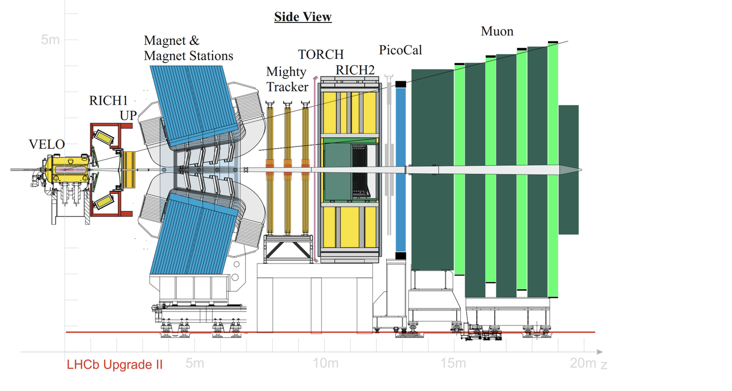
Optimized optical design of the LHCb RICH detectors for Upgrade-II

R.Cardinale, A.Petrolini, S.Pezzulo, E.Spadaro Norella*, on behalf of the LHCb/RICH group
University of Genova and INFN, Italy, CERN; *corresponding author.

LHCb Upgrade-II and RICH requirements

The LHCb experiment at CERN [1] is equipped with two RICH detectors [2, 3] for charged hadron identification. In Run3, LHCb is operating at a luminosity of 2×10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with the aim to reach a factor five improvement, in Upgrade-II, during the HL-LHC phase.



LHCb UpgradeII

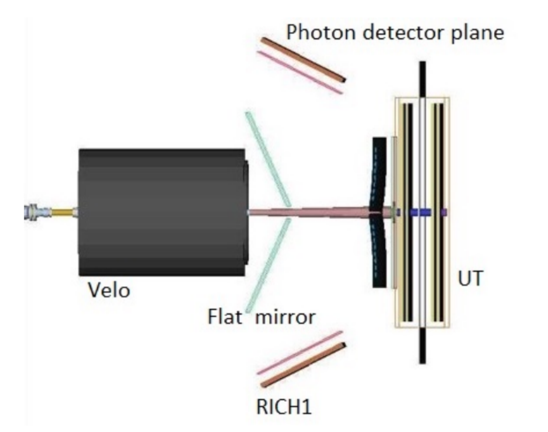
Key performance requirements for the optics of the RICH, aiming not to degrade the PID performance in the harsher conditions of Upgrade-II, include:

- Number of detected photons: $N_\gamma \gtrsim 60/30$ (RICH1/RICH2).
- Single-photon Cherenkov angle uncertainty better than $0.30/0.15$ mrad (RICH1/RICH2), a factor two better than Run 3.
- Single pixel occupancy in one BCO ≤ 0.3, as in Run 3.
- Photo-detector noise: two orders of magnitude less than the signal photons from high-momentum particles, including dark noise, after-pulses and any other correlated noise.

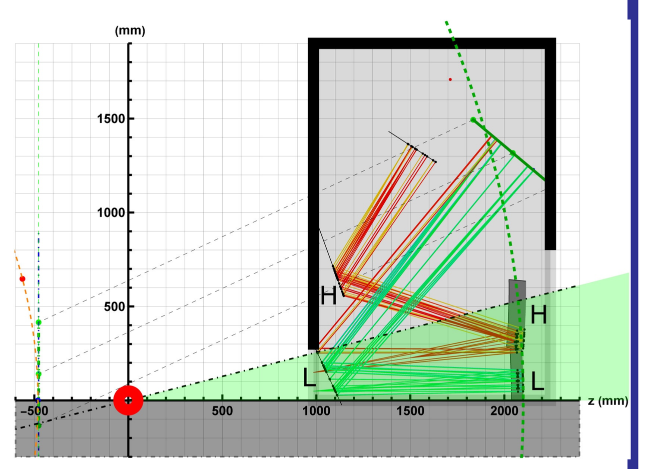
Optical layout proposals

Optics is the most important part of a RICH, driving and affecting all the design. For Ugrade II, the focal length needs to be increased to reduce the occupancy, improve both the emission point uncertainty and pixel uncertainty and leave more room for photon emission. Two layouts are under consideration:

- "FTDR" optics: lightweight monolithic mirror placed in acceptance [4];
- "split-optics" [5], with two smaller mirrors for Low/High (L/H) angle with respect to the beam to fit the large variations of occupancy, control the focusing uncertainty, reduce the size of the mirrors and increase the path length in the gas at low angles.



"FTDR" optics



"split-optics"

The two schematics are shown in the figures, for illustration purposes only.

Layout optimization

For the RICH design definition the main quantities to be optimized are:

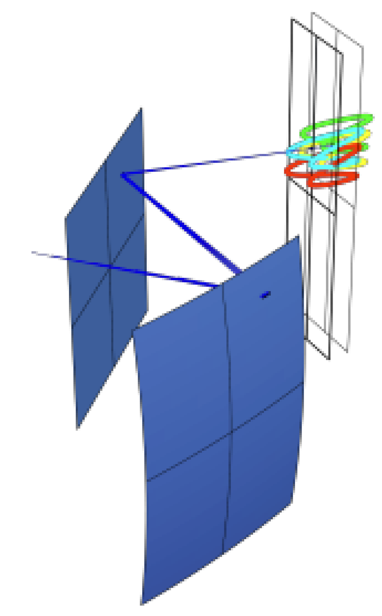
- Cherenkov angle uncertainties, mainly:
  - chromatic := standard deviation of the detected Cherenkov angle distribution;
  - pixel:= $d/(f\sqrt{12})$, d pixel size;
  - emission point (focusing/optical aberration) := for each track, the radial distance on the PDA (converted to angle) between photons emitted at the start and end of the radiator (averaged on azimuth and on tracks).
- Yield and signal versus background/noise. Detected photon yield per unit path length:

$$\frac{dN_{pe}}{dL} = \alpha \int \epsilon(E,\ldots)\sin^2\theta_C dE,$$

where $\alpha = 370\mathrm{cm}^{-1}\mathrm{eV}^{-1}$, $\epsilon(E,\ldots)$ includes the photon losses from emission to signal recording in the readout, such as: photo-detector efficiency, geometrical acceptance, front-end efficiency, dead times and reflectivity and transmissivity of optical components,...

- Occupancy.

Focusing is not perfect for photons emitted at the same θ and ϕ Cherenkov angles. Moreover, the optimal focus for fixed azimuth (i.e. parallel) photons happens at different depths for different azimuths; that is, even for a single ring, the best focus is not on a plane.

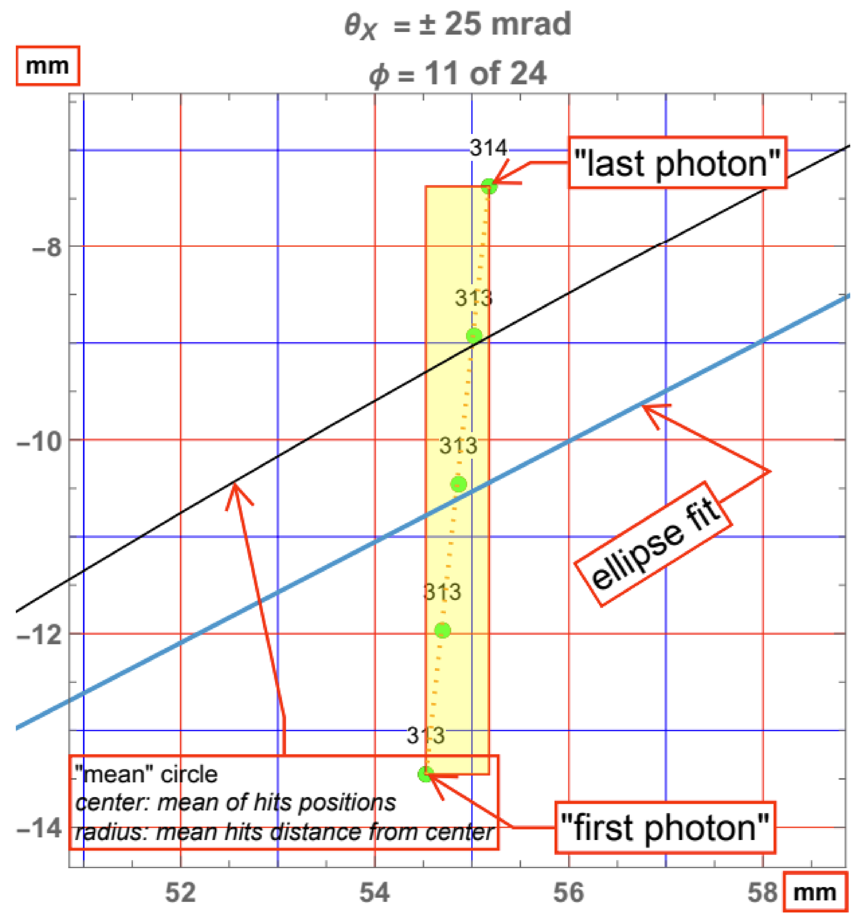


Optimal focus points as a function of azimuth for four different tracks (red, green, yellow, cyan).

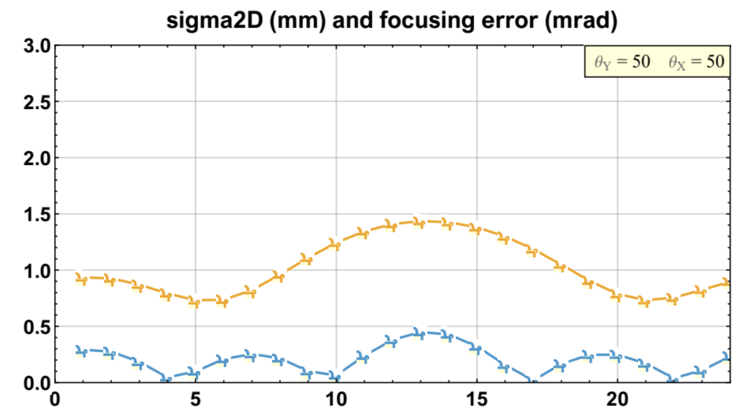
Tool: OpticaEM© [6] is a fully flexible and customizable framework for optics (geometrical and wave) calculations.

Emission point uncertainty

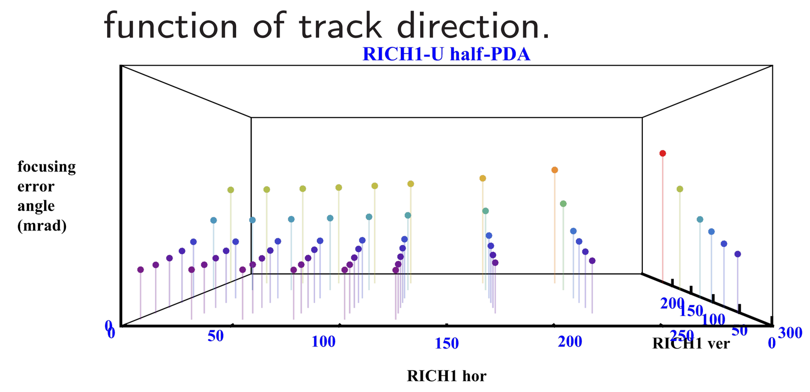
1. For one track, at fixed ϕ a typical layout:



2. Emission point uncertainty versus azimuth: sigma2D (orange) is the standard deviation on PD, focusing uncertainty is cyan.



3. Average on azimuth for each track, as a function of track direction.



RICH 1

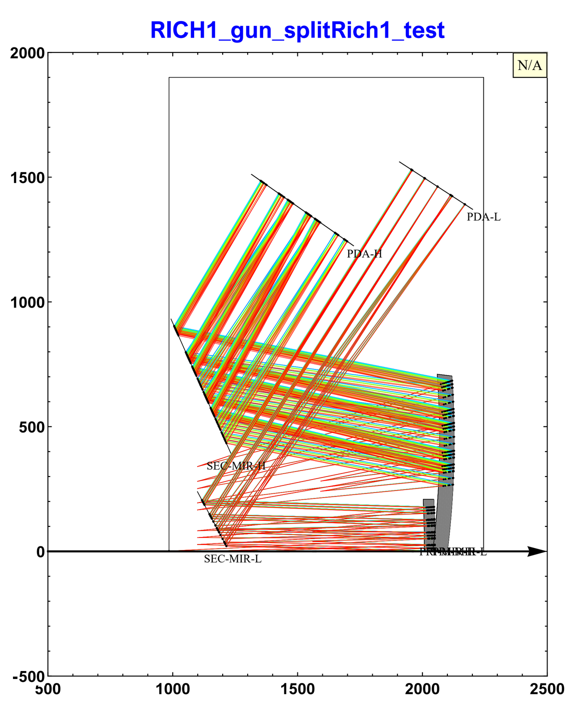
Performance with respect to Run3 (PD sensor = MaPMT):

- **Increase in photon yield**: Mirror Low as close as possible to VELO entrance window to increase gas radiator length with respect to FTDR-optics
- **Reduction of emission point uncertainty**: Mirror Low is inside acceptance allowing reduction of the tilt of primary mirror for small angles
- **Uniform occupancy**: larger focal length/aperture for small angles

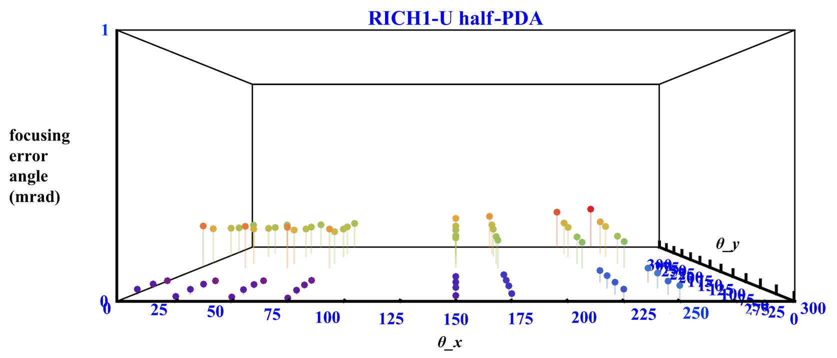
RICH 1 characteristics for low (L) and high (H) regions as for **middle scenario**

- Inner area L = 1/4
- Spherical Mirror ROC (L/H): 5/3.65 m ($\mathrm{ROC}_L \sim \mathrm{ROC}_H \times \sqrt{2}$)
- Photo-detector: SiPM, pixel size = 2/2.8 mm (L/H)

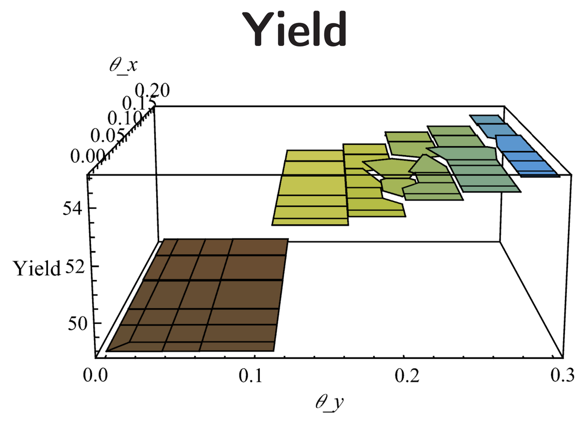
RICH1 (C_4F_{10})
p in 2 - 40 GeV/c
25-300 mrad



Emission point uncertainty



Yield



Results

- Yield increases by $\sim 30\%$.
- Cherenkov angle uncertainty is reduced by a factor of two.

Layouts (L/H)	Run3	Split-Optics
PE yield	38	**49/54**
Chromatic uncertainty (mrad)	0.69	0.36
Emission uncertainty (mrad)	0.22/0.36	0.03/0.16
Pixel uncertainty (mrad)	0.47	0.15/0.47
Total uncertainty (mrad)	0.86/0.91	**0.39/0.61**

RICH 2

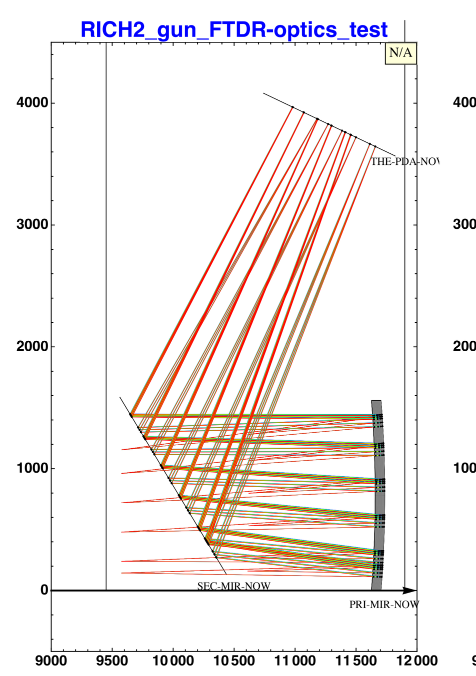
Performance with respect to Run3

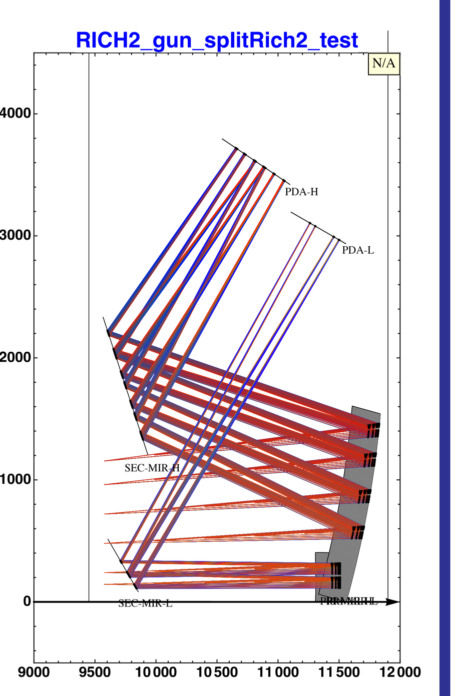
- Increase PID performance for high momentum tracks ⇒ increase yield with split-optics layout
- Rebuild RICH2 vessel to give space to TORCH [3] ⇒ opportunity for new optics optimization.

RICH 2 characteristics for low (L) and high (H) regions as for **middle scenario**

- Inner area L = 1/4
- Focal length: f_L = 5m
- Photo-detector: SiPM, pixel size = 2/2.8 mm (L/H)

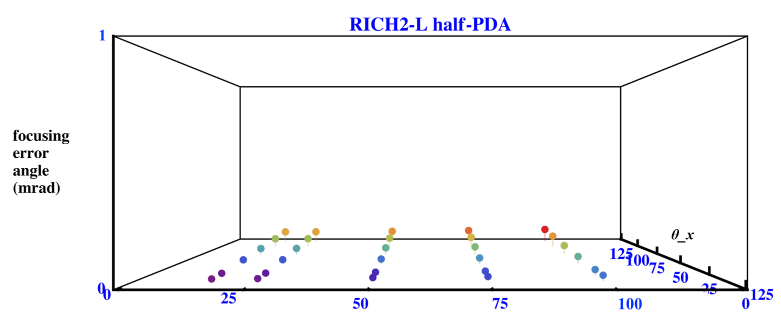
RICH2 (CF_4)
p in 15 - 100 GeV/c
15-120 mrad



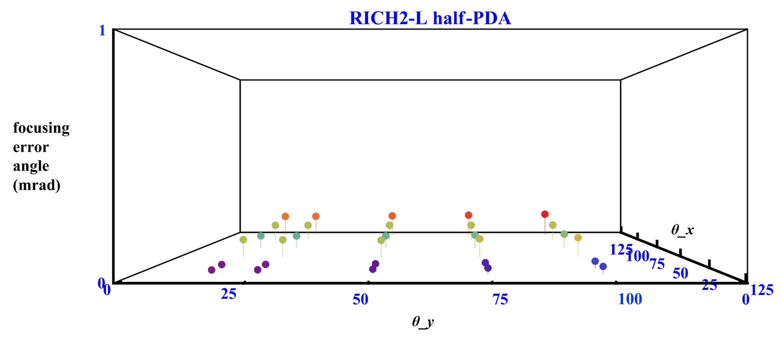


Emission point uncertainty

FTDR

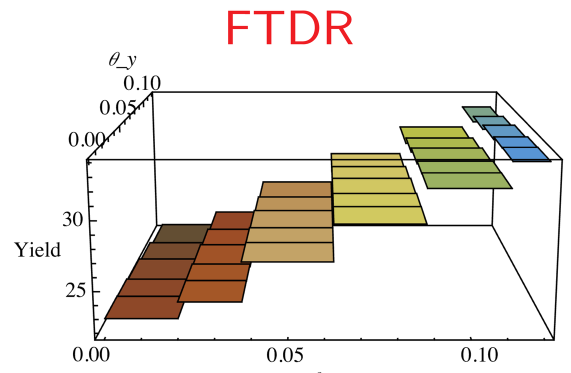


Split-optics

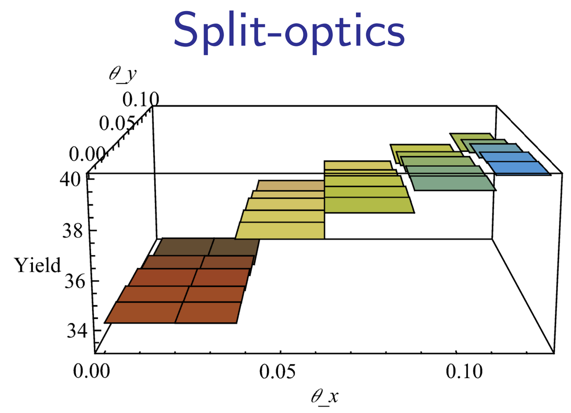


Yields: 15%-25% increase for H and L

FTDR



Split-optics



Results

- **Yield**: Split-optics can achieve 25% increase in photon yield for Low angle tracks.
- **Cherenkov angle uncertainty**: ×2 improvement with respect to Run3 → Emission point uncertainty comparable in the two scenarios
- Same ring uncertainty

Layouts (L/H)	Run3	FTDR	Split-Optics
PE yield	26/33	**23/30**	**34/38**
Chromatic (mrad)	0.27	0.15	0.15
Emission (mrad)	0.18	0.03	0.02/0.1
Pixel (mrad)	0.20/0.40	0.13/0.16	0.13/0.18
Total uncertainty (mrad)	0.38/0.52	**0.20/0.22**	**0.20/0.25**

Full simulation with DD4hep

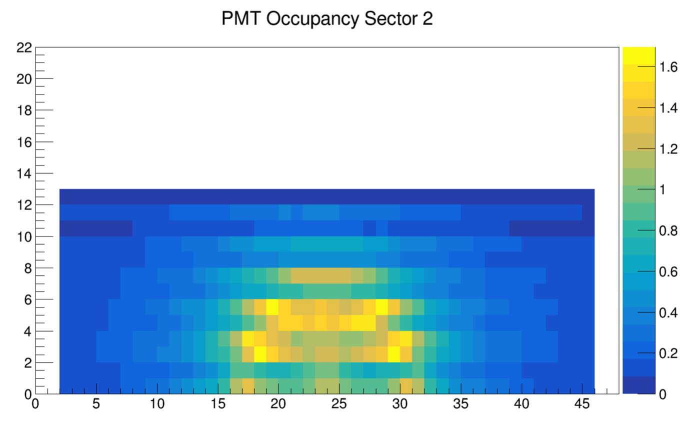
Validation of performance using full simulation: geometry based on DD4hep [7] and simulation on Geant4.

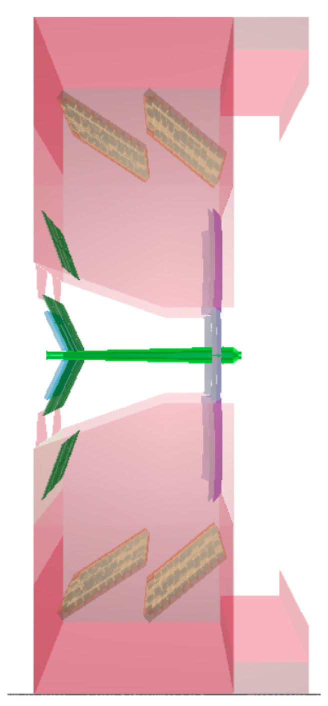
- **Yields and Cherenkov uncertainties**: PGun of 80 GeV muons uniformly distributed in Rich1 acceptance
  - Loss of 20% photon yield with FTDR optical geometry wrt Run3
  - Better Cherenkov angle uncertainty of split-optics wrt FTDR
- **Occupancy**: minimum bias sim. at Run3 conditions, rescaled to U2

Sector	Max Occupancy in U2
High	17.5% [a]
Low	10% [b]

[a] (occupancy*100/64), 3x3 mm pixel
[b] (occupancy*100/625), 1x1 mm pixel

Occupancy Low Sector





RICH1 in DD4hep

References

[1] The LHCb collaboration, R. Aaij *et al.*, *The LHCb upgrade I*, JINST **19** (2024) P05065, arXiv:2305.10515.
[2] R. Calabrese *et al.*, *Performance of the LHCb RICH detectors during LHC run 2*, JINST **17** P07013.
[3] LHCb collaboration, Aaij, Roel , *LHCb Upgrade II Scoping Document* , CERN, Geneva, 2024. doi: 10.17181/CERN.2RXP.HDK0.
[4] The LHCb collaboration, Aaij, Roel et al. , *Framework TDR for the LHCb Upgrade II*, CERN-LHCC-2021-012, LHCb-TDR-023, CERN, 2021.
[5] R. Cardinale and A. Petrolini, *Optical systems for future ring imaging cherenkov detectors*, Nucl. Instrum. Meth. A. **1055** (2023) 168481.
[6] D. Barnhart, *OpticaEM©*, https://www.opticasoft.com/.
[7] M. Frank, F. Gaede, M. Petric, and A. Sailer, *Aidasoft/dd4hep*, 2018. webpage: http://dd4hep.cern.ch/, doi: 10.5281/zenodo.592244.