Hadronic PID with RICH at LHCb Upgrades

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on behalf of the LHCb RICH group

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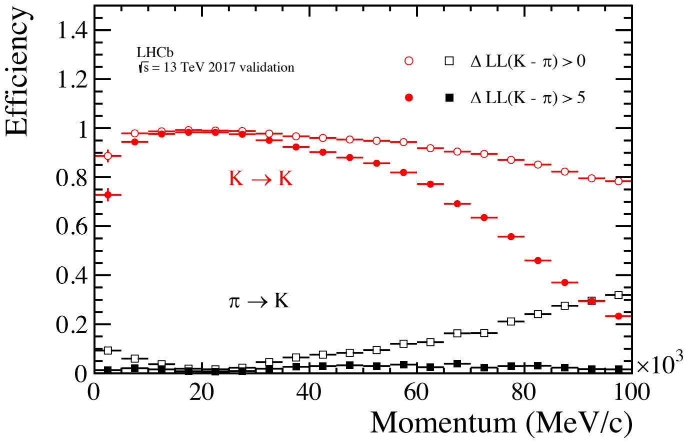
Outline

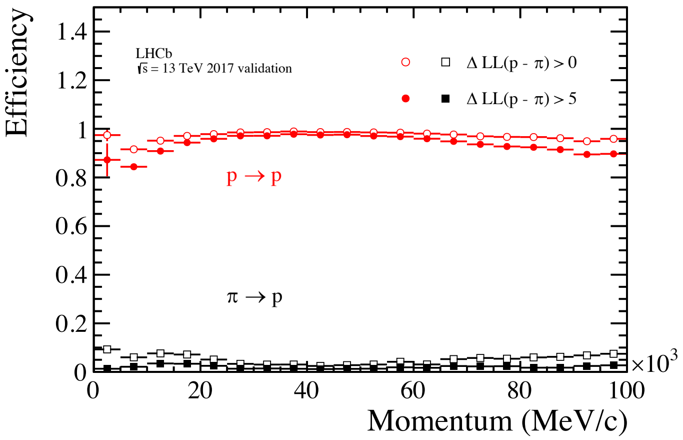
The Ring Imaging Cherenkov (RICH) detectors provide charged hadron identification to the LHCb experiment

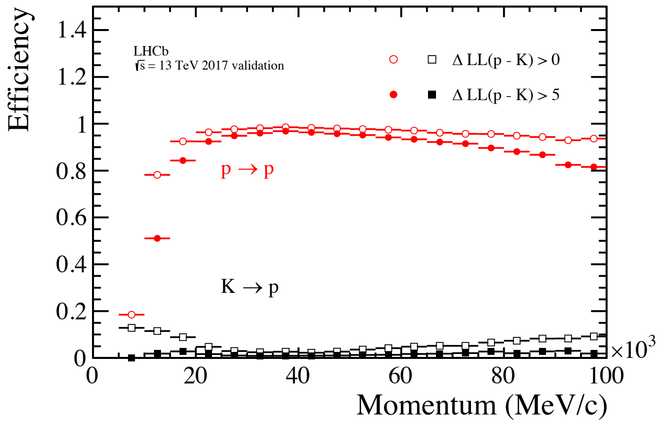
- Impact of hadron identification on LHCb physics
- Design, operations and performance of Upgrade I detectors (2022->2033)
- Evolution of the RICH system for the LHCb Upgrade II (2036->2041?)

Hadron identification with RICH detectors

- Charged hadrons (pions, kaons and protons) identification in a **wide range of momenta between approximately 3 and 100 GeV** (up to ~ 150 GeV for protons)
  - Distinguish final states of otherwise identical topology: : suppress leading order decay modes and efficiently select Cabibbo suppressed decays to improve the precision of rare decay and CP violation studies
  - Powerful combinatorial background rejection (large majority of tracks produced at the LHC are pions) used by all LHCb analyses
- First generation of the LHCb RICH detectors operated in Run 1 and 2 with excellent performance [JINST 17 (2022) 07, P07013]

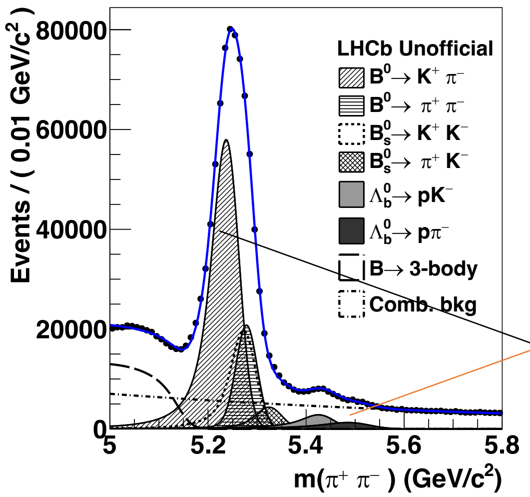




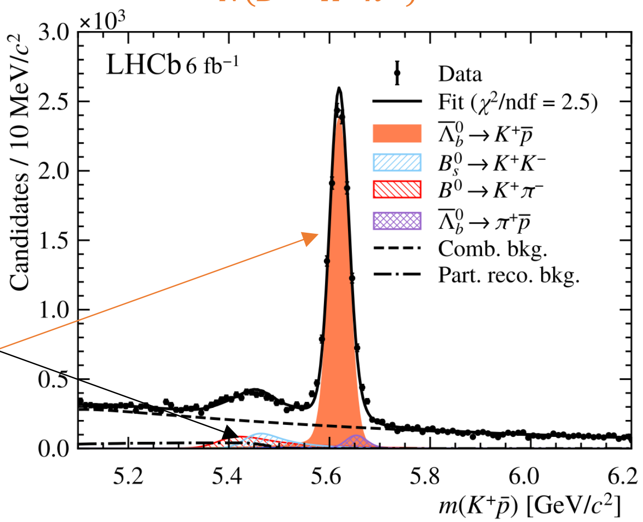


Impact of hadron identification on LHCb physics

$\frac{N(\Lambda_b^0 \to pK^-)}{N(B^0 \to K^+\pi^-)} \sim 1/15$

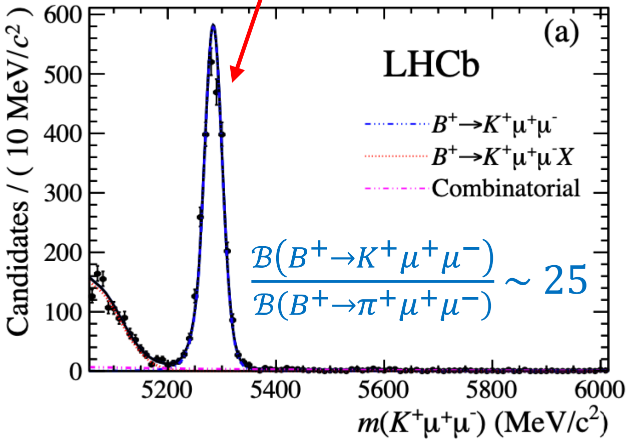


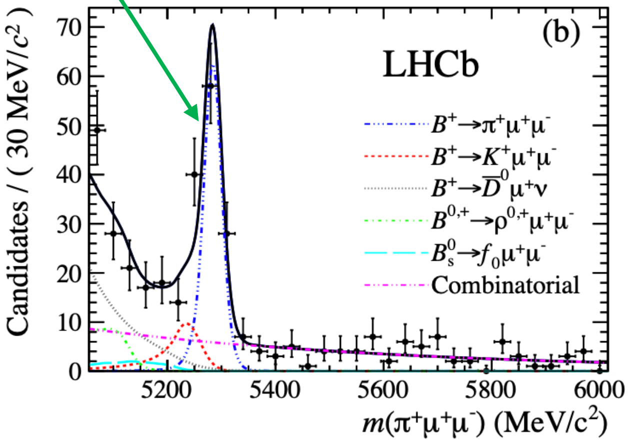
$\frac{N(\Lambda_b^0 \to pK^-)}{N(B^0 \to K^+\pi^-)} \sim 100$



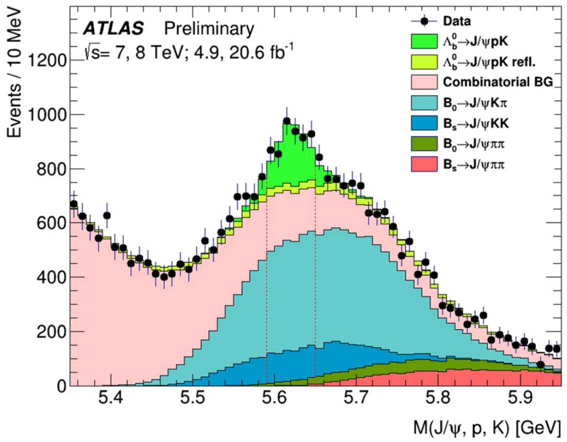
Dominant kaon mode suppressed by factor 80 while retaining 80% of pion candidates

$\frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)} \sim 25$

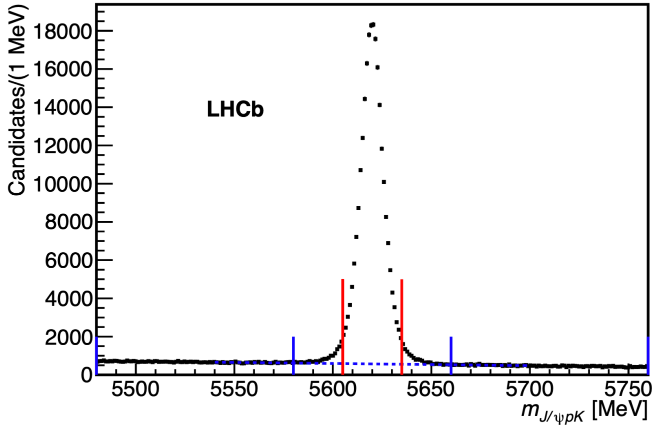




Without hadron ID

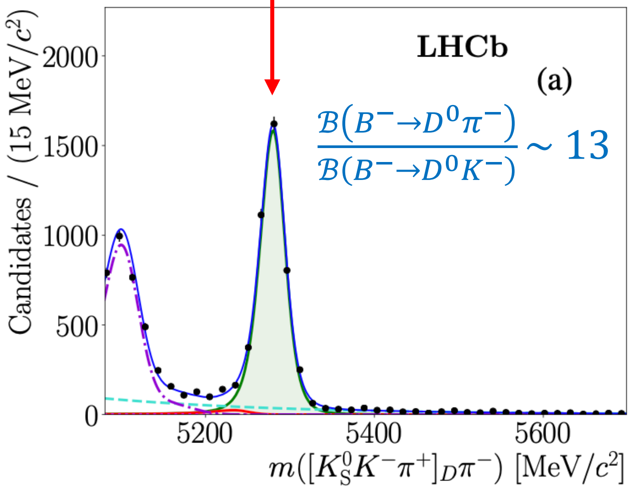


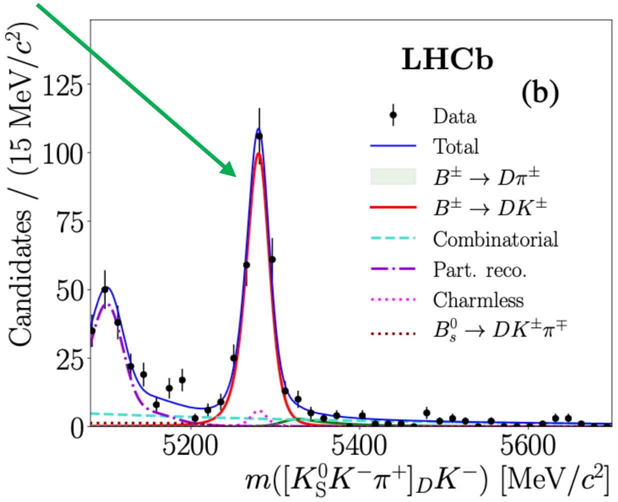
With hadron ID



Dominant pion mode suppressed to negligible levels while retaining 70% of kaon candidates

$\frac{\mathcal{B}(B^- \to D^0\pi^-)}{\mathcal{B}(B^- \to D^0K^-)} \sim 13$





How to get there

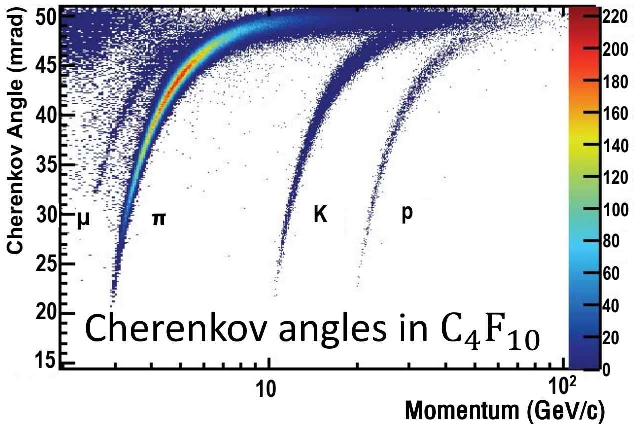
For a single track, mass hypothesis separated at

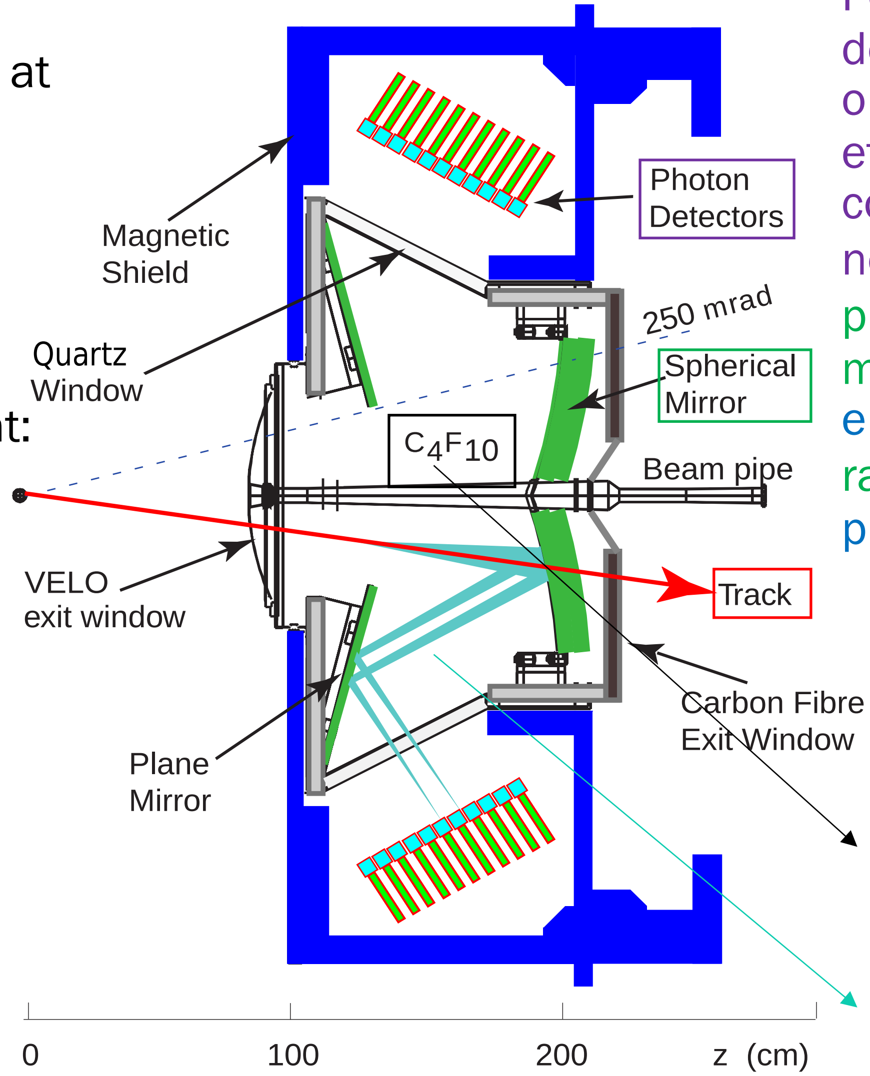
$$n_\sigma = \left|m_1^2 - m_2^2\right| / 2p^2 \Delta\theta_c \tan\theta_c$$

$$\Delta\theta_c = \sigma_c / \sqrt{N_{ph}} \oplus C_{trk}$$

Single photon resolution σ_c relevant at high momenta (and in busy events)

In practice ~ 100 tracks per inelastic pp event: effectively construct a global log-likelihood between measured hits and expected hit patterns from tracks: **robust reconstruction**





Position sensitive single photon detectors (and frontend electronics) outside the acceptance, quantum efficiency to reduce chromatic error contribution, low pixel size d_{px}, low noise

provide focussing with minimal material budget, tilt impacting the emission point error σ_{ep}, curvature radius impacting ring size and the pixel size error σ_{px}

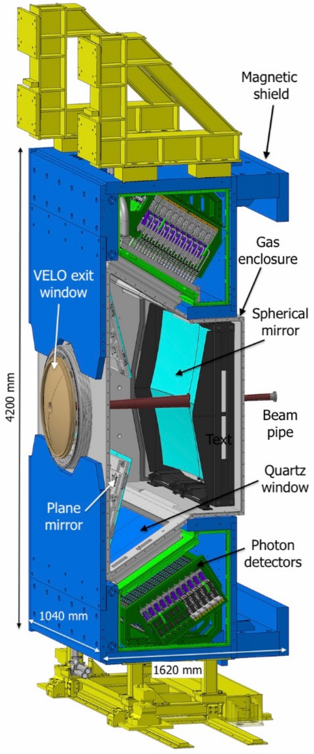
information from the tracking system: trajectory/curvature of track and momentum estimate

Radiator refractive index tuned to match momentum range, low dispersion to minimise chromatic error contribution

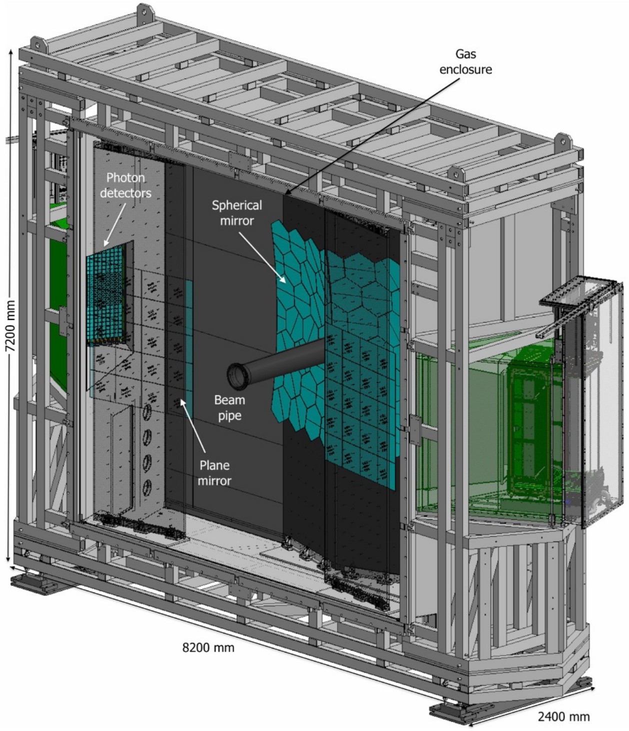
Large radiator volume to maximise track optical paths and therefore number of Cherenkov photons (N_{ph})

The LHCb RICH detectors and their upgrade

- Two RICH detectors
  - RICH1 with C_4F_{10} (n=1.0014 at λ=400 nm STP) to cover 3-40 GeV over 25-300 mrad
  - RICH2 with CF_4 (n=1.0005 at λ=400 nm STP) to cover 15-100 GeV over 15-120 mrad
- Boundary conditions for Run 3 LHCb: run at a five-fold increased instantaneous luminosity ($\boldsymbol{\mathcal{L} = 2 \cdot 10^{33} cm^{-2} s^{-1}}$), with a continuous **40 MHz readout rate** and keeping the **same subdetector envelopes**
  - Upgrade both RICH detectors to target the Run 1 and 2 excellent performances in a harsher environment
  - **New RICH1 optics and mechanics**
  - Replace Hybrid Photon Detectors with embedded 1 MHz readout electronics with **MaPMTs and new electronics in both RICH1 and RICH2**



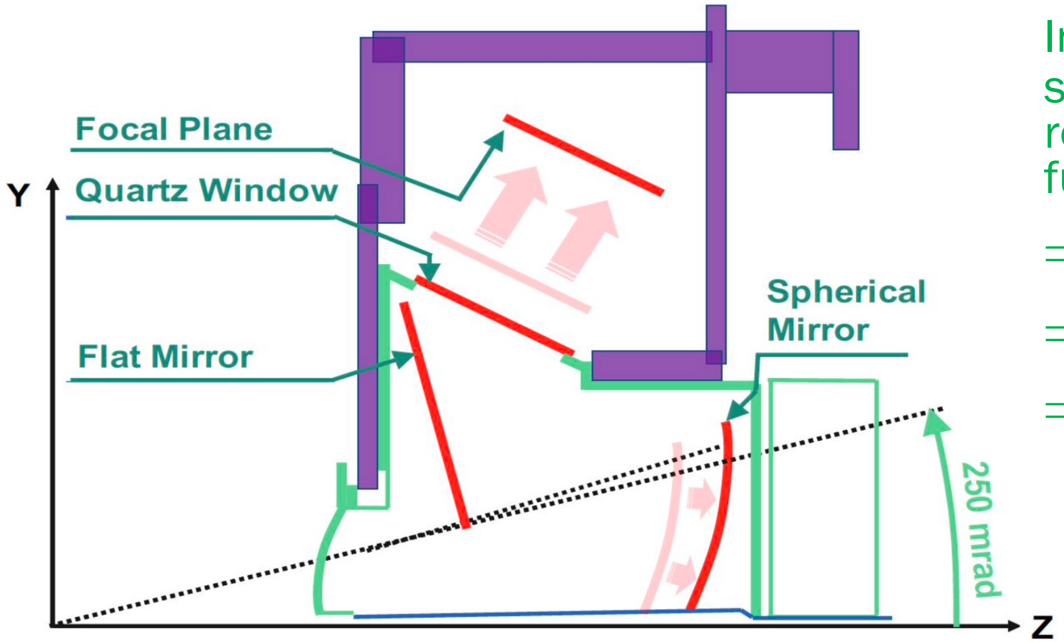
RICH1 (~ $4\ m^3$)



RICH2 (~ $140\ m^3$)

RICH1 optics and mechanics

- Re-design and re-build full RICH1 optics and mechanics to **keep peak occupancy under control (below 30% at 40 MHz)** for optimal photon hits/tracks association (based on Run 1 and 2 experience)

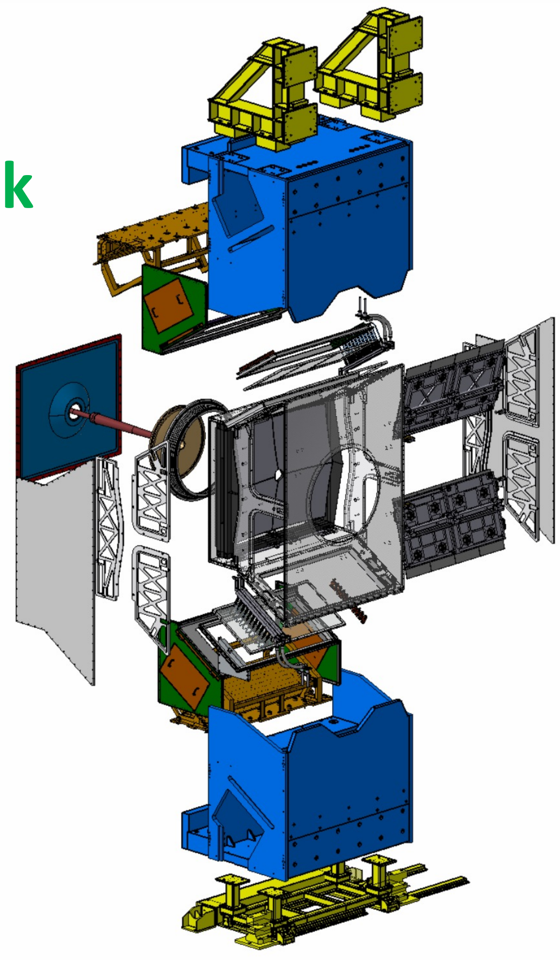


Increase radius of curvature R of spherical mirrors by a factor ~ $\sqrt{2}$, reduce tilt and move the focal plane further outside the acceptance

$\Rightarrow$**peak occupancy halved**

$\Rightarrow$**reduced** $\sigma_{px} = d_{px}/\sqrt{3}R$

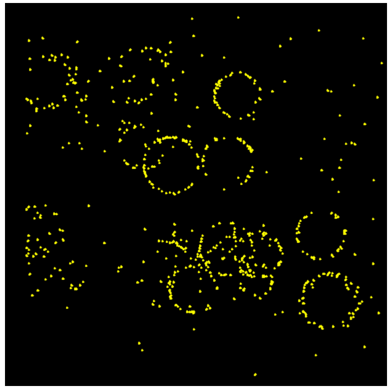
$\Rightarrow$**reduced** σ_{ep}



Extend radiator volume in z by ~ 100 mm => +14% Cherenkov photons per track

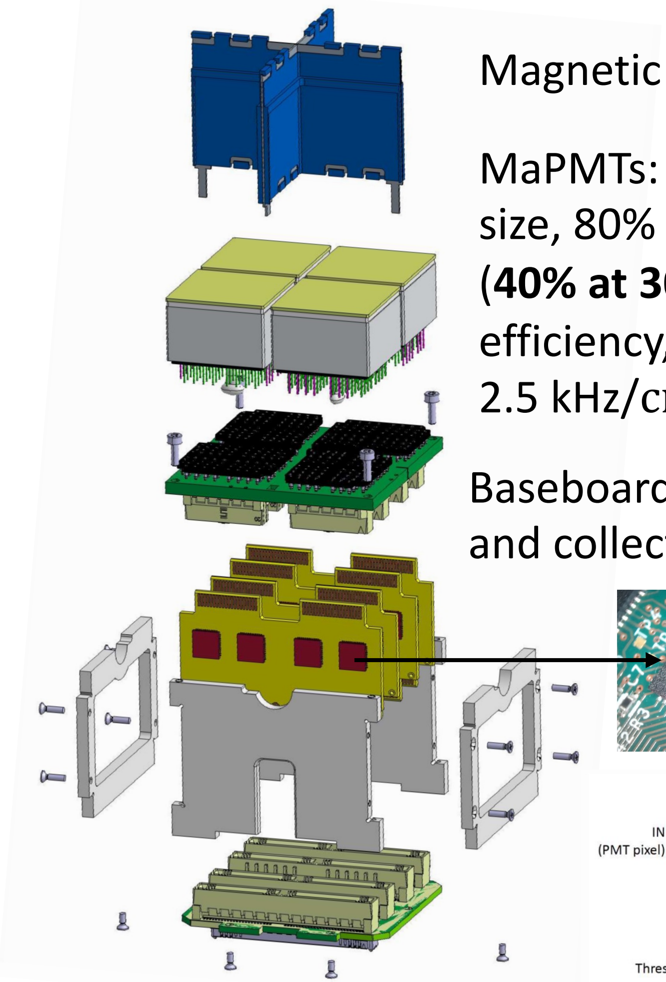
R = 3650 mm in RICH1 => “ring radii” (~ $\theta_c R/2$) for p=30 GeV would be

~ 9.6, 9.2 and 7.8 cm for pions, kaons and protons, respectively (but not exactly rings!)



Photon detection chain

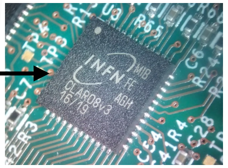
- Replace HPDs with commercial 64 channels Multi-anode photomultipliers Tubes (MaPMTs) and brand new frontend electronics



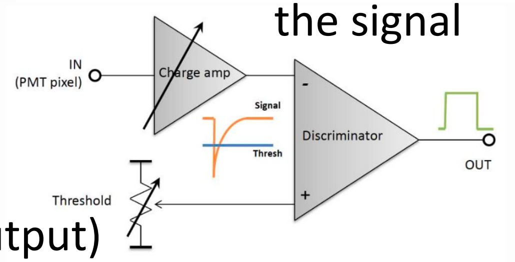
Magnetic shielding (RICH1)

MaPMTs: 2.8 x 2.8 mm^2 pixel size, 80% active area, large (**40% at 300 nm**) quantum efficiency, G > 1 Me, DCR < 2.5 $\mathrm{kHz/cm}^2$

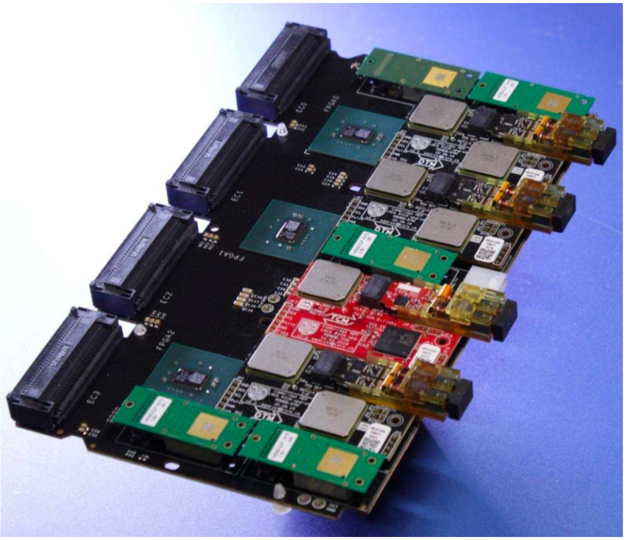
Baseboard (voltage divider and collect analog output)



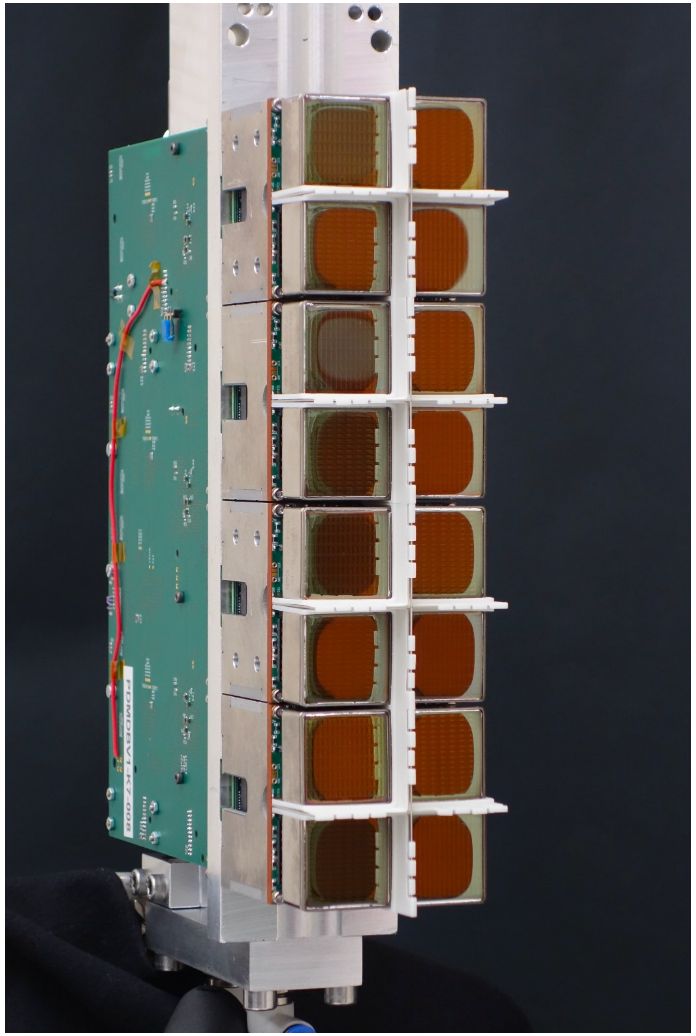
CLARO ASIC to digitise the signal



Backboard (deliver digital output)

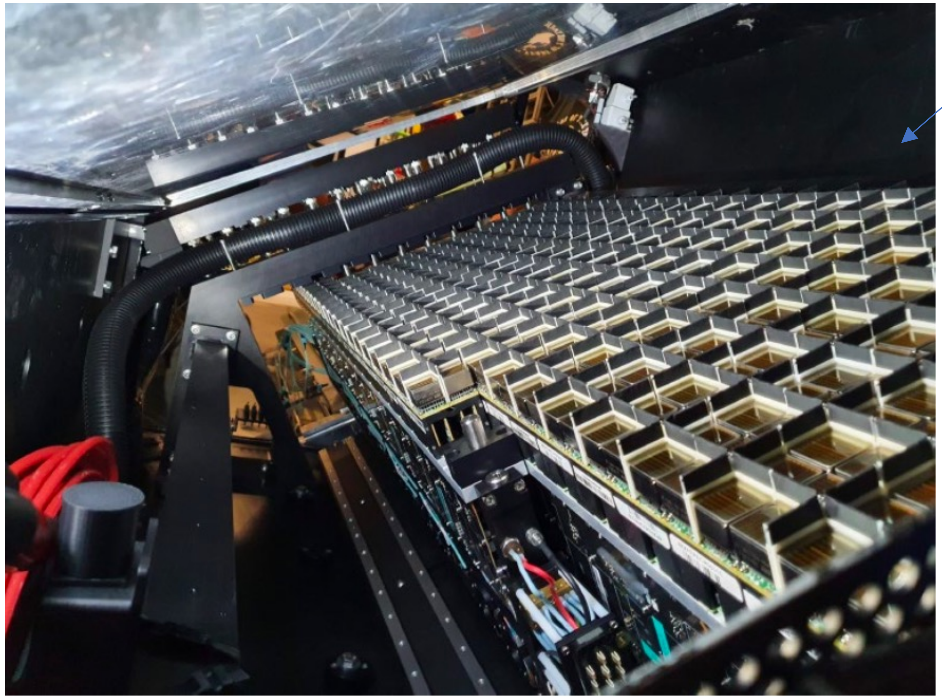


Flexible FPGA-based digital board interfacing with LHCb backend boards using the GigaBit Transceiver protocol



Photon detection planes

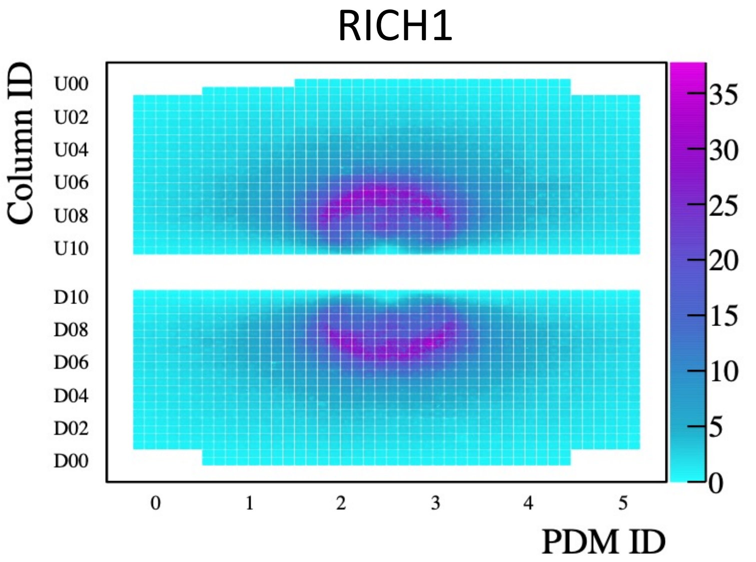
- Cover an area of approximately $4\ \mathrm{m}^2$ with **illumination rates** up to $\mathcal{O}(100\ \mathrm{MHz/cm}^2)$ in the high occupancy region down to $\mathcal{O}(5\ \mathrm{MHz/cm}^2)$ in the peripheral region
  - trade-off between performance and costs achieved by employing coarser granularity MaPMTs (6 x 6 mm^2 pixel size) in the outer region of RICH2

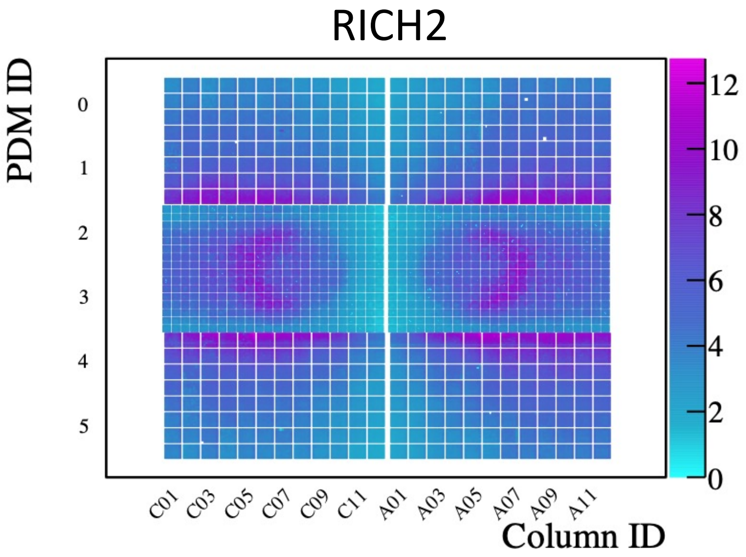


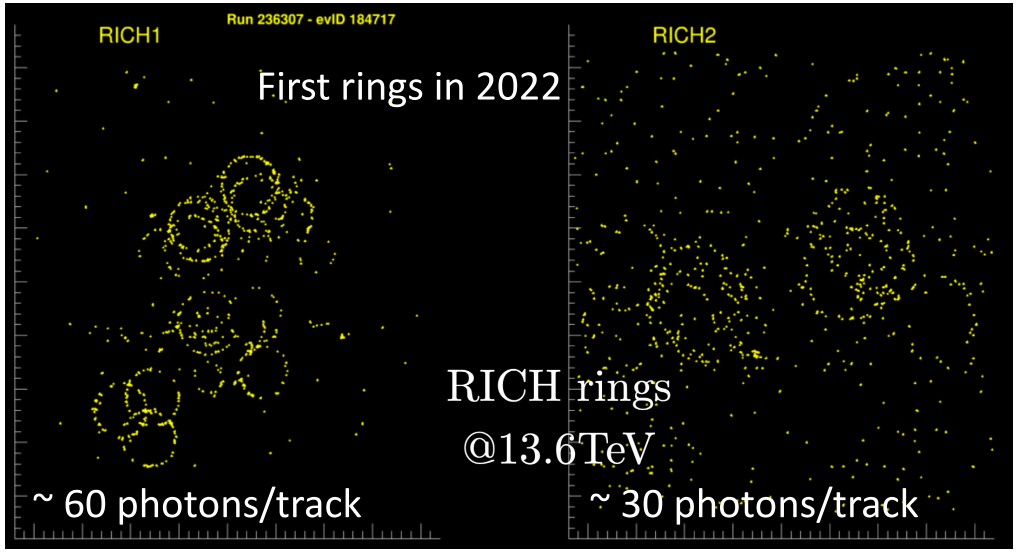
One side of RICH1 installed in the LHCb cavern

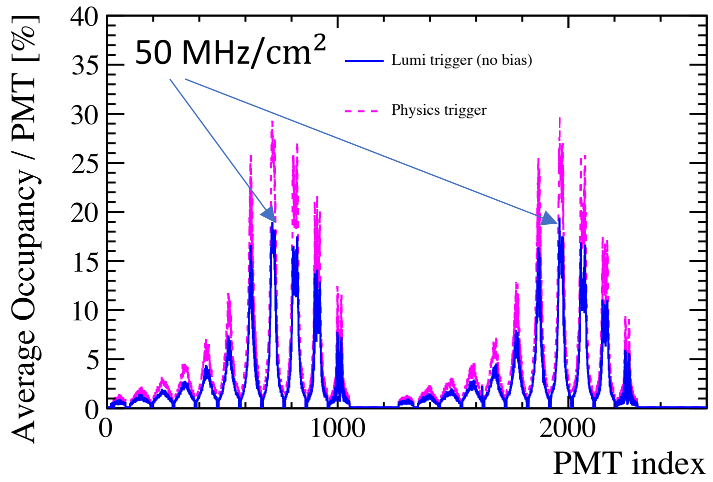
One side of RICH2 in the commissioning lab

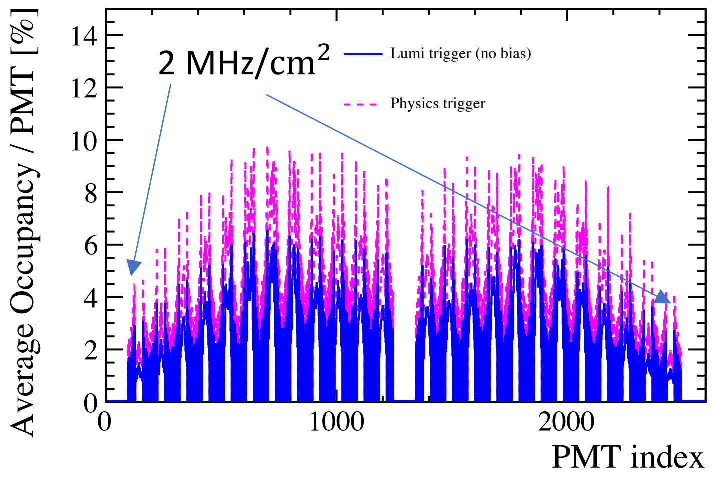
Hitmaps and occupancy

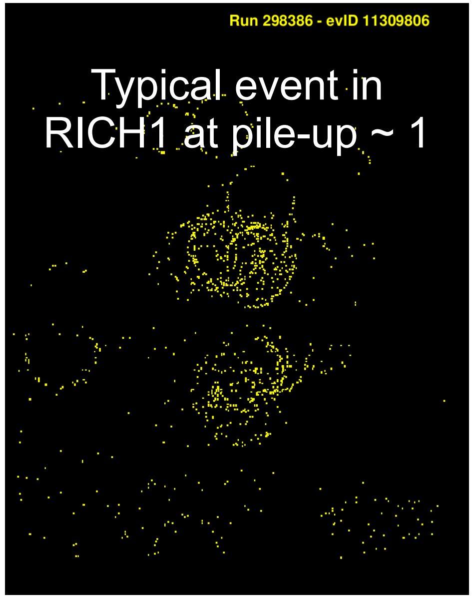


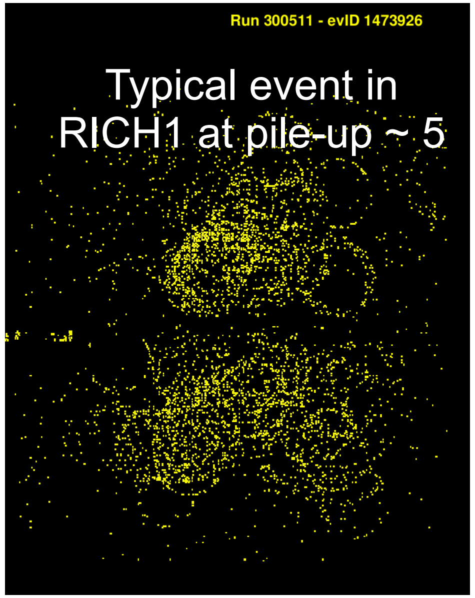










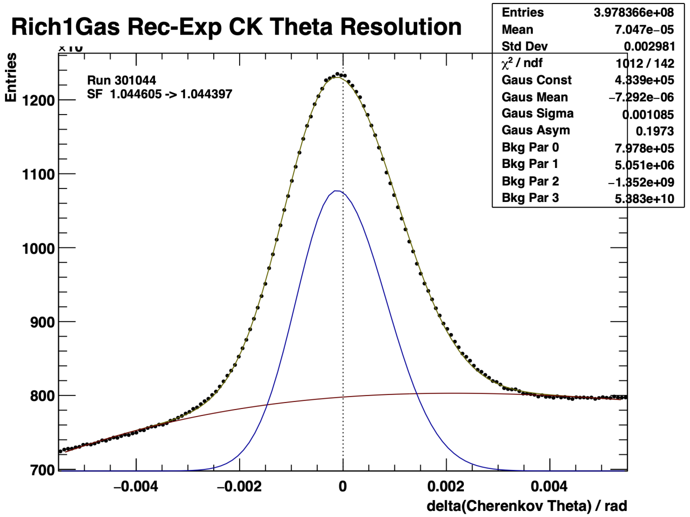


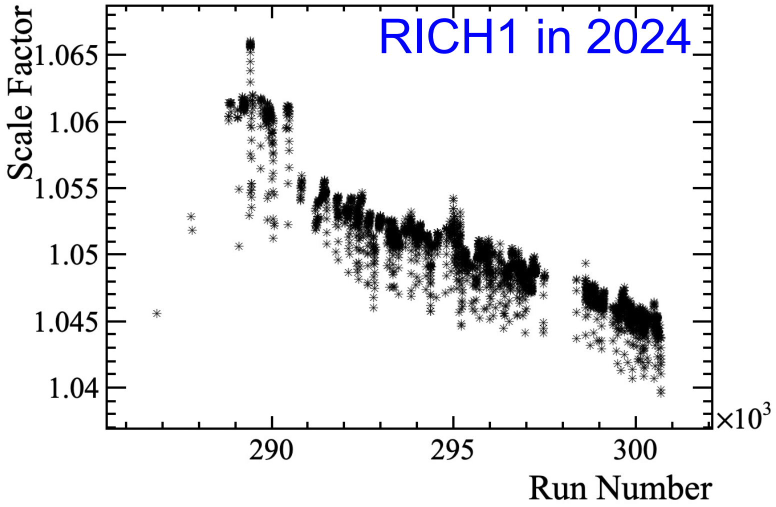
No bias beam-beam occupancy relevant operationally

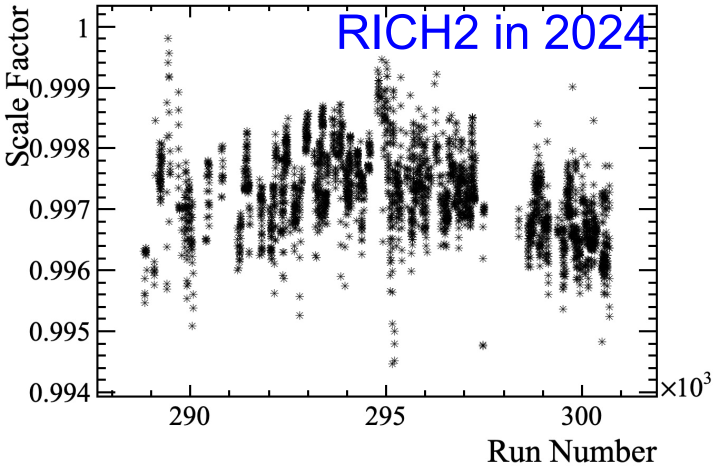
Physics-biased beam-beam occupancy relevant for performance

Online refractive index calibration

- Refractive index calibration required to correct for environmental (temperature and pressure) and purity (small sub-percent/month air contamination) changes of the radiators
  - Starting point determined from several temperature and pressure sensors placed into the gas enclosure
- Reconstructed Cherenkov angle from high momentum tracks ($\cos\theta_c \sim 1/n$) to determine the refractive index scale factors per run directly from data with an online data monitoring task
  - **Same task used to monitor online the single photon resolution trends**

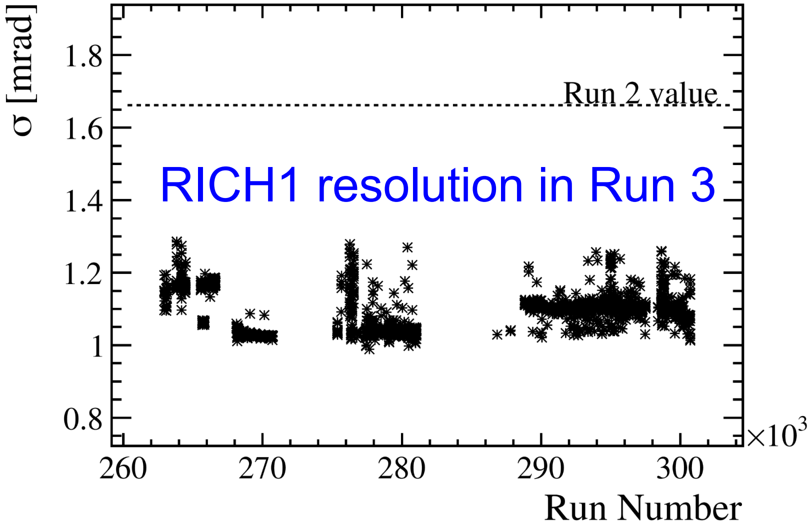


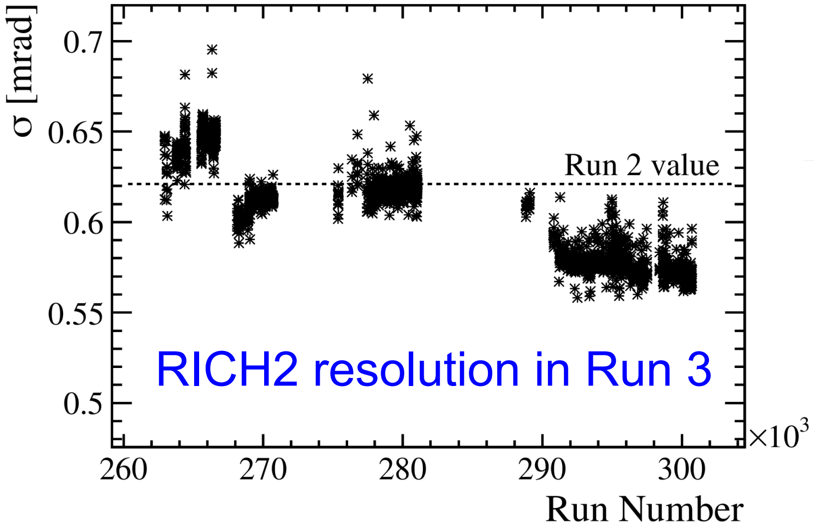


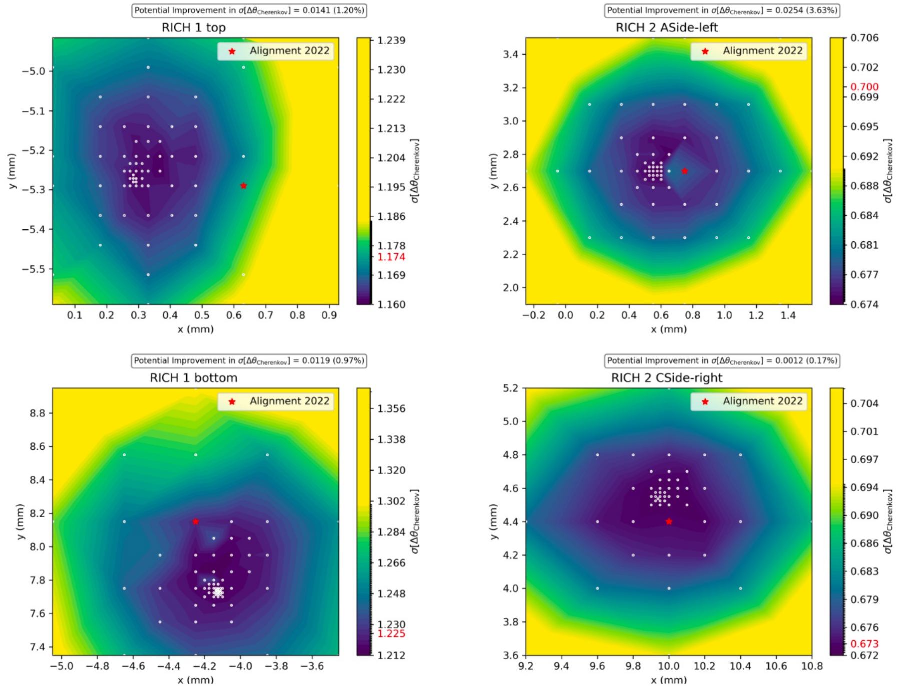


Alignment and Cherenkov angle resolution

- Single photon resolution also has a contribution from the spatial alignment of the optical system and from the relative alignment with the trackers
- Hardware alignment done during the installation
- Software alignment correcting for residual imperfections
  - photon detectors panel alignment done a few times per year to find the absolute minimum
  - Fine tuning corrections with mirrors alignment per run



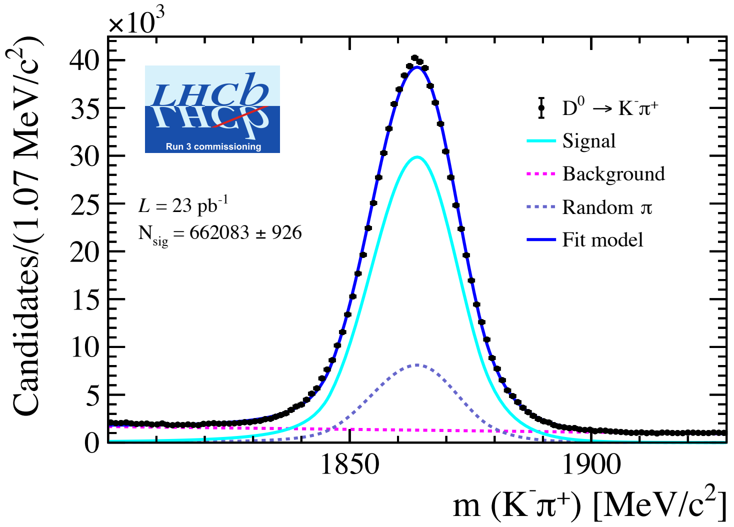


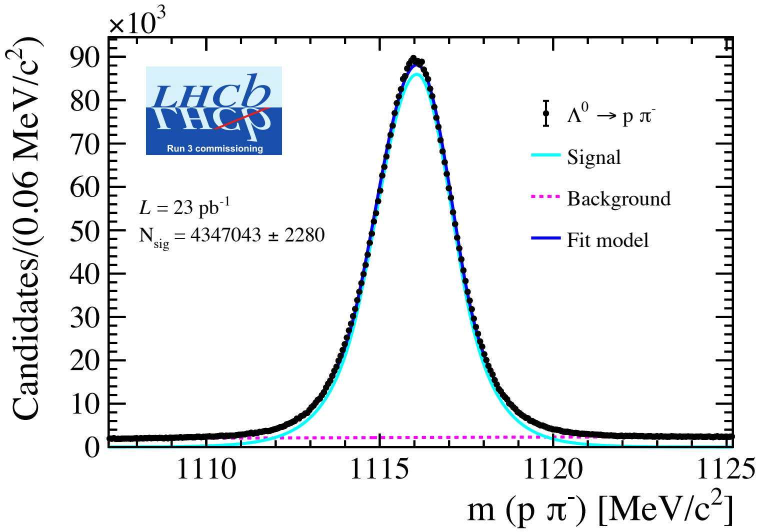


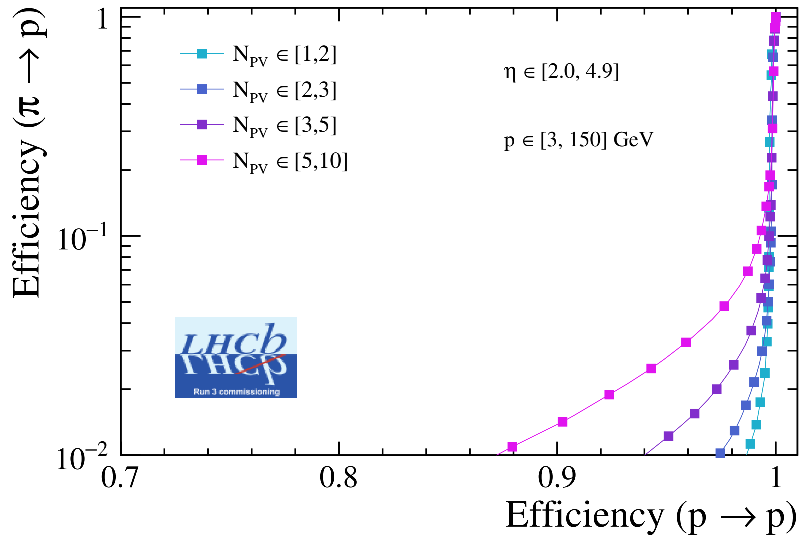
LHCb-FIGURE-2023-007

Hadron identification performance

- RICH detectors single photon resolution, number of detected photons per track, operational stability and calibrations impact the hadron identification performance used in data analyses to select the signal of interest and reject backgrounds
- Performance determined through the studies of calibration samples selected by purely kinematic means: $D^{*+} \rightarrow D^0(\rightarrow \mathbf{K^-\pi^+})\pi^+$ and $\Lambda \rightarrow \mathbf{p}\pi^-$
- Cut on high level variables defined as $DLLh = \ln(h)\,/\ln(\pi)$ in bins of momentum, angular acceptance and event multiplicity

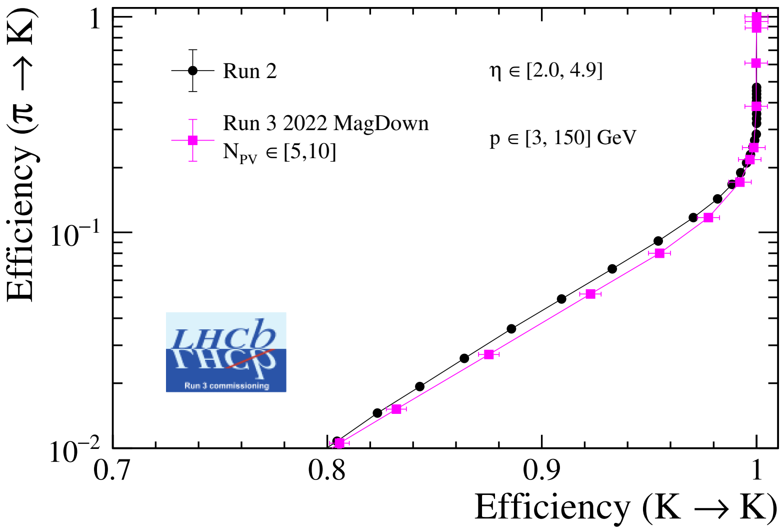


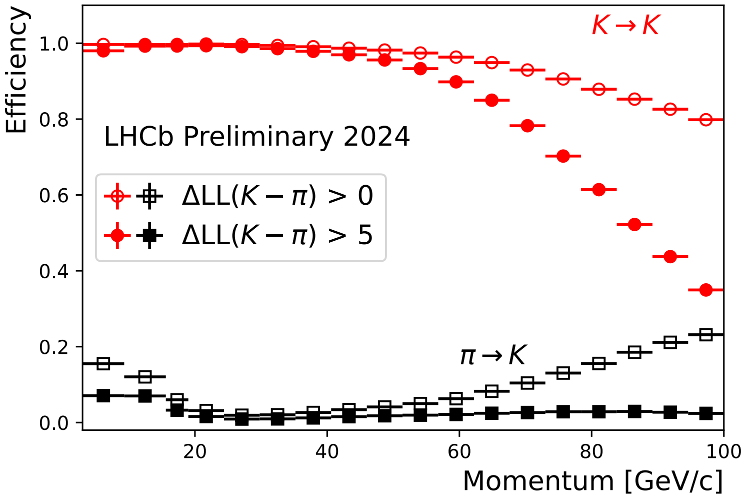


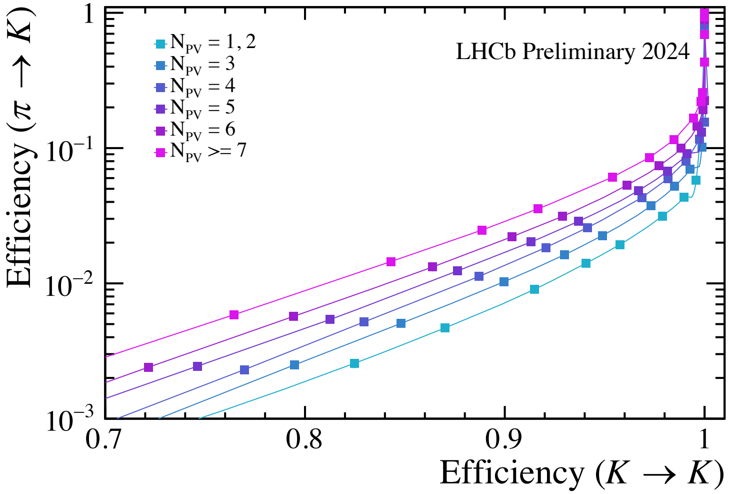


Hadron identification performance: Run 2 vs Run 3

- Preliminary performance evaluated with data collected at the end of 2022
  - 2023 performance even better but biased by VELO open conditions (effectively select low occupancy regions) LHCb-FIGURE-2023-023
- Comparison between Run 2 performance curves and Run 3 curves in events with number of reconstructed primary vertices between 5 and 10
- Demonstrates that already with the preliminary calibrations performed in 2022 the upgraded RICH detectors outperformed the previous generation at the average pile-up value of Run 3 LHCb-FIGURE-2023-019, confirmed in 2024 LHCb-FIGURE-2024-031

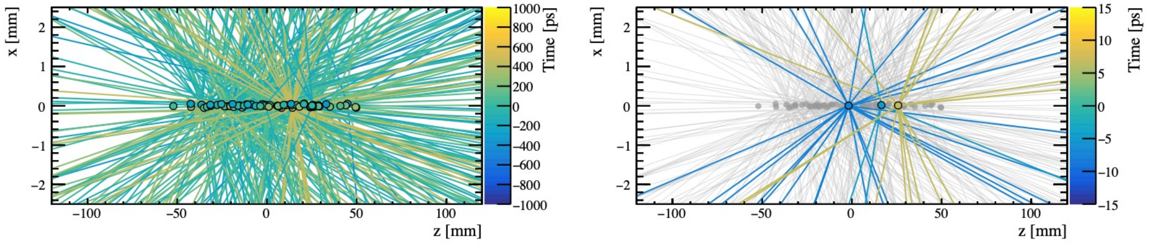






LHCb Upgrade II (2036 – 2041?)

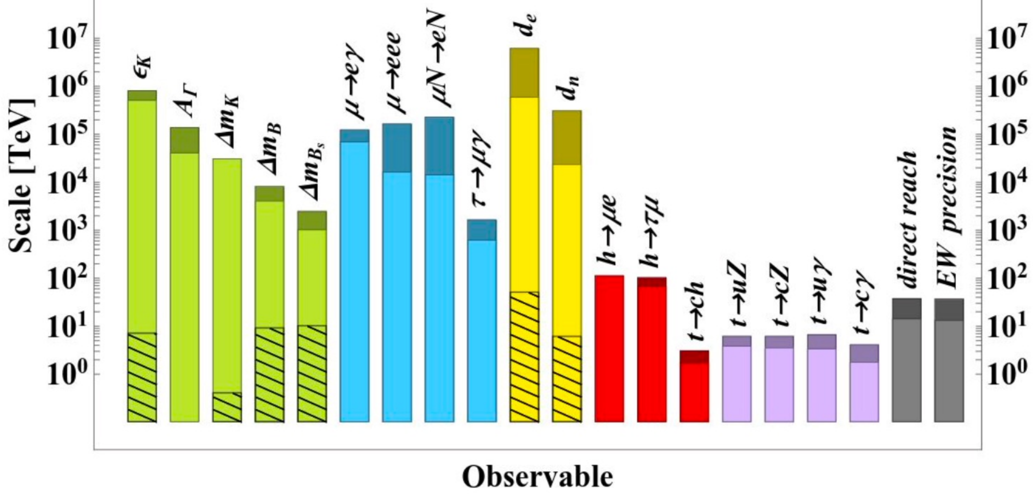
- LHCb (and HL-LHC) reaches full potential with Upgrade II thanks to a possible seven-fold increase in the instantaneous luminosity (**pile-up ~ 40**)
- Factor 2 in BSM mass scales reach with 300/fb of integrated luminosity
- Technological challenges: higher granularity, introduction of timing, extreme radiation hardness, data throughput, bandwidth and distribution



Run 3			LS3				Run 4			LS4		Run 5					
2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
TDR phase			Construction phase							Installation		Exploitation					

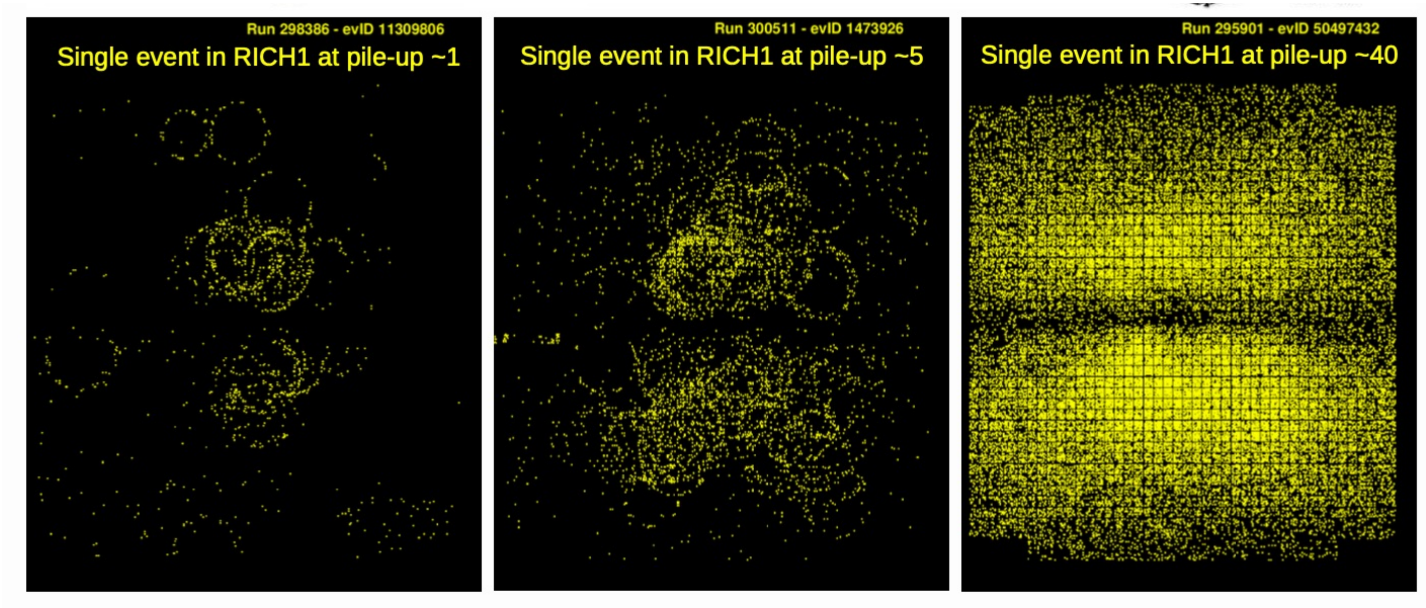
Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	2.8°	[18, 19]	1.3°	0.8°	0.3°
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad	[22]	12 mrad	8 mrad	3 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[55, 56]	3%	2%	1%
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[25]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[29]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[57]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[30, 31]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[58]	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[59]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[60]	0.148	0.097	0.038

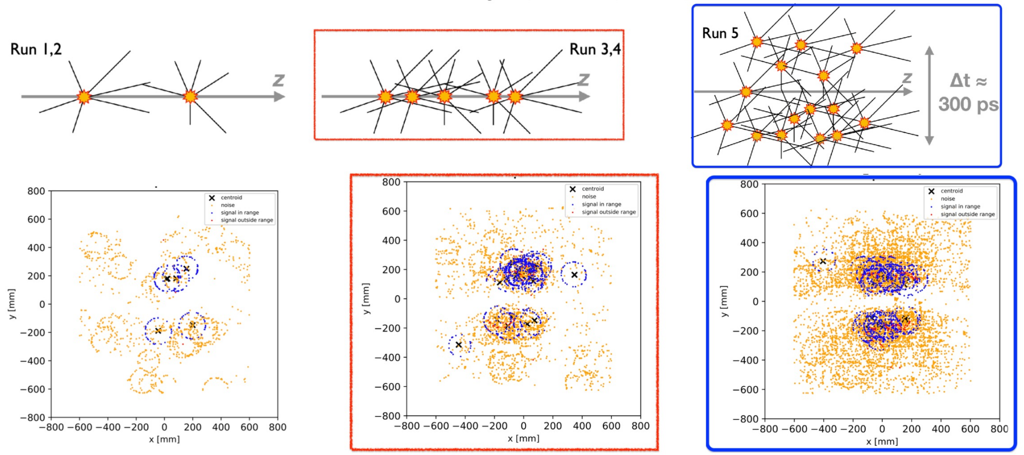
ESPP '20 update



RICH detectors in LHCb Upgrade II

- Keep excellent hadron identification performance in a much harsher environment
  - **illumination rates:** up to 10 $\mathrm{MHz/mm^2}$ (with same geometry and same envelope)
  - **radiation levels:** 2 Mrad TID, $2 \cdot 10^{13}$ 1 MeV $\mathrm{n_{eq}/cm^2}$
- Photon detectors granularity down to ~ 1 x 1 $\mathrm{mm^2}$ (high-density electronics) and improve single-photon-resolution to help pattern recognition
- **Exploit timing properties of the prompt emission of Cherenkov radiation** and **focussing optics** to reduce out of time backgrounds (already employed in Run 3) and associate photons to tracks from the same PV (need < 100 ps rms photon detectors and fast electronics)
- Keep low (less than 100 $\mathrm{kHz/mm^2}$) the dark count rate

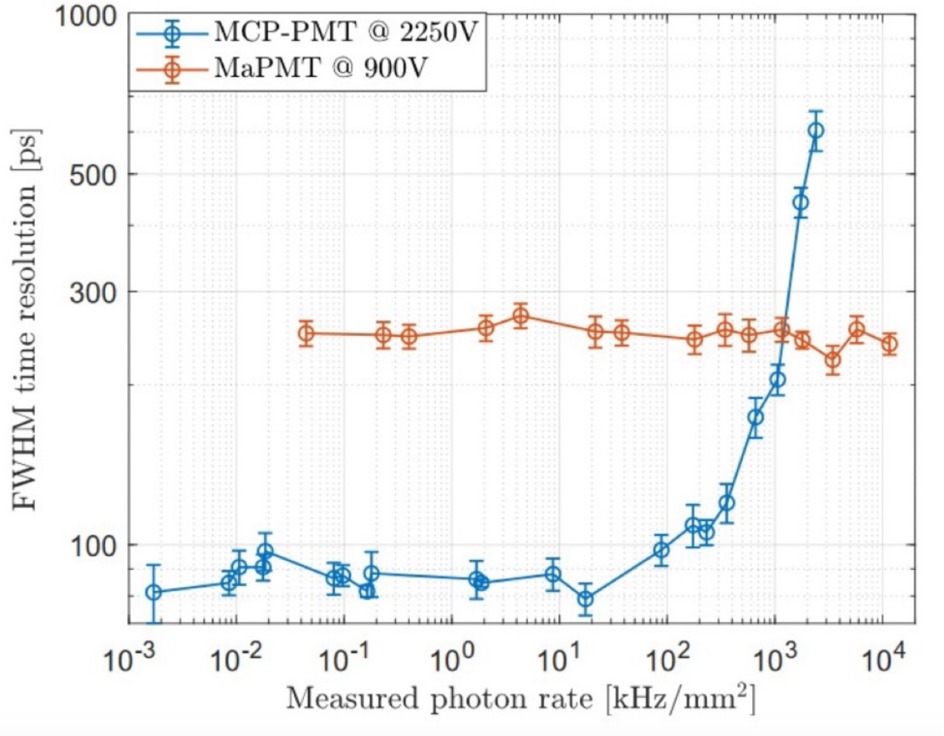




RICH1 rings with 1 PV | RICH1 rings with 5 PVs | RICH1 rings with 10 PVs

Photon detectors R&D

- MCP-based (Hybrid, LAPPD, PMT) and SiPM are two potential classes of sensor that fulfill a good amount of the RICH requirements for Upgrade II
- But with their well known drawbacks: ageing and saturation current for MCPs, dark-counts and radiation hardness for SiPMs
- Vigorous R&D phase ongoing to **steer developments with vendors to find a suitable photon sensor tailored to the LHCb RICH Upgrade II application in the next three years**



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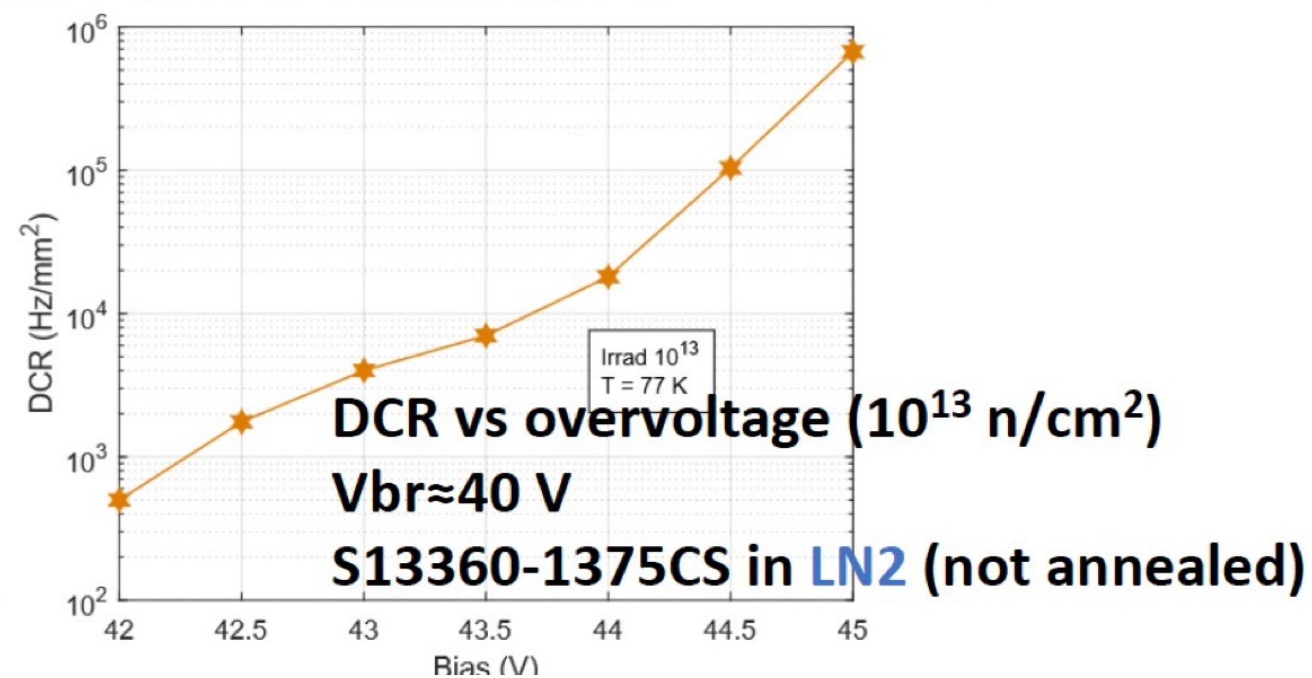

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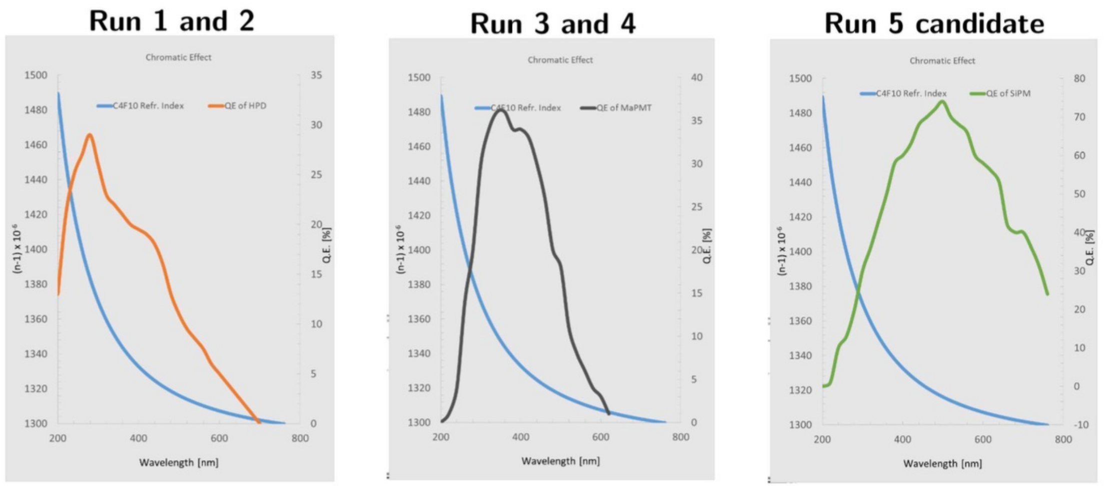
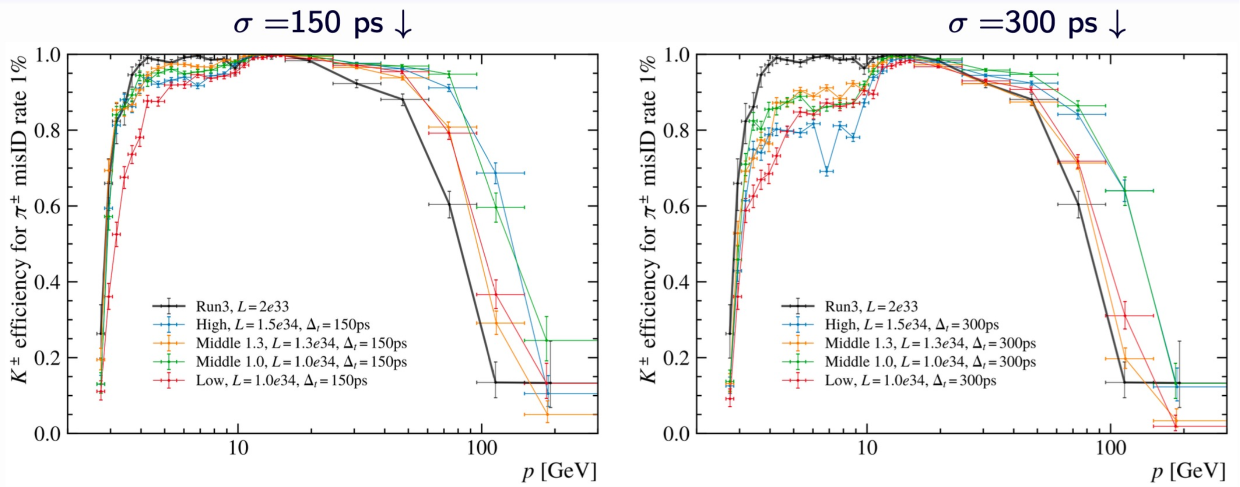
Improvements in single-photon resolution

- Optimisations of the **optical design** to reduce the occupancy and decrease RICH1 pixel σ_{px} and emission point σ_{ep} errors from ~ 0.4 to ~ 0.1 mrad:
  - Flat mirrors in the acceptance (R&D on carbon-fibre flat and radiation hard mirrors) and increase radius of spherical mirror
    - but reduced track optical path => reduced photon yield N_{ph}
  - Flat mirrors in the acceptance and increased number of mirrors with different tilts
    - complications in the pattern recognition algorithms and larger number of photon detectors
- Keep the same fluorocarbon gases and match photon detection efficiency of the sensors to reduce the chromatic error from ~ 0.6 mrad to ~ 0.3 mrad
  - Blue-sky R&D on alternative radiators (e.g. photonic crystals) will not be ready in due time
  - Quest for leakless gas systems

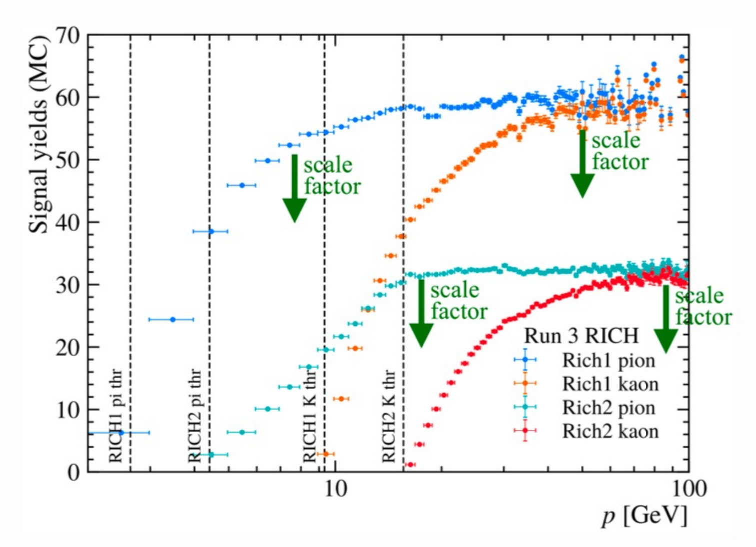


Run 1 and 2	Run 3 and 4	Run 5 candidate
$\sigma^{RICH1}_{chromatic} = 0.84$ mrad	$\sigma^{RICH1}_{chromatic} = 0.52$ mrad	$\sigma^{RICH1}_{chromatic} = 0.11$ mrad
$\sigma^{RICH2}_{chromatic} = 0.48$ mrad	$\sigma^{RICH2}_{chromatic} = 0.34$ mrad	$\sigma^{RICH2}_{chromatic} = 0.10$ mrad

Emulated PID performance in Upgrade II

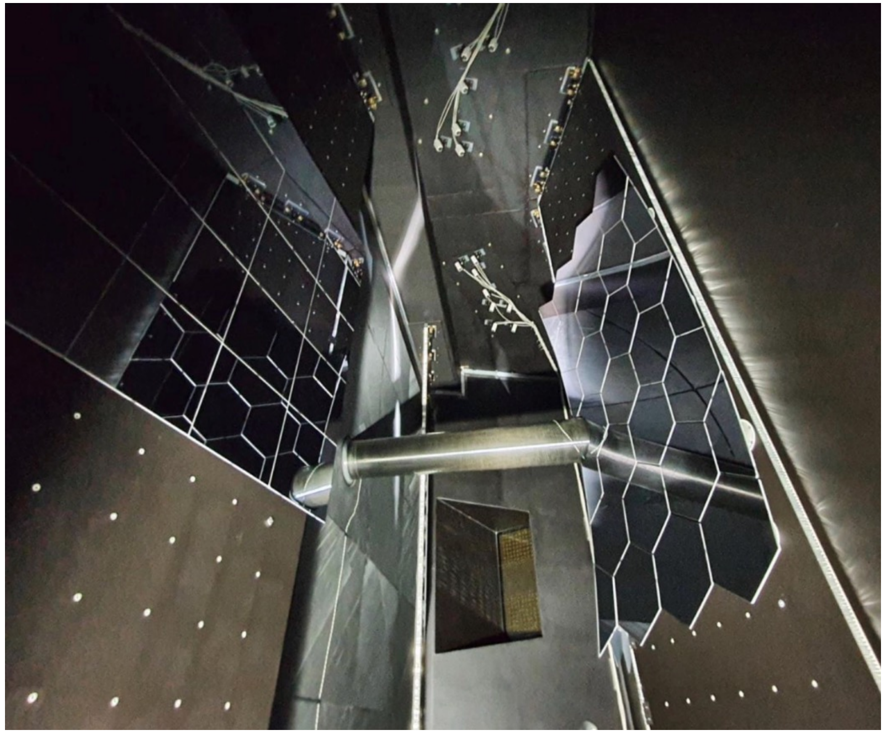


- Emulated different scenarios (luminosity, timing capabilities, photon yield, optical designs) to find the best compromise between performance and cost
  - **Timing is crucial**
- Target improvements in single-photon resolutions
  - RICH1: 0.82 -> 0.38 mrad
  - RICH2: 0.5 -> 0.22 mrad
  - to be accompanied by equivalent improvements in the tracking contributions
  - Photon yield anti-correlated with some improvements in the single-photon resolutions
- **Final decisions will be taken once a suitable photon sensor will be found**
  - R&D on fast electronics is ongoing (e.g. FastRICH ASIC): need to match level of granularity and density of channels in appropriate frontend modules



Conclusions

- The LHCb RICH detectors have been upgraded to run in a more challenging environment with a five-fold increase in the average pile-up per event
  - **Excellent performance as in Run 1 and 2**
- A possible Upgrade II of the LHCb experiment with a further 7.5 increase in the average pile-up/event will result in unprecedented conditions for a RICH detector: **high rates and extreme radiation conditions**
- R&D ongoing on fast and radiation-hard photon detectors, electronics, optics and mechanics to achieve the **ultimate RICH detectors at a hadron collider**
  - Possible intermediate step is a replacement of the electronics chain during LS3 by installing FastRICH+lbGBT+VTRX+ chain



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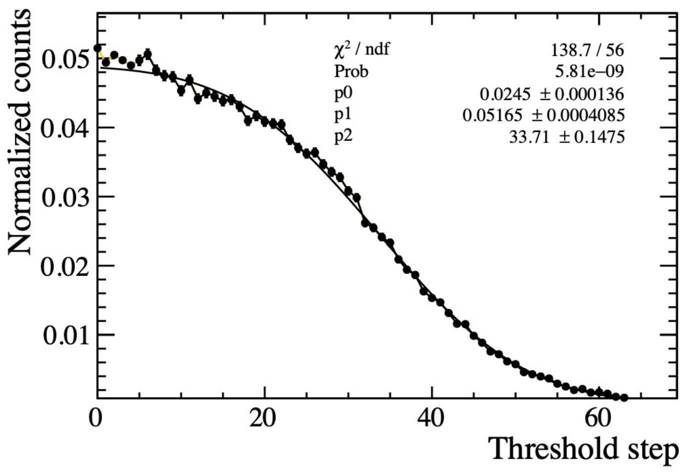
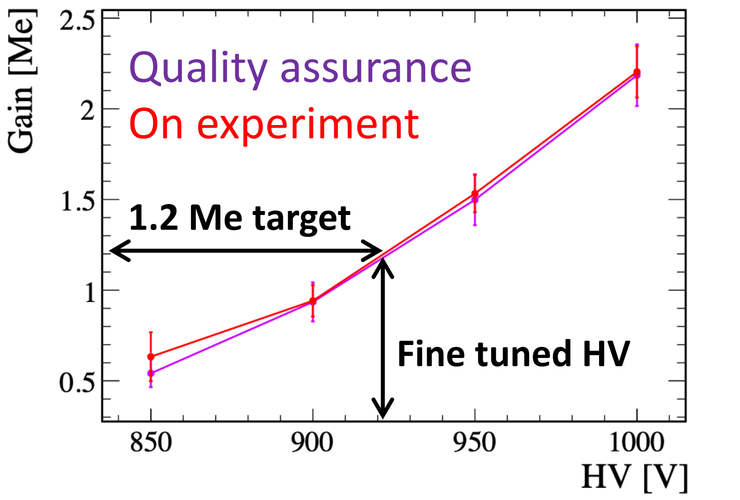
Extra Slides

Photon detection chain calibration and operations

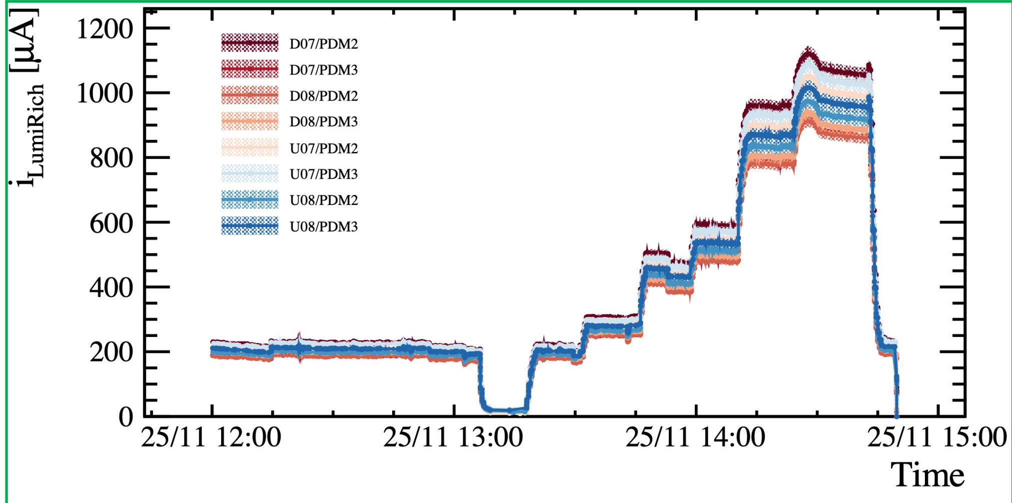
- **Tuning of operational and calibration tools to achieve the best performance**
- Average gain of the 200k MaPMT channels measured and equalised to 1.2 Me by tuning the operating high-voltages through automated threshold scan procedures with beam
  - excellent agreement between quality assurance and on experiment results
  - same procedure used to monitor and correct for ageing
  - frontend thresholds set to 200 ke
- Last dynode of the MaPMTs supplied independently to preserve gain linearity at high rates up to 100 MHz/cm^2
  - Provide online luminosity through the calibrated measurement of the power supply currents



Single channel threshold scan

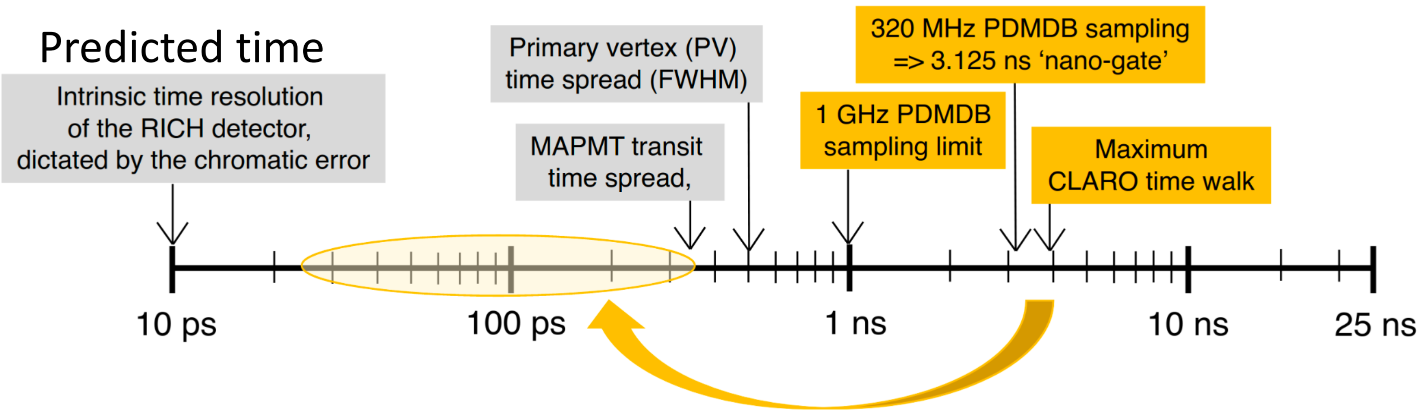


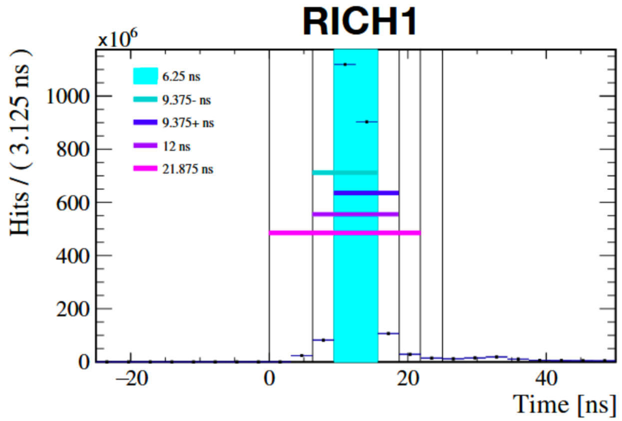
Results for one group of 16 MaPMTs

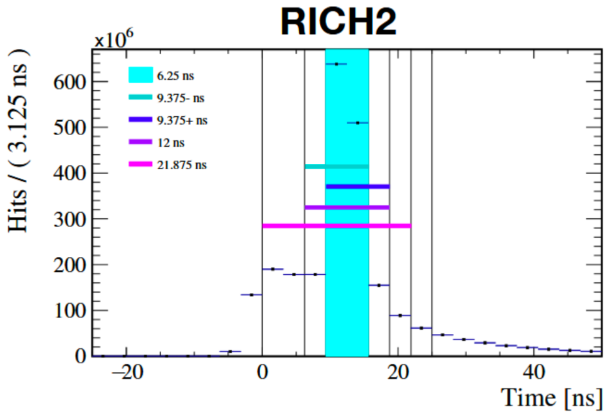


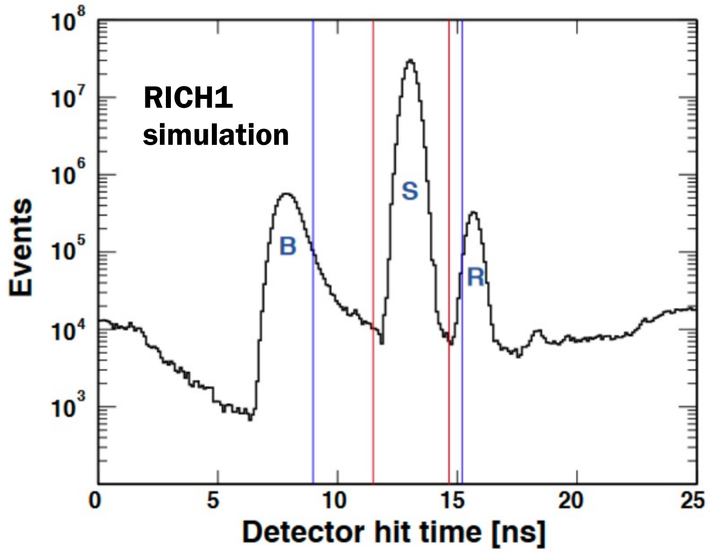
Timing properties

- **Prompt emission of Cherenkov radiation** and **focussing optics** suggestive of a fine time gating to reduce out of time backgrounds









Best trade-off between photon detection efficiency and background rejection found for a 6.25 ns time gating window: already deployed at the start of Run 3

- B: background due to particles travelling directly to the photon detection plane
- S: Cherenkov signal
- R: background due to multiple reflections of Cherenkov photons in the optical system
- \+ incoherent background due to instrumental internal noise/scintillation photons in the radiators