Fermi National Accelerator Laboratory

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Measurement of the Form Factors in the Decay $D^+ \to \bar{K}^{*0} e^+ \nu_e$ *

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ABSTRACT:

We have measured the three form factors governing the decay $D^+ \to \overline{K}^{*0} e^+ \nu_e$, observed in Fermilab photoproduction experiment E691, using the complete decay distribution of the data. The results are $A_1(0) = 0.46 \pm 0.06 \pm 0.03$, $A_2(0) = 0.0 \pm 0.2 \pm 0.1$, and $V(0) = 0.9 \pm 0.3 \pm 0.1$ for the two axial vector and vector form factors, respectively. The $\overline{K}^{*0}$ mesons have a ratio of longitudinal to transverse polarization of $1.8^{+0.6}_{-0.4} \pm 0.3$. These results are significantly different from values predicted by a number of different models.

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The heavy quark decays which are easiest to interpret are the semileptonic decays of heavy mesons. In these decays the effects of the strong interaction are completely contained in the form factors which characterize the formation of the final state meson. The goal is to separate such effects from the weak interaction, described by the element of the quark mixing matrix (Kobayashi-Maskawa mixing matrix.)

For example, to extract the mixing matrix elements for b-quark decay, V_{cb} and V_{ub}, one must rely on theoretical models of the form factors, of which there are now a large number.[1–4] A good test of these models lies in measuring the predicted form factors in charmed meson decay, in which the weak matrix element V_{cs} is well known. In addition, Wise and Isgur[5] have recently published a method of determining the bottom form factors directly from measured charmed form factors, without reference to particular model calculations. In the present paper we present the first measurement of the three form factors in the decay $D^+ \to \overline{K}^{*0} e^+ \nu_e$.

We observed the exclusive semileptonic decay $D^+ \to \overline{K}^{*0} e^+ \nu_e$ in the Fermilab photoproduction experiment E691. In an earlier paper[6] we published a measurement of the decay rate, along with an analysis of the $\overline{K}^{*0}$ polarization. The discrepancy between these results and all of the existing theoretical models stimulated many papers trying to understand the results.[7–9] To get to the source of the problem, it is necessary to extract the form factors directly using the complete angular distribution for this same data sample.

We analyze the decay $D^+ \to \overline{K}^{*0} e^+ \nu_e$ (and its charge conjugate) in which the $\overline{K}^{*0}$ decays to $K^- \pi^+$. This decay rate depends on five variables, of which only two were used for the previous analysis: (1) the mass of the $K^- \pi^+$ system, $M_{K\pi}$; (2) the squared mass of the $e^+ \nu_e$ system, t; (3) the strong decay angle, θ_v, which is the angle, in the frame of $\overline{K}^{*0}$, between the K^- and the direction opposite that of the D^+; (4) the weak decay angle, θ_e, which is the angle between the e^+ and the direction opposite that of the D^+ in the $e^+ \nu_e$ frame; and (5) the axial angle χ between the planes of the $e^+ \nu_e$ and the $K^- \pi^+$ systems in the D^+ rest frame. In terms of these variables the differential decay rate is

$$\frac{d\Gamma}{dM_{K\pi}^2\, dt\, d\cos\theta_v\, d\cos\theta_e\, d\chi} = G_F^2 |V_{cs}|^2 \frac{3}{2(4\pi)^5} \frac{M_{K^*}}{M_D^2 M_{K\pi}} \frac{M_{K^*}\Gamma(M_{K\pi})}{(M_{K\pi}^2 - M_{K^*}^2)^2 + M_{K^*}^2 \Gamma^2(M_{K\pi})} Kt$$

$$\times \Big\{ \Big[(1+\cos\theta_e)^2 |H_+(t)|^2 + (1-\cos\theta_e)^2 |H_-(t)|^2 \Big] \sin^2\theta_v + 4\sin^2\theta_e \cos^2\theta_v |H_0(t)|^2$$

$$-2\sin^2\theta_e \sin^2\theta_v Re(e^{i2\chi} H_+^* H_-) - 4\sin\theta_e (1+\cos\theta_e)\sin\theta_v \cos\theta_v Re(e^{i\chi} H_+^* H_0)$$

$$+\sin\theta_e (1-\cos\theta_e)\sin\theta_v \cos\theta_v Re(e^{i\chi} H_-^* H_0) \Big\}$$

where M_{K^*} is the central mass of the $\overline{K}^{*0}$, V_{cs} is the Kobayashi-Maskawa element, and K is the momentum of the $\overline{K}^{*0}$ in the rest frame of the D^+. We have included the mass dependence of the $\overline{K}^{*0}$ width, $\Gamma(M_{K\pi})$, which is proportional to the third power of the momentum of its decay particles. In the above formula, the helicity amplitudes of the $\overline{K}^{*0}$ are

$$H_\pm(t) = (M_D + M_{K\pi})A_1(t) \mp 2\frac{M_D K}{M_D+M_{K\pi}}V(t)$$

and

$$H_0(t) = \frac{1}{2M_{K\pi}\sqrt{t}}\left[(M_D^2 - M_{K\pi}^2 - t)(M_D + M_{K\pi})A_1(t) - 4\frac{M_D^2 K^2}{M_D+M_{K\pi}}A_2(t)\right],$$

expressed in terms of the two axial vector form factors $A_1(t)$ and $A_2(t)$, and the vector form factor $V(t)$, which parameterize the hadronic current of the matrix element:

$$\langle K^*(p_2,\epsilon)|H_\mu|D(p_1)\rangle = (M_D+M_{K\pi})A_1(t)\epsilon^*_\mu - \frac{2A_2(t)}{M_D+M_{K\pi}}\epsilon^*\cdot p_1 p_{1\mu} - i\frac{2V(t)}{M_D+M_{K\pi}}\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p_1^\rho p_2^\sigma .$$

(We have neglected a fourth form factor in the zero-lepton-mass limit).

We assume a single pole dominance for the form factors such that $A_{1,2}(t) = A_{1,2}(0)/(1-t/M_A^2)$ and $V(t) = V(0)/(1-t/M_V^2)$ where $M_A = 2.53\ GeV$ and $M_V = 2.11\ GeV$ represent the masses of the nearest resonance with the appropriate quantum numbers. The results are not very sensitive to the assumed t dependence because the range of t is only about $1\ GeV^2$. Thus the decay rate distribution is determined entirely by the three parameters $A_1(0)$, $A_2(0)$, and $V(0)$.

The relative magnitudes of these form factors, or of the helicity amplitudes, can be measured by comparing the angular and t distribution of the data to that of the decay rate formula. For example, the longitudinal part (involving $|H_0|^2$) is dominant where $\cos\theta_v$ is large and t is small. Away from this region the transverse terms dominate. Furthermore, the sign of $\cos\theta_e$ separates the H_+ and H_- amplitudes. The relative magnitudes of the form factors then follow from those of the helicity amplitudes. Since the form factor A_1 is common to all three helicity amplitudes, we measure the ratios $R_2 = A_2(0)/A_1(0)$ and $R_V = V(0)/A_1(0)$ from the angular distribution of the data. The value of $A_1(0)$ is thus a function of these ratios, the branching ratio, and the value of the Kobayashi-Maskawa matrix element, V_{cs}.

The determination of the form factor ratios from the angular distribution of the data is complicated by the angular dependence of the detector efficiency and the smearing caused by limited resolution and a quadratic ambiguity in the undetected neutrino momentum.

The major effect of the acceptance is due to the requirement that the electron laboratory energy be greater than 12 GeV, which causes a low efficiency for decays with low t and $\cos\theta_e$ near -1. A Monte Carlo simulation of the experiment, in which the generated events are processed through the same reconstruction and analysis programs as the real data, models this efficiency, as well as the effects of the quadratic ambiguity of the unobserved neutrino.

Monte Carlo events were generated according to phase space, including the Breit-Wigner of the $\overline{K}^{*0}$ resonance. To measure R_2 and R_V, the Monte Carlo events were weighted to produce a distribution given by the differential decay rate shown above, for given values of R_2 and R_V. These events, having passed through reconstruction and analysis programs, were then compared directly to the data to extract a likelihood. This procedure was repeated until the values of R_2 and R_V which maximized the likelihood were found. For each data point, the likelihood was calculated by summing the weights of the Monte Carlo events within a region of that data point and dividing by the volume of the region. The volume of each region was chosen to be small enough so that the nonlinear dependence of the likelihood within the volume was small. The systematic error due to this was estimated by varying the volume size. The volume was chosen to be large enough, however, so that the number of Monte Carlo events within the volume was sufficient to determine the likelihood. This systematic error, due to the Monte Carlo statistics, was estimated by varying the number of Monte Carlo events used.

We used 9000 accepted (10^6 generated) Monte Carlo events to make a 4 dimensional fit in $\cos\theta_v$, $\cos\theta_e$, χ, and t space to 204 data events which were within the $M_{K\pi}$ range of [0.8408, 0.9434] GeV, and which passed loose cuts as described in our previous paper.[6] Of the 204 data events, 21 were assumed to be non-resonant $K^-\pi^+$ and true background events. This number came from our fit of the $K^-\pi^+$ mass distribution to be described below. The angular distribution of these 21 events was chosen to be consistent with that of the wrong sign data.[6]

The results of our measurement are:

$$R_2 = 0.0 \pm 0.5 \pm 0.2 \qquad R_V = 2.0 \pm 0.6 \pm 0.3$$

with correlation coefficient $\rho_{R_2,R_V} = -.23$. With these values we calculate the ratio of longitudinal to transverse widths to be $\Gamma_L/\Gamma_T = 1.8^{+0.6}_{-0.4} \pm 0.3 \simeq \frac{\int Kt|H_0(t)|^2 dt}{\int Kt(|H_+(t)|^2+|H_-(t)|^2)dt}$, and $\Gamma_+/\Gamma_- = 0.15^{+0.07}_{-0.05} \pm 0.03 \simeq \frac{\int Kt|H_+|^2 dt}{\int Kt|H_-|^2 dt}$. Our previous value of $\Gamma_L/\Gamma_T = 2.4^{+1.7}_{-0.9}$ was found using only the $\cos\theta_v$ distribution of the data. The errors on the new result are smaller by a factor of 2. This gain in precision comes about mainly from adding t to the fit. Figures 1 through 4 compare the data and Monte Carlo distributions over various slices through the 4-dimensional space. In all cases the data and Monte Carlo follow each other quite well. The systematic error due to the statistics of the Monte Carlo, as well as the error due to the non-linearities of the Monte Carlo distribution across the region in which the likelihood is calculated, contribute about two-thirds to the total systematic error. The rest is due primarily to our uncertainty in the background distribution.

Having obtained the form factor ratios, we re-analyzed the branching ratio. Our previous measurement of the branching ratio used a value for $|H_+|/|H_-|$ derived from a model[1] and the value of Γ_L/Γ_T derived from the observed $\cos\theta_v$ dependence. The effective form factor ratios implicit in these values are different from those we have measured, which affects the estimate of the efficiency used to obtain the branching ratio. We also included the mass dependence of the $\overline{K}^{*0}$ width in the Breit-Wigner, which increases the $\overline{K}^{*0}$ mass distribution in the high mass region. The effects of these two changes (about 10% each) tended to cancel, so that our new result of $Br(D^+ \to \overline{K}^{*0}e^+\nu_e) = (4.4 \pm 0.4 \pm 0.8)\%$ differs from our previous result by only 0.1%. Here, the error on the Mark III value of $Br(D^+ \to K^-\pi^+\pi^+)$ with which we normalize our branching ratio number, is treated as systematic. The $\overline{K}^{*0}$ mass distribution is shown in Fig. 5. The results of a fit to the distribution as well as the small contribution of the wrong sign background and non-resonant signal are indicated.

We calculate $A_1(0)$ by equating the total decay rate of this mode to the measured branching ratio divided by the lifetime of the D^+. We use the measured values of the form factor ratios, the branching ratio, and the lifetime[10] $\tau_{D_+} = 1.090 \pm 0.030 \pm 0.025$ ps, all obtained from the E691 experiment. With $V_{cs} = 0.975$ we find

$$A_1(0) = 0.46 \pm 0.05 \pm 0.05 \quad A_2(0) = 0.0 \pm 0.2 \pm 0.1 \quad V(0) = 0.9 \pm 0.3 \pm 0.1$$

The error for $A_1(0)$ is divided evenly between the errors in R_2 and R_V, and the error in the branching ratio. Only the uncertainty of R_2 and R_V contributes significantly to the errors of $A_2(0)$ and $V(0)$.

The only assumption that is made in measuring the form factors is the dependence on t. The effect of using different models of the t dependence on the measured form factors is small; $A_2(0)$ changes within its systematic error, and $A_1(0)$ and $V(0)$ vary negligibly. In the $D^0 \to K^-e^+\nu_e$ mode, we measured the t dependence of the form factor directly; it is consistent with the single pole form.[11] The form factors are not significantly changed unless the t dependence is both outside the range predicted by models and in disagreement with that measured in $D^0 \to K^- e^+ \nu_e$.

Table 1 shows the comparison between our measured values of the form factors and those of four models, evaluated at $t = 0$ and $t = t_M$, the maximum value of t. Two of the models (KS and BW) explicitly calculate the form factors at $t = 0$, while the other two calculate at $t = t_M$. We have used the same pole dominant form with which our form factors were measured to extrapolate the models to other values of t. The greatest discrepancy is that the measured $A_2(0)$ is consistent with zero, which leads to a higher value of Γ_L/Γ_T than predicted. In addition, the models predict a value for $A_1(0)$ that is significantly larger than the measured value, which leads to a higher branching ratio than that measured. All of the models fail to describe the data. As a result, they are also suspect for other exclusive decays into light mesons, such as $B \to \rho e \bar{\nu}$.

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	E691	IS[8]	BW[9]	GS[7]	KS[4]
$A_1(0)$	$0.46 \pm 0.05 \pm 0.05$	0.8	0.9	0.8	1.0
$A_2(0)$	$0.0 \pm 0.2 \pm 0.1$	0.8	1.2	0.6	1.0
$V(0)$	$0.9 \pm 0.3 \pm 0.1$	1.1	1.3	1.5	1.0
$A_1(t_M)$	$0.54 \pm 0.06 \pm 0.06$	1.0	1.1	0.9	1.2
$A_2(t_M)$	$0.0 \pm 0.2 \pm 0.1$	1.0	1.4	0.7	1.2
$V(t_M)$	$1.2 \pm 0.4 \pm 0.1$	1.4	1.7	1.9	1.3
$\frac{\Gamma_L}{\Gamma_T}$	$1.8^{+0.6}_{-0.4} \pm 0.3$	1.1	0.9	1.2	1.2

TABLE 1. Measured values from this analysis (E691) compared to predictions of various models (IS, BW, GS, and KS).

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FIGURE CAPTIONS

FIG. 1. Projection of the data (dots with errors) and Monte Carlo (solid histogram) events onto $\cos\theta_e$. The distributions are strongly affected by the low acceptance near $\cos\theta_e = -1$.

FIG. 2. Projection of the data (dots with errors) and Monte Carlo (solid histogram) events onto $\cos\theta_v$ for: (a) $t/t_{max} > 0.5$, and (b) $t/t_{max} < 0.5$.

FIG. 3. Projection of the data (dots with errors) and Monte Carlo (solid histogram) events onto t/t_{max} for: (a) $|\cos\theta_v| > 0.5$ and (b) $|\cos\theta_v| < 0.5$.

FIG. 4. Projection of the data (dots with errors) and Monte Carlo (solid histogram) events onto χ. (a) events are weighted with the coefficient which multiplies the $H_0 H_-$ term in the decay rate. This brings out the $\cos\chi$ dependence. (b) standard projection. This should have a $\cos 2\chi$ dependence; but it is small, as expected given our form factors.

FIG. 5. The $K\pi$ mass distribution for the data (histogram) and the best fit Monte Carlo (solid line) events. The short dashed curve shows the wrong sign contribution and the long dashed curve shows the sum of the non-resonant and wrong sign contributions to the fit.

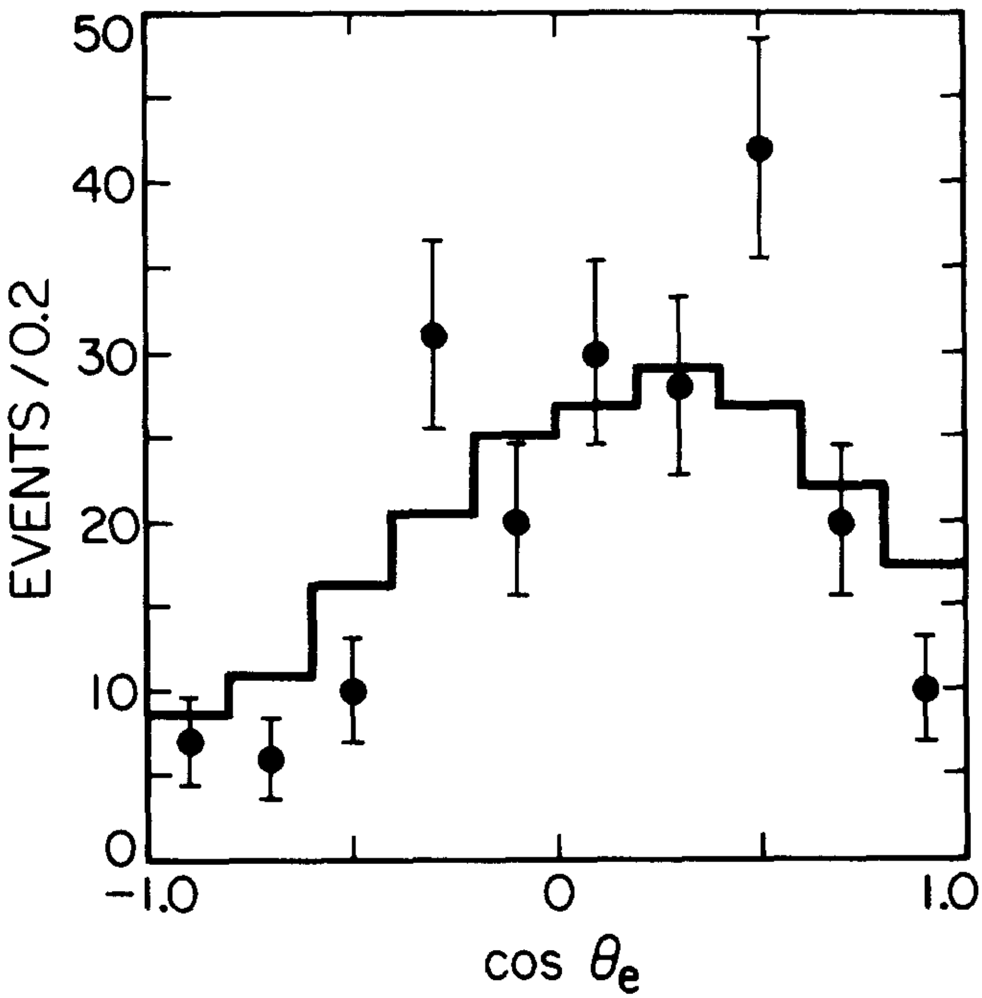

Figure 1

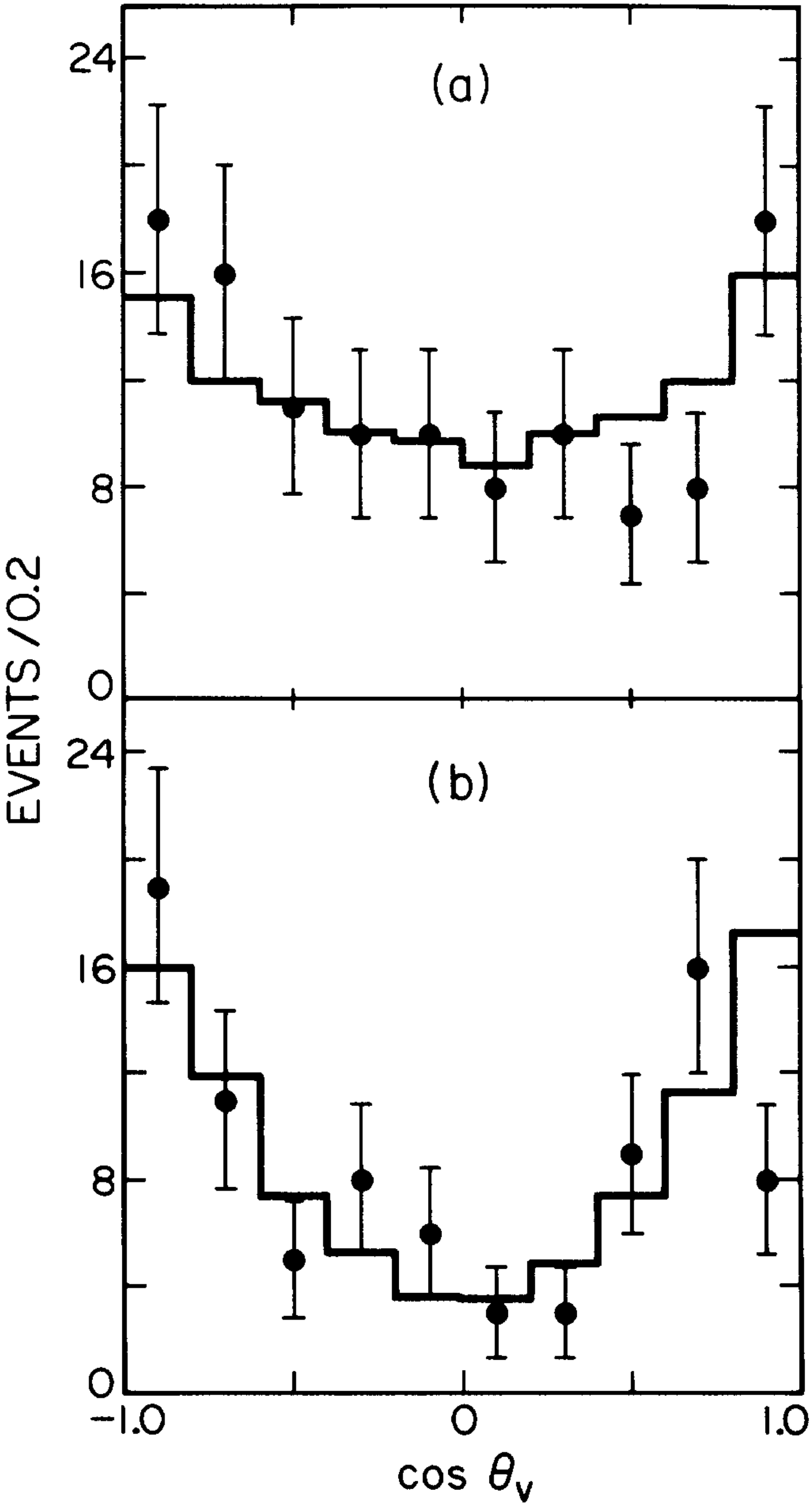

Figure 2

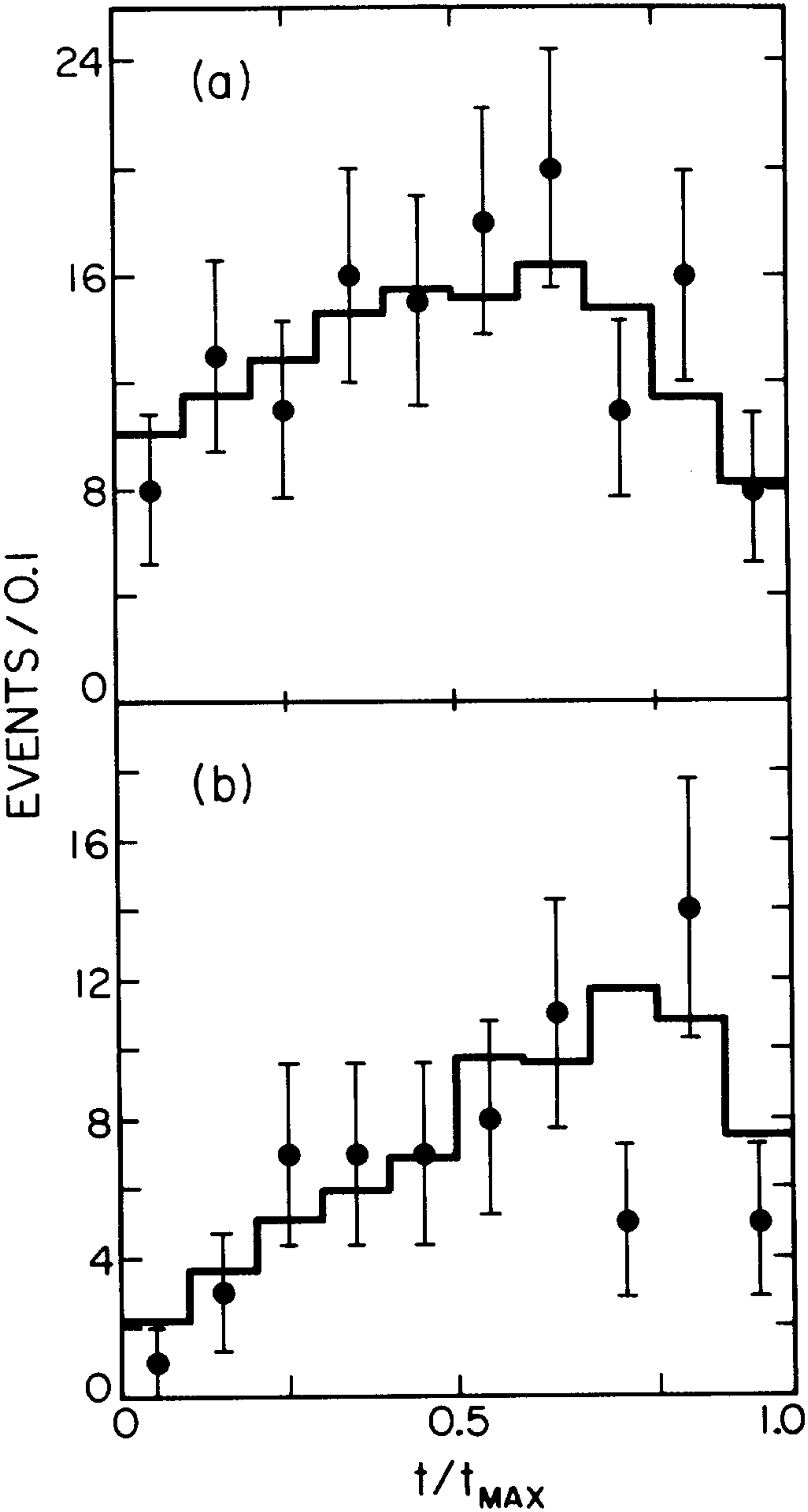

Figure 3

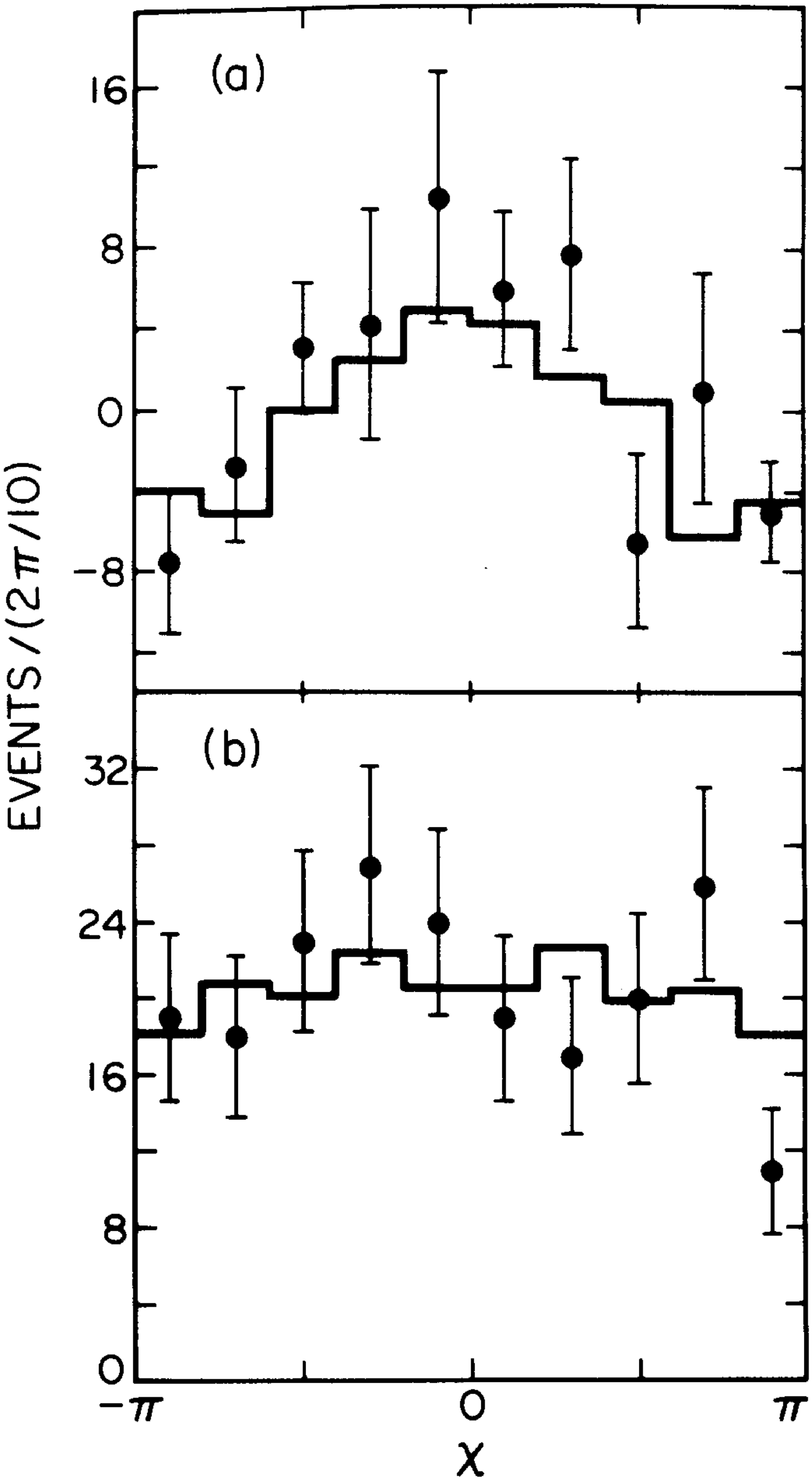

Figure 4

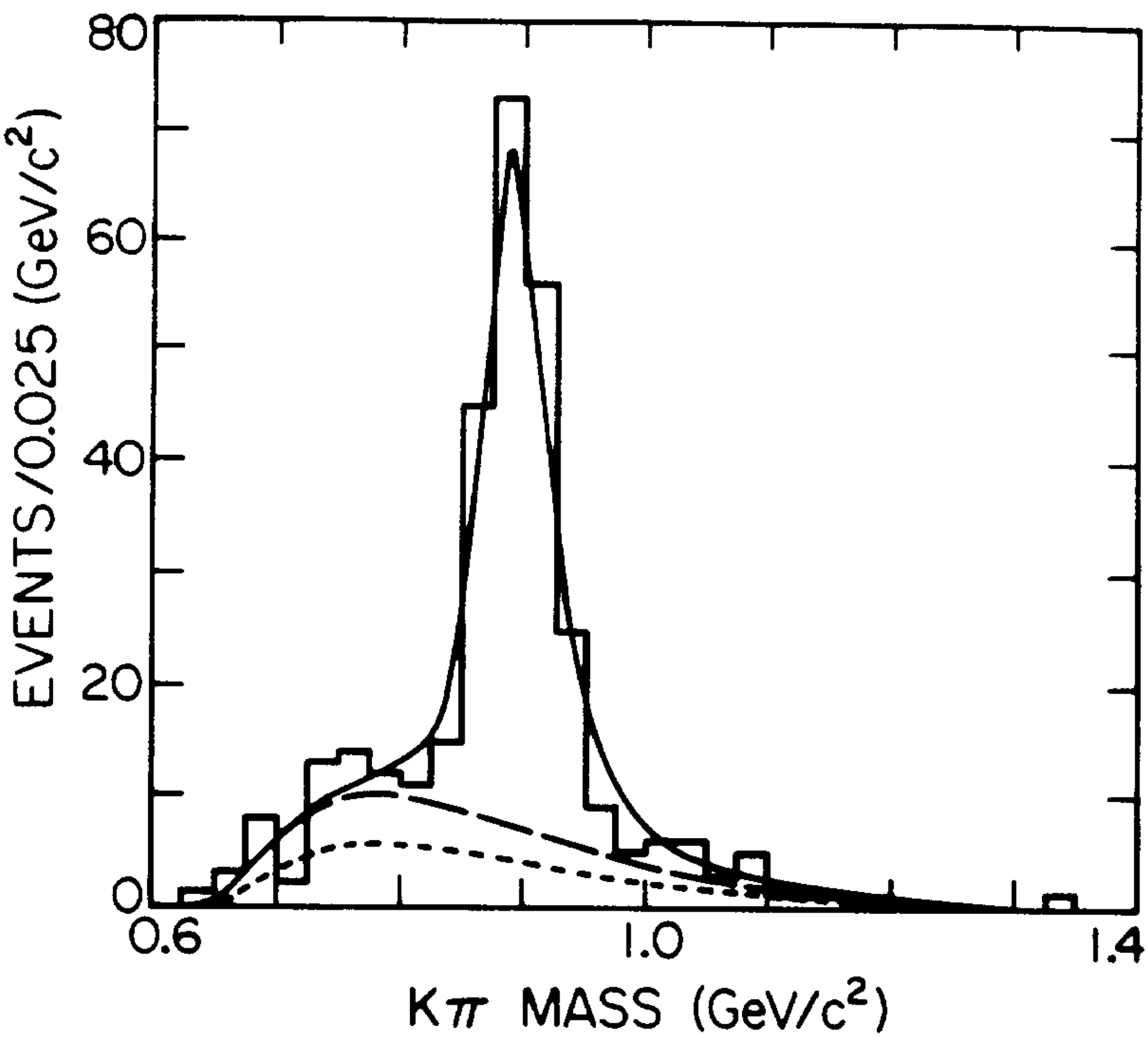

Figure 5