RARE AND FORBIDDEN KAON DECAYS AT THE AGS

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ABSTRACT

An overview of the Rare Kaon Decay program at the Alternating Gradient Synchrotron (AGS) is presented, with particular emphasis on the three major experiments currently running and analyzing data. A brief overview of earlier kaon decay experiments and of the AGS performance improvements is also provided. This review concludes with a discussion of proposed and developing experiments planned to run in the year 2000 and beyond (AGS-2000).

*Supported by DOE Contract DE-AC02-76CH00016.

1 Overview

The study of kaon decays has had a long and rich history at the Alternating Gradient Synchrotron (AGS), including a Nobel Prize for the discovery of CP violation in the K_L decay to two pions[1] in 1963 and the observation of the suppression of Flavor Changing Neutral Currents (FCNC) in the $K_L^0 \to \mu^+\mu^-$ decay.[2] The study of rare kaon decays had a renaissance in the early 1980s that has continued up to the present. The third generation of these experiments is currently running.

This renaissance was motivated primarily by the realization that with the large numbers of kaons available at the AGS and with modern detectors and data acquisition apparatus, a tremendous leap forward in sensitivity was possible. At the same time it was realized that at such sensitivities, the reach in mass scale for possible new interactions of these experiments is quite large indeed.[3,4] For example, a comparison of the lepton flavor violating decay $K_L^0 \to \mu e$ with ordinary $K^+ \to \mu^+\nu_\mu$ decay (see Fig. 1) leads to an expression for the mass (M_X)

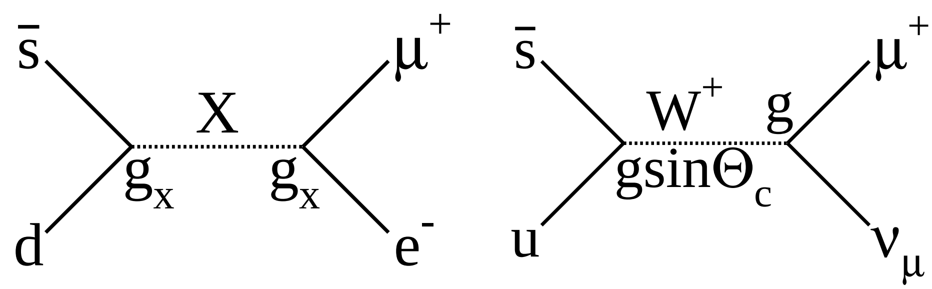

Fig. 1. Heavy gauge boson mediating $K_L^0 \to \mu e$, and W^+ mediating $K^+ \to \mu^+\nu_\mu$.

for a new gauge boson X (assuming the same V-A interaction), in terms of the $K_L^0 \to \mu e$ branching ratio of:

$$M_X \approx 220 \text{ TeV/c}^2 \left[\frac{g_X}{g}\right]^{1/4} \left[\frac{10^{-12}}{B(K_L \to \mu e)}\right]^{1/4}. \tag{1}$$

For $g_X \sim g$ the mass scale reached is far beyond that of any planned accelerator. Likewise, for a purely vector interaction, the companion decay $K^+ \to \pi^+\mu^+e^-$ can probe similarly high mass scales. Lepton flavor violation is not forbidden by an underlying gauge symmetry, so while it is not allowed in the Standard Model (SM), further experimental verification becomes even more compelling. Several proposed extensions to the SM do allow lepton flavor violation.[5–10]

The huge suppression of the decay rates of FCNC by the GIM mechanism[11] leaves a large "window of opportunity" for discovery of non-SM processes. In addition to the searches for physics explicitly beyond the Standard Model, significant increases in sensitivity for SM-allowed decays can close the window on non-SM processes, such as $K_L^0 \to e^+e^-$ or $K^+ \to \pi^+\nu\overline{\nu}$ (Refs. 12–20).

Measurements of the branching ratios for the SM processes $K^+ \to \pi^+\nu\overline{\nu}$ or $K_L^0 \to \mu^+\mu^-$ provide a means to determine fundamental SM parameters, such as the CKM matrix element $|V_{td}|$ (Ref. 21) and ρ (Ref. 22). A proposed experiment to measure $K_L^0 \to \pi^0\nu\overline{\nu}$ would be able to determine the SM parameter η (Ref. 22). From the kaon system alone, a complete determination of the "unitarity triangle" can be made (see Fig. 2). The interpretation of $K_L^0 \to \mu^+\mu^-$ is complicated by the presence of long-distance effects, but both $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L^0 \to \pi^0\nu\overline{\nu}$ give very clean determinations of the fundamental parameters and the two of them together are enough to completely determine the triangle.[23,24]

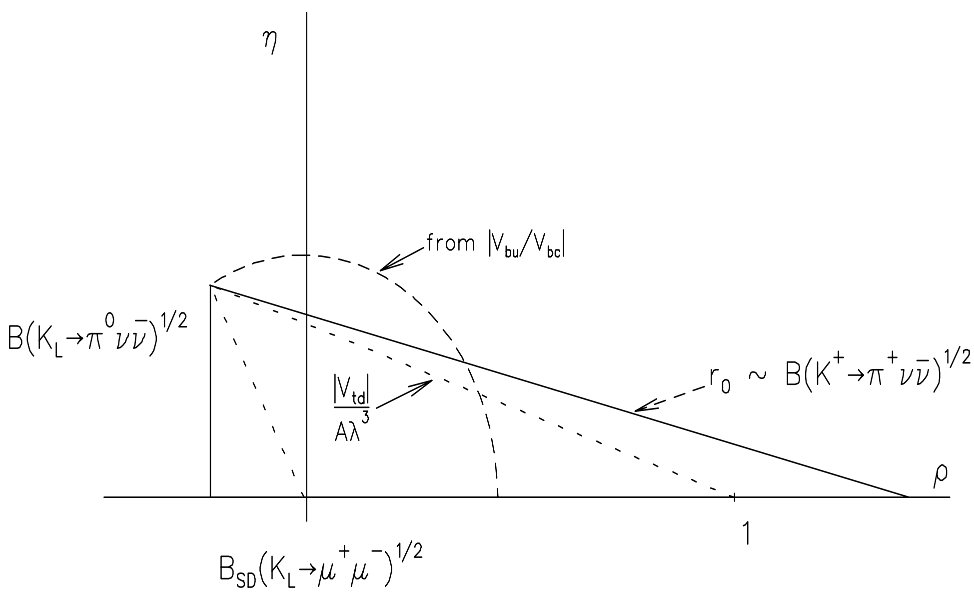

Fig. 2. The unitarity triangle related to the CKM matrix.

Finally, several "modestly rare" decays have been seen, with branching ratios from 10^{-5}–10^{-8}. These are generally long-distance dominated and are difficult to calculate. Many of these serve as a testing ground for low-energy effective theories, such as Chiral Perturbation Theory (CHPT).[25] Some examples include:

$K^+ \to \pi^+ e^+ e^-$, $K^+ \to \pi^+ \mu^+ \mu^-$, $K^+ \to \pi^+ \gamma\gamma$, $K^+ \to \mu^+ \nu_\mu \gamma(\mathrm{SD}^+)$, $K^+ \to \pi^+ \pi^- e^+ \nu_e$, $K^+ \to \mu^+ \nu e^+ e^-$, and $K^+ \to e^+ \nu e^+ e^-$. Some nonrare decays, such as $K^+ \to \pi^0 e^+ \nu_e$, are being pursued to more accurately determine the CKM matrix element $|V_{us}|$.

2 AGS

The AGS has made continued and significant increases in the number of protons accelerated in the machine and available for experiments (see Fig. 3). A very

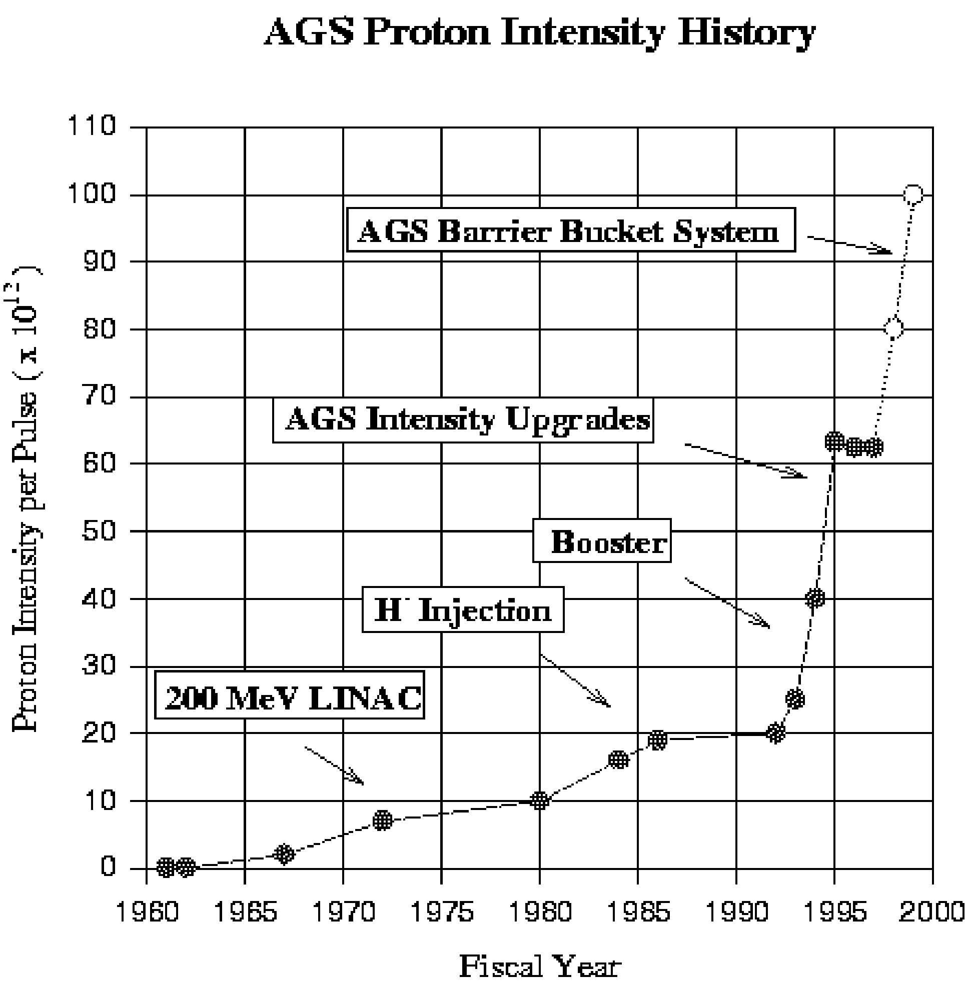

Fig. 3. AGS peak accelerated proton intensity per year.

rapid increase over the last few years has occurred with the addition of the AGS Booster. With the Booster (and several additional AGS upgrades),[26] the intensity of accelerated protons has increased to $\sim$ 60 Tp (Tp $\equiv 10^{12}$ protons/spill). Further increases are expected with the addition of an rf Barrier Bucket during the 1998–99 running cycle. This Barrier Bucket should allow the stacking of additional Booster pulses with the possibility of reaching the AGS space charge limit of $\sim$ 150 Tp.

A large number of other improvements to the operation of the AGS have been achieved. The Duty Factor (DF) has increased both macro- and micro-scopically. The macro DF has been increased from 30% to 44% by increasing the spill length and reducing the interspill period. There are plans to increase this even further. Additional work on reducing ripples in the spill has increased the effective length of the spill, even at the longer spill length. The AGS is also able to switch back and forth between Fast Extracted Beam (FEB) and Slow Extracted Beam (SEB) on a pulse-by-pulse basis. This allows the kaon program (using SEB) to run simultaneously with the tune-up for experiments such as the muon g-2 (using FEB). Studies have also demonstrated the ability to extract SEB with bunching of the extracted beam.[27] This is useful for experiments that want to do time-of-flight for low-energy K_L^0's, for example. Also, a significant amount of work has been dedicated to running kaon production targets at the AGS at $\gtrsim$ 30 Tp/spill.

3 AGS Kaon Experiments in the 1980s

In the early 1980s two major kaon decay experiments took data. Looking for lepton family number violating decays, E780 searched in the neutral kaon system for $K_L^0 \to \mu e$ and E777 searched in the charged kaon system for $K^+ \to \pi^+\mu^+e^-$.

The experiment E780, which ran from 1985–88, followed earlier experiments by the same group looking for T-violation in the transverse polarization of the μ^+ in both neutral[28,29] and charged[30,31] $K_{\mu 3}$ decays (E696, E735) and ϵ'/ϵ (Ref. 32) (E749) from 1978–84. E780 set limits on the decays $K_L^0 \to \mu e$, $K_L^0 \to e^+e^-$, and $K_L^0 \to \pi^0 e^+e^-$ and observed the decay $K_L^0 \to \mu^+\mu^-$ (Refs. 33–35). The experiment E777 set limits on the decay $K^+ \to \pi^+\mu^+e^-$. It also set limits on $\pi^0 \to \mu^+e^-$ and $K^+ \to \pi^+X^0$ and measured the branching ratio for $K^+ \to \pi^+e^+e^-$ (Refs. 36–39).

In the mid-to-late 1980s a second round of experiments was started. Follow-up experiments to both E780 and E777 were commissioned, with modest modifications to the apparatus and triggers, to focus on decays with electrons in the final state. E845 continued E780's work on $K_L^0 \to \pi^0 e^+ e^-$ (Refs. 40 and 41) and measured branching ratios for $K_L^0 \to e^+ e^- \gamma$ (Ref. 42), $K_L^0 \to e^+ e^- \gamma\gamma$ (Ref. 43), and $K_L^0 \to e^+ e^- e^+ e^-$ (Ref. 44). This experiment discovered that $K_L^0 \to e^+ e^- \gamma\gamma$ would be a significant background to $K_L^0 \to \pi^0 e^+ e^-$ (Ref. 45). The experiment was optimized for many-body decays with electrons and photons. The spectrometer was shortened by moving the Cherenkov detector inside the magnet and the size of the first drift chamber was expanded. New triggers were created. The kaon production angle was changed from 0° to 2° to reduce rates and increase acceptance for tracks near the neutral beam. E845 took data during 1989. Results from E780 and E845 are summarized in Table 1.

Table 1. Results from E780/E845.

Mode	Measurement	Comments
$K_L^0 \to \mu e$	$< 1.9 \times 10^{-9}$	(Ref. 35)
$K_L^0 \to \pi^0 e^+ e^-$	$< 5.5 \times 10^{-9}$	(Ref. 41)
$K_L^0 \to e^+ e^-$	$< 1.2 \times 10^{-9}$	(Ref. 35)
$K_L^0 \to e^+ e^- \gamma$	$(9.1 \pm 0.4^{+0.6}_{-0.5}) \times 10^{-6}$	919 events (Ref. 42)
$K_L^0 \to e^+ e^- \gamma\gamma$	$(6.6 \pm 3.2) \times 10^{-7}$	17 events (Ref. 43)
$K_L^0 \to e^+ e^- e^+ e^-$	$(3.07 \pm 1.25 \pm 0.26) \times 10^{-8}$	6 events (Ref. 44)

E851 improved the E777 measurement of $K^+ \to \pi^+ e^+ e^-$ and measured the $\pi^0 \to e^+ e^-$ branching ratio.[46] The Cherenkov detector was optimized for electron detection on both sides of the spectrometer and a new trigger was installed. E777 ran from 1986–88 and E851 ran in 1989. The results from the E777 and E851 experiments are listed in Table 2.

Two other "second generation" experiments also started taking data in the late 1980s: E791 and E787. The primary purpose of E791 was a further improvement in sensitivity in the search for $K_L^0 \to \mu e$. This experiment had a two-arm spectrometer, with high-precision momentum measurements and good e and μ identification. The goal of the experiment was a sensitivity to this lepton flavor violating decay of 10^{-12}. E791 had an engineering run in 1988 and long physics runs in 1989–90. The physics results from E791 are listed in Table 3 (Refs. 47–53).

Another new experiment, E787, was designed to search for the SM allowed decay $K^+ \to \pi^+ \nu\overline{\nu}$. This experiment needs to identify the single, isolated π^+

Table 2. Results from E777/E851.

Mode	Measurement	Comments
$K^+ \to \pi^+\mu^+e^-$	$< 2.1 \times 10^{-10}$	(Ref. 38)
$\pi^0 \to \mu^+e^-$	$< 1.6 \times 10^{-8}$	(Ref. 38)
$\pi^0 \to e^+e^-$	$(6.9 \pm 2.3 \pm 0.6) \times 10^{-8}$	21 events (Ref. 46)
$K^+ \to \pi^+e^+e^-$	$(2.75 \pm 0.23 \pm 0.13) \times 10^{-7}$	487 events (Ref. 39)
$K^+ \to \pi^+X^0$ $\hookrightarrow X^0 \to e^+e^-$	$< 4.5 \times 10^{-7}$	$M_X < 100$ MeV/c^2 (Ref. 36)
$K^+ \to \pi^+X^0$ $\hookrightarrow X^0 \to e^+e^-$	$< 1.5 \times 10^{-8}$	$150 < M_X < 340$ (Ref. 39)

Table 3. Results from E791.

Mode	Measurement	Comments
$K_L^0 \to \mu e$	$< 3.3 \times 10^{-11}$	(Ref. 51)
$K_L^0 \to e^+e^-$	$< 4.1 \times 10^{-11}$	(Ref. 52)
$K_L^0 \to \mu^+\mu^-$	$(6.86 \pm 0.37) \times 10^{-9}$	707 events (Ref. 53)

track from $K^+ \to \pi^+\nu\overline{\nu}$. The experiment used a stopped K^+ beam, rather than the decay in flight beams used by the other experiments. It has a 4π hermetic photon veto system, good kinematic resolution (range, momentum, and energy), and π^+ identification through the decay chain $\pi^+ \to \mu^+ \to e^+$. The first phase of E787 (Ref. 54) had an engineering run in 1988 and took physics data from 1989–91. The results from the first phase of E787 are given in Table 4 (Refs. 55–65). The upgraded E787 experiment and detector will be discussed in more detail in Sec. 4.1. Two new results from the first phase of the experiment have recently been published in *Physical Review Letters*: $K^+ \to \pi^+\gamma\gamma$ (Ref. 64) and $K^+ \to \pi^+\mu^+\mu^-$ (Ref. 65).

E787 reported the first observation of the decay $K^+ \to \pi^+\gamma\gamma$ (Ref. 64). The branching ratio and invariant mass $M_{\gamma\gamma}$ for the decay $K^+ \to \pi^+\gamma\gamma$ are predicted by CHPT (Refs. 66–70). The prediction for $M_{\gamma\gamma}$ is striking. Instead of a smooth phase space distribution, there is a sharp turn-on above $M_{\gamma\gamma} = 2M_\pi$. The mea-

Table 4. Results from the first phase of E787.

Mode	Measurement	Comments
$K^+ \to \pi^+\nu\overline{\nu}$	$< 2.4 \times 10^{-9}$	(Ref. 63)
$K^+ \to \pi^+X^0$	$< 5.2 \times 10^{-10}$	(Ref. 63)
$K^+ \to \pi^+\mu^+\mu^-$	$(5.0 \pm 0.4 \pm 0.7 \pm 0.6) \times 10^{-8}$	207 events (Ref. 65)
$K^+ \to \pi^+\gamma\gamma$	$(1.1 \pm 0.3 \pm 0.1) \times 10^{-6}$	31 events (Ref. 64)
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	(Ref. 59)
$\pi^0 \to \nu\overline{\nu}$	$< 8.3 \times 10^{-7}$	(Ref. 58)
$K^+ \to \mu^+\nu_\mu\mu^+\mu^-$	$< 4.1 \times 10^{-7}$	(Ref. 55)

sured spectrum verifies this prediction, as can be seen from the momentum spectrum of the π^+ shown in Fig. 4. The $K^+ \to \pi^+\gamma\gamma$ trigger had two components: one accepting events with a P_π above the $\mathrm{K}_{\pi 2}$ peak ($\pi\gamma\gamma 1$) and one accepting P_π below the $\mathrm{K}_{\pi 2}$ peak ($\pi\gamma\gamma 2$). There were 31 events observed in the $\pi\gamma\gamma 2$ sample and none observed in the $\pi\gamma\gamma 1$ sample. The model independent branching ratio is

$$B(K^+ \to \pi^+\gamma\gamma : 100 < P_{\pi^+} < 180 \text{ MeV/c}) = (6.0 \pm 1.5 \pm 0.7) \times 10^{-7}. \qquad (2)$$

The fit to the branching ratio and spectrum favors the CHPT parameter of $\hat{c} = 1.8 \pm 0.6$ with the so-called "unitarity corrections."[71,72] The total branching ratio (assuming $\hat{c} = 1.8$) is

$$B(K^+ \to \pi^+\gamma\gamma) = (1.1 \pm 0.3 \pm 0.1) \times 10^{-6}. \qquad (3)$$

In the $\pi\gamma\gamma 1$ region, a 90% C.L. limit of

$$B(K^+ \to \pi^+\gamma\gamma : P_{\pi^+} > 215 \text{ MeV/c}) < 6.1 \times 10^{-8} \qquad (4)$$

was set.

E787 has also reported the first observation of the decay $K^+ \to \pi^+\mu^+\mu^-$ (Ref. 65). Two separate analyses of this decay were made. In the first all three tracks were fully reconstructed. In the second the minimum requirement for the third track was that its energy was measured. In the first analysis a total of 10.6 $\pm$ 4.7 events was observed and in the second analysis 196.0 $\pm$ 16.7 events were

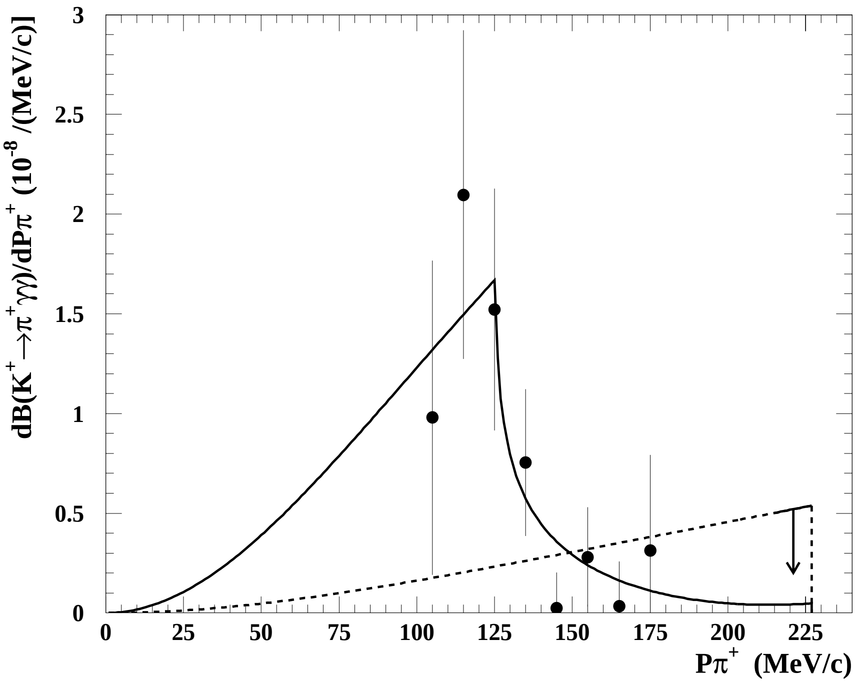

Fig. 4. $K^+ \to \pi^+\gamma\gamma$: 31 events. The solid line is the best CHPT fit. The dashed line is a phase-space distribution normalized to the 90% C.L. limit in the $\pi\gamma\gamma 1$ region.

observed (see Fig. 5). These two analyses were combined to give a branching ratio for this decay of:

$$B(K^+ \to \pi^+\mu^+\mu^-) = (5.0 \pm 0.4^{stat.} \pm 0.7^{syst.} \pm 0.6^{theor.}) \times 10^{-8}. \qquad (5)$$

This branching ratio implies a value for the CHPT parameter[73] $w_+ = 1.07 \pm 0.07$. This value is larger than that derived from $K^+ \to \pi^+e^+e^-$: $w_+ = 0.89^{+0.24}_{-0.14}$ (Ref. 39).

4 Current Kaon Experiments

There are three major rare kaon decay experiments currently running or analyzing data. All three experiments obtained sizable physics data sets from the 1995

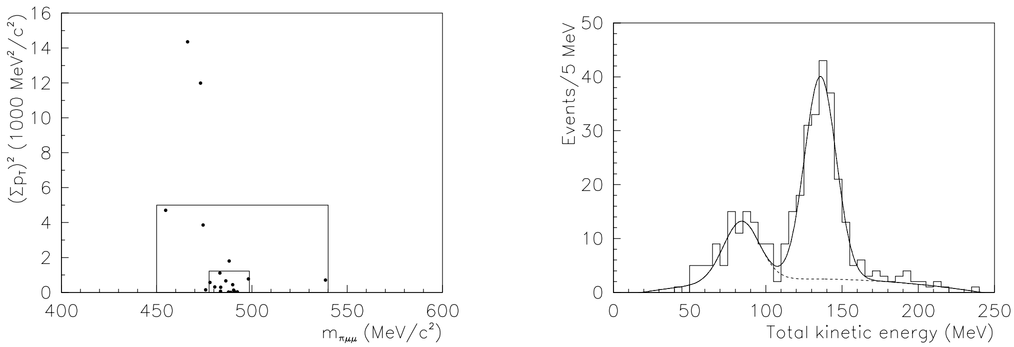

Fig. 5. Final event candidates for $K^+ \to \pi^+\mu^+\mu^-$: (a) three-track events and (b) two-track events.

and 1996 runs. Due to the short length of the 1997 run (funding for only eight weeks), E871 decided to concentrate their efforts on analysis of existing data, and assuming they do not find any $K_L^0 \to \mu e$ events, will probably not take any more data. The E865 experiment chose to use the short 1997 run to collect some special data that is not compatible with their $K^+ \to \pi^+\mu^+e^-$ running. The E787 experiment, after some additional efficiency improvements, was able to collect additional $K^+ \to \pi^+\nu\overline{\nu}$ data ($\sim$ 60% of the sensitivity of the 1996 run). Both E865 and E787 are planning to collect a significant data sample from the 1998–99 running period.

4.1 E787

The E787 experiment was first proposed in 1983 and took significant physics data from 1989–91. The experiment underwent a major upgrade from 1992–94 (keeping the number E787). A drawing of the new detector is shown in Fig. 6. The detector is located in the C4 beam line at the AGS. The C4 beam line, or Low Energy Separated Beam (LESB3) (Ref. 74), transmits kaons of up to 830 MeV/c. At 800 MeV/c, it can transmit up to 6×10^6 K^+ with a K/π ratio of 3:1 for 10^{13} protons. The K^+ are stopped in a scintillating fiber target in the center of the detector. The detector itself covers close to 4π solid angle and is in a 10 kG magnetic field.

The decay $K^+ \to \pi^+\nu\overline{\nu}$ is interesting because of its sensitivity to the CKM matrix element $|V_{td}|$, and because the theoretical uncertainty in calculating the branching ratio is very small:[12,75–81] only 7% (Ref. 23). From current values of

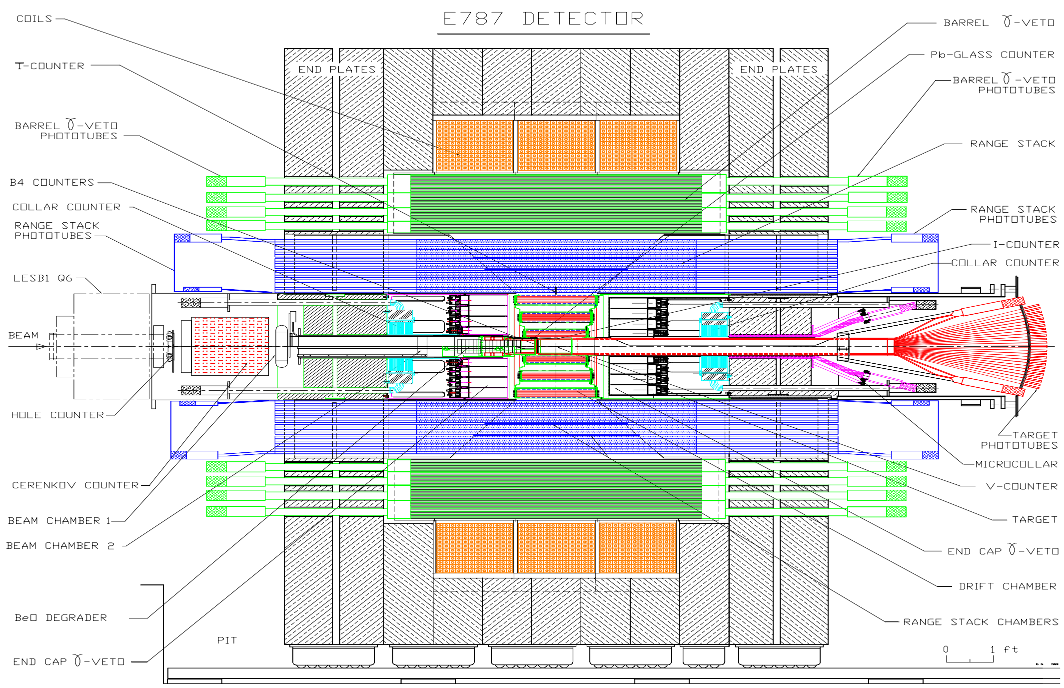

Fig. 6. E787 experimental layout.

SM parameters, the branching ratio is expected to be B($K^+ \to \pi^+ \nu\overline{\nu}$) = (0.6 – 1.5) $\times 10^{-10}$ (Ref. 24).

The observation of $K^+ \to \pi^+ \nu\overline{\nu}$ is complicated by two significant difficulties: (1) the small branching ratio $\sim 10^{-10}$ and (2) the poor experimental signature. Since there are no major K^+ decay modes with a π^+ with momentum above the $K_{\pi 2}$ momentum (205 MeV/c), this experiment chooses to look for $K^+ \to \pi^+ \nu\overline{\nu}$ with a high momentum π^+. Excellent resolution on P_π^{cm} is obtained by working in the K^+ center of mass, so E787 uses a stopped K^+ beam. Since the signature of $K^+ \to \pi^+ \nu\overline{\nu}$ is poor, all backgrounds need to be well-identified. Most K^+ decays with a π^+ also have a π^0, including the $K_{\pi 2}$ decay (BR = 21%). These are identified and vetoed with a fully active 4π detector, where any activity in time with the π^+ track, not associated with the track, is vetoed. The other major background comes from the $K_{\mu 2}$ decay (BR = 64%), which is rejected for not having a $\pi^+ \to \mu^+ \to e^+$ decay chain. Both of these decays are mono-energetic and can also be rejected based on kinematics (range, momentum, and energy). The other significant background comes from either a π^+ in the beam scattering into the detector or from charge exchange. The scattered pions are rejected by good particle identification in the beam, including reconstruction of both the kaon and the pion in the target, and by requiring that the "kaon" decay at rest in the target (i.e., a "delayed coincidence" requiring that the π^+ track occur later than the incident K^+ track). The charge exchange background, $K^+ + n \to p + K_L$ followed by $K_L \to \pi^+ \ell^- \nu_\ell$, is rejected by identification of the extra particles (the proton and lepton) and by the delayed coincidence. Any K_L decay that satisfies the delayed coincidence, yet remains in the target, has to come from a very low momentum K_L.

The beamline was upgraded before the 1992 run (LESB1 $\to$ LESB3), and the detector was upgraded between 1992–94:

- The incident kaon flux was increased and the K/π ratio was increased from 1:3 $\longrightarrow$ 3:1 (Ref. 74).
- The drift chamber was rebuilt. The new Ultra Thin Chamber[82] (UTC) has $\times$ 2 better momentum resolution ($\sim$ 1%) and $\times$ 2 better z-resolution. The z is measured from the charge distribution on helical cathode strips. The total amount of material in the active momentum measuring section of the chamber is $2 \times 10^{-3} X_0$.
- The Pb-scintillator endcaps (EC's) were replaced. The new undoped CsI endcaps[83–85] are fully active (less sensitive to inefficiencies due to photonuclear interactions) and have substantially more light output. The timing resolution is $\times$ 2–3 better than with the old endcaps. This is critical in the EC, which has the highest rates in the detector.
- Transient digitizers made from GaAs CCD's were installed to provide improved timing and multiple pulse finding capability (particularly to find pions on the tails of kaons in the target). The CCD's[86] have eight-bit resolution with 500 MHz sampling. These have been used to instrument the target, endcaps, and beam elements.
- Very low mass Range Stack Straw Chambers (RSSC's) were installed. These have better z-resolution than the previous proportional counters, and even more importantly, have significantly less dead material.
- The range stack (RS) scintillators were demultiplexed. Previously, several counters were multiplexed into one PMT. Now each counter (21 layers $\times$ 24 sectors) is read out on both ends by PMT's. This provides more light and finer resolution for dE/dx measurements.

- A new target with $\times$ 4 more light and significantly less dead material was built.
- Weak regions in the photon veto system were filled by moving the EC's closer to the target and by adding new systems at smaller angles [the collar, microcollar, and lead-glass (PbG) detectors].
- A new trigger/DAQ system was built.[87–89] The DAQ is Fastbus based, with frontend readout into SLAC Scanner Processors (SSP's). The data is transferred via the Cable Segment to a Master SSP, where the event building is done. The data is transferred from the Master SSP to an SGI Challenge computer via a Branch Bus to Fastbus Converter.[90] The data transfer rate has been demonstrated to be $\gtrsim$ 24 Mbytes per spill. (Data transfer to the SGI occurs in the two seconds between spills. Spills occur every 3.6 seconds.) The deadtime, which is dominated by the readout of the front end modules into the SSP's, is $\sim$ 20%.
- New beam elements were built to further aid identification of scattered beam pions. A new Cherenkov counter has larger acceptance for all beam particles. A second beam chamber was added and a lead-glass (PbG) counter was installed for additional photon veto coverage in the beam direction and for beam pion identification.

An engineering run in 1994 produced the first physics result: the first observation of the Structure Dependent (SD$^+$) component of the radiative decay $K^+ \to \mu^+\nu_\mu\gamma$ (Refs. 91 and 92). The $K^+ \to \mu^+\nu_\mu\gamma$ decay is dominated by Inner Bremsstrahlung (IB), which has been well measured;[93] however, the structure dependent component had not previously been seen. Two days of data taking with a special trigger, selecting a high-energy muon accompanied by a high-energy photon, yielded a total of $\sim$ 2,700 $K_{\mu 2\gamma}$ events with a background of 100 events ($K_{\mu 3}$ and $K_{\pi 2}$ with a missing photon and $K_{\mu 2}$ with an accidental photon). Of the 2,700 $K_{\mu 2\gamma}$ events, a clear signal of about 900 events from the SD$^+$ component is seen in Fig. 7. From a more sophisticated analysis, fitting E_{μ^+} and E_γ to IB, SD$^\pm$, and the interference terms, the branching ratio for the SD$^+$ decay is:

$$B(\mathrm{SD}^+) = (1.33 \pm 0.12 \pm 0.18) \times 10^{-5} \tag{6}$$

and the form factor $|F_V + F_A| = 0.165 \pm 0.007 \pm 0.011$. This can be compared to

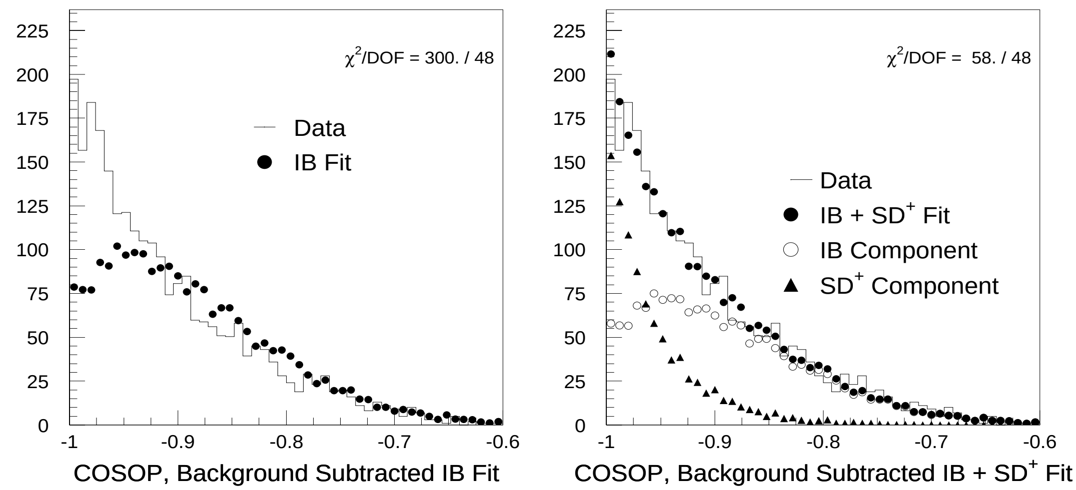

Fig. 7. Distribution of $\cos\theta_{\mu\gamma}$ for E787 $K^+ \rightarrow \mu^+\nu_\mu\gamma$ candidates. A fit to IB alone is shown in (a), and a fit to both IB and SD^+ is shown in (b).

the $O(p^4)$ CHPT calculation of $F_V + F_A = -0.137 \pm 0.006$ and $\mathrm{B(SD^+)} = 9.22 \times 10^{-6}$ (Ref. 94). An $O(p^6)$ calculation is underway.[95,96]

The first results from the search for $K^+ \rightarrow \pi^+\nu\overline{\nu}$ with the upgraded detector have recently been published for the 1995 data set.[97] The range and energy of event candidates passing all other cuts is shown in Fig. 8. One event consistent

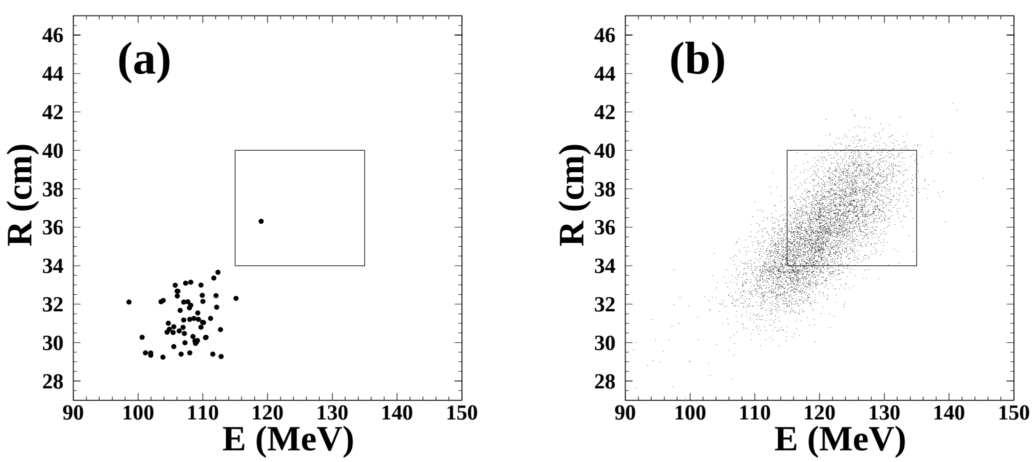

Fig. 8. Final event candidate for $K^+ \rightarrow \pi^+\nu\overline{\nu}$: (a) data and (b) Monte Carlo.

with the decay $K^+ \rightarrow \pi^+\nu\overline{\nu}$ was observed. The expected background from all sources is 0.08 ± 0.03 events. This event is in the so-called "Golden Region" where the expected background is 0.008 ± 0.005 and with 55% of the acceptance of the signal region. A reconstruction of the event is shown in Fig. 9. There is a clean $\pi^+ \to \mu^+$ decay at 27.0 ns, as can be seen in the upper insert in Fig. 9; there is also a clean $\mu^+ \to e^+$ decay at 3201.1 ns. The K^+ decay occurred at 23.9 ns. There is no significant activity anywhere else in the detector at the time of the K^+ decay. The branching ratio for $K^+ \to \pi^+\nu\overline{\nu}$ implied by the observation of

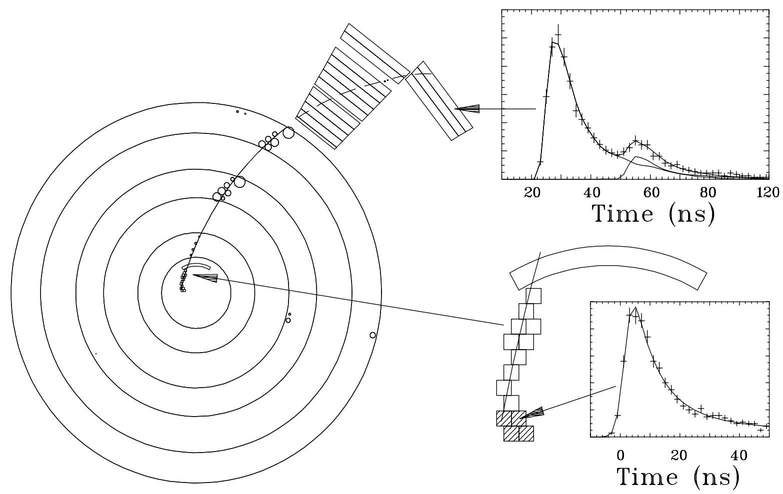

Fig. 9. $K^+ \to \pi^+\nu\overline{\nu}$ event.

this event is $\mathrm{B}(K^+ \to \pi^+\nu\overline{\nu}) = 4.2^{+9.7}_{-3.5} \times 10^{-10}$, compared to the expected value from the SM calculation of $(0.6 - 1.5) \times 10^{-10}$. The expected sensitivity from the data already on tape (1995–97) is $\sim$ 2.4 times that of the 1995 data alone. Additional improvements from more efficient analysis software are also expected. Results of the analysis of the larger data set are expected within the next year. With improved running conditions and a long running period in 1998–99, the E787 sensitivity for $K^+ \to \pi^+\nu\overline{\nu}$ should extend well below the SM level.

4.2 E865

The E865 experiment has been substantially upgraded from the previous experiments (E777/E851). The primary goal is a search for the "forbidden" lepton flavor violating decay $K^+ \to \pi^+\mu^+e^-$. The proposed sensitivity for $K^+ \to \pi^+\mu^+e^-$ is 10^{-12} or about 70 times greater than for E777. The experiment is running in the A2 beamline with an unseparated 6 GeV/c K^+ beam containing 5×10^7 K^+/spill and 1×10^9 π^+ and p^+ per spill. Approximately 9% of the K^+ decay in the 5 m decay volume. The detector rates are $\sim$ 50 M/spill and the first-level trigger rate (three charged tracks) is 2 M/spill. After higher level triggers requiring a good e^- and μ^+, $\sim$ 1,000 events are written to tape each spill.

A drawing of the experimental apparatus is shown in Fig. 10. Good particle identification is essential. The first magnet separates K^+ decay products by charge, so that the left side of the spectrometer is optimized for small e^- misidentification probability and the right side is optimized for small μ^+ and π^+ misidentification probability. A coincidence between the two hydrogen Cherenkov counters on the left side and the Pb-scintillator calorimeter (Shashlyk design: Pb and scintillator plates read out by a wavelength shifting fiber) is required to provide small probability of misidentifying a particle as an electron. The Cherenkov counters on the right side are filled with a lower threshold gas (CO_2 in 1995 and CH_4 in 1996) to more efficiently veto e^+. The trigger rate is reduced significantly by requiring an e^- on the left side. Backgrounds from $K_{\pi 2}$ and $K_{\mu 3}$ decays with a π^0 Dalitz decay are suppressed by assuring that e^+'s on the right side are never misidentified as μ^+'s or π^+'s. The spectrometer consists of four sets of multiwire proportional chambers (P1–4) surrounding the spectrometer magnet. The reconstructed mass resolution for $K_{\pi 3}$ is $\sigma_{M_K} = 2.3$ MeV/c^2.

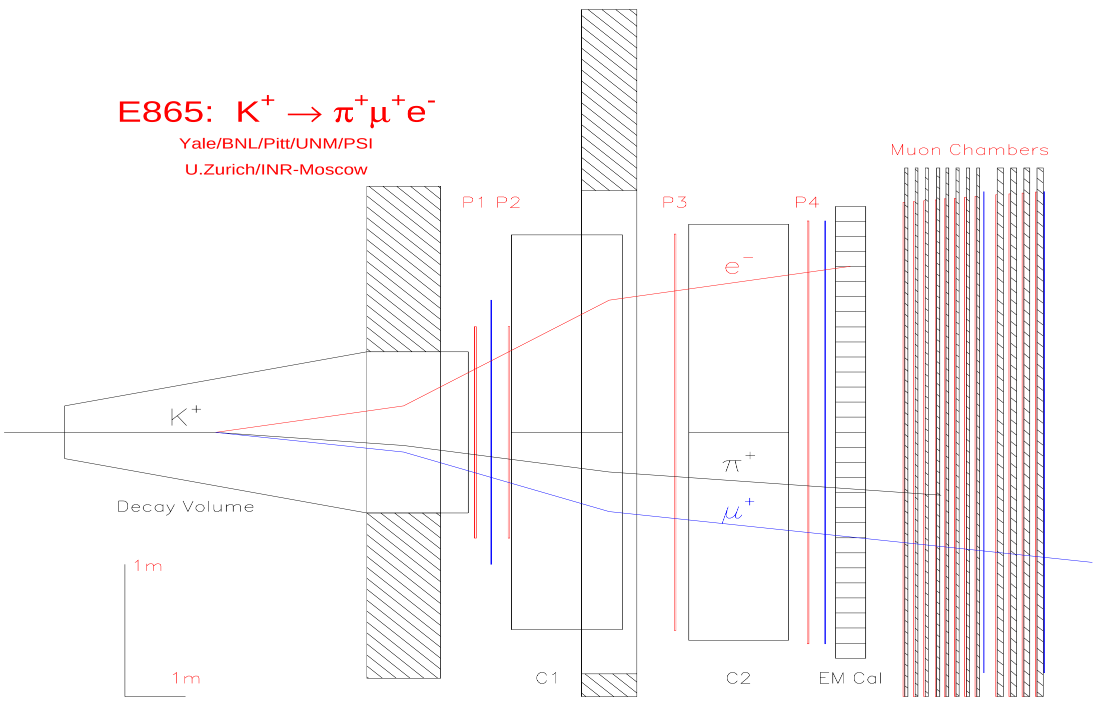

Fig. 10. E865 experimental layout.

A number of upgrades to the E777 experiment include:

- A substantially improved beamline compared to the one used for E777. With $\times$ 5 more K^+, the detector rates are held constant due to improved optics and collimation.
- The spectrometer acceptance is increased by $\times$ 3 by increasing the detector sizes.
- A second muon arm was added for increased acceptance.
- An additional Y view was installed in each chamber for more efficient online and offline event reconstruction.
- Graphite coated Mylar HV foils were used to reduce multiple scattering.

The expected sensitivity for $K^+ \to \pi^+\mu^+e^-$ from the 1995–96 runs is $\sim \times 5$ greater than E777. For $K^+ \to \pi^+e^+e^-$ and $\pi^0 \to e^+e^-$, the sensitivity is $\sim \times 10$ greater ($\sim$ 7000 $K^+ \to \pi^+e^+e^-$ events). In addition, E865 is sensitive to the decay $K^+ \to \pi^+\mu^+\mu^-$ and to the radiative decays $K^+ \to \mu^+\nu e^+e^-$ and $K^+ \to e^+\nu e^+e^-$.

For the primary mode, the lepton flavor violating $K^+ \to \pi^+\mu^+e^-$ decay, a preliminary analysis of the 1995 data shows no $K^+ \to \pi^+\mu^+e^-$ events (see Fig. 11). The plot shows the reconstructed mass $M_{\pi\mu e}$ versus the separation of the three tracks at the vertex. No events are seen in the box at M_K and small vertex separation. E865 has a small data sample for $K^+ \to \pi^+\mu^+e^-$ from 1995 and a much larger sample from 1996 ($\sim \times 4$). The expected single event sensitivity from the combined 1995–96 data set is $\sim 1.6 \times 10^{-11}$. The data set should be increased by another factor of three in the 1998–99 run.

The decays $K^+ \to \pi^+e^+e^-$ and $K^+ \to \pi^+\mu^+\mu^-$ are interesting as tests of CHPT. Both the branching ratios and $M_{\ell\ell}$ for these two decays are expressed in terms of a single parameter w_+, as discussed previously in Sec. 3. A preliminary analysis of the combined 1995–96 data set for the $K^+ \to \pi^+e^+e^-$ decay is shown in Fig. 12. The first plot in Fig. 12 shows the reconstructed "kaon" mass $M_{\pi ee}$ versus the dielectron mass M_{ee}. The $K^+ \to \pi^+e^+e^-$ signal can be seen at $M_{\pi ee} = M_K =$ 494 MeV/c^2 and $M_{ee} > M_{\pi^0}$. The remaining two plots show the reconstructed kaon mass and the dielectron mass for the $K^+ \to \pi^+e^+e^-$ signal. There are more than 7,000 events, as compared to the previous E777 sample of $\sim$ 500 events.[46]

During 1997, due to the very short running time, a special set of triggers was collected at lower intensity. Three different decays were studied: $K^+ \to \pi^+\mu^+\mu^-$

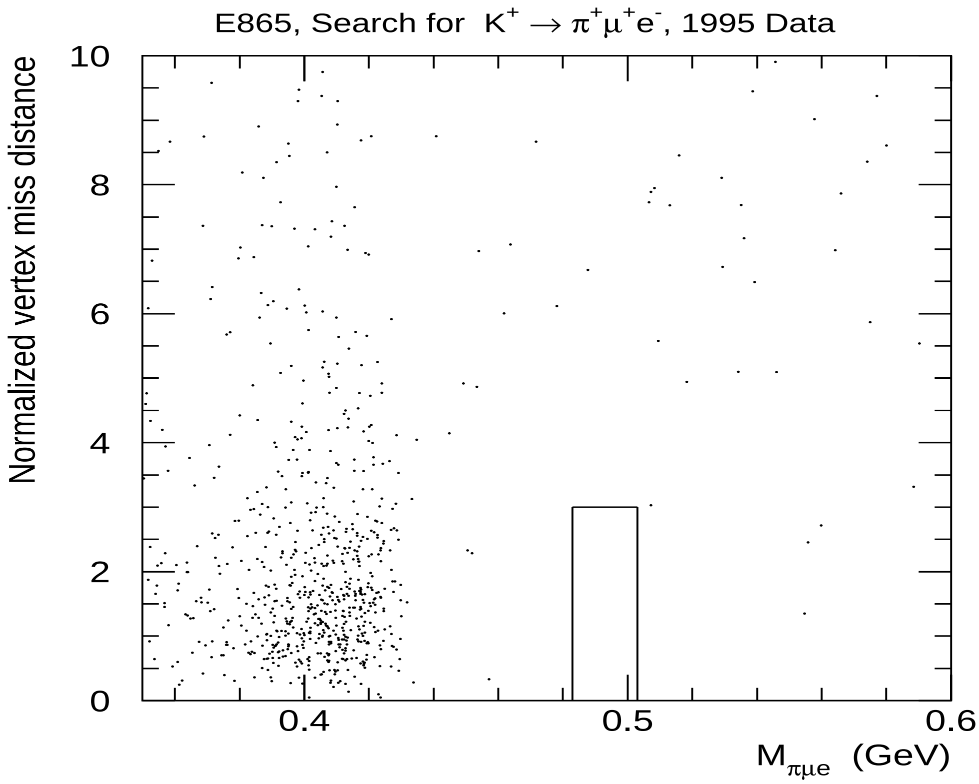

Fig. 11. E865 preliminary $K^+ \to \pi^+\mu^+e^-$ data from 1995.

and $K^+ \to \pi^+\pi^-e^+\nu_e$ were collected at low intensity due to trigger rates, and $K^+ \to \pi^0e^+\nu_e$ were collected at even lower intensity for better control of systematics. In addition, a new beam detector was installed during the 1997 run, which allows for improved resolution on decays with missing neutrinos such as $K^+ \to \pi^0e^+\nu_e$ and $K^+ \to \pi^+\pi^-e^+\nu_e$. E865 approximately tripled the world sample of $K^+ \to \pi^+\mu^+\mu^-$ (previously ~ 200 events from E787). A preliminary analysis of the 1997 $K^+ \to \pi^+\mu^+\mu^-$ data sample shown in Fig. 13 has ~ 400 events at the reconstructed $M_{\pi\mu\mu} = M_K$. In addition, approximately 50,000 $K^+ \to \pi^0e^+\nu_e$ events were collected with the aim of improving the understanding of the CKM matrix element $|V_{us}|$. Analysis of this data should be completed within the next year. Some 300,000 events of $K^+ \to \pi^+\pi^-e^+\nu_e$ were also collected. This is $\sim \times 10$ the previous world sample. This decay mode is important to CHPT, for which it provides significant input, including information on low-energy π–π scattering.

The radiative decays $K^+ \to e^+\nu e^+e^-$ and $K^+ \to \mu^+\nu e^+e^-$, as well as $K^+ \to \mu^+\nu_\mu\gamma$, are governed by the form factors F_A, F_V, and R. These pro-

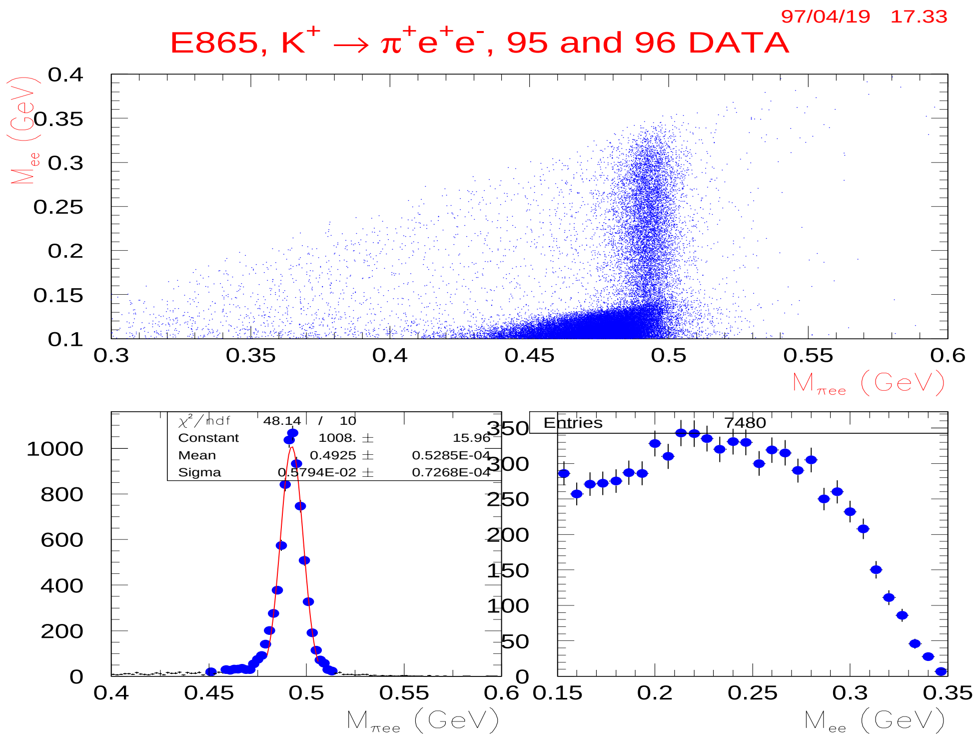

Fig. 12. E865 preliminary $K^+ \to \pi^+ e^+ e^-$ data from 1995–96.

vide a test of CHPT. Preliminary data from the 1996 run for $K^+ \to e^+ \nu e^+ e^-$ and $K^+ \to \mu^+ \nu e^+ e^-$ are shown in Fig. 14. The ~ 100 $K^+ \to e^+ \nu e^+ e^-$ events represent an increase of ~ 20 over the previous world sample of four events. The ~ 700 $K^+ \to \mu^+ \nu e^+ e^-$ events increase the world sample by ~ 50.

Finally, by tagging π^0's from $K^+ \to \pi^+ \pi^0$ decays, the decay $\pi^0 \to e^+ e^-$ can be studied. From the combined 1995–96 data set, a preliminary analysis of $\pi^0 \to e^+ e^-$ is shown in Fig. 15. This decay has had a controversial history, with early experiments measuring a branching ratio much larger than expected in the SM.[98,99] The most recent measurement from E851 is consistent with SM predictions $\mathrm{B}(\pi^0 \to e^+ e^-) = (6.9 \pm 2.3 \pm 0.6) \times 10^{-8}$ (Ref. 46). It was based on ~ 21 events. From the plot in Fig. 15, it is apparent that E865 has significantly more events.

4.3 E871

The goal of the E871 experiment is to push the sensitivity for the lepton flavor violating decay $K_L^0 \to \mu e$ to 10^{-12}. The experiment has tried a novel approach to

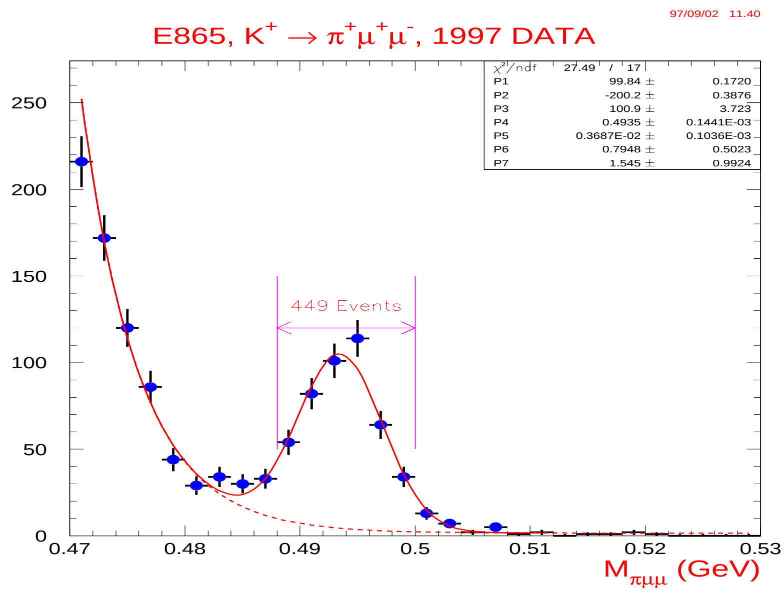

Fig. 13. E865 preliminary $K^+ \to \pi^+\mu^+\mu^-$ data from 1997.

attain this extraordinarily high sensitivity; the very high intensity neutral beam is stopped in a tungsten beam plug in the middle of the first spectrometer magnet.[100] This allows the downstream detectors to operate at relatively low rates. A layout of the E871 detector is shown in Fig. 16. The neutral kaon beam is produced at 3.75° and is defined by a series of collimators and sweeping magnets. The kaons decay in an 11 m vacuum decay volume that is terminated on the downstream end by a thin Kevlar/Mylar window. The neutral beam (n/K $\sim$ 20:1) is stopped in the beam plug, whereas the K_L decay products are tracked in the spectrometer on each side of the beam plug. The first magnet imparts a P_T kick of $\sim$ 440 MeV/c and the second magnet imparts a P_T kick of $\sim$ 220 MeV/c in the opposite direction; this leaves two-body decays parallel to the incident beam.

The general design of the E871 experiment is very similar to E791. It is a two-arm spectrometer with redundant measurements of the momentum in each arm and redundant e and μ identification. Electrons are identified in hydrogen Cherenkov counters and in a PbG array. Muons are identified in an active iron filter (Fe and scintillator) and in a muon range finder (proportional counters separated by Al or marble sheets). One of the primary backgrounds is from $K_L^0 \to \pi^\pm e^\mp \nu_e$ where both the π and e are misidentified: In this case the reconstructed mass can be greater than or equal to M_K. This background is eliminated with redundant lepton identification. The second major background is from $K_L^0 \to \pi^\pm e^\mp \nu_e$ decays where the π decays to or is misidentified as a μ. The endpoint of this spectrum is 8 MeV/c^2 below M_K, so this background can be eliminated by the high-precision, redundant momentum measurements. The mass resolution of the spectrometer is $\sigma_{M_{\pi\pi}} \sim 1.1$ MeV/c^2. If the π decays to a μ and one hit is missing in the x view in one of the upstream tracking stations, the track can have a good χ^2 and the reconstructed mass can be greater than or equal to M_K. This background is eliminated by adding a third x measurement to each tracking station, so that if one hit is missing there are still two hits to constrain the x position, and by making a tight requirement on the muon range compared to the expectation from the momentum.

The experiment is designed to take $\times$ 4 more protons on target than E791 and have a much larger vacuum decay tank ($\times$ 3 larger acceptance). The experiment ran in the B5 beamline with 15–20 Tp on target, giving $\sim 3 \times 10^8$ K_L/spill and $\sim 10^7$ K_L decays per spill. The L0 trigger rate (requiring parallel tracks) was $\sim$ 70 k and the L1 trigger rate (requiring the lepton identification) was 10 k. The final trigger rate, after mass and transverse momentum cuts, was $\sim$ 500/spill.

The upstream drift chambers in E791 have been replaced with 5 mm diameter straw chambers and are operated with faster gas (C_2H_6–CF_4), in order to operate efficiently in the high rate environment near the beam plug. An additional tracking station has been added to the E791 configuration and all of the chambers have added a third x measurement. The trigger was upgraded to take advantage of the "parallelism" of the tracks from two-body decays downstream of the spectrometer magnets. The trigger rate is further reduced by requiring spatial correlations with the lepton identification systems. The lepton identification systems have also been more finely segmented.

The E871 experiment has two large data sets from the 1995 and 1996 running periods. The experiment ran for 25 weeks in 1995 and, after a vacuum window failure forced the rebuilding of the straw chamber system, for 16 weeks in 1996. The 1995–96 data set is being analyzed and results should be forthcoming within the next year. A preliminary study of the $K_L^0 \to \mu^+\mu^-$ decay shows $\sim$ 5,000 events, implying a sensitivity of $\sim 1.5 \times 10^{-12}$, close to the design goal. A plot of the $K_L^0 \to \mu^+\mu^-$ invariant mass is shown in Fig. 17. This is $\gtrsim \times$ 7 more than from E791. With the increased sensitivity, E871 should "close the window" on new physics in $K_L^0 \to e^+e^-$. In the SM the branching ratio is a few $\times\ 10^{-12}$, so E871 should observe several $K_L^0 \to e^+e^-$ events.

5 AGS-2000

The AGS will become the injector for the Relativistic Heavy Ion Collider (RHIC) beginning in 1999. The AGS will be needed for injection up to twice a day for $\sim$ 2 hours; the remaining 20 hours will be available for running fixed target experiments with either heavy ions or protons. The AGS will remain the most intense source of protons with energy above the kaon production threshold. In particular, the AGS will remain the most intense source of low-energy kaons. The marginal cost for the extra running time will be substantially less than the current cost of the program. Several kaon decay experiments are being considered or are already proposed for running in the AGS-2000 era.

5.1 $K^+ \to \pi^+\nu\overline{\nu}$

E787 has seen one event with $B(K^+ \to \pi^+\nu\overline{\nu}) = 4.2^{+9.7}_{-3.5} \times 10^{-10}$. Several improvements have already been made or are underway, including: lowering the kaon momentum (increasing the number of stopped kaons, while keeping the rates in the detector low), increasing the duty factor of the AGS (increasing sensitivity without increasing rates), reduced deadtime through trigger and DAQ upgrades, additional transient digitizers on the beam elements, finer segmentation of the beam chamber, and an additional layer of Pb-scintillator for the central photon veto. Additional improvements were considered at the AGS-2000 Workshop. The goal of the $K^+ \to \pi^+\nu\overline{\nu}$ working group was to design an experiment to measure $|V_{td}|$ to $\lesssim$ 15%. The working group concluded that the optimal strategy would be to build on the vast experience and success of the E787 experiment and that, with modest upgrades to the E787 experiment and beamline, achieving this goal should be possible.[101]

5.2 E926

The decay $K_L^0 \to \pi^0\nu\overline{\nu}$, the so-called "Golden Mode," is a purely CP-violating decay that is entirely dominated by short-distance physics involving the top quark.

As in $K^+ \to \pi^+\nu\overline{\nu}$, the hadronic matrix element can be derived from $K^+ \to \pi^0 e^+\nu_e$. Due to the small size of the imaginary part of the CKM matrix elements, the charm quark contribution is negligible. The remaining theoretical uncertainty is even smaller than that for the charged mode, $[O(1\%)]$ (Ref. 23). The branching ratio is given by

$$B(K_L \to \pi^0\nu\bar{\nu}) \approx 4.3 \times 10^{-10}\eta^2 A^4 \sim 2 \times 10^{-11}. \tag{7}$$

The experimental challenges are formidable, not only because of the small expected branching ratio. The experimental signature is even weaker than in the charged mode. The E926 (Ref. 102) experiment has chosen to measure as many kinematic variables as possible: the direction, time, position, and energies of the photons from the π^0 and the velocity of the K_L. The velocity of the K_L will be determined from the arrival times of the photons, the reconstructed decay vertex, and the time of the K_L creation. This last quantity will be determined to ~ 200 ps from the use of a bunched beam from the AGS. The reconstruction of the γ directions will be achieved with a 1.5 X_0 preconverter (scintillator and chambers). The energy will be measured with a Pb and scintillating fiber calorimeter similar to the KLOE design,[103] but with a much enhanced scintillator to Pb ratio. The rest of the decay volume will be surrounded by photon veto systems. A diagram of the proposed detector is shown in Fig. 18.

To maximize the K_L momentum resolution and to reduce backgrounds from neutron interactions, the experiment will run at a large production angle ($\sim 45°$). The K_L beam will be a flat beam, 125 mr by 4 mr, which provides an additional kinematic constraint (y of the vertex). The neutral beam and decay volume will be at moderately high vacuum (10^{-7} torr) to suppress neutron backgrounds. The largest remaining background is from $K_L^0 \to \pi^0\pi^0$ which, while also CP-violating, is 10^8 times larger. The E926 design goal is a π^0 veto inefficiency of 10^{-8}. Additional suppression of the $K_L^0 \to \pi^0\pi^0$ of a factor of 50 can be achieved with a kinematic cut on the π^0 momentum in the K_L center-of-mass system at about 190 MeV/c (35% acceptance for $K_L^0 \to \pi^0\nu\overline{\nu}$).

The experiment plans to run with 50 Tp on target, giving $\sim 2.5 \times 10^8$ K_L's and $\sim 2 \times 10^7$ K_L decays per pulse. With an 8,000-hour run, ~ 70 $K_L^0 \to \pi^0\nu\overline{\nu}$ decays should be detected, with a background of ~ 7 events (almost entirely from $K_L^0 \to \pi^0\pi^0$).

Measurements of the $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L^0 \to \pi^0\nu\overline{\nu}$ branching ratio may provide the most precise determination of the CKM parameters ρ and η. In any event, a determination of these parameters in the kaon system will make for a valuable comparison with values obtained for the B system from the B-factories.

5.3 E923

E923 (Ref. 104) will search for a T-violating polarization of the μ^+ normal to the decay plane in the decay $K^+ \to \pi^0\mu^+\nu_\mu$. The current limits on this process, $-0.009 < P_\mu^T < 0.007$ (95% C.L.), come from earlier BNL experiments E696 and E735 (Refs. 28–31), which collected data from 1978–80. Although the SM does not predict T-violation in $K^+ \to \pi^0\mu^+\nu_\mu$, CP violation is not well-understood and, for example, some proposed extensions to the SM designed to explain the baryon asymmetry in the universe also predict transverse muon polarization.[105,106]

The earlier experiment collected 2.1×10^7 K^+ (1.2×10^7 K_L) decays with an unseparated 4 GeV/c K^+ beam. The new experiment will use a separated ($K^+/\pi^+ = 1/1.2$) 2 GeV beam with 2 $\times 10^7$ K^+/pulse (30 Tp protons on target) and $6{\times}10^6$ decays/pulse. A drawing of the detector is shown in Fig. 19. The new detector has a larger acceptance and achieves better background rejection. The background rejection is improved by fully reconstructing the event with the large acceptance, finely-segmented calorimeter and the tracking chambers Ch1–3. The γ's from the π^0's are detected in an electromagnetic calorimeter (Pb-scintillator—Shashlyk design). The μ^+'s are tracked into the graphite polarimeter. The polarimeter has 96 graphite wedges, with chambers between each wedge. An asymmetry in the rate of clockwise versus counterclockwise muon decays would signal a possible T-violating muon polarization. An axial magnetic field (along the beam direction) of ~ 70 G is applied to the polarimeter, with the field direction reversed every spill, allowing for the cancellation of many possible systematic errors.

With a total analyzing power of 23% and a 2,000-hour run, the statistical sensitivity will reach 1.3×10^{-4}.

The same apparatus will be used to measure the T-violating polarization in $K^+ \to \mu^+\nu_\mu\gamma$ events. Such a measurement is sensitive to nonstandard pseudo-scalar as well as vector interactions and is therefore complementary to the measurement in $K^+ \to \pi^0\mu^+\nu_\mu$ decays.[107] Studies are in progress to ascertain if a sensitivity of 0.001 can be achieved, at which point final state interactions may produce a non-T-violating polarization out of the decay plane.

5.4 E927

The E927 (Ref. 108) experiment proposes to measure the CKM matrix element $|V_{us}|$. The goal is to measure the $K^+ \to \pi^0 e^+ \nu_e$ branching ratio to 0.7%. A K^+ beam will be stopped in a scintillating fiber target. The outgoing positron will be tracked in a drift chamber and identified in a plastic scintillator and a plexiglass Cherenkov counter. The π^0 photons and e^+ energy will be measured in the Crystal Ball detector. The estimate for $K^+ \to \pi^0 e^+ \nu_e$ acceptance is as high as 98.5% with a 1.3% contamination from predominantly $K^+ \to \pi^+ \pi^0$ with a small $K^+ \to \pi^0 \mu^+ \nu_\mu$ component.

6 Conclusions

The AGS kaon program has a long and rich history. The most rare particle decay yet has been observed in $K^+ \to \pi^+ \nu \overline{\nu}$. The most sensitive kaon decay search comes from $K_L^0 \to \mu e$. A number of interesting new processes have been observed. Further improvements can be expected from the current experiments. Future extensions of the program should provide a significant determination of the CKM matrix element $|V_{td}|$ and the CP-violating parameter η. Significantly improved limits on, or perhaps observation of T violation in, the decay $K^+ \to \pi^0 \mu^+ \nu_\mu$ should be expected. Improvements in the knowledge of the CKM matrix element $|V_{us}|$ should also be forthcoming.

Acknowledgments

I would like to thank Laurie Littenberg, Milind Diwan, Bill Molzon, Hong Ma, Mike Zeller, Bill Morse, Phil Pile, Tom Roser, I.-H. Chiang, Brad Tippens, Robin Appel, and Mike Hebert for comments and useful discussions regarding this paper and for access to the data presented here.

Appendices

Publications from the recent AGS program are listed in Appendices 1–4.

Appendix 1. Publications from AGS experiments E780/E845.

E696/E735/E749/E780/E845
M. P. Schmidt *et al.*, Phys. Rev. Lett. **43**, 556–560 (1979).
W. M. Morse *et al.*, Phys. Rev. D **21**, 1750–1766 (1980).
M. K. Campbell *et al.*, Phys. Rev. Lett. **47**, 1032–1035 (1981).
S. R. Blatt *et al.*, Phys. Rev. D **27**, 1056–1068 (1983).
J. K. Black *et al.*, Phys. Rev. Lett. **54**, 1628–1630 (1985).
H. B. Greenlee *et al.*, Phys. Rev. Lett. **60**, 893–896 (1988).
E. Jastrzembski *et al.*, Phys. Rev. Lett. **61**, 2300–2303 (1988).
S. F. Schaffner *et al.*, Phys. Rev. D **39**, 990–993 (1989).
H. B. Greenlee, Phys. Rev. D **42**, 3724–3731 (1990).
K. E. Ohl *et al.*, Phys. Rev. Lett. **64**, 2755–2758 (1990).
W. M. Morse *et al.*, Nucl. Phys. A **527**, 717–720 (1991).
K. E. Ohl *et al.*, Phys. Rev. Lett. **65**, 1407–1410 (1990).
W. M. Morse *et al.*, Phys. Rev. D **45**, 36–41 (1992).
M. R. Vagins *et al.*, Phys. Rev. Lett. **71**, 35–37 (1993).

Appendix 2. Publications from AGS experiments E777/E851/E865.

E777/E851/E865
N. J. Baker *et al.*, Phys. Rev. Lett. **59**, 2832–2835 (1987).
C. Campagnari *et al.*, Phys. Rev. Lett. **61**, 2062–2065 (1988).
A. M. Lee *et al.*, Phys. Rev. Lett. **64**, 165–168 (1990).
C. Alliegro *et al.*, Phys. Rev. Lett. **68**, 278–281 (1992).
A. Deshpande *et al.*, Phys. Rev. Lett. **71**, 27–30 (1993).

Appendix 3. Publications from AGS experiments E791/E871.

E791/E871
R. D. Cousins *et al.*, Phys. Rev. D **38**, 2914–2917 (1988).
C. Mathiazhagan *et al.*, Phys. Rev. Lett. **63**, 2181–2184 (1989).
C. Mathiazhagan *et al.*, Phys. Rev. Lett. **63**, 2185–2188 (1989).
A. P. Heinson *et al.*, Phys. Rev. D **44**, R1–R5 (1991).
K. Arisaka *et al.*, Phys. Rev. Lett. **70**, 1049–1052 (1993).
A. P. Arisaka *et al.*, Phys. Rev. Lett. **71**, 3910–3913 (1993).
A. P. Heinson *et al.*, Phys. Rev. D **51**, 985–1013 (1995).
J. Frank *et al.*, IEEE Trans. Nucl. Sci. **NS–36**, 79–85 (1989).
C. J. Kenney *et al.*, IEEE Trans. Nucl. Sci. **NS-36**, 74–78 (1989).
D. M. Lee *et al.*, Nucl. Instrum. Methods A **256**, 329–332 (1987).
R. D. Cousins *et al.*, IEEE Trans. Nucl. Sci. **NS-36**, 646–649 (1989).
K. A. Biery *et al.*, IEEE Trans. Nucl. Sci. **NS-36**, 650–652 (1989).
R. D. Cousins *et al.*, Nucl. Instrum. Methods A **277**, 517 (1989).

Appendix 4. Publications from AGS experiment E787.

E787
M. S. Atiya *et al.*, Phys. Rev. Lett. **63**, 2177–2180 (1989).
M. S. Atiya *et al.*, Phys. Rev. Lett. **64**, 21–24 (1990).
M. S. Atiya *et al.*, Phys. Rev. Lett. **65**, 1188–1191 (1990).
M. S. Atiya *et al.*, Phys. Rev. Lett. **66**, 2189–2192 (1991).
M. S. Atiya *et al.*, Phys. Rev. Lett. **69**, 733–736 (1992).
M. S. Atiya *et al.*, Nucl. Phys. A **527**, 727c–729c (1991).
M. S. Atiya *et al.*, Phys. Rev. Lett. **70**, 2521–2524 (1993).
M. S. Atiya *et al.*, Phys. Rev. D **48**, 1–4 (1993).
S. Adler *et al.*, Phys. Rev. Lett. **76**, 1421–1424 (1996).
S. Adler *et al.*, Phys. Rev. Lett. **79**, 2204–2207 (1997).
P. Kitching *et al.*, Phys. Rev. Lett. **79**, 4079–4082 (1997).
S. Adler *et al.*, Phys. Rev. Lett. **79**, 4756–4759 (1997).
M. S. Atiya *et al.*, IEEE Trans. Nucl. Sci. **NS-36**, 813–817 (1989).
M. S. Atiya *et al.*, Nucl. Instrum. Methods A **279**, 180–185 (1989).
M. S. Atiya *et al.*, Nucl. Instrum. Methods A **321**, 129–151 (1992).
M. Burke *et al.*, IEEE Trans. Nucl. Sci. **NS-41**, 131 (1994).
M. Kobayashi *et al.*, Nucl. Instrum. Methods A **337**, 355–361 (1994).
I.-H. Chiang *et al.*, IEEE Trans. Nucl. Sci. **NS-42**, 394–400 (1995).
D. A. Bryman *et al.*, Nucl. Instrum. Methods A **396**, 394–404 (1997).
T. K. Komatsubara *et al.* (accepted for publication in Nucl. Instrum. Methods A).
E. W. Blackmore *et al.* (accepted for publication in Nucl. Instrum. Methods A).

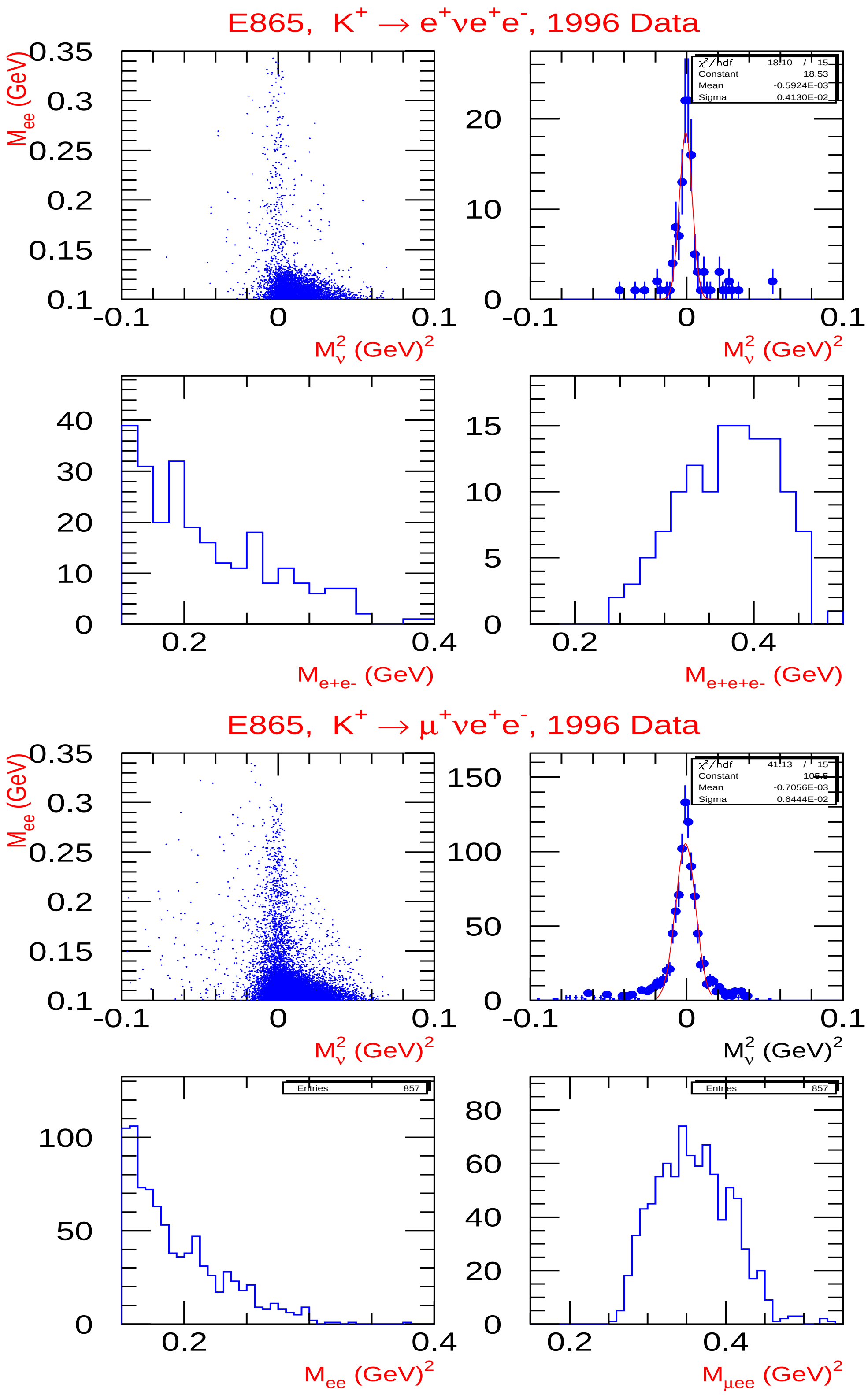

Fig. 14. E865 preliminary $K^+ \to e^+\nu e^+e^-$ and $K^+ \to \mu^+\nu e^+e^-$ data from 1996.

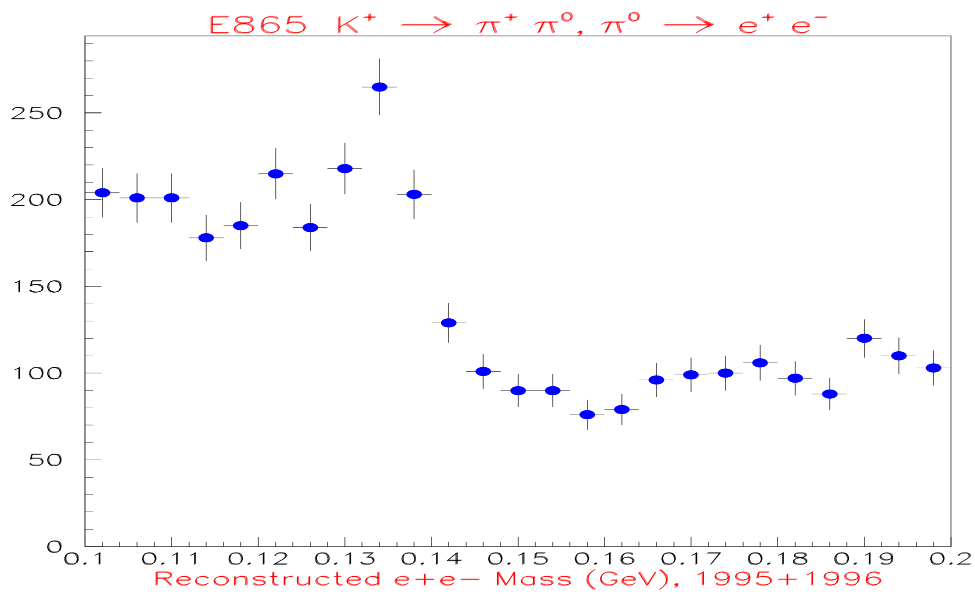

Fig. 15. E865 preliminary $\pi^0 \to e^+e^-$ data from 1995 and 1996.

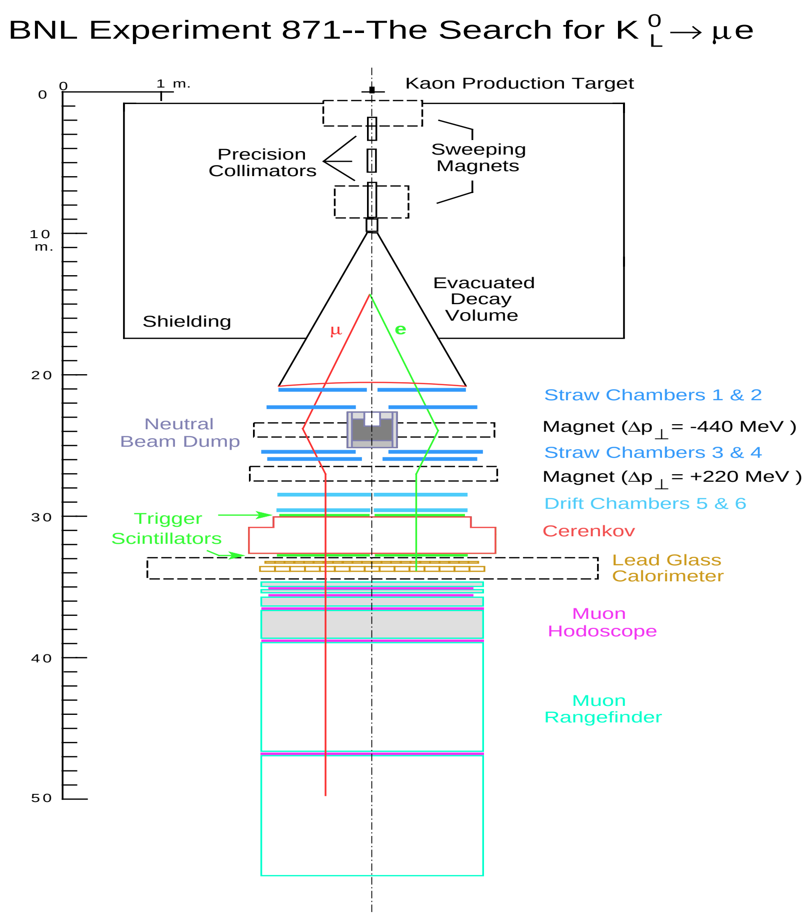

Fig. 16. E871 experimental layout.

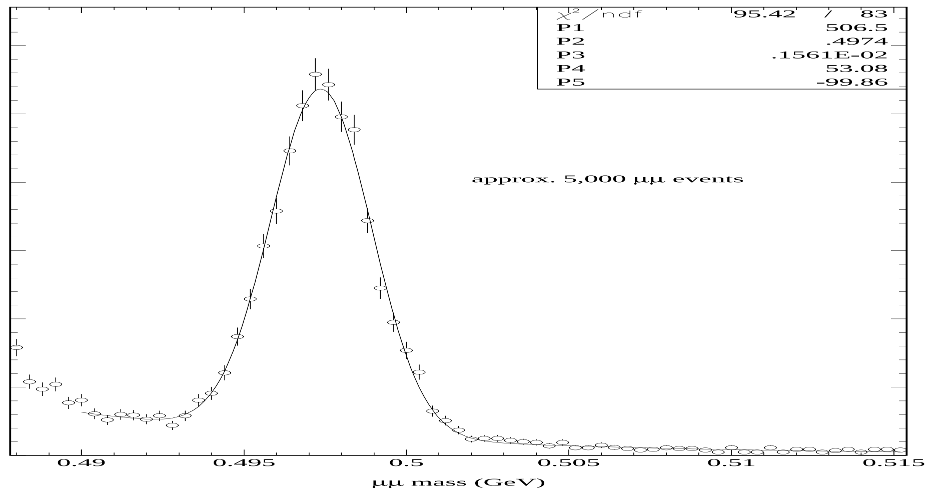

Fig. 17. Preliminary E871 $\mu\mu$ mass plot.

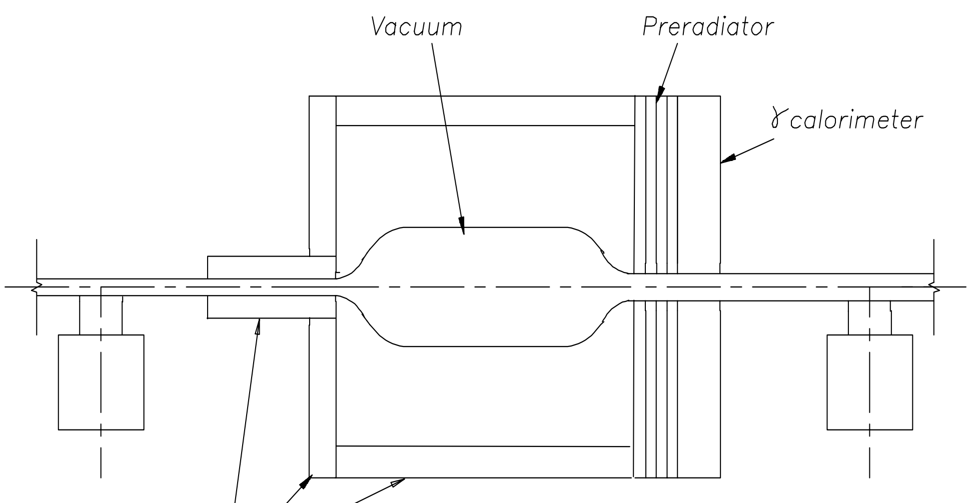

Fig. 18. E926 experimental layout.

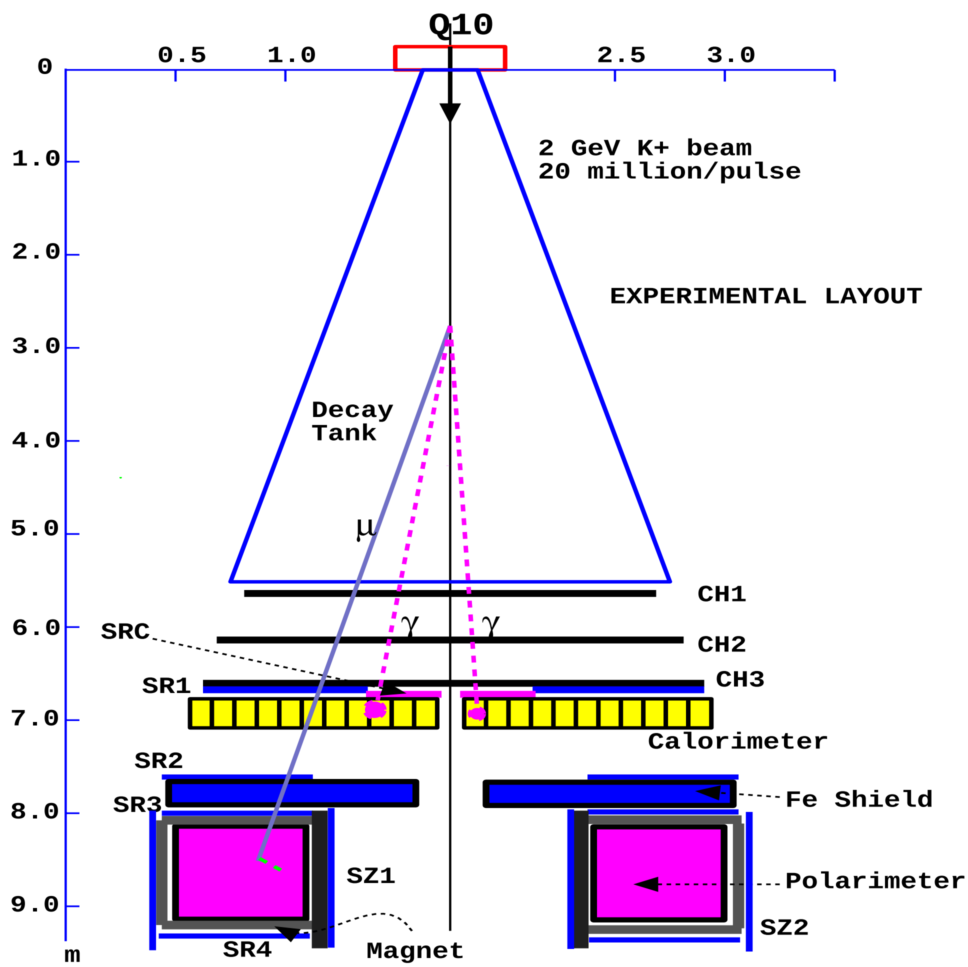

Fig. 19. E923 experimental layout.

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