LHCb Upgrade of the RICH Detectors

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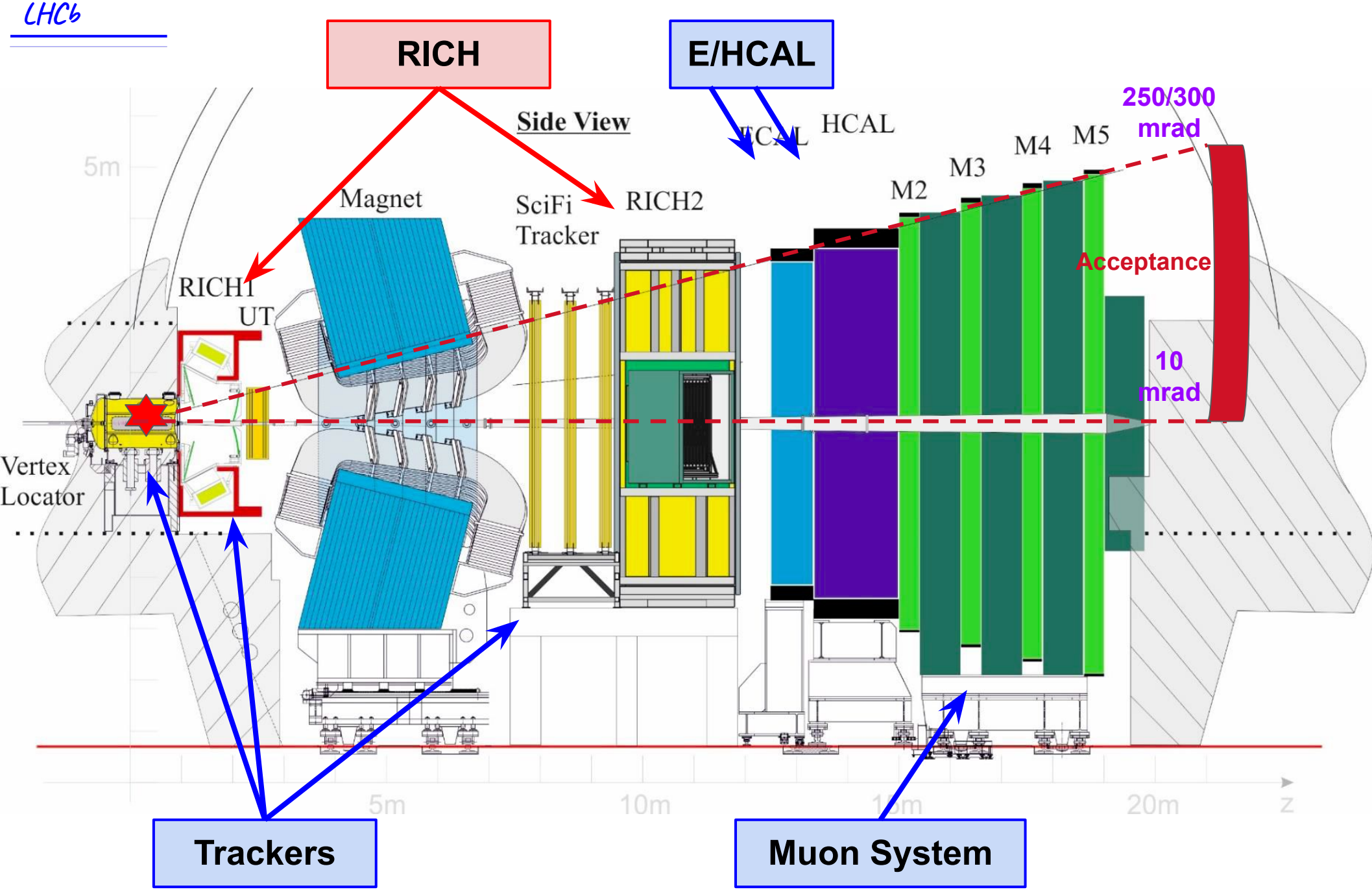
on behalf of the LHCb RICH collaboration

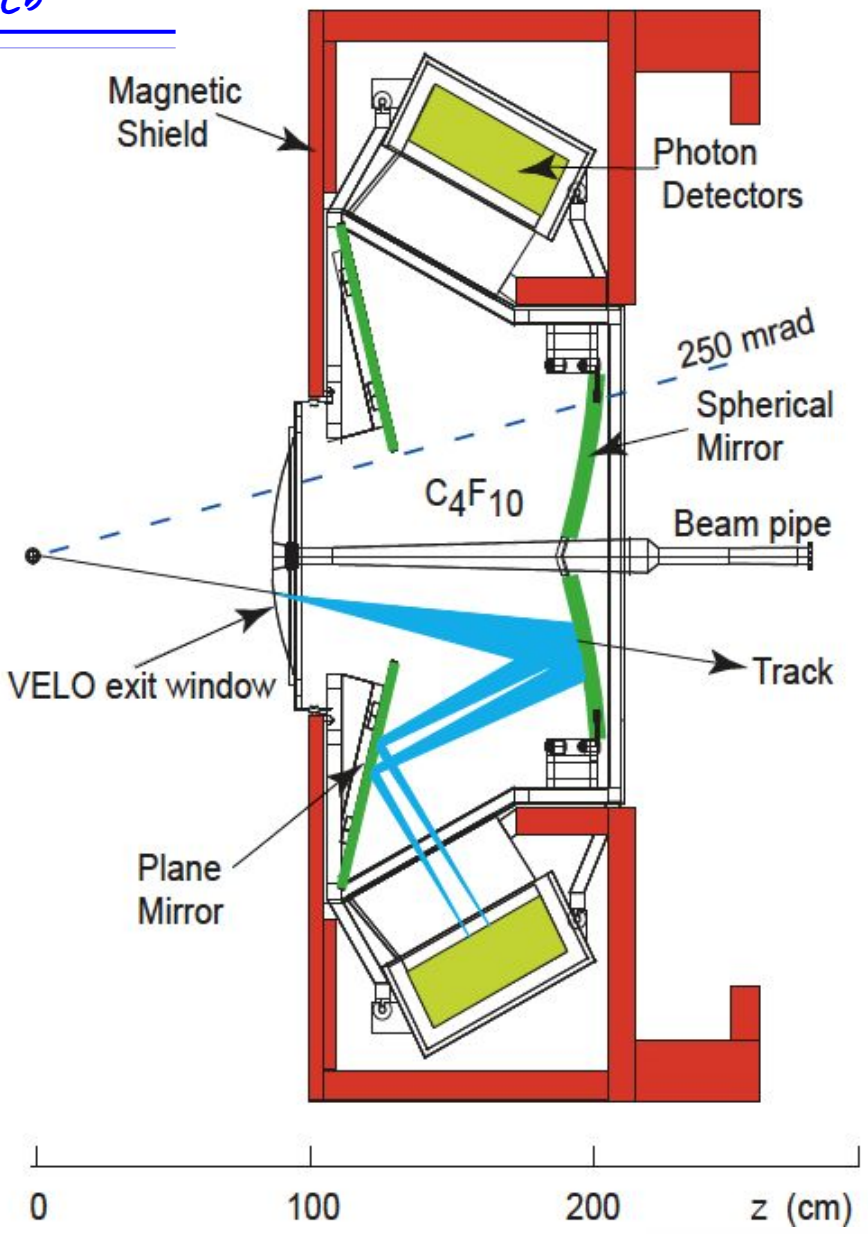
11th International Workshop on Ring Imaging Cherenkov Detectors
"RICH 2022"

THE LHCb Experiment



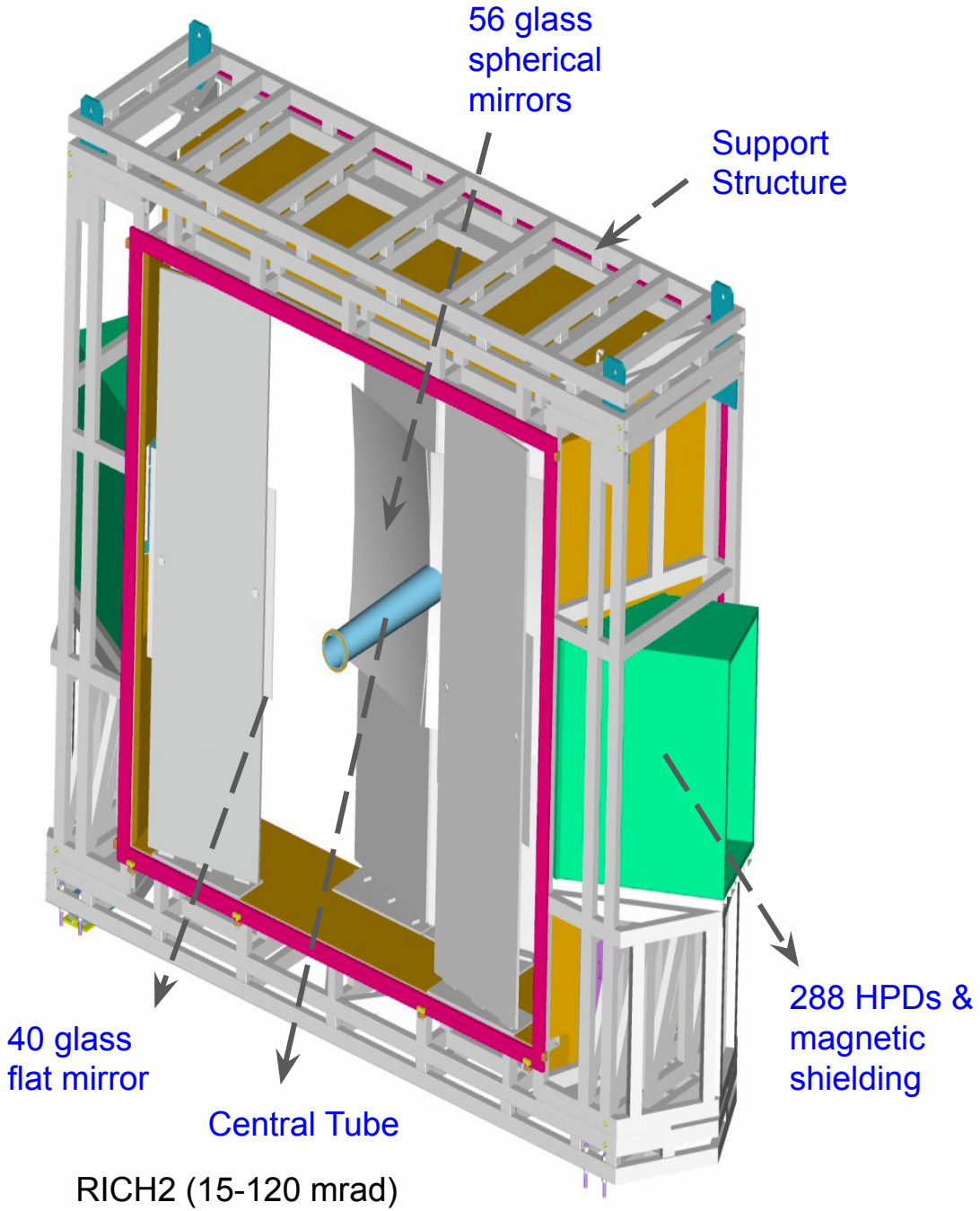
RICH Detectors

LHCb



RICH1 (250-300 mrad)

4 m^3 C_4F_{10} n = 1.0014, up to 60 GeV



RICH2 (15-120 mrad)

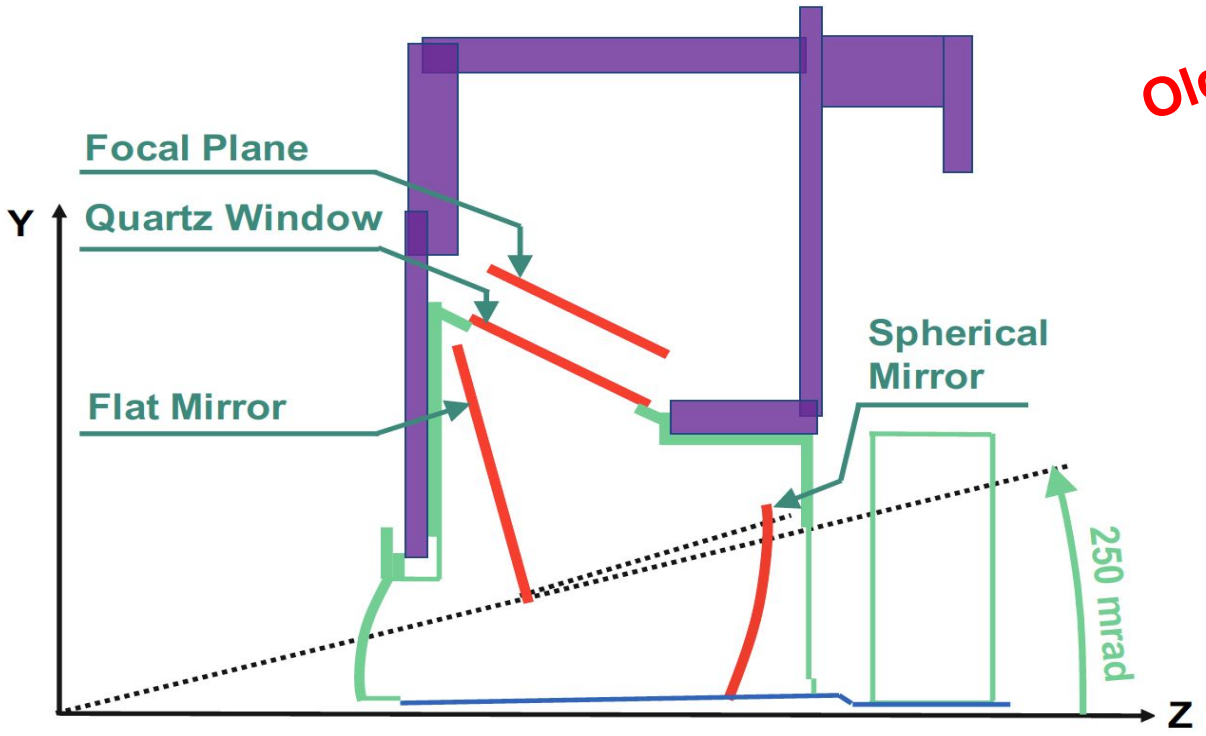
100 m^3 CF_4 n = 1.0005, up to ~100 GeV

RICH Upgrade

- Adapt the current RICH detectors to run at higher luminosity and with continuous 40 MHz read-out
- Mechanical and optical changes
  - RICH1 spherical mirrors focal length increased to reduce occupancy (optical system re-designed)
  - New support mechanics and cooling
- Electronics and data acquisition changes
  - Replace HPDs with commercial MultiAnode PhtotoMultiplier Tubes (MaPMTs) with 64 channels
  - Use 40 MHz front-end electronics and data acquisition
    - CLARO8 amplifier/discriminator ASIC
    - FPGA-based digital board
    - GigaBit Transceiver (GBT) chip for data transmission

New Mechanics

- Peak occupancy should remain < 30% to maintain PID performance
- Focal plane and spherical mirror moved back to increase ring size
- New spherical mirrors with larger curvature radius
- Larger gas enclosure
- Compact photo-detection system required



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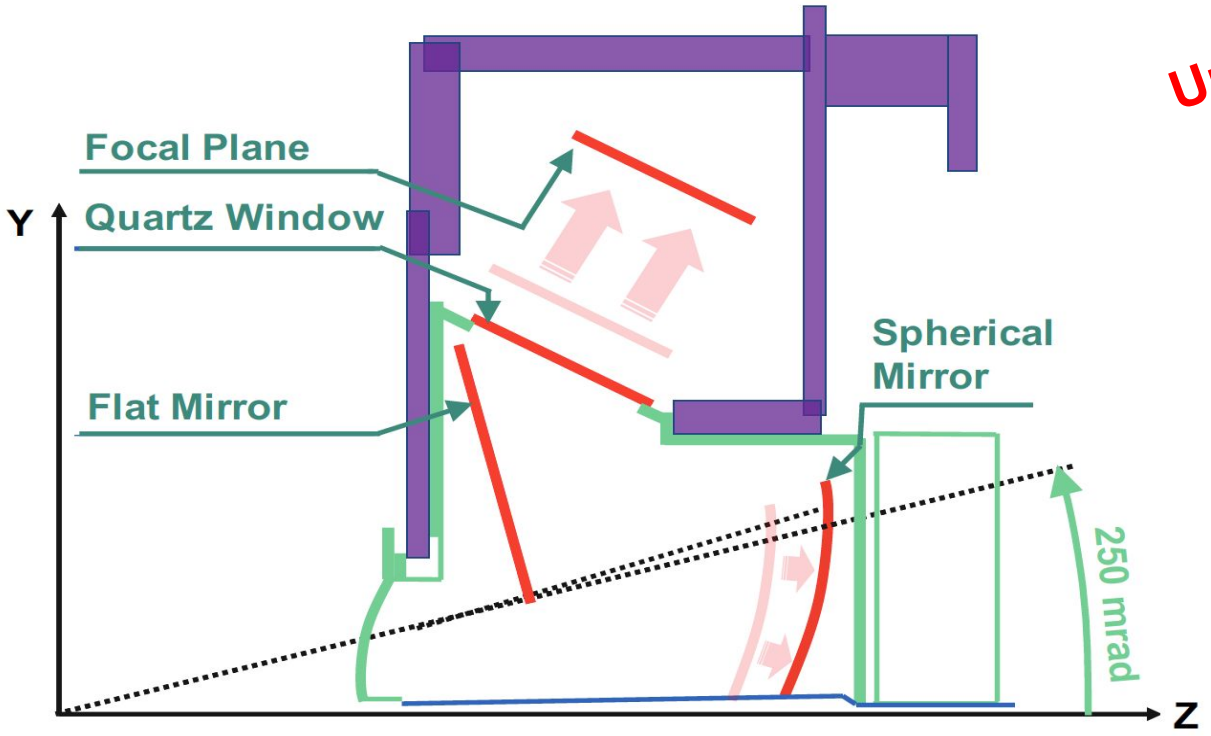
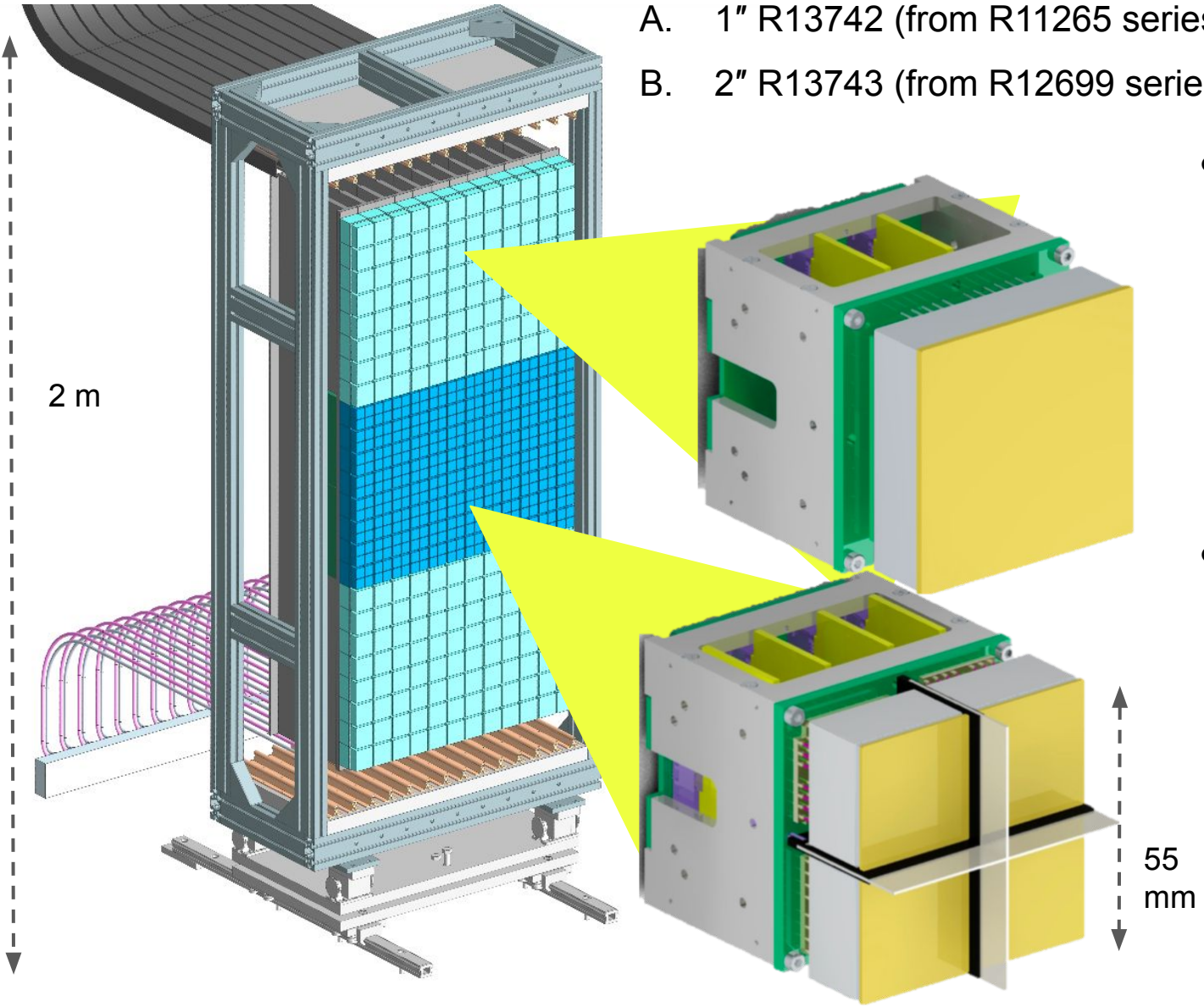


Photo-Detector Assembly

LHCb

I. Hamamatsu MaPMTs with 8×8 pixel matrix, arranged in Elementary Cells (EC)
   A. 1″ R13742 (from R11265 series)
   B. 2″ R13743 (from R12699 series)

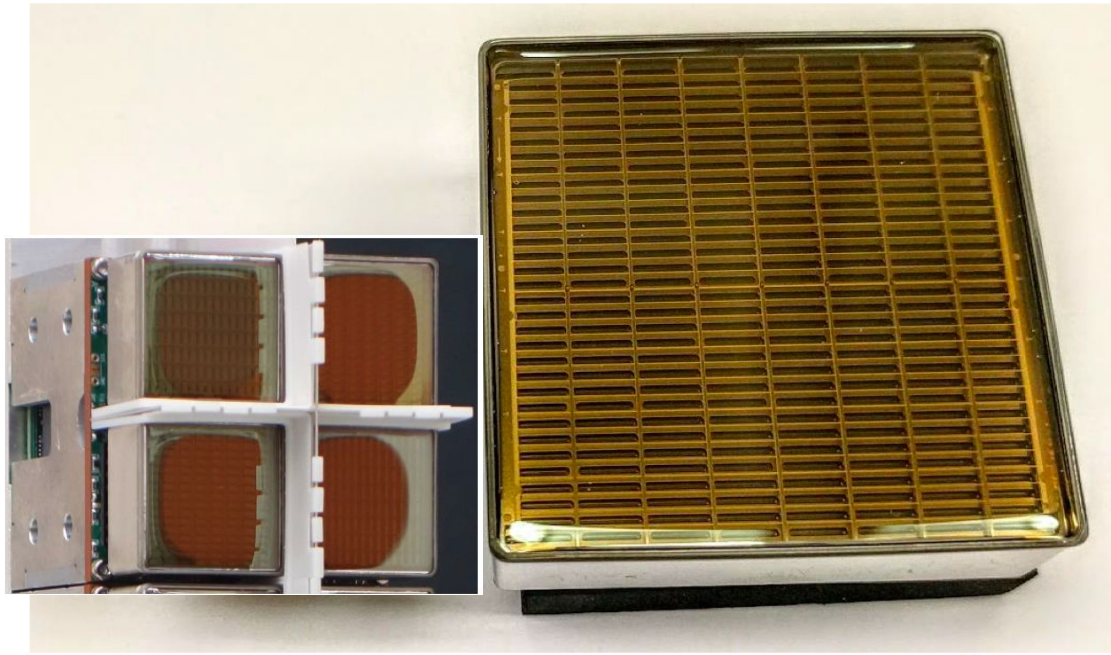


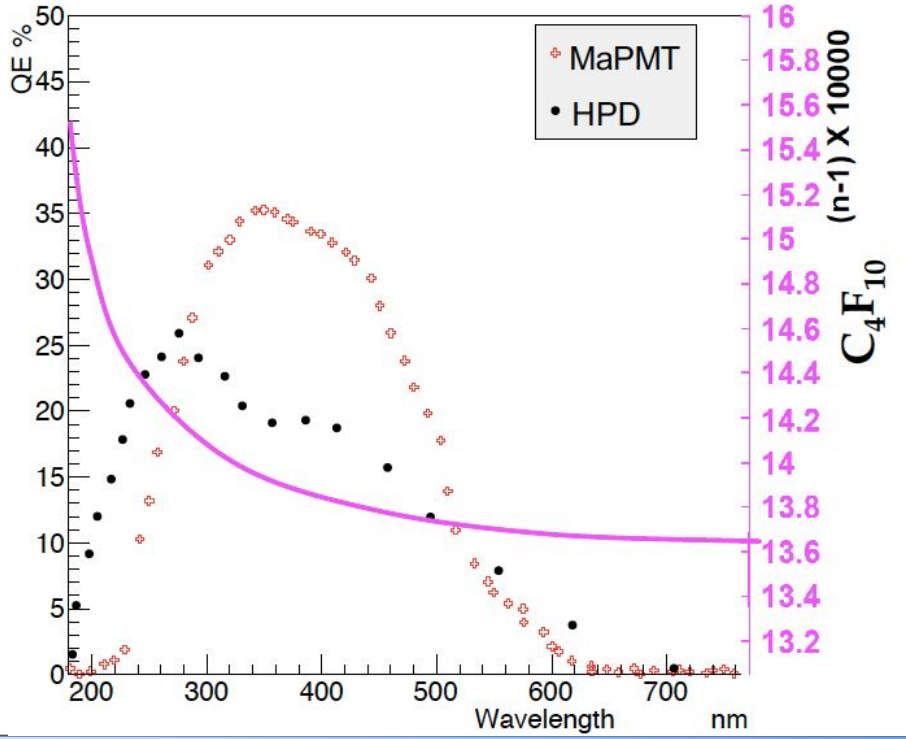
- EC-H type: 2″ MaPMT
  - ~400 modules
  - Outer regions of RICH2
  - One “A”MaPMT per EC (larger model 2×2 inches)
- EC-R type: 4×1″ MaPMTs
  - 2×2 matrix of “B” MaPMT per EC (smaller module 1×1 inches)
  - ~ 2700 MaPMT
  - ~ 700 modules
  - RICH1 and central region of RICH2

MultiAnode PhotoMultipliers

LHCb

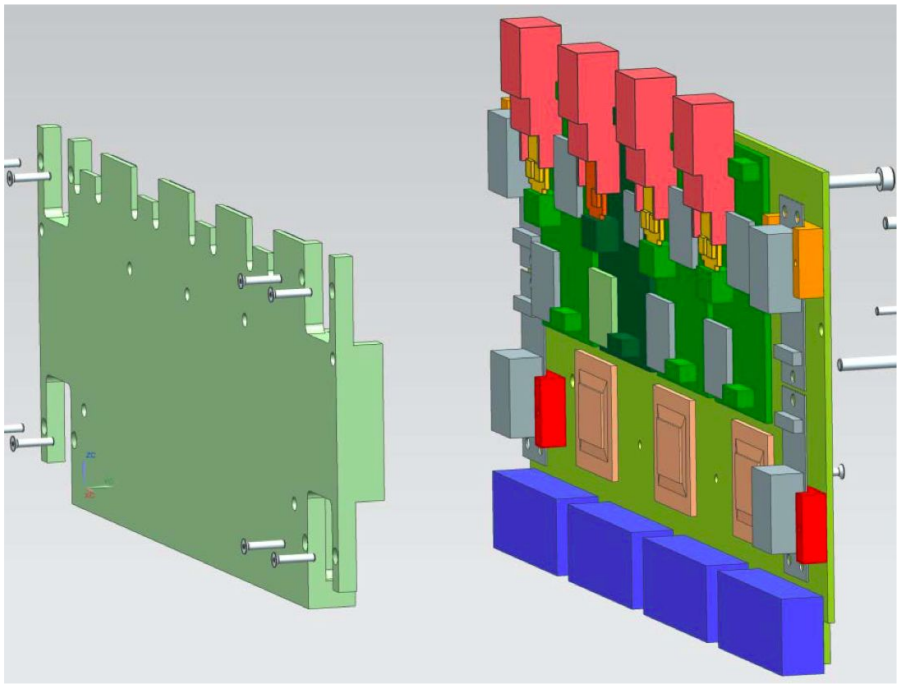
- Hamamatsu MaPMTs
  - 3100 R13742 and 450 R13743, including spares
  - Super-bialkali photocathode
  - UV glass window
  - Minimum gain 1×10^6 at 1 KV
  - 1:4 pixel gain spread in 1” PMTs, 1:3 pixel gain spread in 2” PMTs
  - Low dark count rate
  - Single photon spectrum well separated from the noise pedestal
- Higher QE of MaPMT in the green
  - Chromatic error reduction
- Sensitive to magnetic fields
  - Shielding applied





Front-End Digital Board

- Capture (asynchronous) CLARO outputs, synchronize to LHC clock, data algorithm, format and transmission
- Motherboard with FPGAs and power distribution (PDMDB)
  - Each serves 4 × half EC-R or 4 × EC-H
  - Plugins for control and data link
- Thermally coupled to cooled column



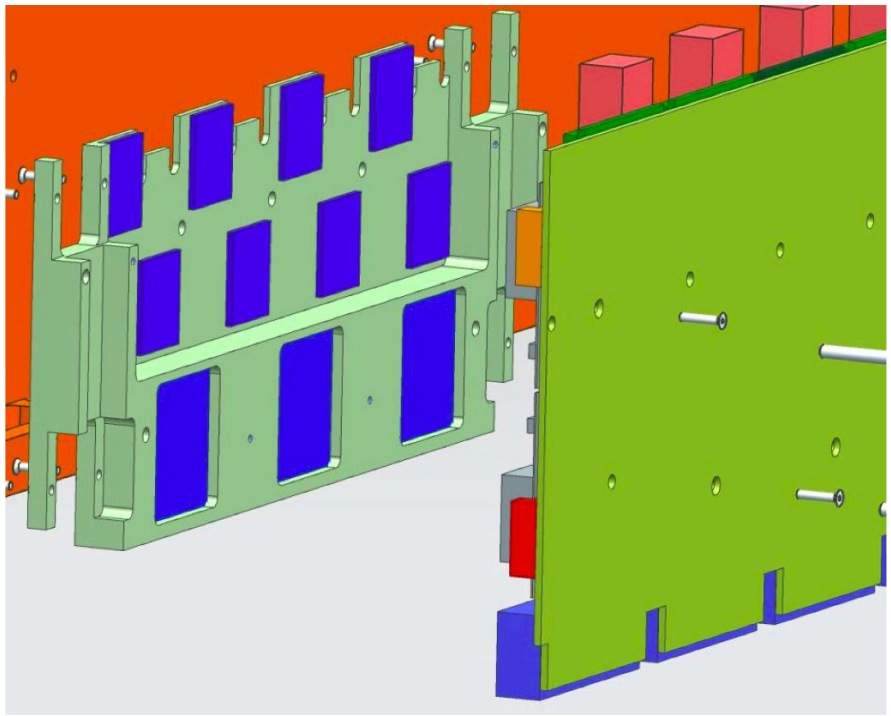
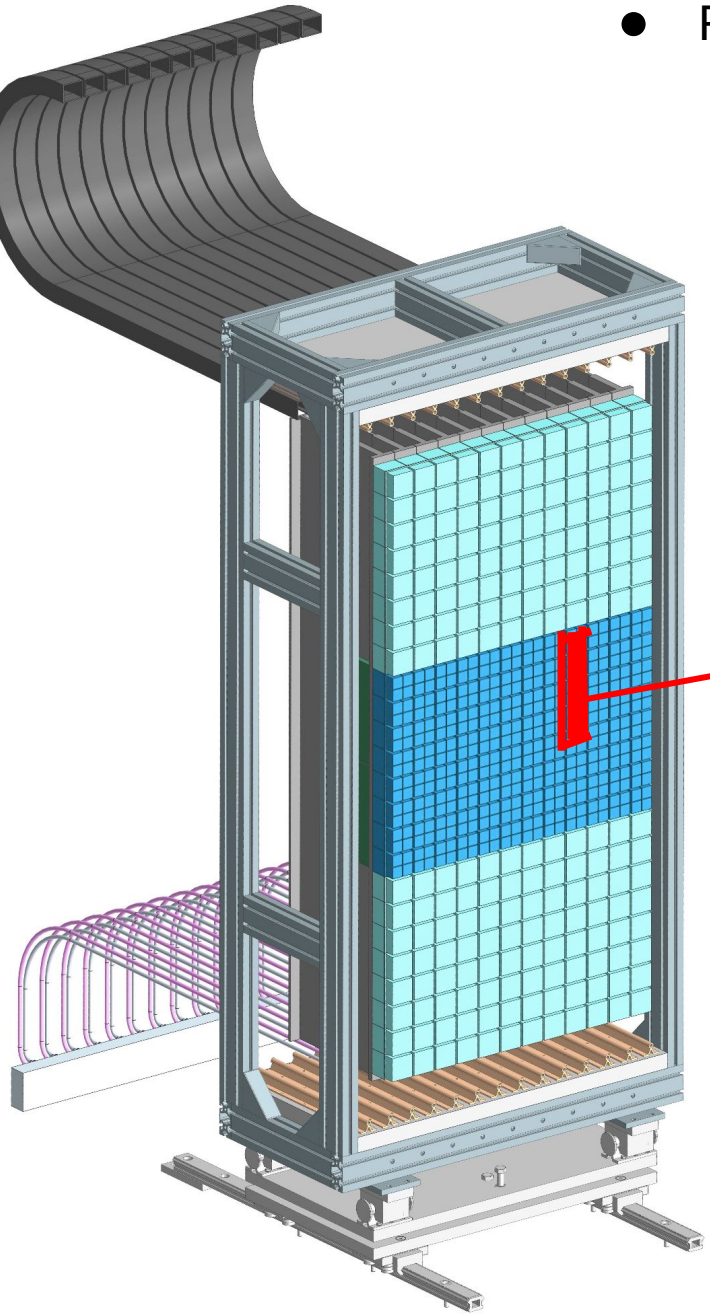
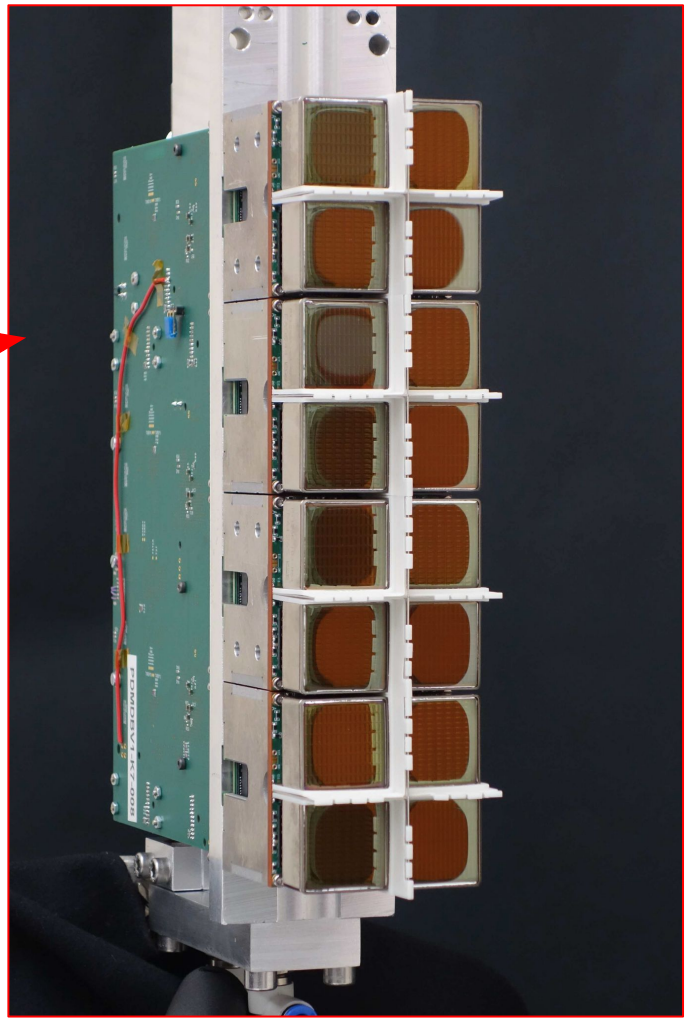


Photo-Detection Module

LHCb

- PDM: 2 digital boards + 4 elementary cells
  - MaPMTs (magnetic shield for RICH1 only), CLARO ASIC read-out, FPGA read-out, fast data transmission

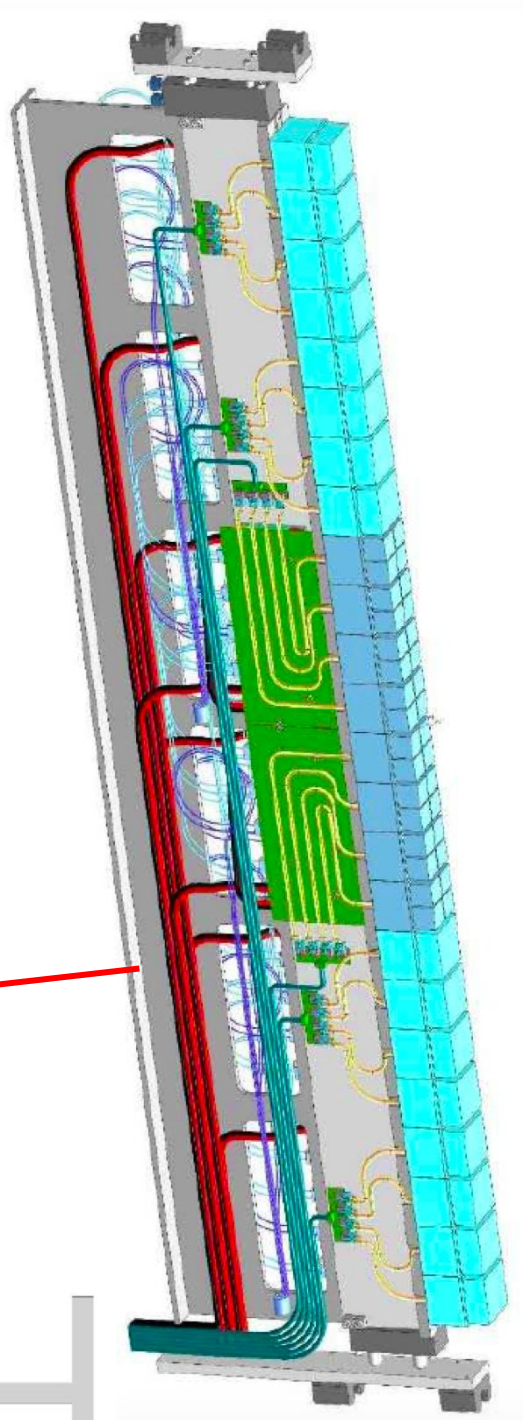


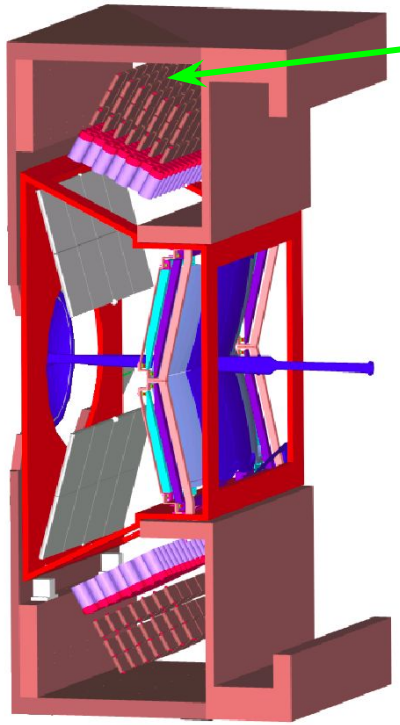


Columns

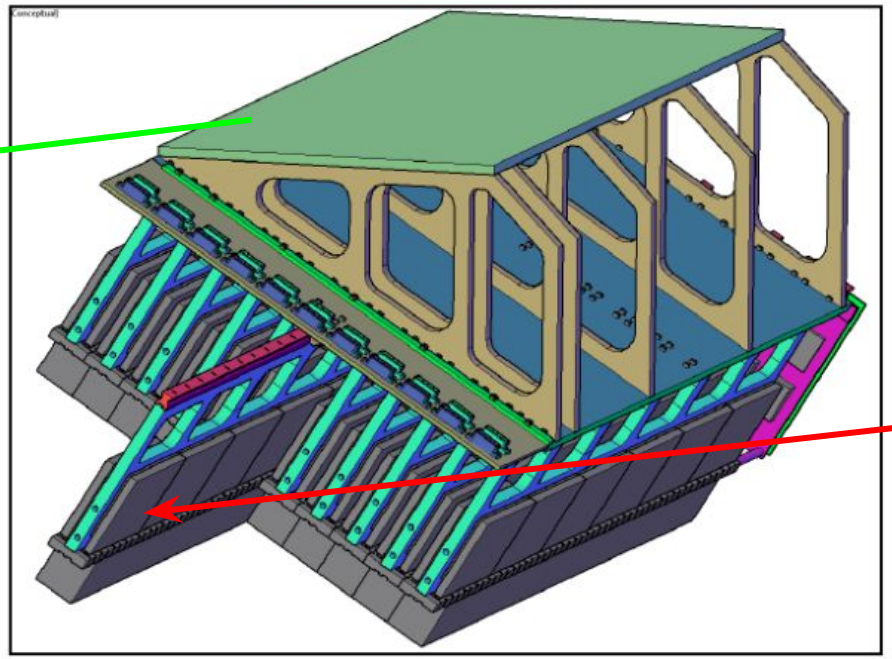
LHCb

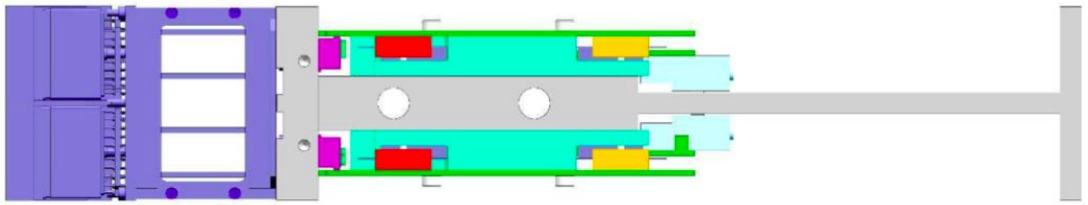
- Mechanical support for Elementary Cells, PDMDB, harness and cooling
  - Easy to remove a column for maintenance
  - Same mechanical structure for columns in RICH1 and RICH2 but different supports





Translation of a column





Brief history

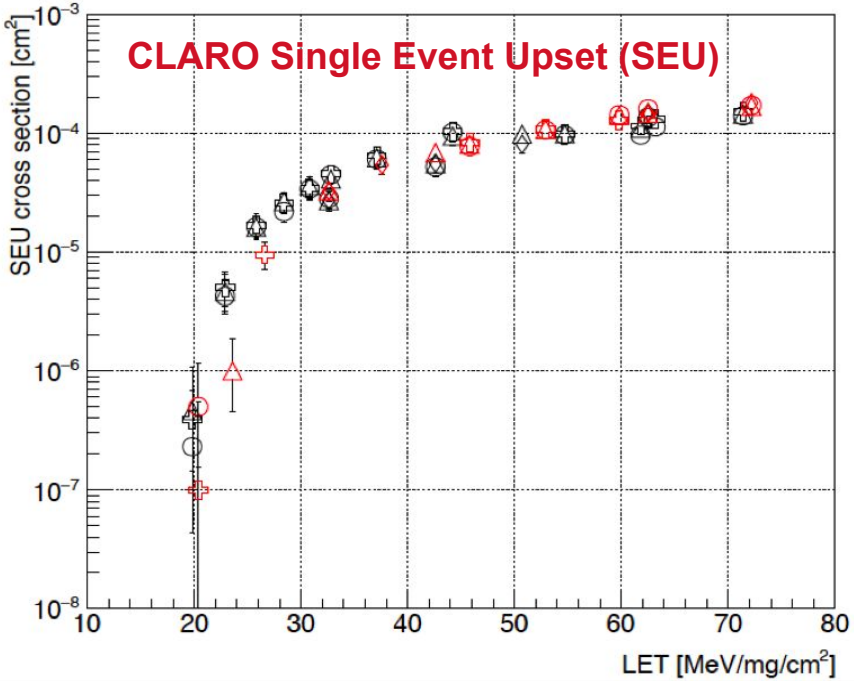
LHCb

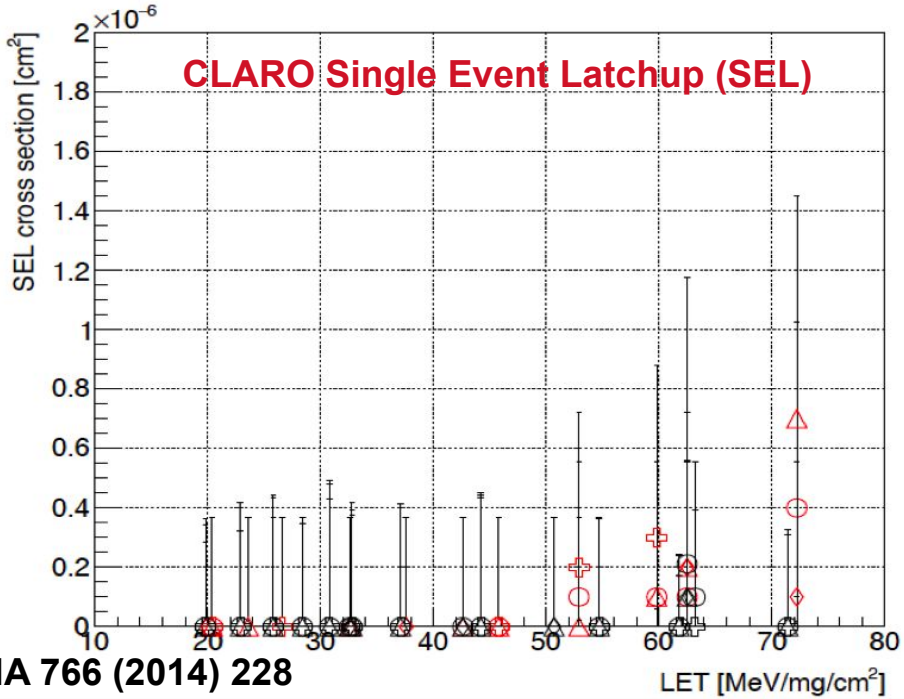
- Lab test of MaPMTs since 2011
- Test beams with MaPMTs and prototype FE electronics since 2014
- Test beams with MaPMTs, analog FE and prototypes FE Digital Board and TELL40 since 2016
- MaPMT Quality Assurance since 2016
- FE Digital Board firmware radiation hardness tests in 2017
  - Triple Module Redundancy, Partial Reconfiguration, stateless architecture (helped by BE)
- Idea to implement lossless compression in TELL40 (BE) firmware
- Integration of 1 prototype Photo-Detection Module in the operational RICH2 in 2018
  - Discovery of Signal-Induced Noise (SIN) in MaPMTs (see Giovanni Cavallero's talk)
- EC Quality Assurance since 2018
- Column assembly and commissioning (at CERN) started towards the end of 2019
- Detector Installation started at the end of 2020
- Detector Commissioning started mid 2021
- First light in October 2021
- Detector Installation finished mid 2022
- Enough with spoilers …

Radiation Hardness

LHCb

- High radiation levels expected for whole upgrade phase (50 fb^{-1}) at the RICH photodetector plane location
  - 200 krad, 3×10^{12} 1 MeV n_{eq}/cm^2 , 1.2×10^{12} HEH/cm^2
- The read-out (CLARO and FPGA) have been tested for Single Event Effects (SEE) and Total Ionizing Dose (TID)
  - CLARO uses radiation-hard by design cells(IMS-CNM Sevilla)
- Xilinx Kintex-7 FPGA is suitable for operation in LHCb RICH
  - Periodic scrubbing foreseen for error mitigation





NIMA 766 (2014) 228

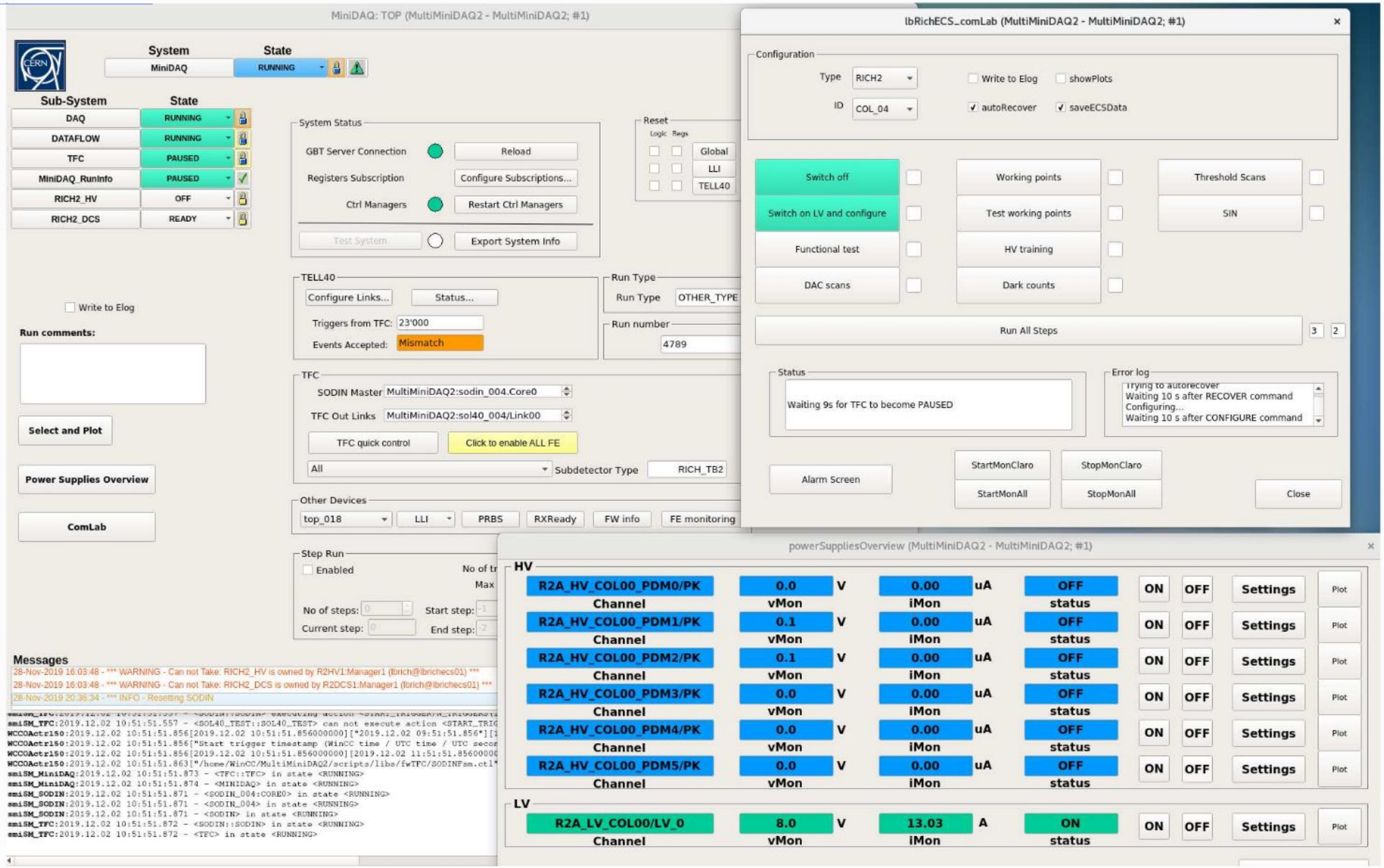
RICH2 Column Commissioning Summary

LHCb

- Fully automated test to commission 24 columns
- Few issues encountered due to software (data-writing speed, firmware programming)
- 258 automatically sent emails on both successful tests but also tests failing
- Experts on call recovering stuck tests whenever needed
- Operation-like experience carried out with the help of many collaborators travelling to CERN until pandemic hit
- Commissioning stopped for ~ 1.5 months during lockdown
- Programme concluded in 07/20 with very limited number of people due to pandemic

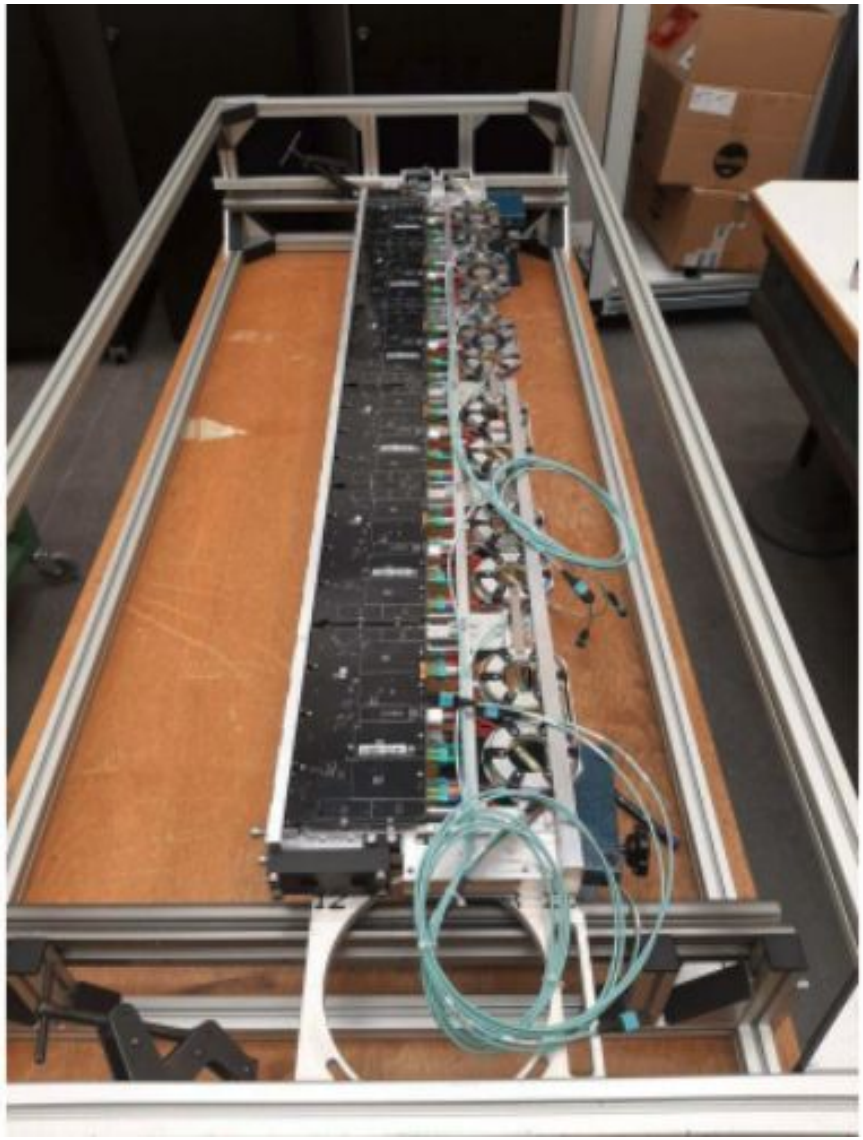
Commissioning automation

LHCb



RICH1 Column assembly

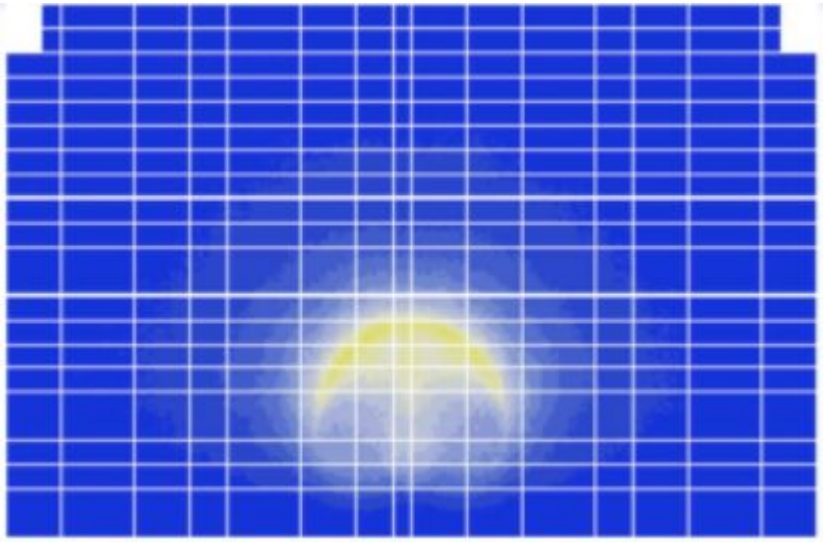
LHCb

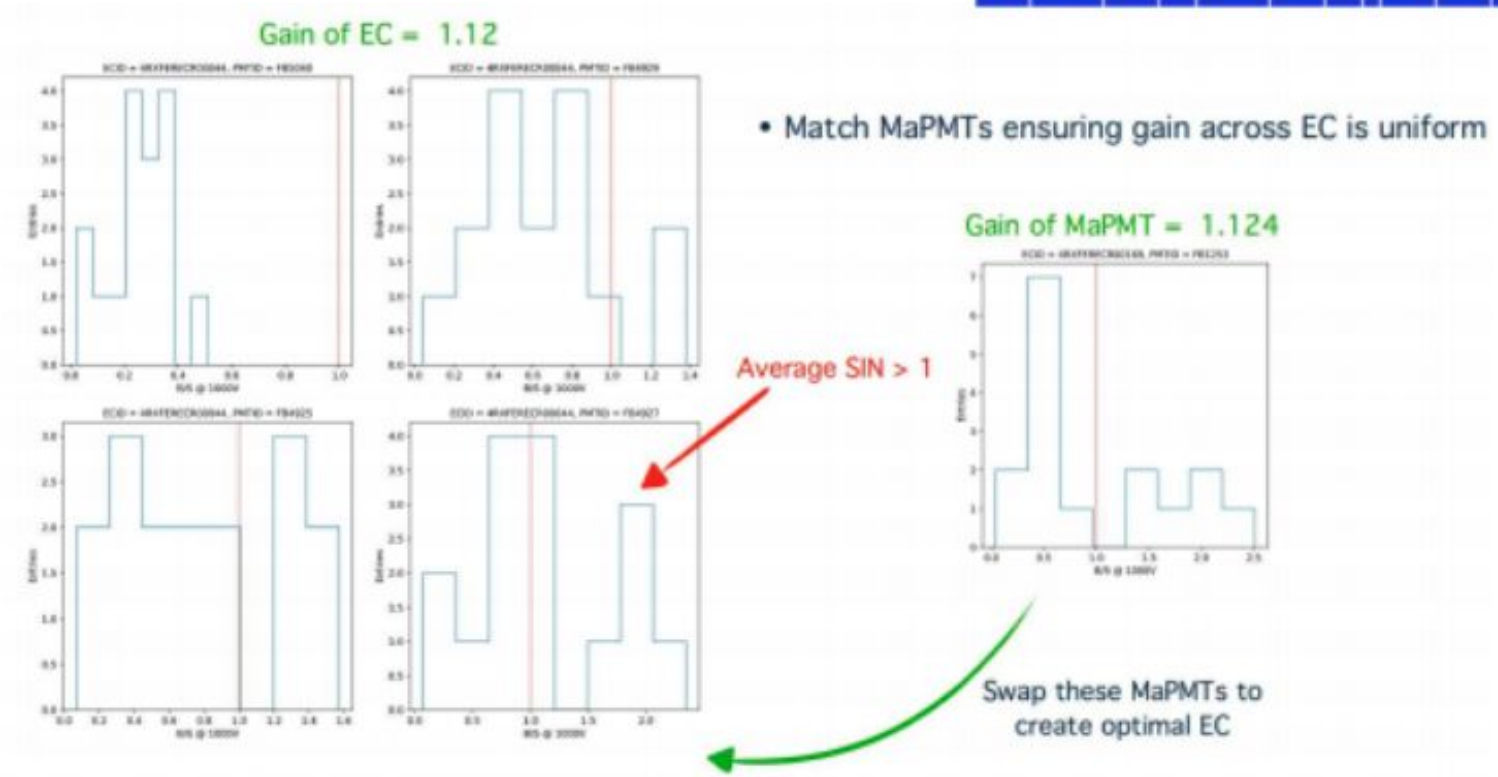


ECs grouping in RICH1: mitigation for SIN

LHCb

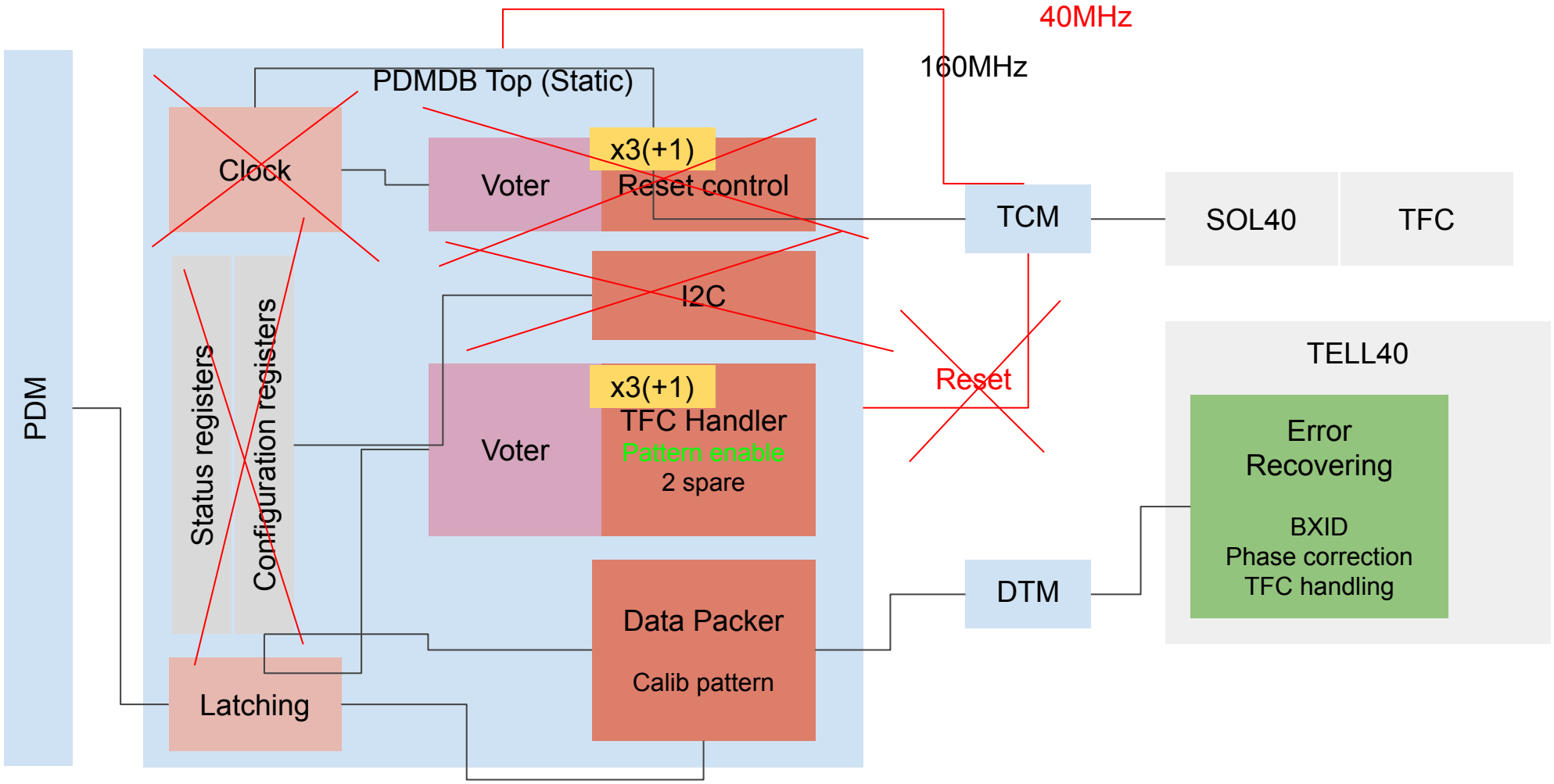
- SIN data collected at ECQA and analysed
- SIN model developed
- Occupancy map with number of MaPMTs per category produced
- Global analysis and selection of “gold” ECs defining regrouping of MaPMTs





PDMDB Firmware for radiation hardness

LHCb



SEE mitigation:

- Minimized (~4% logic)
- Triple Module Redundancy (with monitoring in data frame)
- Partial Reconfiguration
  - No interruption of data stream for SEU not involving I/O pins
  - 2 seconds otherwise

Opportunity:

- Latching at 360MHz allows "nano-gating"

TELL40 Data Processing architecture

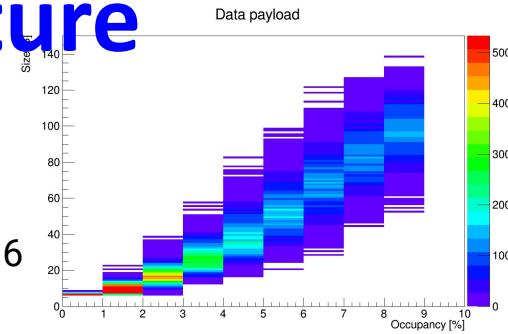
LHCb

TFC_processing output
24 links in parallel
TFC word
Header info

Packetizer
4 links per clock 6
packets per trigger

Packetized data

Payload (modelsim):
- 12 links
- Poisson input
- Link (86 bits) compressed if < 6 hits



Compressed data
Compress
hits
Compressed data
Compress
hits
Compressed data
Compress
hits
Compressed data
Compress
hits

Header

Concatenate

v3.0

12+12 links or 24+24 links at 40MHz, up to 100% occupancy, less resources than generic FF

DP Fixed-Variable output

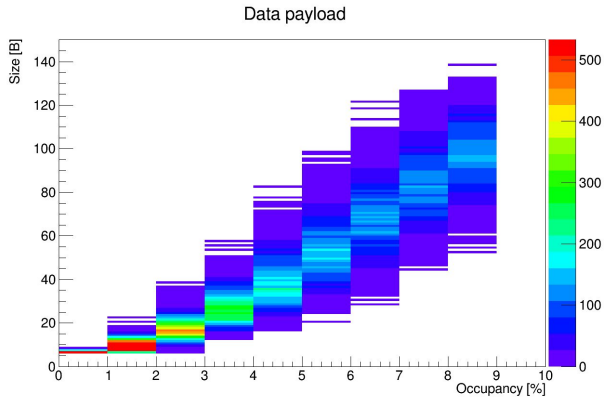
Header

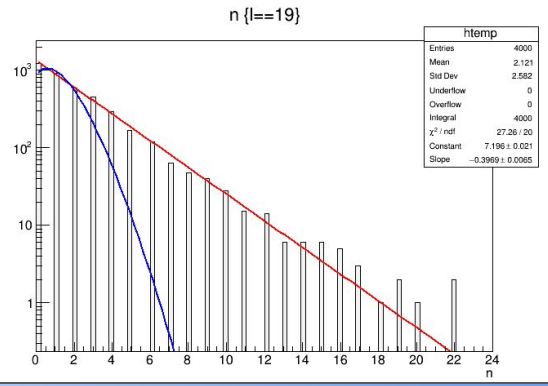
PCie 64Gb/s (on paper): MEP < 51Gb/s

V3.0 Simulation

LHCb

- Generic data generator
  - Link occupancy with Poisson distribution of the number of hits
    - Limited always to the same bits (from MSB down to MSB - # hits)
    - No errors up to the maximum allowed bandwidth
- Text files prepared with Toys
  - Link occupancy with Poisson distribution of the number of hits
    - Random bit location
    - No errors up to the maximum allowed bandwidth
- Text files prepared from Gauss+Boole output
  - Defined a simple file format
    - Samples for minbias and b events in multiple conditions
    - 4000 events per sample
  - Prepared a battery of scripts
    - Convert hits into bits based on PDM-R(H) mapping: data for 2544 links
    - Format link payloads for injection (adding BXID and SYNCH)
    - Map links to TELL40s with preselected 24/12 links assignment
    - Run Modelsim for all TELL40s (4k events in ~2h/#licenses)
  - Some surprises
    - Occupancy is not Poisson distributed
    - Minor bugs found and fixed
  - More realistic bandwidth estimates





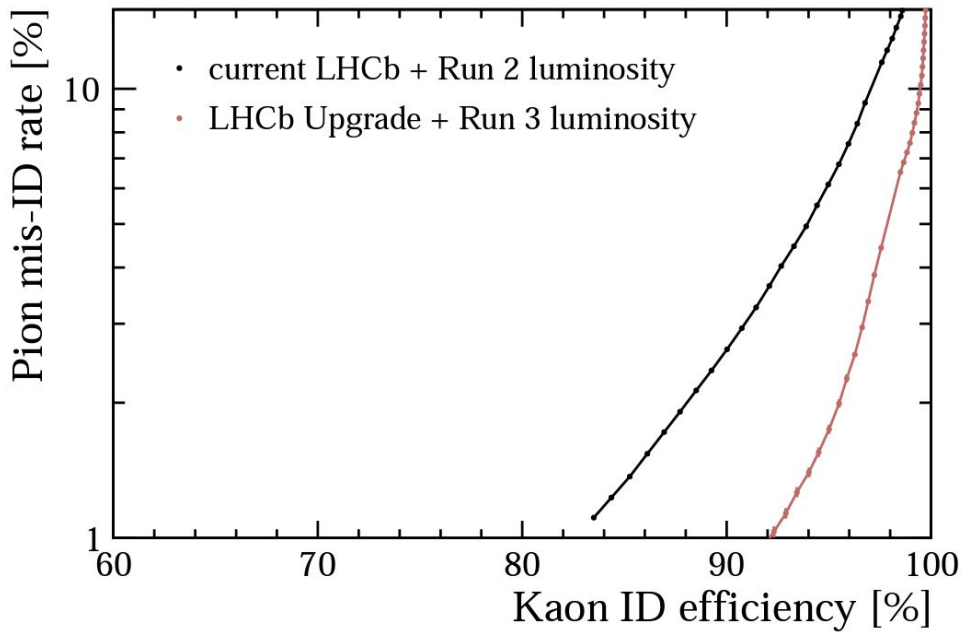
Estimated performance

LHCb

	Photon yield		Cherenkov angle resolution [mrad]				
	$N_{\rm ph}^{\rm optimal}$	$N_{\rm ph}^{\rm typical}$	chromatic	emission point	pixel	σ_θ	$\Delta\theta_{\rm C}$
RICH1	63	59	0.52	0.36	0.50	0.81	0.18
RICH2	34	30	0.34	0.32	0.22	0.52	0.17

Included in the current simulation

- All measured parameters of optical components
- All feedback from test beams and commissioning
- Experience from the simulation of the previous implementation of this detector

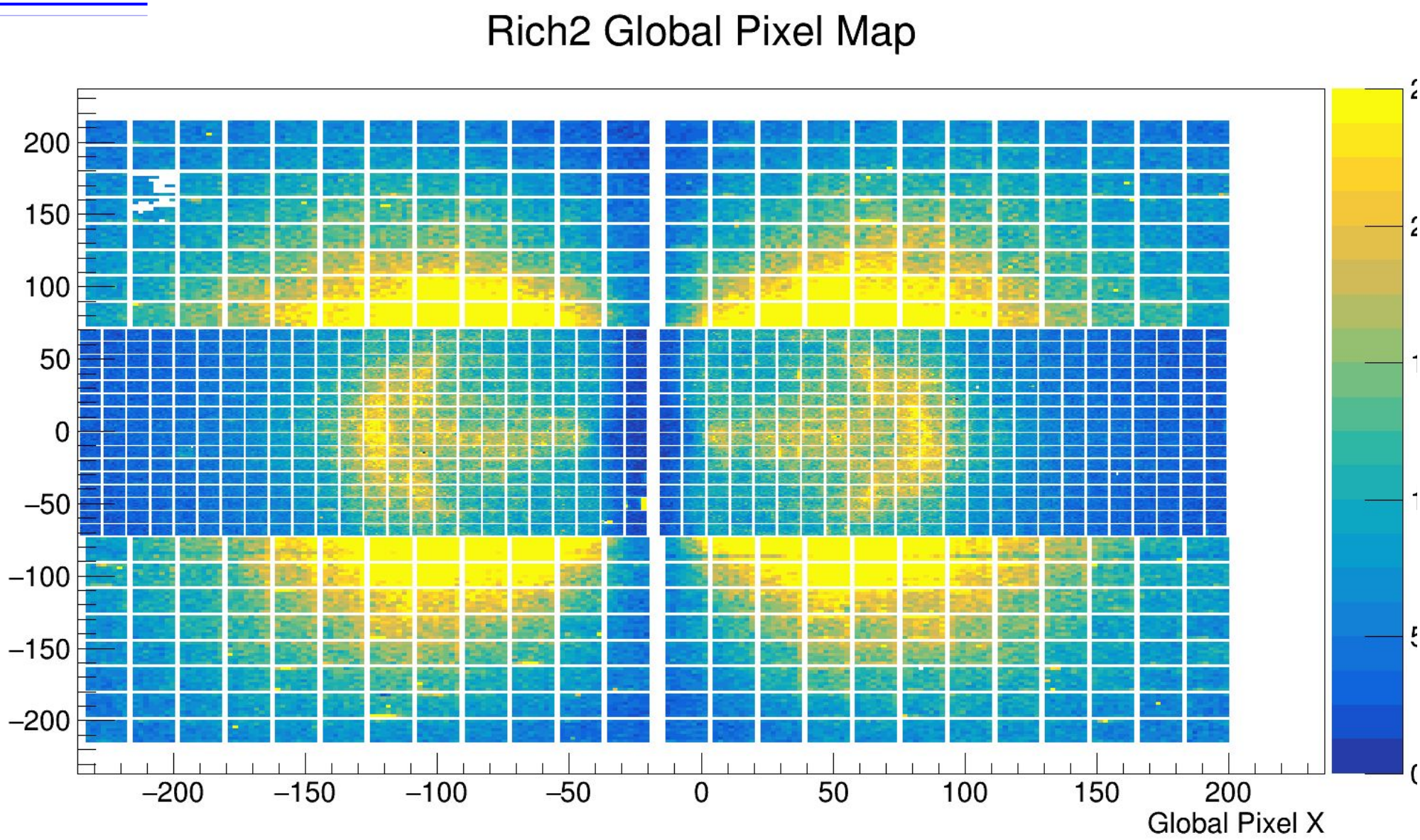


Beam test with RICH2: Frictions in October 2021

LHCb

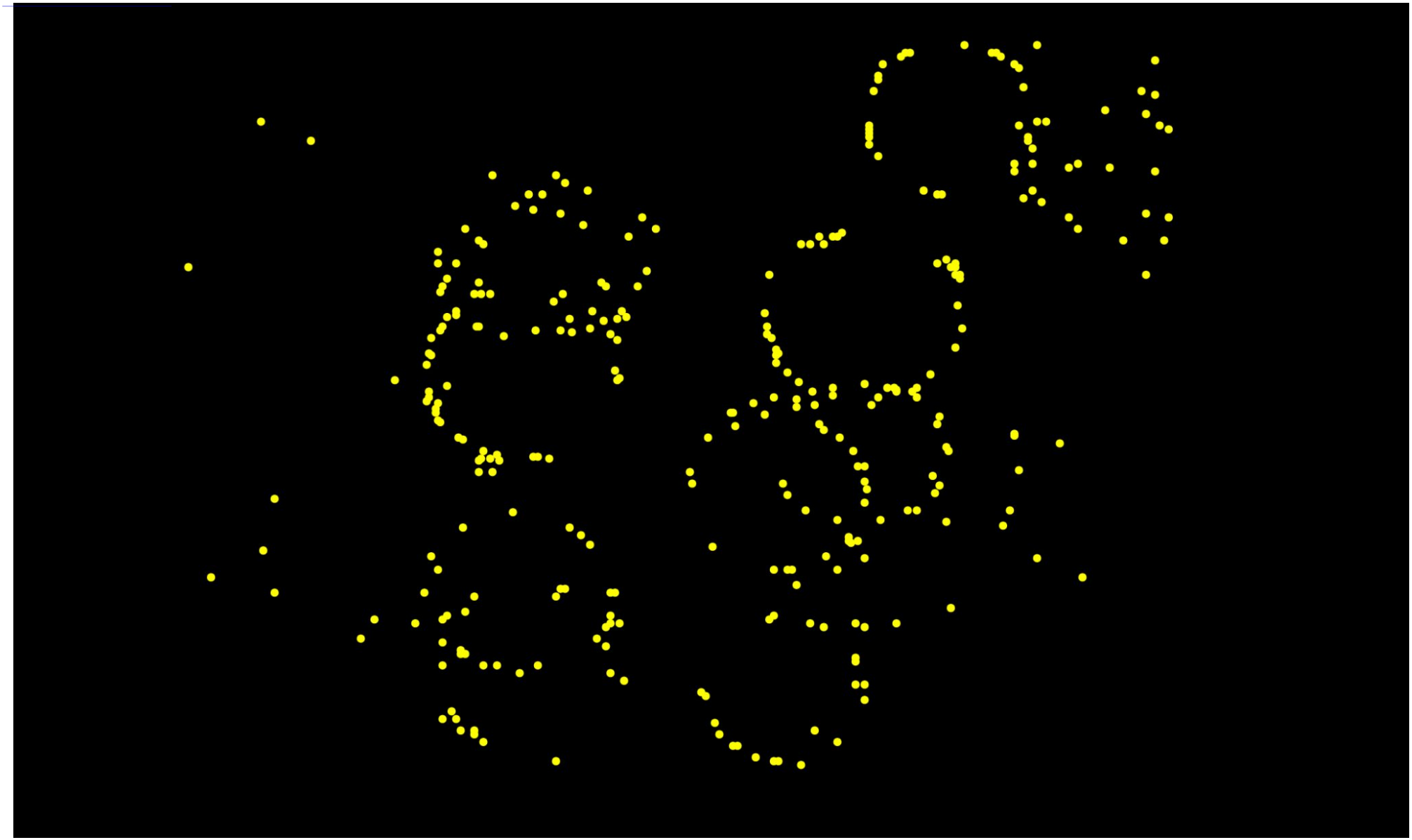
- Setup
  - 2 noisy channels (out of 73728)
  - 1 data link not operational
    - Fixed afterwards
  - Occasional link instabilities
    - Improved since then
- Tests performed
  - Time
    - Synchronized with LHC orbit
    - Identified corresponding delays for test pulses and laser pulses
  - Space
    - Observed rings
    - Occupancy
      - Reasonably as expected
- Control and Software
  - Some instabilities
    - Significant improvement after few days

First Occupancy with Frictions



- Reasonably as expected
  - The hole corresponds to the only inactive data link at the time

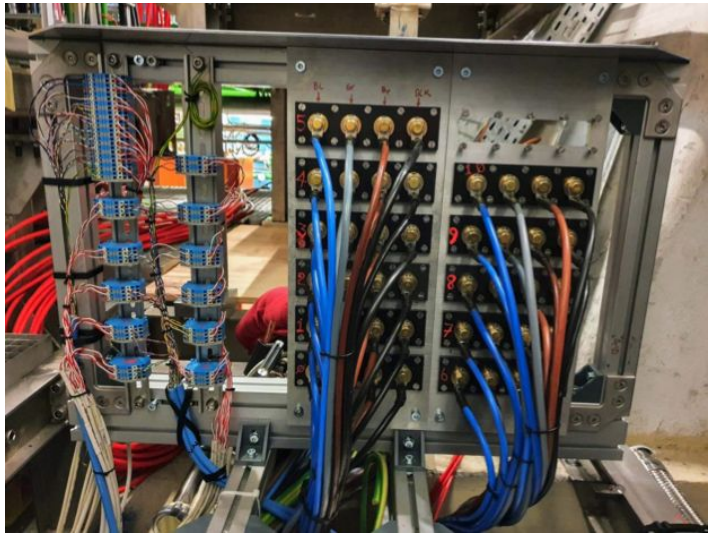
First Rings with Frictions

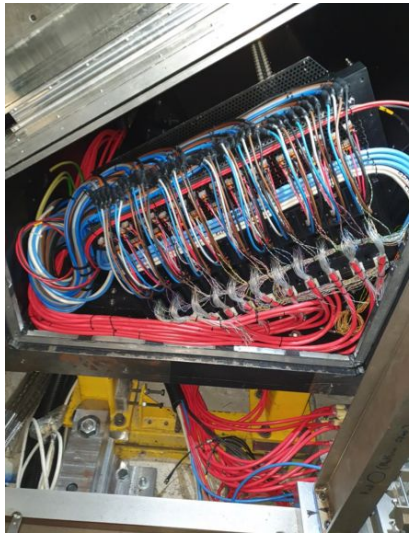


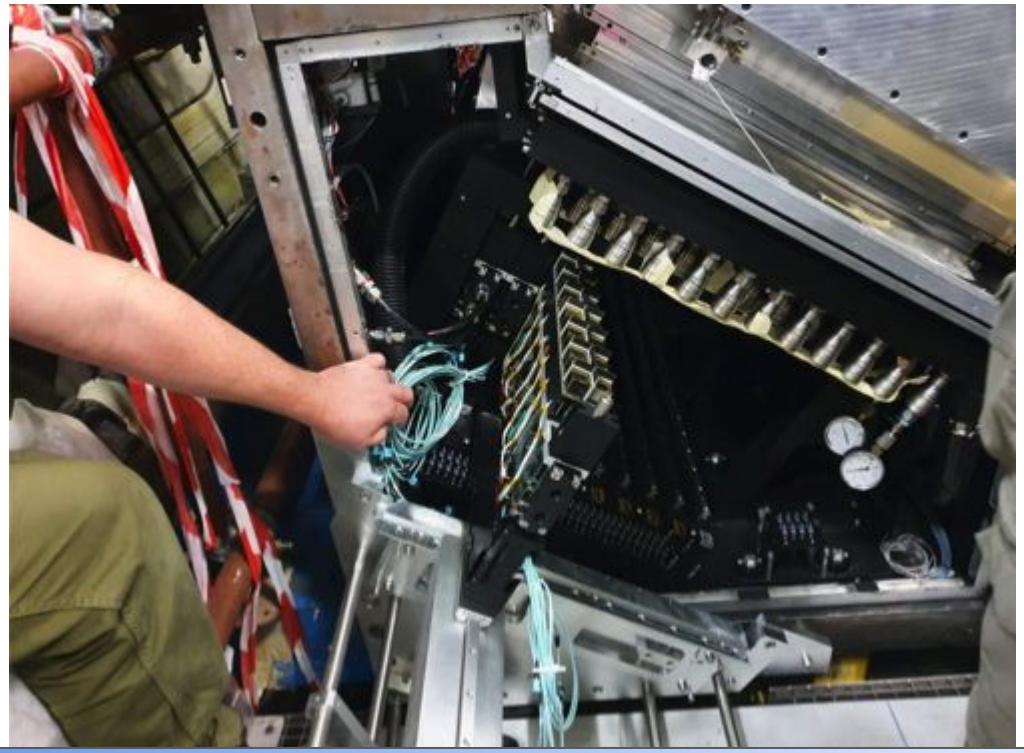
- Nice to see
  - Lots of things to check before claiming anything

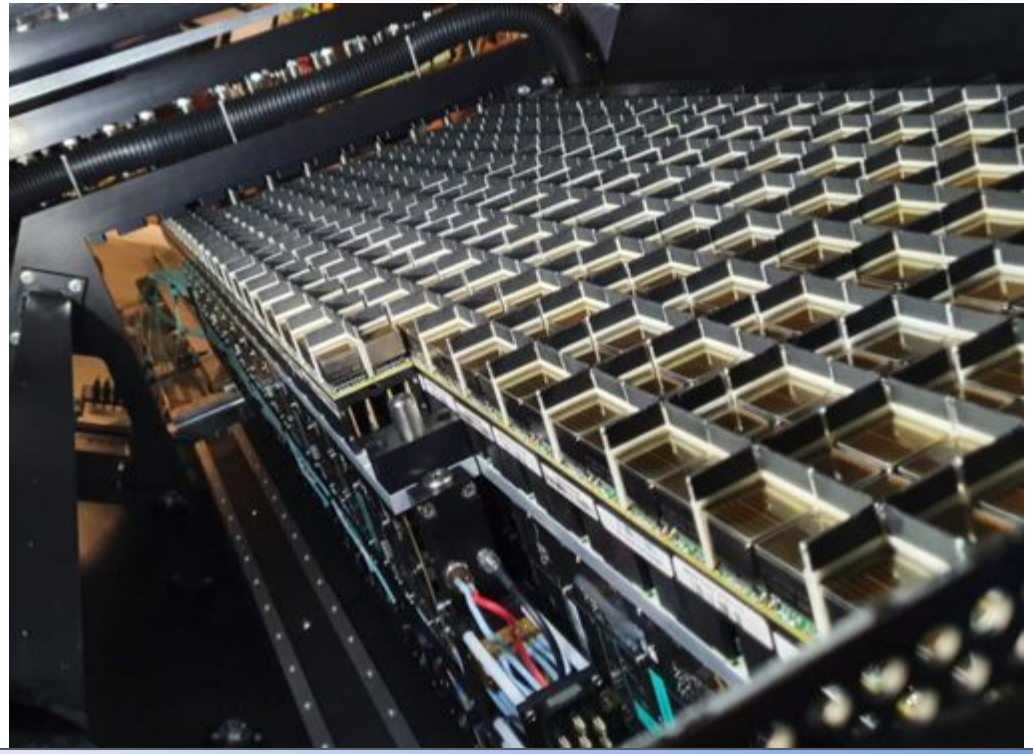
RICH1 Installation: Down Box (12/2021)

LHCb



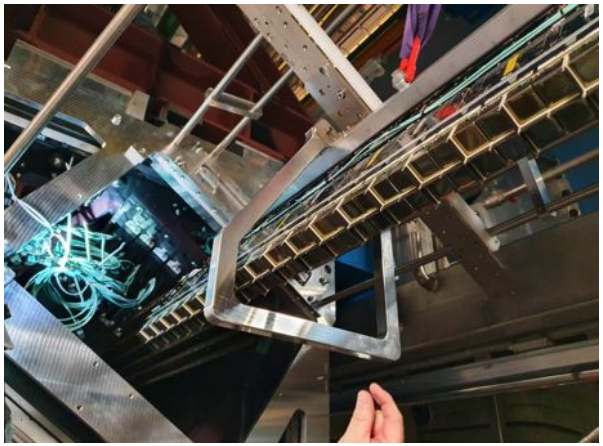


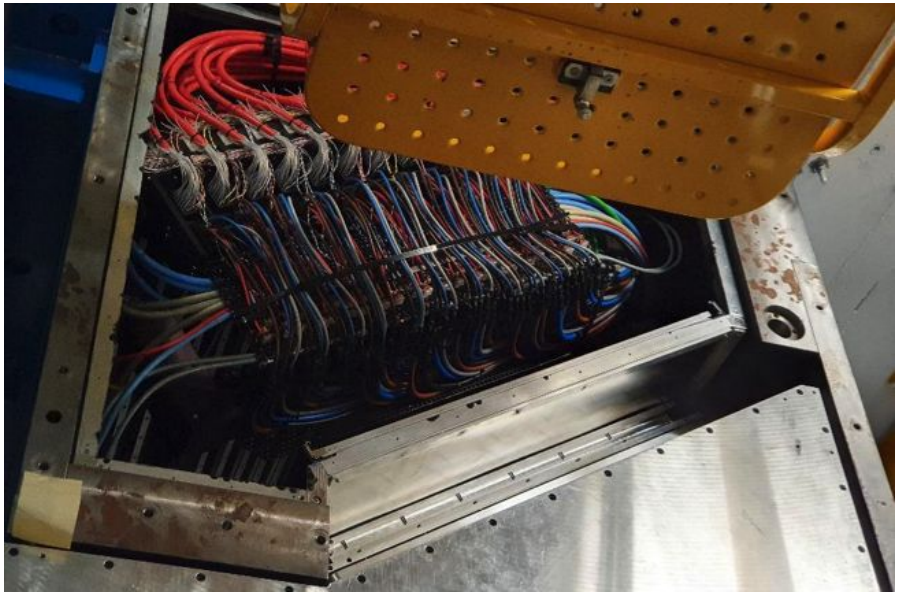


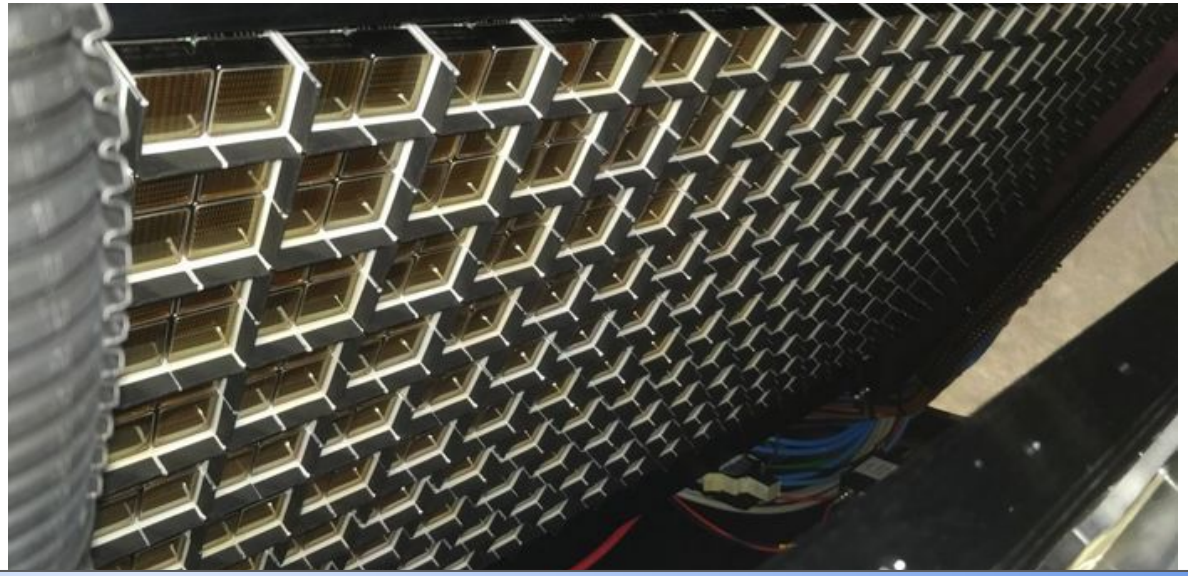


RICH1 Installation: Up Box (01/2022)

LHCb

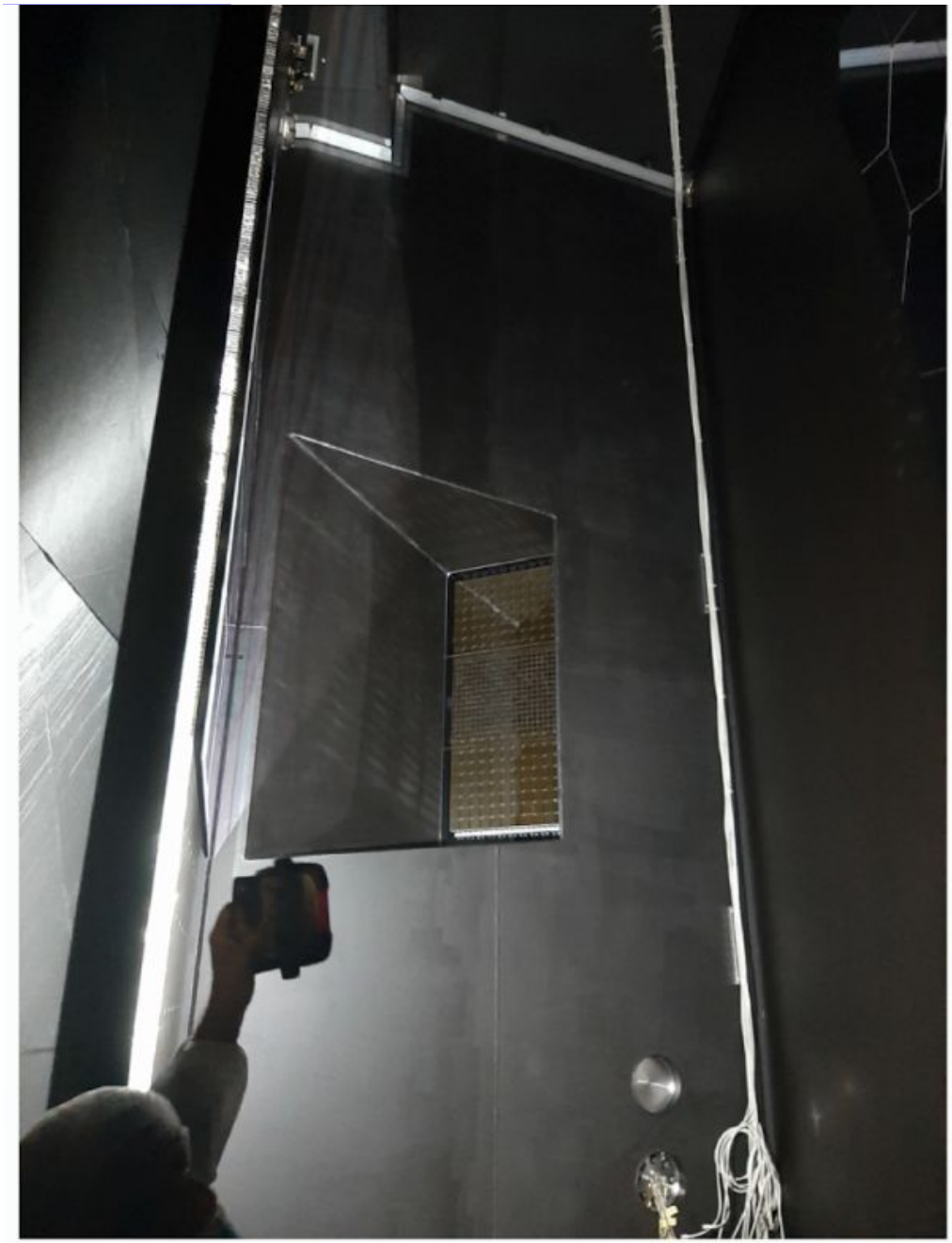






Installation Summary

LHCb

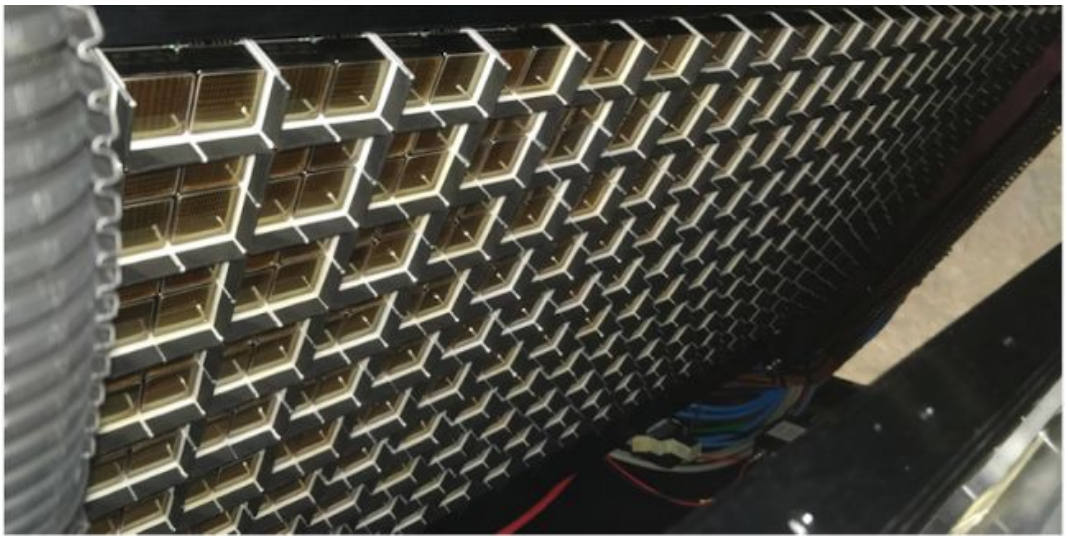


RICH2 :

A-side installed in Feb 2021
C-side installed in Ap 2021

RICH1 :

Down-box installed in Dec 2021
Up-box installed in Jan 2022,
Completed in March 2022

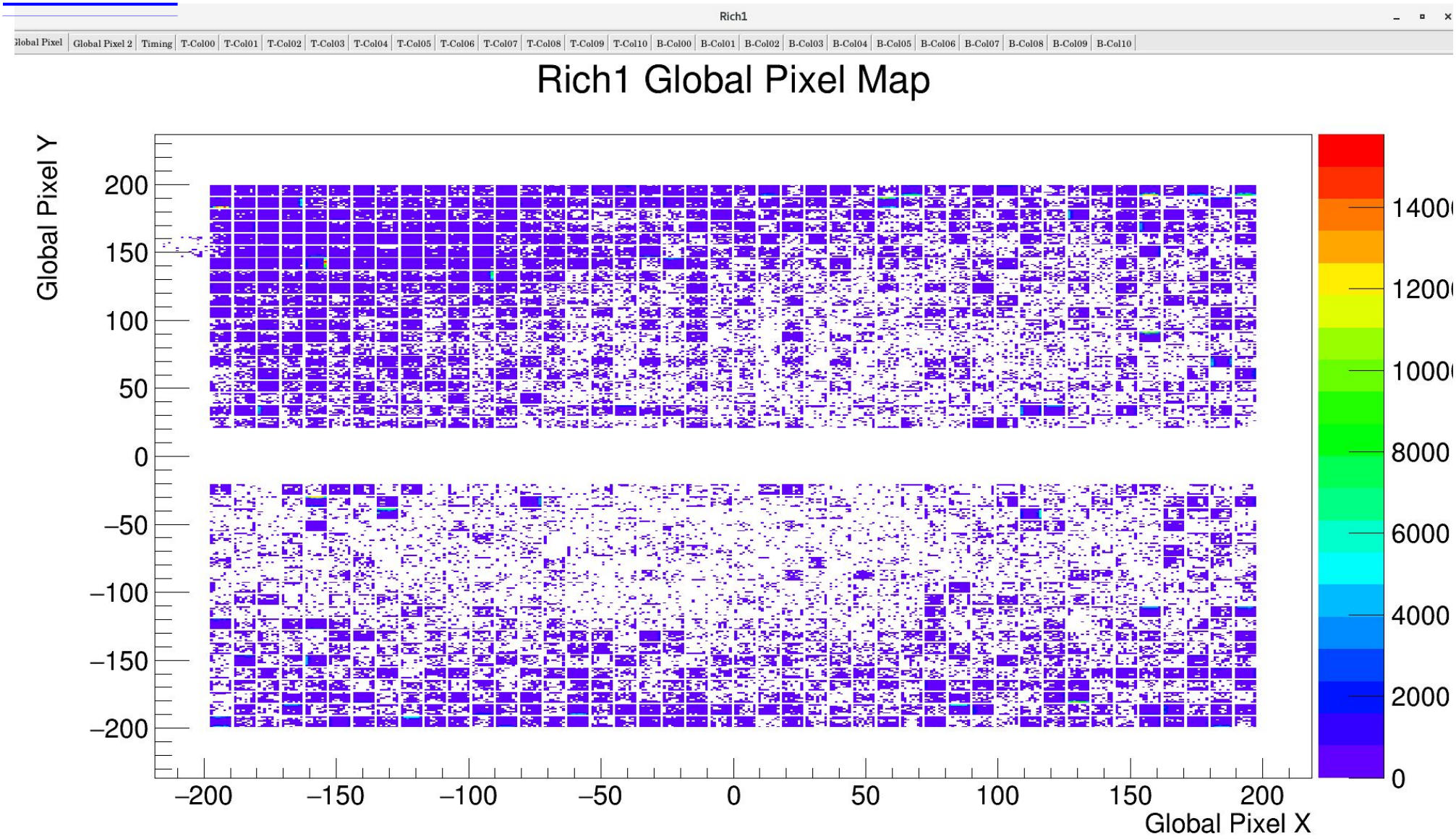


Both RICH1 and RICH2 fully installed:

- Commissioning in Myin completed
- Commissioning at P8 ongoing

RICH1 Early Dark Counts

LHCb



- Mostly ok
  - Few PMTs needed more HV training

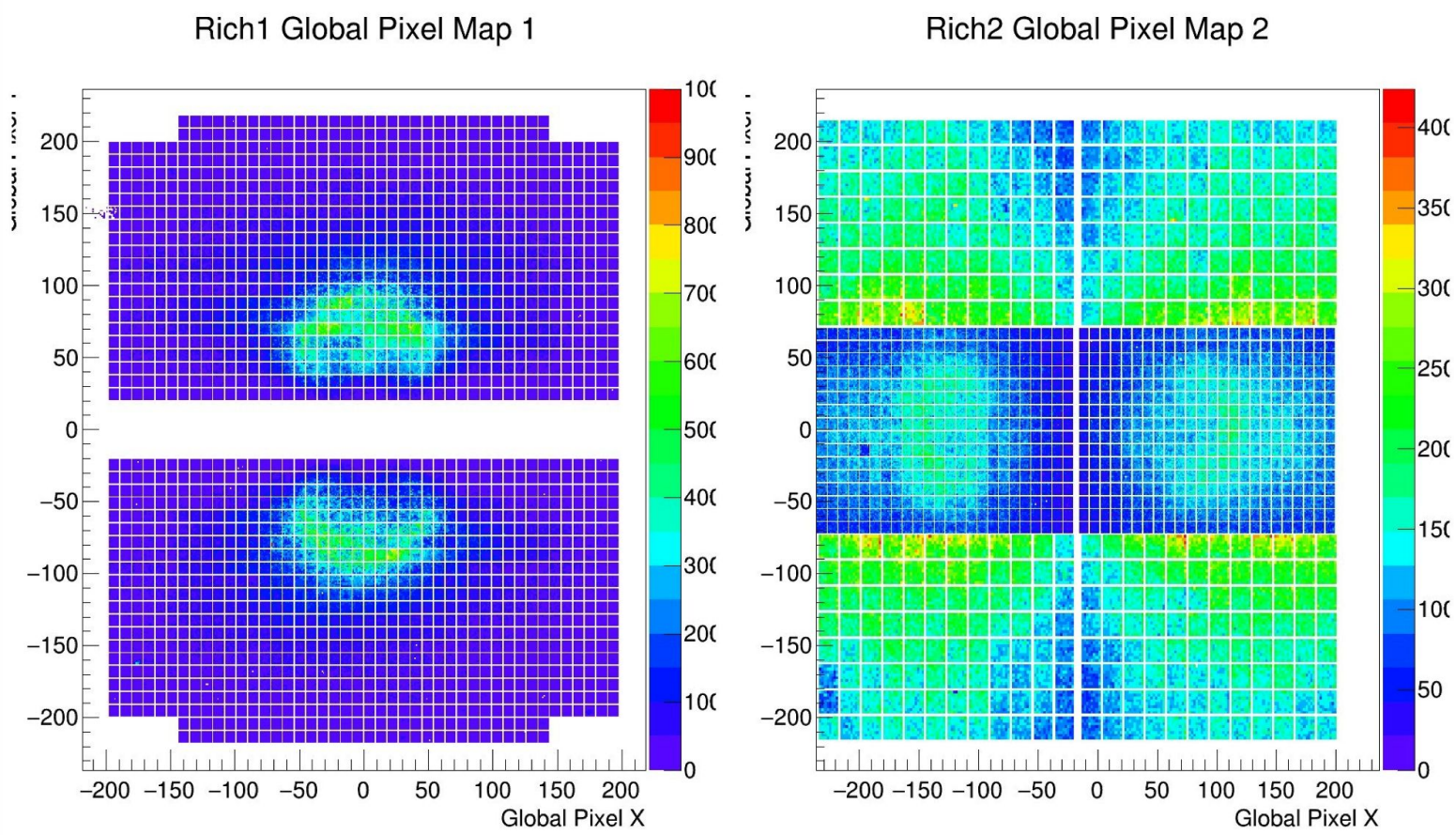
RICH1 and RICH2 FE status

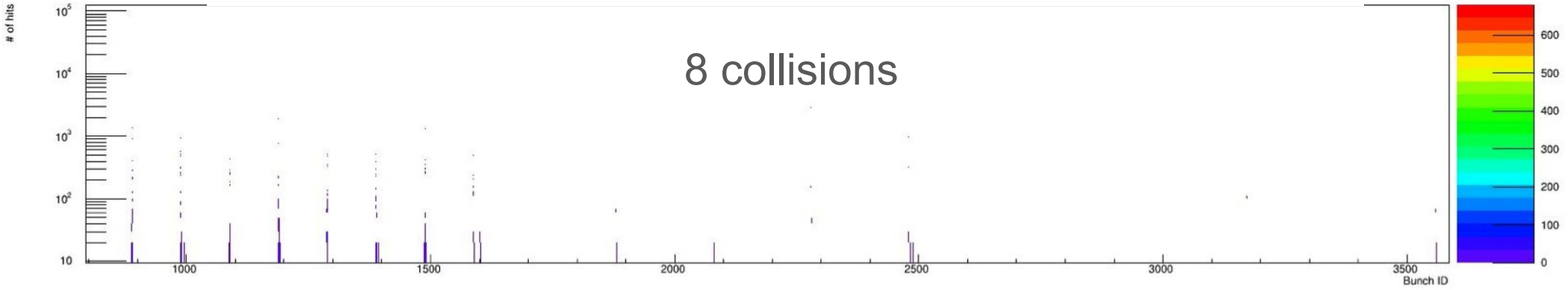
LHCb

- A handful of noisy or dead channels ($<10^{-4}$)
- All control and data links operational
- Controls:
  - DAQ, HV, DCS well advanced and integrated in run control
  - Constant monitoring and alarms implemented
  - Run like recipes for front-end and HV implemented

Collisions and Light (June-July 2022)

LHCb

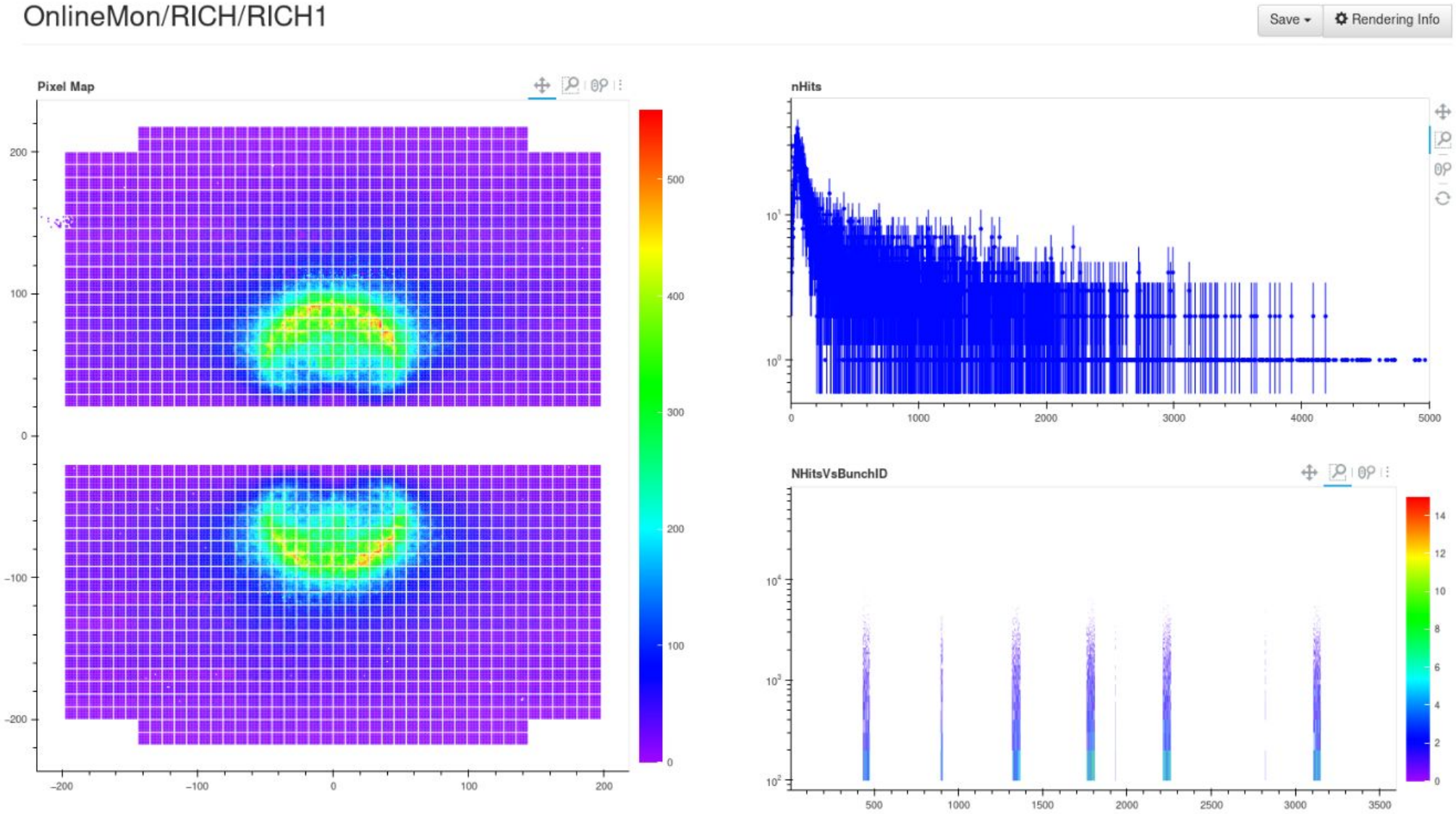




8 collisions

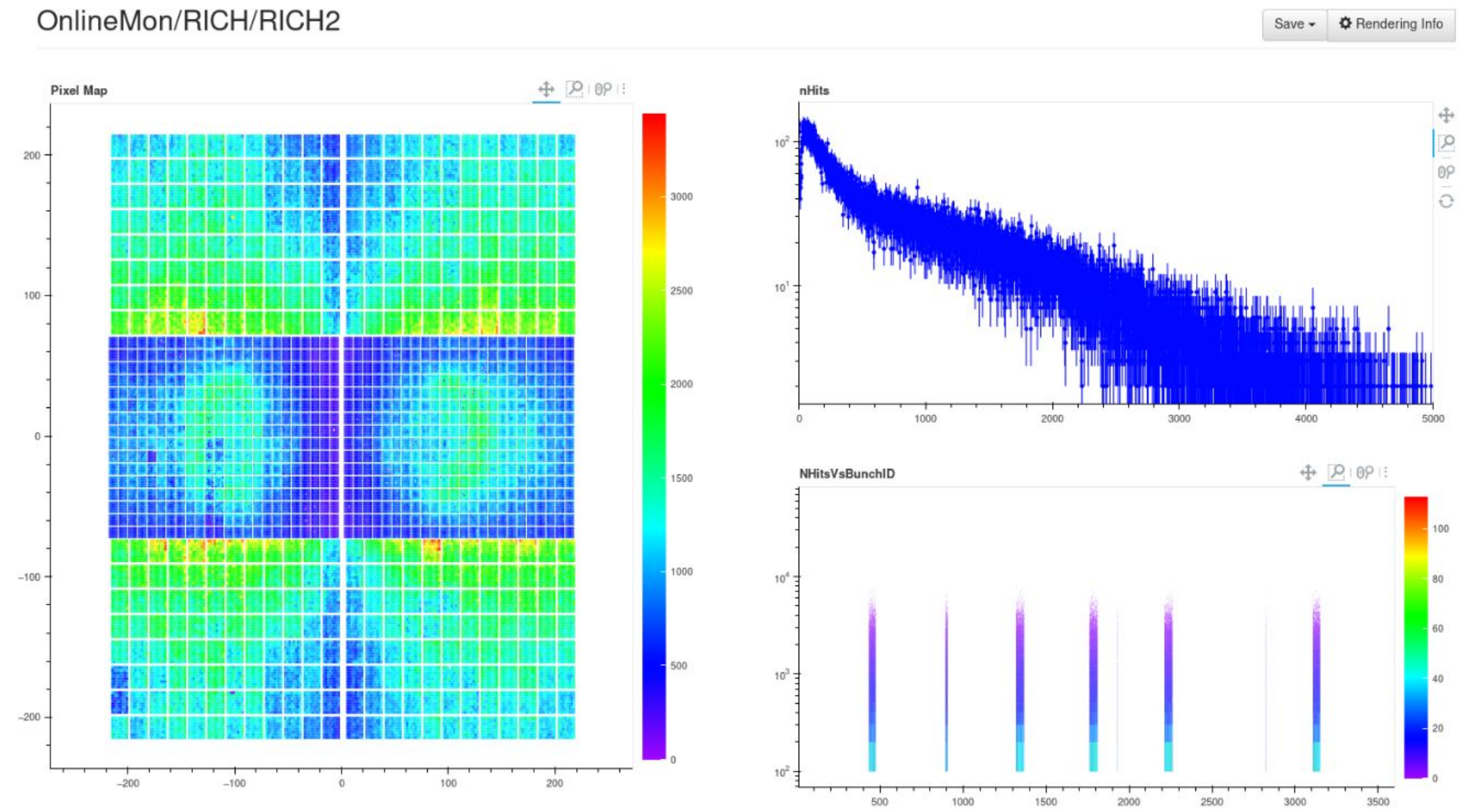
Collisions and Light (June-July 2022)

LHCb



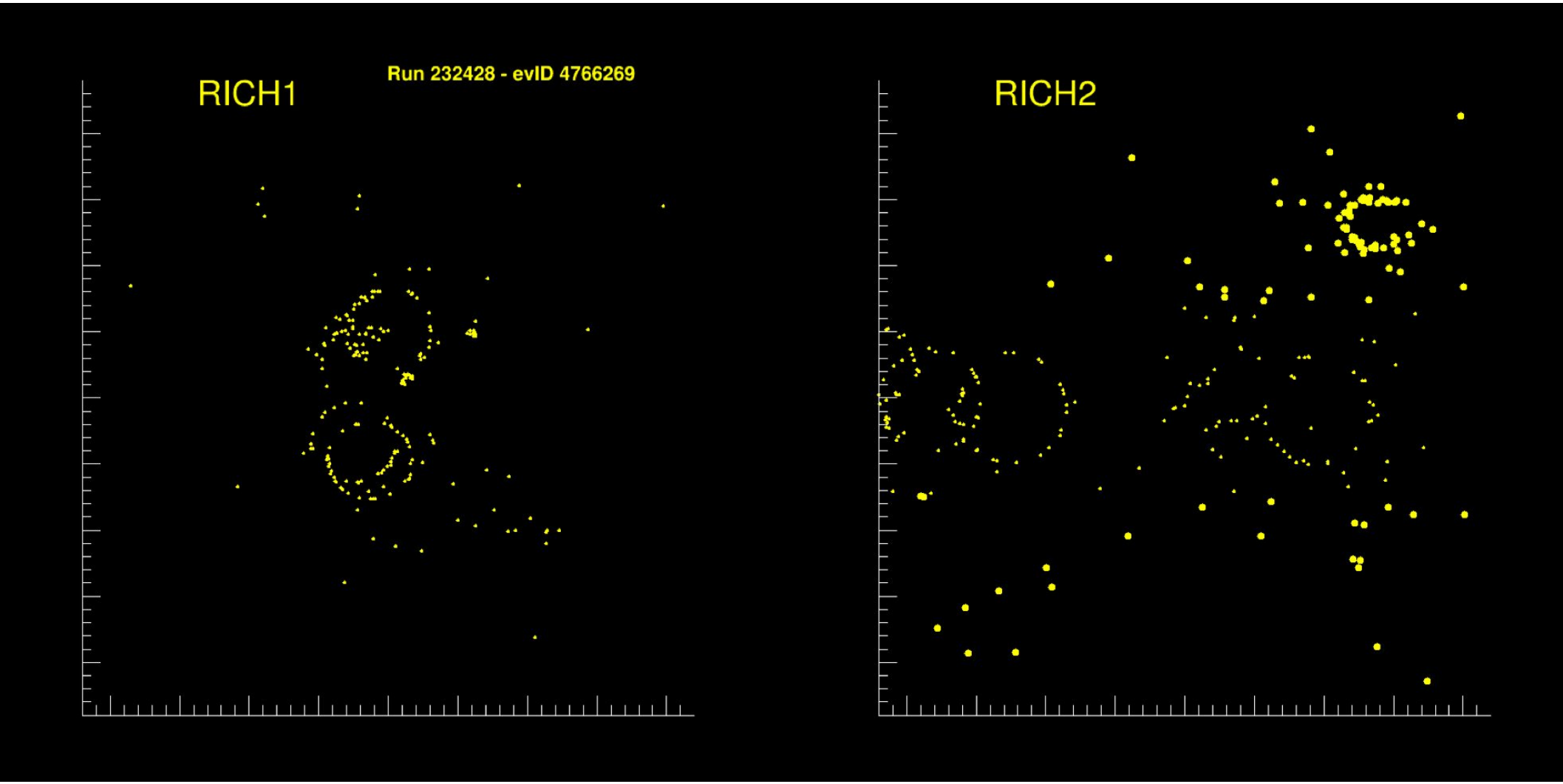
Collisions and Light (June-July 2022)

LHCb



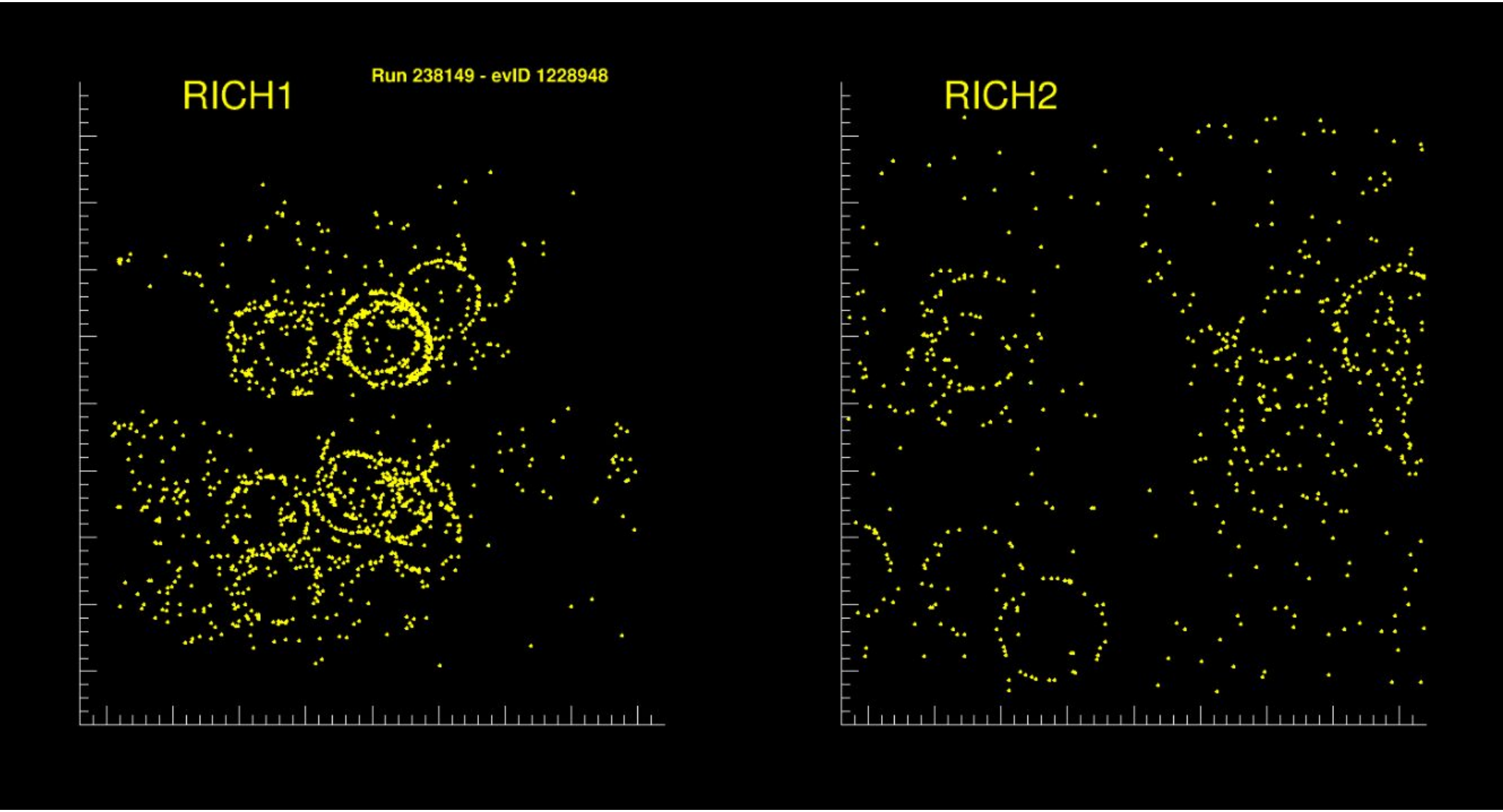
Collisions and Light (June-July 2022)

LHCb



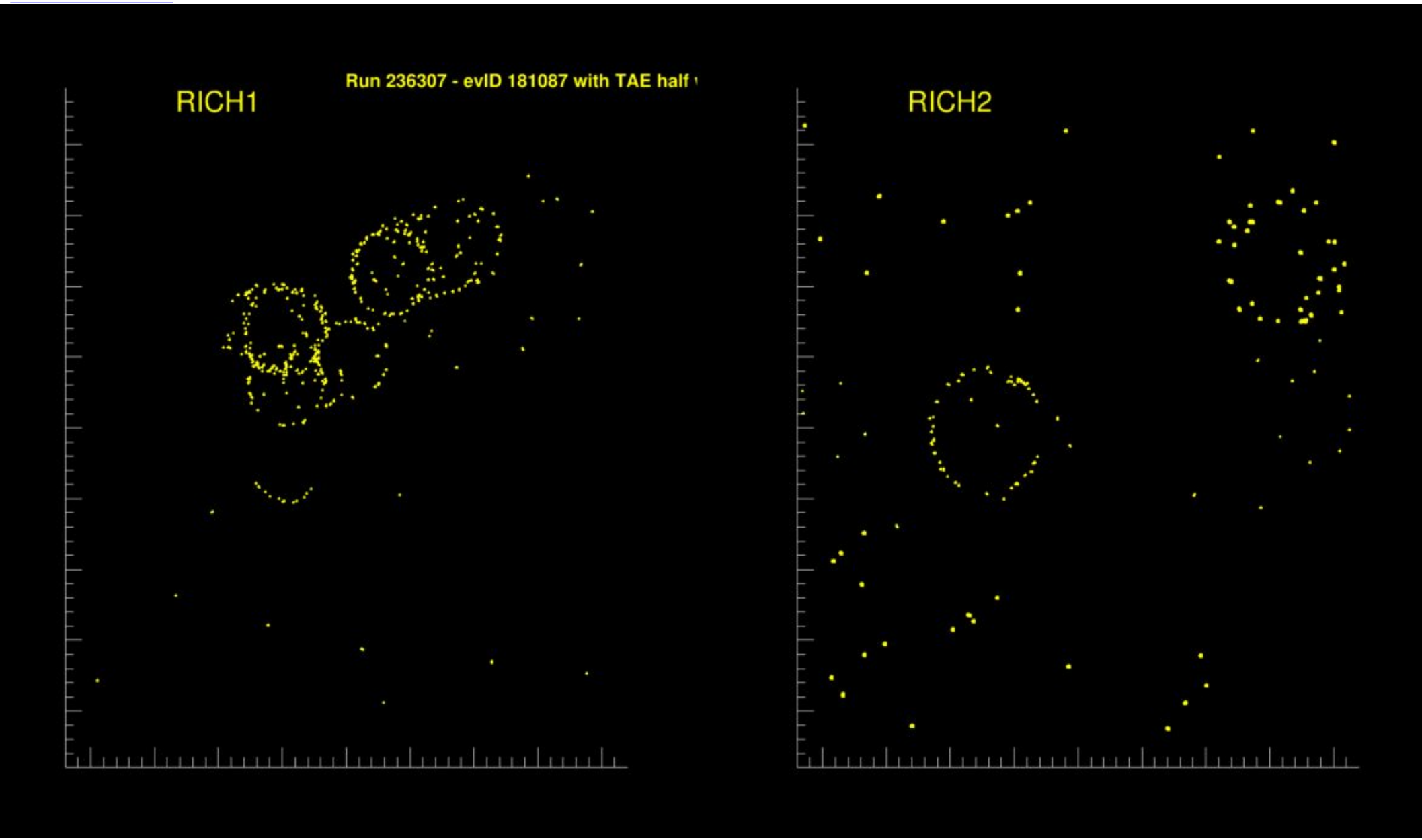
Collisions and Light (June-July 2022)

LHCb



Collisions and Light (June-July 2022)

LHCb



RICH2

- Status
  - Operational
  - Always on, when safe
- Hardware
  - Generally ok
  - A handful of noisy channels (now masked)
  - Thresholds optimized
  - HV tuned

RICH1

- Status
  - Operational
  - Always on, when safe
- Hardware
  - Few channels (at the edge of one column, up box) not readable:1 FPGA rarely configuring
    - Replacement to be scheduled
  - A handful of noisy channels (now masked)
  - Threshold optimized
  - HV tuned
  - 1 control link unstable (~24h) being investigated

- Firmware & Software
  - Minor bugs in the TELL40 firmware; almost completely solved
  - Online monitoring is operational
- Timing
  - Trying to optimize time alignment down to 6ns

LHCb

Summary and Outlook

- A new Detector
  - New photo-detectors, FE and BE electronics
    - Modified optics in RICH1
    - 2 sizes of Hamamatsu MaPMTs
    - CLARO based FE electronics for signal discrimination
    - Kintex-7 based FE electronics for data frame preparation and high speed transmission to BE
    - Arria10 based BE electronics (TELL40) for data compression and packing
  - Larger number of smaller pixels
  - Better performance at higher luminosity
- Development
  - About 10 years
  - Almost smooth sailing, with some surprise along the way (SIN)
- Commissioning
  - Physiological progress
  - Getting close to physics readiness
    - Hardware ok
    - Working point should be achieved by the end of the year

LHCb