Prospects for using sub-nanosecond time information to improve the LHCb RICH performance

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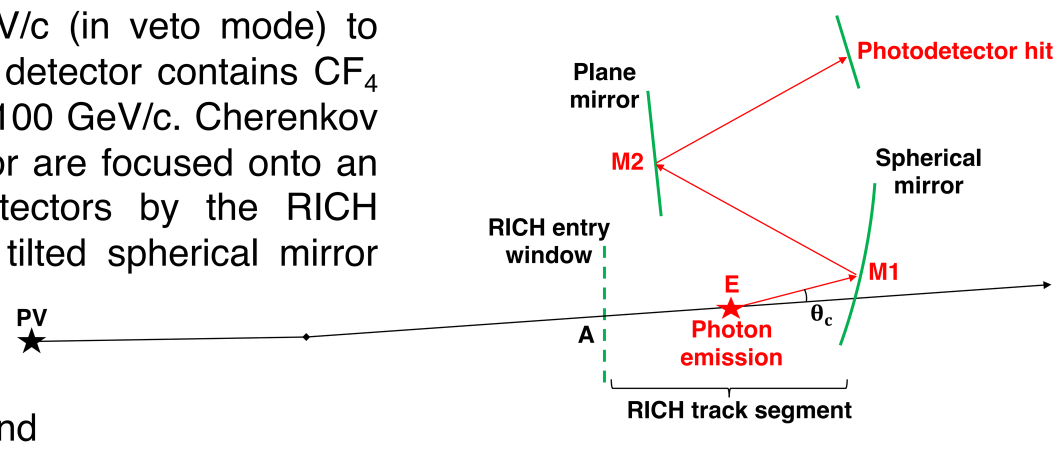
The LHCb RICH detectors : fast timing by design

The Ring-Imaging Cherenkov (RICH) detectors perform charged hadron identification at LHCb. The particle ID is performed using a log-likelihood algorithm which compares the predicted photon hit locations with the measured ones. Reducing the hit occupancy that is used in the algorithm would improve its performance. The RICH detector is critical for the LHCb physics programme.

$$\cos\theta_c = \frac{1}{n(E)\,\beta}$$

Cherenkov angle; Speed / c; Refractive index; Photon energy

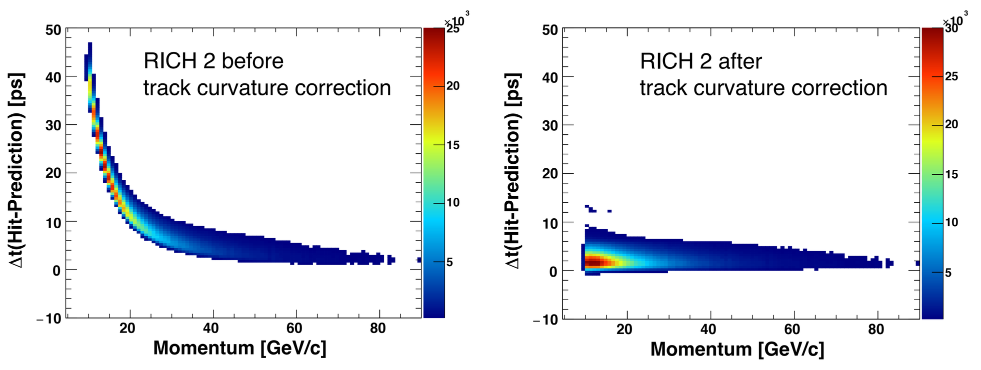
The RICH system consists of two detectors. The RICH 1 detector is located upstream of the LHCb magnet and contains a C_4F_{10} gas radiator for a particle momentum range from about 3 GeV/c (in veto mode) to 65 GeV/c. The downstream RICH 2 detector contains CF_4 gas for a momentum range of 15 to 100 GeV/c. Cherenkov photons generated in the gas radiator are focused onto an array of single-photon-sensitive detectors by the RICH mirror system, which consists of a tilted spherical mirror followed by a plane mirror.



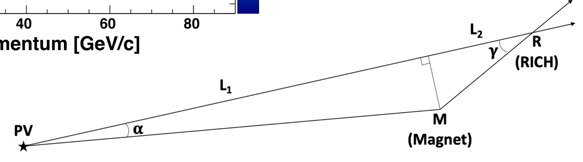
The prompt Cherenkov radiation and focusing mirrors result in an excellent intrinsic time resolution of the RICH detectors. This was demonstrated using the LHCb simulation framework, where an **accurate prediction of the photon time of arrival** at the RICH detector plane was formulated using the primary vertex time and RICH reconstructed parameters.

$$t_{pred} = t_{pv} + \frac{d_{pv,A}}{c}\sqrt{1+\left(\frac{mc}{p}\right)^2} + \frac{d_{A,E}}{c}\, n\cos\theta_c + \left[d_{E,M1} + d_{M1,M2} + d_{M2,hit}\right]\frac{n}{c}$$

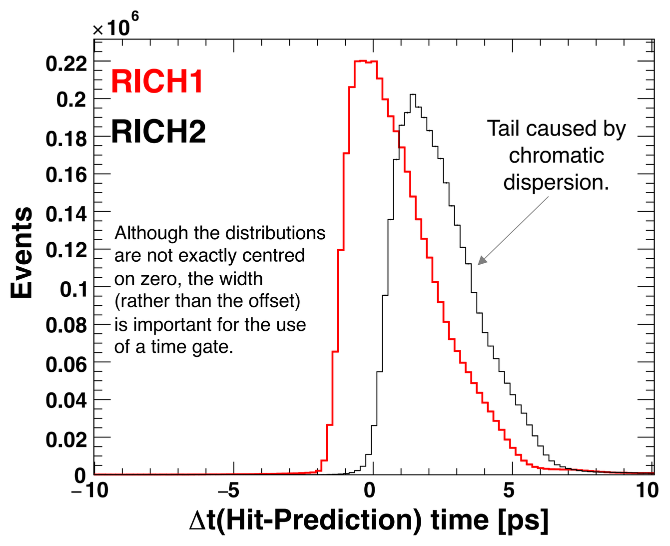
Track path length to the RICH detector; Mass hypothesis in RICH reconstruction; Reconstructed track and photon path lengths; Primary vertex time; Momentum from LHCb tracking; Refractive index



In order to compensate for the curvature of low-momentum particles in the LHCb magnetic field, a correction based on a geometric argument was applied to the track path length for particles reaching the RICH 2 detector.

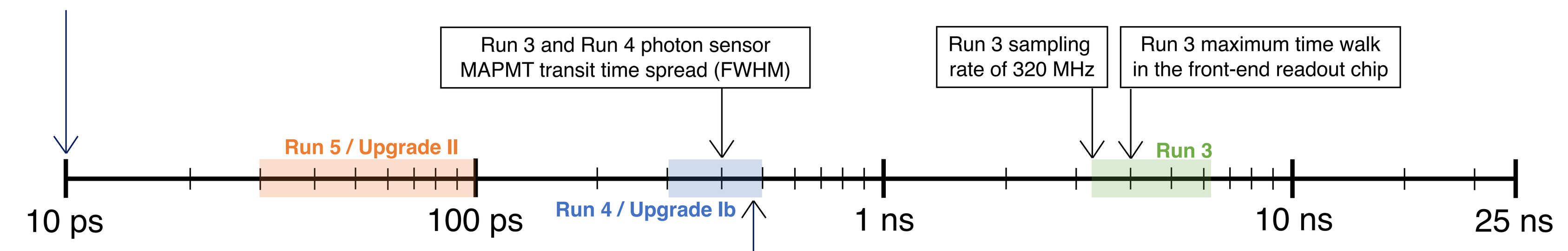


$$\frac{L'}{L} = 1 + \frac{s}{2}\left(\frac{z_R}{z_M} - 1\right)\left(\frac{dx}{dz}\Big|_R - \frac{x}{z}\Big|_R\right)^2$$

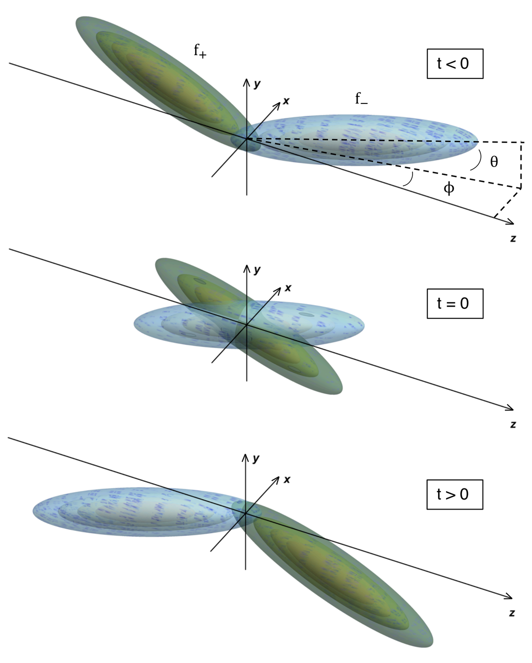


The difference between the simulated photon detector hit time and the prediction shows the RICH detector **time resolution of less than 10 ps**.

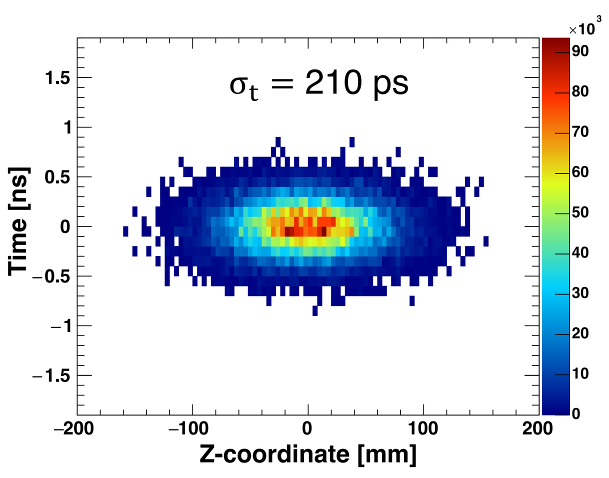
The result does not take the photon detector time resolution into account. Photon detectors and readout electronics with a good time resolution can therefore provide a powerful tool to suppress background and to improve the future particle ID performance. Furthermore, it can help to distinguish hits coming from different primary vertices.



The primary vertex time

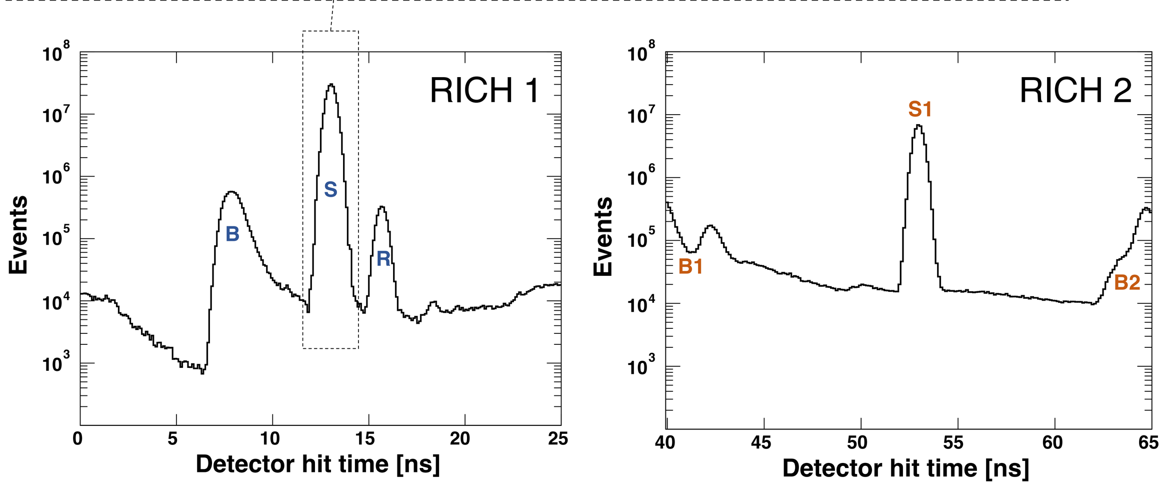


The primary vertex (PV) time spread is an important constraint when utilising the good time resolution of the RICH detectors. To simulate the space-time distribution of PVs, the product of two Gaussian bunches propagating at the beam crossing angles was calculated. The simulation used a Markov chain to sample from this distribution.



Any time gate *applied in hardware* should not exclude PVs, and must therefore have a minimum width of 1 to 2 ns. However, a much finer time gate can be *applied in software*.

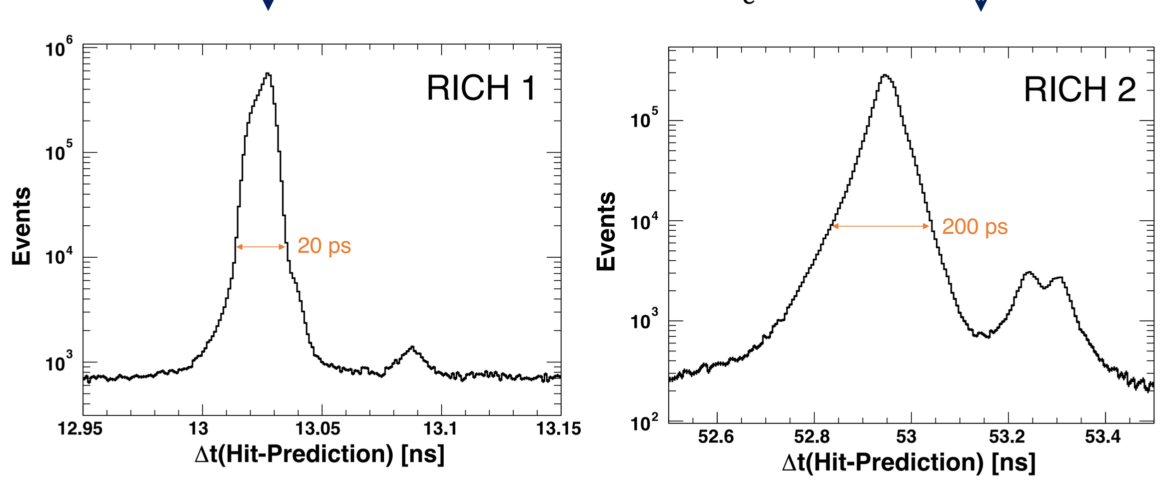
The RICH detector hit time distribution contains background (B) from tracks and photons travelling directly to the detector plane, signal (S) photons that were reflected twice in the mirror system and background (R) due to additional reflections.



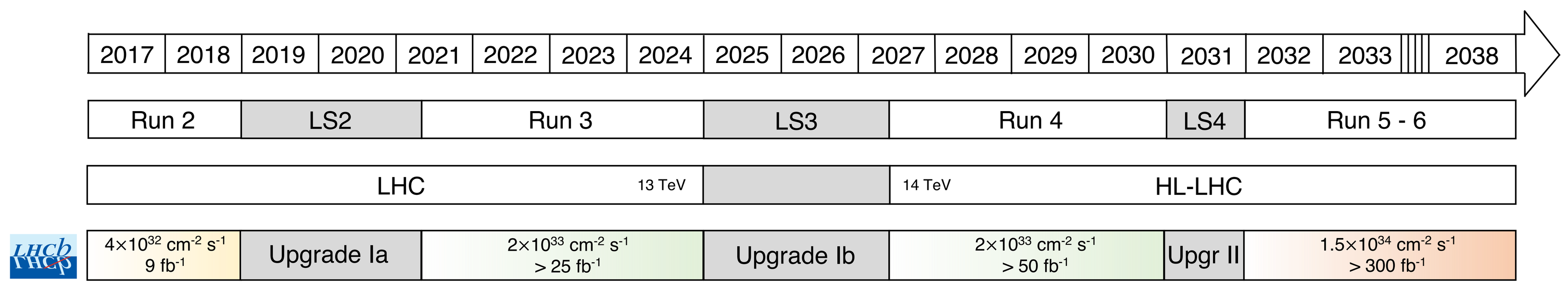
Subtract the primary vertex contribution to the RICH detector hit time distribution

$$\Delta t = t_{hit} - t_{pv} + \frac{z_{pv}}{c}$$

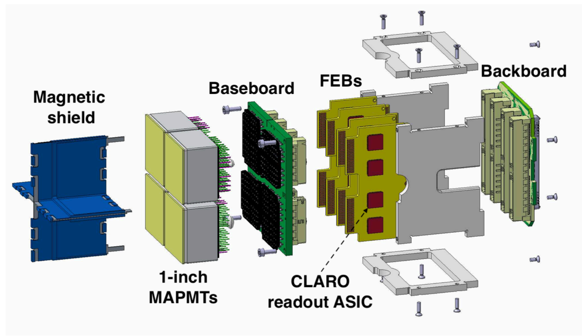
Subtracting the PV coordinates, the remaining spread in the hit time distribution is due to the photon path variations. This spread is larger for the RICH 2 detector, which is physically bigger than the RICH 1 detector.



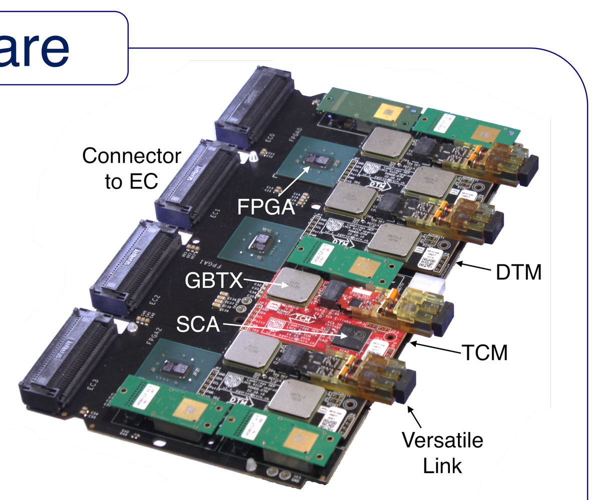
The 20 ps width of the RICH 1 signal peak is small compared to the photon detector time resolutions, where 3 ns and 300 ps are aimed for in LHC Run 3 and Run 4 respectively.



Run 3 : a nanosecond time gate in hardware

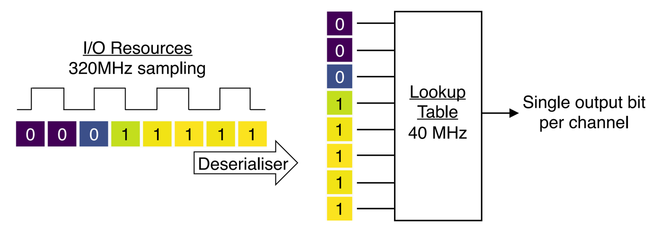


The RICH photon detector consists of elementary cells of multi-anode photon multiplier tubes (MAPMTs). The MAPMT signals are shaped and discriminated by the CLARO readout ASICs.



Photon detector module digital board (PDMDB)

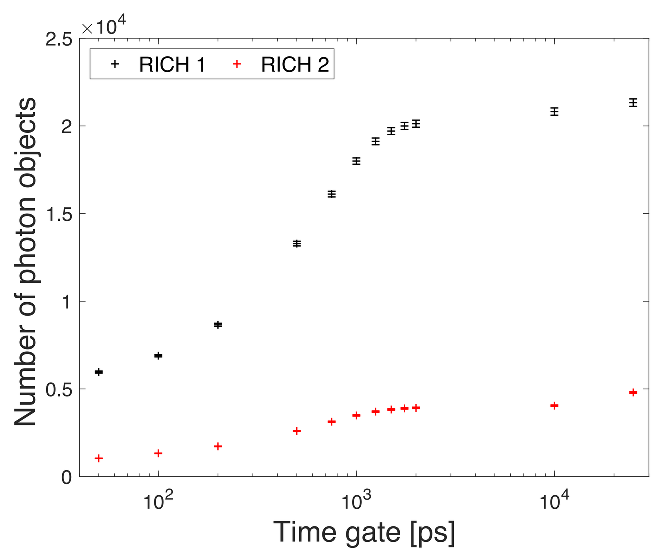
The PDMDB provides the interface between the CLAROs and the Versatile Links to the LHCb readout. The FPGAs capture the digital signals, format the data and transmit it using GBTX transceiver ASICs. The programmable logic in the FPGA can be adapted to sample the CLARO signals at 320 Mbit/s using the deserialiser embedded in every input-output logic block.



The byte from the deserialiser is used to address a lookup table. The value of the bit at this memory location is presented at the output of the lookup table on each 40 MHz clock edge. The lookup table can therefore be programmed to detect specific signal patterns arriving from the CLARO channel and for example, to apply a **time gate of 3.125 ns or 6.25 ns at the front end**. This gate helps to eliminate background photons and sensor noise. It is **unprecedented** in all of LHC to apply a time window of a few nanoseconds within the 25 ns readout.

The RICH reconstruction algorithm

The RICH reconstruction algorithm uses the reconstructed charged particle trajectories to predict where photons are incident on the photon detector plane for a given choice of particle mass hypothesis. Using this prediction, the likelihood of the observed photon detector hits is calculated and the set of mass hypotheses that maximises the overall likelihood is searched for.



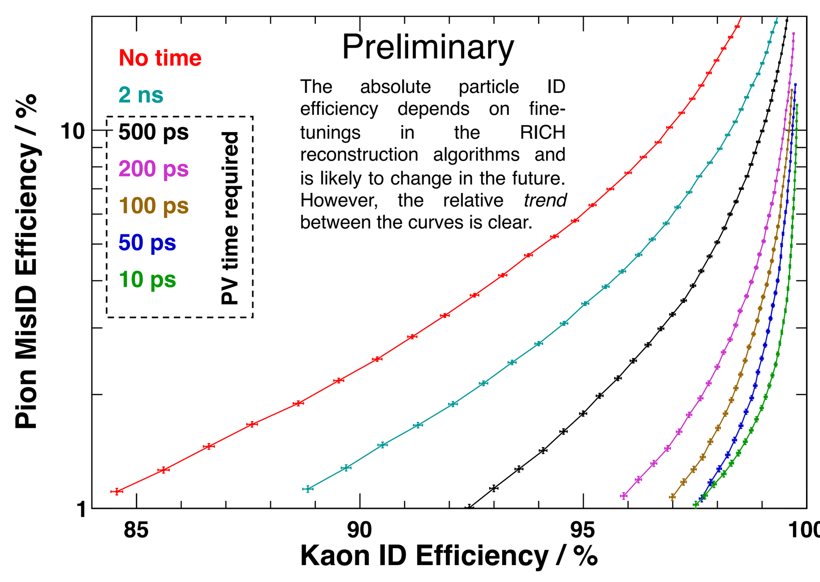
The algorithm creates a 'photon object' for each combination of a track and a photon within spatial constraints. Additional constraints on the hit time can reduce the number of photon objects. The large reduction between 1 ns and 100 ps is due to the combinatorial background from tracks from one primary vertex and photons from other primary vertices.

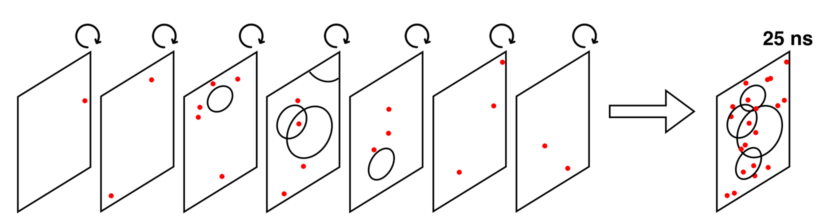
The RICH detectors cannot be used for time-of-flight particle ID due to the relatively high particle momenta. However, a time gate to eliminate background can strongly **improve the particle ID performance and speed up the reconstruction algorithm**.

Run 4 : consolidation to sub-nanosecond time resolution

The particle ID curves provide a standardised and highly sensitive probe of the performance of the RICH detector. The curves show a trend of improving performance as time gates of smaller width are applied around the predicted photon detector hit time.

In order to apply a sub-nanosecond software time gate, a good photon detector time resolution as well as information on the primary vertex time are required. During Upgrade Ib, the electronic readout chain could therefore be modified or replaced in order to correct for time walk. The MAPMT transit time spread of **approximately 300 ps** would then dominate the time resolution.

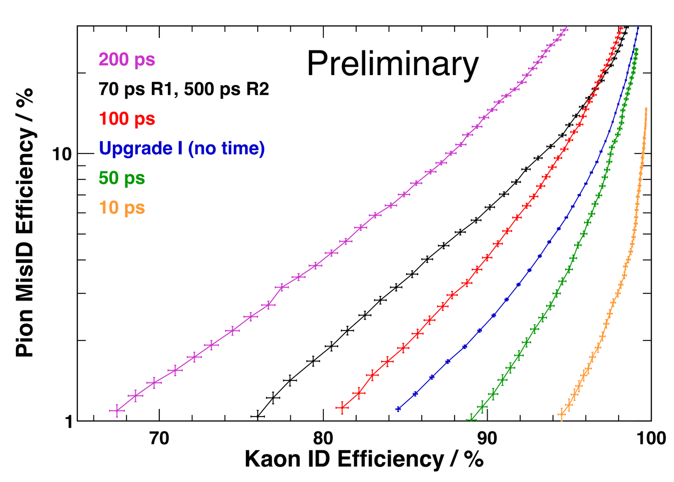




The detector consolidation for Run 4 would allow the particle ID algorithm to be performed on each readout time bin, which effectively lowers the background occupancy. It will also be investigated whether the PV time can be reconstructed or obtained from another sub-detector or timing layer.

Run 5 : the luminosity challenge

The increase in luminosity during the HL-LHC Run 5 causes a challenging rise in particle multiplicity and hit occupancy in the LHCb detector. During Upgrade II, the photon detectors and readout will therefore be redesigned to improve the resolution in space and time, data bandwidth and radiation hardness. R&D of sensor technologies such as silicon photomultipliers and micro-channel plates is ongoing.



The use of time information becomes necessary during Run 5. This was simulated by superimposing the RICH photon detector hits from seven events at the Run 3 luminosity. The same photon sensor geometry as for the Run 3 simulations was used. The particle ID curves are therefore an underestimate of the performance using a higher-granularity future sensor. The results show that the Run 3 performance can be matched using a **50-100 ps time gate in the high-luminosity environment**.

Conclusion

- The LHCb RICH detector has an excellent intrinsic time resolution of less than 10 ps.
- During LHC Run 3, an unprecedented time gate of 3-6 ns can be applied in the readout electronics.
- For Run 4 and Run 5, we aim for a time resolution of 300 ps and 50-100 ps respectively.
- The use of photon detector hit time information is a powerful tool to resolve the high detector occupancy, to improve the particle ID performance and to speed up the reconstruction algorithm.

UNIVERSITY OF CAMBRIDGE

LHCC poster session (19 February 2020)

Further information

These studies are published in *Sub-nanosecond Cherenkov photon detection for LHCb particle identification in high-occupancy conditions and semiconductor tracking for muon scattering tomography,* F. Keizer (Doctoral thesis), January 2020, DOI:10.17863/CAM.45822 .
For details on the Run 3 detector see *LHCb PID Upgrade Technical Design Report,* LHCb collaboration, 2013, LHCB-TDR-014, cern-cds/1624074 .
The principles behind the RICH reconstruction algorithm are explained in *RICH pattern recognition*, R. Forty and O. Schneider, 1998, LHCB/98-040 .
More information on the Upgrade II is available in the *Physics case for an LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era,* LHCb collaboration, 2018, CERN-LHCC-2018-027, arxiv/1808.08865 .