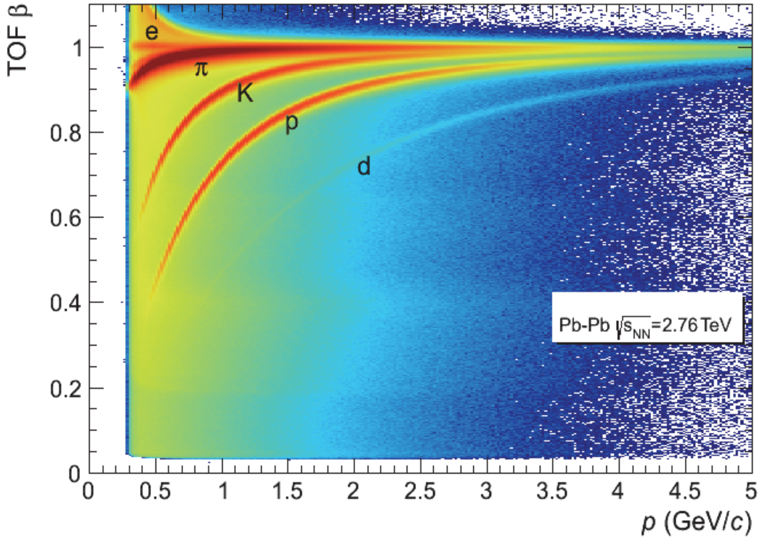

Fig. 8.22. Distribution of particles with given velocity β = *v*/*c* (measured by the TOF barrel) versus their momenta. (Source: ALICE).

8.10 The LHCb RICH: Lord of the Cherenkov Rings

Carmelo D'Ambrosio and Olav Ullaland

The LHCb experiment is dedicated to the study of CP violation [Box 3.4] and the rare decays of heavy flavours [Box 6.4]. A key to these studies is the identification of the many particles produced in the complex decay chains of particles containing the b-quark. The Ring Imaging Cherenkov (RICH) detector system provides charged particle identification over a wide momentum range, from 2 to 100 GeV/*c*.

A major requirement for charged hadron identification in a flavour-physics experiment is the reduction of combinatorial background. Many of the interesting decay modes of b- and c-flavoured hadrons involve hadronic multibody final states. At hadron colliders like the LHC, the most abundantly produced charged particle is the pion. The heavy flavour decays of interest typically contain a number of kaons, pions and protons. It is therefore important when reconstructing the invariant mass of the decaying particle to select the charged hadrons of interest in order to reduce the combinatorial background. Knowledge of the particle identity also helps to distinguish between final states of otherwise identical topology. An example is the two-body hadronic decays, $B \to h^+h^-$, where h indicates a charged hadron. In this case there are many contributions, as illustrated in Fig. 8.23, including $B^0 \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$ and other decay modes of the B^0, B_s^0 and Λ_b [44].

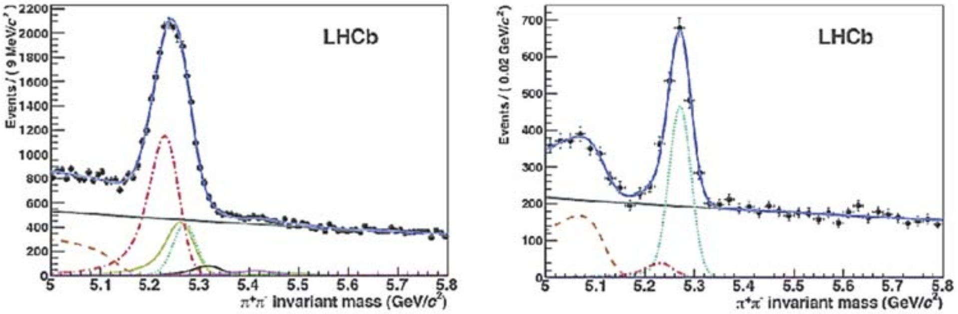

Fig. 8.23. Invariant mass distribution for B → h^+h^- decays in the LHCb data before the use of the RICH information (left), and after applying RICH particle identification (right). The signal under study is the decay $B_0 \rightarrow \pi^+\pi^-$, represented by the turquoise dotted line. The contributions from different b-hadron decay modes (B_0 → Kπ red dashed-dotted line, B_0 → 3-body orange dashed-dashed line, B_s → KK yellow line, B_s → Kπ brown line, Λ_b → pK purple line, Λ_b → pπ green line), are eliminated by positive identification of pions, kaons and protons and only the signal and two background contributions remain visible in the plot on the right. The grey solid line is the combinatorial background [44].

A measurement of the Cherenkov photon emission angle (Θ_C) of a charged particle, together with the knowledge of the refractive index of the Cherenkov medium ($n(\lambda)$), determines its velocity (v), where $v/c = 1/(n \cos\Theta_C)$. A Cherenkov detector is not a stand-alone detector. An accurate determination of the mass is obtained by coupling this information with the knowledge of the momentum and the trajectory of the particle [Boxes 3.2 and 6.3]. As the Cherenkov light is produced along a cone at a polar angle Θ_C relative to the charged particle trajectory, a spherical or parabolic mirror is used to project these photons in a well-defined, ring-like pattern onto a photon detector plane. This is the basic principle behind a Ring Imaging Cherenkov detector [Highlight 7.8].

The LHCb RICH Particle Identifier comprises two separate detectors, RICH 1 and RICH 2, (Fig. 8.24). The first, RICH 1, is upstream of the magnet and covers the momentum range from ~ 2 to 60 GeV/*c*. RICH 2 is placed just in front of the calorimeters and covers momenta up to 100 GeV/*c*. The main task of the two detectors is to efficiently identify charged hadrons, as shown in Fig. 8.23.

Some first generation RICH detectors had problems with ease and reliability of operation. Common to these devices was detection of photons in the far-ultraviolet (VUV) range, with wavelength between 160 mm and 200 nm. The refractive index increases rapidly in this region and uncertainty in determination

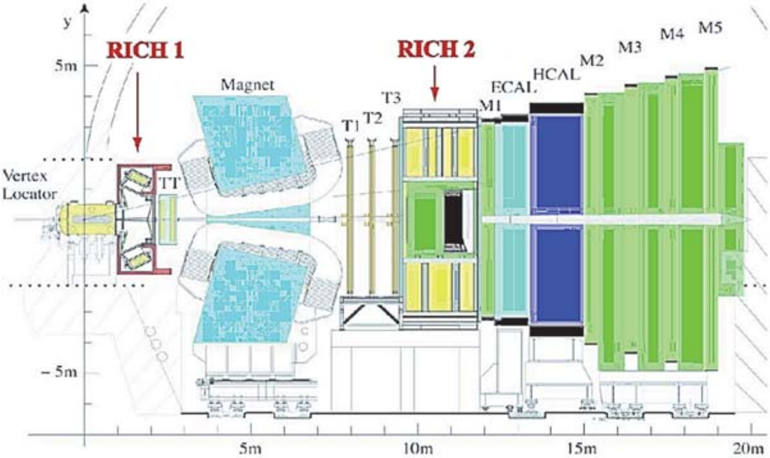

Fig. 8.24. Side view of the LHCb experiment.

of the Cherenkov angle is dominated by the chromaticity of the radiator gas.[a] Operating in the VUV region also meant that impurities, such as O_2, H_2O or CO_2, at the ppm level in the gas would absorb the photons. A very high purity gas was therefore required.

The reason for the detection of photons in the VUV region was simply that no single detector for visible photons with a spatial resolution better than a centimetre had yet been developed. Experiments had to rely on specially adapted gas chamber detectors [Highlight 4.8], which required a photon energy in the VUV region to ionize the gas and generate the signal. This was acceptable, as the number of Cherenkov photons grows quadratically with the photon energy so that sufficient numbers could be detected. However, calculations showed that detecting photons in the visible range (VIS) would decrease the chromatic effects on the overall error and thus pave the way to much more precise detectors. Specifically, the error on the Cherenkov angle is given by $\sigma_\theta/\sqrt{N}$ where σ_θ is the single photon Cherenkov angle error and N the number of detected photons. When working in the VUV, experiments tried to maximize N. In the visible range, giving up photons while simultaneously decreasing σ_θ results in a much improved Cherenkov ring resolution. Such a change of perspective was not easy, as it required a complete re-appraisal of the available tools, instruments, hardware and software, involving all RICH system components, from particle-sensitive hardware to electronics and data acquisition and processing. For the hardware the following steps were taken:

- Choice of gases having intrinsically low chromaticity with good sensitivity to particle momenta between 2 GeV/*c* and 100 GeV/*c*. The gases chosen were

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[a] RICH detectors can also use liquid or solid radiators. Here only gas radiators are considered.

C_4F_{10} in RICH 1 and CF_4 in RICH 2. These gases are relatively easy to handle and, by working in the visible range, acceptable gas impurities are in the percent range rather than the few parts per million (or billion) for VUV.

- Development of efficient single-photon detectors working in the VIS with high spatial resolution (pixel sizes from 0.25 to 2.5 mm), called pixel-HPD (HPD for Hybrid Photon Detector). Their development had been started in the 1990s and was pursued at CERN, triggered by the need for precise photon detectors for scintillating fibres. The basic idea was to insert in a vacuum envelope a silicon pixel detector and electronic chip to directly detect and digitize photo-electron signals produced by the Cherenkov photons. This is not an easy task and it took more than 10 years to realize the first mature example of this completely new class of photon detector. They feature high spatial resolution, an impressive signal to noise ratio and can be assembled in arrays. There are 484 pixel-HPDs in the RICHs covering a surface of ~3.6 m^2.
- Development of thin, light, precise and highly reflective mirrors, together with their support and alignment structures, to focus the photons on the pixel HPDs. Mirrors had to be thin to minimize material traversed by the particles. A mirror array contains hundreds of components totalling a reflective surface of ~19 m^2. They are aligned to a precision of 0.05 mrad to form an almost perfect sphere and minimize the error on σ_θ of the single photon Cherenkov angle.

RICH 1 features carbon fibre composite mirrors and RICH 2 has 6 mm thin glass mirror arrays. They are held in place either by carbon fibre (RICH 1) or by aluminium honeycomb (RICH 2) structures with Polycarbonate micrometric adjustments. With these technologies the mechanical structures for these large RICH detectors represent only ~2.5% and ~10% of a radiation length, respectively. To give an idea of its size, the RICH 2 volume is larger than 100 m^3. After about ten years of development, all the mirrors show excellent alignment stability and tilting errors lower than 0.1 mrad after online corrections. The result of this effort is best illustrated with an example: Fig. 8.25 shows the “world record” distribution of σ_θ, obtained with RICH 2 in 2012 [45].

The ability to detect sharp Cherenkov rings in the LHCb RICH system allows to detect and identify several rings simultaneously. This process is referred to as pattern recognition. A new “global search algorithm” based on statistics and probability was developed. Instead of searching for rings, the probability for each detected photon to belong to a possible ring is evaluated. By constructing and minimizing a likelihood function, the mass and hence the identity of the particles is assigned. The RICH system can handle thousands of photons produced by hundreds of particles up to a million times per second and deliver information about the particles crossing the detector and their underlying physics processes.

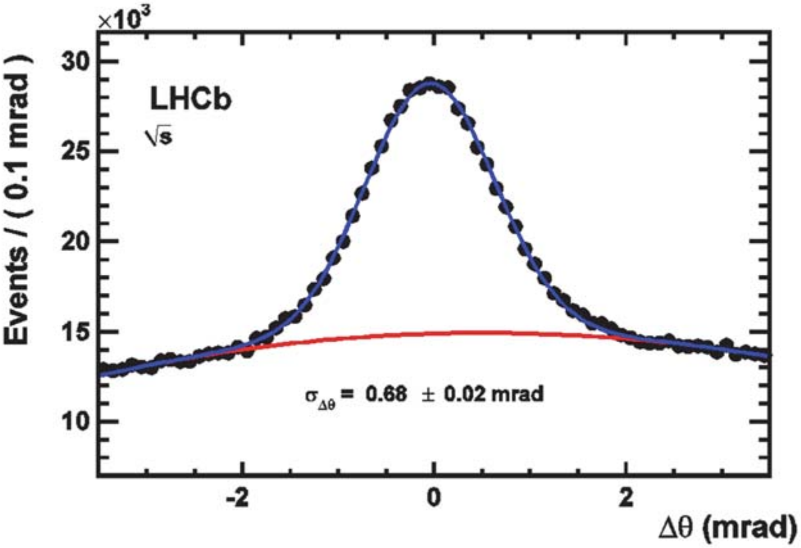

Fig. 8.25. Single-photon Cherenkov angle precision of 0.68 mrad for LHCb RICH 2 [45].

For 2020, LHCb is planning to further improve the RICH detectors aiming for operation at 10 times the present collision rate of 3×10^7 s^{-1} at LHCb and 40 times the readout rate. Beyond that, one can anticipate a new "*quantum leap*" producing the RICH detectors of the future, when new components, ideas and a good dose of human ingenuity will all synergize, thoughtfully and skilfully in the conducive laboratory environment of CERN.

8.11 Signal Processing: Taming the LHC Data Avalanche

Philippe Farthouat

When the concept of the LHC program began to take shape, physicists and engineers were confronted with a seemingly unconquerable world of experimentation: proton bunches colliding 40 million times a second, entailing a billion collisions, 10^{11} particles, and data volume approaching 100 TB (10^{14} Bytes) per second [Box 8.3]. It would take a worldwide-coordinated R&D programme to possibly find solutions to the design and construction of the detectors matching such requirements. Particularly worrisome was the question whether the signal and data processing systems for the hundred million detector channels could be developed and built. It took courage, sweat, stamina, ingenuity, collaboration with industry and a fair dose of luck to write a happy end to this story, as told below.