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STATUS OF THE DIRC DETECTOR AT BABAR: EARLY OPERATIONAL EXPERIENCE*

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Abstract

A novel type of Cherenkov ring imaging particle identification system (DIRC) based on the detection of ring images produced in long, fused silica radiator bars is being used to provide hadronic particle identification in the BABAR detector at PEP-II. The DIRC concept, design, fabrication, and initial performance will be briefly described. The DIRC is now fully commissioned, and has been operating in the BABAR detector on beam line at the PEP-II B Factory since late Spring 1999.

1 Motivation

The BABAR detector [1] is designed to study CP violation in the B^0 meson system from $\Upsilon(4S)$ production, at the SLAC PEP-II asymmetric e^+e^- collider [2]. At the $\Upsilon(4S)$, PEP-II collides 9 GeV electrons on 3.1 GeV at $\beta\gamma(lab) = 0.56$. After initial commissioning, the luminosity is expected to reach about $3 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, increasing ultimately to $3 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with a $B\bar{B}$ production rate of 30 Hz. As of October 1999, a maximum luminosity of about $1.5 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ has been attained.

The study of CP-violation into hadronic final states in the B meson system requires the ability to tag the flavor of one of the B mesons via the cascade decay $b \to c \to s$, while fully reconstructing the final state of the other over a large region of solid angle and momentum. The momenta of the kaons used for flavor tagging extend up to about 2 GeV/c, with most below 1 GeV/c. On the other hand, pions from the rare two-body decays $B^0 \to \pi^+\pi^-(K^-\pi^+)$ must be well-separated from kaons, and have momenta between about 1.5 and 4 GeV/c with a strong momentum-angle correlation between the tracks (with the higher momenta occurring at the more forward angles because of the machine boost). Since the BABAR inner drift chamber tracker can provide π/K separation up to about 700 MeV/c, an additional dedicated particle identification system is required that must perform well over the range of 700 MeV/c to about 4 GeV/c [3]. The system being used in BABAR is a new kind of ring imaging detector called the DIRC. It is expected to be able to provide π/K separation of $\sim 4\sigma$ or greater, for all tracks in BABAR.

2 Detector Environment

The Particle Identification (PID) system in BABAR is surrounded by a high-performance CsI electromagnetic calorimeter. Thus, the PID system inside the calorimeter volume should be thin and uniform in radiation lengths (to minimize degradation of the fine calorimeter energy resolution) and thin in the radial dimension to reduce the volume, and hence, the CsI material and cost of the calorimeter. Finally, for high-luminosity running conditions, the PID system must have fast signal response, and be able to tolerate high backgrounds if necessary.

3 The DIRC Concept

The DIRC [4] is a novel type of ring-imaging Cherenkov detector, based on the symmetry principle that the magnitude of angles are maintained upon reflection from a flat surface. Figure 1 shows a schematic of the DIRC geometry that illustrates the principles of light production, transport, and imaging [5]. The radiator material of the DIRC is fused silica in the form of long, thin bars with rectangular cross section. These bars serve simultaneously both as radiators and as light pipes for that portion of the light trapped in the radiator by total internal reflection. A charged particle with velocity v, traversing the fused silica bar with index of refraction $n(\sim 1.472)$, generates a cone of Cherenkov photons of half-angle θ_c with respect to the particle direction, where $\cos\theta_c = 1/\beta n(\beta = v/c, c =$ velocity of light). For particles above a cut-off velocity, some photons will always lie within the total internal reflection limit, and will be transported to either one or both ends of the bar, depending on the particle incident angle. To avoid having to instrument both bar ends with photon detectors, a mirror is placed at the forward end, perpendicular to the bar axis, to reflect most of the incident photons to the backward (instrumented) bar end.

Once photons arrive at the instrumented end, most of them emerge into an expansion region (called the stand-off box) through a fused silica wedge that reduces the size of the required detection plane. The PMT surface is about 1.2 m from the bar end. The photons are detected by an array of densely packed photomultiplier tubes (PMTs) surrounded by reflecting "light catcher" cones to capture light which would otherwise miss the PMT active area. The expected Cherenkov light pattern at this surface is essentially a conic section [Fig. (1b)], whose cone opening-angle is the Cherenkov production angle modified by refraction as it emerges from the fused silica.

The DIRC is intrinsically a three-dimensional imaging device. Photons are focused onto the phototube detection plane via a "pin-hole" defined by the exit aperture of the bar, so that the photon propagation angles can be measured in two-space. The time taken for the photon to travel down the bar is also related to the photon propagation angle with respect to the bar axis. As the track position and angles are known from the *BaBar* tracking system, these three measured photon propagation angles can be used to (over)-determine the two Cherenkov angles (θ_c, ϕ_c). Imaging in the *BaBar* DIRC occurs in all three of these dimensions, by recording the time at which a given pixel (phototube) is hit. This over-constraint is particularly useful in dealing with high backgrounds.

4 The DIRC at *BaBar*

The *BaBar* detector is shown schematically in the elevation view of Figure 2. It is built inside a solenoid magnet, and thus, is dominated by a cylindrical barrel region. The DIRC bars are arranged in a 12-sided polygonal barrel between the drift chamber and the CsI calorimeter. Because of the beam momentum asymmetry, particles are produced preferentially forward in the laboratory. To minimize interference with other detector subsystems in the crowded-forward region, the DIRC read-out end is in the backward direction.

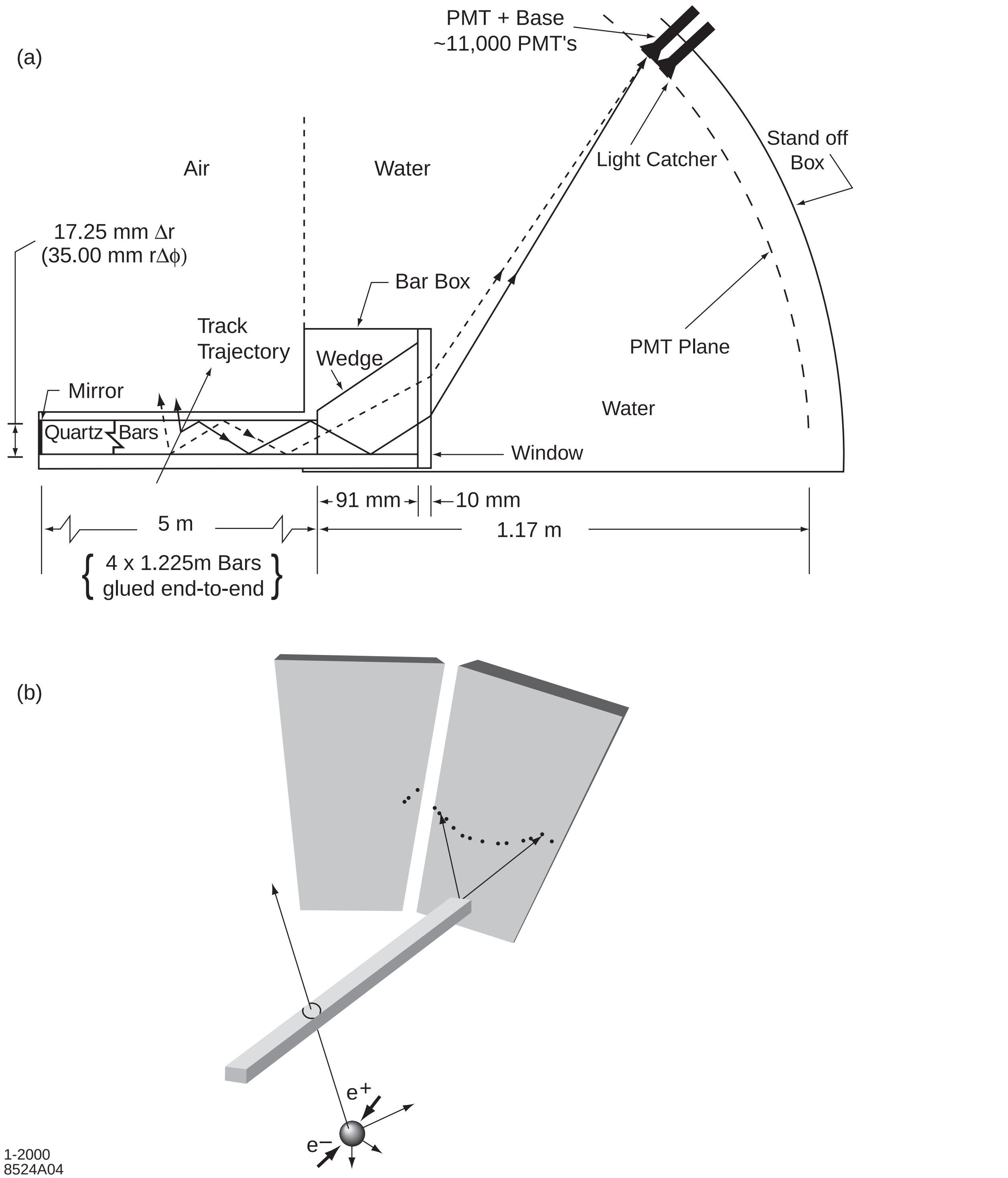


Figure 1: Schematics of the DIRC fused silica radiator bar and imaging region; (a) side view, and (b) isometric view showing PMT plane image.

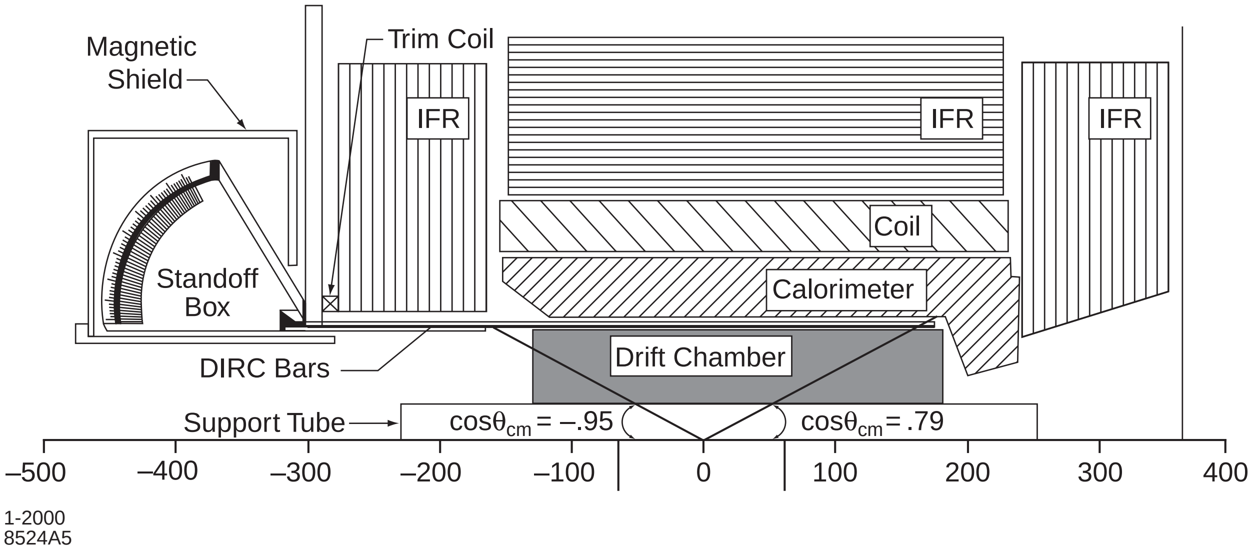


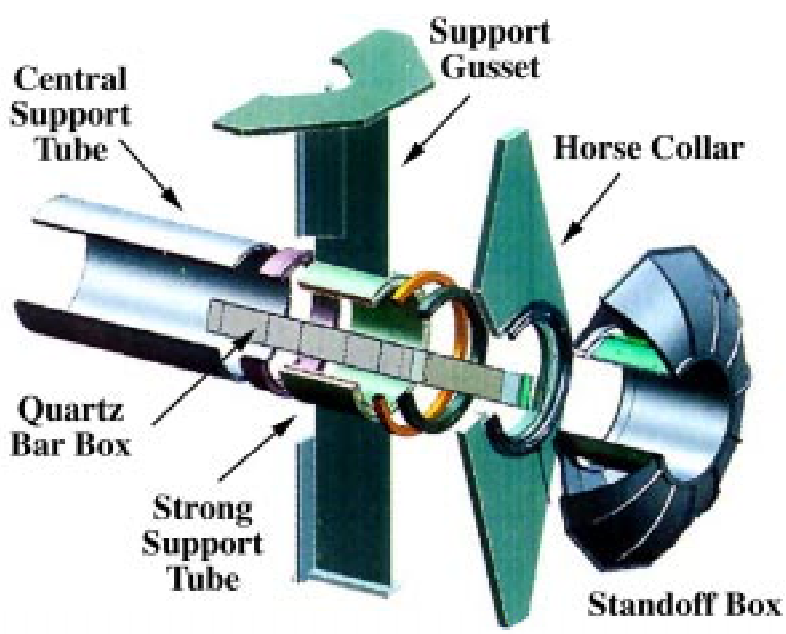
Figure 2: Schematic midplane section of the top half of the BaBar detector. The high-momentum beam is incident from the left.

The principal components of the DIRC are shown schematically in Figure 3. The bars are grouped together into 12 hermetically sealed units, called bar boxes, made of very thin aluminum-hexcel panels. Dry nitrogen gas flows through each box, and is monitored for humidity to ensure that all boxes remain tightly sealed. Each bar box [Figure 3(b)] in turn contains 12 long bars, placed very close together ($\sim$ 150 μm gap) side by side, for a total of 144 long bars. The bars are 1.7 cm thick, 3.5 cm wide, and 4.9 m long. Each long bar is manufactured by gluing four 1.225 m "short" bars end-to-end, that size being the longest high-quality bar currently feasible to obtain from industry. The bars are made from synthetic (Spectrosil) fused silica because of its resistance to ionizing radiation, its large index of refraction, low chromatic dispersion, and because it allows for excellent optical surfaces on the bars [6, 7, 8].

The bars are supported at 60 cm intervals on small nylon buttons for optical isolation. Each long bar has a fused silica wedge glued to it at the readout end. The wedge is made of the same material as the bar, 9 cm long with very nearly the same width as the bars (3.5 cm) and a trapezoidal profile (2.8 cm high at bar end, and 8 cm at the light exit end). The bottom of the wedge has a slight ($\sim$ 0.6 mrad) upward slope to minimize the displacement of the reflected image due to the finite bar thickness. The wedges are glued to a 1 cm thick fused silica window, which provides the interface and seal to the water.

The mechanical support of the DIRC [Figure 3(a)] is cantilevered from the iron end-cap region of the instrumented flux return (IFR). The Strong Support Tube (SST) is a steel cylinder located inside the end doors of the IFR and provides the basic support for the entire DIRC. It, in turn, is supported by an iron gusset plate and "horse collar" that fixes the SST to the Barrel magnet iron. It also minimizes the magnetic flux gap caused by the

(a)



(b)

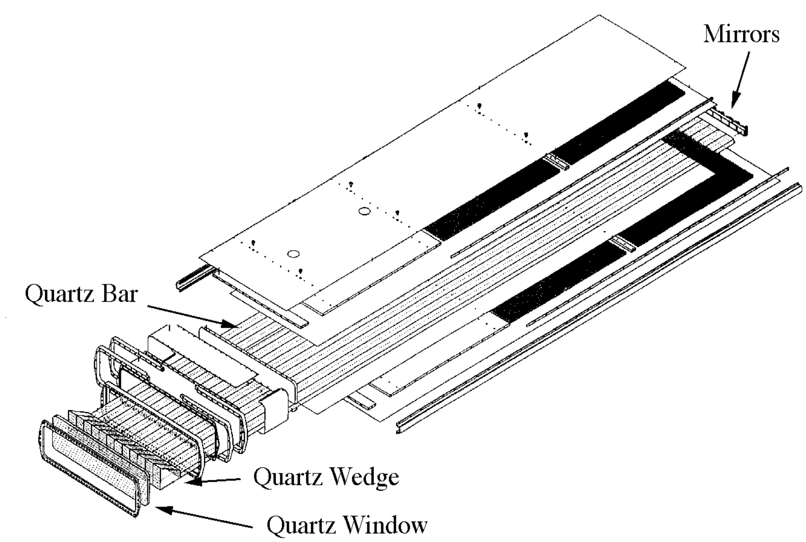


Figure 3: Schematics of the DIRC (a) mechanical components; (b) radiator bar box assembly.

DIRC bars extending through the IFR and takes the axial load of the inner magnetic plug surrounding the beam in this region.

The fused silica radiator bar boxes are supported in the active region by an aluminum tube, the Central Support Tube (CST), attached to the SST via an aluminum transition flange. The CST is a thin, double-walled, cylindrical shell, using aircraft-type construction with stressed aluminum skins and bulkheads with riveted or glued joints. The CST also provides the support for the inner drift chamber.

The Standoff Box (SOB) is made of stainless steel, consisting of a cone, cylinder, and 12 sectors of PMTs. It contains about 6000 liters of pure water. Water was used to fill this region since it is inexpensive, has an index of refraction ($n \sim 1.34$) reasonably close to that of fused silica, thus minimizing the total internal reflection at their interface, and its index chromaticity matches that of fused silica, which effectively eliminates dispersion at the silica-water interface. The gusset and horse collar support the SOB. It is surrounded by an iron shield, supplemented by a bucking coil, to suppress the field in the PMT region to below 1 Gauss. The PMTs at the rear of the SOB lie on a surface that is approximately toroidal. Each sector contains 896 29-mm PMTs (ETL model 9125 [9]), closely packed, inside the water volume. Each PMT is mounted from the inside of the SOB and is connected via a feed-through to a base mounted outside. Each PMT has an associated "light catcher" [Figure 1(a)], which results in an effective active surface area light collection fraction of about 90%. The distance from the bar end to the PMTs is 1.17 m, which together with the size of the bars and PMTs, gives a geometric contribution to the single photon Cherenkov angle resolution of $\sim$ 7 mrad. This is a bit larger than the resolution contribution from production (mostly an $\sim$ 5.4 mrad chromatic term) and transmission dispersions. The overall single photon resolution expected is about 9 mrad.

The DIRC occupies 8 cm of radial space including supports and construction tolerances, with a total radiation length thickness of about 19% at normal incidence. The radiator bars subtend about 94% of the azimuthal angle and 87% of the center-of-mass polar angle cosine.

5 Status and Run Schedule

At present, the DIRC is fully installed in the *BaBar* detector, and taking data in colliding mode. Initial bar delivery from the grinding and polishing vendor [8] was slower than expected, so that the DIRC had only five (of the total 12) bar boxes in place when the *BaBar* detector first rolled onto the beam line in April 1999. The DIRC ran smoothly over the summer of 1999 with these bar boxes, and attained performance rather close to that expected from Monte Carlo in the instrumented region of azimuth. It has been robust and stable, and indeed, serves as a background detector. However, some care in machine tuning is required to stay under a noise limit of about 200 kHz/tube imposed by limited DAQ throughput. Additional shielding in the SOB tunnel region, now being constructed, should reduce this sensitivity. After 10 months of running, about 99.8% of all PMT and electronic channels are still running with nominal performance. The remaining bar boxes were installed on beam line during a two week shut down in October, 1999.

6 Performance

The parameters of expected DIRC performance were derived from extensive studies with a variety of prototypes, culminating with a full-size prototype in a series of test beam runs at CERN [10]. The results were well-described by Monte Carlo simulations of the detector. With the actual DIRC detector now installed in *BaBar* these initial performance parameters can be reviewed, and performance estimates given for initial data based on the present status of the analysis. The present results are already rather close to expectations, and additional offline work on geometrical alignment and software tuning is expected to lead to further improvements in the near future.

In the absence of correlated systematics, the track level angular resolution ($\sigma_{Cherenkov}$) on the Cherenkov angle of the DIRC should scale as

$$\sigma_{Cherenkov} = \sigma_\gamma / \sqrt{N_{pe}}, \tag{1}$$

where σ_γ is the single photon resolution, and N_{pe} is the number of photoelectrons detected. Figure 4(a) shows the single photon resolution obtained for photoelectrons from muons (from cosmic rays). The average single photon resolution obtained for Cherenkov photons is about 9.3 mrad, very close to the expected value of about 9 mrad. There is a broad background of less than 10% relative height under the peak that comes mostly from other track associated sources. The precise nature of these sources remain under investigation. The number of photoelectrons shown in Figure 4(b) varies from a minimum of about 25 in the small dip angle region of the central barrel to well over 50 at large angles. This is within about 10% of the value expected from the Monte Carlo at all angles. This spectrum also demonstrates a very useful feature of the DIRC in the *BaBar* environment; i.e., the performance improves as the tracks become more forward, as is needed to cope with the angle-momentum correlation of particles from the boost.

The typical single track resolution for Bhabha positrons between 3.1 and 3.5 GeV is shown in Figure 5 to be about 2.9 mrad. This is equivalent to a separation between 3 GeV kaons and pions of about 3.8 σ, about 10% larger than predicted by the Monte Carlo. The time resolution (not shown) obtained is consistent with $\sim$ 1.7 ns, as expected from the single-photon resolution of the PMTs.

Figure 6 shows an example of the use of the DIRC for sample selection. Figures 6(a) and 6(b) show the invariant two body mass spectra for tracks assumed to be $K\pi$ pairs without (a), and with (b) the use of the DIRC for kaon identification.

7 Conclusions

The DIRC is a novel ring-imaging Cherenkov detector that is well-matched to the hadronic particle identification requirements of *BaBar*. The DIRC has run with partial azimuthal radiator coverage for all collision data taking since PEP-II start-up in May 1999, and has been fully completed and operational since October 1999. It runs very reliably, and is stable and easy to operate. Initial performance obtained is already rather close to that simulated

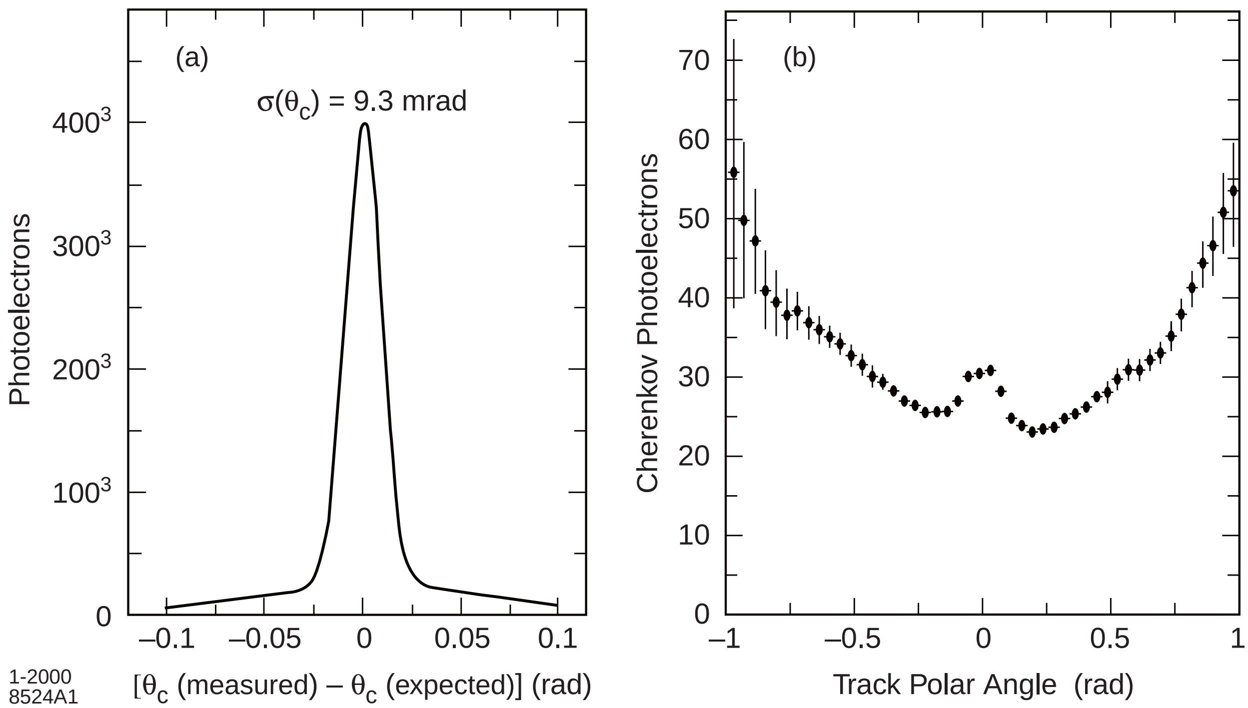


Figure 4: Reconstructed data from cosmic ray muons: (a) resolution of the reconstructed Cherenkov polar angle for single photons and (b) number of detected photoelectrons *vs* track dip angle.

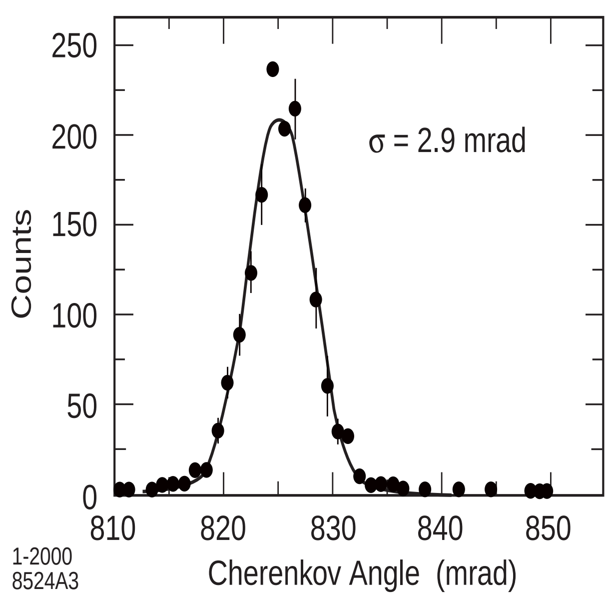


Figure 5: Single-track resolution of the reconstructed Cherenkov polar angle for Bhabha positrons in the backward region.

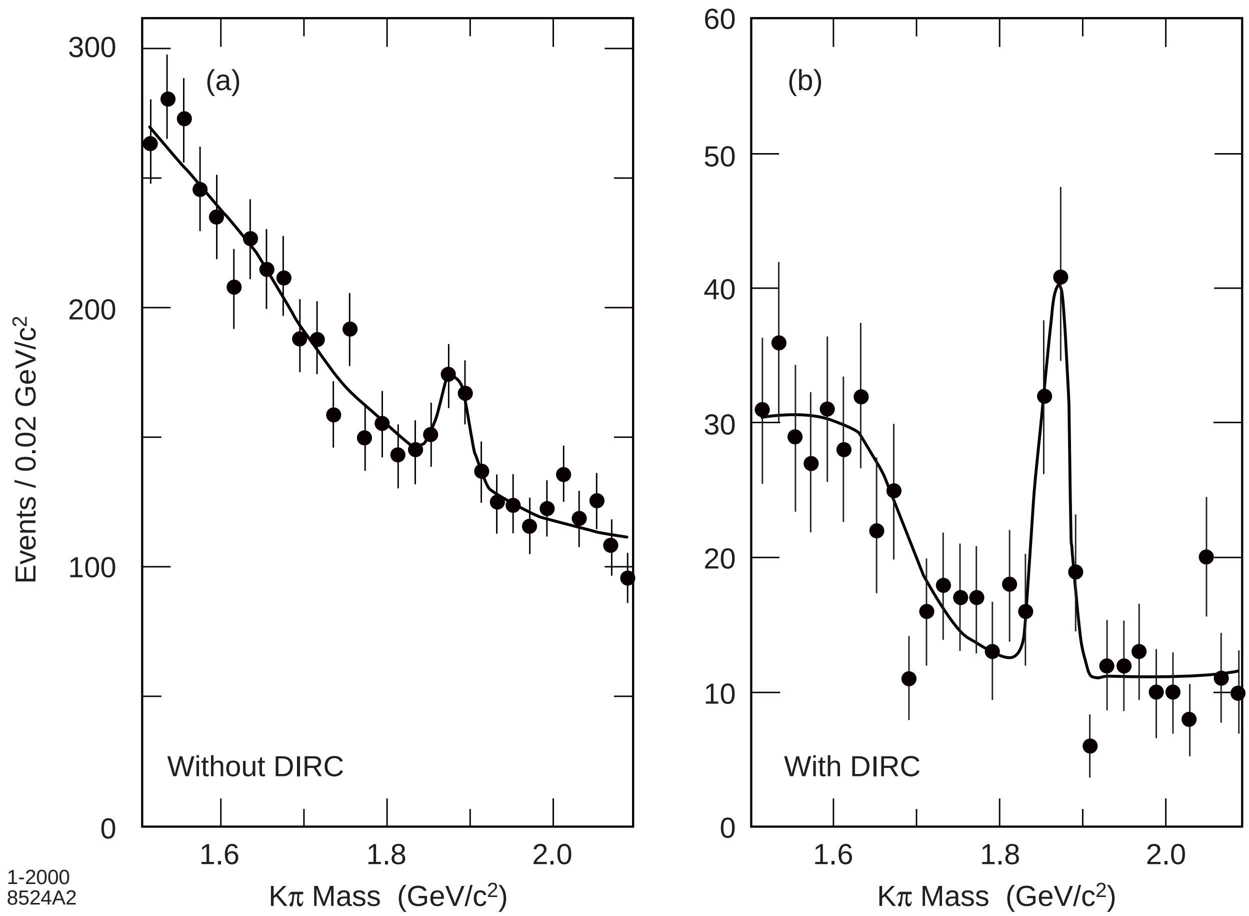


Figure 6: Invariant Kp inclusive mass spectrum without (a) and with (b) the use of the DIRC for kaon identification. The mass peak corresponds to the decay of the D^0 particle.

by the Monte Carlo. Alignment and further code developments are underway which are expected to further improve performance soon.

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