REPORT ON RARE KAON DECAYS FROM BROOKHAVEN NATIONAL LABORATORY

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ABSTRACT

This article reviews the rare kaon decay program at Brookhaven National Laboratory. There are currently three experiments dedicated to rare kaon decays. They were all launched in the mid eighties. In order to take full advantage of the AGS booster they either developed into new experiments or underwent significant upgrades during the last three years. Their past history, current results and prospects for the future are presented.

1 Introduction

Kaons as the lightest meson beyond the up-down isodoublet played an outstanding role in the formulation of the Standard Model of electroweak interaction. The observed decay modes span currently over nine orders of magnitude and thus present a unique system to study particle physics phenomena.

The latest round of rare kaon decay experiments was initiated at Brookhaven National Laboratory (BNL) in the mid eighties. They took data between 1988 and 1991. With the higher kaon flux made possible by the AGS booster, these experiments either underwent signficant upgrades or led to new experiments, which are now ready to take data. This second phase is expected to last until the end of the decade.

In the following we first give a theoretical motivation for rare kaon decays* and describe first briefly some characteristics of kaon decays. Then the current three rare kaon decay experiments at BNL (E791/871, E777/851/865, E787) are presented.

1.1 Theoretical Motivation for Rare Kaon Decays

Rare kaon decays are of special interest for several reasons, among them:

- Search for phenomena outside the Standard Model:
  Processes that are either forbidden or heavily suppressed within the Standard Model are interesting places to look for phenomena outside the Standard Model. Of particular interest are lepton flavor violating processes, which address the family problem of particle physics. The idea is, that in analogy to the $K_{\mu 2}$ decay, the lepton flavor violating process is mediated by a heavy horizontal gauge boson (see figure 1):

  $$B(K_L \rightarrow \mu e) = B(K^+ \rightarrow \mu^+ \nu) \ \frac{\tau_L}{\tau_+} \ (\frac{M_W^2 g_H^2}{M_H^2 g_W^2 sin\Theta_W})^2$$

  These experiments probe extremely high mass scales, e.g. for $B(K_L \rightarrow \mu e) \leq 3.3 \cdot 10^{-11}$ leads to a mass limit of the heavy boson of

  $$M_H \geq 90 \ TeV/c^2$$

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*For recent review articles see[1,2]

whereas it should be stressed that a coupling strength for the horizontal gauge boson must be assumed in order to obtain a mass limit (normally $g_H \simeq g_W$).

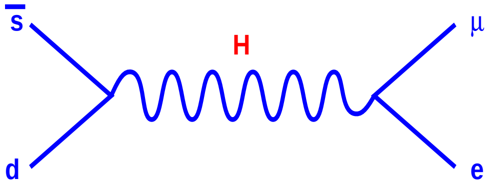

Figure 1: *Feynman diagram for $K_L \rightarrow \mu e$, mediated by a heavy horizontal gauge boson.*

- Study of short distance "Standard Model" physics:
  Some rare kaon decays allow the extraction of Cabbibo-Kobayashi-Maskawa (CKM) matrix elements[†]
- "High statistics" study on "medium rare" kaon decays:
  As the sensitivity of a given rare kaon decay mode is increased, often other (less rare) decay modes are accessible with relatively high statistics. In the ideal case they are of considerable interest themselves, e.g. in the framework of chiral perturbation theory. Examples for these decays are $K^+ \rightarrow \pi^+ e^+ e^-$, $K^+ \rightarrow \pi^+ \mu^+ \mu^-$, $K^+ \rightarrow \pi^+ \gamma\gamma$ or $K_L \rightarrow \mu^+ \mu^-$. In the worst case these processes are tricky sources of background.

1.2 The Alternating Gradient Syncrotron at BNL

The Alternating Gradient Syncrotron (AGS) at BNL is used as the kaon source. The machine accelerates protrons to 24 GeV and has a diameter of 257m. It was commissioned in March 1960. Its operation mode for the kaon experiments is a slow extracted beam, meaning a spill duration of 1.3 - 1.8 sec every 3 sec. Its peak intensity in 1994 was $4 \cdot 10^{13}$ p / spill, the highest proton intensity ever achieved.

[†] The CKM matrix[3] describes the mixing between the flavor and mass eigenstates in the quark sector. One possible representation (due to Wolfenstein) is given below and shows the order of magnitude between the elements (λ is the Cabbibo angle):

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

1.3 Experimental Consideration for Kaon Decays

Some characteristics for kaon decay experiments should be recalled before describing the experiments. Due to the long lifetime of the kaons, the decay region is separated well in space from the production region (in marked contrast to say B decays). The kaons, produced as a secondary beam by a proton beam, are in most cases outnumbered by other particles (pions, neutrons). Due to the big variety of kaon decay modes, the experiments can normally use well known decay modes for calibration and normalisation purposes. The last step in the analysis is typically a two dimensional plot of effective mass of the final state particles (close to the kaon mass for the signal) versus their direction (collinearity angle, sum of transverse momenta, which is normally close to zero for the signal).

2 E791 - Search for $K_L \to \mu e$

The experiment E791* searched for the lepton flavor violating process $K_L \to \mu e$. The neutral beam passed through a 8.4 m long evacuated decay tank and entered the detector (figure 2), which consisted of a two arm spectrometer. Five drift chambers (each with 2 x and 2 y measurements) between two analysing magnets were used as tracking devices. The p_T kick (300 MeV/c) of the two magnets was of equal magnitude but opposite sign, such that the original angle between the two tracks was restored after the second magnet. Electron particle identification was done with a Cherenkov counter (gas mixture of He and N_2) and a lead glass array. Muons were identified with a muon hodoscope downstream of a 0.91 m thick iron wall and a two arm muon range finder consisting of marble and aluminum plates interspersed with x and y drift tube planes. The latter provided a range measurement corresponding to a 10% momentum measurement. Fast trigger signals were given by the muon hodoscope behind the iron wall, trigger scintillators before and after the Cherenkov counter as well as the Cherenkov counter itself. The geometrical acceptance of the detector for the main physics decay mode of this experiment $K_L \to \mu e$ was 4.6%.

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*E791 was a collaboration of University of California - Irvine, University of California - Los Angeles, Los Alamos National Laboratory, Stanford University, Temple University, University of Texas - Austin and College of William and Mary.

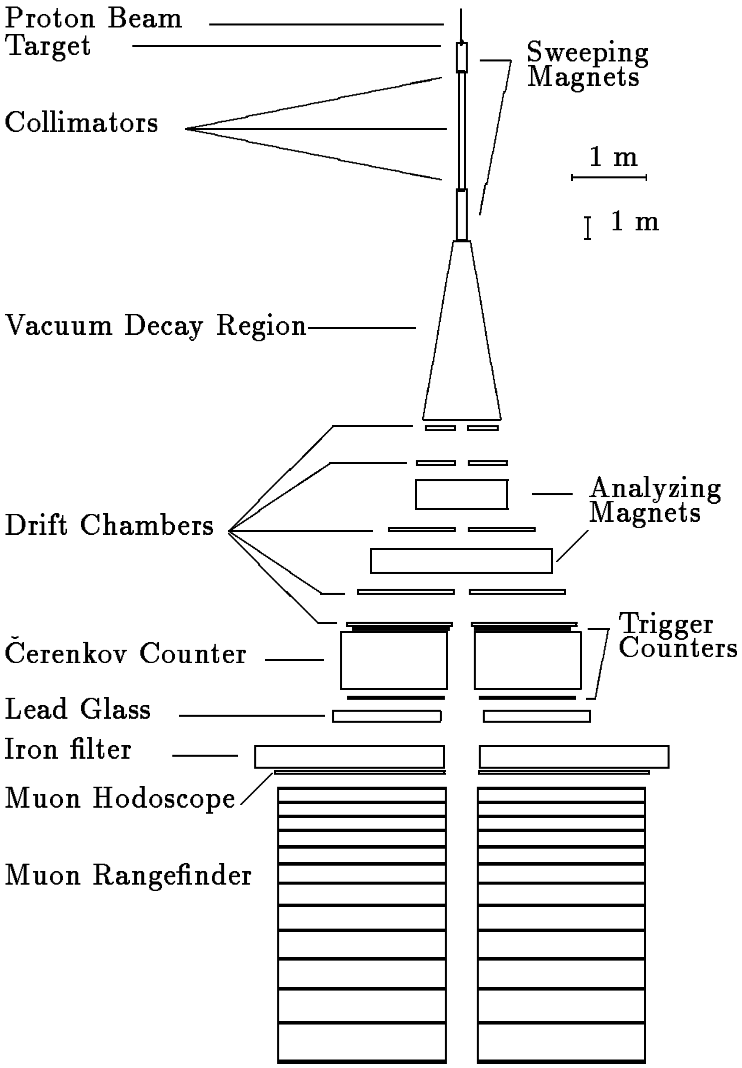

Figure 2: *Detector of E791*

$K_L \to \mu e$

The main physics background for $K_L \to \mu e$ is the decay $K_L \to \pi e \nu$ (branching ratio 38%). There are two distinct cases: The first is a misidentification of the pion as a muon, which gives a kinematic endpoint of 8.4 MeV below the kaon mass. This has to be compared with the achieved mass resolution of $K_L \to \pi^+\pi^-$ calibration events of 1.4 MeV . However tracking errors can move this background closer to the signal region, thus the importance of redundant and precise tracking information. The second source of background is a double misidentification of the pion as a electron and the electron as a muon. Due to the wrong mass assignment this background can extend into the signal region. Other backgrounds like overlap of events etc are estimated to be of minor importance.

A blind analysis of the data taken in 1989 and 90, combined with the earlier result based on 1988 data, yielded no candidates in the signal region (figure 3). The CP violating decay $K_L \to \pi^+\pi^-$ was used for normalization and an upper limit of[4]

$$BR(K_L \to \mu e) < 3.3 \cdot 10^{-11} \quad 90\% \; CL$$

was obtained. This is the highest sensitivity ever achieved in a rare kaon decay experiment.

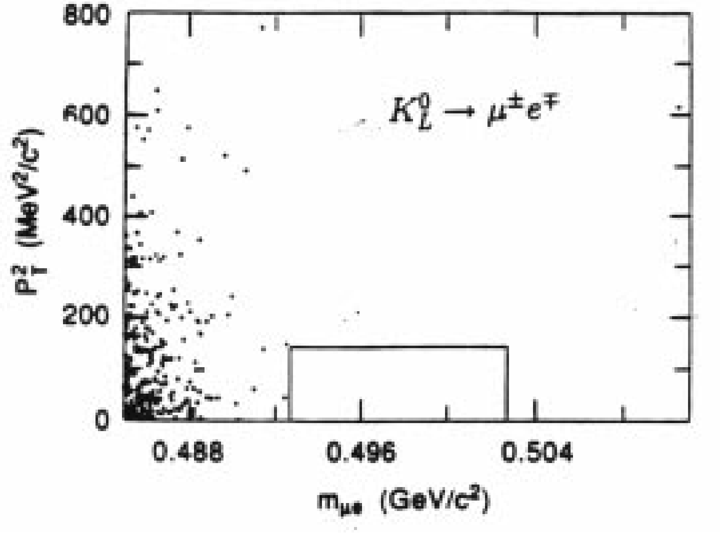

Figure 3: *E791 - Invariant mass of the μe pair vs transversal momentum squared for final event sample.*

$K_L \to \mu^+\mu^-$

The decay $K_L \to \mu^+\mu^-$ is a flavor changing neutral current, suppressed[†] within the Standard Model by the quark mixing. The amplitude for $K_L \to \mu^+\mu^-$ has two contributions: 1. a real dispersive part, which is the sum of long and short distance diagrams (figure 4), 2. an imaginary absorptive part, dominated by the two gamma intermediate state (figure 5), yielding a lower bound of $6.81 \cdot 10^{-9}$ for $K_L \to \mu^+\mu^-$. Knowledge of the short distance contributions can be used to extract the CKM matrix element ρ (if m_t is known). However our current limited knowledge of the long distance part does not allow us to obtain stringent limits.

The main backgrounds for $K_L \to \mu^+\mu^-$ are $K_L \to \pi e \nu$ and $K_L \to \pi \mu \nu$. They can be subtracted from the signal. E791 reported 707 events (figure 6), yielding a preliminary branching ratio of[5]

$$B(K_L \to \mu^+\mu^-) = (6.86 \pm 0.37) \cdot 10^{-9}$$

very close to the unitarity limit quoted above.

The related decay $K_L \to e^+e^-$ is suppressed by the helicity of the electron to an expected branching ratio of the order of 10^{-12}. No candidates were found, yielding an upper limit of[6]

$$B(K_L \to e^+e^-) < 4.1 \cdot 10^{-11} \qquad 90\%\ CL$$

[†] More precisely: Flavor changing neutral currents would be strictly forbidden within the Standard Model if the quark masses were all equal. However due to the quark mass differences they are possible, but heavily suppressed. This property makes them a sensitive test for the Standard Model as well as a window for new physics.

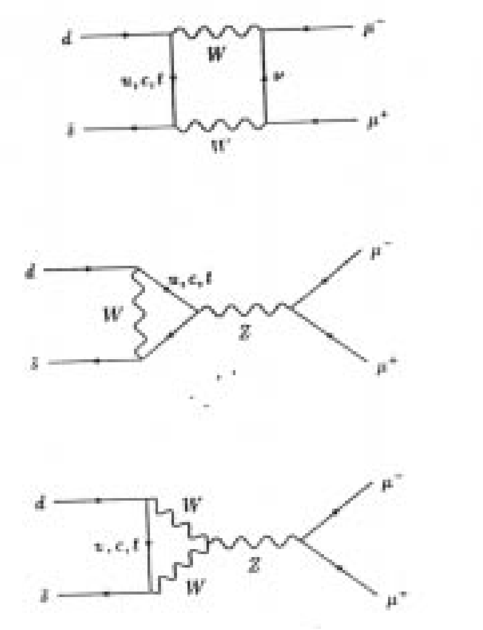

Figure 4: *Short distance contributions to* $K_L \rightarrow \mu^+\mu^-$

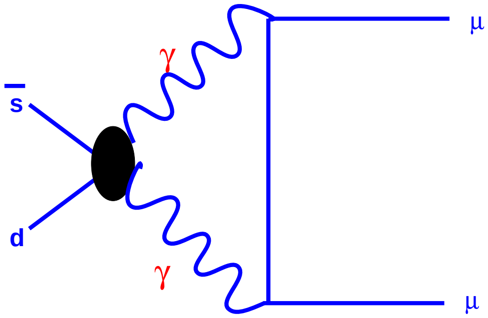

Figure 5: *Two gamma intermediate state diagram for* $K_L \rightarrow \mu^+\mu^-$

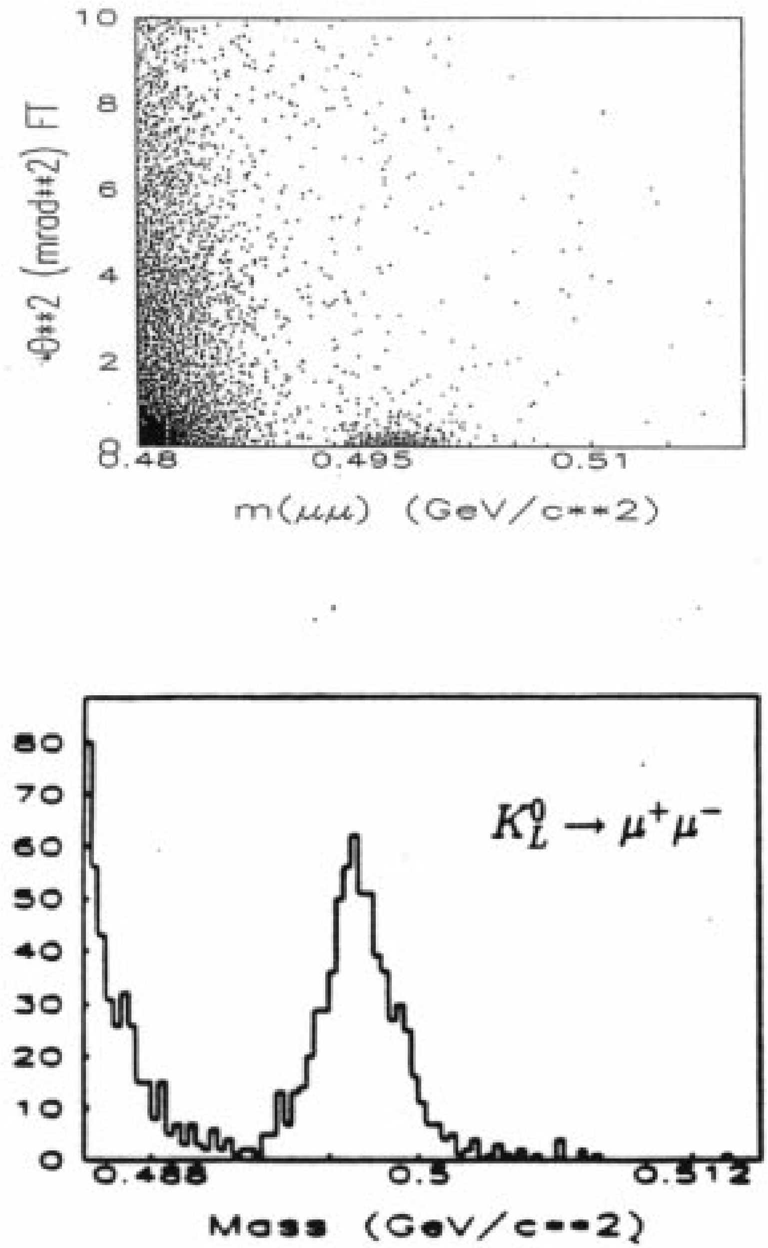

Figure 6: *E791: Search for* $K_L \to \mu^+\mu^-$*: Top: reconstructed kaon mass versus collinearity angle squared, bottom: reconstructed kaon mass*

E871

Motivated by the success of E791, an upgrade as experiment E871 is underway [‡]. The experimental goal is the search for $K_L \rightarrow \mu e$ at a sensitivity of 10^{-12} (corresponding to a mass scale of 200 TeV/c^2 for a hypothetical horizontal gauge boson as discussed above). In addition 10,000 $\mu^+\mu^-$ will be accumulated and the decay $K_L \rightarrow e^+e^-$ might be seen.

The upgraded detector (figure 7) has an improved beam (factor of 4), bigger decay volume and magnet aperture (factor of 2) and various detector component upgrades. Small straw chambers with fast gas are used for the tracking in the upstream part of the detector. The p_T kick of the two magnets is now such that the tracks for two body decays are parallel in the downstream part of the detector. This gives a strong trigger constraint. A notable feature of E871 is the beam plug in the middle of the detector, where the neutral beam is stopped. It reduces the rates in the downstream tracking chambers and particle identification devices. E871 had its first engineering run in summer 1994 and is expected to take data for the next three years.

3 E777 - Search for $K^+ \rightarrow \pi^+\mu^+e^-$

The experiment E777[*] searched for the rare kaon decay $K^+ \rightarrow \pi^+\mu^+e^-$. This lepton flavor violating decay mode is complementary to the previously described mode $K_L \rightarrow \mu e$ (E791) as it is sensitive to scalar and vector interaction, whereas $K_L \rightarrow \mu e$ is sensitive to pseudoscalar and axialvector interaction.
E777 searched experimentally for the charge combination $\pi^+\mu^+e^-$. This has the experimental advantage that only few electrons are present in the decay of a K^+ (the biggest source of e^- are dalitz decays of π^0).

[‡] E871 is a collaboration of physicists from University of California - Irvine, Stanford University, University of Texas - Austin and College of William and Mary.

[*] E77 was a collaboration of BNL, PSI, U. of Washington and Yale

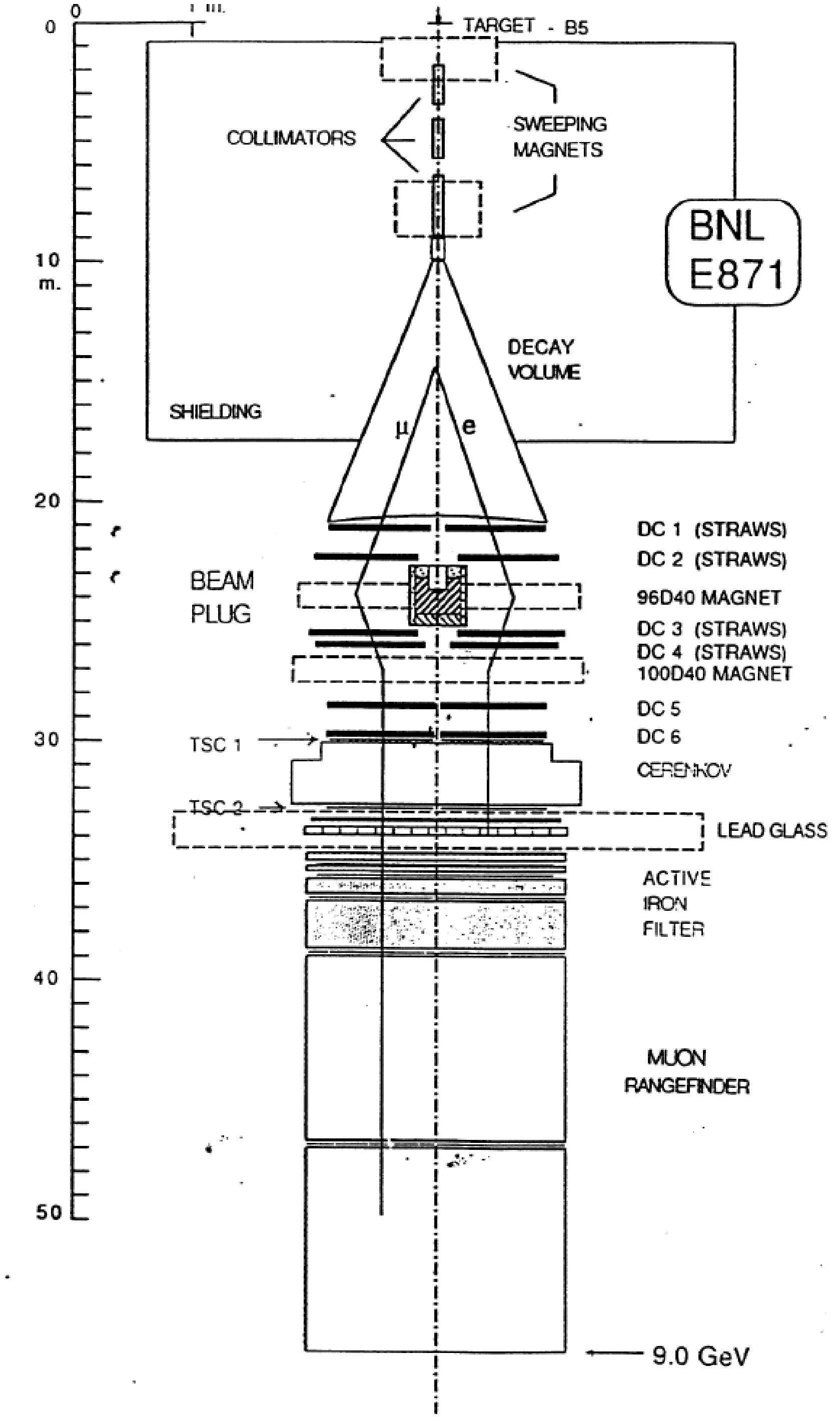

Figure 7: *E871 Detector*

The experiment used an unseparated 6 GeV/c beam ($2 \cdot 10^8$ particles per spill, of which 5% are K^+). Approximately 11% of the K^+ decayed in the 5 m long evacuated decay tank (figure 8). The detector was a two arm spectrometer. A first magnet sweeped the charged kaon decay products out of the beam. Four MWPC around a second magnet were used for tracking. The particle identification devices in the two arms of the spectrometer were different. The right arm of the spectrometer was optimized for vetoing positrons and had two CO_2 Cherenkov counters and a iron/proportional tube muon range finder. The left side was optimized for identifying electrons and had two H_2 Cherenkov counters. A lead scintillator calorimeter extending to both arms was also used for particle identification.

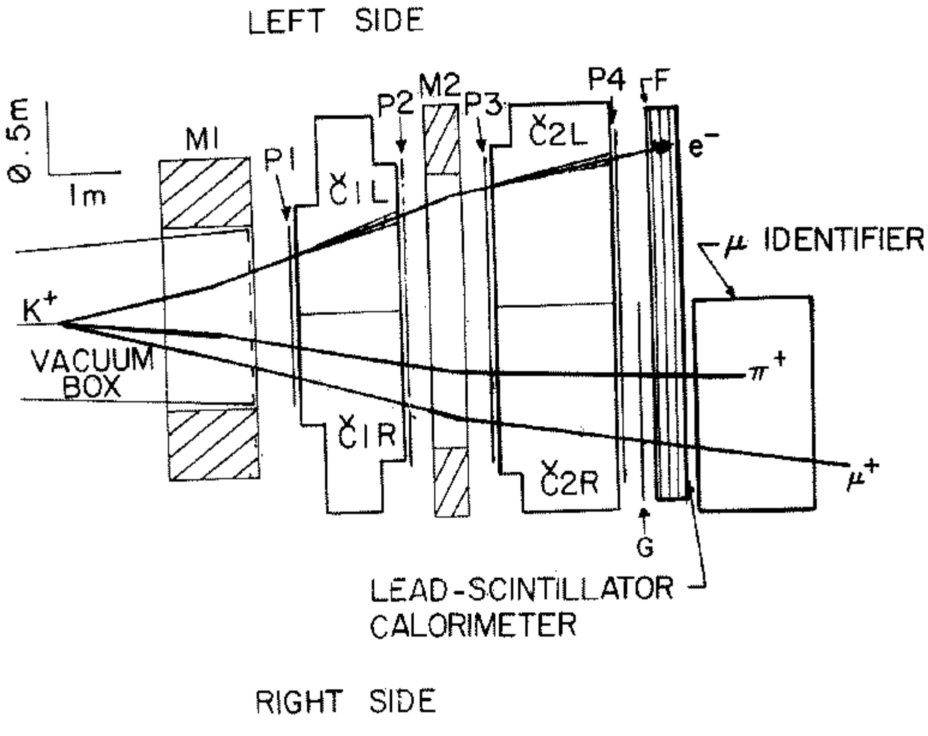

Figure 8: *Detector of E777*

There are three main sources of background in the search for $K^+ \rightarrow \pi^+\mu^+e^-$. 1. $K^+ \rightarrow \pi^+ \pi^0$ decay followed by the Dalitz decay $\pi^0 \rightarrow e^+e^-\gamma$ and particle misidentification, 2. $K^+ \rightarrow \pi^0\mu^+\nu$ with Dalitz decay of the π^0 and misidentification of the e^+ as a π^+ , 3. $K^+ \rightarrow \pi^+\pi^-\pi^+$ with particle misidentification/decay and tracking errors.
$K^+ \rightarrow \pi^+ \pi^- \pi^+$ decays were used for calibration and normalization (figure 9). No $K^+ \rightarrow \pi^+\mu^+e^-$ candidates were found, yielding an upper limit of[7]

$$B(K^+ \rightarrow \pi^+\mu^+e^-) < 2.1 \cdot 10^{-10} \quad 90\% \ CL$$

This limit restricts a hypothetical horizontal gauge boson to a mass bigger than 57 TeV/c^2. Note that this limit is less stringent than the one for $K_L \rightarrow \mu e$, due to the longer K_L lifetime and the additional phasespace of two body over three body decays.

E851: $K^+ \rightarrow \pi^+e^+e^-$

The E777 collaboration also searched in a dedicated run for the rare kaon decay $K^+ \rightarrow \pi^+e^+e^-$ (E851). This decay, a flavor changing neutral current, is of special interest in the context of chiral perturbation theory (χPT) in order to study the e^+e^- decay spectrum and extract χPT constants.[8] These can then be used to predict other decay rates. In particular $K^+ \rightarrow \pi^+e^+e^-$ can help to disentangle the various CP allowed and forbidden contributions to the decay $K_L \rightarrow \pi^0e^+e^-$[†]. Extracting the short distance contribution of $K^+ \rightarrow \pi^+e^+e^-$ (figure 10), one encounters the same difficulties as in $K_L \rightarrow \mu^+\mu^-$, namely the interesting short distance contributions are buried under long distance ones.

E851 found a total of 500 $K^+ \rightarrow \pi^+e^+e^-$ (figure 11). Assuming a vector interaction a branching ratio of[9]

$$B(K^+ \rightarrow \pi^+e^+e^-) = (2.75 \pm 0.23 \pm 0.13) \cdot 10^{-7}$$

was obtained.
E851 also published a branching ratio of $\pi^0 \rightarrow e^+e^-$.[10]

[†] More precisely it can be related to the indirect CP violating part of the decay $K_L \rightarrow \pi^0e^+e^-$

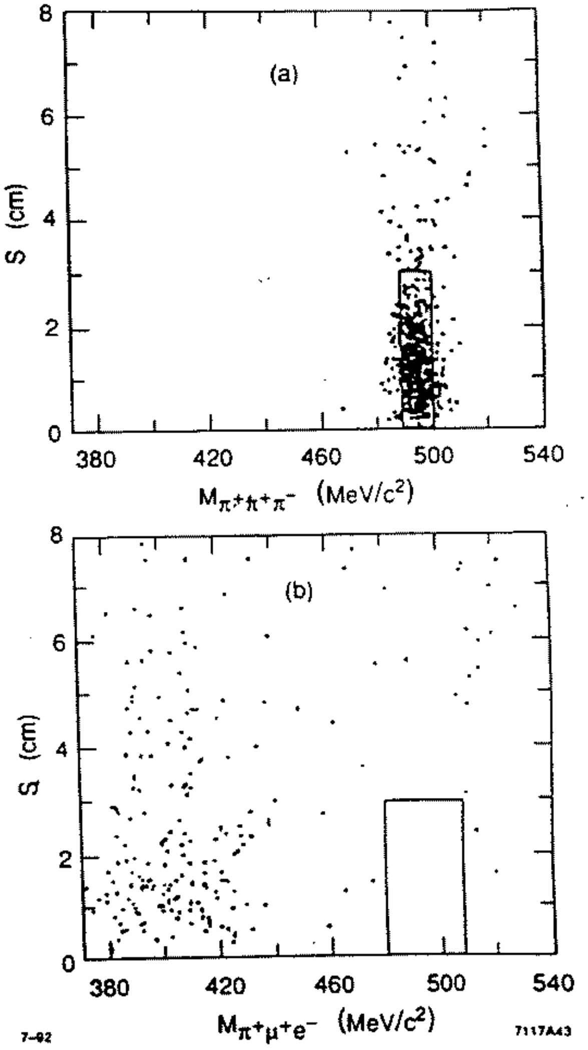

Figure 9: *E777: Top: S versus reconstructed kaon mass for* $K^+ \rightarrow \pi^+\pi^-\pi^+$ *normalisation events. S is the vertex miss distance (square root of the sum of the squares of the distances of closest approach of each track to a common vertex) Bottom: Same for* $K^+ \rightarrow \pi^+\mu^+e^-$ *candidates.*

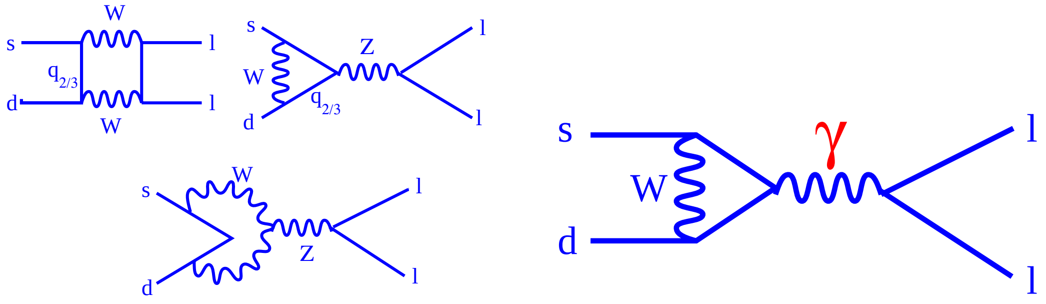

Figure 10: *Short (left) and dominant long (right) distance contributions to* $K^+ \rightarrow \pi^+ l^+ l^-$ *(l for lepton, e, μ)*

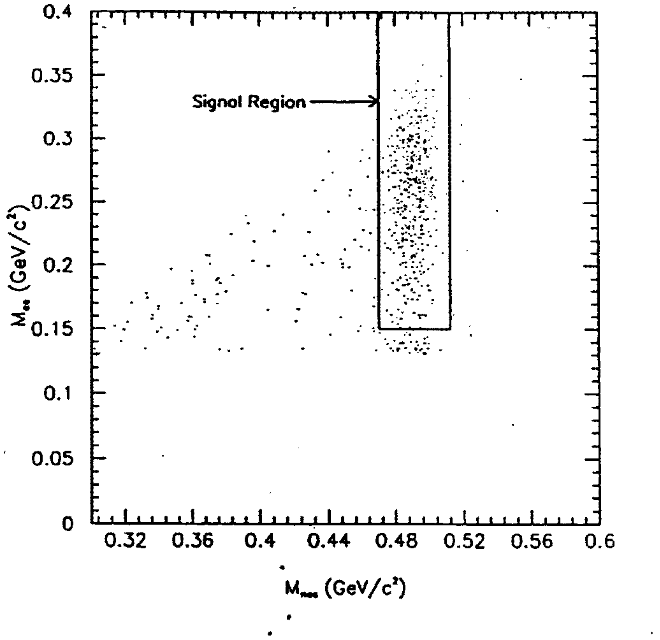

Figure 11: *E851:* $K^+ \rightarrow \pi^+ e^+ e^-$*: Effective three body mass versus invariant mass of the dielectron pair.*

E865: $K^+ \rightarrow \pi^+\mu^+e^-$

The experiment E865[‡] (figure 12) is the extension of E777 with the goal to reach a sensitivity of $3 \cdot 10^{-12}$ for the decay $K^+ \rightarrow \pi^+\mu^+e^-$, an improvement of a factor of 70 over E777. The upgrades include a new beam line (higher flux and less halo, which were the main limitations of E777), bigger spectrometer acceptance, new tracking devices and Cherenkov counters. The muon identifier now covers the entire downstream region.

In addition 50,000 $K^+ \rightarrow \pi^+e^+e^-$ are expected to be accumulated, which allow detailed study of the e^+e^- spectrum. With special runs or modest upgrades the experiment could search for CP violation in $K^+ \rightarrow \pi^\pm\pi^-\pi^+$ or for the muon polarization in $K^+ \rightarrow \pi^+\mu^+\mu^-$ (see below).

E865 had its first engineering run in summer 1994.

4 E787 - Search for $K^+ \rightarrow \pi^+\nu\overline{\nu}$

The experiment E787[*] searches for the flavor changing neutral current $K^+ \rightarrow \pi^+\nu\overline{\nu}$. This decay mode is predicted by the Standard Model to occur at a level of a few 10^{-10}. The long distance contributions to this decay are expected to be much smaller than the short distance ones (figure 13) due to the presence of two neutrinos in the final state. This is in marked difference to the previously discussed decays $K_L \rightarrow \mu^+\mu^-$ and $K^+ \rightarrow \pi^+e^+e^-$, which are long distance dominated. Thus $K^+ \rightarrow \pi^+\nu\overline{\nu}$ is a unique probe of short distance physics. In particular the CKM matrix element $\mid V_{td} \mid$ can be extracted with little theoretical uncertainty[†] out of the branching ratio. However this comes at the price of detecting a decay mode at a level of 10^{-10}. This very low branching ratio on the other hand offers also a window for exotic physics. An observation of $K^+ \rightarrow \pi^+\nu\overline{\nu}$ outside the Standard Model prediction would clearly be a sign for new physics.

[‡] A collaboration of Basel, BNL, INR-Moscow, JINR-Dubna, New Mexico, PSI, Basel, Pittsburgh, HEPI-Tiblisi, Yale and Zurich

[*] E787 was originally a collaboration of Brookhaven, Princeton and Triumf. It was later joined by INS-Tokyo and KEK.

[†] $\mid V_{td} \mid$ could theoretically also be obtained from $B - \overline{B}$ mixing, but this method suffers from considerable theoretical uncertainties. It is the very absence of these uncertainties that make $K^+ \rightarrow \pi^+\nu\overline{\nu}$ such an attractive way to obtain $\mid V_{td} \mid$

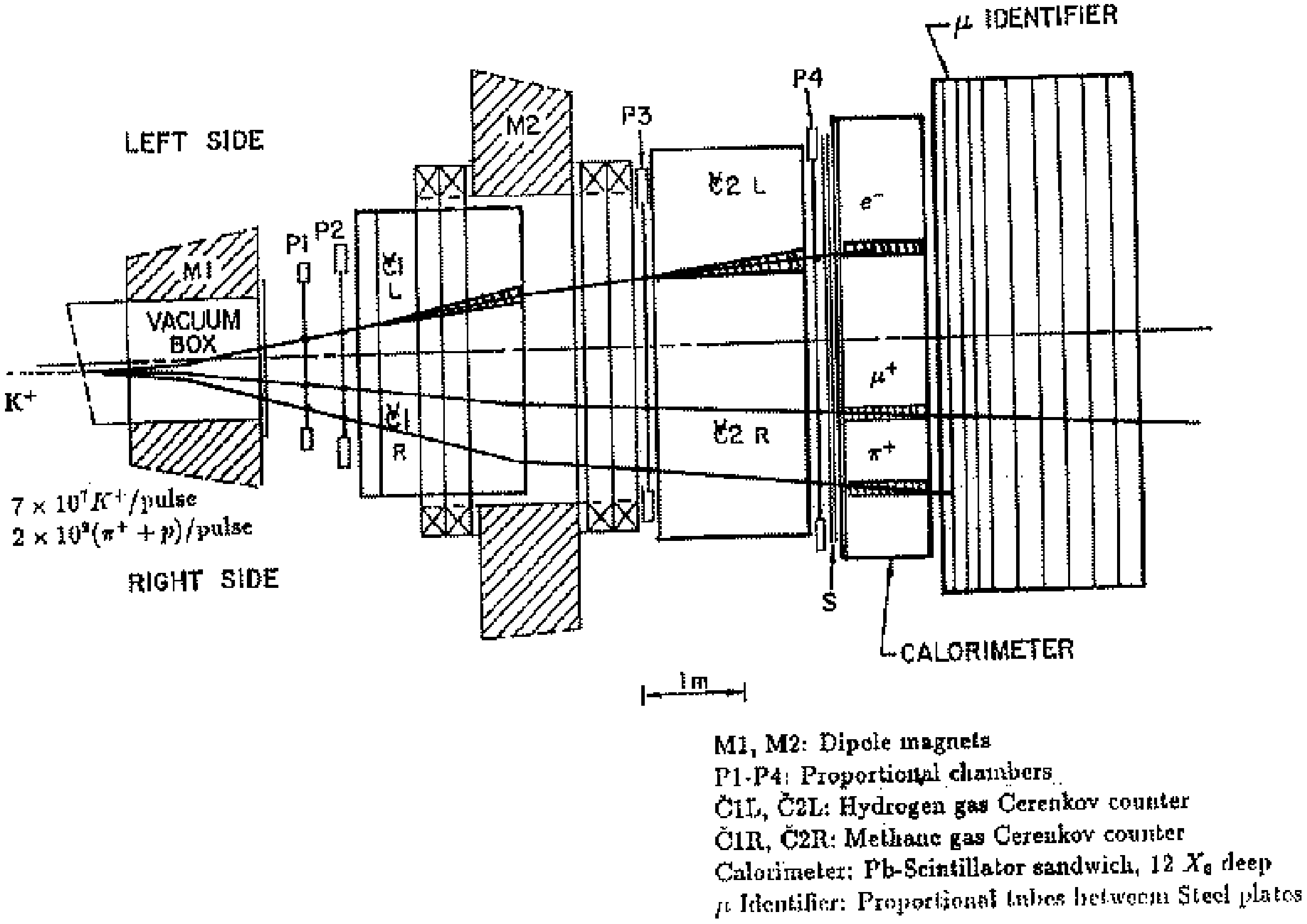

Figure 12: *E865 detector.*

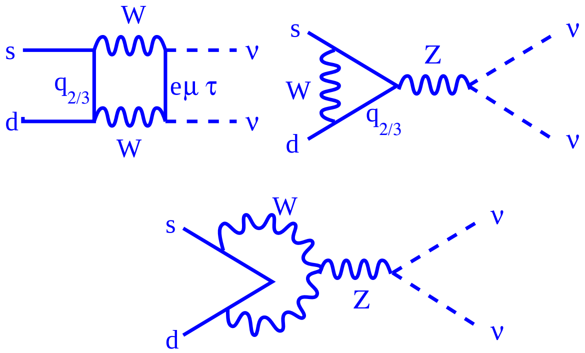

Figure 13: *Short distance contributions to* $K^+ \rightarrow \pi^+\nu\overline{\nu}$.

The detector (figure 14[11]) is a collider-like symmetric detector in a solenoid with a field of 10kG. The K^+ are stopped in the center of the detector in a scintillating fiber target, which allows the reconstruction of the event at the kaon decay vertex. Around the target is a drift chamber, followed radially by a range stack consisting of 21 layers of 2 cm thick scintillators, read out on the upstream and downstream end by phototubes. A barrel veto and two endcaps serve as photon veto and complete the 4π solid angle coverage.

The decay signature of $K^+ \rightarrow \pi^+\nu\overline{\nu}$ is one pion and nothing else. The π^+ from $\pi^+\nu\overline{\nu}$ have a kinematic endpoint of 227 MeV/c , which is between the fixed momentum of the two body decays $K^+ \rightarrow \pi^+\pi^0$ (205 MeV/c) and $K^+ \rightarrow \mu^+\nu$ (236 MeV/c). E787 concentrates its search in the momentum region between these two decays, where no other π^+ from K^+ decay is expected other than from $\pi^+\nu\overline{\nu}$.

The pions are required to stop in the range stack. Transient digitisers (“flash ADC”) are attached to the range stack PMT’s and sample the charge at the PMT’s every two ns. This allows the observation of the decay signature $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ (figure 15). A muon rejection of $1.3 \cdot 10^6$ has been achieved. Photon vetoing is important for the $K^+ \rightarrow \pi^+\pi^0$ decay background. A π^0 detection inefficiency of 10^{-6} has been achieved. A combined analysis of the data taken in 1989, 90 and 91 (figure 16) gave a preliminary upper limit of

$$B(K^+ \rightarrow \pi^+\nu\overline{\nu}) < 3.0 \cdot 10^{-9} \quad 90\%\ CL$$

For the related decay $K^+ \rightarrow \pi^+X^0$, where X^0 is a missing massless new particle, a preliminary upper limit is reported

$$B(K^+ \rightarrow \pi^+X^0) < 6.1 \cdot 10^{-10} \quad 90\%\ CL$$

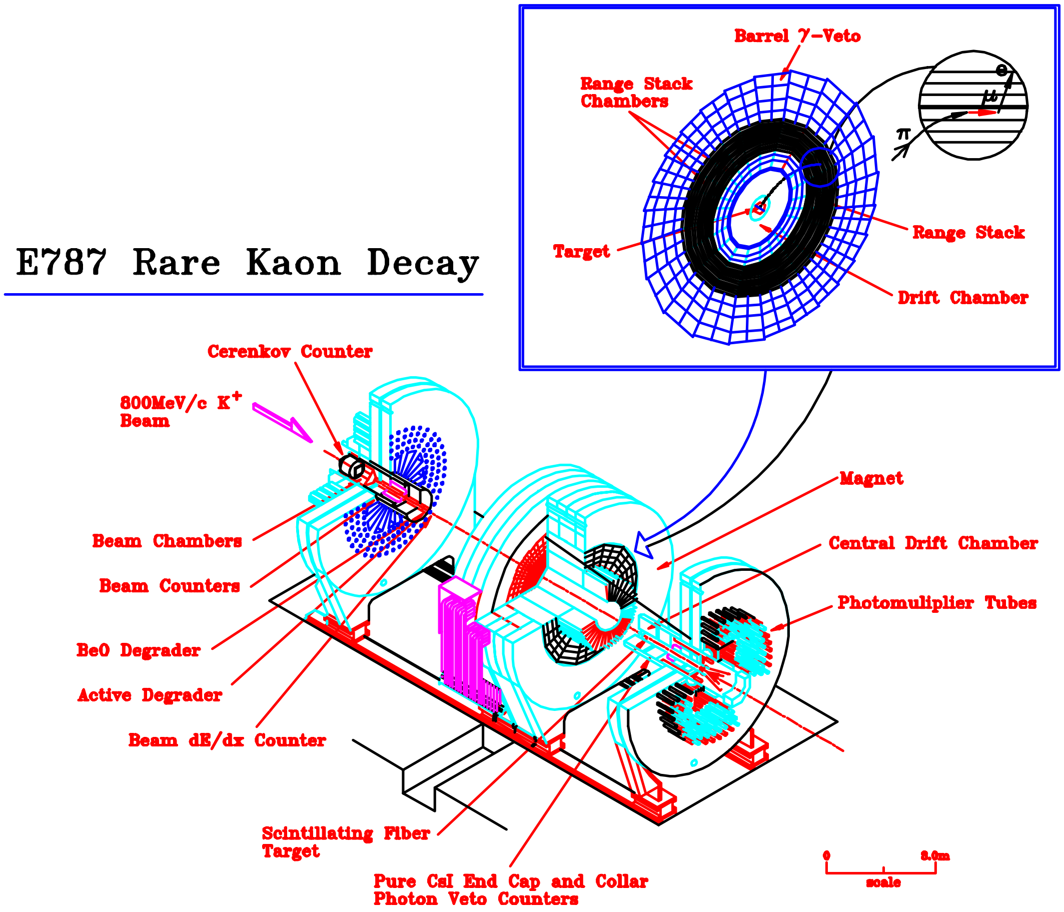

Figure 14: *E787 detector. Bottom: Detector with endplates separated from magnet. Top: Experimental idea for the search of* $K^+ \to \pi^+ \nu \overline{\nu}$*: The kaon stops in the target and the decay pion is required to stop in the range stack, where the decay sequence* $\pi^+ \to \mu^+ \to e^+$ *is observed in order to identify it as a pion.*

$K^+ \to \pi^+ \mu^+ \mu^-$

E787 also searches for the rare kaon decay $K^+ \to \pi^+ \mu^+ \mu^-$, which is related to the previously discussed decay $K^+ \to \pi^+ e^+ e^-$. The short distance contributions to $K^+ \to \pi^+ \mu^+ \mu^-$ are as in the case $K^+ \to \pi^+ e^+ e^-$ hidden by the long distance one photon exchange diagram (figure 10). However a parity violating asymmetry in the polarization of the muon is predicted due to the interference of the long and short distance diagrams.

E787 requires in its search for $K^+ \to \pi^+ \mu^+ \mu^-$ that all three particles leave the scintillating fiber target and two of them reach the range stack. The main background is K_{e4} decays $K^+ \to \pi^+ \pi^- e^+ \nu$ and is subtracted from the signal (figure 17). 13 candidate events have been found.

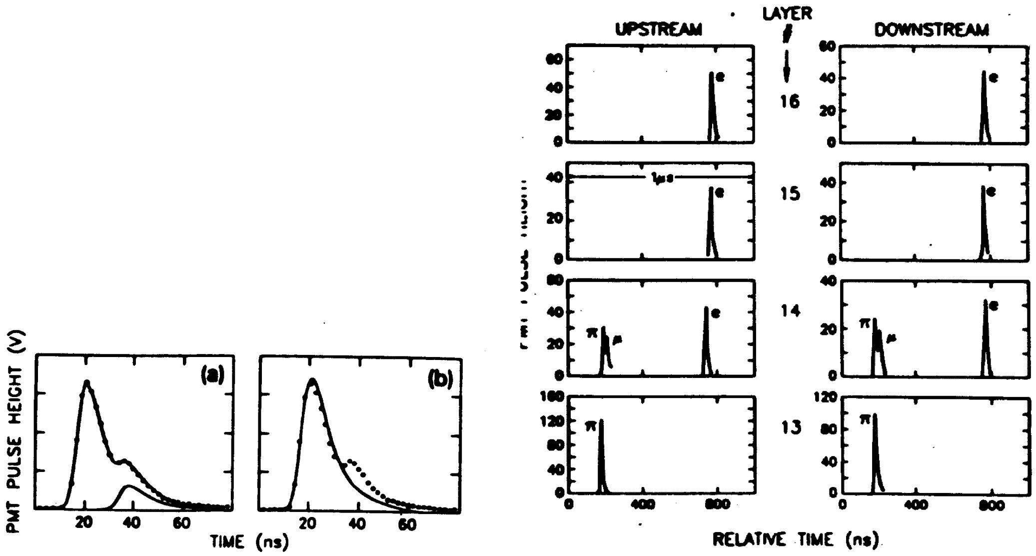

Figure 15: *E787: Pion identification using the PMT pulse shapes of the pion stopping counters: Left: Double pulse signature of stopping pions with an overlayed pulse due to the pion decay* $\pi^+ \to \mu^+\nu$*. a) Fit to two pulses, b) fit to one pulse. Right: Observation of the subsequent muon decay* $\mu^+ \to e^+\nu\overline{\nu}$ *in four adjacent range stack layers.*

E787 is also searching for the the rare kaon decay $K^+ \to \pi^+\gamma\gamma$ and published limits on the decays[12]

$$B(\pi^0 \to \gamma X) < 5.0 \cdot 10^{-4} \quad 90\ \%\ CL$$
$$B(\pi^0 \to \nu\overline{\nu}) < 8.3 \cdot 10^{-7} \quad 90\ \%\ CL$$

E787 underwent considerable upgrades in the last three years, replacing or upgrading virtually every subdetector except the barrel veto: A new target has been built (less dead material and higher light yield) and a new drift chamber. The range stack segmentation readout has been increased and the lead scintillator endcap has been replaced with pure CsI crystals. The experiment had its first engineering run in the new configuration in summer 1994. With the upgraded detector a single event sensitivity of 10^{-10} should be reached and the first $K^+ \to \pi^+\nu\overline{\nu}$ events might be seen.

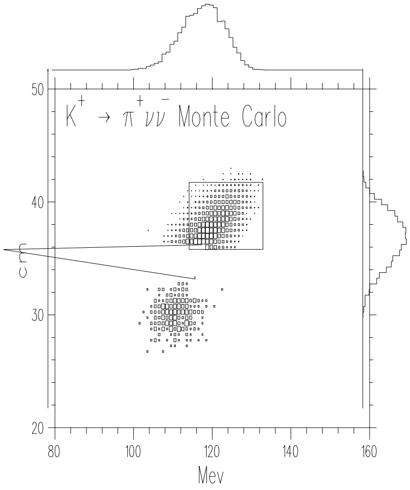

Figure 16: *E787: Range vs energy of* π^+ *from* $K^+ \rightarrow \pi^+\nu\overline{\nu}$*. Left: data , right: Monte Carlo.*

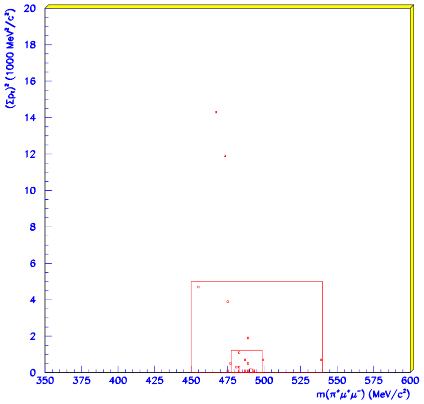

Figure 17: *E787:* $K^+ \rightarrow \pi^+\mu^+\mu^-$*: Effective three body mass versus sum of the transverse momentum squared for the final candidates. 13 candidates are found in the signal region(inner box).*

5 Conclusion

The Brookhaven rare kaon decay program, launched 10 years ago, has successfully completed a first phase, pushing limits on rare kaon decay to the $10^{-9} - 10^{-11}$ level. Considerable upgrades were done in the last three years with the goal to take full advantage of the AGS booster and to pushing down these limits by at least another order of magnitude The future of high energy physics program at the AGS is currently unclear. The RHIC collider (relativistic heavy ion collider) comes into operation in 1999. However RHIC is designed to coexist with the high energy physics operation of the AGS and there is thus a great potential for future experiments waiting to be realized.

References

[1] Littenberg, Valencia, Annu. Rev. Nucl. Part. Sci. **43** (1993) 729.

[2] Ritchie, Wojcicki, Rev. Mod. Phys., **65** (1993) 1199.

[3] Kobayashi, Maskawa, Prog. Theor. Phys. **49** (1973) 652.

[4] Arisaka et al, Phys. Rev. Lett. **70** (1993) 1049.

[5] submitted to PRL

[6] Arisaka et al., Phys. Rev. Lett. **71** (1993) 3910

[7] Lee et al, Phys. Lett. **64** (1990) 165.

[8] Ecker et al, Nucl. Phys. **B291** (1987) 692.

[9] Alliegro et al, Phys. Rev. Lett. **68** (1992) 278.

[10] Deshpande et al., Phys. Rev. Lett. **71** (1993) 27.

[11] Atiya et al., Nucl. Inst. Meth. **A321** (1992) 129.

[12] Atiya et al., Phys. Rev. Lett. **69** (1992) 733.