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Study of the Doubly Cabibbo Suppressed Decay $D^+ \to \phi K^+$ and the Singly Cabibbo Suppressed Decay $D_s^+ \to \phi K^+$

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Study of the Doubly Cabibbo Suppressed Decay $D^+ \to \phi\ K^+$ and the Singly Cabibbo Suppressed Decay $D_s^+ \to \phi\ K^+$

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We have searched for the doubly Cabibbo suppressed decay (DCSD) $D^{\pm} \to \phi\ K^{\pm}$ and the singly Cabibbo suppressed decay (SCSD) $D_s^{\pm} \to \phi\ K^{\pm}$ in data from the Fermilab photoproduction experiment E691. The $D^{\pm}$ decay mode is of particular interest because it cannot result from simple spectator decay. We observe a $D^{\pm}$ signal with a statistical significance of 3.3 standard deviations, corresponding to a branching ratio of $B(D^{\pm} \to \phi\ K^{\pm}) = (4.0\ ^{+2.2}_{-1.8} \pm 0.6) \times 10^{-4}$. In the $D_s^{\pm}$ mode we measure an upper limit $B(D_s^{\pm} \to \phi\ K^{\pm}) < 0.17\%$.

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Most of the Cabibbo allowed decays of D mesons are now accounted for, as are many of the Cabibbo suppressed decays.[1] These measurements allow a fairly systematic study of the mechanism of nonleptonic charm decay. No observations of doubly Cabibbo suppressed decays (DCSD) have been published, which is not surprising given that the typical branching ratio of the dominant modes is expected to be roughly 10% $\times$ $\tan^2\theta_c$ or about 0.03%. It is interesting to pursue the study of DCSD modes, not only to test our understanding of the decay mechanism,[2] but also because it will aid in the interpretation of searches for D^0–$\bar{D}^0$ mixing.[3,4] In this paper we report the results of sensitive searches for the DCSD decay mode $D^\pm \rightarrow \phi\ K^\pm$ and the singly Cabibbo suppressed mode (SCSD) $D_s^\pm \rightarrow \phi\ K^\pm$. Throughout this paper the charge conjugate states are implicitly included.

The DCSD charm decays are characterized by a $\Delta C = -\Delta S$ rule, such as in the decay $D^+ \rightarrow \rho\ K^+$; allowed decays follow the $\Delta C = \Delta S$ rule. The decay $D^+ \rightarrow \phi\ K^+$ is a special case, because it can not result from the simple spectator decay, shown in Fig. 1(a), which is naïvely expected to dominate the total decay rate. It requires either final state rescattering, as in Fig. 1(b), or W annihilation, as in Fig. 1(c), to get rid of the $\bar{d}$ quark in the D^+. In allowed decays, such decays are generally smaller than spectator decays, most notably in the case of $D_s^+ \rightarrow \rho\ \pi^+$.[5] The one clear exception to this rule is in $D^0 \rightarrow \phi\ \bar{K}^0$, which does have a relatively large branching ratio.[6–8] Thus the $D^+ \rightarrow \phi\ K^+$ branching ratio should be even smaller than the typical DCSD, unless it is enhanced in the same manner as that for $D^0 \rightarrow \phi\ \bar{K}^0$.

No SCSD decays of the D_s^+ have been observed. The decay $D_s^+ \rightarrow \phi\ K^+$ can proceed by the same nonspectator diagrams as discussed for the D^+, but with only one Cabibbo suppression. In addition, the two spectator diagrams can also result in this decay. They should destructively interfere in the same way they do for allowed D^+ decays such as $D^+ \rightarrow \bar{K}^{*0}\ \pi^+$. If only those spectator diagrams contribute, the branching ratio should be roughly 0.02%. There can also be a Penguin diagram contributing, but it is generally expected to be even smaller than the spectator decays.

The results presented here are from E691, a high-energy photoproduction experiment at the Fermilab Tagged Photon Spectrometer. The two-magnet spectrometer had a large acceptance, with drift chambers to measure momentum, Čerenkov counters to identify charged hadrons, and calorimetry used for lepton identification and for the trigger. In addition, a series of silicon microstrip detectors were used to find separate production and decay vertices, making it possible to reduce the noncharm background. Photons of average energy 145 GeV/c^2 struck a 5 cm Be target. More details on the detector can be found elsewhere.[9]

To study the ϕK^+ decay channel, we chose events satisfying the particle identification assignment $K^+K^-K^+$, with one K^+K^- pair having an invariant mass lying in the ϕ mass region. We imposed a requirement on the joint Čerenkov probability which has the effect of accepting only tracks for which the pion assignment is excluded. We also required these tracks to form a well constrained vertex, and the line of flight of the reconstructed charm candidate to pass within 60 μm of a reconstructed primary vertex candidate. To reduce the noncharm background, only charm candidates were chosen which decayed at least a distance $L = 13\sigma$ downstream of the primary vertex, where σ is the error in the distance between primary and secondary vertices (typically 300 μm for a 60 GeV/c charmed particle, and linearly dependent on momentum). In addition, if any other track in the event passes within 80 μm of the secondary vertex, this event is discarded.

The possible feedthroughs from misidentification of the more abundant decays D^+ $(D_s^+) \to \phi\ \pi^+$ were investigated using the $\phi\pi^+$ mass spectrum of the candidates which pass the ϕK^+ selection, which is shown in Fig. 2. The plot shows 2 D^+ and 3 D_s^+ events, with almost no background. Because the background level in this plot is so low, we can remove these events with a cut around the two narrow peaks, without significantly distorting the underlying background. The dips caused in the ϕK^+ mass spectrum are about 50 MeV/c^2 in width, centered at 2.0 and 2.1 GeV/c^2, with an integrated area of 0.2 and 0.05 events. They thus have negligible effect on the number of events observed in the D^+ and D_s^+ peaks when fitting the ϕK^+ mass plot.

The ϕ K^+ mass spectrum for all combinations after the feedthroughs are removed is shown in Fig. 3(a). The curve shown is the projection of the results of a two-dimensional maximum likelihood fit to the distribution in mass and $\cos\theta$, where θ is the angle between the two positive kaons in the ϕ rest frame. To fit the mass spectrum, we use two gaussians at the D^+ and the D_s^+ masses, over a background parameterized with a smooth exponential modulated by a linear function. The resulting number of events in the peaks are $4.5\,^{+2.4}_{-2.2}$ D^+ and $1.8\,^{+1.7}_{-1.1}$ D_s^+ decays. The significance of the D^+ peak, as determined by the change in the log of the likelihood functions when the signal is set to zero, is 3.3 standard deviations. Fig. 3(b) shows the ϕ K^+ mass spectrum of those events satisfying $|\cos\ \theta| > 0.5$. The angular distribution is shown for the signal and background regions in Fig. 4. It shows that the signal region is consistent with the expected $\cos^2\theta$ distribution, while the background is consistent with a flat distribution.

To turn the D^+ signal into a branching ratio, we compare this mode with the $D^+ \to K^-\pi^+\pi^+$ signal seen in the E691 data. After correcting for relative efficiencies, we find

$$\frac{B(D^+ \to \phi\ K^+)}{B(D^+ \to K^-\pi^+\pi^+)} = (5.2\,^{+2.9}_{-2.4} \pm 0.8) \times 10^{-3} \qquad (1)$$

We estimate a systematic error of ± 0.3 events due to the uncertainty in the background shape. The uncertainty in the kaon identification probability is $\pm$ 14%. Using

$B(D^+ \to K^-\pi^+\pi^+) = (7.7 \pm 1.0)\%$,[1] we find

$$B(D^+ \to \phi\ K^+) = (4.0\ ^{+2.2}_{-1.8} \pm 0.6) \times 10^{-4} \tag{2}$$

We can compare the D_s^+ measurement to the benchmark mode $D_s^+ \to \phi\ \pi^+$, also measured in this experiment. The result is

$$\frac{B(D_s^+ \to \phi\ K^+)}{B(D_s^+ \to \phi\ \pi^+)} = (2.6\ ^{+2.5}_{-1.7} \pm 0.5) \times 10^{-2} < 5.6 \times 10^{-2} \qquad (90\%\ C.L.) \tag{3}$$

Using the $D_s^+ \to \phi\ \pi^+$ branching ratio of approximately 3%,[1,10] this corresponds to an upper limit $B(D_s^+ \to \phi\ K^+) < 0.17\ \%$.

The $D^+ \to \phi\ K^+$ branching ratio we have measured is comparable with the expectations for the largest DCSD branching ratios.[2] This is rather surprising, given that this process does not proceed by simple spectator decay. It is interesting to note, however, that the measured value for $B(D^+ \to \phi\ K^+)$ is compatible with what we would expect from the related decay $D^0 \to \phi\ \bar{K}^0$, assuming that it is governed by either of the two diagrams shown in Fig. 1(b) or (c):

$$\frac{B(D^+ \to \phi\ K^+)}{B(D^0 \to \phi \bar{K}^0)} = \frac{a_1^2}{a_2^2} \tan^4\theta_c \frac{\tau(D^+)}{\tau(D^0)} \tag{4}$$

The ratio $|\, a_1/a_2 \,|$ is the ratio of amplitudes with and without automatic color conservation, which experimentally is roughly 3.[11] Using $B(D^0 \to \phi\ \bar{K}^0) = (0.80 \pm 0.16)\%$[1] and $\tau(D^+)/\tau(D^0) = (2.52 \pm 0.09)$,[1] we obtain $B(D^+ \to \phi\ K^+) =$

$(4.8 \pm 1.0) \times 10^{-4}$. Although there is no generally accepted explanation for the large branching ratio for $D^0 \to \phi \bar{K}^0$,[11,12] the same mechanism may be responsible for the relatively large value for $B(D^+ \to \phi\ K^+)$.

For the SCSD mode $D_s^+ \to \phi\ K^+$, we can estimate the expected branching ratio under two different assumptions. If only the spectator decays contribute, we can directly relate this decay to the decay mode $D^+ \to \bar{K}^{*0}\pi^+$:

$$\frac{B(D_s^+ \to \phi\ K^+)}{B(D^+ \to \bar{K}^{*0}\pi^+)} = \tan^2\theta_c \frac{\tau(D_s^+)}{\tau(D^+)} \frac{p_K^3}{p_\pi^3} \tag{5}$$

where p_K and p_π are the momenta of the decay products in the decaying particle rest frame. Using $B(D^+ \to \bar{K}^{*0}\pi^+) = (1.8 \pm 0.8)\%$, we estimate the D_s^+ branching ratio to be about 0.02%. Similar relations between allowed D^0 and D_s^+ decays are typically good to better than a factor of 2. On the other hand, if we estimate the branching ratio assuming that only the nonspectator diagram contributes, and scale the result from the DCSD D^+ decay above, the result is $B(D_s^+ \to \phi\ K^+) \cong 0.5\%$. Interference with the very small spectator decays can not substantially change this estimate. Thus the experimental limit of 0.17% for the SCSD D_s^+ decay is below the nonspectator estimate from the D^+ decay, but is well above the level expected from spectator decays alone.

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Figure Captions

Fig. 1 - Some quark diagrams for D^+ meson decays:

(a) Spectator diagram;

(b) Contribution of final state rescattering effect in $D^+ \to \phi\ K^+$ channel;

(c) Contribution from annihilation diagram for $D^+ \to \phi\ K^+$ channel.

Fig. 2 - Invariant $\phi\ \pi^+$ mass spectrum of selected $\phi\ K^+$ events.

Fig. 3 - Invariant $\phi\ K^+$ mass spectra of selected events:

(a) Events used in the Maximum Likelihood fit described in the text;

(b) Spectrum with the additional requirement $|\cos\ \theta| >\ 0.5$.

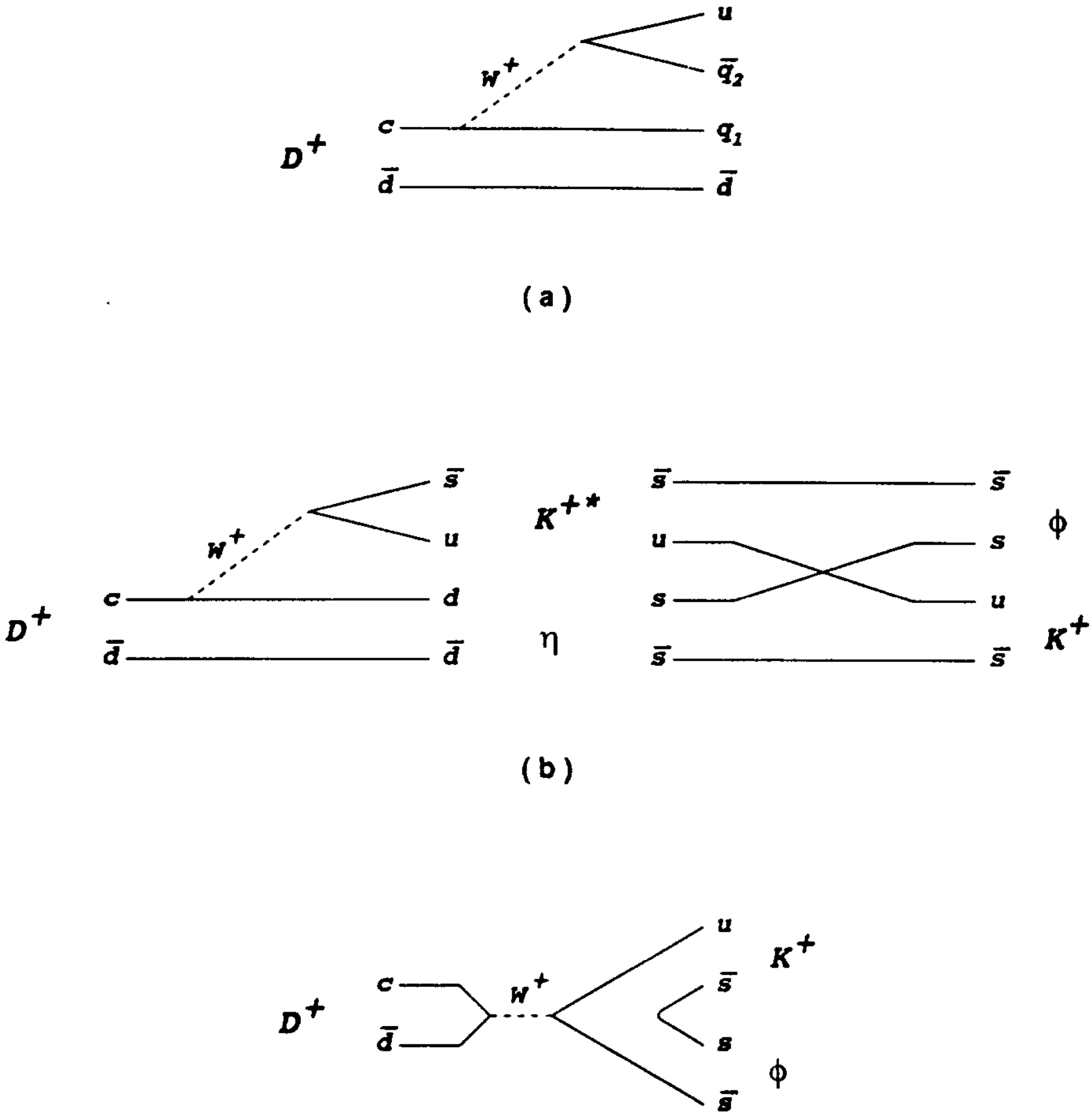
Fig. 4 - Comparison of $|\cos\ \theta|$ distributions:

(a) Monte Carlo simulated events;

(b) Real data, D^+ mass region;

(c) Real data, outside D^+ mass region.

Fig. 1



u
$\bar{q}_2$
W^+
c
q_1
D^+
$\bar{d}$
$\bar{d}$
(a)
$\bar{s}$
u
W^+
c
d
D^+
$\bar{d}$
$\bar{d}$
K^{+*}
η
$\bar{s}$
u
s
$\bar{s}$
$\bar{s}$
s
u
$\bar{s}$
φ
K^+
(b)
c
$\bar{d}$
D^+
W^+
u
$\bar{s}$
s
$\bar{s}$
K^+
φ

(c)

Fig. 2

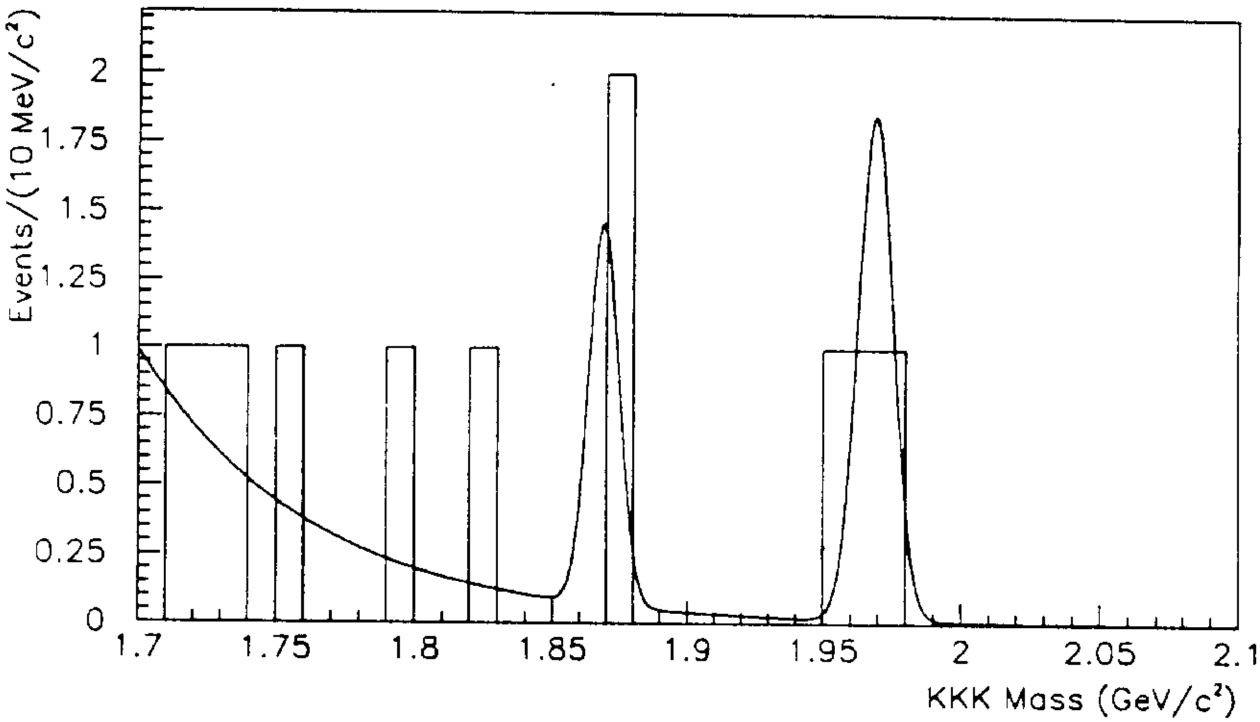
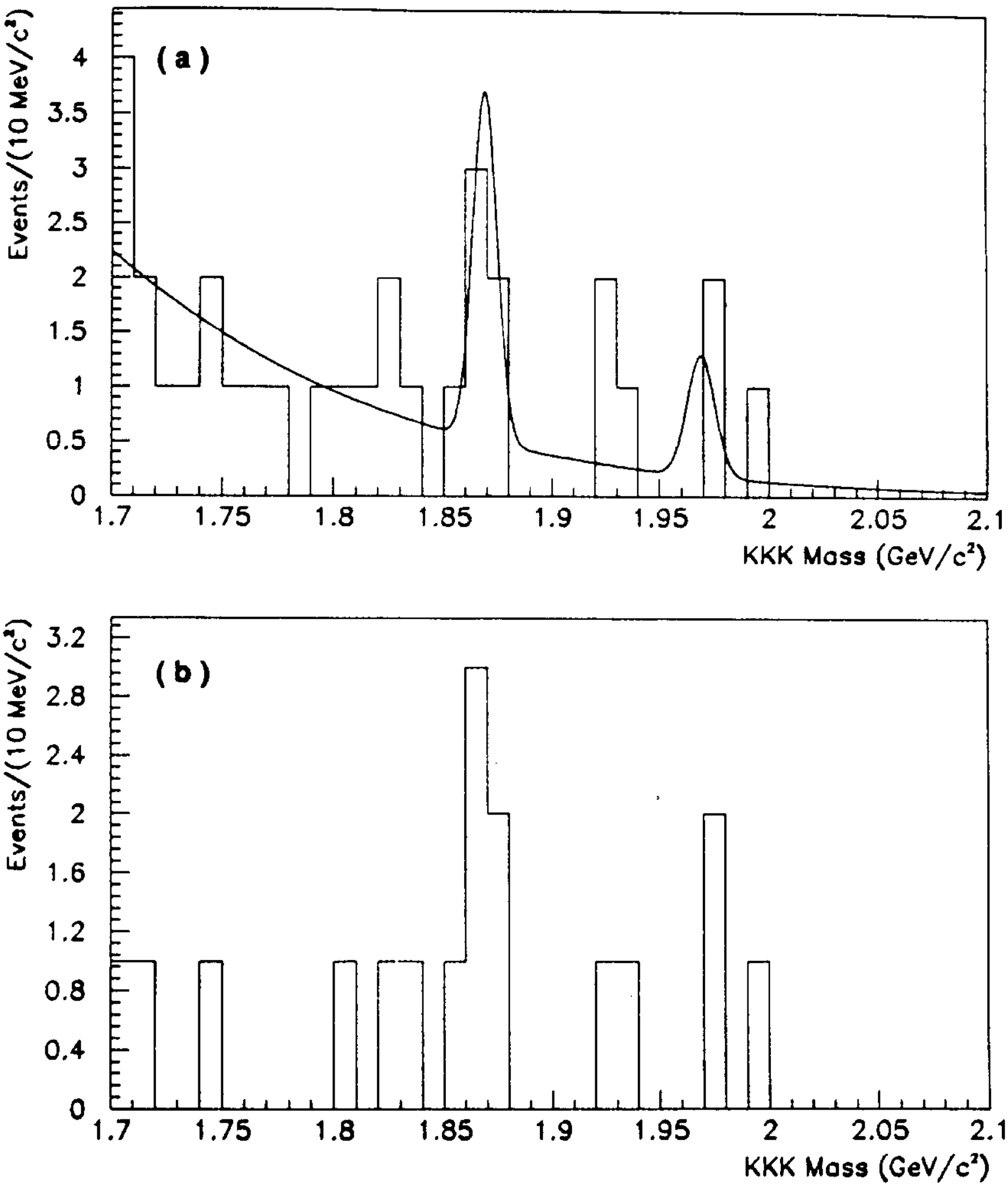
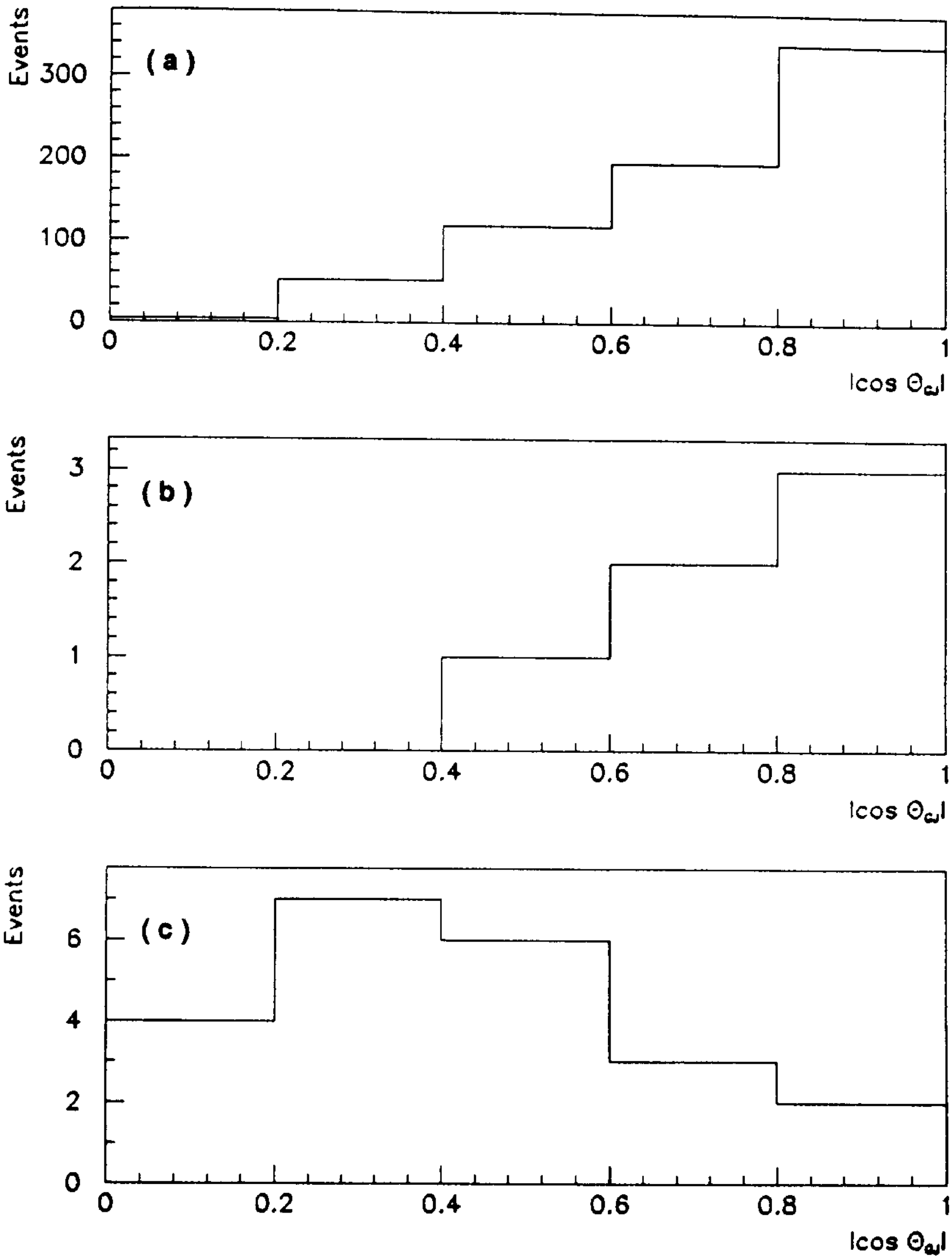

Events/(10 MeV/c²)
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
1.7
1.75
1.8
1.85
1.9
1.95
2
2.05
2.1
KKK Mass (GeV/c²)

Fig. 3



(a)
Events/(10 MeV/c²)
KKK Mass (GeV/c²)
(b)
Events/(10 MeV/c²)
KKK Mass (GeV/c²)

Fig. 4



Events
(a)
300
200
100
0
0
0.2
0.4
0.6
0.8
1
|cos Θω|
Events
(b)
3
2
1
0
0
0.2
0.4
0.6
0.8
1
|cos Θω|
Events
(c)
6
4
2
0
0
0.2
0.4
0.6
0.8
1
|cos Θω|