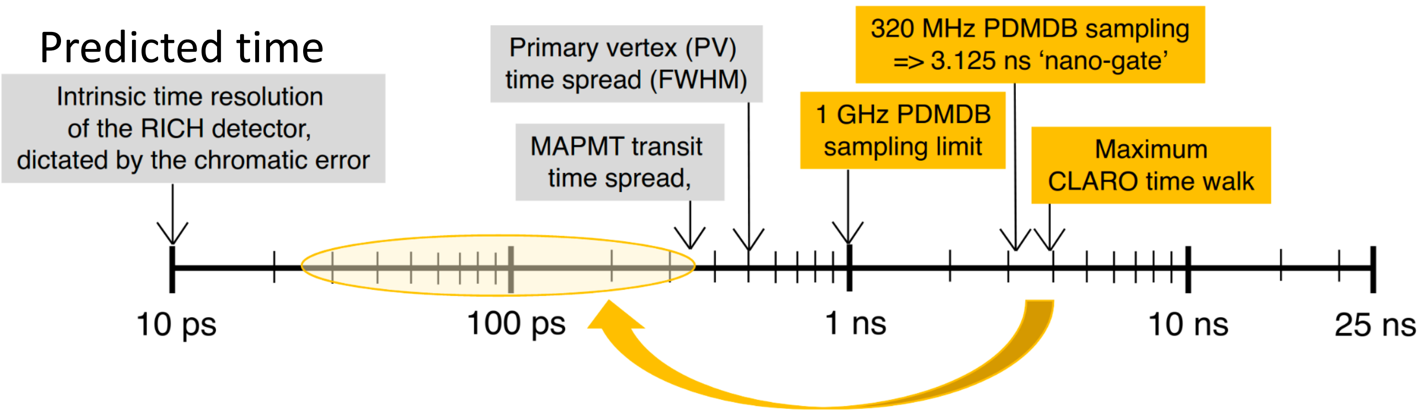


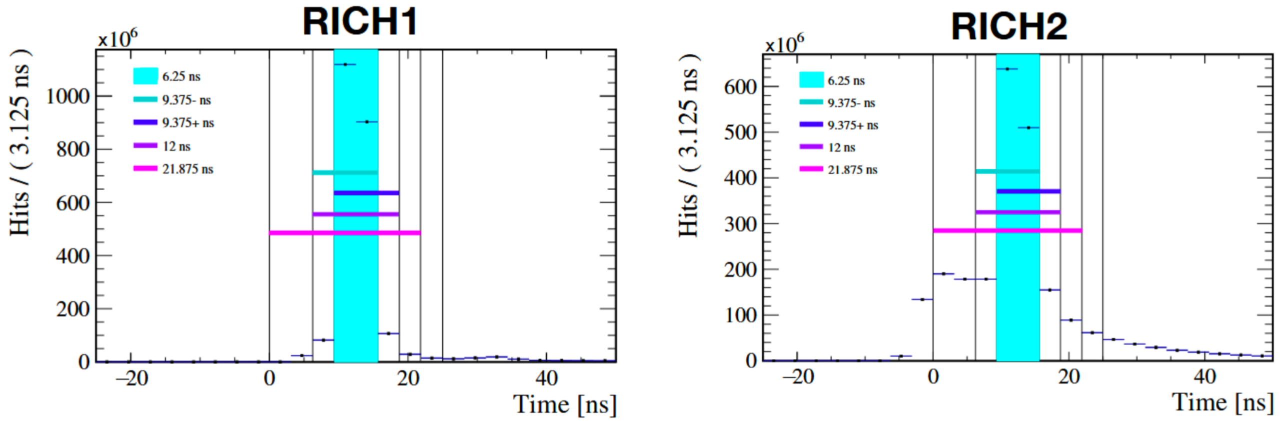
Results for one group of 16 MaPMTs

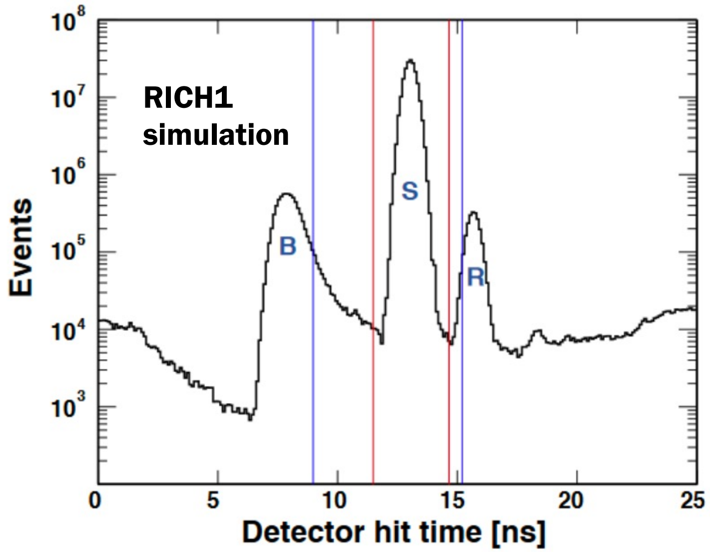


Time alignment

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





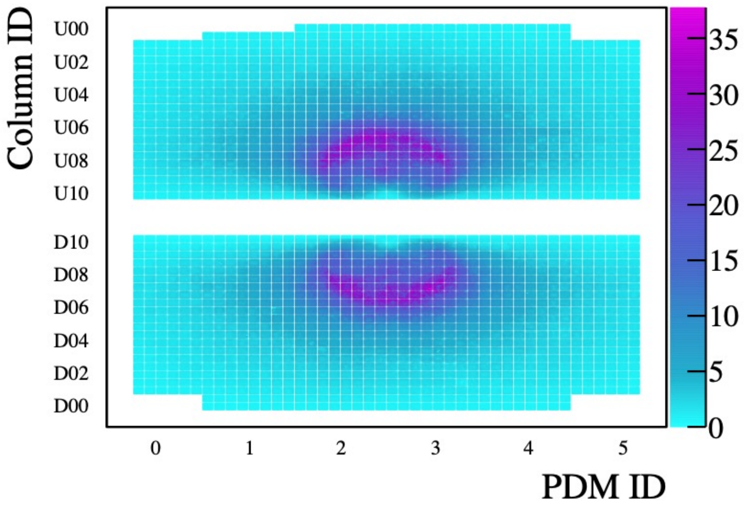


Best trade-off between photon detection efficiency and background rejection found for a 6.25 ns time gating window: deployed since end of 2022

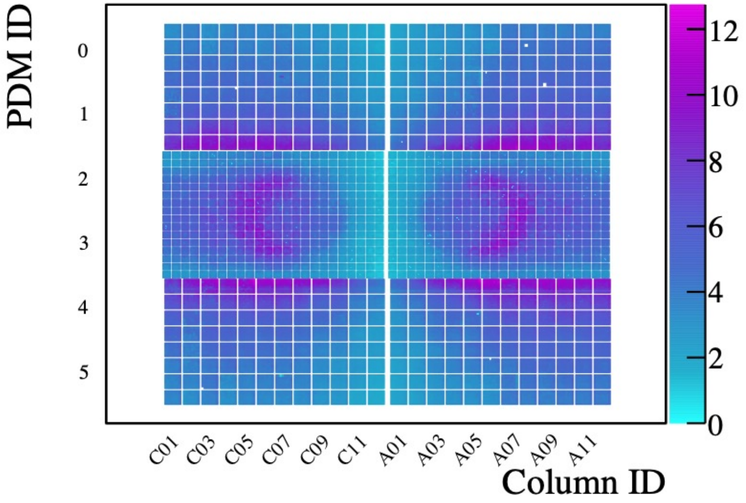
- B: background due to particles travelling directly to the photon detection plane
- S: Cherenkov signal
- R: background due to multiple reflections of Cherenkov photons in the optical system
- + incoherent background due to instrumental internal noise/scintillation photons in the radiators

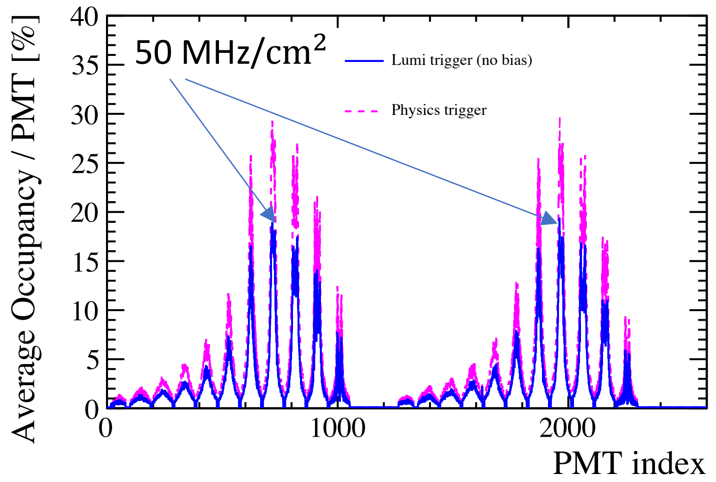
Hitmaps and occupancy

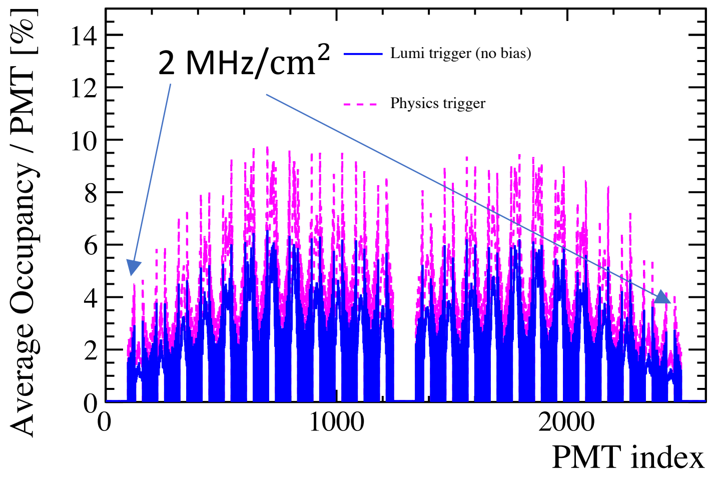
RICH1

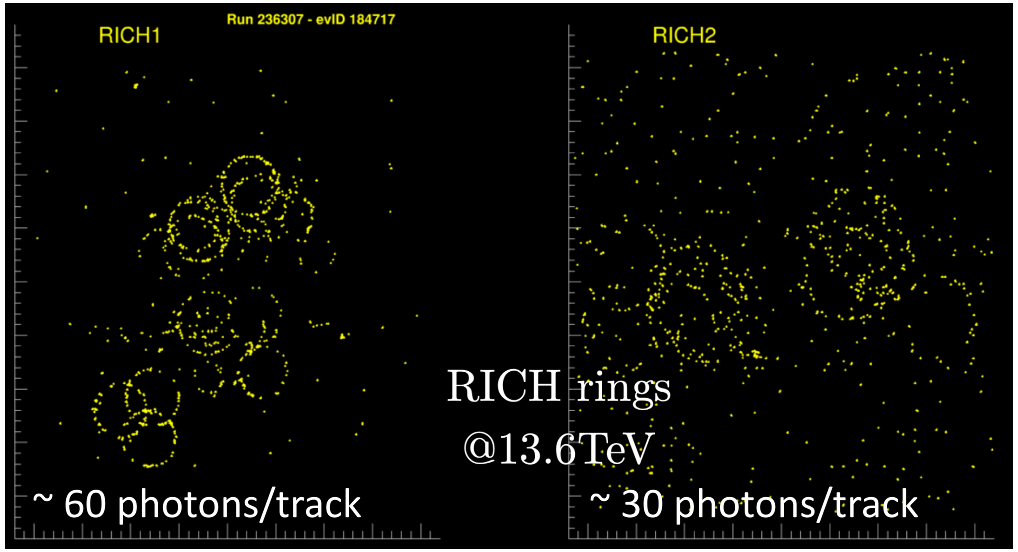


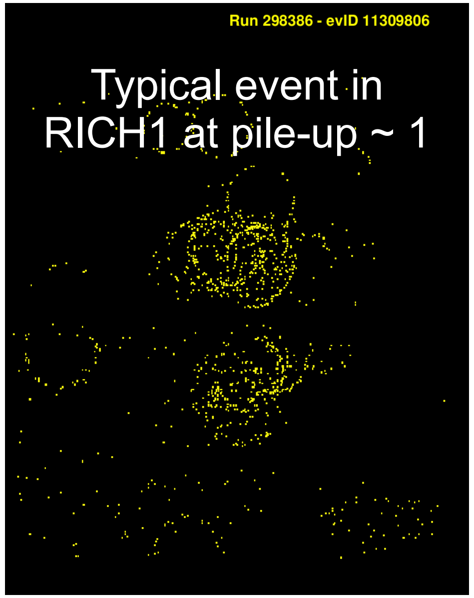
RICH2

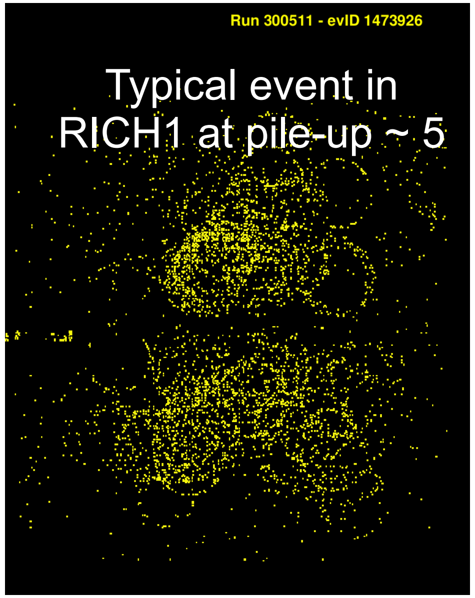










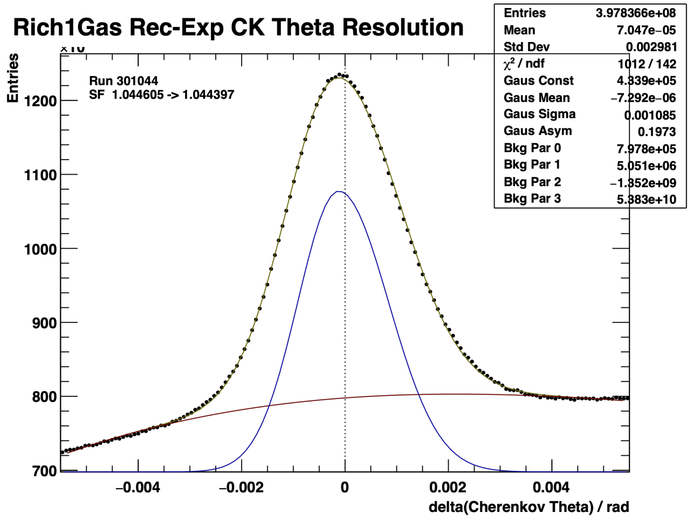


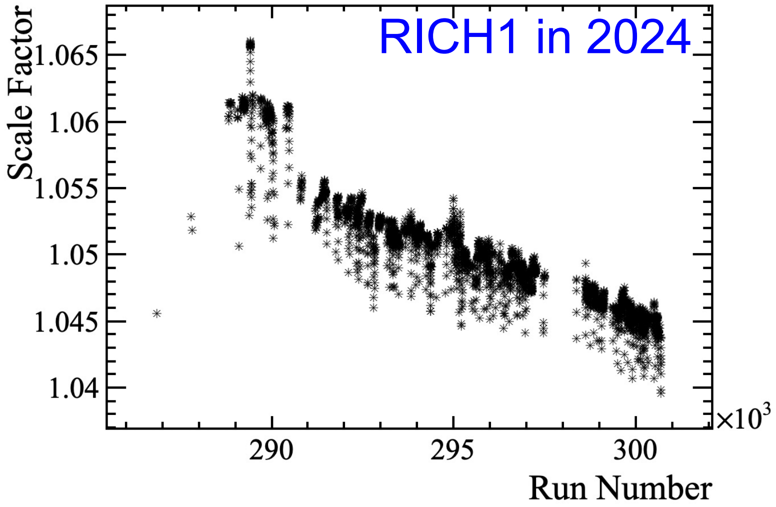
No bias beam-beam occupancy relevant operationally

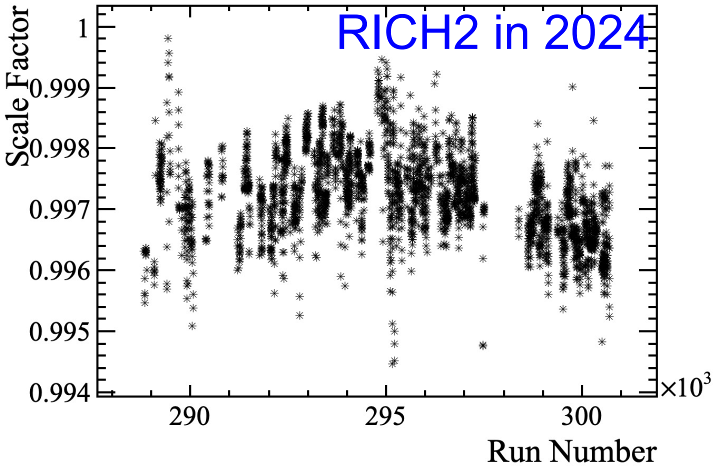
Physics-biased beam-beam occupancy relevant for performance

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

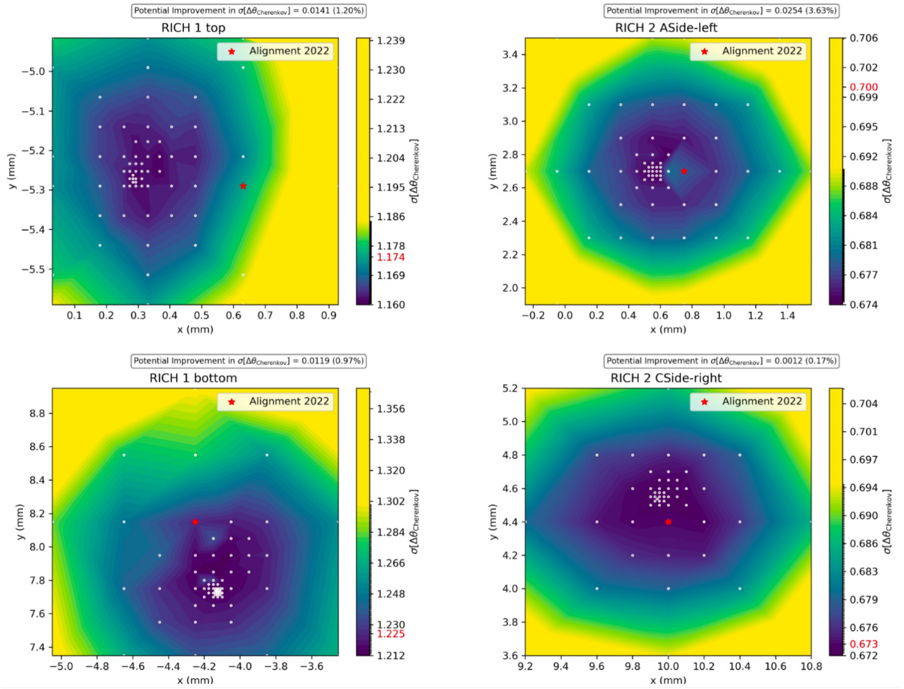


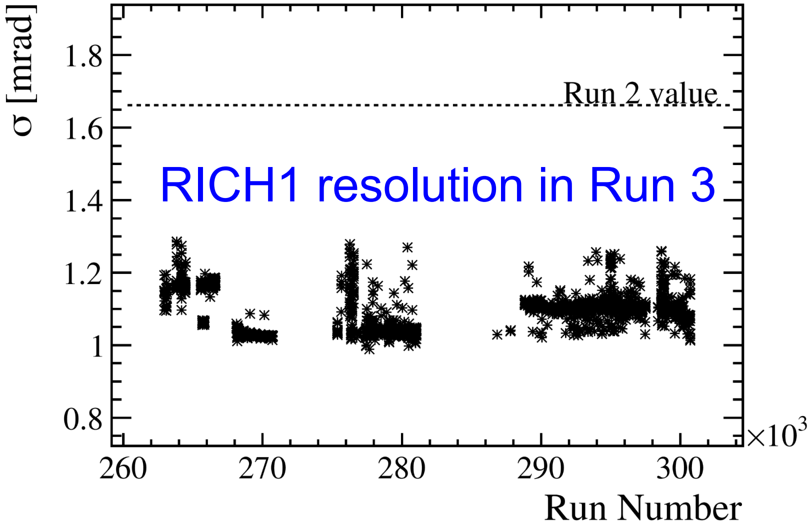


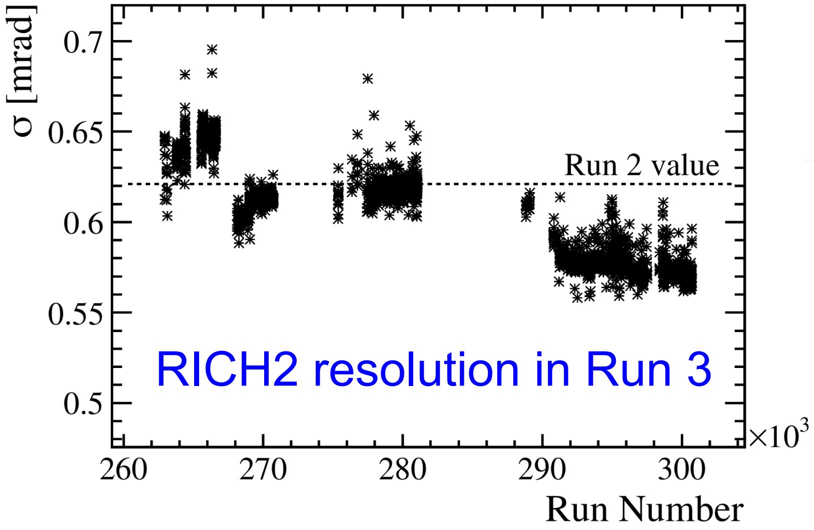


Alignment and Cherenkov angle resolution

- 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



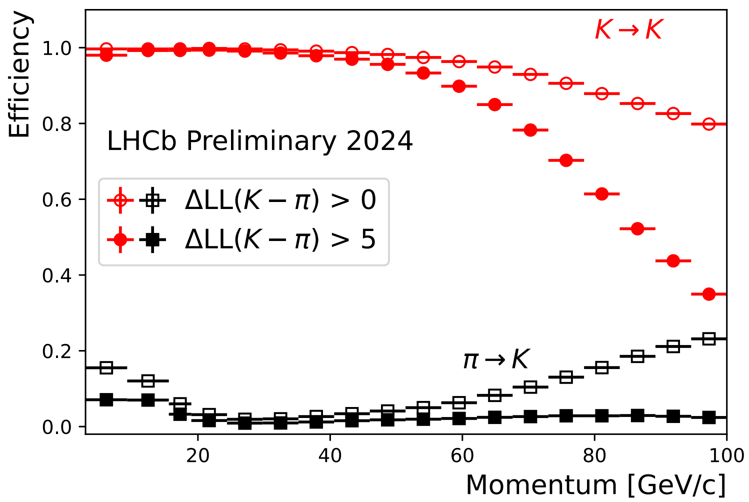


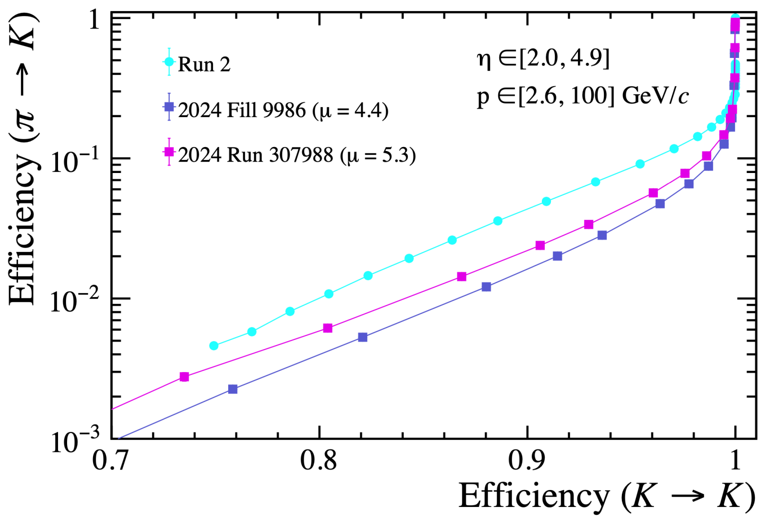


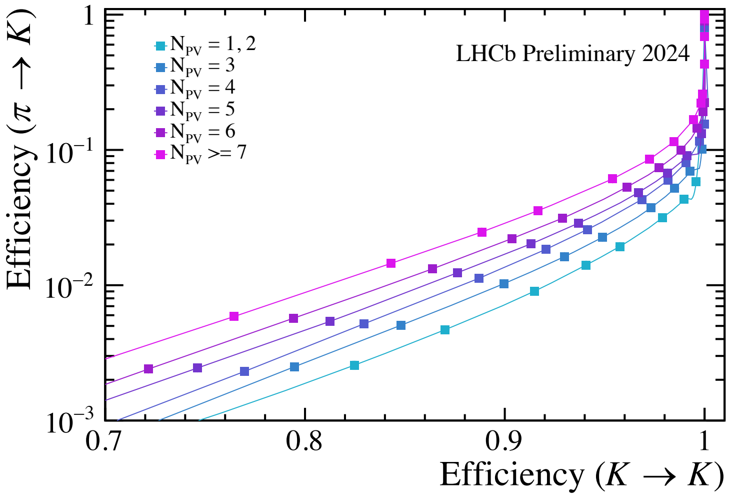
LHCb-FIGURE-2023-007

Hadron identification performance: Run 2 vs Run 3

- Preliminary performance evaluated with data collected at the end of 2022, showing that already with preliminary calibrations the upgraded RICH detectors outperformed the previous generation at the average pile-up of Run 3 LHCb-FIGURE-2023-019
- Confirmed in 2024 LHCb-FIGURE-2024-031 at nominal running conditions







Conclusions

- The LHCb RICH upgrade has been a successful programme
  - R&D on detector components that have been installed and are operating at the LHC are an extremely rewarding experience
  - Some unexpected events along the path but effectively tackled and many lessons learned for the future
- Now a new phase is starting with the recent approval by CERN of the second upgrade of LHCb experiment foreseen to be installed in 10 years from now
  - unique opportunity to participate to the construction of a High Energy Physics experiment
  - new design and advanced R&D required by the RICH detectors in which the Ferrara group is involved in several aspects

Acknowledgments

- Some materials for this talk have been took from:
  - The LHCb RICH upgrade: from design to early performance, S. Gambetta, CERN-EP Detector Seminar
  - PID lectures, O. Ullaland, Italo-Hellenic School of Physics in Lecce, Italy
  - Particle Identification: Detectors, R. Forty, ICFA Instrumentation School, Bariloche, Argentine
  - Fotografare l'invisibile: rivelatori di particelle elementari, M. Fiorini, I venerdì dell'Universo
  - The LHCb RICH Upgrade: from design to early performance