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Primary vertex time reconstruction using the LHCb ring-imaging Cherenkov detectors

F. Keizer[1] and *L.* Malentacca[1,2] on behalf of the LHCb RICH Collaboration

[1]European Organization for Nuclear Research (CERN), Geneva, Switzerland
[2]Università degli Studi di Milano-Bicocca, Milano, Italy

Abstract. The introduction of picosecond time information in the LHCb ring-imaging Cherenkov (RICH) detectors during LHC Run 4 will allow the primary vertex time (PV t_0) to be estimated using only RICH detector information. The presented method can be integrated into the RICH reconstruction algorithm to determine the PV t_0. This PV t_0 is a necessary input for the application of a time gate around the predicted photon time-of-arrival for each track, which reduces out-of-time photon background from other tracks and improves particle identification (PID) performance. In the RICH reconstruction, each photon object (PO), which is a possible association of a photon detector hit to a particle track, has a PV assigned to it. However, only a fraction of POs is correct and the resolution of the RICH PV t_0 strongly depends on the fraction of correct POs for the PV, called the PV purity. To improve the PV purity while maintaining sufficient photon statistics, two PO selection criteria are introduced: the PO signal amplitude and the selection of POs uniquely associated with a pixel hit. The resulting increase in PV purity is 34 % for each selection criteria, while maintaining more than 20 POs for 98 % and 95 % of the PVs in the sample for the first and second selection respectively.

1 Introduction

This study introduces a novel method to estimate the primary vertex time (PV t_0) in the LHCb experiment during LHC Run 4. The algorithm is implemented in the ring-imaging Cherenkov (RICH) detector reconstruction and uses the picosecond time capabilities of the LHC Run 4 RICH detectors [1]. This PV t_0 estimation will be a new measurement for the LHCb experiment.

The LHCb RICH system performs particle identification (PID) over a wide momentum range. The system consists of two separate gaseous RICH detectors: RICH 1, located upstream of the LHCb magnet, and RICH 2 downstream. Charged particles passing through the gas radiators emit Cherenkov photons, which are focused onto the detector plane using a spherical and flat mirror system.

The RICH reconstruction algorithm identifies the particle types by maximising the likelihood of observed photon detector pixel hits for a given set of tracks whilst changing the track mass hypotheses [2]. The algorithm combines pixel hits from the RICH photon detectors with tracks from the LHCb tracking reconstruction, creating a photon-object (PO) for each valid hit-track combination. Based on these associations, the algorithm computes the expected signal in each pixel for a given set of track mass hypotheses. The expected signals are then used to calculate the event likelihood. The reconstruction initially assumes all tracks are pions, the most abundant particles in LHCb, and then updates one track hypothesis at a time in order to apply the mass hypothesis change that maximises the likelihood. This process continues until no further improvement is possible, yielding the most probable set of mass hypotheses for the event.

The particle multiplicity and high photon detector occupancy pose a challenge for the LHCb experiment, especially during the high-luminosity LHC phase. Picosecond time information in the detectors is a powerful tool to reduce the pile-up of events. When two tracks produce Cherenkov photons that are spatially overlapping at the photon detector, their photon time-of-arrival may still differ. The RICH reconstruction can predict this time-of-arrival of Cherenkov photons at the photon detector plane with a precision of better than 10 ps [3]. The prediction is made using the reconstructed tracks from the LHCb tracking detectors and the reconstructed photon paths inside the RICH detectors. As the start time of the tracks, the PV t_0 is a key input into this prediction. In the reconstruction algorithm, a time gate can be applied around each track's predicted photon time-of-arrival in order to reduce the out-of-time photon background from other tracks. This reduction in combinatorial background leads to a strongly improved PID performance [4].

The PV t_0 resolution plays an important role for the novel RICH timing concepts. Any error in the PV t_0 propagates through to the prediction of the Cherenkov photon time-of-arrival for a given track. Given the time spread of approximately 200 ps during the production of the PVs in the LHCb experiment [5], the application of a time gate to select RICH detector hits around the predicted time-of-arrival relies on the ability to first find the PV t_0. During LHC Run 4, the RICH detectors will be the only sub-detector system in LHCb with picosecond time information, owing to the new FastRICH ASIC with about 25 ps time resolution [6]. The FastRICH will be coupled to the existing RICH photon sensors which have an approximately 150 ps time resolution. The presented method aims to determine the LHCb PV t_0 for each PV in the bunch crossing with a resolution better than 100 ps using the RICH detector.

2 Primary vertex time estimation with the RICH detectors

Figure 1 (left) shows the PO time-of-arrival distribution in the RICH 1 detector for an event with 5 PVs, which is the average number of PVs during LHC Run 4. Each peak corresponds

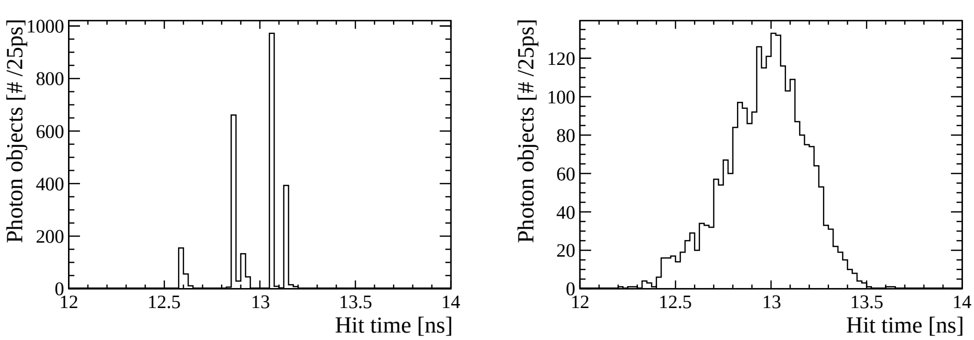

Figure 1: Photon time-of-arrival distribution in RICH 1 for all reconstructed photon-objects in an event with 5 PVs: without sensor time jitter (left) and including a 150 ps sensor time jitter (right).

to one PV in the event and in this case, the photon time-of-arrival could be directly used to determine the RICH PV t_0. However, when the photon detector time jitter of about 150 ps is included, the PV peaks become indistinguishable as shown in Figure 1 (right). This complicates the direct identification of the RICH PV t_0 from the PO time-of-arrival alone. Instead, a dedicated approach is required for the RICH PV t_0 reconstruction.

The PV time $t_{0,i}$ for each PO is calculated by inverting the photon time-of-arrival prediction described in [3], where the PV time was taken from Monte-Carlo (MC) information, and replacing the predicted hit time by the detected hit time t_{hit}:

$$t_{0,i} = t_{hit} - \frac{|r_A|}{c}\sqrt{1+\left(\frac{mc}{p}\right)^2} - \frac{d_{A,E}}{c}\, n\cos\theta_c - [d_{E,M_1} + d_{M_1,M_2} + d_{M_2,hit}]\,\frac{n}{c} \tag{1}$$

Here, $|r_A|$ is the reconstructed track path from the PV to the RICH entrance window, $d_{A,E}$ is the reconstructed track path inside the RICH gas radiator from the entrance window to the Cherenkov emission point, and d_{E,M_1}, d_{M_1,M_2} and $d_{M_2,hit}$ are the reconstructed photon paths from the emission point to the photon detector plane through the mirror reflection points [3]. In addition, p is the particle momentum from the LHCb tracking detectors, n is the refractive index at the average photon emission energy and m is the mass hypothesis for the particle. Since the RICH PV t_0 is calculated before the likelihood maximisation, the mass hypothesis is set to the pion mass.

The RICH PV t_0 is then obtained by averaging the reconstructed PV time ($t_{0,i}$) over N number of POs for the PV:

$$RICH\,PV\,t_0 = \frac{1}{N}\sum_{i=1}^{N} t_{0,i} \tag{2}$$

A key consideration for this summation is that the number N does not need to include all the POs produced for the PV, but can instead contain only those POs that are considered highly likely to be correctly associated to the PV, which strongly improves the resolution of the RICH PV t_0. Especially in high pile-up events, a significant number of POs is incorrect, with the pixel hit not associated to the right track and PV, and would increase the spread of the RICH PV t_0 if included in the summation. Each PO is associated with a track, which is in turn associated with a PV using the LHCb tracking system. Given that each PV produces, on average, more than 15 tracks, the number of POs per PV is sufficiently high, on the order

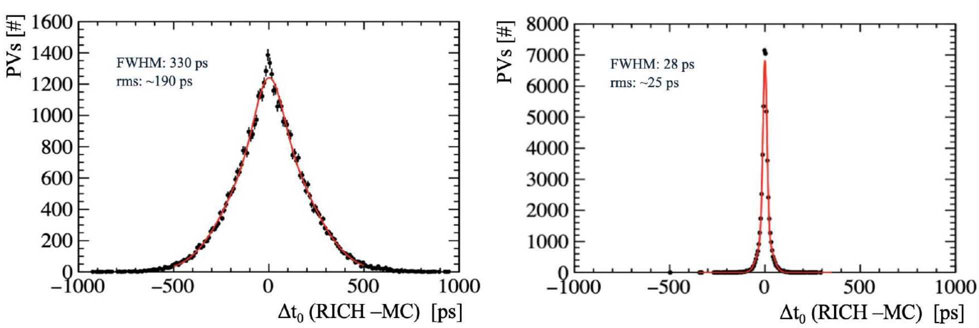

Figure 2: Difference between the RICH PV t_0 and Monte-Carlo PV t_0 using all the photon-objects (left) and selecting only the correct ones using MC information (right).

of a thousand POs per PV in each RICH detector, to allow for such a selection. After the PV t_0 is determined for all PVs in the event, the PV t_0 will be used to apply the novel time gate on the original set of POs to enter into the likelihood maximisation.

The RICH PV t_0 reconstruction method was studied using a simulation sample of ten thousand bunch-crossing events at LHC Run 4 beam conditions. Figure 2 shows the difference between the RICH PV t_0 and MC PV t_0. In Figure 2 (left), the RICH PV t_0 is calculated using all POs associated with each PV. The RMS of the resulting distribution is approximately 190 ps, consistent with the PV time spread in the simulation sample. In contrast, Figure 2 (right) includes only the correct POs using MC information. The resulting spread of 25 ps indicates the best possible RICH PV t_0 resolution that could be achieved using an ideal PO selection. The strong improvement observed between the two distributions in Figure 2 emphasises the critical role of the PO selection.

3 Photon-object selection for the PV t_0

This section explores the PO properties that can improve the PV purity, which is defined as follows:

$$PV\ purity = \frac{N_{correct\ POs\ associated\ with\ PV}}{N_{all\ POs\ associated\ with\ PV}} \tag{3}$$

The effect of the PV purity on the RICH PV t_0 resolution is shown in Figure 3, where the resolution of the RICH PV t_0 improves significantly as the PV purity increases. Additionally, increasing the number of POs per PV improves RICH PV t_0 resolution by reducing statistical fluctuations. However, at low PV purity, incorrectly associated POs degrade the resolution, limiting the benefit of having more POs per PV. A higher PV purity typically results in a reduced number of POs per PV. During LHC Run 4, the average PV purity is approximately 20 %. High-quality PO selections are therefore required to improve the PV purity without reducing the number of POs too strongly. The following two selection criteria aim to enhance the PV purity while maintaining adequate photon statistics.

The first selection criterion is based on the PO signal amplitude, calculated as part of the RICH reconstruction algorithm. The PO signal amplitude $a_{ij}(h_j)$ represents the probability

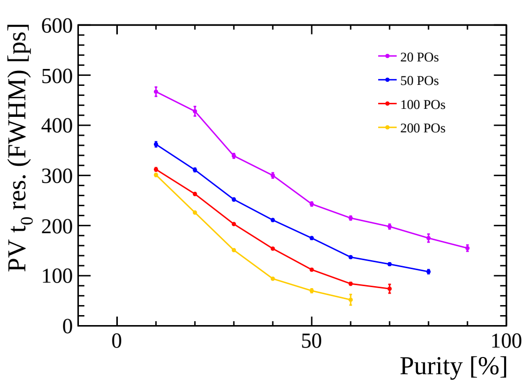

Figure 3: The RICH PV t_0 resolution as a function of the photon-object purity and of the number of photon-objects per PV.

that the pixel hit i originates from the associated track j with a given mass hypothesis h_j:

$$a_{ij}(h_j) = \epsilon_i \, b_{ij}(h_j), \qquad b_{ij}(h_j) = \lambda_j(h_j) \iint_{pixel\ i} f_{h_j}(\theta, \phi) \, \mathrm{d}\theta \, \mathrm{d}\phi \tag{4}$$

where ϵ_i is the photon detector pixel efficiency, $\lambda_j(h_j)$ is the track photon yield and $f_{h_j}(\theta, \phi)$ is the probability density function of the emitted Cherenkov photons [2]. Since the selection is applied before the likelihood maximisation stage of the reconstruction, the mass hypothesis h_j is set to the pion mass. Figure 4 shows the number of POs per PV and the PV purity as a function of a PO signal amplitude cut. As the cut becomes more stringent, the PV purity increases while the number of POs per PV decreases. For 78 % of the PVs, the PV purity can reach up to 83 % in the RICH 2 detector. Notably, even a cut of 0.025 leads to a significant improvement in purity for both detectors. Due to differences in detector geometry, hit occupancy and background level, RICH 2 achieves higher PV purity than RICH 1 [1]. However, the gain in the PV purity results in a more significant reduction in the number of POs per PV for RICH 2. A signal amplitude cut of 0.1 for RICH 1 and 0.05 for RICH 2 increases the PV purity by 32 % and 35 %, respectively. It also preserves an average of 450 POs per PV in RICH 1 and 170 POs in RICH 2. Applying the selection, 94 % of the PVs in the sample can be reconstructed with more than 20 POs in RICH 1, and 88 % in RICH 2. The fraction of PVs with more than 20 POs increases to 98 % when combining the POs from both the detectors.

The second proposed criterion is the selection of POs that are uniquely associated to a pixel hit. This is equivalent to selecting pixel hits associated with only one track, as shown in Figure 5. The hitmap in Figure 5 (left) represents the pixel hit distribution of all POs generated in an event with 5 PVs. A single pixel hit can be associated with more than 12 tracks on average in densely populated regions of the detector. The same hitmap is shown in the hitmap in Figure 5 (right), after the selection criterion is applied. The effect of the selection is more pronounced in high-occupancy regions where track multiplicity is high, while peripheral regions remain largely unaffected. As a result of the selection, the average PV purity increases by 35 % in RICH 1 and 33 % in RICH 2. Despite a reduction in the number of POs per PV by 80 % due to this selection, 84 % of the PVs in the sample retain more than 20 POs in RICH 1 and 81 % in RICH 2. Combining the POs from the two detectors, the fraction of PVs with more than 20 POs increases to 95 %.

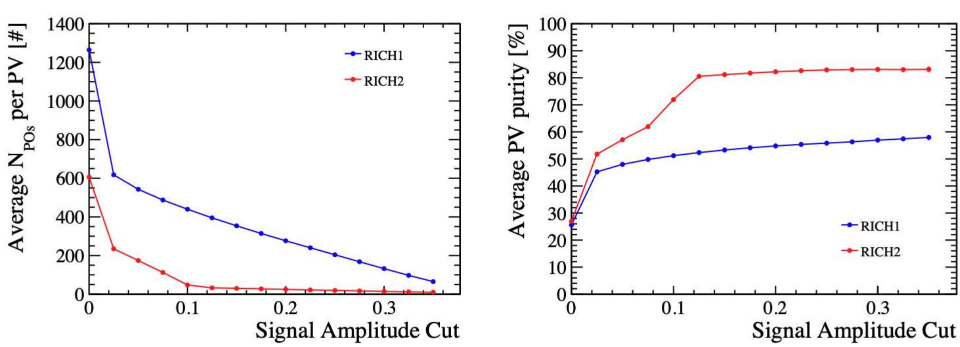

Figure 4: Average number of POs per PV (left) and average PV purity (right) as a function of the PO signal amplitude cut.

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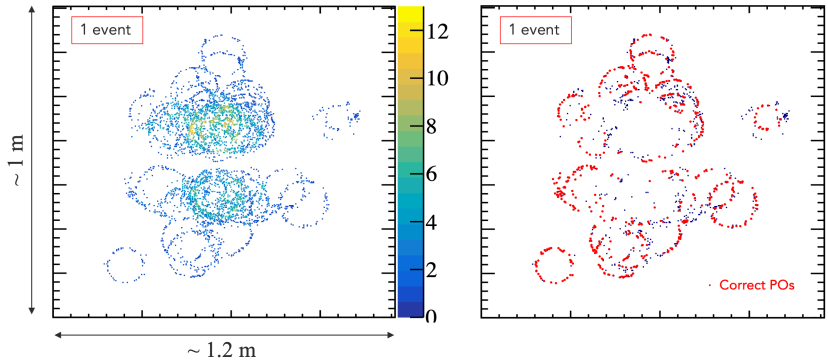

Figure 5: Pixel hit distribution for all photon-objects (left) and for the photon-objects uniquely associated with a pixel hit (right), for a simulated event with 5 PVs. The hitmap on the right includes only pixel hits associated with a single track, and the correct associations are highlighted in red.

When the two selections are applied simultaneously, the average PV purity increases by 66 % for RICH 1 and 62 % for RICH 2, indicating that the two selections are complementary and can be used together to enhance the RICH PV t_0 resolution for a subset of PVs. During the next phase of the development of the algorithm, the impact of the selections on the PV t_0 will be evaluated in detail. The presented results show that the PV purity is significantly increased using the selections and, following the trend in Figure 3, this is expected to improve the PV t_0 resolution, especially after tuning the selections on an event-by-event basis depending on the bunch-crossing event topology. Furthermore, during LHC Run 4 the PV purity values, which contain MC information, will not be available. Instead, an uncertainty may be assigned to each estimate of the PV t_0 based on the event topology and applied selections. This uncertainty will be useful for the subsequent application of a time gate on the POs. Additionally, Monte-Carlo information was used to associate tracks to PVs. In the experiment, this association is performed using the tracking detectors, which can introduce some inefficiencies depending on the tracking performance.

During high-luminosity LHC Run 5, the expected pile-up in LHCb will reach approximately 40 PVs per event, significantly increasing the detector occupancy. Under these conditions, spatial information alone will no longer be sufficient to apply these PO selection criteria effectively for the RICH PV t_0 estimation. In this scenario, the PV time will instead be provided by the LHCb Upgrade II tracking system [4].

4 Conclusions

A novel method to estimate the primary vertex time (PV t_0) using the RICH reconstruction during LHC Run 4 was presented, which will be a first-time measurement for the LHCb experiment. The method reconstructs the RICH PV t_0 using the picosecond hit time information from the RICH photon detectors with new electronics during LHC Run 4. The RICH PV t_0 is estimated using the association between photon-objects (POs) and PVs. The accuracy of these associations determines the PV purity. The study has shown that a higher PV purity results in a better RICH PV t_0 resolution. Two complementary PO selection criteria were identified to improve the PV purity: the PO signal amplitude and the POs uniquely associated with a pixel hit. The first selection increases PV purity by 34 % (32 % in RICH 1 and

35 % in RICH 2) while maintaining more than 20 POs for 98 % of the PVs in the sample. The second selection also results in a PV purity increase of 34 % (35 % in RICH 1 and 33 % in RICH 2), with 95 % of PVs retaining more than 20 POs. These criteria lay the groundwork for future optimisations aimed at improving the RICH PV t_0 resolution.

References

[1] LHCb Collaboration. LHCb Particle Identification Enhancement Technical Design Report. LHCB-TDR-024. (2023). 10.17181/CERN.LAZM.F5OH

[2] R. Forty. RICH pattern recognition for LHCb, NIMA **433**, 257 (1999). https://doi.org/10.1016/S0168-9002(99)00310-1

[3] F. Keizer. Sub-nanosecond Cherenkov photon detection for LHCb particle identification in high-occupancy conditions and semiconductor tracking for muon scattering tomography, CERN-THESIS-2019-203 (2020). 10.17863/CAM.45822

[4] LHCb Collaboration. Framework TDR for the LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era (2021), CERN-LHCC-2021-012 https://cds.cern.ch/record/2776420.

[5] F. Keizer. Novel photon timing techniques applied to the LHCb RICH upgrade programme, Journal of Physics: Conference Series **2374**, 012074 (2022). 10.1088/1742-6596/2374/1/012074

[6] R. Manera et al. The analog front end for FastRICH: an ASIC for the LHCb RICH detector upgrade, JINST **19**, C04030 (2024). 10.1088/1748-0221/19/04/C04030