RICH detectors at LHCb

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on behalf of the LHCb RICH collaboration

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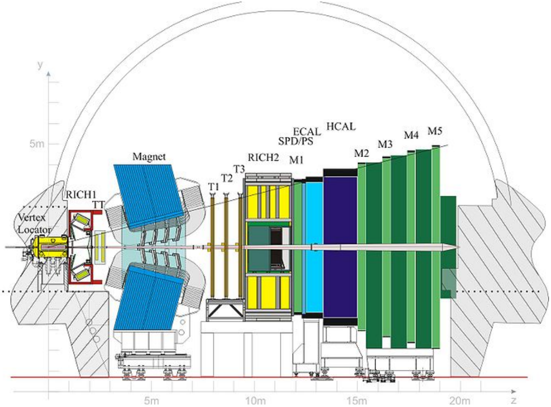
Outline

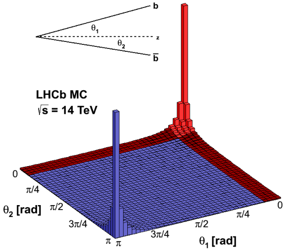
- rationale and challenges of hadron identification at LHC
- the LHCb RICH detectors
- evolutions of the RICH system: past, current and future R&D

The LHCb detector during Run 1 and 2

[JINST 3 (2008) S08005]

- the LHCb detector covers the forward region in the $2 < \eta < 5$ range
- $\sim 25\%$ of the $b\bar{b}$ pairs are produced inside the LHCb acceptance
- LHCb ran with an instantaneuos luminosity of $\mathcal{L} = 4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, pile-up ~ 1
- **CPV, rare *b*-hadron decays, spectroscopy, EW, pQCD, heavy ions**

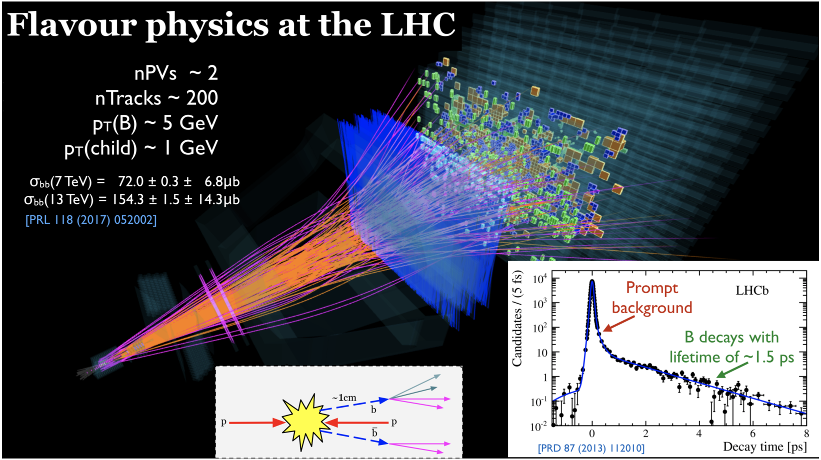




$\sim$ 60k $b\bar{b}/s$ and $\sim$ 1M $c\bar{c}/s$ in acceptance at 13 TeV

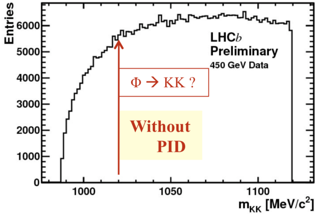
A typical *b*-event in LHCb during Run 1 and 2

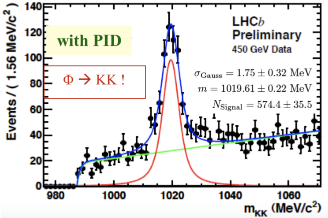
Hundreds of photons, $\pi^0 \to \gamma\gamma$ and $\pi^\pm$ are produced in average at the primary vertex (PV) in the full solid angle; tens of K_L^0 and $K^\pm$ are produced as well
$\Rightarrow$ **Large combinatorial background emerging from hadronisation, initial and final state radiation, and from the underlying event**



Why hadron identification?

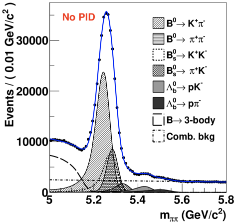
Reduce the combinatorial background

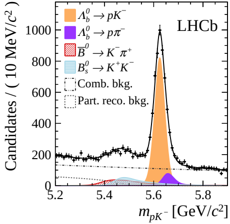




Input to flavour tagging (through the detection of the $b \to c \to s$ decay chain) and to the second level of software trigger (HLT2)

Distinguish final states of identical topology



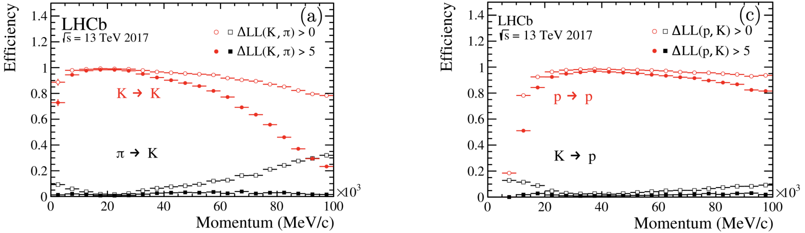


$\sigma(m_{hh}) \sim 20$ MeV

[Phys. Lett. B 787 (2018) 124-133]

LHCb requirements and hadron identification techniques

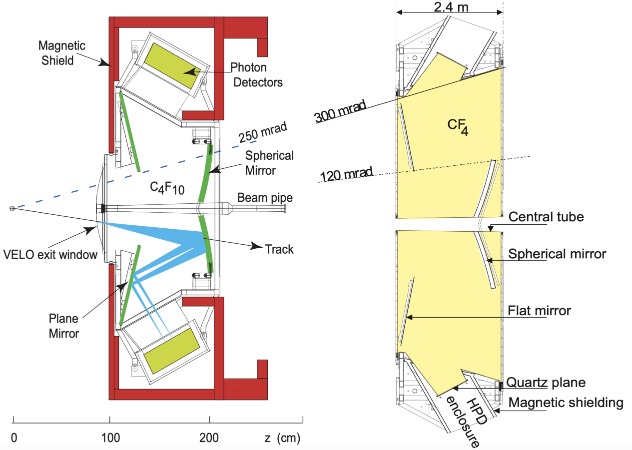
- p, $\bar{p}$, $K^{\pm}$ and $\pi^{\pm}$ can be distinguished by determining their mass: $p = m\gamma\beta \Rightarrow$ equivalent to measure their velocity β since the momentum is known from the tracking system
- different mechanisms can in principle be exploited to measure β: difference in the time of flight, energy loss via ionisation, transition radiation and Cherenkov radiation
- need to adopt a technique to allow precise (at a per-mille relative precision level) flavour physics measurements, in a harsh hadronic environment with large backgrounds, studying decays involving final state particles of momenta up to 100 GeV
- **Ring-Imaging Cherenkov (RICH) detectors with gas radiators are suitable to measure β in a wide range of momenta**



[JINST 17 (2022) 07, P07013]

LHCb RICH detectors

- RICH1 (C_4F_{10}): $3\,\mathrm{GeV}$–$40\,\mathrm{GeV}$, 25–$300\,\mathrm{mrad}$, $2 \times 3 \times 1\,\mathrm{m}^3$
- RICH2 (CF_4): $30\,\mathrm{GeV}$–$100\,\mathrm{GeV}$, 15–$120\,\mathrm{mrad}$, $100\,\mathrm{m}^3$

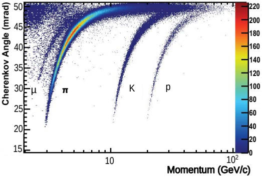


The main ingredients driving the performance are **radiators**, **optics and mirrors**, **photon detectors** and **electronics**: any evolution of a RICH system passes through R&D on at least one of these aspects!

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%)

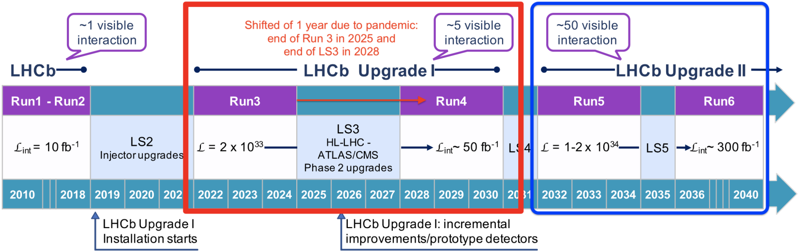
Excellent performance in Run 1 and 2 thanks to an overall single photon Cherenkov angle resolution $\sigma_c^{\text{RICH1}} \sim 1.7$ mrad and $\sigma_c^{\text{RICH2}} \sim 0.6$ mrad

LHCb upgrades

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	49 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	—	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	17×10^{-5}	—	3.0×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	13×10^{-5}	[38]	4.3×10^{-5}	—	1.0×10^{-5}
Δx ($D^0 \to K_{\mathrm{S}}^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	71%	[40, 41]	34%	—	10%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.10	[61]	0.031	0.021	0.008
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	—	0.002

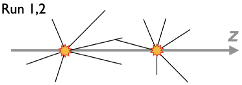
LHCb upgrades

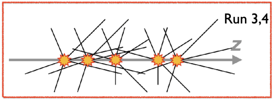
- in order to achieve the required statistical uncertainties, the instantaneous luminosity (*i.e.* the pile-up) needs to be increased
- starting from Run 3 we have a shift of paradigm, removing the hardware level trigger and running the LHCb experiment with a triggerless readout system at 40 MHz

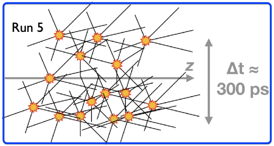


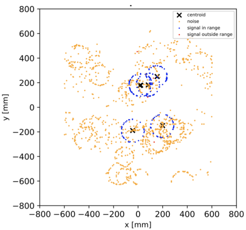
Requirements for the evolution of the LHCb RICH system

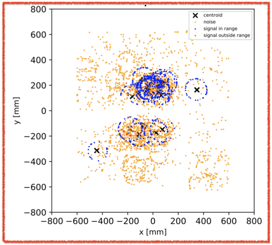
Keep the excellent Run 1 and 2 performance while increasing the instantaneous luminosity up to a pile-up of $\sim$ 40!

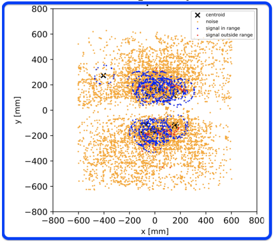










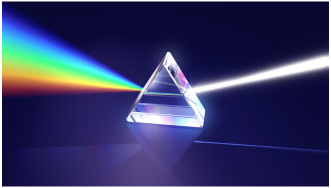


RICH1 rings with 1 PV | RICH1 rings with 5 PVs | RICH1 rings with 10 PVs

Introduction of timing concept more and more relevant! (rings in blue matching search window for the input tracks)

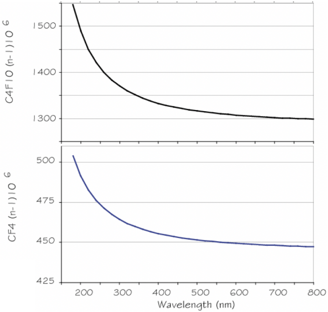
https://doi.org/10.17863/CAM.78867

Radiators



LHCb RICH radiators

- fluorocarbon gases were chosen because of the relatively low chromatic dispersion
- C_4F_{10}: $n = 1.0014$ at $400\,\mathrm{nm}$, gas vessel: $2 \times 3 \times 1\,\mathrm{m}^3$
- CF_4: $n = 1.0005$ at $400\,\mathrm{nm}$, gas vessel: $100\,\mathrm{m}^3$

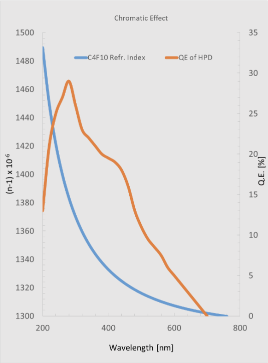


Aerogel ($n = 1.03$ at $540\,\mathrm{nm}$) was used for $p < 10\,\mathrm{GeV}$: not optimal discrimination due to lower than expected signal to noise ratio (Rayleigh scattering producing backgrounds), absorption of C_4F_{10} degrading the overall RICH1 performance $\Rightarrow$ **abandoned after Run 1**

Improvements related to radiators

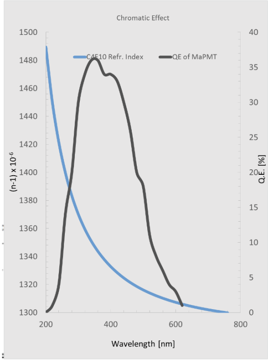
The chromatic error depends on the convolution between the dispersion and the photon detector quantum efficiency (QE)

Run 1 and 2



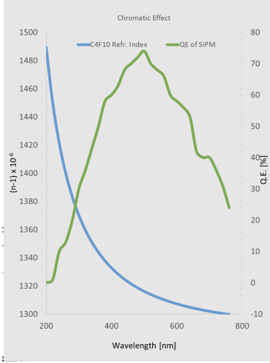
$\sigma^{\text{RICH1}}_{\text{chromatic}} = 0.84$ mrad
$\sigma^{\text{RICH2}}_{\text{chromatic}} = 0.48$ mrad

Run 3 and 4



$\sigma^{\text{RICH1}}_{\text{chromatic}} = 0.52$ mrad
$\sigma^{\text{RICH2}}_{\text{chromatic}} = 0.34$ mrad

Run 5 candidate



$\sigma^{\text{RICH1}}_{\text{chromatic}} = 0.11$ mrad
$\sigma^{\text{RICH2}}_{\text{chromatic}} = 0.10$ mrad

Radiators R&D

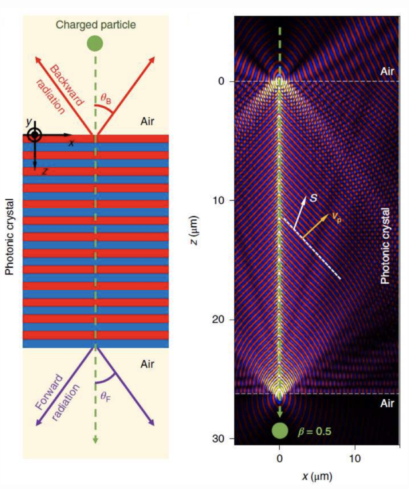
- fluorocarbon gases have large Global Warming Potential
  $GWP(C_4F_{10}) = 8500\ CO_2$, $GWP(CF_4) = 7000\ CO_2$
  G. Hallewell's talk at RICH2022

- could replace CF_4 (n=1.0005) with CO_2 (n=1.0004): photon yield ($\propto 1 - 1/n^2$) marginally lower, but worse chromaticity (from 0.34 to 0.53 mrad for MaPMT QE)

- intense R&D and studies at CERN to find alternatives to C_4F_{10}, matching its refractive index and allowing operations in the LHCb environment

Radiators R&D

- R&D on aerogel with improved clarity to extend the coverage to low momenta at hadron colliders
- very interesting early stages R&D on metamaterials: layers of dielectrics resulting in an effective and tunable refractive index
- possibility to tune emission angle as well to completely rethink the geometry of RICH detectors and make them compact



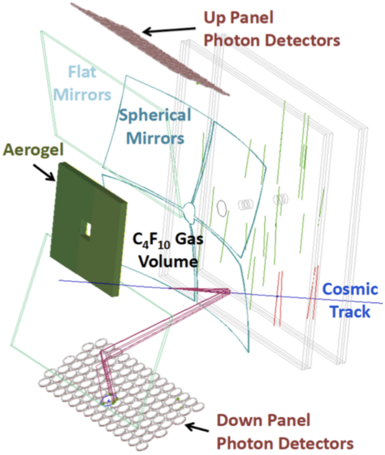
Nature Physics volume 14, pages 816-821 (2018)

Optical system

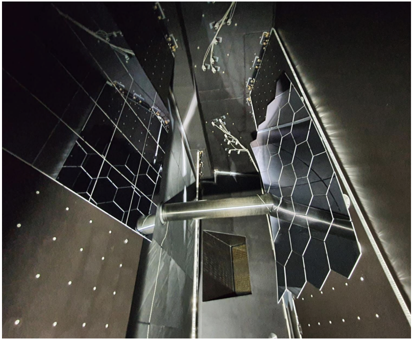
LHCb RICH mirrors

- high reflectivity ($>$ 90% in the wavelengths of interest) to maximise the number of Cherenkov photons in the photon detector planes
- carbon fibre reinforced polymer substrates are used in RICH1 spherical mirrors to **minimise the material budget in the acceptance**: $\sim 1\%\ X_0$

RICH1

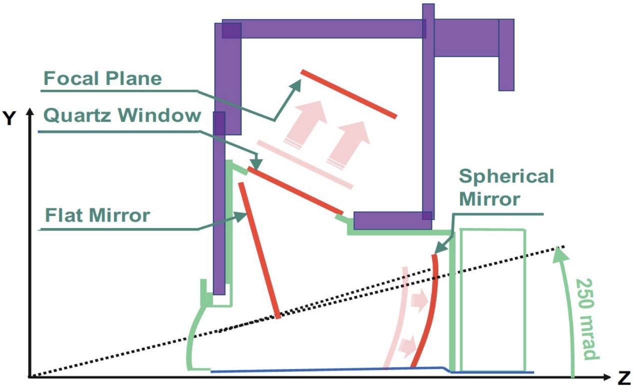


RICH2



26x2 (20x2) spherical (flat) mirror segments

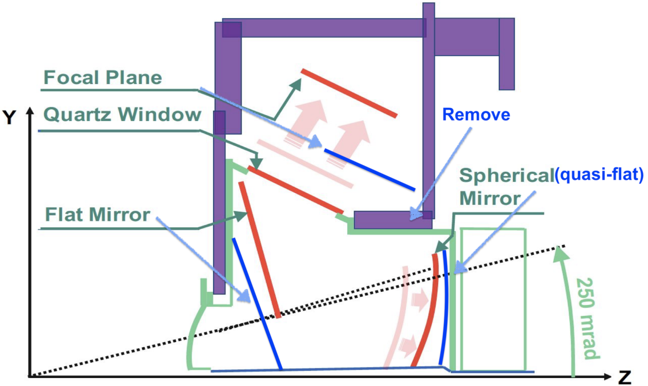
Evolution of RICH1 optical system in the current Run 3 system



- curvature radius R increased of a factor $\sim \sqrt{2} \Rightarrow$ peak occupancy $\sim$ halved, reduced $\sigma_{\text{pixel}} \propto 1/R$
- emission point error from 0.61 mrad to 0.36 mrad
- extend overall gas volume of 100 mm $\Rightarrow +14\%$ Cherenkov photons

New mirrors, gas enclosure, quartz window

Possible further evolutions of the optical system

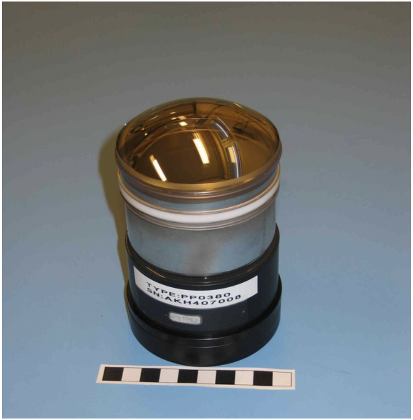


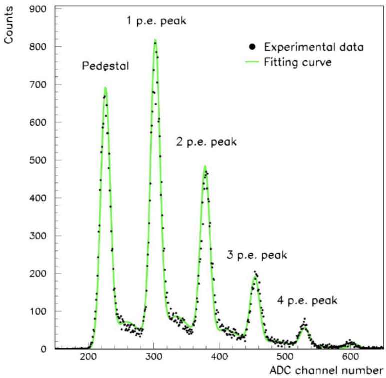
- move the flat mirror in the acceptance: **requires R&D on carbon fibre flat mirrors, light-weight supports and with good resistance to radiation**
- emission point error can go down to ~ 0.1 mrad in RICH1 and from 0.32 to 0.05 mrad in RICH2
- further increase in spherical mirror curvature radius $\Rightarrow$ reduced occupancy and decreased pixel error

Photon detectors, electronics and DAQ

Photon detectors during Run 1 and 2

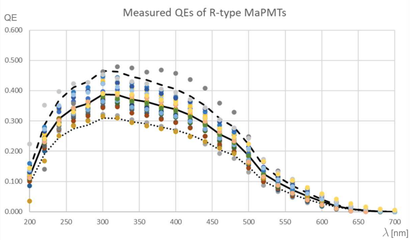
- Cherenkov radiation focused on Hybrid Photon Detectors (HPDs) plane
- HPDs equipped with embedded frontend electronics working at $1\,\mathrm{MHz}$ readout
- photoelectron accelerated by a $-20\,\mathrm{kV}$ potential towards a silicon matrix of 1024 pixels
- band gap in Si is $3.6\,\mathrm{eV} \Rightarrow\sim 5000$ *e*-*h* pairs/photoelectron

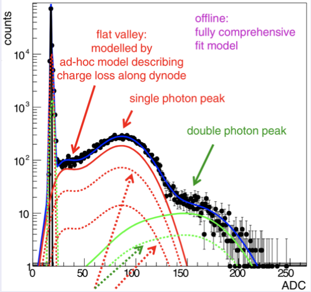




Photon detectors in Run 3

- removing the hardware level trigger in LHCb means that we have to readout the RICH detectors at 40 MHz $\Rightarrow$ replace HPDs with Hamamatsu Multi-anode Photo-Multiplier Tubes with external readout
- R11265 and R12699 types, commercial candidates chosen given the excellent active area ($\sim$ 80%), good spatial granularity $\mathcal{O}(10\text{mm}^2)$, and excellent response to detection rates up to $\mathcal{O}(100\ \text{MHz/cm}^2)$
- **impressive quantum efficiency of 40% at 300 nm in average!**





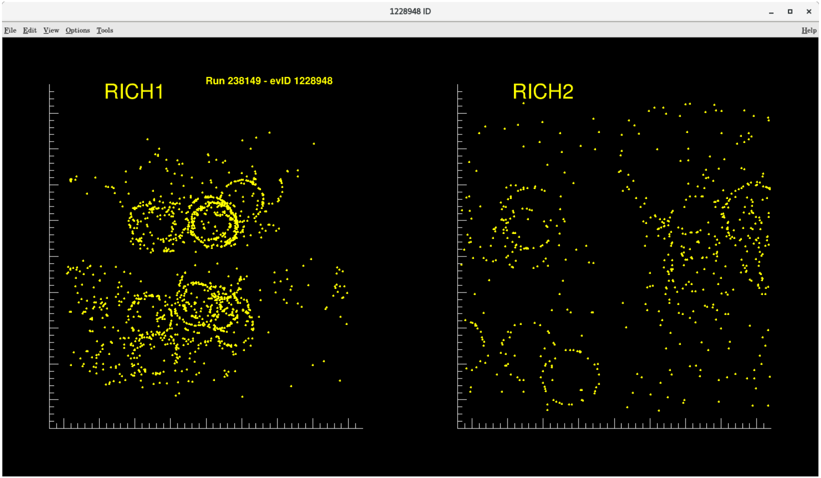
Signal + Contribution needed to describe right side of pedestal

Photon detection planes in Run 3

RICH1

RICH2

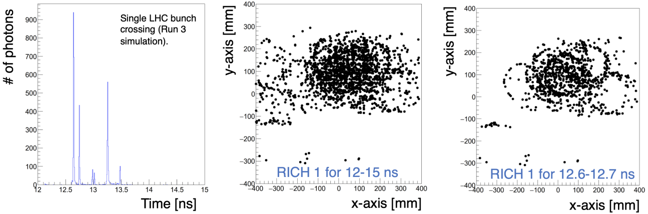
First rings in Run 3 at 13.6 TeV



Photon detectors and electronics for further upgrades

- in order to run with a further increase in the pile-up (from 5 to 40), the reduction of the pixel size and the introduction of the time coordinate is necessary: fast ($\mathcal{O}(100)$ ps) photon detectors and fast electronics
- detection rates up to $\mathcal{O}(1\ \mathrm{GHz/cm^2})$, corresponding to a neutron fluence (10y) of $6 \cdot 10^{13}\ \mathrm{n_{eq}\ cm^{-2}}$
- can exploit the prompt production of Cherenkov radiation

doi:10.17863/CAM.45822

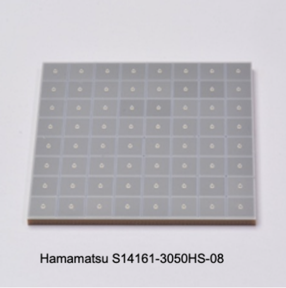


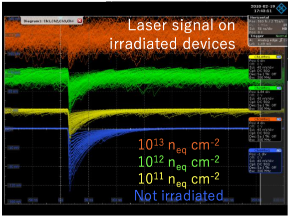
$$\sigma_t^2 = \sigma_{\mathrm{det}}^2 + \sigma_{\mathrm{elec}}^2 + \sigma_{\mathrm{clk}}^2$$

- need for very precise clock distribution across tens of km from LHC machine and accurate length+quality of data distribution optical fibres
- need for operationally feasible calibration strategies to achieve a **stable** sub-ns time alignment across an area of $\sim 4\ \mathrm{m}^2$

Candidate photon detectors for future upgrades: SiPMs

- SiPMs have several advantages: extremely fine granularity, resiliance to magnetic fields, high photon detection efficiency, green-enhanced quantum efficiency, good timing
- **but important drawbacks**: dark count rates after irradiation at 10^{13} $\mathrm{n_{eq}}$ cm^{-2} ($\sim 1\mathrm{y} = 6e+6$ s of data taking) are larger than expected signal rate
- could be compensated by annealing and cryogenics operations: but very challenging from the operational point of view and requiring R&D on a possible interface between the photon detectors environment and the gas radiator envelope

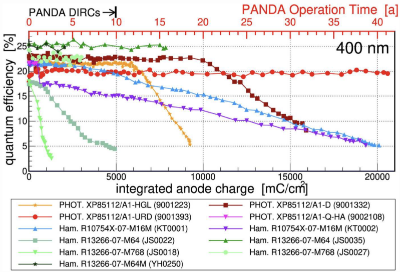




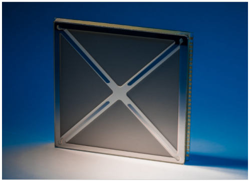
Candidate photon detectors for future upgrades: MCP-based

Extremely good time resolution < 100 ps, custom pixelisation tailored for individual applications, **but important drawbacks** related to lifetime and rate capability: R&D ongoing

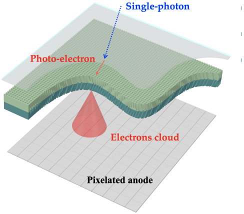
Conventional MCPs



Large Area Picosecond PhotoDetector



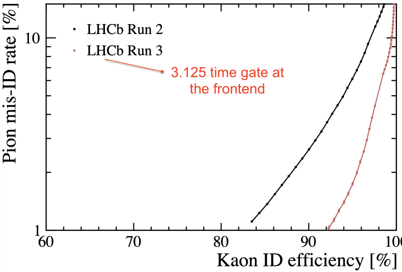
MCP-HPD **[JINST 13 C12005 2018]**

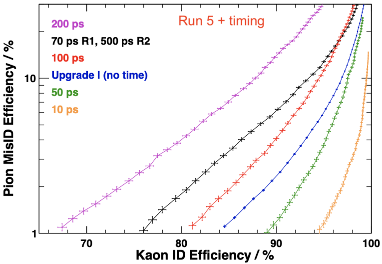


Performances in a nutshell

[CERN-LHCC-2021-012]

Radiator	C_4F_{10}			CF_4		
Detector version	RICH1 HPD	RICH1 MaPMT	RICH1 SiPM+optics	RICH2 HPD	RICH2 MaPMT	RICH2 SiPM+optics
Photon yield	30	60	40-30	18	30	30-20
Single photon errors [mrad]						
Chromatic	0.84	0.52	0.11	0.48	0.34	0.10
Pixel	0.99	0.50	0.15	0.35	0.22	0.07
Emission point	0.61	0.36	0.12	0.32	0.32	0.05
Overall	1.66	0.81	0.22	0.62	0.52	0.13





Conclusions

- the LHCb RICH detectors have been upgraded to keep the excellent Run 1 and 2 performance with a five-fold increase in luminosity, a first introduction of the timing concept and with improvements in the overall Chrenkov angle resolution: **now operational**
- a first enhancement of the RICH system is foreseen between Run 3 and Run 4 with fast frontend electronics **F. Keizer talk at RICH2022**
- R&D ongoing on optics, radiators, photon detectors, fast electronics, mechanics to achieve the **ultimate performance of a RICH detector in a hadronic enviroment**, to allow operations at the High-Lumi LHC with a pile-up in LHCb of 40 interactions per bunch crossing