



## A Study of the Decay $D^+ \rightarrow K^0 e^+ \nu_e$

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**ABSTRACT:**

We have studied the exclusive semileptonic decay mode  $D^+ \rightarrow \overline{K}^0 e^+ \nu_e$  in the Fermilab photoproduction experiment E691. We find the ratio of branching ratios  $B(D^+ \rightarrow \overline{K}^0 e^+ \nu_e) / B(D^+ \rightarrow K^- \pi^+ \pi^+)$  to be  $(0.66 \pm 0.09 \pm 0.14)$ , corresponding to a  $D^+ \rightarrow \overline{K}^0 e^+ \nu_e$  branching ratio of  $(6.1 \pm 0.9 \pm 1.6)\%$ . Combining this result with our measurement of the  $D^+$  lifetime, we find  $\Gamma(D^+ \rightarrow \overline{K}^0 e^+ \nu_e) = (5.6 \pm 0.8 \pm 1.5) \cdot 10^{10} s^{-1}$ . We also find, using E691 averages, the ratio of decay rates  $\Gamma(D \rightarrow K^* e \nu) / \Gamma(D \rightarrow K e \nu)$  to be  $(0.62 \pm 0.13)$ .

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GROUP	$\Gamma(D^+ \rightarrow K^0 \ell^+ \nu_e)$	$\Gamma(D^0 \rightarrow K^- \ell^+ \nu_e)$	AVG
E691 <sup>11</sup>	$5.6 \pm 0.8 \pm 1.5$	$9.1 \pm 0.7 \pm 1.7$	$7.3 \pm 1.2$
Mark III <sup>16</sup>	$6.1^{+1.5}_{-1.0} \pm 0.7$	$8.1 \pm 1.2 \pm 0.9$	$7.0 \pm 1.0$
E653 <sup>17</sup>		$5.6 \pm 0.9 \pm 1.2$	$5.6 \pm 1.5$
AVG	$5.9 \pm 1.1$	$7.4 \pm 0.9$	$6.8 \pm 0.7$

GROUP	$\Gamma(D^+ \rightarrow K^{*0} \ell^+ \nu_e)$	$\Gamma(D^0 \rightarrow K^{*-} \ell^+ \nu_e)$	AVG
E691 <sup>12</sup>	$4.2 \pm 0.6 \pm 0.5$		$4.2 \pm 0.8$
Mark III <sup>16</sup>	$5.0^{+1.8}_{-1.0} \pm 0.6$	$10.4^{+4.5}_{-2.4} \pm 1.7$	$5.7 \pm 1.4$
ARGUS <sup>18</sup>	$3.9 \pm 0.6 \pm 0.9$		$3.9 \pm 1.1$
CLEO <sup>19</sup>		$3.6 \pm 0.9 \pm 0.9$	$3.6 \pm 1.3$
AVG	$4.2 \pm 0.6$	$4.3 \pm 1.2$	$4.2 \pm 0.5$

Table 1: Summary of exclusive charm semileptonic rates. All widths in  $10^{10} s^{-1}$ .

Mode	Source	Decay Width ( $10^{10} s^{-1}$ )
$D \rightarrow K e \nu$	E691	$7.3 \pm 1.2$
$D \rightarrow K^* e \nu$	E691	$4.2 \pm 0.8$
$D \rightarrow (K\pi)_{NR} e \nu$	E691	$0.4 \pm 0.4$
$D \rightarrow (\pi, \rho) e \nu$	$V_{cd}/V_{cs}$	$0.9 \pm 0.3$
Total		$12.8 \pm 1.5$
$D \rightarrow X e \nu$	Mark III avg. <sup>16</sup>	$16.5 \pm 1.6$
Missing decays		$3.7 \pm 2.2$

Table 2: Summary of exclusive and inclusive charm decay rates

## INTRODUCTION

The exclusive semileptonic decays of mesons containing heavy quarks are particularly interesting because they are the simplest decays to interpret. The strong interaction effects are completely contained in the form factors, which describe how the final state quark from the weak decay combines with the spectator quark to produce a final state meson, or mesons. Because of this simplicity, these decays are used to measure the Cabibbo-Kobayashi-Maskawa matrix elements, which parameterize the mixing between the quark mass eigenstates and the weak eigenstates. The form factors are interesting both because the precise measurement of the K-M elements is important and because the form factors themselves represent a rare window on the structure of heavy mesons. There has been intense theoretical effort on calculating the form factors using both analytical models and lattice gauge techniques.<sup>1–9</sup>

The matrix element  $V_{cs}$ , which is relevant for Cabibbo-favored charm decays, is known to an error of  $\pm 0.001$  assuming three-generation unitarity. It is therefore possible to measure the  $c \rightarrow s$  form factors using semileptonic decays. There are arguments that these form factors are closely related to those in  $b \rightarrow u$  semileptonic decays, and will therefore be useful in extracting an accurate value of  $V_{ub}$  when exclusive measurements of those decays are available.<sup>10</sup>

The two dominant semileptonic decays are expected to be  $D \rightarrow Ke\nu$  and  $D \rightarrow K^*e\nu$ . The decay rates for  $D^+$  and  $D^0$  are equal, by isospin. We have already measured the decay rate  $\Gamma(D^0 \rightarrow K^-e^+\nu_e) = (9.1 \pm 0.7 \pm 1.7) \cdot 10^{10} s^{-1}$ ,<sup>11</sup> which agrees well with various form factor calculations. We have also measured the mode  $D^+ \rightarrow K^-\pi^+e^+\nu_e$ , and have found it to be dominated by the  $\overline{K}^{*0}$ .<sup>12</sup> For the  $K^*$  final state, there are three form factors, which we have extracted directly.<sup>13</sup> The resulting form factors do not agree very well with model predictions. In this paper we present a measurement of the decay rate for  $D^+ \rightarrow \overline{K}^0e^+\nu_e$ . (Charge conjugate states are implicitly included throughout this paper.) This gives a second measurement of the  $Ke\nu$  form factor with quite different systematic errors.

## EXPERIMENT

We have used the data from the Fermilab charm photoproduction experiment *E691* in this analysis. The apparatus, the Tagged Photon Spectrometer, is an open geometry, two-magnet spectrometer. Photons with energy between 80 and 240 GeV interacted in a 5 cm beryllium target. The charged particles were tracked using silicon microstrip detectors (SMDs) and drift chambers. As in the earlier semileptonic decay studies, we take advantage of the precise vertex resolution of the SMDs and the good electron identification to isolate

the signal of exclusive semileptonic decays. The spectrometer and the use of the silicon microstrip detector are discussed elsewhere.<sup>14</sup>

The  $\overline{K}^0$  sample was observed in the channel  $K_s \rightarrow \pi^+\pi^-$ . Candidates were found by forming two track vertices with tracks seen in the drift chambers but not in the SMDs. The electron identification relied on the electromagnetic shower shape in the calorimeter and the agreement of the energy deposit with the momentum from the tracking chambers. We selected electrons with an electron probability corresponding to a typical efficiency for electrons and pions of 61% and 0.3%, respectively. To lower backgrounds, especially those due to electrons from  $\pi^0 \rightarrow \gamma\gamma, \gamma \rightarrow e^+e^-$ , we restricted the angle ( $\theta^*$ ) of the electron relative to the  $\overline{K}^0e^+$  boost direction in the  $\overline{K}^0e^+$  frame such that  $\cos\theta^* < 0.7$ . The electrons should be distributed isotropically in this frame, whereas the background tends to be peaked forward.

In this experiment the  $K^0$  decays well downstream of the precision vertex detector and so only one track, the electron track, is determined with enough precision to be useful for identifying a separated  $D^+$  vertex. We selected electrons which formed no more than one well-defined vertex with any other single track in the event. The present analysis proceeds in a manner similar to that in our analysis of  $D^+ \rightarrow \overline{K}^0\pi^+$ .<sup>15</sup> In that analysis, we required that the production vertex lie in the plane defined by the kaon and pion, to within a resolution factor. Here we extend the technique to allow for the momentum of the neutrino. We define a vector  $\vec{r}$  from the event production vertex to the electron track, such that  $\vec{r}$  is perpendicular to the track. We resolve  $\vec{r}$  into two components, a component ( $r_{in}$ ) in the  $\overline{K}^0e^+$  plane and a component ( $r_t$ ) transverse to that plane. If we assume the neutrino energy to be zero (a limit in which the present decay very nearly resembles  $D^+ \rightarrow \overline{K}^0\pi^+$ ), we can relate  $r_{in}$  to the decay distance through

$$d = r_{in} \cdot \frac{\gamma(p^* \cos\theta^* + \beta E^*)}{p^* \sin\theta^*} = r_{in} \gamma \cdot \frac{\cos\theta^* + 1}{\sin\theta^*}$$

In this expression,  $\gamma = E(\overline{K}^0e^+)/M(\overline{K}^0e^+)$ ,  $\beta = p(\overline{K}^0e^+)/E(\overline{K}^0e^+)$  and  $p^*$  is the momentum of the electron in the  $\overline{K}^0e^+$  rest frame. Thus an estimate of the proper decay time is  $t' = \frac{r_{in}}{c} \cdot \frac{\cos\theta^* + 1}{\sin\theta^*}$ . We required  $r_{in}$  to be greater than  $210\mu m$ , which removes tracks that come from the primary vertex. This cut removes 85% of the background and retains 50% of the signal. We also required  $t' < 4 \cdot \tau_{D^+}$ . The distance  $r_t$  is maximized when the neutrino momentum is perpendicular to the  $\overline{K}^0e^+$  plane in the lab frame, and is minimized (limited by resolution) when  $E_\nu \rightarrow 0$ . We require that  $r_t$  be less than the sum of  $80\mu m$  (twice the resolution) and the contribution to  $r_t$  assuming the maximum transverse

momentum of the neutrino, added in quadrature. This cut depends on  $\overline{K^0}e^+$  mass, because the neutrino energy in the center of mass of the  $D^+$  is a function of  $M(\overline{K^0}e^+)$ . The  $M(\overline{K^0}e^+)$  distribution of events which pass these cuts is shown in figure 1.

To extract the signal from the  $\overline{K^0}e^+$  mass spectrum it is necessary to know the background shape. There is no wrong sign background to use, as there was in the case of  $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$ . There is fairly consistent experience from many background spectra observed in our experiment that the mass shape depends very little on vertex separation. We effectively factor the background shape into two parts: (a) a smooth shape which should be independent of vertex separation and should look like the other two-body mass spectra, and (b) a shape which describes the efficiency of the  $r_t$  cut for background, because the  $r_t$  cut depends on  $\overline{K^0}e^+$  mass. To parameterize shape (a), we selected events with  $r_{in}$  less than the cut used to select charm, which produces a sample that has only a small fraction of charm. The sample, along with the parameterized shape, is shown in figure 2. The parameterization includes a small term for a signal feedthrough as well as a term for  $\overline{K^{*0}} \rightarrow \overline{K^0} \pi^+$  background in which the pion is misidentified as an electron. This  $K^*$  peak is marginally significant, but its inclusion has almost no effect on the signal size.

To model the shape (b), we cannot use the low- $r_{in}$  sample discussed above, since the efficiency of the  $r_t$  cut depends on  $r_{in}$ . Instead we use background events with relatively low electron probability, but which pass all the vertex cuts. We explicitly take advantage of the fact that the  $r_t$  cut is a constant for  $M(\overline{K^0}e^+) > M(D^+)$ , and so that efficiency is flat in that region. In figure 3 we show the measured efficiency of the  $r_t$  cut for this background sample and the function by which we describe it. The final background shape is obtained by multiplying this shape times the shape (a) discussed above.

The general shape of the  $M(\overline{K^0}e^+)$  spectrum shows a rather flat shape from 1.0 to 1.7 GeV, dramatically different from the background shape of this or any other two-body sample. The signal shape and the reconstruction efficiency ( $0.77 \pm 0.02\%$ ) were determined from Monte Carlo studies. We assumed the usual pole form for the semileptonic decay form factor, but have found our results to be insensitive to pole mass. The fit uses the signal shape, the background shape discussed above, and a feedthrough from the decay  $D^+ \rightarrow \overline{K^{*0}}e^+ \nu_e (\overline{K^{*0}} \rightarrow \overline{K^0} \pi^0)$  of  $40 \pm 5$  events. The fit gives  $249 \pm 34 \pm 51$   $D^+ \rightarrow K_s e^+ \nu_e$  events. The systematic errors stem mainly from uncertainty in the background shape ( $\pm 40$  events), electron efficiency ( $\pm 17$  events), and neutral kaon efficiency ( $\pm 21$  events), and whether or not we include a  $K^*$  term in the background shape ( $\pm 14$  events). We studied a wide variety of background shapes and different background samples to estimate the

uncertainty in this shape, which is the dominant systematic error. Normalizing this result with our  $D^+ \rightarrow K^- \pi^+ \pi^+$  sample and using the absolute branching ratio for that mode from Mark III of  $(9.1 \pm 1.3 \pm 0.4)\%$ , we find  $B(D^+ \rightarrow \overline{K}^0 e \nu_e) = (6.1 \pm 0.9 \pm 1.6)\%$ . Using the E691 value for the  $D^+$  lifetime we find  $\Gamma(D^+ \rightarrow \overline{K}^0 e \nu_e) = (5.6 \pm 0.8 \pm 1.5) \cdot 10^{10} s^{-1}$ .

As noted above, we have measured  $\Gamma(D^0 \rightarrow K^- e^+ \nu_e) = (9.1 \pm 0.7 \pm 1.7) \cdot 10^{10} s^{-1}$ . Our two measurements of  $\Gamma(D \rightarrow K e \nu)$  differ by 1.4 standard deviations. These measurements are effectively independent: the dominant systematic errors in  $D^+ \rightarrow \overline{K}^0 e^+ \nu_e$  are due to the uncertainty in the background shape, neutral kaon and electron efficiency, and the Mark III value for the absolute  $D^+$  branching ratio, whereas the dominant systematic errors in  $D^0 \rightarrow K^- e^+ \nu_e$  are due to the uncertainty in electron and charged kaon efficiency, and the Mark III value for the absolute  $D^0$  branching ratio. Only the electron detection efficiency is common. Our weighted average for  $\Gamma(D \rightarrow K e \nu)$  is  $(7.3 \pm 1.3) \times 10^{10} s^{-1}$ , where we have taken into account the part of the systematic error which is in common.

The semileptonic rate can be expressed as

$$\Gamma(D \rightarrow K e \nu) = |V_{cs}|^2 |f_+(0)|^2 (1.53 \times 10^{11}) s^{-1}.$$

If we take  $|V_{cs}| = 0.975$ , we find the form factor intercept  $|f_+(0)| = 0.71 \pm 0.06$ , in good agreement with theoretical predictions.<sup>1,2,4,6,9</sup> In a previous paper<sup>13</sup> we reported a measurement of the form factors in  $D^+ \rightarrow \overline{K}^{*0} e^+ \nu_e$  and found that the axial vector form factors do not agree well with theory.

In Table 1 we give a summary of Cabibbo-favored charm semileptonic rates. For  $D \rightarrow K \ell \nu$  the measurements agree quite well. The world average for  $\Gamma(D \rightarrow K \ell \nu)$  is  $(6.8 \pm 0.7) \cdot 10^{10} s^{-1}$ . There is also acceptable agreement in the rates for  $D \rightarrow K^* e \nu$ , although the Mark III  $D^0$  rate differs from the other rates by about 2 standard deviations. Besides the measurement shown in Table 1, Mark III also reported the results of a fit which assumed the unmeasured  $D \rightarrow X e \nu$  rates to be exactly zero; in this fit  $\Gamma(D^0 \rightarrow K^{*-} e^+ \nu_e) = (7.2 \pm 1.7) \cdot 10^{10} s^{-1}$ .<sup>16</sup> Since the uncertainties in decay rates for higher  $K^*$  resonances are still large, we do not use that constraint. The ARGUS result on  $D^+ \rightarrow \overline{K}^{*0} e^+ \nu_e$  and the CLEO result on  $D^0 \rightarrow K^{*-} e^+ \nu_e$  agree well with the E691 result.

In Table 2 we show data relevant to the question of whether the lowest resonances  $K$  and  $K^*$  saturate the  $c \rightarrow s e^+ \nu_e$  rate. The total of exclusive decay rates is  $(12.8 \pm 1.5) \cdot 10^{10} s^{-1}$ , compared to  $(16.5 \pm 1.6) \cdot 10^{10} s^{-1}$  for the inclusive decay rate from Mark III. Thus the rate for missing decays is  $(3.7 \pm 2.2) \cdot 10^{10} s^{-1}$ , which is marginally consistent with zero, but is also consistent with being as large as the major decays. To determine

the importance of remaining channels it will be necessary to measure directly exclusive channels such as  $D \rightarrow K\pi\pi e\nu$ .

Using E691 averages we find the ratio  $\Gamma(D \rightarrow K^*e\nu)/\Gamma(D \rightarrow Ke\nu) = (0.62 \pm 0.13)$ . If we use world averages the same ratio is  $(0.63 \pm 0.10)$ . These numbers are somewhat smaller than the predicted value of 1.0-1.2.<sup>1,2</sup> Since the absolute rates agree with theory for the  $D \rightarrow Ke\nu$  decay, the source of this discrepancy appears to be in the  $K^*e\nu$ , not the  $Ke\nu$ , form factors.

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## FIGURE CAPTIONS

FIG. 1. Invariant  $\overline{K^0}e^+$  mass distribution, with the final fit (solid) and background (dashed).

FIG. 2. Invariant  $\overline{K^0}e^+$  mass distribution for background events prior to  $r_t$  cut. The solid line is the fit, the dashed line is the background shape and the dot-dashed line is signal feedthrough.

FIG. 3. Measured efficiency of  $r_t$  cut versus  $M(\overline{K^0}e^+)$ , with the best fit.

Figure 1

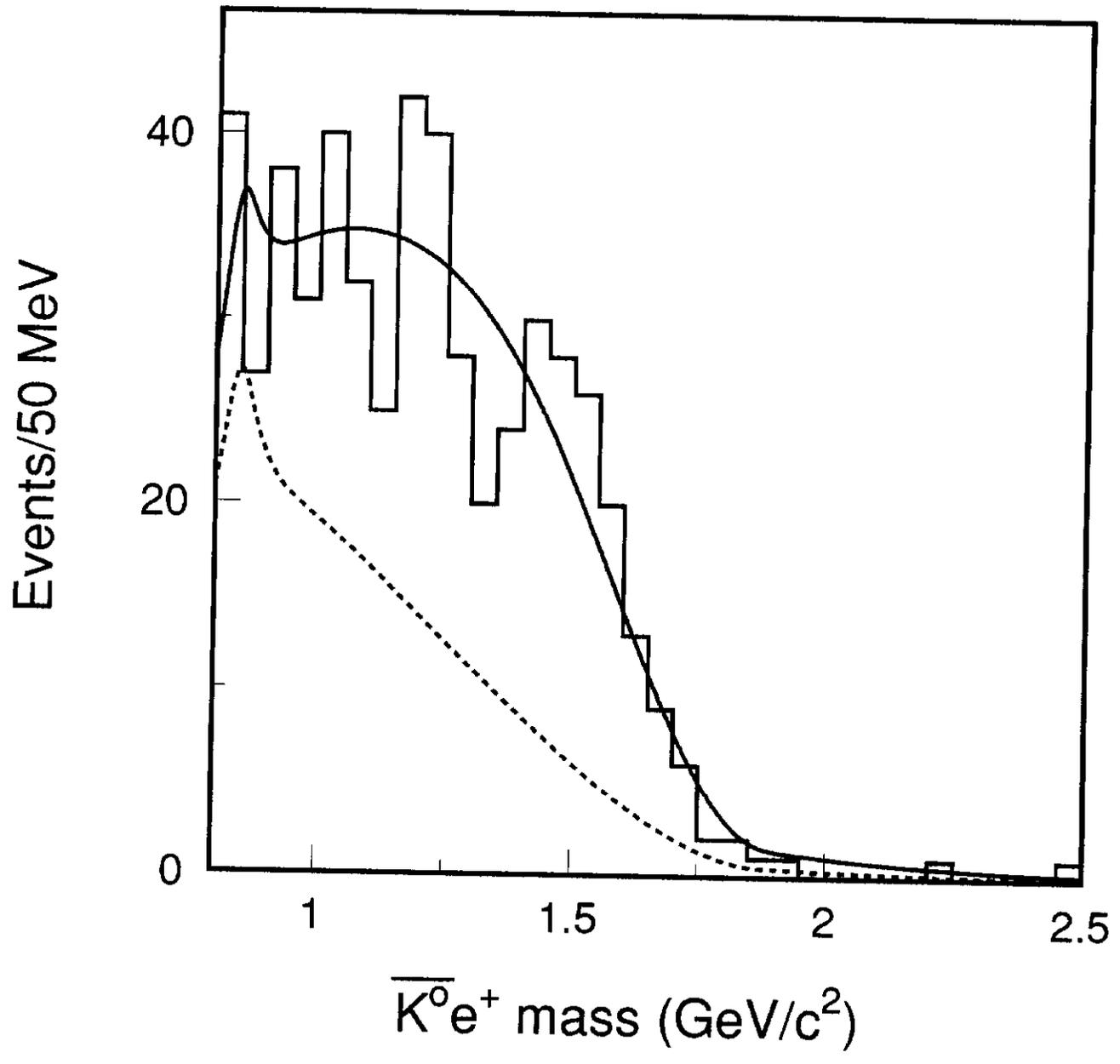


Figure 2

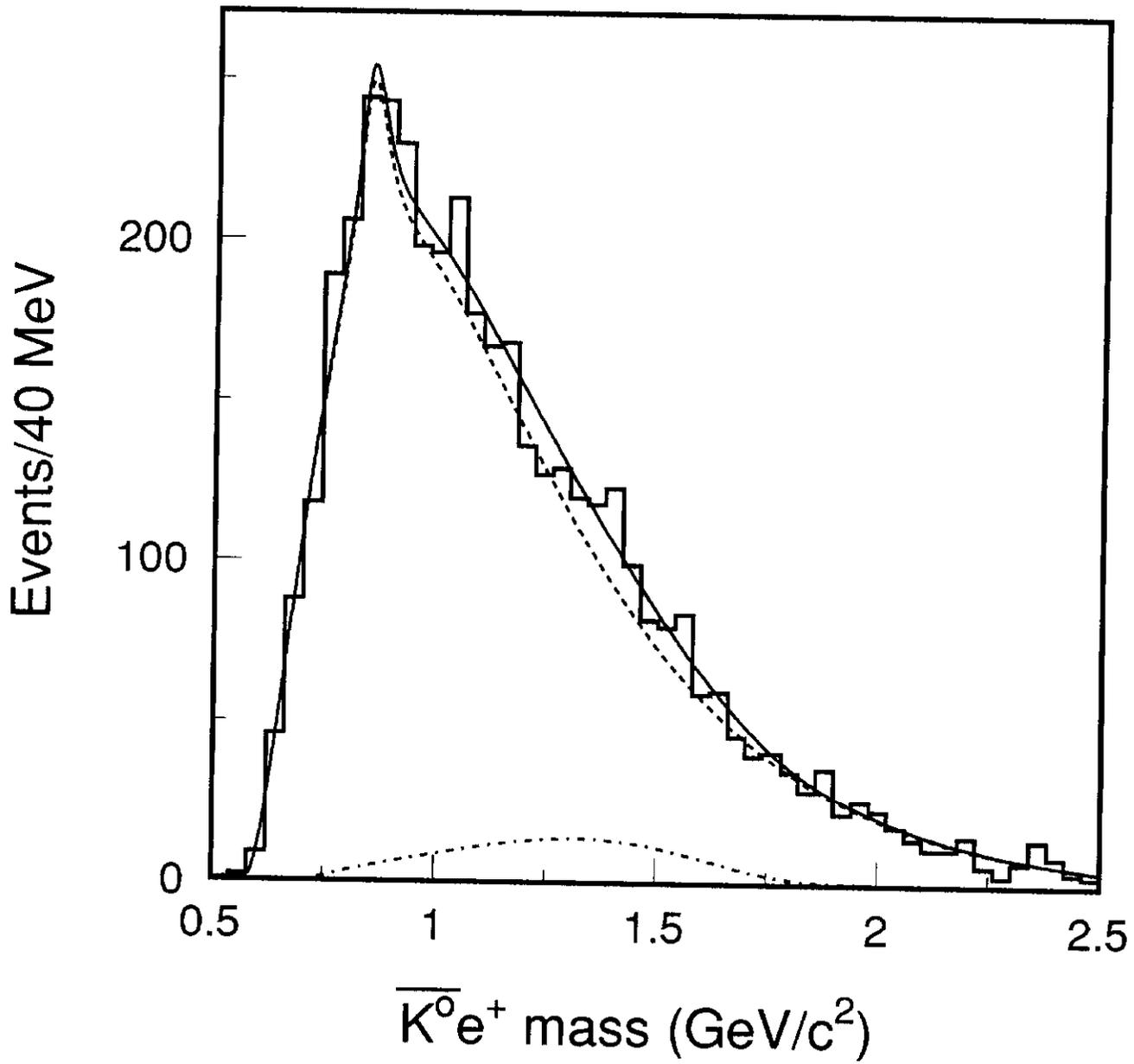


Figure 3

