Study of the Decay $K^+ \rightarrow \pi^+ e^+ e^-$

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We present results of an experiment in which approximately 500 events of the decay $K^+ \rightarrow \pi^+ e^+ e^-$ were observed. We have measured the branching ratio for $K^+_{\pi ee}$ to be $(2.75 \pm 0.23 \pm 0.13) \times 10^{-7}$ assuming a vector interaction with a form factor of $\lambda = 0.105 \pm 0.035 \pm 0.015$. We have also found the branching ratio times decay probability for $K^+ \rightarrow \pi^+ X^0$, $X^0 \rightarrow e^+ e^-$ to be less than 1.5×10^{-8} (99% C.L.) over an X^0 invariant mass range from 150 to 340 MeV/c^2.

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The decay $K^+ \rightarrow \pi^+ e^+ e^-$, $K^+_{\pi ee}$, has several facets that make it an interesting decay mode for study. First, even though there are no experimental data beyond a first branching ratio measurement employing 41 events, $\Gamma(K^+_{\pi ee})/\Gamma(K^+ \rightarrow \text{all}) = (2.7 \pm 0.5) \times 10^{-7}$ [1], the literature contains many calculations of the branching ratio and the e^+e^- invariant mass spectrum for this process [2]. Early in this history it was recognized that the parameters describing this decay were dominated by long-range hadronic effects. The challenge has been to calculate them in a theoretically consistent manner. With the small data sample, however, tests of these calculations have been quite limited. Once parametrized, and with some model-dependent assumptions, $K^+_{\pi ee}$ can also be used to predict the properties of $K^0_S \rightarrow \pi^0 e^+ e^-$, $K^S_{\pi ee}$ [3].

Finally, a reason for studying $K^+_{\pi ee}$ arises because this mode involves a strangeness-changing neutral current. As such, this decay is greatly suppressed in comparison to similar charged-current modes, $\Gamma(K^+_{\pi ee})/\Gamma(K^+_{e3}) \approx 5.6 \times 10^{-6}$. This heightens the relative sensitivity of this mode to physics outside of the standard model.

The experiment was performed at the Brookhaven Alternating Gradient Synchrotron employing an apparatus that has been described in previous publications [4]. The $K^+_{\pi ee}$ candidates selected for this work were required to have decay products with unambiguous particle identification and trajectories consistent with having come from a common vertex. The reader is referred to the previous publications for details on how this analysis was performed [4,5].

The selected events are displayed in Fig. 1 on a scatter plot of the invariant mass of the e^+e^- pair, M_{ee}, versus the invariant mass of all three decay products, $M_{\pi ee}$. This figure is divided into two regions, one containing events with M_{ee} less than 130 MeV/c^2, "low mass," and one containing events with higher M_{ee}. The low-mass region is dominated by events originating from the decay chain $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow e^+ e^- \gamma$, K_{Dal} events. This chain has a branching ratio times decay probability of $\sim 2.54 \times 10^{-3}$, which is about 4 orders of magnitude greater than the $K^+_{\pi ee}$ mode. For this reason, events occurring in this region of the figure were first prescaled by a weighted average of 3.87 during data acquisition, and then by a factor of 140 for display purposes. The hardware prescale was accomplished by taking advantage of the kinematics of the low invariant ee mass, and is described in Ref. [5]. Because K_{Dal} events are reconstructed without inclusion of the photon, the πee invariant mass does not reconstruct to the K^+ mass.

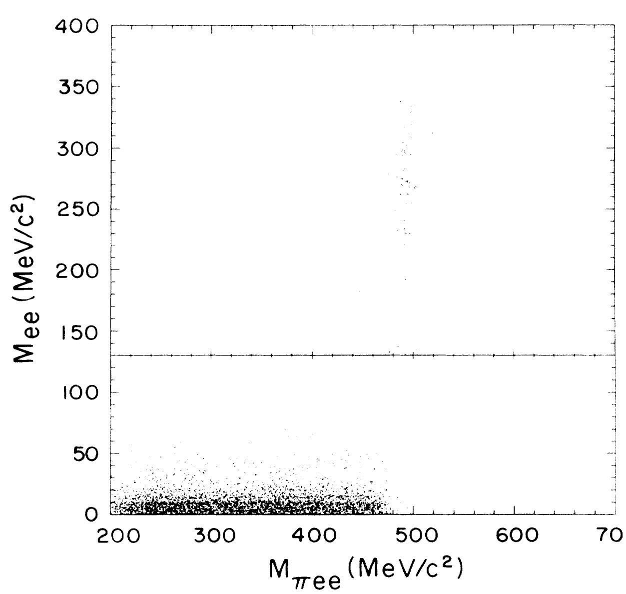

FIG. 1. Scatter plot of the e^+e^- invariant mass, M_{ee}, vs $\pi^+e^+e^-$ invariant mass, $M_{\pi ee}$, for selected events with a π^+, e^+, and e^- in the final state. The number of events with M_{ee} less than 130 MeV/c^2 is scaled down by 140.

Since the $K_{\rm Dal}$ decay process is well understood theoretically, and well studied experimentally [6], the low-mass events were used to verify our understanding of the acceptance of our apparatus and as the normalization for the $K^+_{\pi ee}$ branching ratio. In this process we simulated various kinematic distributions from the $K_{\rm Dal}$ mode and compared them with corresponding data distributions. All such comparisons showed consistency, e.g., the χ^2 per degree of freedom for the M_{ee} spectrum was 0.9 for 39 degrees of freedom.

In Fig. 1, one sees a clear signal of $K^+_{\pi ee}$ events above the M_{ee} value of 130 MeV/c^2. Figure 2 shows the $M_{\pi ee}$ spectrum of those events with M_{ee} greater than 150 MeV/c^2. Superimposed on the data is a Monte Carlo simulation of this distribution added to an estimated background shown as a shaded region. The shape of the background is that of the distribution of events whose reconstructed K^+ trajectory originated from outside of the production target, normalized to the number of events with $400 < M_{\pi ee} < 440$ MeV/c^2. From this plot, and confirmed by evaluation of backgrounds as observed in other distributions, we estimate that there are 23 ± 6 background events in the signal region. The "signal region" is defined as $470 < M_{\pi ee} < 512$ MeV/c^2.

Selecting events in the signal region with $M_{ee} > 150$ MeV/c^2, we display the M_{ee} distribution, containing 510 events, in Fig. 3. Also shown in Fig. 3 is our simulation of this distribution. In the simulation we employed as theoretical input the known properties of the detection apparatus and the semileptonic decay spectrum as calculated for a vector interaction: $d\Gamma/dM_{ee} = CM_{ee}p_\pi^3(1.0 + \lambda M_{ee}^2/M_\pi^2)^2$. In this expression p_π is the pion momentum in the K^+ center-of-mass frame, C is an overall normalization constant, and λ is a constant which adjusts the M_{ee} dependence of the form factor for the decay; we ignore terms of order M_e^2/M_K^2, where M_e is the electron mass. The distribution shown in the figure is for the best fit value of λ, and the resultant fit has a value of χ^2 per degree of freedom of 1.1 for 19 degrees of freedom.

To find the M_{ee} dependence of the form factor and the branching ratio for the decay mode we first generated M_{ee} distributions, such as that shown in Fig. 3, for different values of λ. From these the fraction of $K^+_{\pi ee}$ events which appear in the ith M_{ee} bin for the given hypothesis of λ, $f(\lambda)_i$, was determined. For a given πee branching ratio, $B_{\pi ee}$, the expected number of events in each bin was then calculated as

$$\langle N(B_{\pi ee},\lambda)_i\rangle = B_{\pi ee} f(\lambda)_i N_{\rm Dal}/P_{\rm Dal}F_{\rm Dal}\,.$$

Here $N_{\rm Dal}$ is the number of $K_{\rm Dal}$ events selected in our sample ($M_{\pi ee} > 350$ MeV/c^2, $M_{ee} < 135$ MeV/c^2) and scaled to the same number of incident kaons as that in the πee sample, $P_{\rm Dal}$ is the branching ratio times decay probability for the $K_{\rm Dal}$ mode [$P_{\rm Dal} = (2.536 \pm 0.072) \times 10^{-3}$] [7], and $F_{\rm Dal}$ is the fraction of Dalitz decay events accepted by the apparatus as simulated in the Monte Carlo calculation. By comparing the expected and observed number of events in each bin, we performed a χ^2 minimization with $B_{\pi ee}$ and λ as free parameters. We note that by normalizing to $K_{\rm Dal}$ we can cancel most effects due to uncertainties in detector acceptance and efficiences.

Figure 4 displays contours of branching ratio versus λ for constant values of χ^2 equal to $\chi^2_{\rm min} + n$, with n having the indicated values. The large correlation between these

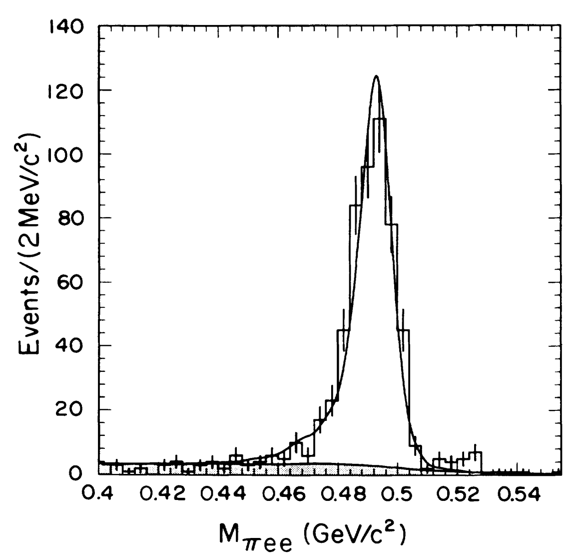

FIG. 2. $M_{\pi ee}$ invariant mass distribution for events with $M_{ee} > 150$ MeV/c^2. Histogram, with error bars, is experimental data; solid curve is the result of the Monte Carlo calculation of $K^+_{\pi ee}$ decays; shaded region is the estimated background.

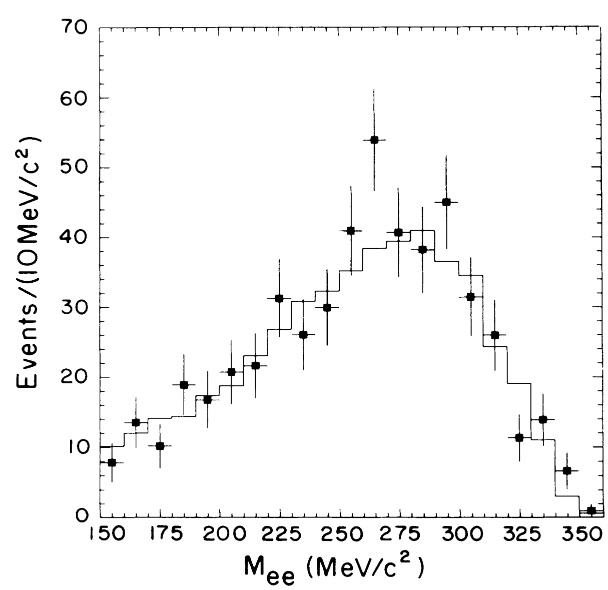

FIG. 3. M_{ee} invariant mass spectrum for high-mass events with $470 < M_{\pi ee} < 512$ MeV/c^2. Solid line is the result of the Monte Carlo calculation with $\lambda = 0.105$.

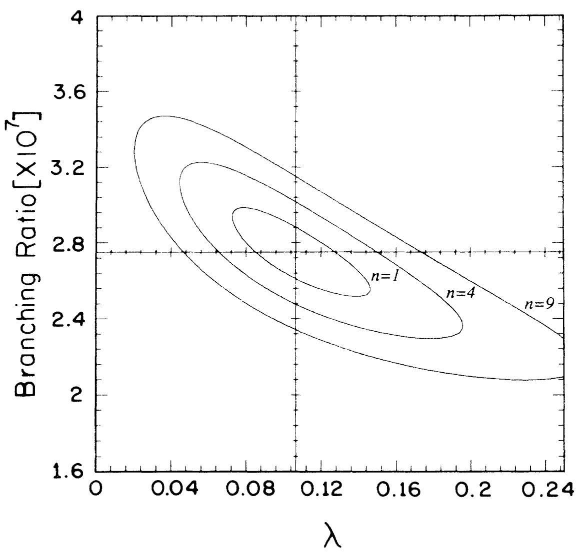

FIG. 4. $K^+_{\pi ee}$ branching ratio vs λ for constant values of χ^2 equal to $\chi^2_{min}+n$, with n as indicated, for a semileptonic decay form for the M_{ee} distribution. χ^2_{min} per degree of freedom equals 1.1.

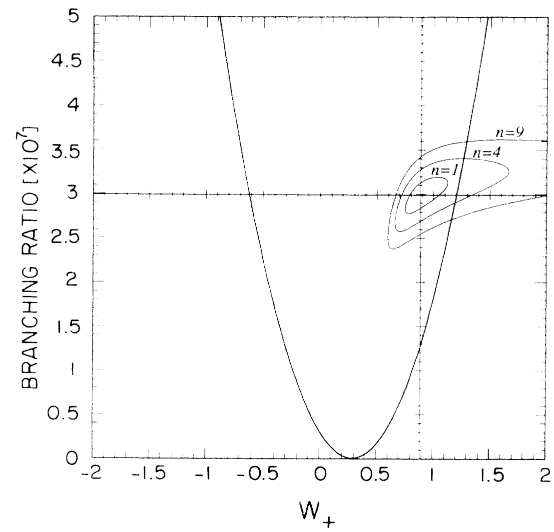

FIG. 5. $K^+_{\pi ee}$ branching ratio vs w_+ contours with constant values of χ^2 equal to $\chi^2_{min}+n$ for a decay hypothesis of Ref. [3] and described in the text. The parabolic curve is the predicted relationship. χ^2_{min} per degree of freedom equals 1.2.

two parameters is due to the acceptance of the apparatus which is weighted towards high values of M_{ee}, and to the fact that we only use events with $M_{ee} > 150$ MeV/c^2 in the evaluation. From this plot we obtain values for the branching ratio and λ of $B_{\pi ee} = (2.75 \pm 0.23 \pm 0.13) \times 10^{-7}$ and $\lambda = 0.105 \pm 0.035 \pm 0.015$, with a correlation coefficient of −0.82. The first uncertainties quoted are statistical and are the extrema of the 1σ ($n=1$) confidence-level contour. The second are systematic, and include contributions (combined in quadrature) from detector efficiencies (0.012, 0.006), apparatus acceptance (0.036, 0.142), background uncertainties (0.012, 0.01), and the uncertainty in $P_{\rm Dal}$ (0.028, 0.0); the quantities in parentheses are the corresponding fractional uncertainties in $B_{\pi ee}$ and λ, respectively.

To investigate the effects of radiative corrections we have modified the M_{ee} spectrum according to the prescription of Lautrup and Smith [8] for internal bremsstrahlung. This modification results in an increase in λ of 5.5% of its value and a corresponding increase in the branching ratio of 4.5%. Since other radiative corrections are of the same order, but model dependent, we prefer to leave our results expressed without any radiative corrections.

The decay rate and e^+e^- invariant mass spectrum was recently modeled by Ecker, Pich, and de Rafael employing an effective chiral Lagrangian [3]. Their mass spectrum is formulated as follows: $d\Gamma/dM_{ee} = 16 M_{ee}\bar{\Gamma} p_\pi^3 \times |\hat{\phi}_+|^2/M_K^5$, where $\hat{\phi}_+ = -(\phi_K + \phi_\pi + w_+)$, ϕ_K and ϕ_π are functions of M_{ee}^2, w_+ is a dimensionless constant to be determined from experiment, and $\bar{\Gamma}$ is a theoretically determined normalization factor. We have performed the same χ^2 minimization with the above M_{ee} spectrum as input, and display in Fig. 5 the resulting constant χ^2 contours of branching ratio versus w_+. The parabola shown in the figure is the relationship expected from the model. We note that if only the branching ratio is known, two values of w_+ are predicted. From this figure we extract a branching ratio of $(2.99 \pm 0.22) \times 10^{-7}$ with $w_+ = 0.89^{+0.24}_{-0.14}$. The spectral shape for these parameters is quite similar to that shown in Fig. 3.

In this model the expression describing the $K^S_{\pi ee}$ decay is the same as that of $K^+_{\pi ee}$ except $\hat{\phi}_+$ is replaced by $\hat{\phi}_S$: $\hat{\phi}_S = 2\phi_K + \frac{1}{6}\ln(M_\pi^2/M_K^2) + w_+$. With our results incorporated into the model, the predicted ratio of rates, $\Gamma(K^S_{\pi ee})/\Gamma(K^+_{\pi ee})$, ranges over 3 orders of magnitude, from 0.21 to 0.20×10^{-3} (corresponding to the upper and lower limits on the uncertainty in w_+, respectively), and the predicted branching ratio for $K^S_{\pi ee}$ becomes less than 4.5×10^{-10}. The latter result yields a calculated branching ratio for $K^L_{\pi ee}$ of less than 1.6×10^{-12} if this decay were to proceed only through the CP-violating piece of the K^0-$\bar{K}^0$ mass matrix.

We have also made a direct comparison of our M_{ee} spectrum with that predicted by Bergström and Singer [9] as published. We find their spectrum, with a value of their parameter ξ equal to 0.76, to fit our data with consistency comparable to the fit with λ equal to 0.105. Their branching ratio prediction is $(5.6 \pm 2.3) \times 10^{-7}$, in comparison with our measured value of $(2.75 \pm 0.23) \times 10^{-7}$ for that value of λ.

Finally, we have used the M_{ee} spectrum to place upper limits on the branching ratio times decay probability for the decay chain $K^+ \to \pi^+ X^0$, $X^0 \to e^+e^-$, with the result that this quantity is less than 1.5×10^{-8} (99% C.L.), 1.1×10^{-8} (90% C.L.), over an X^0 mass range from 150 to 340 MeV/c^2. To set the sensitivity of this measurement in context, we note that for all X^0 masses above 160 MeV/c^2 and less than the mass of two muons this result is at least an order of magnitude below that predicted in the literature for standard Higgs particle formation and decay [10].

In summary, we have measured the branching ratio for $K^+_{\pi ee}$ to be $(2.75 \pm 0.23 \pm 0.13) \times 10^{-7}$ assuming a vector interaction with a form factor of $\lambda = 0.105 \pm 0.035 \pm 0.015$. We have also placed new upper limits on the branching ratio times decay probability for the decay chain $K^+ \to \pi^+ X^0$, $X^0 \to e^+ e^-$.

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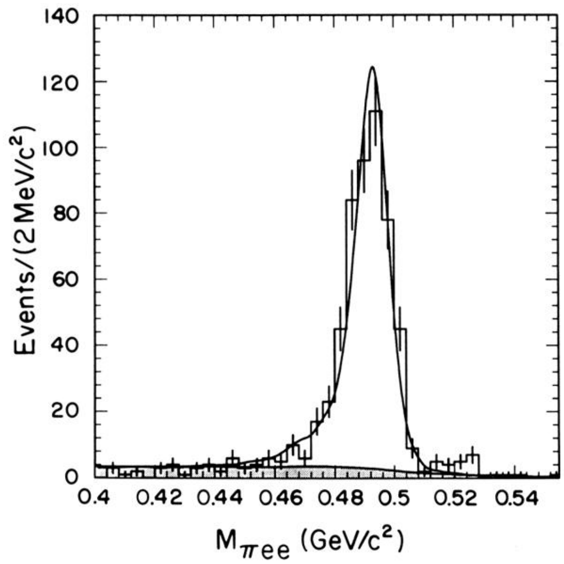

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