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III The Physics Reach of the Program

1 The CLEO-c Physics Program

The CLEO-c physics program includes a broad program of measurements that will contribute to our understanding of important Standard Model processes as well as providing the opportunity to probe the physics that lies beyond the Standard Model. The dominant themes of the program are:

- We will explore the weak decays of charm mesons and baryons and perform high precision studies of fundamental quantities important for testing many aspects of the Standard Model and probing for physics beyond the Standard Model. We will determine charm meson decay constants to the order of 1 – 2% accuracy. This will provide a crucially important test of lattice gauge calculations that should soon reach a similar level of accuracy. We will also measure the CKM parameters $|V_{cs}|$ and $|V_{cd}|$ at the 1 – 2% level using matrix elements determined from lattice gauge theory. These can provide important unitarity constraints and can therefore be used to probe non-standard model physics.
- We will measure absolute branching fractions for charm mesons with a precision of the order of 1 – 2%, depending upon the mode. This is a critical input for b physics studies at the B -Factories and at hadron colliders.
- We will investigate processes in charm and τ decays that are expected to be highly suppressed within the Standard Model. These processes have exciting discovery potential according to some ‘beyond the Standard Model’ predictions. A considerable advantage of CLEO-c is the coherent nature of the $D^0\bar{D}^0$ pair produced, allowing unique ways to determine charm meson mixing and CP violation parameters.
- We will perform detailed studies of QCD in the strongly-coupled nonperturbative regime. In particular we will explore the spectrum of glue-enriched hadrons by studying a very large sample of J/ψ decays.

Thus a reconfigured CESR electron-positron collider operating at a center of mass energy range between 3.1 GeV (the J/ψ resonance) and about 5 GeV (above the threshold for $\Lambda_c^+\bar{\Lambda}_c^-$ production) can give significant contributions to our understanding of fundamental Standard Model properties and has the opportunity of probing avenues beyond the Standard Model.

The expected peak luminosity is between $1.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ and $5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. The time scale of the modifications is such that one can anticipate first data taking in late 2002 or early 2003. Extrapolating from the current success of the CESR storage ring in production running, CLEO-c can anticipate integrated luminosities of 1 – 4 fb^{-1} per year where the highest luminosities would be achieved at 5 GeV and the lower luminosities apply to running at 3 GeV. Table 1 gives a summary of the energies included in our present run plan and the expected data samples.

We will start with a scan of the center-of-mass energy region near 3.77 GeV to measure the shape of the ψ'' resonance, determine its electronic and total widths, and measure the $D\bar{D}$ cross section at the ψ'' peak. This is necessary because there appears to be a discrepancy [1] of as much as a factor of two between the measured values of the peak ψ'' cross section $\hat{\sigma}_{\psi''}$ and the $D\bar{D}$ cross section $\hat{\sigma}_{D\bar{D}}$ at this energy [2,3]. According to conventional wisdom, these two cross sections should be very nearly equal, but current data tend to cluster around

values of $\hat{\sigma}_{\psi''} \sim 10$ nb and $\hat{\sigma}_{D\bar{D}} \sim 5$ nb. This situation is discussed in somewhat more detail in Appendix A. A scan of about 100 pb^{-1} should provide accurate measurements of these parameters and resolve the apparent discrepancy. If $\hat{\sigma}_{\psi''}$ and $\hat{\sigma}_{D\bar{D}}$ do indeed differ by about a factor of two, demonstration of this fact would be a sensational discovery. In the rate estimates in this study we use $\hat{\sigma}_{D^0\bar{D}^0} = 5.8$ nb and $\hat{\sigma}_{D^+D^-} = 4.2$ nb, or a total of 10 nb which is consistent with measurements of $\hat{\sigma}_{\psi''}$.

Next we will scan the center-of-mass energy region between 3.77 and 4.2 GeV to determine the cross sections for the various $D_{(s)}\bar{D}_{(s)}^{(*)}$ final states that populate this energy range. This will allow us to determine the optimum energy for D_s production. The data sample necessary to this study will be about 150 pb^{-1} .

We are expecting to accumulate 3 fb^{-1} on the ψ'' resonance and 3 fb^{-1} near 4.14 GeV during the first two years of running. The ψ'' data sample will be primarily for studies of charged and neutral D mesons. We will perform precision measurements of branching fractions, the D^+ meson decay constant, form factors and CKM matrix elements accessible with D meson semileptonic decays. Furthermore we will explore rare decays, and mixing and CP violation measurements that exploit the coherent nature of $C = -1$ $D^0\bar{D}^0$ pair produced. Several D_s studies will be performed at the higher energy. In addition, the $D^0\bar{D}^{*0}$ sample, containing a mixture of $C = +1$ ($\gamma D^0\bar{D}^0$) states and $C = -1$ ($\pi^0 D^0\bar{D}^0$) states will complete our mixing and CP violation experimental program.

We will then run for a year on the J/ψ resonance to accumulate approximately 1 fb^{-1} of data for the study of traditional and exotic hadronic states. Running on the resonances will be accompanied by some off-resonance running for background evaluation.

Finally we will accumulate about 1 fb^{-1} around 4.6 GeV for Λ_c studies, including a precision determination of its absolute branching fractions. We are also considering a short, dedicated scan near the τ threshold region and running time at the ψ' resonance.

This program will produce a substantial improvement upon previous measurements. Although some of the quantities studied at this center-of-mass energy range can be investigated also at the B -factories, the errors in measurements of the same quantities will be much smaller so that our determination may be considered unique. Thus the proposed plan will provide a very important contribution to our understanding of the Standard Model and some experimental guidance in the maze of paths ‘beyond the Standard Model’.

TABLE 1. Numbers of events in the CLEO-c program.

CM Energy (GeV)	Type of Events	Integrated Luminosity (fb^{-1})	Number of Events
3.77	$D\bar{D}$	3	3×10^7
4.14	$D_s^+ D_s^-$	3	$\sim 1.5 \times 10^6$
4.14	$D^0 \bar{D}^{*0}$	3	$\sim 3 \times 10^6$
3.1	J/ψ	1	$\sim 10^9$
4.6	$\Lambda_c \bar{\Lambda}_c$	1	$\sim 3.7 \times 10^5$

2 Simulation, Validation, and Systematic Errors

2.1 Introduction

Our estimate of the physics reach of CLEO-c has been evaluated using simulation tools developed during our long experience with heavy flavor physics. The package includes three different components. The first is an event generator that includes all the known features of charm meson decays. The second component is a detector simulation package. We have chosen to employ a fast parametric Monte Carlo program, TRKSIM, tuned to the measured properties of the CLEO III detector. (The CLEO III detector and its performance are described in Chapter IV.) Finally, the analysis tools developed for our heavy flavor physics studies at CLEO are used to obtain the projected reach.

2.2 Event Generation

The physics simulation is provided by standard event generating packages, including JETSET7.3/LUND [4], KORALB and TAUOLA [5]. Decays are simulated using the CLEO QQ [6] program. Known branching fractions and angular distributions for tau lepton and charmed meson and baryon decays are included.

2.3 Detector Simulation

The performance of the CLEO-c experiment is modeled using TRKSIM, a fast parametric Monte Carlo program that was originally developed for CLEO II analyses that required huge Monte Carlo samples. It provides an adequate model of the detector performance by tuning several parameters to the measured properties of CLEO III sub-detectors. In particular we have striven to match the measured resolution and efficiency both for charged particles and photons. Although a more detailed GEANT-based [7] simulation would have been a more realistic tool, TRKSIM provides a much quicker and less CPU demanding exploration of our physics reach. A GEANT-based simulation program, CLEOG3, has provided important validation checks of many of the TRKSIM predictions. A few examples will be given below.

CLEO III is a detector ideally suited to pursue precision charm decay studies. It features excellent efficiency and resolution for charged particles and photons within 93% of the solid angle. The central drift chamber also provides measurements of dE/dx for particle identification. Excellent π/K separation is achieved over the entire momentum range studied at CLEO-c using dE/dx measurements in the drift chamber and a dedicated hadron identification device: the Ring Imaging Cherenkov (RICH) detector. Finally, the CsI calorimeter, in combination with the tracking system, provides the basis for excellent electron identification.

2.3.1 Tracking

The tracking system is simulated by propagating charged particles along their helical trajectories in the 1 T solenoidal magnetic field. The track position uncertainties due to dE/dx and multiple scattering are calculated at every hit point and their effect on the error matrix is included. The track parameters of the charged particles are then reconstructed from the

deposited hits using a Kalman filter [8]. Thus the errors in the track momentum vector are realistic. The efficiency is modeled separately, since no track finding is implemented. An empirical function of the polar angle θ and the particle momentum p , $\varepsilon(\theta, p)$ is extracted from CLEO III data for each particle species.

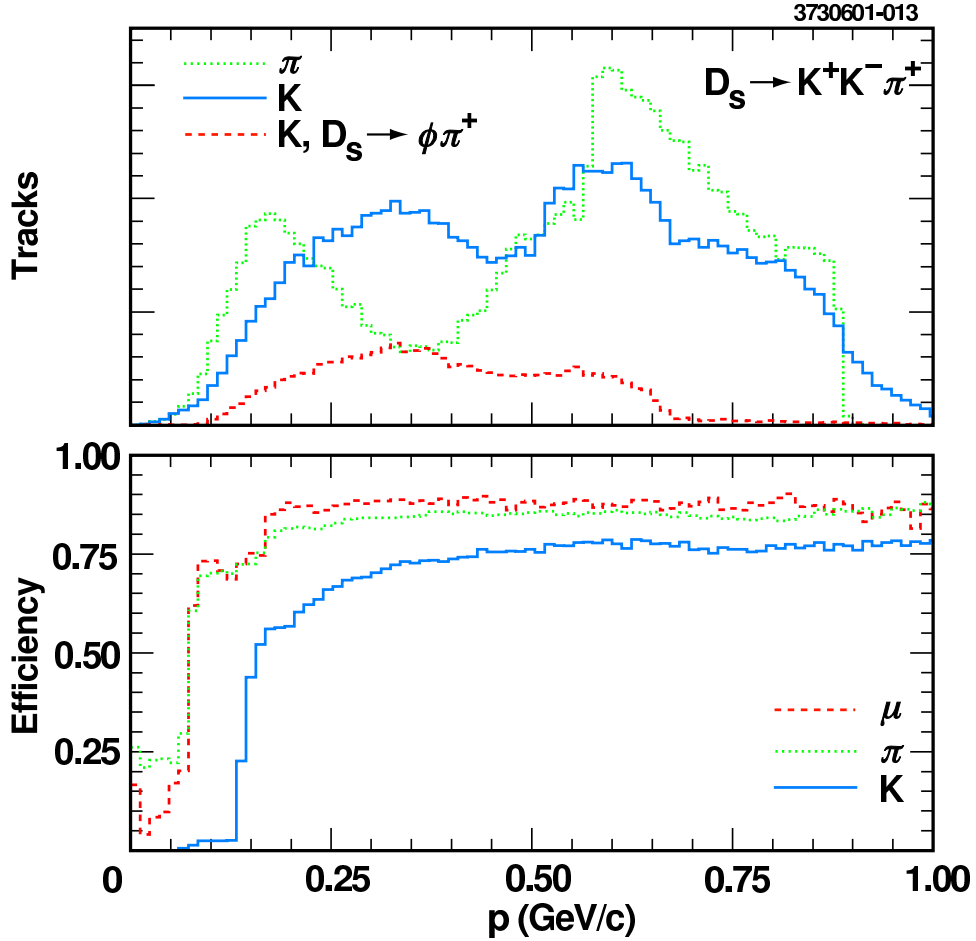


FIGURE 1. Reconstruction efficiencies for muons, charged kaons and pions (lower plot). For comparison we show the momentum spectra for charged kaons and pions from $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \phi \pi^+$ (upper plot).

Figure 1 shows the momentum dependent efficiencies for π 's, K 's and μ 's. For charged kaons, there is a momentum cut-off at about 150 MeV/c and a generally lower reconstruction efficiency. This is largely due to the fact that the CLEO III track finding and reconstruction algorithms are not optimized for particles decaying in flight, which is more important for the momenta of particles at these lower center-of-mass energies. Optimization of track finding for CLEO-c energies, taking account decays in flight, will improve this performance. For comparison we also show the momentum spectra of K 's and π 's from all $D_s^+ \rightarrow K^- K^+ \pi^+$ decay modes and the spectrum for K 's from $D_s^+ \rightarrow \phi \pi$ decays. The daughter momentum in two-body decays (*e.g.*, $D^0 \rightarrow K^- \pi^+$) at $\sqrt{s} = 3.77$ GeV is about 0.9 GeV/c in the D meson center-of-mass frame and is smeared by a very modest boost at the energies that we

are considering.

Excellent momentum and mass resolution are key features of the detector which enable many precision analyses. In Figure 2 we show a comparison between the smearing in transverse momentum in full CLEOG Monte Carlo and in TRKSIM. TRKSIM simulates the core of the smearing very well.

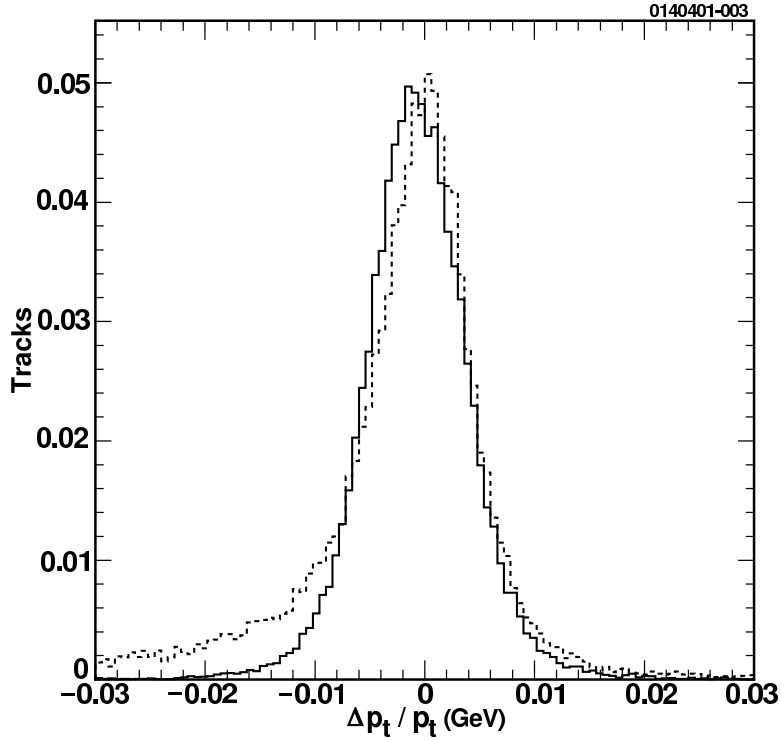


FIGURE 2. The ratio of the discrepancy between the reconstructed transverse momentum and the generated transverse momentum, to the generated transverse momentum for TRKSIM (solid histogram) and GEANT3 (dashed histogram) Monte Carlo simulations.

2.3.2 Particle Identification

Hadrons are identified over the full momentum range using dE/dx measurements from the drift chamber and Cherenkov angle measurements in the RICH detector. The dE/dx measurements are useful for π/K separation below about 700 MeV/ c and the RICH detector works well up to the highest momenta $\gtrsim 1$ GeV/ c . In TRKSIM, the dE/dx performance is modeled with Gaussian distributions based on data. The RICH detector is modeled with a stand-alone routine (run in analysis rather than in TRKSIM) that generates the probability for a particle of being identified as being of a given species based on the known acceptance, single photon Cherenkov angle resolution, and photon statistics. Figure 3 shows the Cherenkov angle as a function of the momentum for the particle species identified by the RICH.

The RICH performance is particularly important for the high momentum π 's and K 's from the decay $D^0 \rightarrow K^- \pi^+$. This mode is a principal mode for studying $D^0 \bar{D}^0$ mixing, and misidentification of the π 's and K 's in an event would lead to dilution of the measurement. An estimate of particle discrimination at various momenta (P) when both mass hypotheses are above the Cherenkov radiation threshold is shown in Figure 4. The average Cherenkov angle resolution and the average Cherenkov photon yield for fast particles have been obtained from a sample of Bhabha electrons: $\sigma^{\beta=1} \approx 4.3$ mrad and $N_{\gamma}^{\beta=1} \approx 11.4$. This calculation neglects effects of poorly reconstructed tracks, background hits in the RICH detector and decays in flight that dominate the fake rates, once the Cherenkov angles corresponding to different particle species are far apart. We have studied these effects using a full GEANT3 simulation, using a sample of $\psi(3770) \rightarrow D^0 \bar{D}^0$, with $D^0 \rightarrow K^- \pi^+$ and $\bar{D}^0$ decaying generically.

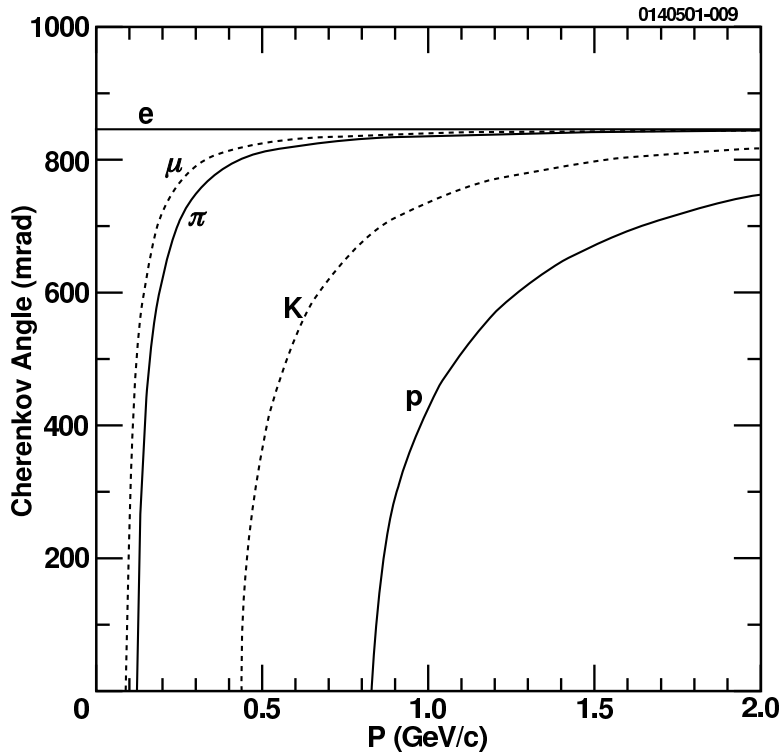


FIGURE 3. Mean Cherenkov Angle in LiF radiators for various particle species as a function of the particle momentum.

The probability of π - K misidentification at about 1 GeV is obtained by studying the D^0 $K - \pi$ combinations within the RICH acceptance, which have a total energy within 3σ of the expected D^0 energy. Figure 5 shows the log-likelihood difference (denoted as $\chi_K^2 - \chi_\pi^2$) between the K and π hypotheses after requiring at least 4 Cherenkov photons detected for the track (90% of tracks within the RICH acceptance satisfy this requirement). A symmetric cut ($\chi_K^2 - \chi_\pi^2 < 0$) is $(98.7 \pm 0.2)\%$ efficient for kaons with $(0.37 \pm 0.05)\%$ pion fake rate. A stronger cut ($\chi_K^2 - \chi_\pi^2 < -25$) gives a $(97.5 \pm 0.2)\%$ efficiency of K 's and a $(0.18 \pm 0.05)\%$ π fake rate. The background in the $K^- \pi^+$ final state is even more severely suppressed because

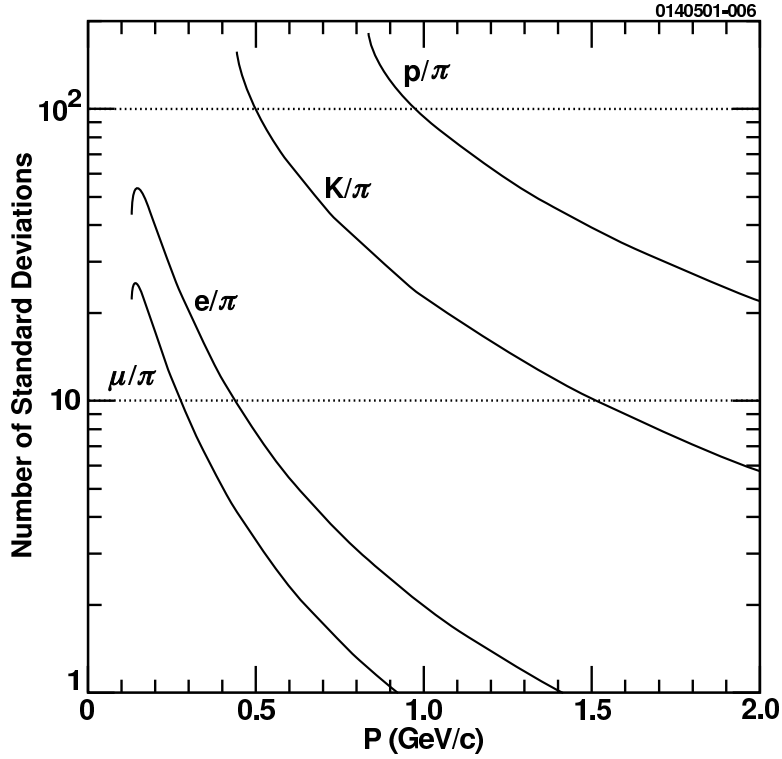


FIGURE 4. Particle separation in the RICH detector. Note the logarithmic scale on the vertical axis. The quantity plotted is $|\theta_X(P) - \theta_\pi(P)|/\sigma(P)$ versus particle momentum for $X = e, \mu, K, p$, where the r.m.s. resolution $\sigma(P) = \sigma^{\beta=1} \sqrt{N_\gamma^{\beta=1}/N_\gamma(P)}$.

it is associated with double misidentification. Figure 6 shows the $D^0 \rightarrow K^- \pi^+$ total energy distribution from a CLEOG3 sample including the full particle identification simulation. The background associated with doubly-misidentified particles that would be present in the absence of particle identification is completely removed if the cut is applied to the sum of the log-likelihood difference for both K and π candidates. The single event out of 10,000 passing the RICH cuts is outside the signal region in the energy plot, so it is justified to consider this mode background free.

There is an excellent separation between π 's, K 's and p 's in the whole range of momenta relevant to CLEO-c. At low momenta the particle identification algorithm needs to be tuned to a mode of operation where some of the particle species to be identified produce rings in the detector, while others are below threshold. An optimization of the TRKSIM particle identification algorithm, including the best treatment of this case and an integration of the information provided by the RICH and dE/dx , that features a good particle separation in this lower momentum range, is under way. The RICH is also the only device that produces some discrimination between low momentum π 's and μ 's, since the CLEO III μ detector has some efficiency only above 0.8 GeV/c. Figure 4 shows that we can achieve a 3σ separation between π 's and μ 's up to about 550 MeV/c and 3σ separation between π 's and e 's up to about 800 MeV/c. This separation power in conjunction with kinematics criteria based

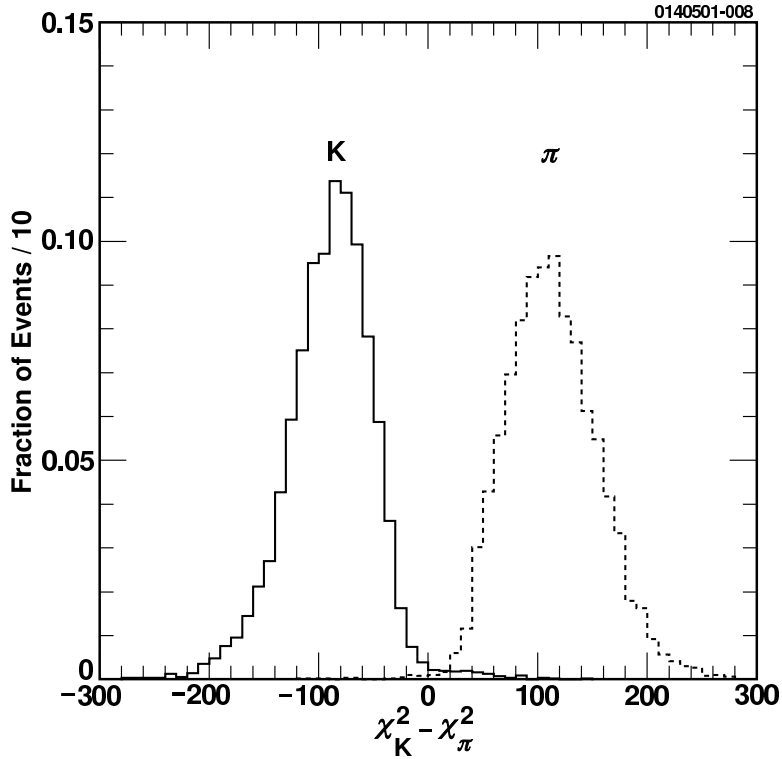


FIGURE 5. Separation between K 's and π 's from $D^0 \rightarrow K^- \pi^+$ determined with CLEOG3 Monte Carlo and RICH based particle identification algorithm.

on fully contained events is adequate for some of the semileptonic analyses. Note that the decay constant studies have enough kinematics constraints to reduce potential background to eliminate the need of full μ identification.

2.3.3 Electromagnetic calorimeter

The excellent energy and π^0 mass resolution of the CLEO CsI calorimeter are described in Chapter IV. The CsI electromagnetic calorimeter is divided into three regions for the TRKSIM simulation and the subsequent analysis of the simulated data:

- the barrel region $|\cos \theta| < 0.81$,
- the transition region $0.81 < |\cos \theta| < 0.85$, and
- the endcap region $0.85 < |\cos \theta| < 0.95$.

Photons in the transition region, where the energy resolution is poor are not accepted in this TRKSIM simulation. The efficiency for photons with $|\cos \theta| < 0.93$ and energy $E_\gamma > 30$ MeV is about 85% in the barrel and 70% in the endcap region. This efficiency has been estimated on the basis of our measured efficiencies at the $\Upsilon(4S)$ with the CLEO II data sample, taking into account that the material in front of the calorimeter is less, in particular in the endcap region and the multiplicities are lower, making it easier to identify isolated photon. The energies and angles of accepted photons are smeared using parameters derived from CLEO III data. The energy resolution in the endcap region is about 20% worse than it

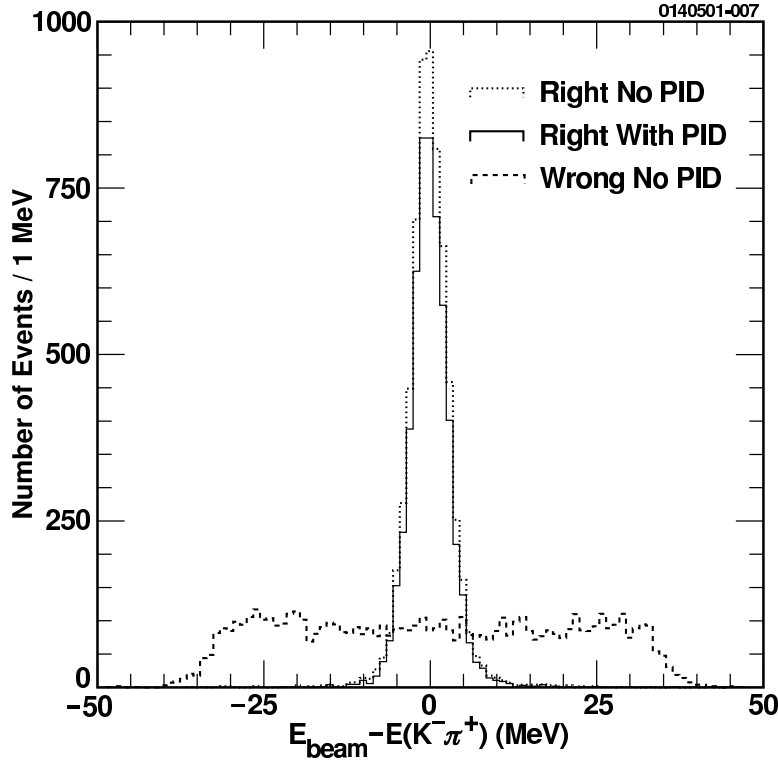


FIGURE 6. Candidate total energy plot for $D^0 \rightarrow K^-\pi^+$ showing the negligible background associated with charged tracks doubly misidentified in the RICH. There is only 1 background combination when the particle identification cuts described in the text are applied and it is outside the signal region.

is in the good barrel region, due to the extra material in the drift chamber endplates and electronics that photons must traverse on their way to the endcaps.

We reconstruct neutral pions from $\pi^0 \rightarrow \gamma\gamma$ decays using the photons observed in the good barrel and endcap regions of the electromagnetic calorimeter. At the energies of interest, a π^0 decays into two isolated photons. In particular, it is straightforward to distinguish $\bar{D}^0 D^{*0}$ where $D^{*0} \rightarrow \gamma D^0$ from $D^{*0} \rightarrow \pi^0 D^0$. We reconstruct neutral kaons from $K_S^0 \rightarrow \pi^+\pi^-$ decays using the observed charged pions. In this study we have not reconstructed K_S^0 from $K_S^0 \rightarrow \pi^0\pi^0$ decays. The average detection efficiency for $\pi^0 \rightarrow \gamma\gamma$ is about 64% and for $K_S^0 \rightarrow \pi^+\pi^-$ about 67%.

2.4 Analysis Tools

The TRKSIM program writes data out in the same format as our CLEOII data sample. This allows us to employ the analysis programs developed over the years to study heavy flavors at CLEO to extract the physics reach information that will be presented in the following sections. One such package, CABS [9], supports an object-like approach to specifying decay chains and particle reconstruction with minimal syntactical worries. More traditional FORTRAN based access is also supported. Both types of analysis have been used in studying

the physics reach of CLEO-c, and consistency between the results obtained from the two approaches reinforces confidence in the results.

2.5 Validation of the Simulation

The accuracy of this simulation has been tested by comparing its predictions with the more detailed CLEOG3 results for some key reference modes. For example, Figure 7 shows reconstructed $D_s^+ \rightarrow \phi\pi^+$, $\phi \rightarrow K^+K^-$ peaks from GLEOG3 and TRKSIM simulations. The D_s^+ is forced to decay to a $\phi\pi^+$ state, while the D_s^- is allowed to decay generically. The selection criteria were based on simple kinematics constraints imposed by momentum and energy conservation in the decay $e^+e^- \rightarrow D_s\bar{D}_s$ and on the mass constraint from the secondary decay $\phi \rightarrow K^+K^-$. Note that both the mass resolution and the level of background are very similar in the two plots. The reconstruction efficiency for $D_s^+ \rightarrow \phi\pi^+$ generated with TRKSIM is 19%, in excellent agreement with the efficiency of 17% for CLEOG3 simulations.

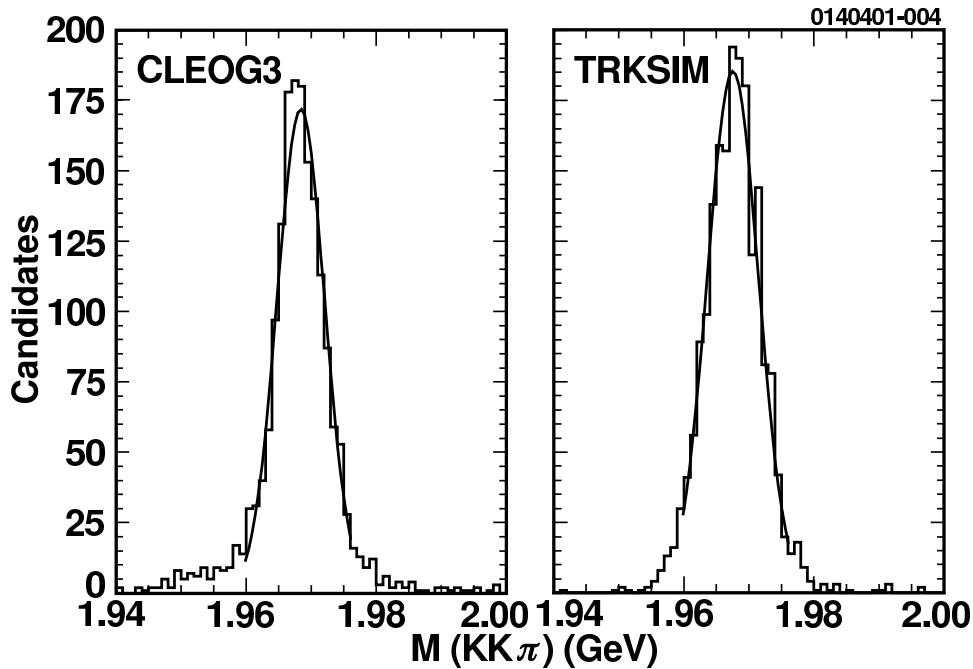


FIGURE 7. Reconstruction of $D_s \rightarrow \phi\pi$, $\phi \rightarrow K^+K^-$ decays from CLEOG3 (left) and TRKSIM (right) simulations. For each simulation, 10,000 events were generated with $D_s \rightarrow \phi\pi$ decays recoiling against generic D_s decays. Note the similar widths and background levels.

The detector's response to Bhabha events is also well described by TRKSIM. Figure 8 shows the reconstructed electron momentum spectrum for $e^+e^- \rightarrow e^+e^-$ events for a TRKSIM sample with $E_{\text{beam}} = 5.29$ GeV and $B = 1.5$ T. The energy resolution is well simulated: TRKSIM predicts a standard deviation $\sigma = 37$ MeV, compared to $\sigma = 41$ MeV in CLEO III data.

The analyses presented here rely on simple kinematics constraints to separate signals from

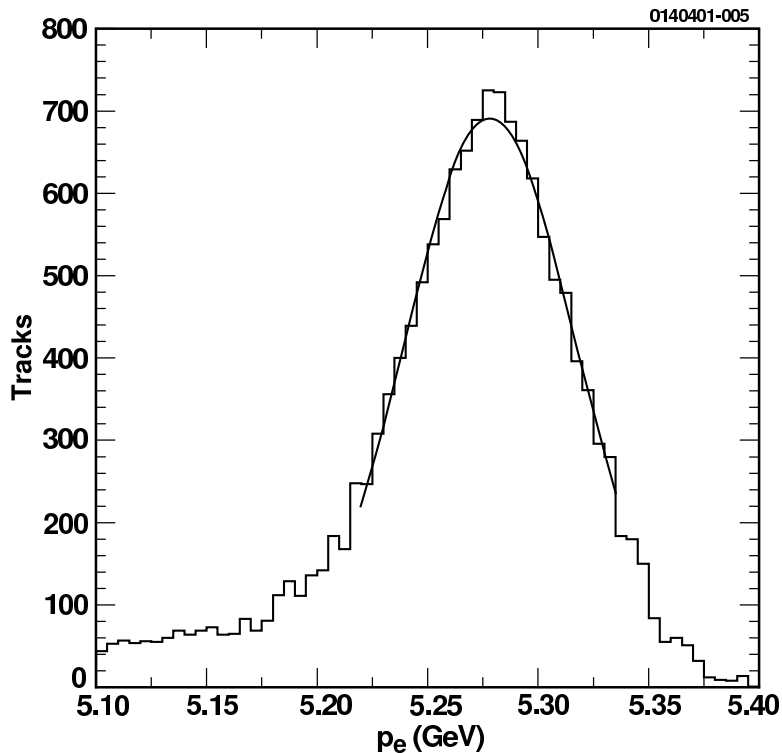


FIGURE 8. The reconstructed electron momentum spectrum for $e^+e^- \rightarrow e^+e^-$ events for a TRKSIM sample at $E_{\text{beam}} = 5.29$ GeV and $B = 1.5$ T. The width of the peak is $\sigma = 37$ MeV, in good agreement with $\sigma = 41$ MeV in CLEO III data.

backgrounds, but they do not fully exploit the simplicity of the final state. In particular no attempt to use full kinematic constrained fitting techniques similar to the ones used in the MARK III analyses [2,3] have been attempted.

2.6 Systematic Error Assessment

$D\bar{D}$ production near threshold is characterized by low multiplicity and powerful kinematic constraints. For many final states, our systematic error is determined by how well we will measure the absolute tracking efficiency. We have explored simple methods to determine systematic errors associated with the absolute tracking efficiency with unprecedented accuracy.

In the more complicated environment of $\sqrt{s} = 10.58$ GeV collisions CLEO has achieved tracking efficiency systematic errors of 0.7% (0.5% for leptons). At $D\bar{D}$ threshold we anticipate we will be able to improve these systematic errors substantially.

Here we will discuss the high momentum π and K reconstruction efficiency as an example. The method exploits the large tagged data sample available. For example, as we will discuss in more detail below, we are anticipating approximately 5,000,000 tagged D^0 mesons in 3 fb^{-1} collected at the ψ'' . In 200,000 of these tagged D^0 mesons, the other D in the event will decay to $K^-\pi^+$. If we use strict cuts to identify both K 's and π 's, including the RICH

information, we can expect a sample of about 125,000 events where the final state $K^-\pi^+$ is reconstructed by selecting a K candidate and demanding that the missing mass of the “rest of the event”, recoiling against the tag- K system, be equal to the π mass. Subsequently, we can apply the usual criteria for a fully reconstructed final state, with a corresponding sample of 80,000 events. In this case, where we require that the track is in the solid angle of the RICH detector and is well identified, we obtain an efficiency of $64 \pm 0.14\%$. Similar procedures can be applied to tagged samples of $D^+ \rightarrow K^-\pi^+\pi^+$ with comparable statistics to study the efficiency as a function of momentum. This method is much more straightforward than alternative procedures, such as embedding studies, that rely on a mixture of Monte Carlo and data information.

For projections in this document we will assume that based on methods such as those outlined above, we will be able to determine the absolute tracking efficiency to within 0.2% of itself.

3 Physics Reach in Charm Decays

3.1 Introduction

The efficacy of studying weak decays of mesons containing heavy quarks was first established in the charm region with investigations of D^0 and D^+ decays at the $\psi(3770)$ (or ψ'') resonance. Here we have decays into only $D^0\bar{D}^0$ and D^+D^- with no other particles produced, strikingly similar to the studies of $\Upsilon(4S)$ decays into B mesons that CLEO pioneered.

The ψ'' cross-section is large (~ 10 nb), leading to large event rates with even modest luminosities (modest here means $\text{few} \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$). In comparison with B decays, the product branching fractions for charm decays are large and multiplicities are low. (The averaged charged multiplicity in charm decay is ~ 2.5 and the neutral multiplicity is ~ 1.3 [10].) The large event yield and large product of cross-section and branching fraction allow us to exploit threshold production by reconstructing both D mesons. The system is well over-constrained when all the particles are observed. That the three-momentum must be zero leads to three constraints. That the energy must be twice the individual beam energy gives one more. We can require that both D mesons have the same mass, giving a fifth constraint. It is also possible to require that this mass is the known D mass which gives a sixth constraint, although not imposing this requirement and viewing the reconstructed D mass distribution can be a good way to view signal and background contributions.

This situation is so well suited to measurements of absolute branching fractions and even the relatively rare decay $D^+ \rightarrow \mu^+\nu$ that one must wonder why definitive measurements have not yet been done. The Mark III group did make measurements at the ψ'' to find absolute branching fractions, unfortunately with a small amount of data, 9.56 pb^{-1} . They used a technique where they fully reconstructed a sample of single D decays and another sample where both D mesons in the event were reconstructed. Then the absolute branching fractions can be determined directly without the use of any continuum subtraction. Their data [3] are shown in Figure 9.

The Mark III results for absolute branching fractions are $\mathcal{B}(D^0 \rightarrow K^-\pi^+) = (4.2 \pm 0.4) \%$ and $\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^+) = (9.1 \pm 1.3 \pm 0.4) \%$. In CLEO-c we expect 300 times

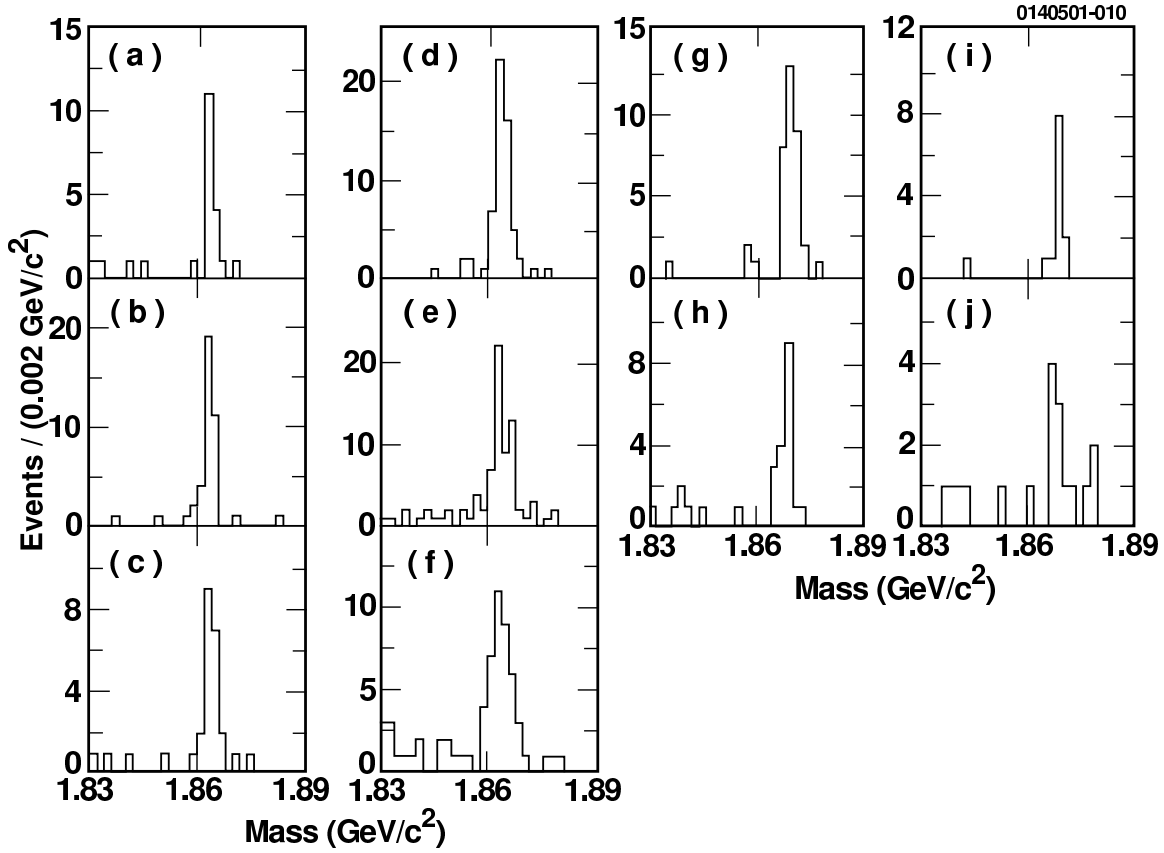


FIGURE 9. The reconstructed double tag D samples from Mark III. $D^0\bar{D}^0$ double tags: (a) $K^-\pi^+$ vs $K^+\pi^-$, (b) $K^-\pi^+$ vs $K^+\pi^-\pi^-\pi^+$, (c) $K^-\pi^+\pi^+\pi^-$ vs $K^+\pi^-\pi^-\pi^+$, (d) $K^-\pi^+$ vs $K^+\pi^-\pi^0$, (e) $K^-\pi^+\pi^+\pi^-$ vs $K^+\pi^-\pi^0$, and (f) $K^-\pi^+\pi^0$ vs $K^+\pi^-\pi^0$. D^+D^- double tags: (g) $K^-\pi^+\pi^+$ vs $K^+\pi^-\pi^-$, (h) $K^-\pi^+\pi^+$ vs $K^0\pi^-\pi^0$, (i) $K^-\pi^+\pi^+$ vs $K^0\pi^-$, and (j) $K^-\pi^+\pi^+$ vs $K^0\pi^-\pi^-\pi^+$. The beam constrained mass is plotted for all their samples.

more integrated luminosity and have a detector with far better photon detection and particle identification. It is clear from simple scaling that we will be in the 1% error regime on these absolute branching fractions

The same considerations are applicable to the measurements of D_s^+ and Λ_c^+ absolute branching fractions. Cross-sections in the CLEO-c region are shown in Figure 10 [11]. Measurement of the $D_s^+D_s^-$ yield has been made by BES [12] at 4.03 GeV center-of-mass energy. Taking the cross-section to be 0.5 nb we would produce one-half million $D_s^+D_s^-$ pairs per fb^{-1} . BES took data here to search for purely leptonic decays of the D_s^+ . They found one $D_s^+ \rightarrow \mu^+\nu$ and two $D_s^+ \rightarrow \tau^+\nu$ candidates with a 22.3 pb^{-1} data sample. We expect 150 times more data with a much better detector, especially for η 's and η' 's that are present in D_s^+ decays with large branching fractions.

The Mark II Collaboration measured a statistically significant yield of Λ_c^+ charmed baryons at a center-of-mass energy of 5.2 GeV [13]. They found that the product of cross-section times branching fraction for the decay mode $\Lambda_c^+ \rightarrow pK^-\pi^+$ is $0.037 \pm 0.012 \text{ nb}$. Thus

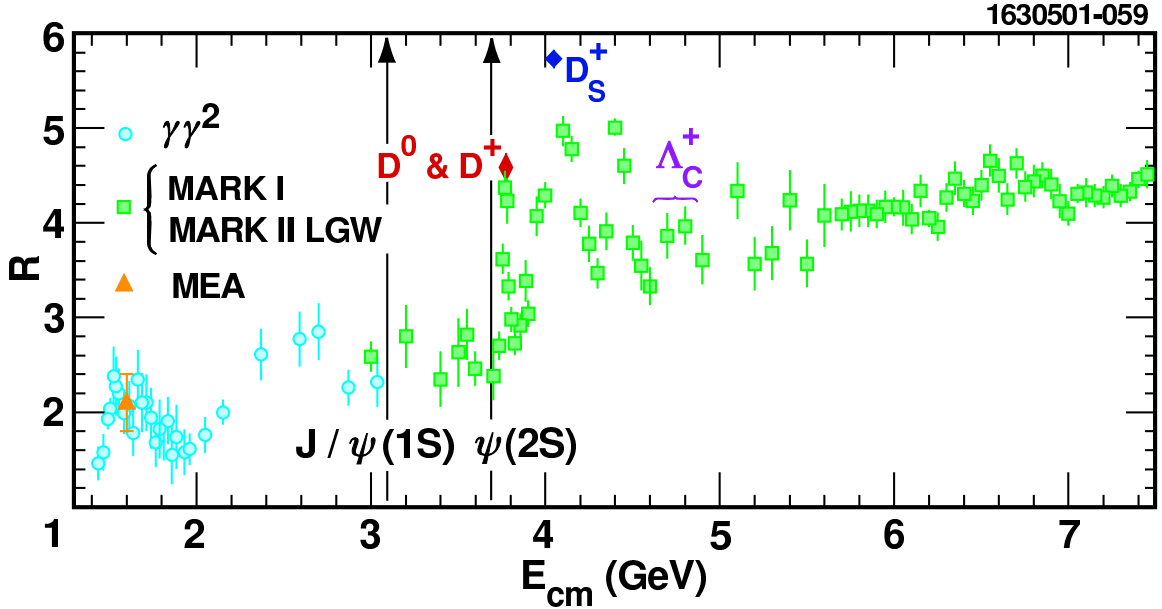


FIGURE 10. Measurement of the total hadronic cross-section normalized to $\mu^+\mu^-$ production for e^+e^- collisions in the charm region.

we would produce 37,000 single $pK^-\pi^+$ events in 1 fb^{-1} .

In subsequent sections we refine our estimates of the errors obtainable on leptonic, semileptonic and hadronic charm branching fractions by giving the results of Monte Carlo simulations. We also show the obtainable accuracies on decay constants and CKM matrix elements that can be derived from studies of leptonic and semileptonic charm decays. Simulated samples of $D\bar{D}$ mesons corresponding to 1 fb^{-1} of integrated luminosity were produced with the TRKSIM Monte Carlo program described in the previous Section. In each of these Monte Carlo samples, the D and $\bar{D}$ meson generic decays and uds backgrounds were simulated using the CLEO QQ [6] program. Simulated events were then studied using standard CLEO II analysis tools as described in Section 2.4. Simulated samples of charm baryons were also produced.

3.2 Tagging Technology: Estimates of D Decay Reconstruction Efficiencies and Rates

Studying the efficiencies and backgrounds for reconstructing decays of D mesons (single tags) is the first step toward understanding the physics reach of CLEO-c for studying charm meson decays. To be accepted as single tags, candidate combinations of final particles with the reconstructed total energy $E(D)$, total momentum $p(D)$, and mass $M(D)$ must fulfill three requirements:

- the energy difference $\Delta E = E(D) - E_{\text{beam}}$ of a D candidate is consistent with zero to within 3 standard deviations (σ_E),
- particle identification (PID) cuts using the RICH detector and dE/dx information from the drift chamber must be satisfied, and

- the beam constrained mass of the candidate, $M(D)^2 = E_{\text{beam}}^2 - p(D)^2$, is consistent with the nominal mass to within 3 standard deviations (σ_M).

These requirements are familiar from many studies of charm meson decays in the charm threshold region and numerous measurements of B meson decays at the $\Upsilon(4S)$.

The reconstruction of charged particles, π^0 and K_S^0 has been described in Section 2.3. In addition we also reconstruct η candidates in the modes $\eta \rightarrow \gamma\gamma$, $\eta \rightarrow \pi^0\pi^0\pi^0$, and $\eta \rightarrow \pi^+\pi^-\pi^0$. For these modes, we require 3σ consistency with the η mass, followed by a kinematic mass constraint. We reconstruct η' candidates from $\eta' \rightarrow \pi^+\pi^-\eta$ and $\eta' \rightarrow \gamma\rho$, requiring again 3σ consistency with the η' mass.

Since the particle identification in the CLEO III detector was designed for higher momentum tracks from B meson decays, it is much better than required for charm decays. The dE/dx identification works very well up to about 700 MeV/ c , where kaons and pions are separated by better than 4 standard deviations (difference between pion and kaon peak pulse heights divided by the error). The RICH detector will see rings for both pions and kaons above ~ 470 MeV/ c . Below that the kaons do not produce Cherenkov light. Separation can be done in the below threshold region but the dE/dx covers this region so well that RICH systematic errors have not been well studied. The separation for RICH identification at 900 MeV/ c is extremely good as shown in the previous section. Thus kaon-pion separation is well covered over the entire momentum range. Fakes that occur will be at very low levels (3.7×10^{-3}) and can be combatted if important with some efficiency loss.

Examples of reconstructed D mass distributions for the most important decays are given in Figures 11 – 13. They illustrate the power of the excellent kinematic reconstruction and particle identification of the CLEO-c detector by showing the effect of the sequential selection criteria. These figures serve as a basis for understanding efficiencies and backgrounds. Note that the backgrounds in all cases are small, and we present the data on a logarithmic scale so they can be seen.

Table 2 and Table 3 give the reconstruction efficiency, ϵ_{MC} and reconstructed event yields for a number of D decay modes with reasonably large branching fractions. The rates given are for data samples of 1 fb^{-1} . We give the branching fractions, $\mathcal{B}$, for each decay mode, including the branching fraction for K^0 or $\bar{K}^0$ to K_S . The efficiency ϵ_{MC} includes the branching fractions and efficiencies for all daughter decays. The total yields are based on measured D^0 , D^+ and D_s^+ cross-sections of 5.8 nb, 4.2 nb, and 0.5 nb, respectively. The $D_s^+ D_s^-$ cross-section used is an estimate. It has been measured as $0.67 \pm 0.16 \pm 0.17$ nb at a center-of-mass energy of 4.14 GeV, and $0.31 \pm 0.06 \pm 0.10$ nb at 4.03 GeV [14].

In addition to the Monte Carlo efficiencies, we estimate detection efficiencies based on the product of the absolute species-dependent single particle efficiencies. This numerically calculated efficiency, ϵ_S , assumes that the particles in a decay are uncorrelated. The single particle detection efficiencies ϵ used in estimating detection efficiencies for D meson decay modes are:

- 82% for high momentum $K^\pm$ and all $\pi^\pm$ and $\mu^\pm$,
- 67% for low momentum $K^\pm$, and
- 65% for π^0 or $\eta \rightarrow \gamma\gamma$.

The π^0 efficiency in the barrel region is 50% in B decay data at the $\Upsilon(4S)$. Some of this loss, about 1/3 is due to conversions in material in front of the calorimeter, while the rest

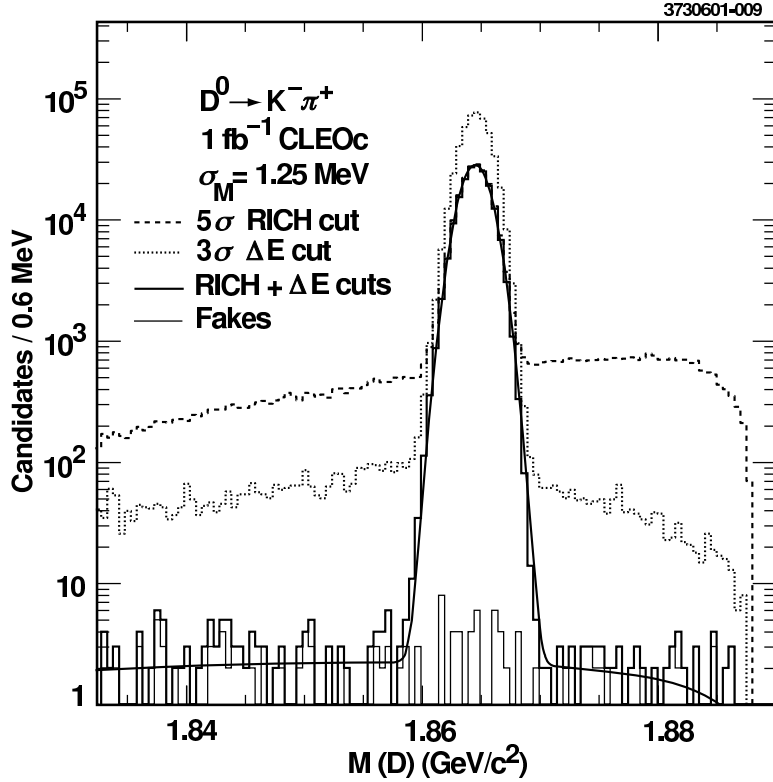


FIGURE 11. The reconstructed D mass distribution for $D^0 \rightarrow K^-\pi^+$ decays.

is due to overlaps with other B decay products. The later essentially disappears in CLEO-c due to the much smaller multiplicities in charm decay. In CLEO-c we estimate the barrel efficiency at 83%. Adding the endcaps gives us an overall solid angle of 91% and an overall π^0 efficiency of 65%, where we have used the fact that at higher momentum the two-photons are correlated in solid angle.

The efficiency for high momentum charged particles ($\mu^\pm$, $\pi^\pm$), is about 10% less than the geometric acceptance (93%) of the charged particle tracking system. This reduction is meant to account for tracking efficiencies and decays in flight. The efficiency for lower momentum $K^\pm$ is reduced by approximately another 10% to account for more decays in flight. This efficiency is used for any charged K 's in modes with 3 or more particles in the final state of the D decay.

The values for the numerically calculated efficiency, ϵ_S , generally reproduce the Monte Carlo efficiencies, ϵ_{MC} , within 15%, and are used in later sections of this chapter to estimate CLEO-c reach for a variety of rare charm decay processes.

3.3 Charm Meson Decay Constants

Pseudoscalar meson decay constants can be determined by measuring lifetimes and lepton decay branching fractions, if the relevant CKM matrix elements are assumed to be well known from the unitarity of the CKM matrix. Charm lifetimes are well measured [11] at the

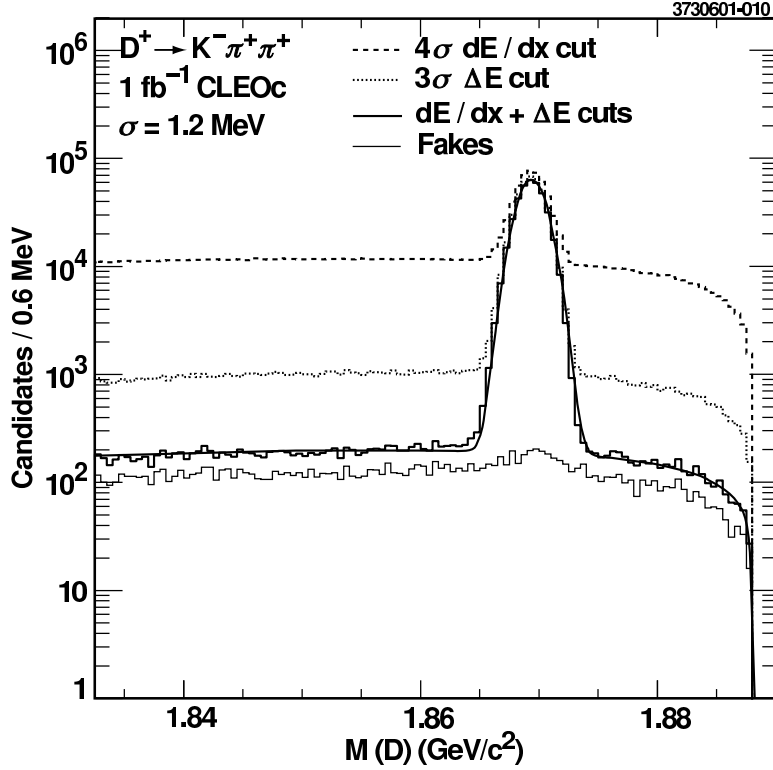


FIGURE 12. Reconstructed D mass $M(D)$ for $D^+ \rightarrow K^- \pi^+ \pi^+$.

1-2% level. It is our task to precisely measure the leptonic branching fractions.

We reconstruct $D^+ \rightarrow \mu^+ \nu$, and $D_s^+ \rightarrow \mu^+ \nu$ decays by using our single tag sample (primary tags). Starting from this sample we require exactly one single primary tag found in the event and exactly one charged track of correct sign in addition to the tracks used to reconstruct the primary tag. Backgrounds with neutral massive particles are reduced by a cut on E_{extra} , the extra energy in the CsI Calorimeter. This quantity is the sum of energy depositions not caused by any neutral particle contributing to the primary tag, and separated by more than 15° from any track. For the event to be accepted E_{extra} has to be less than 0.5 GeV.

The kinematic requirement used in this analysis is that the 4-momentum of the neutrino as the only missing particle can be completely reconstructed from its recoil against the primary tag and the single track assumed to be a muon. Since we know that the total center-of-mass energy is twice the beam energy and the total three-momentum must be zero we can calculate

$$M(\nu)^2 = [E(D) - E(\mu)]^2 - [\mathbf{p}(D) - \mathbf{p}(\mu)]^2, \quad (1)$$

where E_D and $\mathbf{p}(D)$ are the components of the 4-momentum vector of the single tag, after it has been constrained to the nominal D meson mass, the energy component set to the beam energy and the 3-momentum kinematically fit to these parameters [15].

We do not attempt to identify the single track as a muon as the CLEO III muon system is not very efficient at these momenta. Remarkably, it is advantageous to not have to use

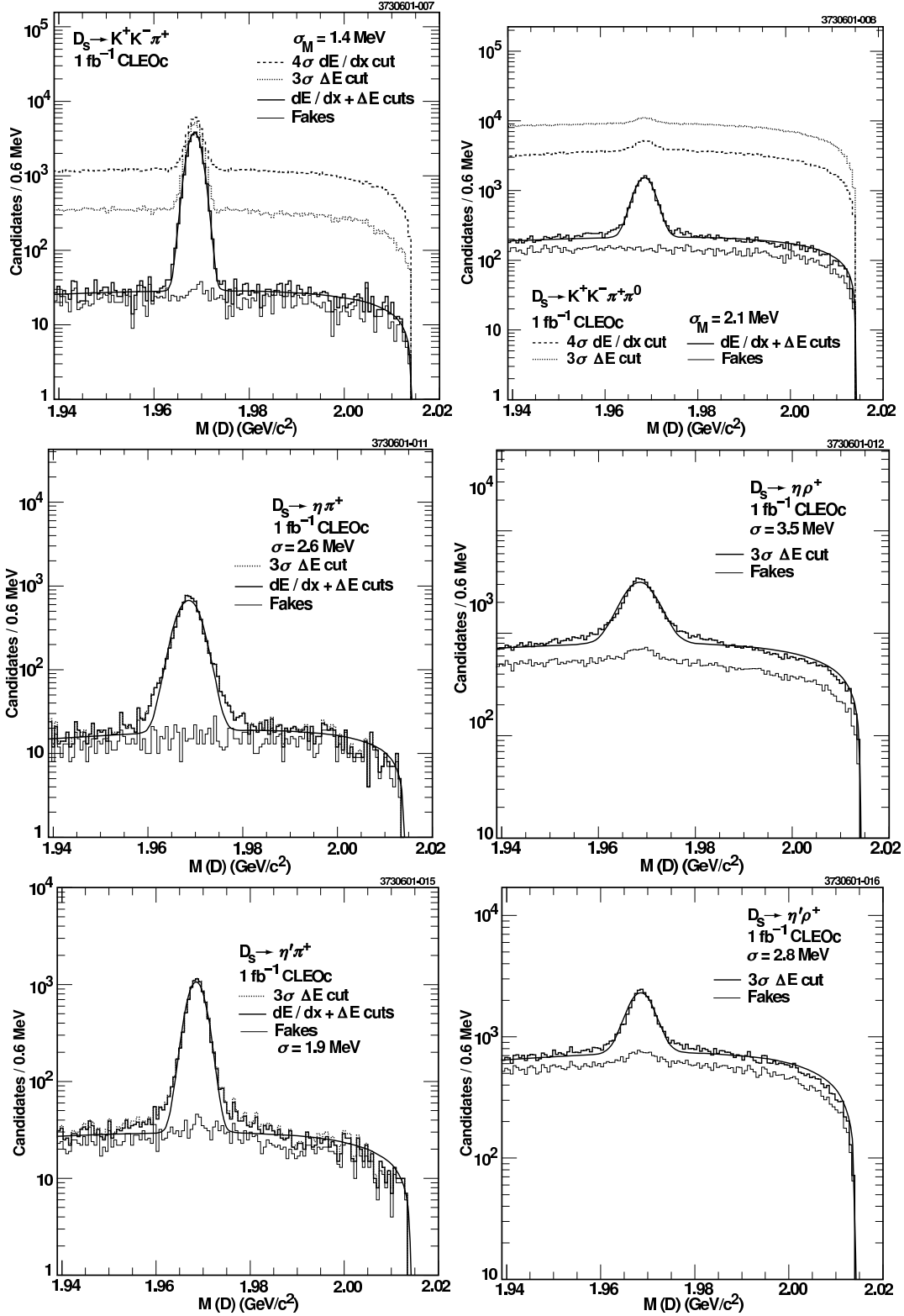


FIGURE 13. Reconstructed D mass $M(D)$ for different D_s decays.

TABLE 2. Production and detection rates with 1 fb^{-1} of data for a number of D^0 and D^+ decay modes at $\sqrt{s} = 3.77 \text{ GeV}$. The efficiencies ϵ_{MC} and ϵ_{S} are from the Monte Carlo and numerical calculations, respectively.

D and Daughter Decay Modes	$\mathcal{B}$ (%)	Produced	ϵ_{MC} (%)	ϵ_{S} (%)	Detected
$D^0 \rightarrow K^- \pi^+$	3.83	442,703	41.1	42.4	182,068
$D^0 \rightarrow K_S^0 \pi^0$ $K_S^0 \rightarrow \pi^+ \pi^-$	0.72	83,954	47.4	43.7	39,790
$D^0 \rightarrow K^- \pi^+ \pi^0$	13.90	1,611,401	41.9	35.7	675,201
$D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$	7.49	886,682	38.0	36.9	336,595
$D^0 \rightarrow K^- \pi^+ \pi^0 \pi^0$	15.00	1,133,552	31.8	23.2	360,178
		4,158,292			1,593,832
$D^+ \rightarrow K^- \pi^+ \pi^-$	9.00	755,816	50.0	45.1	377,747
$D^+ \rightarrow K_S^0 \pi^+ \pi^0$ $K_S^0 \rightarrow \pi^+ \pi^-$	3.33	297,891	33.0	35.8	98,263
$D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$	6.40	537,468	29.6	29.3	159,225
		1,591,175			635,235

the muon identification system because it removes a large source of systematic error.

The distributions of the square of the invariant mass of the ν candidates for $D^+ \rightarrow \mu^+ \nu$ and $D_s^+ \rightarrow \mu^+ \nu$ decays are shown in Figures 14 and 15. Candidates with $M(\nu)^2$ within 3σ of zero were then accepted as $D^+ \rightarrow \mu^+ \nu$ or $D_s^+ \rightarrow \mu^+ \nu$ decays. A breakdown into the different primary tagging channels and the nature of the background events in the signal region are given in Table 4.

Reconstruction of $D_s \rightarrow \tau \nu$ is complicated by the occurrence of additional neutrinos from the decay of the τ , which makes a complete kinematic reconstruction impossible. Nevertheless we used a set of cuts targeted to suppress the most prominent background sources in a generic $D_s^+ D_s^-$ environment [16]. To suppress backgrounds from other sources we rely again on the requirement to fully reconstruct the primary tag.

- In particular we are targeting events with a subsequent $\tau^- \rightarrow \pi^- \nu$ decay. We again require exactly one primary tag and exactly one additional track. The large mass of the τ compared to the D_s limits the allowed region for the momentum of the pion in the D_s rest frame. We used an equivalent cut of $-1 < \cos \theta_{\pi\nu} < -0.975$ with $\theta_{\pi\nu}$ the angle between the pion and the neutrino from the τ decay in the D_s rest frame.
- We require the extra energy, the sum of energy depositions in the calorimeter not caused by any neutral particle contributing to the primary tag, and separated by more than 15° from any track, to be less than 0.5 GeV.
- A considerable source of backgrounds comes from D_s decays into $K_L \pi$ or $K_L K$. These are suppressed by calculating the hypothetical thrust direction of the K_L meson under the assumption of such a decay and requiring that the sum of the energy depositions in a cone with an opening angle of 15° around this direction is less than 30 MeV.
- Another prominent source of background can be completely eliminated by inverting the

TABLE 3. Production and detection rates with 1 fb^{-1} of data for a number of D_s decay modes at $s = 4.028 \text{ GeV}$. The efficiencies ϵ_{MC} and ϵ_{S} are from the Monte Carlo and numerical calculations, respectively.

D and Daughter Decay Modes	$\mathcal{B}$ (%)	Produced	ϵ_{MC} (%)	ϵ_{S} (%)	Detected
$D_s^+ \rightarrow K^- K^+ \pi^+$	4.40	54,405	40.4	36.8	21,965
$D_s^+ \rightarrow K^- K^+ \pi^+ \pi^0$	4.43	57,026	19.8	23.9	11,314
$D_s^+ \rightarrow \eta \pi^+$	1.70				
$\eta \rightarrow \gamma \gamma$	0.67	6,738	57.1	53.3	3,849
$\eta \rightarrow \pi^0 \pi^0 \pi^0$	0.54	5,520	25.0	22.5	1,378
$\eta \rightarrow \pi^+ \pi^- \pi^0$	0.39	4,122	43.5	35.8	1,793
$D_s^+ \rightarrow \eta \rho^+$	10.8				
$\eta \rightarrow \gamma \gamma$	4.24	41,731	37.4	34.6	15,612
$\eta \rightarrow \pi^0 \pi^0 \pi^0$	3.46	34,066	18.4	14.6	6,260
$\eta \rightarrow \pi^+ \pi^- \pi^0$	2.48	25,306	26.8	23.3	6,791
$D_s^+ \rightarrow \eta' \pi^+$	3.9				
$\eta' \rightarrow \eta \pi^+ \pi^-$ $\eta \rightarrow \gamma \gamma$	0.68	6,191	28.2	35.8	1,743
$\eta' \rightarrow \eta \pi^+ \pi^-$ $\eta \rightarrow \pi^0 \pi^0 \pi^0$	0.55	5,232	11.9	15.1	624
$\eta' \rightarrow \eta \pi^+ \pi^-$ $\eta \rightarrow \pi^+ \pi^- \pi^0$	0.40	3,872	17.8	24.1	690
$\eta' \rightarrow \gamma \rho$	1.15	11,277	40.6	44.5	4,583
$D_s^+ \rightarrow \eta' \rho^+$	10.1				
$\eta' \rightarrow \eta \pi^+ \pi^-$ $\eta \rightarrow \gamma \gamma$	1.8	17,011	16.6	23.3	2,819
$\eta' \rightarrow \eta \pi^+ \pi^-$ $\eta \rightarrow \pi^0 \pi^0 \pi^0$	1.4	13,982	7.9	9.8	1,108
$\eta' \rightarrow \eta \pi^+ \pi^-$ $\eta \rightarrow \pi^+ \pi^- \pi^0$	1.0	10,417	10.4	15.7	1,086
$\eta' \rightarrow \gamma \rho$	3.0	30,072	29.1	28.9	8,747
		326,968			90,362

TABLE 4. Number of events reconstructed as $D \rightarrow \mu\nu$ from generic (D^+D^- or $D_s^+D_s^-$) TRKSIM Monte Carlo data corresponding to 1 fb^{-1} using different primary tagging modes. We have assumed $f_D = 220 \text{ MeV}$ and $f_{D_s} = 260 \text{ MeV}$ for these estimates. The columns give the type of decay generated in the Monte Carlo.

Reconstructed as	Tagging mode	$\mu^+\nu$	$\tau^+\nu$	Background
$D^+ \rightarrow \mu^+\nu$	$D^+ \rightarrow K^-\pi^+\pi^+$	136	6	11
	$D^+ \rightarrow K_S^0\pi^+\pi^0$	32	1	4
	$D^+ \rightarrow K^-\pi^+\pi^+\pi^0$	56	3	5
	Sum	224	10	20
$D_s \rightarrow \mu^+\nu$	$D_s^+ \rightarrow K^-K^+\pi^+$	99	10	1
	$D_s^+ \rightarrow K^-K^+\pi^+\pi^0$	50	5	1
	$D_s^+ \rightarrow \eta\pi^+$			
	$\eta \rightarrow \gamma\gamma$	22	5	1
	$\eta \rightarrow \pi^0\pi^0\pi^0$	7	3	0
	$\eta \rightarrow \pi^+\pi^-\pi^0$	10	2	0
	$D_s^+ \rightarrow \eta\rho^+$			
	$\eta \rightarrow \gamma\gamma$	71	12	6
	$\eta \rightarrow \pi^0\pi^0\pi^0$	25	4	4
	$\eta \rightarrow \pi^+\pi^-\pi^0$	21	5	3
	$D_s^+ \rightarrow \eta'\pi^+$			
	$\eta' \rightarrow \eta\pi^+\pi^-, \eta \rightarrow \gamma\gamma$	13	1	0
	$\eta' \rightarrow \eta\pi^+\pi^-, \eta \rightarrow \pi^0\pi^0\pi^0$	2	0	0
	$\eta' \rightarrow \eta\pi^+\pi^-, \eta \rightarrow \pi^+\pi^-\pi^0$	2	0	0
	$\eta' \rightarrow \gamma\rho$	29	1	0
	$D_s^+ \rightarrow \eta'\rho^+$			
	$\eta' \rightarrow \eta\pi^+\pi^-, \eta \rightarrow \gamma\gamma$	17	1	2
	$\eta' \rightarrow \eta\pi^+\pi^-, \eta \rightarrow \pi^0\pi^0\pi^0$	6	1	0
	$\eta' \rightarrow \eta\pi^+\pi^-, \eta \rightarrow \pi^+\pi^-\pi^0$	0	0	0
	$\eta' \rightarrow \gamma\rho$	33	5	11
	Sum	407	55	29

strategy of the $\mu\nu$ analysis: $D_s \rightarrow \mu\nu$ events are suppressed by requiring that the invariant mass of the system recoiling against the primary tag D_s and the single track (under the assumption that it is a muon) must not be consistent with zero ($M_X^2 > 0.1 \text{ GeV}^2/c^4$).

- Remaining $K_L K$ and semileptonic decays involving charged kaons are suppressed by not accepting events where the RICH information for the track is consistent with a kaon hypothesis.

A breakdown into the different primary tagging channels and the nature of the background events are given in Table 5.

TABLE 5. Number of events reconstructed as $D_s \rightarrow \tau \nu$ from generic TRKSIM Monte Carlo data corresponding to 1 fb^{-1} using different primary tagging modes. We have assumed $f_{D_s} = 260 \text{ MeV}$ for these estimates. The columns give the type of decay generated in the Monte Carlo.

Tagging mode	$\tau^+ \nu$	$\mu^+ \nu$	Background
$D_s^+ \rightarrow K^- K^+ \pi^+$	149	0	8
$D_s^+ \rightarrow K^- K^+ \pi^+ \pi^0$	57	0	5
$D_s^+ \rightarrow \eta \pi^+$			
$\eta \rightarrow \gamma \gamma$	24	0	0
$\eta \rightarrow \pi^0 \pi^0 \pi^0$	11	0	1
$\eta \rightarrow \pi^+ \pi^- \pi^0$	12	0	0
$D_s^+ \rightarrow \eta \rho^+$			
$\eta \rightarrow \gamma \gamma$	119	0	8
$\eta \rightarrow \pi^0 \pi^0 \pi^0$	42	0	5
$\eta \rightarrow \pi^+ \pi^- \pi^0$	36	0	3
$D_s^+ \rightarrow \eta' \pi^+$			
$\eta' \rightarrow \eta \pi^+ \pi^-, \eta \rightarrow \gamma \gamma$	15	0	0
$\eta' \rightarrow \eta \pi^+ \pi^-, \eta \rightarrow \pi^0 \pi^0 \pi^0$	10	0	0
$\eta' \rightarrow \eta \pi^+ \pi^-, \eta \rightarrow \pi^+ \pi^- \pi^0$	1	0	0
$\eta' \rightarrow \gamma \rho$	28	0	2
$D_s^+ \rightarrow \eta' \rho^+$			
$\eta' \rightarrow \eta \pi^+ \pi^-, \eta \rightarrow \gamma \gamma$	18	0	2
$\eta' \rightarrow \eta \pi^+ \pi^-, \eta \rightarrow \pi^0 \pi^0 \pi^0$	2	0	0
$\eta' \rightarrow \eta \pi^+ \pi^-, \eta \rightarrow \pi^+ \pi^- \pi^0$	5	0	0
$\eta' \rightarrow \gamma \rho$	51	0	4
Sum	580	0	38

In Table 6 we give the expected yields and errors on the leptonic branching fractions for 3 fb^{-1} data samples, where we have assumed $f_D = 220 \text{ MeV}$ and $f_{D_s} = 260 \text{ MeV}$. The decay constants can be extracted from the measured branching ratios for the leptonic decays using the measured charm meson lifetimes, and under the assumption that the CKM matrix

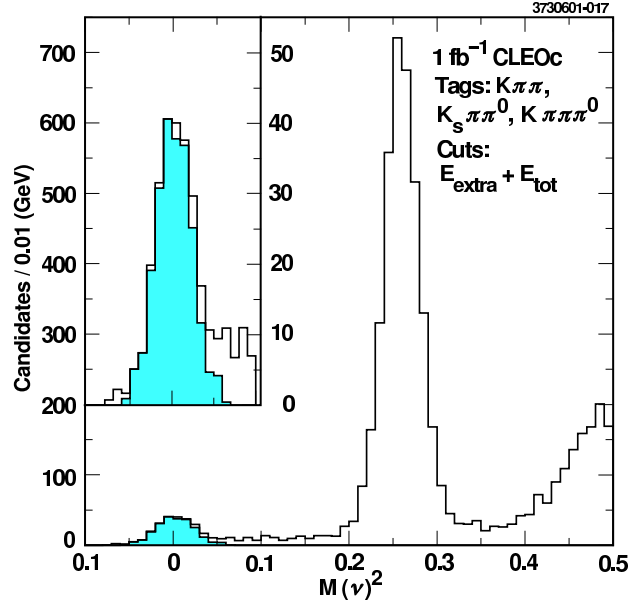


FIGURE 14. Square of the invariant mass of the ν candidate in $D^+ \rightarrow \mu^+ \nu$ from 1 fb^{-1} TRKSIM events. The shaded area shows correctly tagged candidates, and the insert shows the signal region on an expanded vertical scale.

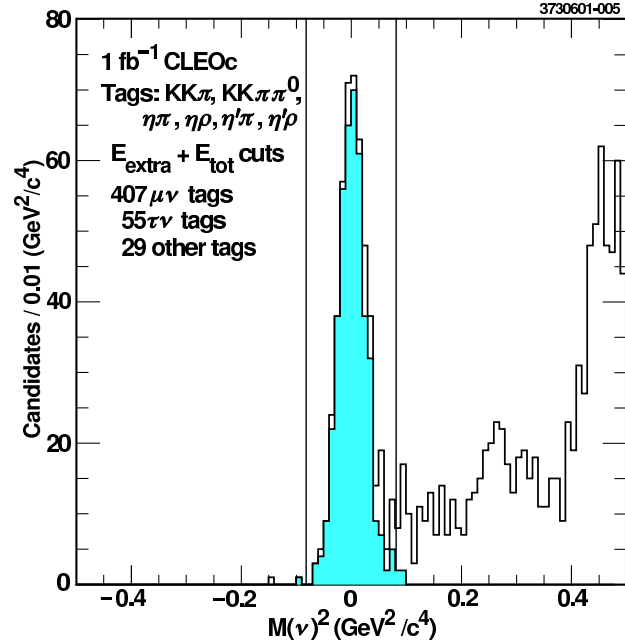


FIGURE 15. Square of the invariant mass of the ν candidate in $D_s^+ \rightarrow \mu^+ \nu$ from 1 fb^{-1} TRKSIM events. The shaded area shows correctly tagged candidates. Vertical lines show the 3σ limits.

TABLE 6. Errors in the leptonic branching fractions expected in 3 fb^{-1} each of D^+D^- and $D_s^+D_s^-$ data.

Decay Mode	Signal Yield	$\tau^+\nu/\mu^+\nu$	Bkgrnd	Statistical Error	$\tau^+\nu/\mu^+\nu$ Error	Bkgrnd Error
$D^+ \rightarrow \mu^+\nu$	672	30	60	3.8%	0.4%	0.9%
$D_s^+ \rightarrow \mu^+\nu$	1221	165	87	2.9%	1.4%	0.7%
$D_s^+ \rightarrow \tau^+\nu$	1740	0	114	2.4%	0 %	0.7%

elements, $|V_{cd}|$ and $|V_{cs}|$, are known from unitarity to 1.1% and 0.1%, respectively. We have assumed that we will be able to determine the background components to 10% in making our estimates.

In Table 7 we give the expected contributions to the errors on the decay constants, including the errors on the measured D^+ and D_s lifetimes. The lifetime errors are significant and they will surely be reduced in the coming years. Using the current lifetime errors, we project that the total error on f_{D^+} will be 2.3%. For f_{D_s} we project an error of 1.9 % based on the muon mode alone.

TABLE 7. Contributions to the errors in the decay constants expected in 3 fb^{-1} each of D^+D^- and $D_s^+D_s^-$ data.

Decay Mode	Decay Constant	$\frac{1}{2}(\Delta\mathcal{B}/\mathcal{B})$	$\frac{1}{2}(\Delta\tau/\tau)$	$\Delta V_{cq} / V_{cq} $	$\Delta f_{D_q}/f_{D_q}$
$D^+ \rightarrow \mu^+\nu$	f_D	1.9%	0.6%	1.1%	2.3%
$D_s^+ \rightarrow \mu^+\nu$	f_{D_s}	1.6%	1.0%	0.1%	1.9%
$D_s^+ \rightarrow \tau^+\nu$	f_{D_s}	1.2%	1.0%	0.1%	1.6%

3.4 Semileptonic Decays

3.4.1 Analysis technique for semileptonic decays

The best place to study charm meson semileptonic decays is at the $\psi(3770)$ for D^0 and D^+ modes and above $D_s^+D_s^-$ threshold at $\sqrt{s} = 4.028 \text{ GeV}$ or $\sqrt{s} = 4.140 \text{ GeV}$, depending on where the cross section turns out to be larger. We plan on fully reconstructing one of the D mesons in the event which determines the charge and flavor of the semileptonic decay and vastly reduces the backgrounds. The reconstruction of the tag follows the method described in Section 3.2.

When the D meson recoiling against the tag decays semileptonically it is detected by identifying an electron and a set of hadrons and reconstructing the missing momentum and missing energy. The hermeticity of the CLEO-c detector and excellent particle identification

are ideally suited to this task.

The CLEO III detector has excellent electron identification capabilities and excellent muon identification above 1.2 GeV/ c . However as the kinematic limit for the decay products of charm mesons produced at ~ 4 GeV center-of-mass energy does not exceed 1.1 GeV/ c , muons are not used for the analyses presented here.

Electrons are identified by requiring E/p to be near unity, where E is the measured energy in the electromagnetic calorimeter and p is the momentum measured by the drift chamber. The calorimeter information is combined with a measurement of the specific ionization (dE/dx) of the track in the drift chamber. The CLEO III collaboration has a great deal of experience with electron identification above 500 MeV/ c . Because of the reduction in B field to 1T for CLEO-c and the resulting alteration in the track curvature-momentum relationship the calorimeter will play a role in electron identification down to 300 MeV/ c . For the efficiencies reported in this Section we have conservatively placed a lower limit on electron identification of 400 MeV/ c for exclusive decay modes. We can lower this threshold to the cutoff imposed by tracking by using the RICH and dE/dx information. The efficiency for identifying electrons is evaluated at the $\Upsilon(4S)$ using radiative Bhabha events embedded in hadronic events and, for CLEO II, had an uncertainty of about 2%. The lower multiplicity at the $\psi(3770)$ combined with the ability to check the traditional algorithms with the RICH will lead to an uncertainty in electron identification of 0.8%.

Kaons from semileptonic decays are identified by their specific ionization in the drift chamber and from RICH information. The RICH provides powerful K/π rejection above 500 MeV/ c where the K/π separation is small in the drift chamber. Therefore kaons with a momentum less than 500 MeV/ c were identified solely by dE/dx information, and kaons with a momentum greater than 500 MeV/ c were identified using both the drift chamber and the RICH.

The unique kinematics of threshold production provide additional and very powerful means of rejecting background from misidentified or undetected particles. Following earlier work we define U as the difference between the missing energy and missing momentum in the event, $U = E_{miss} - P_{miss}$ [17]. U will be close to zero if the event is correctly reconstructed. In Figure 16 we plot the U distribution for the dominant Cabibbo allowed decay $D^0 \rightarrow K^- e^+ \nu$ for an integrated luminosity of 1 fb $^{-1}$ at the $\psi(3770)$.

The resolution of the detector without particle identification is sufficient to separate the Cabibbo suppressed decay $D^0 \rightarrow \pi^- e^+ \nu$ from the ten times more copiously produced $D^0 \rightarrow K^- e^+ \nu$. In Figure 17 we show the U distribution for $D^0 \rightarrow \pi^- e^+ \nu$. A sample of $D^0 \rightarrow K^- e^+ \nu$ where the K^- is outside the fiducial volume of the RICH enter the plot but are clearly separated from the signal. The sample corresponds to a integrated luminosity of 1 fb $^{-1}$ at the $\psi(3770)$.

Table 8 gives the number of events with a hadronic tag where a semileptonic decay is reconstructed at the $\psi(3770)$ and at $\sqrt{s} = 4.14$ GeV per fb $^{-1}$ with CLEO-c.

For every semileptonic decay mode there are several potential sources of background; $e^+e^- \rightarrow q\bar{q}$ non-resonant continuum, hadronic tracks that fake electrons, and other D decays. Each of these backgrounds is evaluated by simulation and found to be small. Table 9 gives the number of events produced by these background sources per 1 fb $^{-1}$ for each of the semileptonic decay modes we have simulated at the $\psi(3770)$.

At the $\psi(3770)$ random combinations of hadronic tracks produced in the decay of the

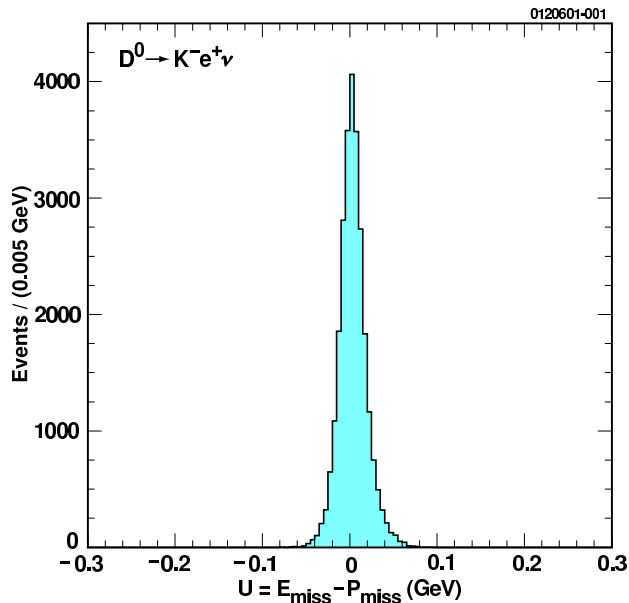


FIGURE 16. Reconstruction of the mode $D^0 \rightarrow K^- e^+ \nu$ in events with a hadronic tag, following the analysis technique described in the text. The simulation corresponds to an integrated luminosity of 1 fb^{-1} .

$D^0 \bar{D}^0$ or $D^+ D^-$ pair can satisfy the ΔE , particle identification and beam constrained invariant mass requirements of a tag producing a mistag. Our simulations show that mistags are the main source of background from D decay for the pseudoscalar final states. For the Cabibbo allowed vector final states the main source of background is correctly tagged events in which the second D undergoes semileptonic non-resonant decay. For Cabibbo suppressed vector final states there is no experimental information on the amount of non-resonant decay and this is set to zero in the event generator. For this reason the background in $D \rightarrow \rho e^+ \nu$ is smaller than for Cabibbo allowed vector final states. Background from D decay at the $\psi(3770)$ is given in the second and third columns of Table 9 for $D^0 \bar{D}^0$ and $D^+ D^-$ pairs, respectively.

To estimate the contribution from hadronic tracks faking electrons we repeat the analysis of each mode, multiplying the number of tracks which are not positively identified as an electron by the hadronic track probability to fake an electron measured in CLEO data. In this simple estimate we have not corrected the fake probability for the difference between the relative population of particle species at the $\psi(3770)$ and the $\Upsilon(4S)$. The results are given in the fourth column of Table 9. Non-resonant continuum at 3.77 GeV is not a significant source of mistags or electrons, hence the background from this source is very small. It is given in the fifth column of Table 9. Summing all the sources of background the signal-to-noise ratio is seen to be excellent in all cases.

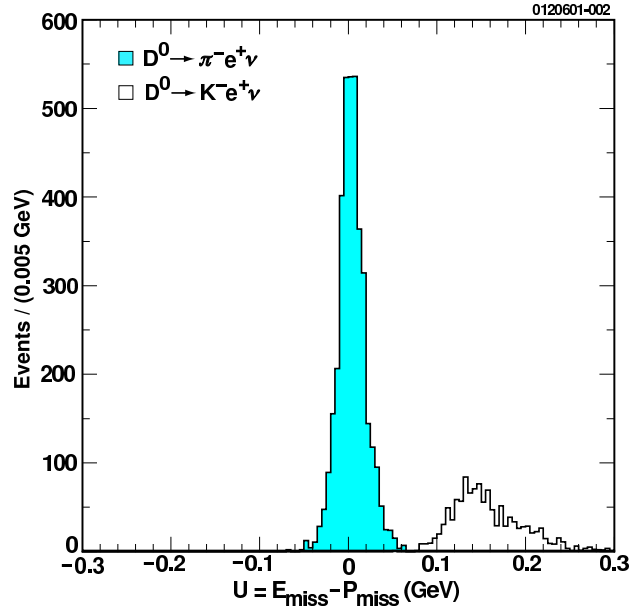


FIGURE 17. Reconstruction of the mode $D^0 \rightarrow \pi^- e^+ \nu$ (shaded histogram) in events with a hadronic tag, following the analysis technique described in the text. The unshaded histogram is from $D^0 \rightarrow K^- e^+ \nu$ events where the K^- has been misidentified as a π^- . The simulation corresponds to an integrated luminosity of 1 fb^{-1} .

3.4.2 Exclusive Semileptonic Decays

In order to determine a CKM matrix element it is necessary to know an absolute branching fraction. Charm exclusive semileptonic decay branching fractions are currently not well known (see Table 10). Using the tagged measured yields from Table 8 we obtain the precision with which absolute charm exclusive semileptonic branching fractions can be measured with CLEO-c per 3 fb^{-1} . The results are given in Table 10. It can be seen that CLEO-c will allow a dramatic improvement in the precision with which all absolute charm exclusive semileptonic decay branching fractions are known. We will use several of these absolute branching fractions in the next section to determine $|V_{cs}|$ and $|V_{cd}|$.

3.4.2.1 Determination of $|V_{cd}|$ and $|V_{cs}|$

The origin of quark flavor mixing is unknown. It is described by the three generation Cabibbo-Kobayashi-Maskawa (CKM) matrix, whose elements are fundamental parameters of the Standard Model. When unitarity is not imposed $|V_{cs}|$ and $|V_{cd}|$ are known to 15% and 7%, respectively. CLEO-c can make an approximately one order of magnitude improvement in current measurements.

For pseudoscalar-to-pseudoscalar transitions the decay width can be expressed as [18]

$$\frac{d\Gamma(D \rightarrow P \ell^+ \nu)}{dq^2} = \frac{|V_{cq}|^2 p^3}{24\pi^3} |f_+(q^2)|^2, \quad (2)$$

TABLE 8. Number of semileptonic decays reconstructed in tagged events per 1 fb^{-1} . For modes containing a $\bar{K}^*$ only the $K^{*-} \rightarrow K^-\pi^0$ and $\bar{K}^{*0} \rightarrow K^-\pi^+$ decay chains are reconstructed. The branching fractions listed do not include subsidiary branching fractions, which, however, are taken into account in calculating the number of events produced in each mode.

D^0 Mode	$\mathcal{B}(\%)$	$N_{Xe\nu}^{\text{Produced}}(10^5)$	$N_{Xe\nu}^{\text{Detected}}$	$N_{Xe\nu+Tag}^{\text{Detected}}$	CKM
$K^-e^+\nu$	3.47	4.03	186,500	25,890	V_{cs}
$K^{*-}e^+\nu$	2.02	0.78	9,400	1,300	V_{cs}
$\pi^-e^+\nu$	0.37	0.43	27,000	3,730	V_{cd}
$\rho^-e^+\nu$	0.20	0.23	5,200	730	V_{cd}
D^+ Mode					
$K_S^0e^+\nu$	3.40	1.96	73,000	5,520	V_{cs}
$\bar{K}^{*0}e^+\nu$	4.65	2.60	50,500	3,750	V_{cs}
$\pi^0e^+\nu$	0.31	0.26	11,500	860	V_{cd}
$\rho^0e^+\nu$	0.25	0.21	8,000	590	V_{cd}
D_s^+ Mode					
$K_S^0e^+\nu$	0.06	600	350	34	V_{cd}
$\phi e^+\nu$	2.00	9,800	3,400	350	V_{cs}
$\bar{K}^{*0}e^+\nu$	0.10	650	180	18	V_{cd}

where q^2 is the four-momentum transfer squared between the parent D meson and the final state hadron, p is the momentum of the decay pseudoscalar hadron in the D rest frame and $|V_{cq}|$ is the relevant CKM matrix element, either V_{cs} or V_{cd} .

There are several approaches to determine $|V_{cd}|$, $|V_{cs}|$ and $|V_{cd}|/|V_{cs}|$ with semileptonic decays at CLEO-c. In order to determine an individual matrix element theory must provide the absolute normalization of the form factor describing the decay at some fixed q^2 point. Since theory also provides the q^2 dependence of the form factor, we can check the theory by *measuring* the form factor shape. As examples we will look at the $D^0 \rightarrow K^-e^+\nu$ to determine $|V_{cs}|$ and $D^0 \rightarrow \pi^-e^+\nu$ to determine $|V_{cd}|$.

Using the tagged measured yield from Table 8 for $D^0 \rightarrow K^-e^+\nu$ and correcting by the efficiency ϵ we obtain the absolute branching fraction $\mathcal{B}(D^0 \rightarrow K^-e^+\nu)$. We may calculate the rate Γ from the absolute branching fraction and the mean lifetime of the D^0 , τ_{D^0} . The rate is related to $|V_{cs}|$ as:

$$\Gamma(D^0 \rightarrow K^-e^+\nu) = \frac{\mathcal{B}(D^0 \rightarrow K^-e^+\nu)}{\tau_{D^0}} = \gamma_s |V_{cs}|^2 \quad (3)$$

where γ_s is given by theory. The error on $|V_{cs}|$ is:

TABLE 9. Number of background events to the semileptonic decay modes indicated in reconstructed tagged events per 1 fb^{-1} .

D^0 Mode	D^0 background	D^+ background	Fake electron	Continuum
$K^- e^+ \nu$	6	2	328	< 1
$K^{*-} e^+ \nu$	222	4	8	< 1
$\pi^- e^+ \nu$	0	22	38	< 1
$\rho^- e^+ \nu$	6	22	54	< 1
D^+ Mode	D^+ background	D^0 background	Fake electron	Continuum
$K_S^0 e^+ \nu$	20	2	50	< 1
$\bar{K}^{*0} e^+ \nu$	142	2	62	< 1
$\pi^0 e^+ \nu$	2	4	8	< 1
$\rho^0 e^+ \nu$	48	2	42	< 1

$$\frac{\delta V_{cs}}{V_{cs}} = \sqrt{\left(\frac{\delta \Gamma}{2\Gamma}\right)^2 + \left(\frac{\delta \gamma_s}{2\gamma_s}\right)^2} \quad (4)$$

From the CLEO-c measurement of the branching fraction, the world average value of τ_{D^0} ($\delta\tau_{D^0}/\tau_{D^0} = 0.7\%$) and taking the systematic uncertainty in the efficiency to be $\delta\epsilon/\epsilon = 0.9\%$ which includes contributions from track finding efficiency (0.2% per track) and electron ID (0.8%), we have

$$\frac{\delta \Gamma}{\Gamma} = 1.2\%. \quad (5)$$

We see that for $\delta\gamma_s/\gamma_s > 1.2\%$ the theoretical error dominates. Taking $\delta\gamma_s/\gamma_s = 3\%$, an error that may be achievable with lattice QCD in several years (note that these projections are for a 3 fb^{-1} data sample):

$$\frac{\delta V_{cs}}{V_{cs}} = 1.6\%. \quad (6)$$

The above procedure can be repeated to determine $|V_{cd}|$ from $D^0 \rightarrow \pi^- e^+ \nu$. Using the tagged measured yield from Table 8 and correcting by the efficiency we obtain the absolute branching fraction $\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu)$. We again calculate the rate Γ from the absolute branching fraction and the mean lifetime of the D^0 . Using Equations (3) and (4) and making the appropriate substitutions γ_d for γ_s and $|V_{cd}|$ for $|V_{cs}|$, we obtain

$$\frac{\delta \Gamma}{\Gamma} = 1.5\%. \quad (7)$$

For $\delta\gamma_d/\gamma_d > 1.5\%$ the theoretical error dominates. Taking the same theory error as above:

$$\frac{\delta V_{cd}}{V_{cd}} = 1.7\%. \quad (8)$$

TABLE 10. Current knowledge (PDG 2000) [11] of charm exclusive semileptonic decay branching fractions and the precision with which absolute charm exclusive semileptonic branching fractions can be measured in 3 fb^{-1} of reconstructed tagged events with CLEO-c. (Note: only statistical uncertainties are included in the error estimates in this table.)

D modes	PDG $\mathcal{B}(\%)$	PDG $\Delta\mathcal{B}/\mathcal{B}(\%)$	CLEO-c $\Delta\mathcal{B}/\mathcal{B}(\%)$
$D^0 \rightarrow K^- e^+ \nu$	3.47 ± 0.17	4.9	0.36
$D^0 \rightarrow K^{*-} e^+ \nu$	2.02 ± 0.33	16.3	1.60
$D^0 \rightarrow \pi^- e^+ \nu$	0.37 ± 0.06	16.2	0.95
$D^0 \rightarrow \rho^- e^+ \nu$	—	—	2.14
$D^+ \rightarrow \bar{K}^0 e^+ \nu$	6.7 ± 0.9	13.4	0.63
$D^+ \rightarrow \bar{K}^{*0} e^+ \nu$	4.7 ± 0.4	9.4	0.94
$D^+ \rightarrow \pi^0 e^+ \nu$	0.31 ± 0.15	48.4	1.97
$D^+ \rightarrow \rho^0 e^+ \nu$	0.22 ± 0.08	36.4	2.38
$D_s \rightarrow \bar{K}^0 e^+ \nu$	—	—	9.9
$D_s \rightarrow \bar{K}^{*0} e^+ \nu$	—	—	13.6
$D_s \rightarrow \phi e^+ \nu$	2.0 ± 0.5	25.0	3.1
$\Lambda_c \rightarrow \Lambda e^+ \nu X$	1.1 ± 0.8	72.7	16

3.4.2.2 Determination of the Ratio $|V_{cd}|/|V_{cs}|$

A comparison of $|V_{cs}|$ and $|V_{cd}|$ may be made through two approaches. The first involves the comparison of reactions of like initial states and different final states. For example:

$$\frac{\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu)}{\mathcal{B}(D^0 \rightarrow K^- e^+ \nu)} = \frac{\Gamma(D^0 \rightarrow \pi^- e^+ \nu)}{\Gamma(D^0 \rightarrow K^- e^+ \nu)} = \left(\frac{\gamma_d}{\gamma_s} \right) R^2. \quad (9)$$

The advantage of this approach is that the ratio $R = |V_{cd}|/|V_{cs}|$ can be determined more precisely than either of its elements separately, because the requirement on theory is less stringent as the absolute value of the form factors is replaced by a ratio of form factors. The ratio of form factors may differ from unity at the level of SU(3) breaking.

From the yields in Table 8 the ratio $\mathcal{B}(D \rightarrow \pi e^+ \nu)/\mathcal{B}(D \rightarrow K e^+ \nu)$ can be determined with an experimental error of about 1%. Since the data for both modes are taken simultaneously at the $\psi(3770)$ the systematic error associated with track finding and from electron identification will largely cancel in the ratio. Cancellations also occur in the lattice QCD calculation of the rate ratio. To illustrate the precision achievable we take the theory error on the ratio of rates to be 2%. Finally, the ratio of branching fractions determines the ratio

R independent of the D^0 lifetime. For 3 fb^{-1} we have:

$$R = \frac{\Gamma(D^0 \rightarrow \pi^- e^+ \nu)}{\Gamma(D^0 \rightarrow K^- e^+ \nu)} : \frac{\delta R}{R} = 1.2\% \quad . \quad (10)$$

The second approach is to compare reactions with different initial states and identical final states. For example, $D_s \rightarrow K^* e^+ \nu$ and $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$ or $D_s \rightarrow K_s^0 e^+ \nu$ and $D^+ \rightarrow K_s^0 e^+ \nu$. As the final states are identical uncertainties in the ratio of form factors should be reduced below the level of SU(3) corrections. A drawback in using D_s Cabibbo suppressed final states is that the statistics are reduced. From the yields in Table 8 we compute $\delta R/R = 5.4\%$ for the $K_s^0 e^+ \nu$ final state in 3 fb^{-1} .

3.4.2.3 Measurement of Form Factors in Pseudoscalar-to-Pseudoscalar Semileptonic Decays

Form factors in charm semileptonic decay play an important role in calibrating lattice QCD and testing other theories of heavy quark decay. The form factors in charm semileptonic decays are related to those in B decay by Heavy Quark Symmetry and so aid the determination of $|V_{ub}|$, and the Standard Model prediction for the rate for certain rare B decays processes. Some examples of decays related in this way are discussed in Chapter II. The charm semileptonic decays that have received the most interest are $D \rightarrow K e^+ \nu$, $D \rightarrow \pi e^+ \nu$, $D \rightarrow \rho e^+ \nu$ and $D \rightarrow \bar{K}^* e^+ \nu$.

The shape of the form factors governing semileptonic decays have not been measured with the exception of the decay $D^0 \rightarrow K^- e^+ \nu$. At B Factories and at fixed target experiments the presence of background provides a significant source of systematic uncertainty in form factor analyses of semileptonic decays. Whereas at CLEO-c the kinematics of threshold production allow for the isolation of background free samples of semileptonic decays. This in turn allows measurements of the form factors with unprecedented signal-to-background fractions for all decays. In addition the resolution in q^2 , which is the invariant mass of the W in the decay, is typically a factor three better than has been obtained in analyses performed at $\sqrt{s} = 10 \text{ GeV}$.

Pseudoscalar-to-pseudoscalar transitions such as $D^0 \rightarrow \pi^- e^+ \nu$ and $D^0 \rightarrow K^- e^+ \nu$ are governed by a single form factor. This means they are the only decays where a measurement of $d\Gamma/p^3 dq^2$ is a direct measure of the form factor q^2 dependence. This makes the measurement simple to interpret and provides a challenge for theory. Any theory, from Lattice QCD [19] to ChPTHH [20], which is used to extract a CKM matrix element from a semileptonic decay, must first be able to predict a shape of the $d\Gamma/p^3 dq^2$ distribution that agrees with data.

There are several ways to determine the value of q^2 . The method used here is:

$$E_W = E_{beam} - E_X \quad (11)$$

$$\vec{p}_W = -\vec{p}_{tag} - \vec{p}_X \quad (12)$$

$$q^2 = E_W^2 - |p_W|^2 \quad (13)$$

where E_X is the energy of the hadronic particle X . E_{beam} is the energy of the beam and p_{tag} is the momentum of the tag.

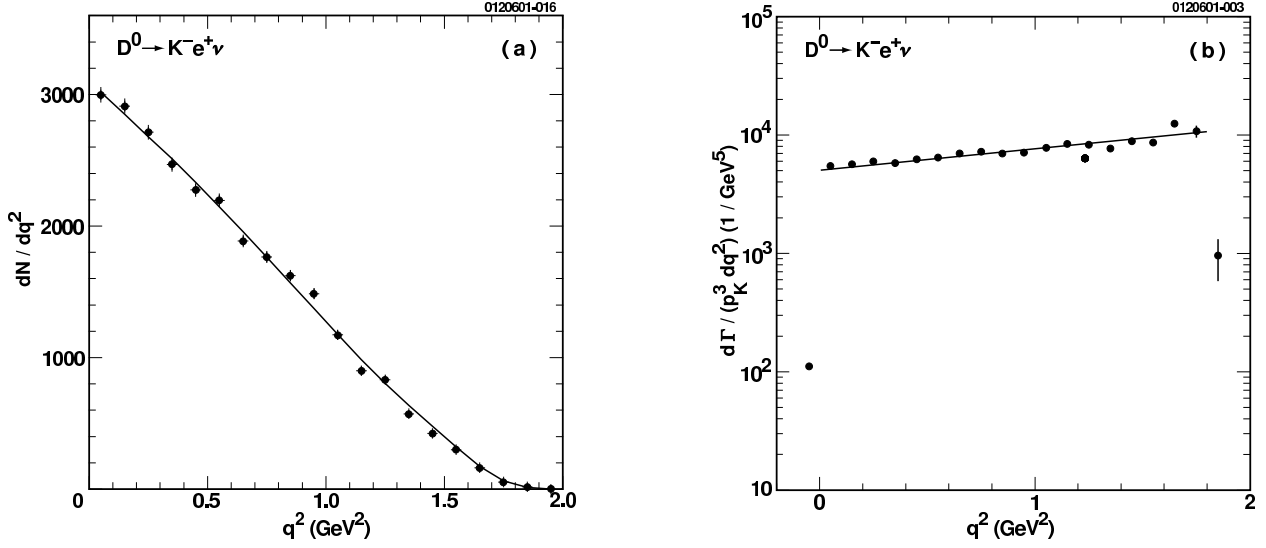


FIGURE 18. (a) The q^2 distribution for $D^0 \rightarrow K^- e^+ \nu$ events. The histogram corresponds to the yield expected for an integrated luminosity of 1 fb^{-1} . The line is the projection of the fit described in the text. (b) $d\Gamma/p_K^3 dq^2$ for $D^0 \rightarrow K^- e^+ \nu$ events. The line is the result of a fit to the data points. The plot corresponds to an integrated luminosity of 1 fb^{-1} .

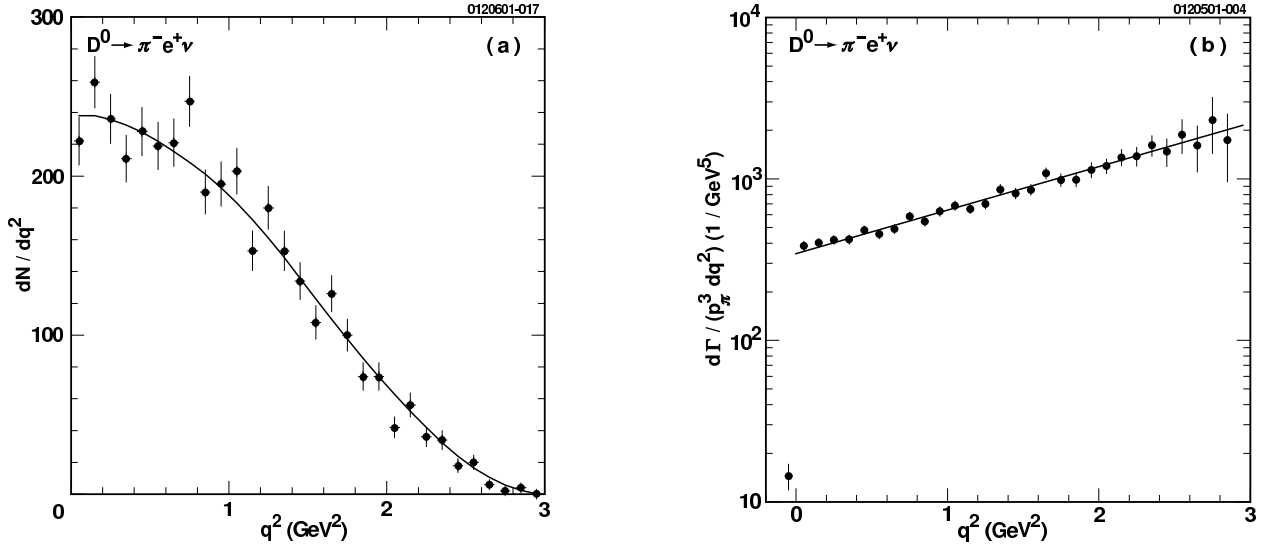


FIGURE 19. (a) The q^2 distribution for $D^0 \rightarrow \pi^- e^+ \nu$ events. The histogram corresponds to the yield expected for an integrated luminosity of 1 fb^{-1} . The line is the projection of the fit described in the text. (b) $d\Gamma/p_\pi^3 dq^2$ for $D^0 \rightarrow \pi^- e^+ \nu$ events. The line is the result of a fit to the data points. The plot corresponds to an integrated luminosity of 1 fb^{-1} .

The left plot in Figures 18 and 19 is the $d\Gamma/dq^2$ distribution reconstructed for $D^0 \rightarrow K^- e^+ \nu$ and $D^0 \rightarrow \pi^- e^+ \nu$ in tagged events. The events have been generated with the ISGW

model [21] which parameterizes the form factor as $f_+(q)^2 = f_+(0)e^{\alpha q^2}$, where α is the slope parameter. In these plots the histogram is a sample of Monte Carlo events corresponding to the signal yield expected from an integrated luminosity of 1 fb^{-1} . We will refer to this sample as the data. The form factor slope for these events is measured in a one dimensional unbinned maximum likelihood fit to the differential decay rate distribution. The probability function of the signal is determined by generating one high statistics MC signal sample with a known value of α . The generated events are processed through TRKSIM. Using the generated value of α accepted MC events are weighted by the ratio of the decay distribution for the trial value of α to that of the generated distribution. By such weighting a likelihood may be evaluated for each data event for trial values of α and a fit performed. The probability for each event is determined by sampling the decay distribution using a search element centered on each data point. Background can readily be incorporated into the fitting technique. However, since the background in the decay modes under study is negligible we have not included background in this analysis. The validity of the analysis procedure is determined by constructing artificial data sets consisting of MC events with known slope. In all cases the fit returns unbiased values of the slope.

Applying the fit procedure to the data, we find $\delta\alpha/\alpha = 4\%$ for $D^0 \rightarrow K^- e^+ \nu$ and $\delta\alpha/\alpha = 4\%$ for $D^0 \rightarrow \pi^- e^+ \nu$. The projections of the fit for each mode are shown as lines in the plots. The slopes are determined with equal precision despite the massive statistical advantage for the Cabibbo allowed decay. The reason is that the ISGW model is used as the generator for both processes. In the ISGW model the slopes are: $\alpha = 0.22$ for $D^0 \rightarrow K^- e^+ \nu$, and $\alpha = 0.32$ for $D^0 \rightarrow \pi^- e^+ \nu$.

The q^2 dependence of $D \rightarrow K/\pi e^+ \nu$ is dominated by the p^3 factor arising from the P wave nature of the amplitude. By dividing the differential rate by $1/p^3$ we can remove the kinematic factor and the rate dependence from the form factor alone can be seen. The right plots of Figures 18 and 19 show $d\Gamma/p^3 dq^2$ reconstructed for $D^0 \rightarrow K^- e^+ \nu$ and $D^0 \rightarrow \pi^- e^+ \nu$ in tagged events. Both plots correspond to an integrated luminosity of 1 fb^{-1} .

Figures 20 and 21 show the statistical errors on the rates for each mode per 1 fb^{-1} in each bin of q^2 . Also shown are the efficiencies for the signal modes as a function of q^2 . The lattice, and other theoretical approaches, predict the form factor slope and absolute rate. The precision measurement of the form factor slope and absolute rate with CLEO-c will provide a very stringent test of theory.

3.4.2.4 Measurement of Form Factors in Pseudoscalar-to-Vector Semileptonic Decays

Measurement of form factors in pseudoscalar-to-pseudoscalar transitions are the easiest to perform, but the measurements of the form factors in all charm semileptonic decays are important. Among the pseudoscalar-to-vector transitions two modes of particular interest are $D \rightarrow \rho e^+ \nu$ and $D \rightarrow \bar{K}^* e^+ \nu$. Figures 22 and 23 show clean signals for both modes in tagged events with CLEO-c.

The form factors governing the transition $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$ are related by SU(3) and heavy quark symmetry to the form factors in $B \rightarrow \rho e^+ \nu$ which can be used to determine V_{ub} at a B factory. The unique kinematics of threshold production will allow CLEO-c to make excellent measurements of the form factors in pseudoscalar-to-vector transitions. Here there are three form factors to measure, both the normalizations and the shapes.

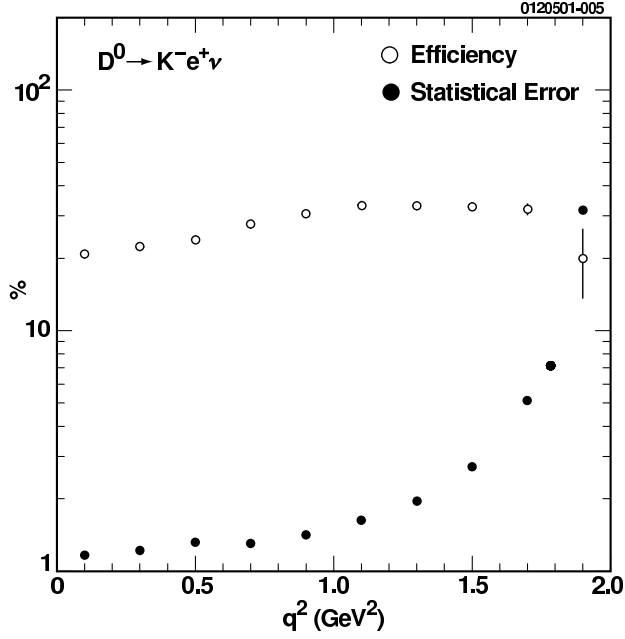


FIGURE 20. The statistical error on $d\Gamma/p^3 dq^2$ and the detection efficiency for $D^0 \rightarrow K^- e^+ \nu$ as a function of q^2 . The binning corresponds to the resolution in q^2 . The simulation corresponds to an integrated luminosity of 1 fb^{-1} .

For pseudoscalar-to-vector transitions, and using $D \rightarrow \bar{K}^* e^+ \nu$ as an example, there are four independent variables that can be used to describe this decay. They are q^2 , the angle θ_V between the momentum vector of the K^- in the $\bar{K}^{*0}$ rest frame and the $\bar{K}^{*0}$ momentum in the D^0 rest frame, the angle θ_e between the momentum vector of the electron in the virtual W rest frame ($W \rightarrow e^+ \nu$) and the W momentum in the D^+ rest frame, and the angle χ between the decay planes of the $\bar{K}^{*0}$ and the W in the D^+ rest frame. A decay diagram showing the four variables is given in Figure 24.

In terms of the four variables the decay width can be expressed as

$$\begin{aligned}
 \frac{d\Gamma}{dq^2 d\cos\theta_V d\cos\theta_e d\chi} &= \frac{3G_F^2}{8(4\pi)^4} |V_{cs}|^2 \\
 &\times \frac{p_{K^*} q^2}{M_D^2} [(1 + \cos\theta_e)^2 \sin^2\theta_V |H_+(q^2)|^2 \\
 &+ (1 - \cos\theta_e)^2 \sin^2\theta_V |H_-(q^2)|^2 \\
 &+ 4 \sin^2\theta_e \cos^2\theta_V |H_0(q^2)|^2 \\
 &+ 4 \sin\theta_e (1 + \cos\theta_e) \sin\theta_V \cos\theta_V \cos\chi H_+(q^2) H_0(q^2) \\
 &- 4 \sin\theta_e (1 - \cos\theta_e) \sin\theta_V \cos\theta_V \cos\chi H_-(q^2) H_0(q^2) \\
 &- 2 \sin^2\theta_e \sin^2\theta_V \cos 2\chi H_+(q^2) H_-(q^2)] \\
 &\times \mathcal{B}(\bar{K}^* \rightarrow K\pi).
 \end{aligned} \tag{14}$$

The three helicity amplitudes, $H_+(q^2)$, $H_-(q^2)$, and $H_0(q^2)$ which are functions of the vector and axial vector form factors characterize the probabilities that the strange quark and the spectator will form a $\bar{K}^*$ with the various indicated helicities. Explicitly the helicity

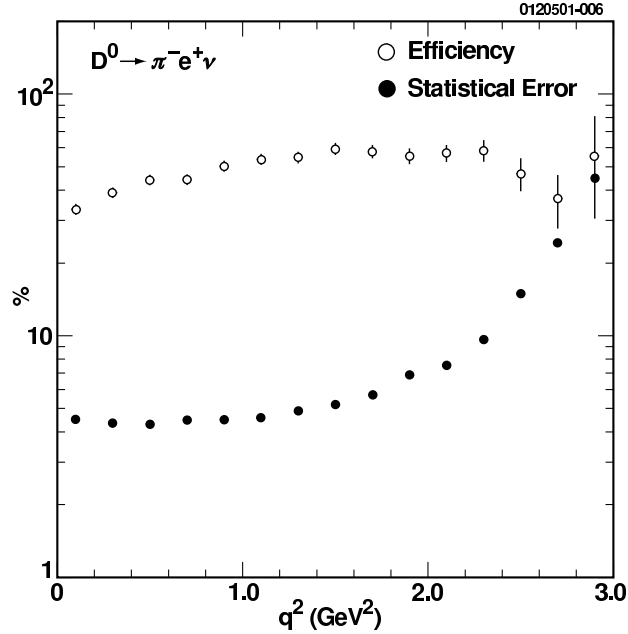


FIGURE 21. The statistical error on $d\Gamma/p^3 dq^2$ and the detection efficiency for $D^0 \rightarrow \pi^- e^+ \nu$ as a function of q^2 . The binning corresponds to the resolution in q^2 . The simulation corresponds to an integrated luminosity of 1 fb^{-1} .

amplitudes are:

$$H_{\pm}(q^2) = (M_D + M_{K\pi})A_1(q^2) \mp 2\frac{M_D p_{K\pi}}{M_D + M_{K\pi}}V(q^2),$$

$$H_0(q^2) = \frac{1}{2M_{K\pi}\sqrt{q^2}}[(M_D^2 - M_{K\pi}^2 - q^2)(M_D + M_{K\pi})A_1(q^2) - 4\frac{M_D^2 p_{K\pi}^2}{M_D + M_{K\pi}}A_2(q^2)] \quad (15)$$

where $A_1(q^2)$ and $A_2(q^2)$ are axial vector form factors and $V(q^2)$ is a vector form factor.

As the range of q^2 in the decay is small, the decay rate distribution is determined entirely by the three parameters $A_1(0)$, $A_2(0)$ and $V(0)$. The relative magnitude of the form factors can be measured by comparing the angular and q^2 distributions of the data to the differential decay rate formula. Since the form factor A_1 is common to all three helicity amplitudes, we measure the ratios $R_V = V(0)/A_1(0)$ and $R_2 = A_2(0)/A_1(0)$ from the angular distributions of the data. The value of $A_1(0)$ is a function of these ratios, the branching fraction, D^+ lifetime and V_{cs} .

In Figure 25 we show the resolution in the four variables for $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$ reconstructed in tagged events at the $\psi(3770)$. At threshold the resolution in each variable is excellent. Figure 26 shows projections for a sample of $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$ tagged events (points with error bars) for q^2/q_{max}^2 , $\cos\theta_V$, $\cos\theta_e$ and χ . The events have been generated with the ISGW model. The form factor ratios $R_V = V(0)/A_1(0)$ and $R_2 = A_2(0)/A_1(0)$ for these events are measured in a multi-dimensional unbinned maximum likelihood fit to the differential decay rate distribution. The fit procedure is the same as that described for the pseudoscalar-to-pseudoscalar transitions. As the background in the decay mode under study is negligible we have not included background in this analysis. The validity of the analysis procedure is

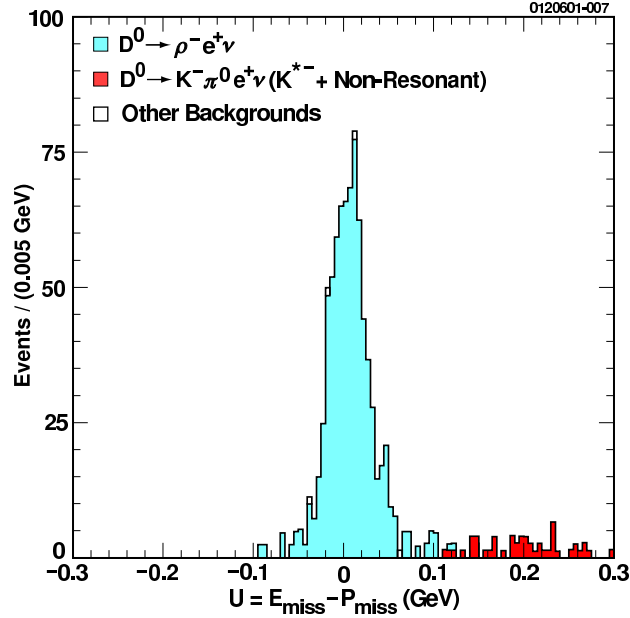


FIGURE 22. Reconstruction of the mode $D^0 \rightarrow \rho^- e^+ \nu$ (light shaded histogram) in events with a hadronic tag, following the analysis technique described in the text. The simulation corresponds to an integrated luminosity of 1 fb^{-1} . The dark shaded histogram is from background events.

determined by constructing artificial data sets consisting of MC events with known values of R_V and R_2 . When the fit is run on each data set it returns an unbiased value of R_V and R_2 . Applying the fit procedure to the events in Figure 26 we find $\delta R_V/R_V = 4\%$ and $\delta R_2/R_2 = 5\%$.

We calculate $A_1(0)$ by equating the total decay rate for $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$ to our measured branching fraction divided by the lifetime of the D^+ . We obtain $\delta \Gamma/\Gamma = 2.2\%$. Using the above measured values of the form factor ratios, and assuming three generation unitarity we can measure the absolute value of each form factor. We obtain $\delta A_1(0)/A_1(0) = 2\%$, $\delta A_2(0)/A_2(0) = 5\%$, and $\delta V(0)/V(0) = 5\%$. The error on $A_1(0)$ has approximately equal contributions from R_2 and R_V and the error in the branching fraction. Only the errors on R_2 and R_V contribute significantly to the errors on $A_2(0)$ and $V(0)$.

We proceed in a similar fashion to determine the form factor ratios in $D^+ \rightarrow \rho^0 e^+ \nu$. The form factors governing $D^+ \rightarrow \rho^0 e^+ \nu$ are related by heavy quark symmetry to the form factors in $B \rightarrow \rho \ell \nu$. In Figure 27 we show the resolution in the four variables for reconstructed $D^+ \rightarrow \rho^0 e^+ \nu$ in tagged events. In Figure 28 we show projections for a sample of $D^+ \rightarrow \rho^0 e^+ \nu$ tagged events (points with error bars) for q^2/q_{max}^2 , $\cos\theta_V$, $\cos\theta_e$ and χ . The events have been generated with the ISGW model. The form factor ratios $R_V = V(0)/A_1(0)$ and $R_2 = A_2(0)/A_1(0)$ for these events can be measured with the same fit technique used for $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$. We are in the process of evaluating the form factor ratios and absolute values of the form factors for this decay.

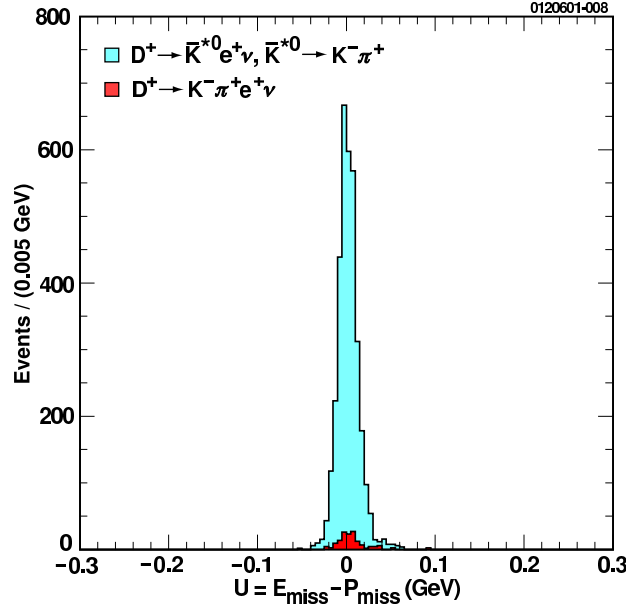


FIGURE 23. Reconstruction of the mode $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$ in events with a hadronic tag, following the analysis technique described in the text. The simulation corresponds to an integrated luminosity of 1 fb^{-1} . The dark shaded histogram is from background events.

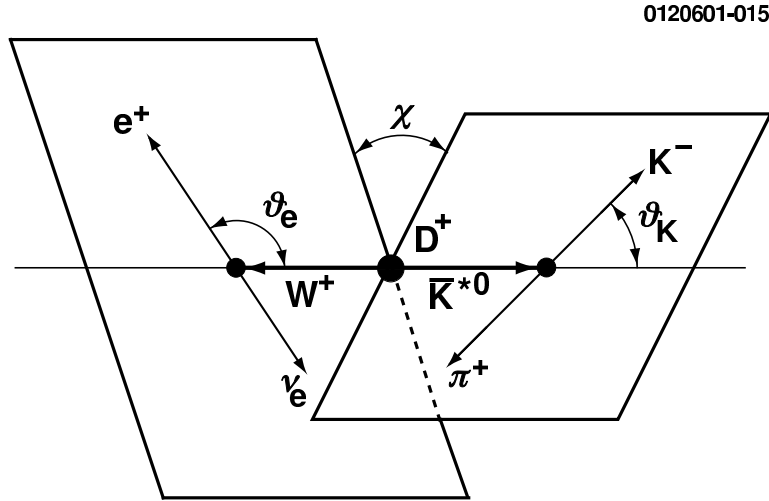


FIGURE 24. Three of the four variables used to describe a semileptonic decay (see text). The fourth variable is q^2 . The example given is $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$. Related variables are used to describe $D \rightarrow \rho e^+ \nu$. To include vector mesons other than $\bar{K}^{*0}$, θ_K is called θ_V in the text and other figures.

3.4.3 Inclusive Semileptonic Decay

HQET [22] provides a successful description of the lifetimes of charm hadrons and of the absolute semileptonic branching fractions of the D^0 and D_s . Isospin invariance of the strong

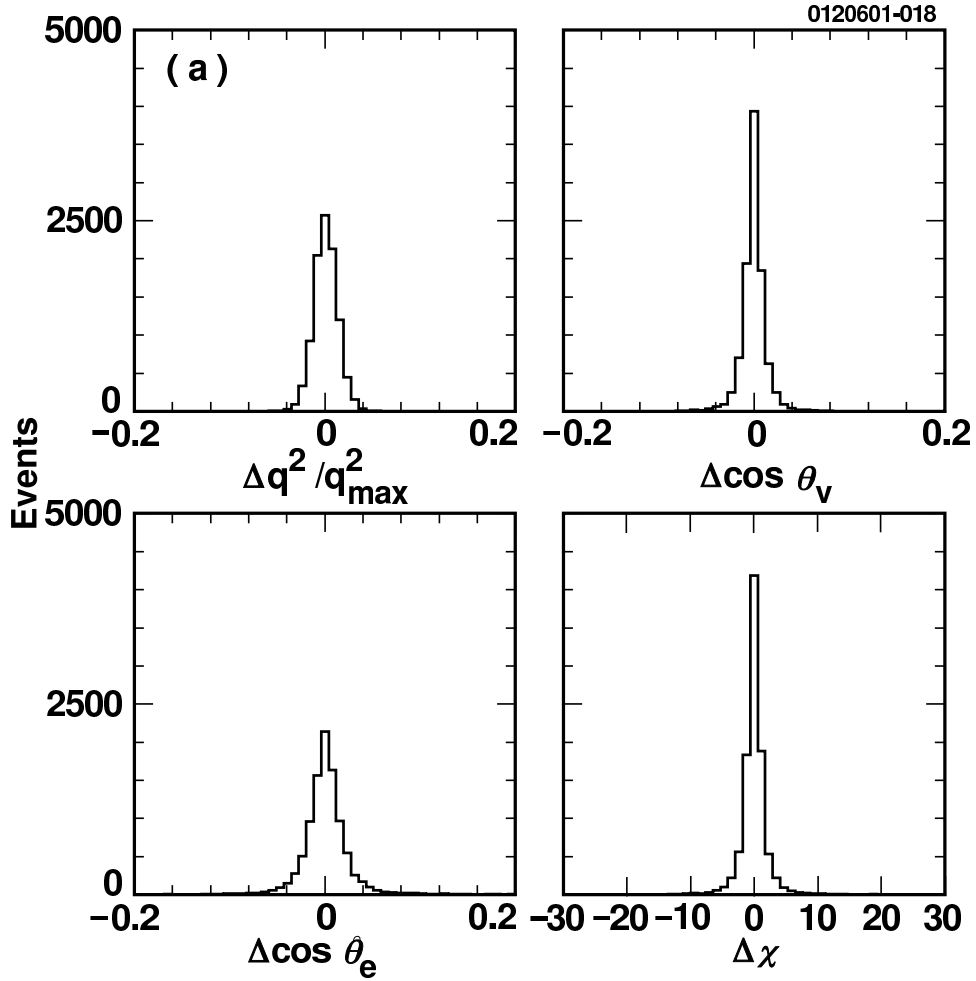


FIGURE 25. The resolutions in q^2 and the three variables, $\cos\theta_K$, $\cos\theta_e$ and χ defined in the Figure 24 for the decay $D \rightarrow \bar{K}^{*0}e^+\nu$.

force informs us that $\Gamma_{SL}(D^0) \simeq \Gamma_{SL}(D^+)$ holds up to corrections $\sim \mathcal{O}(\tan^2\theta_C) \simeq 0.05$. Likewise $SU(3)_{Fl}$ symmetry relates $\Gamma_{SL}(D^0)$ and $\Gamma_{SL}(D_s)$, but a priori would allow them to differ by as much as 30%. However HQET tell us that they should agree to within a few percent. Remarkably, current data is consistent with the equality of the semileptonic widths of all three charm mesons and the Λ_c (see Table 11 and Table 12).

A charm factory is the best place to measure absolute exclusive semileptonic charm branching fractions, in particular $\mathcal{B}(D_s \rightarrow X\ell\nu)$ and thus $\Gamma_{SL}(D_s)$, where no good measurement currently exists. The analysis method is to count the number of positrons recoiling against a hadronic tag. A summary of the expected precision attainable with CLEO-c is given in Table 11 and Table 12. There is a dramatic improvement in the precision with which each inclusive semileptonic branching fraction, and hence inclusive semileptonic width, is determined. For $\mathcal{B}(D_s \rightarrow X\ell\nu)$, and thus $\Gamma_{SL}(D_s)$, the improvement is a factor 30.

It is a prediction of HQET that the inclusive charged lepton spectra should coincide for D^0 , D^+ and D_s $c \rightarrow s$ transitions. However, the endpoint region which is populated by $c \rightarrow d$

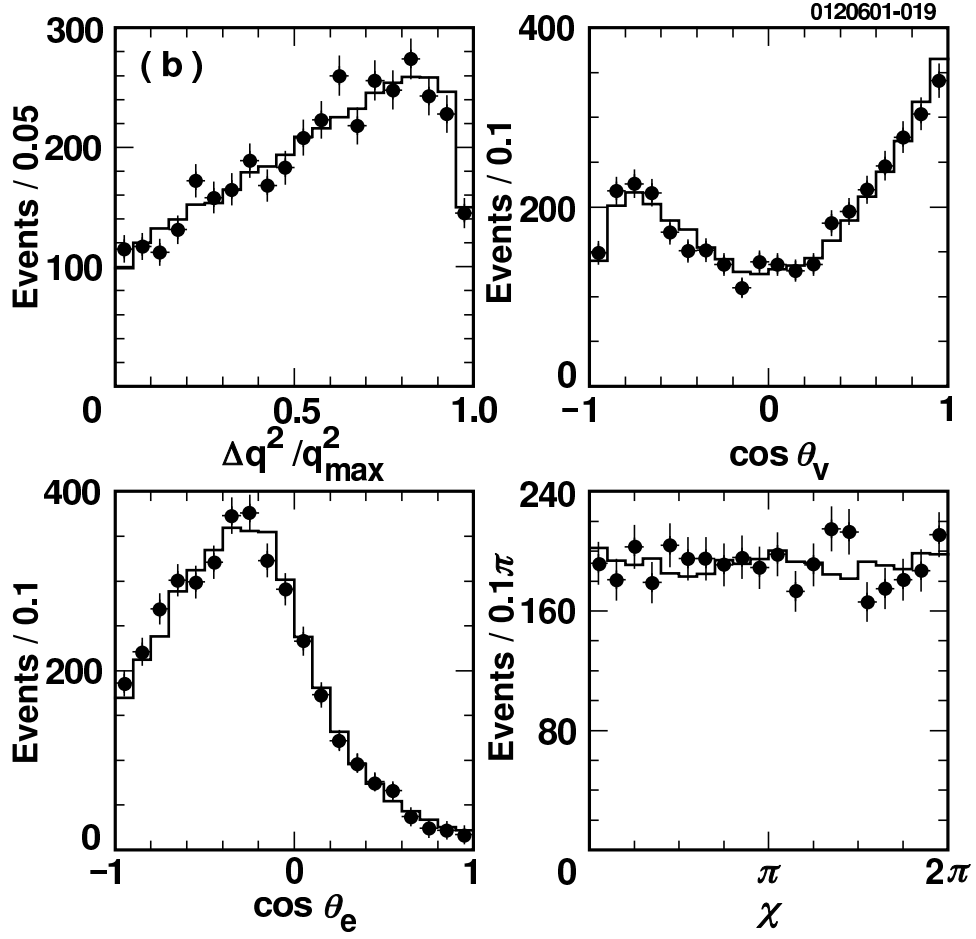


FIGURE 26. Distributions in the kinematic variables for the decay $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$. Projections of Monte Carlo ‘data’ (points with error bars) and the fit function (solid histogram) onto $\cos\theta_e$, q^2/q_{max}^2 , χ and $\cos\theta_V$. The simulation, which uses the ISGW model, corresponds to an integrated luminosity of 1 fb^{-1} .

TABLE 11. Status of current knowledge of inclusive charm semileptonic branching fractions and the improvement expected with CLEO-c with 3 fb^{-1} . The CLEO-c measurements include a common systematic error of 0.8%.

Mode	$\mathcal{B}(\% \text{ PDG2000})$	$\frac{\Delta\mathcal{B}}{\mathcal{B}}(\% \text{ PDG2000})$	CLEO-c (3 fb^{-1}): $\frac{\Delta\mathcal{B}}{\mathcal{B}}(\%)$
$D^0 \rightarrow e^+ X$	6.8 ± 0.3	4.4	0.8
$D^+ \rightarrow e^+ X$	17.2 ± 1.9	11.0	0.8
$D_s \rightarrow e^+ X$	8_{-5}^{+6}	63	1.7
$\Lambda_c \rightarrow e^+ X$	4.5 ± 1.7	38	5.1

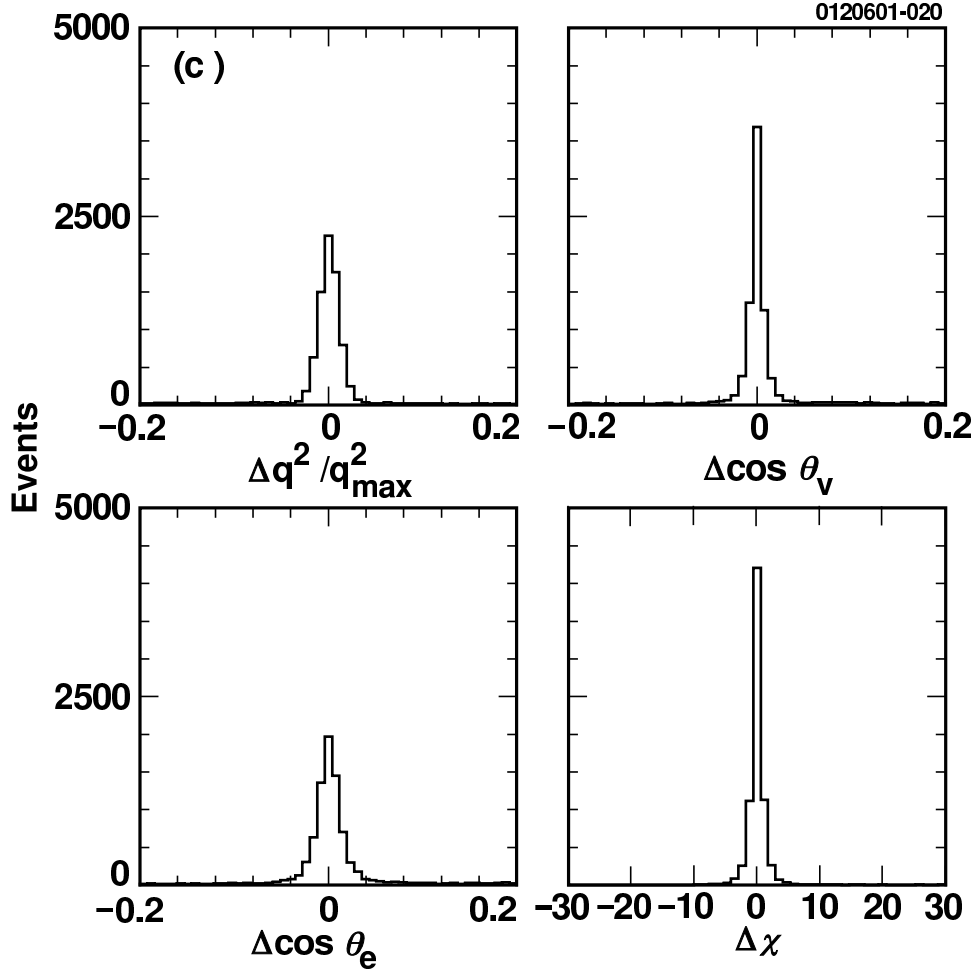


FIGURE 27. The resolutions in q^2 and the three variables, $\cos \theta_K$, $\cos \theta_e$ and χ defined in the Figure 24 for the decay $D^+ \rightarrow \rho^0 e^+ \nu$.

TABLE 12. Status of current knowledge of inclusive semileptonic charm semileptonic widths and the improvement expected with CLEO-c with 3 fb^{-1} . The CLEO-c measurements include a common systematic error of 0.8%.

Mode	$\Gamma(10^{-2}\text{ps}^{-1})$	$\frac{\Delta\Gamma}{\Gamma}(\%)$	CLEO-c (3 fb^{-1}): $\frac{\Delta\Gamma}{\Gamma}(\%)$
$D^0 \rightarrow e^+ X$	16.4 ± 0.7	4.4	1.4
$D^+ \rightarrow e^+ X$	16.4 ± 1.8	11.0	1.1
$D_s \rightarrow e^+ X$	16.1 ± 10.1	62.7	2.8
$\Lambda_c \rightarrow e^+ X$	21.8 ± 8.4	38.5	7.7

transitions is expected to exhibit different behavior for the three mesons, since in D_s and

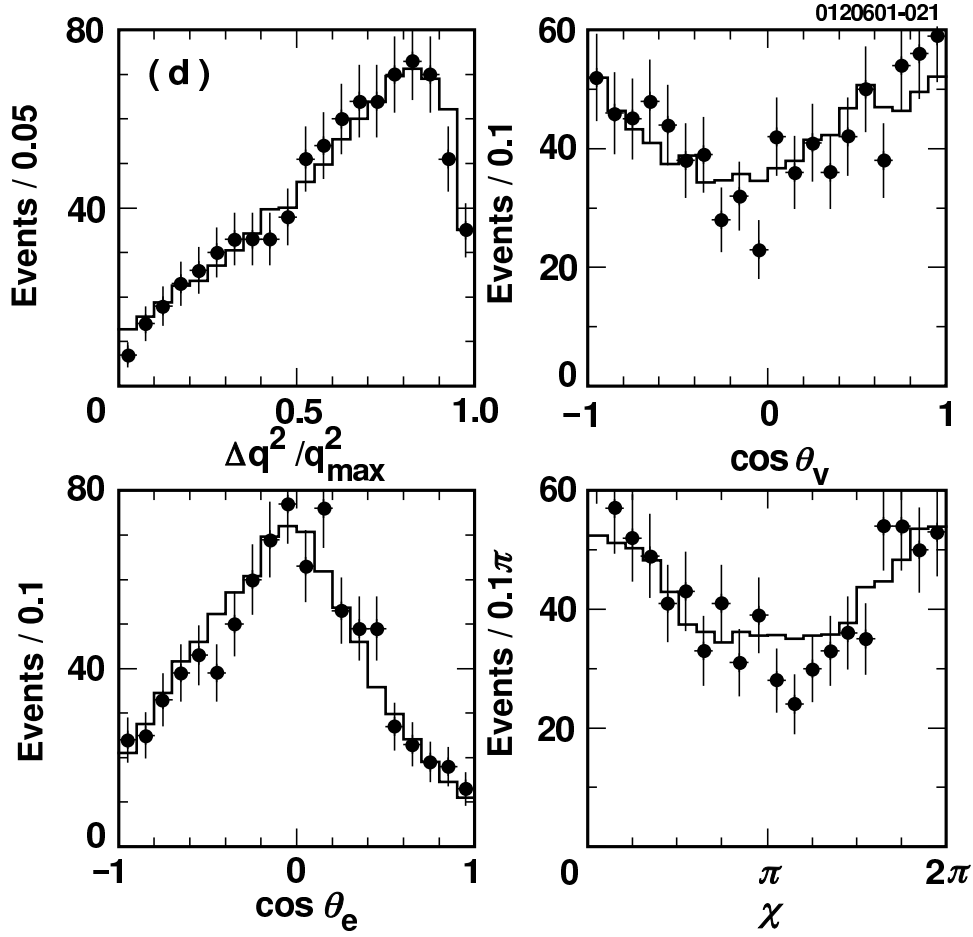


FIGURE 28. Distributions in the kinematic variables for the decay $D^+ \rightarrow \rho^0 e^+ \nu$. Projections of Monte Carlo ‘data’ (points with error bars) and the fit function (solid histogram) onto $\cos\theta_e$, q^2/q_{max}^2 , χ and $\cos\theta_V$. The simulation, which uses the ISGW model, corresponds to an integrated luminosity of 1 fb^{-1} .

D^+ decays one has contributions from weak annihilation (WA) that are Cabibbo allowed in the former and suppressed in the latter case. Semileptonic D^0 decays should not be sensitive to WA. Semileptonic Λ_c decays differ from semileptonic D decays through non-perturbative corrections of order $1/m_c^2$ and $1/m_c^3$.

Spectra have three advantages compared to semileptonic branching fractions as a probe of theory: First, the theoretical interpretation is cleaner as spectra are independent of the hadronic width. Second, spectra contain shape and rate information. Third, non-perturbative effects are pronounced in the lepton endpoint region. Figure 29 (left) is the inclusive electron spectrum from $D^+ \rightarrow X e^+ \nu$. The upper line shows the generated electron spectrum. The second line shows the CLEO-c measured spectrum using one fully reconstructed D meson as a tag, corresponding to an integrated luminosity of 3 fb^{-1} . The individual contributions to the measured spectrum from the final states $\bar{K}^{*0} e^+ \nu$, $\rho^- e^+ \nu$, $\pi^0 e^+ \nu$ and $\bar{K}^0 e^+ \nu$ are shown. Cabibbo allowed non-resonant contributions are included in

the generator, but are not explicitly shown on Figure 29. The measured spectrum cuts off at 300 MeV/ c in this study. From this figure one is able to obtain an estimate of how well the shape of the spectrum can be measured. Figure 30 shows the generator level spectra for $D^+ \rightarrow Xe^+\nu$, $D^0 \rightarrow Xe^+\nu$ and $D_s \rightarrow Xe^+\nu$ overlaid. The three spectra are normalized. In order to differentiate between the three spectra a fit would be performed to each measured spectrum.

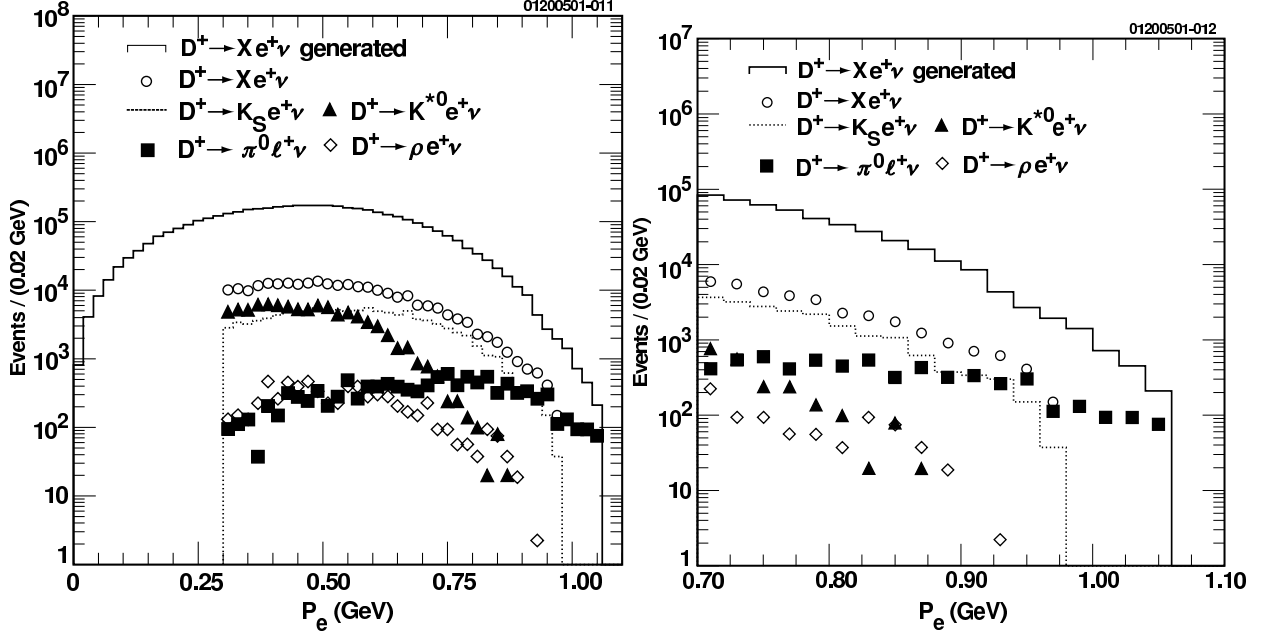


FIGURE 29. (Left) the inclusive spectrum for $D^+ \rightarrow Xe^+\nu$. The upper line shows the generated electron spectrum. The second line shows the CLEO-c measured spectrum corresponding to an integrated luminosity of 3 fb^{-1} . The individual contributions to the measured spectrum from the final states $\bar{K}^{*0}e^+\nu$, $\rho^-e^+\nu$, $\pi^0e^+\nu$ and $\bar{K}^0e^+\nu$ are shown. Cabibbo allowed non-resonant contributions are included in the generator but are not explicitly shown in the figure. The measured spectrum cuts off at 300 MeV/ c in this study. (Right) enlargement of momentum scale to better show the endpoint region of the inclusive electron spectrum.

This study has not yet been carried out. As a crude estimate of the sensitivity, one can take the observed yields for the D^+ and calculate by how much the corresponding yield for the D^0 in the same momentum bin must differ for the difference in yields to be statistically significant. With an integrated luminosity of 3 fb^{-1} a difference in yields of 3% could be measured with four sigma significance in a 0.1 GeV bin. Figure 29 (right) is an enlargement of the endpoint region. The endpoint region is dominated by leptons from Cabibbo suppressed decay modes. The endpoint is the most sensitive region to search for non-perturbative effects but the statistics are, however, much reduced in that region. Rate measurements in the end point will be possible to better than 10 per cent.

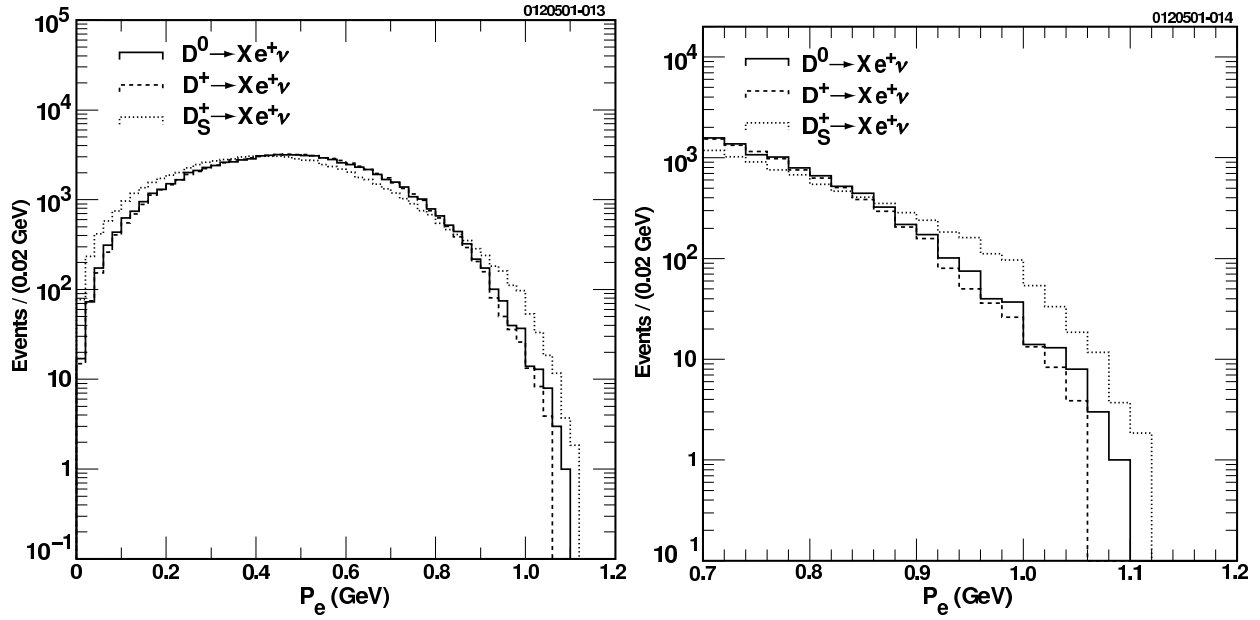


FIGURE 30. The generator level spectra for $D^+ \rightarrow X e^+ \nu$ and $D^0 \rightarrow X e^+ \nu$ and $D_s \rightarrow X e^+ \nu$ overlaid. The three spectra are normalized to the same area.

3.4.4 Summary

Charm semileptonic decays are an excellent laboratory in which to study both weak physics and QCD physics. CLEO-c offers the first opportunity to fully measure and exploit both of these facets of charm semileptonic decays. As a tool to understand non-perturbative QCD, CLEO-c is the only experiment that will be able to measure the form factors in all the D to pseudoscalar and vector transitions. This will allow decisive tests of all the theoretical approaches that describe exclusive semileptonic decays. Measurements of the inclusive electron spectrum CLEO-c will also allow tests the framework for inclusive semileptonic decays. Testing the theoretical description of semileptonic decays in the charm sector is an essential step in applying the same theoretical description, coupled with Heavy Quark Symmetry, to B decays. Finally, semileptonic charm decays will allow CLEO-c to make order of magnitude improvements in the precision with which $|V_{cs}|$, $|V_{cd}|$, and $|V_{cd}|/|V_{cs}|$ are known.

3.5 Absolute Hadronic Charm Meson Branching Fractions

The absolute branching fractions for D decay modes will be measured accurately using the numbers of single-tag and double-tag D candidates. To illustrate the statistical precision that can be obtained we used a simplified version of the method used by MARK III [2].

To obtain double-tag events, we combine the single tags described in Section 3.2 to make double-tag candidates. Then we:

- require that the flavor-defining charge of the second candidate in an event be opposite to that of the first candidate;
- require that there be no shared tracks or showers between the two candidates;

TABLE 13. Double tag rates and double tagging efficiencies for $D^0\bar{D}^0$ and D^+D^- double tags from 1 fb^{-1} of simulated data for each D species at 3.77 GeV. The first line for each combination of modes gives the numbers of reconstructed events. The second line gives the reconstruction efficiencies for the double tag. The third line gives estimates of the number of fake events in the signal region.

$D^0\bar{D}^0$				
Mode	$K^+\pi^-$	$K_S^0\pi^0$	$K^+\pi^-\pi^0$	$K^+\pi^-\pi^+\pi^-$
$K^-\pi^+$	1,500	604	10,251	5,255
	17.7%	19.2%	16.7%	15.4%
	<i>0</i>	<i>26</i>	<i>16</i>	<i>57</i>
$K_S^0\pi^0$		55	2,242	1,162
		17.9%	19.2%	17.9%
		<i>7</i>	<i>135</i>	<i>94</i>
$K^-\pi^+\pi^0$			18,289	18,571
			16.3%	15.1%
			<i>64</i>	<i>327</i>
$K^-\pi^+\pi^+\pi^-$				4,946
				14.6%
				<i>148</i>
D^+D^-				
Mode	$K^+\pi^-\pi^-$	$K_S^0\pi^-\pi^0$	$K^+\pi^-\pi^-\pi^0$	
$K^-\pi^+\pi^+$	8,446	4,344	7,135	
	25.1%	16.2%	14.6%	
	<i>25</i>	<i>194</i>	<i>57</i>	
$K_S^0\pi^+\pi^0$		521	1,736	
		10.0%	9.1%	
		<i>40</i>	<i>120</i>	
$K^-\pi^+\pi^+\pi^0$			1,498	
			8.7%	
			<i>86</i>	

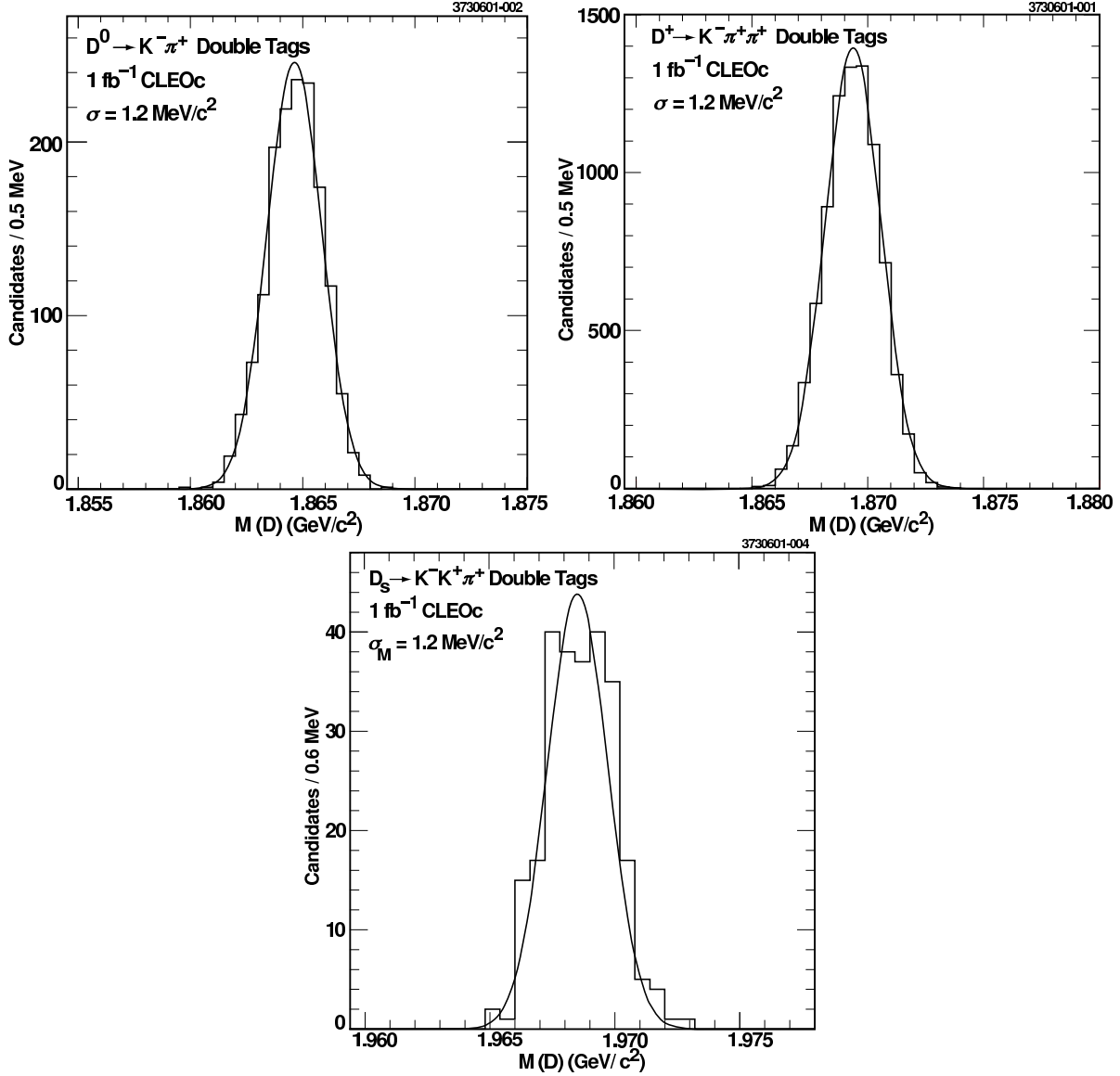


FIGURE 31. Reconstructed D mass for $D^0 \rightarrow K^- \pi^+$ (top left), $D^+ \rightarrow K^- \pi^+ \pi^+$ (top right), and $D_s^+ \rightarrow K^- K^+ \pi^+$ (bottom) double tags. Distributions show candidates after another tag of opposite charge has been found in the event as described in Section 3.2.

- set the energy $E(D)$ and mass $M(D)$ of each candidate to the the beam energy and the PDG [11] mass value, respectively;
- use the momentum errors and kinematic constraints to obtain candidate momenta consistent with the candidate mass and beam energy; and
- require that the angle between the momenta of the two candidates be larger than 170° .

The signal yields, efficiencies and backgrounds for a variety of double tag modes are listed in Table 13 and Table 14. Examples of double tag mass distributions of the simplest modes are shown in Figure 31. Generally the efficiency for double tags is well approximated by the

product of the efficiencies for the two contributing single tags.

TABLE 14. Double tag rates and double tagging efficiencies for $D_s^+ D_s^-$ double tags from 1 fb^{-1} of simulated data at 4.028 GeV. The first line for each combination of modes gives the numbers of reconstructed events. The second line gives the reconstruction efficiency for the double tag. The third line gives estimates of the number of fake events in the signal region. The “not included in” sign ($\notin$) indicates that the final state is *not used* in the absolute branching fraction measurement due to the large fake rate.

$D_s^+ D_s^-$					
Mode	$K^- K^+ \pi^-$	$K^- K^+ \pi^- \pi^0$	$\eta \pi^-$	$\eta \rho^-$	$\eta' \pi^-$
$K^- K^+ \pi^+$	251 16.9% 8	192 6.6% 22	146 16.0% 4	592 10.9% 64	170 11.5% 1
$K^- K^+ \pi^+ \pi^0$		52 $\notin$ 3.2% 23	90 9.0% 10	284 $\notin$ 5.0% 118	88 5.9% 4
$\eta \pi^+$			23 17.4% 2	191 11.6% 37	40 9.0% 0
$\eta \rho^+$				284 $\notin$ 5.6% 119	197 7.3% 22
$\eta' \pi^+$					25 6.7% 4

To measure the absolute D branching fractions we can use all double tags listed in the tables. However, the statistics are so large in the case of D^0 and D^+ that we choose to minimize our systematic errors by using only the simplest decay modes as part of the double tagged sample. For D^0 we use only the $K^- \pi^+$ mode and for D^+ we use only the $K^- \pi^+ \pi^+$ mode. Thus the event samples for D^0 and D^+ are given in the first rows for each species in Table 13.

For D^0 we have two distinct advantages: the backgrounds are very small due to the presence of the clean $K^- \pi^+$ decay and there are only two charged tracks in the $K^+ \pi^-$ final state so the efficiency can easily be determined. In fact, using the missing mass technique described in section 2.6 we can measure the efficiency with an accuracy of $\pm 0.2\%$ per track, resulting in a systematic error on the efficiency of $\sim 0.4\%$.

In the case of the D^+ we use the $K^-\pi^+\pi^+$ mode. Here the systematic error on the efficiency is $\sim 0.6\%$. In the case of the D_s^+ it is necessary to use most of the tags. The ones used are indicated by check marks in Table 14. The ones not used have a signal to background ratio high enough to allow the precision of the background to become an important source of error. Determination of the relative branching ratios of these modes using the single tag events is necessary in this case and we have included the errors expected here as part of the systematic uncertainty.

Table 15 gives the resulting event sample and the relevant errors. The errors due to the background are determined by assuming that the background level is known to $\pm 10\%$. The precision on the absolute branching fractions is below 1% for D^0 and D^+ and about 2% for D_s^+ .

TABLE 15. Total number of double tag events and statistical precisions on absolute charm branching fractions for 3 fb^{-1} of data for each type of D meson.

Particle	# of Double tags	Statistical Error	Systematic Error	Background Error	Total Error
D^0	53,000	0.4%	0.4%	0.06%	0.6%
D^+	60,000	0.4%	0.6%	0.1%	0.7%
D_s^+	6,000	1.3%	1.1%	0.9%	1.9%

3.6 Charm Baryon Decays

10 GeV center-of-mass e^+e^- annihilation has proved to be the most fertile of the accelerator choices for charmed baryon studies in the past decade. However, there are some measurements that are not easily made in this energy regime, and which are essential for our further understanding of the charm baryon sector. For example, there have been many different Λ_c^+ decay modes measured, but they are always measured as branching ratios with respect to $\Lambda_c^+ \rightarrow pK^-\pi^+$. There have been attempts to measure the absolute branching fraction of this decay mode, but any such measurement relies upon some estimate of the total number of Λ_c^+ baryons in the sample. These estimates depend at least in part on Monte Carlo modeling of the production mechanisms of charmed baryons, and this brings in systematic uncertainties which limit the accuracy of the measurement even if a huge data sample is available. With a lower center of mass energy these problems can be avoided. The most direct method of measuring Λ_c^+ branching fractions is to run a little above the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold. Every event at this energy found to contain a Λ_c^+ or $\bar{\Lambda}_c^-$ must necessarily contain its antiparticle. The systematic uncertainties are then limited by the Monte Carlo calculation of the efficiency, and the model dependence is small.

The cross-section for $\Lambda_c^+\bar{\Lambda}_c^-$ production at 4.6 GeV can be estimated by Monte Carlo simulation, using a generator that represents the data well at 10.6 GeV. In 1 fb^{-1} of data the Monte Carlo predicts 270,000 $\Lambda_c^+\bar{\Lambda}_c^-$ pairs produced. This energy range was investigated by the MARK II detector at SPEAR. They published a branching fraction times cross section

of 0.037 ± 0.012 nb for $\Lambda_c^+ \rightarrow pK^-\pi^+$. Assuming a branching fraction of 5% (which is the Particle Data Group's latest average [11]), this translates into 370,000 $\Lambda_c^+\bar{\Lambda}_c^-$ pairs. For convenience, we will assume a production of a total 600,000 Λ_c^+ and $\bar{\Lambda}_c^-$ baryons in 1 fb^{-1} of data.

Of the large number of decay modes of the Λ_c^+ detected by CLEO, $pK^-\pi^+$ has both the largest branching fraction and the highest efficiency. Monte Carlo studies using the CLEO-III geometry and $\sqrt{s} = 4.6$ GeV indicate a detection efficiency of 45%. All the decay products will be in a momentum range where particle identification is straightforward. The two next 'best' decay modes for detection at these energies are $\Lambda\pi^+$ and $p\bar{K}^0$. Together these should add around 25% to the yield of reconstructed Λ_c^+ candidates. Again assuming a 5% branching fraction for $\Lambda_c^+ \rightarrow pK^-\pi^+$, the number of reconstructed charmed baryons will be around 17,000, and backgrounds are expected to be low. The number of fully reconstructed $\Lambda_c^+\bar{\Lambda}_c^-$ events will be around 500; here backgrounds will be minimal and the statistical error will thus be $\sqrt{500} = 22$, and the branching fraction can be found with an accuracy of $\sim 4\%$ of itself. These numbers are by necessity rough, as neither the cross section nor the branching fraction into $pK^-\pi^+$ are known. The systematic uncertainty will be dominated by track finding uncertainties and should not be a limiting factor in the analysis.

A large sample of reconstructed Λ_c candidates in events at 4.6 GeV will also allow for other measurements that are not possible in other environments. These include inclusive studies, such as $\Lambda_c^+ \rightarrow \Lambda X$ and $\Lambda_c^+ \rightarrow pX$, and checks that the sum of all detected decay modes is unity. Furthermore, studies will be possible of the mechanism of semi-leptonic Λ_c^+ decays. At present only studies of the decay $\Lambda_c^+ \rightarrow \Lambda l\nu$ have been possible and it is not known what fraction of the total semi-leptonic rate this represents. In short, running at around 4.6 GeV gives a unique opportunity to study in depth the complete decay characteristics of the Λ_c^+ .

3.7 Charm Beyond the Standard Model

3.7.1 Mixing and CP Violation

Mixing and CP violation in charm decays are expected to be highly suppressed in the Standard Model. "All the more reason to study them, of course," as Jonathan Rosner wrote very succinctly [23].

The study of neutral flavor oscillations in the D meson system is a wonderful low energy phenomenon to pursue. In general, neutral D hadronic decays are affected both by mixing and doubly Cabibbo suppressed (DCSD) amplitudes. As explained in Chapter II, the mixing matrix introduces two parameters: ΔM represents the mass difference of the two eigenstates of the mixing matrix and $\Delta\Gamma$ represents their width difference. In general, the time evolution of a particle produced as a D^0 or a $\bar{D}^0$ is governed by four parameters: $x \equiv \Delta M/\bar{\Gamma}$, $y \equiv \Delta\Gamma/2\bar{\Gamma}$, characterizing the flavor oscillation matrix, δ , the difference between 'right-sign' and 'wrong-sign' strong phases in the $K^-\pi^+$ system and r represents the ratio between the DCSD and Cabibbo favored (CF) amplitudes. Recent data from CLEO [24] and FOCUS [25] hint that the phase δ may be big [26]. Frequently, the mixing parameter r_D is used, being defined as the ratio of the number of events exhibiting mixing to the number of events not exhibiting mixing. Integrating over time we have $r_D = [x^2 + y^2]/2$.

Standard Model based predictions, as well as a variety of non-Standard model expecta-

tions, span several orders of magnitude [27]. It is reasonable to assume $r_D \approx 10^{-6}$ in the Standard Model, with $x \approx y \approx 10^{-3}$ [28]. While CLEO-c does not have the sensitivity to measure x and y if they are governed by Standard Model physics, we have some discovery potential if new physics intervenes and indeed some of the ‘beyond the Standard Model’ calculations predict significant enhancements [27]. The parameter driving the enhancement predicted by some ‘beyond the Standard Model’ theories is x ; thus individual determination of x and y would be an important element of our ability to confirm the physics origin of any observation.

Similarly, Standard Model CP violation is strongly suppressed in charm. As in B decays, CP violation can manifest itself through mixing (indirect CP violation), in the decay (direct CP violation) or as a combination of both terms. While theoretical predictions have significant uncertainties, Standard Model CP violation asymmetries are expected to be of the order of 10^{-3} for neutral D^0 decays, and as high as 10^{-2} in some D^+ and D_s decays [29].

Experimental studies of mixing and CP violation take advantage of complementary information from neutral D ’s produced at the $\psi(3770)$ and at the $\psi(4140)$ center-of-mass energy. The former sample consists of 1.7×10^7 $D^0 \bar{D}^0$ pairs. It is difficult to make precise predictions of the expected sensitivity of studies of the $\gamma D^0 \bar{D}^0$ sample from the $\psi(4140)$, due to the lack of precise data on the production cross-section. Assuming the same cross-sections used in previous studies [30], we predict 2.7×10^6 $\bar{D}^0 D^{*0}$ pairs in 3 fb^{-1} , corresponding to 1.6×10^6 $D^0 \bar{D}^0 \pi^0$ and 1.0×10^6 $D^0 \bar{D}^0 \gamma$ events. These data will allow us to make several $\mathcal{O}(1\%)$ sensitivity mixing and CP violation studies.

3.7.1.1 $D^0 \bar{D}^0$ Mixing: Experimental Techniques

Unambiguous signatures for $D^0 \bar{D}^0$ mixing can in principle be found exploiting the quantum coherence of the initial states produced at the $\psi(3770) \rightarrow D^0 \bar{D}^0$ and $\psi(4140) \rightarrow \gamma D^0 \bar{D}^0$. A detailed analysis of the quantities that can be studied at these two resonances has been performed recently by Gronau, Grossman and Rosner [31], who lay out a comprehensive road map for a systematic study of the decays of $C = -1$ $D^0 \bar{D}^0$ pairs, including $D^0 \bar{D}^0$ or $\pi^0 D^0 \bar{D}^0$, and $C = +1$ $D^0 \bar{D}^0$ pairs, produced as $\gamma D^0 \bar{D}^0$. The final states considered, as well as theoretical predictions for their decay widths are summarized in Table 16.

Of particular interest is a class of final states including one D meson decaying into $K\pi$ and the other decaying into a CP eigenstate S_ζ (we denote a generic CP eigenstate as S_ζ , where ζ denotes the CP eigenvalue). The CP eigenstates accessible to CLEO-c measurements are summarized in Table 17 together with the rates expected in 3 fb^{-1} for the $C = -1$ ψ'' and $C = +1$ $\gamma D^0 \bar{D}^0$ data sets. The study of these final states can be performed with high efficiency by exploiting the simplicity of the final state, including two energetic charged tracks (the $K^-\pi^+$ system) and the CP eigenstate. We do not need to fully reconstruct the latter, since we can employ a missing mass technique similar to the one described previously in the section summarizing our reach for f_{D_s} and f_{D^+} . In particular, for the modes involving K_S the final state is identified by requiring that the meson recoiling against the $K^-\pi^+ K_S$ combination has an invariant mass consistent with the final state assumed. Note that $\Gamma^-(K^-\pi^+, S_\zeta)$ is proportional to $1 + 2\zeta r \cos \delta$, where $\zeta = \pm 1$ is the CP eigenvalue of the final state S_ζ . By comparing the rates with $\zeta = +1$ and $\zeta = -1$ and using independent determinations of r ,

the phase δ can be determined. An asymmetry $\mathcal{A}$ can be defined as:

$$\mathcal{A} \equiv \frac{\Gamma^{(-)}(S_+) - \Gamma^{(-)}(S_-)}{\Gamma^{(-)}(S_+) + \Gamma^{(-)}(S_-)} = 2r \cos \delta. \quad (16)$$

The asymmetry $\mathcal{A}$ is expected to be small. Thus we have:

$$\Delta(\cos \delta) \approx \frac{1}{2r\sqrt{N}}, \quad (17)$$

where N is the total number of CP tagged $K^-\pi^+$ from the $C = -1$ initial state. From the results in Table 17, we expect the total number N to be about 32,000, thus leading to an expected accuracy of about ± 0.05 in $\cos \delta$.

TABLE 16. Decay widths for $D^0\bar{D}^0$ decays. Mixing appears through x, y and the strong phase δ ; $\tilde{y} = y \cos \delta + x \sin \delta$, $y' = y \cos \delta - x \sin \delta$, r is the DCSD/CF ratio; $\langle K^-\pi^+ | D^0 \rangle \equiv A \exp i\delta_R$, $\langle K^-\pi^+ | \bar{D}^0 \rangle \equiv \bar{A} \exp i\delta_W$, $\delta \equiv \delta_R - \delta_W$, S_ζ and A_{S_ζ} are the amplitude and the CP eigenvalue, respectively, for D^0 decays to specific eigenstates.

Final state	$\Gamma(C = -1)$	$\Gamma(C = +1)$
$K^-\pi^+(\hat{p})K^-\pi^+(-\hat{p})$	$A^4(x^2 + y^2)/2$	$4A^4 \left[r^2 + ry' + \frac{3}{8}(x^2 + y^2) \right]$
$K^-\pi^+(\hat{p})K^+\pi^-(-\hat{p})$	$A^4 \left[1 - 2r^2 \cos 2\delta - \frac{1}{2}(x^2 - y^2) \right]$	$A^4 \left[1 + 2r^2 \cos 2\delta + 4r\tilde{y} - \frac{3}{2}(x^2 - y^2) \right]$
$K^-\pi^+(\hat{p})S_\zeta(-\hat{p})$	$A^2 A_{S_\zeta}^2 (1 + 2\zeta r \cos \delta)$	$A^2 A_{S_\zeta}^2 (1 - 2\zeta y)$
$K^-\pi^+(\hat{p})\ell^-(-\hat{p})$	$A^2 A_{\ell^-}^2 \left[1 - \frac{1}{2}(x^2 - y^2) \right]$	$A^2 A_{\ell^-}^2 \left[1 + 2r\tilde{y} - \frac{3}{2}(x^2 - y^2) \right]$
$K^-\pi^+(\hat{p})\ell^+(-\hat{p})$	$A^2 A_{\ell^+}^2 \left[r^2 - \frac{1}{2}(x^2 + y^2) \right]$	$A^2 A_{\ell^+}^2 \left[r^2 + 2ry' + \frac{3}{2}(x^2 + y^2) \right]$
$S_\zeta(\hat{p})\ell^+(-\hat{p})$	$A_{\ell^+}^2 A_{S_\zeta}^2 (1 + y^2)$	$A_{\ell^+}^2 A_{S_\zeta}^2 (1 - 2\zeta y + 3y^2)$

The measurement of r_D can be performed unambiguously considering the decays $\psi'' \rightarrow K^-\pi^+K^-\pi^+$ and $\psi'' \rightarrow \ell^\pm(KX)^\mp\nu\ell^\pm(KX)^\mp\nu$. The hadronic final state cannot be produced from DCSD due to a quantum statistics argument, because the odd C initial state cannot produce the symmetric final state required by Bose statistics if both D^0 and $\bar{D}^0$ decay into the same final state ($K^-\pi^+$). This final state is also very appealing from the experimental point of view, because it involves a 2-body decay from both the charm mesons, with energetic charged particles in the final state that form an overconstrained system. A fit utilizing 6 constraints can improve the selection criteria for this channel, making it absolutely background free. Moreover we have demonstrated previously that the particle identification provided by the RICH detector makes this channel completely free from the otherwise dominant background produced by doubly-misidentified decays. The double semileptonic channel has less kinematics constraints because of the lack of information on the neutrino 4-vectors. However the semileptonic studies discussed before give a good indication that the level of background expected in this channel is also negligible. The number of right-sign events in

TABLE 17. Estimate of the number of CP Eigenstates reconstructed with the technique described in the text in data samples of 3 fb^{-1} of $\psi(3770)$ and $\gamma D^0 \bar{D}^0$ data sets.

Eigenstate	CP	$N_{tags}(C = -1)$	$N_{tags}(C = +1)$
$K_S^0 \rho^0$	-1	98,400	8,400
$K_S^0 \eta$	-1	61,600	5,300
$K_S^0 \phi$	-1	68,700	5,900
$K_S^0 \pi^0$	-1	176,000	15,000
$K_S^0 \omega$	-1	290,600	24,000
$K_S^0 \eta'$	-1	140,900	12,000
$\rho^0 \pi^0$	+1	54,200	4,600
$\pi^+ \pi^-$	+1	35,800	3,000
$K^+ K^-$	+1	110,000	9,400

the two channels combined, produced in 3 fb^{-1} , is expected to be about 60,000 corresponding to $\sqrt{r_D} \leq 1\%$ at 95% C.L.

The investigation of mixing parameters at the $\psi(4140)$ provides valuable complementary constraints and represents a useful consistency check. Note that the final state $K^- \pi^+ K^- \pi^+$ and $K^- \pi^+ \ell^+$ from the $C = +1$ initial state have a decay width proportional to ry' . Since r is bigger than x or y , the determination of y' from $C = +1$ initial states has comparable sensitivity as the measurements from the higher statistics $C = -1$ initial state.

$D^0 \bar{D}^0$ flavor oscillations are an exciting laboratory to study physics beyond the Standard Model. While the facility that we are proposing will not reach the level of sensitivity to probe the Standard Model predictions, it represents an excellent opportunity to measure new physics unambiguously related to mixing parameters.

3.7.1.2 CP Violation in $D^0 \bar{D}^0$ Decays: Experimental Techniques

If the $D^0 \bar{D}^0$ pair is produced in a $C = -1$ initial state, a final state involving two CP eigenstates with the same CP eigenvalue is an unambiguous manifestation of CP violation. Table 18 gives estimates for the total number of events that would be observed for maximal CP violation. The numbers are not large, but the experiment is essentially background free, since we are looking for a rate into final states that are over-constrained. Moreover this method is important because it has unique sensitivity to the quantum mechanical phase in the amplitude.

The coherent nature of the wave function prevents measurements of time integrated mixing induced CP asymmetries from a CP-odd initial state like $D^0 \bar{D}^0$ pairs produced at the $\psi(3770)$. Thus at this energy non-zero time integrated asymmetries would be a manifestation of direct CP violation. The expected sensitivity for direct CP violation is summarized in Table 19.

TABLE 18. Rates for Direct CP Violation in $\psi(3770) \rightarrow (\text{CP Eigenstate1}) (\text{CP Eigenstate2})$.

CP Eigenstate 1	CP Eigenstate 2	Events for 100% CP
$K^+ K^-$	$K^+ K^-$	174
$K^+ K^-$	$\rho^0 \pi^0$	171
$K_S^0 \pi^0$	$K_S^0 \pi^0$	183
$K_S^0 K_S^0$	$K^+ K^-$	136

TABLE 19. Direct CP Violation asymmetry $\delta\mathcal{A}$ reach from $\psi(3770) \rightarrow \ell \text{ } CP\text{eigenstate}$.

CP Eigenstate	flavor tagged sample	$\delta\mathcal{A}$
$K^+ K^-$	10,200	0.01
$K_S^0 \pi^0$	10,400	0.01
$K_S^0 \omega$	3,500	0.02

On the other hand, CP-even initial states, like the ones produced in $\psi(4140) \rightarrow \gamma D^0 \bar{D}^0$, are amenable to time integrated CP asymmetries that are non-vanishing and depend only linearly on the mixing parameter x . In this case we have a smaller statistical accuracy and we expect an overall sensitivity of the order of 3%. This estimate has been obtained by considering only lepton flavor tagging. Improvements can be obtained by including K flavor tags. Backgrounds are expected to be modest and to have a negligible effect on the measured asymmetries, in agreement with previous studies [32], [30].

In conclusion several CP violation observables are amenable to our investigation, some of them unique to this experimental approach. Note that the studies described in this Section are only some examples of the many search strategies [33] that can be pursued. In particular, Dalitz plot analyses uncover interference effects that are sensitive probes of CP violating phases. Although some of these measurements can be performed with comparable accuracy at the B Factories, the number of studies that can be performed at this center-of-mass energy range is very broad and includes some unique measurements exploiting the quantum coherence of the initial state. Thus we have an opportunity to make exciting discoveries.

3.7.2 Rare Charm Decays

As was discussed in Chapter II, rare decays of charmed mesons and baryons provide probes of new physics effects that are essentially free of background. In the framework of the Standard Model (SM) these processes occur only at one loop level with vanishingly small branching

ratios because of the almost perfect GIM cancellation between the contributions of s and d quarks. New Physics (NP) effects, on the other hand, need not be suppressed and many models of NP, including supersymmetric extensions of the SM, either involve heavy particles that need not suffer from GIM-type cancellations or include other mechanisms that give appreciable contribution to flavor-changing neutral currents in D decays.

Monte Carlo studies have been done to estimate detection efficiencies for single tracks, π^0 's and η 's. Based on this we can make rough estimates of sensitivities to various rare decay modes, such as those shown in Tables 20 and 21.

Table 20 shows the current experimental status as well as projected sensitivities for a collection of rare D^0 decays. The first set of three columns represents the best limit currently available from an e^+e^- experiment running at or near the $\Upsilon(4S)$ resonance. The second set of three columns shows cases where the best limit was not obtained on the $\Upsilon(4S)$. The second to last column is an estimate of the sensitivity of an e^+e^- experiment with 400 fb^{-1} of integrated luminosity at or near the $\Upsilon(4S)$, based on the efficiencies and background levels found by CLEO, and the final column shows the projected CLEO-c limits based on Monte Carlo estimates of efficiency and tagging rates, and assuming an integrated luminosity of 3 fb^{-1} on the $\psi(3770)$ with a 10% tagging probability. The assumption is made in all cases that the signal is background free.

Table 21 shows the current experimental status as well as projected sensitivities for a collection of rare D^+ decays. In these cases there are no recent limits available from e^+e^- experiments, hence only the current worlds best measurement and the projected CLEO-c sensitivity (again based on 3 fb^{-1} of integrated luminosity on the $\psi(3770)$) are shown.

Although these estimated limits are quite rough, we can draw some general conclusions based on them. In general, it seems that we will probably end up being very competitive with the B Factory experiments; better in many modes, worse in some, and comparable in others. They will be a valuable part of the overall physics program.

4 Reach for Tau Lepton Physics

In this Section, we explore the capabilities of CLEO-c to carry out some of the measurements in tau lepton physics described in Part II of this document. After characterizing the experimental conditions corresponding to the choice of beam energy, we consider the capabilities in the two broadly defined areas of ‘tau threshold’ measurements and ‘high-statistics’ measurements (nominally in the charm region).

4.1 Experimental Aspects of Tau Physics at CLEO-c

The main issues for a tau physics program at CLEO-c are: (1) sample size, (2) event kinematics, and (3) backgrounds.

TABLE 20. Current and projected 90% CL upper limits on rare D^0 decay modes.

Mode	$\Upsilon(4S)$ CLEO			Best Upper Limit			B-Factory	CLEO-c
	Ref.	UL $\times 10^6$	Evnt	Ref.	UL $\times 10^6$	Evnt	UL $\times 10^6$	UL $\times 10^6$
e^+e^-	[34]	13	0	[35]	6.2		0.6	1.2
$\mu^+\mu^-$	[34]	34	1	[36]	4.1		3.4	1.2
$\mu^\pm e^\mp$	[34]	19	2	[35]	8.1		1.9	1.2
$\pi^0 e^+e^-$	[34]	45	0				1.0	4
$\pi^0 \mu^+\mu^-$	[34]	540	3	[37]	810	2	53	4
$\pi^0 \mu^\pm e^\mp$	[34]	86	2				8.5	4
$\bar{K}^0 e^+e^-$	[34]	110	0				2.6	7
$\bar{K}^0 \mu^+\mu^-$	[34]	670	1	[37]	260	2	46	7
$\bar{K}^0 \mu^\pm e^\mp$	[34]	100	0				2.3	7
ηe^+e^-	[34]	110	0				1.1	10
$\eta \mu^+\mu^-$	[34]	530	0				5.1	10
$\eta \mu^\pm e^\mp$	[34]	100	0				1	10
ρe^+e^-	[34]	100	2	[38]	120	1	9.9	2.5
$\rho \mu^+\mu^-$	[34]	490	1	[37]	230	0	48	2.5
$\rho \mu^\pm e^\mp$	[34]	49	0	[38]	66	1	4.8	2.5
ωe^+e^-	[34]	180	1				17	9
$\omega \mu^+\mu^-$	[34]	830	0				57	9
$\omega \mu^\pm e^\mp$	[34]	120	0				11	9
$K^*(892)^0 e^+e^-$	[34]	140	1	[38]	24	3	14	4
$K^*(892)^0 \mu^+\mu^-$	[34]	1200	1	[38]	47	2	54	4
$K^*(892)^0 \mu^\pm e^\mp$	[34]	100	0	[38]	83	9	6.9	4
ϕe^+e^-	[34]	52	2	[38]	59	0	5.1	5
$\phi \mu^+\mu^-$	[34]	410	0	[38]	31	0	28	5
$\phi \mu^\pm e^\mp$	[34]	34	0	[38]	47	0	3.4	5
$\pi^+\pi^-\pi^0 \mu^+\mu^-$	none			[37]	810	1		6
$\rho\gamma$	[39]	240					26	1.5
$\omega\gamma$	[39]	240					26	8
$\phi\gamma$	[39]	190					21	4
$K^*(892)^0\gamma$	[39]	760					380	12
$\gamma\gamma$								1.2

TABLE 21. Current and projected 90% CL upper limits on rare D^+ decay modes.

Mode	Best Upper Limit		CLEO-c
	Ref.	UL $\times 10^6$	UL $\times 10^6$
$\pi^+ e^+ e^-$	[35]	52	1.5
$\pi^+ \mu^+ \mu^-$	[35]	15	1.5
$\pi^+ \mu^\pm e^\mp$	[35]	34	1.5
$\pi^- e^+ e^+$	[35]	96	1.5
$\pi^- \mu^+ \mu^+$	[35]	17	1.5
$\pi^- \mu^+ e^+$	[35]	50	1.5
$K^+ e^+ e^-$	[35]	200	1.5
$K^+ \mu^+ \mu^-$	[35]	44	1.5
$K^+ \mu^\pm e^\mp$	[35]	68	1.5
$K^- e^+ e^+$	[40]	120	1.5
$K^- \mu^+ \mu^+$	[40]	120	1.5
$K^- \mu^+ e^+$	[40]	130	1.5
$\rho^+ e^+ e^-$			7
$\rho^+ \mu^+ \mu^-$	[37]	560	7
$\rho^+ \mu^\pm e^\mp$			7
$\rho^- e^+ e^+$			7
$\rho^- \mu^+ \mu^+$	[37]	560	7
$\rho^- \mu^+ e^+$			7
$K^*(892)^+ e^+ e^-$			10
$K^*(892)^+ \mu^+ \mu^-$			10
$K^*(892)^+ \mu^\pm e^\mp$			10
$K^*(892)^- e^+ e^+$			10
$K^*(892)^- \mu^+ \mu^+$	[37]	850	10
$K^*(892)^- \mu^+ e^+$			10

4.1.1 Sample Sizes

The lowest order Born cross section for τ -pair production is

$$\sigma_{\tau\tau}^{(0)} = \frac{4\pi\alpha^2}{3s} \frac{(3\beta - \beta^3)}{2}. \quad (18)$$

In practice, this is modified by radiative effects as well as the finite beam energy spread characteristic of the storage ring in which the collisions are taking place. The cross section turns on rapidly at threshold, reaching a maximum of ~ 3.6 nb at $\sqrt{s} = 4.25$ GeV before beginning its asymptotic $1/s$ dependence at higher energies.

In this report, two sets of running conditions are considered:

- short, dedicated running in the tau threshold region where, at $\sqrt{s} = (2m_\tau + 3 \text{ MeV}) = 3,557$ MeV, for example, $\sigma_{\tau\tau} \sim 0.4$ nb.
(Running just below the ψ' at $\sqrt{s} \sim 3.67$ GeV, where $\sigma_{\tau\tau} \sim 2.4$ nb, may also be desired.)
- extended multipurpose running in the charm region at the $\psi(3770)$ and around D_s threshold at 4 GeV, where on average $\sigma_{\tau\tau} \sim 3$ nb.

For comparison, the tau-pair production cross section in the vicinity of the $\Upsilon(4S)$ is ~ 0.9 nb. Thus, integrating $\sim 0.25 \text{ fb}^{-1}$ in the tau threshold region (approximately two to four weeks at CESR-c) would lead to a sample of $\mathcal{O}(10^5)$ tau-pair events. Accumulation of 6 fb^{-1} in the charm region would yield roughly 2×10^7 tau pairs. Again for comparison, with 400 fb^{-1} at the $\Upsilon(4S)$, the asymmetric B factories will produce $\sim 4 \times 10^8$ tau pairs. The expected τ -pair samples for CLEO-c are summarized in Table 22.

TABLE 22. Summary of possible CLEO-c $\tau\tau$ samples. The threshold running, listed as $E_{cm} = 3.557$ GeV, would be over a range of energies. Also given are the τ momentum (p_τ) and velocity (β_τ).

$E_{cm}(\text{GeV})$	$\int \mathcal{L} dt \text{ (fb}^{-1}\text{)}$	$\sigma_{\tau\tau}^{(0)} \text{ (nb)}$	$N_{\tau\tau}$	$p_\tau \text{ (GeV)}$	β_τ
3.557	0.25	0.42	$\mathcal{O}(10^5)$	0.07	0.04
3.770 (ψ'')	3.0	2.95	0.9×10^7	0.63	0.33
4.14 ($D_s^+ D_s^-$)	3.0	3.56	1.1×10^7	1.06	0.51

4.1.2 Event Kinematics

The kinematics in τ -pair events at low energies depend strongly on $\sqrt{s}$. In the threshold region, tau leptons are produced nearly at rest. In the charm region, the tau's are not fully relativistic (see Table 22), and the energy spectra of the decay particles are Doppler-broadened versions of the ones at threshold. This is illustrated for leptonic decays and for the two-body decay $\tau^- \rightarrow \pi^- \nu_\tau$ in Figure 32, where the scaled energy spectra of the charged particles are plotted for different values of $\sqrt{s}$. Also shown for comparison are the corresponding spectra at $\Upsilon(4S)$ energies.

The nearly-at-rest kinematics at the lower energies offer several advantages over the smeared spectra that are present at higher energies. For example, in the threshold and lower energy charm regions, the momentum spectrum of a hadronic system X produced in $\tau^- \rightarrow [X]^- \nu_\tau$ is nearly monochromatic. This provides a way of rejecting cross-feed from channels in which additional particles present in the decay are not observed.

A second advantage is that the maximum energy of a decay particle is significantly less than the beam energy, unlike the case at $E_{beam} \sim 5$ GeV (see Figure 32). This suggests that

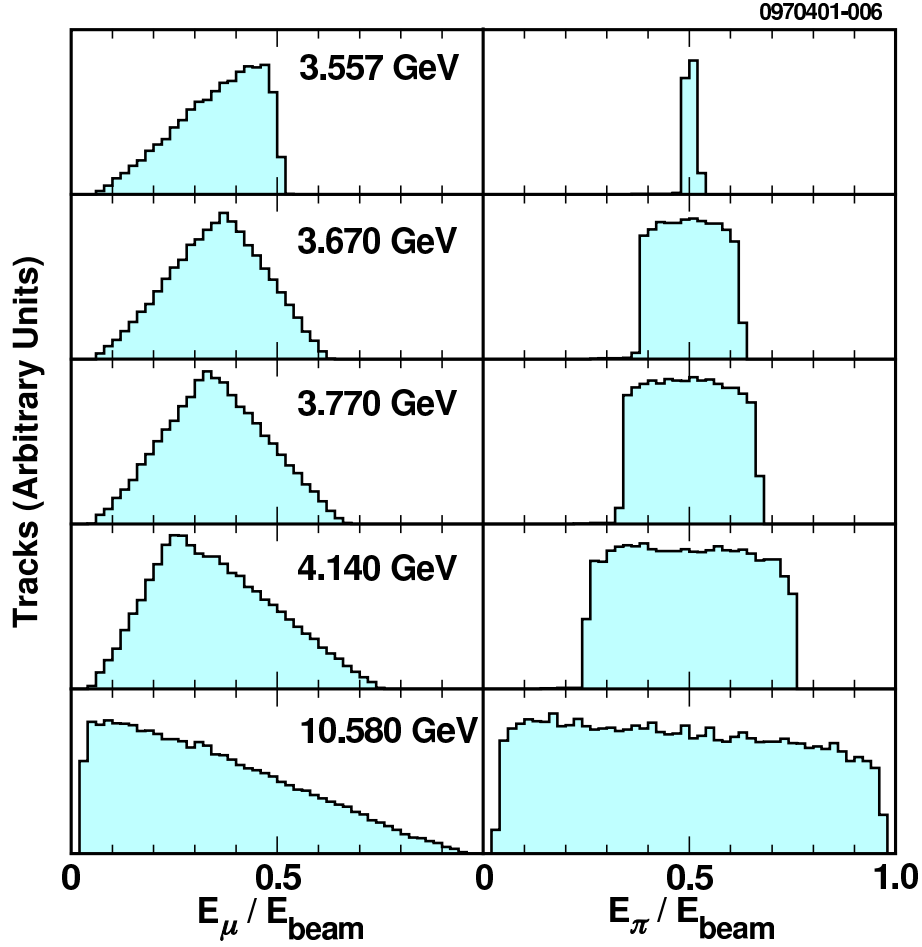


FIGURE 32. The plots on the left show the scaled muon energy in $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ decays for different values of $\sqrt{s}$. The corresponding plots on right show the scaled pion energy in $\tau^- \rightarrow \pi^- \nu_\tau$.

it should be possible to reject backgrounds from Bhabha scattering and μ -pair production.

A third advantage is that, particularly near threshold, initial- and final-state radiation is suppressed in tau-pair production. Thus, any energetic photons observed are most likely associated with the decay of one of the τ 's in the event.

One possible disadvantage of the kinematics of tau decays near threshold is that the orientation of decay particles relative to the tau flight direction is considerably more isotropic than at higher energies. Thus it may be difficult to disentangle the final state particles of the two tau decays in every event.

4.1.3 Backgrounds

Backgrounds from QED processes such as Bhabha scattering, and from misidentified tau lepton decays can be made less serious through exploitation of the kinematic features described in the preceding section. Other characteristics of tau decays, namely the low multiplic-

ity and missing energy/momentum in neutrinos, distinguish them from continuum multihadronic (uds quark production) events. For example an inclusive ‘ e -versus-1’ tau sample could be obtained by selecting events with two oppositely charged particles, one being an electron with an energy well below the beam energy, and by requiring significant missing energy and momentum. This is in contrast with the situation at the $\Upsilon(4S)$, where QED and multihadronic backgrounds preclude selection of pure inclusive tau samples.

One possible concern is background from charm events at the ψ'' and D_s threshold energies. Semi-leptonic charmed meson decays or events containing K_L^0 ’s could be difficult to separate out from τ -pair events. This is currently under study. However, the background rates are necessarily small by virtue of the low probability for both charmed mesons in an event to decay to final states consisting of one charged particle plus neutrals. Differences between data taken just above and just below charm threshold could help estimate the magnitude of such backgrounds. Brief periods of running just below the J/ψ , ψ' and ψ'' resonances are anticipated in the default CLEO-c run plan. Whether these datasets will be adequate for the study of backgrounds to tau-pair events requires further study.

4.2 Tau Threshold Measurements

Unique measurements that can be done with CLEO-c data collected at tau threshold energies include:

- the tau mass measurement,
- searches for massive neutrinos,
- searches for weakly interacting bosons in $\tau^- \rightarrow e^- G$, and
- searches for anomalous radiative tau decays.

The CLEO-c reach in these areas is described in the following Sections.

4.2.1 Tau Mass Measurement

The measurement of m_τ at CLEO-c would likely follow the strategy and techniques used by the BES Collaboration in their scan of the threshold region [41]. The BES scan was carried out over a period of about two months in 1991, during which an integrated luminosity of about 5 pb^{-1} was accumulated. As mentioned above, a factor of 50 or more times this can be obtained with CESR-c operating for a comparable period. Most of the luminosity in the BES scan was collected at values of $\sqrt{s}$ within $\sim \pm 1 \text{ MeV}$ of $2m_\tau c^2$, since that is where the radiatively-corrected, beam-energy-spread-averaged cross-section is most rapidly varying.

The BES measurement has roughly equal contributions to the error from statistical and systematic sources. The statistical error can be made negligible at CLEO-c (despite a beam energy spread that is twice as large at CESR-c than at BEPC). Some of the systematic errors (for example, those due to uncertainties in the acceptance and reconstruction efficiencies) can be improved with larger control samples.

The main sources of systematic error for CLEO-c will likely be associated with the knowledge of the beam energy scale and the beam energy spread. For BES, these contributed errors of ± 0.09 and $\pm 0.02 \text{ MeV}/c^2$ to the uncertainty in m_τ , respectively. The energy scale error was based on scans at the J/ψ and ψ' , as well as on the repeatability of the scan procedure. The relative beam energy spread for CESR-c is expected to be about 8×10^{-4} ; as mentioned

above, this is twice as large as the energy spread at BEPC. If needed, this can be reduced to 4.7×10^{-4} at the cost of some luminosity by running without the CESR-c wigglers. (Running without both CESR-c and CHESS wigglers would lead to a relative energy spread of 2.1×10^{-4} .)

In summary, a precision of $\pm 0.1 \text{ MeV}/c^2$ on m_τ can be achieved in a short dedicated run at $\sqrt{s} \sim 3.554 \text{ GeV}$ with CLEO-c. This precision represents a factor of three improvement over the BES measurement. A threshold scan with this sensitivity would also allow for a search for anomalous τ -pair production effects. It bears repeating that the tau lepton mass is a fundamental quantity, and opportunities to measure it are few. It is important for the CLEO-c run plan to be structured so as to take advantage of this opportunity.

4.2.2 Search for a Massive Neutrino in $\tau^- \rightarrow \pi^- \nu_X$

With data collected at threshold, one can examine the nominally monochromatic energy spectrum of the pion in $\tau^- \rightarrow \pi^- \nu$ for evidence of neutrino mass. For such studies, the decay of the recoiling τ^+ to e , μ , or π plus neutrino(s) can be used to tag events as being $\tau\tau$ -like. Because of smearing due to the beam energy spread as well as the τ momentum, a sensitive search for a non-zero ν_τ mass is not possible with this technique. However, an admixture of decays involving a massive exotic neutrino ν_X would give rise to a small peak in the pion energy spectrum at lower energies.

Assuming 90% geometric acceptance for the signal pion and for the tagging particles, the number of tagged pion decays for 0.25 fb^{-1} is

$$N_{\pi\nu} \sim 8 \times 10^3.$$

One difficulty with this measurement is that muon identification below $1 \text{ GeV}/c$ is marginal with the CLEO detector given the location of the innermost muon chambers at a depth of 3 interaction lengths for normally incident particles. As a result, the small peak in the pion energy spectrum has to contend with a slowly varying, but large background from $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ decays. As an example, setting $\sqrt{s}$ at 3 MeV above threshold, Figure 33 shows the pion+muon energy spectrum for the Standard Model decays plus an admixture of $\tau^- \rightarrow \pi^- \nu_X$ with $m_{\nu_X} = 600 \text{ MeV}/c^2$ corresponding to a 0.2% branching fraction. For successively larger values of m_{ν_X} , the peaks become sharper as well as further separated from the Standard Model $\tau^- \rightarrow \pi^- \nu_\tau$ peak.

4.2.3 Search for the Exotic Decay $\tau^- \rightarrow e^- G$

Experimentally, the search for this process is very similar to that described in the preceding Section, except that now one is looking for distortions in the electron energy spectrum due to a small admixture from the two-body decay $\tau^- \rightarrow e^- G$. Here G is a weakly interacting massive spin-0 or spin-1 boson, as described in Part II of this report. In Figure 34 the spectrum is shown for several values of the G -boson mass, with $\sqrt{s}$ set to 2 MeV above threshold and assuming a Gaussian beam energy spread of $8 \times 10^{-4} E_{cm}$.

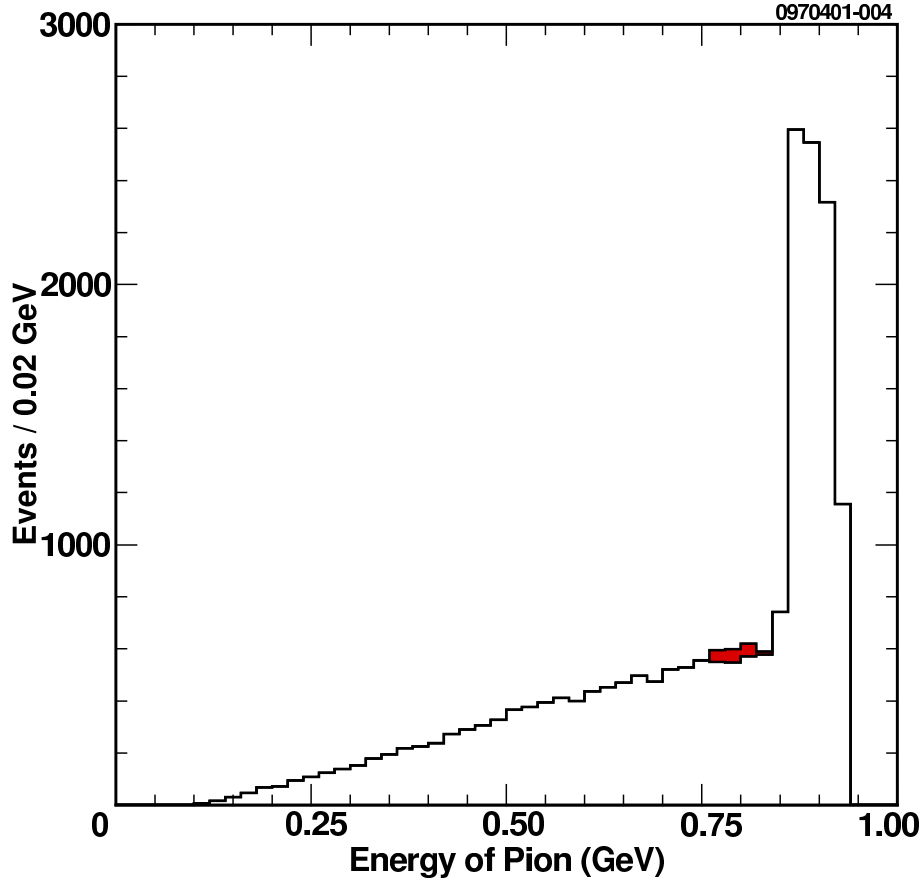


FIGURE 33. The pion+muon energy spectra at 3 MeV above $\tau\tau$ threshold for Standard Model decays, with an admixture (shaded region) of $\tau^- \rightarrow \pi^- \nu_X$ with $m_{\nu_X} = 600$ GeV corresponding to a 0.2% branching fraction.

4.2.4 Study of the radiative decay $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau \gamma$

The recent CLEO II measurement of the radiative decays $\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau \gamma$ [42] currently provides the most sensitive test of anomalous couplings in these decays. However, for this measurement CLEO was able to study only the small $\theta_{e\gamma}$ region, because the radiative decay cross section is overwhelmed by the cross section from the radiative production process $e^+e^- \rightarrow \tau^+\tau^-\gamma$. This is illustrated in Figure 35. There is no kinematic separation between the two processes. The background from the initial/final state radiative production process has to be subtracted statistically from the total $e\bar{\nu}_e\nu_\tau\gamma$ sample based on Monte Carlo simulations in order to measure the cross section for the radiative decay. At tau threshold, however, the initial- and final-state radiative production processes are absent, and thus any detected photon is necessarily a decay product of one of the tau leptons in an event.

It is likely that CLEO-c could carry out a measurement in the small $\theta_{e\gamma}$ region with a precision comparable to the existing CLEO II measurement, but with different systematics. For this, data collected in the charm region can also be useful. Even in the charm region, there are advantages over Υ energies. For example, photons from initial- and final-state ra-

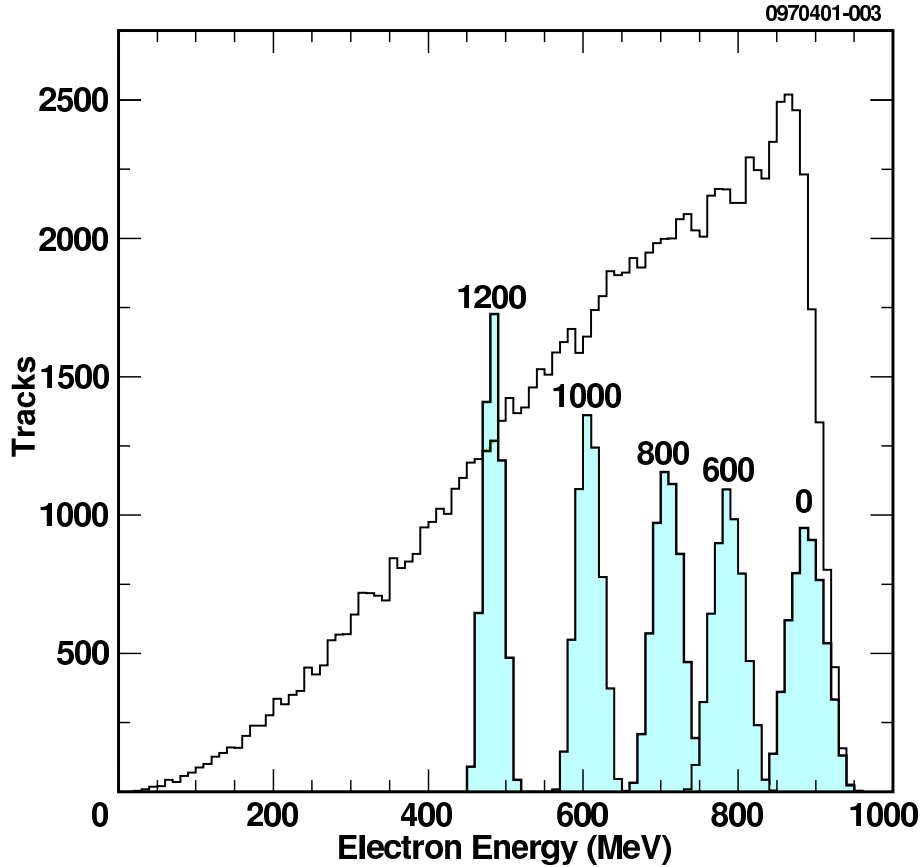


FIGURE 34. The unshaded histogram shows the electron energy spectrum in MeV for $\sqrt{s}$ set to 2 MeV above τ -pair threshold. The shaded histograms are the electron energy spectra from $\tau \rightarrow eG$ decays, where the number above each histogram is the mass of the boson G in MeV/c^2 . These spectra correspond to a branching fraction of 1%.

diation will be limited to a known maximum energy. In addition, with softer decay electrons, separating the shower made by a radiative photon in the calorimeter from that due to the electron will be less difficult than at $\sqrt{s} \sim 10$ GeV.

On the other hand, it would be very interesting to look for anomalies in radiative electronic decays of the tau in the large $\theta_{e\gamma}$ region. It could be easier to find an anomaly here because the cross section will not be dominated by the conventional quantum electrodynamics of the small $\theta_{e\gamma}$ region. Furthermore, this is uniquely done at, or slightly above, tau-pair threshold: at a few MeV above threshold, the photon produced in $e^+e^- \rightarrow \tau^+\tau^-\gamma$ is limited to a few MeV. This is well below a threshold of $\mathcal{O}(40 \text{ MeV})$ at which a search for photons from radiative tau decays would be carried out.

What is the sensitivity of such a search? For a 0.25 pb^{-1} exposure, we estimate a sample of $\sim 2 \times 10^4$ $e\nu\nu$ events using electron, muon, pion, and rho tags. If we take 10 events with $E_\gamma > 40$ MeV to be an anomalous signal, then the sensitivity is about 10^{-4} in branching fraction. The question of contamination from photons coming from the tag modes requires

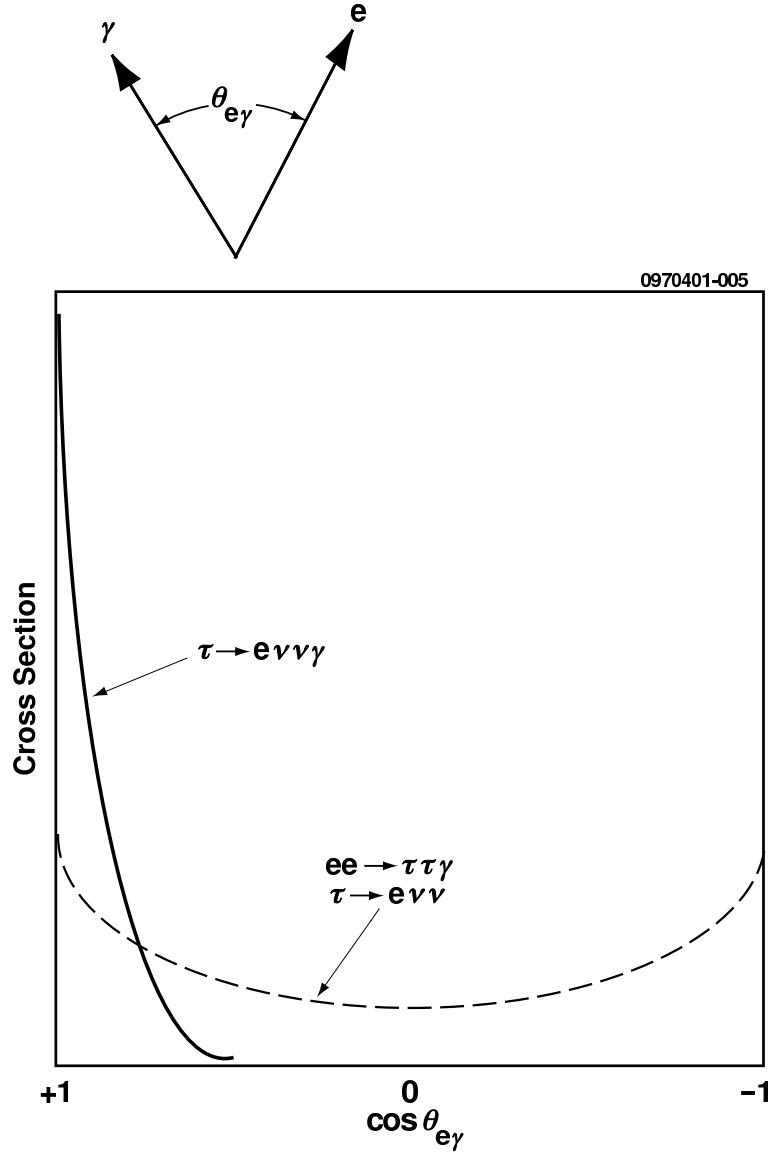


FIGURE 35. Cross section for $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau \gamma$ in the Standard Model, as a function of $\cos(\theta_{e\gamma})$, compared to $e^+e^- \rightarrow \tau^+\tau^-\gamma$ followed by $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$.

further study.

Using higher energy CLEO-c data to study the large $\theta_{e\gamma}$ region would be more difficult because of the turn-on of initial-state radiation. Compensating somewhat would be the increased statistics due to luminosity and cross section, and different polar angle distributions for signal and background.

Finally, it should be noted that measurements of radiative tau decays to hadronic final states, such as $\tau^- \rightarrow \pi^- \nu_\tau \gamma$, can also be done. Currently there are no measurements of such decays, and it is not clear whether they are accessible at the asymmetric B -factories. CLEO-c will provide a unique opportunity to study these channels.

4.3 High Statistics Measurements

High statistics measurements include branching fraction measurements, studies of Lorentz structure, studies of strong interaction dynamics in semi-hadronic decays, and searches for CP violation in decay channels with large branching fractions. In this Section, we focus on the first two of these topics.

4.3.1 Precision Branching Fractions

As discussed in Part II of this document, two targets of opportunity for CLEO-c in ‘precision’ τ physics are measurements of the $\tau^- \rightarrow \pi^- \nu_\tau$ and $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ branching fractions at the sub-1% level. At the $\Upsilon(4S)$, CLEO II measured these to be $(11.59 \pm 0.05 \pm 0.12)\%$ for $\pi\nu + K\nu$ [43], and $(25.87 \pm 0.12 \pm 0.42)\%$ for $\pi\pi^0\nu + K\pi^0\nu$ [44]. These are systematics-dominated measurements, and it will be a challenge for the B -factory experiments to obtain substantially smaller systematic errors.

A significant source of systematic error at the $\Upsilon(4S)$ comes about from the need to normalize to the number of produced tau-pairs as determined by the theoretical tau-pair production cross section times the measured luminosity. Each of these carries an uncertainty of $\sim 1\%$ from mainly theoretical sources, for an overall uncertainty on $N_{\tau\tau}$ of 1.4%. (The CLEO II analyses were conceived so as to effectively determine the squares of the branching fractions of interest, and thus the errors on the branching fractions themselves due to $N_{\tau\tau}$ were reduced by a factor of two to 0.7%.)

At CLEO-c, this potentially limiting source of error can be eliminated altogether. It will be possible to select inclusively an ‘e-versus-1’ tau sample in which both tau leptons decay to a single charged particle plus neutrals, one of these charged particles being an electron. With some additional requirements on missing momentum in these events, such a sample should be mostly free of backgrounds from non- τ processes. Conservatively, assuming an acceptance (including electron identification efficiency) of 20%, a 3 fb^{-1} sample at the ψ'' should yield roughly 6×10^5 events, of which 8×10^4 have a $\tau^- \rightarrow \pi^- \nu_\tau$ decay recoiling against the tagging electron. There would also be a comparable number of reconstructed $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ decays, after taking into account the π^0 -finding efficiency. The normalization would be with respect to the inclusive ‘one-prong’ branching fraction which is measured to better than 0.2%. Thus, sub-1% measurements of $B(\tau^- \rightarrow \pi^- \nu_\tau)$ and $B(\tau^- \rightarrow \pi^- \pi^0 \nu_\tau)$ are possible from the standpoints of statistics and normalization error.

For the $\tau^- \rightarrow \pi^- \nu_\tau$ mode, additional challenges exist in rejecting/estimating backgrounds from $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ decays in which the photons from the π^0 are not observed. Also, as mentioned in preceding Sections, the background from $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ cannot be rejected directly. However, the bulk of the Michel spectrum for muons situated below the kinematic region populated by the nearly-monochromatic $\pi^- \nu$ decays (see Figure 32) can be used to estimate this background.

4.3.2 Lorentz Structure

Contributions from non-Standard Model interactions with Lorentz structures other than $V - A$ can reveal themselves through distortions in the energy spectrum of the lepton produced

in $\tau^- \rightarrow l^- \bar{\nu}_l \nu_\tau$ decays. Such distortions can be parameterized via the Michel parameters, as described in Part II of this project description.

At CLEO-c, the ‘low energy’ Michel parameter η can be measured in $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ decays to high precision, with good control over systematic errors. The scaled muon energy spectrum is plotted in Figure 36 for colliders operating at the ψ'' and at the $\Upsilon(4S)$. In both cases, the effect of a non-zero value of η appears as an excess at low energies. The measurement of η at CLEO II [45] was limited because this excess occurs in regions where muon identification is not robust. Without assuming e - μ universality, a value of $\eta = 0.010 \pm 0.149 \pm 0.171$ was obtained, based on a sample of $\sim 20,000$ events. At CLEO-c, however, muon identification is not necessary in the sensitive region for η . This is because rejection of semi-hadronic decays can be achieved by a combination of kinematics and photon vetoes, and because electrons are easily rejected. With e , μ and π tags, a sample of $2\text{--}4 \times 10^5$ $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ decays can be collected with 3 fb^{-1} of data at the ψ'' .

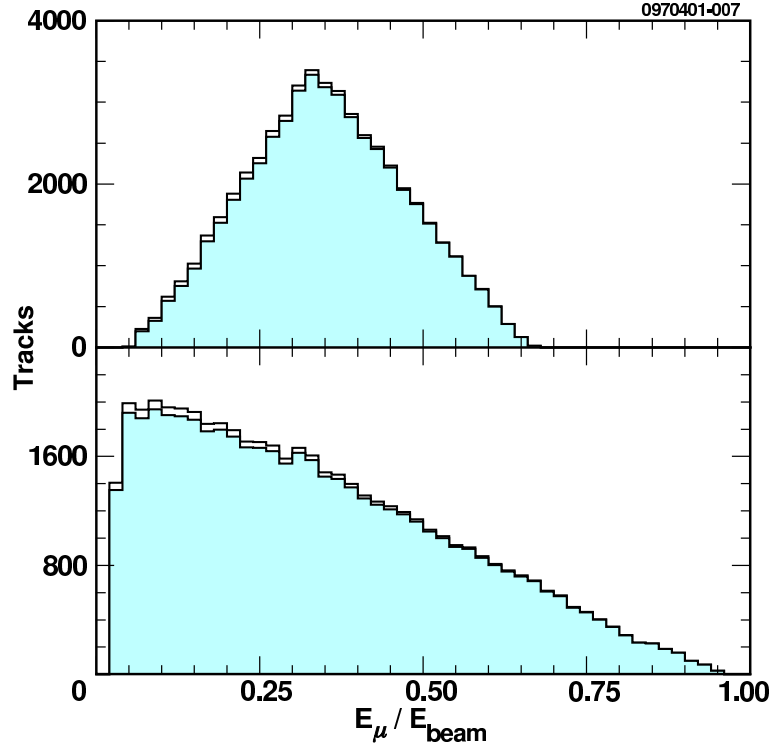


FIGURE 36. The scaled muon energy spectra in $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ for $\sqrt{s} = 3.770$ GeV (top plot) and 10.580 GeV (bottom plot), each with $50,000$ events. The shaded spectra correspond to the Standard Model value (0) for the Michel Parameter η . The unshaded spectra correspond to $\eta = 0.2$.

The effect of a non-zero η is largest in the tau rest frame. At CLEO II, kinematic constraints from the tagging tau decay were used both to suppress backgrounds and to approximately boost into the tau rest frame. Similar techniques can be employed at CLEO-c, in the subsample consisting of μ -versus- π events where the π is near its maximum energy. Extrapolating from CLEO II, the entire CLEO-c sample should allow η to be constrained at

the level of 0.05 or better.

Although the benefits for measuring η at CLEO-c are evident, the lepton spectra as measured in decays of tau's at rest are intrinsically more sensitive to the other Michel parameters as well. The method used by CLEO II [46] to obtain sensitivity to the tau spin-dependent Michel parameters ξ and δ via $\tau\tau$ spin correlations can also be applied at lower energies. Furthermore, there is a clear advantage in that the suppression of initial-state radiation leads to a smaller dilution of the spin correlations than what one finds at $\sqrt{s} \sim 10$ GeV. Finally, the use of tagging $\tau^+ \rightarrow \rho^+ \bar{\nu}_\tau$ decays as tau spin analyzers is possibly more potent at CLEO-c energies than at B -factory energies. This is because the angle of the $\rho \rightarrow \pi\pi$ decay in the ρ rest frame relative to the ρ direction in the lab frame better approximates the helicity angle of the decay as the τ momentum in the lab frame goes to zero. In light of these considerations, detailed studies are needed in order to make quantitative estimates of CLEO-c's sensitivity to ξ and δ .

4.4 Tau Physics Reach Summary

Although not envisioned as the main component of the CLEO-c physics program, it is clear that some very interesting tau physics can be done. The tau physics capabilities in the charm region are a bonus: they come at no cost to the rest of the program. With a short run at tau threshold, additional unique capabilities come at a very modest cost (in luminosity) to the charm program. Together, both components of the tau physics program add breadth to the contributions that CLEO-c will make to the field of high energy physics.

During the past decade, the complementary capabilities of CLEO and the LEP experiments made tau physics an exciting and dynamic field. During the next decade, CLEO-c will provide the only counterpoint to the asymmetric B -factory experiments in this field. The existence of experiments running in both energy ranges will surely bring out the best from those at each energy.

5 Physics Reach in Nonperturbative QCD

5.1 Data Samples

The CLEO-c program will focus on a broad range of studies of QCD in the non perturbative regime. There are three data samples that will be used to address this physics. Before the conversion to low energy operation, CLEO will have accumulated over 25 fb^{-1} of two photon data (14 fb^{-1} in the CLEO II.V configuration and 13 fb^{-1} in the CLEO III configuration) along with approximately 1 fb^{-1} on each of the $\Upsilon(1S)$ and $\Upsilon(3S)$ resonances, and 500 pb^{-1} on the $\Upsilon(2S)$ resonance. After the conversion to allow low energy operation of the CESR storage ring, CLEO-c will run for approximately one year on the $J/\psi(3100)$ resonance, in addition to running at charm meson production thresholds. With the projected CESR luminosity of $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ at this energy and a beam energy spread of 8×10^{-4} , CLEO-c will accumulate in excess of one billion J/ψ decays. These data samples will allow detailed studies of the strong interactions in the strongly coupled non perturbative regime. Given the complexity of the problems we are trying to address, it is very important to have several

different strategies to illuminate the physics. These studies of the spectra and properties of the light hadronic resonances will provide valuable information to facilitate the calculation of non perturbative processes from first principles. This is essential for a complete understanding of QCD, and will quite likely be crucial for understanding the new theories that will be revealed in the next generation of energy-frontier accelerators. The theoretical analysis of strongly-coupled, nonperturbative quantum field theories remains one of the foremost challenges in modern physics, affecting not only high energy physics, but many areas of condensed matter and atomic physics, where strongly-coupled systems often arise.

5.1.1 Comparison with existing/projected data samples

The CLEO-c data samples that will contribute to our understanding of non perturbative QCD are listed in Table 23 along with the currently available J/ψ and $\Upsilon(nS)$ data samples from CLEO, BES and MARKIII. Table 24 gives the projected numbers of events in a variety of reconstructed radiative J/ψ decay modes, along with existing and projected reconstructed samples from BES. Note that the significant increase in reconstructed yields comes both from the larger data sample and the higher efficiency of the CLEO detector as compared with the BES detector. As is clear from Table 24, the CLEO-c data samples represent a very substantial increase in the world's sample of J/ψ decays.

TABLE 23. Current analyzed data samples and projected CLEO-c and BES data samples. (Note that BESII is currently running on the J/ψ with the goal of accumulating 5×10^7 decays in total.)

	CLEO (projected)	CLEO (analyzed)	BESII (analyzed)	BESII (projected)	MARK III (analyzed)
J/ψ	10^9	—	8×10^6	5×10^7	6×10^6
$\Upsilon(1S)$	1 fb^{-1}	61 pb^{-1}	—	—	—
$\Upsilon(2S)$	0.5 fb^{-1}	74 pb^{-1}	—	—	—
$\Upsilon(3S)$	1 fb^{-1}	110 pb^{-1}	—	—	—
$e^+e^- \rightarrow e^+e^-\gamma\gamma$	13 fb^{-1}	14 fb^{-1}	—	—	—

5.2 Detector issues

The CLEO detector represents a significant advance in detector capability over previous experiments that have operated at e^+e^- colliders in the J/ψ energy region. A detailed description of the CLEO detector and a review of the detector performance will be given in Chapter IV. However there are several features of the CLEO detector that are particularly important for addressing the QCD part of the physics program that we will discuss here.

The radiative decays of the J/ψ provide a particularly fruitful laboratory to search for glue rich hadronic matter [51]. Previous detectors such as MARKIII and BES had limited

TABLE 24. Projected numbers of reconstructed events in a variety of radiative J/ψ decay modes for CLEO-c . The projected yields are based on the BES measured branching ratios. For comparison the existing and projected yields from BESII are also given [47,48,49,50].

Mode	CLEO-c $10^9 J/\psi$ (projected)	BESII $\sim 8 \times 10^6 J/\psi$ (analyzed)	BESII $\sim 50 \times 10^6 J/\psi$ (projected)
$J/\psi \rightarrow \gamma f_J(2220), f_J(2220) \rightarrow \pi^+\pi^-$	23,000	74	462
$J/\psi \rightarrow \gamma f_J(2220), f_J(2220) \rightarrow \pi^0\pi^0$	13,000	18.4	115
$J/\psi \rightarrow \gamma K^+K^-\pi^0$ ($m < 1.8 \text{ GeV}/c^2$)	576,000	410	2,300
$J/\psi \rightarrow \gamma \eta(1440), \eta(1440) \rightarrow \eta\pi^+\pi^-$	40,600		

capabilities for detecting photons and as a result, particularly in BES, reconstructed radiative J/ψ decays have significant background contamination from hadronic J/ψ decays in which one photon from a π^0 in the final state was lost. In both the partial wave analyses of $J/\psi \rightarrow \gamma(K^\pm K_S^0 \pi^\pm)$ and $J/\psi \rightarrow \gamma(\pi^+\pi^-\pi^+\pi^-)$ the backgrounds from $J/\psi \rightarrow \pi^0(K^\pm K_S^0 \pi^\pm)$ and $J/\psi \rightarrow \pi^0(\pi^+\pi^-\pi^+\pi^-)$ are estimated to be 30% [52,53]. In CLEO, the high resolution CsI calorimeter covers 93% of 4π solid angle and the energy threshold for photon detection is very low. Reconstruction efficiencies for decay modes with photons in the final state are significantly higher than for BES and backgrounds to radiative J/ψ decays from misreconstructed hadronic J/ψ decays, as evaluated in full Monte Carlo simulation, appear to be negligible.

Identification of many of the hadronic states produced in J/ψ decays will necessitate partial wave analysis (PWA) to determine the quantum numbers of the state. The increased solid angle coverage with both tracking and photon detectors in CLEO-c combined with excellent photon and tracking resolution and particle ID over the full momentum range of the decay products, will greatly strengthen the capability of CLEO-c to perform PWA.

Table 25 gives a comparison of the CLEO detector [54] with the BESII detector [55] which is collecting data in this energy region.

5.3 Specific Examples

In Chapter II the goals for the QCD part of the CLEO-c physics program were outlined. To quantitatively illustrate the physics reach of the CLEO-c program we have chosen a few specific examples to discuss:

5.3.1 Exclusive Measurements

Exotic states may reveal themselves in a variety of ways. We consider three examples: (1) a search for a narrow resonance produced in radiative J/ψ decays using the unconfirmed $f_J(2220)$ as a model; (2) a search for a broad resonance produced in radiative J/ψ decays

TABLE 25. A comparison of the CLEO-c detector with BESII.

Detector Element	CLEO-c	BESII
Tracking Resolution		
at 1 GeV/ c	0.5%	1.2%
Maximum momentum for π/K Separation	1.5 GeV/ c	600 MeV/ c
dE/dx Resolution	4.9%	9%
Photon Energy Resolution		
at 1 GeV	21.5 MeV	220 MeV
at 100 MeV	3.9 MeV	70 MeV
Minimum Photon Energy	30 MeV	80 MeV
Solid Angle for Tracking	0.93	0.8
Solid Angle for Photons	0.93	0.75

where significant mixing with other hadronic states occurs and we use the scalar 0^{++} glueball candidates as an example; (3) a search for charm hybrids above the $\psi(3770)$.

5.3.1.1 Reach for $f_J(2220)$

The existence of a narrow $f_J(2220)$ state still needs confirmation [11]. The experimental evidence from J/ψ radiative decays, πp and $K p$ scattering, and $p\bar{p}$ annihilation is mutually contradictory and inconclusive [47,48,56,57]. BES observes a signal in radiative J/ψ decays in a variety of final states, including $K\bar{K}$, $\pi^+\pi^-$, and $p\bar{p}$ [47]. The BES signals, based on $8.0 \times 10^6 J/\psi$ decays are shown in Figure 37. The BES product branching fractions are given in Table 26.

With $10^9 J/\psi$ decays, if the $f_J(2220)$ exists and the BES branching ratios are correct, CLEO-c will reconstruct over 10^4 events in each of many decay modes. The event yields based on the BES branching ratios and efficiencies modeled in the CLEO detector are given in Table 26. In addition, CLEO will have the capability to reconstruct the $f_J(2220)$ in modes not easily accessible to BES such as $\eta\eta$, $\eta'\eta$, $\eta'\eta'$, and others.

A detailed analysis of the backgrounds to these decay channels has not been published making realistic Monte Carlo studies of CLEO-c capabilities to discover narrow resonances such as the $f_J(2220)$ difficult. We have chosen to consider two extreme cases, with the confidence that reality lies somewhere between the extremes we have explored.

Both MARK III and BES claimed that hadronic J/ψ decays were an important background source to their reconstruction of radiative J/ψ decays. For example, the decay $J/\psi \rightarrow \rho^+\pi^-$ where the π^0 from the decay of the ρ decayed asymmetrically and one photon was not detected, was a potentially serious background in the $J/\psi \rightarrow \gamma\pi^+\pi^-$ channel. To investigate this potential source of background, we model hadronic J/ψ decays and reconstruct them to evaluate how significant a background they are to the reconstruction of signals in radiative J/ψ decays. In CLEO-c, the high efficiency, nearly hermetic, calorime-

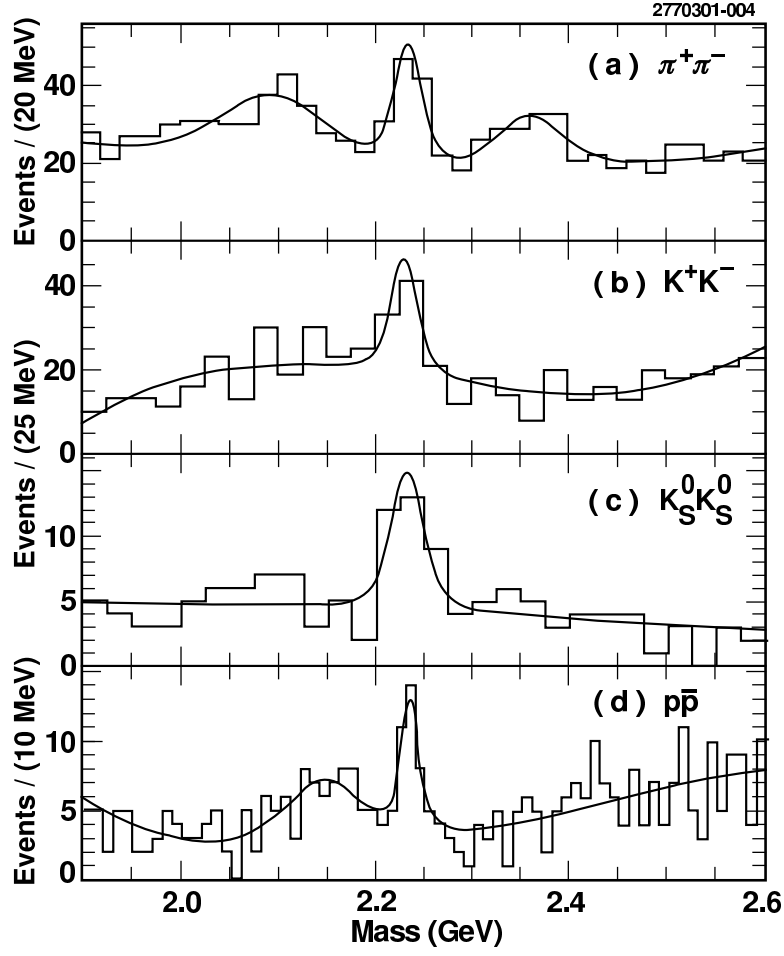


FIGURE 37. The fitted invariant mass spectra from the BES detector showing signals for the $f_J(2220)$ [47].

ter can be used to greatly suppress backgrounds to radiative J/ψ decays from asymmetric π^0 decays and other hadronic J/ψ decay modes. The expected CLEO-c background level from hadronic J/ψ decays is shown in Figure 38 for the $\pi^+\pi^-$ and $\pi^0\pi^0$ decay modes of the $f_J(2220)$ and compared with the expected signal level assuming the BES branching ratios. We see that hadronic backgrounds from misreconstructed decays will be negligible.

We believe that the dominant backgrounds to the reconstruction of the $f_J(2220)$ (and most other resonances, narrow or wide) in CLEO-c will come from other resonances produced in J/ψ radiative decay and decaying to the same final state. There may also be nonresonant radiative decays of the J/ψ that will be a source of background. However, many of the relevant branching fractions that would allow us to make a precise prediction of these backgrounds have not yet been measured. Furthermore, some of the branching fractions that have been measured by other experiments appear to be in contradiction with the BES data. For illustration, we consider the CLEO-c $\pi\pi$ invariant mass spectra from a Monte Carlo study of radiative J/ψ decay, where we assume $\mathcal{B}(J/\psi \rightarrow \gamma f_4(2050)) = 2.7 \times 10^{-3}$, $\mathcal{B}(f_4(2050) \rightarrow \pi\pi) = 0.17$ [11] and we assume the BES branching fractions for the $f_J(2220)$.

TABLE 26. The measured product branching ratios,
 $\mathcal{B}(J/\psi \rightarrow \gamma f_J(2220))\mathcal{B}(f_J(2220) \rightarrow X)$ from BES and MARK III.

Decay mode	$\mathcal{B}(J/\psi \rightarrow \gamma f_J)\mathcal{B}(f_J \rightarrow X)$ (10^{-5})	Ref	Yield (actual)	CLEO-c Yield (projected)
$\pi^+\pi^-$	$5.6^{+1.8}_{-1.6} \pm 2.0$	BES	74	23,000
$\pi^0\pi^0$	$4.5 \pm 2.6 \pm 1.3$	BES	18.4	13,000
K^+K^-	$3.3^{+1.6}_{-1.3} \pm 1.2$	BES	46	15,600
$K_S^0 K_S^0$	$2.7^{+1.1}_{-0.9} \pm 0.8$	BES	23	4,500
$p\bar{p}$	$1.5^{+0.6}_{-0.5} \pm 0.5$	BES	32	8,500
K^+K^-	$4.2^{+1.7}_{-1.4} \pm 0.8$	MARK III	93	
$K_S^0 K_S^0$	$3.1^{+1.6}_{-1.3} \pm 0.7$	MARK III	23	

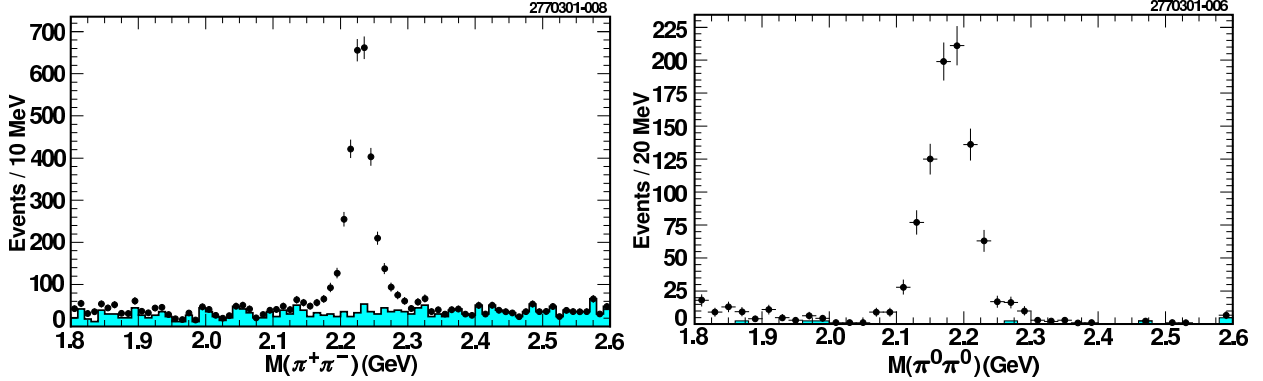


FIGURE 38. The expected $J/\psi \rightarrow \gamma\pi^+\pi^-$ (left plot) and $J/\psi \rightarrow \gamma\pi^0\pi^0$ (right plot) signals (points) shown compared with the background expected from hadronic J/ψ decays (shaded) in CLEO-c. The Monte Carlo signal sample corresponds to 167(134) million J/ψ decays for the left (right) plot.

The resulting $\pi\pi$ invariant mass spectra are shown in Figure 39. These figures represent approximately 150 million J/ψ decays; less than 1/6 of our projected data sample. A clear, broad $f_4(2050)$ peak is visible in the $\pi\pi$ channel with the narrow $f_J(2220)$ signal on the shoulder. At first comparison this seems perhaps consistent with the low mass enhancement in the BES $\pi\pi$ channel as shown in Figure 37. However, a fine bin $\pi\pi$ invariant mass spectrum in the original BES reference shows marginal evidence for a broad f_4 peak and does not appear to be consistent with the quoted $J/\psi \rightarrow \gamma f_4$ branching ratios, leading us to believe that this study overestimates the potential background from this source. However, even in this worst case scenario where a nearby resonance (such as the $f_4(2050)$ in this case) is copiously produced in radiative J/ψ decays, resulting in significant back-

grounds in the invariant mass range of interest, clean signals are still possible in other final states. For example, the $f_4(2050)$ decays to KK are highly suppressed relative to the $\pi\pi$ final state ($\Gamma(KK)/\Gamma(\pi\pi) \sim 4\%$ [11]), while BES reports KK and $\pi\pi$ produced almost equally in $f_J(2220)$ decays. Figure 40 shows the anticipated invariant mass spectrum for $J/\psi \rightarrow \gamma K^+ K^-$ including all backgrounds from hadronic and radiative J/ψ decay. Here the $f_J(2220)$ shows up very cleanly on a relatively flat background.

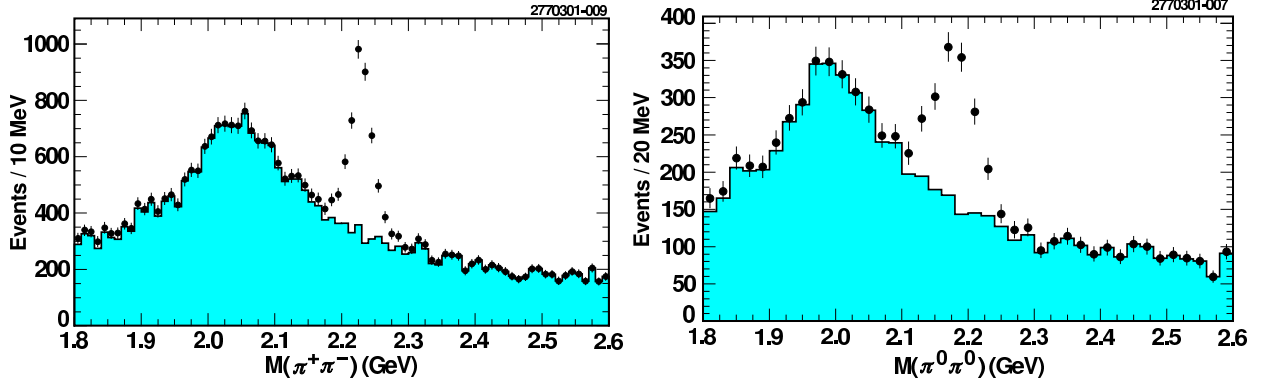


FIGURE 39. The expected invariant mass spectrum for $J/\psi \rightarrow \gamma\pi^+\pi^-$ (left plot) and $J/\psi \rightarrow \gamma\pi^0\pi^0$ (right plot) (points) including all hadronic and radiative backgrounds (shaded). The large enhancement to the left of the signal is from $J/\psi \rightarrow \gamma f_4(2050); f_4(2050) \rightarrow \pi\pi$ where we have assumed $\mathcal{B}(J/\psi \rightarrow \gamma f_4(2050)) = 2.7 \times 10^{-3}$, $\mathcal{B}(f_4(2050) \rightarrow \pi\pi) = 0.17$.

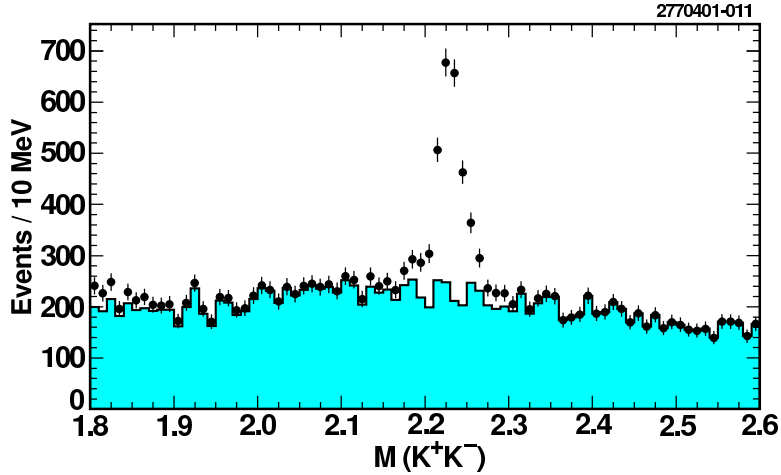


FIGURE 40. The expected invariant mass spectrum for $J/\psi \rightarrow \gamma K^+ K^-$ (points) including all hadronic and radiative backgrounds (shaded).

Even though background sources cannot be fully evaluated on the basis of current information, we conclude that with the very low background levels from misreconstructed events and abundant statistics, CLEO-c will be able to definitively establish whether or not the

$f_J(2220)$ exists and, using partial wave analysis, what its quantum numbers (J^{PC}) are in a variety of final states.

Crucial to establishing the glueball nature of the $f_J(2220)$ (if it exists) or any other narrow glueball candidate, will be to antiseach in two photon collisions. CLEO has searched for the $f_J(2220)$ and, based on 4.8 fb^{-1} of data, has set an upper limit for the two photon production of the $f_J(2220)$ of $\Gamma(\gamma\gamma \rightarrow f_J(2220))\mathcal{B}(f_J(2220) \rightarrow \pi^+\pi^-(K_S^0 K_S^0)) < 2.5(1.3) \text{ eV}$ [58]. The CLEO upper limits already provide strong evidence for the glueball nature of the state *if* it exists. With the full $\gamma\gamma$ sample, CLEO will be sensitive to two photon couplings of the $f_2(2220)$ or similar states at the sub-eV level.

Radiative $\Upsilon(1S)$ decays also provide a glue rich environment for producing exotic states. With 1 fb^{-1} of data we anticipate being able to independently confirm the existence of exotic states produced in radiative J/ψ decays. Using the narrow $f_J(2220)$ candidate from BES as an example we anticipate we would reconstruct a few tens of decays from the 1 fb^{-1} $\Upsilon(1S)$ sample.

5.3.1.2 Scalar 0^{++} glueball story

The 0^{++} states are complicated. There is a long standing puzzle in the identification of the scalar mesons. The problem originates in their large decay widths causing overlap of resonances within the same partial wave [11]. In addition, with 5 isoscalar resonances well-established, it appears that some must be supernumerary and open to interpretation as exotics. A variety of interpretations of these states exists in the literature. Many feel that the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ may all contain substantial scalar glueball components in their wavefunctions [59,60]. Table 27 from reference [59] summarizes currently available information from Crystal Barrel [61] where the decay branching fractions have been inferred from the Crystal Barrel data, and are not directly measured. The Particle Data Group is only willing to list the decay modes of these states as 'seen' with no quantitative information on their branching fractions. The situation is likely to remain unresolved until more experimental data becomes available, particularly from experiments that can cleanly separate contributions to many different decays modes from different partial waves.

TABLE 27. Branching fractions for several scalar resonances as measured by the Crystal Barrel detector and interpreted in reference [59].

Resonance X	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$
$\Gamma_{\gamma\gamma}(X) \text{ (keV)}$	5.4 ± 2.3	< 3.1	< 11
$\mathcal{B}(X \rightarrow \pi\pi) \text{ (\%)}$	26 ± 9	29.0 ± 7.5	15 ± 5
$\mathcal{B}(X \rightarrow KK) \text{ (\%)}$	35 ± 13	3.5 ± 0.3	60 ± 14
$\mathcal{B}(X \rightarrow \eta\eta) \text{ (\%)}$	14 ± 5	4.6 ± 1.3	24 ± 10
$\mathcal{B}(X \rightarrow \eta\eta') \text{ (\%)}$		1.2 ± 0.3	
$\mathcal{B}(X \rightarrow 4\pi) \text{ (\%)}$		61.7 ± 9.6	

In Table 28 we give the expected reconstructed event yields for a variety of $f_0(1500)$ and

$f_0(1710)$ decay modes, based on BES results on the production of these states in radiative J/ψ decays. Extrapolating from BES and MARK III analyses, CLEO-c will be able to definitively determine the spin parity of the $f_0(1710)$ and confirm the spin parity of the $f_0(1500)$. The decay branching ratios will be measured in a wide variety of modes. We anticipate these data will be useful to help sort out the variety of interpretations that currently exist for these states. Crucial to this experimental program will be the capability for the CLEO detector to suppress the backgrounds from hadronic J/ψ decays that make up over 30% of the events in the BES analyses.

TABLE 28. Projected CLEO-c event yields for the $f_0(1500)$ and the $f_0(1710)$ produced in radiative J/ψ decay based on the measured decay branching fractions [53,62,11].

Decay Mode	Product Branching Fraction ($\times 10^4$)	CLEO-c Yield (projected)
$J/\psi \rightarrow \gamma f_0(1500), f_0(1500) \rightarrow \pi^+\pi^-\pi^+\pi^-$	3.1 ± 1.1	123,000
$J/\psi \rightarrow \gamma f_0(1710), f_0(1710) \rightarrow \pi^+\pi^-\pi^+\pi^-$	3.1 ± 1.1	123,000
$J/\psi \rightarrow \gamma f_0(1710), f_0(1710) \rightarrow \pi\pi$	2.5 ± 1.8	93,000
$J/\psi \rightarrow \gamma f_0(1710), f_0(1710) \rightarrow KK$	$8.5^{+1.2}_{-0.9}$	250,000

Although positive identification of a glueball is difficult, the two photon yield provides a clean way to establish the mesonic (conventional) part of a state. To further probe our understanding of the isoscalar states, we will use the two photon data sample to make precise measurements of their two photon partial widths, $\Gamma_{\gamma\gamma}$. Table 29 shows the sensitivity that could be achieved in the measurements of the two-photon partial widths of these states with a subsample (15 fb^{-1}) of the data. The production cross sections for the states in two photon collisions are calculated based on the formalism of reference [63], and are given in Table 29 along with estimates of the background levels. If we assume that no signals are seen, then with the calculated production cross sections and the estimated background levels, we can quote upper limits that are the products of limits on $\Gamma_{\gamma\gamma}$ (in keV) and the branching fractions for $\pi\pi$ decays. These limits represent over two orders of magnitude improvement in our knowledge of $\Gamma_{\gamma\gamma}$ partial widths for the f_0 resonances, and will provide substantial constraints for any model that attempts to explain them.

With 1 fb^{-1} of data on the $\Upsilon(1S)$ CLEO will also search for evidence of the scalar mesons in $\Upsilon(1S)$ decay. The comparisons between the production rates in J/ψ and Υ decay for these states will provide useful input to the model builders.

5.3.1.3 Heavy Hybrids

Charm and bottom vector hybrid masses are predicted with confidence by a variety of lattice and model calculations [64]. So far we have no evidence for such states. The most often suggested way to look for evidence of heavy hybrids is in e^+e^- collisions. One strategy is to scan the center of mass energy of the machine, and measure the total cross section as

TABLE 29. Estimates of the CLEO reach to measure the two photon partial widths of some of the scalar 0^{++} states. Upper limits on the product branching ratio are given assuming no signal is seen.

Resonance	Production Cross Section (estimated)(nb)	$N_{background}$	90%CL Upper Limit ($\Gamma_{\gamma\gamma}\mathcal{B}_{\pi\pi}$) (keV)
$f_0(1370)$	0.10	300	< 0.002
$f_0(1500)$	0.13	200	< 0.003
$f_0(1710)$	0.16	200	< 0.003

a function of center of mass energy. Heavy hybrids will appear (along with radially excited $c\bar{c}$ and $b\bar{b}$ states) in the energy region above open charm and open bottom production, respectively [65]. The widths of these hybrid states are expected to be narrow enough and their partial widths Γ_{ee} large enough that they can be discovered with a dedicated scan [66]. We anticipate a multi-pronged attack on these measurements. The best data will likely come from dedicated runs (described below) once the CESR-c machine is commissioned. Inclusive J/ψ production from the $\Upsilon(1S)$ has been established for many years [67]. The $\Upsilon(1S)$ should also be a good source of vector mesons and vector hybrids. With 1 fb^{-1} of $\Upsilon(1S)$ data we may be able to determine the masses of the candidate charm vector hybrid states. After the conversion to low energy we would then go to the correct center of mass energy to produce the states directly and study the hybrid resonance shape and decay modes.

5.3.2 Inclusive Measurements

5.3.2.1 Inclusive Photons

The inclusive photon spectrum from radiative J/ψ decays can be used to search for new states. The Crystal Ball produced the most detailed such spectrum, and it shows no clear signal for $J/\psi \rightarrow \gamma f_J(2220)$ [68]. However, a numerical upper limit on inclusive $f_J(2220)$ production in radiative J/ψ decays was never published because of uncertainties in the photon efficiency as a function of energy.

A Monte Carlo study of inclusive radiative J/ψ decays in CLEO-c is shown in Figure 41 based on a sample of 60 million J/ψ decays and assuming $\mathcal{B}(J/\psi \rightarrow \gamma f_J(2220)) = 8 \times 10^{-4}$. A monochromatic photon line from the $J/\psi \rightarrow \gamma f_J(2220)$ decay is seen clearly. The signal efficiency is 24%. With 10^9 J/ψ decays, CLEO-c should be able to discover any narrow resonances produced in radiative J/ψ decay with inclusive branching fractions of order 10^{-4} or greater.

5.3.2.2 Measuring R

CLEO-c can measure R in two ways. In the first approach, a scan of the energy range between 3 and 5 GeV will clarify the energy dependence of R just below the open charm threshold, from J/ψ to $\psi(3770)$, and above it where several relatively broad $c\bar{c}$ resonances exist. A possible scenario is to scan this energy range with steps of 100 and 20 MeV, below

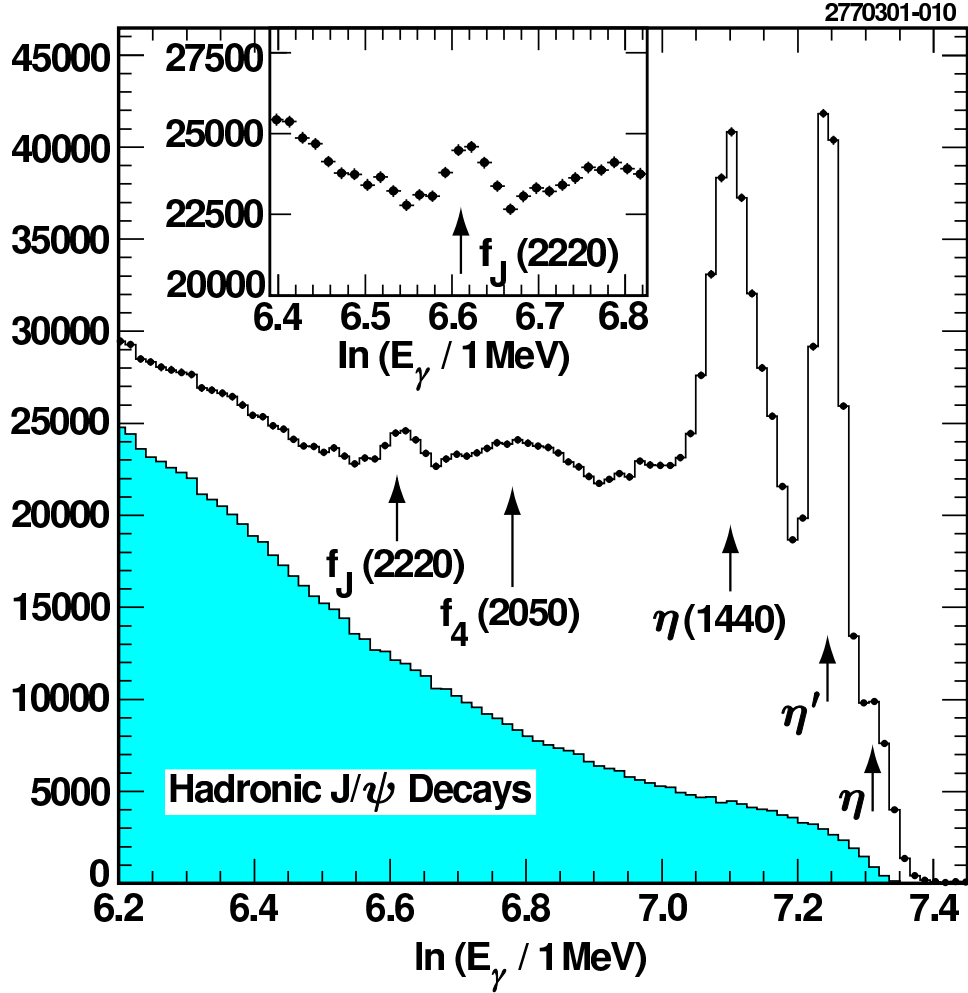


FIGURE 41. The inclusive photon spectrum from J/ψ decay from a Monte Carlo simulation in CLEO-c. Signals from η' , $\eta(1440)$, and $f_J(2220)$ are clearly visible. We have assumed $\mathcal{B}(J/\psi \rightarrow \gamma f_J(2220)) = 8 \times 10^{-4}$ and $\mathcal{B}(J/\psi \rightarrow \gamma \eta(1440)) = 4.5 \times 10^{-3}$. A broad signal from $f_4(2050)$ production is also evident.

and above $\psi(3770)$ respectively, collecting about 10^4 hadronic events per point. Such a scan will require an integrated luminosity of about 100 pb^{-1} . It will also serve as an introduction to a later, more detailed study of the $c\bar{c}$ resonances in this energy range as well as D^* and D_s mesons copiously produced in their decays. The previous experience of CLEO (which measured R with an accuracy of 2% in the vicinity of the $\Upsilon(4S)$ resonance [69]) and recent progress in the calculations of radiative corrections together with the hermeticity of the CLEO-III detector allows one to expect a systematic uncertainty of about 2%. After that a scan of the energy range from 5 to 7 GeV will be needed to solve the dramatic contradiction between the old measurement of MARK-I [70] and the unpublished results of Crystal Ball [71]. Here a scan in steps of 100 MeV with 10^4 events per point will be adequate, requiring an integrated luminosity of 50 pb^{-1} . At an average luminosity of $3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ it will take one week to scan the entire energy range between 3 and 7 GeV.

The second approach to measuring R at CLEO-c will be to use radiative return events [72,73]. Such events would allow CLEO-c to measure R in the 1-3 GeV energy range which is of crucial importance to reduce the overall uncertainty in $\alpha(M_Z)$ and $(g-2)_\mu$. Recent experience of BaBar confirms statistical feasibility of such R measurements [74]. While running at the $\psi(3770)$ one can expect $\sim 10^4$ fully contained radiative return events in the range 1-3 GeV per 1 fb^{-1} of data. However, it is still unclear whether systematic errors can be controlled well enough to make the radiative return measurements meaningful, *i.e.*, to reach an uncertainty of less than 5%.

Various dedicated experiments have recently been proposed to improve our knowledge of R in the crucial 1–3 GeV energy range [75]. If they are approved, the CLEO-c measurements would be most valuable as an independent check of the dedicated experiments.

A 2% measurement of R between 3 and 7 GeV will significantly reduce the uncertainty of the hadronic contribution to $(g-2)_\mu$ and especially $\alpha(M_Z)$. If radiative return events can be utilized to reach the 5% accuracy between 1 and 3 GeV, remarkable improvement is expected. For example, the $\alpha(M_Z)$ uncertainty would be a factor of 2 smaller than it is at present.

5.3.2.3 ‘Modern R ’ Measurement for Charm Spectroscopy Studies

Although $c\bar{c}$ states below strong decay threshold (3.7 GeV) were studied at e^+e^- machines some time ago, higher mass states are very poorly defined. Most quark model analyses [76] find 3 poorly defined L=2 states above a mass of 4 GeV based on on low statistics R data from 30 years ago. A detailed study of the properties of these states will test the long-range $q\bar{q}$ potential in a controlled way. In addition, the energy region from 4-5 GeV is where lattice calculations have predicted charmed hybrids to be, as detailed in other sections of this document.

Thus, a means to study this spectroscopy with more detail than the previous experiments is required. Here, we propose a study that will provide a direct look at the states through a scan of the energy region 3.7-5 GeV. Because very little is known about the states above $D\bar{D}$ threshold, a broad look is appropriate. However, the complexities of extraction above the inelastic threshold require more detailed information about the final state. The proposed study will be similar to the R measurement proposed above. However it will measure the final state whenever possible by reconstructing D mesons in that the dominant decay modes will be $D\bar{D}$, $D^*\bar{D}$, $D^*\bar{D}^*$, and $D^{**}\bar{D}$. Previous measurements of these decay rates are strongly in disagreement with quark model calculations [76], but the data is of poor quality.

We propose to take data with a loose trigger in the region 3.7-5 GeV. Similar to an R measurement, runs will be at closely spaced energies (steps of 20 MeV). However, the runs will be much longer ($\sim 100,000$ events) than is typical [77]. Although the BES data have higher statistics than the older SLAC experiments, no attempts have been made to analyze the composition of the final state because of detector limitations. With the larger event samples and the acceptance of CLEO, we will be able to reconstruct at least one D meson in about 10% of the events. This is sufficient to characterize the final state and measure the angular distribution. The overall efficiency (summed decay branching ratio times detection efficiency) is about 16% for D^0 mesons and 6% for D^+ mesons for prominent decay modes (see Table 2 of this document). At a luminosity of $3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, each step will take

about 2 days of data taking.

Existing quark model calculations for charmed hybrid mesons [78] assume the quarks to have orbital angular momentum 1. For decay mechanisms normally used in quark models, decays to $D\bar{D}$ mesons will be suppressed. If this symmetry is correct, a state with very low decay rate to $D\bar{D}$ would signal the possibility of a hybrid. Total widths are about 10-30 MeV in these models, similar to the conventional $c\bar{c}$ states at the same mass.

This measurement is related to other CLEO-c measurements proposed in this document. It is closely related to the R measurement discussed in the previous section, but will require much larger statistics. Although initial measurements will be made with $\Upsilon(1S)$ decays in CLEO running before CLEO-c conversion, the yields are expected to be low and more detailed studies will be required.

5.3.3 Υ Resonance Running

5.3.3.1 General Comments on the Run Plan for 2001-2002

The last day of CLEO taking data at the $\Upsilon(4S)$ was 26 June 2001. While there may be some test running for CESR at $\sqrt{s} \sim 10.56$ GeV and while running for synchrotron radiation (CHESS) physics will likely continue at that energy, the era of CLEO collecting $B\bar{B}$ events has ended.

From fall 2001 to summer 2002 CLEO will collect data on the Υ resonances below the $\Upsilon(4S)$. The “landscape” of this region, in terms of the hadronic cross section, is shown in Figure 42. Recall that in this energy range the cross section for $e^+e^- \rightarrow \mu^+\mu^-$ is roughly 1 nb.

At these energies CESR can deliver approximately 30 pb⁻¹/day and 180 pb⁻¹/week throughout the energy range being discussed. During the resonance running CLEO anticipates in excess of 4 fb⁻¹ of accumulated data.

5.3.3.2 Opportunities at the Three Narrow Resonances

The energy levels of the Υ system are shown in Figure 43; the only ‘established’ states below $B\bar{B}$ threshold are the three vector singlet Υ resonances ($^3S_1$) and the six χ_b and χ'_b (two triplets of ^3P_J) that are accessible from these parent vectors via E1 radiative transitions. By collecting substantial data samples at the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$, CLEO will address a variety of outstanding physics issues.

5.3.3.2.1 Discovery of η_b

Perhaps the most interesting physics goals are the discovery of several states, some of which are unique to the $b\bar{b}$ system.

The η_b is the ground state of $b\bar{b}$. This *alone* makes its discovery important. Most present theories [79] would indicate the best approach would be the hindered M1 transition from the $\Upsilon(3S)$, with which we might have a signal of 5σ significance in 1 fb⁻¹ of data. Even our present data sample of roughly 110 pb⁻¹ tests some of the predictions and our observation, or lack thereof, in the upcoming data will determine the validity of these approaches. If models that cite the importance of ‘exchange terms’ [80] are correct, then our discovery of the η_b would have to rely on the ‘allowed’ M1 transition from the $\Upsilon(1S)$.

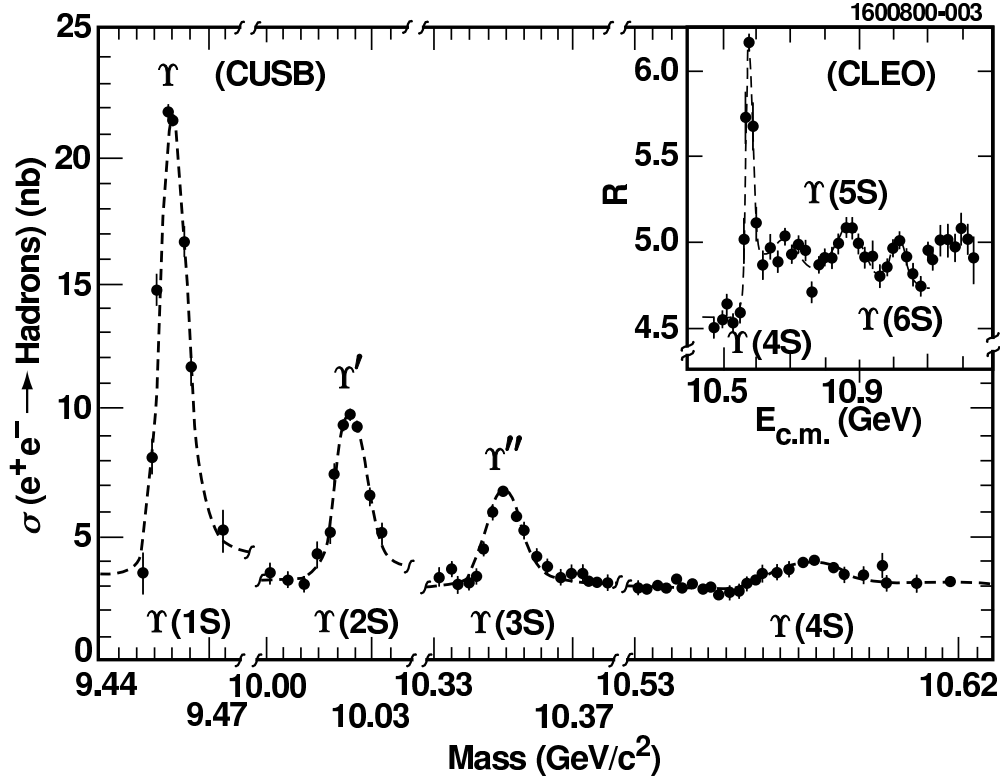


FIGURE 42. Hadronic cross section in the Υ region.

The predictions of various models [79] for the hyperfine splitting between the $^3S_1 = \Upsilon(1S)$ and the $^1S_0 = \eta_b$ vary from 35 to 100 MeV. Of some note, lattice QCD [81] should soon be able to give this splitting to within ± 1 MeV. This compares to our uncertainty on the M1 photon energy, for a signal of 5σ significance, of ~ 5 MeV. Further, this hyperfine splitting tests the spin-dependent part of the b -quark action which contributes to the $1/M$ terms in corrections to B physics results.

5.3.3.2.2 Observation of h_b

Previously CLEO [82] placed an upper limit of $\mathcal{B}(\Upsilon(3S) \rightarrow \pi^+\pi^-h_b) < 0.18\%$ at 90% C.L. This result, again based on $\sim 110 \text{ pb}^{-1}$, already tests the theoretical predictions [83] for this transition which range from 0.1–1.0%. Our program will measure the mass of the h_b , assuming the predictions are valid, to $\sim 5 \text{ MeV}/c^2$. In addition, the radiative transition to the η_b is predicted to have a branching fraction of $\mathcal{B}(h_b \rightarrow \gamma\eta_b) \sim 50\%$, affording another avenue to the discovery and/or verification of the η_b and a good measurement of their mass difference.

5.3.3.2.3 Observation of 1^3D_J states

The $b\bar{b}$ system is unique in that it has states with $L = 2$ that lie below open-flavor threshold (see Figure 43). These states have been of considerable theoretical interest, as indicated by the many predictions of the center-of-gravity (see Figure 45) of the triplet,

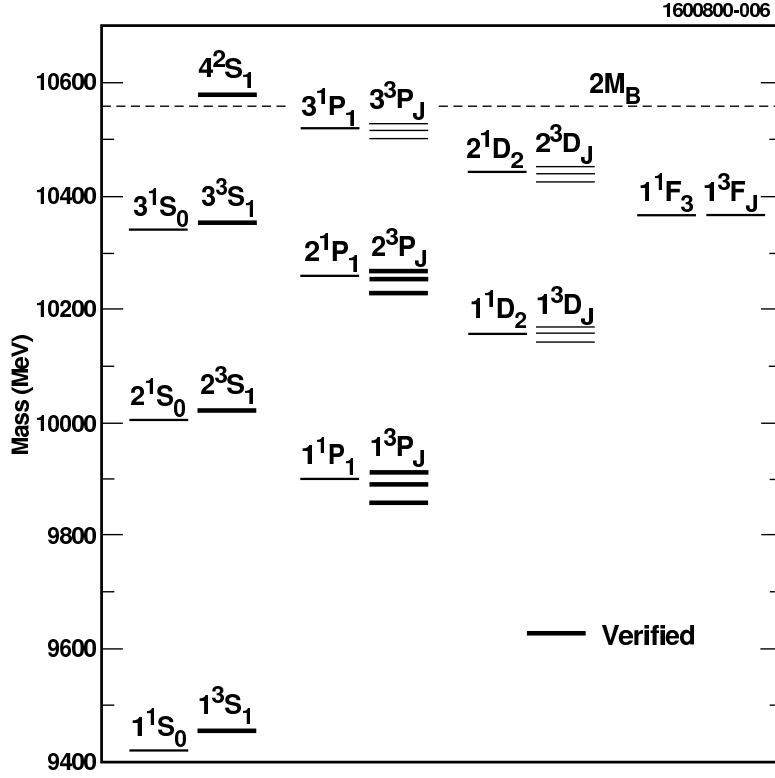


FIGURE 43. Approximate levels of the $b\bar{b}$ states. The names associated with the spin-parity assignments are: $^1S_0 = \eta_b$, $^3S_1 = \Upsilon$, $^1P_1 = h_b$, and $^3P_J = \chi_b$ (triplets with $J = 0, 1, 2$).

and by a recent review [84]. Unquenched lattice calculations [81] will soon give this *cog* to ~ 5 MeV.

Based on both theoretical estimates and our look at the previous data samples, CLEO should see 20-40 events in the four-photon cascade $\Upsilon(3S) \rightarrow \gamma_1 \chi'_b \rightarrow \gamma_1 \gamma_2 (^3D_J) \rightarrow \gamma_1 \gamma_2 \gamma_3 \chi_b \rightarrow \gamma_1 \gamma_2 \gamma_3 \gamma_4 \Upsilon(1S) \rightarrow \gamma_1 \gamma_2 \gamma_3 \gamma_4 \ell^+ \ell^-$. There may be some ambiguities and backgrounds from four-photon cascades that go through the $\Upsilon(2S)$ instead of through the D states. But, assuming we can pick out all three members of the triplet, we could measure the *cog* to perhaps ± 3 MeV.

Once the 1^3D_J states are observed in the four-photon cascade, we will know the approximate mass of the lowest state which has $J^{PC} = 1^{--}$ and can do a scan to produce this vector state in direct e^+e^- annihilations, thus independently establishing its mass and gaining a measure of the S - D mixing in the $b\bar{b}$ system.

5.3.3.2.4 Precision measurements of Γ_{ee} and Γ_{tot} for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$

Given that these three resonances are produced in e^+e^- annihilation, the integral of the hadronic line shape is proportional to $\Gamma_{ee} \Gamma_{had} / \Gamma_{tot}$. From this and rudimentary knowledge of the branching fraction to lepton pairs, one can extract Γ_{ee} . Examples of this for previous CLEO scans [95] are shown in Figure 46. While other experiments [11] have also measured

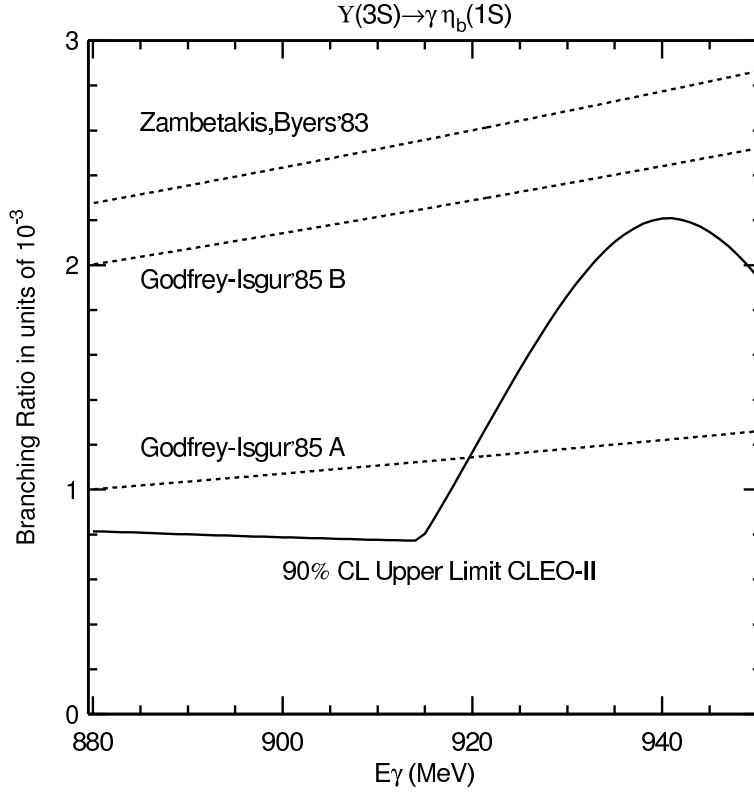


FIGURE 44. Upper limit on branching ratio for $\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$ plotted as a function of the photon energy (the solid line). The dashed lines represent several theoretical predictions.

this combination for the $\Upsilon(1S)$ and $\Upsilon(2S)$, only the old CLEO measurement exists for the $\Upsilon(3S)$; this situation is shown in Table 30. Scans of the line shape using 100 pb^{-1} at each resonance would give 3% measurements of Γ_{ee} for each, with some common systematic uncertainties that would cancel in their ratios. These widths are as important as the resonance masses for many models. Lattice QCD [81] hopes to be able to give individual Γ_{ee} values at the 4% level and ratios at the 2% level in the near future.

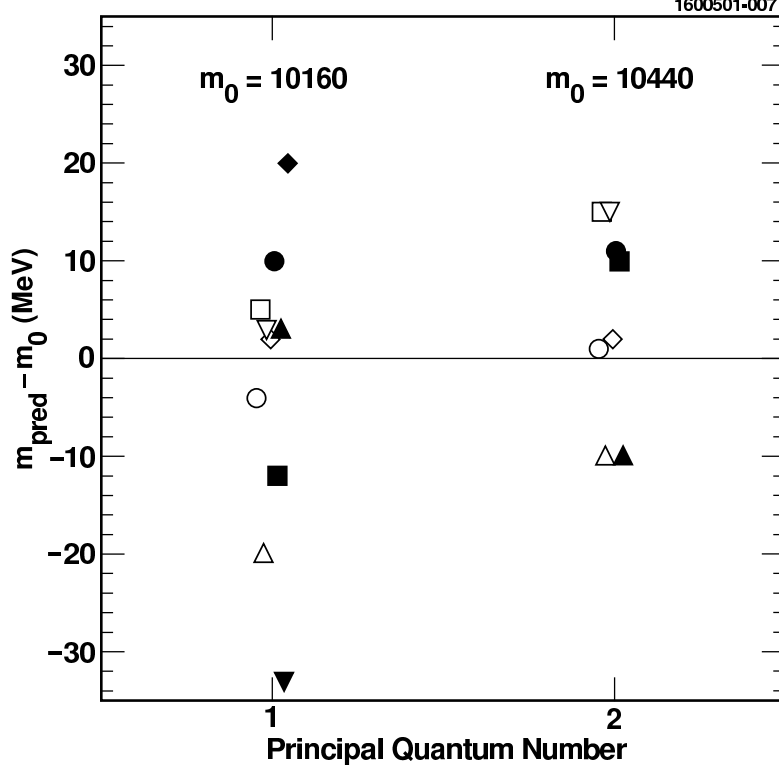


FIGURE 45. Predictions for the spin-weighted averages of ${}^3D_J b\bar{b}$ states. Open circle ($\circ$) - KR [85] - inverse scattering; open square ($\square$) - Cornell [86] - QCD-based potential; open triangle ($\triangle$) - BT [87] - QCD-based potential (published masses only quoted to nearest 10 MeV); open inverted triangle (∇) - Gupta *et al.* [88] - QCD-based potential; open diamond ($\diamond$) - MR [89] - QCD-based potential; solid circle ($\bullet$) - MB [90] - relativistic corrections - mass of ${}^3D_1$; solid square ($\blacksquare$) - GI [91] - QCD-based potential - *calculated* to nearest MeV; solid triangle - Grant *et al.* [92] - power-law potential; solid inverted triangle - EQ [93] - QCD-based potential [87] - only quoted for $n = 1$; solid diamond - Lattice [94] - quenched approximation with $\beta = 6.0$ - only quoted for $n = 1$.

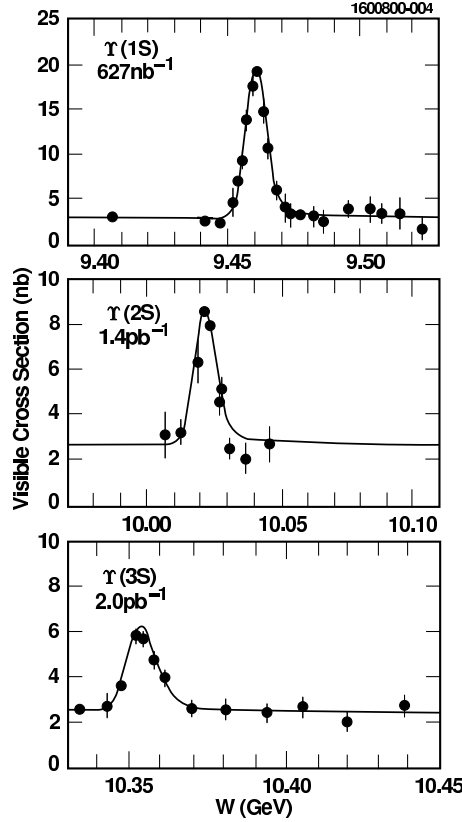


FIGURE 46. The line shapes for the three bound states from the CLEO publication [95] which determined the partial widths Γ_{ee} .

Having continuum data sets of roughly 100 pb^{-1} slightly below each resonance will allow us to measure the branching fraction to $\mu^+\mu^-$, $\mathcal{B}_{\mu\mu}$, to about 3.5% precision. Coupled with the precision measurements of Γ_{ee} , this allows Γ_{tot} to be measured to about 5%, which is a big improvement for the $\Upsilon(2S)$ and $\Upsilon(3S)$ [11]. These full widths, which are on the order of 40 keV, are not directly measured in their production due to the energy spread of the colliding beams (see Figure 42). Total widths are of interest to theorists in that they enter many perturbative QCD calculations.

5.3.3.2.5 Search for glueball candidates in radiative $\Upsilon(1S)$ decays

As detailed in the sections describing the physics reach of our running at the J/ψ , the BES collaboration has reported [47] signals for a glueball candidate in radiative J/ψ decay - a ‘glue-rich’ environment. This candidate is alternatively called $f_J(2220)$ or the $\xi(2230)$, the latter harking back to its earlier observation at MARK III. The measured product branching fractions $\mathcal{B}(J/\psi \rightarrow \gamma f_J) \times \mathcal{B}(f_J \rightarrow XY)$ are roughly 4×10^{-5} for $XY = \pi^+\pi^-, \pi^0\pi^0, K^+K^-, K_S K_S$ and $p\bar{p}$. Naively one would expect the exclusive radiative decay rate to be suppressed in Υ decay by a factor of $[(q_b m_c)/(q_c m_b)]^2$, which is roughly 40. This implies product branching fractions for Υ radiative decay of $\sim 10^{-6}$.

With 1 fb^{-1} of data we would have 2.4×10^7 Υ decays. Previous analyses suggest

TABLE 30. Table of results for $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ and Γ_{ee} ; values are in keV and uncertainties are in %.

Prior Results on Dilepton Widths						
Resonance	Group	$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ (keV)	Γ_{ee} (keV)	σ_{stat} (%)	σ_{syst} (%)	σ_{tot} (%)
$\Upsilon(1S)$	PDG2000	1.216				2.2
	MD1	1.187		1.9	2.6	
	CBAL	1.23		1.6	4.1	
	CLEO	1.37		4.3	6.6	
	DASP	1.23		6.5	3.2	
	ARGUS		1.32	3.0	2.5	
$\Upsilon(2S)$	PDG2000	0.553				4.1
	MD1	0.552		5.6	3.1	
	CBAL	0.54		7.4	3.7	
	CLEO	0.58		5.1	6.9	
	ARGUS		0.52	5.8	1.9	
$\Upsilon(3S)$	CLEO	0.45		6.7	6.7	

efficiencies on the order of 30%, so we would expect to see ~ 10 events in each of the exclusive channels. This would be important confirmation of the J/ψ studies and shed more light on the nature of such production.

There are *many* other interesting analyses that can be performed with data sets of roughly 1 fb^{-1} at each of the three bound state resonances. Among these are: measurement of $\mathcal{B}_{\tau\tau}$ for each of the three; hadronic transitions among the three; the inclusive γ spectrum for each of them; search for η'_b ; further studies of χ_b and χ'_b radiative decays and hadronic transitions between these P states; first significant measurements of radiative transitions from χ_{b0} and χ'_{b0} ; radiative decays $\Upsilon(1S) \rightarrow \gamma (f_2/\eta/\eta')$; inclusive $\Upsilon(1S) \rightarrow (J/\psi)X$ and $\Upsilon(1S) \rightarrow \psi'X$; two-body $\Upsilon(1S)$ and $\Upsilon(2S)$ decays to V - P ; search for vector $c\bar{g}\bar{c}$ hybrids in $\Upsilon(1S)$ decays; and baryon production in $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ decays.

5.3.3.3 Possible Running at Energies above the $\Upsilon(4S)$

Hybrid vector mesons of the form $b\bar{g}\bar{b}$ are predicted above the $\Upsilon(4S)$ but within the reach of CESR. These would be in the region shown in the insert of Figure 42. Even without such a hybrid, better data in this region would allow for a better understanding of the structures in the region and a determination of R in the five-flavor continuum. Given that the data in the insert of Figure 42 represent an integrated luminosity [96] of 70 pb^{-1} , a new run of $500\text{-}700 \text{ pb}^{-1}$ is contemplated at $\sqrt{s} \sim 11 \text{ GeV}$ as part of the resonance program.

6 Comparison with Other Facilities

To assess the impact of the CLEO-c physics program, we have compared the CLEO-c physics reach to the capabilities of other facilities that will be operating between now and 2006. The main competition for charm meson physics will come from the B -factory detectors, Belle and BaBar, which both operate at asymmetric energy e^+e^- storage rings with a center of mass energy of 10.58 GeV. The BESII detector operating at the BEPC accelerator will also collect data in the 3-5 GeV energy range in this period. Longer term, the Hall-D project at TJNAL will search for QCD hybrid states in a photo-production experiment, and both BEPC and BESII will be upgraded. Moreover dedicated heavy flavor experiments at hadron colliders will collect huge samples of charm data that will study rare and forbidden decays, mixing and CP violation asymmetries with unprecedented accuracy. We will focus our discussion on the B -factories, BES and Hall-D.

6.1 Comparison with B -factories

By the end of 2004, after integrating approximately 3 fb^{-1} each on the ψ'' resonance and above $D_s\bar{D}_s$ threshold, the CLEO-c data samples will include approximately 30 million $D\bar{D}$ pairs and approximately 1.5 million $D_s\bar{D}_s$ pairs. Approximately 20% of these events will have one D meson fully reconstructed. By the end of 2004, PEP-II anticipates delivering 400 fb^{-1} of data to BaBar [97]. Approximately $5 \times 10^8 c\bar{c}$ and $\tau^+\tau^-$ pairs will be contained in that data set. Belle hopes to have a comparable data set at that time. Babar and Belle will use their enormous data sets to do precision charm and tau physics in addition to B meson physics, just as CLEO has done for the past two decades. Many analyses will compete with CLEO-c analyses.

In order to assess the reach of the B -factories in measuring charm decay constants and branching fractions, we extrapolate from current CLEO analyses that have addressed this physics with smaller data samples. We acknowledge from the outset that such extrapolations are challenging, especially since many of the measurements of charm decay rates made at a center of mass energy of 10.58 GeV have significant backgrounds and significant systematic errors. Some error sources could be reduced using larger data samples. On the other hand, some errors are inherent and will not improve. Signal to background ratios can often be improved by reducing efficiencies, but aim is to improve statistical precision and backgrounds can have limiting systematic as well as statistical effects.

We present one example in detail. A summary of the reach of the B -factory detectors compared with CLEO-c for a variety of important measurements is given in Table 32.

To illustrate how we evaluate the B -factory reach, we use the measurement of f_{D_s} . CLEO has published a measurement of f_{D_s} based on 4.8 fb^{-1} of data [98]. In the CLEO measurement, $\Gamma(D_s^+ \rightarrow \mu^+\nu)$ is measured using the decay chain $D_s^{*+} \rightarrow D_s^+\gamma$; $D_s^+ \rightarrow \mu^+\nu$, where the γ and μ^+ are detected directly and the hermeticity of the detector is used to reconstruct the unobserved neutrino. Figure 47 shows the CLEO signal. The backgrounds, indicated in Figure 47 by the dashed line and shaded area, are large and the precision of the rate measurement is limited by the background determination. The current CLEO result is:

$$\Gamma(D_s^+ \rightarrow \mu^+\nu)/\Gamma(D_s^+ \rightarrow \pi^+\phi) = 0.173 \pm 0.023 \pm 0.035$$

with a 13% statistical error and a 20% systematic error. To extract the pseudo-scalar decay constant f_{D_s} , we use the value $\mathcal{B}(D_s^+ \rightarrow \pi^+\phi) = (3.6 \pm 0.9)\%$ [11] and get $f_{D_s} = (280 \pm 19 \pm 28 \pm 34)$ MeV where the third error is due to the uncertainty on the normalizing branching fraction.

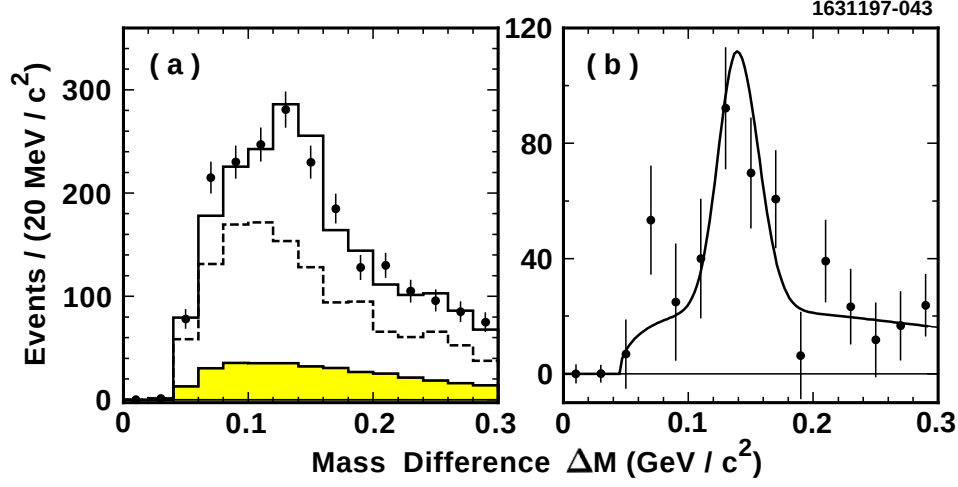


FIGURE 47. (a) The ΔM mass difference distribution for D_s^{*+} candidates for both muon (solid points) and electron (dashed histogram) data from CLEO. The shaded histogram is the excess of muon fakes over electron fakes. (b) The ΔM mass difference distribution for D_s^{*+} candidates with electron and muon fakes subtracted. The curve is a fit to the signal shape.

With a data sample of 400 fb^{-1} , the statistical error on $\Gamma(D_s^+ \rightarrow \mu^+\nu)/\Gamma(D_s^+ \rightarrow \pi^+\phi)$ will be negligible using the CLEO analysis method. Table 31 lists the contributions to the systematic error on the CLEO measurement and our attempt to estimate how these systematic errors will improve with almost 100 times more data.

A key feature of the CLEO analysis is the use of the decay $D_s^{*+} \rightarrow D_s^+\gamma$; $D_s^+ \rightarrow e^+\nu$, where the signal contribution is negligible, to provide an estimate of the backgrounds. A detailed understanding of muon and electron fake rates is required. In our judgment it will be difficult to improve the current errors on fake rates ($\sim (1 \pm 0.1)\%$ for muons and $(0.25 \pm 0.06)\%$ for electrons) by more than a factor of 2 – 3 even with 100 times the data sample. Similarly, the ratio of normalization of $\mu\nu$ and $e\nu$ events is not exactly 1 (the current value is 1.01 ± 0.03) and the error on this is dominated by understanding of detector material, inner Bremsstrahlung, and differences in e and μ detection efficiencies, all of which will be difficult to improve. Finally, the detection efficiency currently has an uncertainty of 7%, limited largely by the systematic error in the neutrino reconstruction efficiency. This will also be very difficult to improve even with much more data, because it is affected by several systematics, including not only tracking and photon detection, but also K_L and n detection.

The other entries in the systematic error table will improve more substantially with increased statistics. Our best estimate is that with 400 fb^{-1} , the B -factory detectors will measure $\Gamma(D_s^+ \rightarrow \mu^+\nu)/\Gamma(D_s^+ \rightarrow \pi^+\phi)$ with a precision of 6 – 12%. If we assume, based on

CLEO experience, that they will also measure $\mathcal{B}(D_s^+ \rightarrow \pi^+ \phi)$ with a precision of $6 - 12\%$, we conclude that the overall reach on f_{D_s} will be $6 - 9\%$.

TABLE 31. Summary of the systematic errors from the CLEO f_{D_s} analysis based on 4.8 fb^{-1} and projection of systematic errors to a 400 fb^{-1} data set.

Source of Error	Systematic Error (4.8 fb^{-1} data set)	Projected Systematic Error (400 fb^{-1} data set)
Muon fake rate	9	4 – 8
Electron fake rate	7	2 – 4
$\pi/K/p$ fractions (sources of fakes)	7	2
μ/e normalization	9	7 – 9
Detection efficiency	7	4 – 6
D_s^{*+}/D_s^+ production ratio	8	1
$\phi\pi^+$ normalization	3	< 1
Total systematic error (%)	20	10 - 14

We have considered alternative analysis strategies that might be possible with the enormous B -factory data samples to access this physics. For example, one might be able to use fully reconstructed B mesons to tag events and reduce backgrounds. Another possibility is to use events where, after radiation of a hard initial state photon, the effective center of mass energy is in the charm resonance region (radiative return events) [99]. All alternative analysis strategies give errors in the same range as quoted above or larger. While averaging several different analyses may help reduce overall errors, we note that systematic errors will dominate these analyses, making averaging problematic. Table 32 summarizes the B -factory reach compared with CLEO-c in a variety of interesting decay channels.

TABLE 32. Comparison of the physics reach of CLEO-c and the B -factories on a variety of physics topics.

Measurement	CLEO-c	B -factories (400 fb^{-1} data set)
f_{D^+}	2.3%	10 – * * * %
f_{D_s}	1.7%	6 – 9%
$\mathcal{B}(D^0 \rightarrow K^- \pi^+)$	0.6%	2 – 3%
$\mathcal{B}(D^+ \rightarrow K^- \pi^+ \pi^+)$	0.7%	3 – 5%
$\mathcal{B}(D_s^+ \rightarrow \phi \pi^+)$	1.9%	5 – 10%

6.2 BESII and BESIII

The BESII detector is operating at the BEPC e^+e^- storage ring in Beijing. The current luminosity of BEPC is $5 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$. Table 33 lists the current and projected BES data samples [100]. These data samples are orders of magnitude smaller than the anticipated CLEO-c data samples.

TABLE 33. Current and projected data samples for the BESII detector

Data	Energy(GeV)	Current	Projected
J/ψ	3.1	9M	35M
ψ'	3.69	3.7M	15M
ψ''	3.77		40 pb^{-1}
D_s	4.03	22.3 pb^{-1}	45 pb^{-1}

BES/BEPC is currently proposing to upgrade the machine and detector. The design goal for the machine has recently changed from a peak luminosity of $5 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ to consideration of a two-ring design with a peak luminosity in excess of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. The goals of the detector upgrade are energy resolution in the electromagnetic calorimeter of $10\%/\sqrt{E}$, improved TOF, a new low mass drift chamber, a new DAQ system to accommodate the increase in machine luminosity, and a new vertex chamber to accommodate the modified machine IR. The target date for completion of the machine and detector upgrades is 2005.

6.3 Hall-D

A program is underway at TJNAL to systematically explore the light mesons with masses up to $2.5 \text{ GeV}/c^2$ using photo production with the high quality, low emittance CW photon beams available at JLab. The program will be capable of exploring both light meson states and searching for exotic states in this mass region. A new detector is proposed along with an upgrade of CEBAF to 12 GeV operation. The target date for completing construction is in 2006.

While the goals of the Hall-D program and CLEO-c have some overlap, there is also substantial complementarity. CLEO-c focuses on glue rich states and vector hybrids, both light and heavy. Hall-D is more focussed on states with exotic quantum numbers.

Appendix A

The $e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$ Cross Section

The Mark III Measurement of $\sigma_{D\bar{D}}$

In our simulations, we use $\sigma_{D\bar{D}} = 10$ nb, for $e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$, with $\sigma_{D^0\bar{D}^0} = 5.8$ nb and $\sigma_{D^+D^-} = 4.2$ nb. This is based partly on the MARK III double-tag measurements [3]. Patrick Roudeau [1] pointed out that this is a misreading of the MARK III paper. The paper actually states: $\sigma_{D^0} = (5.8 \pm 0.5 \pm 0.6)$ nb and $\sigma_{D^+} = (4.2 \pm 0.6 \pm 0.3)$ nb, so $\sigma_D = (10.0 \pm 1.0)$ nb. However, a footnote in an earlier paper [2] states that the corresponding numbers in that paper are the cross sections for single D 's, rather than for $D\bar{D}$. Since $\sigma_D = 2\sigma_{D\bar{D}}$, this footnote implies that $\sigma_{D\bar{D}} = 5$ nb [101] instead of 10 nb.

MARK III [3] also reported the total number of produced $D\bar{D}$ events, $N_{D^0\bar{D}^0} = 27,700 \pm 2,400 \pm 2,600$ and $N_{D^+D^-} = 20,300 \pm 2,900 \pm 1,100$ (after efficiency corrections) and a luminosity of 9.56 pb^{-1} . These numbers give $\sigma_{D^0\bar{D}^0} = 2.9 \pm 0.4$ nb and $\sigma_{D^+D^-} = 2.1 \pm 0.3$ nb, so $\sigma_{D\bar{D}} = 5.0 \pm 0.5$ nb in agreement with the footnote [2]. If there are no other decay modes of the ψ'' ($\psi(3770)$) than $D^0\bar{D}^0$ and D^+D^- , and if MARK III data were taken at the peak of the ψ'' , then $\hat{\sigma}_{\psi''}$ (the peak value of the ψ'' production cross section) would be $\sigma_{D\bar{D}}$. This value of $\hat{\sigma}_{\psi''}$ is labeled “MARK III” in Figure 48.

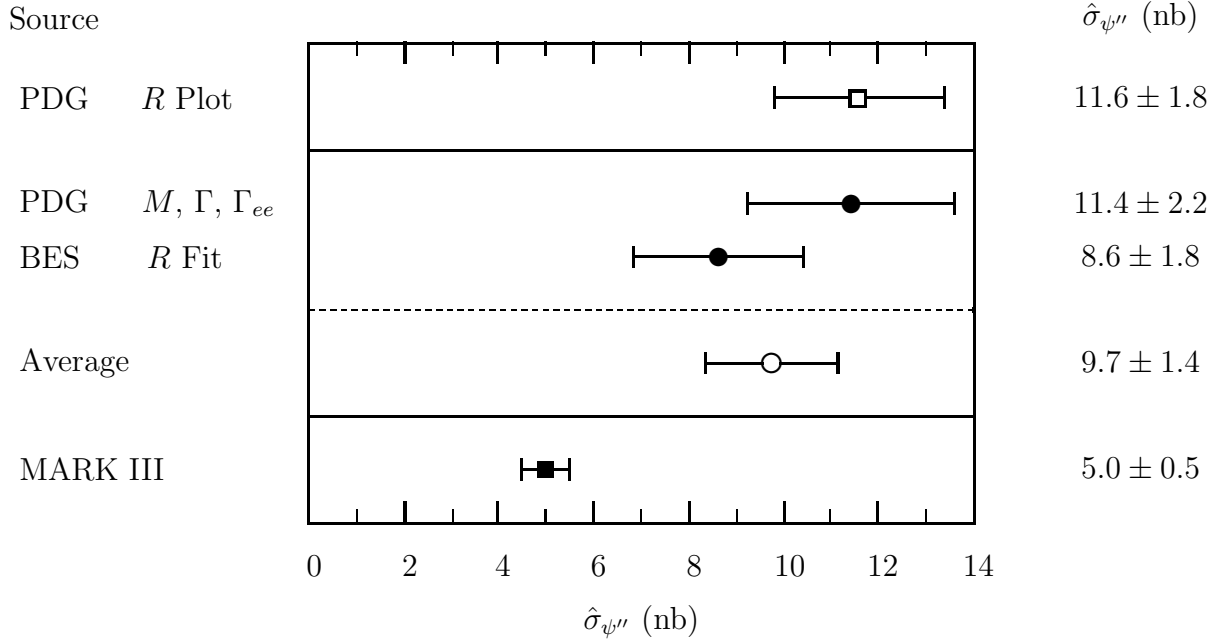


FIGURE 48. Measurements of the peak cross section $\hat{\sigma}_{\psi''}$ for $e^+e^- \rightarrow \psi''(3770)$. The value labeled Average is the average of the “PDG M, Γ, Γ_{ee} ” and “BES R Fit” values. The MARK III value is actually their value of $\sigma_{D\bar{D}}$.

Measurements of the ψ'' Production Cross Section

The Breit-Wigner cross section for $e^+e^- \rightarrow V$ (where V is a neutral vector meson) is

$$\sigma(V) = \sigma(e^+e^- \rightarrow V) = \frac{3\pi\lambda^2}{4} \frac{\Gamma_{ee}\Gamma}{(W-M)^2 + \Gamma^2/4} \quad (19)$$

where Γ_{ee} and Γ are the electronic and total widths, respectively, M is the mass of the vector meson, $W = \sqrt{s} = E_{cm}$ is the center-of-mass energy, and $\lambda \equiv \lambda/(2\pi) = 1/p_e$ where p_e is the momentum of the electrons and positrons in the center of mass. The peak cross section at $W = M$ is

$$\hat{\sigma}(V) = (3\pi\lambda^2) \frac{\Gamma_{ee}}{\Gamma} . \quad (20)$$

Since the mass of the electron is small, $\lambda = 1/p_e \cong 2/W = 2/M$,

$$\hat{\sigma}(V) = \frac{12\pi}{M^2} \frac{\Gamma_{ee}}{\Gamma} . \quad (21)$$

According to the PDG [11], $M = 3,769.9 \pm 2.5$ MeV, $\Gamma = 23.6 \pm 2.7$ MeV, and $\Gamma_{ee} = 0.26 \pm 0.04$ keV, for the $\psi(3770)$ resonance, so

$$\hat{\sigma}_{\psi''} = 11.4 \pm 2.2 \text{ nb}, \quad (22)$$

in excellent agreement with 10 ± 1 nb but not with 5.0 ± 0.5 nb. (Correlations between Γ and Γ_{ee} were ignored in estimating the error of $\hat{\sigma}_{\psi''}$.) This value of $\hat{\sigma}_{\psi''}$ is labeled “PDG M, Γ, Γ_{ee} ” in Figure 48.

Another method of estimating $\hat{\sigma}_{\psi''}$ is to estimate $\hat{R}_{\psi''}$ (the peak value of R) from the plot of R versus E_{cm} [102] in the PDG. This gives $\hat{R}_{\psi''} = 1.9 \pm 0.3$ after subtracting interpolated background contributions estimated by hand. Since the cross section for $e^+e^- \rightarrow \mu^+\mu^-$ is

$$\sigma_{\mu\mu} = \frac{86.8 \text{ nb}}{W^2 (\text{GeV})^2} , \quad (23)$$

$\sigma_{\mu\mu} = 6.1$ nb at $W = 3,770$ MeV. Combining this with the estimated $\hat{R}_{\psi''}$ value gives, $\hat{\sigma}_{\psi''} = 11.6 \pm 1.8$ nb. This value is labeled “PDG R Plot” on Figure 48.

Recent BES data on $R(W)$ [103] provide an additional estimate of $\hat{R}_{\psi''}$ and $\hat{\sigma}_{\psi''}$. A fit of their data in the neighborhood of the ψ'' to a Breit-Wigner and a linear background yields, $\Gamma = 27.9 \pm 5.3$ MeV, in excellent agreement with the PDG value $\Gamma = 23.6 \pm 2.7$ MeV given above. The area of the Breit-Wigner from the fit is $A = 61.7 \pm 13.1$ MeV. The relationship between the area of the Breit-Wigner and $\hat{R}$ is

$$\hat{R} = \frac{\pi A}{(2\Gamma)} \quad (24)$$

so $\hat{R}_{\psi''} = 1.4 \pm 0.3$ and $\hat{\sigma}_{\psi''} = 8.6 \pm 1.8$ nb. This value is labeled “BES R Fit” on Figure 48. (The correlation between A and Γ is ignored in estimating the error in $\hat{R}$.)

Two measurements, the “PDG M, Γ, Γ_{ee} ” and the “BES Fit” are independent and can be averaged. The result is $\langle \hat{\sigma}_{\psi''} \rangle = 9.7 \pm 1.4$ nb. This average is not very consistent with

the MARK III value: $\chi^2 = 10.4$ for $n_{\text{degf}} = 1$ or $p(\chi^2) = 0.14\%$. The agreement between the PDG M, Γ, Γ_{ee} and the MARK III values is also not great: $\chi^2 = 8.0$ for $n_{\text{degf}} = 1$ or $p(\chi^2) = 0.46\%$. However, BES alone is not in serious disagreement with MARK III: $\chi^2 = 3.7$ for $n_{\text{degf}} = 1$ or $p(\chi^2) = 5.4\%$.

These estimates suggest that $\hat{\sigma}_{\psi''} \approx 10$ nb, whatever the value of $\sigma_{D\bar{D}}$ may be.

Earlier Measurements of σ_D

There is yet another way to determine the branching fractions of the $\psi(3770)$ to single D 's. Several experiments [104,105,106] have published their results, at this energy in terms of the products of the D production cross-section times the value of the branching fraction for the analyzed D final state. These values have been collected in [3].

Using the current PDG values of D^0 and D^+ branching fractions it is possible to obtain values for σ_{D^0} and σ_{D^+} . The averages of the results from each experiment are given in Figure 49. The averages are in good agreement with the MARKIII results interpreted as σ_D rather than $\sigma_{D\bar{D}}$.

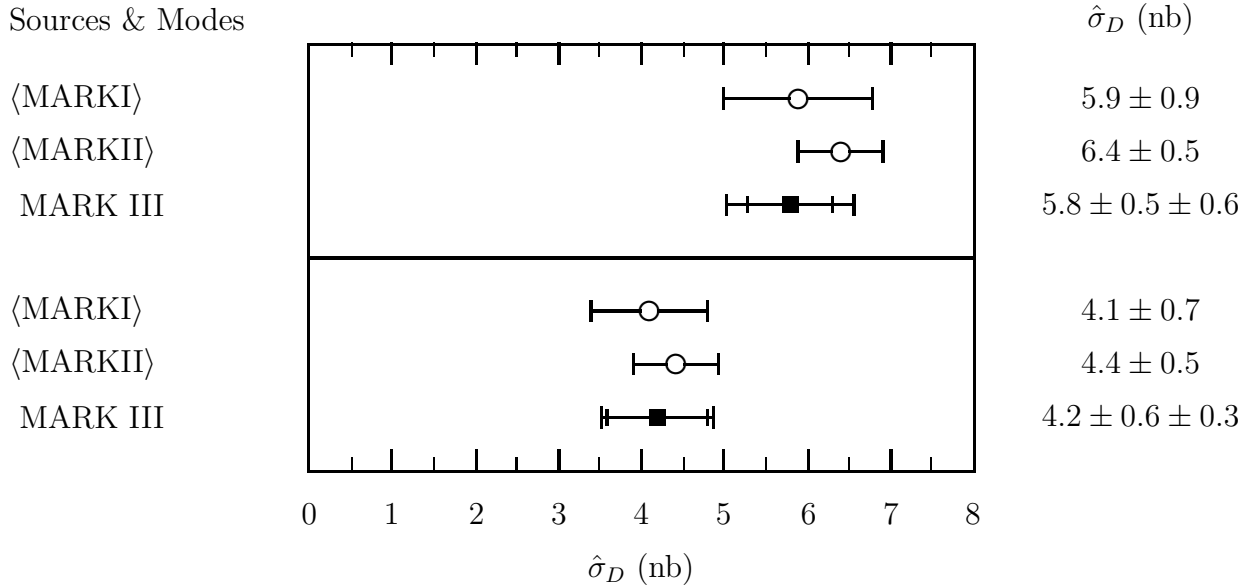


FIGURE 49. The cross sections σ_{D^0} and σ_{D^+} that were obtained from measurements of $\sigma(e^+e^- \rightarrow \psi'') \mathcal{B}(\psi'' \rightarrow DX)$, compared to MARK III results.

The dependence of the PDG branching fractions on MARK I, MARK II, and MARK III measurements is a possible concern in this check of D production cross sections. Briefly, the PDG value for the reference branching fraction for D^0 modes, $\mathcal{B}(D^0 \rightarrow K^-\pi^+) = (3.83 \pm 0.09)\%$ is dominated by CLEO and ALEPH measurements with significant contributions from ARGUS, none of which ran at the charm threshold. MARK I, MARK II, and MARK III measurements are included in the average but their weights are not substantial. In the PDG value for the reference branching fraction for D^+ modes, $\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^+) = (9.0 \pm 0.6)\%$, the sum of the weights of the MARK I, MARK II, and MARK III measurements is close to the weight of the CLEO measurement. In any event, the PDG uncertainties, 2.4% and 7%, in the reference branching fractions for D^0 and D^+ decays, respectively, are very much

smaller than the factor of 2 discrepancy that we are trying to understand or resolve. Even if we have some doubts concerning the accuracy of the PDG uncertainties, it would be very difficult to accommodate a factor of 2 in these reference branching fractions.

Values of $\sigma_{D\bar{D}}$ Used in Tau-Charm Workshops

It appears that earlier tau-charm workshops [107,108,109,110] have generally – but not always – used $\sigma_{D\bar{D}} = 5$ nb. In fact, the cross sections and/or the luminosities used are not always stated clearly in the workshop reports, leading to some confusion. In some cases $\sigma_{D\bar{D}} = 10$ nb even appears explicitly in transparencies or reports. Hence, these workshops do not provide an unambiguous guide for what production cross sections to use.

Discussion

There are a number of possible sources of the apparent discrepancy between measurements of the cross section for D production and the ψ'' cross section. For example, it is possible that:

- there is a factor of 2 misunderstanding somewhere or
- the ψ'' has decay modes other than $D^0\bar{D}^0$ and D^+D^- and $\mathcal{B}(\psi'' \rightarrow D\bar{D}) \sim \frac{1}{2}$ or
- MARK III was not actually taking data at the peak of the ψ'' or
- the resonance shape of the ψ'' is very different from a Breit-Wigner resonance shape and this somehow introduces a discrepancy between $\hat{\sigma}_{\psi''}$ and $\sigma_{D\bar{D}}$ or
- some other systematic error(s) that are not well understood in one or more of the experiments are large enough to accommodate the apparent discrepancy.

There is not enough information at this time to sort out which of these possibilities is really correct.

If we assume that the systematic errors are reasonably well-understood in all of the experiments that measure the ψ'' cross section and D decays at the ψ'' , then it is very difficult to escape the conclusion that some of the hadronic cross section in the ψ'' peak is not due to $c\bar{c}$ pairs. On the other hand, this is *very hard* to understand for a number of reasons, including:

- The ψ'' is quite wide while the ψ' is very narrow. The most obvious significant difference between these two very closely spaced states is the fact that the $D\bar{D}$ threshold lies between them.
- From the agreement between single and double tag measurements of the B meson semileptonic branching fraction, the $\Upsilon(4S)$ appears to decay to $b\bar{b}$ only.

The ψ'' is thought to be a mixture of $^3D_1$ and $^3S_1$ states, but it is hard to imagine how this could reduce the $\psi'' \rightarrow D\bar{D}$ branching fraction to something near $\frac{1}{2}$.

Conclusions

After studying the information available, we have decided to use $\sigma_{D\bar{D}} = 10$ nb based on the value of $\hat{\sigma}_{\psi''}$ determined from measured values of the resonance parameters Γ_{ee} and Γ of the ψ'' and the assumption that the ψ'' decays only to $D^0\bar{D}^0$ and D^+D^- . We will certainly be able to measure both $\hat{\sigma}_{\psi''}$ and $\hat{\sigma}_{D\bar{D}}$ with high precision. If it turns out that:

- $\hat{\sigma}_{D\bar{D}} = \hat{\sigma}_{\psi''} \sim 10$ nb, then we have made the correct choice for our estimates of rates and statistical errors in D^0 and D^+ measurements, or
- $\hat{\sigma}_{D\bar{D}} = \hat{\sigma}_{\psi''} \sim 5$ nb, then the statistical errors for D^0 and D^+ measurements in this document would increase by a factor of $\sqrt{2}$ above our estimates, or
- $2\hat{\sigma}_{D\bar{D}} \approx \hat{\sigma}_{\psi''} \sim 10$ nb, our understanding of the charmonium system will be profoundly affected.

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