Highlights from the RICH 2022 Conference

Antonis Papanestis

STFC/RAL

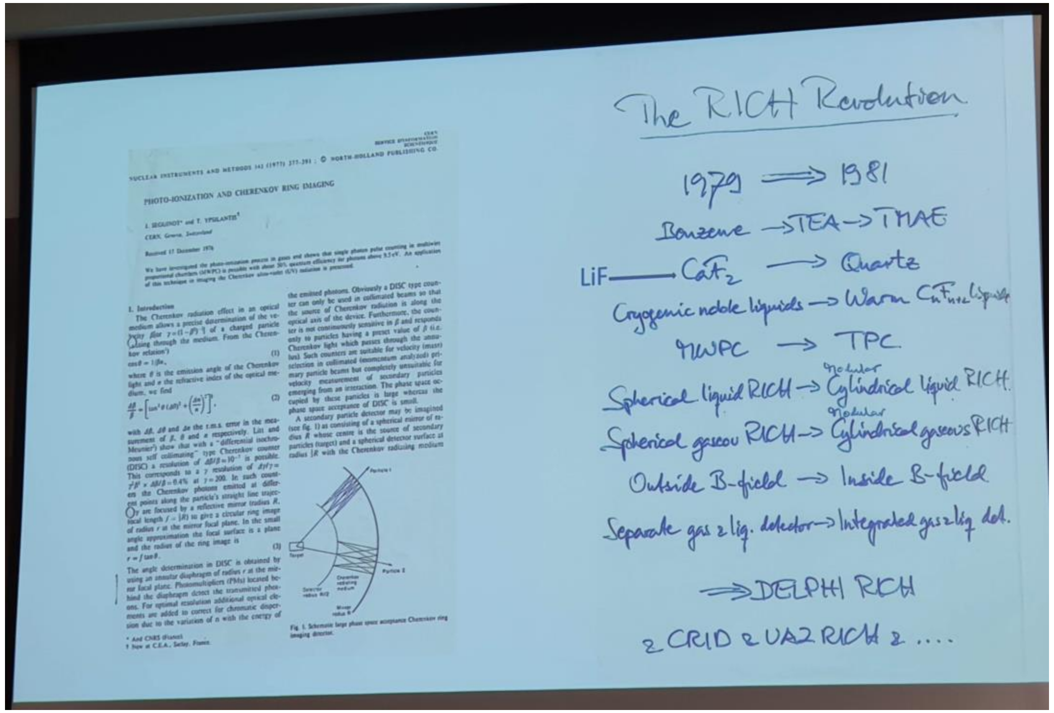
RICH = Ring Imaging Cherenkov detector

Edinburgh Sep 2022

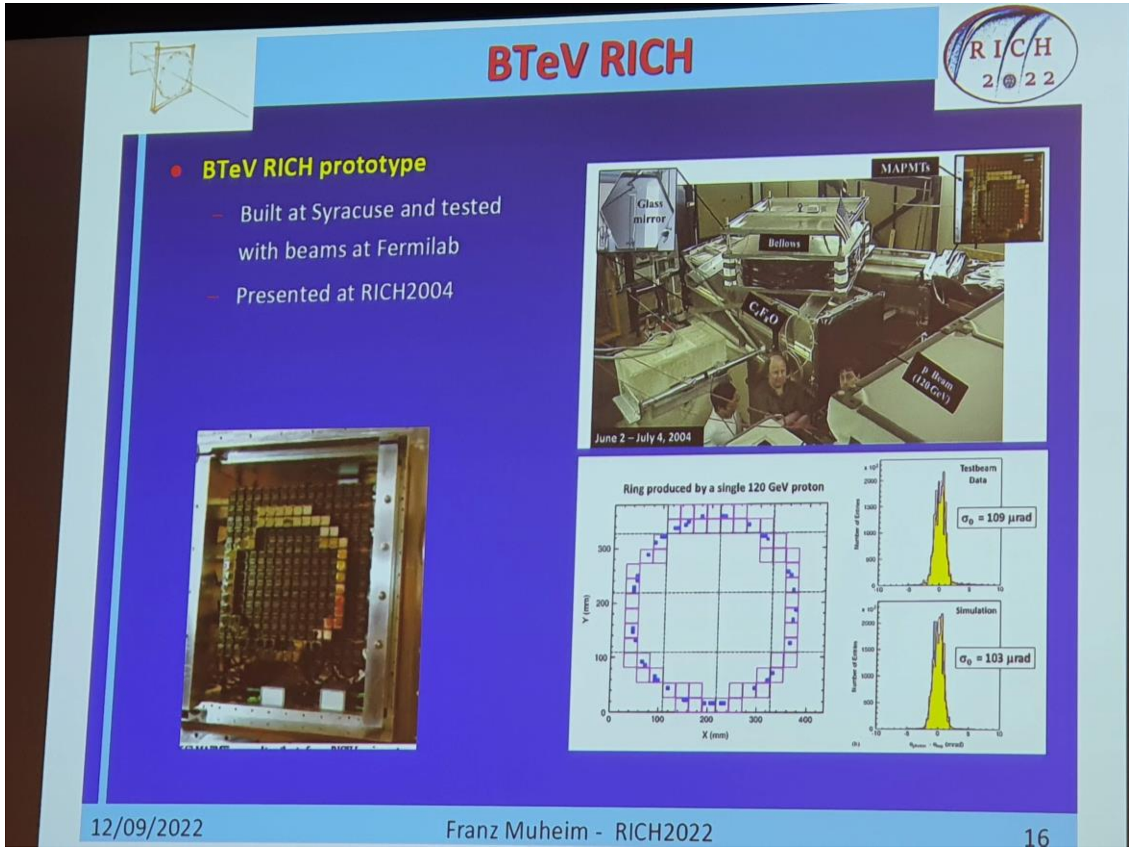
CARBERRY TOWER

Science and Technology Facilities Council

Looking back as well as forward



Homage to Jacques Seguinot



Homage to Sheldon Stone

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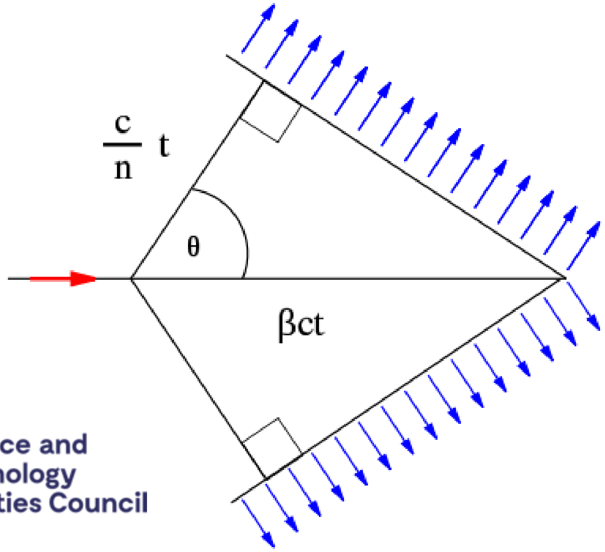
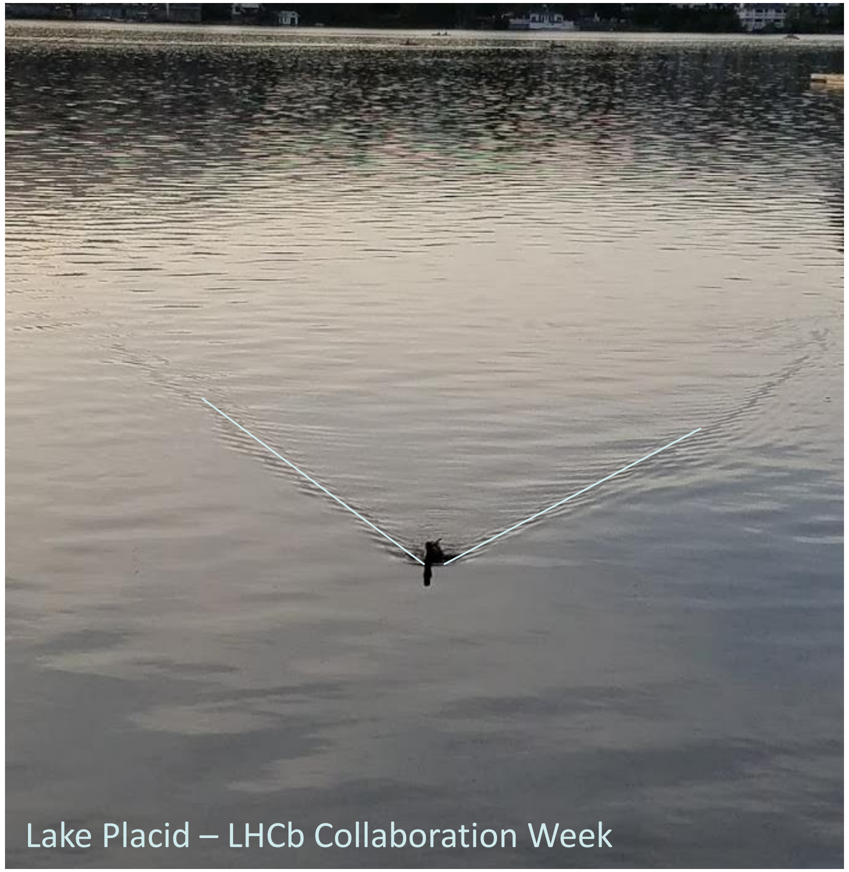
Cherenkov radiation





Lake Placid – LHCb Collaboration Week

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Cherenkov principles

Threshold: $$\beta_{th} = \frac{v_{th}}{c} = \frac{1}{n(\lambda)}$$

Cherenkov angle: $$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$

Number of produced photons: $$N_{photons} = L\frac{\alpha}{\hbar c}Z^2\int \sin^2\theta_c(E)dE$$

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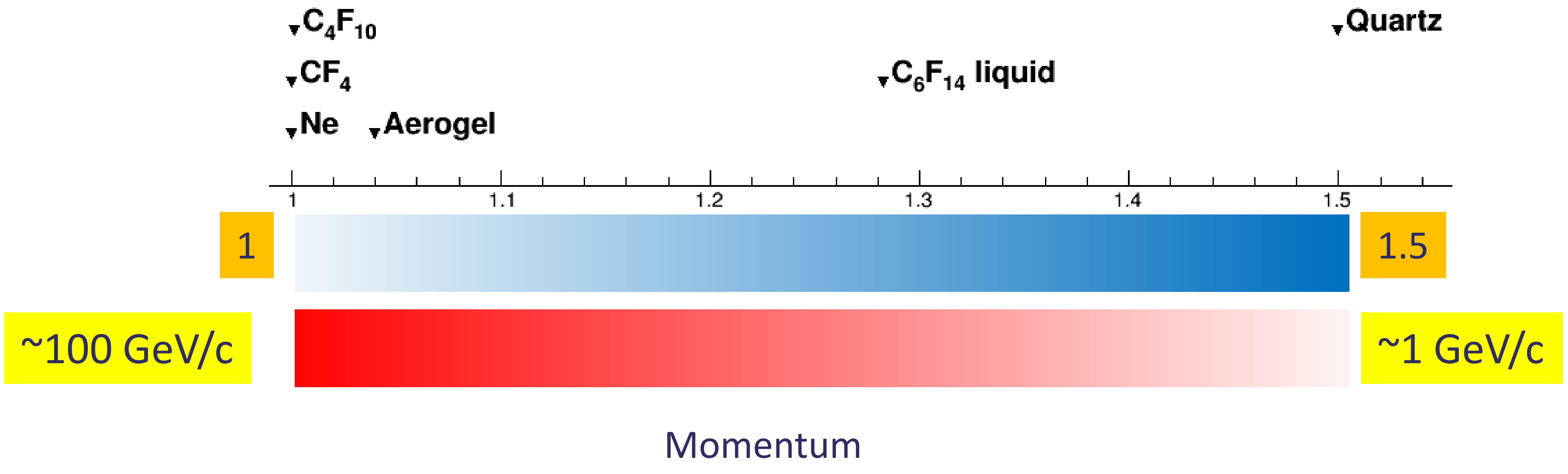
Refractive index range



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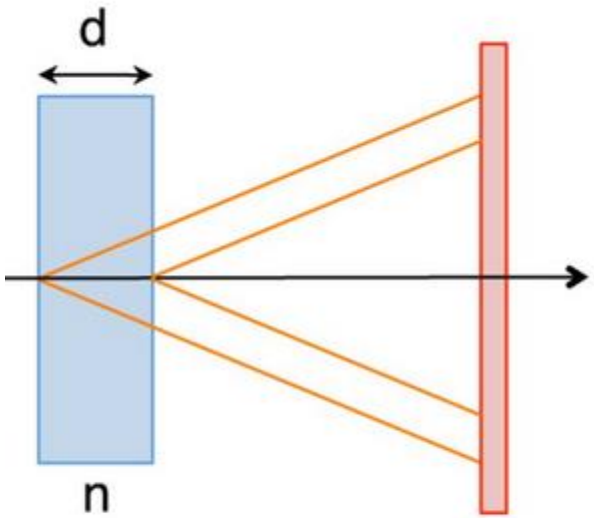
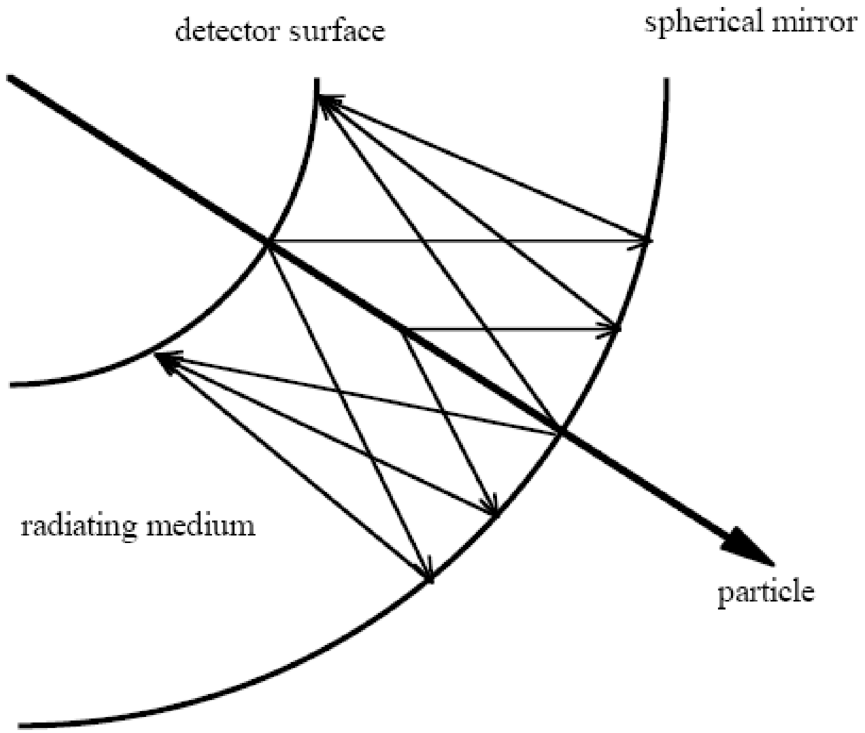
RICH Detectors

Proximity focusing geometry





- Measures both the Cherenkov angle and the number of photoelectrons detected.
- Can be used over particle identification over large surfaces.
- Requires photodetectors with single photon identification capability.

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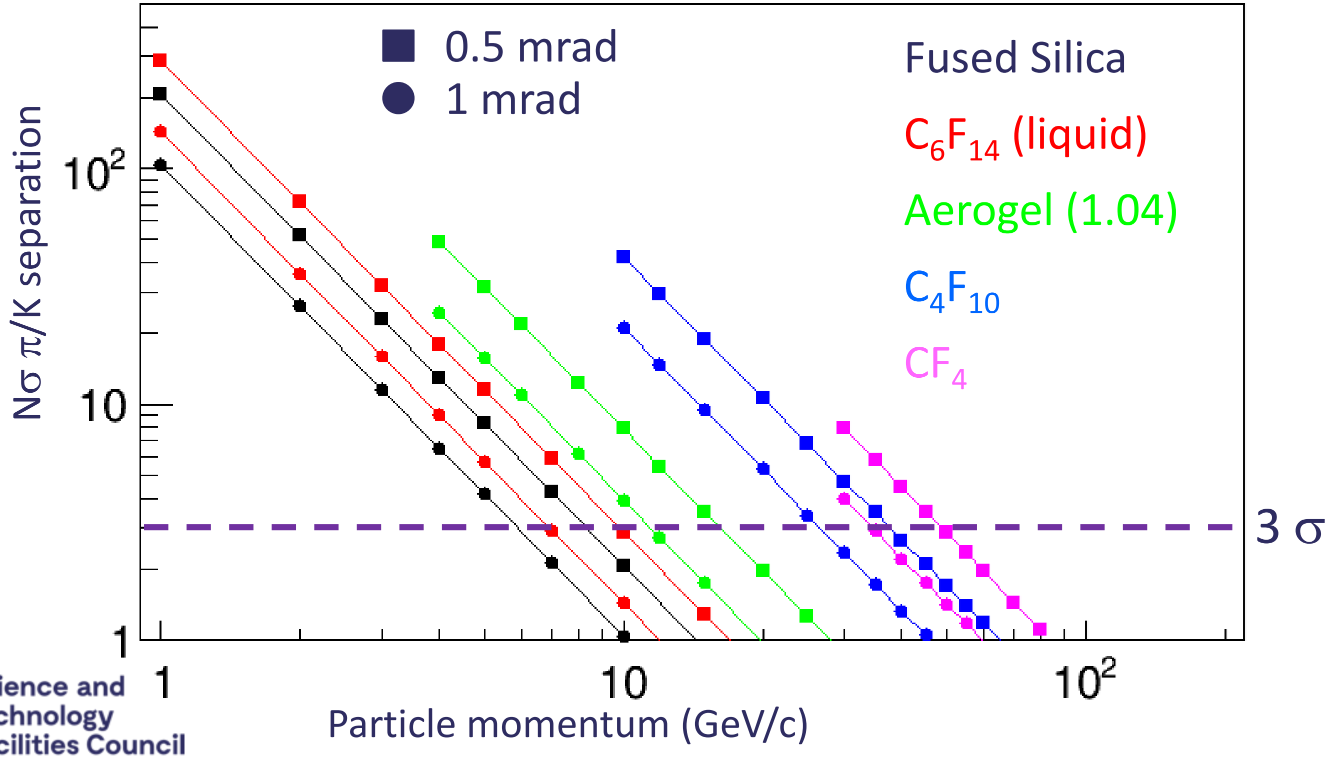
RICH performance

$$N_\sigma \approx \frac{\left|m_1^2 - m_2^2\right|}{2P^2\sigma[\theta_c(tot)]\sqrt{n^2-1}}$$

For particles well above threshold

B. N. Ratcliff, NIMA 502 (2003) 211-221



$\sigma[\theta_c(tot)]$ components:

- Emission point error
- Detection point error (pixel size)
- Chromatic error

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The performance of the LHCb RICH detectors during the runs 1 and 2 of the LHC

Antonis Papanestis
STFC – RAL
on behalf of the LHCb RICH Collaboration

Overview

- The LHCb RICH detectors
- Cherenkov angle resolution and alignment
- Number of photons
- Real-time Online calibration
- PID performance
- Physics impact

Performance of the LHCb RICH detectors during LHC Run 2
R. Calabrese et al 2022 *JINST 17 P07013*

Performance of the LHCb RICH detector at the LHC
Adinolfi, M. et al. Eur. Phys. J. C 73, 2431 (2013).

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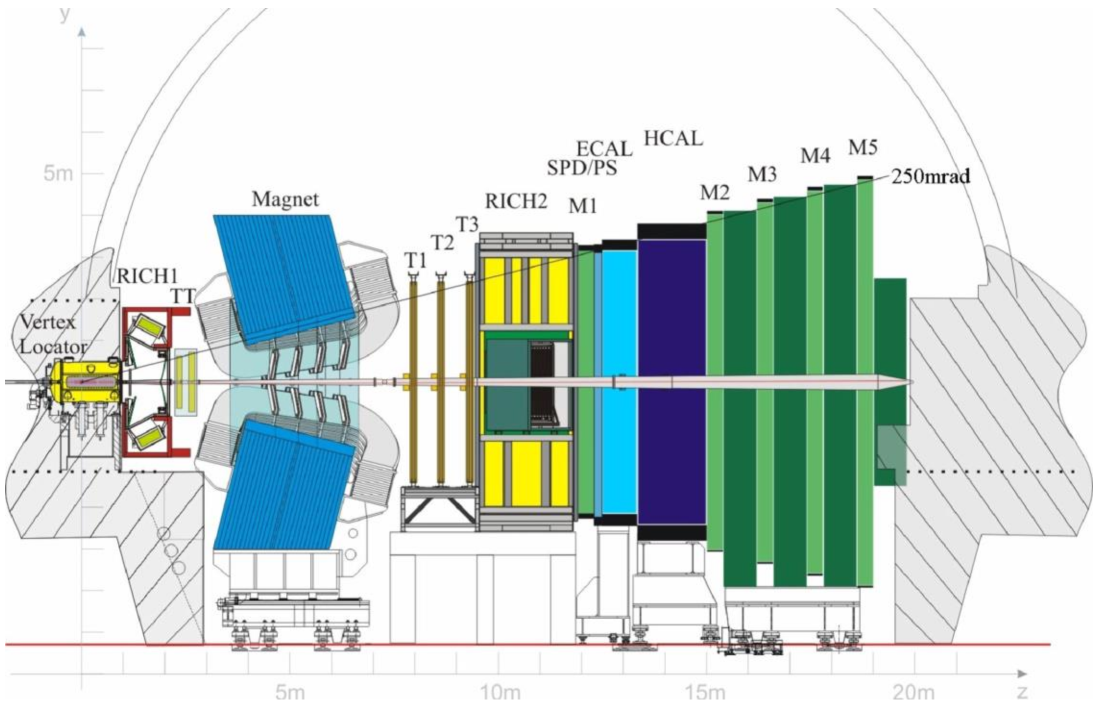
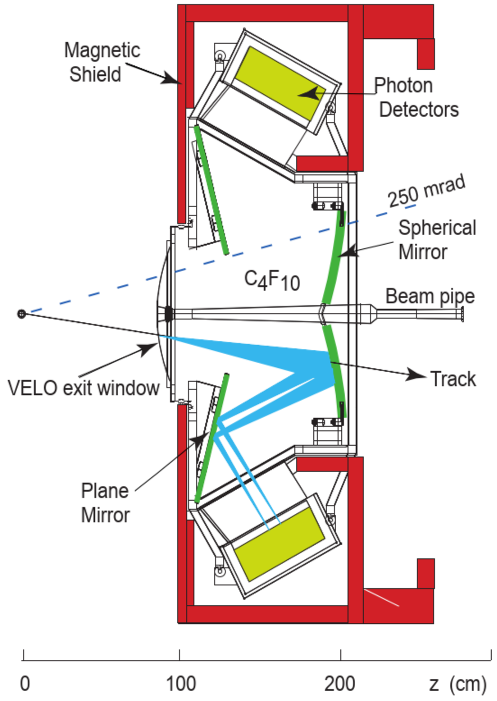
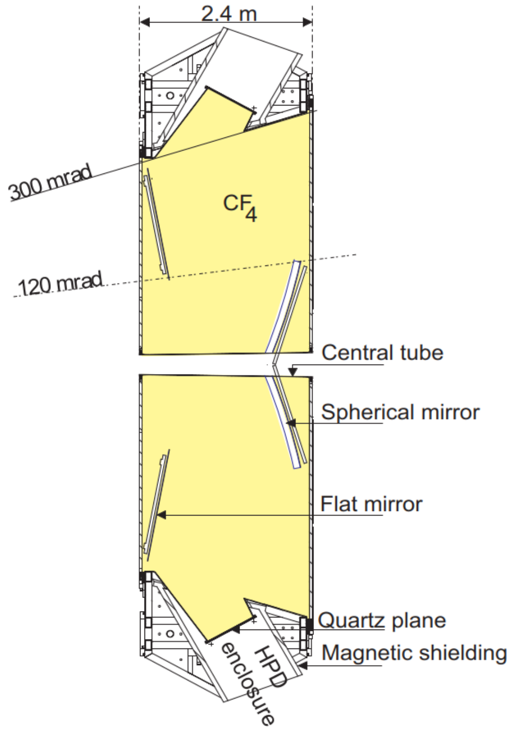
The LHCb experiment





RICH 1



RICH 2

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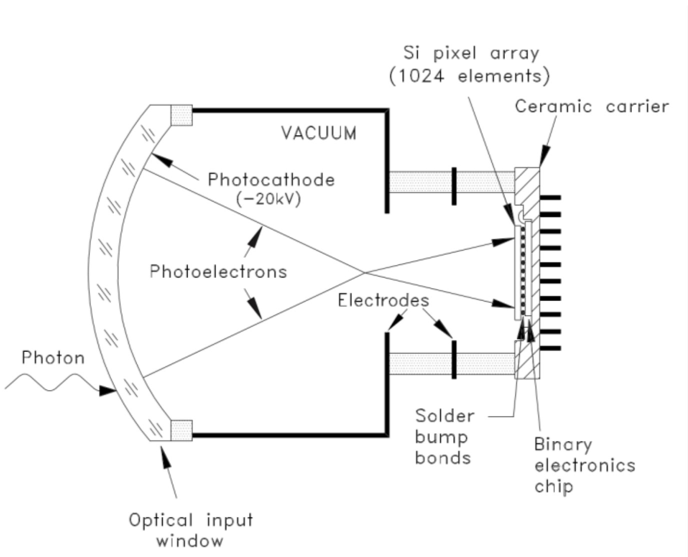
The Pixel Hybrid Photon Detectors



The encapsulated electronics operate at a maximum read-out rate of 1 MHz; not compatible with 40 MHz readout

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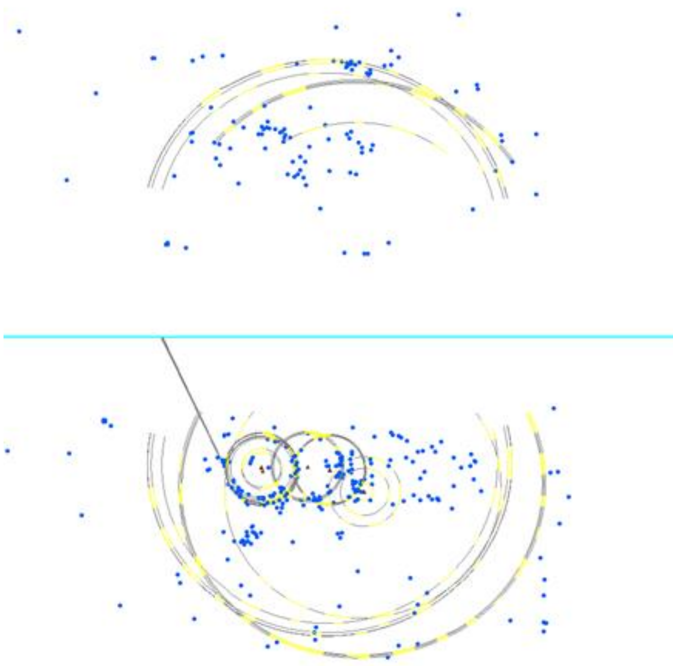
RICH 1: From 2 radiators to 1

- Original design of RICH 1 was to accommodate 2 radiators to cover a wider momentum range:
  - C_4F_{10}
  - Aerogel
- However:
  - Increased luminosity compared to original design and increased background (and underestimate of track multiplicity) made aerogel photons difficult to identify
  - The requirement for offline quality results from High-Level Trigger output put strict conditions for processing time
    - Online alignment and calibration before HLT
- Removal of aerogel extended the length of the gas radiator



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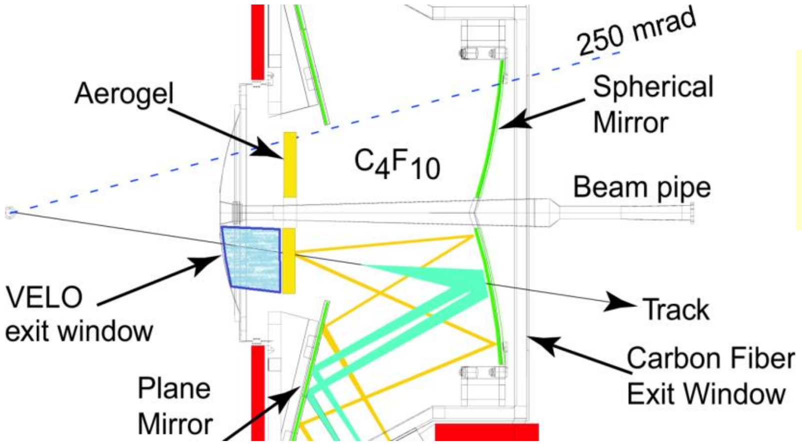
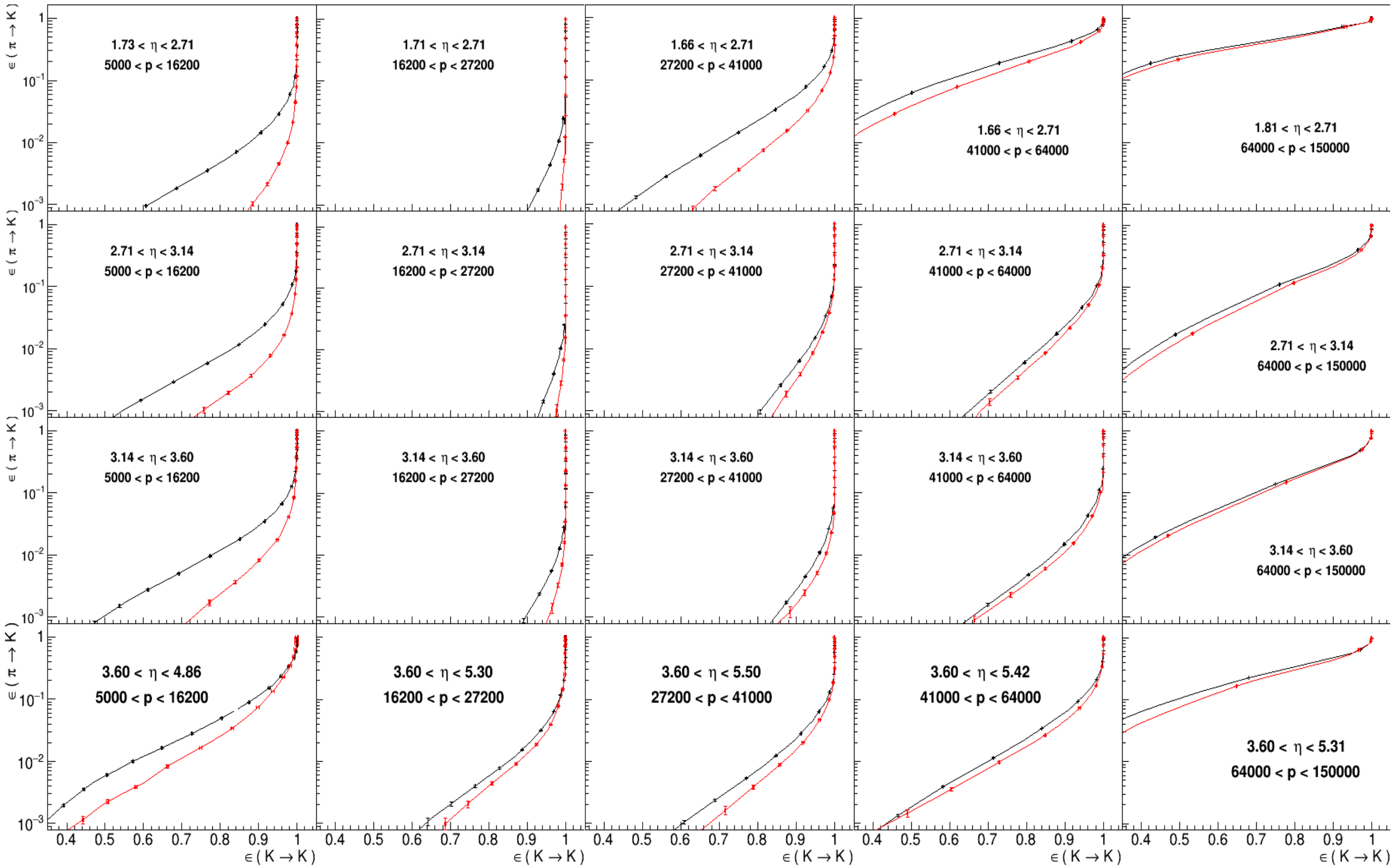
Aerogel removal

π/K PID 2012/2015



Mis-ID π→K

← η



Momentum →

Efficiency K→K

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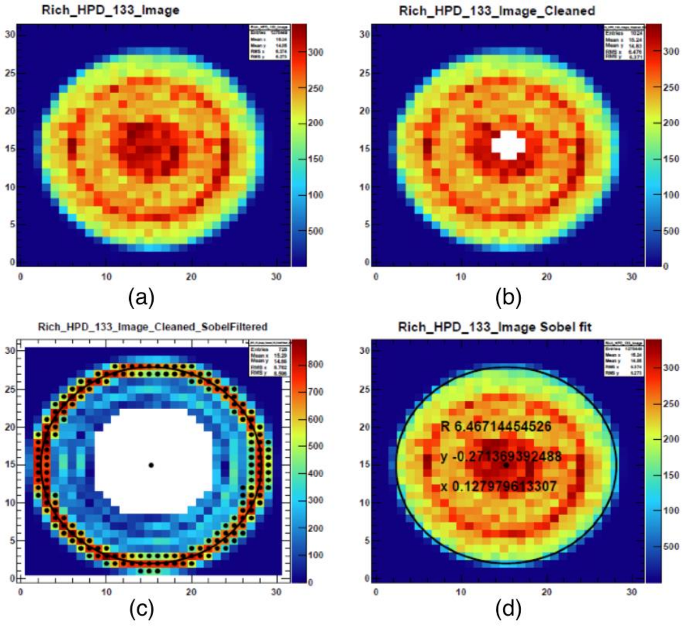
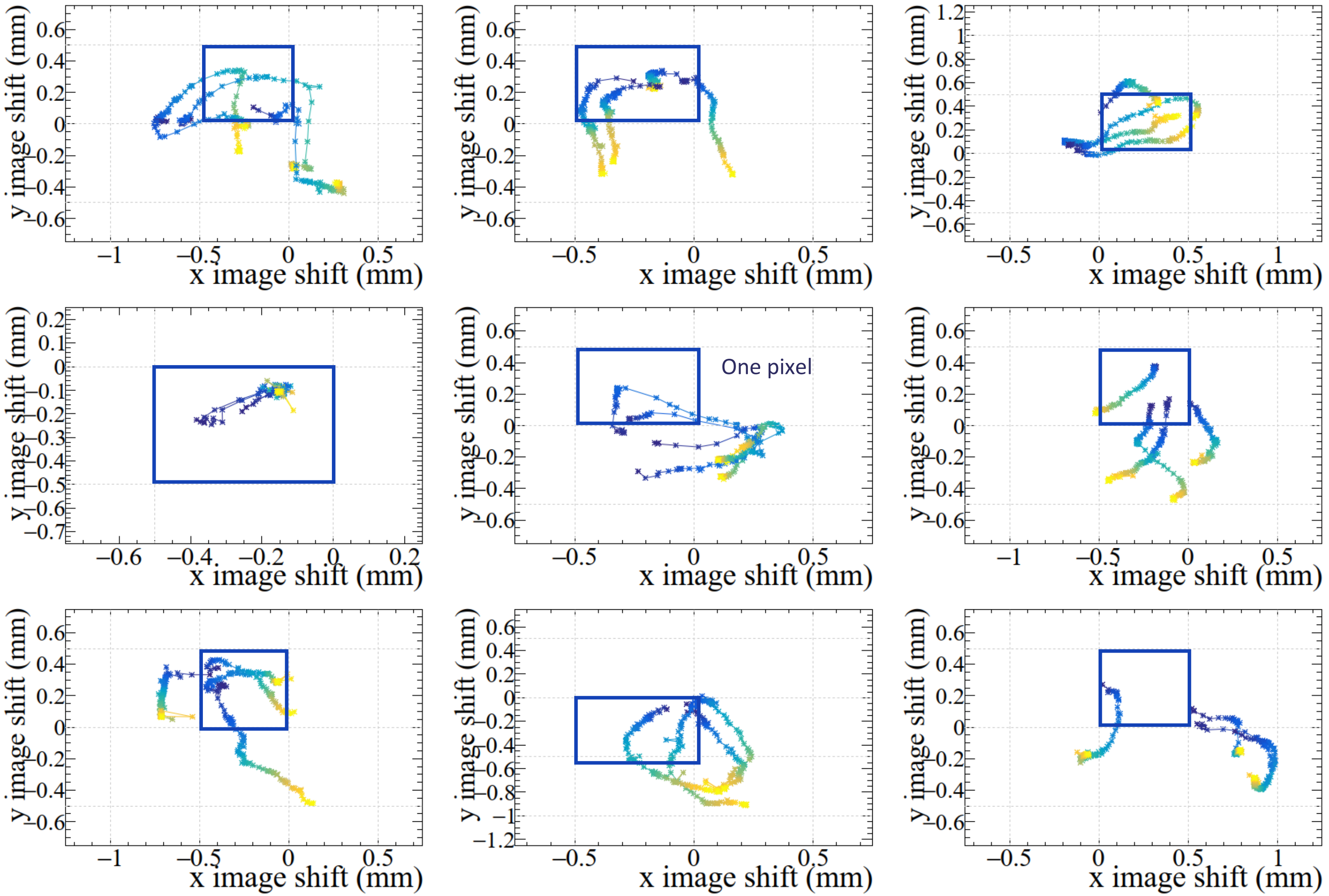
Cherenkov angle reconstruction

HPD photocathode position





Automatic Online calibration for every run (max 1 hour)

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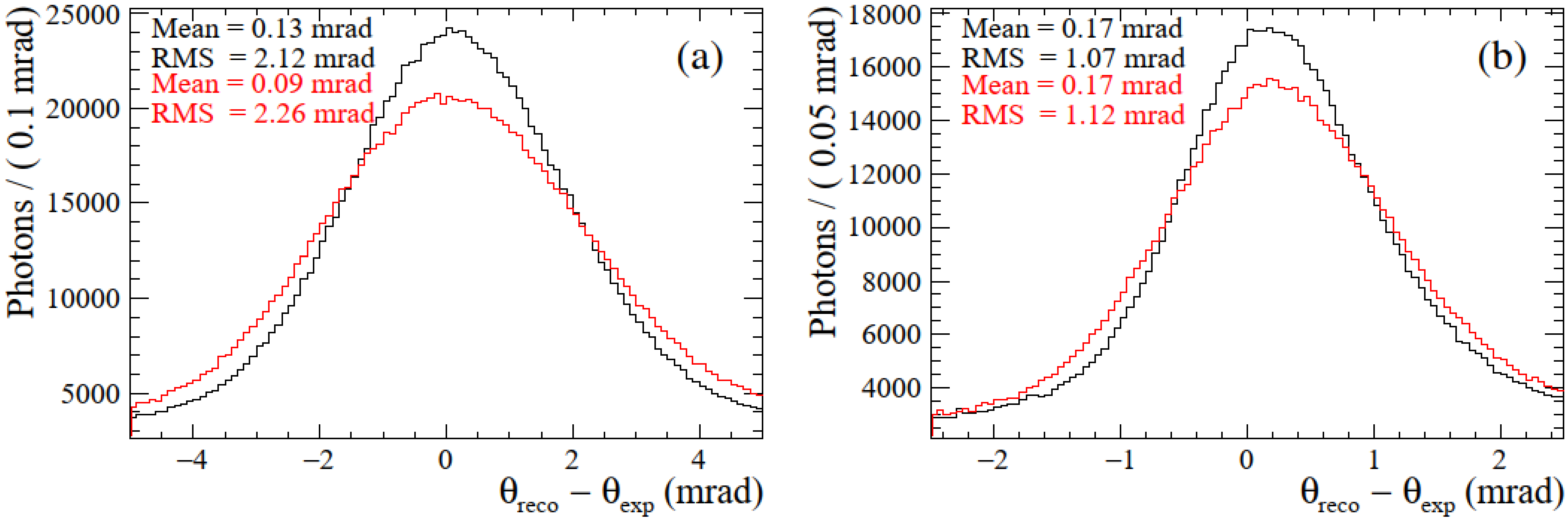
HPD Image centre effect



RICH 1

RICH 2

Before corrections

After corrections

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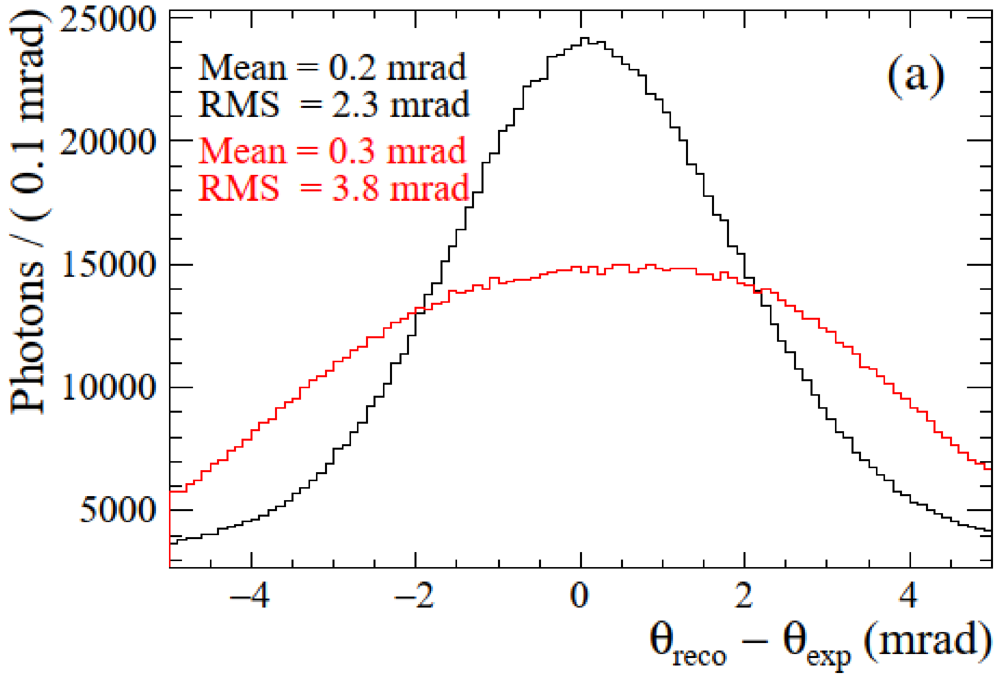
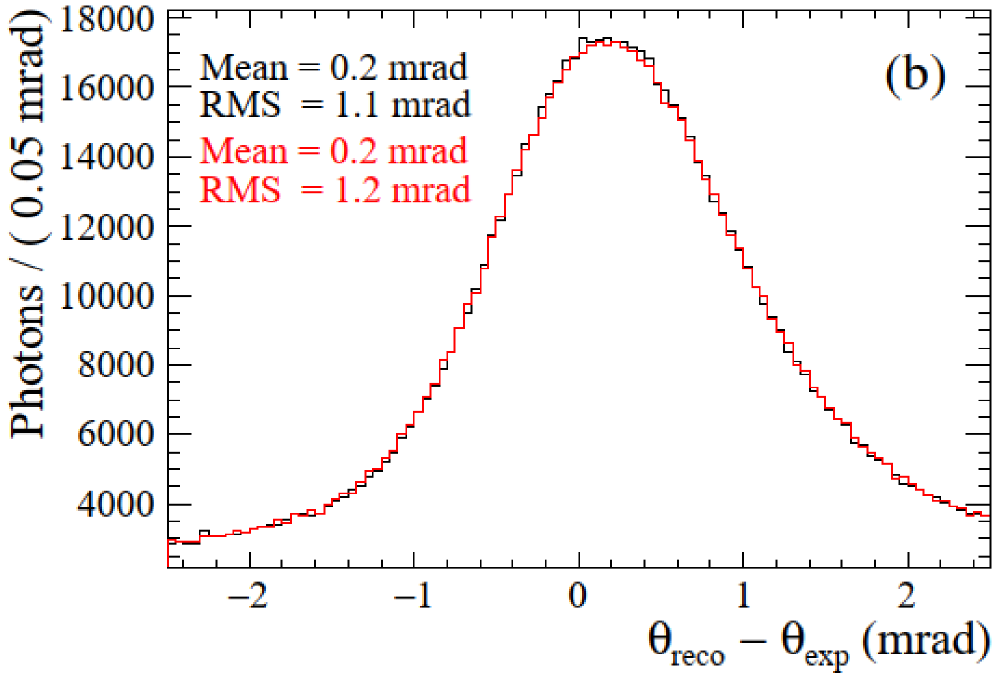
Magnetic field distortions





A Borgia *et al*, NIM A 735 (2014) 44-52

R Cardinale *et al*, 2011 *JINST* **6** P06010

RICH 1

Before corrections
After corrections

RICH 2

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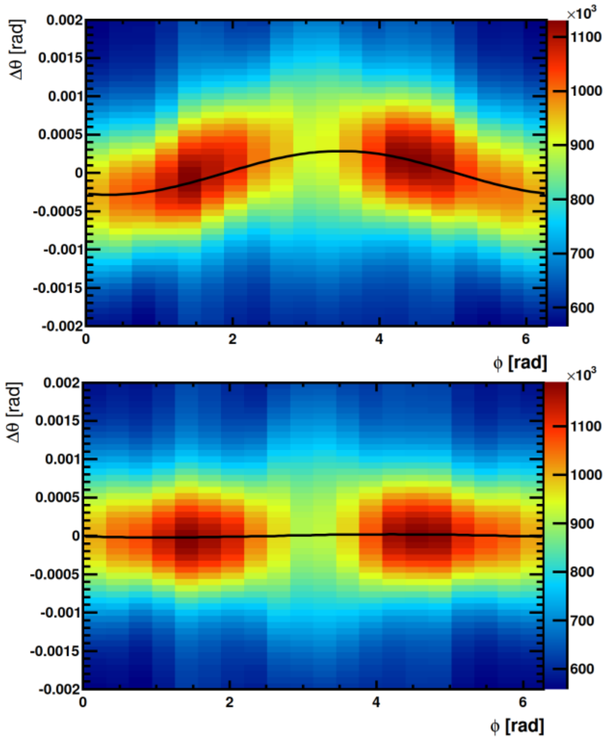
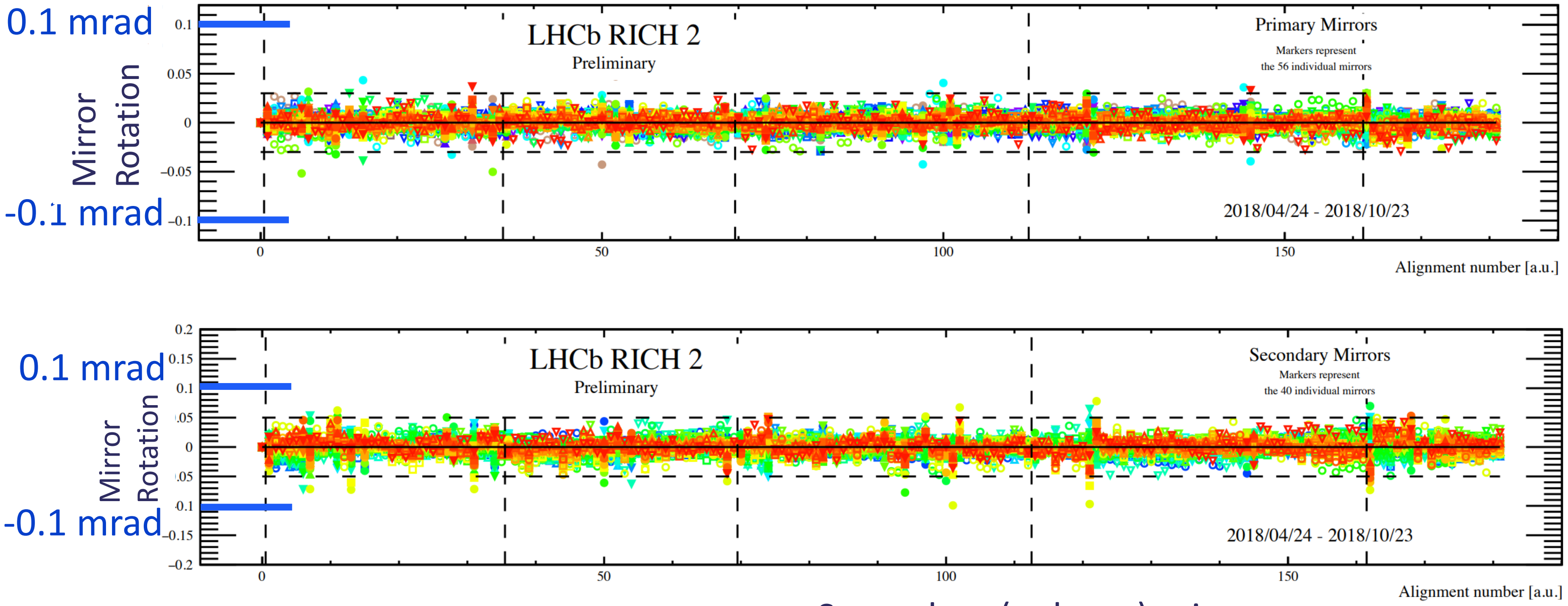
Mirror alignment



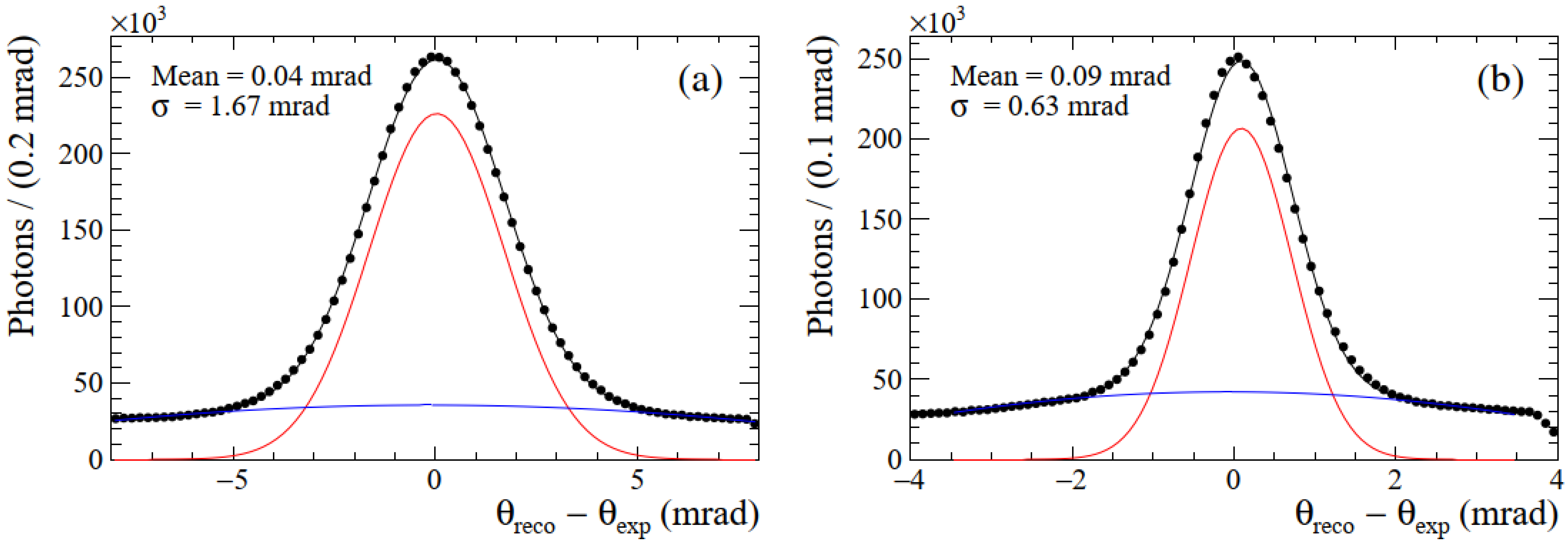
Primary (spherical) mirrors



Secondary (~planar) mirrors

Cherenkov angle resolution

From low track multiplicity events



RICH 1 **RICH 2**

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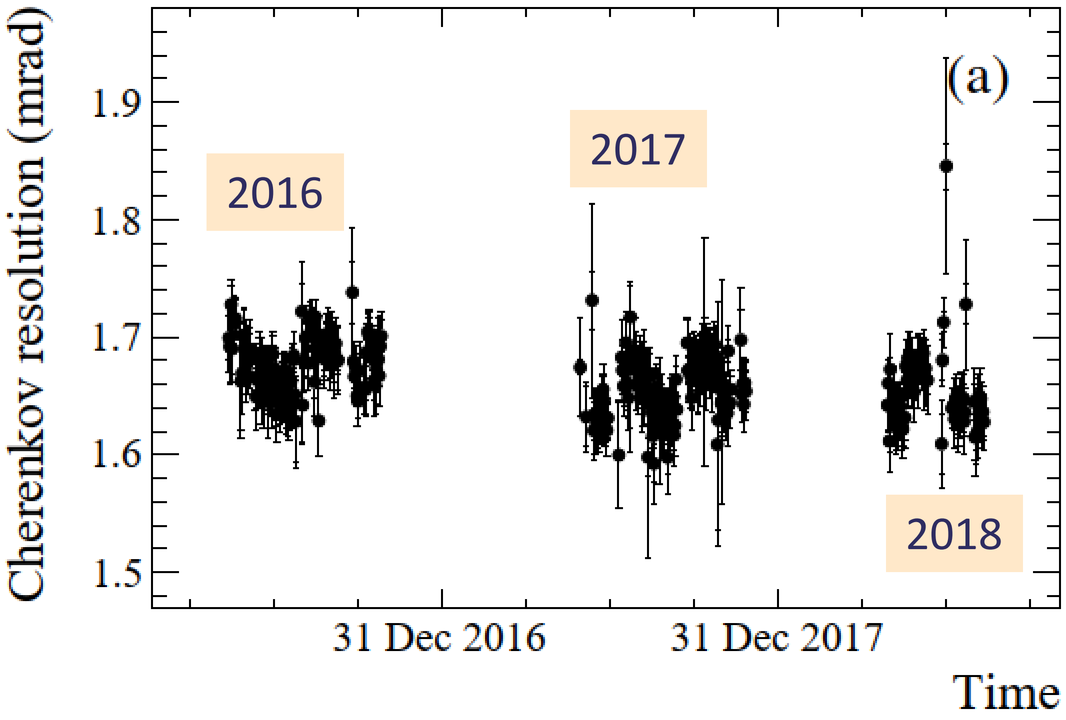
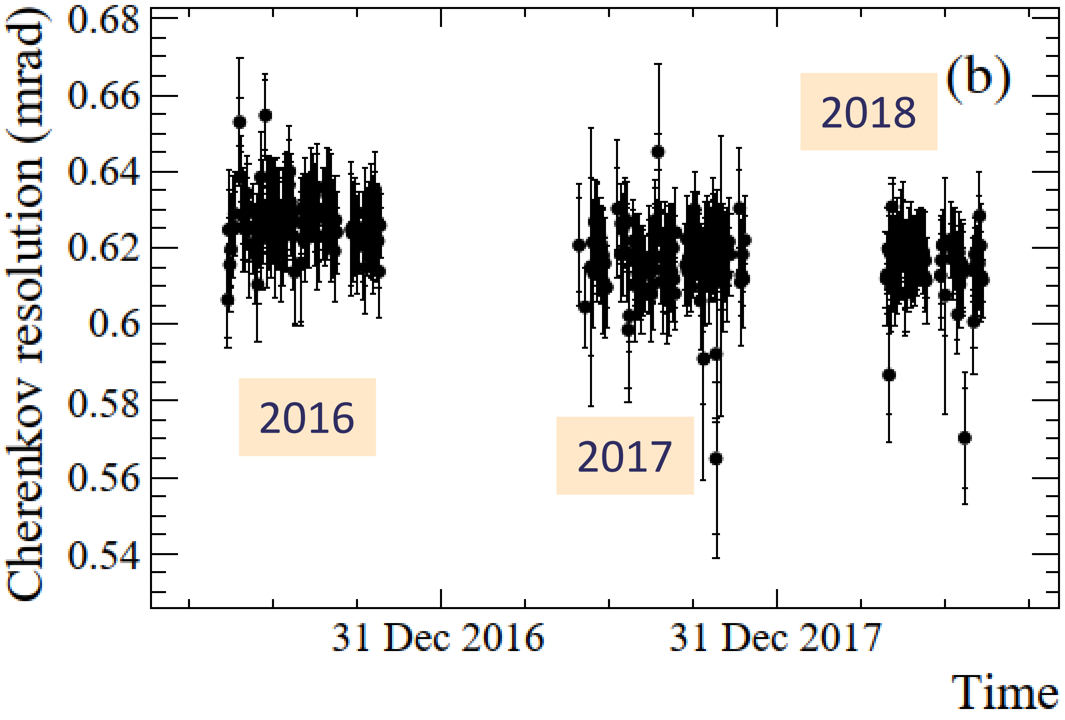
Cherenkov angle resolution stability



RICH 1



RICH 2

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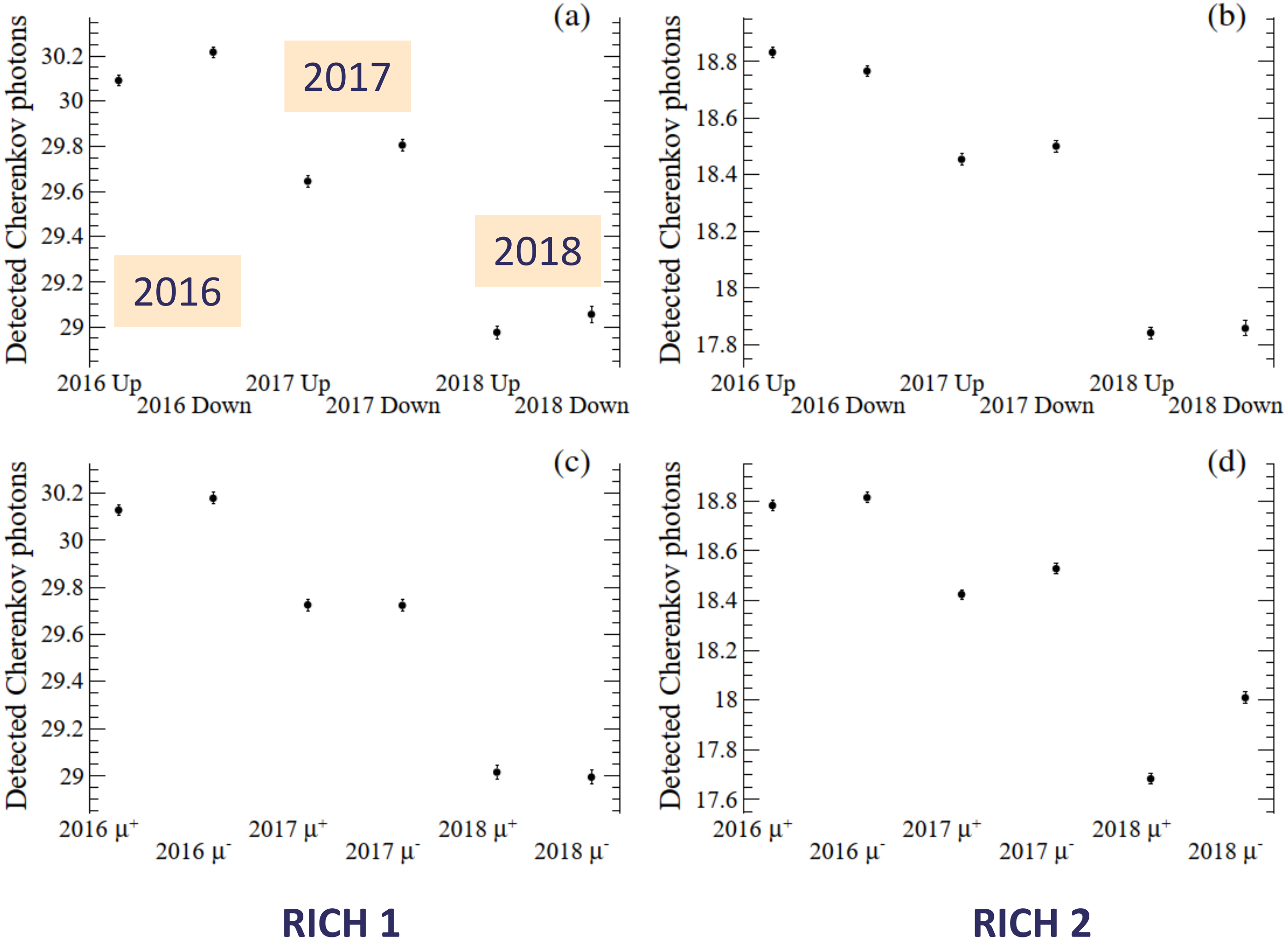
Number of detected photons

Using low multiplicity events, identified as muons by the muon system

The number of photons is estimated per track from the resolution plot with the background subtracted



LHCb operates with two magnetic field polarities to avoid systematic errors:
Field UP
Filed DOWN

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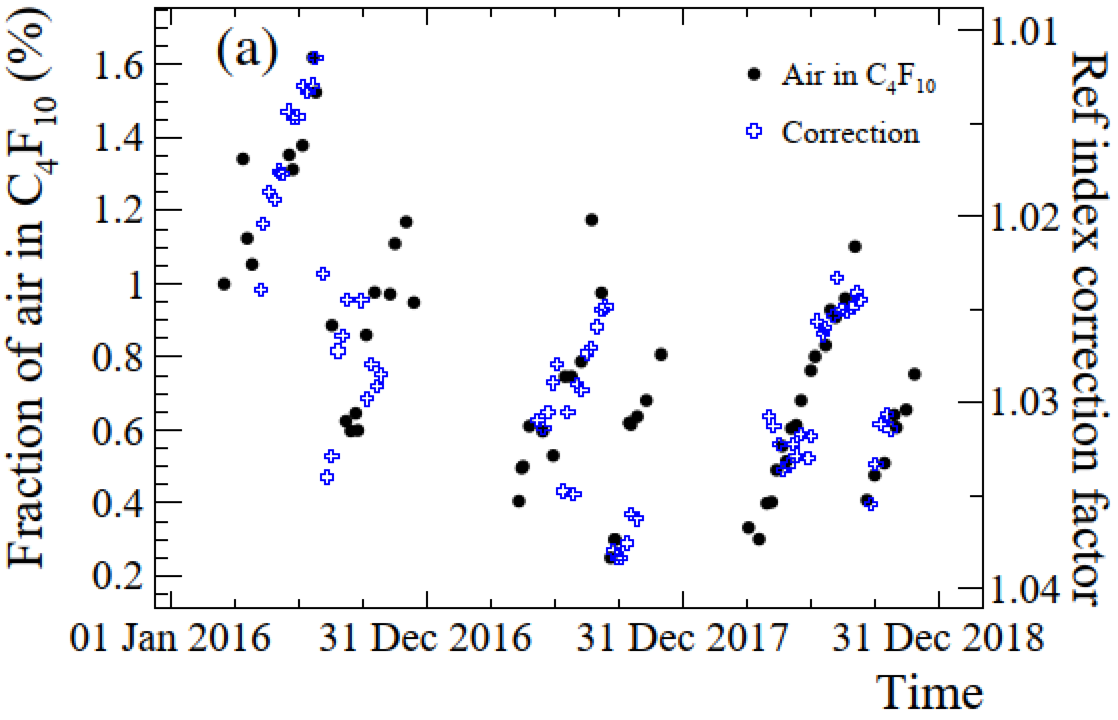
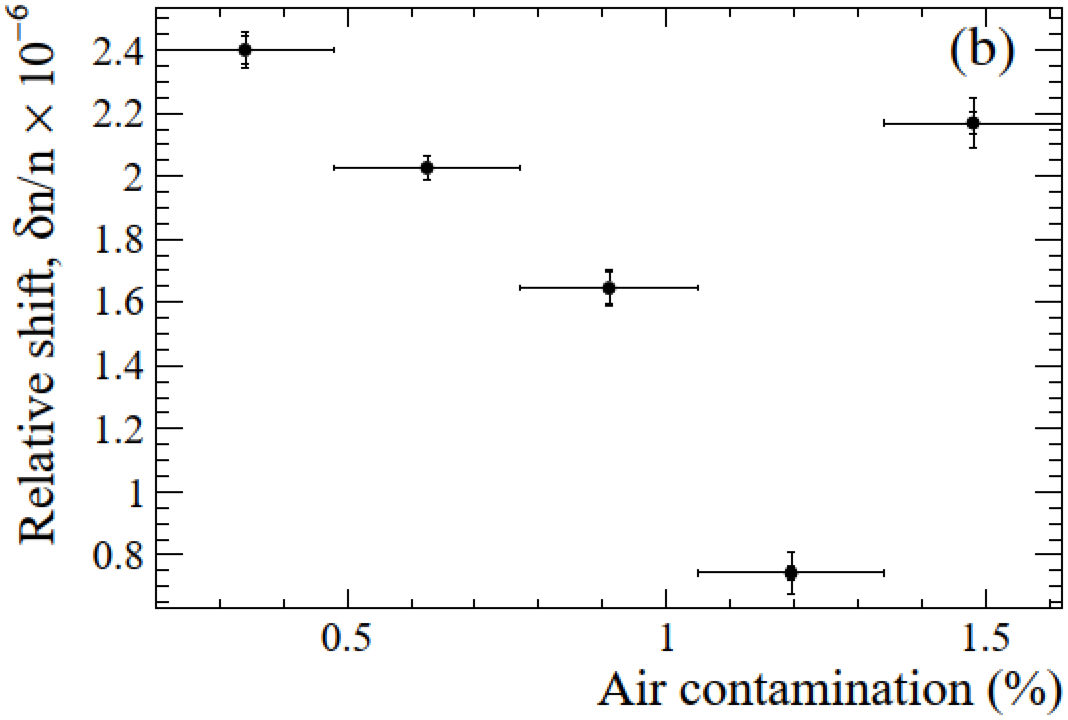
Calibration

Refractive index calibration



Correction factor and air contamination



Residual refractive index bias after correction

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Decays for PID calibration

Identified without RICH information

Species	Low momentum	High momentum
$e^{\pm}$	$B^+ \to J/\psi K^+$ with $J/\psi \to e^+e^-$	
$\mu^{\pm}$	$B^+ \to J/\psi K^+$ with $J/\psi \to \mu^+\mu^-$	$J/\psi \to \mu^+\mu^-$
$\pi^{\pm}$	$K^0_S \to \pi^+\pi^-$	$D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$
$K^{\pm}$	$D_s^+ \to \phi\pi^+$ with $\phi \to K^+K^-$	$D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$
$p, \overline{p}$	$\Lambda^0 \to p\pi^-$	$\Lambda^0 \to p\pi^-$; $\Lambda_c^+ \to pK^-\pi^+$

EPJ Techn Instrum 6, 1 (2019). https://doi.org/10.1140/epjti/s40485-019-0050-z

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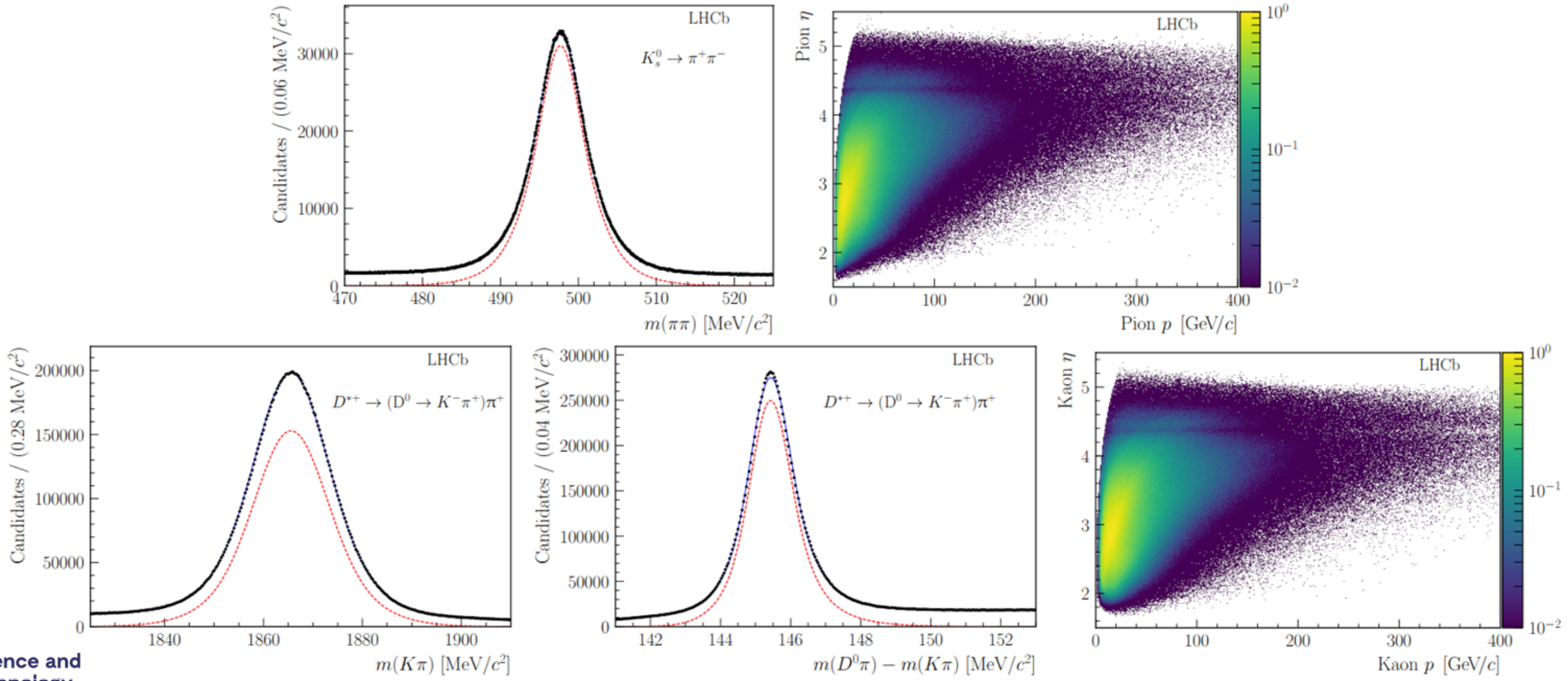
Kinematic range (K, π)



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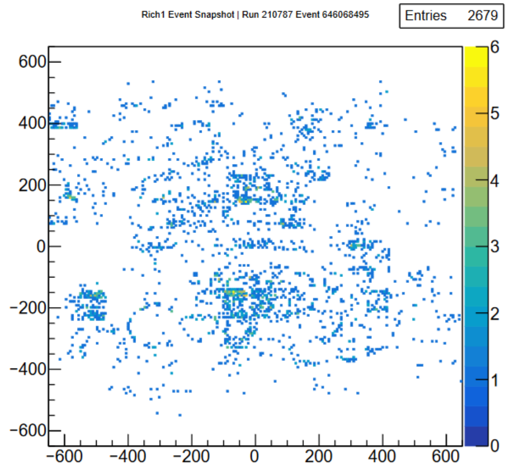
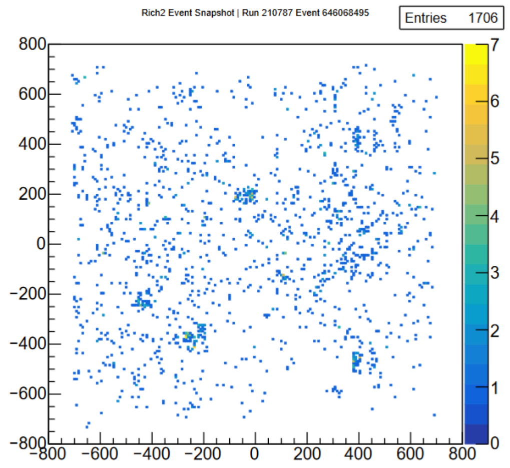
PID performance

Global likelihood PID method

- In the busy LHC environment, most of the “background” to the identification of a given track comes from signals of other tracks in the event
  - → make a global optimisation of the mass hypotheses
- For each track in the event, for a given mass hypothesis, determine the expected distribution of Cherenkov photons on the detector plane using the knowledge of the geometry of the detector and its optical properties
- Repeat for all the tracks in the event
- From the photon distribution on the detector plane calculate the probability that a signal would be seen in each pixel of the detector from all tracks
- Compare this with the observed set of photoelectron signal on the pixels and calculate a likelihood
- Repeat the above, changing the set of mass hypothesis of the tracks to find the set of mass hypotheses which maximize the likelihood





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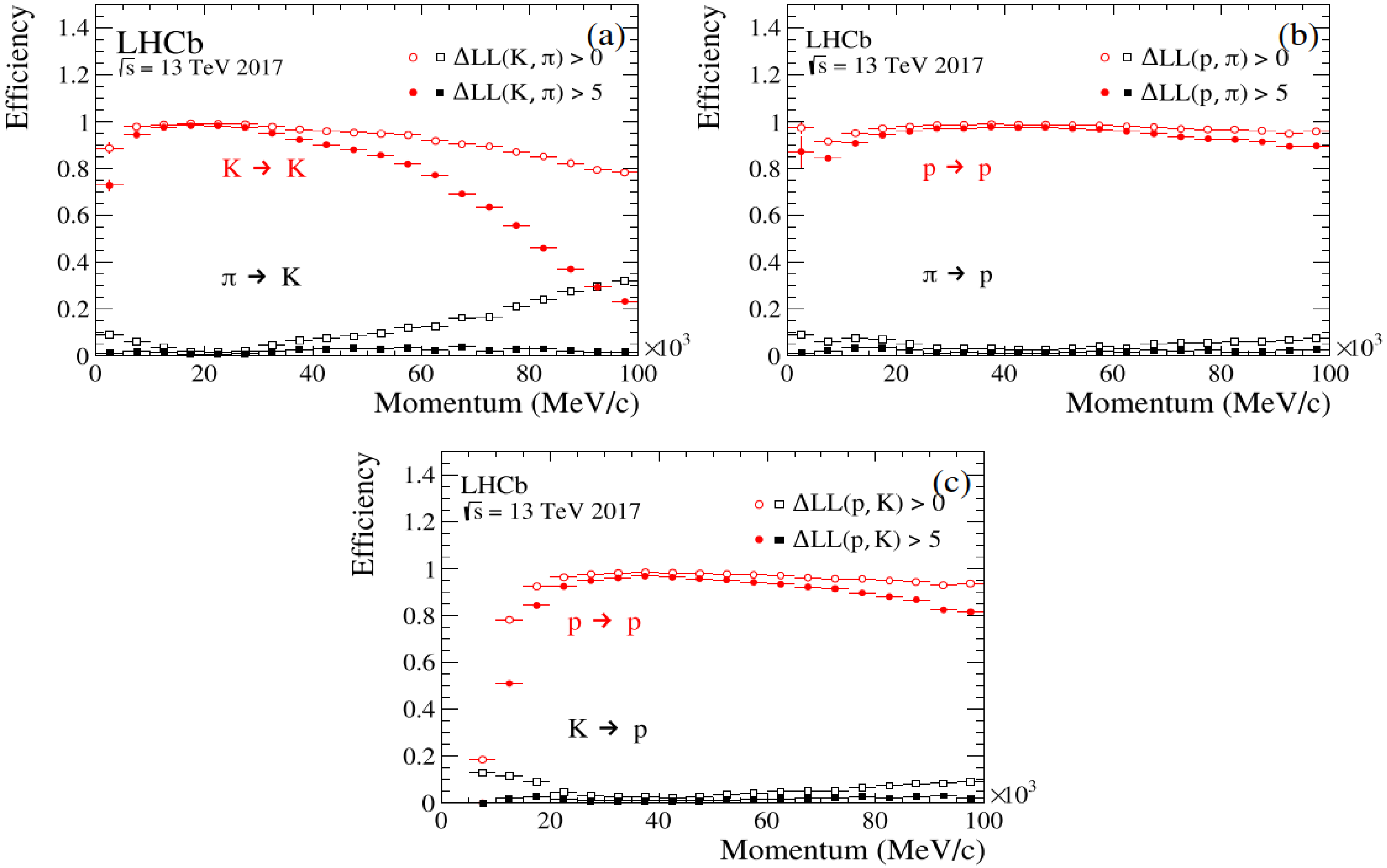
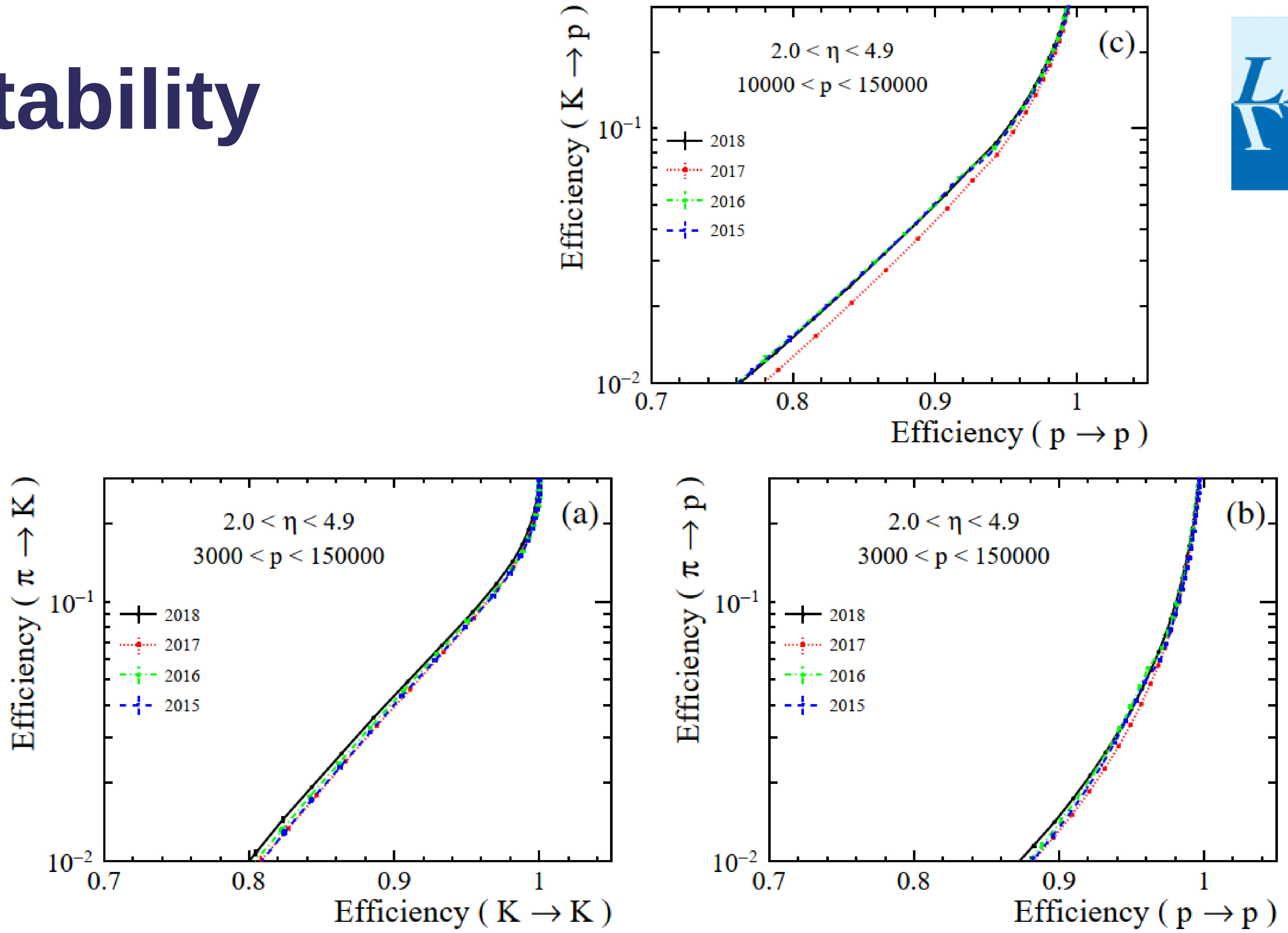
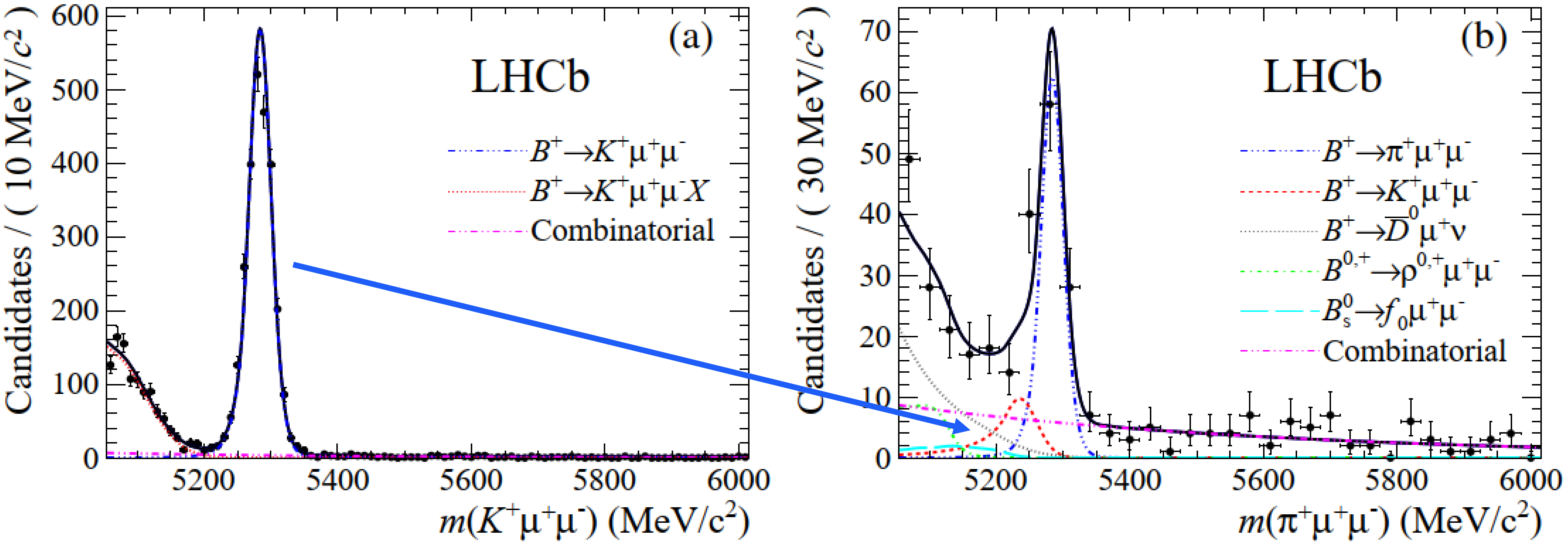
PID performance (2017)



PID stability



Physics impact of hadron PID



First measurement of the differential branching fraction and CP asymmetry of the $B\pm \to \pi\pm\ \mu+\ \mu-$ decay, JHEP 10 (2015) 034 [arXiv:1509.00414]

Summary

- The data from years 2016 to 2018 have been analysed leading to a better understanding of the detectors and knowledge towards future designs
- The original LHCb RICH detectors have been replaced with the new upgraded versions
  - Brand new RICH 1, new photon detectors and new electronics everywhere
- This is an opportunity to celebrate the success of the original design showing the exceptional performance and stability in a difficult hadron environment

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LHCb Upgrade of the RICH Detectors

Antonino Sergi
University of Genova and INFN
on behalf of the LHCb RICH collaboration

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

Edinburgh, 12-16 Sept

RICH Upgrade

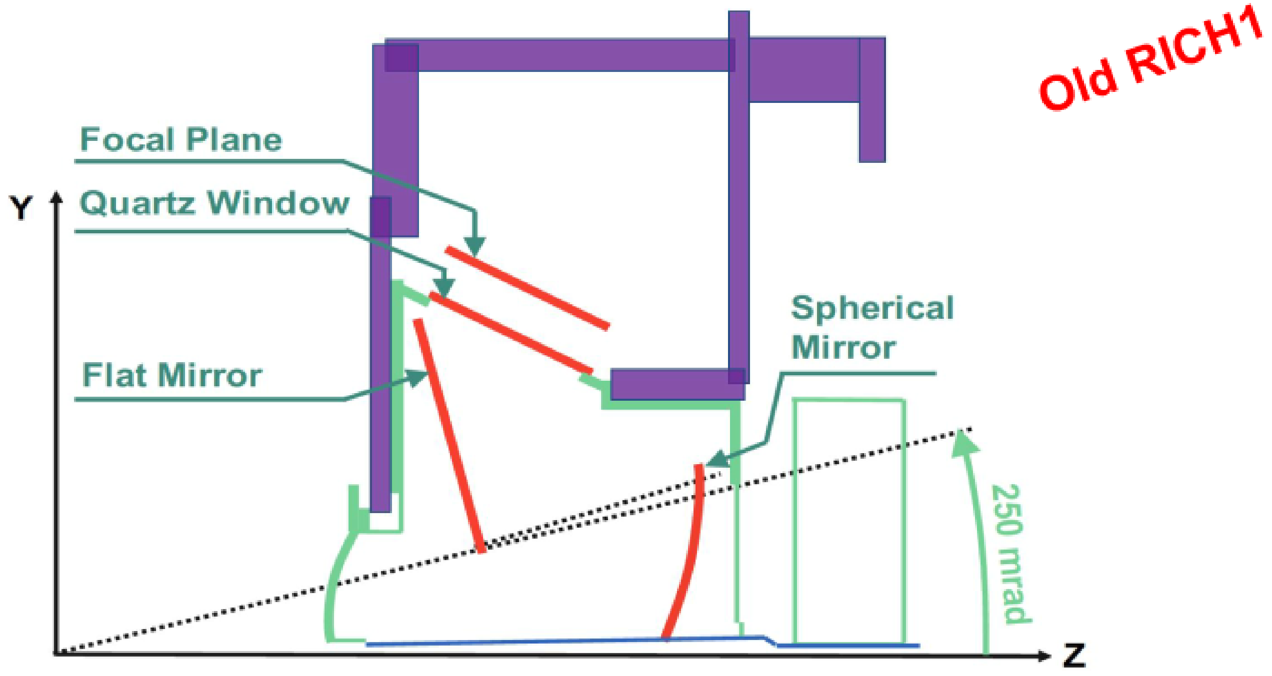
LHCb

- 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

LHCb

- 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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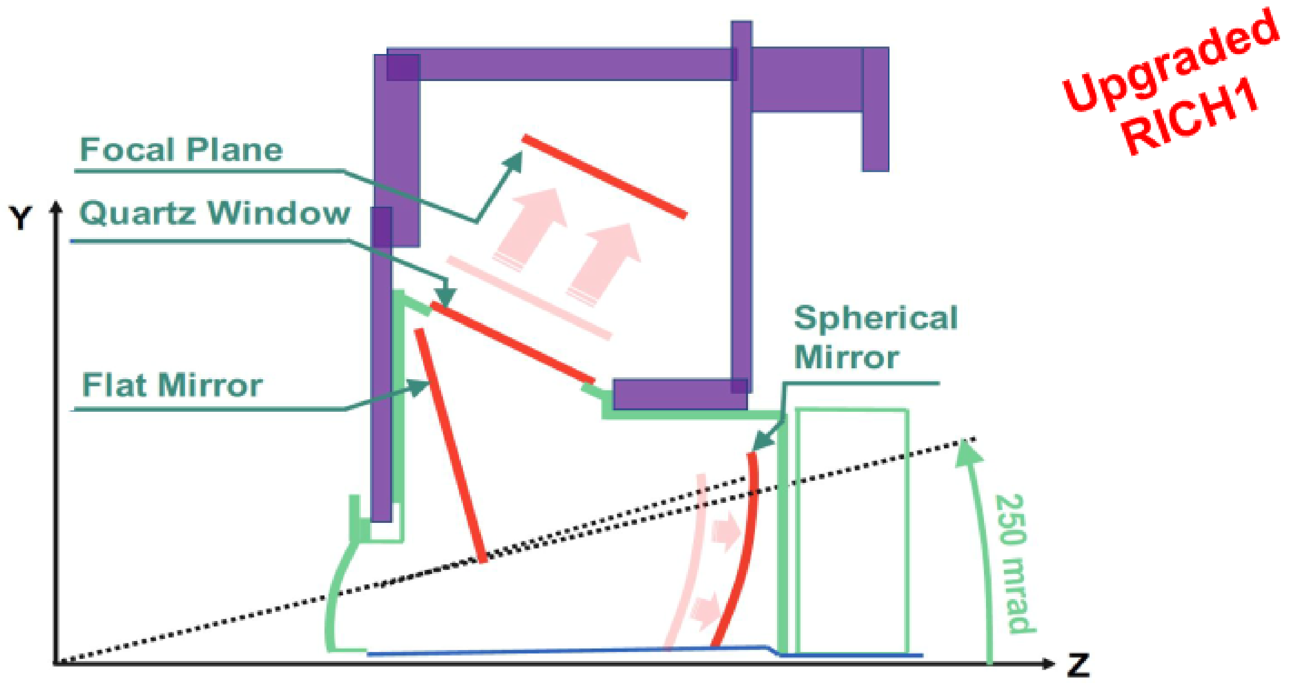
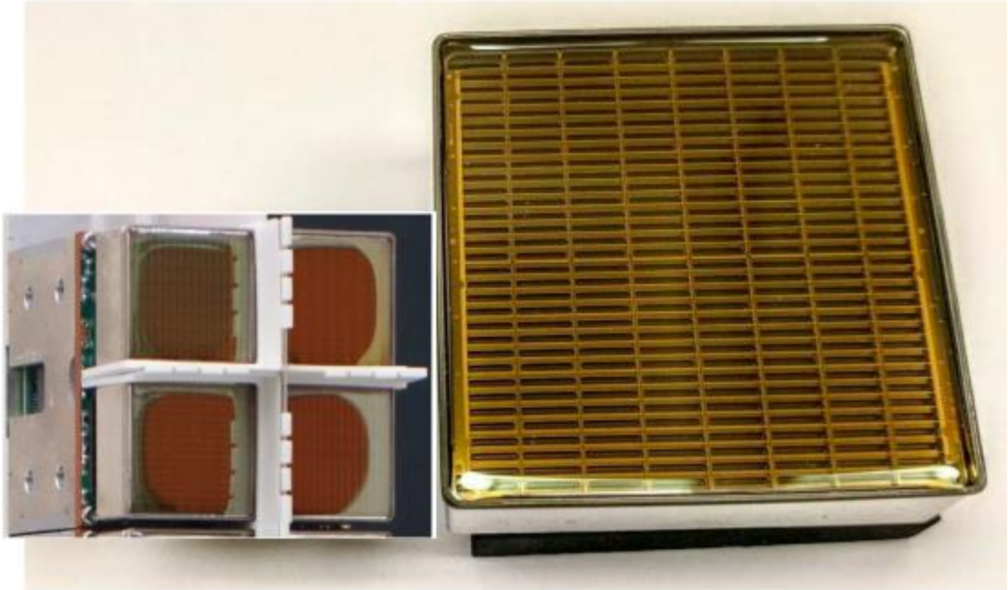


MultiAnode PhotoMultipliers

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



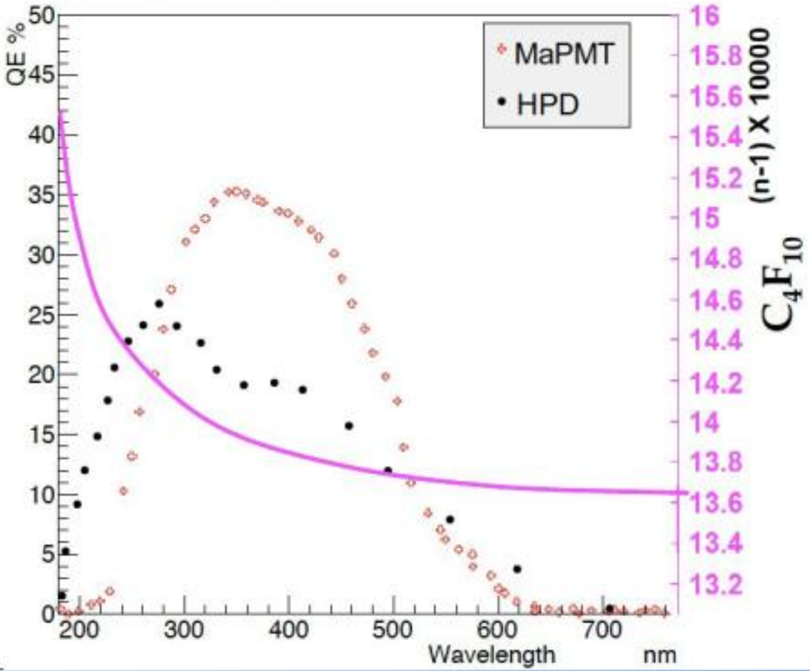


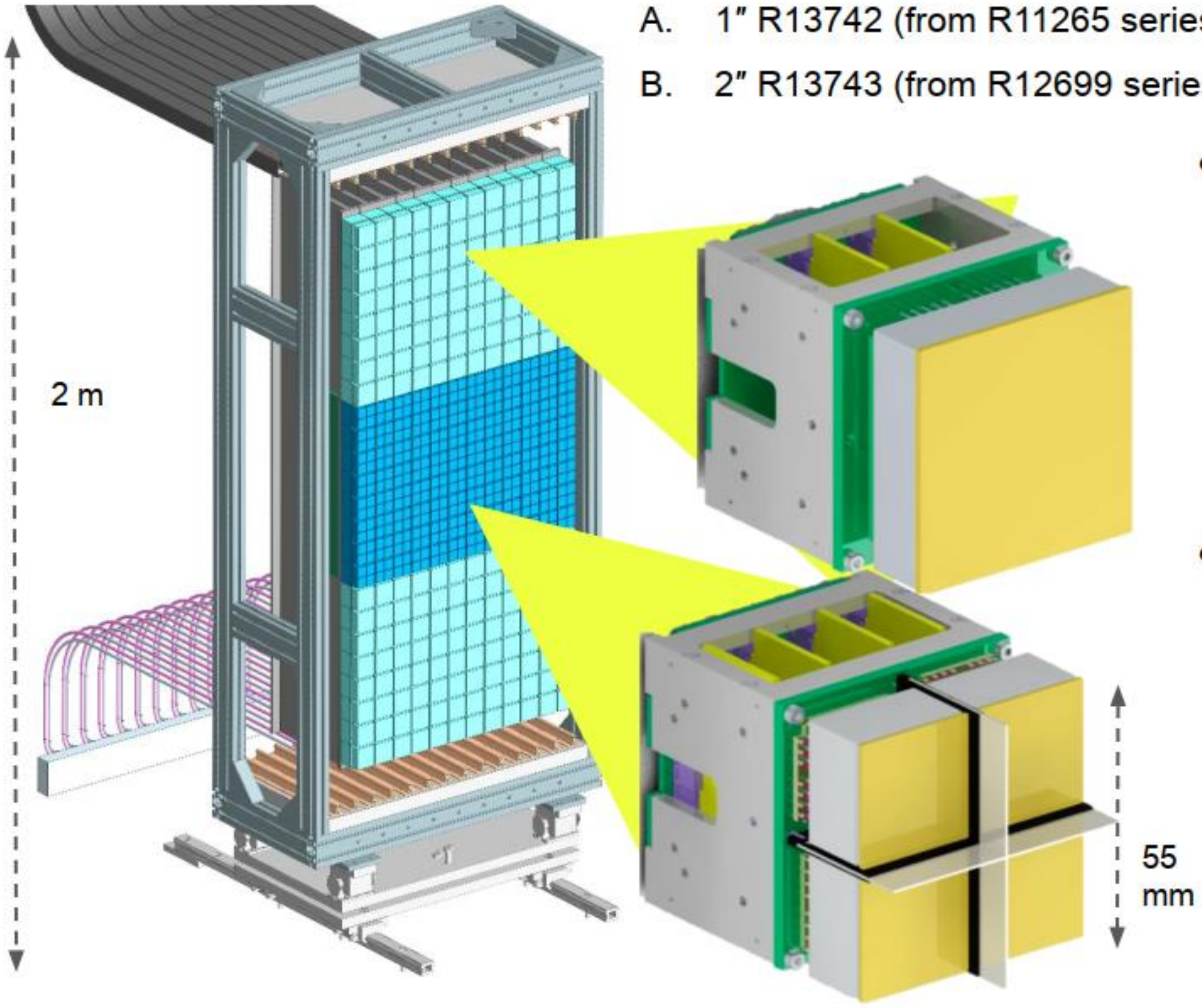
Photo-Detector Assembly

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)



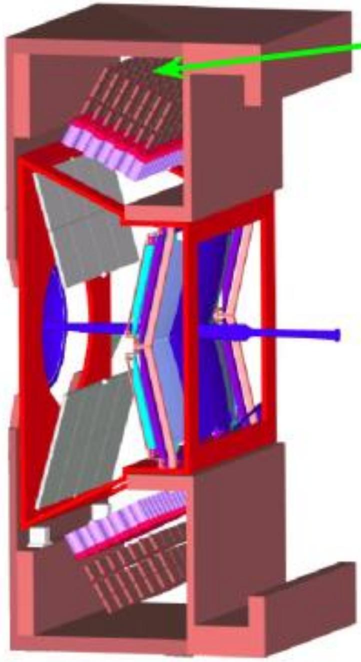
- EC-H type: 2″ MaPMT
  - ~400 modules
  - Outer regions of RICH2
  - One "A"MaPMT per EC (larger model 2×2 inches)
- EC-R type: 4×1″ MaPMTs
  - 2×2 matrix of "B" MaPMT per EC (smaller module 1×1 inches)
  - ~ 2700 MaPMT
  - ~ 700 modules
  - RICH1 and central region of RICH2

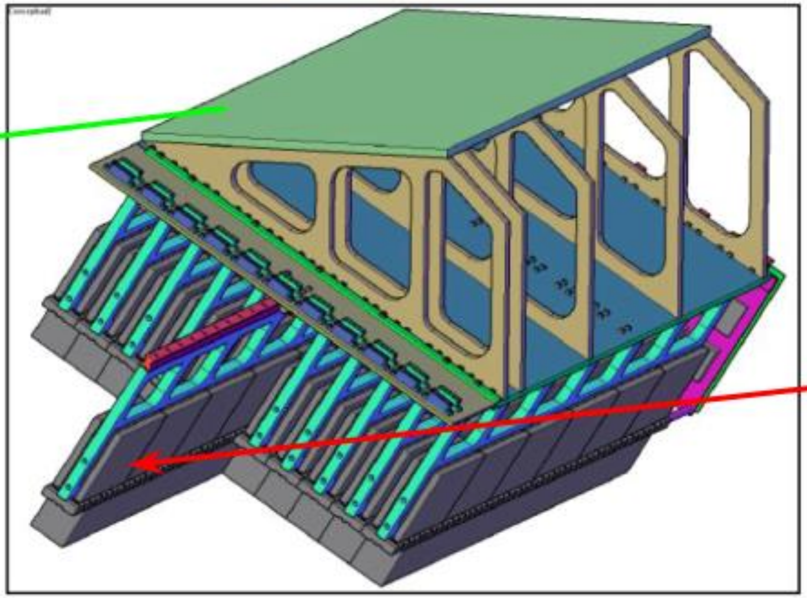
Columns

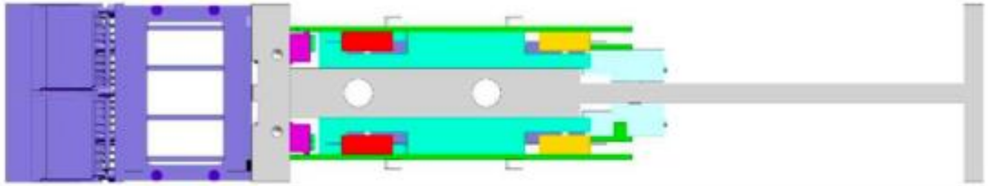
LHCb

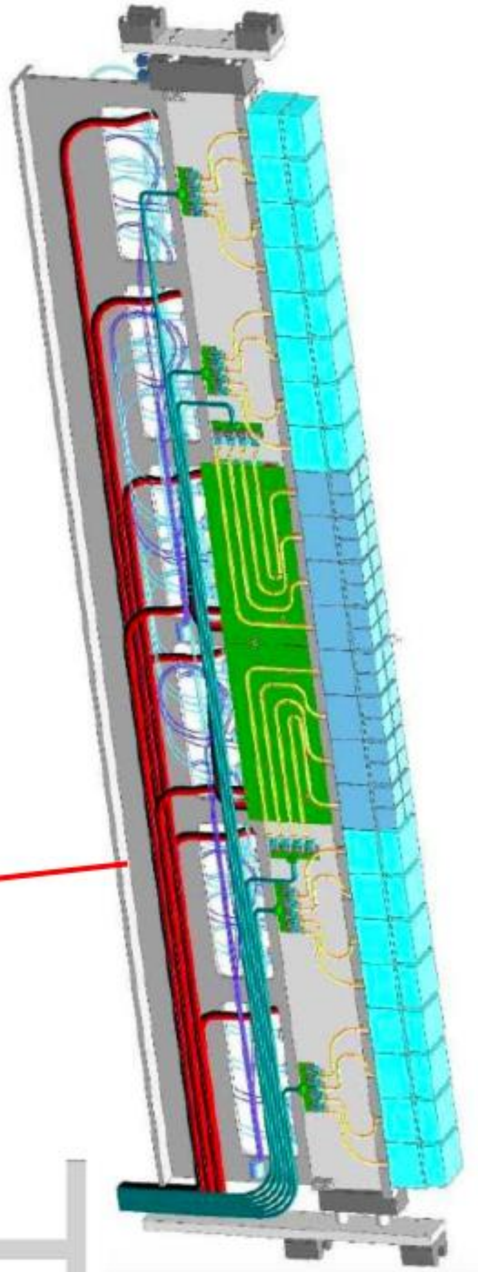
- Mechanical support for Elementary Cells, PDMDB, harness and cooling
  - Easy to remove a column for maintenance
  - Same mechanical structure for columns in RICH1 and RICH2 but different supports

Translation of a column





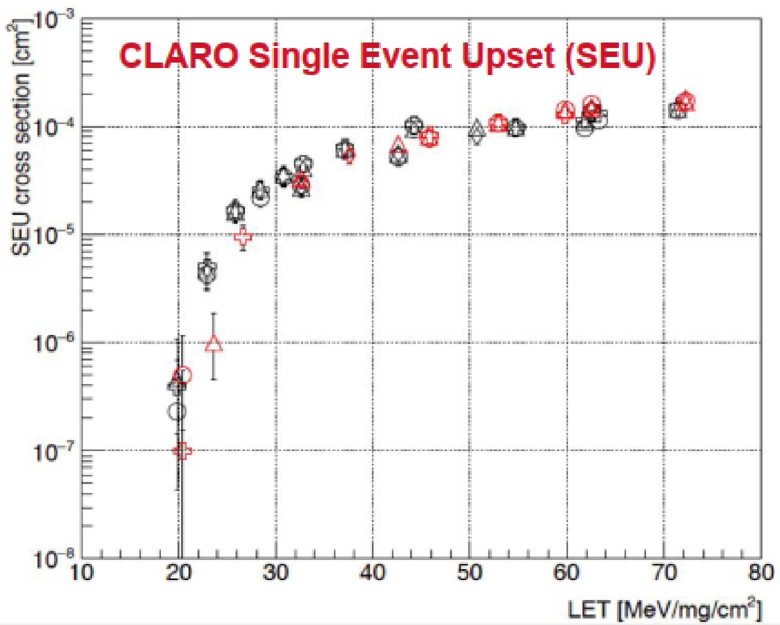


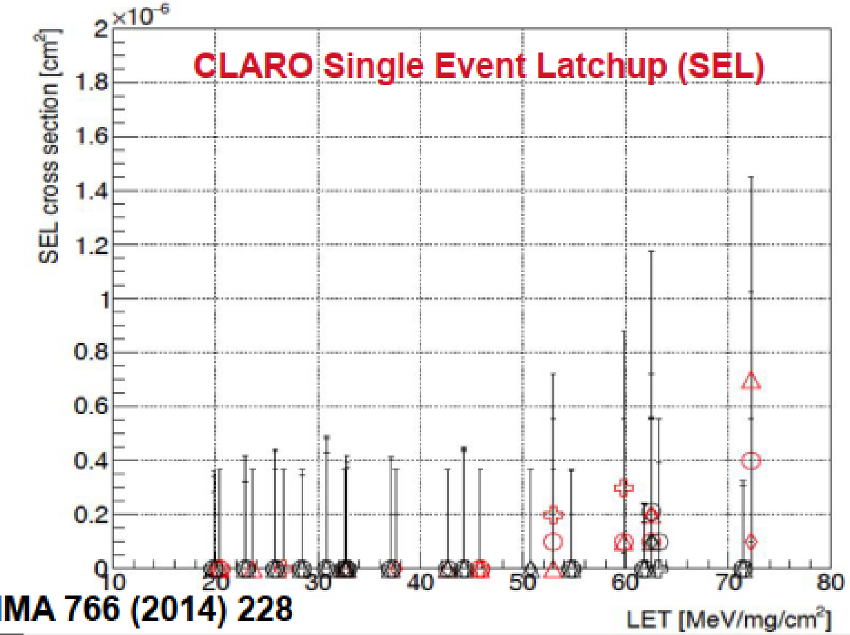


Radiation Hardness

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

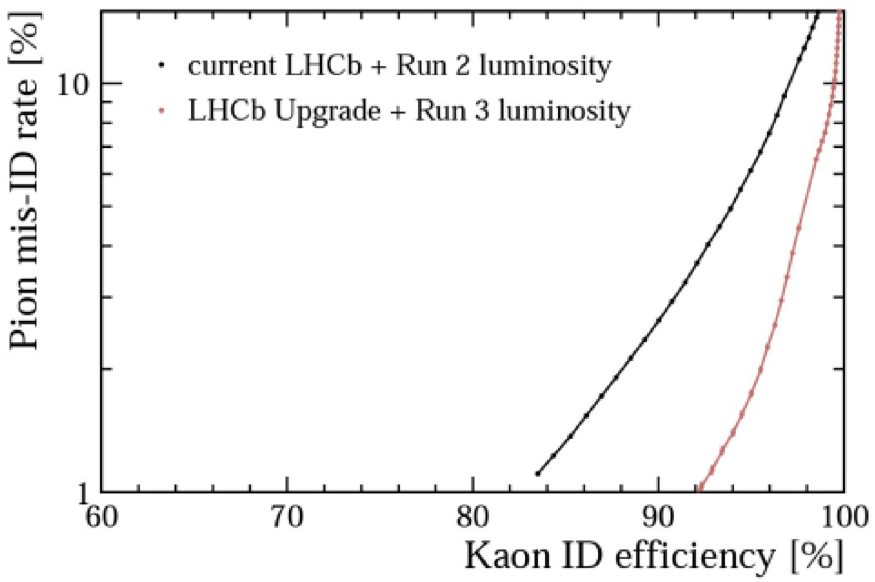
Estimated performance

LHCb

	Photon yield		Cherenkov angle resolution [mrad]				
	${N_{ph}}^{optimal}$	${N_{ph}}^{typical}$	chromatic	emission point	pixel	σ_θ	$\Delta\theta_C$
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

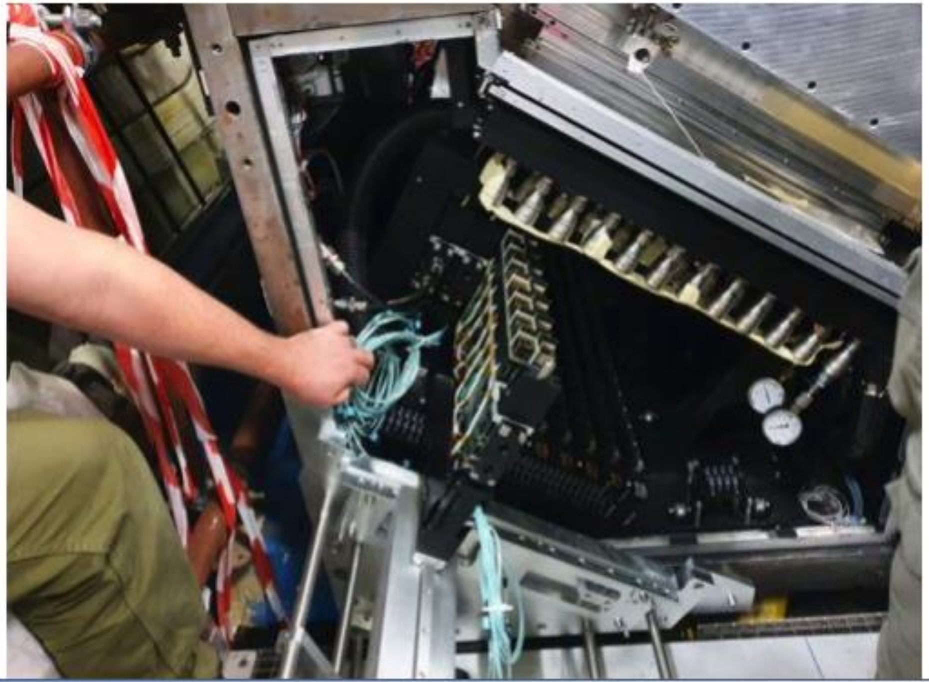
Included in the current simulation

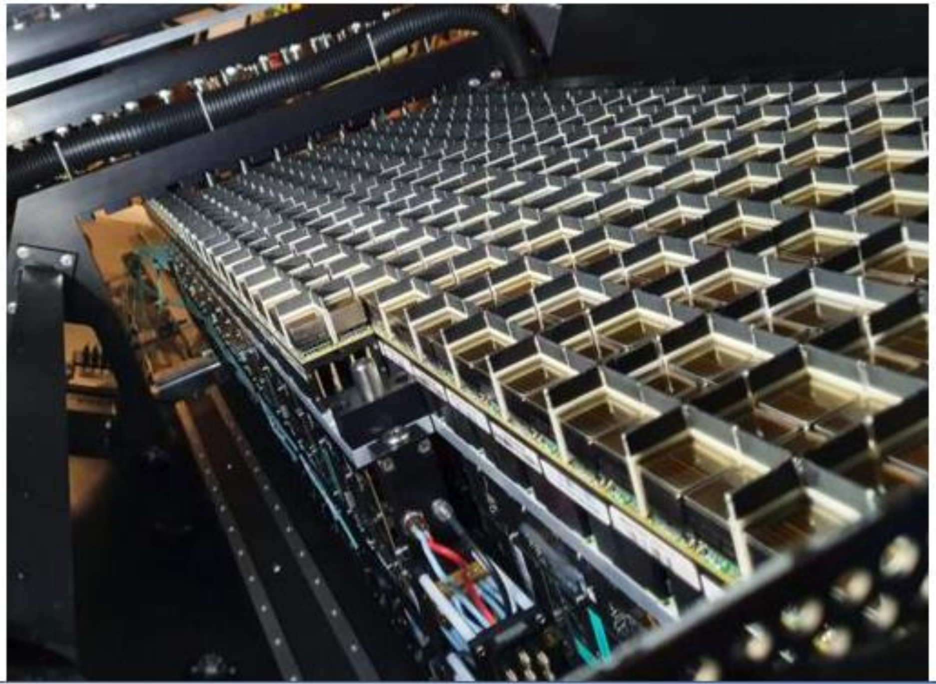
- All measured parameters of optical components
- All feedback from test beams and commissioning
- Experience from the simulation of the previous implementation of this detector



RICH1 Installation: Down Box (12/2021)

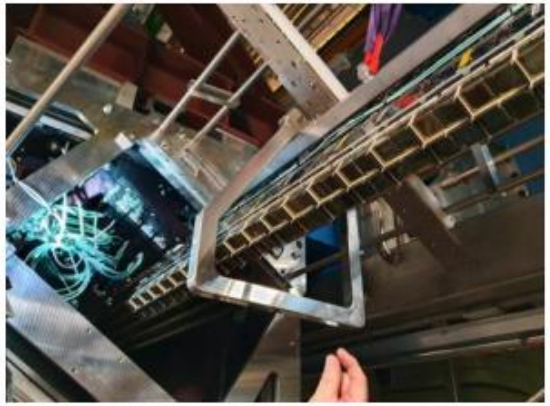
LHCb

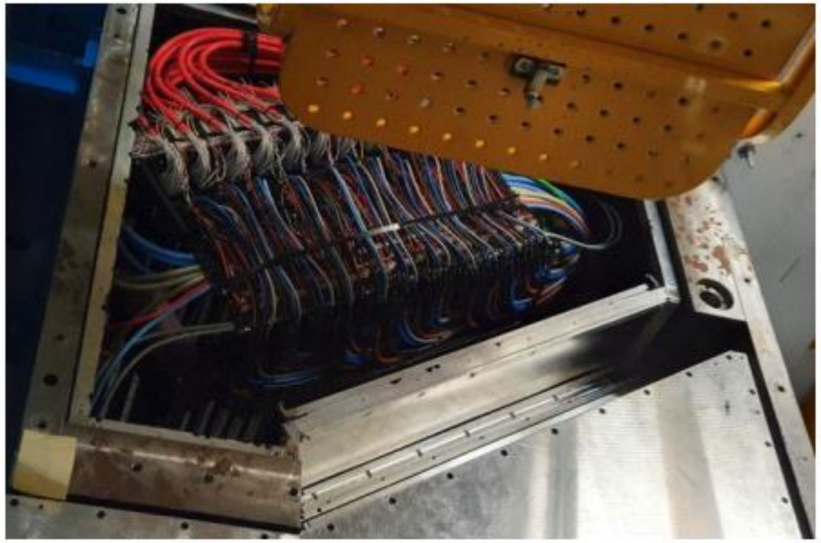


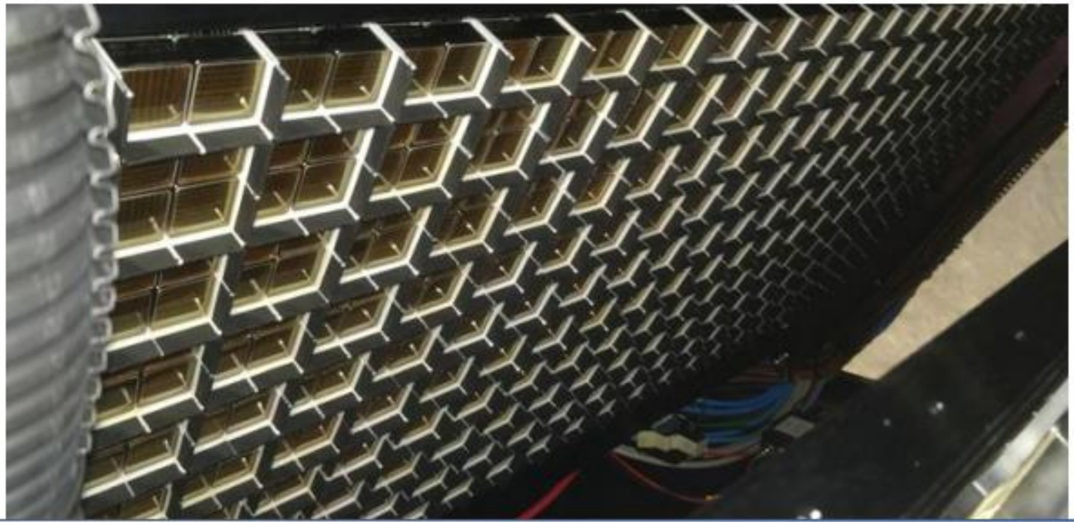


RICH1 Installation: Up Box (01/2022)

LHCb

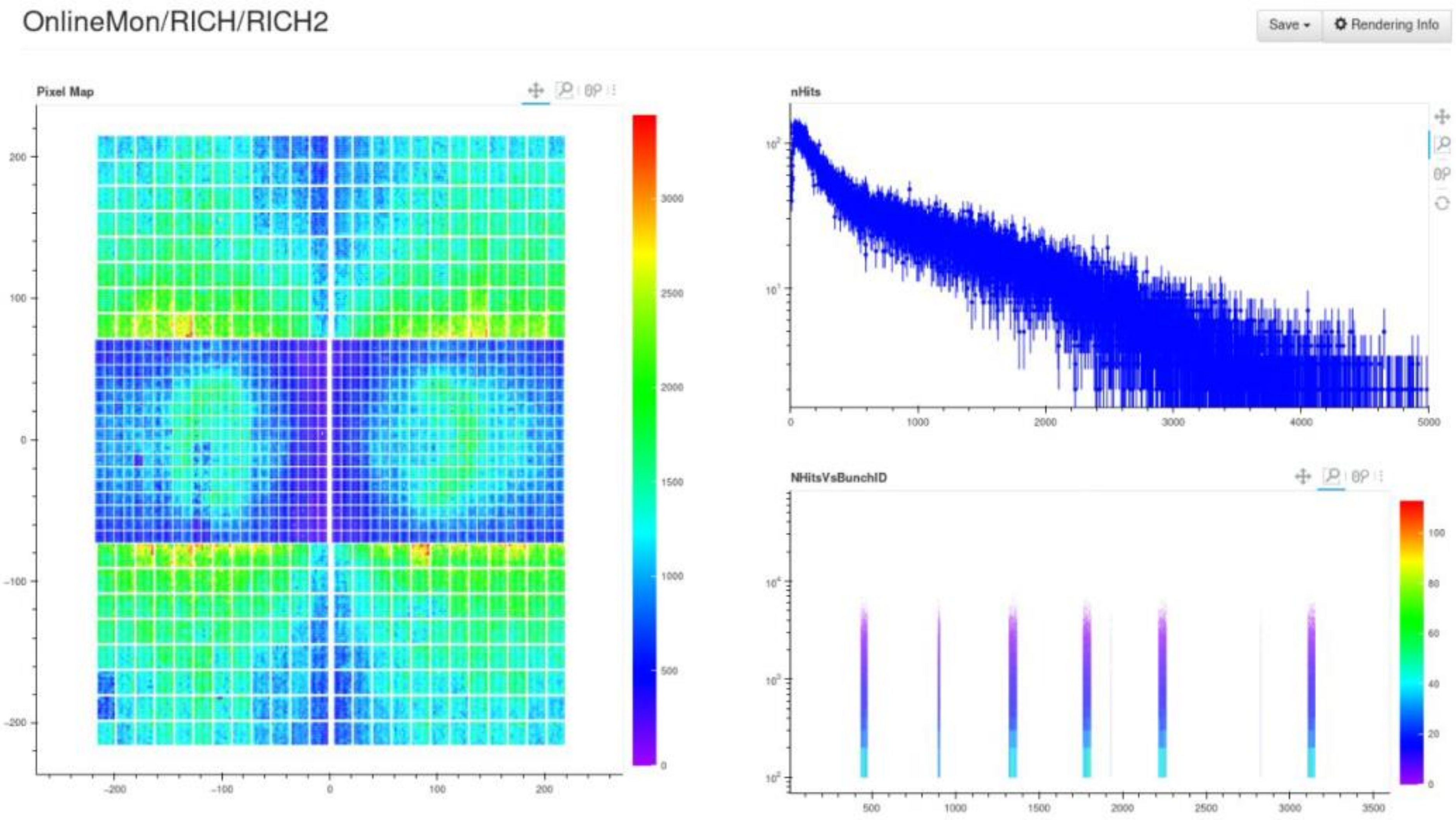






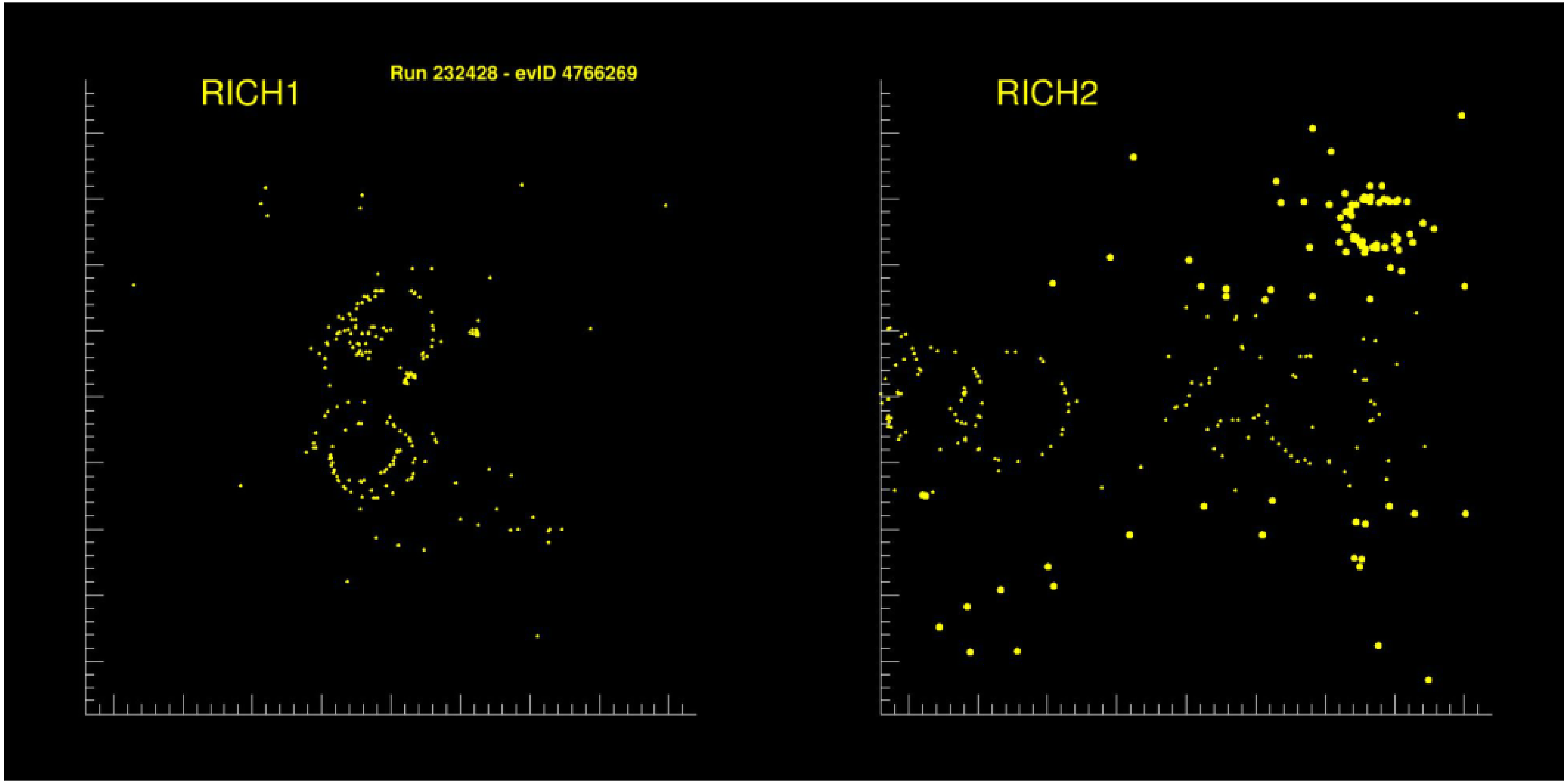
Collisions and Light (June-July 2022)

LHCb



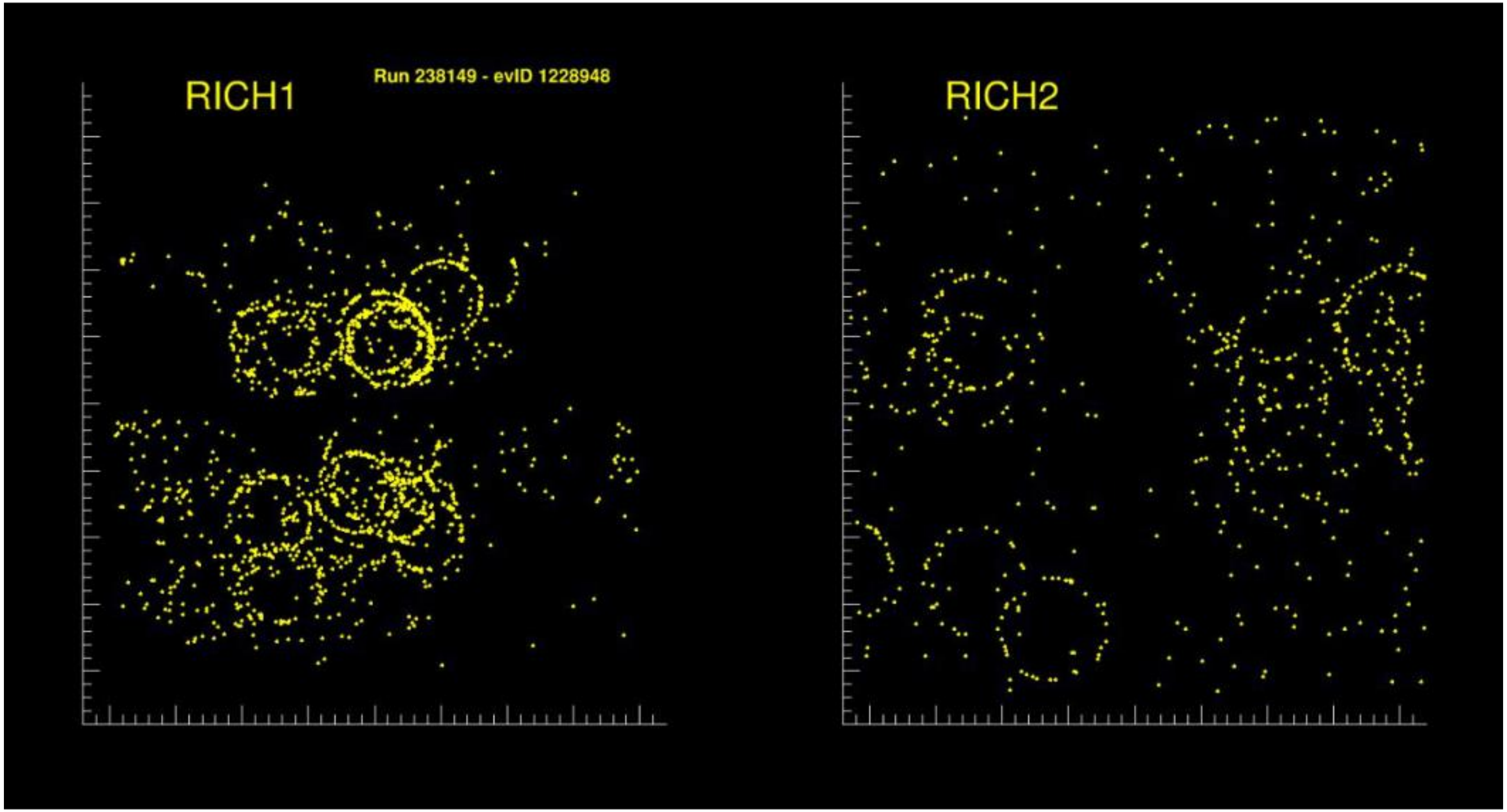
Collisions and Light (June-July 2022)

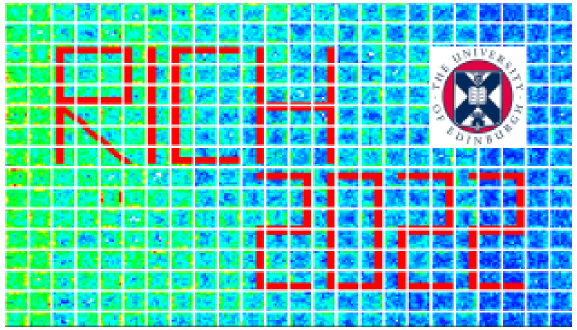
LHCb

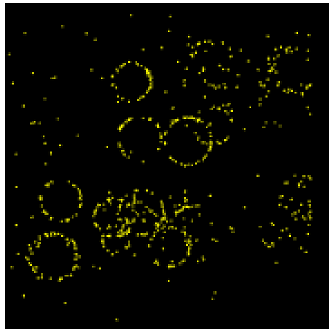


Collisions and Light (June-July 2022)

LHCb







Characterisation and operations of the Multianode Photomultiplier Tubes for the LHCb RICH detectors

Giovanni Cavallero

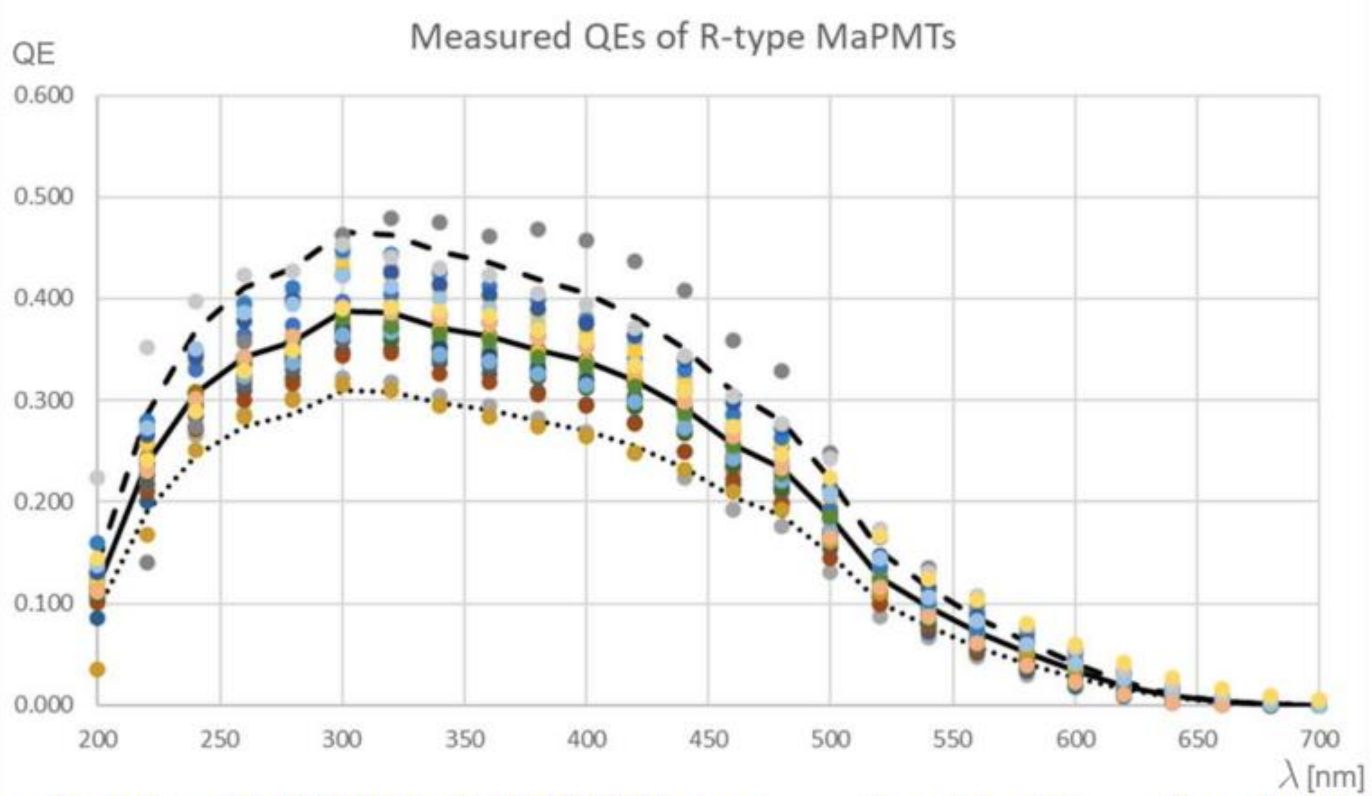
CERN and Imperial College London

on behalf of the LHCb RICH collaboration

RICH 2022,
12-16 September, Edinburgh, UK

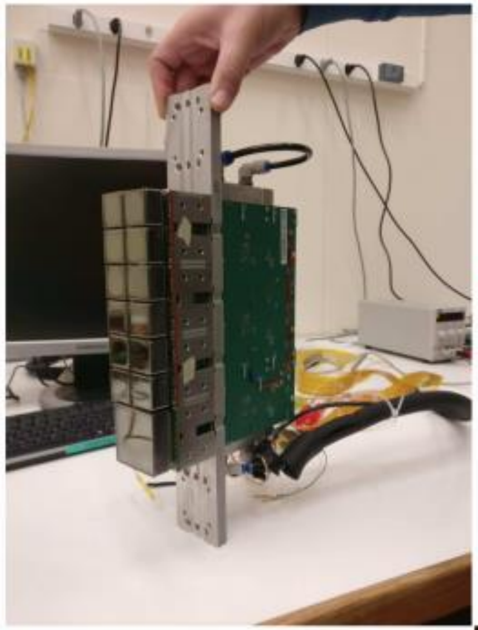
Quantum efficiency

- quantum efficiency measured in a dedicated setup at CERN on a subsample of devices (technical specification from Hamamatsu on the Blue Sensitivity Index)
- UV-glass entrance window: sensitivity to single-photon between 200 and 600 nm
- **ultra bi-alkali photocathodes allow to reach an excellent quantum efficiency of 40% at 300 nm in average!**

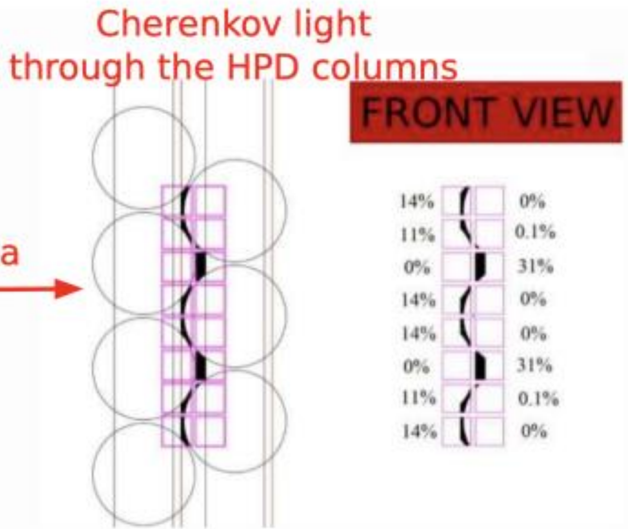


MaPMTs in the LHCb experiment during 2018 operations

Aim: test a photon detection module in a realistic environment

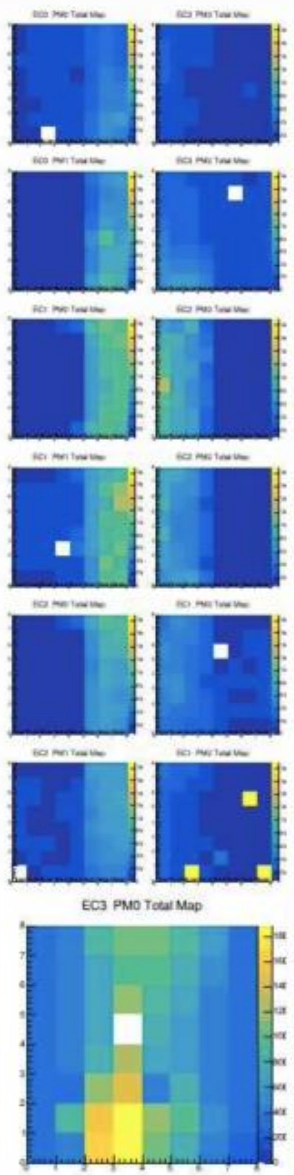


Idea



Installation

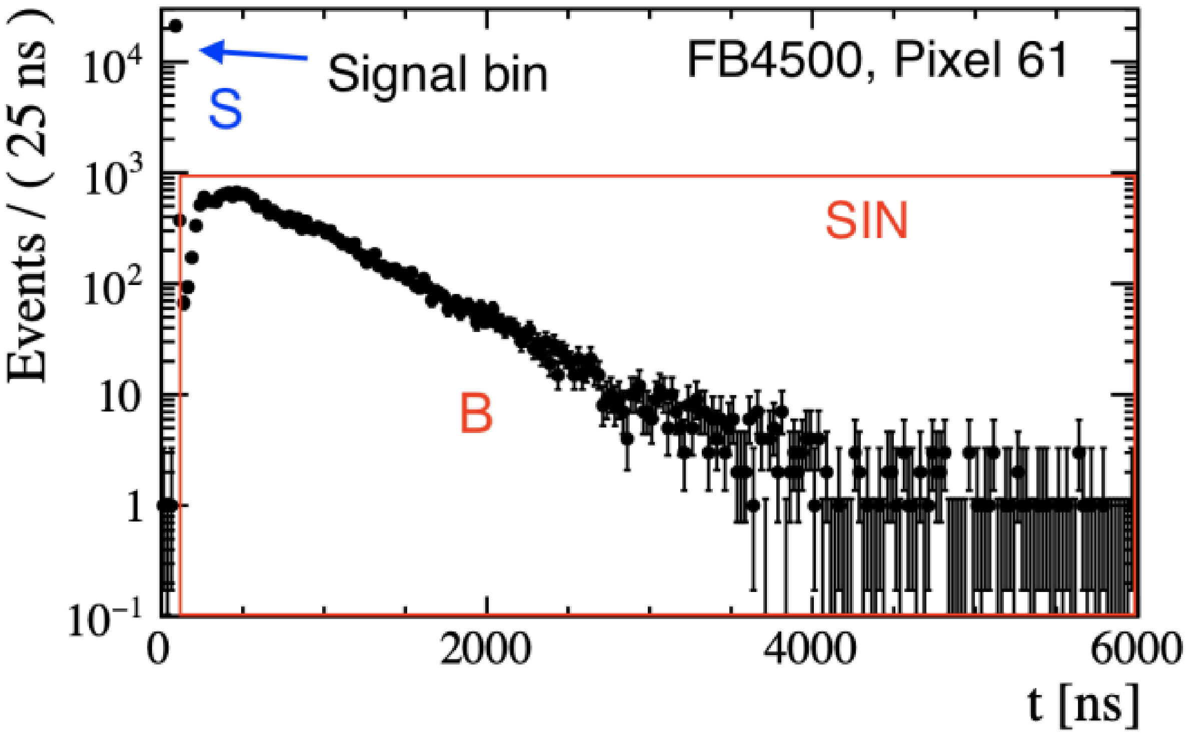
First collisions



Observation of Signal Induced Noise (SIN)

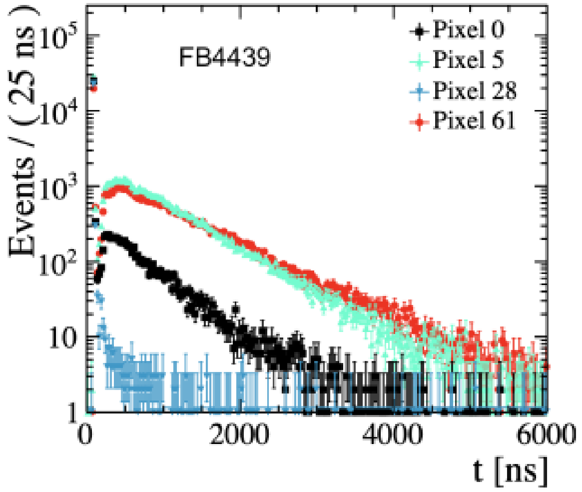
JINST 16 (2021) P11030

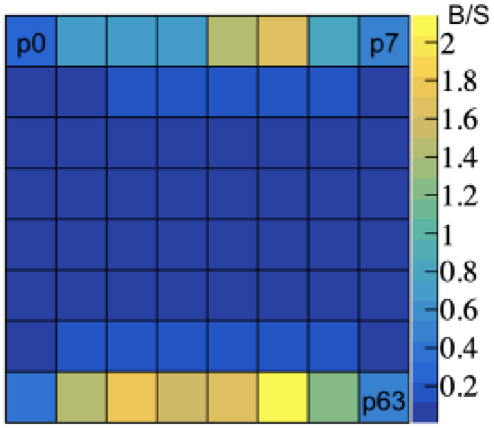
- first data acquired in an LHC collision scheme with isolated bunches (to synchronise the system) and with a 3 μs-wide acquisition window
- detection of **out-of-time hits** in R11265 tubes, delayed with respect to the expected arrival time of Cherenkov photons, indicating an unexpected source of noise
- characterised by the mean number of SIN pulses $\mu_{\mathrm{SIN}} = B/S$



Localisation of SIN and device dependence

JINST 16 (2021) P11030





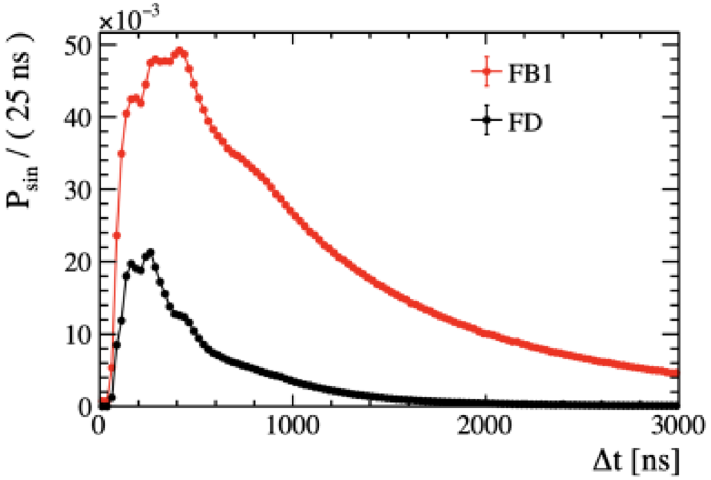
MaPMT	μ^0_{sin}	μ^5_{sin}	μ^{28}_{sin}	μ^{61}_{sin}
FB4439	0.2457 ± 0.0035	1.695 ± 0.013	0.0109 ± 0.0007	2.139 ± 0.018
FB2294	0.0745 ± 0.0012	0.3715 ± 0.0029	0.0076 ± 0.0004	0.491 ± 0.003
FB2312	0.132 ± 0.0017	0.747 ± 0.004	0.0081 ± 0.0004	2.231 ± 0.011
FB4500	0.266 ± 0.004	1.398 ± 0.012	0.0103 ± 0.0007	1.034 ± 0.010

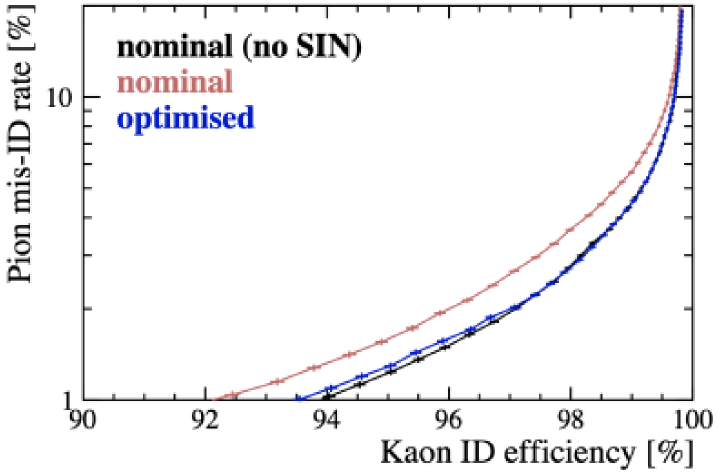
- the localisation is a **general feature of SIN, but with absolute values of μ_{SIN} strongly depending on the device under consideration**
- weak correlation against the pixel gain, increasing at lower high-voltages
- no correlation with other MaPMT properties
- no connection between ageing effects and SIN and no significant changes when testing different voltage dividers

Mitigation strategies

JINST 16 (2021) P11030

- a **new series (FD) of R11265 MaPMTs** has been produced in 2019 by Hamamatsu to reduce the contributions of SIN pulses by means of a change of the internal mechanical design of the tube ⇒ installed in the central region of RICH1
- exploit the strong dependance on the HV to operate at the **lowest possible HV** as a compromise between single-photon detection efficiency and low SIN rate
- exploit the prompt (time spread: $\mathcal{O}$(10 or 100 ps)) arrival time of Cherenkov photons on the photon detector planes to implement of a **6.25 ns time gate at the frontend readout** to increase the signal to noise ratio of a factor four (**see Floris Keizer's** talk)





A novel fast-timing readout chain for LHCb RICH LS3 enhancements and prototype beam tests

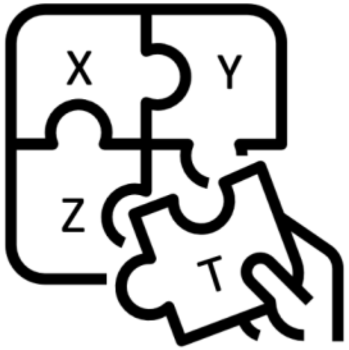
Floris Keizer on behalf of the LHCb RICH collaboration

11th International workshop on Ring Imaging Cherenkov Detectors,
RICH 2022, 12–16 September, Edinburgh

A time-resolved RICH detector

Promptly emitted Cherenkov photons + focusing mirror geometry

= For each track the signal arrives ~ simultaneously



In this presentation, aim to address:

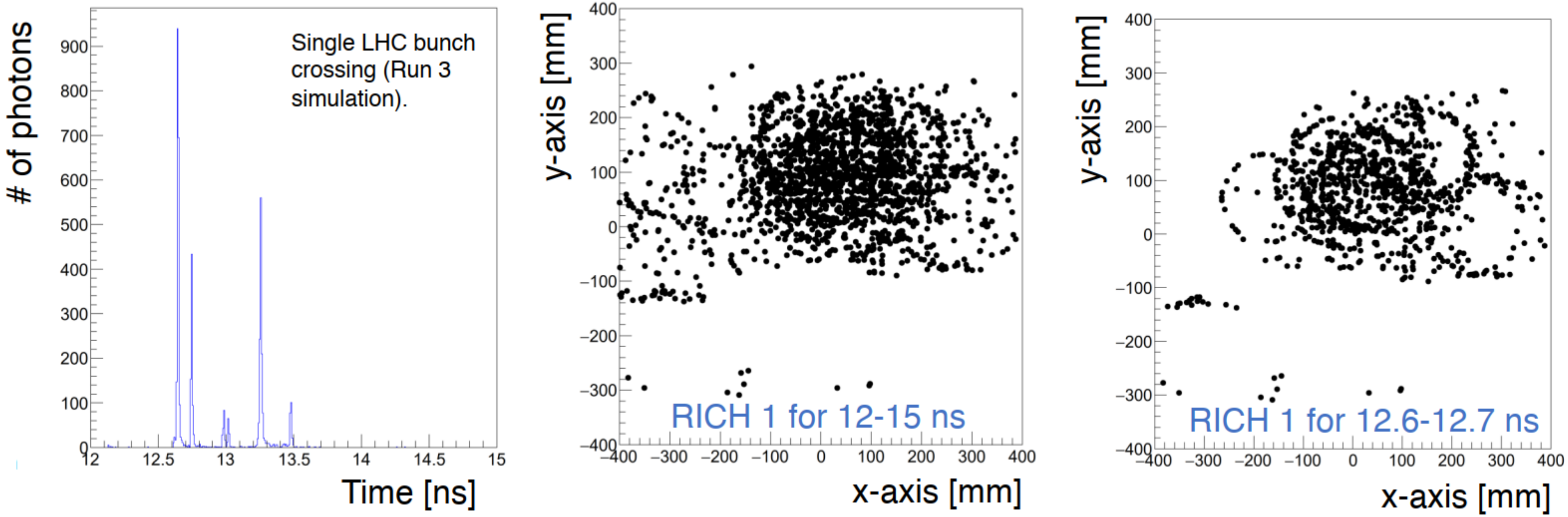
- **How** to make use of this feature to improve the PID.
- **Which** readout technologies and functionality to install during LHC Long Shutdown 3.
- **Prototype** developments and the ongoing test beam campaign.

Hit map for a single LHC bunch crossing (Run 3 simulation)

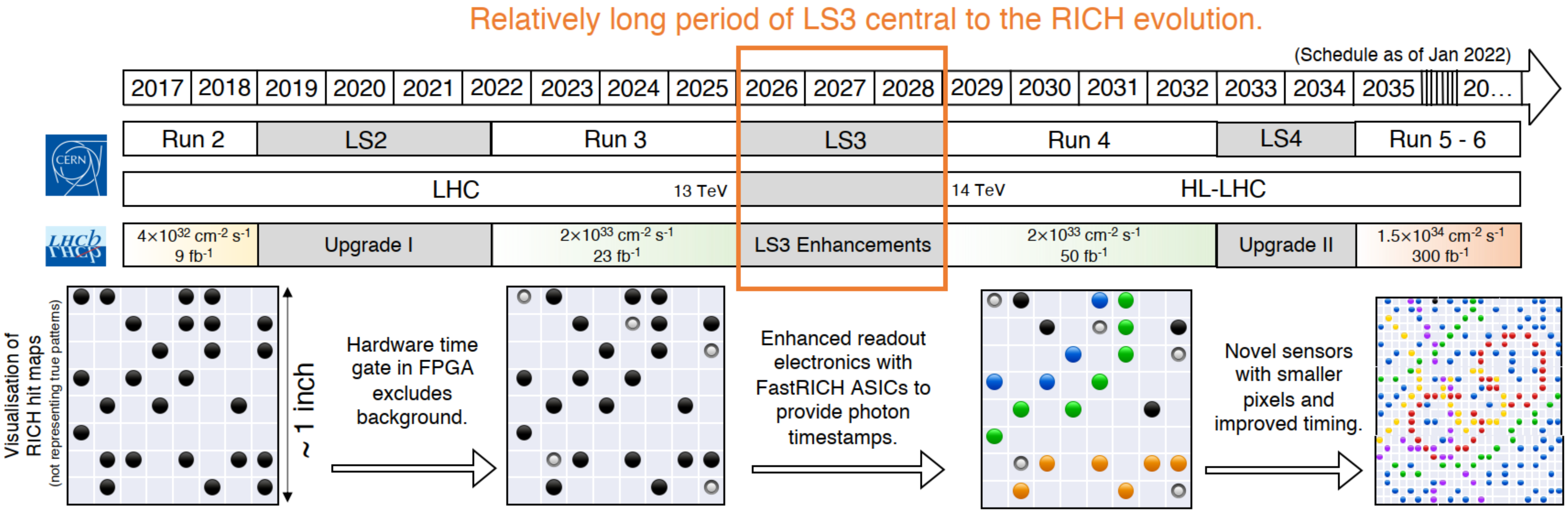
Simulating the Run 3 detector with an **‘ideal’ photon detector** with zero time jitter shows distinct peaks originating from different Primary Vertices (PVs).

- In practice, the photon detector time **resolution blurs** the image in time.
- The RICH reconstruction maximum-likelihood approach works with **tracks and single hits**.

To reduce background and improve PID, need to accurately predict **<u>when</u>** the photons from a given track ought to arrive.



Evolution of the RICH photon detector



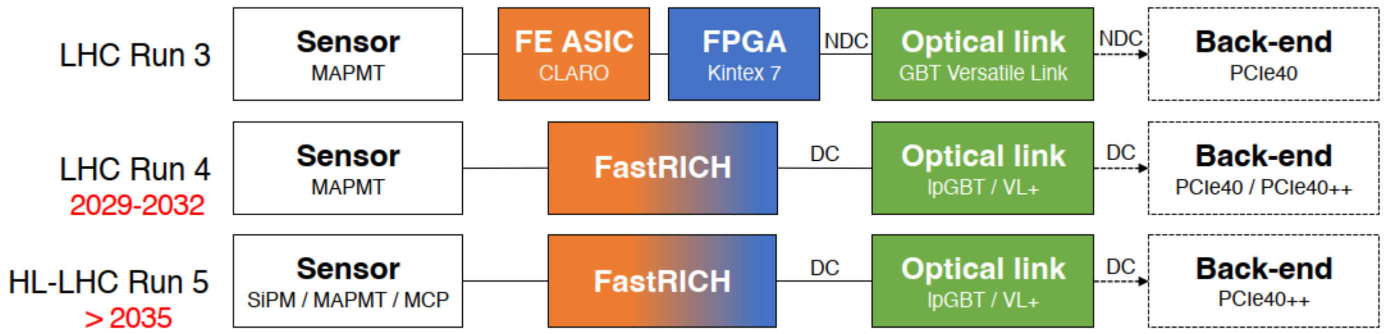
- ➢ LS3 / Run 4 : focus on **FastRICH** readout electronics
  with fast timing and wide input dynamic range.

- ➢ LS4 / Run 5 : focus on **sensor technology**.
  Fast-timing is essential for the luminosity challenge after Upgrade II. [Talk by Stephen Wotton]

Readout chain for LS3 and LS4

The LHCb RICH LS3 enhancements aim to equip the detector with new front-end readout electronics including the **FastRICH ASIC** capable of timestamping photon detector hits with ~ 25 ps time bins.

- ✓ Improve **PID performance during Run 4**.
- ✓ Introduce technologies for high-luminosity operation **ahead of Upgrade II**.
- ✓ Gather valuable experience with novel fast-timing and data compression techniques.



LS3 enhancements:

- Introduce FastRICH with 25 ps bins.
- Change to Data Compressed (DC) format.
- Introduce lpGBT/VL+.
- Small expansion at the back-end.

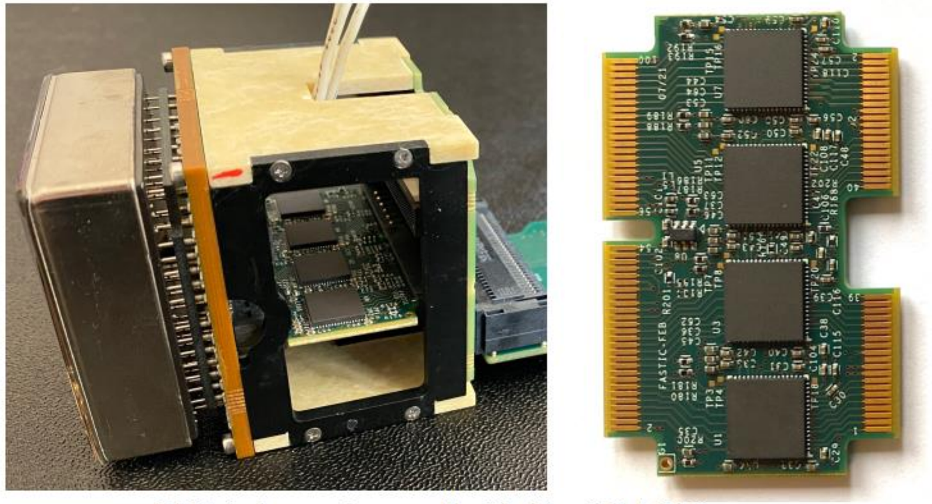
	Sensor	ASIC timewalk	FE time gate	TDC time bin
LHC Run 3	150 ps	< 4 ns	6.25 ns	None
LHC Run 4	150 ps	CFD correction	2 ns	25 ps
HL-LHC Run 5	~ 50 ps	CFD correction	2 ns	25 ps

FastIC and FastRICH ASICs

[Poster by Rafael Ballabriga et al].

The Fast Integrated Circuit (FastIC) is an ASIC designed in 65 nm CMOS technology by the University of Barcelona (ICCUB) and CERN-EP-ESE.

- 8-channel chip with **wide input dynamic range** (5 uA to 25 mA) for pos/neg signal polarities.
- **'Analog' ASIC** with fast discriminator (~ 30 ps jitter).
- **Not** designed to be specifically **radiation hard**.



RICH elementary cell with FastIC ASICs.

Next-generation FastRICH is based on the FastIC and specific requirements of the RICH detector.

- 16-channel chip with **analog and digital** signal processing.
- **Hardware shutter time** (configurable) to limit the timestamp range to ~ 1 to 2 ns.
- **Constant-fraction discrimination** (CFD).
- **Zero-suppressed** output over configurable number of output links to lpGBT.
- TDC with ~ 25 ps time bins and 40 MHz readout rate.
- Radiation hard by design (~ 10^{13} n_{eq}/cm^2 and ~ 5 kGy).
- Compatibility with lpGBT and the architecture of the Run 4 and Run 5 DAQ.

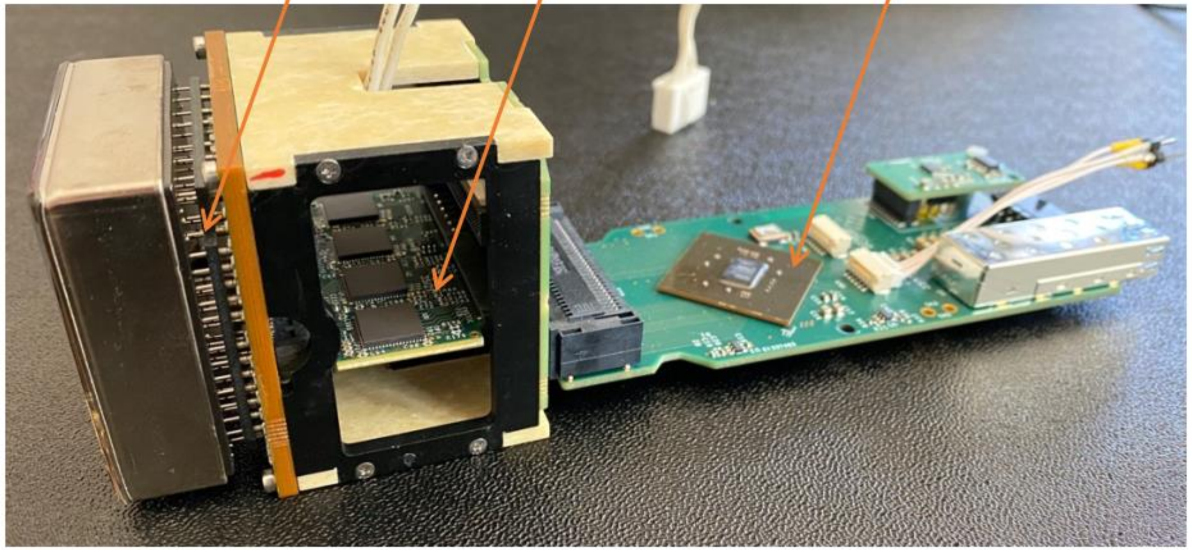
FastRICH design is ongoing (CERN-ICCUB) with the analog parts far advanced.

The prototype fast-timing readout chain

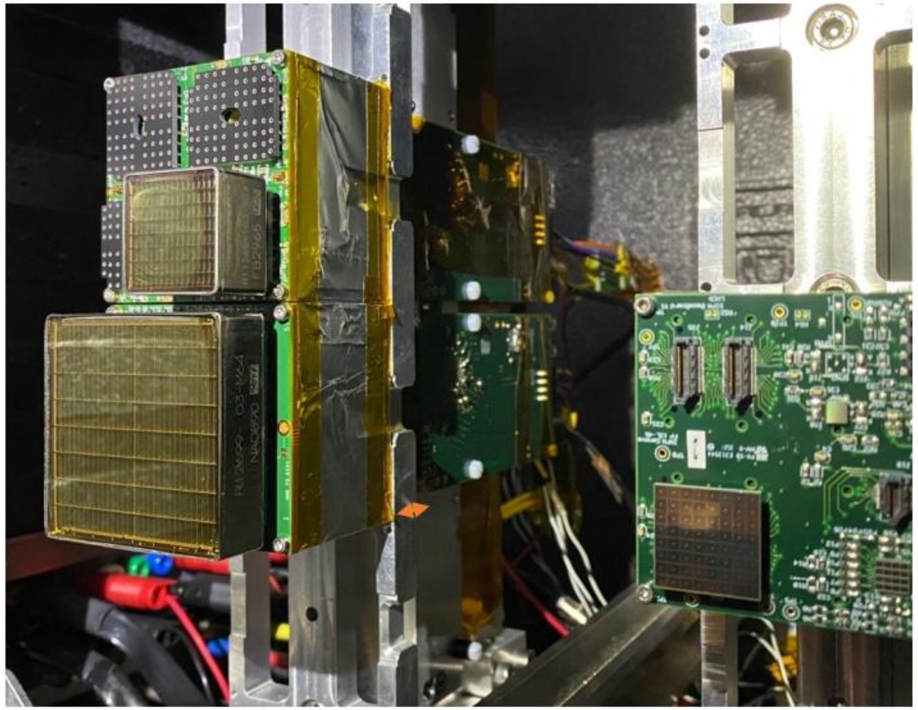
Digital board for the testbeam, containing a Kintex7 **FPGA with 34-channel TDC** with 150 ps time bins
- [Poster by Lucian Cojocariu et al].

FEBs with **FastIC** ASICs.
- Output of fast-timing channel: ToA + **non-linear ToT**.

MAPMT / SiPM baseboard.
- [Talk by Roberta Cardinale]



FastICs coupled to MAPMTs (1 and 2-inch devices, Run 4) and an SiPM array (Run 5 candidate).



LHCb RICH Upgrade II

XI International Workshop on Ring Imaging Cherenkov Detectors,
RICH 2022, 12th-16th September

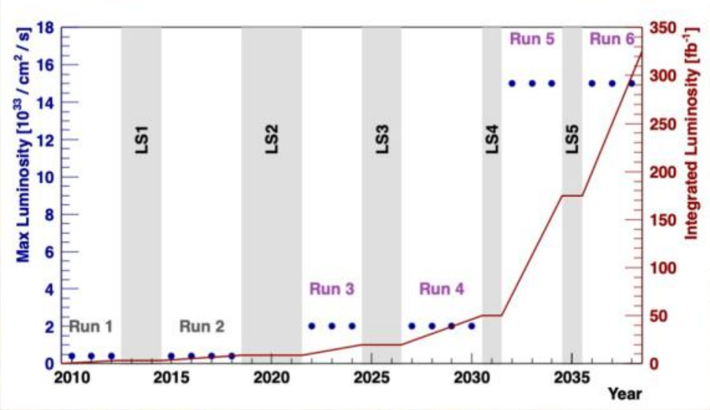
Steve Wotton
University of Cambridge

on behalf of the LHCb RICH collaboration

LHCb & the High Luminosity LHC

From around 2035 the LHCb physics program will benefit from a factor 7.5 increased luminosity compared to Run 4. The full Upgrade program is described in the recently published FTDR.

The RICH detectors will remain a vital element of LHCb and will be essential to exploit new physics opportunities in this new high luminosity era (Run 5 & Run 6).



Luminosity: $1.5 \times 10^{34}\,cm^{-2}\,s^{-1}$
RICH1 n-equivalent dose: $\sim 10^{13}\,cm^{-2}$ (1 MeV equivalent)
Total Ionising Dose: ~ 5 kGy for 350 fb^{-1}

https://cdsweb.cern.ch/record/2776420/

Chromatic Error

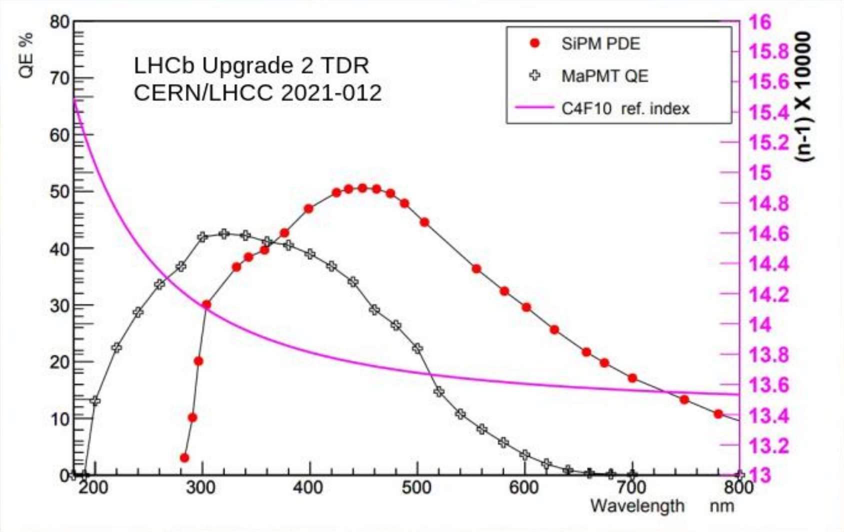
The wavelength dependence of the refractive index gives rise to a chromatic error that can be a significant contribution to the overall error.

This chromatic error is driven by the convolution of:

- Cherenkov photon spectrum;
- spectral sensitivity of the sensor;
- absorption coefficients;
- reflectivity.

There is a clear benefit to operating at longer wavelength where the photon spectrum is flatter.

For example, by using SiPMs as the photon sensor and with optimisation of the optical layout, we estimate a contribution of about 0.1 mrad.



	Current	Future
RICH1 [mrad]	0.52	0.11
RICH2 [mrad]	0.34	0.10

Emission Point Error

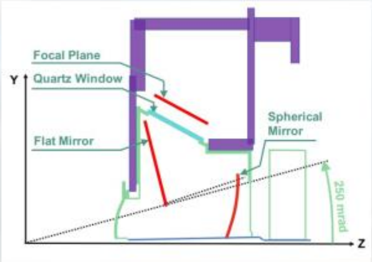
In LHCb, the spherical mirror is tilted to allow the sensor region to be kept outside the detector acceptance.

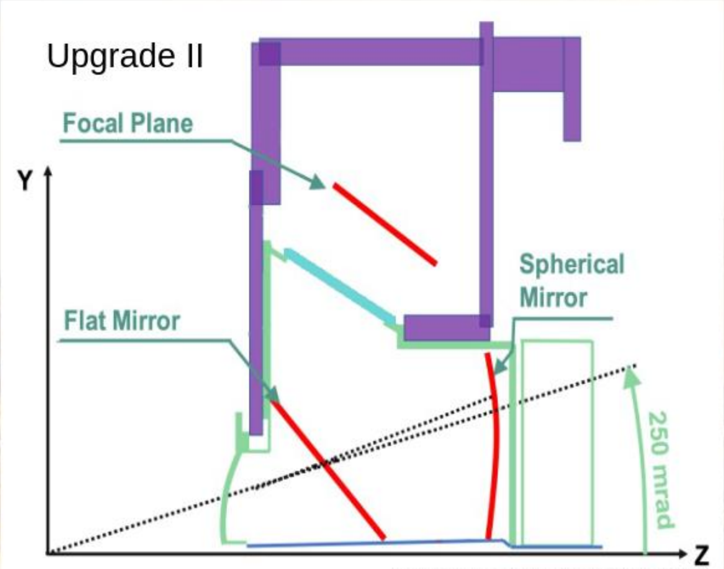
This introduces an error that arises from optical aberrations that make the detected photon position depend on its emission point within the radiator volume.

Closer to ideal geometry can be achieved with smaller mirror tilt:

- Flat mirrors move inside the acceptance
- Must be made of light materials

By making this change we estimate that the emission point error can be reduced to 0.12mrad





https://doi.org/10.17863/CAM.78867

	Current	Future
RICH1 [mrad]	0.36	0.12
RICH2 [mrad]	0.32	0.05

Summary of contributions to angular resolution

Configuration	Overall [mrad]	Chromatic [mrad]	Emission pt [mrad]	Pixel [mrad]	Yield
RICH 1					
MaPMT	0.8	0.52	0.36	0.5	63
SiPM	0.40	0.11	0.36	0.15	47
SiPM+geom	0.22	0.11	0.12	0.15	34
RICH2					
MaPMT	0.50	0.34	0.32	0.22	34
SiPM+geom	0.13	0.10	0.05	0.07	20-30

Significant improvements are possible with respect to the current LHCb RICH configuration.

The table compares expectations for the current MaPMT RICH with a possible future design using SiPMs

Realising these improvements also requires corresponding improvements in tracking performance.

The impact on PID performance

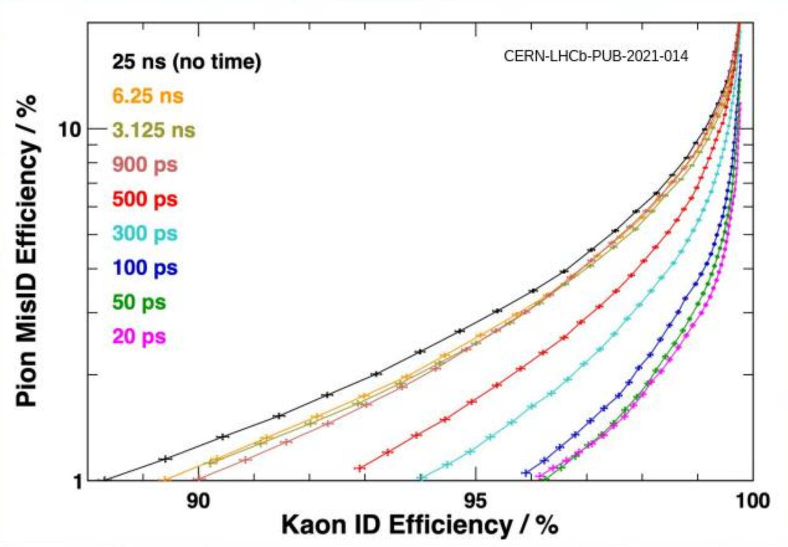
The better the photon time resolution the better the PID performance.

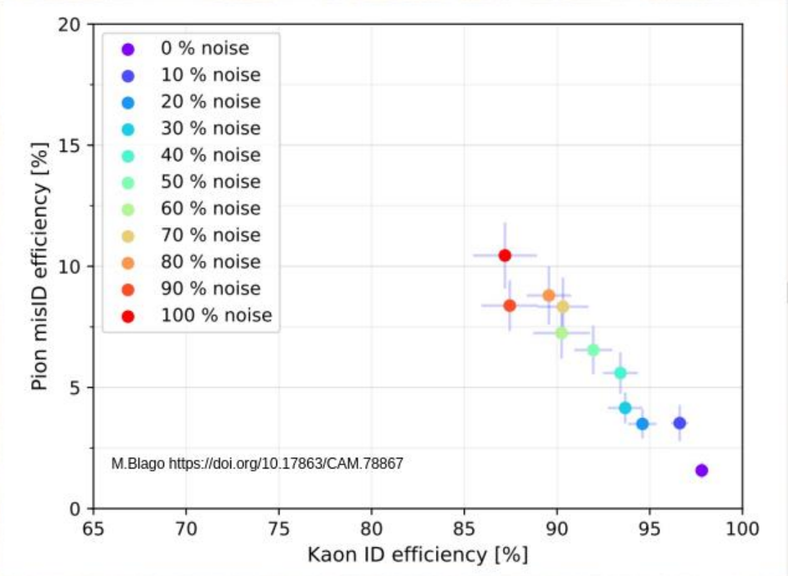
The curves in upper plot are a standard metric that we use in LHCb to characterise PID performance.

- Best performance is furthest to the right and bottom.
- i.e. High Kaon efficiency with low Pion misidentification probability

Effect seen in both conventional (global maximum likelihood) reconstruction and when using CNNs (lower plot).

The benefit arises because better timing allows tighter cuts to remove out-of-time photons.





Summary of Sensor Attributes

	MaPMT	SiPM	MCP/LAPPD
σ_t [ps]	150	60	30
Pixel size [mm]	≥ 2.8	≥ 1	Custom (R&D)
QE	> 35% at 350 nm	> 45% at 460 nm	20-30% at 350 nm
Dark count rate [Hz mm^{-2}]	1	10^5 - 10^7	1
Typical operating voltage	1 kV	< 100 V	1 kV
B-field	< 5 mT	Insensitive	< 2 T
Radiation tolerance	Entrance window	Lattice defects	Entrance window
Gain ageing limits	I_{anode} 100 μA	N/A	10 C cm^{-2}

There is not yet a candidate sensor that is proven to meet all LHCb Upgrade 2 requirements but there are candidates that come very close.

Further R&D is needed.

FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

Status and perspectives of SiPMs

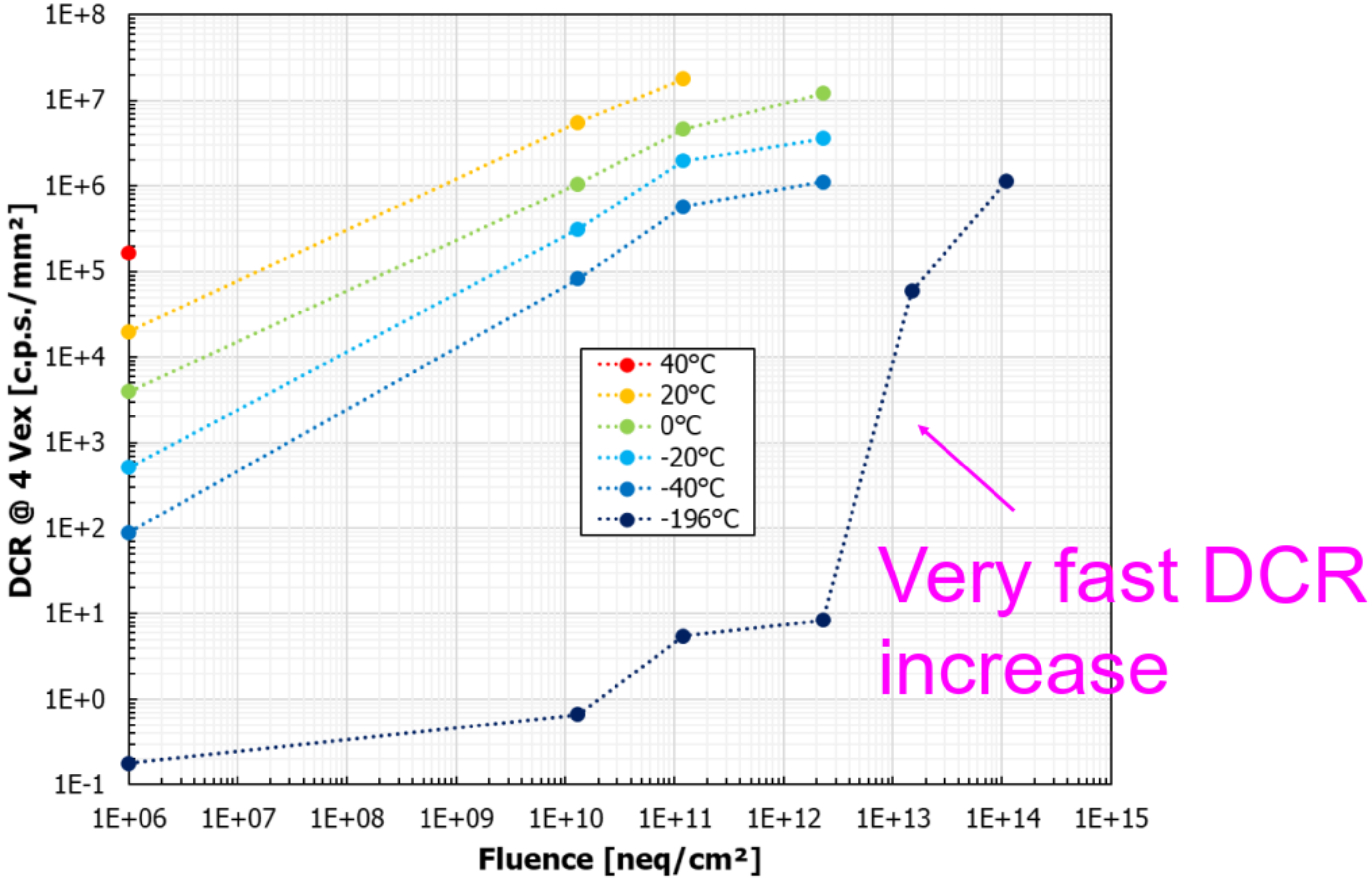
Alberto Gola
Chief Scientist

F. Acerbi, A. Ficorella, S. Merzi, L.P. Monreal, E .Moretti, G. Paternoster, M. Penna, M. Ruzzarin, N. Zorzi

gola@fbk.eu

Test Beam 2 – LNS Catania
DCR at LN after irradiation

PRELIMINARY



- Cooling is *extremely effective in reducing DCR after irradiation up to ~$1 \cdot 10^{12}$ n_{eq}/cm^2*
- Further investigations needed to understand what happens at the higher doses
- Worth checking different / new SiPM structures
- Check possible effect of annealing

Radiation Hardness
Definition + Mitigation strategies

It is rather obvious that *we cannot prevent the bulk damage from increasing the DCR* of the SIPM.

A *possible definition of Rad-Hardened / tolerant SiPM* is a *SiPM that retains its target performance in a given application* even after radiation damage.

→ Depends on the application!

→ *Radiation damage mitigation strategies* (+ annealing)

Use of small cells + Engineering of electric field

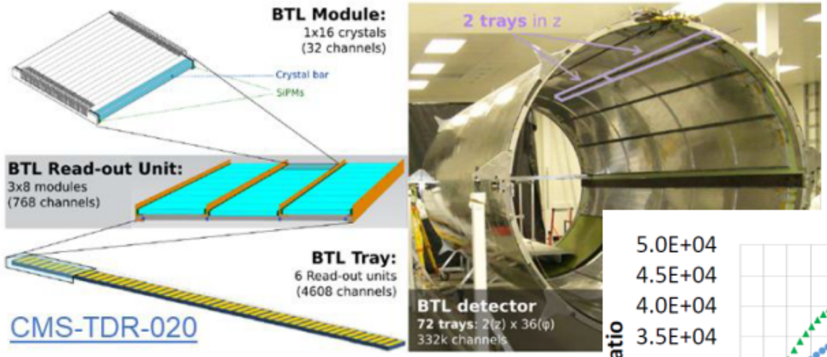
Issue / Hypothesis	Technical Solution	Mitigation
Increase of primary DCR	Electric field engineering	Better DCR temperature coefficient High PDE at lower bias (to reduce field-enhanced effects)
PDE loss due to cells busy triggering dark counts.	Smaller Cells	More cells and faster recharge: lower PDE loss.
Increased power consumption due to higher DCR.	Smaller Cells	Lower gain: less current (for a given DCR).

.. But, at the same time, we need high PDE!

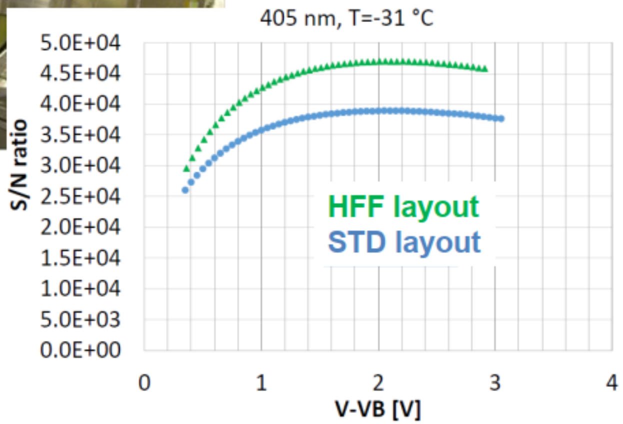
Mitigation of Radiation Damage
NUV-HD-RH SiPMs for CMS-BTL

SiPMs with extreme radiation tolerance are required for the Barrel Timing Layer of the CMS experiment, at CERN: 1.9×10^{14} 1 MeV n_{eq}/cm^2.

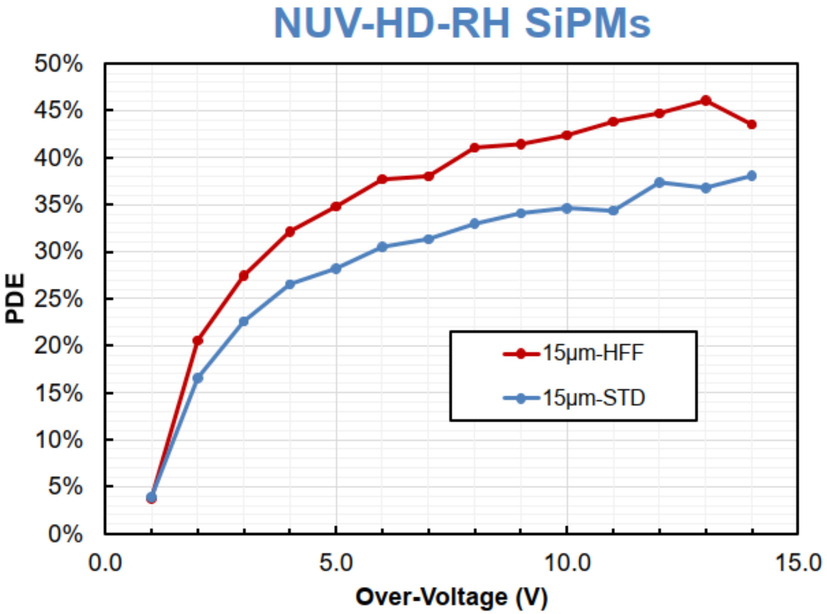
Custom SiPM technology was developed, combining *electric field engineering with small-pitch SiPM technology*, for enhanced radiation hardness.



CMS-TDR-020



FoM measured by from CMS collaboration: A. Heering, Y. Musienko, M. Lucchini et al.)



The advantage of using small cells for radiation hardness is relevant *only if they can still provide very high PDE*