Optical Systems For Future RICH Detectors

R. Cardinale, A. Petrolini - on behalf of the LHCb/RICH collaboration.
University of Genova and INFN, Italy; CERN - European Laboratory for Particle Physics.

ABSTRACT

Optical systems for RICH detectors have historically taken a variety of designs. Nowadays, technological developments allow more flexibility in the design and construction than allowed in the past, such as lightweight secondary mirrors to be placed in acceptance, widespread use of non-spherical optical surfaces, flexible and fast tools for parametric optimization of the optical systems before feeding into a full detector simulation. Within this context, the design of the LHCb/RICH optical system for the current Run-3 data-taking of the LHC which is starting now, will be presented and compared to the parametric design of the proposed optics for Upgrade II during the HL-LHC phase.

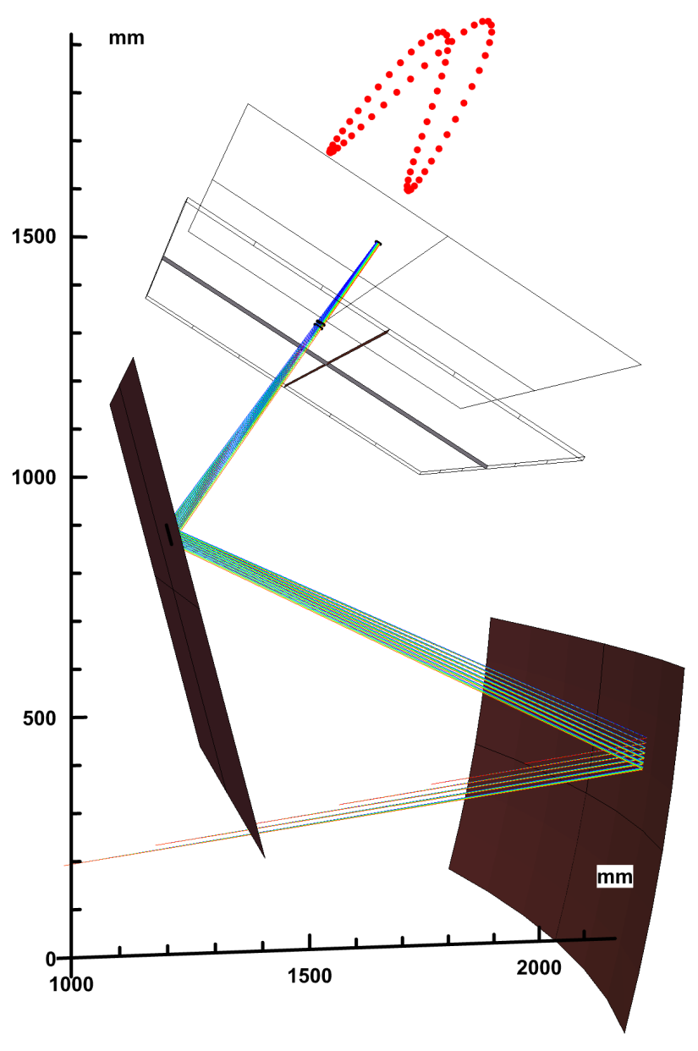
MOTIVATIONS

- The two RICH detectors of the LHCb at CERN are described in [1,2]; the optics of RICH1 is presented.
- In a RICH detector, optics is affecting all major detector performance figures and uncertainties.
- The Cherenkov emission is a rather peculiar type of light source and standard optics methodologies for studying aberrations are not directly applicable to a RICH.
- Specific merit functions must be used to quantify the performance of the optics.
- A plane focal surface is commonly used, because the photon detector has to be placed there. The orientation of the plane detector breaks the spherical symmetry, introducing a privileged direction and allowing to unambiguously define the optical axis of the RICH optics.
- Practical problems usually prevent a design such that the optical ray-tracing can be treated as a paraxial one, that is with photon trajectories having small impact parameter with respect to the center of curvature and small angle with respect to the optical axis.

FOCUSING UNCERTAINTY IN A RICH DETECTOR

- Design and understanding a particle detector requires a careful identification, understanding and modeling of the different measurement uncertainties, in order to be able to disentangle the different effects and to direct the efforts in the correct directions.
- The design of a particle detector starts from parametric studies, in order to set approximate values for the main detector parameters, restricting the range of variability of the parameters to a set manageable with full Monte Carlo simulations.

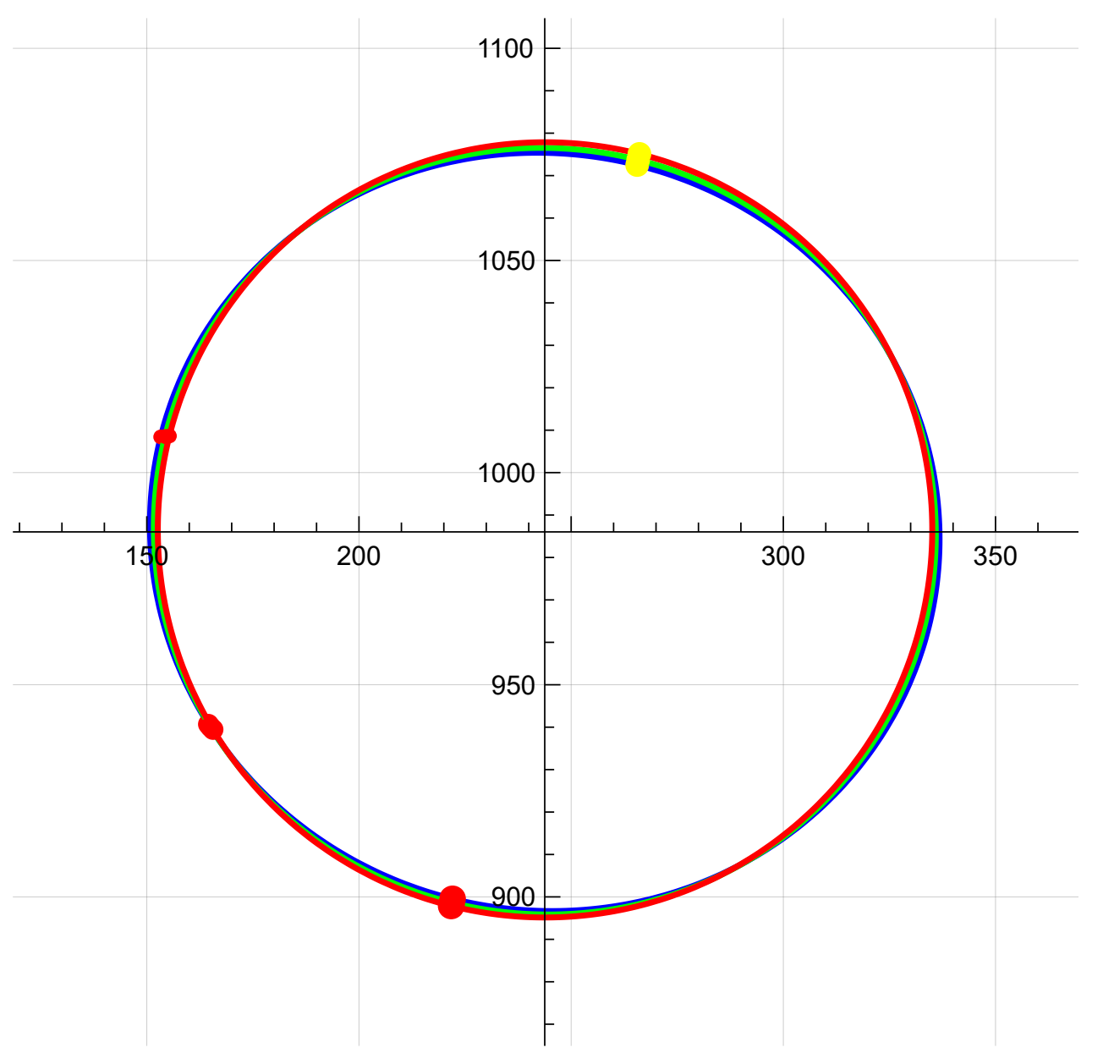
FIGURE 1



- Optics determines directly the focusing uncertainty, given that focusing is not perfect for photons emitted at the same polar and azimuthal Cherenkov angles by a particle moving in a straight trajectory, due to the usually non-paraxial light ray trajectories and to the plane photo-detector approximating the ideal focal surface. The latter is not in general a spherical one, due to the large and varying impact parameters. Therefore emissions at a fixed polar Cherenkov angle, but different Cherenkov azimuth angles, do not reach a best focus, though not ideal, neither on a plane nor on a spherical surface. An example of a 3D focus is shown in figure 1, where each red dot represent the best focus for Cherenkov photons emitted by a straight track at fixed polar and different azimuth angles. For a typical track in RICH1 the best-focus points at different Cherenkov azimuth fill a 3D region of approximate size of $(0.2 \div 0.3)$ m.

- Any uncertainty in the Cherenkov angle measurements should be expressed as angle. However, given that it is measured via the position on the photo-detector, and that the effective pixel size is often determined by extrinsic factors, results are often presented in terms of distances in the photo-detector and one should not forget that the two are related by the effective focal length.
- In order to fine-tune the relative magnitude among focusing, chromatic and pixel uncertainties, emission point displacements azimuth curves on the focal plane detector are necessary, as shown by the Cherenkov rings in figure 2, for photons emitted at three different positions along the particle trajectory.

FIGURE 2

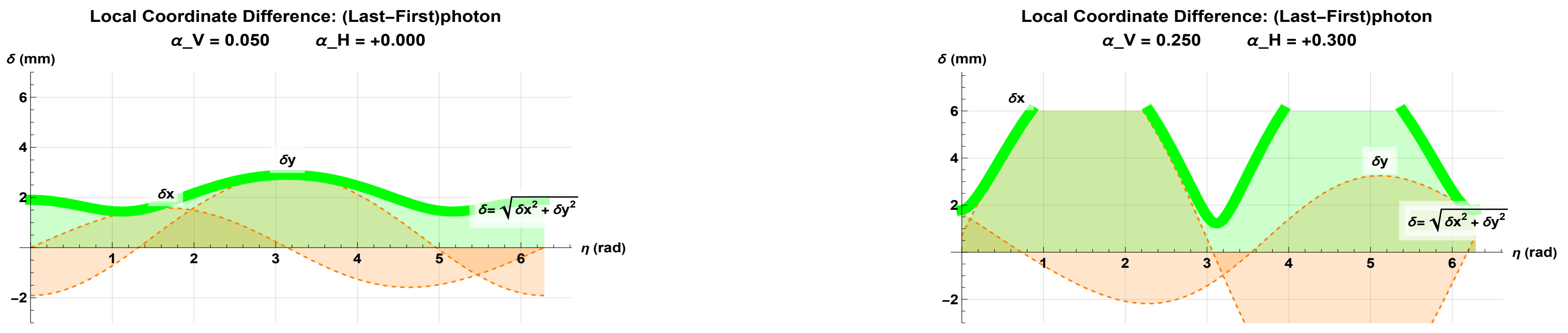


- Focusing is shown to strongly depend on the Cherenkov azimuth angle and this dependence, in turn, depends on the particle trajectory. While a uniform uncertainty in the polar Cherenkov angle is often assumed for different azimuth angle, this is clearly not true ad information provided by the RICH is therefore lost.

OPTICAL PERFORMANCE OF LHCB/RICH1-2022

- From the emission point displacements azimuth curves one can quantify the performance of the optics.
- A sensible merit function is the maximum distance on the focal plane detector of any two photons emitted at the same Cherenkov polar and azimuthal angles at different position along the particle trajectory, averaged in azimuth.
- This is shown in the figures 3 for particle trajectories at smaller (left figure) and at larger (right figure) angles from the beam axis; the worsening focusing capabilities of the optics while increasing the particle angle are visible and can be measured and modeled.

FIGURE 3



Photon hits for particle trajectory at small (left) and large (right) angles with respect to the beam-line.

- Clearly, the above figures are essential in the definition of the effective pixel size, which has to be comparable with the focusing uncertainty. In fact, due to the small number of photons typical produced by a RICH, no gain is expected by over-sampling with a smaller effective pixel size.
- The performance of the LHCb/RICH1-2022 optics is summarized in table 1 and compared to the that for Upgrade II.

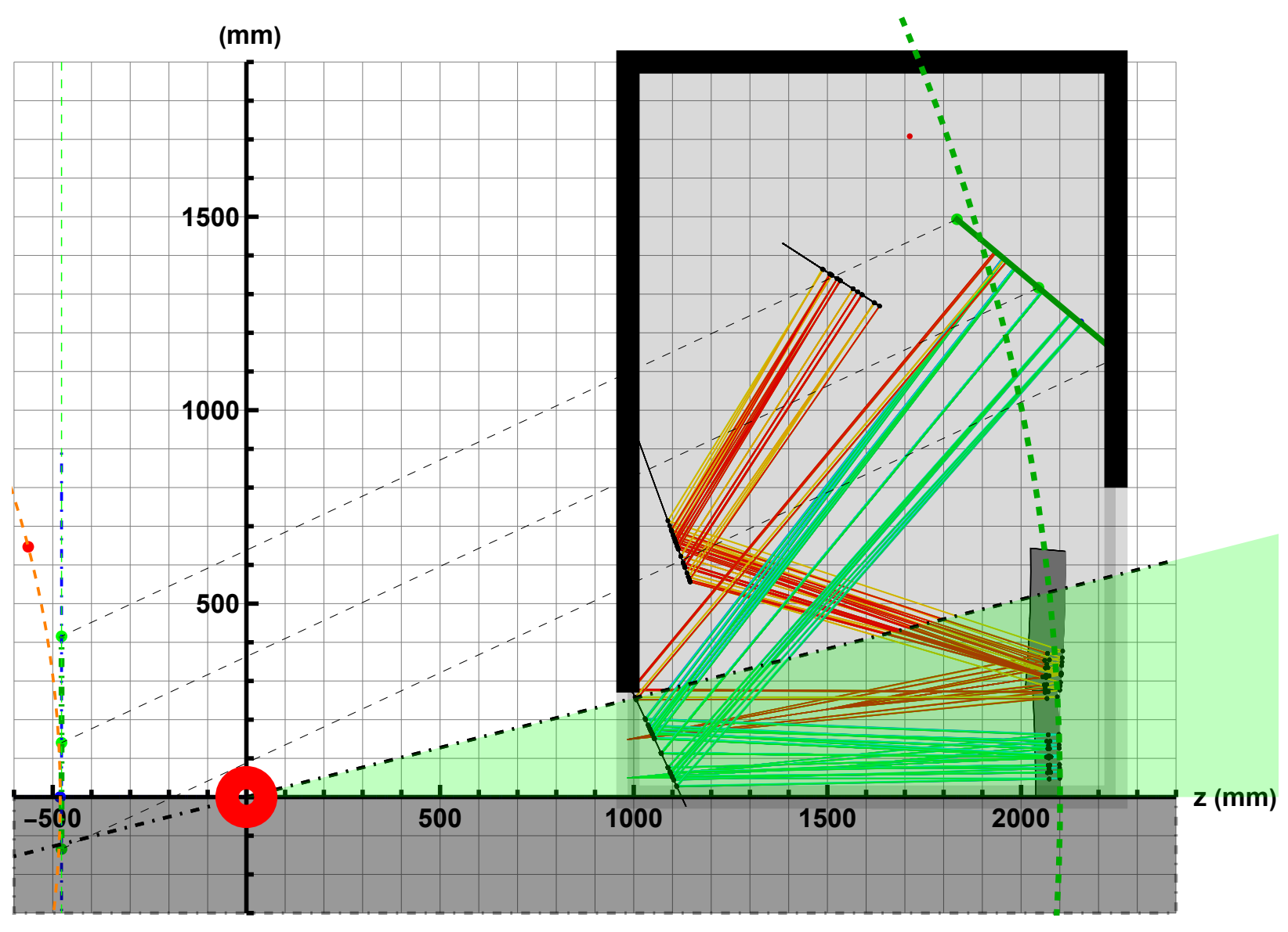
IMPROVING THE OPTICAL PERFORMANCE OF RICH DETECTORS

- With one spherical mirror, focusing can be improved only by reducing the impact parameter of the photon trajectory with respect to the center of curvature while ensuring a nearly normal incidence on the flat photo-detector.
- In HEP experiments, many practical considerations came into play, such as the impossibility to increase the radius of curvature at will.
- Nowadays, it is conceivable to place inside the geometrical acceptance not only the primary mirror, but also the secondary flat one, permitting to reduce the tilting of the mirror, at least for a small angular region.
- Many possibilities exist to improve the focusing including segmented optics (with changing optical properties), helping focusing by allowing light-weight optical components to be placed inside the geometrical acceptance, using non spherical surfaces, including aberration correcting elements. In the rest of the poster it is shown that implementing the first two possibilities is sufficient to obtain an excellent performance.

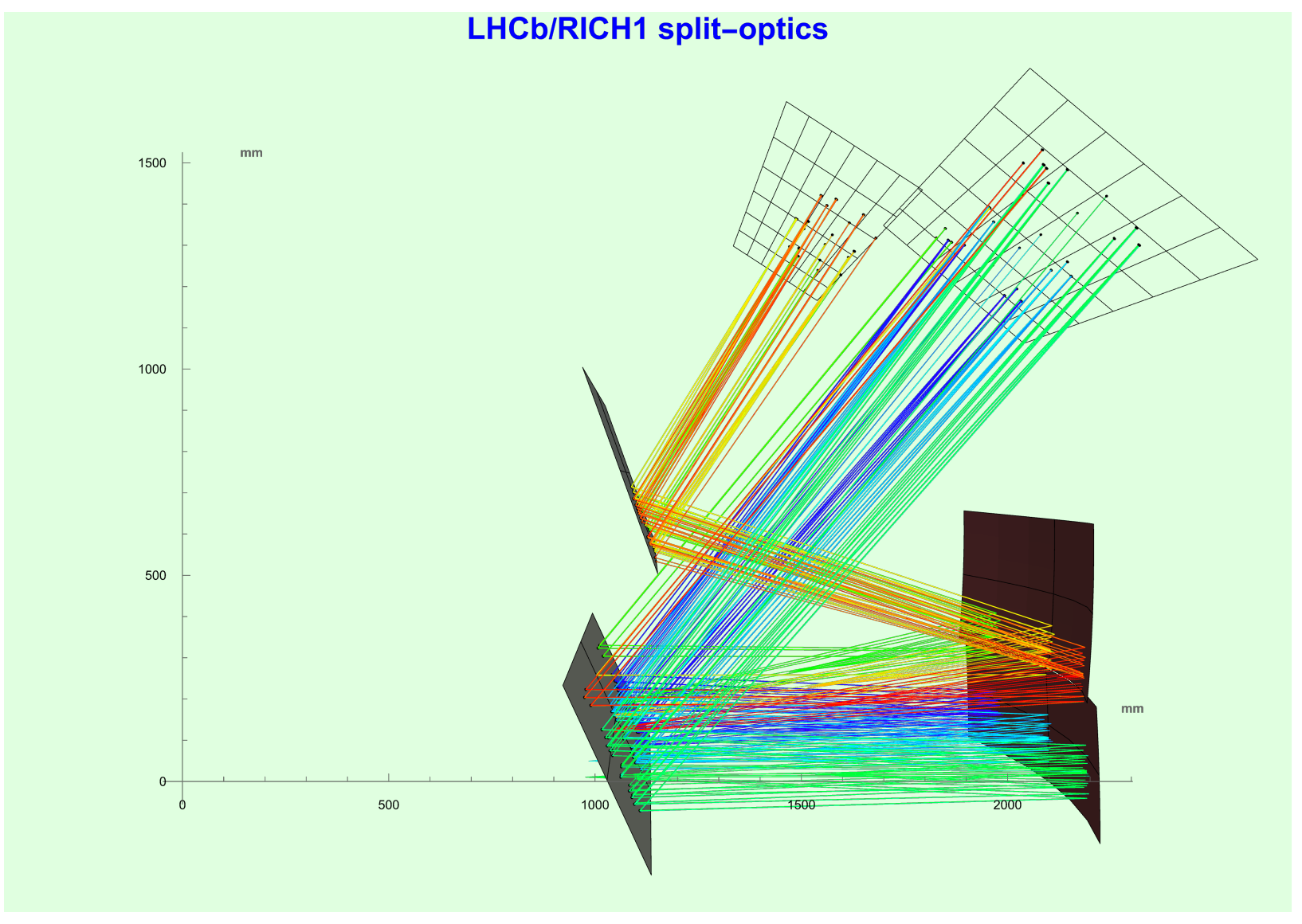
DESIGN FOR LHCB/RICH1-UPGRADE II

- Currently, the occupancy is uneven, and large in the central region of RICH1. This requires a very large dynamic range in occupancy (orders of magnitude), which limits the optimization of the detector, and high-occupancy adversely affects the pattern recognition. In fact, a suitable optics can deal differently with high/low occupancy regions. It is possible to optimize the layout, to cope with the particle density at different angles, by segmenting the optics and photo-detector.
- Additionally, increasing the radius of curvature for the primary mirror allows to improve angular resolution (with the same granularity on the focal plane photo-detector) and reduce the occupancy.
- Additionally, it is planned to increase the granularity on the focal plane photo-detector to further improve angular resolution.
- Concept design, for the Upgrade II of RICH1 is shown in figure 4, schema on the left and 3D view on the right; the acceptance of the inner mirror - which is the one studied here - is the same as the one of RICH2.

FIGURE 4



Geometrical schema of the split-optics optics. The vertical dot-dashed line perpendicular to the beam axis at $z \approx -500$ mm represents the virtual focal surface plane, whose reflection on the flat secondary inner mirror is the real focal surface plane with the Photo-Detector Array.



3D view schematics of the split-optics optics.

REQUIREMENTS FOR LHCB/RICH1-UPGRADE II

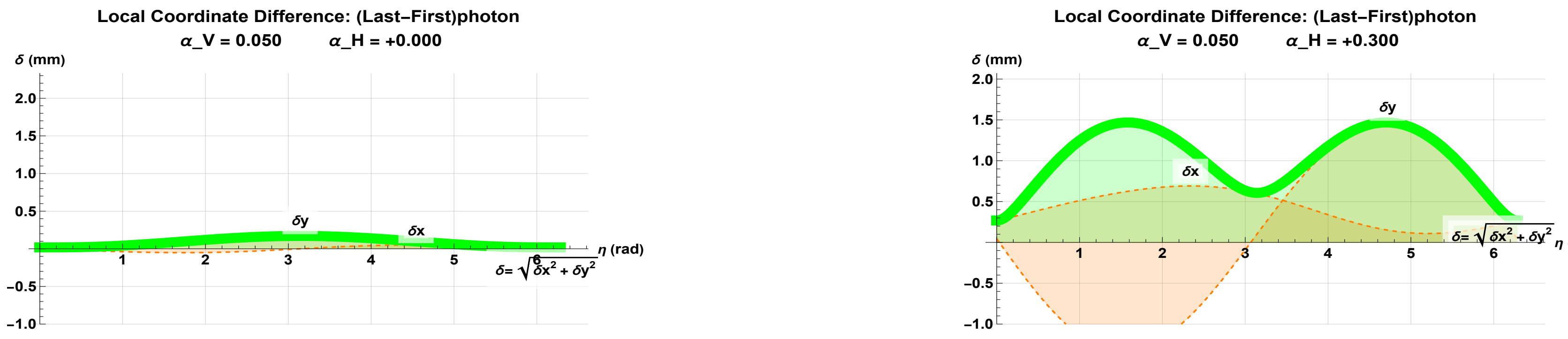
The most relevant RICH1 detector requirements relevant for the optics design are the following ones.

- Keep the number of detected Cherenkov photons per high-momentum isolated track: $N_\gamma \gtrsim 40/30$ (RICH1/RICH2), that is comparable with what expected for Run-3, to keep statistical fluctuations to a manageable level, especially for low-momentum tracks, to get enough photons for pattern recognition and to improve Cherenkov ring angle precision.
- Improve the single-photon Cherenkov angle uncertainty down to a target goal of $\approx 0.30/0.15$ mrad (RICH1/RICH2), that is a factor two better than expected for Run-3, thus increasing the highest-momentum two-particle separation limit by a factor $\approx \sqrt{2}$.
- Keep the peak occupancy (in both time and space bins) less than ≈ 0.3, which is known from the current experience, to be manageable.
- Keep the DCR, accounting for space and times bins, two orders of magnitude less than the signal photons from saturated tracks.

EXPECTED PERFORMANCE FOR LHCB/RICH1-UPGRADE II

- The inner region features a focusing uncertainty well below the pixel granularity. Compare, at a fixed wavelength, in figure 5, the focusing spread with the one in figure 3; note the different scales.

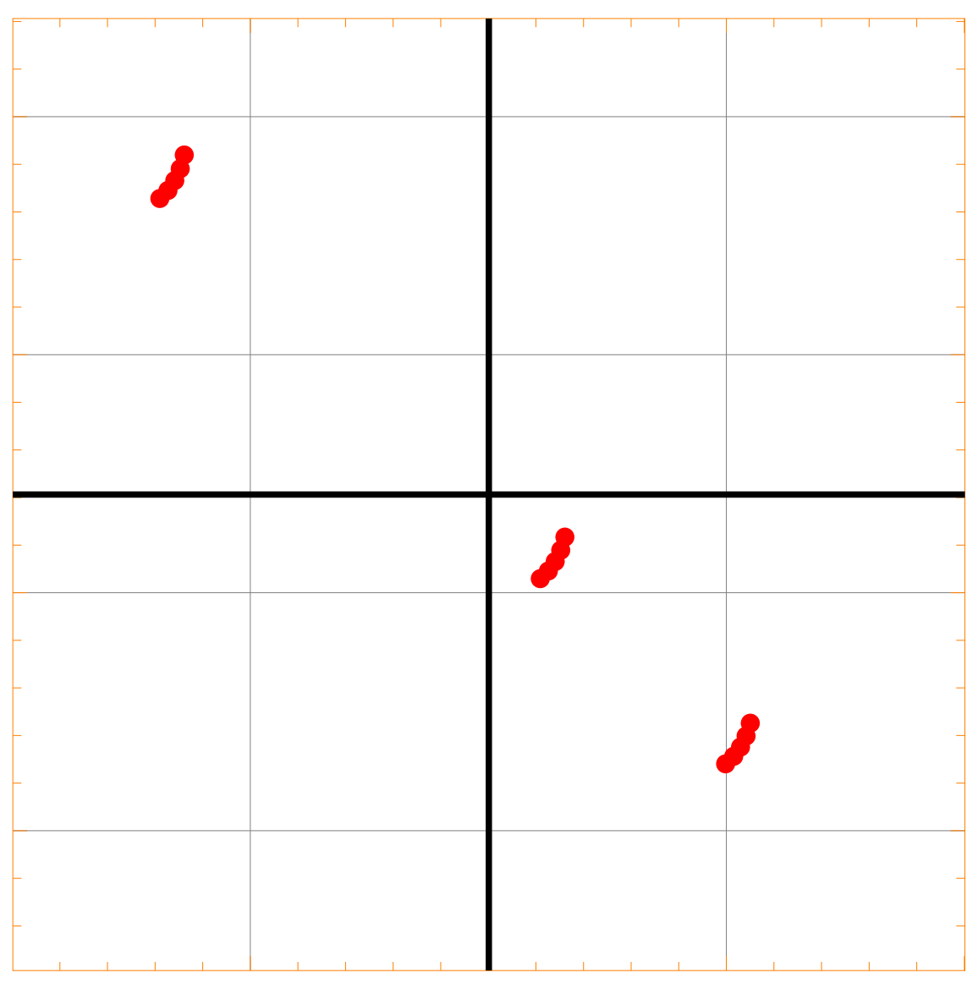
FIGURE 5



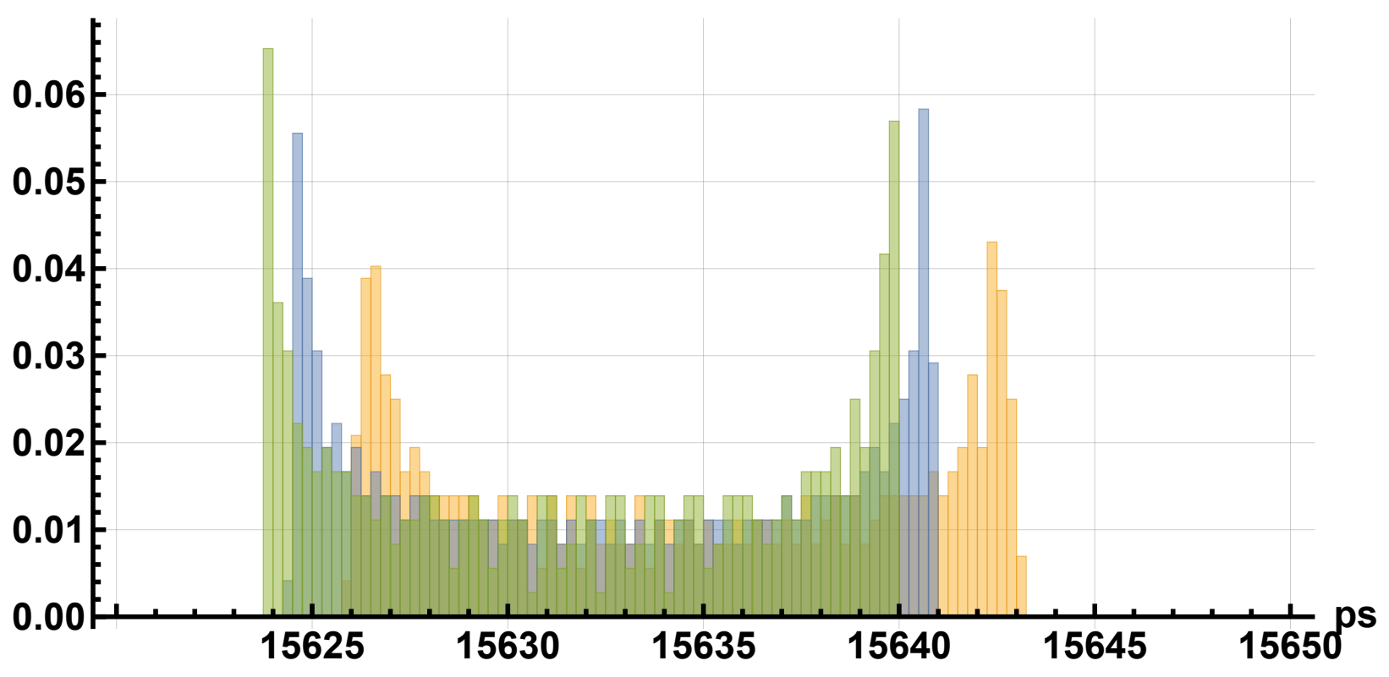
Photon hits for particle trajectory at small (left) and large (right) angles with respect to the beam-line.

- Wavelength selectivity, if the photo-detector granularity is good enough, is shown in Figure 6.
- The performance of the design for Upgrade II. is summarized in table 1 and compared to the LHCb/RICH1-2022 optics.

FIGURE 6



Example of the hits on the Photo-Detector Array, with one mm effective pixel size, from photons of three different wavelengths, (300, 444, 700) nm, and five different emission points along the particle trajectory at a fixed Cherenkov azimuth angle. As each of the different wavelengths gives bunches of hits well-focused within the effective pixel size, the plots shows how the detector has the capability to discriminate, although roughly, the photon energy/wavelength, thus helping to control the chromatic uncertainty.



Total time from PV for the three different wavelengths, (300, 444, 700) nm. For a fixed wavelength, the spread of arrival times of individual photons from a single central high-momentum track is within ≈ 20 ps. Times for different wavelengths are offset by non more than a few ps. When extending the timing to tracks at different angles on the inner mirror, coming from the same PV, the spread of arrival times increases to about ≈ 100 ps.

TABLE 1

RICH1 2022

α_H	α_V	$\langle\delta\rangle$ (mm)	maxδ (mm)	$\langle\delta\theta\rangle_{1/2}$	max$(\delta\theta)_{1/2}$	mm to mrad	θ_C
0.05	0.00	2.05	2.90	0.56	0.80	0.55	0.05
0.05	± 0.30	2.43	3.32	0.67	0.91	0.55	0.05
0.25	0.00	4.21	6.54	1.15	1.80	0.55	0.05
0.25	± 0.30	5.28	7.97	1.45	2.18	0.55	0.05

RICH1 Upgrade II

α_H	α_V	$\langle\delta\rangle$ (mm)	maxδ (mm)	$\langle\delta\theta\rangle_{1/2}$	max$(\delta\theta)_{1/2}$	mm to mrad	θ_C
0.50	0.00	0.09	0.17	0.02	0.03	0.39	0.05
0.50	±0.30	1.03	1.47	0.20	0.28	0.39	0.05

Comparison of performance of the two designs.

CONCLUSIONS

- Assuming some flexibility in the engineering will be allowed, the RICH1 detector for the Upgrade II will feature excellent performances.
- The focusing uncertainty in the central high-occupancy region of RICH1 will be totally negligible, with respect to the pixel uncertainty, thus also helping with noise reduction.
- Depending on the detector design, the chromatic uncertainty might be turned into a wavelength selector for the detected Cherenkov photons.
- The optical performance for this study was optimised with Optica4 [a], running on Wolfram Mathematica 12.

REFERENCES AND LINKS

(1) The LHCb Collaboration, CERN, *Framework TDR for the LHCb Upgrade II*, CERN-LHCC-2021-012, LHCB-TDR-023, https://cds.cern.ch/record/2776420.

(2) The LHCb Collaboration, CERN, *LHCb RICH: Plans and options for future upgrades* CERN-LHCb-PUB-2021-013, LHCb-PUB-2021-013, https://cds.cern.ch/record/2798271.

---

[a] *Optica Software*, https://www.opticasoft.com/, funding by grant *Dipartimenti Eccellenza MUR 2018-2022*.