The LHCb RICH system: current detector performance and status of the upgrade program

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on behalf of the LHCb RICH Collaboration

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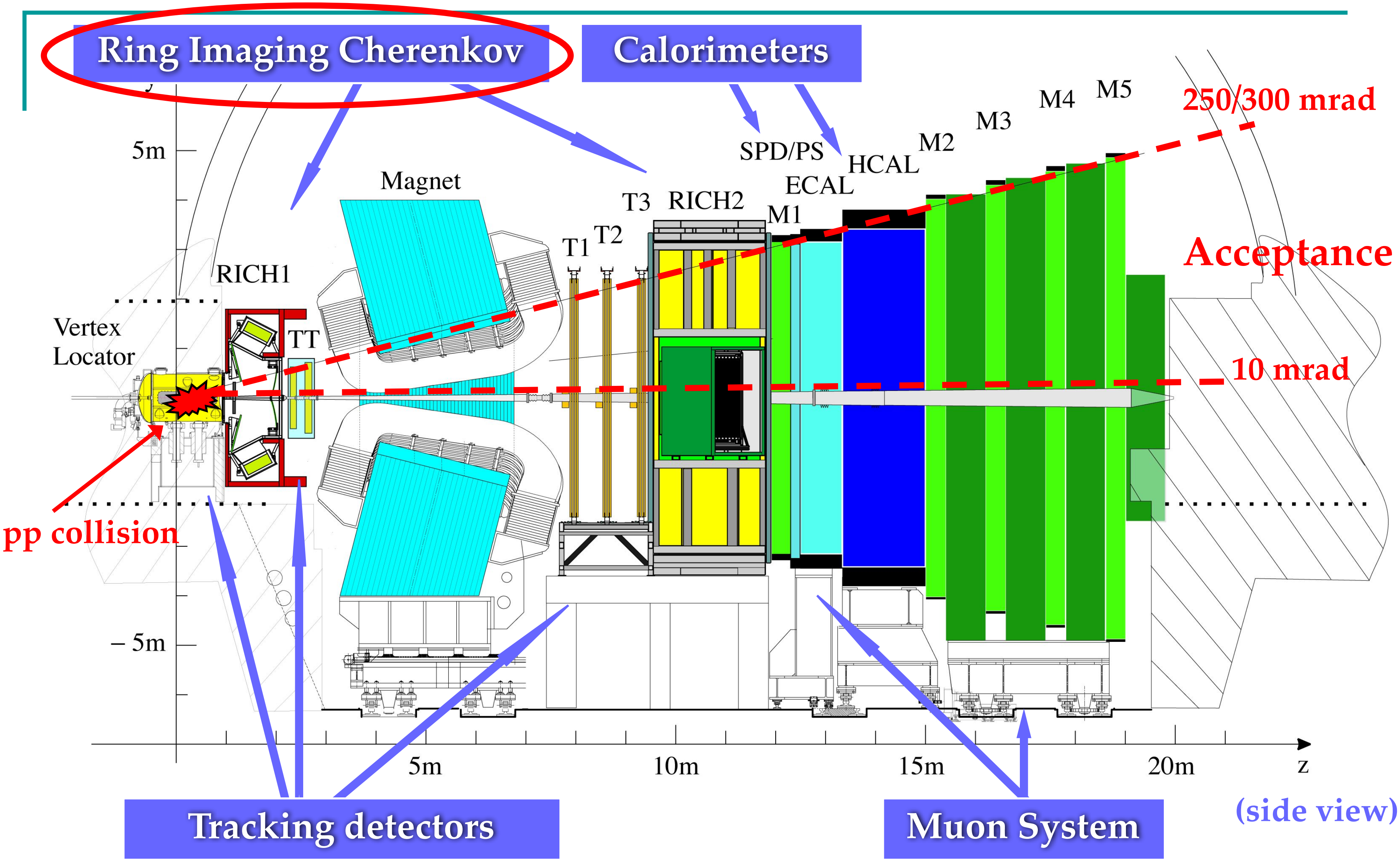
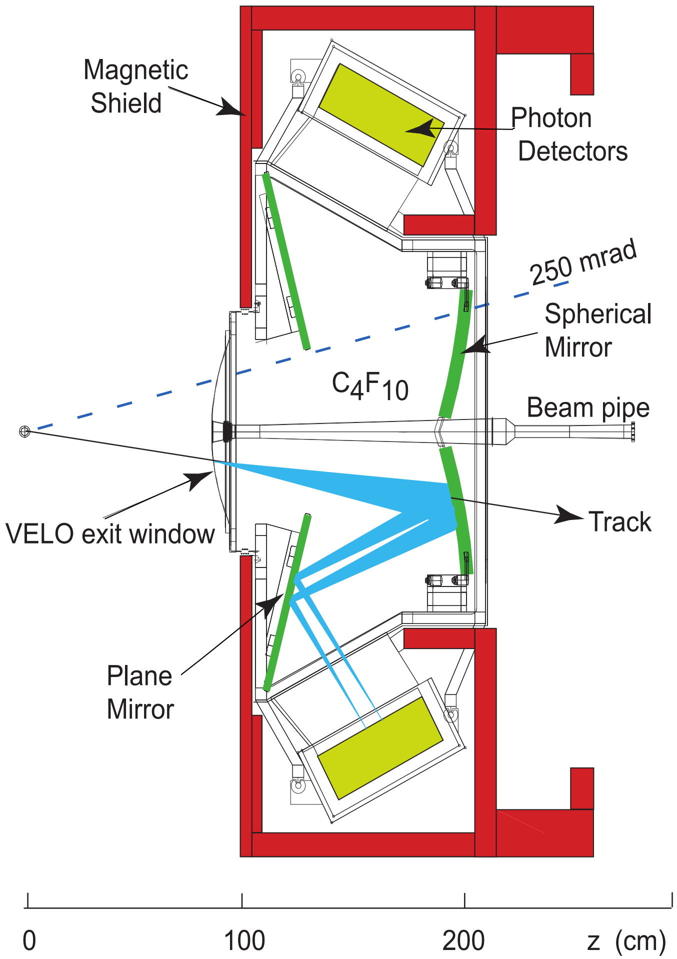
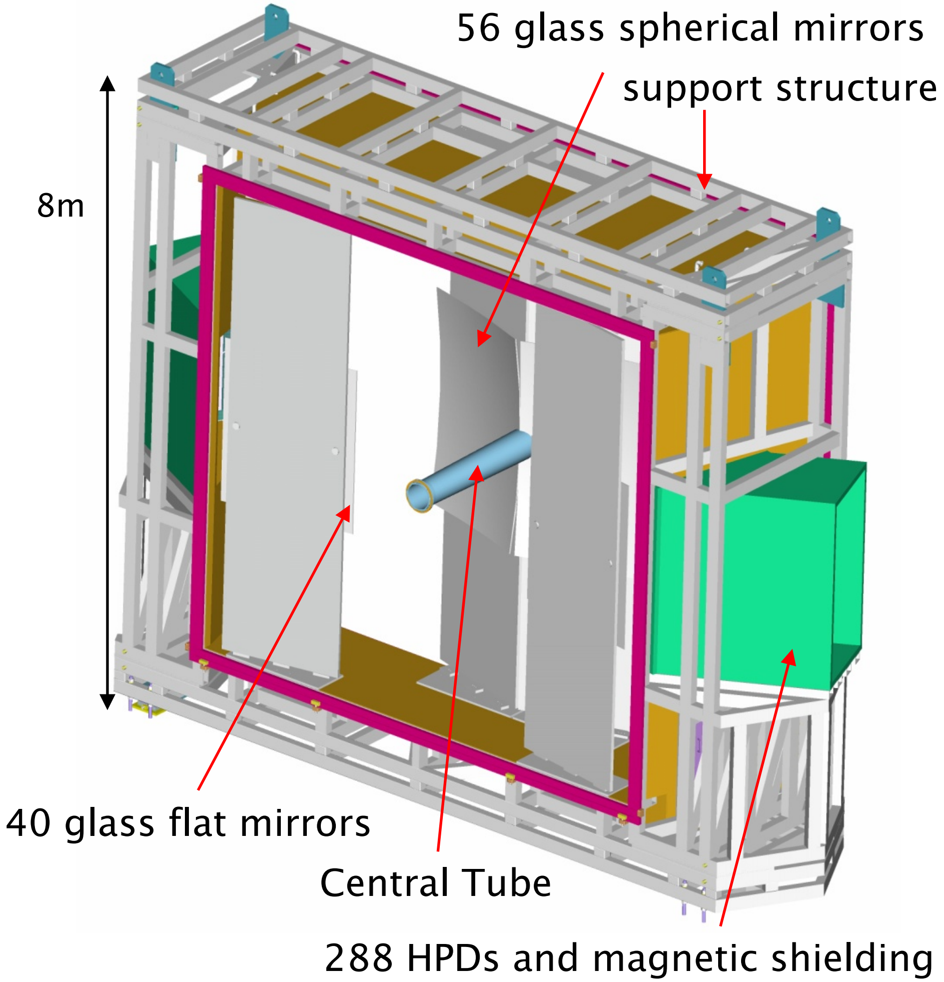
The LHCb Experiment



RICH Detectors





RICH-1 (25-300 mrad)

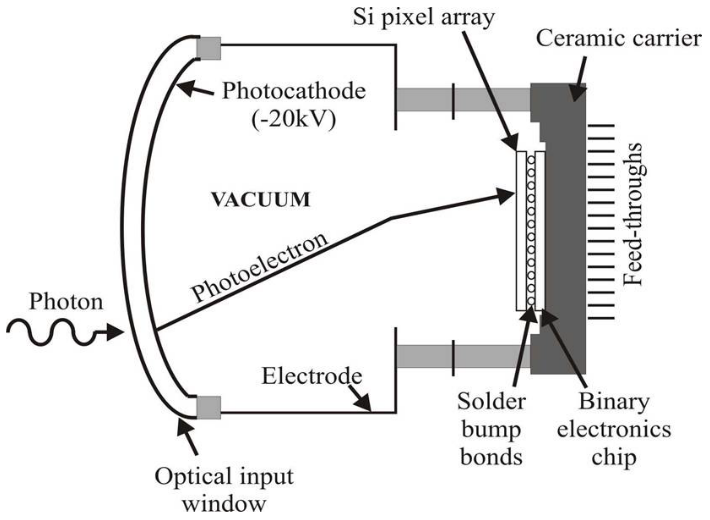
4 m^3 C_4F_{10} n = 1.0014, up to 60 GeV

RICH-2 (15-120 mrad)

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

Hybrid Photo-Detectors (HPD)

- Pixel HPD developed in collaboration with industry
  - Vacuum technology and silicon pixel read-out
- 484 HPDs for a total area of 3.3 m^2
- 32×32=1024 pixels, 0.5×0.5 mm^2
- Very good QE (~27% @270nm)
- Silicon sensor bump-bonded to binary read-out chip (1.1 MHz)
- Very low noise
  - 145 e^- (signal 5000 e^- typ.)

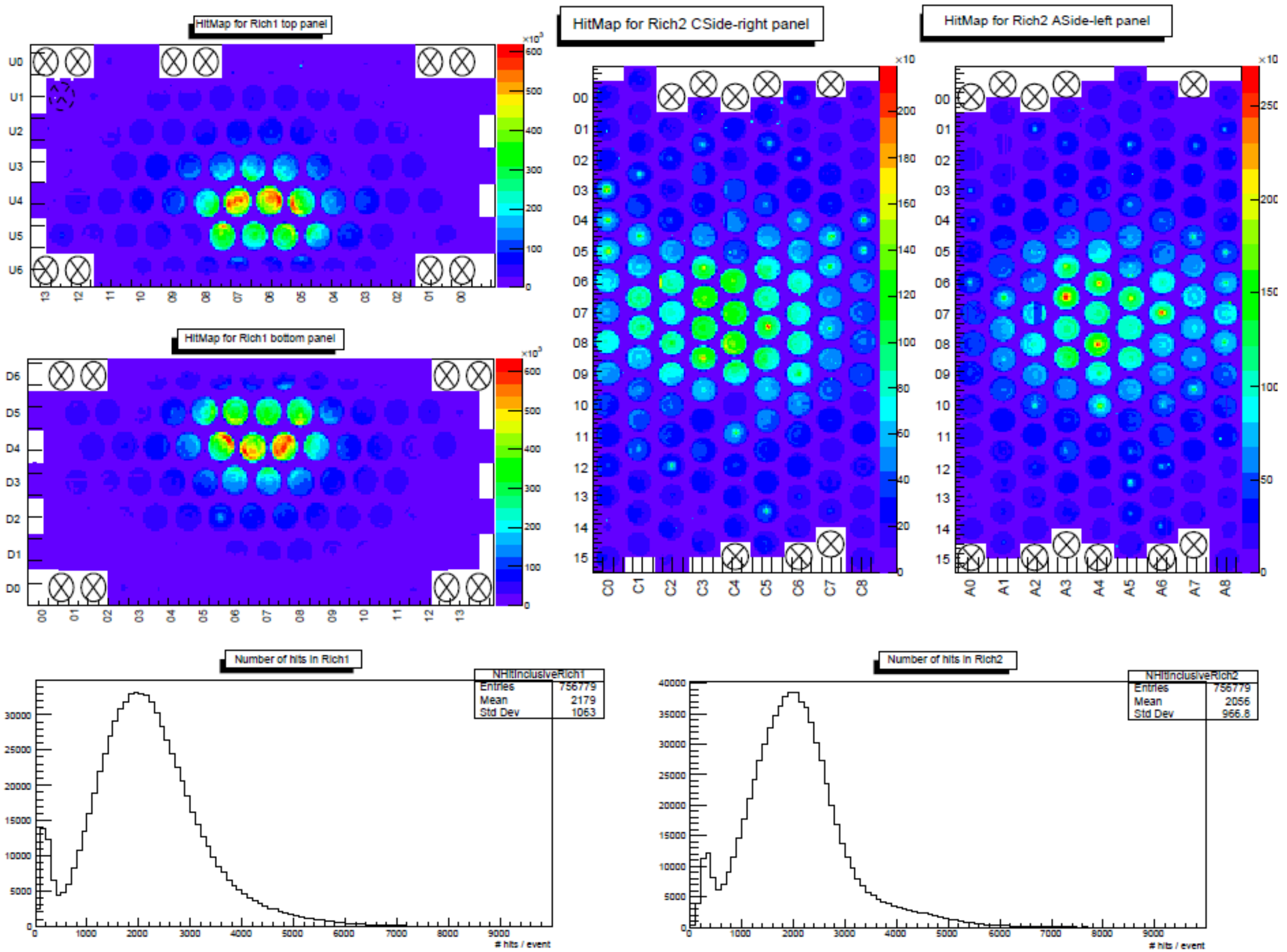


References: NIMA 595 (2008) 142
EPJ C 73 (2013) 2431

Detector occupancy

RICH-1

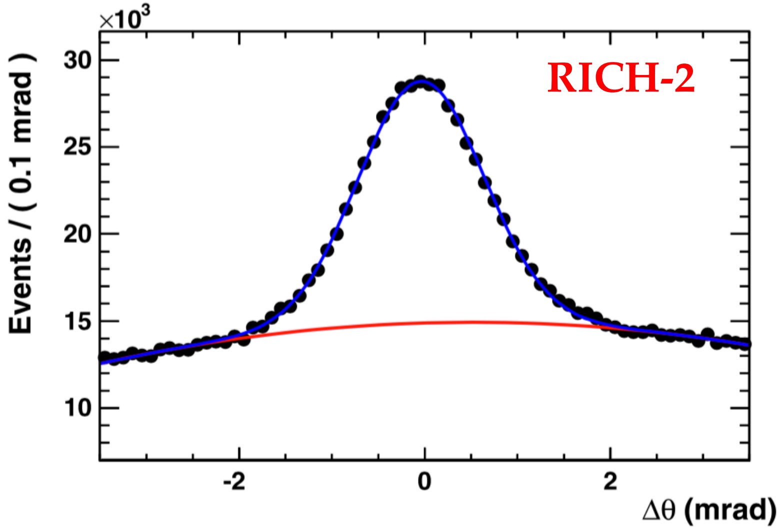
RICH-2



Online calibrations (1)

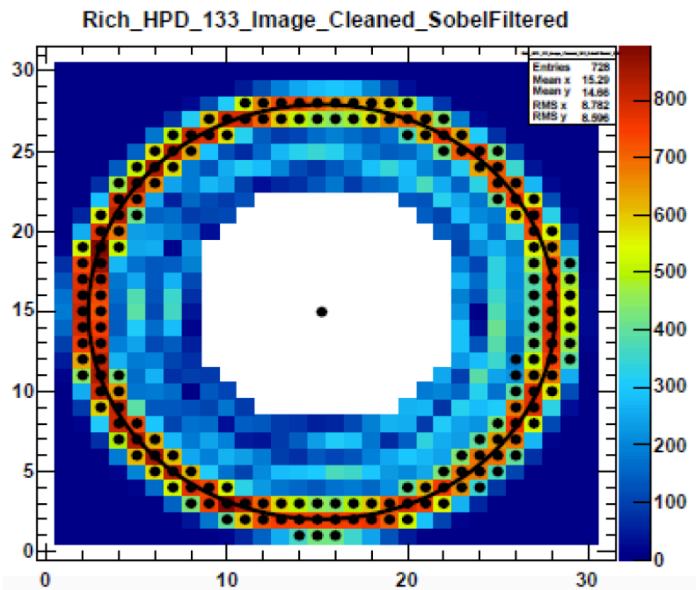
- Performed online since the beginning of Run 2
- Refractive index
  - May change due to temperature, pressure and gas mixture variation
  - Fit the Cherenkov angle distribution for $\beta=1$ tracks

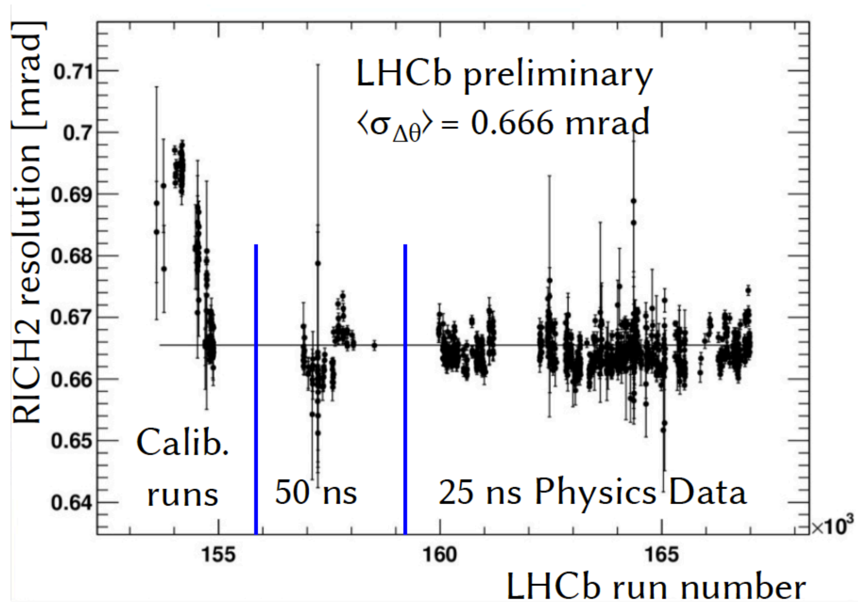
Talk on LHCb real-time calibration/alignment by R. Aaij



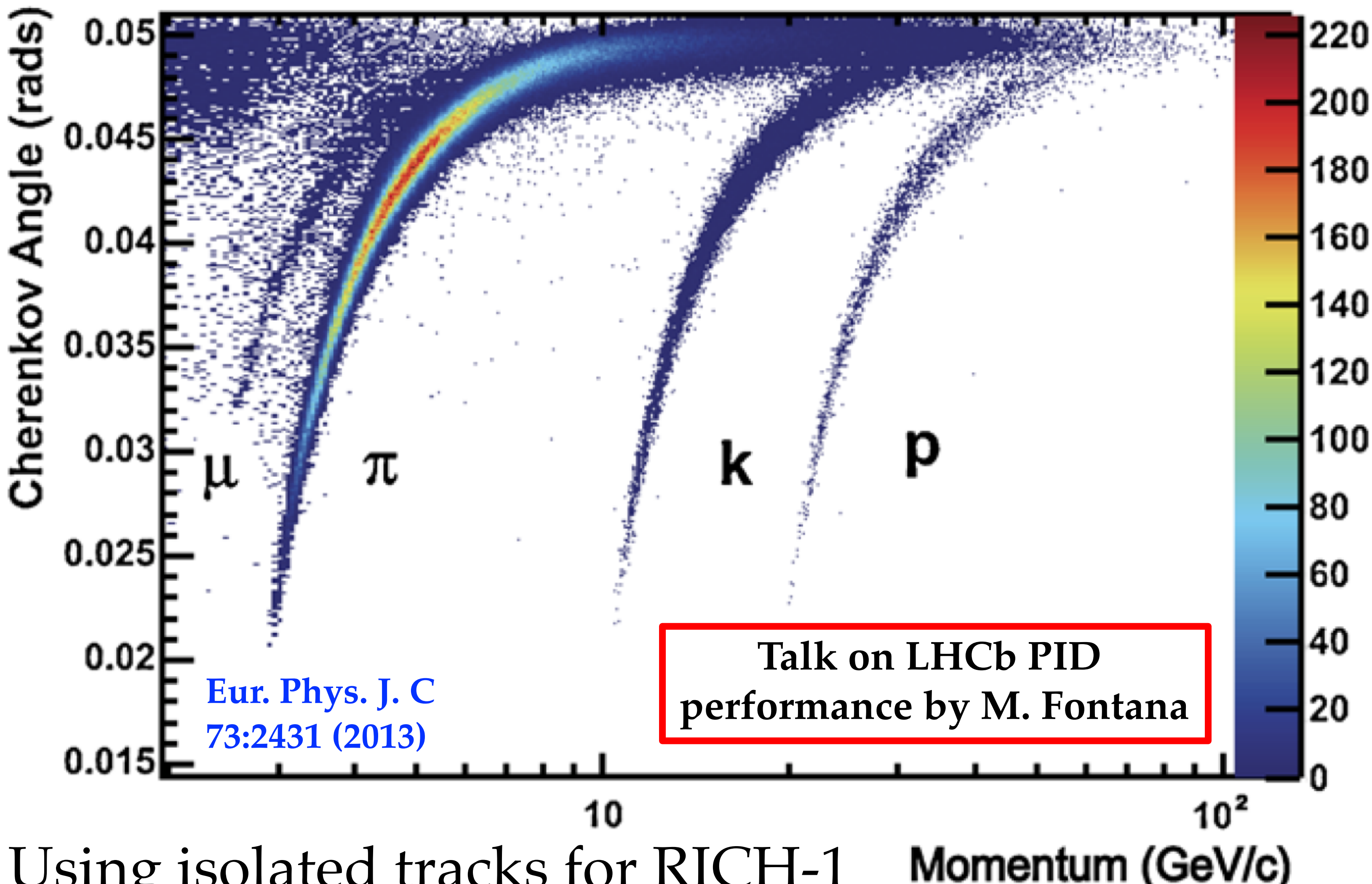
Online calibrations (2)

- HPD image
  - Position of the photocathode image on the anode can change due to charging effects
  - Anode images are cleaned and a Sobel filter used to detect the edge
  - Automatic update of the photo-cathode center position





θ_C versus Momentum



- Using isolated tracks for RICH-1

LHCb Upgrade Plans

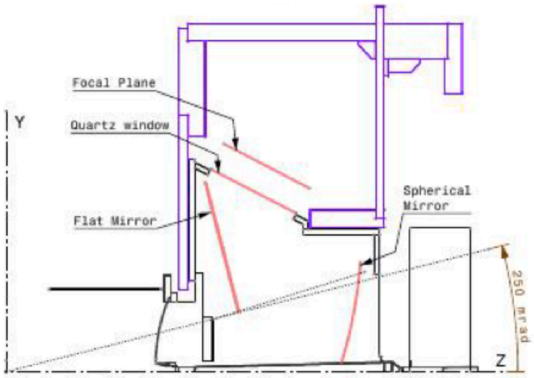
- During Run 1 operated at tunable leveled luminosities up to $\sim 4 \times 10^{32}$ cm^{-2}s^{-1}, 2 × higher than design value
- In Run 2 we should collect ~5 fb^{-1} more
  - Main limitation: 1 MHz L0 trigger rate

LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-23)	Run 4 (2027-29)	Run 5+ (2031+)
3 fb^{-1}	8 fb^{-1}	~25 fb^{-1}	~50 fb^{-1}	~100 fb^{-1}

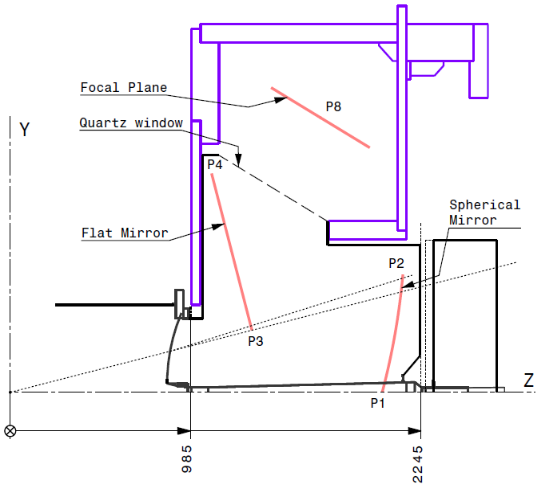
- LHCb Upgrade
  - Operate detector at luminosities of $\sim 2 \times 10^{33}$ cm^{-2}s^{-1}
  - Upgrade detectors to be able to readout at 40 MHz
  - Install upgraded LHCb during long shutdown 2 (2019-20)

RICH Upgrade

Current RICH-1



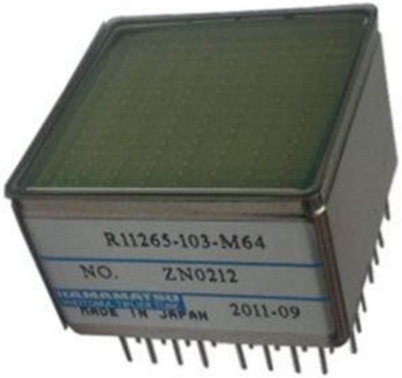
Upgraded RICH-1

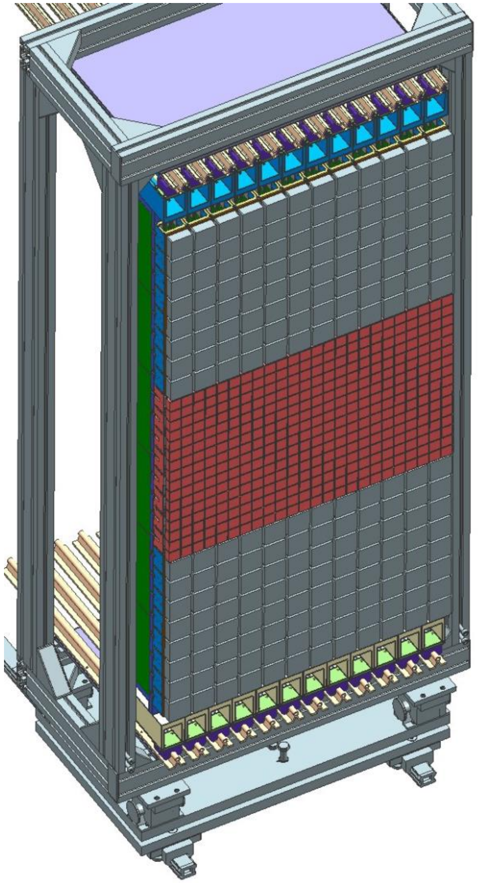


- Adapt to higher luminosity
  - RICH-1 spherical mirrors focal length increased to reduce occupancy (optical system redesigned)
  - Support mechanics and cooling
- 40 MHz readout → replace HPDs with commercial Multi-Anode Photo-Multiplier Tubes (Ma-PMTs) and new front-end electronics
  - 64 ch. Ma-PMTs
  - 40 MHz Front-End: CLARO8 chip plus FPGA-based digital board and GBT chip for data transmission

Photo-multiplier tubes

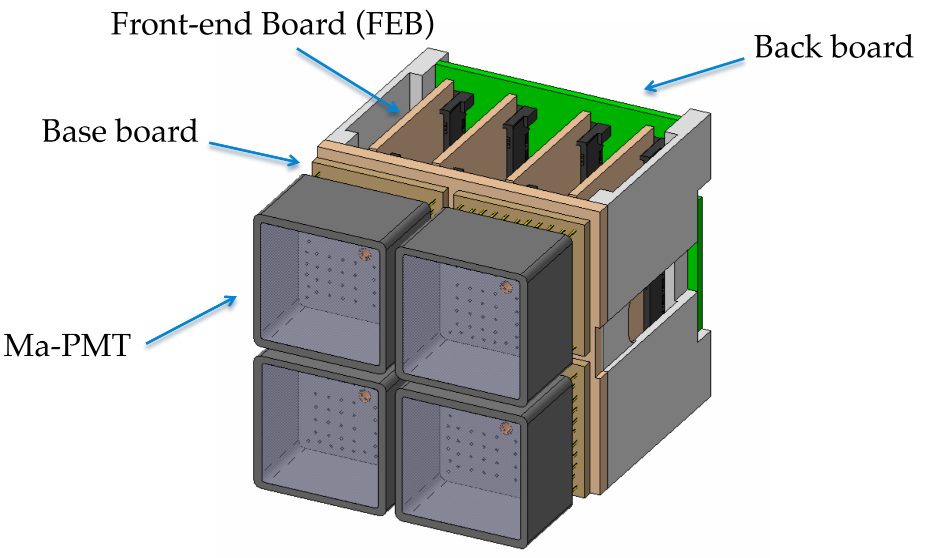
- Hamamatsu R11265 (1'', 64 pixels) for RICH-1 and RICH-2
- Hamamatsu R12699 (2'', 64 pixels) for RICH-2 only
  - Outer (low occupancy) regions of RICH-2

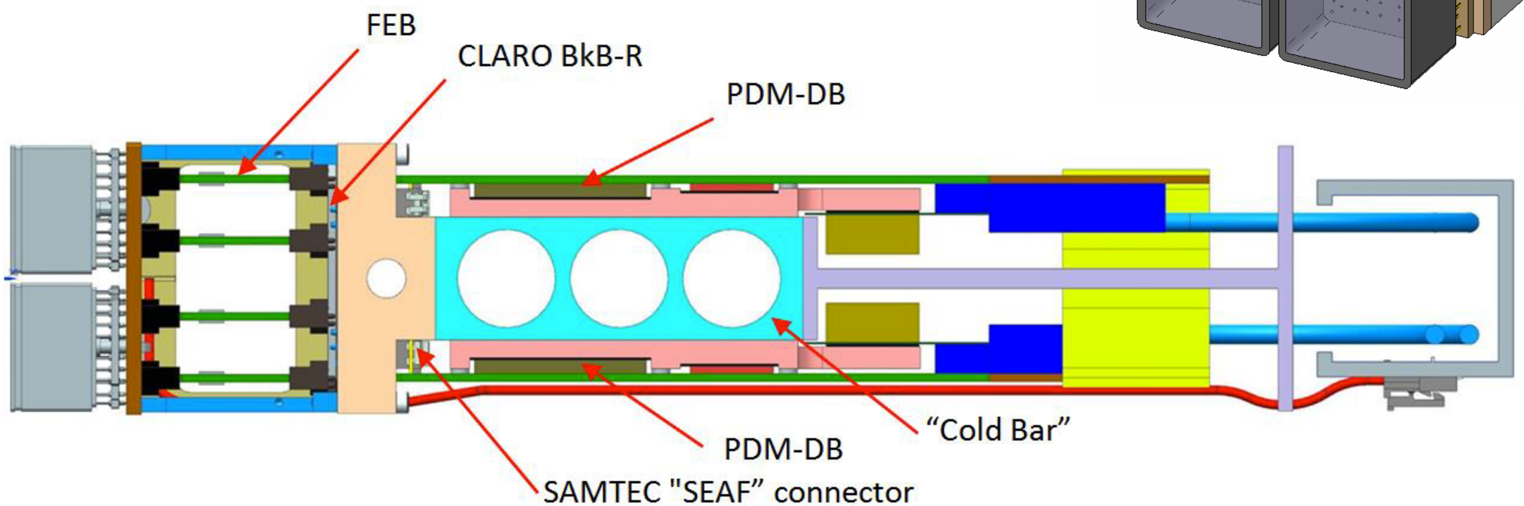




The Elementary Cell (EC)

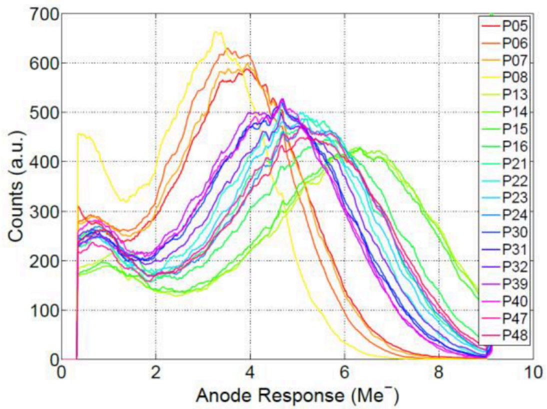
- Two versions for small (and large) Ma-PMTs
  - 4 (1) Ma-PMTs
  - 1 Base-board, 1 Back-board
  - 4 (2) Front-end boards (FEB)
  - Magnetic shield
  - Mechanics

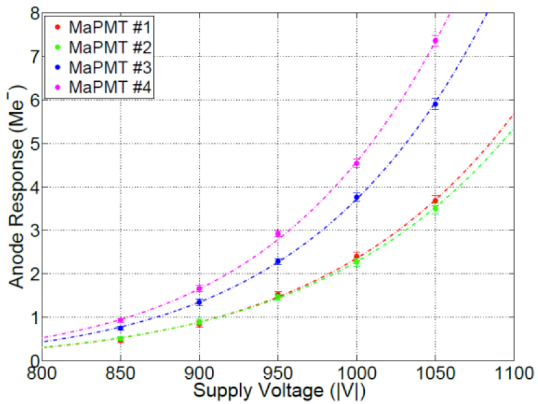




Electronics requirements

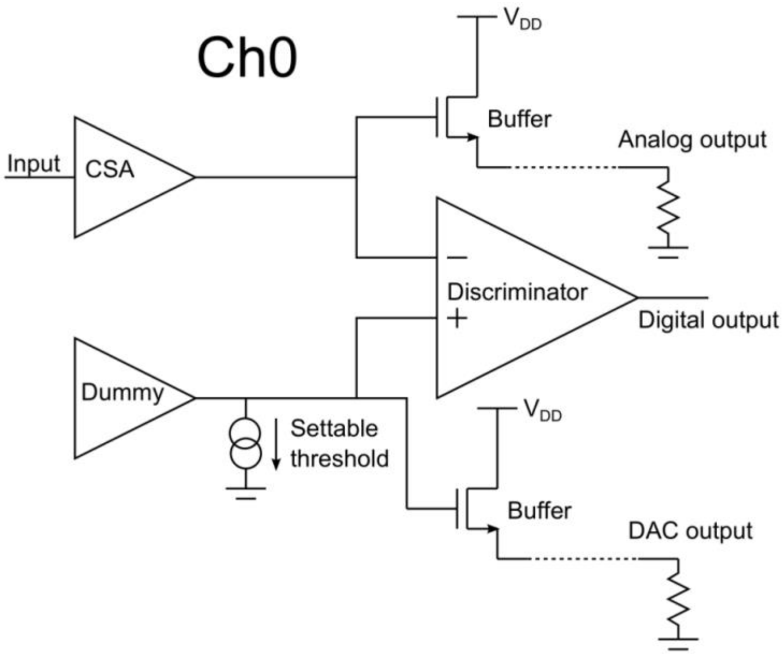
- Hamamatsu Ma-PMTs main characteristics
  - Typical gain at 1000 V for R11265 is ~1×10^6
  - 1:3 pixel gain spread in PMT, 1:3 spread in different PMTs
- Requirements coming from the LHCb environment:
  - Single photon counting at 40 MHz with Ma-PMTs (no dead time at 25 ns)
  - Radiation hardness for 50 fb^{-1} total integrated luminosity (200 krad, 3×10^{12} 1 MeV n_{eq}/cm^2, 1.2×10^{12} HEH/cm^2)





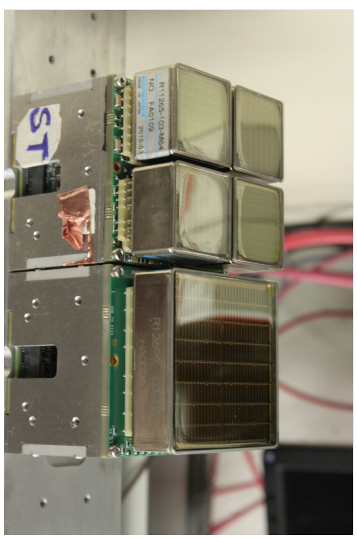
The CLARO8 chip

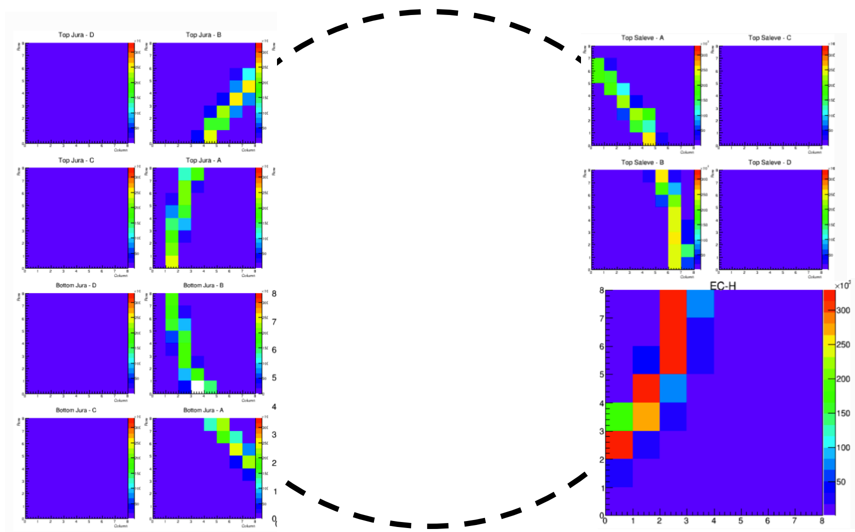
- The CLARO8 is a 8-channel amplifier/discriminator ASIC designed for single-photon counting with Ma-PMTs
- Main features:
  - 0.35 μm CMOS technology from AMS (→ low cost, high yield)
  - Allows 40 MHz operation (recovery < 25 ns)
  - Power consumption ~1 mW/ch.
  - Adjustable threshold (6 bits)
  - Adjustable gain (2 bits)
  - Binary read-out
  - 128 bit register TMR protected
  - Radiation-hard by design cells
- Block diagram:

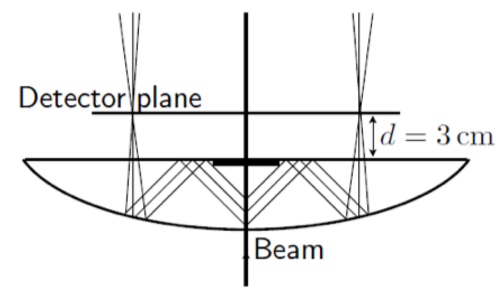


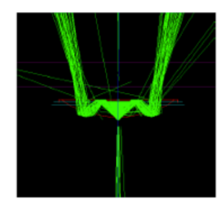
Test beam activities

- A compact detector based on solid radiator was proposed and tested in 2014 – 2016 to measure the performance of close-to-final opto-electronics chain
- Operation of a complete setup in a realistic environment
  - Calibrations, noise, thermal test, Cherenkov ring fitting
  - Validation of both EC types









Conclusions

- The LHCb RICH detectors have been operating with high efficiency in a high multiplicity environment and form an essential part of the experiment
  - Online calibrations and alignment in Run 2
- The LHCb RICH upgrade program, proposed to cope with 2×10^{33} cm^{-2}s^{-1} luminosity, is progressing well
  - New photo-detectors and electronics chain for full detector read-out at 40 MHz
  - Modified RICH optics and mechanics
  - Very successful test-beams validated the close-to-final opto-electronics chain in realistic conditions
  - We recently had the first production readiness review
  - On schedule for installation during 2019-20

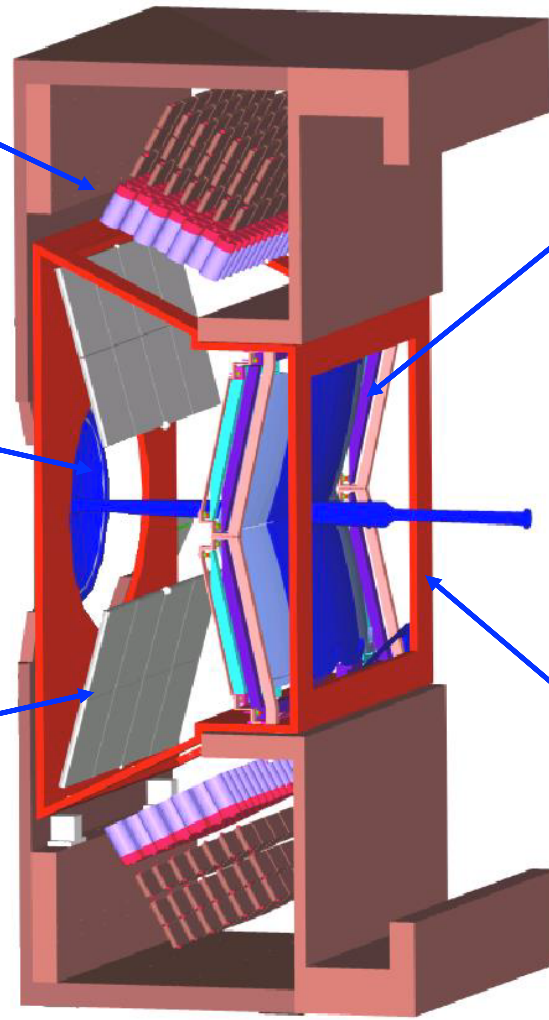
SPARES

RICH-1

Photon detector plane:
14×7 HPDs

VELO Exit Window
2 mm aluminum
Sealed to gas enclosure
No RICH-1 entrance window

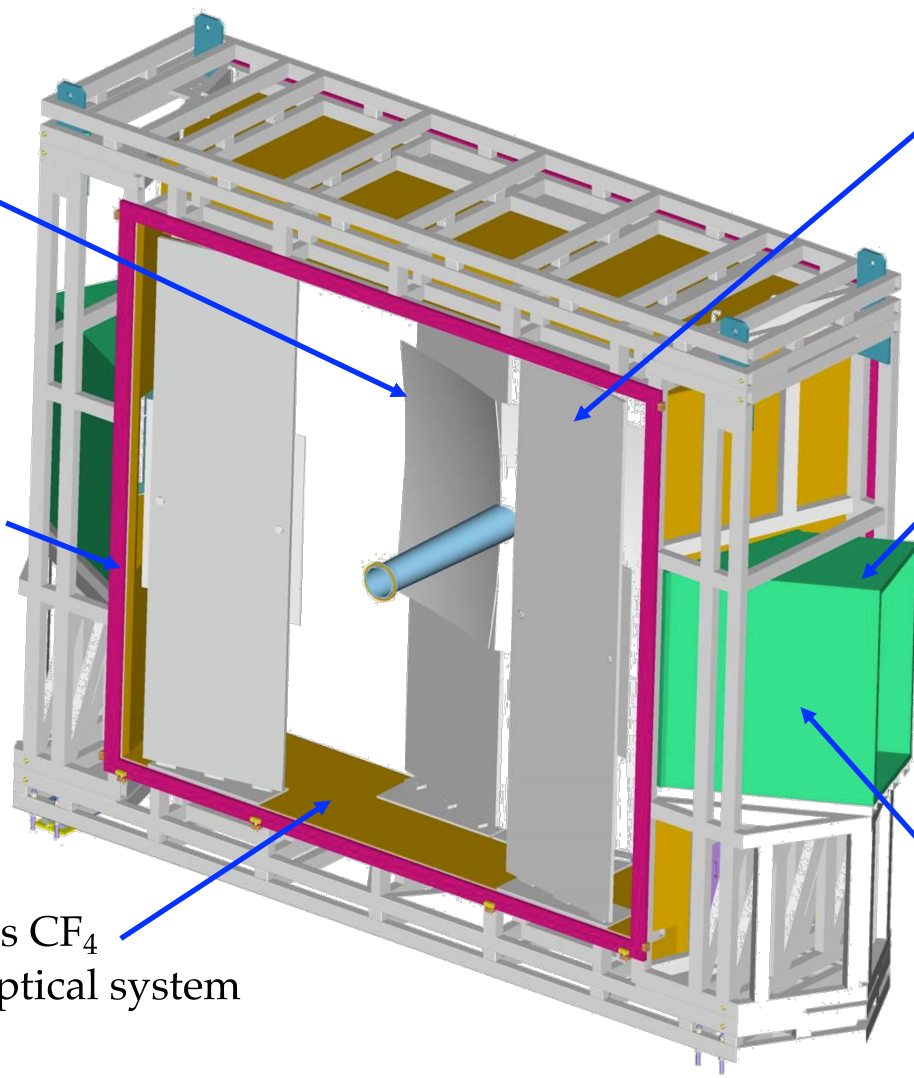
Flat Mirrors
(16 segments)



Spherical Mirrors Lightweight
carbon fiber mirrors
1.5% radiation length
(4 segments)

RICH-1 Exit Window
Carbon fiber and foam
Sealed direct to the beam pipe

RICH-2



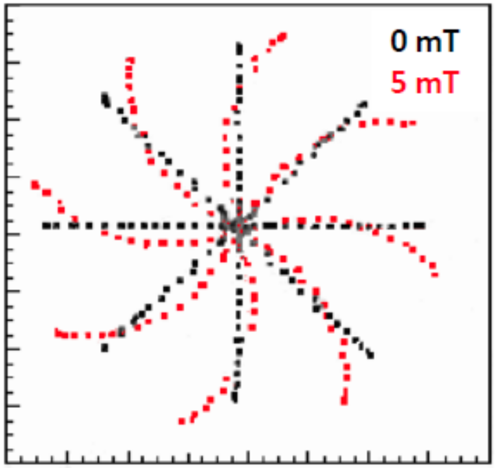
Spherical Mirrors (56 segments)
Flat Mirrors each made from 40 square glass segments
Magnetic Shields protect the HPD planes
RICH-2 entrance/exit windows carbon fiber and foam sandwich
Photon detector plane: 9×16 HPDs
Gas Enclosure contains CF_4 gas radiator and the optical system

Radiators and material budget

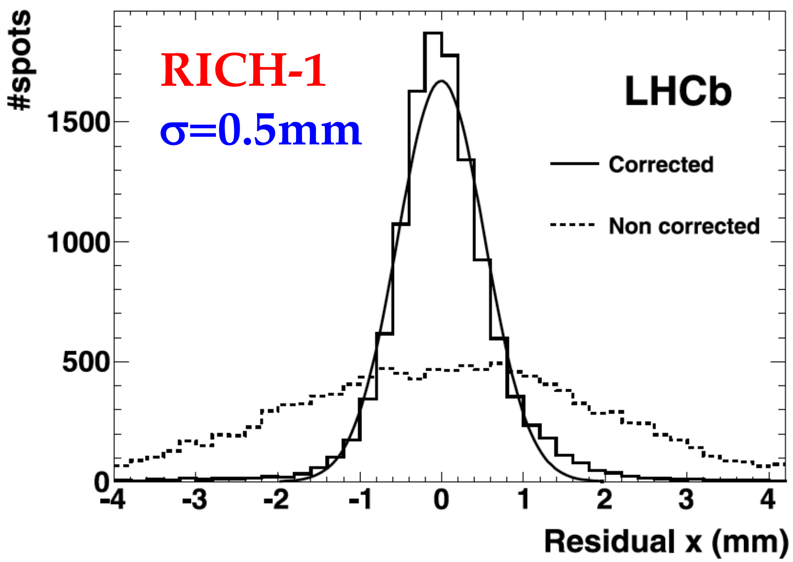
Parameter		C_4F_{10}	CF_4
L	[cm]	$\sim$110	167
n		1.0014	1.0005
θ_c^{max}	[mrad]	53	32
$p_{thresh}(\pi)$	[GeV/c]	2.6	4.4
p_{thresh}(K)	[GeV/c]	9.3	15.6
p_{thresh}(p)	[GeV/c]	17.7	29.7

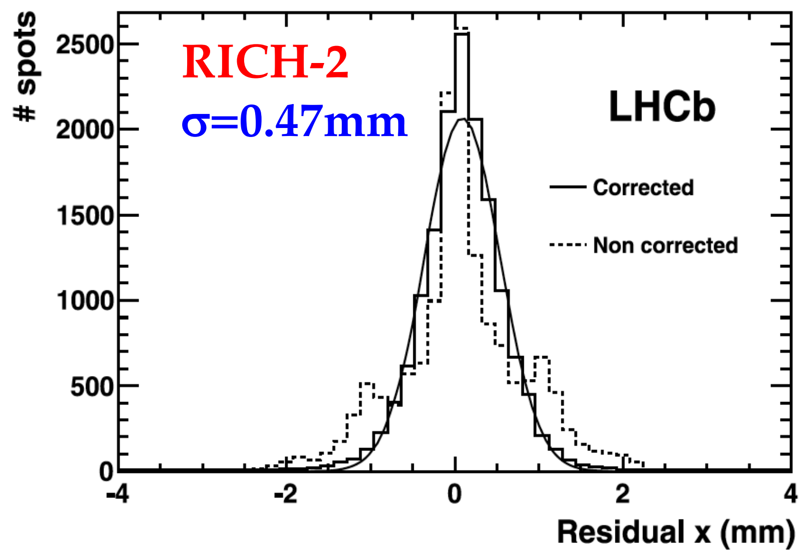
Item	RICH 1	RICH 2
Entrance window	0.001	0.014
Gas radiator	0.026	0.017
Mirror	0.015	0.079
Exit window	0.006	0.014
Total (X_0)	0.048	0.124

Magnetic field corrections



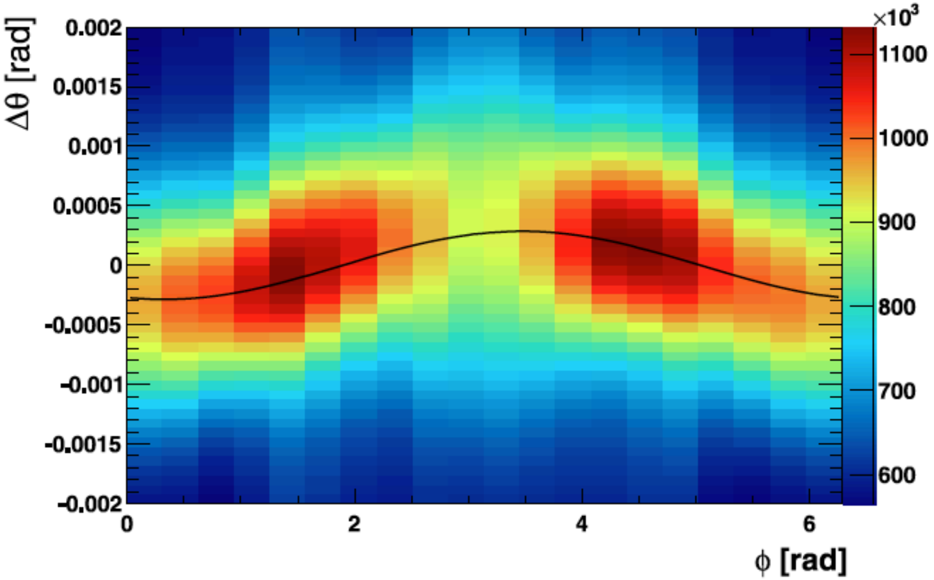
- HPD image distortion due to magnetic field
- Projection of test pattern with and without magnetic field to extract correction parameters

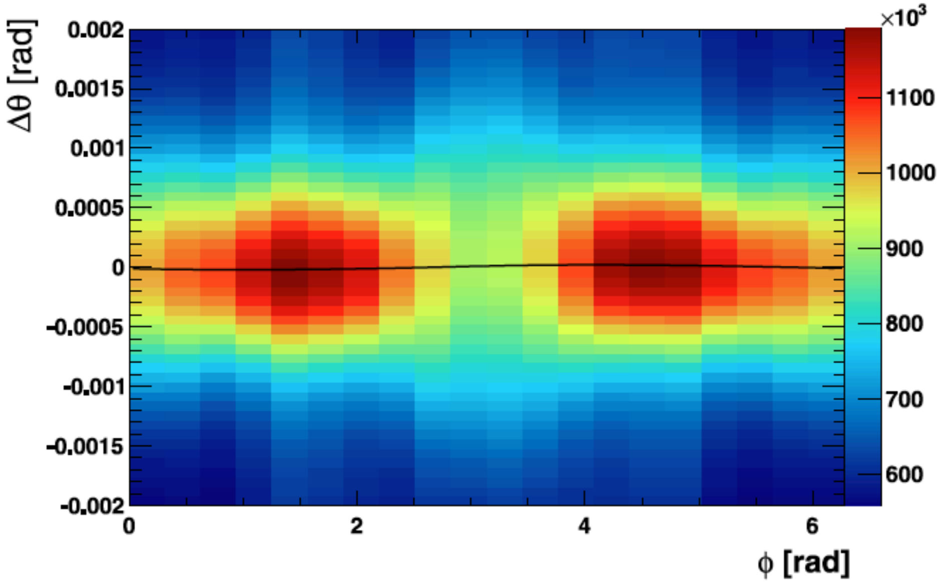




Alignment

- Many components aligned with an accuracy of 0.1 mrad
  - Whole detector, detector halves, mirror segment and HPD

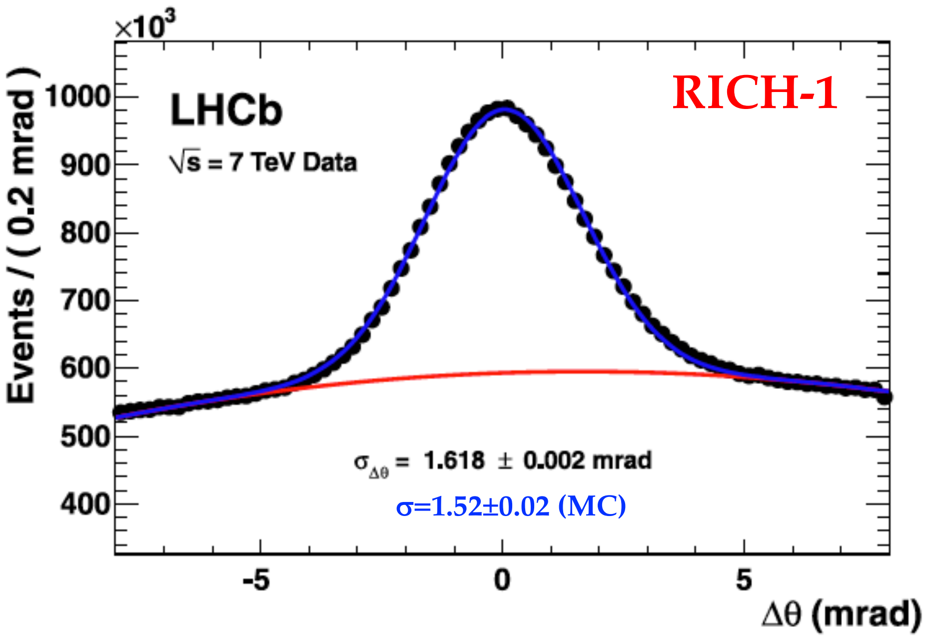


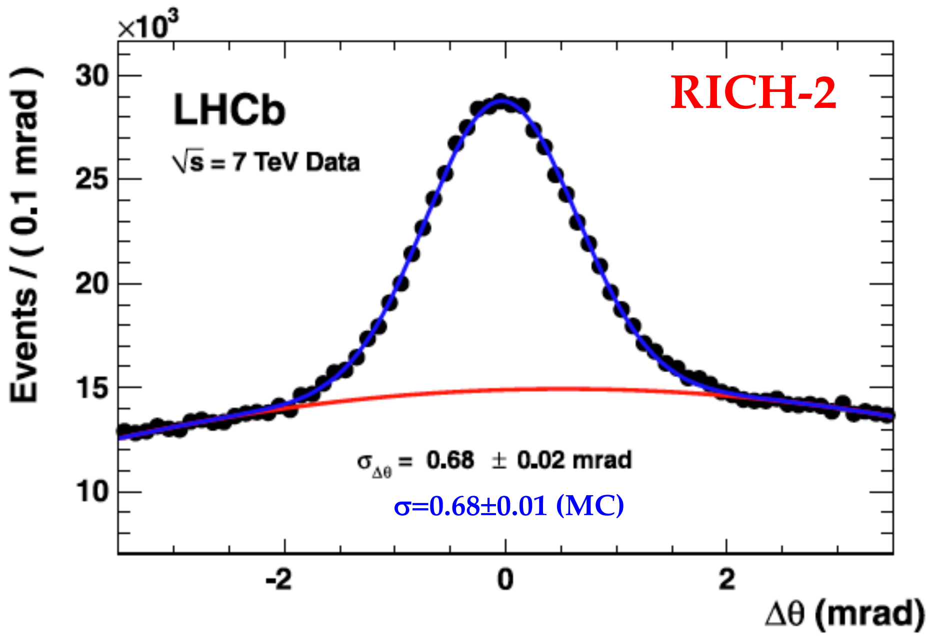


- Then use reconstructed Cherenkov angle for β=1 tracks
  - Misalignment observed as shift of track projection point w.r.t. the center of the corresponding Cherenkov ring

Cherenkov angle resolution

- Single photon resolution
  - Distributions for saturated (β=1) tracks





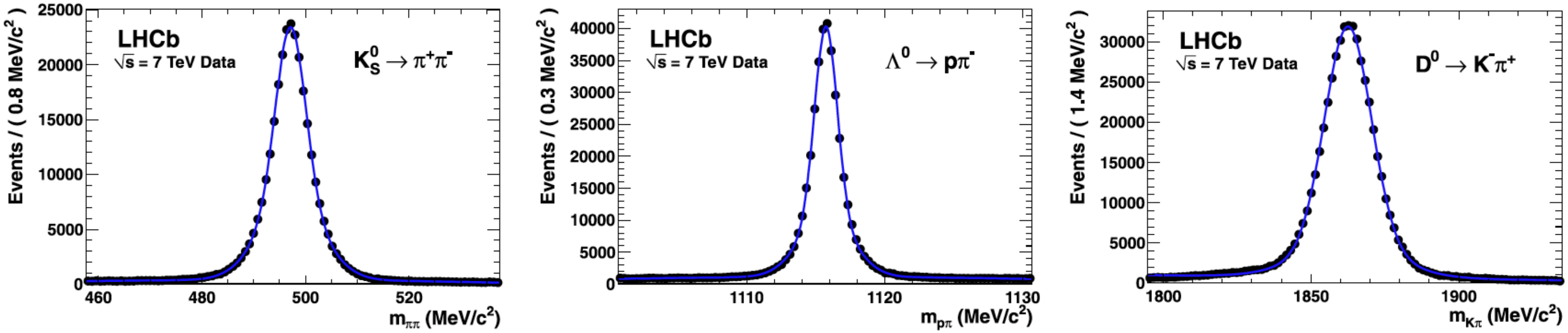
PID algorithm

- Consider all photons and all tracks and all radiators at once and maximize likelihood function:

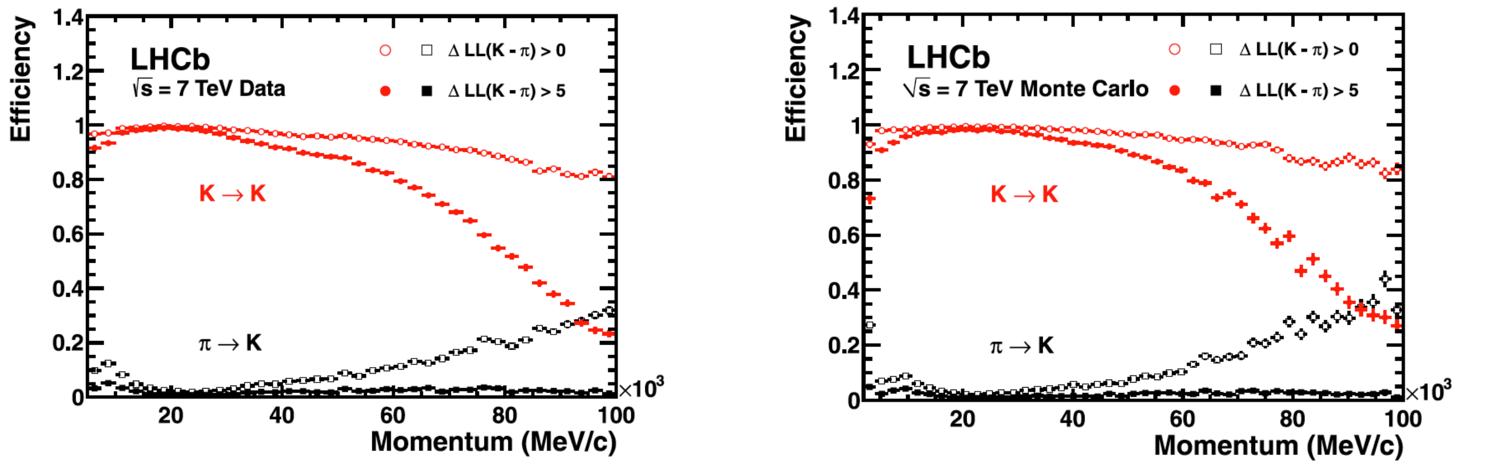
$$L = L(n_{pixel}, \sum_{track} e_{pixel,track}, b_{pixel})$$

- Take all PIDs to be pions
  - Estimate background parameter b_{pixel} per HPD
- Calculate likelihood of given pixel distribution
- Iterate
  - Change PID hypothesis one track at a time
  - Recalculate likelihood
  - Choose change that had biggest impact
  - Assign new PID to that track
- Until no significant improvement is found
  - As signal photons are now identified better, update background estimate and start a 2nd (and usually final) iteration

PID Performance (1)

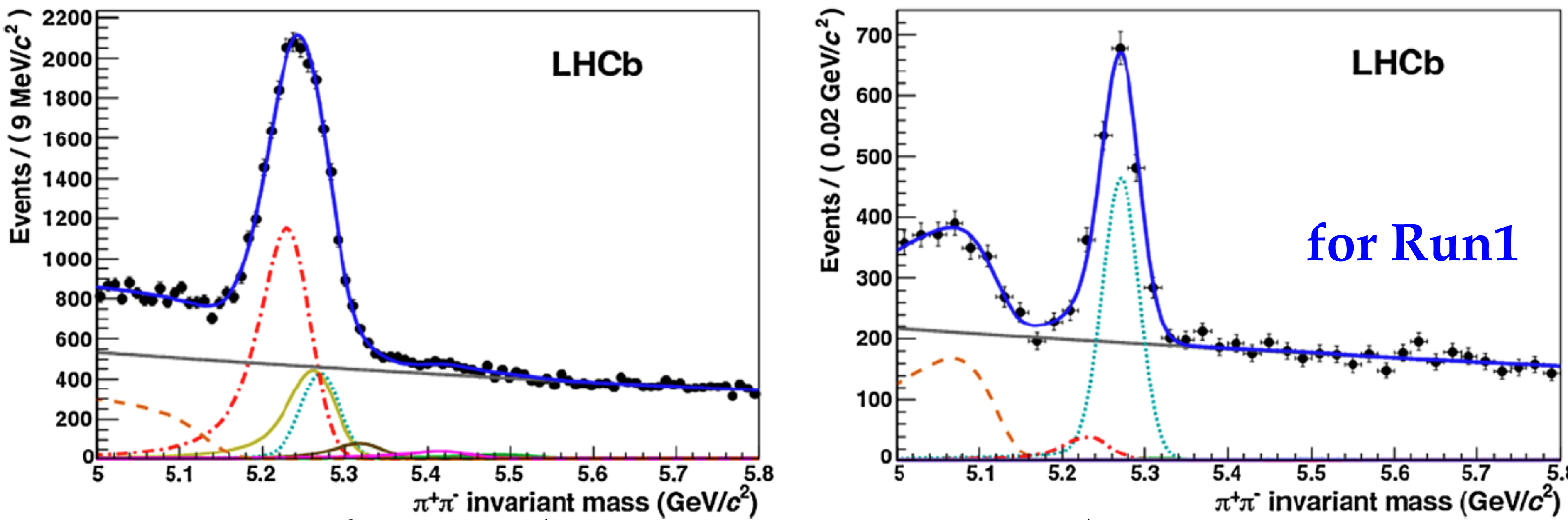


- PID performance evaluated from data **for Run1**
  - Genuine $\pi/K/p$ samples identified from kinematics only



PID Performance (2)

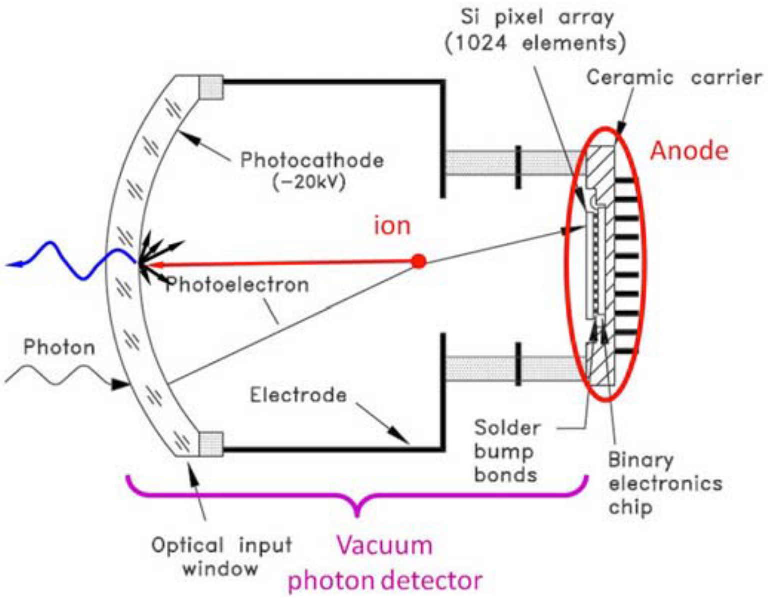
- Invariant mass distribution for B → h^+h^- decays
  - before (left) and after (right) using RICH PID information



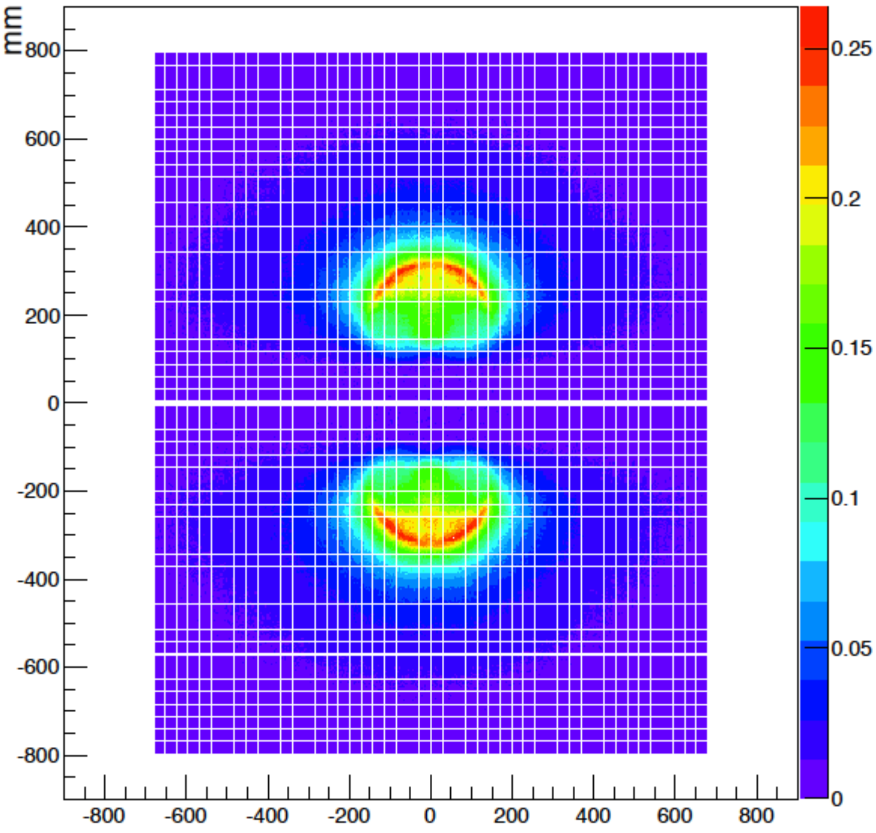
- Signal: $B^0 \rightarrow \pi^+\pi^-$ (turquoise dotted line)
- Other contributions are eliminated ($B^0 \rightarrow K\pi$, $B^0 \rightarrow$ 3–body, $B_s \rightarrow KK$, $B_s \rightarrow K\pi$, $\Lambda_b \rightarrow pK$, $\Lambda_b \rightarrow p\pi$)

Ion Feedback (IFB)

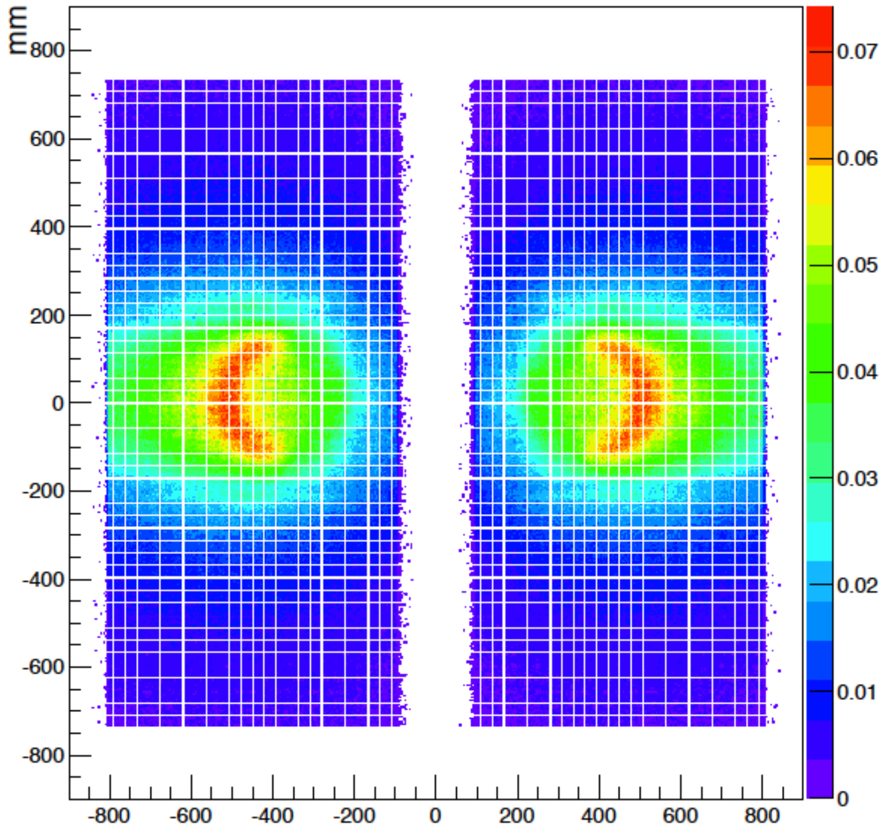
- Ion Feedback (IFB) occurs when a photoelectron ionises a residual gas atom
  - The ion drifts to the photocathode and produces on impact a cluster of secondary electrons
  - The cluster of electrons arrives at the sensor with a characteristic delay of typically 200-300 ns due to the drift time of the ion



Occupancy for upgrade phase

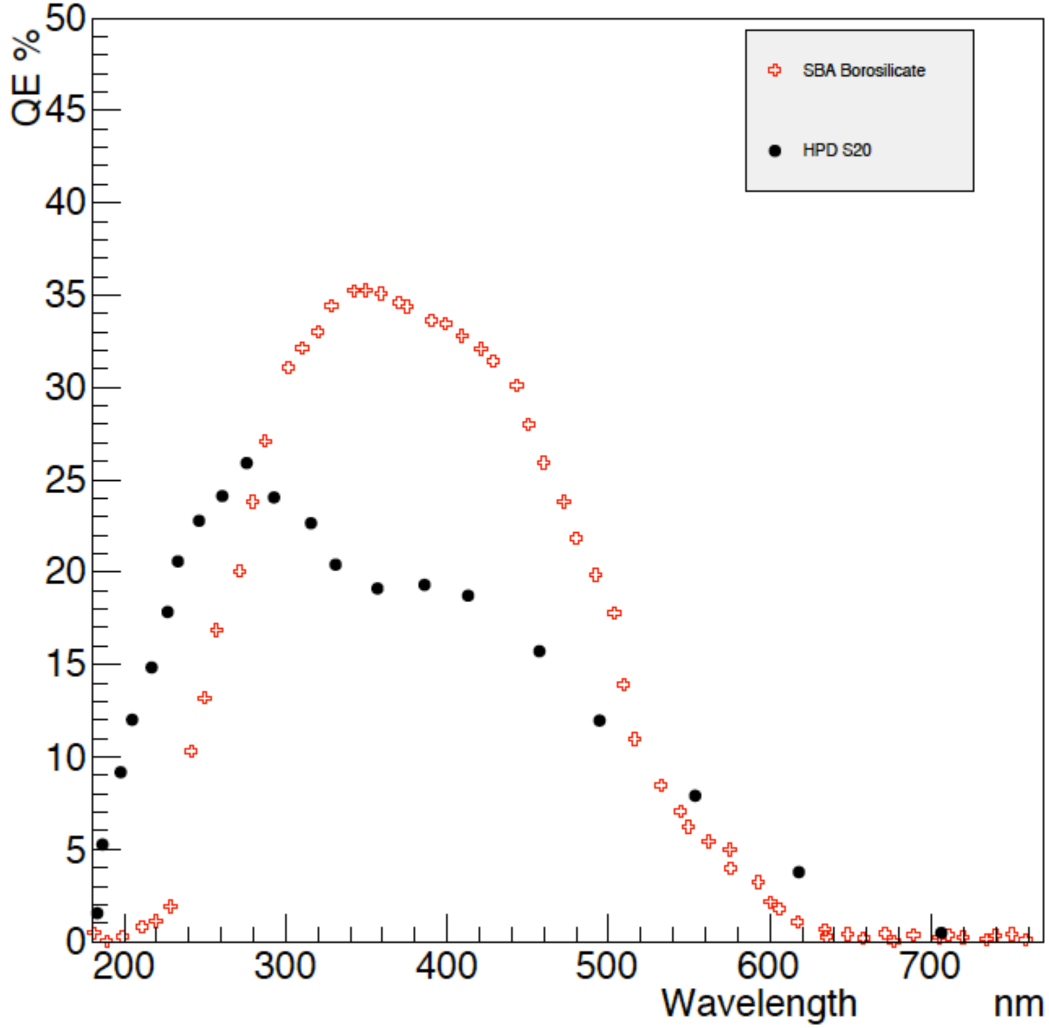


(a)



(b)

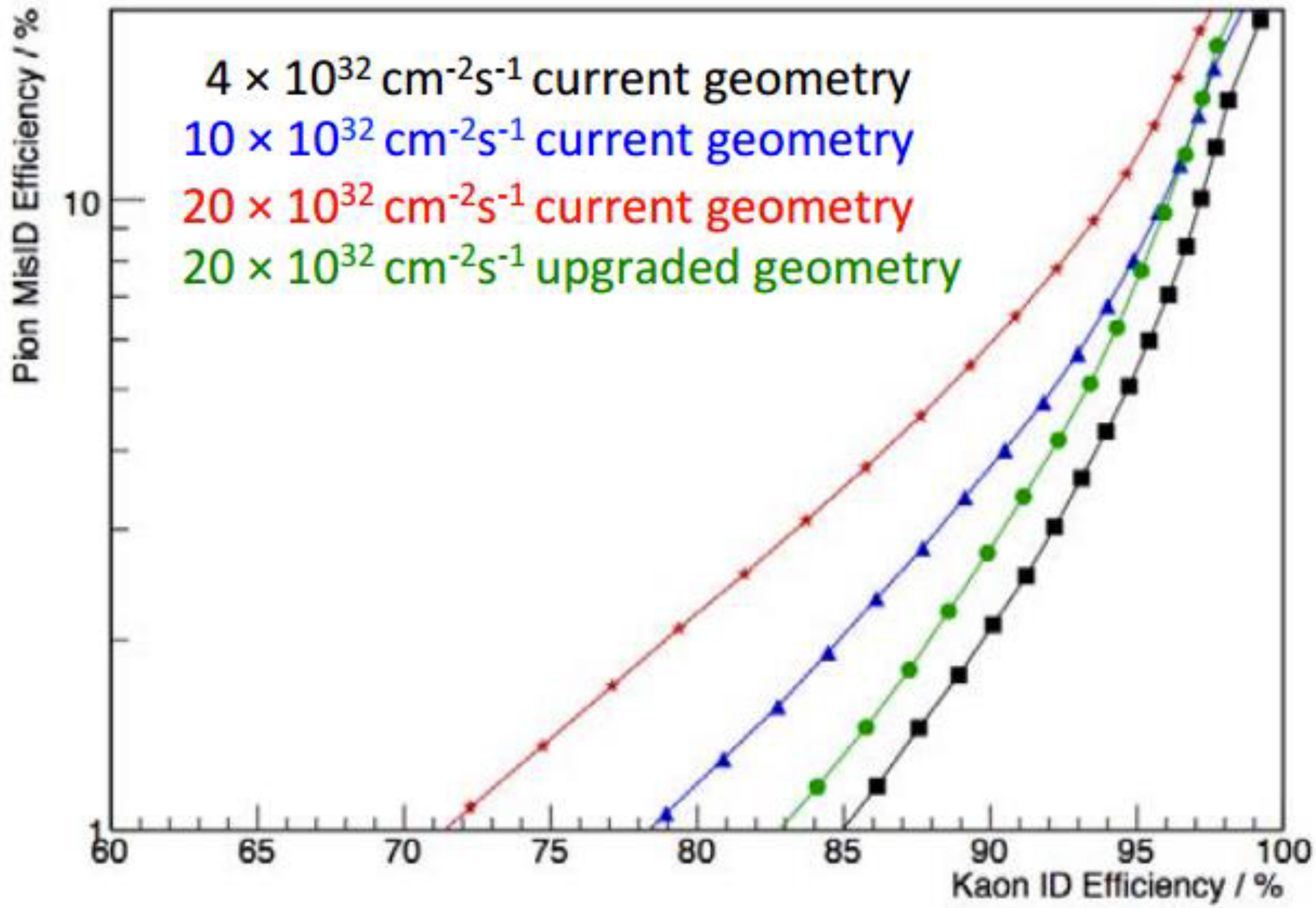
Ma-PMT Vs HPD QE



Angular resolutions

Resolutions [mrad]	Current RICH 1 (HPDs)	Upgraded RICH 1	Upgraded RICH 2
Emission point	0.61	0.37	0.27
Chromatic	0.84	0.58	0.31
Pixel	0.99	0.44	0.20
Tracking	0.40	0.40	0.40
Total resolution	1.50	0.88	0.60

PID performance

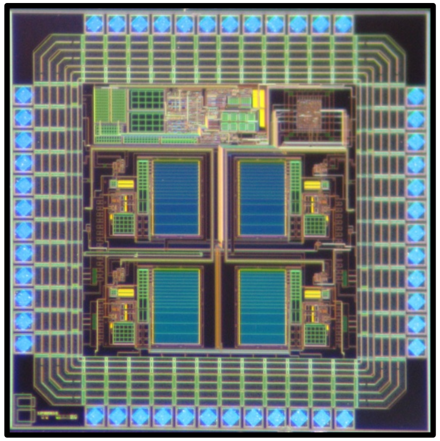


CLARO timeline

(2011)
- Design of the 4 ch. CLARO prototype
- Deep characterization on the test bench

(2012)
- First tests with R11265 Ma-PMTs and Silicon Photomultipliers

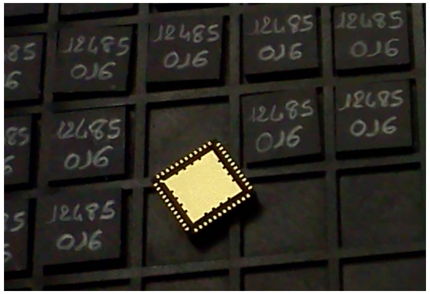
(2013)
- Radiation hardness tests
- More tests with the R11265 Ma-PMTs
- Chosen as the baseline front-end ASIC for the LHCb RICH Upgrade



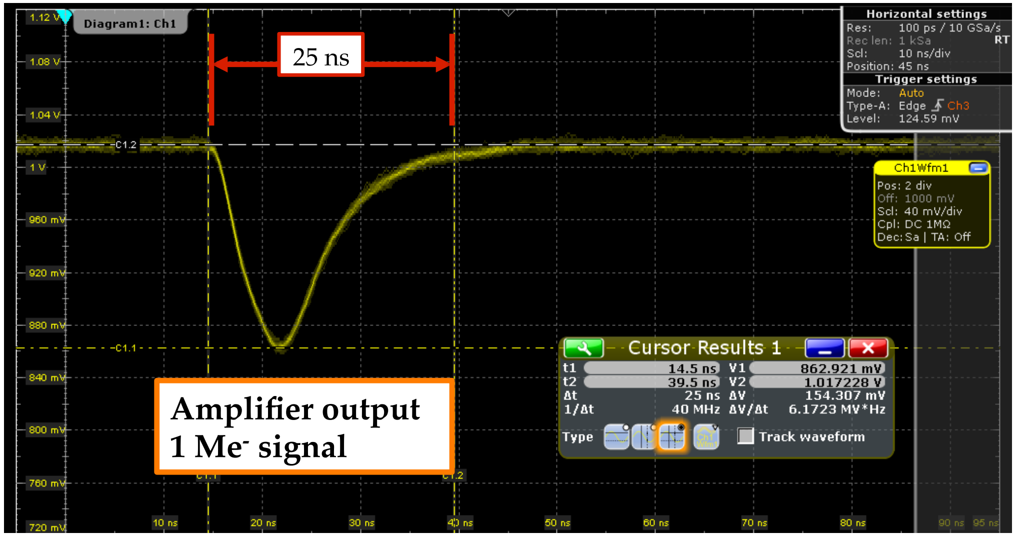
(2014)
- CLARO8 designed and produced (v0, v1)
- CLARO8 bench, beam and radiation hardness tests

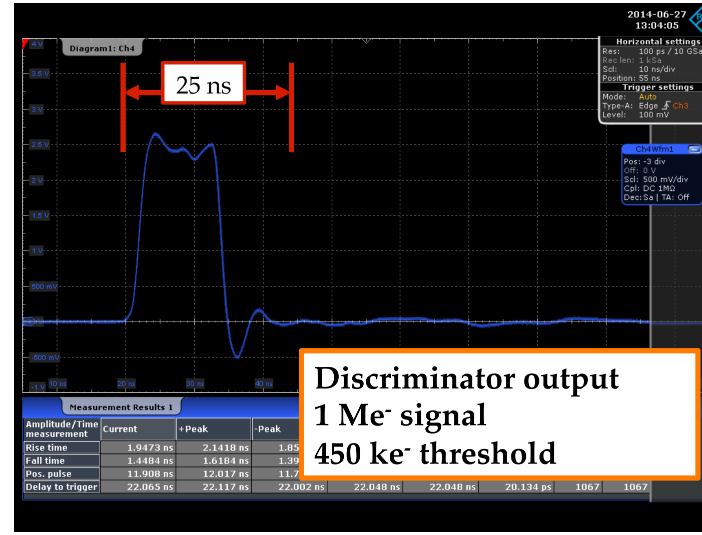
(2015)
- CLARO8 v2 designed and produced
- CLARO8 v2 bench and beam test

(2016)
- CLARO8 v3 designed, produced and tested
- CLARO8 Production Readiness Review (PRR)



CLARO8 signals

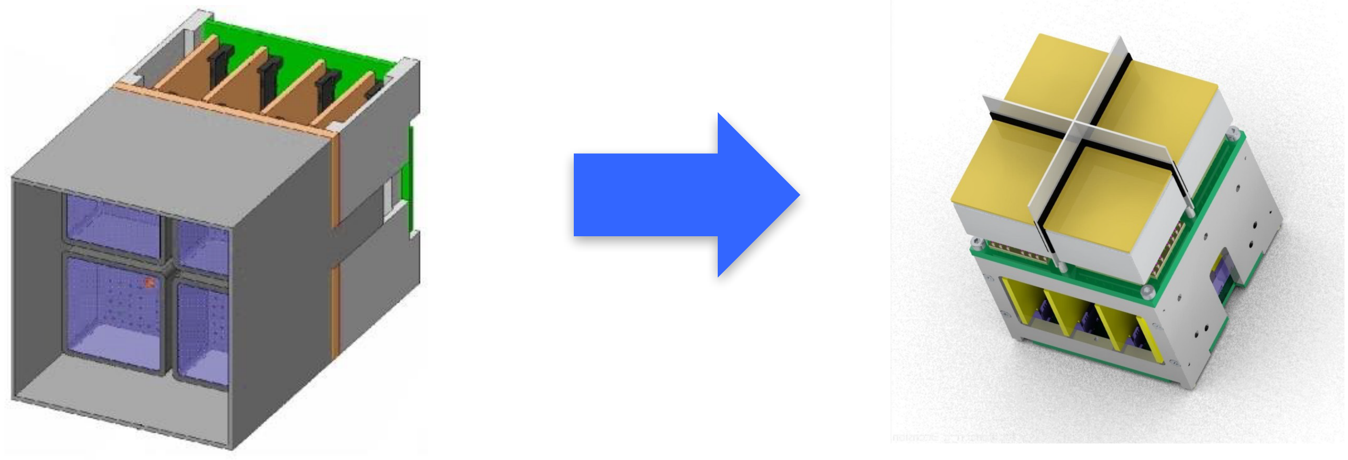


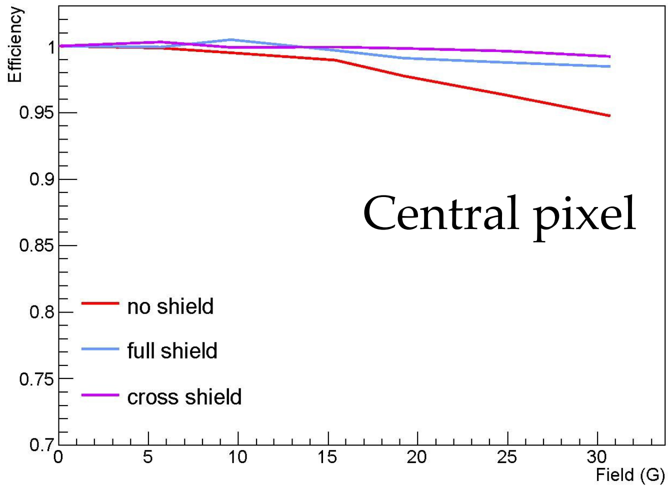


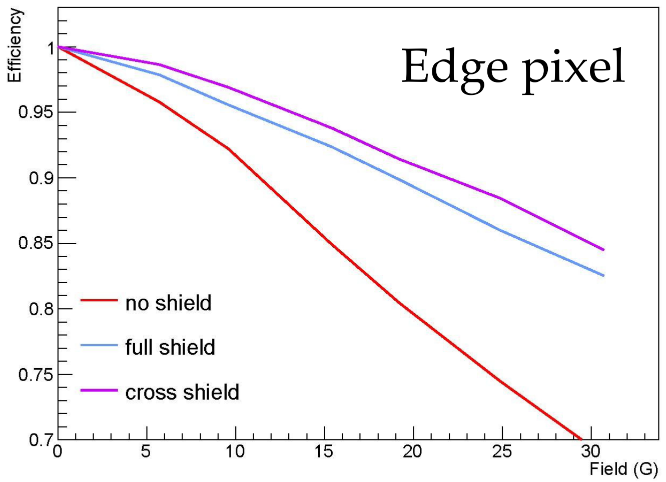
- The amplifier and DAC of any channel are buffered to output pins through a multiplexer controlled by global bits in the configuration register
- LHCb RICH binary read-out: hit or no-hit information for each bunch crossing at 40 MHz
  - Hits are "collected" by FPGA and sent off-detector

Magnetic shield design

- Design almost finalized

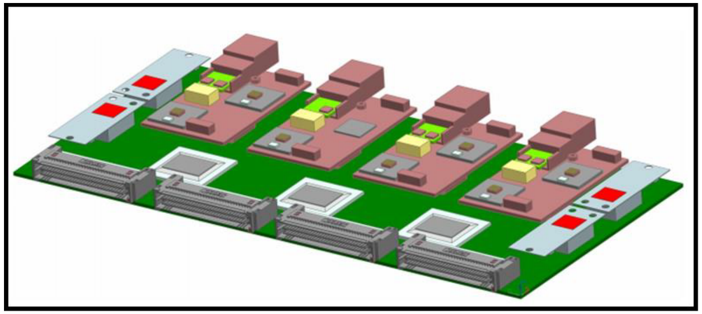


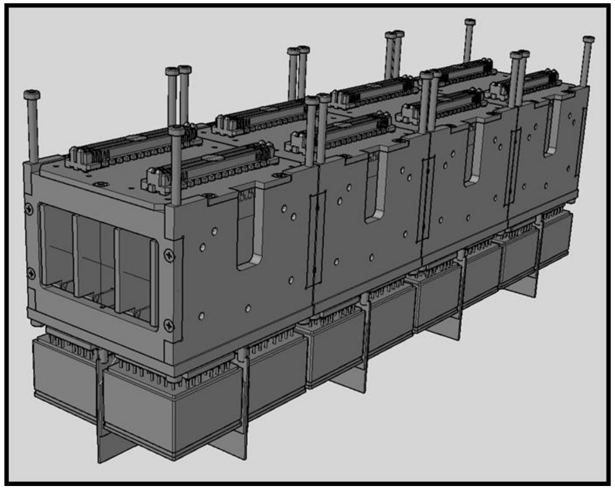


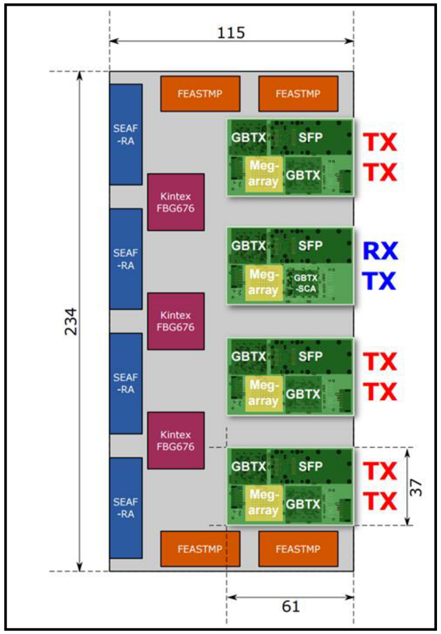


Digital board

- Motherboard with FPGAs and power distribution (DC-DC)
- Plugins for control and data link
- Thermally coupled to cold bar







RICH columns

- Ultimate mechanical support for (MaPMTs → Elementary Cells) + PDMDB + harness + cooling + …
- Photo Detector Assembly (PDA)