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

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The LHCb RICH detectors : fast 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.

The RICH system consists of two detectors. The RICH 1 detector is located upstream of the LHCb magnet and contains a CuF₂ gas radiator for a particle momentum range from about 3 GeV/c (in veto mode) to 500 GeV/c. The downstream RICH 2 detector contains CF₅ 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 reconstructions.

Image: Graph showing the distribution of photon hits at the vertex plane versus the predicted photon hit location.

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.

Δφ = 1/1 + (1 - L/(L - L₀))

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.

Image: Graph showing the distribution of hit times versus the time prediction.

Run 3 : a nanosecond time gate in hardware

The RICH photon detector consists of elementary cells of multi-anode photomultiplier tubes (MAPMTs). The MAPMT signals are shaped and discriminated by the CLARO readout ASICs. The PDMDB provides the interface between the CLAROs and the Versatile Links to the LHCb readout. The FPGA can 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 Mbius using the deserializer embedded in each input-output logic block.

The byte from the deserializer 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 signal noise. It is unprecedented in all of LHC to apply a time window of a few nanoseconds within the 25 ns readout.

Image: Diagram of the RICH detector layout with the time gate and ASICs.

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 II, the electronic readout chain could therefore be modified or replaced in order to access for time walk. The MAPMT transit time spread of approximately 300 ps would then dominate the time resolution.

Image: Graph showing the particle ID performance curves with different time gate widths.

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 IV 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.

Image: Graph showing the particle ID performance curves with different luminosity conditions.

Conclusion

• The LHCb RICH detectors have 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.