Semileptonic Decays of D_s Particles

Maria Castro and Katherine Plass
Department of Physics
Wayne State University, Detroit, MI, 48202

Abstract

The aim of the analysis is to detect the decays of the D_s particle into $\pi^0\ell\nu$ and $\omega\ell\nu$. The purpose is to test the theory of intrinsic states. The decays of D_s into $\eta\ell\nu$ and $\phi\ell\nu$ are used to normalize the branching ratios of D_s into $\pi^0\ell\nu$ and $\omega\ell\nu$. Since the η and the ω share a common decay mode, and the η and the π^0 share a common decay mode, we can compare their respective reconstruction, and in normalization, many of the systematic errors cancel out. The η and ϕ decays of the D_s have previously been well measured at CLEO. We used CLEO II and CLEO II.V detector data taken at the Cornell Electron Storage Ring.

Introduction

Present theories of meson structure predict that mesons are quark-antiquark pairs [1], while intrinsic state theory predicts mesons are made up of additional quark-antiquark pairs [2]. To test the intrinsic state theory, we look for the semi-leptonic decays of the D_s meson. Semi-leptonic decays of a meson are decays into a lepton (ℓ), a neutrino (ν), and a hadron. We look for $D_s \to \pi^0\ell\nu$ and $D_s \to \omega\ell\nu$, which are suppressed by current theory, as well as the previously observed decays of $D_s \to \eta\ell\nu$ and $D_s \to \phi\ell\nu$ [3]. If the D_s^+ particle is made up only of $c\bar{s}$, and the D_s^- is only $\bar{c}s$, then when the charm quark decays into a lepton, a neutrino, and a strange quark, only hadrons which have a $s\bar{s}$ component will be formed (Fig. 1). The decays of $D_s \to \eta\ell\nu$ and $D_s \to \phi\ell\nu$ are allowed by this theory, as they have a large $s\bar{s}$ component [1]. The decays of $D_s \to \pi^0\ell\nu$ and $D_s \to \omega\ell\nu$ are not predicted at the 10% level because ω and π^0 do not have a significant $s\bar{s}$ makeup. The quark makeup of the π^0 is $\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$, and the ω is $\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$ [4]. One way the D_s can decay into hadrons with no strangeness is if other quarks are present in the D_s particle to provide the $u\bar{u}$ and $d\bar{d}$ components (Fig. 2).

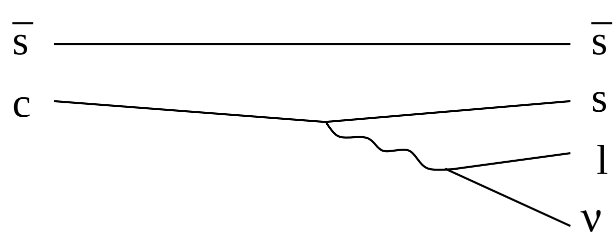

FIGURE 1. A Feynman diagram of the semileptonic decay of D_s^+ in the Standard Model.

The particles we are looking for, the ϕ, ω, η, and π^0, do not live long enough to be detected by CLEO. We must use tracks and energy left by their decay products, which are photons, kaons, pions, and leptons, to reconstruct where the particle have been, how

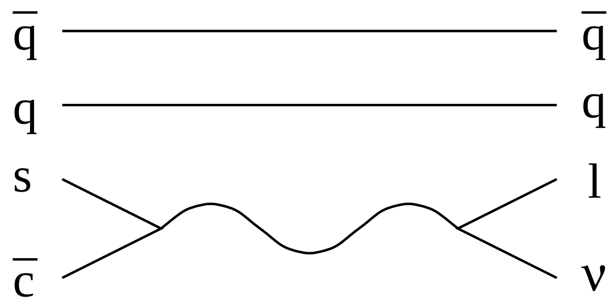

FIGURE 2. A Feynman diagram of the semileptonic decay of D_s^+ with Intrinsic states.

fast were they moving, how much energy they were made of, where they decayed and what they decayed into. CLEO collects important information about the particles including the momentum of the particle, its charge, and how much energy it deposits into the calorimeter. To reconstruct and analyze these decays, we use information on the tracks and showers contained in the CLEO II and the CLEO II.V reprocessed data sets. The collective data set contains e^+e^- collision events with center-of-mass energies on the $\Upsilon(4S)$ resonance and in the nearby continuum. From the information in the data, we reconstruct events using relativistic mechanics, conservation laws, and well measured decays of other particles.

We skim through all of the data, looking for events rich in $D_s \rightarrow X\ell\nu$, where X is η, ϕ, ω, or π^0. We use a tag analysis where we look for a low momentum photon from the decay of $D_s^* \rightarrow D_s\gamma$. We also look for events that contain a lepton, and a π^0, an ω, an η, or a ϕ. We look for the decays of $\phi \rightarrow K^+K^-$, $\eta \rightarrow 2\gamma$, $\eta \rightarrow \pi^+\pi^-\pi^0$, $\omega \rightarrow \pi^+\pi^-\pi^0$, and $\pi^0 \rightarrow 2\gamma$. The neutrino is non-reactive and not charged. It does not interact with CLEO and must be reconstructed indirectly. Several methods of neutrino reconstruction were tried and are discussed below. Event selection criteria are applied and the invariant mass of the X, lepton, and neutrino combination is calculated. We look for combinations with an invariant mass consistent with the invariant mass of the D_s particle.

Our Analysis

CLEO runs at a center of mass energy on the $\Upsilon(4S)$ resonance (10.58 GeV) and in the continuum approximately 50 MeV below this resonance. At the $\Upsilon(4S)$ energy level, B mesons are produced with low background. However, three and a half times more continuum events are produced and detected by CLEO.

The reason for difference is in the way that decays in continuum and B events take shape. A continuum event is “jet-like” because the charm and anti-charm quark take with them most of the energy and momentum of the collision, forming an elongated event. In the hard fragmentation, the D_s will be very energetic, but many other low momentum quarks are produced in the jet. The continuum event is littered with particles that we are not interested in observing for this analysis.

The B event has the potential to produce much less background because only the B mesons are formed, almost at rest from the $\Upsilon(4S)$. The daughters of the B, one being the D_s particle, share the energy and momentum nearly equally. The momentum and energy is shared neatly between a small population of particles.

In order to suppress the combinatoric background due to low momentum particles produced in the continuum event, we take advantage of the hard fragmentation of the charm and anti-charm quarks. We require that the momenta of the final states be more energetic than those in the B event decays. For example, in reconstructing a π^0 in a continuum event, we require its momentum to be at least 1 GeV where in the B event reconstruction the π^0 is required to have a minimum momentum of 130 MeV.

One important restriction we put on the B event is a D-tag. We use only B events that have a D, a D^*, or a D^{**} from the decay of B$\rightarrow$ $D^{(*)(*)}$ D_s^*. Though tagging the B events greatly reduces efficiencies, it aids in neutrino reconstruction. We know the mass and momentum of the D particles in the collision and we can kinematically constrain the neutrino missing from the event.

For both B-events and continuum events, we require a D_s^*-tag. We look for a photon which came from the decay of $D_s^* \rightarrow D_s\gamma$. The tagging method is used to reduce the background due to $X\ell\nu$ combinations not coming from the D_s decay.

All of the mesons we are looking for have such short lifetimes that they decay in the detector. The η and the ω share a common decay mode and the η and the π^0 share a common decay mode. This commonality is beneficial because we can compare their respective reconstructions. In normalization, many of the systematic errors cancel out. In order to reconstruct the π^0 and η, we look for their decays into two photons. We look for ω and η decays into $\pi^+\pi^-\pi^0$. We also look for $\phi \rightarrow K^+K^-$, as a test of our accuracy and sensitivity.

Data Selection

Here we discuss some basic cuts used for determining which events were likely to contain the desired decay modes of the D_s. An extensive list of the cuts we use to reconstruct the $\pi^0, \phi, \omega, \eta$ and the D_s mesons is included in Tables 1-4.

Events is this analysis are required to be class 10 events, which means that they are events likely to be hadronic. The event must have a minimum of three charged tracks and the energy in the calorimeter must be greater than 15% of the center of mass energy. We also require that all the tracks be well reconstructed. We select as photons the energy clusters in the calorimeter which are not matched to tracks.

In finding π^0 candidates, paired photons are kinematically constrained to the π^0 mass to improve momentum resolution. We require the invariant mass of the combined photons to be within 3σ of the π^0 invariant mass, where sigma is equal to the rms mass resolution. The π^0 candidates are required to have a minimum momentum to reduce random combinations of low momentum photons.

Leptons are required to be well-constructed. Electron and muon candidates are required to be energetic and lie in the fiducial regions $|\cos\theta| < 0.905$ and $|\cos\theta| < 0.81$, respectively, where θ is the polar angle of the track with respect to the beam axis. This ensures that the leptons are well reconstructed because the leptons aren't hitting the end cap, and the background in this region tends to have low momentum. The leptons are selected using quality cuts. The muons selected have to traverse five interaction lengths of iron into the muon chamber. In addition, electrons from photon conversions are excluded by requiring that the electron candidate, when paired with another track of opposite charge, have an invariant mass greater than 20 MeV.

Single photons are selected from energy clusters in the electromagnetic calorimeter. The cluster is required not to be paired with other photon candidates to form a π^0, and to have a transverse shape consistent with an electromagnetic shower.

In constructing the $\eta \rightarrow 2\gamma$, we require that the invariant mass of the two photons be consistent with the η mass. We veto any photon which, when combined with another photon, has invariant mass consistent with the π^0 mass and combined momentum greater than 0.8 GeV. This cut suppresses background photons from π^0 decays. To further suppress combinatoric background, we require the η candidates to have a minimum momentum. For the continuum analysis, we add a cut to the decay angle of the photons in the η rest frame. This reduces the error in the photon energy by requiring that the momentum be shared between the photons equally. These cuts were taken from a previous analysis [3].

In constructing η and $\omega \rightarrow \pi^+\pi{-}\pi^0$, two oppositely charged pion tracks are combined with a π^0 candidate. We require that the tracks have specific ionization consistent with a pion. Candidates were required to have an invariant mass consistent with an η or ω. For continuum events, we cut on $|\cos\theta|$, where θ is the angle with respect to the beam axis, for the pions and the photons of the π^0. Additionally, we cut on the energy of the photons and the π^0 momentum, to further reduce the background.

We reconstruct $\phi \rightarrow\ K^+K^-$ because this decay from the D$_s$ has been previously detected by the CLEO collaboration [3]. We require that the specific ionization of the tracks be consistent with a kaon. We make mass and momentum cuts. These cuts were taken from a previous analysis [3].

The neutrino is reconstructed using the methods described in the next section.

Each of the above mesons, π^0, ϕ, ω, and η are then combined with a lepton and a reconstructed neutrino to form the D$_s$ candidates. When reconstructing the D$_s$ from the continuum events, we require that the combinations of particles be in the same hemisphere of the event. For both the B and continuum events, we make sure that the tracks we are using for reconstruction are only used once in each combination. This reduces the background due to misidentification of a track.

Tables 1 and 2 show a list of cuts on continuum events. Tables 3 and 4 show a list of cuts on B events.

Neutrino Reconstruction Methods

Different neutrino reconstruction methods were tried for the continuum and B-events. The different methods took advantage of different aspects of the decays. The first method for the continuum events treats CLEO as an hermetic detector, trying to measure all energy and momentum in the event. The second method also applies to the continuum events, taking advantage of the fact that almost all momentum in the event is given to the D$_s^*$. The third method is for the B events, and uses the knowledge of the entire decay from the B meson. These methods all made different assumptions and had different advantages.

The first method used for continuum events simply tries to measure everything in the detector. We measure all of the energy in the calorimeter, and all of the momentum of the charged tracks. Neutrinos are nearly massless, so an event missing a neutrino should have the missing momentum approximately equal to the missing energy Eq. (1). We reconstruct the events using the neutrinos that fit this parameter.

$$E_{missing} = p_{missing} \tag{1}$$

The inefficiency in this method is due to the fact that CLEO is an imperfect detector. Rarely is all energy and momentum detected. Particles fly down the beam pipe, or hit inactive parts of the detector, introducing error into the calculated missing mass.

The second method makes more assumptions about the decay, while reducing the error in measurement. We find the energy and momentum of neutrinos in continuum events assuming that the D_s^* traveled along the thrust axis. The momentum of all tracks was subtracted from twice the beam energy (all the energy going into the event), and we calculate the missing momentum. There is less error in measuring the momentum of all tracks in the detector than there is with measuring the energy because the momentum resolution is far better. We then calculate the missing momentum, assume it is equal to the missing energy, and calculate a missing invariant mass. The missing energy was assumed to equal the missing momentum. We assume that the momentum vector of the neutrino added to the momentum vector of the $X\ell\gamma$ combination will be in the direction of the thrust axis. The momentum of the neutrino is given by Eq. (2), where $\hat{r}$ is the unit vector in the direction of the thrust axis.

$$\vec{p}_\nu = \vec{p}_{transverse} + \vec{p}_{longitudinal} = -(\vec{p}_{X\ell\gamma} - \hat{r}(\vec{p}_{X\ell\gamma} \cdot \hat{r})) + (\vec{p}_{missing} \cdot \hat{r})\hat{r} \tag{2}$$

All neutrinos found by this method were combined with the $X\ell\gamma$ combination used to calculate it. We feel justified in making the assumption that the D_s^* takes nearly all of the beam energy because it is so massive it would leave little energy left in the jet.

For the B-events, the neutrino was reconstructed using our knowledge of the entire decay from the B. For B-events we require that there be a D, a D^*, or a D^{**}, coming from the decay of $B \to D^{(*)(*)} D_s^*$. The overall decay from the $\Upsilon(4S)$ shown in Fig. 3. As the $\Upsilon(4S)$ decays into either $B^0\bar{B}^0$ or B^+B^-, we know that each B has the beam energy. We then get four constraints we use to solve for the energy and momentum of the neutrino. We know the energy of all other products of the decay of the B, allowing us to use Eq. (3) to calculate the energy of the neutrino.

$$E_\nu = E_{beam} - E_D - E_X - E_\ell - E_\gamma \tag{3}$$

The invariant mass of the D, X, ℓ, γ,and neutrino must give the B mass, while the X,ℓ, γ and neutrino must give the D_s^* mass. Solving these three equations gives us the energy and momentum vector of the neutrino.

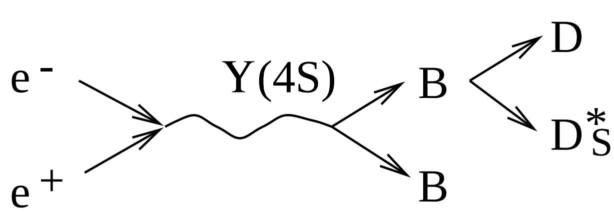

FIGURE 3. A Feynman diagram of the Decay of B Events

Conclusions

The $D_s \to \pi^0\ell\nu$ was not found for either of the continuum analyses (Fig. 4). Many π^0s are formed in every event, leading to a very large background. Requiring combinations of higher energy π^0s may allow this decay mode to be seen in the future.

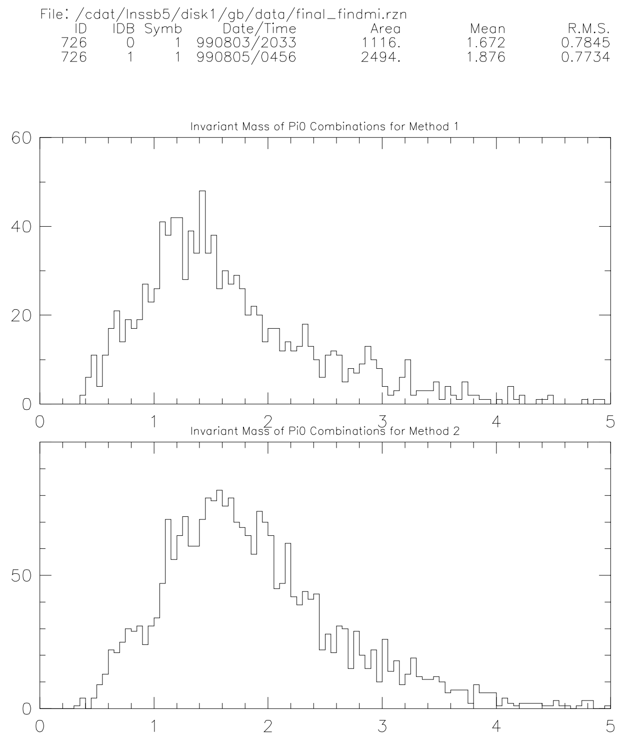

FIGURE 4. (top figure) $\pi^0\ell\nu$ invariant mass using neutrinos from direct calculation. (bottom figure) $\pi^0\ell\nu$ invariant mass using the thrust axis to find neutrinos.

For the continuum analysis which used neutrinos calculated directly from the missing energy and momentum in the event, we observed the decays of $D_s \to \eta\ell\nu$, for both decay modes of η, the decay $D_s \to \omega\ell\nu$, and $D_s \to \phi\ell\nu$ (Fig. 5). The figures show the invariant mass of $X\ell\nu$ combinations which have a photon tag from the $D_s^* \to D_s$ decay. Peaks can be seen at approximately, 1968 MeV, the mass of the D_s particle [1]. The η decay channels show less distinct peaks than the ϕ and ω decay modes. The ω has a much higher background than the rest of the decays. We reduce the background in the ω decay by cutting on the angle of the pions with respect to the D_s in the ω rest frame. Because ω has an angular momentum, the pions will tend to decay perpendicular to the direction of the D_s. Cutting out the ω candidates made of pions traveling along the D_s direction reduces background and improves the signal to noise ratio (Fig. 6) [5].

For the continuum analysis which assumed the D_s^* to be moving along the thrust axis, we observed peaks at the D_s mass for $D_s \to \eta\ell\nu$,$D_s \to \phi\ell\nu$, and $D_s \to \omega\ell\nu$. The peaks are less distinct than those for the other continuum analysis Fig. 7. This leads us to believe that the first neutrino reconstruction method was superior.

For the B event analysis, neither the decays of $D_s \rightarrow \phi\ell\nu$ nor $D_s \rightarrow \omega\ell\nu$ were detected. We mistakenly cut too hard on the ω and ϕ. We required the momentum to be too great, which drastically reduced our signal. We do not see the decays of $D_s \rightarrow \eta\ell\nu$ due to problems with our program.

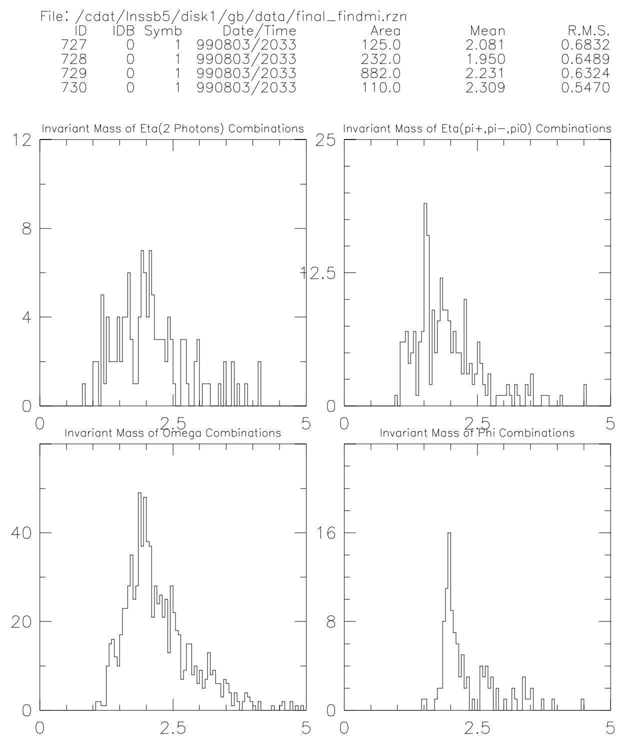

FIGURE 5. Continuum mass plots made using neutrinos from direct calculation.

Acknowledgments

We are pleased to acknowledge Prof. Giovanni Bonvicini of Wayne State University, who proposed this Research Experience for Undergraduates project and guided our effort. We would like to acknowledge the help of D. Cinabro, of Wayne State University, in preparing us for this project and in conducting the project. A special thanks to CLEO graduate students, Sean McGee of Wayne State University, Anton Eppich of UC Santa Barbara, and Elliot Lipeles of Caltech, for answering our questions and encouraging our research. This work was supported by National Science Foundation REU grants PHY-9820306 and PHY-9731882 and research grant PHY-9809799.

Footnotes and References

1. Particle Data Group, C. Caso *et al.*, Eur. Phys. J. **C 3**, 1 (1998)
2. Brodsky, S.J., SLAC-PUB-7645, (1997)
3. CLEO Collaboration, G. Brandenburg *et al.*, Phys. Rev. Lett. **77** 3804, (1995).
4. Halzen, F., Martin A.D., "Quarks and Leptons: An Introductory Course in Modern Physics", (1994)
5. CLEO Collaboration, R. Balest *et al.*, Preprint, CLNS 97/1479 CLEO 97-8, (1997)

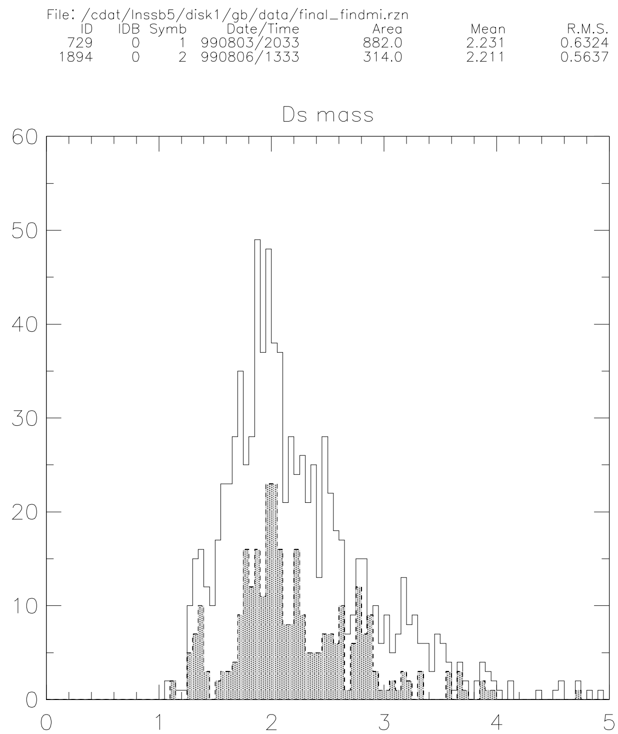

FIGURE 6. $\omega\ell\nu$ plots before and after cuts on decay angle of pions.

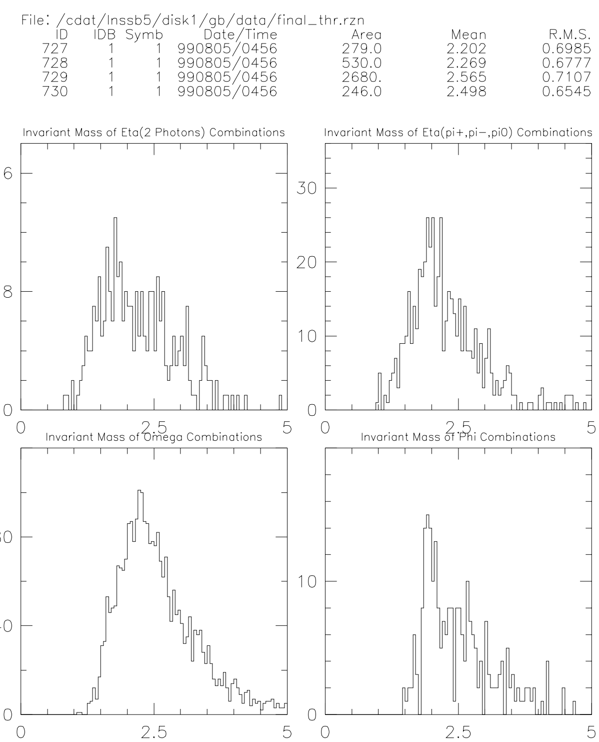

FIGURE 7. Continuum mass plots made using the thrust axis to find neutrinos.

TABLE 1. Cuts On Continuum Events.

Particle	Quantity	Value
π_0	Sigma from π_0 mass	$\pm 3\sigma$
π_0	$\cos\theta$ of photons in rest frame	< 0.9
π_0	momentum	> 1.0 GeV
Isolated Shower	not matched to π^0 with momentum	> 0.8 GeV
Isolated Shower	energy in center 9 crystals/center 25 crystals	> 0.9 GeV
Isolated Shower	$\cos\theta$	< 0.71 GeV
Isolated Shower	energy	> 0.12 GeV
electrons	mass when combine with another track	> 20 MeV
electrons	r2elec > 3 and $\cos\theta < 0.71$	
	or r2elec > 2 and $\cos\theta > 0.71$	
electrons	$\cos\theta$	< 0.905
electrons	momentum	> 1.0 GeV
muons	$\cos\theta$	< 0.81
muons	muon quality	> 0
muons	depth in muon chamber	geq 5 interaction lengths
muons	momentum > 1.50 GeV and $\cos\theta < 0.61$	
muons	momentum > 1.90 GeV and $\cos\theta > 0.61$	
Kaons	dE/dx compared to true Kaons	$\pm 3\sigma$

TABLE 2. Cuts On Continuum Events continuued.

ω	mass	< 0.762 GeV and > 0.802 GeV
ω	dE/dx of tracks compared to true pions	$\pm 3\sigma$
ω	π^0 momentum	> 0.35 GeV
ω	momentum	> 0.800 GeV
ω	$\cos\theta$ of photons and tracks	< 0.71
ω	energy of γ from π^0	> 0.030 MeV
$\eta \to 2\gamma$	mass	< 0.558 GeV and > 0.538 GeV
η	shower not matched to π^0 with momentum	> 0.8 GeV
η	shower energy in center 9 crystals/25 crystals	> 0.9 GeV
η	$\cos\theta$ of photon relative to beam axis	< 0.71 GeV
η	momentum	> 0.80 GeV
η	$\cos\theta$ photon decay in the rest frame	<0.90
$\eta \to \pi^+\pi^-\pi^0$	mass	< 0.558 GeV and > 0.538 GeV
η	dE/dx of pions compared to true pions	$\pm\ 2.5\sigma$
η	momentum	>0.40 GeV
η	π^0 momentum	> 0.35 GeV
η	$\cos\theta$ of photons and tracks	< 0.71
η	energy of γ from π^0	> 0.030 MeV
ϕ	dE/dx of tracks compared to true kaons	$\pm\ 3\sigma$
ϕ	mass	< 1.03 GeV and > 1.01 GeV
ϕ	momentum	> 0.80 GeV

TABLE 3. Cuts On B Events.

Particle	Quantity	Value
π_0	Sigma from π_0 mass	$\pm 3\sigma$
π_0	$\cos\theta$ photon decay in the rest frame	< 0.9
π_0	momentum	> 0.13 GeV
Isolated Shower	not matched to π^0 with momentum	> 0.8 GeV
Isolated Shower	energy in center 9 crystals/center 25 crystals	> 0.9 GeV
Isolated Shower	$\cos\theta$	< 0.71
electrons	mass when combine with another track	> 20 MeV
electrons	r2elec > 3 and $\cos\theta < 0.71$	
	or r2elec > 2 and $\cos\theta > 0.71$	
electrons	$\cos\theta$	< 0.905
electrons	momentum	> 0.40 GeV
muons	$\cos\theta$	< 0.81
muons	muon quality	> 0
muons	depth in muon chamber	> 5 interaction lengths
muons	momentum > 1.50 GeV and $\cos\theta < 0.61$	
muons	or momentum > 1.90 GeV and $\cos\theta > 0.61$	
Kaons	dE/dx compared to that of true Kaons	$\pm 3\sigma$
K_s^0	V hypothesis index	$= 2$
K_s^0	χ^2 of vertex fit	$\pm 2.5\sigma$
K_s^0	Radius of vertex from beam position	> 0.1 cm
K_s^0	mass	< 0.700 GeV and > 0.300 GeV

TABLE 4. Cuts On B Events continued.

ω	mass	< 0.762 GeV and > 0.802 GeV
ω	dE/dx of tracks compared to true pions	$\pm 3\sigma$
ω	π^0 momentum	> 0.35 GeV
ω	momentum	> 0.800 GeV
$\eta \to 2\gamma$	mass	< 0.558 GeV and > 0.538 GeV
η	shower not matched to π^0 with momentum	> 0.8 GeV
η	shower energy in center 9 crystals/25 crystals	> 0.9 GeV
η	$\cos\theta$	< 0.71
η	momentum	> 0.40 GeV
$\eta \to \pi^+\pi^-\pi^0$	mass	< 0.558 and > 0.538
η	dE/dx of tracks compared to true pions	$\pm 2.5\sigma$
η	momentum	0.40 GeV
η	π^0 momentum	> 0.35 GeV
ϕ	dE/dx of kaons compared to true kaons	$\pm 3\sigma$
ϕ	mass	< 1.03 GeV and > 1.01 GeV