2 Rare kaon decays

S. Pislak (until July 1997), P. Robmann and P. Truöl,
in collaboration with
J. Egger, W. D. Herold, H. Kaspar, and H. Weyer,
Paul–Scherrer–Institut, CH-5234 Villigen
Brookhaven National Laboratory, Upton, NY-11973, USA
University of New Mexico, Albuquerque, NM-87131, USA
University of Pittsburgh, Pittsburgh, PA-15260, USA
Yale University, Newhaven, CT-06511, USA
Institute for Nuclear Research, Academy of Sciences, 117 312 Moscow, Russia
Experiment E-865 at Brookhaven AGS

During our last 28 week long data taking run, which ended on the last day of 1998, we reached the primary goal of experiment E865. This experiment at the Brookhaven AGS was designed to reach a sensitivity limit for the lepton flavor non-conserving (LFNC) decay $K^+ \to \pi^+\mu^+e^-$ below a branching ratio level of 10^{-11}. Lepton flavor conservation is incorporated in the standard model of electroweak interaction, is experimentally well proven, but has no theoretical foundation within this model. The LFNC-decay mode searches are therefore driven by the curiosity to find out where the conservation ends, and by the hope, that there, where it ends, signals for non-standard model physics may appear.

Compared to the two prior data taking runs of 1995, which has been completely analysed, lead to two theses [1, 2] and a limit of 2×10^{-10} (95 % confidence), and of 1996, for which the analysis is nearly completed (4×10^{-11} expected [3]), a further factor of six in improvement seems possible. This estimate assumes, that no hitherto unkwnon sources of background are discovered during the analysis, which has only recently been started.

The 1998 run primarily benefitted from a longer accelerator spill (2.5 s instead of 1.2 s) and a microbunched beam (approximately 200 ps wide pulses appearing at 93 MHz repetition rate) which showed less spikes. This was important, because it reduced the trigger rate, which was dominated by accidental coincidences. We also implemented additional faster processors and buffers, which allowed us to accept 1600 events per spill with deadtimes around 10 % compared to previously only 600 events. Improved mirrors for the Čerenkov counters lead to higher efficiency and finally the on-line filter code was tailored further.

We will concentrate in this report on a result [4], which we are going to publish shortly, and which concerns the decay $\mathrm{K}^+ \to \pi^+e^+e^-$. This rare decay (branching ratio $\sim 2.7 \times 10^{-7}$) involves a flavor changing neutral current (FCNC). Its rate was first calculated assuming the decay to occur through a short distance $s \to d\gamma$ transition [5]. Since then, however, it has been realized that the decay mechanism is dominated by long-distance effects. In chiral perturbation theory (CHPT), which successfully modeled many decay modes of the light mesons, predictions for the decay rate and invariant electron-positron mass (M_{ee}) distribution exist. Previous measurements [6, 7] were only marginally consistent with next to leading order predictions of this theory [8]. Our new measurements with significantly improved statistics and greater acceptance over the M_{ee} range, which were first reported at the Vancouver conference [9], require higher order contributions [10, 11]. Our data on $K^+ \to \pi^+\mu^-\mu^+$, refered to last year explore the same physics. Assuming the dominance of one-photon exchange process, the difference between the two decays lies only in the available phase space.

The primary trigger for this data required three charged particles defined by signals in the hodoscopes before the analysing magnet and in front of the electromagnetic calorimeter, and the calorimeter itself. This trigger rate is dominated by accidentals, and $K^+ \to \pi^+\pi^+\pi^-$decays. For $K^+ \to \pi^+e^+e^-$ decays, Čerenkov signals were required on each side of the detector in addition. This trigger was then dominated by events originating from the decay chain $K^+ \to \pi^+\pi^0$; $\pi^0 \to e^+e^-\gamma$ ($K_{\pi 2Dal}$), where the typical e^+e^- invariant mass was low. Taking advantage of the fact that the low mass e^+e^- pair were not separated vertically in the non-bending plane, a "high mass" trigger was configured by requiring a vertical separation of calorimeter hits associated with the Čerenkov counter response.

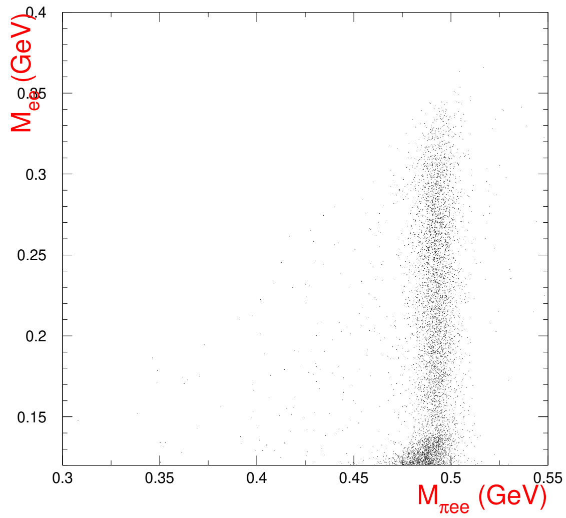

Figure 2.1: e^+e^- invariant mass versus $\pi^+e^+e^-$ invariant mass for $K^+ \to \pi^+e^+e^-$ candidates.

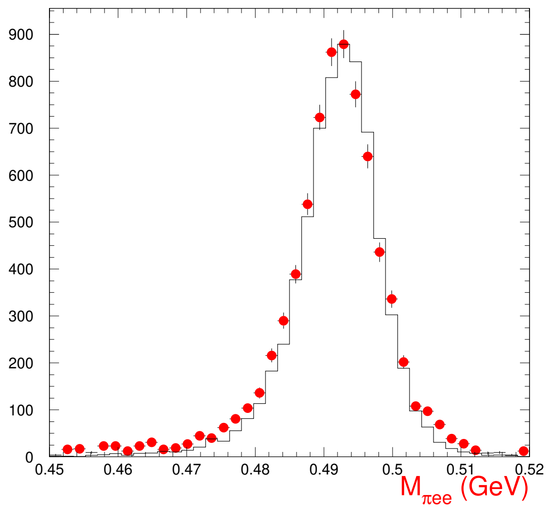

Figure 2.2: $\pi^+e^+e^-$ invariant mass for $K^+ \to \pi^+e^+e^-$ candidates with $M_{ee} > 150$ MeV (histogram: Monte Carlo simulation).

The $K^+ \to \pi^+e^+e^-$ data were taken in 1995 and 1996, running typically at 7×10^{12} protons/pulse for about 25 weeks. Events were selected which contained unambiguous identification of a positive pion, and the lepton pair, whose trajectories were consistent with having come from a common vertex located within the 5 m long evacuated decay volume. The reconstructed kaon was required to have come from the target upstream of the beam magnets.

Figure 2.1 displays the M_{ee} versus the invariant mass of the three final state particles, $M_{\pi ee}$, for the $K^+ \to \pi^+e^+e^-$ candidates. The cluster of events below 130 MeV are the background from $K_{\pi 2Dal}$, where the $M_{\pi ee}$ is just below M_K because of a missing soft photon. Figure 2.2 shows $M_{\pi ee}$ for events with $M_{ee} > 0.15$ GeV. About 10,000 events are selected after all the cuts. The background is insignificant.

Assuming a pure vector interaction the decay distribution for $\pi^+e^+e^-$ can be described by

$$\frac{d\Gamma(q^2,\cos\theta)}{dq^2 d\cos\theta} = \frac{G^2\alpha^2 M_K^3}{16\pi}\rho^{3/2}(1,\frac{q^2}{M_K^2},\frac{m_\pi^2}{M_K^2})(1-\frac{4m_e^2}{q^2})^{1/2}\left[1-(1-\frac{2m_e^2}{q^2})\cos^2\theta\right]|f(q^2)|^2 \ ,$$

where $\rho(a,b,c) = a^2+b^2+c^2-2(ab+bc+ac)$, G is a constant and θ the angle between the positron and pion momentum vectors in the e^+e^- center of mass frame. The form factor $f(q^2)$ is a dimensionless function of $q^2 = M_{ee}^2$. The data shown in Figure 2.3 are consistent with this assumption.

The branching ratio and the decay spectrum for the $K_{\pi 2Dal}$ decay are known. We normalize our $K^+ \to \pi^+e^+e^-$ data to this decay, which has the advantage, that almost all efficiency factors cancel (e. g. those for the Čerenkov counters). The relative acceptances and their

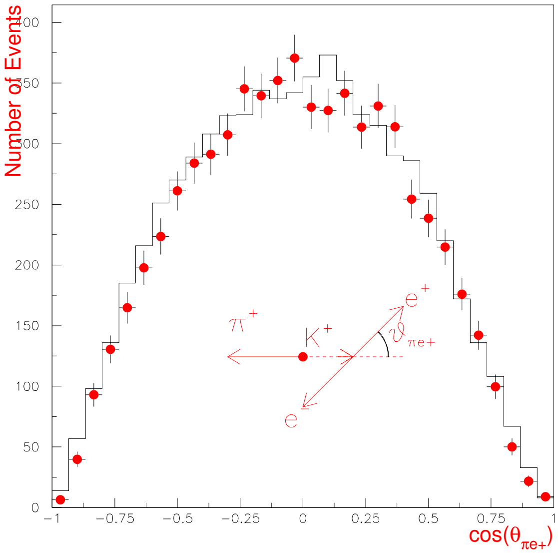

Figure 2.3: Angular distribution ($\cos\theta$) of $K^+ \to \pi^+ e^+ e^-$ events in comparison with Monte Carlo simulation with pure vector interaction.

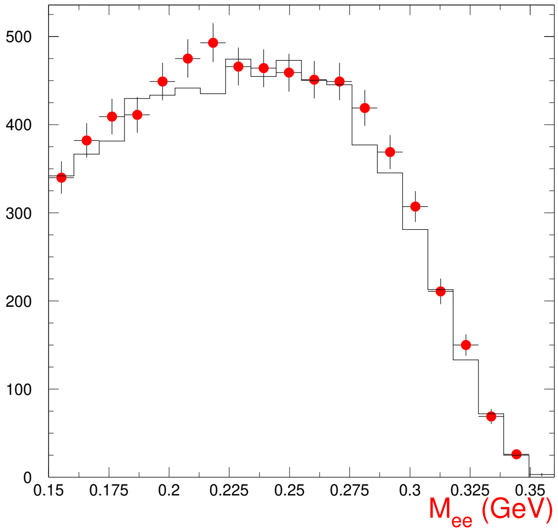

Figure 2.4: Invariant mass (M_{ee}) distribution for accepted $K^+ \to \pi^+ e^+ e^-$ events in comparison with Monte Carlo simulation with $\lambda = 0.2$.

mass and angular dependence are taken from a Monte Carlo simulation, which represents the data well, as e. g. demonstrated in Figure 2.2.

The form factor $f(q^2)$ can be determined by fitting the normalized M_{ee} spectrum. Several parametrisations are possible. Vector meson dominance suggests a parametrisation analogous to the semi-leptonic decay $\mathrm{K}^+ \to \pi^0 e^+ \nu_e$

$$f(q^2) = f_+(1 + \lambda \frac{q^2}{M_\pi^2}) \ ,$$

while chiral perturbation theory (CHPT) [8] leads to

$$f(q^2) = -(\phi_K(q^2) + \phi_\pi(q^2) + w_+) \ .$$

ϕ_K and ϕ_π are analytic functions of q^2, and w_+ is a parameter to be determined from the data. The results are summarized in Table 2.1.

Ansatz	Parameters	Branching ratio	χ^2/n_{df}
Model independent	$\lambda = 0.175 \pm 0.010$	$(2.68 \pm 0.03) \cdot 10^{-7}$	29/19
CHPT $\mathcal{O}(p^4)$ [8]	$w_+ = 0.574 \pm 0.011$	$(2.83 \pm 0.03) \cdot 10^{-7}$	16/19
CHPT [11]	$a_+ = 0.56 \pm 0.01$, $b_+ = 0.65 \pm 0.04$	$(2.77 \pm 0.03) \cdot 10^{-7}$	17/19

Table 2.1: Parameters extracted from the form factor fits to the ee mass spectrum (preliminary values and statistical errors only [4].

CHPT up to $\mathcal{O}(p^4)$ also predicts a correlation between the branching ratio and the value of w_+, which is shown in Figure 2.5. Though the M_{ee} spectrum is fit very well, the corresponding branching ratio does not match the predicted curve. The previous data [6, 7] already indicated a similar trend. We therefore conclude that CHPT of $\mathcal{O}(p^4)$ is insufficient to describe the $K^+ \to \pi^+ e^+ e^-$ data.

While in CHPT up to order $\mathcal{O}(p^4)$ almost all the mass dependence is given by a pion loop term [8], later refinements [10, 11] point to additional terms. These are cast somewhat arbitrarily e. g. in the form $a_+ + b_+ M_{ee}^2/M_K^2$ [11]. The corresponding fit shows a good χ^2 and remedies the problem with the branching ratio, but certainly does not lead to a deeper understanding of the details of the decay mechanism yet.

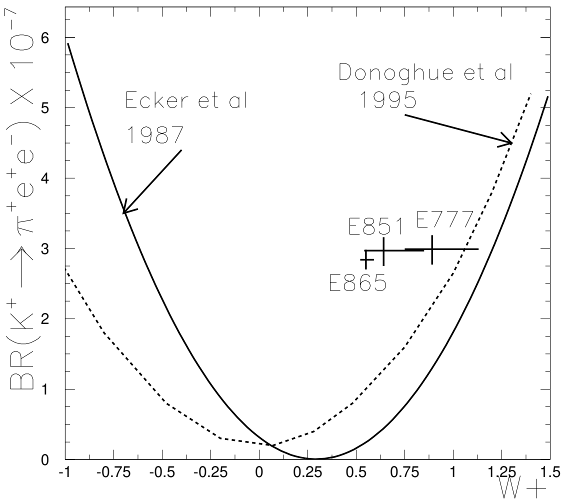

Figure 2.5: Comparison of the experimental data on the branching ratio and w_+ to theoretical predictions: solid curve [8], dashed curve [10]; previous measurements [6, 7].

References

[1] *Experiment E865 at BNL: a search for the decay* $K^+ \to \pi^+\mu^+e^-$, S. Pislak, Thesis, University of Zürich (1997).

[2] *A search for the decay* $K^+ \to \pi^+\mu^+e^-$, D. Bergman, Thesis, Yale University, New Haven (1997).

[3] H. Do, Thesis, Yale University, New Haven, in preparation.

[4] *A high-precision study of the rare decay of a charged kaon into a charged pion and an electron-positron pair*, S. Eilerts, University of New Mexico, Albuquerque (1998).

[5] M. K. Gaillard, and B. W. Lee, Phys. Rev. **D10** (1974, 897.

[6] C. J. Alliegro et al., Phys. Rev. Lett. **68** (1991), 278.

[7] *A study of the decay* $K^+ \to \pi^+e^+e^-$ *and a measurement of the decay* $\pi^0 \to e^+e^-$, A. L. Deshpande, Thesis, Yale University, New Haven (1995).

[8] G. Ecker, A. Pich and E. de Rafael, Nucl. Phys. **B291** (1987), 692.

[9] *Study of* $K^+ \to \pi^+e^+e^-$ *and* $K^+ \to \pi^+\mu^+\mu^-$ *decays in E865 at the AGS*, H. Ma et al., Proc. Int. Conf. on High Energy Physics 98, Vancouver (July 1998).

[10] J. Donoghue, and F. Gabbiani, Phys. Rev **D51** (1995), 2187.

[11] G. D. Ambrosio et al., JHEP **8** (1998), 4.