Recent Progress in Ring Imaging Čerenkov Counters with Vacuum based Photon Detectors

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The paper reviews the status of ring imaging Čerenkov (RICH) counters with vacuum based photon detectors by first discussing the main motivation, the physics case. It then presents the results from the counters employed in the BaBar, HERA-B, SELEX and Hermes experiments, status of the next generation of precision B physics experiments BTeV and LHCb, and possible solutions for the upgrades of existing spectrometers BaBar and Belle.

1. Introduction

One of the main driving forces of the research and development for the RICH counters was in the last decade the need to have excellent hadron identification for precision B physics measurements. For a statistically significant measurement of CP violation in the B system, tagging of B meson flavour with kaon charge is an indispensable method. In addition, in order to study the rare few body hadronic decays of B mesons it is essential to separate $\pi\pi$ from πK as well as $K\pi\pi$ from $KK\pi$.

After considerable efforts went into developing an efficient gas based Čerenkov photon detector for high interaction rates, all experiments which aimed at CP violation measurement, chose Čerenkov counters with vacuum based photodetectors. BaBar chose single channel photomultiplers in their DIRC counter, Belle fine mesh single channel PMTs in an aerogel threshold Čerenkov counter, while HERA-B decided to employ multianode PMTs in a rather conventional RICH with a gaseous radiator.

It is worth noting that all three Čerenkov counters perform extremely well, and at Belle and BaBar they have contributed considerably to the success of the CP violation measurements. This is illustrated in an example shown in Fig. 1 where an efficient selection of $D^0 \to K^-\pi^+$ was possible by employing the DIRC counter of the BaBar spectrometer.

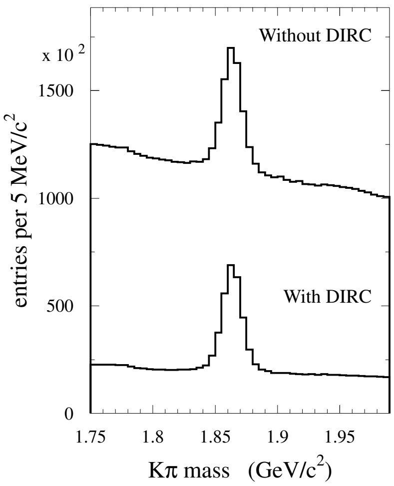

Figure 1. Selection of $D^0 \to K^-\pi^+$ candidates by using the information from the DIRC counter of the BaBar spectrometer.

In the present review we shall first present the results from the Čerenkov ring imaging counters employed in the BaBar, HERA-B, SELEX and Hermes experiments, examine the status of the next generation of precision B physics experiments BTeV and LHCb, and present possible solutions for the upgrades of existing BaBar and Belle spectrometers.

2. Present RICH counters

2.1. DIRC - Detector of Internally Reflected Cherenkov Light

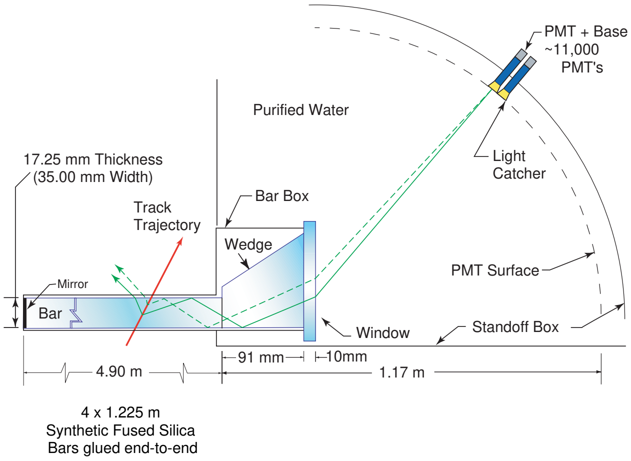

Figure 2. Principle of the DIRC counter.

The DIRC counter of the BaBar spectrometer [1] is a novel type of a ring-imaging Čerenkov counter, based on the detection of internally reflected Čerenkov light (Fig. 2). The patterns on the photon detector (Fig. 3) are quite complicated, but result in well resolved peaks in the Čerenkov angle distribution. The time of arrival of photons is used to reject background from conversions in the water tank, assign photons to proper tracks, and to eliminate most of the ambiguities in the photon-track reconstruction.

The basic performance parameters of the counter are in excellent agreement with the expectations [1,2]. The single photon resolution

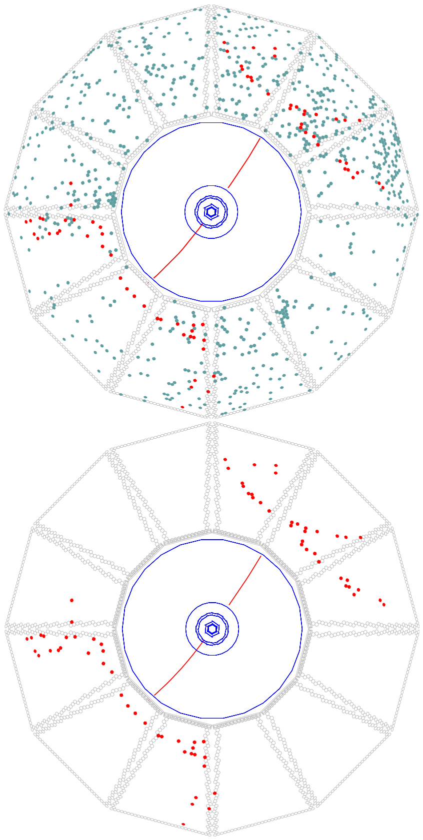

Figure 3. Event with two muons in the final state, as recorded in the DIRC counter, no time cut (left), with time filtering of ±8 ns (right).

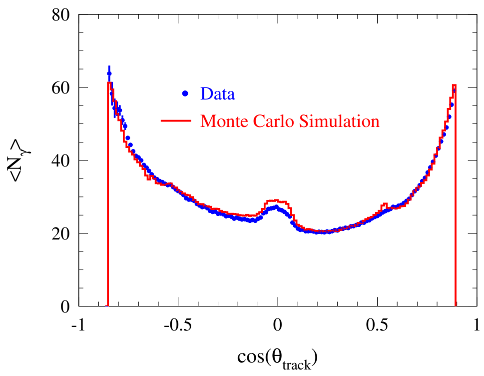

Figure 4. DIRC performance: average number ($< N_\gamma >$) of detected photons per track.

amounts to 9.6 mrad. The number of photons per saturated ring depends on the polar angle of the charged track, but always stays above 20 as shown in Fig. 4. The identification efficiency was determined by using charged tracks from the decay sequence $D^{*+} \to \pi^+ D^0 \to \pi^+ K^- \pi^+$. The efficiency for kaon identification exceeds 90% in the momentum range 0.5 GeV/c - 3 GeV/c, while the probability that a pion is identified as a kaon stays at a few percent level (Fig. 5).

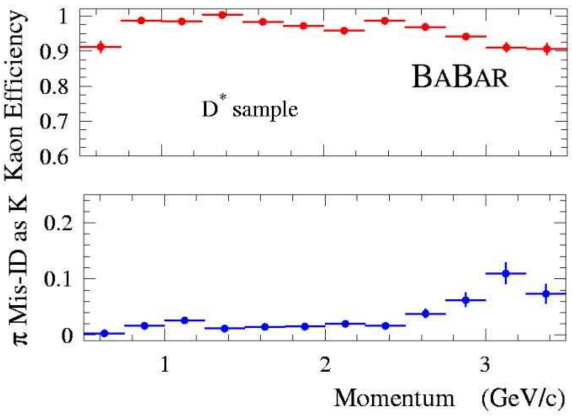

Figure 5. Particle identification with DIRC: K efficiency and $\pi \to K$ misidentification probability.

2.2. HERA-B

The HERA-B collaboration was the first to employ multianode photomultiplier tubes in a RICH counter (Fig. 6), after they have shown [3] that the tubes considered (Hamamatsu R5900, versions M16 and M4 with 16 and 4 square shaped channels, respectively) have a capability to detect single photons with high efficiency, and little cross-talk among the channels (Fig. 7). A series of measurements was carried out to understand the single photon response of the full set of 2250 multianode photomultiplier tubes [3], [4] prior to the installation. The installed photon detector behaves very well even in a very hostile environment of a hadron machine, showing clear rings

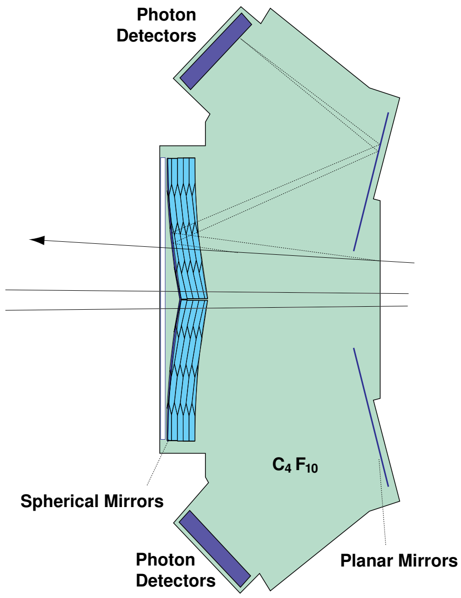

Figure 6. Layout of the HERA-B RICH counter.

with very few noisy channels (< 0.5%), as can be seen from Fig. 8 [5,6].

A common drawback of vacuum based photon detectors is a rather large fraction of dead area. While for single channel devices reflective cones can be used, multichannel devices need an imaging system. In the HERA-B RICH a system of two lenses is used to demagnify the image on the focal surface by a factor of 2 [7]. The system of lenses is in this case used both to diminish the dead area, as well as to adapt the required granularity of the photon detector to the granularity of the multianode PMT. The transparency of the system matches the quantum efficiency of the tube. It also has a flat acceptance for photons with incidence angles below 140 mrad as required in the design specifications.

The accumulated experience of the HERA-B collaboration shows that a RICH counter can safely be operated even at high track densities with counting rates exceeding 1 MHz per channel in the hottest part of the photon detector [6]. A typical event is in this case shown in the lower plot of Fig. 8. The counter has been in opera-

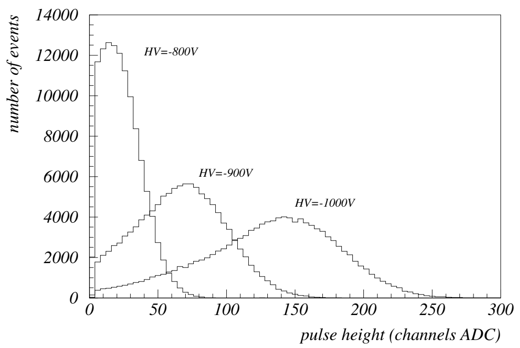

Figure 7. Pulse height distributions due to single photoelectrons as observed with the R5900-M16 photomultiplier tubes [3].

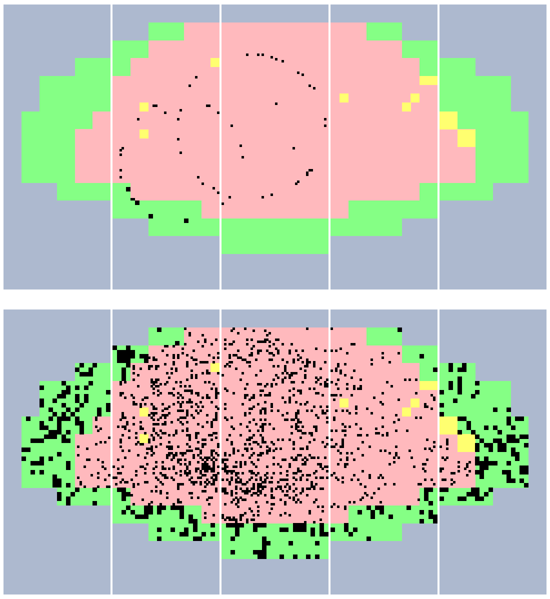

Figure 8. Events recorded in the lower half of the HERA-B rich: a low multiplicity event (top) with two clear rings, and a typical event (bottom).

tion since summer 1998, and no degradation of performance has been observed.

The relevant RICH parameters were determined from the data. The figure of merit is $N_0 = 43/cm$, resulting in 32 photons per saturated ring. The single photon resolution is 0.7 mrad in the finer granularity area covered by R5900-M16 tubes, and 1.0 mrad with R5900-M4 PMTs. All parameters are in very good agreement with expectations [6]. Preliminary results of particle identification as shown in Fig. 9 are promising [8]. It is expected that they will improve while the tracking system is getting better aligned.

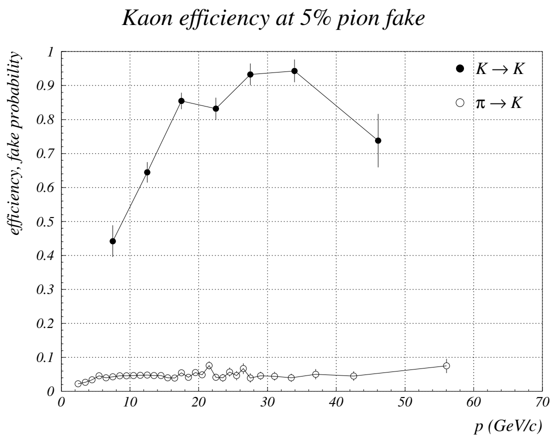

Figure 9. Particle identification in the HERA-B RICH: efficiency to identify a kaon (at 5% π fake probability), as deduced from the $\phi \to K^-K^+$ decays.

2.3. SELEX and HERMES

SELEX RICH counter [9] uses 10 m of neon as radiator gas in a fixed target experiment. The photon detector is built of single anode PMTs with light cones to increase the active fraction of the photon detector area. The performance of the counter is illustrated in Fig. 10, with clearly visible bands corresponding not only to stable decay products but also to Σ, Ξ and Ω barions.

The experience accumulated in running this

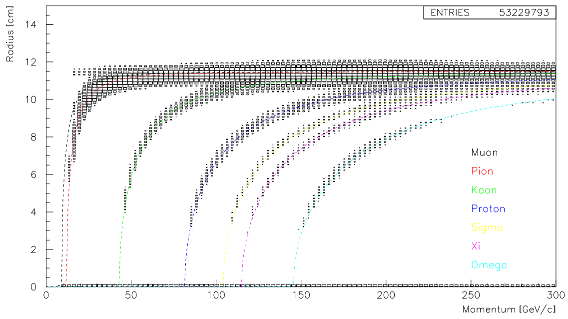

Figure 10. Identification performance of the SELEX RICH.

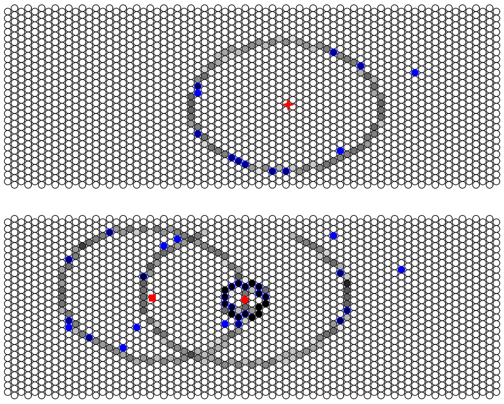

Figure 11. An event as recorded in the two halves of the HERMES RICH counter. Black circles correspond to hit PMTs, grey indicate the ring for the most probable hypothesis. The large rings are due to Čerenkov photons emitted in the aerogel radiator.

RICH counter will be used in the CKM experiment [10] with two RICH counters to identify the K and π from the $K \to \pi\nu\nu$ decay.

The HERMES experiment employs a very similar photon detector as the SELEX RICH, but uses two radiators, aerogel and C_4F_{10}, to fully cover the kinematically allowed interval of final state particle momenta [12]. It also is the first RICH counter to employ aerogel as radiator [13]. An example of rings originating in the aerogel radiator are shown in Fig. 11. With two radiators, the counter is very efficient even in the kinematic region where kaons and protons are below the threshold in the gas radiator [14]. As an example, at 5 GeV/c the efficiency for kaon detection is $\epsilon(K \to K) = 0.97$ at fake probabilities $\epsilon(\pi \to K) = 0.003$, $\epsilon(p \to K) = 0.026$. The experience of the HERMES RICH counter will be very useful for the next generation of RICH counters with aerogel as radiator.

3. Next generation: BTeV and LHCb

For the next generation of B physics experiments at hadron colliders the identification of hadrons will again be essential for both the tagging of b-flavour in CP violation and mixing measurements, as well as for the identification of particles in hadronic final states such as $B \to \pi^+\pi^-$, in particular since more channels contribute to the background than in the case of experiments at $\Upsilon(4s)$ (e.g. $B_s \to K^+K^-$). The corresponding momentum spectra of the kaons and pions the identification device has to cover, are shown in Fig. 12 for the case of the BTeV experiment. The minimum requirement for a RICH counter is to cover the π/K separation over the interval $3 < p < 70$ GeV/c.

In the BTeV RICH counter (Fig. 13) the same radiator gas, C_4F_{10}, will be used as in the case of HERA-B. To supplement the performance in the low momentum region and to improve the p/K separation, plans are discussed to add a 1 cm thick layer of a liquid radiator (C_5F_{12}) [15].

In the LHCb experiment the RICH counter is designed to cover π/K separation between 1 GeV/c and 150 GeV/c [17,18]. The kinematic region covered by a RICH counter, from p_{min} to

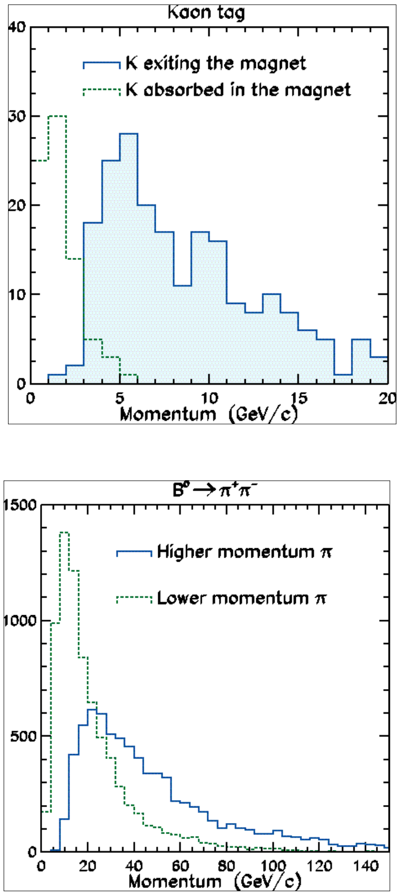

Figure 12. Momentum spectra of tagging kaons (top) and pions from $B \to \pi^+\pi^-$ (bottom) for the BTeV experiment.

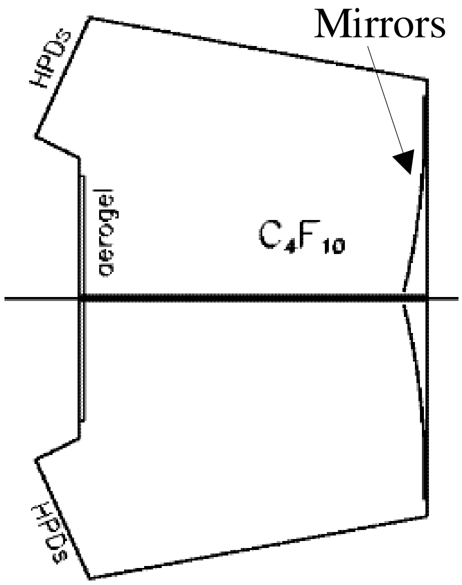

Figure 13. BTeV RICH radiators and detector layout.

p_{max}, depends on the threshold momentum for the lighter of the two particles we want to separate, $p_t = \beta_t \gamma_t mc$, $\beta_t = 1/n$ (typically $p_{min} \approx \sqrt{2} p_t$), and on the resolution in Čerenkov angle (ultimately given by the dispersion in the radiator medium). It turns out that for most radiators $p_{max}/p_{min} \approx 4-7$ [16]. This, in turn, tells us that for the large kinematic interval in the LHCb experiment we need three radiators. They are arranged in two counters [17] as shown in Fig. 14.

All photon detector candidates for the BTeV and LHCb RICH counters are vacuum based. In the framework of the LHCb experiment several photon detectors were considered as candidates for their system of RICH counters [17]. Two of them are hybrid photon detectors (HPD) based on a new technique which combines a vacuum photosensitive device with charge particle detection in a silicon detector with pixel readout. As shown in Fig. 15, photoelectrons are accelerated by an electric field over a potential difference of about 20 kV towards a silicon detector with integrated electronics, and result in a signal of ≈ 5000e. The baseline solution is being developed in collaboration with the DEP company [19]. A CERN based development [20] lead to a pad HPD with 2048 pixels. In a beam test four tubes of this type were employed, and aerogel was used as the radiator. The results, illustrated in Fig. 16, are quite encouraging [21]. As an alternative, a multianode PMT based photon detector is studied [22]. In this case a single quartz lens light collection system is used to increase the fraction of the active area of each individual PMT.

In the BTeV RICH two types of photon detectors will be used. HPD counters will detect

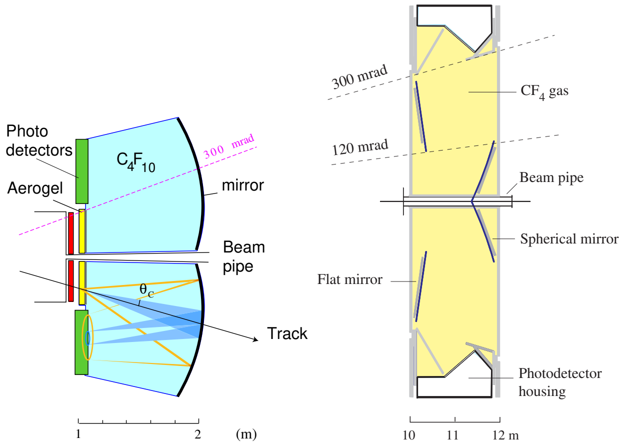

Figure 14. RICH counters for LHCb [17].

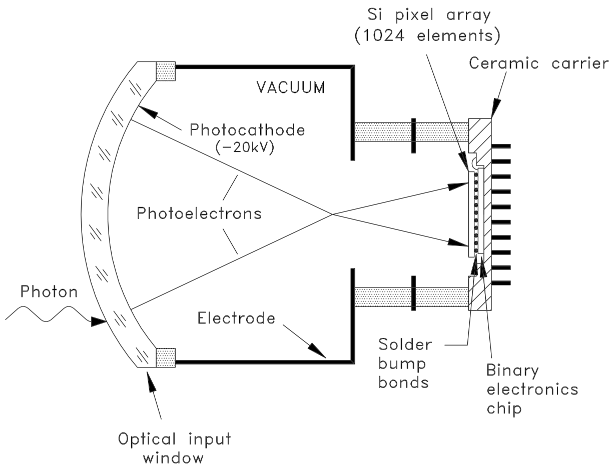

Figure 15. Hybrid photon detector (HPD) of the LHCb experiment [17]. The outer diameter of the detector is 17 cm.

Čerenkov photons from the gas, and single channel PMTs will be used for the Čerenkov photons from the liquid radiator [15].

3.1. Belle and BaBar PID upgrades

For the next round of B physics experiments at upgraded e^+e^- machines ('Super B factories') considerable upgrades of particle identification devices are envisaged to cope with higher rates and with stricter separation requirements for rare decay channels. At BaBar an upgrade of the DIRC counter with a considerably smaller expansion volume is being considered [24,25]. To keep the angular resolution, single channel PMTs would have to be replaced by smaller pitch multichannel devices among which Hamamatsu flat panel 64 channel PMTs, proximity focusing DEP HPDs, and 64 channel multianode PMTs are being studied.

In the present Belle spectrometer the separation of kaons from pions is performed with a threshold Čerenkov counter by properly choosing the index of refraction for a given kinematic region [26,27]. While in the central (barrel) part it is possible to correctly identify both the tagging kaons and $B \to \pi\pi, K\pi$ decay products, in the forward (endcap) direction only the former can be covered. Two systems are being considered for the upgrade of the Belle spectrometer. For

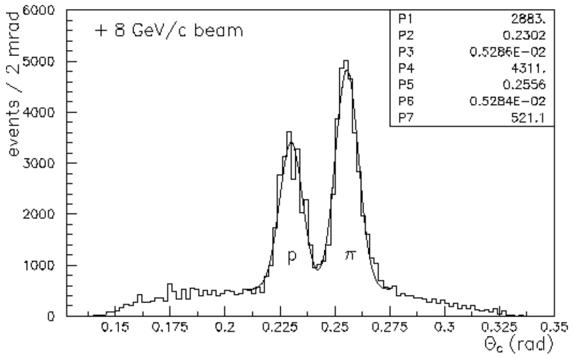

Figure 16. Čerenkov angle distribution for single photons as recorded in a beam test with four HPD tubes of CERN pad type, each with 2048 pixels, and with aerogel as radiator.

the barrel region a time-of-propagation counter is being studied, a kind of 'inverted DIRC' which combines the time of arrival of Čerenkov photons with a rough measurement of the Čerenkov angle [28]. For the endcap region, where momenta extend up to 4 GeV/c, a proximity focusing RICH with aerogel as radiator is being tested [29]. The

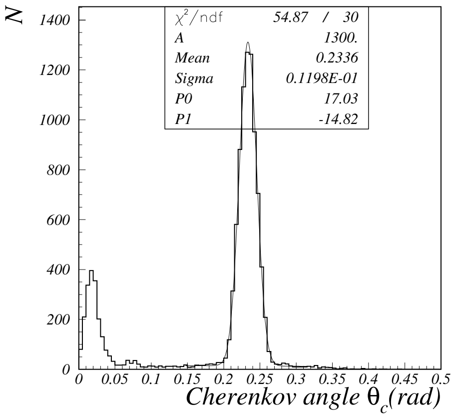

Figure 17. Single photon distribution for pions with 3 GeV/c momentum. The aerogel employed as the radiator had a refractive index of 1.050, and Hamamatsu R5900-M16 multianode PMTs were used as photon detectors.

performance of a prototype in a recent beam test is illustrated in Fig. 17. Another benefit of an improved identification of pions and kaons with momenta around 4 GeV/c by means of a proximity focusing RICH would also be that such a counter allows a separation of $e/\mu/\pi$ (Fig. 18), essential for studies of rare $B \to K\ell\ell$ decays, in the momentum region around 1 GeV/c, where other methods become less reliable.

4. Summary

Čerenkov counters of the BaBar and Belle spectrometers with vacuum based photon detectors have contributed significantly to the incredible B physics harvest of the last two years. HERA-B has shown that a vacuum photodetector based

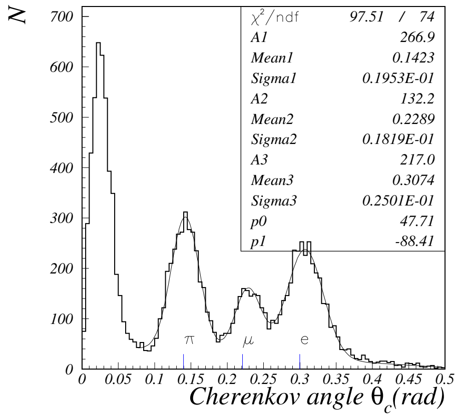

Figure 18. Same as in Fig. 17 for beam particles with 0.8 GeV/c momentum.

RICH can operate in the very rough environment of a hadron machine. By now, multianode PMTs have become a well established single photon counter with excellent record. New multichannel photon detectors are entering the field, hybrid photon detectors and flat panel PMTs. RICH counters based on these devices will play a decisive role in the next generation of precision B physics experiments (LHCb, BTeV), and at the next generation of e^+e^- 'super' B factories.

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