SLAC–PUB–5853
July 1992
(A)

COMMENTS ON PARTICLE IDENTIFICATION AT THE B FACTORY*

B. N. Ratcliff
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309 USA

ABSTRACT

The importance of particle identification at an asymmetric B factory is discussed, and the general status of a number of particle identification technologies which might be included in B factory detectors is briefly reviewed.

1. INTRODUCTION

It is generally agreed that high quality hadronic particle identification is fundamental to the central mission of understanding CP violation at the B factory, but there is as yet no clear "consensus" solution for such a detector [1]. In a sense, this lack of a particle identification solution is a matter of definition. There is, in fact, a perfectly reasonable, "conventional technology," particle identification system which makes use of a large tracking chamber with excellent (i.e., relativistic rise quality) dE/dx surrounded by a good TOF with a rather long flight path. The chamber must be rather large (around 2 meters in outer radius) and perhaps high pressure as well, but similar devices are rather well understood and it would appear to be possible to meet the particle identification performance required at B factory momenta [2]. This solution has not been embraced by any of the detector groups, however, because of the effect it has on the electromagnetic calorimetry. "Everyone" wants high quality calorimetry (such as can be provided by CsI crystals), but such devices cost a great deal per unit volume, and the cost scales roughly like the inner radius squared. Moreover, no one wants to see the high quality (expensive) calorimetry compromised by excessive mass in front. Thus, the essence of the particle identification problem is that there is no approximately massless, very thin particle identification device known with adequate performance. Of course, it might equally well be said that there is no high quality calorimeter known which is sufficiently cost-effective to be placed outside an appropriately sized tracking plus particle identification system. To date, detector groups have generally optimized their detectors, and proposals, for tracking and calorimetry, and have continued to work on particle identification systems which might be able to meet the requirements [3]. There are a number of interesting ideas and a substantial amount of R&D being carried out around the world, about which we will learn more today. We all hope that some of this work will turn out to lead to a thin device which can be integrated into a detector with high quality calorimetry as has been proposed. However, in the final analysis, the detector parameters and cost/benefit trade-offs should be determined by the relative importance of the physics topics, and not by the seductive power of a beautiful technology for a particular piece of that physics.

* Work supported by Department of Energy contract DE-AC03-76SF00515.

2. PHYSICS

This section briefly summarizes the particle identification criteria which are dictated by the physics objectives of an asymmetric B Factory, and presents some examples. This review is of necessity very abbreviated. Most of this material has been discussed in much more detail elsewhere [4]. In what follows, we will consider an asymmetric machine with beam energies of 9 on 3.1 GeV/c.

2.1 General Production Properties

As shown in Figs. 1(a) and (b), the typical momentum distributions for particles produced at the B factory are quite soft; the average value for pions is 0.56 GeV/c, and for kaons it is 0.85 GeV/c.

The lab angular distribution for pions shown in Fig. 1(c) is asymmetric and very strongly forward peaked due to the asymmetry in the beam momentum. The distribution for kaons (not shown) is similar. From Figs. 1(d) and (e), we see that not only are more particles produced in the forward direction than the backward, but that their average momenta are about a factor of two higher. Thus, particle identification will

Contributed to the International Conference on B Factories: The State-of-the-Art in Accelerators, Detectors and Physics, Stanford, CA, April 6–10, 1992.

typically be both more important and more difficult (i.e., extend to higher momenta) in the forward region. Generally, forward going particles tend to have longer path lengths in the detector than do central tracks, and therefore might be expected to be somewhat better measured in devices which have significant path length dependences such as dE/dx and TOF. On the other hand, the increased path lengths lead to an increased number of particle decays, and these will provide an absolute upper limit to the performance of the total detector in the presence of even the best particle identification device.

2.2 B-Tagging with Kaons

Particle identification is important to separate pions from kaons for tagging B's. This technique relies on the fact that in the cascade decay $b \to c \to s$, the b quark will produce a K^+ while the $\bar{b}$ quark will produce a K^-. There is some wrong sign contamination from Cabibbo–suppressed decays, which ultimately limits the total performance that can be achieved, although this can be reduced by rejecting events with extra kaons. The semi-leptonic decays are also useful for tagging, of course, but they have a smaller total branching fraction. The momentum distribution for tagging kaons is shown in Fig. 2. Although it is quite soft, it is somewhat harder than the momentum distribution for all kaons (the mean momentum is 0.92 GeV/c); and the particle identification should extend well above 1.0 GeV/c for good tagging efficiency.

2.3 Two-Body B Decays

Two body decay processes such as $B \to \pi^+ \pi^-$ and $B \to K^+ \pi^-$ are important to measure but must be cleanly separated if the physics is to be understood. In particular, a measurement of $B \to \pi^+ \pi^-$ can be used to extract V_{ub}, and, if the other B is tagged, to measure CP violation. However, these processes are expected to be rare, with calculated branching ratios on the order of 10^{-4} to 10^{-5}, and the relative branching ratios are unknown. The momentum distribution of the pions is

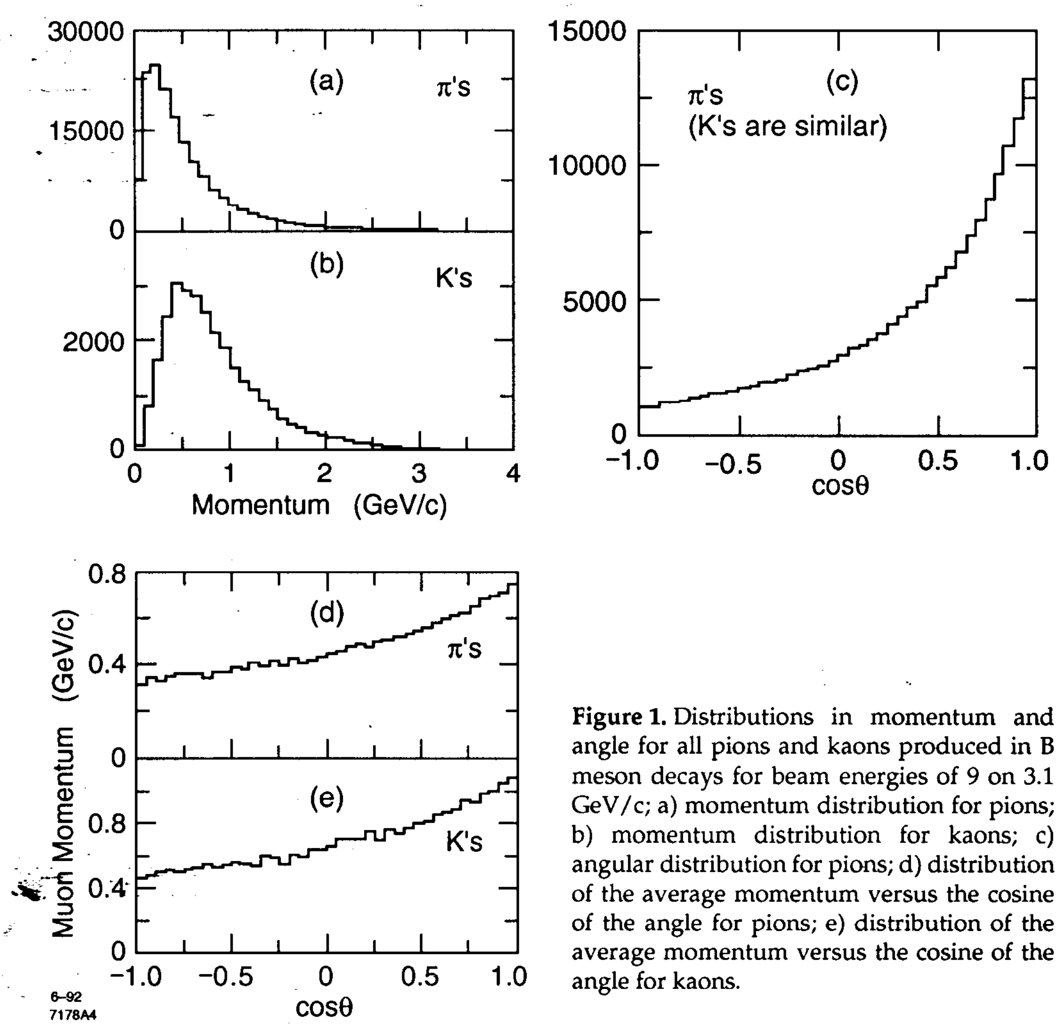

Figure 1. Distributions in momentum and angle for all pions and kaons produced in B meson decays for beam energies of 9 on 3.1 GeV/c; a) momentum distribution for pions; b) momentum distribution for kaons; c) angular distribution for pions; d) distribution of the average momentum versus the cosine of the angle for pions; e) distribution of the average momentum versus the cosine of the angle for kaons.

shown in Fig. 3 (a), and the mean momentum as a function of lab angle is shown in Fig. 3 (b). The decay pions have much higher momenta than the average pions shown in Figs. 1 and 2, and will obviously tax the capabilities of the particle identification system. In principle, these processes could be separated kinematically. Figure 3 (c) compares the mass distributions for $\pi\pi$ and $K\pi$ final states in a model where the resolution on transverse momentum is assumed to be very good, $\sigma_{P_T}/P_T^2=0.23\ (\mathrm{GeV/c})^{-1}$. The masses are reconstructed assuming the pion mass for both particles. The two distributions are separated by about 2σ, and it is clearly difficult to separate them kinematically. In principle, a fairly clean $\pi\pi$ sample could be produced by cutting hard on the tail region, but any such cut will reduce the statistics significantly in a channel with too few events already, and the tails of the separation distributions would need to be very well understood. Moreover, the relative branching ratios are unknown at the moment and may be unfavorable.

It would clearly be desirable for these rare processes to

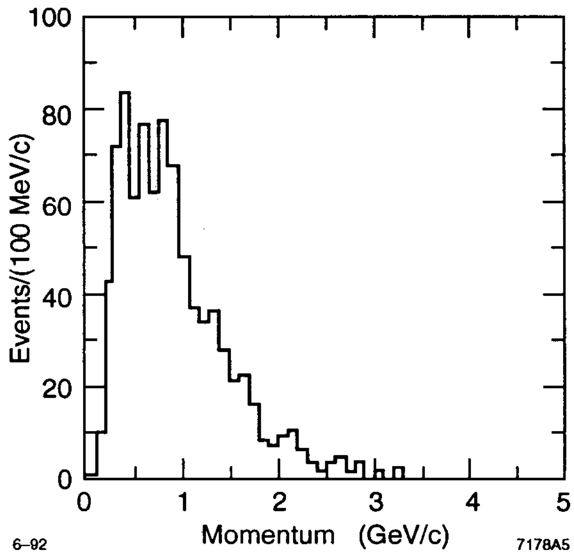

Figure 2. The momentum distribution for all tagging kaons.

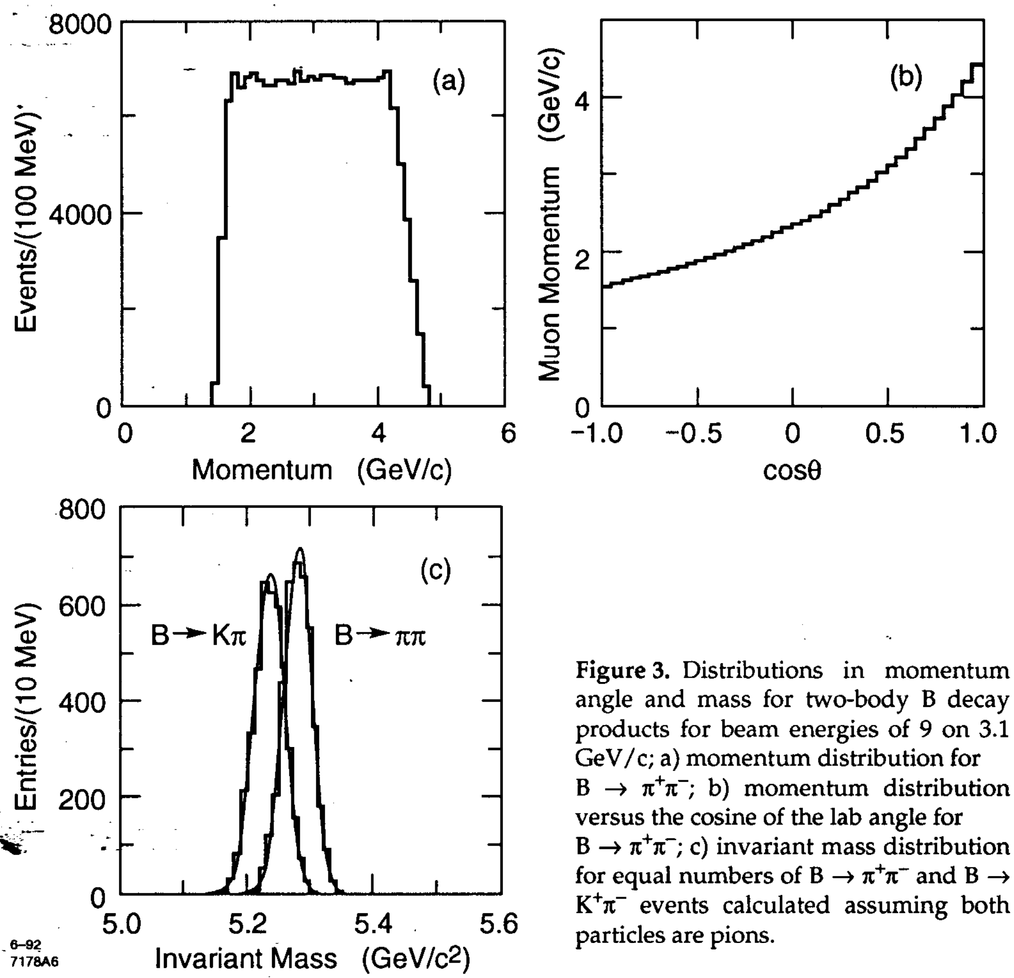

Figure 3. Distributions in momentum angle and mass for two-body B decay products for beam energies of 9 on 3.1 GeV/c; a) momentum distribution for $B \rightarrow \pi^+\pi^-$; b) momentum distribution versus the cosine of the lab angle for $B \rightarrow \pi^+\pi^-$; c) invariant mass distribution for equal numbers of $B \rightarrow \pi^+\pi^-$ and $B \rightarrow K^+\pi^-$ events calculated assuming both particles are pions.

have a hadronic particle identification system capable of performing high quality separation up to about 4.5 GeV/c.

2.4 τ Decays

As a final example, hadrons from τ decays tend to be rather hard as shown in Fig. 4, and require particle identification in the 1-4 GeV/c region if the efficiency is to be reasonably large.

2.5 Synopsis of Physics Requirements

To summarize the physics requirements, Table 1 suggests some possible particle identification techniques which might be applied to each of these examples. In this table, we distinguish between "easy dE/dx" in the $1/\beta^2$ region and "good dE/dx" as required to do separation in the relativistic rise region. We also

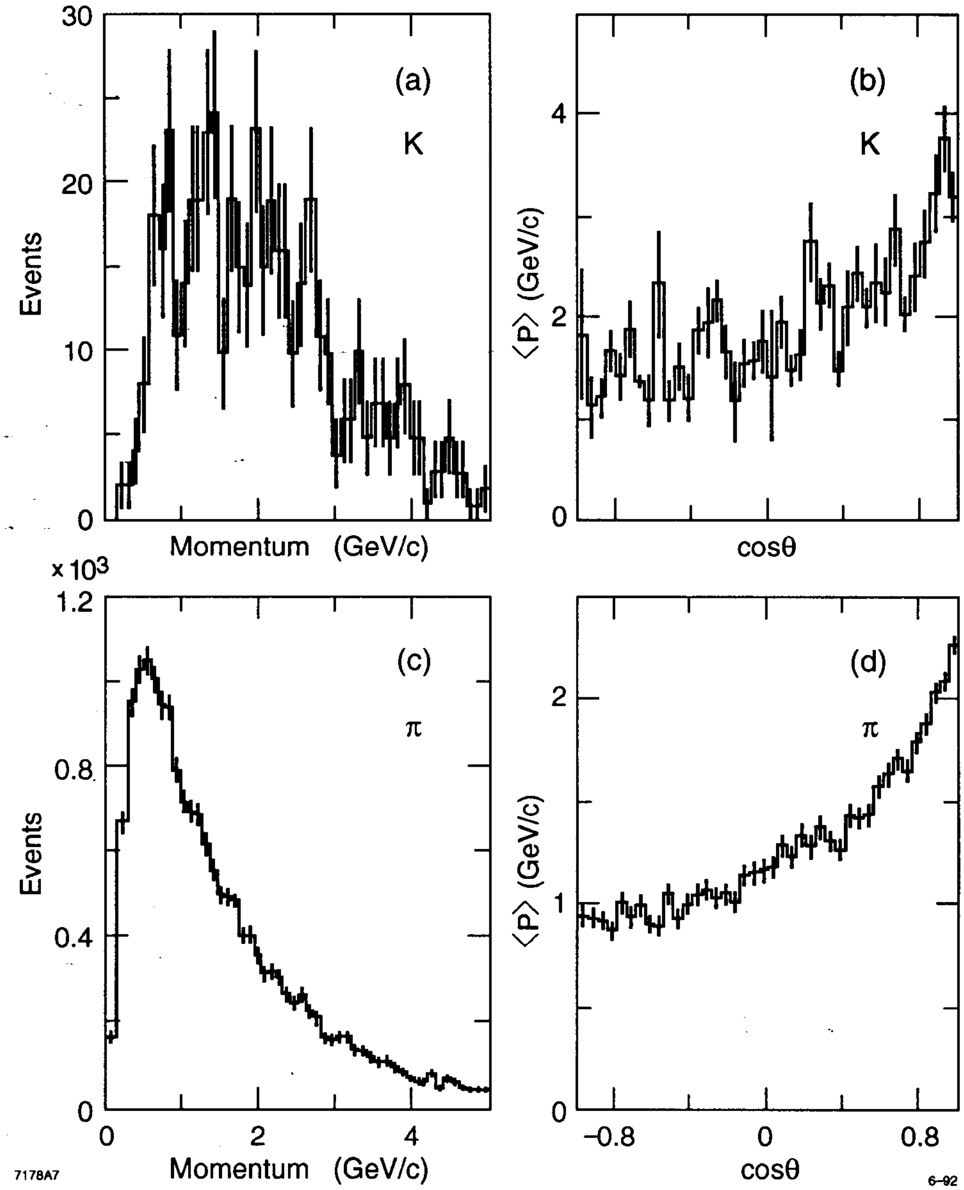

Figure 4. Momentum distribution of hadrons from τ decays for: (a) kaons; (c) pions; average momentum versus cosine of the lab angle for; (b) kaons; (d) pions.

distinguish between "easy TOF" as required to separate particles with several σ up to around 1–1.2 GeV/c; and "good TOF" which is needed to fully cover the "hole" in dE/dx coverage, and perhaps to extend some TOF separation into the 2.0 GeV/c region. Finally, the imaging Cherenkov technique can (at least in principle) cover the entire momentum range for all particles, while threshold Cherenkovs can cover the momentum region from below 1.0 GeV/c to the kinematic limit. More details on the performance and experimental status of each of these techniques is given below.

Table 1: Synopsis of Physics Requirements

Physics Process	Possible Particle Identification Techniques
KAON TAGGING	
For "Low |P|" region ($\|P\| \leq 0.7$ GeV/c)	"Easy dE/dx" "Easy TOF" Imaging Cherenkov
For "Medium |P|" region ($0.7 \leq \|P\| \leq 1.4$ GeV/c)	"Good TOF" Imaging Cherenkov Threshold Cherenkov
RARE TWO BODY PROCESSES	Good tracking (for kinematic separation) "Good dE/dx" Imaging Cherenkov Threshold Cherenkov
CONTINUUM DECAYS (e.g. τs)	"Good dE/dx" + "Good TOF" Imaging Cherenkov + "Easy dE/dx" Threshold Cherenkov + "Easy dE/dx"

3. CHOICES FOR PARTICLE IDENTIFICATION

There appear to be three primary candidates for particle identification devices to be included in a B Factory detector: (1) time-of-flight (TOF); (2) ionization loss in a gaseous medium (dE/dx); and (3) Cherenkov counters, both imaging and threshold. In this section, I will briefly highlight a few of the relevant performance characteristics of each device type, and a few examples of device R&D issues which would help delineate some of the difficulties associated with each candidate. In addition to specific performance, there are, of course, a large number of properties which must be considered for each technology including: (1) the detector mass, its distribution, and whether it is active or passive; (2) the geometrical properties of each detector, its thickness, placement in the detector, and its coverage of the detector aperture; (3) limits to performance from decays in flight, interactions in the material, or detector backgrounds; (4) triggering considerations; (5) technical difficulty and risk; (6) construction and operating costs. In the short time available here, most of these items can only be discussed in outline. Much more complete discussions of many of these points can be found in the references [2, 3], and in the talks of this session.

3.1 TOF

The TOF technique using scintillation counters is simple, well understood, and robust. The problem for the B factory is that the resolution on particle masses scales like γ^2, so that is becomes very difficult to attain good separation at high momentum with a reasonable flight path.

Figure 5 gives the upper limit of the momentum range over which 3σ π/K separation is possible as a function of the radius of the TOF system. It is quite difficult to maintain timing resolutions of better than 100 ps with long counters, so that π/K separation is limited to below about 1.1 GeV/c for a TOF with a 1 m radius. If a TOF is to be combined with a dE/dx device to make a full coverage system, the radius of counter needs to be sufficient to cover the dE/dx cross over region which

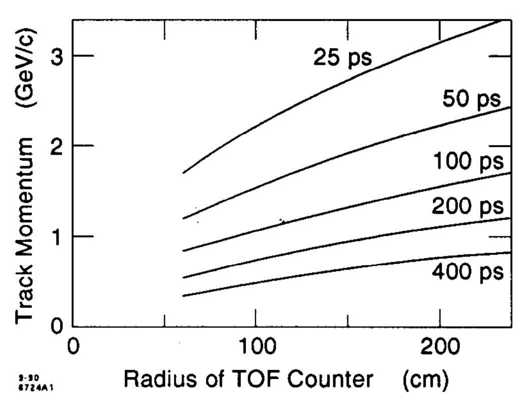

Figure 5. Maximum momentum at which π/K separation exceeds 3σ as a function of the TOF counter radius and resolution.

extends from about 0.8 to 1.6 GeV/c. This leads to a minimum radius counter of about 2 m, assuming 100 ps resolution. Though this is reasonably consistent with the radius needed for a good dE/dx device operating in the relativistic rise region, it leads to large, expensive calorimetry, and the large path lengths before the calorimeter can lead to misidentification problems for particles which decay.

A few R&D issues should be mentioned. First, it is important to know how far the timing resolution can be pushed in long counters like those of a B factory detector. Second, it is important to know how the mass of a TOF effects the calorimetry behind it, and how much this can be alleviated using the "active" nature of this mass. Finally, other techniques to attain superior fast timing resolution, such as spark gap counters, or Cherenkov light based counters, could be extremely useful and are worthy of further study.

3.2 dE/dx

Ionization energy loss (dE/dx) in gaseous tracking detectors is a central element of many modern detectors. As shown in Fig. 6, separation in the $1/\beta^2$ region is large, and is usually made available (almost for "free") in modern chamber designs, but, even so, it does require substantial attention during chamber design and operation. There are ambiguities in the so-called "crossover" regions, where two particles of different mass but the same momentum produce equal energy loss. In these regions, another method of particle identification is required. Attaining good resolution in the relativistic rise region is more difficult and requires either a large chamber with many samples, or high gas pressure, or most probably, both. There is no unique prescription for such a chamber. As an example, Fig. 6 shows the expected results for a device with 200 samples each 1 cm long, running at 2 atm., with a helium-based gas. Clearly, while π/p, and π/K separations are acceptable in both the $1/\beta^2$ and relativistic rise regions, p/K separation in the region above 2 GeV/c is not. Moreover, the crossover regions are large and would require a rather good TOF to cover completely. As mentioned earlier, the biggest problem with such a device is its sheer size, which increases the cost of the calorimetry greatly.

The basic dE/dx processes and technology are rather well understood, and it appears unlikely that large improvements in performance can be realized through more R&D. One fundamental performance issue that still appears to be open is the whether a significant improvement can be attained with cluster counting. The specific dE/dx performance of suggested designs (such as the SLAC small cell design) should also be

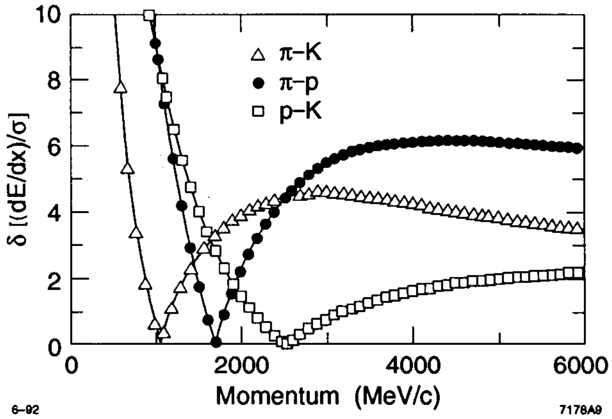

Figure 6. Predicted particle separation versus momentum for a 200 cm B factory chamber design.

investigated, and a study of whether new "high tech" materials would allow a chamber to be constructed with much lower mass walls, perhaps even when pressurized, would be very valuable for the B factory.

3.3 Cherenkov Counters

A number of different types of imaging counters have been suggested for use at a B factory [2]. The typical performance of these counters is excellent as is seen in Fig. 7.

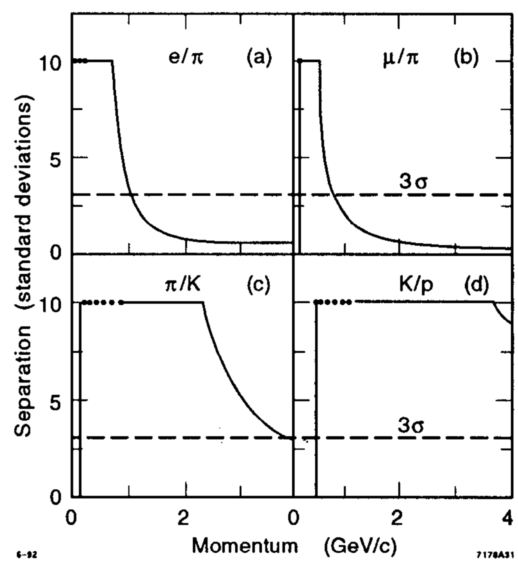

Figure 7. Predicted particle separation capability of a liquid CRID imaging counter at 64^0. Typically, the performance of other imaging counters suggested for the B factory is similar. The curves are saturated at 10σ. The separation is shown for (a) e/p; (b) μ/π; (c) π/K; (d) K/p.

However, they do have some problems. First and foremost, they tend to be rather massive and the mass is not very well distributed from the perspective of the calorimeter. Secondly, the 4π acceptance devices now in operation at DELPHI and SLD are long drift devices which are slow and sensitive to backgrounds (which may be quite troublesome at the B factory). This lack of speed has led to R&D now underway to develop the so-called FAST RICH, about which we will hear much more today.

Finally, a new type of imaging device (the DIRC), which uses internally reflected imaged Cherenkov light has been suggested which appears to solve many of the problems associated with other imaging Cherenkovs [5].

There are a great many promising avenues for R&D of which I will mention only a few examples. For the CRID type device, one would like to learn if the gain can be rapidly gated, if the detector trigger can be made sufficiently selective and fast, and if a different photodetector can be used which would be less sensitive to backgrounds than those now in use. The FAST RICH is a new device and much remains to be learned. For example, work directed toward the detector design, to minimizing the radiation length of the detector and improving its distribution, and work on photocathodes (particularly CsI +TMAE) is ongoing and will be very valuable in helping to better understand if these devices will be useful at a B factory. Finally the DIRC is a completely new device on which work is just beginning.

The number of photoelectrons (N_{pe}) which can be collected in a threshold Cherenkov counter is given by

$$N_{pe} = 2\eta N_0 L \varepsilon$$

where η=n-1, N_0=150 cm^{-1} for a good phototube, L is the length of radiator, and ε is the photon collection efficiency. If η is chosen to be 0.008 to optimize the high momentum π/K separation performance, the π threshold is 1.1 GeV/c, and the K threshold is 3.89 GeV/c. The number of photons is then given by

$$N_{pe} = 2.4 L \varepsilon$$

If L is chosen to be 15 cm, and the collection efficiency ε were about 0.4, the performance shown in Fig. 8 could be attained.

The momentum range of separation of a threshold Cherenkov counter extends from ~20% above the light particle threshold to about 20% above the heavy particle threshold. Though such a counter does not cover such a wide momentum range as the imaging Cherenkovs; when combined with another technique (e.g. "easy TOF") or perhaps with a two radiator system plus "easy dE/dx" it could cover the entire momentum range of a B factory. Since such a counter is quite simple in principle, it is worth a hard look. The main difficulties are two. First, there are no conventional non-pressurized radiators that have indices in the required range. Either high pressure gas or aerogel must be used. In both cases, it is hard to get the light to a detection surface, either because the material is highly scattering (as in the case of aerogel), or because the geometry is difficult. The second major difficulty is that the photons must either be collected by a photodetector in the magnetic field, or transported a substantial distance. Neither of these problems is easily solved, but R&D directed toward these problems is clearly warranted. For a pressurized gas device, the photon collection, transport, and detection scheme must be carefully studied, and attention paid to the possibility of building a low mass "high tech" gas containment vessel. For an aerogel device, it must be shown that a sufficient number of photons can be detected to reach the desired performance. Work to demonstrate the mechanical stability of aerogel and to show that is does not scintillate would also be very valuable.

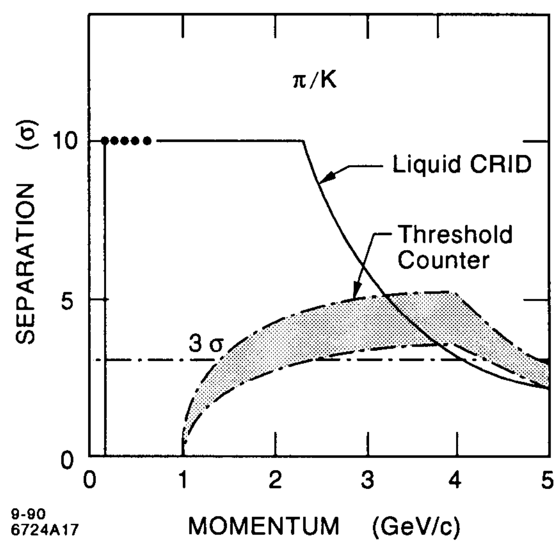

Figure 8. The separation of a liquid CRID compared with that of a single radiator threshold counter filling the same space. The index of refraction of the threshold counter is selected to give optimum performance in the high momentum region, and the number of photoelectrons are assumed equal, for the two devices.

4. SUMMARY

At this time, there is no obvious "magic bullet" which solves the dilemma of incorporating hadronic particle identification into a detector along with expensive, high quality calorimetry. Perhaps some of the promising R&D presented at this conference will lead to such a device. However, it must be recognized that there are complicated interactions between the physics capabilities of a device, the particle identification technology chosen, and the rest of the detector design. Ultimately, the detector design should be optimized for the physics, and not built around a particular choice of technology for a portion of the detector.

REFERENCES

[1] See for example, D. MacFarlane, Proceedings of this conference.

[2] See for example, P Coyle et al., SLAC-PUB-5594 (1991).

[3] See for example, KEK-90-23 (1991); CLNS-91-1047 (1991); SLAC-REP-373 (1991).

[4] See for example, KEK-90-23 (1991); CLNS-91-1043 (1991); SLAC-REP-373 (1991).

[5] See for example, P. Coyle and B. Ratcliff, Particle Identification Working Group Notes (1990); B. Ratcliff, in SLAC BaBar Notes 37 and 44 (1990); B. Ratcliff, Particle Identification Working Group Notes (1992).