The Future of RICH Detectors through the Evolution of the LHCb RICHes

(Carmelo D'Ambrosio on behalf of the LHCb RICH collaboration)

The LHCb-RICH system was born in the 20th century, what will it be in 2035?

Drive for upgrades in LHC: more physics and physics reach.
How? By increasing Luminosity … and detectors must follow.
Drag: Resources, Space (the sub-det envelopes are defined).

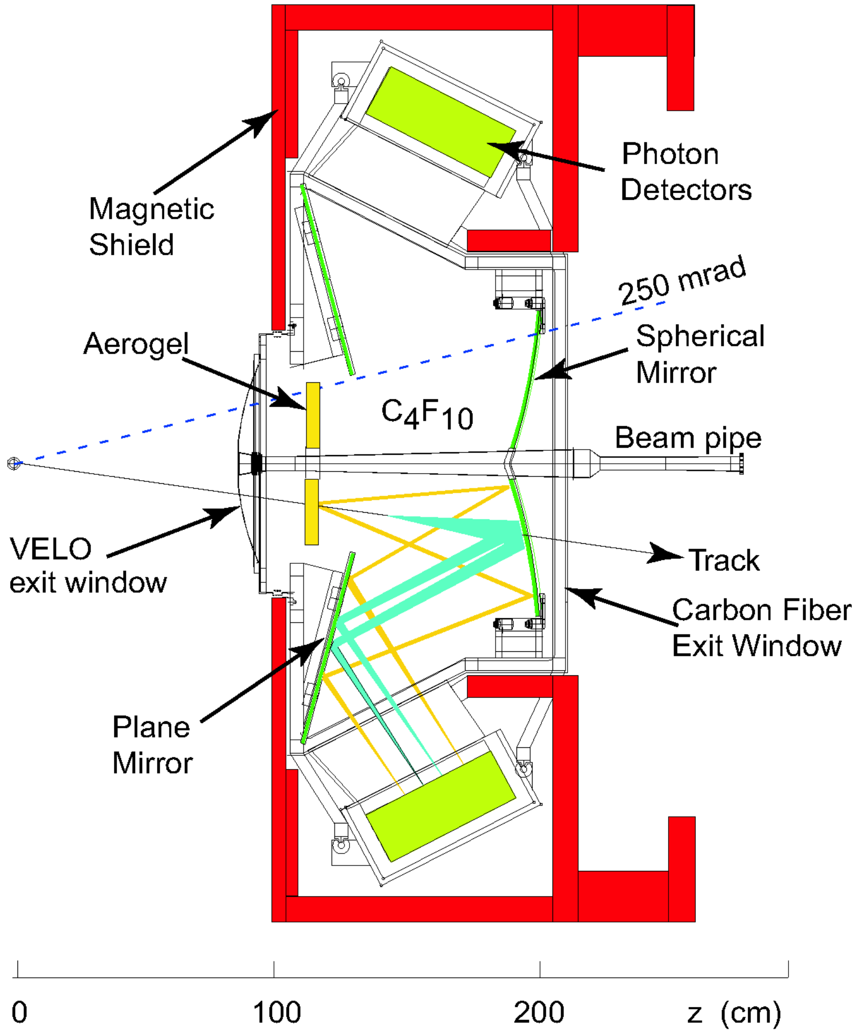
In the LHCb framework*:

Upg1 2021 will see the first upgrade of the RICHes and LHCb (x10 present Lumi);

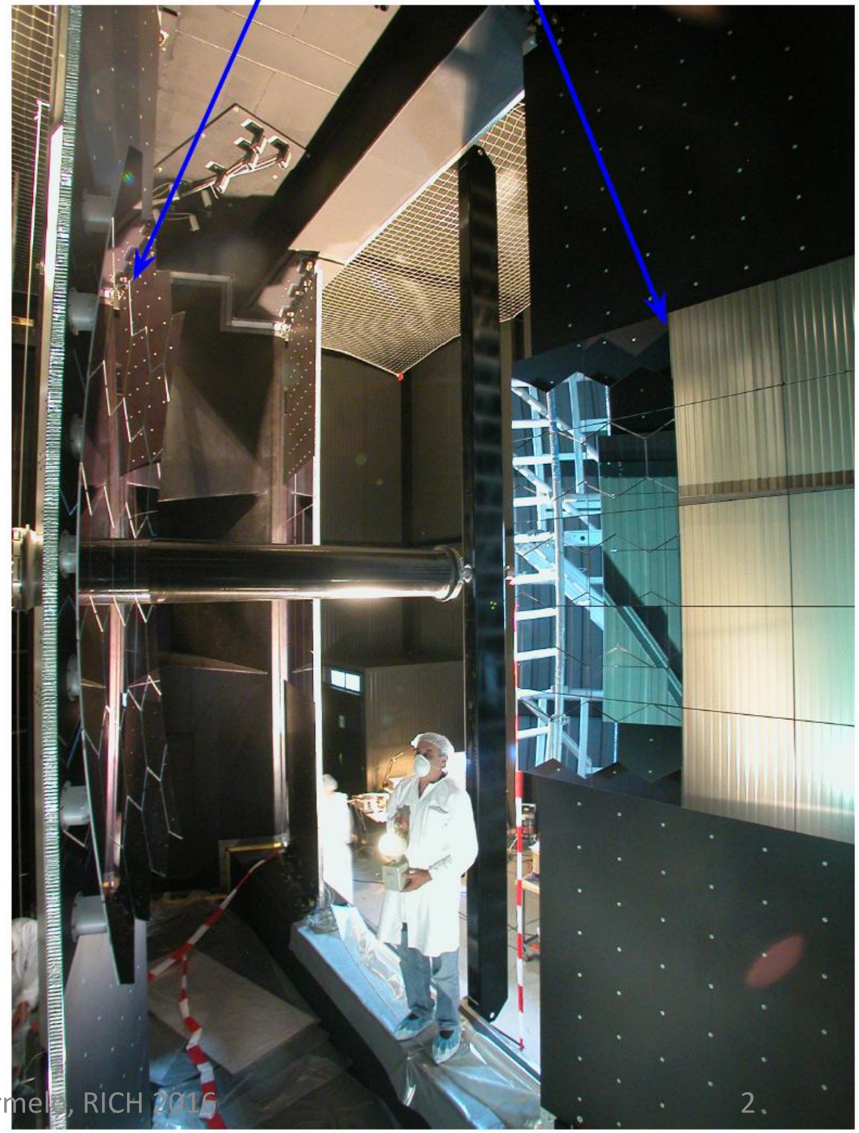
Upg2a 2025 may see a small upgrade in preparation for
Upg2b 203x, a major possible upgrade (HL-LHC, x50 present Lumi).

* Disclaimer: apart from the 2021 upgrade, there are no official requests for the successive upgrades. But LHC is like a train, either you are on it or you are left behind...

RICH1 and RICH2



Spherical & Flat Mirrors

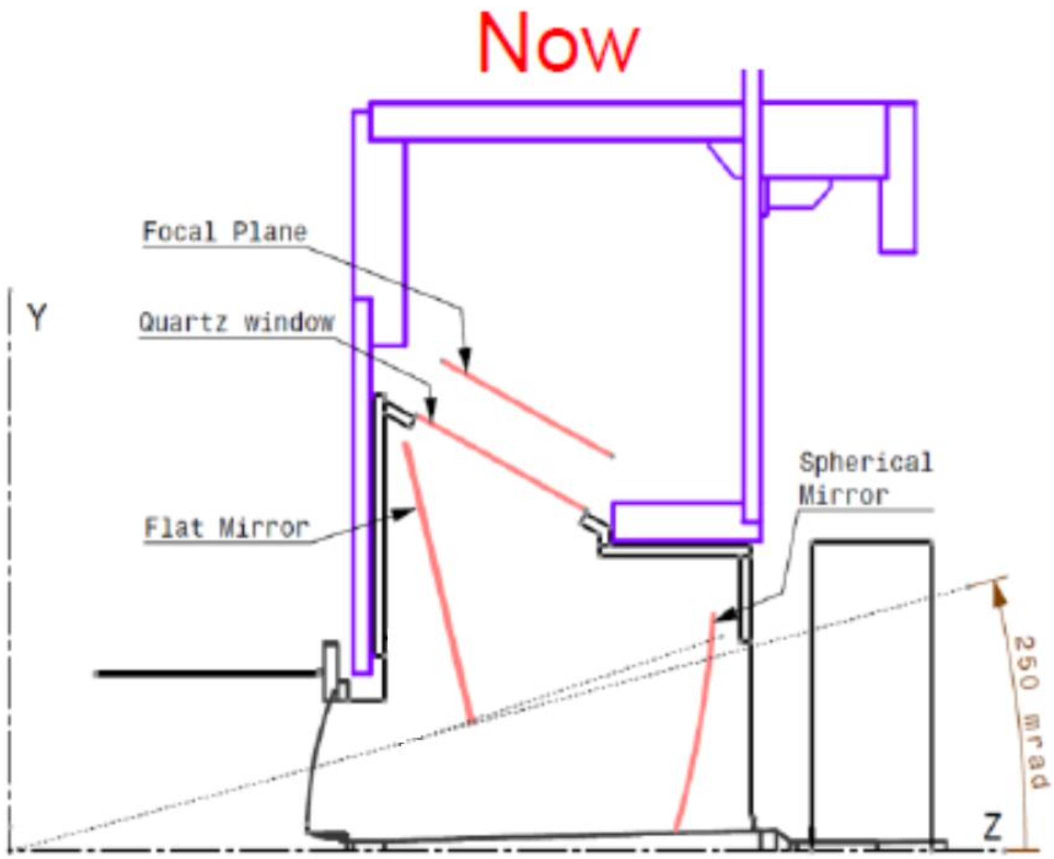


Present, Run II, 25 ns, ~2 x 10^{32} cm^{-2} s^{-1}

RICH 1
Wide acceptance (300 mrad), tight space
Low-medium mom. range (~10 to ~ 60 GeV/c)
High photon yields
and medium resolutions (1.60 mrad per hit).

RICH 2
Small acceptance (120 mrad), wide space
Medium-high mom. range (~50 to ~100 GeV/c)
Lower photon yields
and high resolutions (0.67 mrad per hit).

Improved PID and online cal. and mon.;
RICH system fully included in HLT.



Contents

- Detector limitations and improvements with increasing luminosity
- The case for RICH 1
- Critical issues and associated R&D
- Photodetectors still own the game!
- Conclusions

With Luminosities increasing:

1. Occupancies jump up: improve granularity;
2. Pattern recognition a challenge: improve cherenkov angle resolution.

With Luminosities increasing and Physics Reach extending

1. Occupancies jump up: improve granularity;

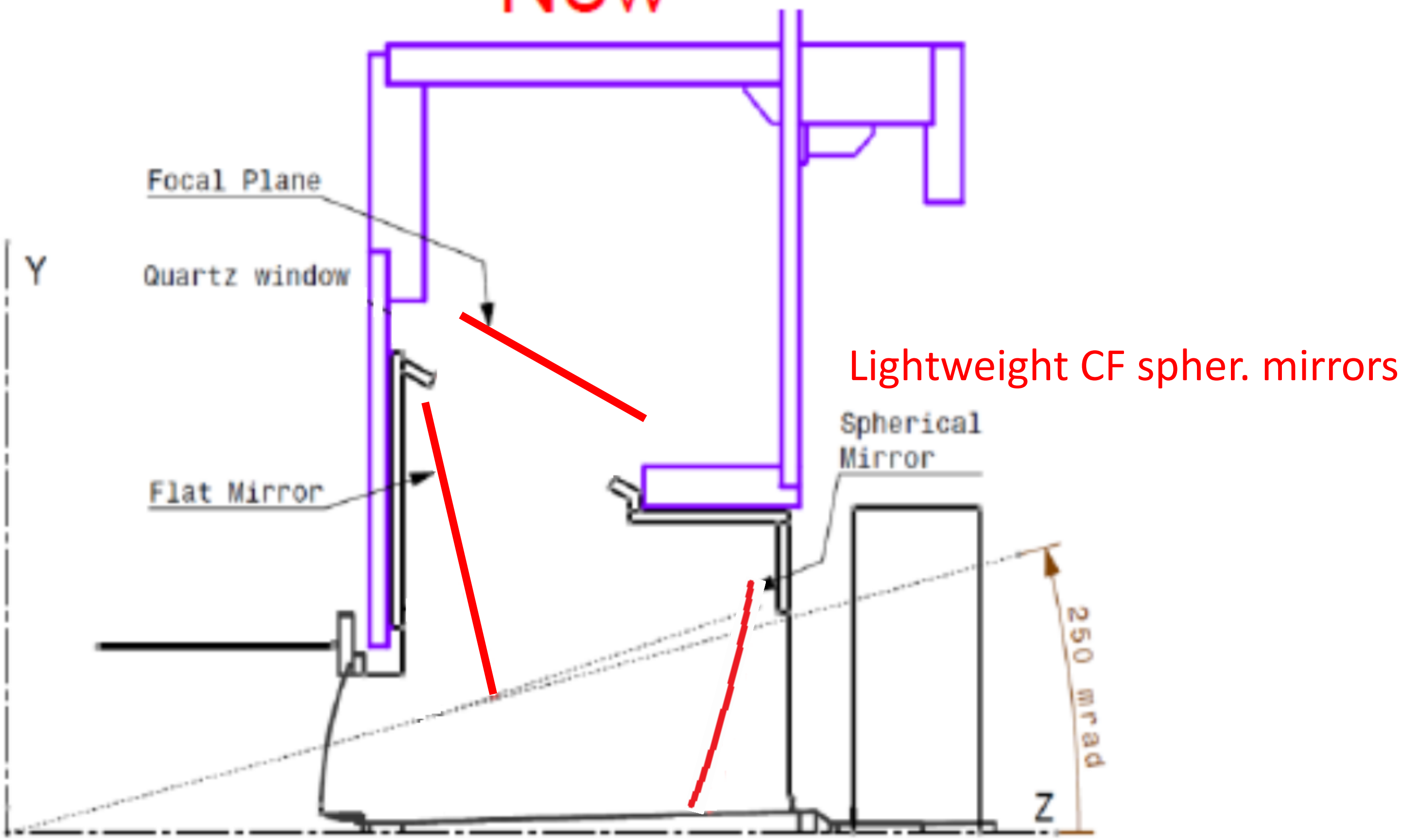
$$\frac{A_p}{A_i} \propto \frac{A_p}{f^2}$$

A_p is the pixel area
A_i is the image area
f is the mirror focal length

Example:

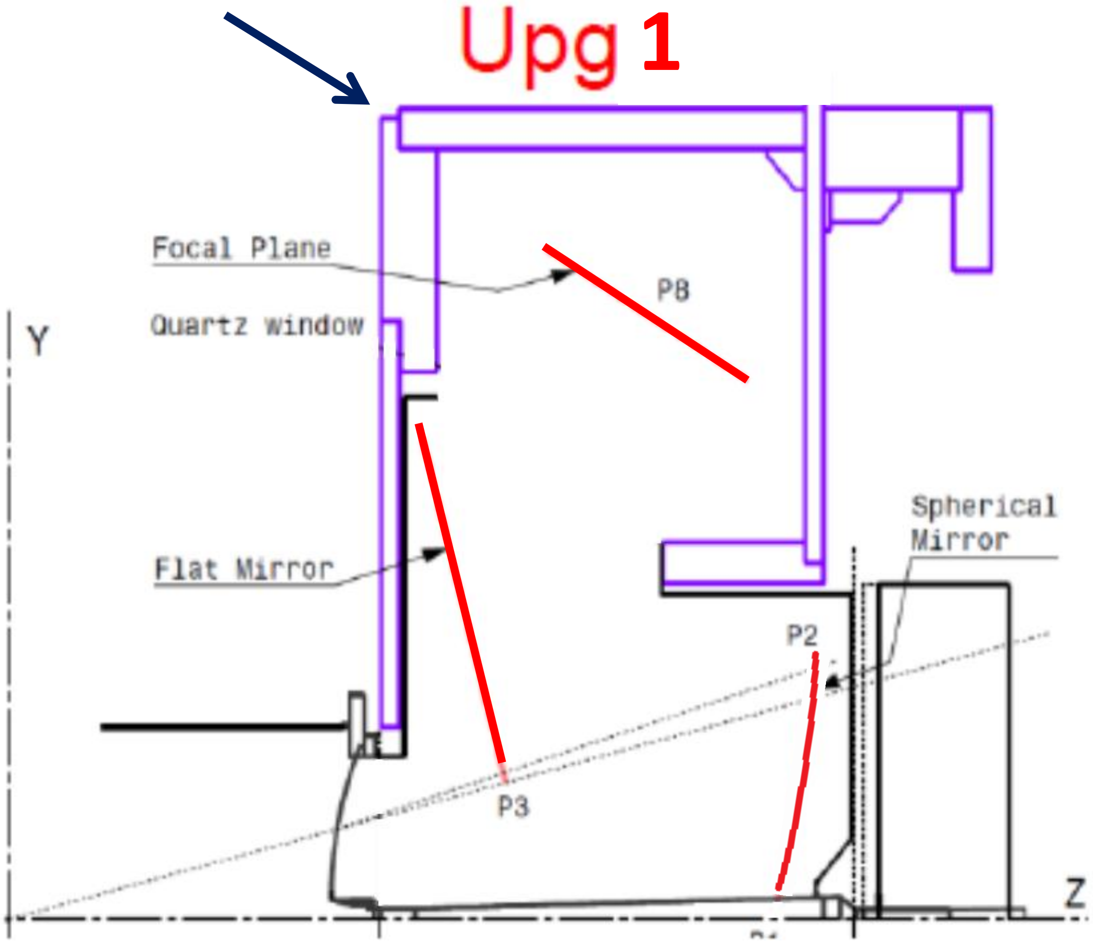
In the Upg1 RICH1, we are increasing the mirror focal length (x 2 Occupancy decrease).

Now



Focal Plane
Y
Quartz window
Lightweight CF spher. mirrors
Spherical
Mirror
Flat Mirror
250 mrad
Z

The RICH1 Magnetic Shield defines the available volume (unless it is not needed …)



VeLo detector on this side

UT on this side

With Luminosities increasing

1. Occupancies jump up: improve granularity;

$$\frac{A_p}{A_i} \propto \frac{A_p}{f^2}$$

A_p is the pixel area
A_i is the image area
f is the mirror focal length

In the Upg2 and in RICH1, we can decrease the pixel area (from ~7mm^2 to 1mm^2).

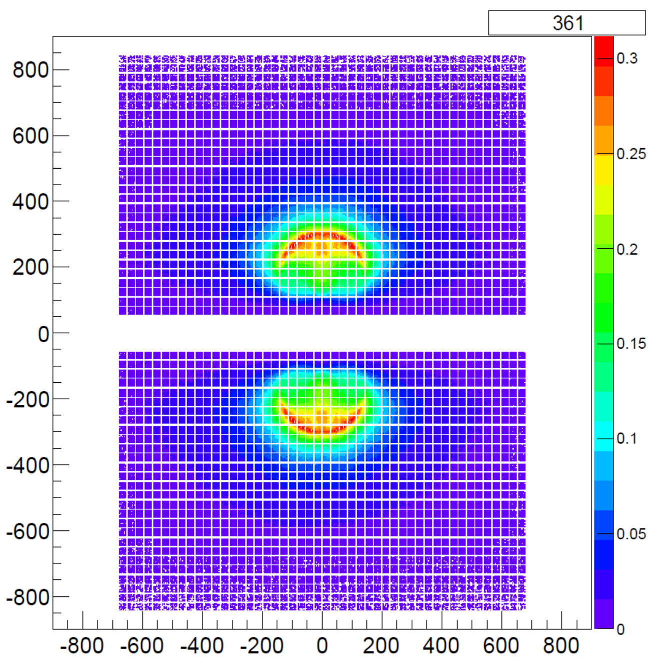
Worth noting, in some cases* a 2-bits readout can be equivalent to /4 in pixel surface.

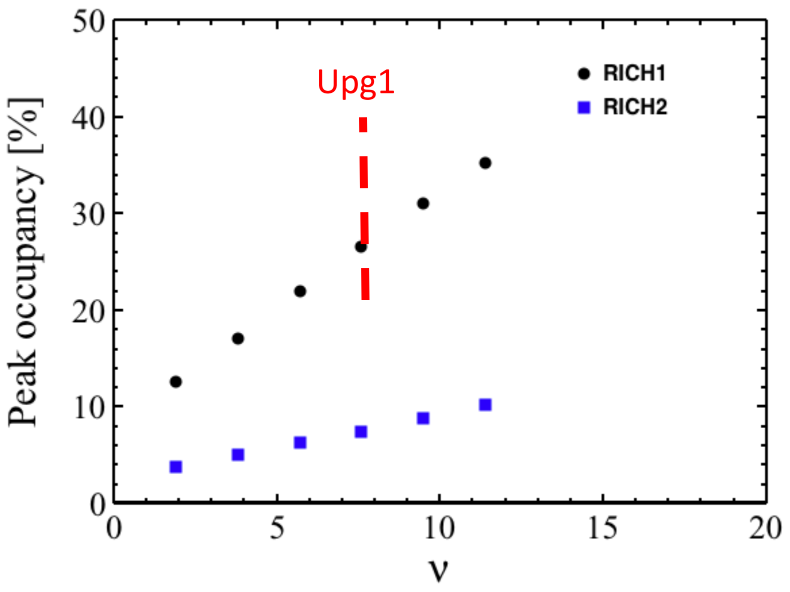
*This is strictly true for HPDs and SiPMs, where the 1st and 2nd photoelectron peaks are well separated.

Going to L = 10^{34}cm^{-2}s^{-1} increases occupancies on both RICH 1 and 2

At a ν = 38*, peak occupancies are in excess of 100% in RICH 1. However the region of extreme occupancies is limited.

XY Location of Rich1 Gas PMT hits on PMT Plane





From experience, we try to keep Occupancies always below ~30%

Present	30%	A_p=6.3mm², f=1.35 m
Upg1	½ 2 x 30%	A_p=6.8 mm², f=1.9 m
Upg2	$^{1}/_{7.5}$ 10 x 30%	A_p=1 mm², f=2 m

* $\nu = 38$ is the number of primary vertices per collision at 10^{34}cm^{-2}s^{-1} (upg2).

With Luminosities increasing

2. Pattern recognition a challenge:

Granularity is a necessary but not sufficient condition to ensure pattern recognition: improve the single photon Cherenkov angle resolution.

$$(\sigma_\vartheta \cdot f) \lesssim \sqrt{A_p}$$

Essentially keep this smaller than the pixel size!!

For Upg2*, $\sigma_\vartheta \lesssim 0.5 mrad$ (present 1.6 mrad)

σ_ϑ is the Cherenkov angle resolution
$f \sim 2m$ is the mirror focal length
A_p is the pixel area

*and for RICH1 regions with high occupancies

Improve Cherenkov angle resolution…

σ_ϑ depends on a sum (in quadrature) of uncertainties:

Pixel size, $\sim\sqrt{\frac{A_p}{12}};$

Emission Point, optical system aberrations

Chromatic dispersion, $\cos\vartheta_c(\lambda) = \frac{c}{n(\lambda)\cdot v}$

of course ultimately we want $\frac{\sigma_\vartheta}{\sqrt{N}}$

ϑ_c is the Cherenkov angle
σ_ϑ is the Cherenkov angle resolution
N is the number of detected photons
A_p is the pixel area

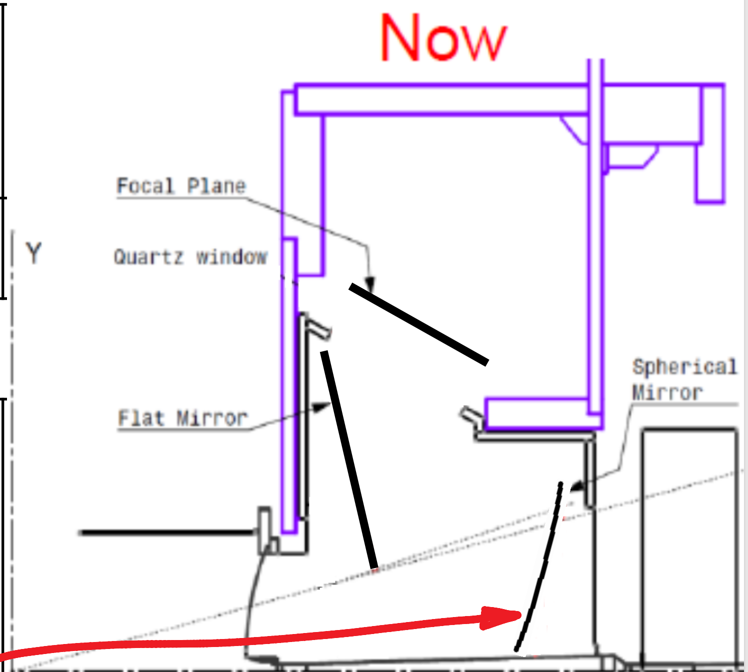
A few slides to show a possible way to improve the LHCb RICH System*

*For the sake of simplicity, let us suppose to be able to use SiPM detectors.

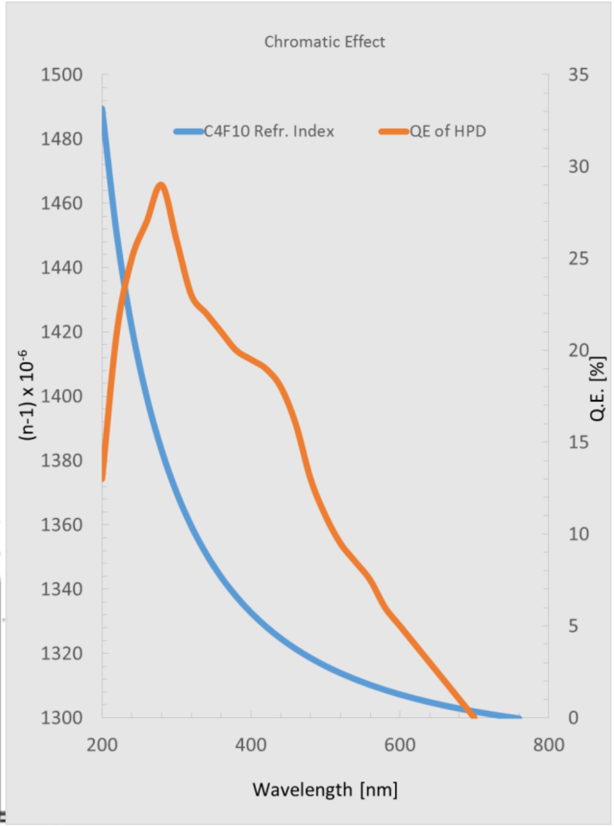
Optical Performance and Photon Yields

Lumi = 2×10^{32} cm^{-2} s^{-1} ; Occupancy < 30%

Detector Version	RICH-1 Current (HPD)
Avr. Phel. Yield	30
Single Photon Errors [mrad]	
Chromatic	0.84
Pixel	0.9
Emission Point	0.8
Track resolution	0.4
Overall	1.52



depends on spherical mirror tilt and focal length



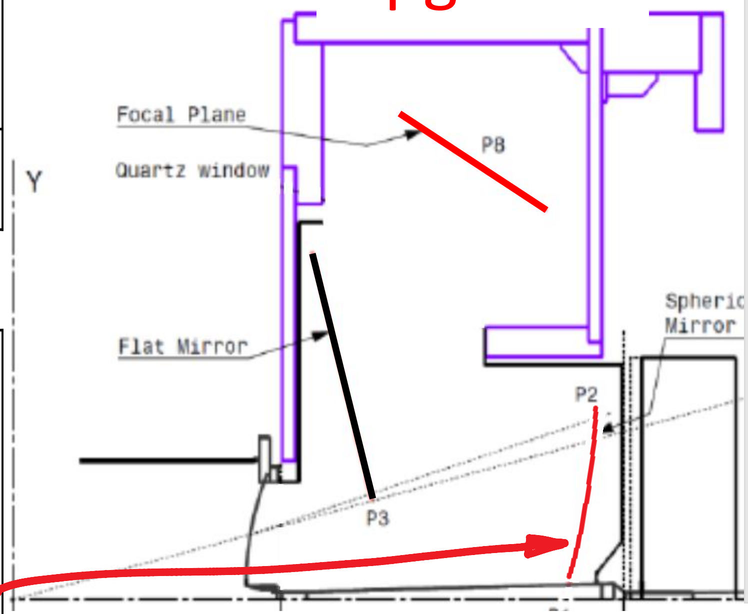
Chromatic depends on the overlap between dispersion and photodet. QE

Optical Performance and Photon Yields

Lumi ≤ 2 x 10^{33} cm^{-2} s^{-1} ; Occupancy < 30%

Detector Version	RICH-1 Upg1
Avr. Phel. Yield	40
Single Photon Errors [mrad]	
Chromatic	0.58
Pixel	0.44
Emission Point	0.37
Track resolution	0.4
Overall	0.9

Upg1



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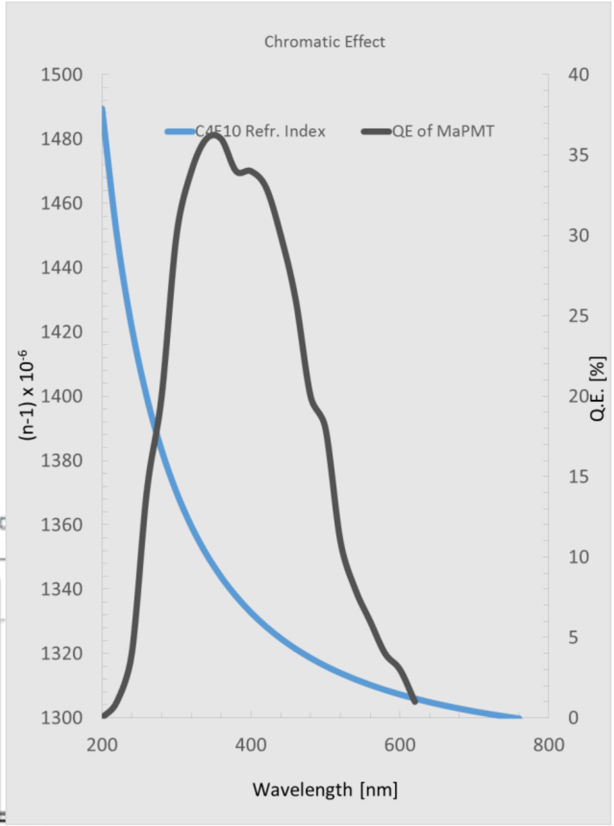


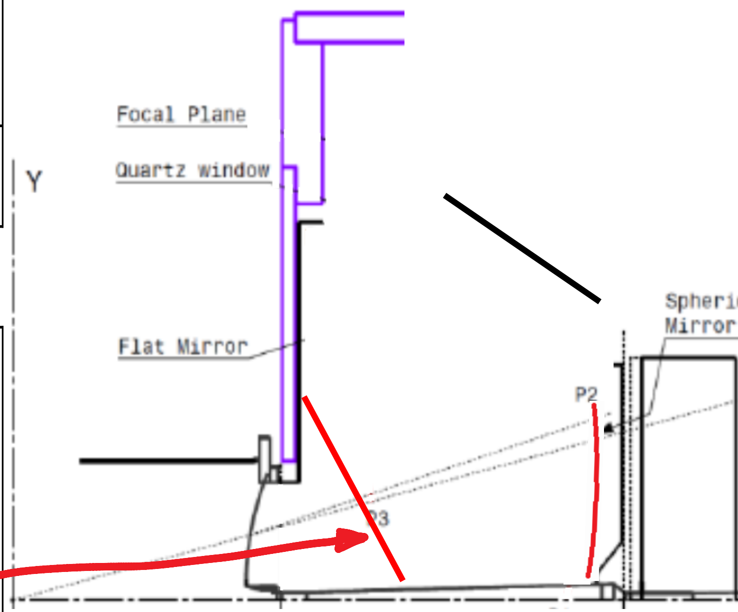
Chromatic depends on the overlap between dispersion and photodet. QE

Optical Performance and Photon Yields

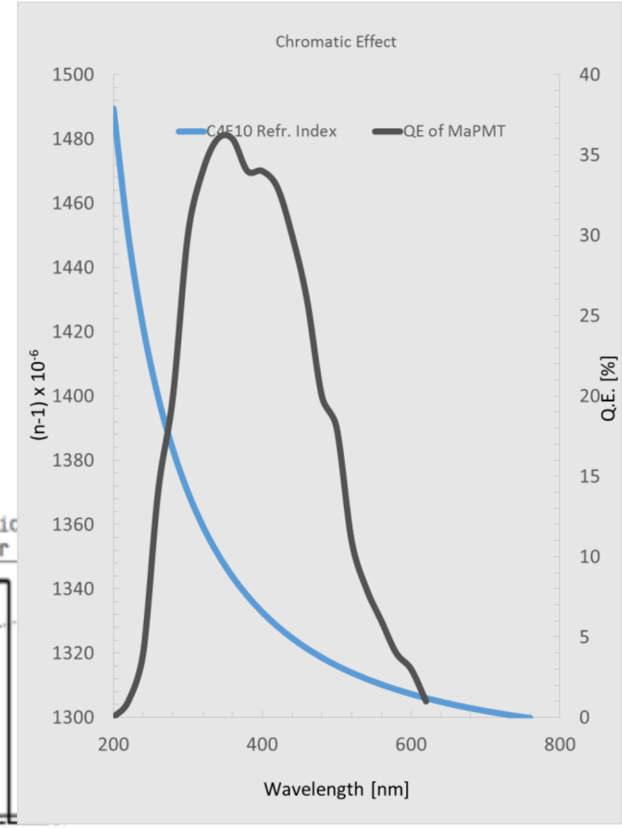
Lumi = 10^{34} cm^{-2} s^{-1} ; Occupancy > 100%

Detector Version	RICH-1 Upg2
Avr. Phel. Yield	
Single Photon Errors [mrad]	
Chromatic	0.58
Pixel	0.44
Emission Point	0.1
Track resolution	?
Overall	0.7

Upg2



Use lightweight flat mirror in the acceptance (reduce aberrations)



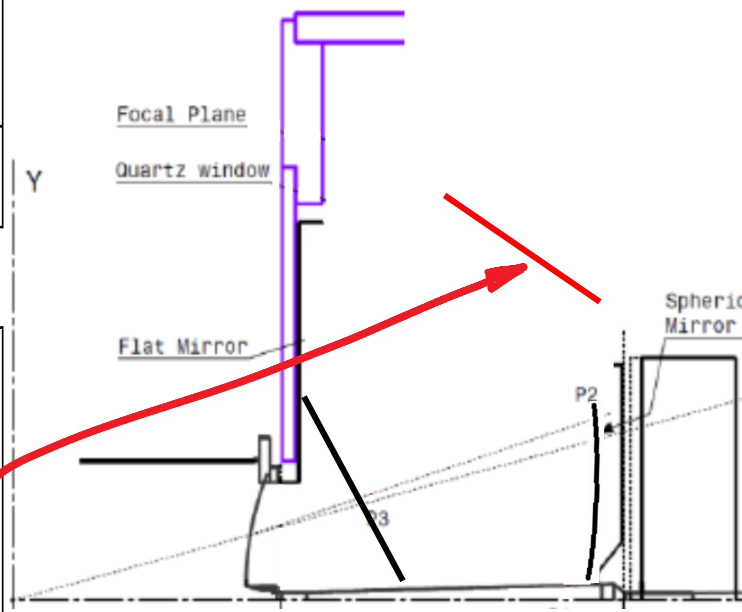
Chromatic depends on the overlap between dispersion and photodet. QE

Optical Performance and Photon Yields

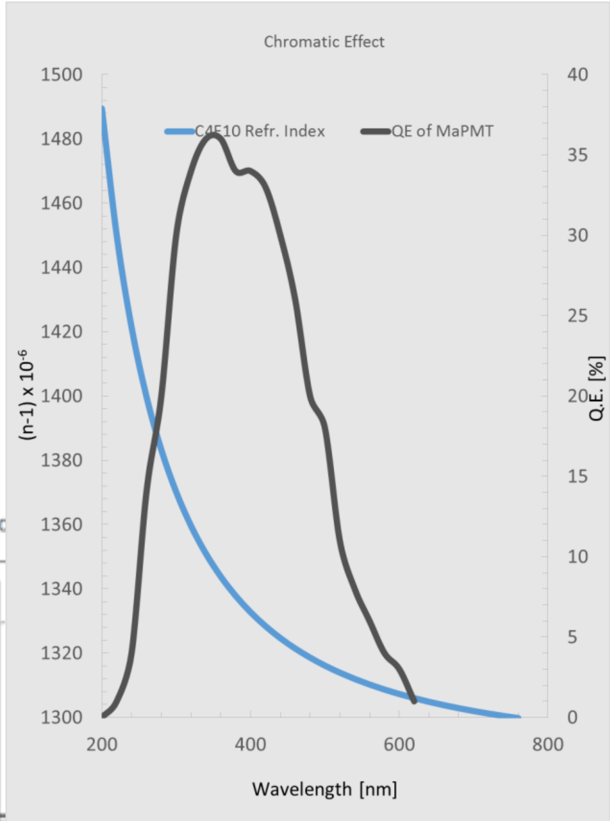
Lumi = 10^{34} cm^{-2} s^{-1} ; Occupancy < 30%

Detector Version	RICH-1 Upg2
Avr. Phel. Yield	
Single Photon Errors [mrad]	
Chromatic	0.58
Pixel	0.15
Emission Point	0.1
Track resolution	?
Overall	0.6

Upg2



Reduce pixel size to ~1mm



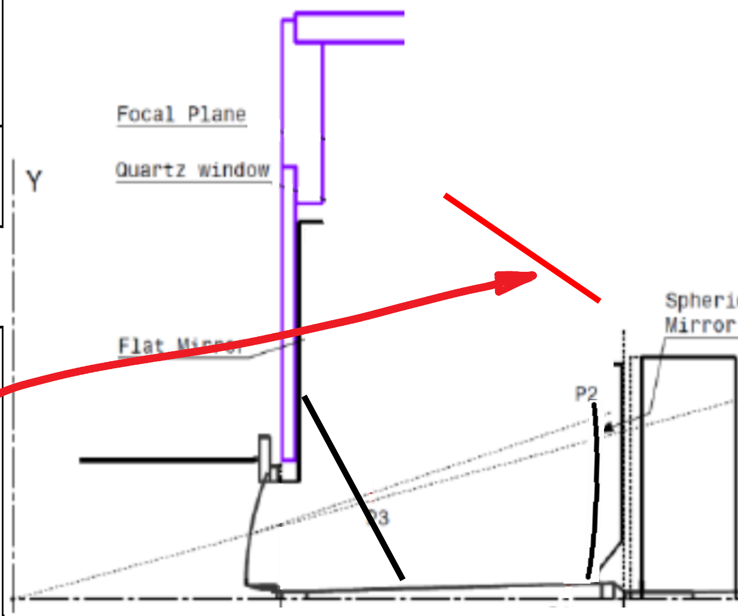
Chromatic depends on the overlap between dispersion and photodet. QE

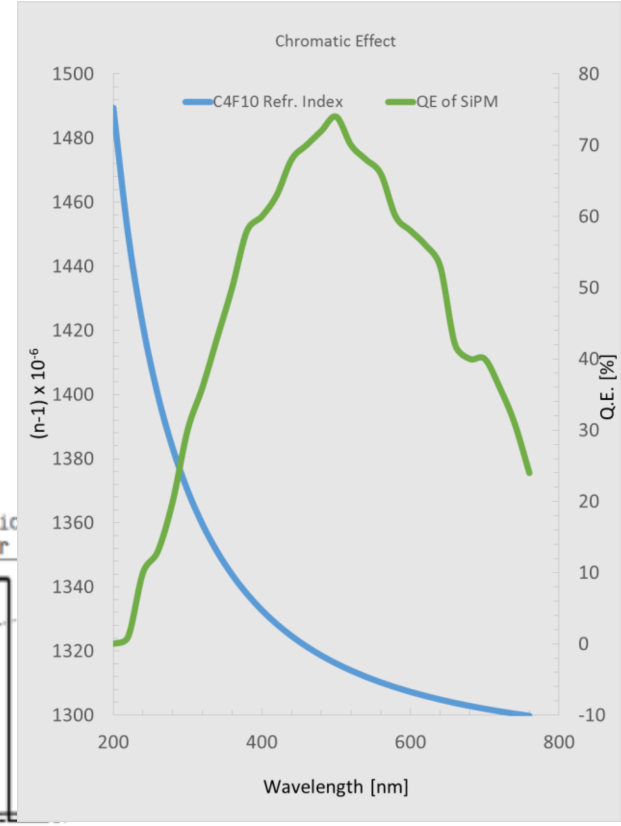
Optical Performance and Photon Yields

Lumi = 10^{34} cm^{-2} s^{-1} ; Occupancy < 30%

Detector Version	RICH-1 Upg2
Avr. Phel. Yield	60 - 40
Single Photon Errors [mrad]	
Chromatic	0.24
Pixel	0.15
Emission Point	0.1
Track resolution	?
Overall	0.3

Upg2





Reduce chromatic by choosing a photodetector with a “green-shifted” QE curve (and filter the shorter wavelengths)

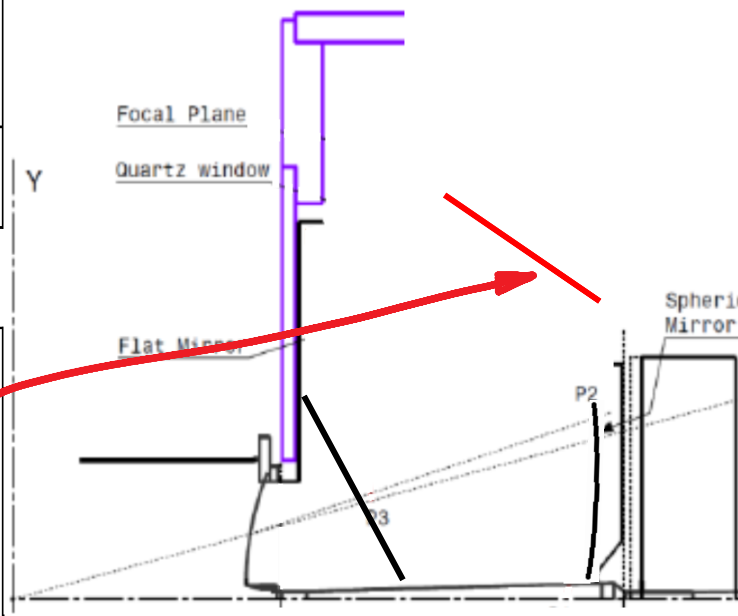
Chromatic depends on the overlap between dispersion and photodet. QE

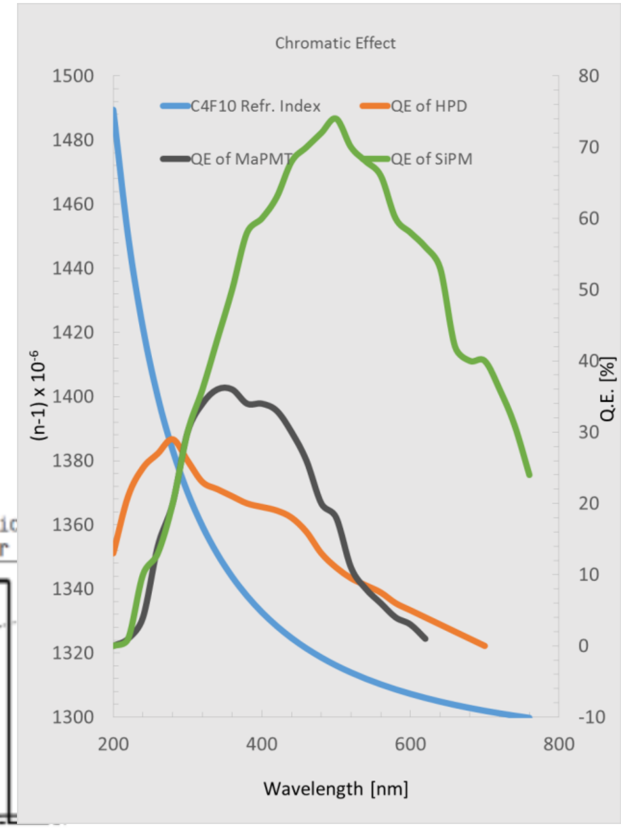
Optical Performance and Photon Yields

Lumi = 10^{34} cm^{-2} s^{-1} ; Occupancy < 30%

Detector Version	RICH-1 Upg2
Avr. Phel. Yield	60 - 40
Single Photon Errors [mrad]	
Chromatic	0.24
Pixel	0.15
Emission Point	0.1
Track resolution	?
Overall	0.3

Upg2





Reduce chromatic by choosing a photodetector with a "green-shifted" QE curve (and filter the shorter wavelengths)

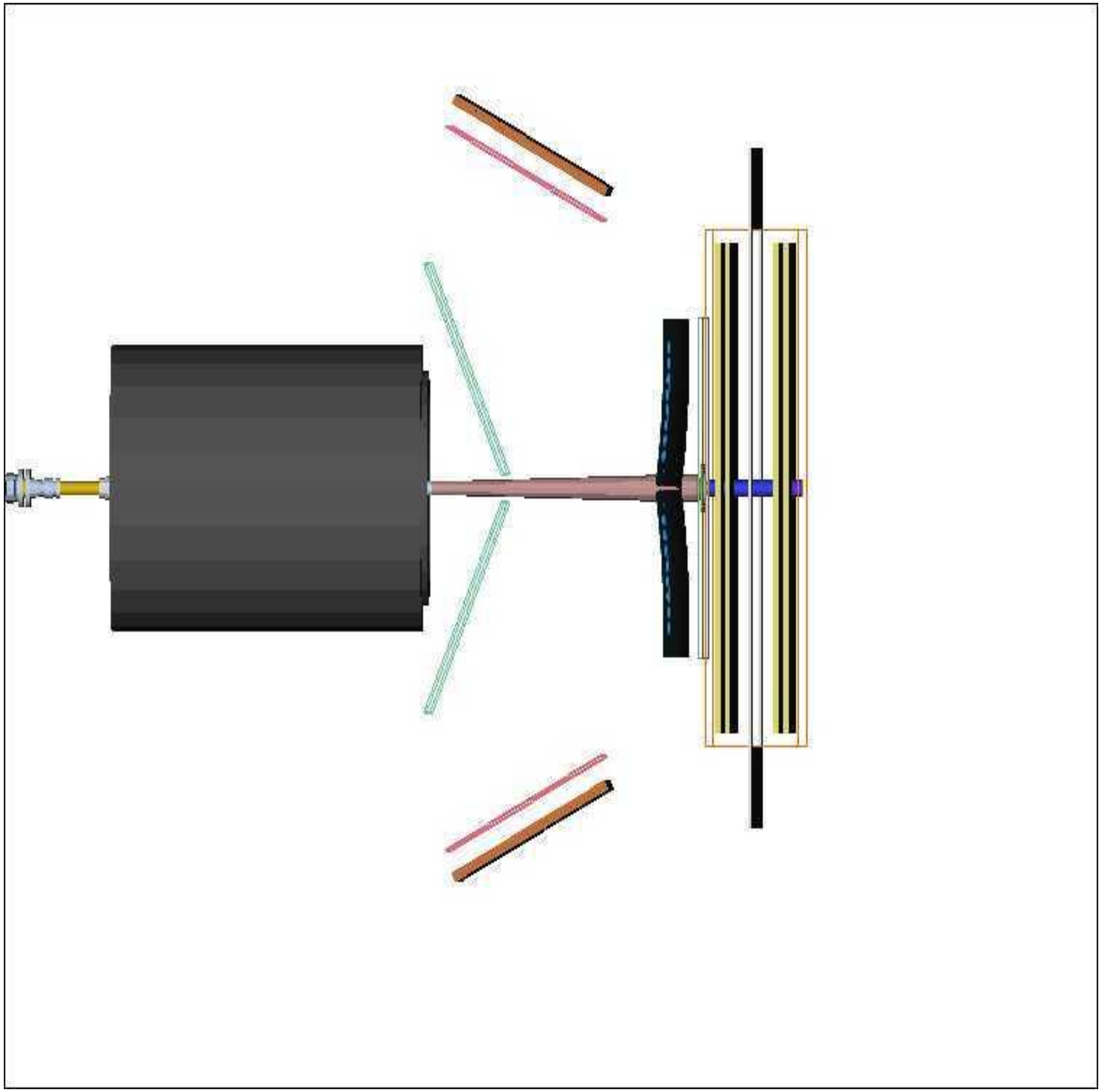
Chromatic depends on the overlap between dispersion and photodet. QE

Simulated Optical Performance and Photon Yields

Radiator	C_4F_{10}			CF_4	
Detector Version	RICH-1 Current (HPD)	RICH-1 Upg1	RICH-1 Upg2	RICH-2 Upg1	RICH-2 Upg2
Avr. Ph.Electron Yield	25 (30)*	40 (rms=8)	40 - 30	22 (rms=5)	30 - 20
Single Photon Errors [mrad]					
Chromatic	0.84	0.58	0.24 – 0.12	0.31	~0.1
Pixel	0.9	0.44	0.15	0.20	0.07
Emission Point	0.8	0.37	0.1	0.27	0.05
Track resolution	0.4	?0.4?	?0.4?	?0.4?	?0.4?
Overall	1.52	0.9	0.5 (0.3 – 0.2)	0.60	0.42 (0.13)

*Value from data (expected)

RICH1 using SiPM and improved geometry (version7, upg2)

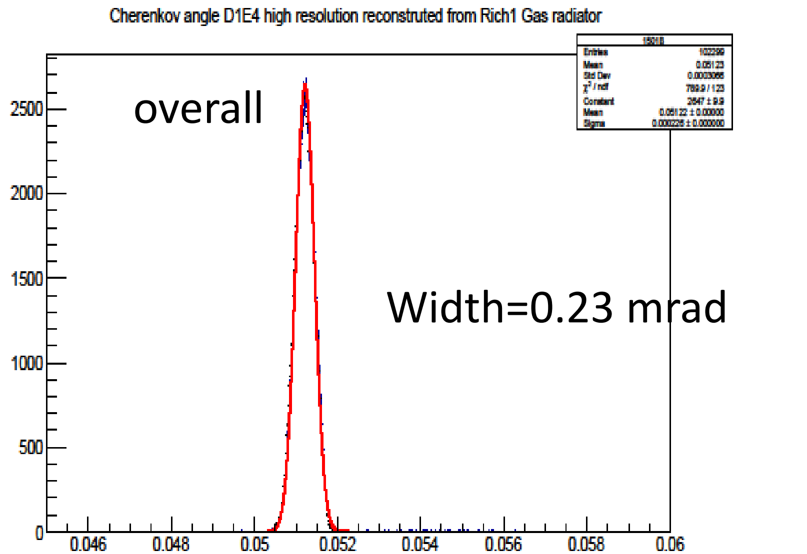


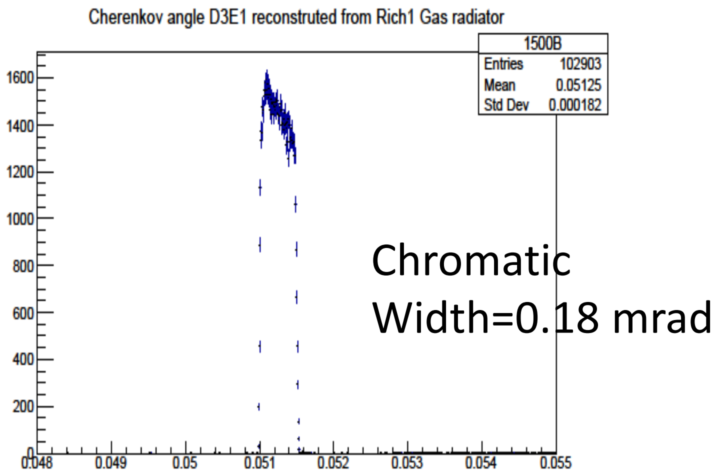
Compared to upg1:
spherical mirror tilt reduced;
flat mirror extends to the charge particle acceptance.

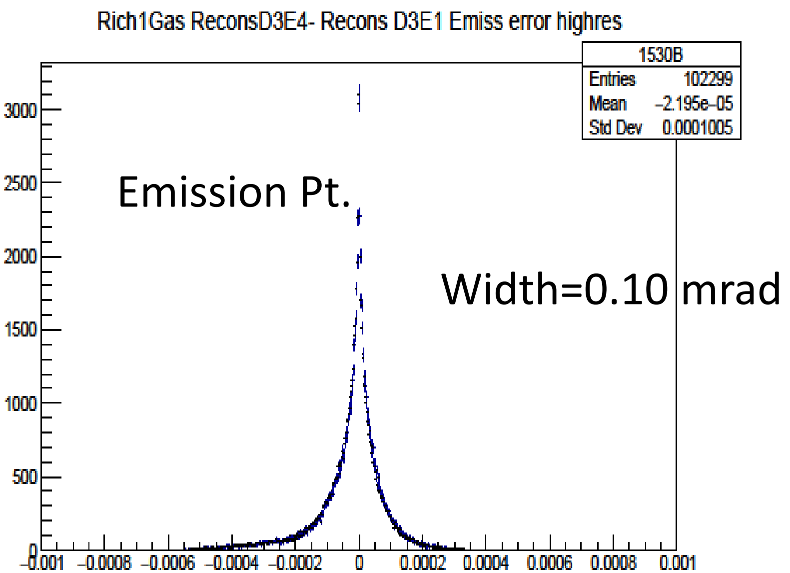
Sph Mirror RoC=3800 mm

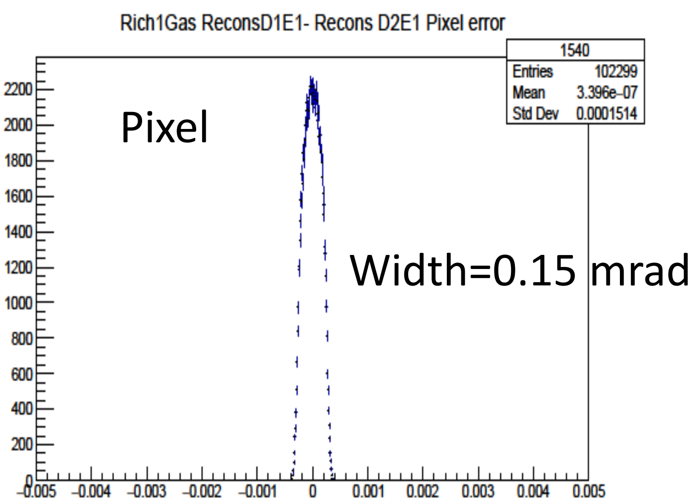
The detector plane with SiPM
SiPM pixel size = 1mm X 1 mm

RICH1 resolutions: SiPM with low WL cut-off , new geometry, upg2









Resolution is improved compared to current upgrade geometry

With Luminosities increasing

Time resolution (time granularity) will also help disentangle busy events, while delivering more information:

Provide the system with time resolution

~0.2 to 1 ns (time resolution on single photon)

and ~50 to 150 ps (time resolution with ~40 detected photons).

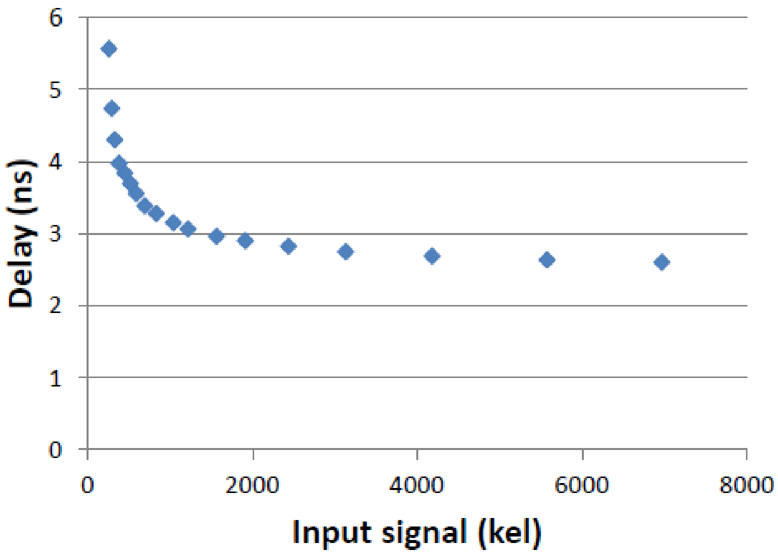
Provide a time-over-threshold information (similar to 2-bits readout).

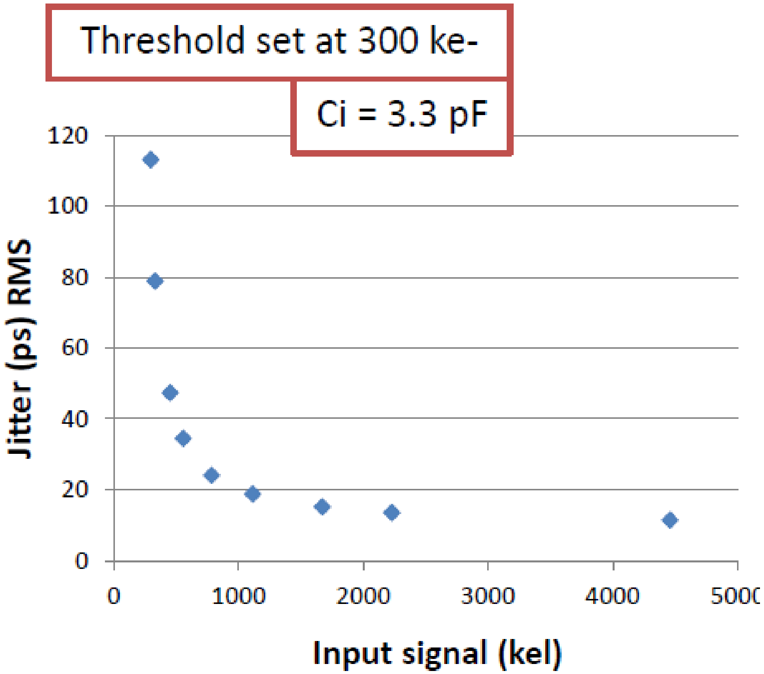
Already our existing electronics could provide figures close to the aforementioned.

Timing performance of the CLARO8 chip

Excellent timing performance at 0.7 mW/channel:

- Time walk < 3 ns
- Leading edge jitter from 110 ps RMS (just above threshold) to 11 ps RMS (large signals)





Even better berformance could be achieved by doubling the power to 1.5 mW/channel.

C. Gotti - TIPP 2014

Upg2, Run XX, 25 ns, up to 10^{34} cm^{-2} s^{-1}, 202x onwards

The recipe ☺

Increase granularity, or/and provide a 2-bits readout electronics

Improve optical error,

- by moving light-weight flat mirrors into the acceptance,
- by further reducing mirror tilts

Further reduce chromatic error

- by tuning the gas
- by further moving the photodetector sensitive region towards the green
- by increasing photodetector QE

Provide the system with time resolution

Work on new and specific pattern recognition algorithms

Perhaps get rid of the magnetic shielding by using B-insensitive photodetectors

Upg2, Run XX, 25 ns, up to 10^{34} cm^{-2} s^{-1}, 202x onwards

The shopping list ☹

Light-weight flat mirrors and supports :
CF spherical mirrors and supports already in RICH1;
First CF flat mirror prototype for RICH1 produced;
Good resistance to radiation.

Photodetectors :
Vacuum devices: MaPMTs, HPDs and MCP-PMTs with green-enhanced QE response;
Solid State: -50^{o}C cooled SiPMs (see LHCb SciFi detector);

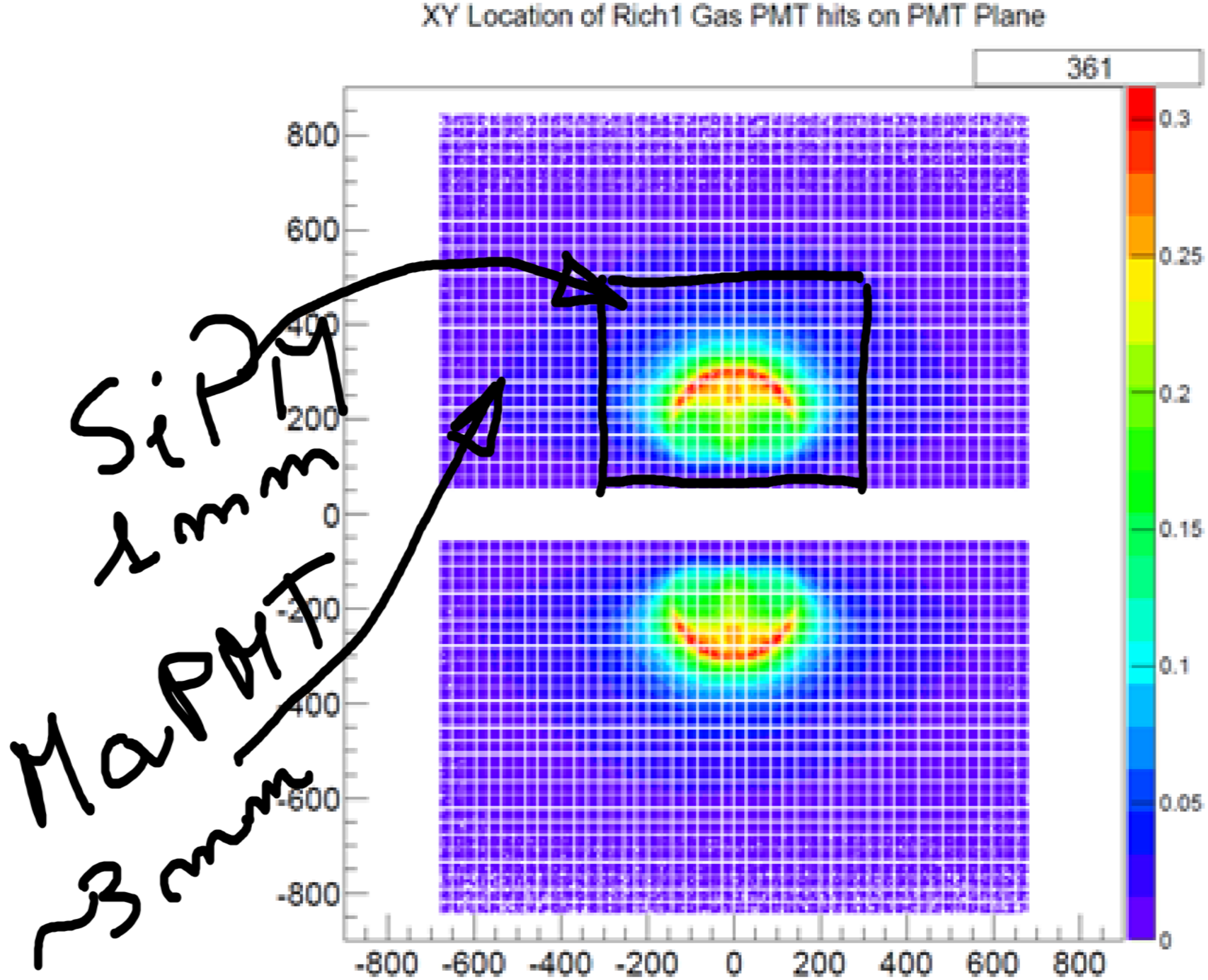
On-detector electronics with space and time resolution:
CLARO8 already features some of the needed functionalities;
The PDM Digi Board can be developed accordingly.

DAQ is a challenge; compress/reduce data on detector.
Work on new and specific pattern recognition algorithms.

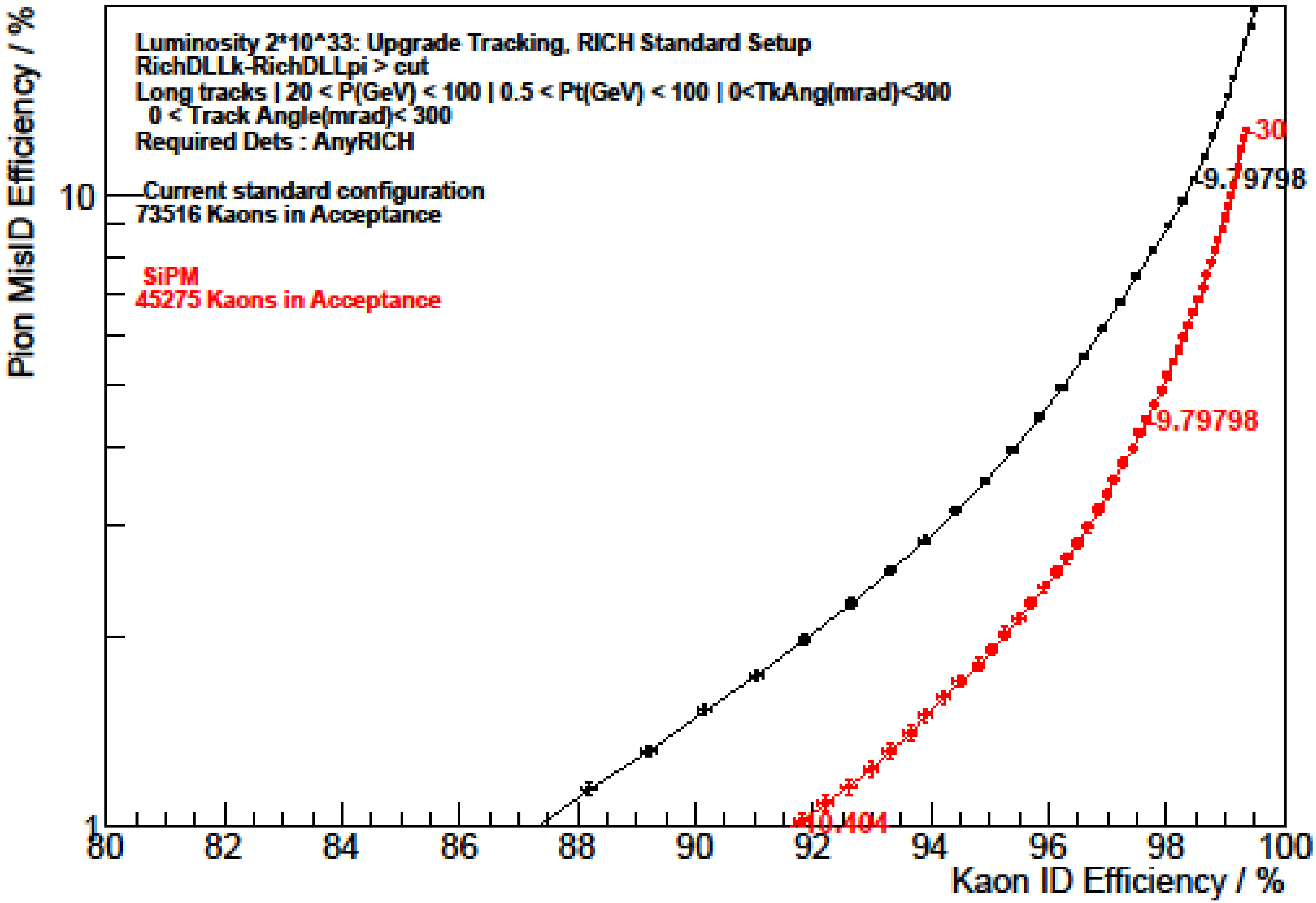
All marked in red needs R&D!!

… If we want to be ready for LS3!! … (2025, upg2a)

Perhaps only in the central regions of RICH 1



RICH Upgrade Kaon ID : RICH PID performance



Improvement in PID in the 20-100 GeV/c region,when using SiPM.

Conclusions

"The politics of small steps may nicely reward the patient ones", (from an old saying)
… especially if there is no other choice!

Through further improvements and staying in the present envelope, the LHCb RICHes could continue to perform PID efficiently at luminosities up to 10^{34} cm^{-2} s^{-1}.

The single-photon cherenkov angle resolution could be squeezed from 1.6/0.7 mrad (present system) to 0.2/0.1 mrad for RICH 1 and 2 respectively.

A critical point will be the development of green-enhanced photodetectors with high space and good time resolution.

We see the future of LHCb RICHes as high-precision, green-enhanced, compact machines.