1 Introduction

The CLEO collaboration has made major contributions to many aspects of b, c, τ, and $\gamma\gamma$ physics with precision unmatched anywhere in the world. This has been made possible by the CLEO II detector, with its combination of excellent tracking and CsI electromagnetic calorimetry, and the large integrated luminosity provided by the CESR accelerator. CESR is embarking on an upgrade program over the next five years after which integrated luminosities up to 15 fb^{-1}/year—10 fb^{-1} on the $\Upsilon(4S)$ resonance and 5 fb^{-1} below the $\Upsilon(4S)$—will be provided. CLEO data sets can be increased by up to an order of magnitude which will allow further, significant strides forward in our studies of heavy quarks and third generation leptons.

A central feature of the CESR upgrade, called Phase 3, is larger focussing quadrupoles that intrude into space now occupied by the CLEO II tracking detectors (see Fig. 1), necessitating replacement of these aging devices. It should be noted that the VD wire chamber is now 10 years old and the main drift chamber is 6 years old. These elements need replacing regardless of the accelerator upgrade and in addition the drift chamber endplates and mounting structure compromise the performance of the CsI calorimeter. The other sub-detectors—CsI calorimeter, magnet coil, and muon system—are compatible with the machine upgrade and our future physics goals with only small modifications, although higher data rates will require more sophisticated readout electronics. The new tracking system design compatible with the upgraded IR design will also provide the space for a high-quality particle identification system (see Fig. 2) that will allow 4σ π/K separation up to 2.8 GeV/c. This upgrade program will produce the CLEO III detector and will benefit all areas of CLEO physics and will be particularly important for the study of B decays, especially rare decays as a window to observe physics beyond the Standard Model.

The most important physics goals for CLEO remain those for B physics. While additional integrated luminosity would itself add to our knowledge, greater detection and reconstruction efficiency from pion and kaon identification up to momenta of 2.8 GeV/c will bring faster rewards. This is analogous to the introduction of excellent photon detection in the CLEO II detector which increased the number of reconstructed B's per unit luminosity. Other important topics which may become accessible include the measurement of Cabibbo-suppressed "penguin" decays such as $\rho\gamma$. A measurement of the ratio of $\rho\gamma$ to $K^*\gamma$, the latter recently measured by CLEO II [1], is an excellent way to determine V_{td}/V_{ts}. High momentum particle identification coupled with the large CLEO III data sample will make it possible to attempt the observation of CP violation in B decays by, for example, measuring the rate asymmetries in the decays $K^-\pi^+$ and $K^+\pi^-$ [2]. In addition, direct measurement of one of the CP violating angles can be attempted by measuring the branching ratios for B decays to D^0 where the D^0 decays into a CP eigenstate.

CLEO III will also be able to address many new topics in the areas of charm and tau physics. For example, with high momentum particle identification, the Cabibbo-suppressed semileptonic charm decays such as $\rho^- \ell^+ \nu$ can be measured even though there is a much larger rate from $K^{*-}\ell^+\nu$. For both charm physics and the study of fragmentation, the momentum range for which such particle separation is useful extends up to near the kinematic limit of approximately 5 GeV/c. Also, the tau neutrino mass can best be limited from studies of the decay $\tau^- \to (K^* K)^- \bar{\nu}$ due to the large minimum hadronic mass in this channel (the present acceptance is <1%). Again, particle identification is crucial.

1.1 Lessons from the CLEO II detector

The CLEO II detector was designed with the goal of reconstructing thousands of B mesons. The detector philosophy was to create a device with excellent charged particle momentum resolution and excellent electromagnetic (electron and photon) energy resolution. This has been achieved. As implemented, the CLEO II detector has *attained* a charged particle momentum resolution of

$$(\sigma_p/p)^2 = (0.0015 p_t)^2 + (0.0056)^2 \text{ for } p_t > 0.75\ GeV/c \tag{1}$$

and an electromagnetic (e and γ) energy resolution of

$$\sigma_e/E = 0.0035/E^{0.75} + 0.019 - 0.001E \qquad Barrel \tag{2}$$

$$\sigma_e/E = 0.0026/E \quad + 0.025 \qquad Endcap \tag{3}$$

where momentum is in GeV/c and energy is in GeV. In addition, particle identification is provided by a measurement of specific ionization ($\mathrm{d}E/\mathrm{d}x$) in the central tracking chambers—2σ π/K separation level for momenta below 750 MeV/c and 1.6σ at 2.3 GeV/c—and by a scintillator-based time-of flight system in front of the calorimeter—2σ below 1 GeV/c.

Although the CLEO II detector has performed admirably, there are weaknesses and design limitations which affect its performance at high luminosity:

1. The mechanical structure of the inner tracking system—Precision Tracking Layer (PTL) detector, Vertex Detector (VD), and the Drift Chamber (DR 2)— is incompatible with the CESR Phase 3 interaction region. The severe magnetic field requirements for a high luminosity interaction region imply a stepped permanent quadrupole (17 cm radius) along a 300 mrad line from the interaction region followed by a superconducting quadrupole (20 cm radius). The 300 mrad line is shown superimposed on the CLEO II detector in Fig. 1, indicating that the CLEO II tracking system is not compatible with the high luminosity collider.

2. The drift chamber mounting and stabilizing ring is a solid aluminum structure which shadows the last 6 rows of crystals of the barrel calorimeter (shaded in Fig. 1) and causes inferior energy and angular resolution and lost efficiency.

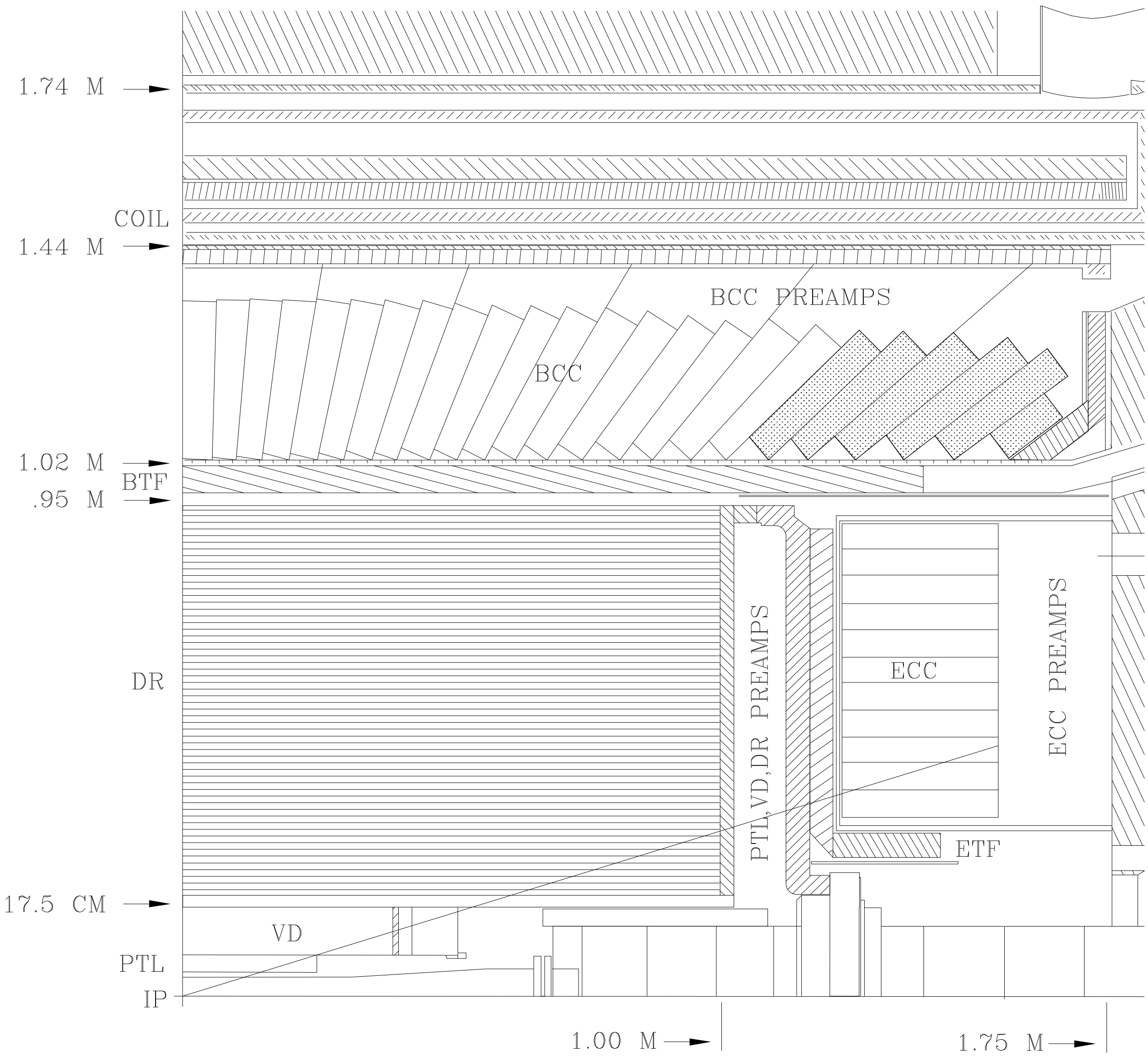

Figure 1: A quarter-section of the CLEO II detector showing the drift chambers (PTL,VD, and DR 2), the CsI calorimeters (BCC and ECC), the time-of-flight (BTF and ETF), and the superconducting solenoid (COIL). The muon counters are beyond the coil and the endcap. The angled line originating at the interaction point (IP) is 300 mrad from the beam line. At about 35 cm from the IP, the territory between this line and the beam line will be occupied by the CESR Phase 3 upgrade.

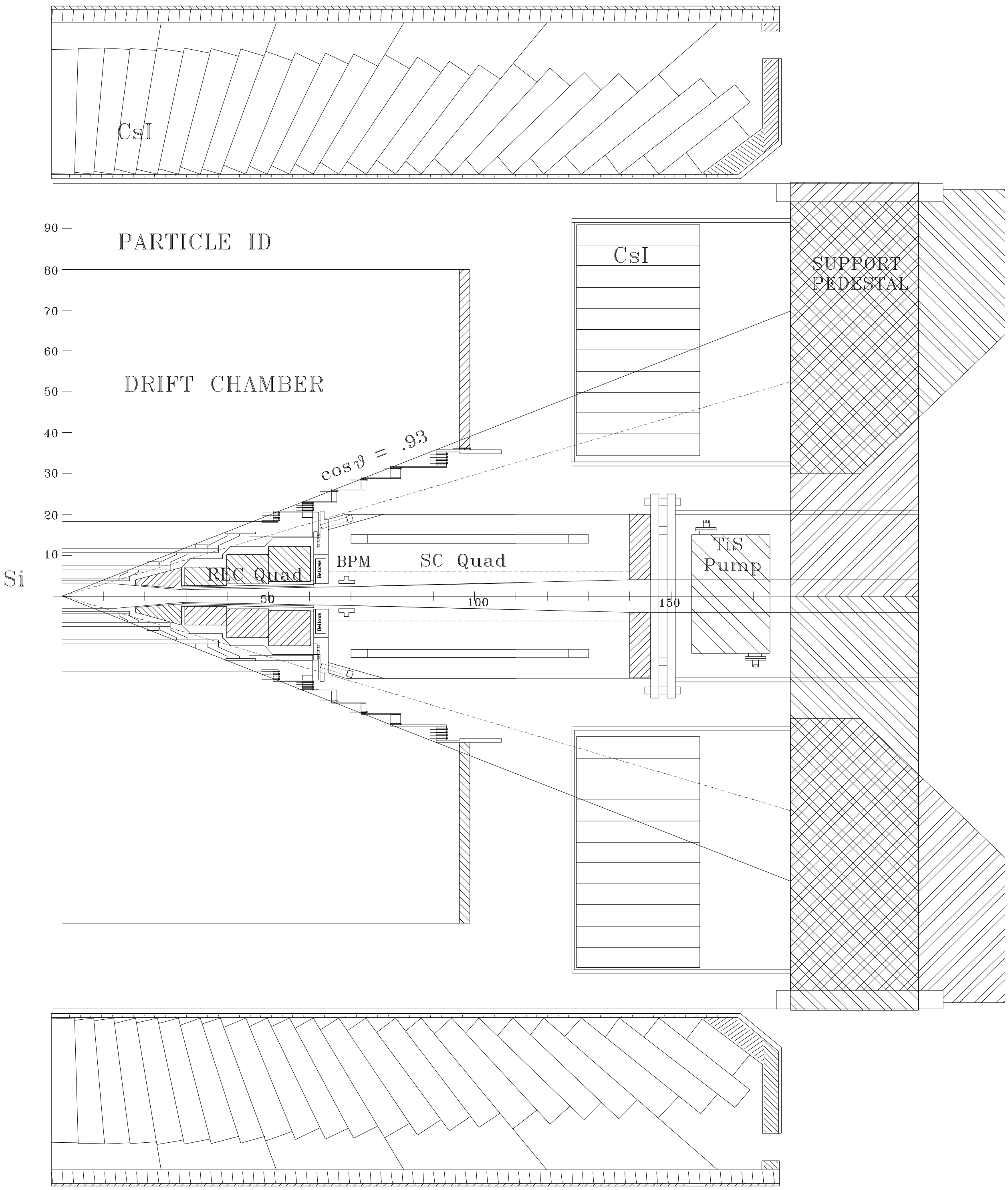

Figure 2: A half-section view of the CLEO III detector inside the superconducting solenoid and the CESR Phase 3 interaction region components. The 20 cm clear space around the drift chamber is reserved for the particle identification system—the detector technology is yet to be chosen.

3. The momentum range for π/K separation is limited. The present detector uses a combination of dE/dx and time-of-flight below 750 MeV/c, time-of-flight alone up to 1 GeV/c, and dE/dx alone above 2.3 GeV/c.

4. The endcap calorimeter, which represents 18% of the solid angle, has not been used in most analyses due to its low efficiency and poor resolution caused primarily by the large amount of material in front of it and its non-projective geometry.

5. The present electronics will not support the large data rates associated with 10^{33} cm^{-2}sec^{-1} operation.

1.2 Design philosophy for CLEO III

There are several constraints placed on the design of CLEO III. They are:

1. The requirements of the new CESR IR clearly determine that the inner detector must be replaced and that the maximum attainable acceptance is determined by the 330 mrad line (93% of 4π) in Fig. 2. This leaves adequate clearance between CESR and CLEO III for a shared space for cabling and plumbing.

2. The new particle identification system must fit inside the existing CsI calorimeter volume.

3. The new tracking system must allow space for the particle identification system without compromising the tracking performance or the total acceptance.

4. The barrel CsI calorimeter will remain intact but we may rework the endcap calorimeter if it can be demonstrated to greatly enhance the quality of the data.

1.2.1 Tracking

The performance of a tracking system may be quantified in terms of its resolution in momentum, angle, impact parameter, and vertexing. The present CLEO II tracking system has demonstrated that it meets all the requirements in these variables to study the physics we anticipate at high luminosity. We have therefore defined this as the *minimum goal* for the CLEO III tracking system. This is challenging since the tracking length in CLEO III will be shorter than in CLEO II. Consider the charged particle momentum resolution which is given by:

$$\left(\frac{\mathrm{d}p}{p}\right)^2 = \left(\sqrt{\frac{720}{N+5}} \cdot \frac{\sigma}{0.3B\ell^2} \cdot p_t\right)^2 + \left(\frac{0.016}{0.3B\ell\beta} \cdot \sqrt{\frac{\ell/sin\theta}{X_0}}\right)^2 \qquad (4)$$

where B is the magnetic field strength (Tesla), N is the number of measurements along the track, ℓ is the projected track length onto the bending plane (m), X_0 is the radiation length of the scattering medium (m), σ is the average space point resolution (m), β is v/c, and θ is the dip angle. The first term in the resolution formula is due to tracking variables, namely resolution, track length and number of measurements. The second term is the contribution due to multiple scattering. Thus, to maintain a fixed momentum resolution as ℓ is reduced requires that X_0 must be increased correspondingly. Similar arguments hold for other parameters. Therefore, the general philosophy of the CLEO III design is to reduce the tracking length of the drift chamber to provide space for particle identification while maintaining the performance by simultaneously reducing the amount of material in that tracking length.

1.2.2 Particle identification

A major goal of the physics program is to cleanly measure rare decays to test the Standard Model and be sensitive to possible new physics. This requires excellent charged hadron identification with 4σ separation of pions and kaons up to 2.8 GeV/c. Even though a $\mathrm{d}E/\mathrm{d}x$ capability will be retained in the readout of the new drift chamber, the momentum range over which we have good identification needs to be extended upward in order to access many of the most important physics issues. The new system must also be no thicker than 12% of a radiation length—the present time-of-flight scintillator thickness—in order not to compromise the performance of the CsI calorimeter.

The required performance of a particle identification system depends on the process being studied. The number of standard deviations of separation, n_σ, is defined as

$$\mathrm{n}_\sigma = \frac{(\mathrm{M_K} - \mathrm{M}_\pi)}{\sqrt{\left(\frac{1}{2}\right)(\sigma_\mathrm{K}^2 + \sigma_\pi^2)}}, \tag{5}$$

where $\mathrm{M_K}$, M_π, σ_K, σ_π are the means and standard deviations of the K and π distributions respectively. Excellent work on all B decay physics can be accomplished if one has 4σ separation at 2.8 GeV/c, the maximum momentum reached in B decays. As an example, consider the problem of separating $\bar{B}^0 \to K^-\pi^+$ from $\pi^+\pi^-$. The separation needed depends on the relative populations in the two channels, and the signal purity desired. In Fig. 3, the plot of separation versus fraction of the signal which is $\pi^+\pi^-$ is shown. If the $\pi^+\pi^-$ fraction is only 10%, the rejection required is at the 3–4 σ level for reasonable ($> 90\%$) purities (ignoring other sources of background). For the $B \to D^0K^-$ modes, the background just from $D^0\pi^-$ is about 20 times the signal without particle identification and thus 4 σ rejection is essential. The separation at even higher momentum is also useful for other physics such as light quark fragmentation, charm decays, and τ decays. Although we have specifically mentioned π/K separation, another important consideration is the ability to separate protons from kaons.

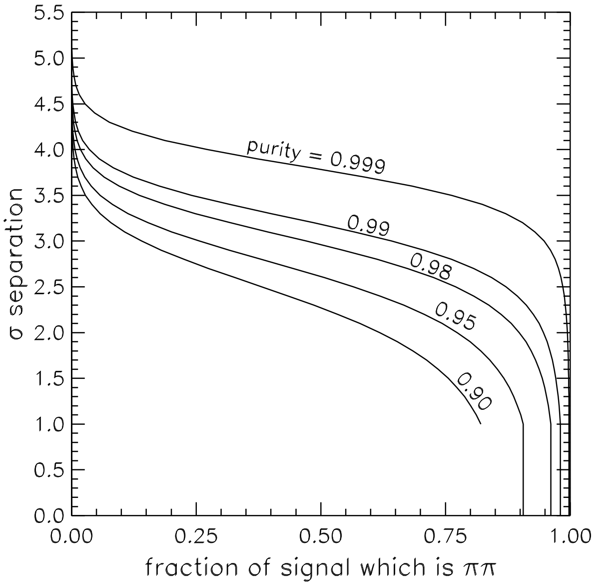

Figure 3: The number of σ separation between kaons and pions required to separate $K^-\pi^+$ from $\pi^+\pi^-$ as a function of the fraction of $\pi^+\pi^-$ and the required purity in in the $K^-\pi^+$ sample.

1.3 Physics overview

In this section we briefly describe some of the physics reach of the CLEO III detector. Much more detail is provided in the next section.

1.3.1 B physics

Two topics at the frontier of B physics are $b \to u$ decays and penguin decays, both of which occur in the decays of B mesons to two light mesons. The decay $B^0 \to \pi^+ \pi^-$ is an example of a two-body $b \to u$ decay, and it is most likely the mode in which CP violation in such decays will eventually be seen. The decay $B^0 \to K^+ \pi^-$ is an example of a hadronic penguin decay which should be observed in the near future. For each of these modes, the other one is a serious background, depending on the relative branching ratios and the ability to separate pions from kaons. Measuring both decays will also give some estimate of the effect of penguins in the $B^0 \to \pi^+ \pi^-$ decay. A statistically significant signal has been observed in CLEO II data in the sum of these two modes and limits on the individual branching ratios are found to be less than 3×10^{-5}. At the present level of statistics the separation of the two channels is not possible. With the increased luminosity of the upgrade, these two modes will both be measurable. Unfortunately as the expected branching ratios decrease, the background suppression becomes more difficult. The existing analyses show that good momentum resolution is critical. It will be necessary to separate the two modes cleanly, especially if one turns out to be much larger than the other. This requires π/K identification at momenta of 2.8 GeV/c. Furthermore, an attempt to measure CP violation would involve telling $K^+\pi^-$ from $K^-\pi^+$. In this case there is no help from kinematic constraints and the particle identification system must provide full discrimination.

One of the centerpieces of the physics program at the upgraded CESR will be measuring the CKM matrix elements as precisely as possible. These are important not only as fundamental parameters of the Standard Model, but also as the information needed to predict the CP asymmetries to be measured later. V_{ub} will be measured using the exclusive decay channels $B \rightarrow \rho(\omega)\ell^- \bar{\nu}_\ell$ because they are the likely dominant modes beyond the $b \rightarrow c$ endpoint in the lepton energy spectrum, and because the form factors will be reasonably well understood. Although the recent CLEO analysis sets upper limits on the branching ratios for these decay modes, the size of the $b \rightarrow u$ signal in the inclusive spectrum implies that they will be observed very soon. The analysis requires a large background suppression, which relies on almost every aspect of the CLEO detector. In the present analysis, the dominant background is due to continuum leptons combined with other pions in the event, which happen to pass the strict kinematic cuts. Information from the silicon vertex detector will provide an extra handle to remove this background. Real leptons coming from charm decays will tend to have a three-dimensional impact parameter removed from the event vertex, while those from B decay will not. Light quark events which include fake leptons will be consistent with having only one vertex, while $\Upsilon(4S)$ events will have multiple vertices. Thus suppressing these backgrounds will give a good measure of performance for the measurement of vertices.

The familiar decay chain $\bar{B}^0 \rightarrow D^{*+}\pi^-$, $D^{*+} \rightarrow \pi^+ D^0$, although not as interesting a physics mode in the future, serves as a useful measure of performance for many other B decays, such as $\bar{B}^0 \rightarrow D^{*+}\ell^- \bar{\nu}_\ell$. The comparison of efficiency and background suppression with the present detector tests many performance characteristics. In particular, the acceptance for the slow pion and the resolution in mass difference must be studied carefully. We already know from CLEO II how important, but difficult, it is to measure this pion's parameters well. The D^{*+} mass difference is one case in which the angle measurement dominates the resolution, so it tests the measurement of $\tan\theta$ particularly well. It has already been shown that the event vertex constraint is needed to get full use of the silicon detector in measuring this angle.

We have studied in some detail the practicality of the suggestion of Gronau and Wyler[3] to measure CP violation with self-tagging modes. Although it is unclear if such an effect could be seen with the luminosity available with the CESR upgrade, the B decay modes involved are interesting in their own right, and provide a good test of the proposed detector. It also makes it possible to look for the CP violation, in case the relevant branching ratios turn out to be larger than expected. In particular, we have examined the decay mode $B^- \rightarrow \bar{D}^0 K^-$. This is a $b \rightarrow u$ decay and color suppressed, so that the branching ratio is expected to be in the range of 10^{-6}. The decay $B^- \rightarrow D^0 K^-$, which is a Cabibbo-suppressed $b \rightarrow c$ decay, has a branching ratio in the range of 10^{-4} and represents a more accessible mode with the same experimental requirements. Even measuring this mode is well beyond the capability of CLEO II.

Studying these modes will give a good measure of the background suppression for a wide range of rare B decays. We will need high efficiency for detecting D^0's with small background.

We will use many decay modes, most of which have higher multiplicities than the familiar $K^-\pi^+$ decays. The experimental requirements are large acceptance for tracks, including those at small angles and low momentum, and good mass resolution. To separate the $D\ K^-$ decays from $D\ \pi^-$ decays will require good hadron identification at momenta around 2.3 GeV/c. Finally, it will be necessary to observe these decays with the D^0 decaying to CP eigenstates such as K^+K^- and $K_S\eta$ before one can attempt the CP measurement discussed above.

1.3.2 Charm physics

Some of the most important charm physics will be the study of semileptonic decays, especially Cabibbo-suppressed decays. Already the decays $D{\rightarrow}K\ell\nu$ and $D{\rightarrow}K^*\ell\nu$ are providing important information on the form factors for a heavy quark decaying into a light quark. This serves to improve the picture of the form factors in exclusive $B{\rightarrow}\rho\ell\nu$ decay. Even better would be to make good measurements of the decays $D{\rightarrow}\rho\ell\nu$ and $D{\rightarrow}\omega\ell\nu$.

At present, the CLEO II sample for $D^0{\rightarrow}K^-\ell^+\nu_\ell$, obtained by using $D^{*+}{\rightarrow}\pi^+D^0$, is the largest in the world. The other Cabibbo-favored decays also use the D^* tag technique to remove backgrounds, but in some D^+ modes, the background is still fairly large. The ability to separate charm vertices will help somewhat, especially in the case of D^+ decay, because of the long lifetime. CLEO has seen a good $D^+{\rightarrow}\pi^0\ell^+\nu_\ell$ signal, but the other Cabibbo-suppressed decays are obscured by their Cabibbo-favored counterparts. The decay modes $D^+{\rightarrow}\omega\ell^+\nu_\ell$ and $D^{*+}{\rightarrow}\pi^0D^+, D^+{\rightarrow}K^{*-}\ell^+\nu_\ell$ require good detection of soft π^0's and charm vertex separation to improve the measurements.

A rare charm decay mode of special importance is the pure leptonic decay $D_s^+{\rightarrow}\mu^+\nu_\mu$, which measures the important decay constant f_{D_s}. This decay has been observed in CLEO II but will be measured with much higher precision in the upgraded CLEO experiment using the $D_s^*{\rightarrow}\gamma D_s$ decay. It will require excellent measurement of the soft photon parameters, and the ability to reject photons from π^0 decay. It will also require good reconstruction of the missing neutrino using the technique of hermetic measurement of missing momentum.

1.3.3 Tau physics

At present, CLEO II is providing competitive information on almost every aspect of τ physics including decays, lifetime, and mass. With the improved CESR luminosity, CLEO will continue to have the largest τ sample in the world. The addition of particle identification will increase the number of modes that will be measured well. One measurement which should continue to improve is the limit on the ν_τ mass. In particular, the mode $\tau^-{\rightarrow}(K^*K)^-\nu_\tau$ will provide a good limit because of the large hadronic mass and the reasonable rate; the mode $\tau^-{\rightarrow}(5\pi)^-\nu_\tau$ is another good possibility. Each utilizes different aspects of the detector performance.

Much of the advantage that CLEO has in measuring τ or D branching ratios is its good efficiency and resolution for events with one or more neutrals. We have ensured that in optimizing other, newer aspects of the detector, we lose no performance in this area. A good test of this is the decay mode $\tau^- \rightarrow \eta\pi^0\nu_\tau$, which requires a final state with four photons. In all cases the CLEO III detector meets or exceeds the performance of CLEO II.