The LHCb RICH Upgrade: from design to early performance

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EP Detector Seminar

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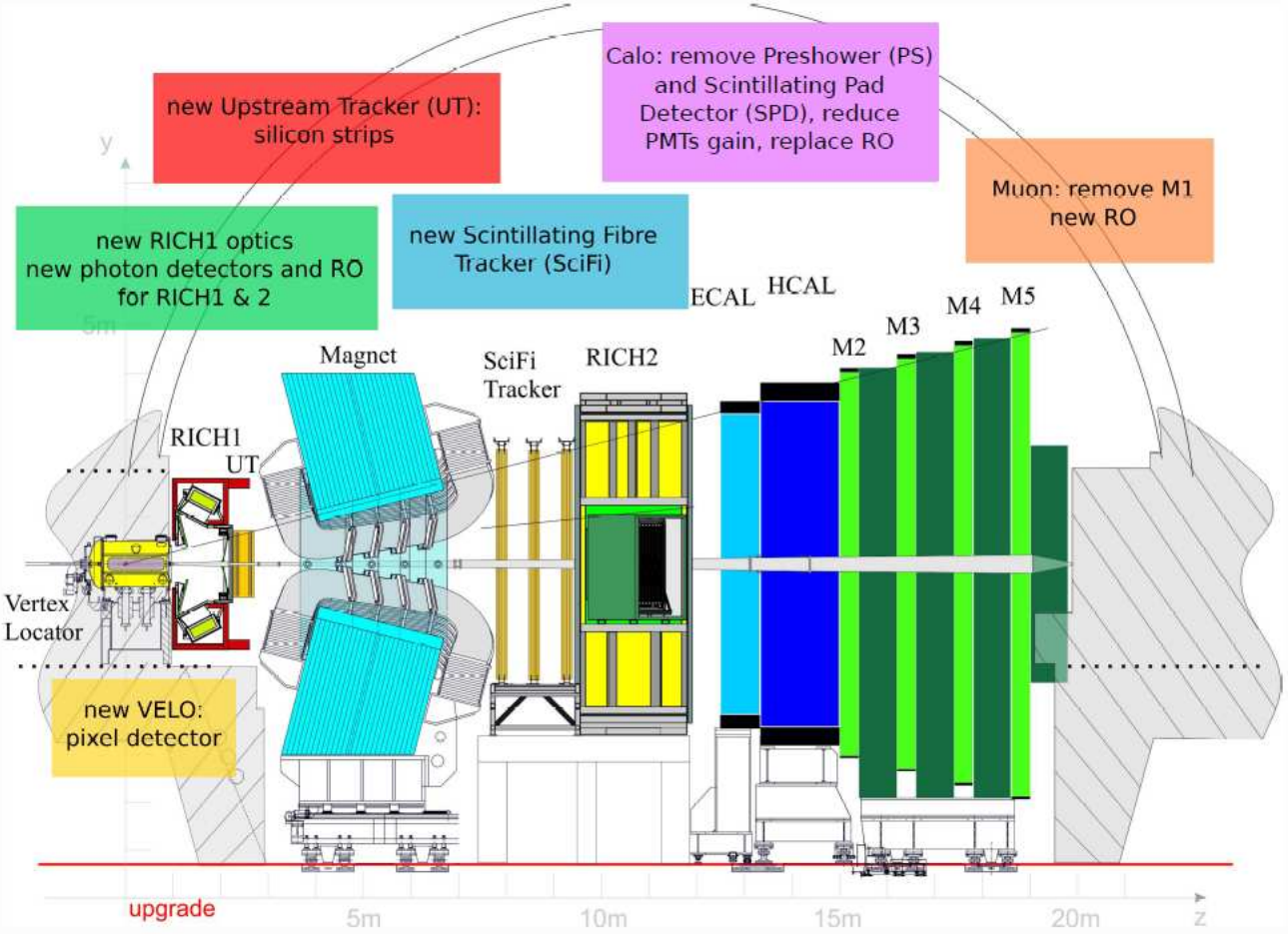
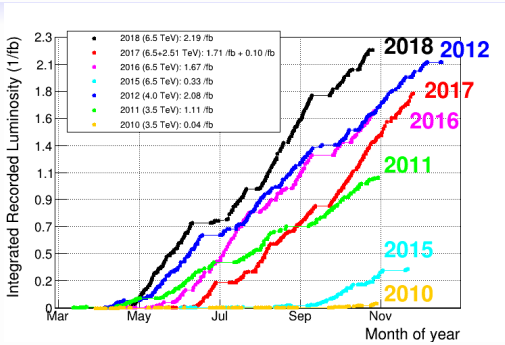
Overview of the LHCb Upgrade

LHCb successfully operated until the end of Run2, collecting $\sim 9 fb^{-1}$, delivering a successful physics programme, well beyond the original goals!





remove hardware trigger

all front-end electronics read out @40MHz

$2 \times 10^{33} cm^{-2} s^{-1}$

$50\ fb^{-1}$

CERN-LHCC-2008-007

CERN-LHCC-2011-001

CERN-LHCC-2012-007

CERN-LHCC-2013-021

CERN-LHCC-2013-022

CERN-LHCC-2014-001

CERN-LHCC-2014-016

CERN-LHCC-2018-007

CERN-LHCC-2018-014

CERN-LHCC-2019-005

a new experiment installed during LS2: maintain current reconstruction performance in harsher environment!

this talk: summarise a decade of RICH Upgrade, from design to the first year of operations

The importance of the RICH system

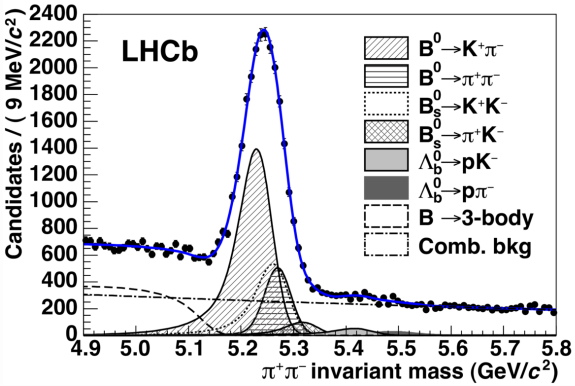
Reduce the combinatorial background

Distinguishing between final states with the same topology

b-hadrons two-body decays into charmless charged hadrons at LHCb

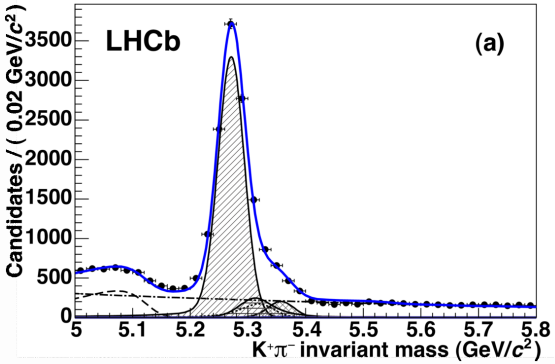
→ with PID

↓ without PID

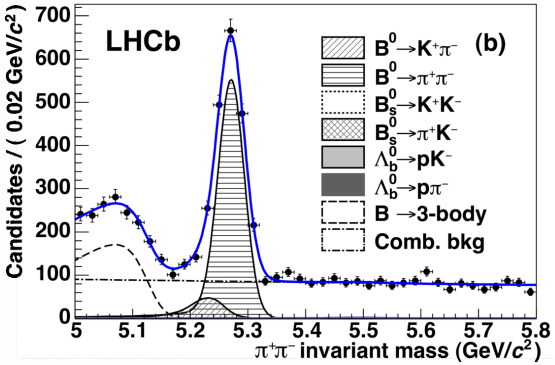


[LHCb, JHEP 10 (2012) 37]

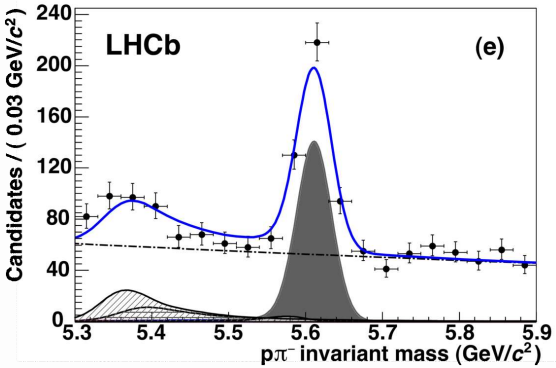
$B^0 \to K\pi$



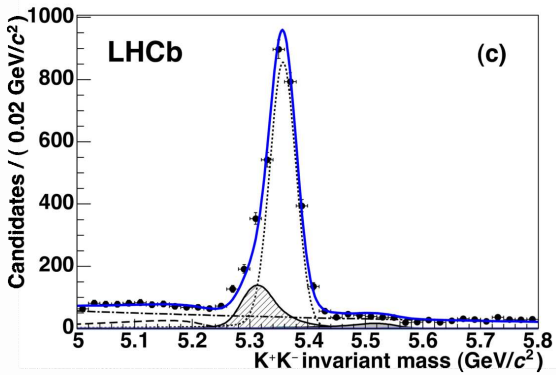
$B^0 \to \pi\pi$



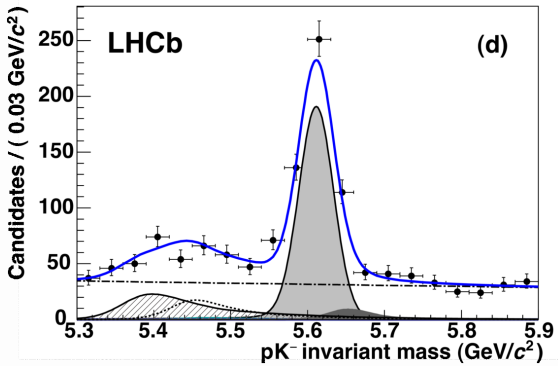
$\Lambda_b \to p\pi$



$B_s^0 \to KK$



$\Lambda_b \to pK$



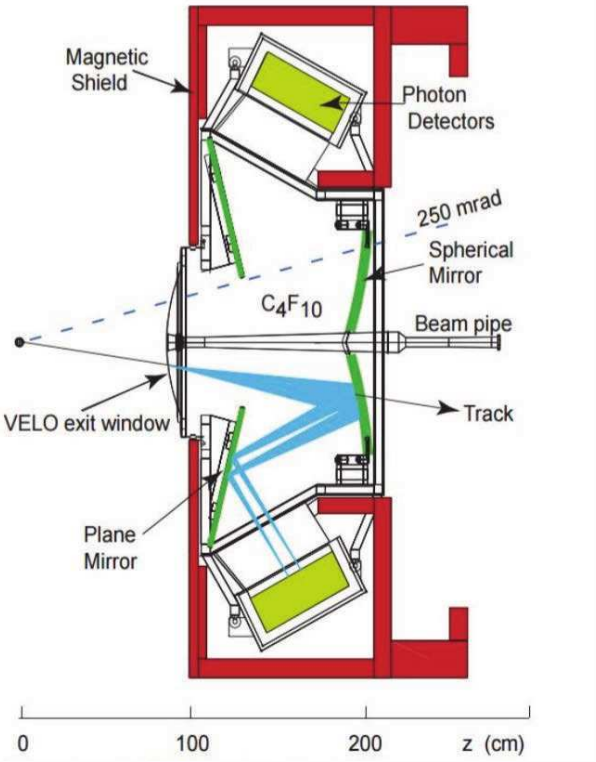
Hadron identification is a key ingredient in *b*-physics & hadron spectroscopy

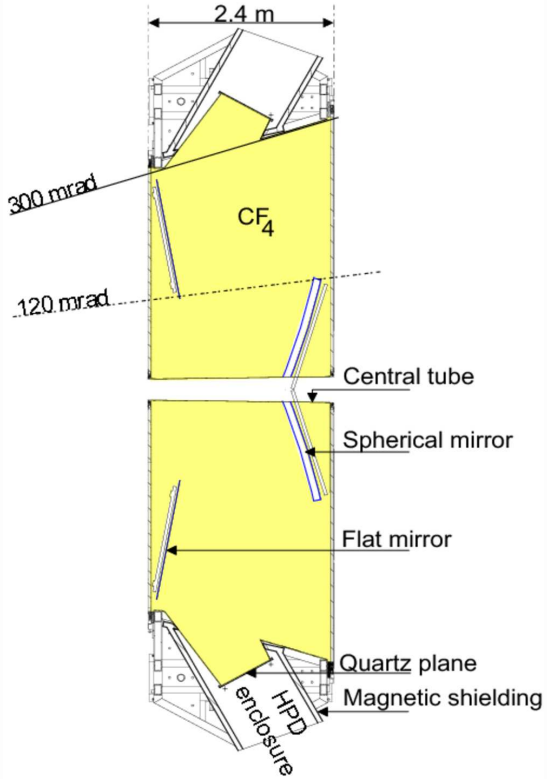
The RICH system at LHCb

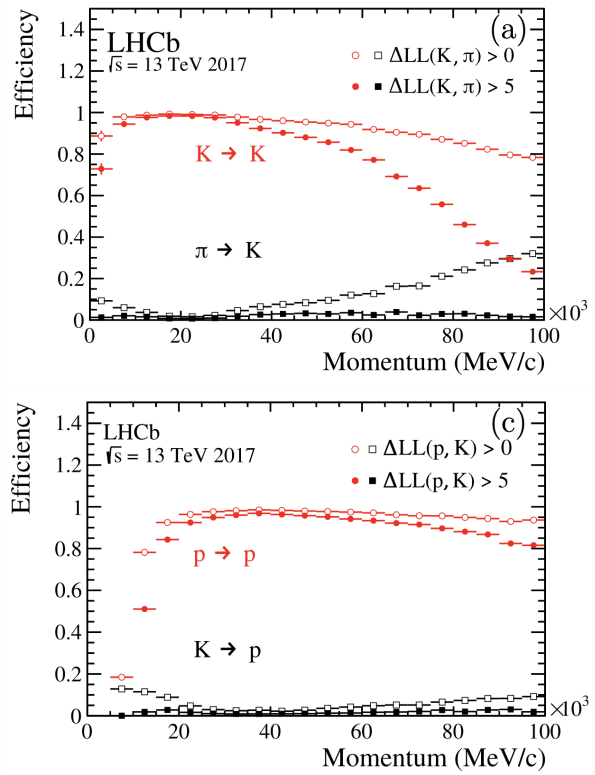
Two Ring Imaging Cherenkov detectors installed and operated in LHCb (2008-2018)

[Eur. Phys. J. C 73 (2013) 2431]

- RICH 1 (C_4F_{10}): upstream, 2 GeV/c - 60 GeV/c over 25 mrad - 300 mrad
- RICH 2 (CF_4): downstream, 30 GeV/c - 100 GeV/c over 15 mrad - 120 mrad





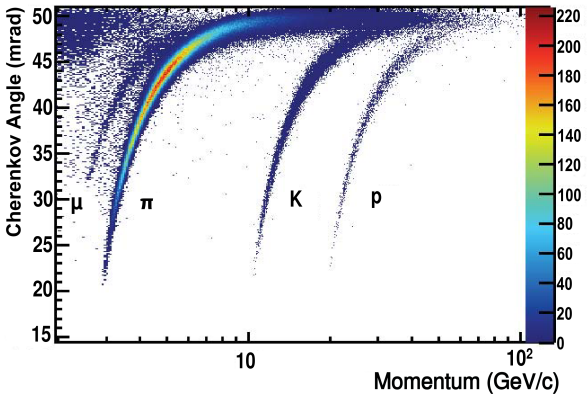


- gas enclosure containing radiator: Cherenkov photons from charged particles
- optical system composed by spherical and flat mirrors: magnification, focusing and reflection of photons
- opto-electronics chain composed by position sensitive photon detectors and electronics outside the LHCb acceptance: detection of rings

RICH performance = Cherenkov angle resolution

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

- σ_c is the resolution per single photon in a ring. The main contributions to keep under control (disk $\rightarrow$ ring) are:
  - emission point error due to the unknown emission point of the Cherenkov light: optimise the optics of the mirror system to focus the Cherenkov light
  - pixel size error due to the finite size of the photon detectors: choose photon detectors with optimal spatial granularity
  - chromatic error due to the radiator dispersion (different Cherenkov angles from the same track): appropriate choice of the radiator material to avoid large variations of the refractive index with the Cherenkov photons energy



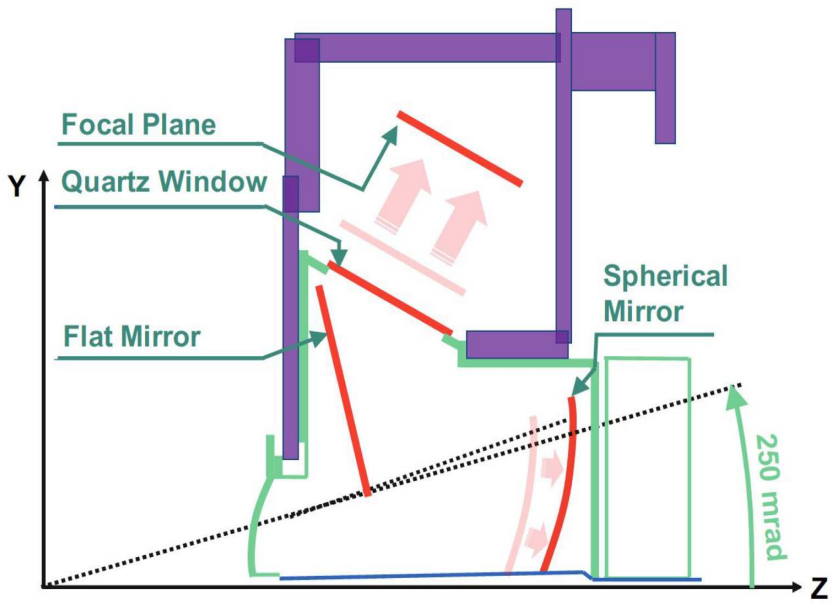
- photon yield (N_{ph}) as large as possible
- background counts as low as possible
- efficient pattern recognition keeping the peak occupancy under control (around 30%)

Excellent performance in Run 1 and 2 thanks to an overall single photon Cherenkov angle resolution $\sigma_c^{\text{RICH1}} \sim 1.7$ mrad and $\sigma_c^{\text{RICH2}} \sim 0.6$ mrad [JINST 17 (2022), P07013]

The RICH upgrade programme

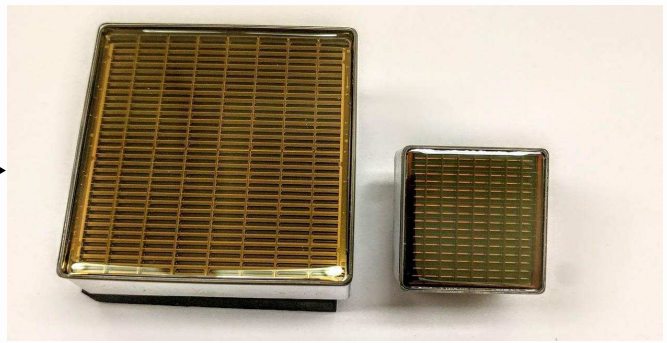
optics and mechanics:

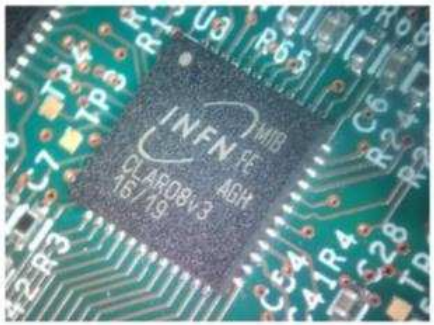
- keep peak occupancy $\sim 30\%$ to maintain PID performance
- need to redesign optics in RICH1 to spread photons over a larger area
- new mirrors, new gas enclosure, new quartz window... a fully new RICH1!
- new mechanics to support new opto-electronics chain in RICH1 and RICH2



opto-electronics chain:

- need to replace front-end electronics to operate at 40 MHz $\rightarrow$ HPDs have embedded electronics $\rightarrow$ need to replace HPDs $\rightarrow$ MaPMTs
- custom ASIC designed by the RICH group: Claro
- FPGA-based digital electronics equipped with GigaBit Transceiver (GBT) chip for data transmission

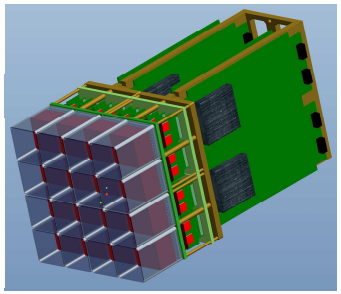




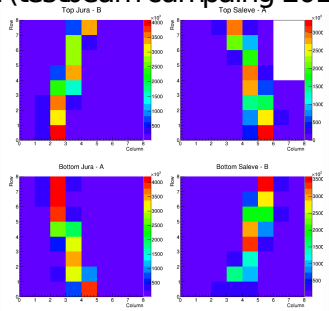

Opto-electronics chain

Timeline of the opto-electronics chain

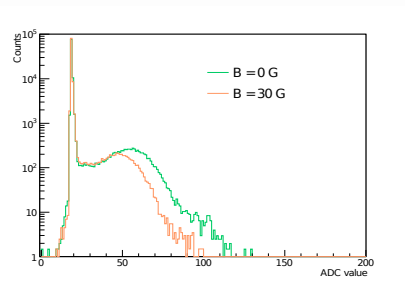
end of 2013: Technical Design Report
proposal of MaPMT module
HPD with external readout (backup)



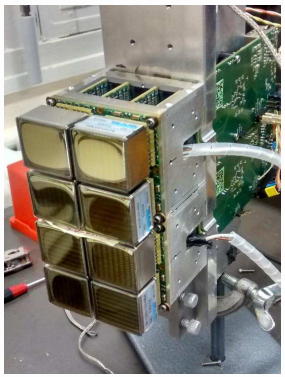
end of 2014: first concept of
Elementary Cell tested
on beam (testbeam campaing 2014-2018)



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



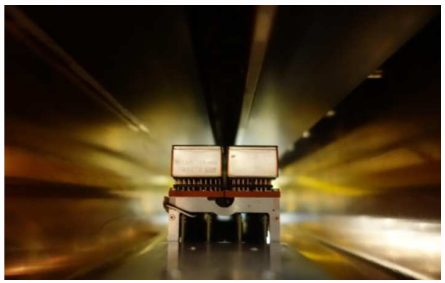
2015-2016: Elementary Cell validated
as basic unit of optoelectronics chain
Claro chip validate, Production Readiness Review



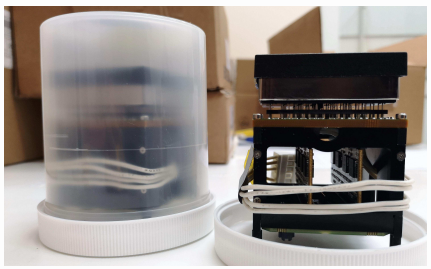
Photon Detector Quality Assurance
2016-2018
to qualify ~3500 units

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

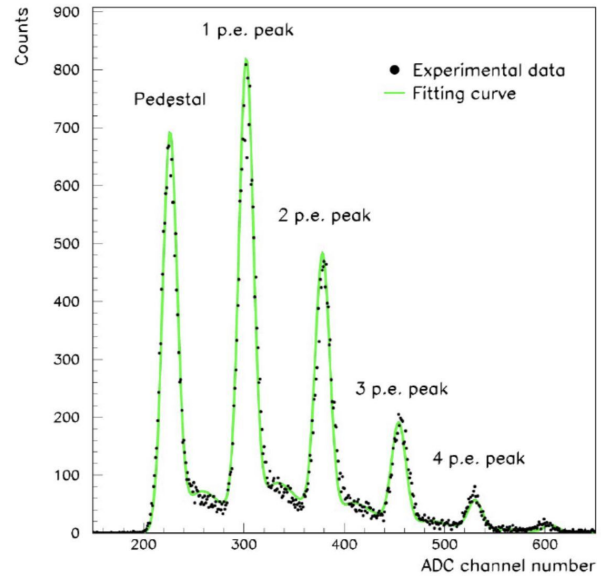
Photon Detectors

Hamamatsu Multi-anode Photomultiplier Tubes:

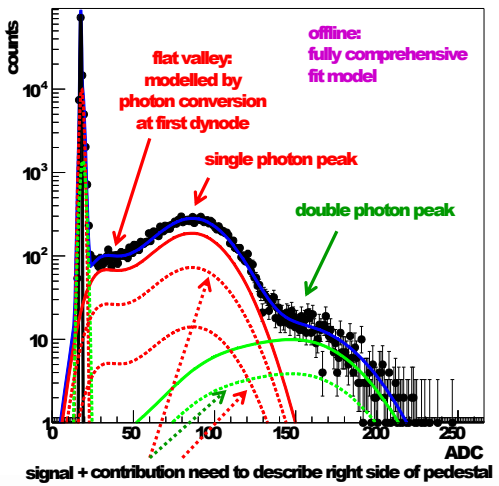
R13742 : 1 inch, 8x8 pixels, custom modification of R11265 for RICH1 and central region of RICH2 $\Rightarrow \sim$ 3100 units, including spares
[Nucl.Instrum.Meth.A 766 (2014) 156-159]

R13743 : 2 inches, 8x8 pixels, custom modification of R12699 for RICH2 peripheral region of $\Rightarrow \sim$ 450 units, including spares [JINST 10 (2015) 09, P09021]

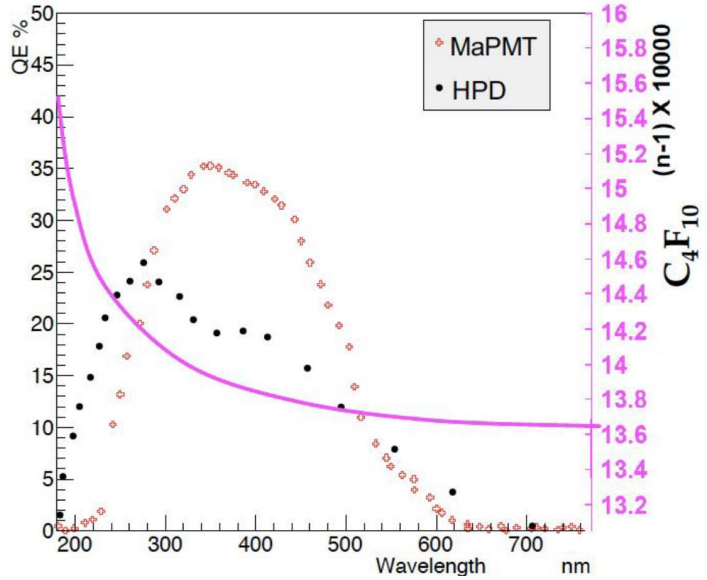
typical single photon spectrum (HPDs)



typical single photon spectrum (MaPMTs)



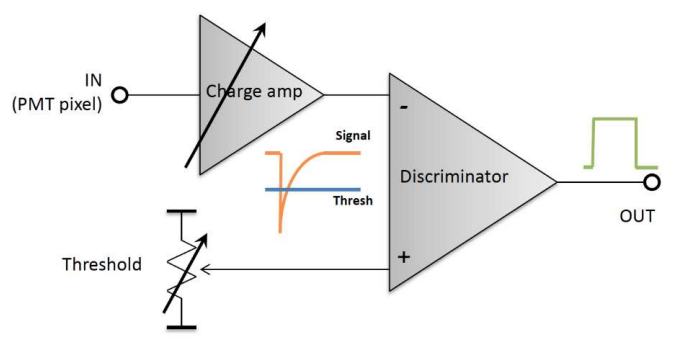
typical QEs and C_4F_{10} refractive index

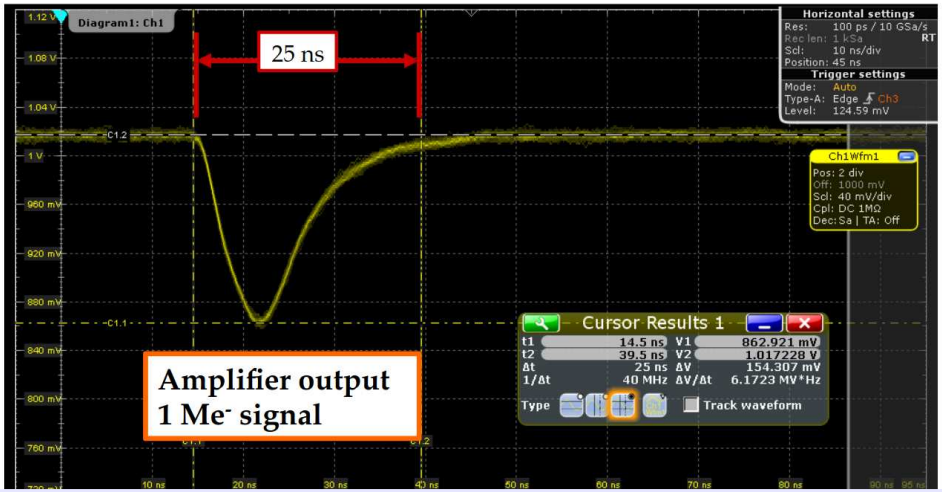


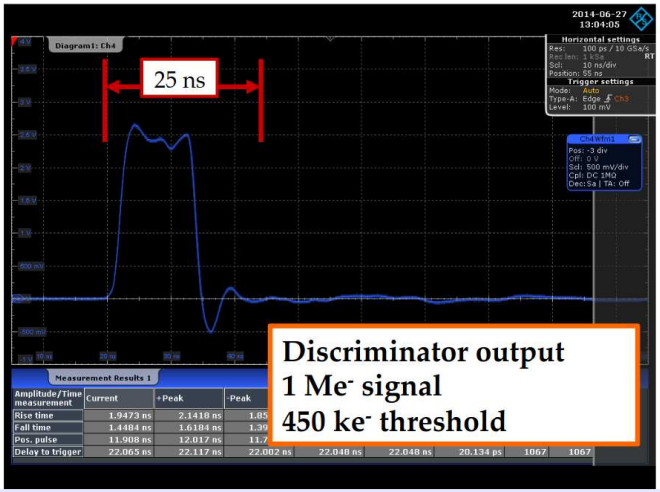
- robust technology with excellent spatial resolution, low noise, high active area (83%), high gain
- signal to noise separation more delicate than in HPDs: characterisation and study of performance key to correct operations
- excellent Quantum Efficiency: increase in photon yield while lowering chromatic

The Claro ASIC

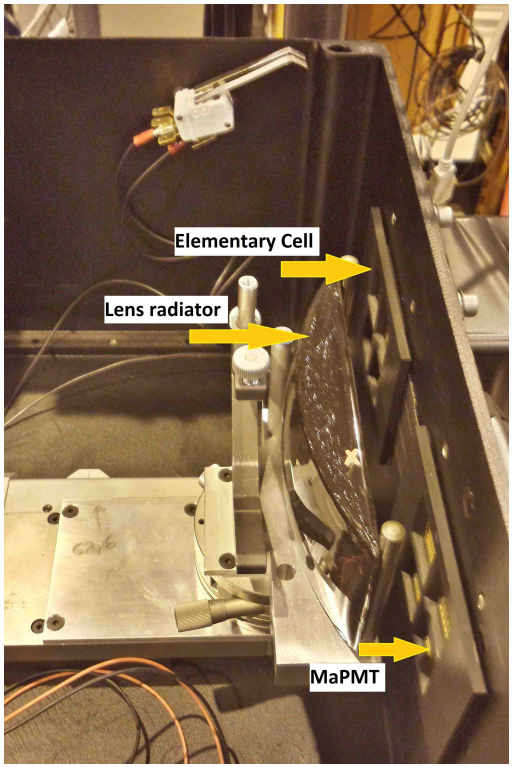
- 8-channel amplifier/discriminator ASIC (Ferrara, Kracow and Milan Bicocca)
- designed and optimised for single-photon counting with MaPMTs
- 0.35 μm CMOS technology from AMS (low cost, high yield)
- 40 MHz operation (recovery time <25 ns)
- low power consumption ~1 mW/channel
- adjustable threshold and gain (6+2 bits), to compensate for MaPMT gain variation
- binary read-out
- 128-bit register protected by triple modular redundancy
- radiation-hard by design cells

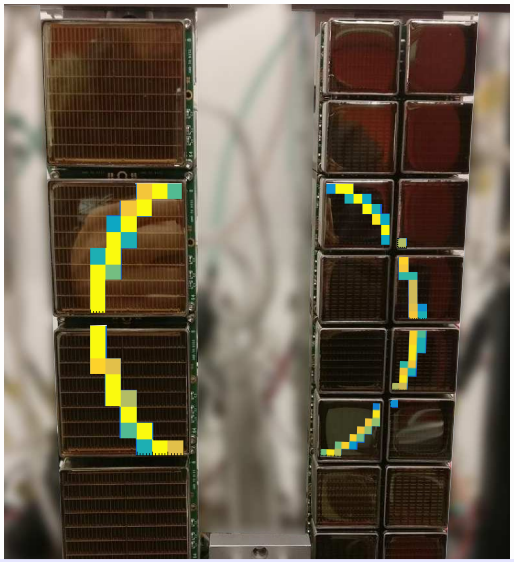






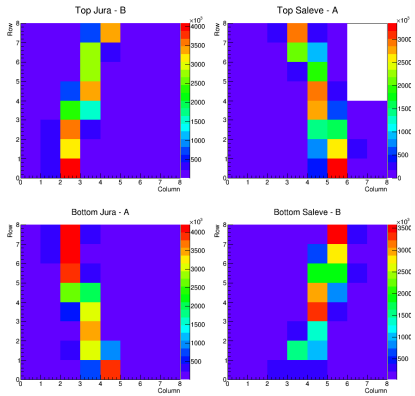
The testbeam campaign





- 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 solid radiator and focusing element
- well characterised optical setup allowing to perform data/simulation comparison, e.g. on the photon yield

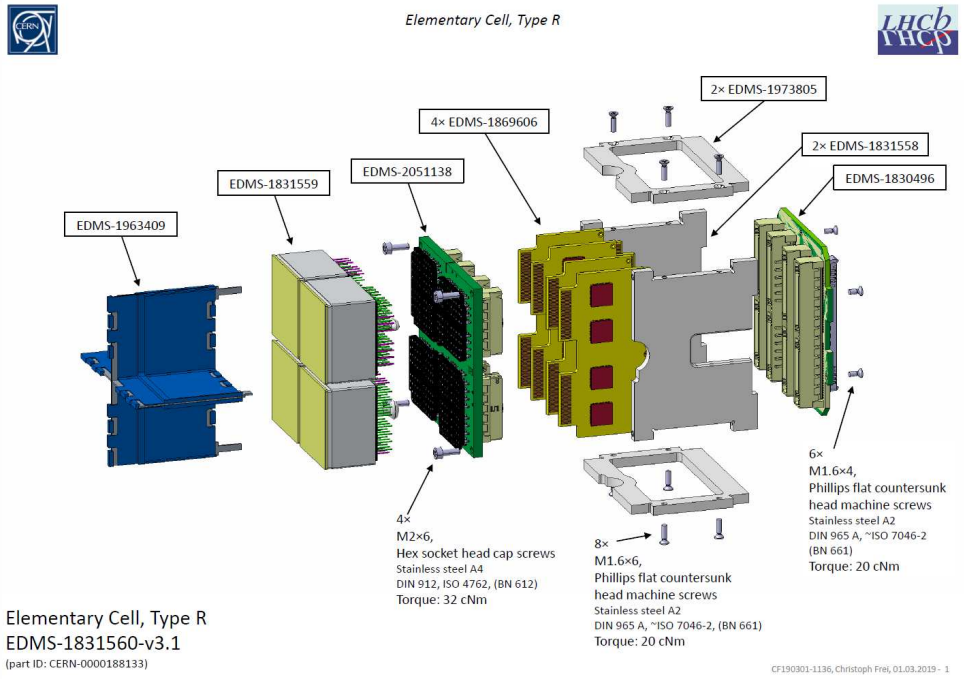
  [JINST 12 (2017) 01, P01012]

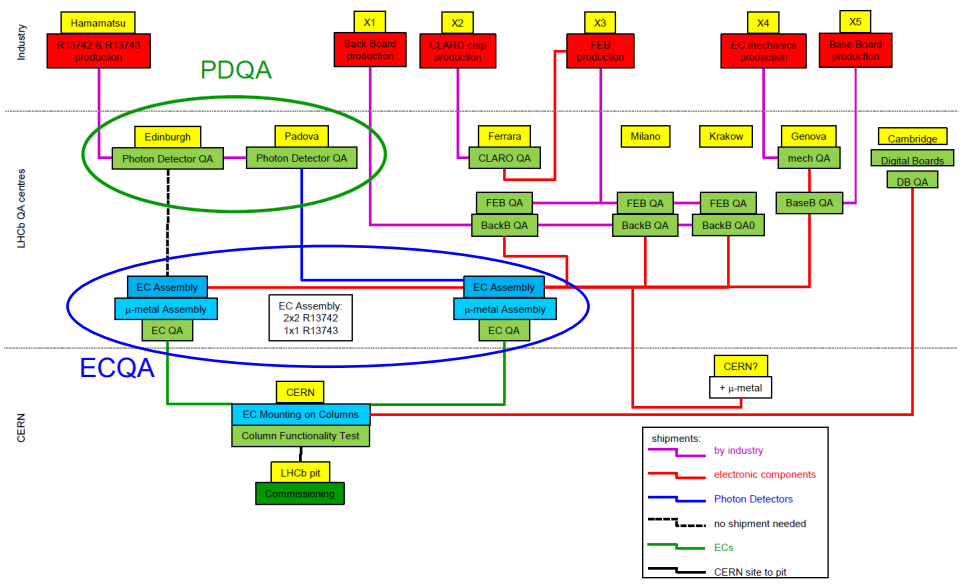


	Data		Simulation		Analytical estimate
	mean	RMS	mean	RMS	mean
Total	13.4	3.8	13.1	2.9	-
PMT A	3.6	1.7	3.1	1.5	3.8
PMT B	3.3	1.6	3.1	1.5	4.1
PMT C	4.4	1.9	3.3	1.5	3.9
PMT D	4.2	1.8	3.3	1.5	4.1

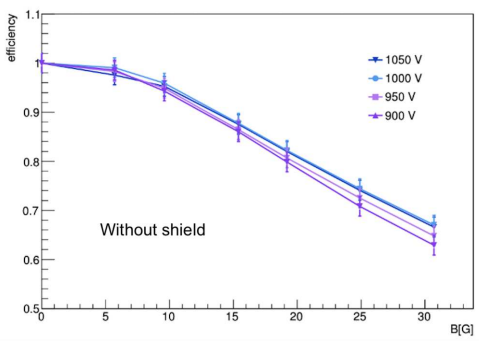
- validation of opto-electronics chain and design of modular unit: the Elementary Cell
- intense and continue testbeam campaigns up to 2018
- validation of components prior to production
- larger systems to validate grounding and shielding strategy and integration with LHCb new DAQ system

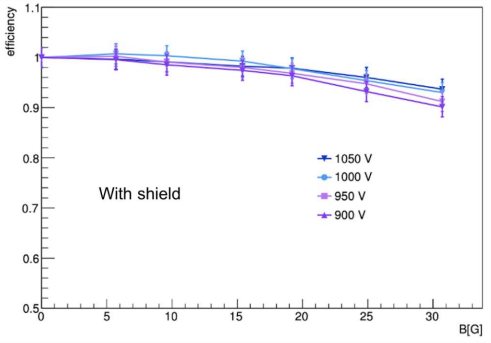
The Elementary Cell





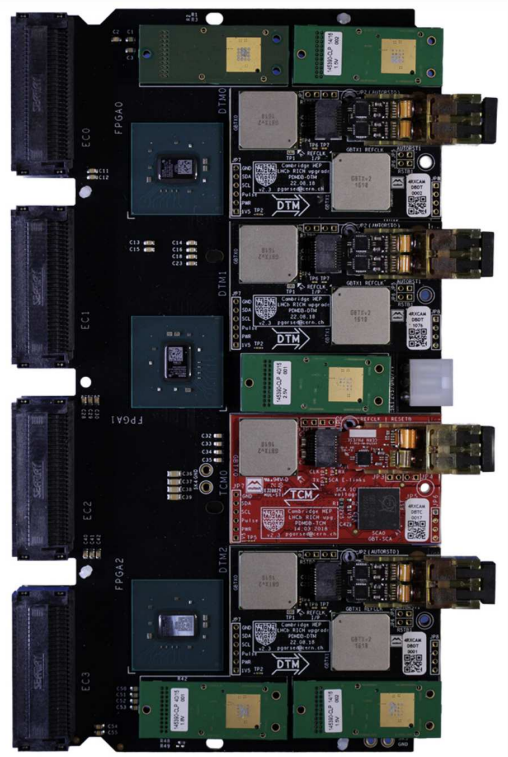
- MaPMTs
- baseboard: HV delivered to MaPMTs, analog output collected (Genova)
- front-end board: Claro ASIC chip, digitisation of signal (Ferrara)
- backboard: digital output delivered to readout (Ferrara)
- aluminium case: support structure (Genova)
- two types of EC: EC-R (4 R13742) in RICH 1 and central part of RICH 2; EC-H (1 R13743) in outer regions of RICH 2
- magnetic shield foreseen only in RICH 1: peak residual field < 30 G
- shield designed to maintain the active area of the EC (CERN, Edinburgh, Genova)

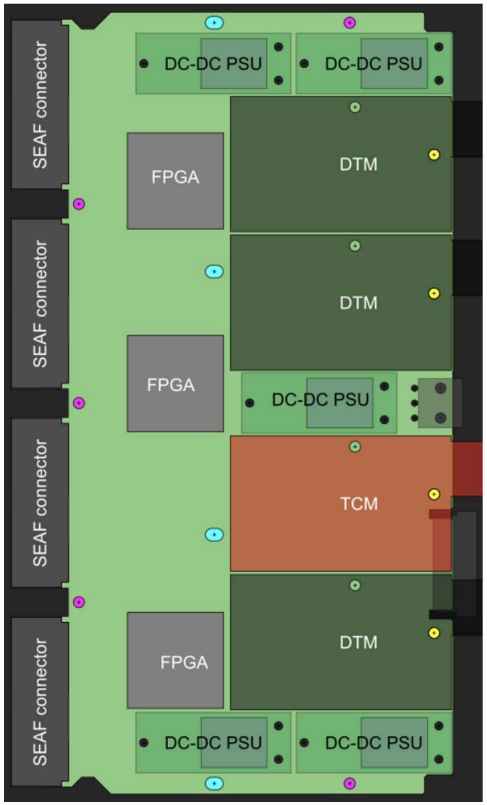




intricate logistics plan of production of components, QA campaigns across Europe to converge on final assembly and commissioning at CERN

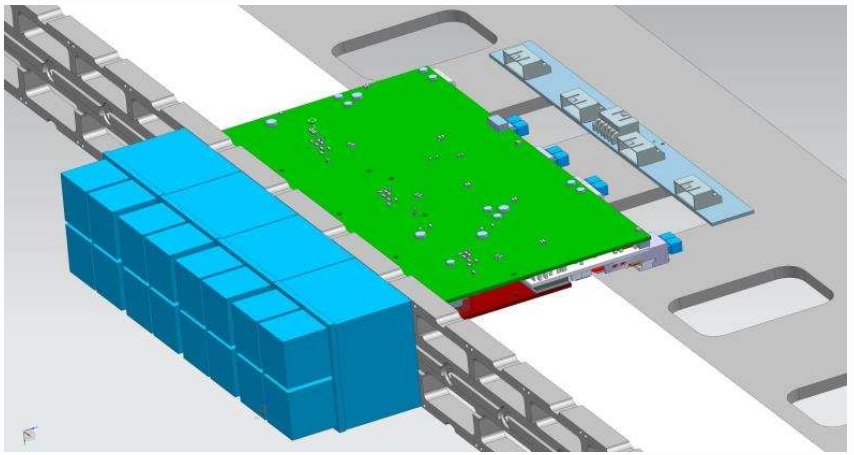
The Photon Detector Module



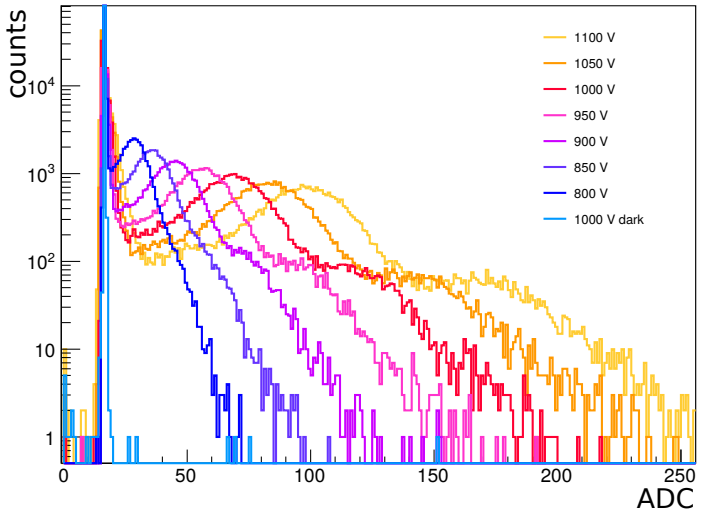


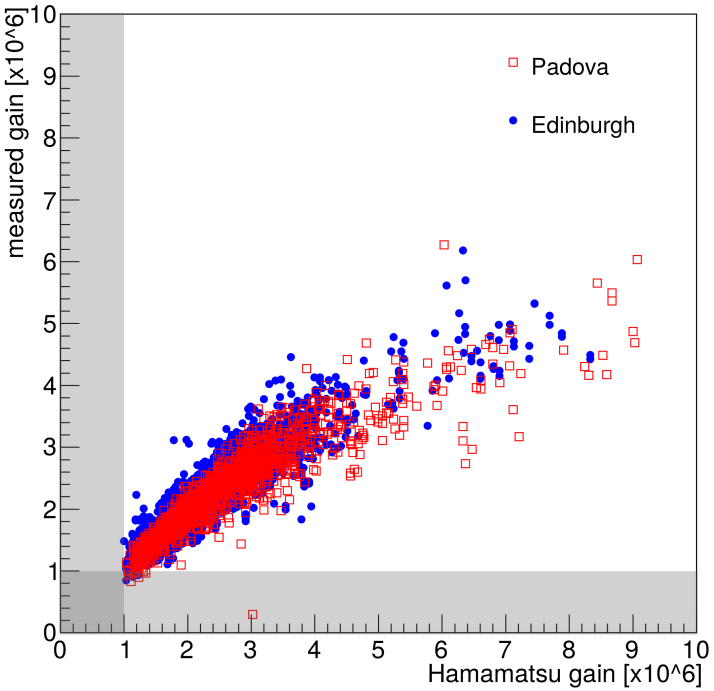
- front-end digital board: capture CLARO outputs, synchronise to LHC clock, data algorithm, format and transmission
- motherboard with FPGAs and power distribution, PDMDB (Cambridge)
- plugins for controls and data transmission, DTM and TCM (Cambridge)
- each element with dedicated quality assurance programme (Bucharest, Cambridge and Oxford)

- two flavours of PDMDBs, one for each type of EC
- one PDMDB-R served four half EC-R
- one PDMDB-H served four EC-H
- EC+PDMDB form the logical unit called the Photon Detector Module: share common LV and HV distribution



Photon Detector Quality Assurance



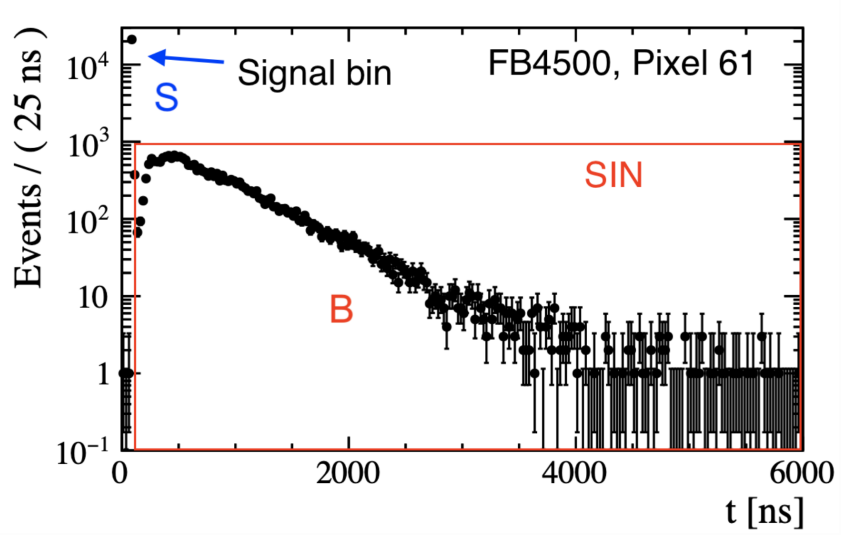


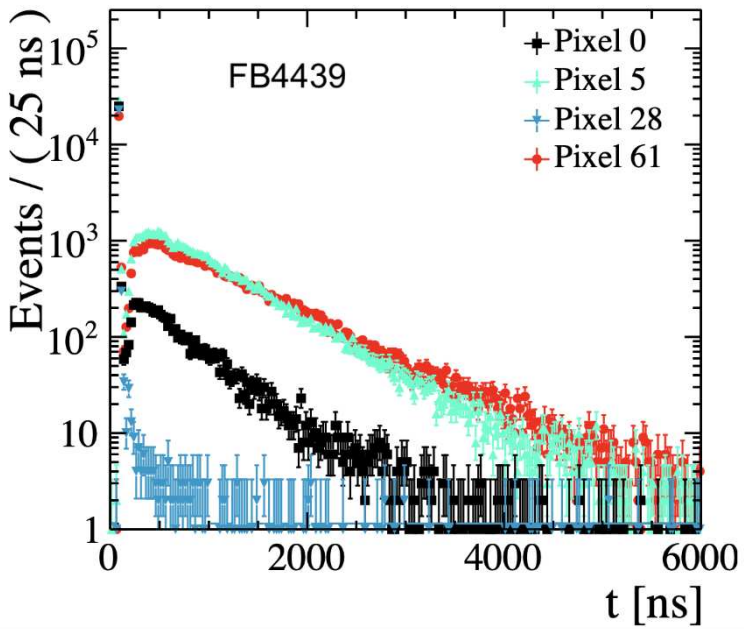
- verify minimal contractual specifications
  - gain: $> 10^6$ at 1 kV
  - uniformity: $1 \div 4$ R12742 and $1 \div 3$ R13743
  - dark count rate: $<$ 1kHz per pixel, total dcr $<$ 25 kHz in R13742 and $<$ 72 kHz in R13743
  - peak-to-valley ratio: up to 3 pixels with $P/V < 1.3$
- gain per pixel determined at 1000 V $\rightarrow$ 800 V in steps of 50 V
- very large number of units to test in two years ($\sim$ 3500): high level of automation needed!
- two facility built: one in Edinburgh and one in Padova
- over 1.5M spectra fitted successfully
- determine parameters for the selection of photon detectors: grouping in EC and placement in photon detector planes
- gather initial calibration variables
- very low rejection rate: 2.1% R13742 and 8.2% R13743)

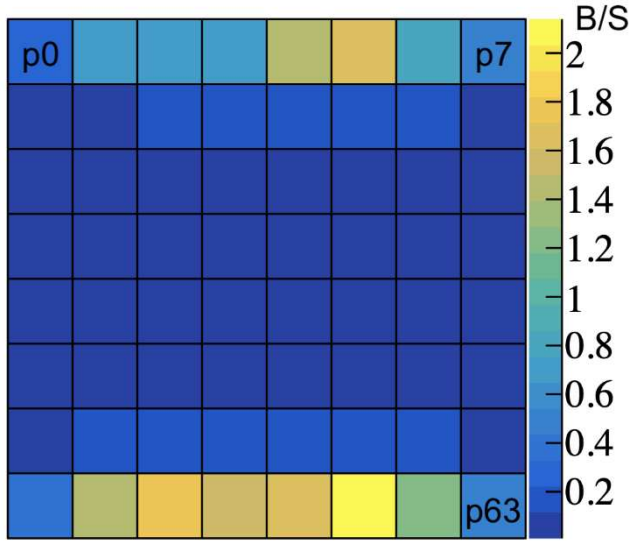
[NIM A 876 (2017) 206-208]

Signal-Induced Noise

- one photon detector module installed inside RICH2 and operated in 2018 in realistic conditions
- detection of out-of-time hits in R13742 tubes, delayed with respect to the expected arrival time of Cherenkov photons, indicating an unexpected source of noise
- noise present only in correlation with signal and located in specific areas of the MaPMT
- absolute value of SIN varying by unit, no obvious correlation with MaPMT gain or other properties of the unit

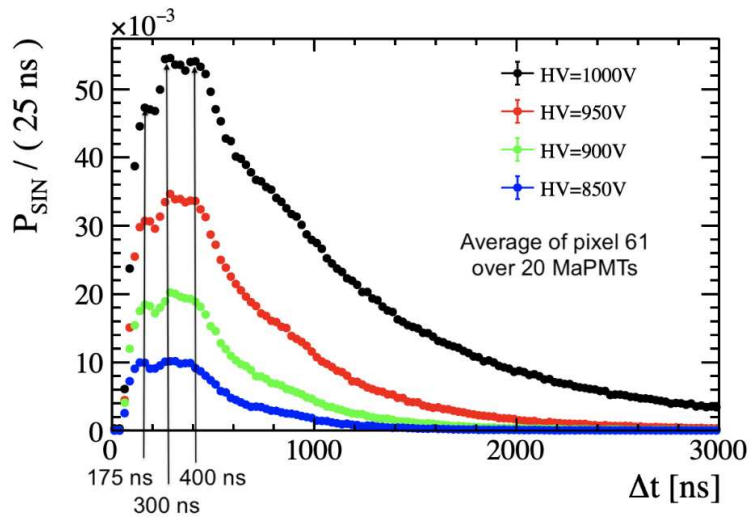


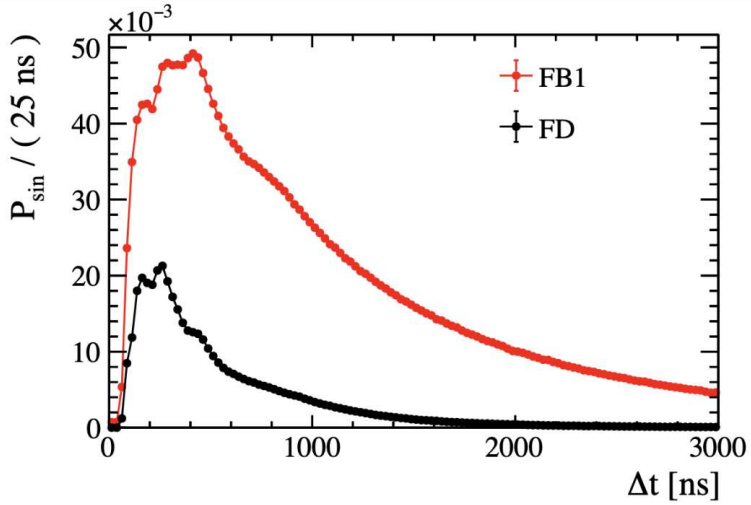




The Elementary Cell Quality Assurance

- 1 inch MaPMTs grouped by gain and assembled in 800 EC-R
- 2 inches MaPMTs mounted on 450 EC-H
- electronics boards composing the ECs tested in dedicated QA facilities and shipped to two centres for ECQA: Edinburgh and Ferrara
  - connectivity check and basic functionality
  - full calibration of Claro channels (thresholds and gains)
  - characterisation of MaPMTs at different HV values
  - dedicated characterisation of SIN at different HV values
- large pool of data acquired allowing to complete study of SIN and prepare further regrouping based on both gain and SIN
- HV is the main mitigation to reduce SIN: ECQA data central to define operating parameters of the detectors
- mechanical mitigation implemented by Hamamatsu: sub-set of units procured for most critical areas of the RICH system





mechanism consistent with internal light emission and fluorescence decay

[JINST 16 (2021) 11, P11030]

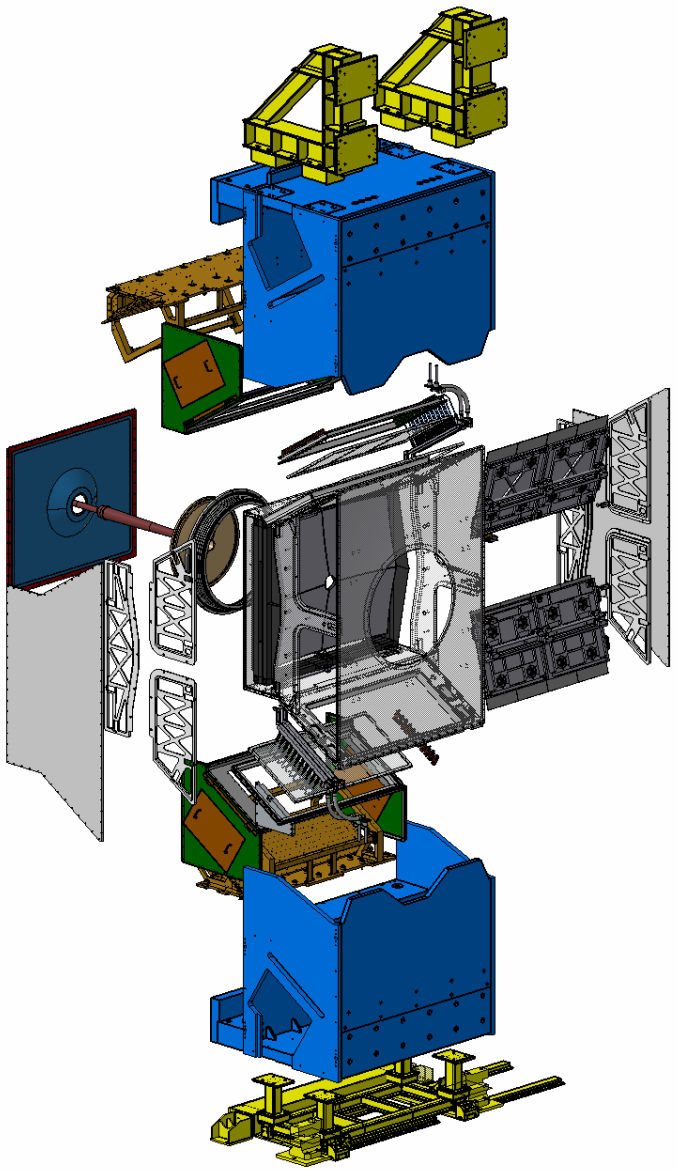
Optics and mechanics

RICH1 mechanics: 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: each composed by 3 panes coated against reflections and glued (Oxford, CERN)
- RICH1 sealed to Velo on the upstream side
- new carbon fibre exit window sealing the gas enclosure downstream (RAL)
- new flat mirrors: 16 glass planar segments (Bristol, CERN)
- new spherical mirrors: 4 CFRP segments (Bristol, CERN)

- new MaPMT enclosures equipped with new chassis to host opto-electronics chains mounted on columns (Imperial, Oxford)
- new tooling for installation and maintenance

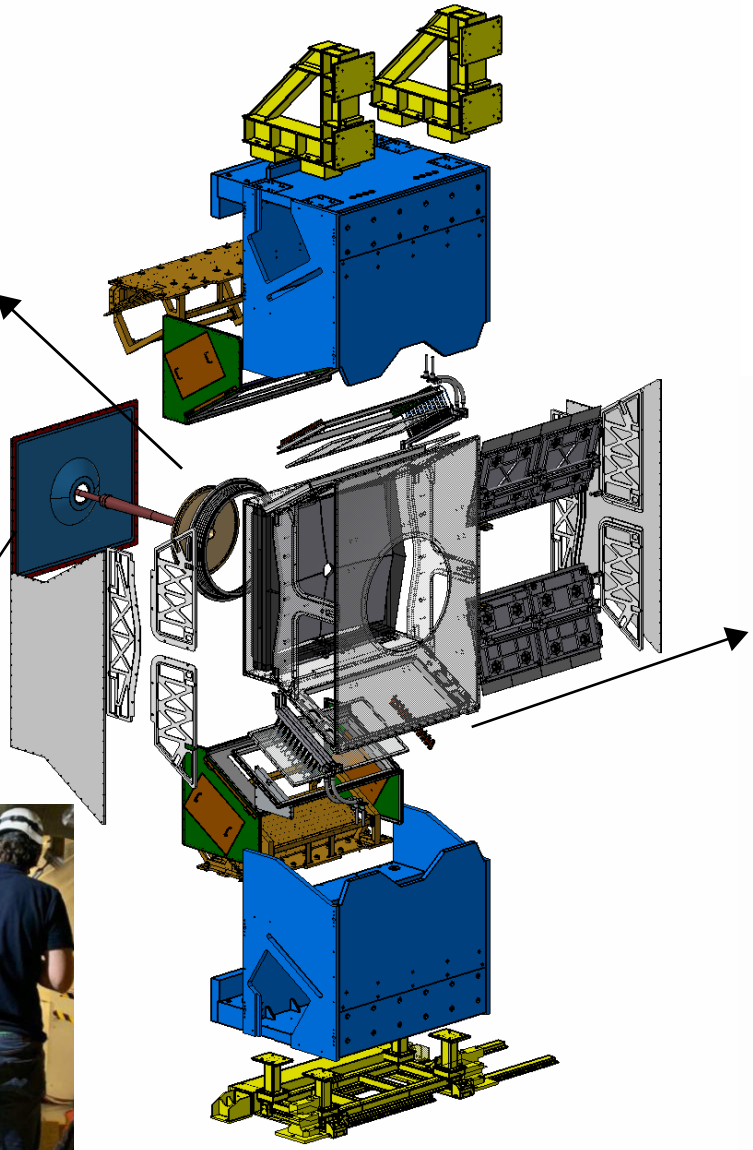
full re-design by RICH UK groups
gluing of mirrors and quartz panes at CERN
coating of quartz and mirrors by EP-DT Thin Film and Glass Service (TFG)

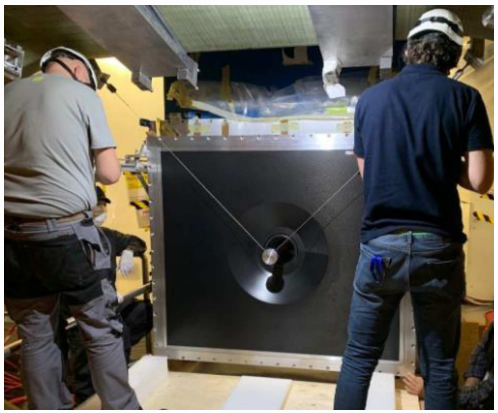


RICH1 mechanics installed in 2020 and 2021

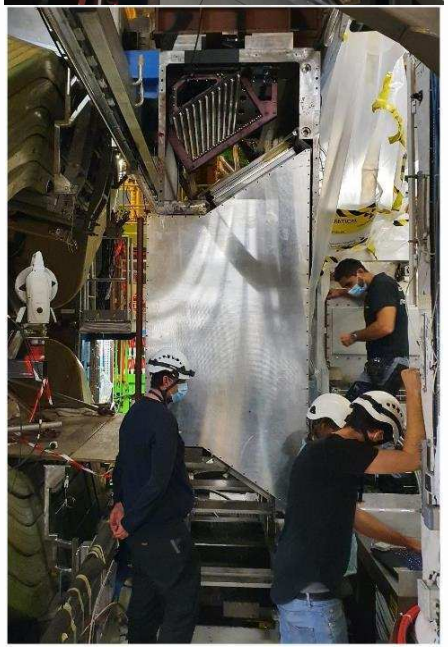
The RICH1 mechanics installation

Seal to VELO





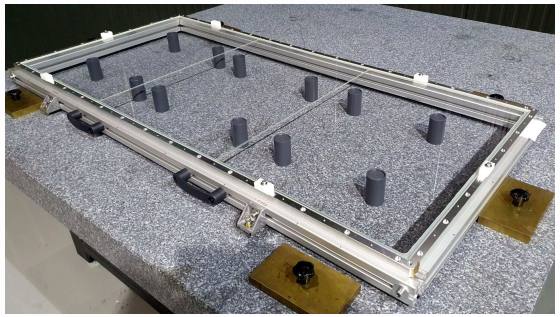
exit window

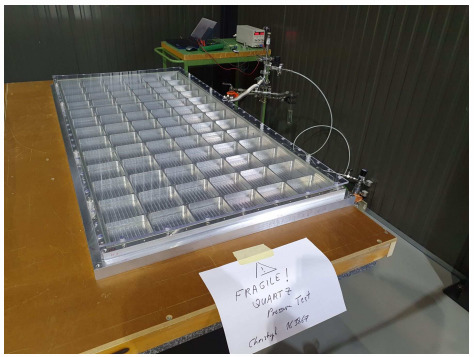


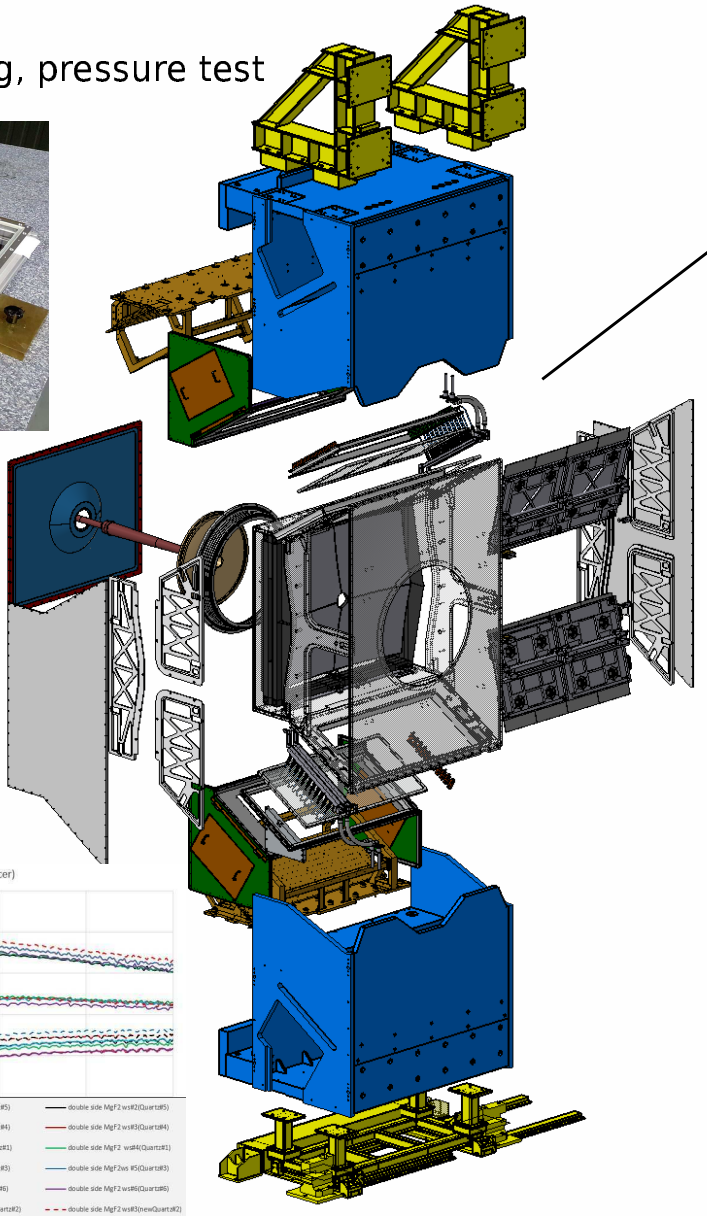
gas enclosure

The RICH1 mechanics installation

quartz window: coating, gluing, pressure test

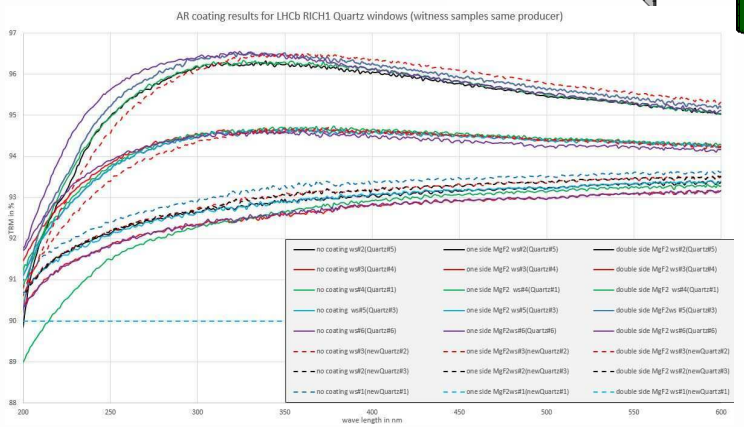




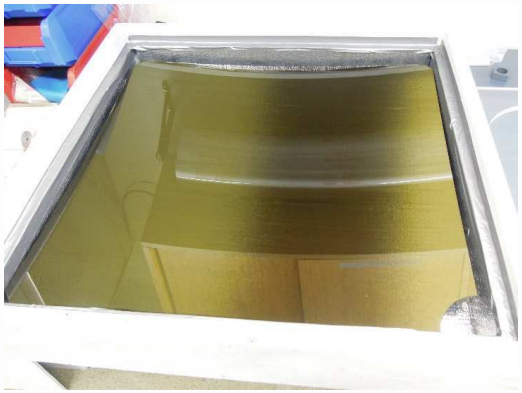


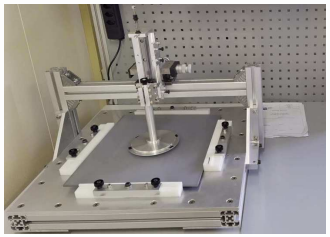
quartz window (up)

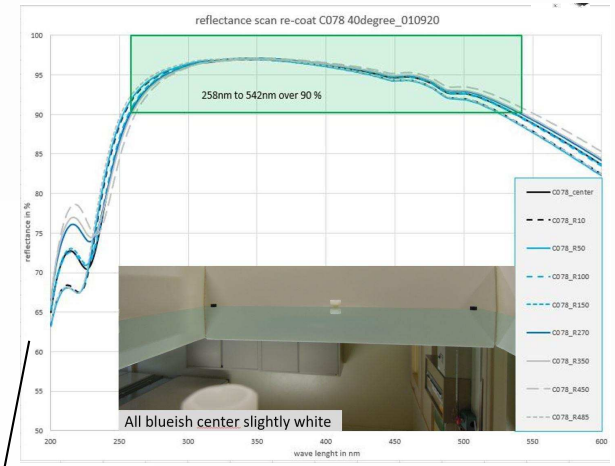
quartz window (down)



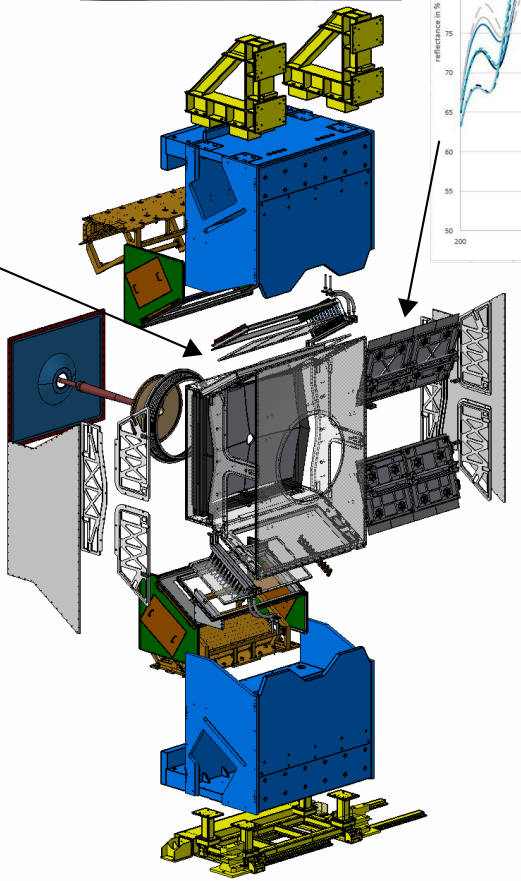
The RICH1 mechanics installation



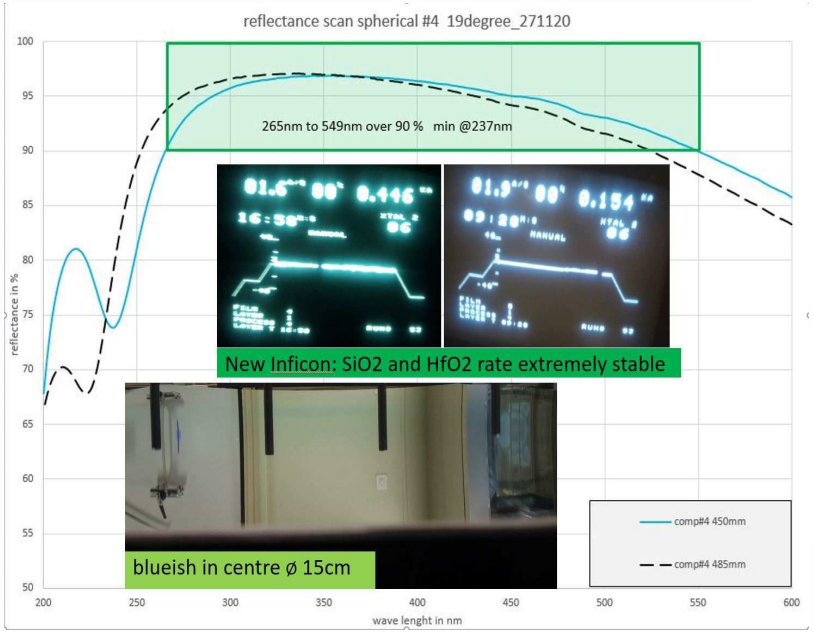


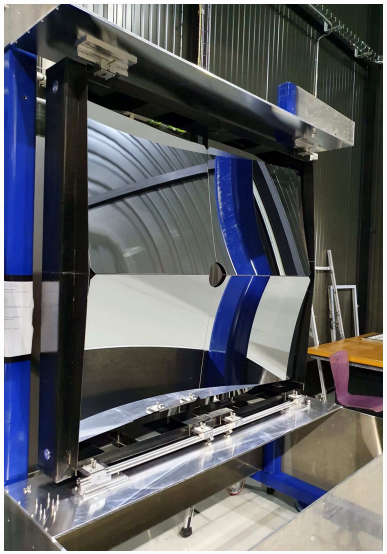


spherical mirrors



flat mirrors

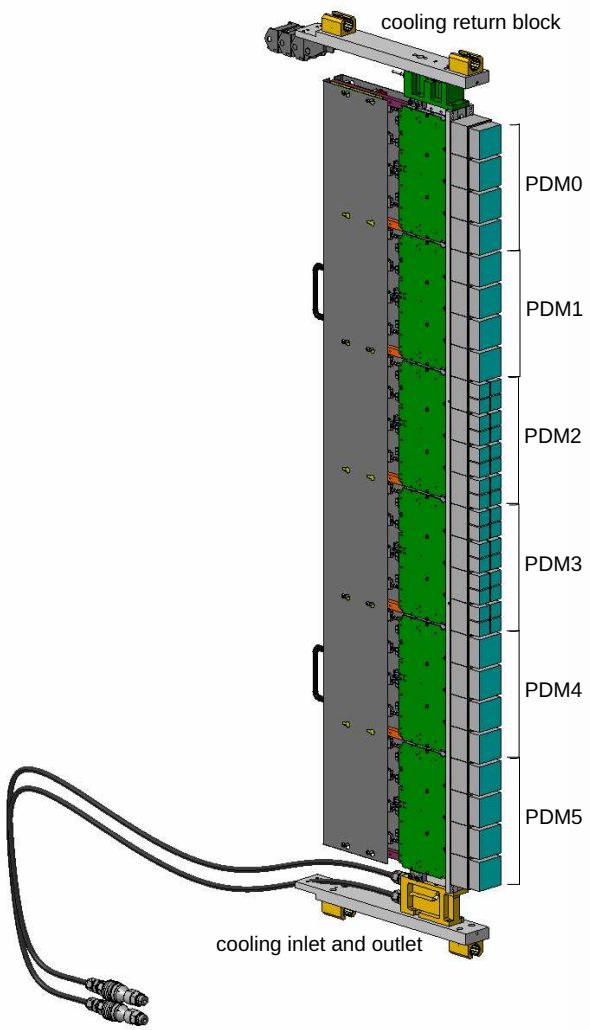




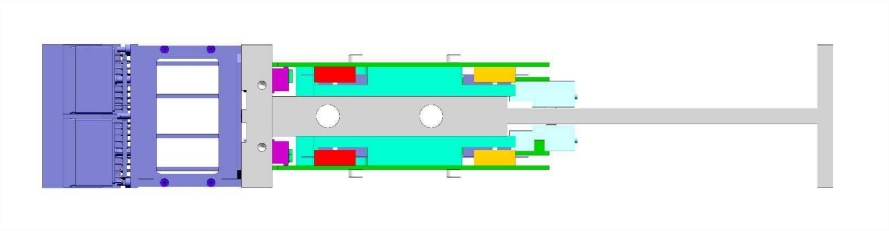
spherical mirrors alignment

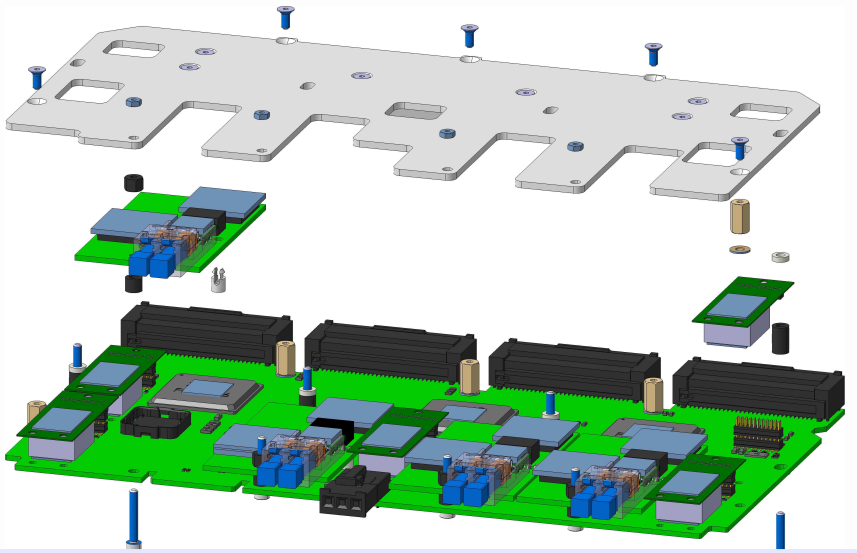
RICH mechanics: columns

columns: mechanical support structure for opto-electronics chain and services



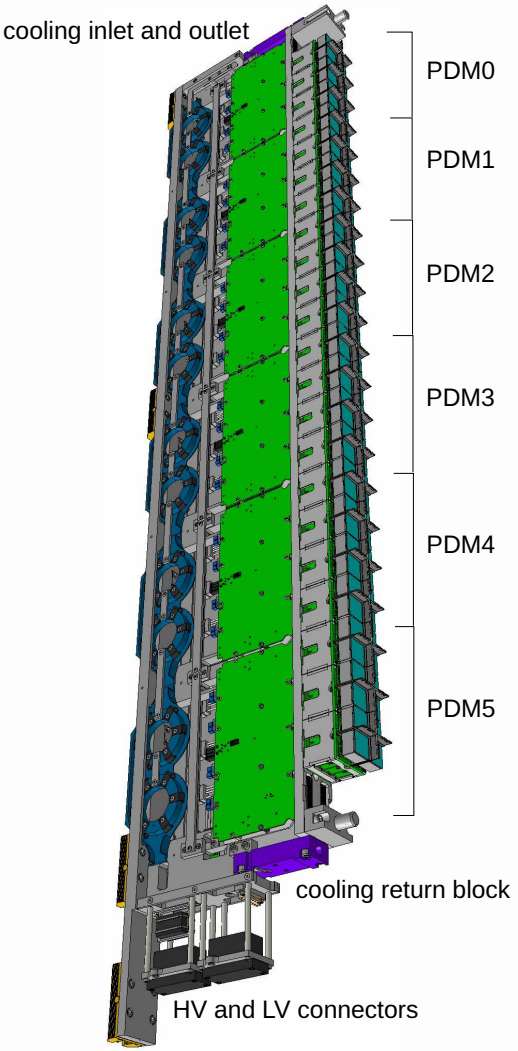
- T-shaped aluminium bar (Padova): 1.6 m support structure and active cooling element
- 6 mm ducts deep drilled along T-bars, Novec employed as coolant
- PDMDB equipped with thermal pads and levelling plate to maximise coupling to the T-bar
- T-bar design common to RICH1 and RICH2, dedicated design of harness and services (Imperial and Padova respectively)



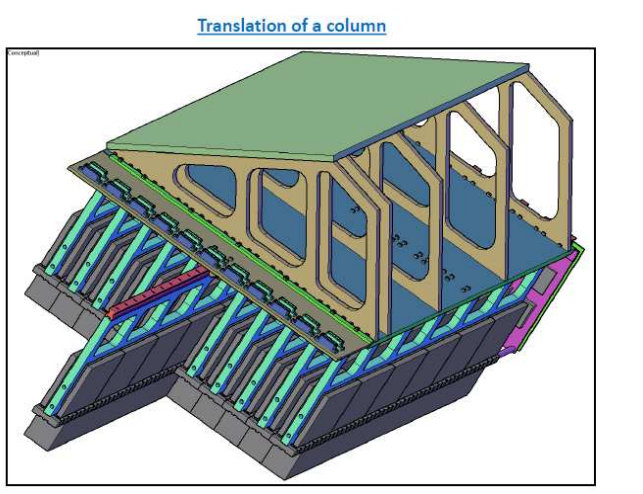


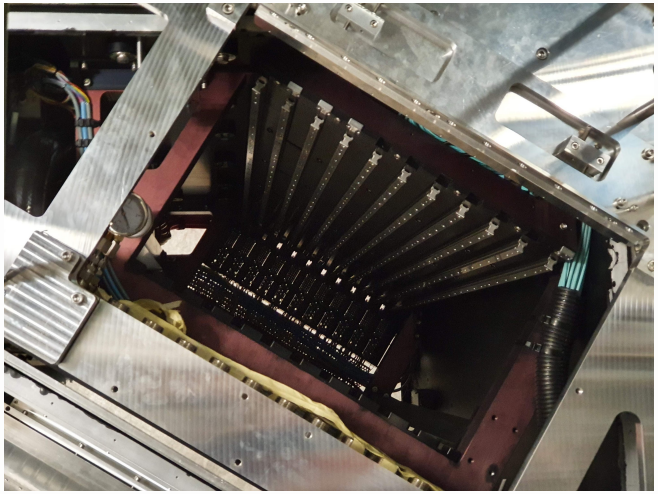
Novec circulated at $\sim 16^{\circ}C$ ensures MaPMT temperature at $\sim 25^{\circ}C$

RICH1 columns and housing



- design of RICH1 columns and housing especially delicate due to very little space available and the need for easy accessibility for interventions
- harness and services distribution extremely compact: LV and HV distributed via patch panel connector plugged at column insertion
- new chassis design allowing interventions extracting individual columns (former RICH1 design requiring extraction of entire photon detector box)



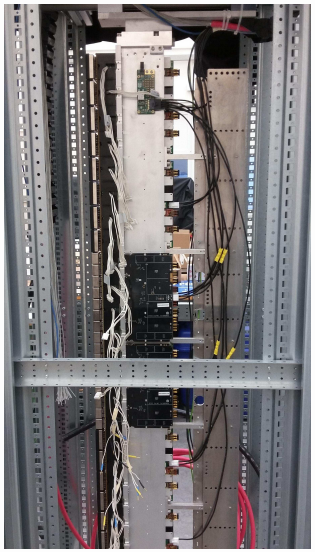


Columns assembly, commissioning and installation

Column commissioning programme

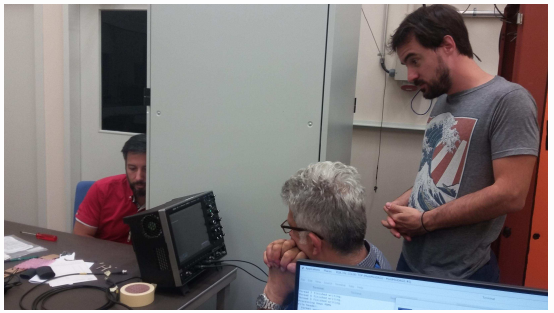
opto-electronics chain components shipped to CERN after quality assurance to be mounted on columns: column commissioning the last QA programme in the laboratory merging all previous QA on final mechanics

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 column production

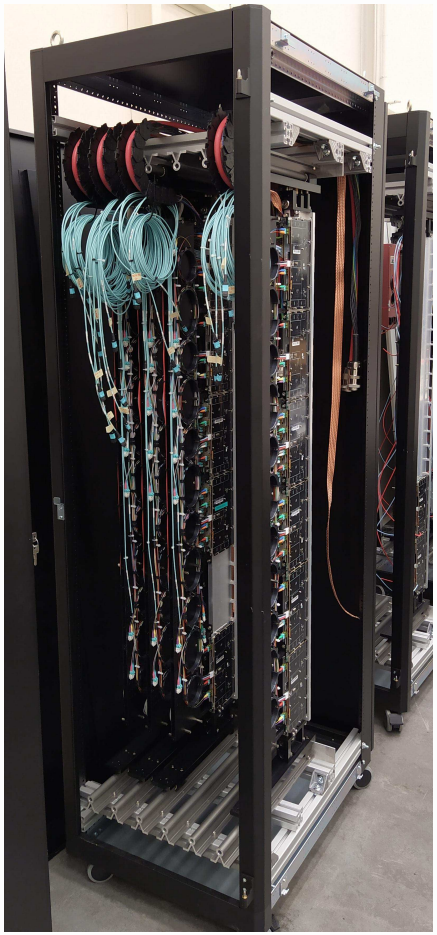
cabling started in October 2019
assembly completed in December 2019

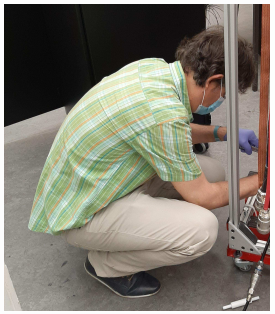
work in parallel on all elements composing the RICH2 columns

RICH2 column commissioning: pilot project at CERN

column commissioning interrupted temporarily in 2020 due to pandemic and resumed as pilot project thanks to the invaluable local support

Assembled columns in ComLab
select next column to test from cabinets





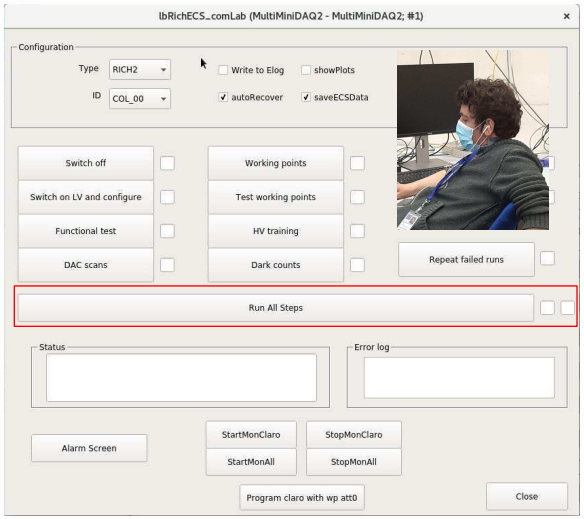
Check cooling tightness

Elementary Cells mounted on column

Column installed in SSB

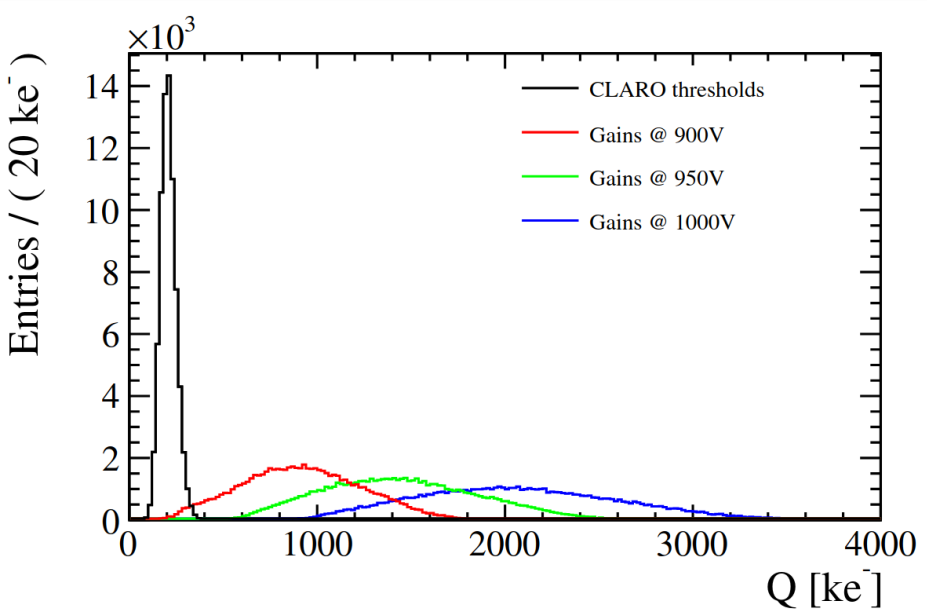
Start of commissioning protocol::

1) connectivity tests
2) automated test protocol



Column commissioning protocol

- initial functionality test (switch on LV, HV, check channel connectivity, check temperature sensors)
- perform set of test pulse injection scan to re-calibrate Claro thresholds and gains (15 scans)
- 2 sets of threshold scans to determine 2 sets of working points for each channel
- HV training for one night followed by dark count measurement

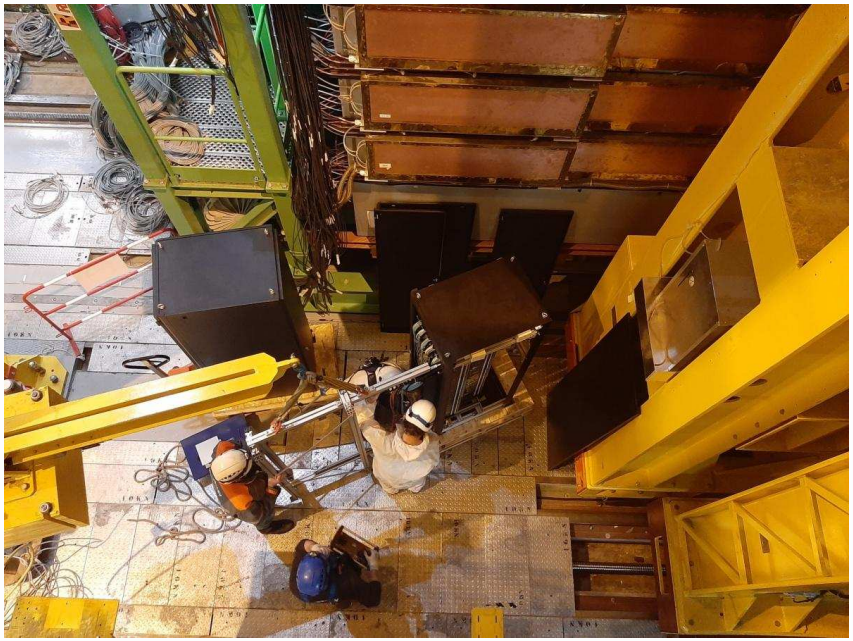


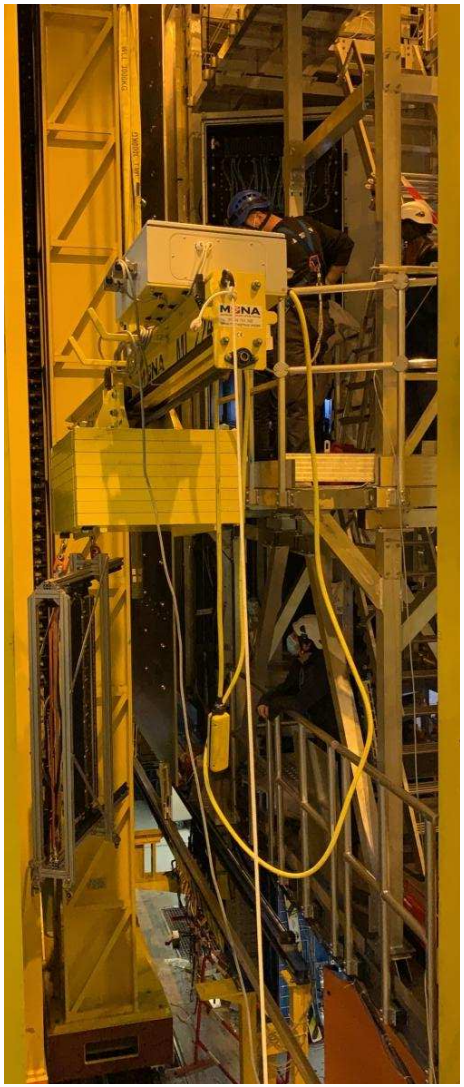
- set of threshold scans with different settings to characterise gain of each MaPMT pixel at different HV values (20 scans)
- set of runs, with WP defined during commissioning procedure, at different HV values and offsets in time to re-characterise SIN (15 runs)

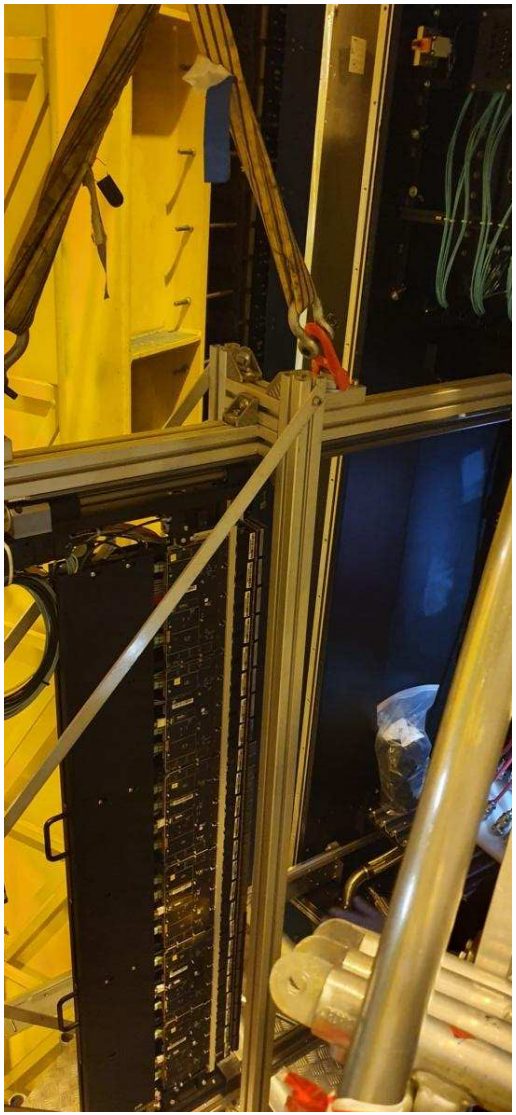
column commissioning conceived to fully validate hardware, gather operating parameters, evaluate performance before operations including high level operations: time alignment of all channels within 25ns performed for the first time in the lab

high level of automation: very robust firmware, very advanced controls development already in WinCC prior to installation in the cavern following the philosophy of reproducibility, redundancy and anticipation

RICH2 installation procedure







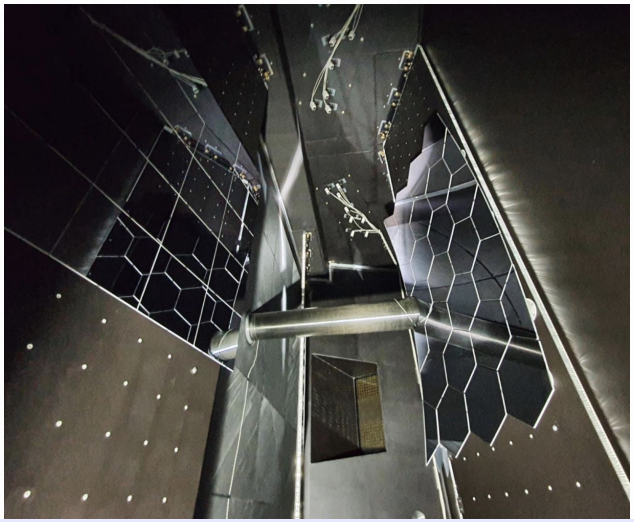
- rack housing columns installed
- column transported with cabinet to P8, extracted and inserted in dedicated frame
- frame lifted to RICH2 tower
- column inserted into RICH2

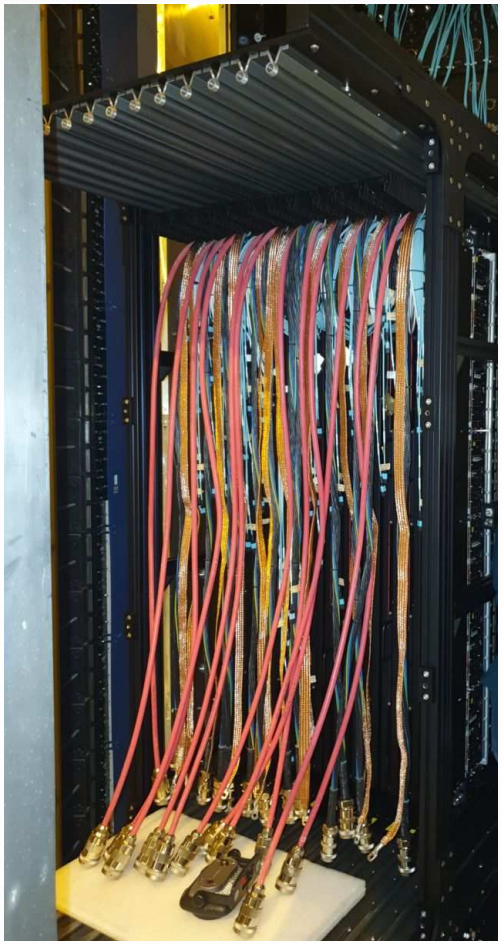
the transport team is central, as always, in all installations at P8

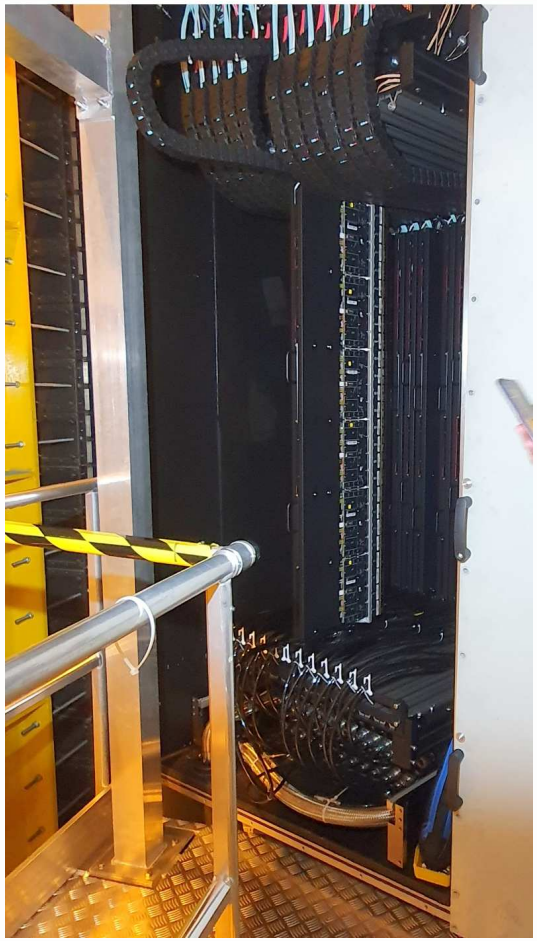
A-side installed in February 2021: the first new active detector installed in the P8 cavern in LS2

C-side installed in April 2021

RICH2 installed





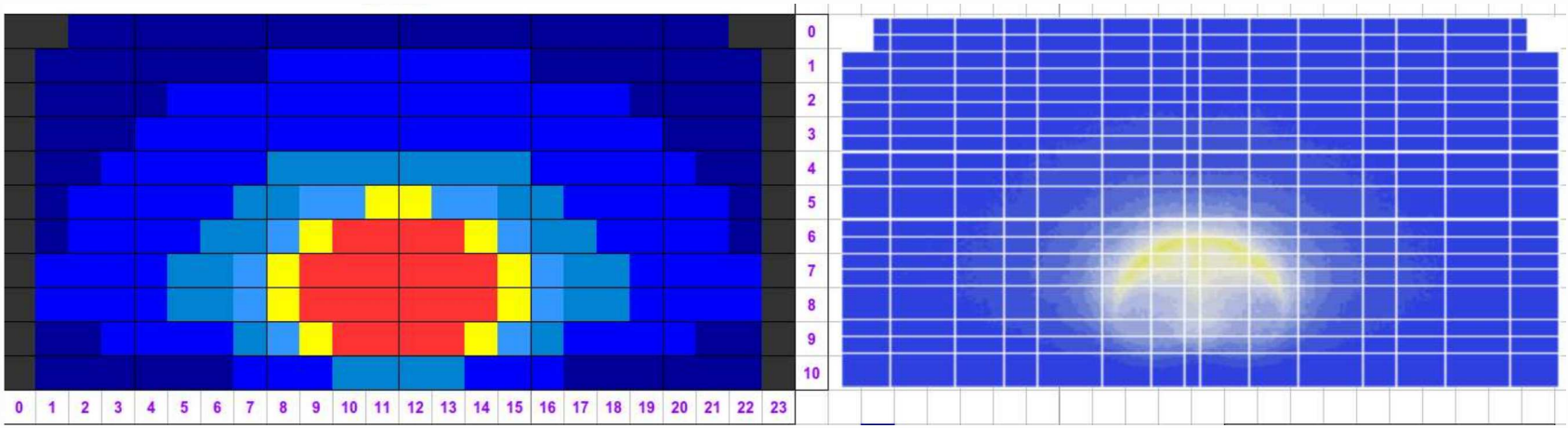


- installation of columns followed by connection of cable chains to services: LV (Maratons), HV CAEN A1538D, safety gnd, optical fibres, temperature pressure humidity sensors, cooling manifold
- refurbishment of RICH2 gas enclosure during LS2 to improve calibration system for MaPMTs

RICH1 columns production

- RICH1 column assembly well advanced when issue on VTRX optical modules was observed by other experiment
- we decided to replace all VTRX in RICH1 with units baked by the EP-ESE-BE team
- all PDMDBs removed from columns, levelling plates dismounted, VTRX exchanged, columns assembled and commissioned

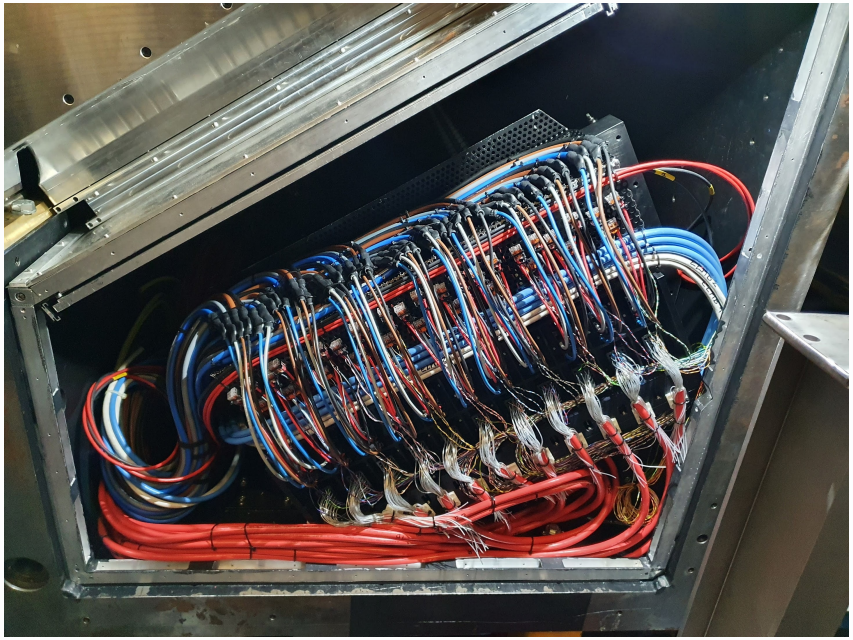
EC grouping in RICH1

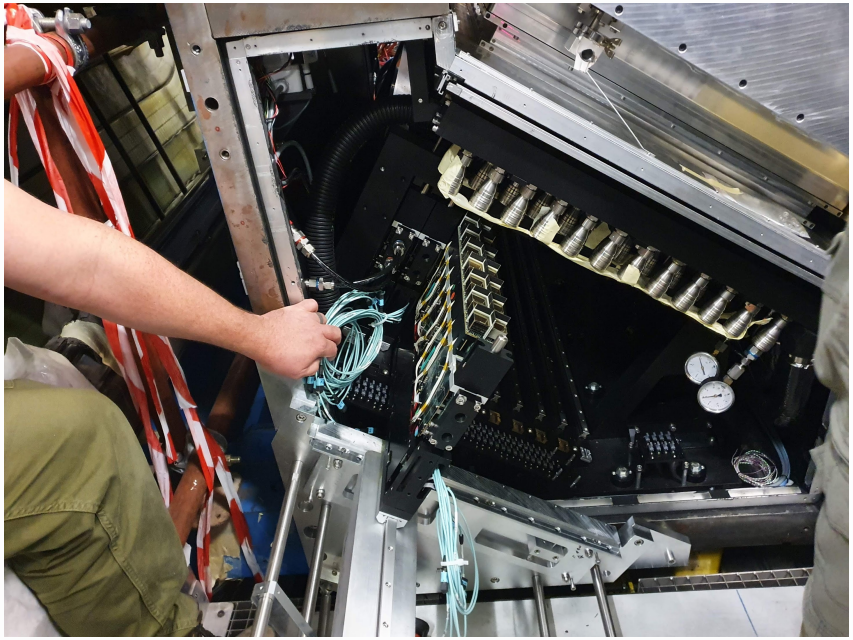


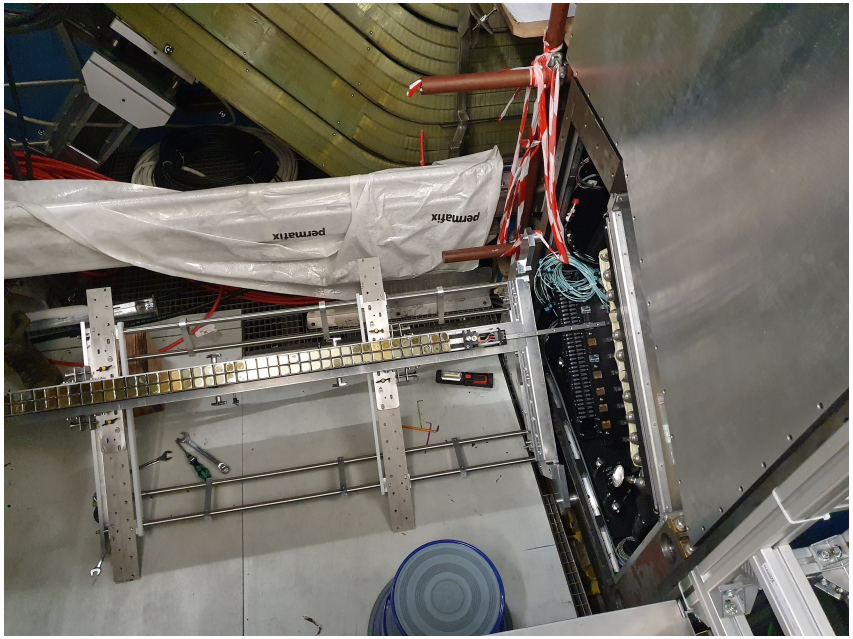
- SIN particularly critical in high occupancy region of RICH1 where pile-up may occur
- dedicated re-shuffling procedure of MaPMTs across ECs to match units with same gain and low SIN
- HV shared by 16 MaPMTs $\Rightarrow$ delicated procedure of two-dimensional grouping combining simulation results with PDQA and ECQA data
- plan feasible thank to excellent database developed to summarise all datasheets and data from all QA programmes

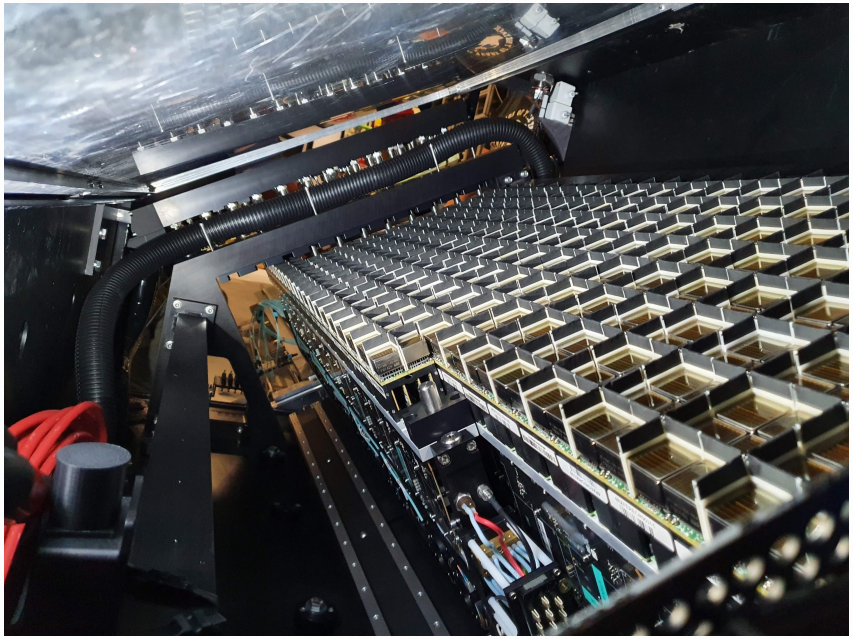
- finally ECs mounted and RICH1 columns commissioned following the same protocol as RICH2

RICH1 columns installation

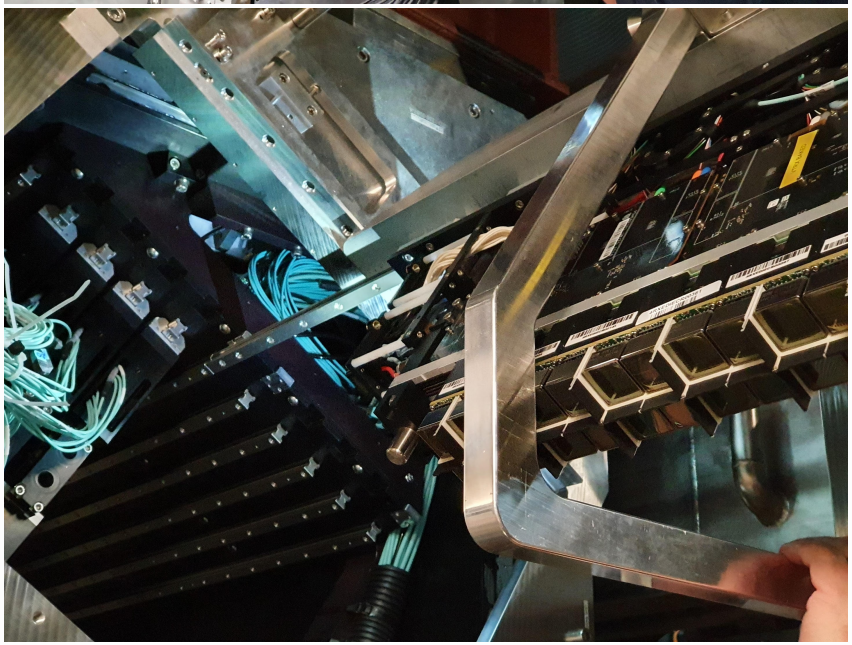


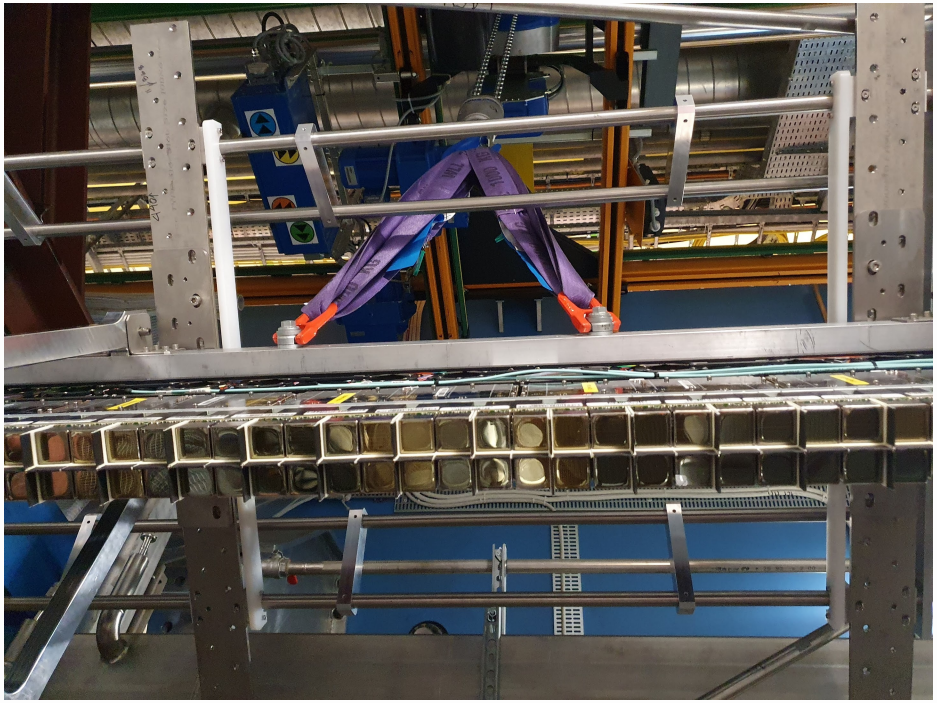


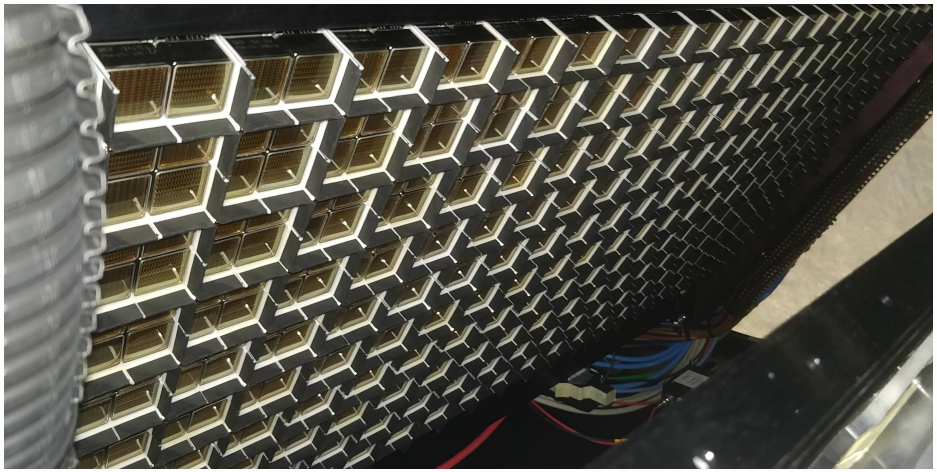




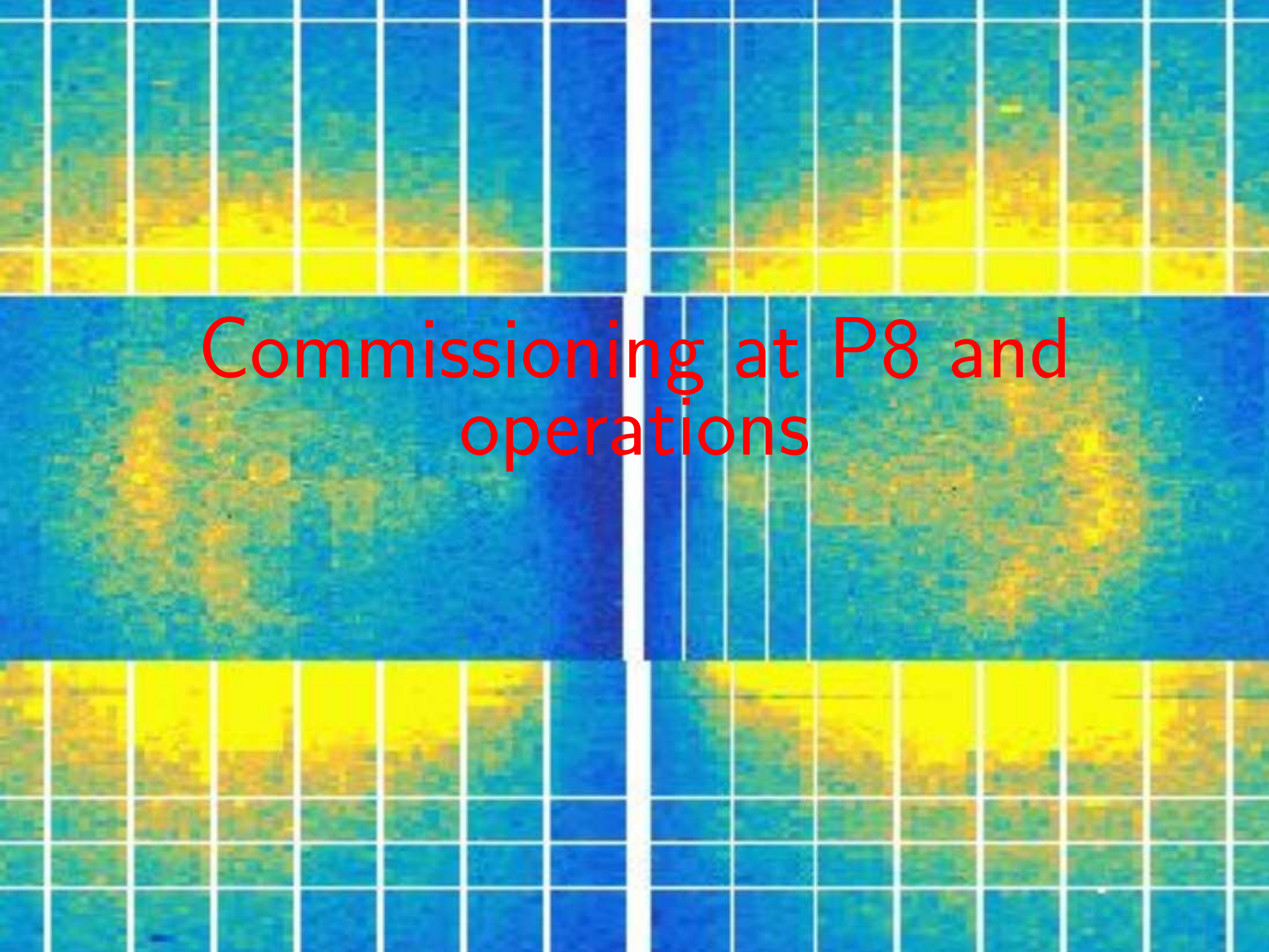
RICH1 columns installation







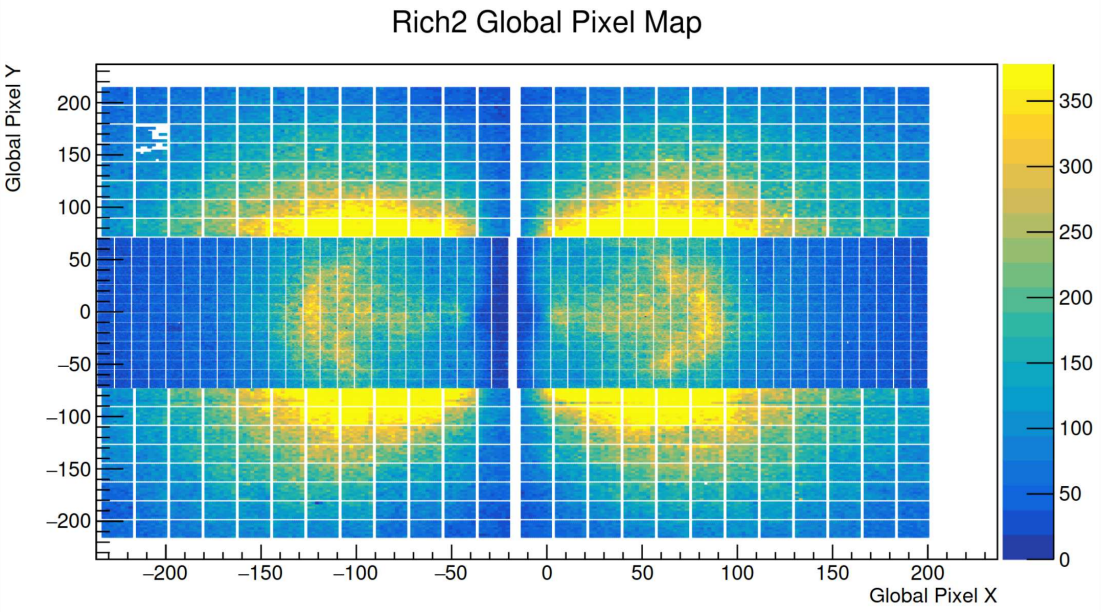
Down columns installed in December 2021
Up columns installed in January 2021

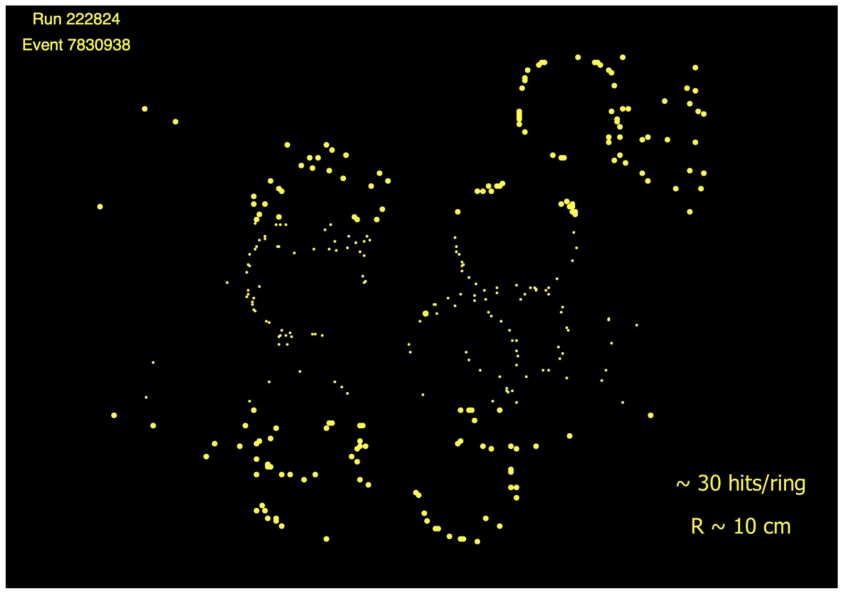

Commissioning at P8 and
operations

LHC pilot beam

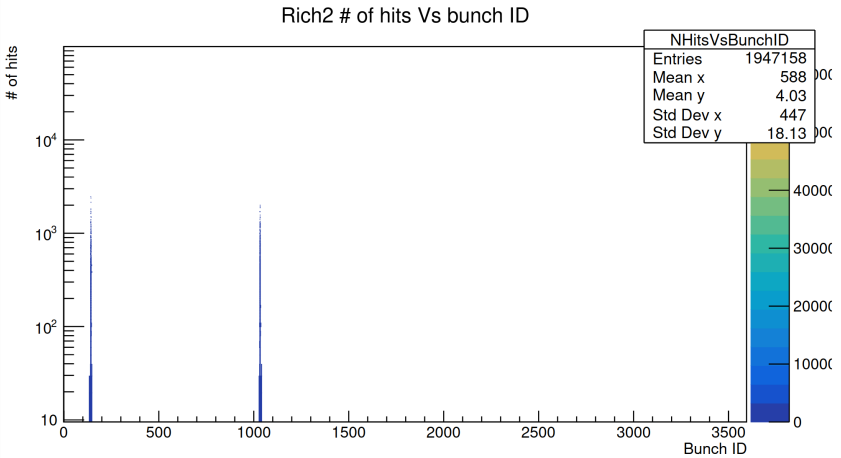
first test with beam performed on RICH2 during pilot beam provided by LHC in November 2021 (LHCb magnet off and RICH2 gas enclosure still filled with CO_2)

https://ep-news.web.cern.ch/content/lhc-pilot-beam-lhcb-preparation-run-3-start



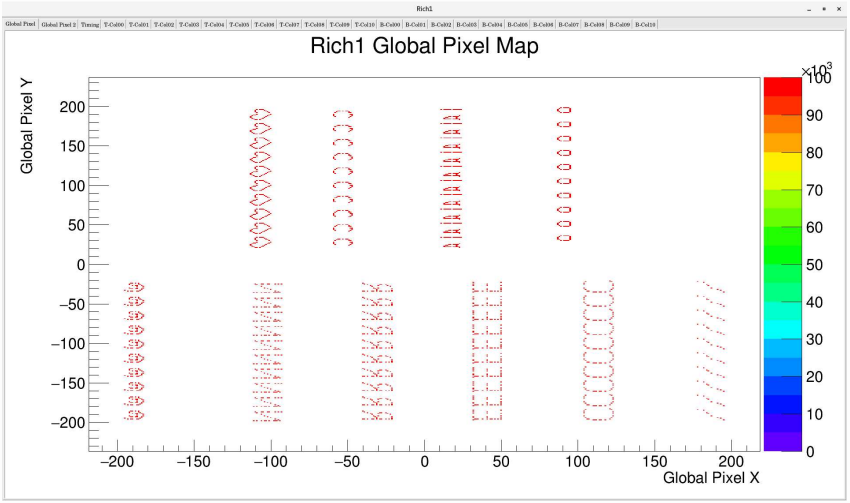


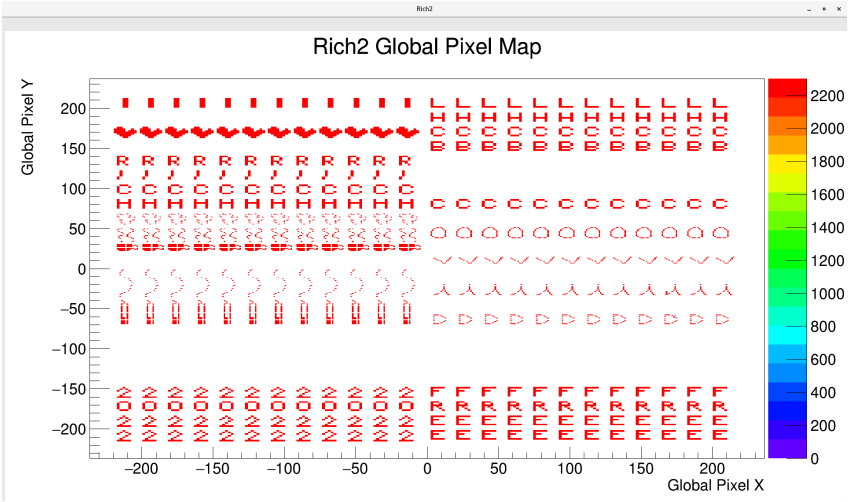
- RICH2 hardware validation and development of controls well advanced
- collisions quickly detected and single event display developed
- test of working points from commissioning successful
- first time alignment test with beam
- first tuning of HV values per PDM



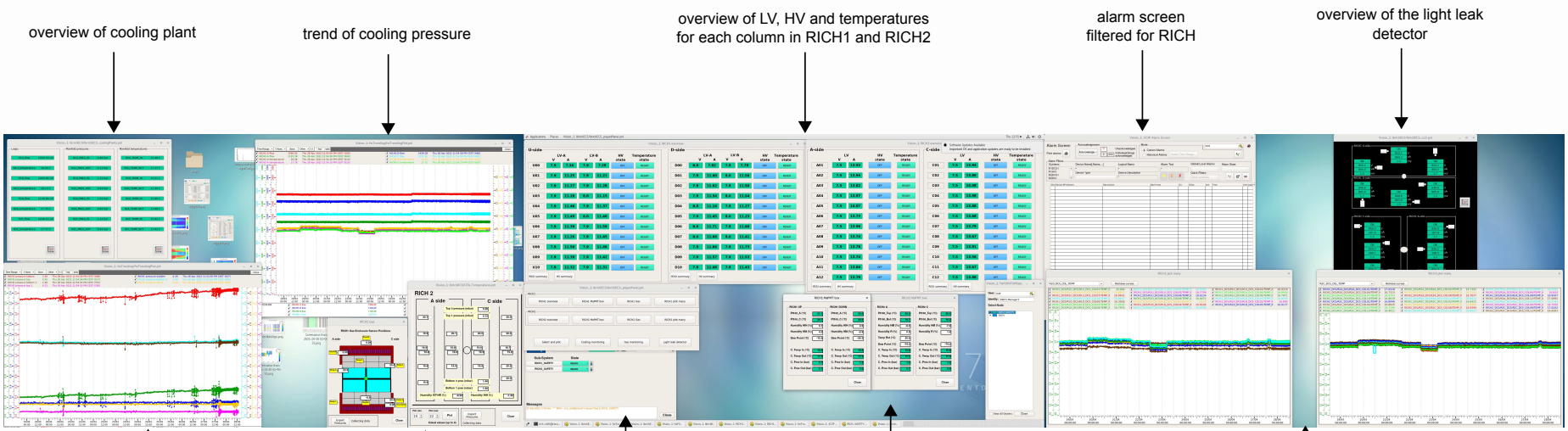
Detector validation

mapping validation injecting pattern in FE



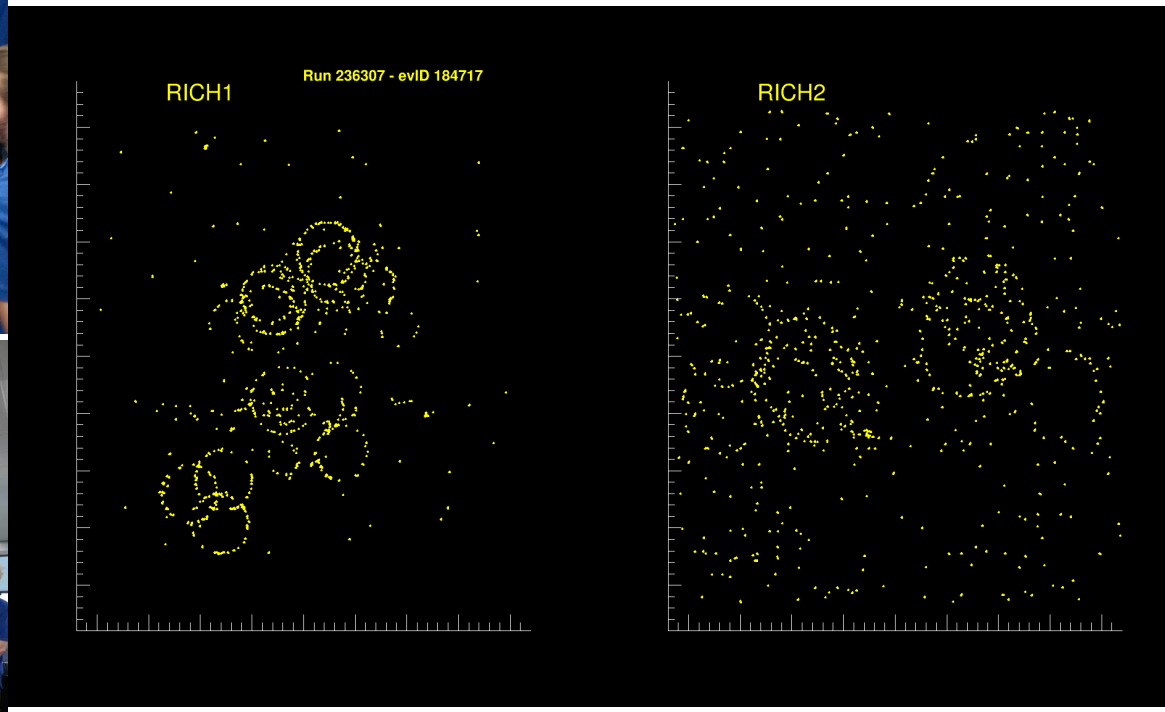


advanced monitoring facility for detector safety and operations



High energy beam

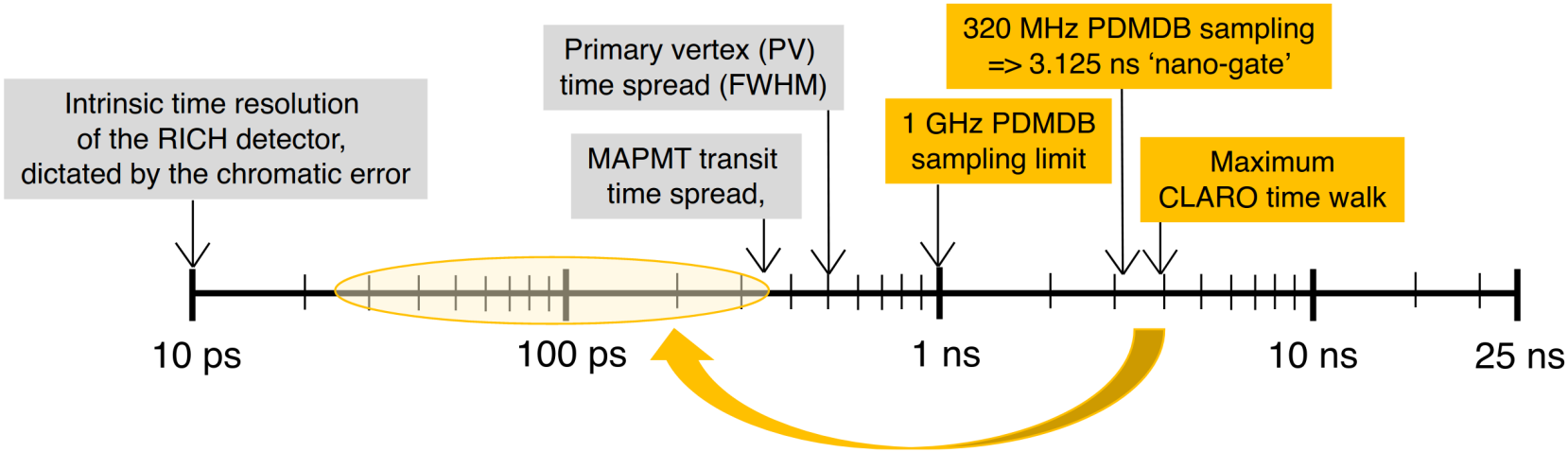
- beam delivered since May 2022
- first high energy beam on 5 July: media event
- RICHes ready to take data with tune HV and thresholds across both detectors



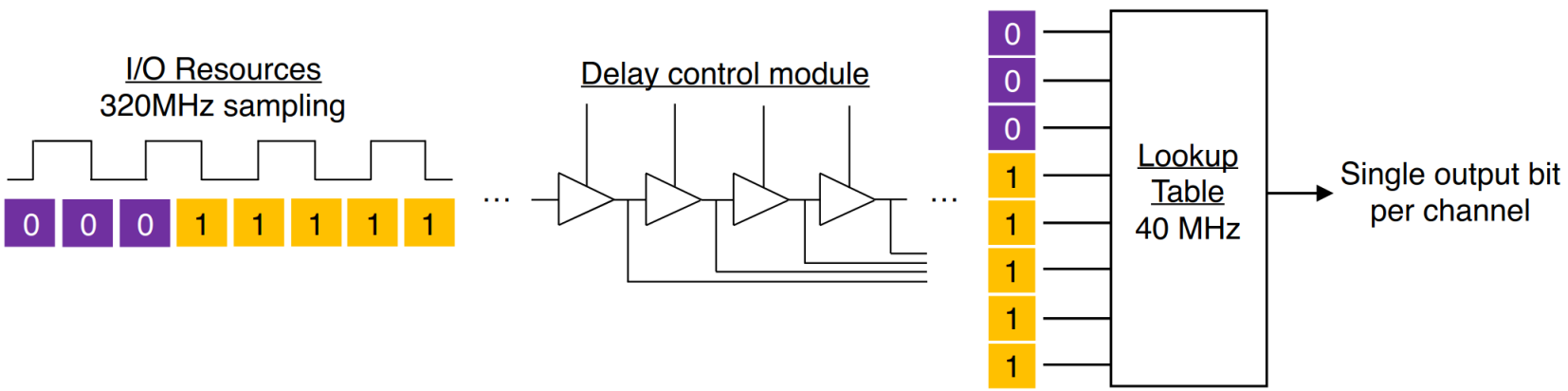
one of the highlight of LHCb at ICHEP

Detector tuning: time alignment

signal latching scheme based on gating in few ns to maximise detection efficiency while reducing out-of-time background

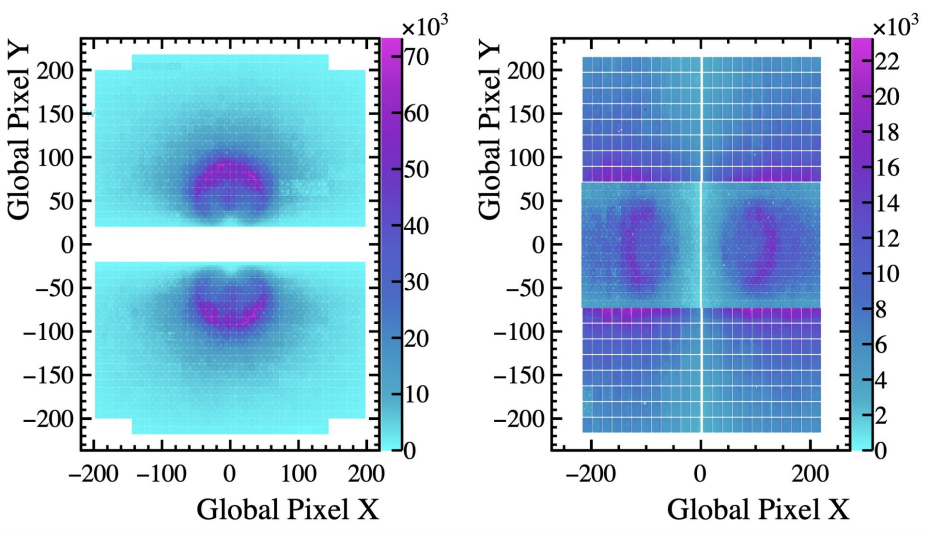


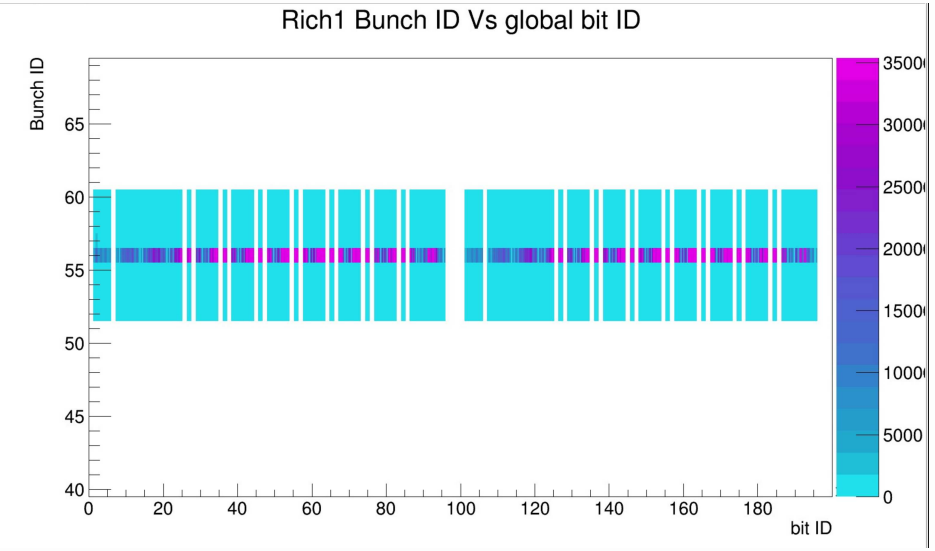
the window of 25 ns is divided in 8 minislot and a lookup table is used to identify the rising edge of the Claro signal (minimum gating is 3.125 ns)

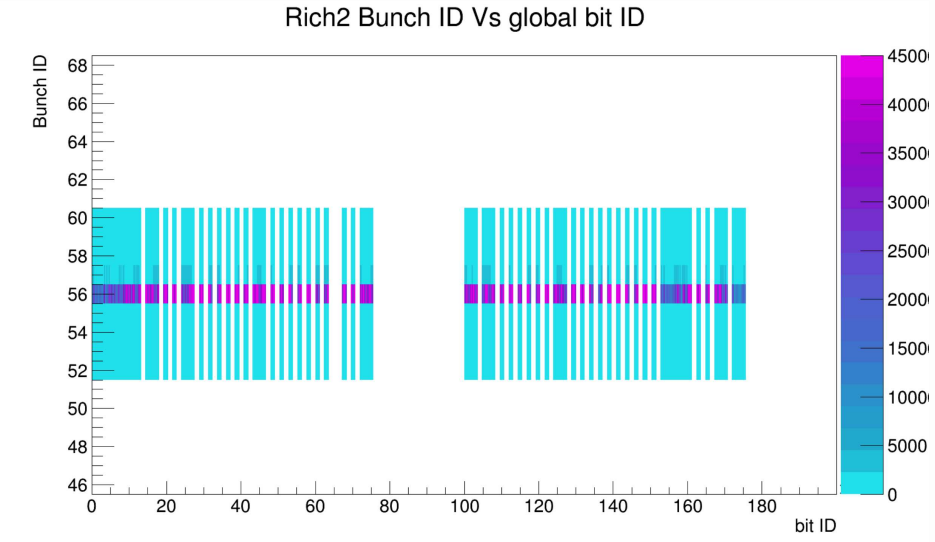


time alignment has been a core activity for all LHCb sub-system in 2022

RICH time aligned



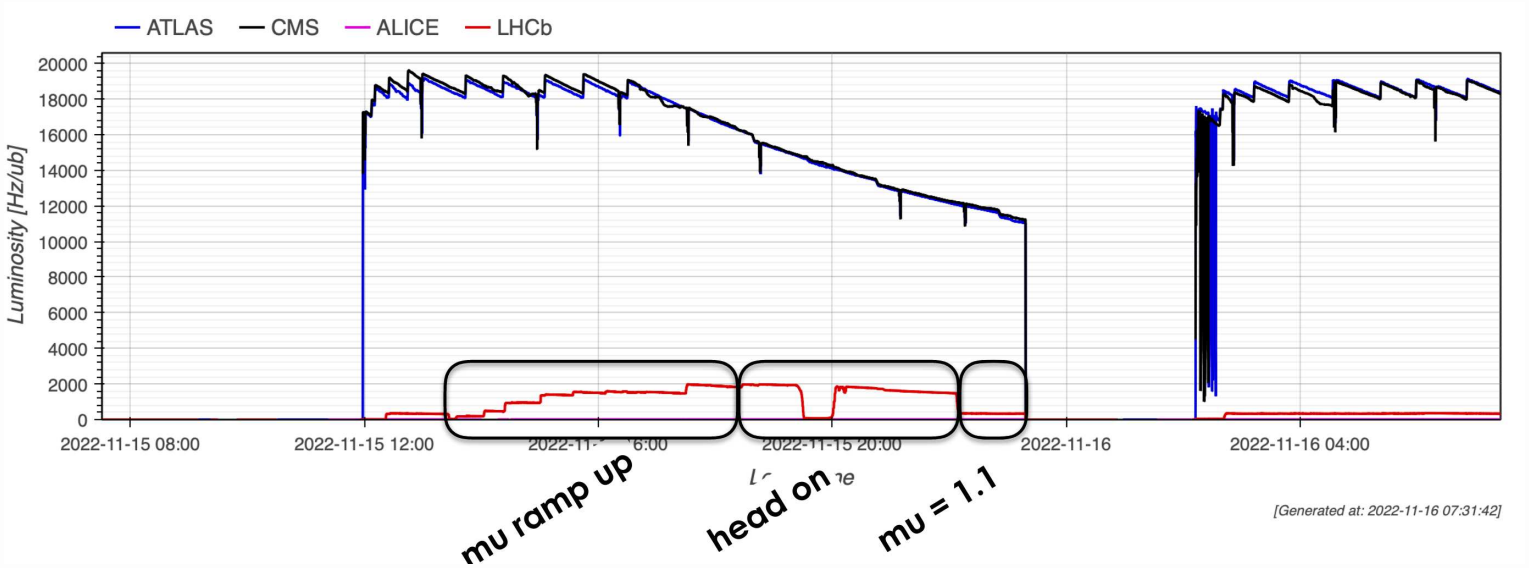




- coarse time alignment procedure developed during column commissioning: routine operation that can be performed at every fill
- fine time alignment within 6.25 ns achieved: scan varying minislot selection in lookup table
- [⇒] RICH detectors able to operate at 40 MHz, as by LHCb Upgrade design, and with further background suppression

RICH and luminosity

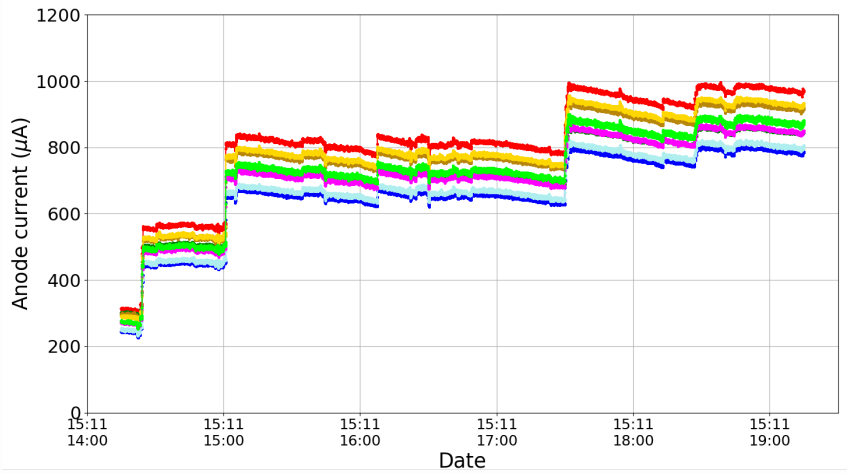
LHC steers the beams to level luminosity according to the value provided by LHCb



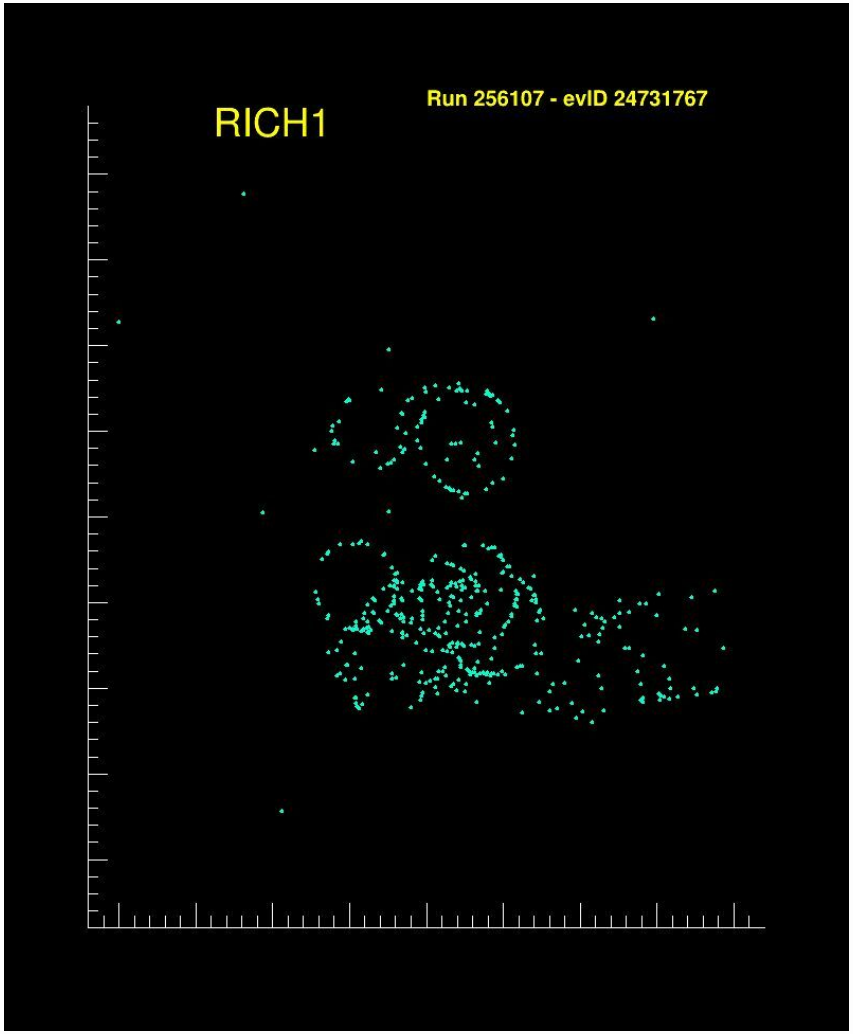
PLUME is the new luminometer, included in the Run control, providing the Lumi to LHC when running

RMS takes over as backup system

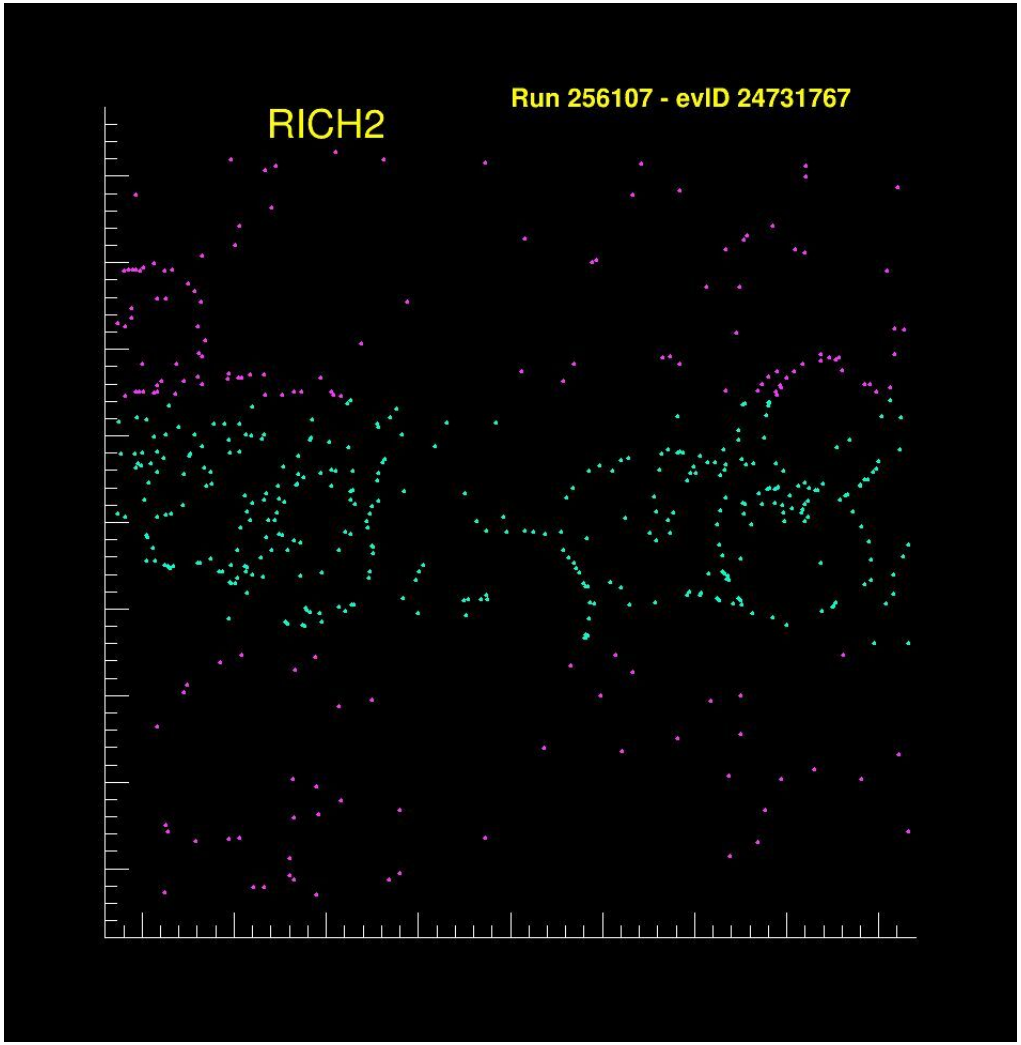
RICH1 played a major role in studying luminosity measurement in LHCb using MaPMT currents and the light leak detector monitoring; number of hits in the RICH system is under study as further variable proportional to luminosity



RICH1 and RICH2 rings: low occupancy events

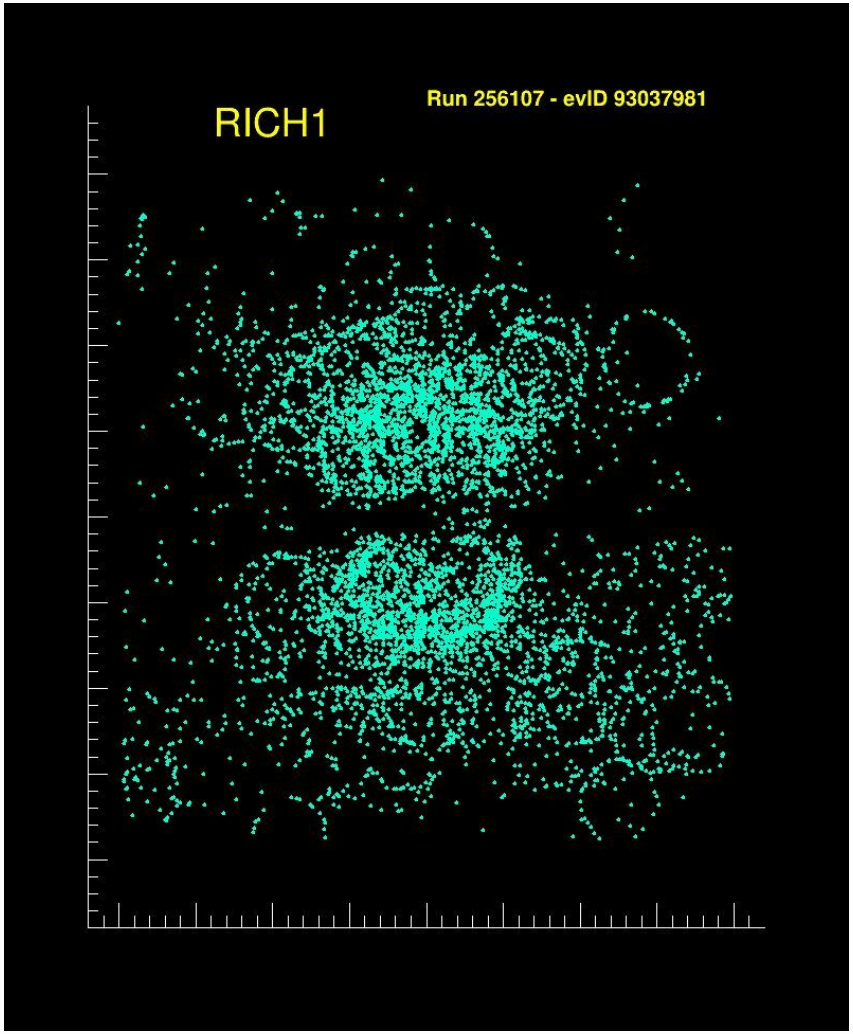


483 hits in RICH1

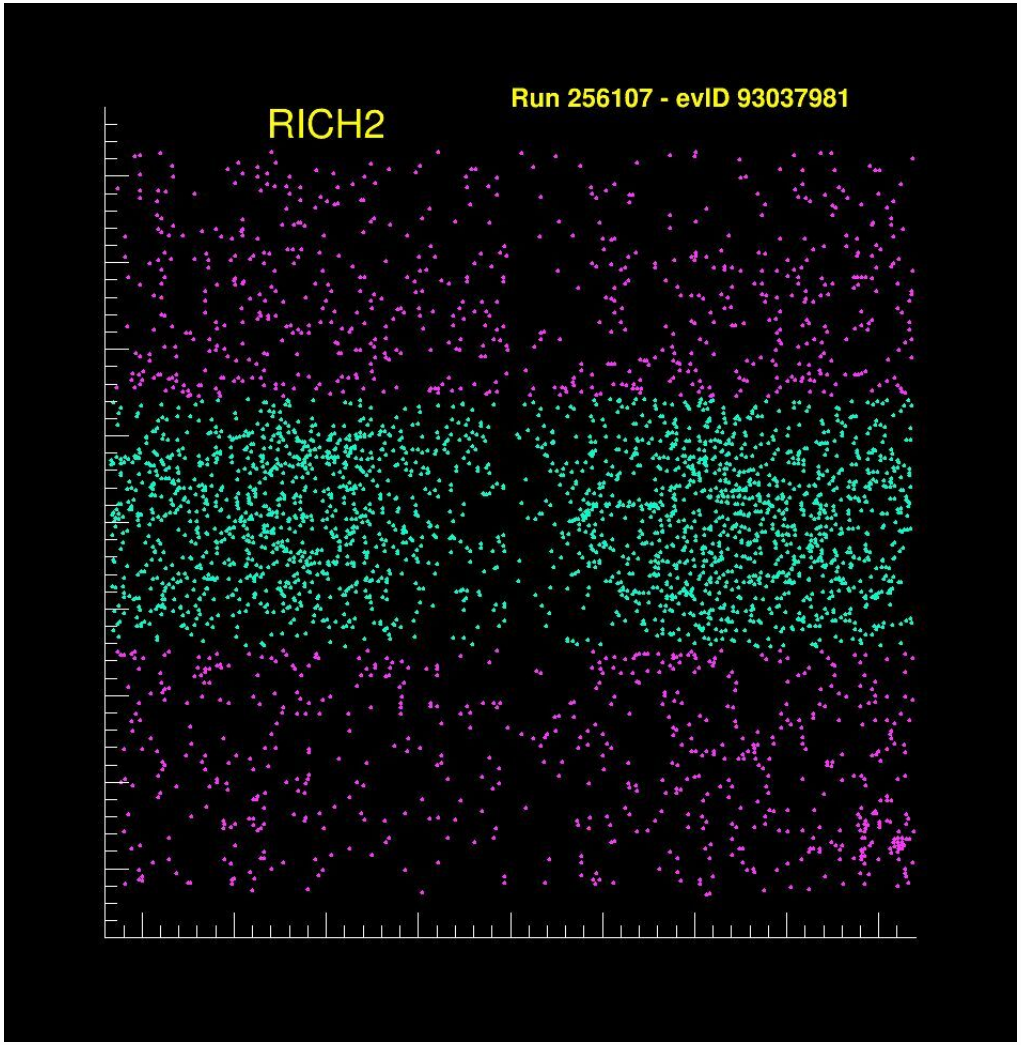


494 hits in RICH2

RICH1 and RICH2 rings: towards nominal mu



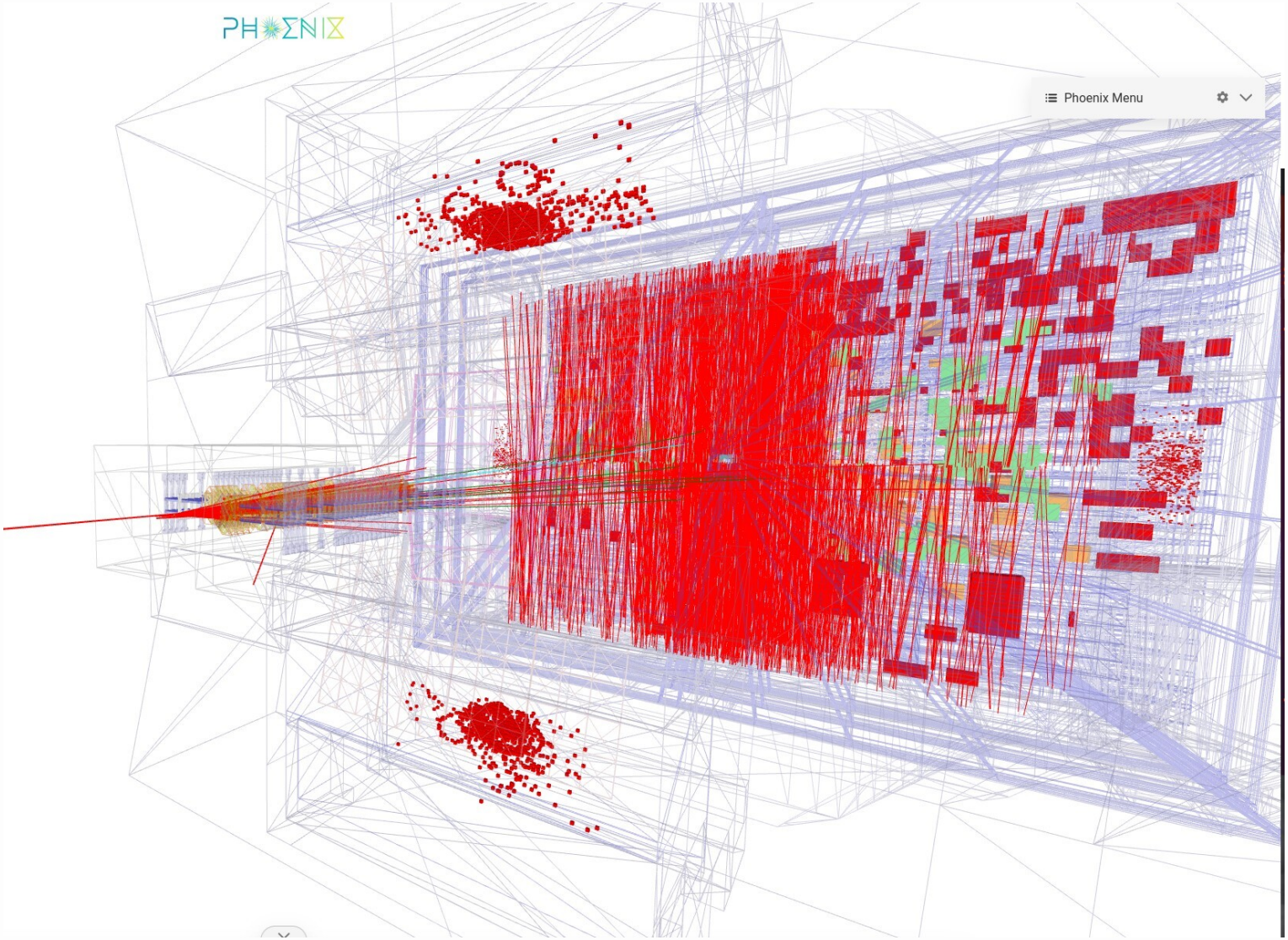
5720 hits in RICH1



3733 hits in RICH2

RICH and special runs

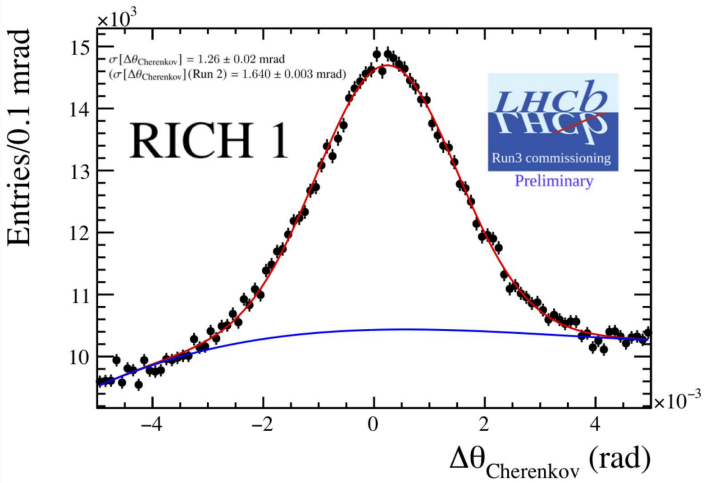
new SMOG2 system installed in LS2: gas injected in cell at $\sim$ -40 cm with respect to the p-p interaction region. SMOG2 system commissioned this year: example of p-Ar collision with clearly displaced primary vertex with respect to p-p

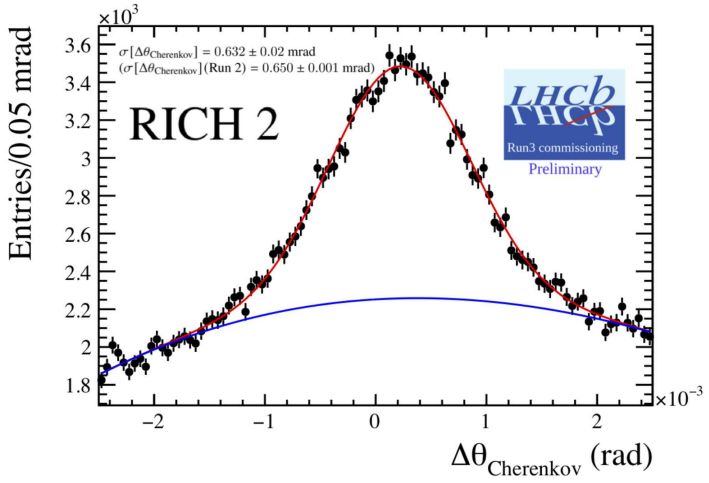


[LHCb Preliminary]

Preliminary performance of the RICH system

very preliminary estimate of Cherenkov angle resolution: preliminary photon detector panel alignment, no mirror alignment, no refractive index calibration and very preliminary tracking performance (Bristol, Cambridge)





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

RICH1 already better that its predecessor, RICH2 approaching the expected performance!

Conclusions

- the LHCb RICH system is a unique PID system: PID over unprecedented large momentum range with extremely challenging peak occupancy
- a decade of design, construction, commissioning, installation and now operations of the RICH upgrade
- the first year of Run3 has just come to an end
- smooth RICH commissioning with beam thanks to the experience gathered during the intricate plan of quality assurance
- preliminary performance is already very prosiming: a bright future ahead!