Fermi National Accelerator Laboratory

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A Study of the Semileptonic Decay Mode $D^0 \rightarrow K^- e^+ \nu_e$*

The Tagged Photon Spectrometer Collaboration

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ABSTRACT

We present an analysis of the exclusive semileptonic decay mode $D^0 \to K^- e^+ \nu_e$. We have measured the ratio of decay rates $\Gamma(D^0 \to K^- e^+ \nu_e)/\Gamma(D^0 \to K^- \pi^+)$. After correcting for the reconstruction efficiencies and subtracting the contribution from other decay modes we have found the ratio to be equal to $0.77 \pm 0.12(stat) \pm 0.13(syst)$.

1. Introduction

The study of exclusive semileptonic decays is particularly interesting because of the simplicity of the underlying interaction and the wide scope of physics one can learn from it. The Cabibbo-favoured decays can proceed only through flavour decay (spectator) processes and, unlike the situation in hadronic decays, there is no uncertainty due to the possible presence of other diagrams. Also, there is no interference or final state interactions between leptons and hadrons in the final state. Since the leptonic part of the matrix element is well understood, the study of semileptonic decays probes the structure of the hadronic part.

The decay $D^0 \to K^- e^+ \nu_e$ has been widely discussed in the literature[1]. (Throughout the paper the charge conjugate states are implicitly included.) Because of the $V - A$ nature of the weak current and D,K being pseudoscalars, the $D - K$ interaction is purely vector. The relevant matrix element is given by

$$M = \frac{G}{\sqrt{2}} V_{cs}[(p_D + p_K)_a f_+(t) + (p_D - p_K)_a f_-(t)] \times \bar{u}_e \gamma_a (1 + \gamma_5) u_\nu \tag{1}$$

where p are the four-momenta, u are Dirac bispinors, and t is the four-momentum transfer from D to K (or $M_{e\nu}^2$). The form factor $f_-(t)$ always appears in a final result with m_e, the lepton mass and its contribution to the decay rate is negligible for the electron mode. The decay rate can then be shown (in the D^0 center of momentum system-cms) to be proportional to

$$\Gamma \propto G^2 |V_{cs}|^2 |f_+(t)|^2 [(E_K)^2 - (M_K)^2 - (M_D - E_K - 2 \times E_e)^2] \tag{2}$$

Analysis of the distributions in the D^0 cms makes it possible to extract the vector form factor $f_+(t)$. This, combined with branching fraction and lifetime measurements (plus theoretical input[2] about $f_+(0)$), allows a measurement of the $|V_{cs}|$ element of K-M matrix.

Additional interest stems from the fact that observation of the decay $D^{*+} \to K^+ e^- \bar{\nu}_e \pi^+$ would be an unambiguous signature of $D^0 - \bar{D}^0$ mixing.

This paper presents results from the analysis of 30% of the data sample from E691, a high energy photoproduction experiment performed at the Fermilab Tagged Photon Spectrometer. The detector, a two-magnet spectrometer of large acceptance, very good mass resolution, particle identification (Cerenkov counters, electromagnetic and hadronic calorimetry, muon filter) and equipped with a high resolution silicon microstrip detector, has been described elsewhere[3]. The electron identification used information on the E/p ratio, size of the signals in the electromagnetic and hadronic calorimeters, and the transverse shower shapes. The electron efficiency and the pion misidentification probability, while being position and energy dependent, had the typical values of 70% and 0.5% respectively. The incident photons, produced via the bremsstrahlung of 260 GeV electrons, had an average tagged energy of 145 GeV. We used an open trigger, based on the total transverse energy detected in the calorimeters. This accepted $\sim 30\%$ of the total hadronic cross section while being $\sim 75\%$ efficient for charm. The experiment recorded 10^8 triggers, this paper is based on the analysis of 3×10^7 events.

2. The method

We have selected the candidate events through the cascade decay $D^* \to D^0\pi^+$ followed by $D^0 \to K^-e^+\nu_e$. We have used two techniques to identify the candidates.

The first method is based on the fact that it is possible to reconstruct the missing neutrino momentum providing that the D^0 direction is measured with sufficient precision in the vertex detector. The algebra is by far the easiest in the Lorentz frame with z-axis along the D^0 path, and such that p^Z_{Ke} is equal to zero, where one writes

$$p^Z_\nu = p^Z_D; \tag{3}$$
$$p^T_\nu = p^T_{Ke}; \tag{4}$$
$$E_D = E_{Ke} + E_\nu. \tag{5}$$

Assuming the masses, $M_{Ke\nu} = M_D$ and $M_\nu = 0$, one solves easily for p^Z of ν_e *or* D^0 :

$$(p^Z)^2 = (p^Z_D)^2 = (p^Z_\nu)^2 = \frac{F^2}{4 \times \ (E_{Ke})^2} - (p^T_{Ke})^2; \tag{6}$$

$$\begin{aligned} F &= (M_D)^2 - (p^T_{Ke})^2 - (E_{Ke})^2 \\ &= 2 \times E_{Ke}E_\nu \geq 0. \end{aligned} \tag{7}$$

Because equation (6) is quadratic there exist two solutions for the $E_{Ke\nu}$. In some cases, one of them can be discarded as being non-physical (*e.g.* $E_{Ke\nu} > 260\ GeV$). In the remaining events, for every π^+ we will obtain two D^{*+} solutions, corresponding to the two p^Z_ν solutions. We choose the one which gives the *lower* D^* mass[4]. (Calculating the $M_{(K^-e^+\nu)\pi^+}$ acts as an analyser of the correctness of both the p^Z_ν solution and the choice of a π^+).

In the second technique, the candidate events are required to fall into the kinematically allowed region of the M_{Ke} vs $M_{Ke\pi} - M_{Ke}$ plane. (The end-point of the allowed boundary occurs for $M_{Ke} = M_D$, corresponding to the neutrino carrying zero momentum in the laboratory frame). This method, which ignores a neutrino is complementary to the first one, which is based on the ability to reconstruct the missing neutrino.

The experimental procedure consists of selecting K^-e^+ pairs originating from a common vertex significantly separated from a primary one, solving for the ν_e, and then combining the $K^-e^+\nu_e$ four-momentum (constrained to M_D) with that of a π^+ candidate. Background distributions were obtained using the same approach, but using the *wrong charge* $K^+e^+\nu_e\pi^+$, $K^+e^+\nu_e\pi^-$ and $K^+e^-\nu_e\pi^+$ combinations. They were added together, and subtracted from the final $M_{K^-e^+\nu_e\pi^+}$ distribution after being normalized to the integral over the mass interval $2.03 - 2.40\ GeV$.

The reconstruction efficiencies were obtained using Monte Carlo generated events. The Monte Carlo $K^-e^+\nu_e$ events were weighted to reproduce the decay t distribution expected from the assumed single pole form of the form factor

$$f_+(t) = f_+(0) \times \frac{M_{F^*}^2}{M_{F^*}^2 - t} \tag{8}$$

with $M_{F^*} = 2.11\ \ GeV$, as measured by Mark III[5]. (The sensitivity of our result to the shape of the form factor $f_+(t)$ and the value of M_{F^*} is small.)

The largest physics background comes from another semileptonic decay mode, namely $D^0 \to K^-e^+\pi^0\nu_e$. What we actually measure is the sum of contributions from the $K^-e^+\nu_e$ and $K^-e^+\pi^0\nu_e$ modes, with obviously different efficiencies. The uncertainties in the t distribution in the $K^-e^+\pi^0\nu_e$ decay lead at this moment to a sizable ($\sim 7\%$) systematic error in the final result. We have assumed here, following Mark III[6], that $\Gamma(K^-e^+\nu_e)/\Gamma(K^-e^+\pi^0\nu_e) = 3$.

3. Results

We required the kaon and electron candidates to be good quality, well identified tracks. A cut on electron momentum, $p_e \geq 12\ GeV$ was applied to improve the signal to noise ratio in the electron identification. The K^-e^+ vertex was required to be well separated from the primary one ($\Delta\vec{x} \geq 6\sigma_{\vec{x}}$) and both vertices were required to be of good quality. The primary vertex should have at least two tracks associated with it, a slow pion from the D^* decay being one of them.

In Figures 1,2 and 3 we present $M_{Ke\nu\pi}$ distributions for the signal, normalized background and background subtracted signal respectively. This particular analysis was performed with a $7\sigma_{\vec{x}}$ separation cut between the primary and decay vertices, and a cut on $M_{Ke} > 0.8\ GeV$. We find in the signal region ($2.000 - 2.025\ GeV$) 110 events, out of which 72 are identified (after background subtraction) as signal. The reconstruction efficiency for this set of cuts was 2.1%. To estimate the systematic error, due to the background subtraction and uncertainties in the t distribution for the $K^-e^+\pi^0\nu_e$ mode, we have varied the primary-decay vertex decay separation (6,7,8 and 9 σ), changed track quality cuts, and finally made different assumptions about the t distribution for the $D^0 \to K^-e^+\pi^0\nu_e$ decay. The errors on the reconstruction efficiencies (the largest contribution, 14%, comes from the uncertainty in the electron reconstruction efficiency) were added in quadrature. Comparing the number of events found (corrected for the reconstruction efficiencies) with the number of events *produced* in the mode $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ we have measured the ratio of decay rates $\Gamma(D^0 \to K^-e^+\nu_e)/\Gamma(D^0 \to K^-\pi^+) = 0.77 \pm 0.13(stat) \pm 0.12(syst)$.

In Figure 4 we present the results of an analysis of the data with a second method, counting events in the kinematically allowed region in the M_{Ke} vs $M_{Ke\pi} - M_{Ke}$ plane. To reduce background, only events in a region $M_{Ke} > 1.2\ GeV$ were accepted. We found 71 correct sign events and 14 events of wrong sign. This translates into a result which is in a very good agreement with the one obtained with a sample of events with reconstructed ν_e, with slightly larger errors.

Assuming the Mark III[7] branching fraction for $D^0 \to K^-\pi^+ = 4.2 \pm 0.4 \pm 0.3\%$ we have obtained the preliminary result $BF(D^0 \to K^-e^+\nu_e) = 3.2 \pm 0.6 \pm 0.5\%$. Our measurement agrees very well with the Mark III measurement of the same branching fraction[6], who found a value $3.9 \pm 0.6 \pm 0.6\%$.

4. Future improvements and developments

We have completed a detailed study of the electron identification scheme. As a result, we have not only significantly reduced the uncertainties in our knowledge of electron efficiency and backgrounds, but we have also increased the electron reconstruction efficiency itself by $\sim 25\%$, without compromising its pion rejection capabilities.

With the full data sample and the improved electron identification scheme we should have of the order of 300 fully reconstructed events. A paper presenting the new measurement of the branching fraction, results of a study of the vector form factor and $|V_{cs}|$, and the limit on the $D^0 - \bar{D}^0$ mixing is in preparation.

5. Acknowledgements

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FIGURE CAPTIONS

Figure 1. Effective mass distribution for $K^-e^+\nu_e\pi^+$ (signal) combinations, mass of $K^-e^+\nu_e$ system constrained to that of a D^0.

Figure 2. Effective mass distribution for $K^+e^+\nu_e\pi^+$, $K^-e^-\nu_e\pi^+$ and $K^+e^-\nu_e\pi^+$ combinations (background), normalized to the integral over the mass interval $2.03 - 2.40 GeV$ of the correct sign (signal) distribution.

Figure 3. Background subtracted (see above) effective mass distribution for $K^-e^+\nu_e\pi^+$ (signal) combinations.

Figure 4. Scatterplots of the $M_{Ke\pi} vs M_{Ke}$ for the correct $(K^-e^+\pi^+)$ and wrong $(K^-e^+\pi^-)$ charge combinations. The curves shown represent the boundary of kinematically allowed region for the events originating from the $D*^+ \to D^0\pi^+, D^0 \to K^-e^+\nu_e$ cascade decay.

Figure 1

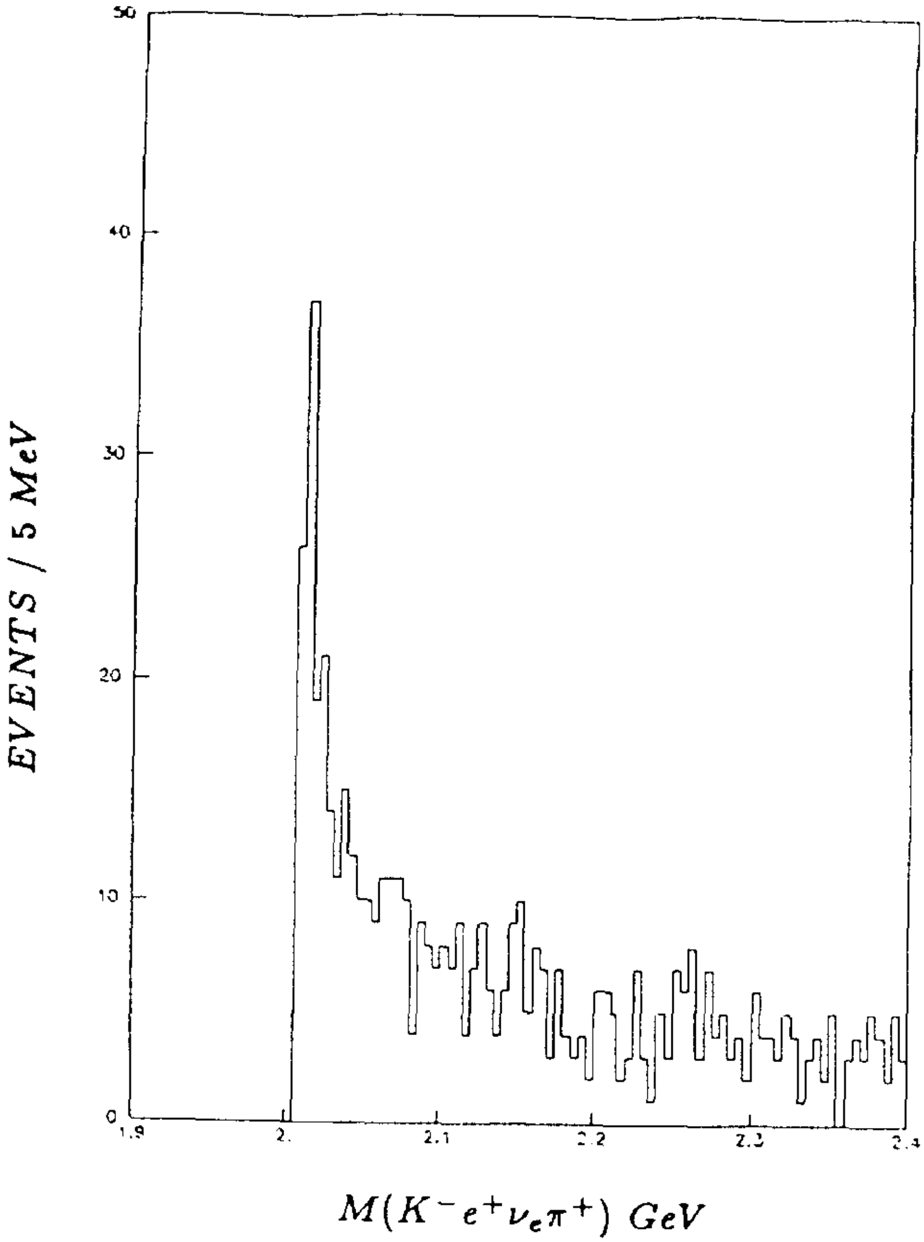
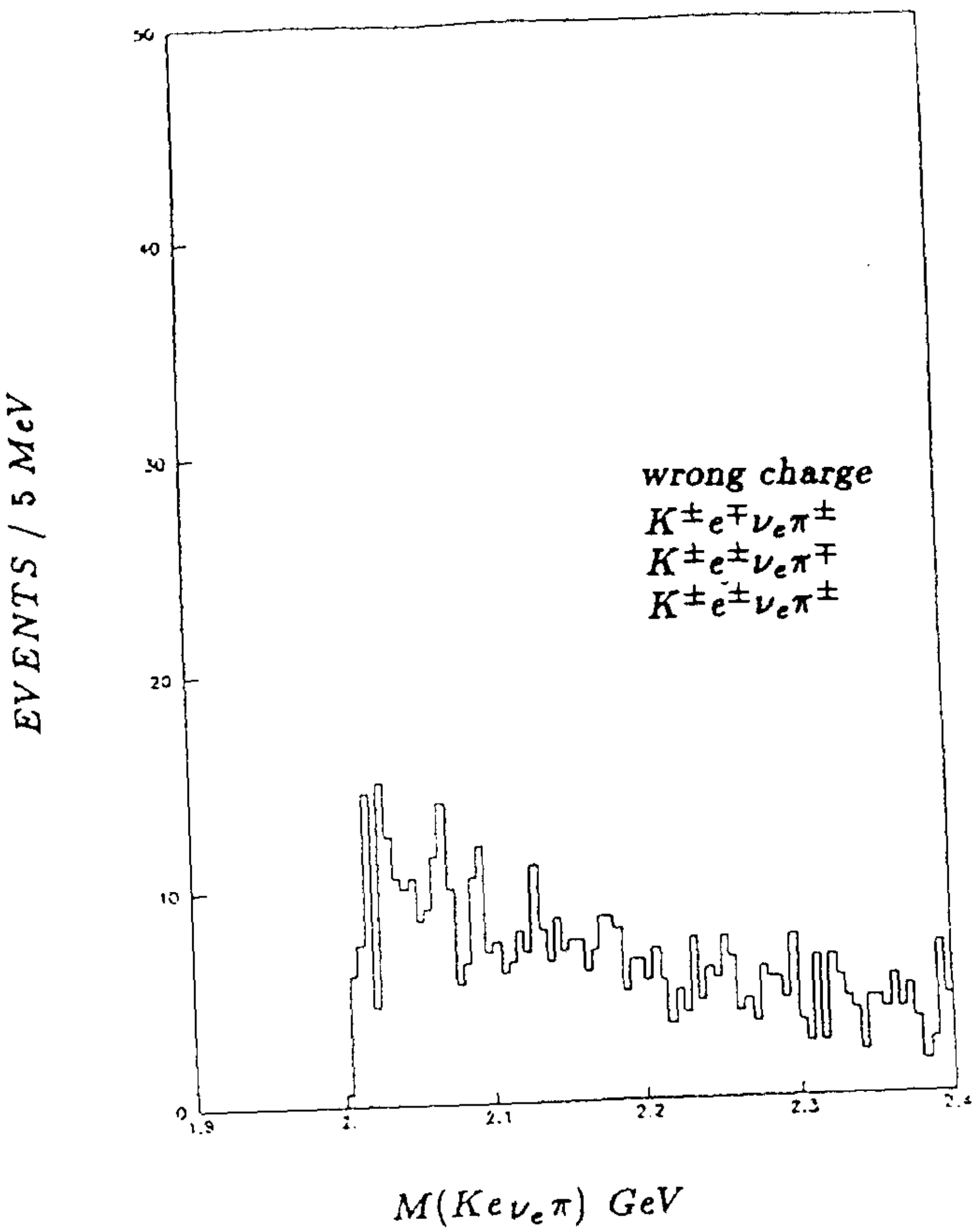


Figure 2



wrong charge
$K^{\pm}e^{\mp}\nu_e\pi^{\pm}$
$K^{\pm}e^{\pm}\nu_e\pi^{\mp}$
$K^{\pm}e^{\pm}\nu_e\pi^{\pm}$
EVENTS / 5 MeV
$M(Ke\nu_e\pi)$ GeV

Figure 3

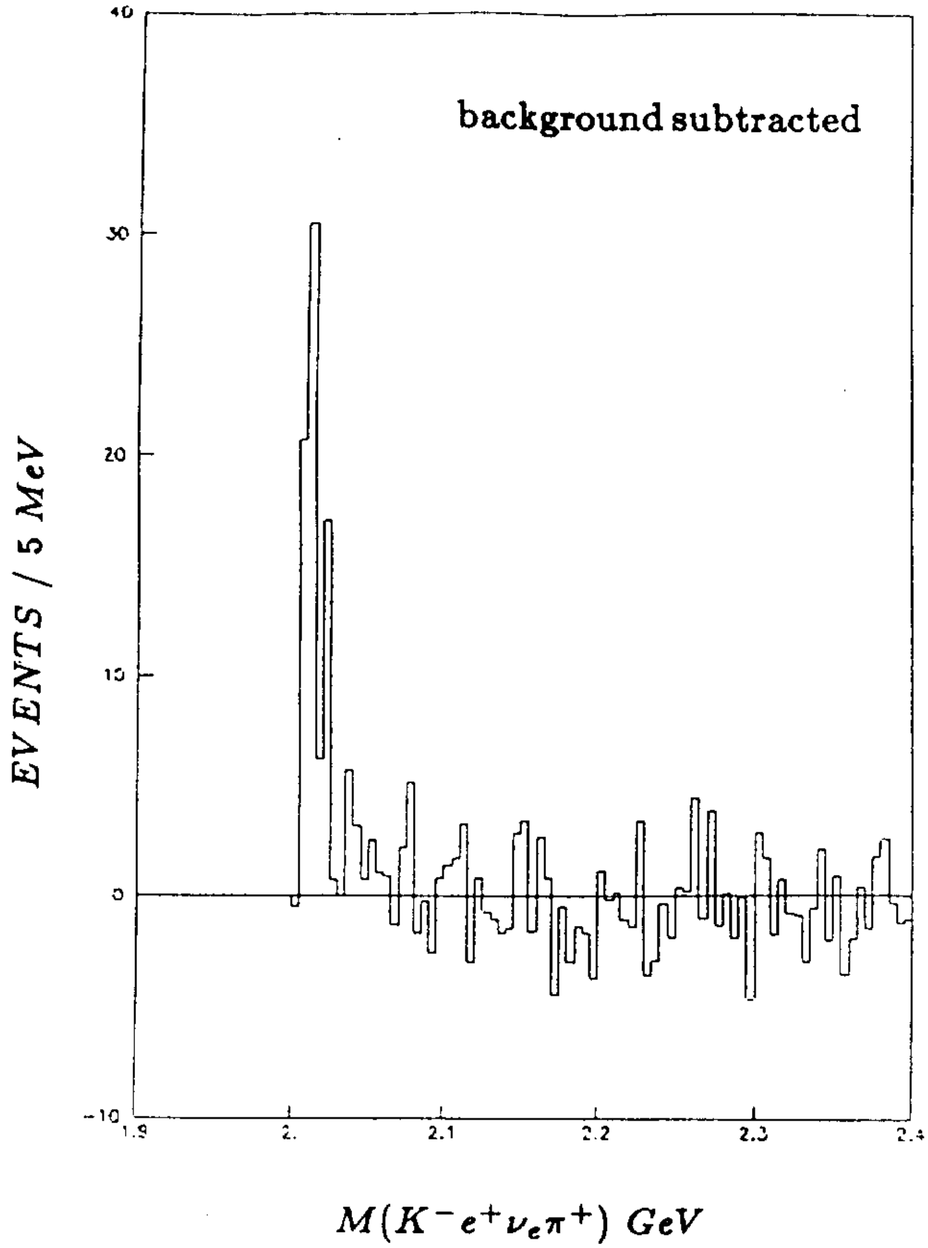
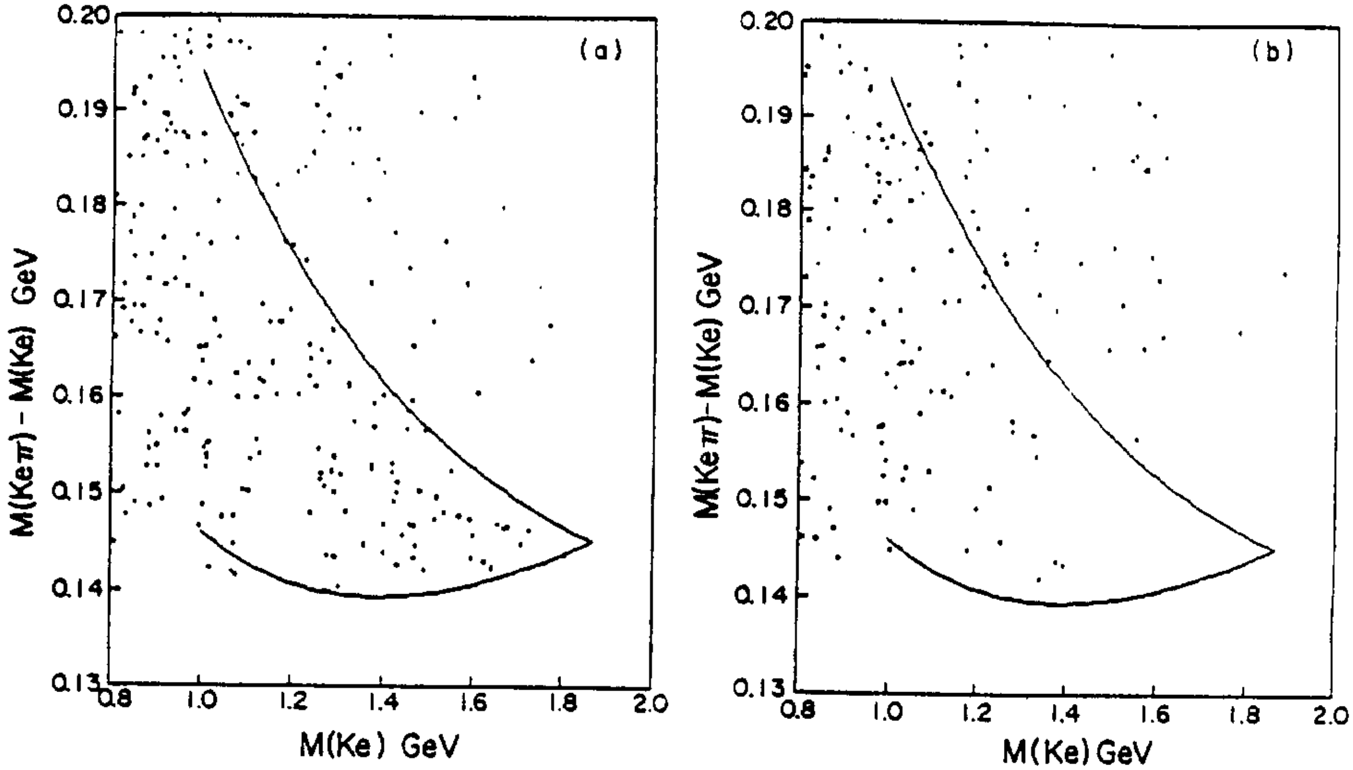

background subtracted
40
30
20
10
0
-10
1.9
2.
2.1
2.2
2.3
2.4
EVENTS / 5 MeV
$M(K^- e^+ \nu_e \pi^+)$ GeV

Figure 4



$M(Ke)$ *vs.* Mass difference $M(Ke\pi)-M(Ke)$ for: (a) right-sign; and (b) wrong-sign combinations.