SEMILEPTONIC AND LEPTONIC DECAYS OF D MESONS

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ABSTRACT We present an analysis of the exclusive semileptonic decay modes $D^0 \to K^-e^+\nu_e$ and $D^+ \to K^-\pi^+e^+\nu_e$. We have measured their branching fractions relative to those of dominant hadronic modes, $BF(D^0 \to K^-e^+\nu_e)/BF(D^0 \to K^-\pi^+) = 0.77 \pm 0.06 \pm 0.08$ and $BF(D^+ \to K^*e^+\nu_e)/BF(D^+ \to K^-\pi^+\pi^+) = 0.45 \pm 0.04 \pm 0.04$. The non-resonant $K\pi$ component in the $D^+ \to K\pi e\nu$ decay mode is found to be small. Combining the measurements of D^0 lifetime, branching fraction for the mode $D^0 \to K^-\pi^+$ and predicted partial rate $\Gamma(D^0 \to K^-e^+\nu_e)$ we find $|V_{cs}|^2|f_+(0)|^2 = 0.42 \pm 0.06 \pm 0.07$. We also present limits on flavour-changing neutral current decays $D^0 \to e^+e^-$ and $D^0 \to \mu e$.

1. Introduction

This paper presents results from the analysis of 100% of the data sample from E691, a high energy photoproduction experiment performed at the Fermilab Tagged Photon Spectrometer. 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.

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[2]. Based on experience with the spectrometer from previous experiment, the E516, we have increased the magnetic field in the analysing dipoles (momentum resolution), added six new drift chamber planes (tracking efficiency) and installed new mirrors in Cerenkov counters (particle identification). (The improvement in mass resolution resulting from spectrometer upgrades exceeds a factor of two.) Also, very importantly, we have taken advantage of advances in technology. We have added a high resolution silicon microstrip (SMD) vertex detector (transverse resolution of $20\mu m$, longitudinal of $300\mu m$). This allows to identify charm particles decay vertices and further reduce backgrounds. Finally, we made use of the Advanced Computer Program[3] system of parallel 32-bit microprocessors at Fermilab, offering very large computing power. We have finished our data reconstruction in 1986, without ACP it would take us 3 years.

For the results discussed below it is essential to identify electrons well. We used information on the E/p ratio, size of the signals in the electromagnetic and hadronic calorimeters, and the on transverse energy deposition in the electromagnetic calorimeter. The electron efficiency and the pion misidentification probability, while being position and energy dependent, had the typical values of 61% and 0.3% respectively.

2. Semileptonic decays of D mesons

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.

2.1 $D^0 \to K^- e^+ \nu_e$

In the $D^0 \to K^- e^+ \nu_e$ decay, because of the $V - A$ nature of the weak current and D, K being pseudoscalars, the $D - K$ interaction is purely vector. (Throughout the paper the charge conjugate states are implicitly included.) There are two formfactors involved, $f_+(t)$ and $f_-(t)$, the latter 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

$$\Gamma \propto G^2 |V_{cs}|^2 |f_+(t)|^2 [(E_K)^2 - (M_K)^2 - (M_D - E_K - 2 \times E_e)^2] \tag{1}$$

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[4] about $f_+(0)$), allows a measurement of the $|V_{cs}|$ element of K-M matrix.

We have selected the candidate events through the cascade decay $D^* \to D^0 \pi^+$ followed by $D^0 \to K^- e^+ \nu_e$. The technique used 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. Assuming the masses, $M_{Ke\nu} = M_D$ and $M_\nu = 0$, one solves easily for p^Z of ν_e *or* D^0 :

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

Because equation (2) 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[5]. (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^+).

The experimental procedure consists of selecting $K^- e^+$ pairs originating from a common vertex significantly separated from a primary one, $(\Delta\vec{x} \geq 7\sigma_{\vec{x}})$, 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. These 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. A cut on electron momentum, $p_e \geq 12$ GeV was applied to improve the signal to noise ratio in the electron identification. The primary vertex should have at least two tracks associated with it, a slow pion from the D^* decay being one of them. To reduce background, an additional cut on $M_{Ke} > 0.8$ GeV has been applied.

The largest, and the only considered important, physics background comes from another semileptonic decay mode, namely $D^0 \rightarrow K^-e^+\pi^0\nu_e$. To determine the its contribution in our signal we assume isospin symmetry and make use of our measurement of the ratio $\Gamma(K^*e^+\nu_e/\Gamma(K^-e^+\nu_e)$. (I an analysis (see below) of $D^+ \rightarrow K^-e^+\pi^+\nu_e$ mode, we have found that $K^-\pi^+$ system is dominated by $K^*(890)$ and we have measured $\Gamma(K^*e^+\pi^+\nu_e) = (3.8 \pm .4 \pm .7) \times 10^{10}$ s^{-1}. Taking the ratio $\Gamma(K^-e^+\nu_e)/\Gamma(K^*e^+\nu_e) = 2.03 \pm .34 \pm .47$, and assuming K^* dominance, leads to a 7% correction.)

In Figures 1, 2 and 3 we present $M_{Ke\nu\pi}$ distributions for the signal, normalized background and background subtracted signal respectively. We find in the signal region (2.000 – 2.025 GeV) 347 events, out of which 250 are identified (after background subtraction) as signal. The reconstruction efficiency for this set of cuts was 1.72%. The errors on the reconstruction efficiencies (the uncertainty in the electron reconstruction efficiency is estimated to be 5%) were added in quadrature. Comparing the number of events *produced* (corrected for the reconstruction efficiencies and with 7% of signal subtracted to account for contribution from $K^-e^+\pi^0\nu_e$) with the number of events *produced* in the mode $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$, we obtain the ratio of decay rates $\Gamma(D^0 \rightarrow K^-e^+\nu_e)/\Gamma(D^0 \rightarrow K^-\pi^+) = 0.77 \pm 0.06(stat) \pm 0.08(syst)$. Assuming the Mark III[6] branching fraction for $D^0 \rightarrow K^-\pi^+ = 4.2 \pm 0.4 \pm 0.4\%$, this translates to $BF(D^0 \rightarrow K^-e^+\nu_e) = 3.2 \pm 0.4 \pm 0.5\%$.

Figure 4 presents the distribution of the four-momentum transfer t (or $M^2_{e\nu}$). Fitting to this distribution, assuming a single pole form of vector formfactor, we obtain for the mass of the exchanged particle, $M_{F^*} = 2.1 \pm^{0.3}_{0.2}$ GeV, consistent with the directly measured[7] value of $M_{F^*} = 2.11$ GeV. Assuming this latter value for M_{F^*} and after integrating the expression (1) one finds $\Gamma(K^-e^+\nu_e) = |V_{cs}|^2|f_+(0)|^2 \times 1.818 \times 10^{11}s^{-1}$

Combining this result with branching fraction and D^0 lifetime[2] measurements, $\tau_{D^0} = (4.22 \pm 0.08 \pm 0.10) \times 10^{-13}$ s, we find $|V_{cs}|^2|f_+(0)|^2 = 0.42 \pm 0.06 \pm 0.07$. With a knowledge of $|f_+(0)|$ this measurement would translate directly into a measurement of $|V_{cs}|$. At present, formfactor models do not offer enough precision, however, to regard a result of such an exercise too seriously. (Assuming[4] $|f_+(0)| = 0.76$ yields $|V_{cs}| = 0.86 \pm 0.06 \pm 0.07$.) Reversing the argument, we can adopt a value of $|V_{cs}| = 0.975$ (assuming three families and imposing unitarity condition on K-M matrix) and obtain a measurement of $|f_+(0)| = 0.67 \pm 0.05 \pm 0.06$.

2.2 $D^+ \to K^-\pi^+e^-\nu_e$

The theoretical description of this mode in more complicated than in $D^0 \to K^-e^+\nu_e$ mode. Here, five formfactors are involved, instead of two. There exist several calculations[4,8] of their behaviour in the case of $D^+ \to K^*e\nu_e$. Models predicting the relative branching fractions for $D \to Ke\nu_e$ and $D \to K\pi e\nu_e$ are relying on assumption that the $K-\pi$ system is composed entirely of the $K^*(890)$ resonance. Mark III reported recently[9] found $BF(D^+ \to K^*e\nu_e) \approx BF(D^+ \to K\pi e\nu_e)$. Finding a large contribution from the non-resonant mode raises doubts in validity of such an assumption, which is routinely made not not only in case of D mesons, but also in analogous case of semileptonic decays of B mesons.

The technique used in this study exploits a long D^+ lifetime. We have simply required a large separation between the $K\pi e$ and primary vertices, $\Delta\vec{x} \geq 12\sigma_{\vec{x}}$. The primary vertex should have at least two tracks associated with it. If any other track passed within $65\mu m$ from the secondary vertex, the event was rejected. In Figure 5, we present $K\pi$ mass distributions for events in which $K\pi e$ were originating from a secondary vertex. We find 66 events with wrong sign (dashed line) and 318 events with correct sign (solid line). A $K^*(890)$ peak is clearly visible in the latter sample. Comparing the numbers of *produced* (corrected for reconstruction efficiencies) events in $K^*e^+\nu_e$ and $K^-\pi^+\pi^+$ modes we find $BF(D^+ \to K^*e^+\nu_e)/BF(D^+ \to K^-\pi^+\pi^+) = 0.45 \pm 0.04 \pm 0.04$. Taking[6] $9.1 \pm 1.3 \pm 0.4\%$ for $BF(D^+ \to K^-\pi^+\pi^+)$ we obtain $BF(D^+ \to \bar{K}^{*0}e^+\nu_e) = 4.13 \pm 0.38 \pm 0.72\%$. The non-resonant component in the $D^+ \to K\pi e\nu$ decay mode is found to be small, $BF_{NR}(D^+ \to K^-\pi^+e^+\nu_e) = 0.32 \pm^{.23}_{.22} \pm .17\%$.

Taking[2] D^+ lifetime, $\tau_{D^+} = (10.90 \pm 0.30 \pm 0.25) \times 10^{-13}$ s, we find a decay rate for $D^+ \to \bar{K}^{*0}e^+\nu_e$ equal to $3.79 \pm 0.34 \pm 0.66 \times 10^{10} s^{-1}$. It is a surprising result, this rate has been expected to be larger by about a factor of two. (Because of isospin invariance $\Gamma(D^0 \to K^{*-}e^+\nu_e)$ should be equal to $\Gamma(D^+ \to \bar{K}^{*0}e^+\nu_e)$, and most of the models[4] predict $\Gamma(D \to K^*e\nu) \approx \Gamma(D \to Ke\nu)$. The ratio of our two results, $\Gamma(D^0 \to K^-e^+\nu_e)/\Gamma(D^+ \to \bar{K}^{*0}e^+\nu_e) = 2.03 \pm 0.34 \pm 0.47$.) It presents a challenge to the formfactor models. Additional input to such studies may come from our, preliminary, observation that K^* in $D^+ \to K^*e\nu$ decays is almost completely longitudinally polarized.

3. Rare decays of D mesons

Neutral current interactions are known from studies of K meson decays to conserve flavour to a high precision. Although flavour changing neutral currents (FCNC) are forbidden in the Weinberg-Salam model, many extensions of the Standard Model allow such processes. In general, limits for the K decays are $\sim 10^4$ times more stringent than for the corresponding decays of charmed particles. However, there exist models which avoid the K limits by introducing new FCNC interactions. By intruducing different couplings to the "up-type" quarks (u,c,t) and to the "down-like" (d,s,b) quarks, the flavour non-conserving decays of charmed particles can be enhanced with respect to the corresponding decays of strange particles[10].

We present upper limits on FCNC-mediated decays of charmed particles, namely $D^0 \rightarrow e^+e^-$ and $D^0 \rightarrow \mu e$. In the $D^0 \rightarrow e^+e^-$ mode we find, with a 3 σ vertex separation cut, 0.0 ± 2.6 events. After all the corrections we obtain a ($90\% C.L$) limit $BF(D^0 \rightarrow e^+e^-) < 5 \times 10^{-5}$. The fit to the μ^+e^- mass distribution (a vertex separation cut of 6 σ was used here) gives 0.0 ± 2.8 events. After correcting for reconstruction efficiencies, we set a limit $BF(D^0 \rightarrow \mu^+e^-) < 5 \times 10^{-5} (90\% C.L.)$.

4. Future plans

A study of $D^0 \rightarrow \pi^- e^+ \nu_e$ is under way. Combined with analysis of $K^- e^+ \nu_e$ mode, presented above, it would yield a measurement of the $|V_{cd}|/|V_{cs}|$. Also, we are trying to measure the semileptonic rate for decay $D^0 \rightarrow K^* e\nu$, $K^* \rightarrow K^0 \pi^-$, allowing us to measure $\Gamma(D^0 \rightarrow K e\nu)/\Gamma(D^0 \rightarrow K^* e\nu)$.

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REFERENCES

1. The members of The Tagged Photon Collaboration are : J.C. Anjos, J.A. Appel, S.B. Bracker, T.E. Browder, L.M. Cremaldi, J.R. Elliott, C.O. Escobar, P. Estabrooks, M.C. Gibney, G.F. Hartner, P.E. Karchin, B.R. Kumar, M.J. Losty, G.J. Luste, P.M. Mantsch, J.F. Martin, S. McHugh, S.R. Menary, R.J. Morrison, T. Nash, U. Nauenberg, P. Ong, J. Pinfold, G. Punkar, M.V. Purohit,J.R. Raab, A.F.S. Santoro, J.S. Sidhu, K. Sliwa, M.D. Sokoloff, M.H.G. Souza, W.J. Spalding, M.E. Streetman, A.B. Stundžia, M.S. Witherell;

2. J. Raab *et al.*, Phys. Rev. **D37** (1988) 2391.

3. Nash, T., *et al.*, Proc. of "Computing in High Energy Physics", Amsterdam 1985.

4. Wirbel, M., B. Stech and M. Bauer, Z. Phys. ***C29***, 637 (1985); B. Grinstein, M.B. Wise, Phys. Lett. **B197**. 249 (1987); and refernces therein.

5. It has been checked with Monte Carlo events that this procedure does not introduce any serious biases. It removes the ambiguity problem in an experimentally clean way, making the subsequent interpretation of results straightforward.

6. Becker, J.,*et al.*, Mark III Collaboration, SLAC-PUB-4391, May 1987.

7. Schindler, R., Mark III Collaboration, SLAC-PUB-4055, September 1986.

8. Suzuki, M., Phys. Lett. **155B**, 112 (1985), Ali, A. and T.C. Yang, Phys. Lett. **65B**, 275 (1976), also see Ref. 4.

9. Coffman, D., Ph. D. Thesis, California Institute of Technology, CALT-68-1415 (1987).

10. A. Hadeed and B. Holdom, Phys. Lett. **159B** (1985) 379; W. Buchmuller, CERN-TH-4499/86, July 1986.

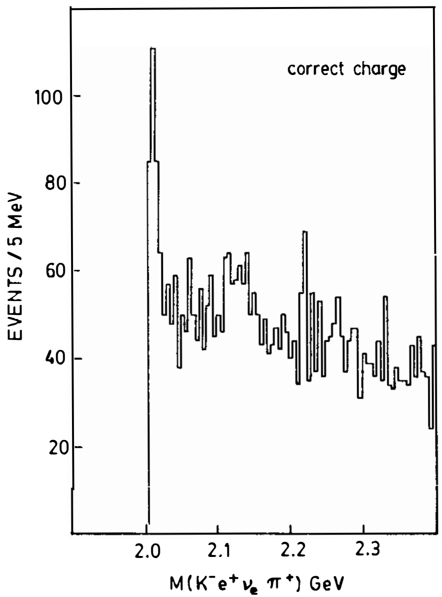

Figure 1. Effective mass distribution for $K^-e^+\nu_e\pi^+$ (signal) combinations, mass of $K^-e^+\nu_e$ system constrained to that of a D^0.

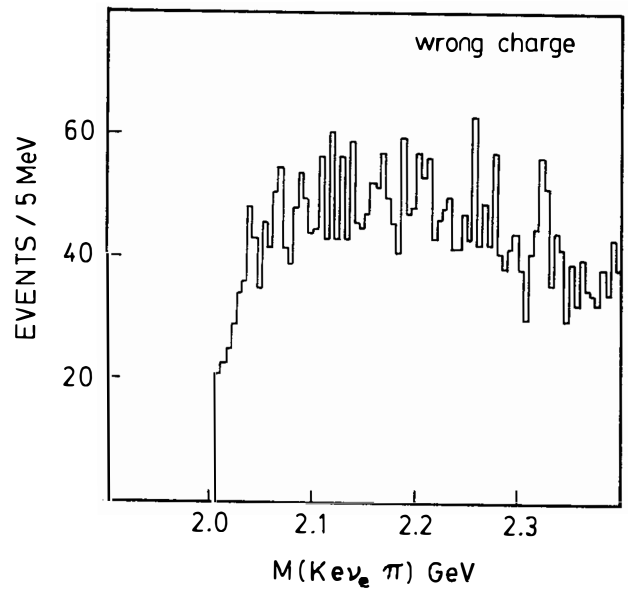

Figure 2. Effective mass distribution for $K^+e^+\nu_e\pi^+$, $K^-e^-\nu_e\pi^+$ and $K^+e^-\nu_e\pi^+$ combinations (back-ground), normalized to the integral over the mass interval $2.03 - 2.40 GeV$ of the correct sign (signal) distribution.

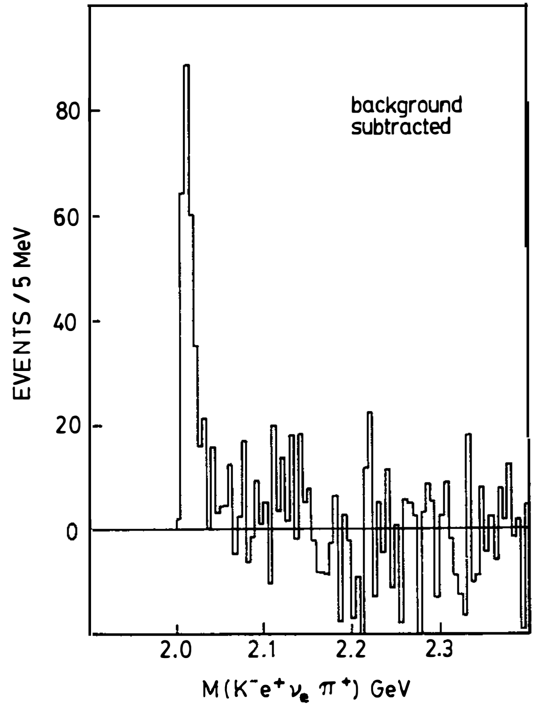

Figure 3. Background subtracted (see above) effective mass distribution for $K^- e^+ \nu_e \pi^+$ (signal) combinations.

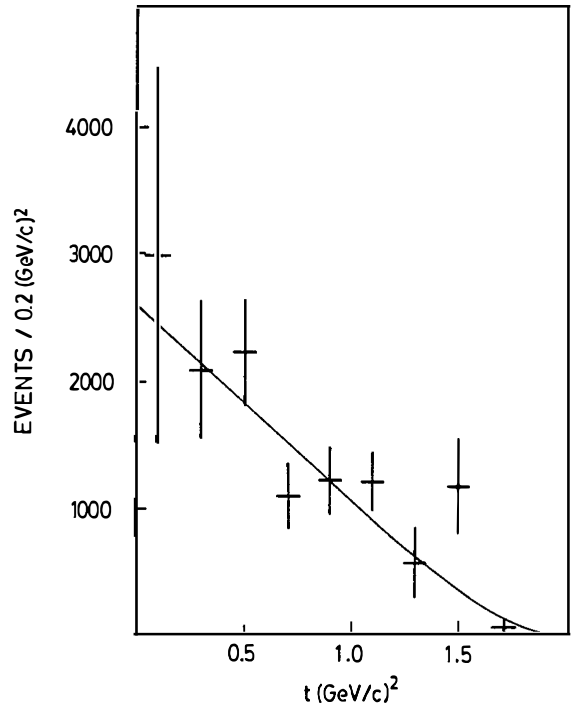

Figure 4. Four-momentum transfer from D to K (or $M^2_{e\nu}$) distribution. The superimposed curve a result of a fit to a t-distribution expected, after integration over phase space, from the assumed single pole form for the vector formfactor. The fit yields a value of $M_{F*} = 2.1\pm^{0.3}_{0.2}$.

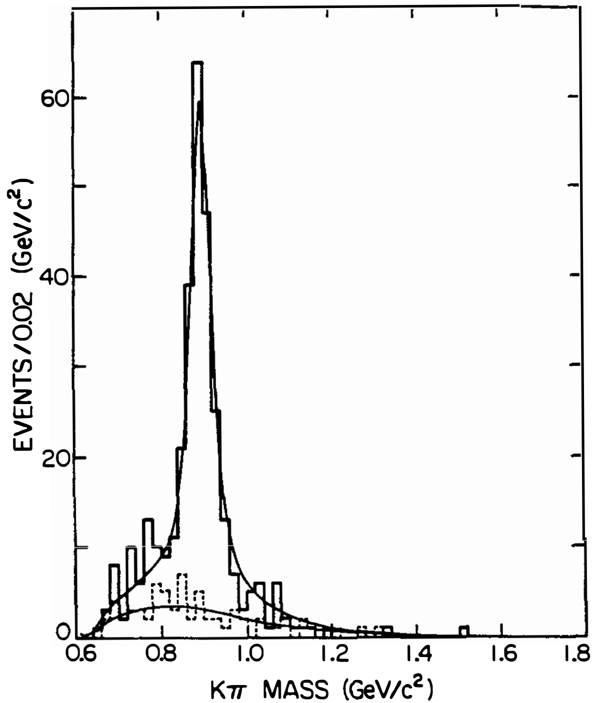

Figure 5. Effective mass distributions of $K\pi$ system for events with wrong $K\pi e$ (dashed line) and correct $K\pi e$ charge combinations (solid line).