Rare Kaon and Pion Decays:
Incisive Probes for New Physics Beyond the Standard Model

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Abstract

The current status and future prospects of rare kaon and pion decay research programs are reviewed. Our emphasis is on experimental probes of new physics beyond the Standard Model via the theoretically pristine $K \to \pi\nu\bar{\nu}$ decays and precision tests of electron-muon universality. These studies test the Standard Model at the level of its quantum loop predictions and have the potential to uncover new interactions beyond the $\mathcal{O}$(1000 TeV) scale.

Introduction

For more than six decades, kaon and pion studies have played leading roles in revealing the secrets of elementary particle physics [1]. Indeed, the concept of hadronic "flavor" has its roots in the associated production of kaons with other "strange" mesons and baryons. That phenomenon required the introduction of a nearly conserved new quantum number, hypercharge (now better known as "strangeness"). Strangeness combined with isospin brought us SU(3) flavor symmetry and the "eightfold way". Later, the quark model and even quantum chromodynamics (QCD), a complete gauge theory of strong interactions, emerged from these early flavor physics studies.

In the case of weak interactions, important insights were also gained from kaons and pions. The stimulus for Lee and Yang's parity violation conjecture [2] came from the $\theta - \tau$ puzzle in $\mathrm{K} \to 2\pi$ and 3π decays. (Why should final states with different parities come from the same parent?) Today, parity violation is routinely accepted as a left-right asymmetry of weak interactions and readily accommodated by the structure of the Standard Model's (SM) $SU(2)_L \times U(1)_Y$ electroweak gauge symmetry. Nevertheless, parity violation remains a fundamental deep mystery, yet to be fully understood. Why is Nature left-handed? Theoretical predictions and experimental measurements of the $\pi \to e\nu / \pi \to \mu\nu$ branching ratio were instrumental in the validation of the V-A theory of the weak interactions.

Even null results in K decay studies provided new insights. For example, the observed absence of weak flavor-changing neutral current (FCNC) decays such as $K^+ \to \pi^+\nu\bar{\nu}$, $\mathrm{K_L} \to \mu^+\mu^-$ and $\mathrm{K} \to \pi\, e^+e^-$ motivated the development of the Glashow-Iliopoulos-Maiani (GIM) mechanism and the introduction of charm. The discovery of charm in 1974 revolutionized elementary particle physics and helped establish the SM. Today, the focus of rare kaon studies is searching for new physics and the state-of-the-art sensitivity is $\mathrm{O}(10^{-13})$; branching ratios of $O(10^{-8})$ such as $\mathrm{K_L} \to \mu^+\mu^-$ are considered only moderately rare and can be studied with very high statistics (thousands of events) .

A special feature of the $\mathrm{K}^0 - \overline{\mathrm{K}^0}$ system, $\Delta S = 2$ mixing, gave rise to $\mathrm{K_L}$ and $\mathrm{K_S}$, nearly degenerate states with very different lifetimes arising from their CP properties. This unique system allowed CP violation to be discovered in $\mathrm{K_L} \to 2\pi$ decays [3]. To explain the "mystery" of CP violation, Kobayashi and Maskawa (KM) proposed the enlargement of 4-flavor Cabibbo mixing to include a 3rd generation of quarks, top (t) and bottom (b) that were subsequently discovered. After absorbing all relative phases, 3 generation quark mixing requires a 3×3 unitary matrix with 3 angles and a CP violating phase shown in equation (1).

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} ;\ where \begin{pmatrix} s_{ij} = \sin\theta_{ij} \\ c_{ij} = \cos\theta_{ij} \end{pmatrix} \tag{1}$$

This enlarged "CKM" mixing accommodates all observed CP violating effects in K and (more recently) B meson decays. In fact, all CP violation must be proportional to the Jarkslog invariant [4]

$$\mathrm{J_{CP}} = \frac{1}{8}\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta \tag{2}$$

which is $J_{CP} \sim 3\text{x}10^{-5}$. The CKM paradigm represents an elegant, yet unexpectedly simple solution to the mystery of CP violation. Is this the final word? Not likely. In fact, new interactions with additional CP violating phases are highly motivated. This conviction stems from a need to explain the observed matter-antimatter asymmetry of the universe, a feature at the heart of our existence. If "New Physics" sources of CP violation exist, they may be observable in places where SM predictions are unobservably small (such as electric dipole moments) or by comparing K and B CP violating effects with high precision and looking for deviations from CKM expectations. Even though CKM mixing provides an elegant solution to CP violation, it leads to a deeper question: "Why are there 3 generations of quarks and their partner leptons?" Might there be a heavy fourth generation? What is the origin of the observed pattern of quark masses and mixing? The more we learn, the more profound the questions become.

What more can we expect to uncover from rare K and π decays? Experiments can certainly attain unprecedented statistics and sensitivity by employing intense meson production facilities; but, have rare decay flavor studies become passé, left behind by the high energy frontier of the Large Hadron Collider (LHC)? In this article, we address this issue by reviewing selected current rare decay experiments and discussing future possibilities. We frame our discussion in terms of SM expectations and "New Physics" effects. As we shall demonstrate, rare K and π decay studies are competitive with and in many cases surpass in sensitivity other experimental searches for "New Physics". Some examples of the types of "New Physics" that could be uncovered include heavy 4th generation quark mixing, super-symmetric loop effects, dynamical symmetry breaking, multi-Higgs, and extra dimensions, a broad and well motivated set of scenarios.

In the case of rare K decays, a continuous program of ongoing experiments has existed for many years and future initiatives promise significant advances. We emphasize the particularly well motivated measurements of the very rare $O(10^{-11})$ "golden" decays $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$. Their predicted SM branching ratios carry little theoretical uncertainty and are very sensitive to "New Physics," with capabilities of exploring short-distance scales beyond $O(1000 TeV)$! Indeed, considerable theoretical effort has gone into refining the SM predictions. Multi-loop QCD corrections [5] as well as electroweak radiative corrections and m_d-m_u isospin violating effects [6] have been computed. Most recently [7], leading two-loop electroweak corrections have been improved, thereby reducing the electroweak theory uncertainty in $K \to \pi\nu\bar{\nu}$ to below 1%. The SM prediction now stands at [8]

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (8.22 \pm 0.69 \pm 0.29) \times 10^{-11} \tag{3}$$

$$B(K_L \to \pi^0 \nu\bar{\nu}) = (2.57 \pm 0.37 \pm 0.04) \times 10^{-11} \tag{4}$$

where the first error stems from CKM parameter uncertainties (which will be further reduced in time) while the second error describes remaining theory input uncertainties.

Numerous new physics contributions [9] to $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$ have been considered including supersymmetry, minimal flavor violation, little Higgs models, among many others. The potential power of the predictions in equations (3) and (4) can be illustrated by considering the appendage of a "new physics" amplitude (M_{NP}) [1]

$$M_{NP} = \frac{4\pi}{\Lambda^2} \; C\bar{d}_L\gamma_\alpha s_L \bar{\nu}\gamma^\alpha \nu \tag{5}$$

to the SM with scale Λ the scale of new physics, for *Re(C) ~ Im(C) ~ O(1)*, a 10% measurement of $K^+ \to \pi^+\nu\bar{\nu}$ or $\mathrm{K_L} \to \pi^0\nu\bar{\nu}$ would probe Λ ~ *O*(3000 TeV), well above LHC capabilities. Of course $\mathrm{K_L} \to \pi^0\nu\bar{\nu}$ has the added bonus of potentially unveiling a new source of CP violation via *Im(C)* in equation (5) measured through a discrepancy of $\mathrm{J_{CP}} = 5.6[\mathrm{BR}(\mathrm{K_L} \to \pi^0\nu\bar{\nu})]^{1/2}$ [1] with $\mathrm{J_{CP}}$ determined from B physics studies.

In this review our principal emphasis for pions is on testing electron-muon universality via the ratio

$$\mathrm{R}^{\pi}_{e/\mu} \equiv \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} \tag{6}$$

predicted [10,11,12,13] to about ±0.02% uncertainty in the SM and for which ongoing experiments are aiming to approach similar sensitivities. We discuss examples of "New Physics" at scales as high as 1000 *TeV* constrained by or conceivably unveiled by that ratio. Other measures of electron-muon current universality have been obtained from various processes [14,15] including tau decay branching ratios [16] and $K \to \pi l \nu$ decays where $l = e, \mu$ [17].

In the case of K decays, an analogous ratio to (6)

$$\mathrm{R}^{K}_{e/\mu} \equiv \frac{\Gamma(\mathrm{K} \to e\nu(\gamma))}{\Gamma(\mathrm{K} \to \mu\nu(\gamma))} \tag{7}$$

can probe similarly high scales and has the added appeal of being particularly sensitive to the lepton flavor violating $\mathrm{K}^+ \to e^+\nu_\tau$ decay which might be induced through loop effects [18]. Other rare pion and kaon decays, reactions such as $\pi^0 \to \nu\bar{\nu}$, $K_L^0 \to \mu e$, and $\pi^0 \to \mu\bar{e}$ are expected to have tiny SM rates and current limits constrain anomalous neutrino couplings and lepton flavor violation couplings. The goal of this review is to describe selected ongoing experiments and future initiatives in rare K and π decays that have great potential to probe the SM at very high mass scales, far beyond the reach of the LHC.

Experimental study of rare kaon decays

Advanced rare-decay kaon experiments have probed branching fractions in the $10^{-11} - 10^{-12}$ range including the rarest particle decay ever observed, $\mathrm{B}(\mathrm{K_L} \to e^+e^-) = 9\mathrm{x}10^{-12}$ [19] and the discovery [20] of the long sought process $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$. These measurements were achieved with 20-50 kW of "slow extracted" proton beam power from proton synchrotrons at BNL and Fermilab. Current experiments at J-PARC and CERN aim to reach the SM level of sensitivity for $K_L^0 \to \pi^0\nu\bar{\nu}$ and improve the measurement of $K^+ \to \pi^+\nu\bar{\nu}$ by an order of magnitude, respectively. Next-generation experiments at

Fermilab will aim at the 1000-event SM level for the $K \rightarrow \pi\nu\bar{\nu}$ processes, requiring branching fraction sensitivities at the 10^{-14} level; the continuous beam from the proposed "Project-X" accelerator at Fermilab [21] will facilitate balancing the competing requirements of high rates necessary to reach ultra high sensitivity in a finite time and the losses incurred due to accidental effects. Here, the status and future prospects of the most promising rare kaon experiments and initiatives are discussed.

Experimental study of $K^+ \rightarrow \pi^+\nu\bar{\nu}$

The E787 experiment at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron (AGS) reported evidence of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ in 1997 [20] with a rate of $B(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 42^{+95}_{-35}\, x10^{-11}$ followed by the BNL E949 experiment [22] which reported a combined E787/E949 result of $B(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 17.3^{+11.5}_{-10.5}\, x10^{-11}$ in 2008 based on the observation of a total of seven events. This can be compared to the SM prediction [9] $B(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (8.22 \pm 0.69 \pm 0.29)\times 10^{-11}$.

E787 and E949 represented the culmination of a long series of experiments using stopped kaons [23,24,25]. Today the CERN experiment NA62 [26] is pursuing the next step beyond discovery with a promising new technique driven by the SPS proton facility which aims for 100-event sensitivity at the SM level. The proven techniques developed at the AGS could further be exploited with the Fermilab accelerator complex to ultimately reach 1000-event sensitivity. These experimental programs will be discussed in turn.

BNL experiments E787 and E949

The BNL E787 and E949 experiments were driven by ~40kW of 24 GeV protons from the AGS that impinged on a platinum target. A magnetic channel selected 700 MeV/c particles which were filtered with electrostatic separators to establish a 700 MeV/c K^+ beam which was 70% pure [27]. This low energy separated K^+ beam was transported to a stopping target illustrated in figure 1 where 20% of the kaons in the beam stopped and decayed with the characteristic lifetime of 12 nsec. The basic experimental principle for these experiments was to measure as much as possible about the incident K^+ and the decay π^+ which are the only observable particles and assure that no extra particles occurred simultaneously. Each kaon was identified, tracked, and had its energy measured. For pions the momentum (p) , energy (E), depth in a range stack (R),and the entire $\pi \rightarrow \mu \rightarrow e$ decay sequence were determined with large solid angle detector systems surrounding the stopping target illustrated in figure 1. Suppression of muons due to $K^+ \rightarrow \mu^+\nu(\gamma)$ decays was crucial; combined particle identification from the observation of the $\pi \rightarrow \mu \rightarrow e$ decay sequence and relative kinematic tests resulted in a suppression factor $> 10^6$ for muons. The region of phase space with the charged track momentum above the two body $K_{\pi 2}$ peak illustrated in figure 2 was the principal measurement region in which potential backgrounds from other kaon decays could be confidently eliminated; a lower region of phase space was more problematic due to additional background sources from pion interactions [22].

The fully active stopping target constructed with scintillating fibers tracked the entrance of the incident K^+ and the decay π^+ as illustrated in figure 1. The decay π^+ momentum was measured with a precision of σ_p=2.3 MeV/c in a low-mass tracking system [28] and the energy and range measured with a range stack with precisions σ_E= 3.0 MeV and σ_R = 0.9cm respectively [22] illustrated in figure 1 . The systems that exhaustively measured the decay π^+ were surrounded by a virtually 100% hermetic photon veto system to reject photons from $K^+ \rightarrow \pi^+\pi^0$ backgrounds. E949 upgraded the photon veto coverage and achieved the highest photon detection performance of any previous experiment, measuring an inefficiency for π^0 of <5x10^{-7} . The combined seven candidate events observed in E787 and E949 are shown in figure 2.

The future CERN program to measure $K^+ \to \pi^+ \nu\bar{\nu}$

The NA62 collaboration proposes [26] to measure the $K^+ \to \pi^+ \nu\bar{\nu}$ process with a sensitivity of 80 SM events with less than 10% background. The NA62 proposal benefits from the succession of experiments at the CERN North Area (NA) that have culminated in the precision measurement of the $K^+ \rightarrow e^+\nu$ decay. The NA62 collaboration is now preparing the detector to measure $K^+ \to \pi^+ \nu\bar{\nu}$ using decay in-flight techniques with the apparatus shown in figure 3. The NA62 design also benefited from developments for the "Charged Kaons at the Main injector" (CKM) Fermilab proposal [29]. The in-flight approach focuses on the lower region of phase space, may have higher $\pi^0 \rightarrow \gamma\gamma$ detection efficiency than the stopped K^+ technique, and does not require tagging the $\pi \rightarrow \mu \rightarrow e$ decay chain which could permit operating in a higher rate environment.

The CERN Superconducting Proton Synchrotron (SPS) will drive the NA62 experiment with 400 GeV protons. In common with the stopping K^+ experiments the NA62 initiative relies critically on high resolution timing, kinematic rejection, particle identification, hermetic vetoing and redundancy of measurements. To realize the necessary sensitivity with an in-flight technique NA62 plans to: perform low-mass tracking of the incident un-separated beam with a ~1 GHz total rate, 40 MHz/cm^2, achieve positive kaon identification in this high rate environment by means of a differential Cherenkov counter insensitive to pions and protons with minimal accidental mis-tagging, achieve a muon rejection of at least 10^5 with a sampling hadron calorimeter, achieve two or more standard deviation π/μ separation up to 35 GeV/c momentum with a Ring Imaging Cherenkov (RICH) counter system, and veto the charged particles originating from three and four-body kaon decays. Initial running in the $K^+ \to \pi^+ \nu\bar{\nu}$ configuration is expected 2012-2013 followed by what is estimated to be a two year exposure to reach a sensitivity of 80 SM events.

Experimental pursuit of $K_L \to \pi^0 \nu\bar{\nu}$

The first dedicated experiment in pursuit of this process was KEK E391a which recently established [30] a limit <2.6 x10^{-8} at the 90% confidence level compared the SM prediction [9] of $B(K_L \to \pi^0 \nu\bar{\nu}) = (2.57 \pm 0.37 \pm 0.04)\times 10^{-11}$. Measuring this highly suppressed process at the SM level requires very intense kaon sources and is a driver of the J-PARC research program in Japan. The KOTO experiment at JPARC is pursuing $K_L^0 \to \pi^0 \nu\bar{\nu}$ discovery with an initially proposed sensitivity of a few events at the SM level; a higher sensitivity experiment is planned for the future. The very high beam power available with the Project-X [21] evolution of the Fermilab complex allows consideration of experiments with much higher sensitivity, at the 1000-event level in the SM. Pursuit of this challenging measurement is complicated by the fact that all particles in both the initial and final states are neutral and consequently difficult to detect. The current state of the art in E391a and the prospects of the KOTO experiment and Project-X experiments will be discussed in turn.

KEK E391a

The signature of the $K_L \to \pi^0 \nu\bar{\nu}$ decay in the E391 detector is two and only two photons with relatively large total transverse momentum. Major backgrounds sources include π^0's that are produced by neutrons outside the beam interacting with detector materials and $K_L \to \pi^0\pi^0$ decays where two out of four photons escaped detection. Thus, the experiment has to have a neutral beam line with a minimum amount of halo (particles outside the beam) and hermetic coverage of the decay region to assure that there are only two photons from the decay.

Kaons were produced by 12 GeV protons impinging on a platinum rod and extracted at an angle of 4 degrees with respect to the primary proton beam. The typical intensity was $2.5x10^{12}$ protons/pulse every four seconds with a spill duration of two seconds. The kaon beam solid angle was conical and formed with six stages of collimation. The beam size at the calorimeter described later was 7 cm in diameter (12.6 μstr). The small beam size was chosen to suppress the background caused by photons escaping through a beam hole in the calorimeter, and to keep a good resolution on the transverse momentum of the π^0 in later analysis. The K_L momentum spectrum was peaked at 2GeV/c at 10 m from the target.

The E391a detector system was located between 12 m and 23 m from the target. Figure 4 shows an elevation view of the detector system. The detector components were arranged to surround a 1.6 m long decay region. The energy and hit position of the photons from the decays were measured with an electromagnetic calorimeter made of 496 pure CsI crystals stacked inside an 1.9 m diameter cylinder. The front face of the CsI calorimeter was covered by plastic scintillator counters (CV) to identify events with charged particles. Photons escaping the calorimeter were detected by a photon veto system surrounding the decay volume. The calorimeter had a (12 cm x 12 cm) beam hole at the center to let the neutral beam pass through. Photons that passed through the beam hole were detected with a beam-plug counter (BA). The decay region was evacuated to $1x10^{-5}$ Pa to reduce the π^0 backgrounds produced by beam-gas interactions. Most of the detector components were placed inside a vacuum tank instead of outside; this suppressed backgrounds caused by photons being absorbed inside the vacuum tank wall, escaping detection.

The experiment ran in three periods in 2004-2005. Figure 5 shows the scatter plot of P_T *vs* the reconstructed vertex position along the beam (Z_{vtx}) for the events with all the selection cuts imposed. The signal region was defined to be $0.120 < P_T < 0.240$ GeV/c, and $340 < Z_{vtx} < 500$ cm in the scale shown in figure 5. The number of background events inside the signal box was predicted to be 0.87 +/- 0.41 based on Monte Carlo simulation and the number of events outside the signal box. These background events were dominated by π^0 s and η's produced by halo neutrons, and the contribution of $K_L \to \pi^0\pi^0$ decay was $(2.4 +/- 1.8)x10^{-2}$ events. No events were found inside the signal box. This set an upper limit on the $K_L \to \pi^0 \nu\bar{\nu}$ branching ratio to be $< 2.6x10^{-8}$ at the 90% confidence level.

The future $K_L \to \pi^0 \nu\bar{\nu}$ experiment in Japan (KOTO)

The KOTO experiment is based at J-PARC, which is a new high intensity proton accelerator research complex in Japan designed to deliver 2×10^{14} protons at 30 GeV every 3.3 sec. The complex began operation in 2009, and is gradually increasing beam intensity to users. The concept of the KOTO experiment is based on KEK PS E391a with several improvements of beamline and detector components. At J-PARC the 30 GeV proton beam impinges on a single target shared by multiple secondary beam lines. A neutral K_L beam-line is at formed 16^o with respect to the incident proton beam. The KOTO beam-line was redesigned to reduce the neutron halo/core ratio to 3×10^{-5}, one order of magnitude smaller than KEK E391a. Based on GEANT simulation studies the number of collimators was reduced to just two and the beam aperture is determined by only three surfaces thereby minimizing the rate of scattered neutrons out of the beam and into the detector. The beam-line was constructed in 2009, and the beam shape and halo component were measured to be consistent with the GEANT simulation, and the kaon yield was also measured in the 2009 run to be x2.3 higher than assumed in the KOTO proposal. The pure CsI calorimeter has been substantially improved with respect to E391a by incorporating the longer and smaller transverse-size crystals from the Fermilab KTeV experiment [31].

In order to cope with the higher KOTO beam intensity and reject accidental activity, all detector element analog waveforms are sampled at 125 MHz with a system that provides both large dynamic range (14 bits) and excellent timing performance (<1 nsec). Decay photons that escape through the calorimeter beam hole are tagged with very high-speed detector modules located inside the neutral beam. The beam-hole tagger is built from modules that consist of a lead plate followed by an aerogel Cherenkov counter. The electron pairs produced by incident photons leave hits in multiple modules, which is less likely for pions produced by neutrons. The detection inefficiency of the beam-hole system is expected to be less than 10^{-3} for photons with energies larger than 2 GeV.

In 2010 KOTO performed an engineering run with 60% of the calorimeter in place which was characterized with momentum-analyzed electrons. In 2011 the experiment plans to complete the calorimeter, install remaining detector elements, and initiate collection of production data. The experiment will initially collect one month of data at 10% of the nominal beam intensity which will be sufficient to probe rates at Grossman-Nir limit [32] above which the $K_L \to \pi^0 \nu\bar{\nu}$ rate is excluded through a model-independent interpretation of the measured $K^+ \to \pi^+ \nu\bar{\nu}$ rate. Beyond KOTO the collaboration is now exploring a following experiment to collect several hundred SM events. Techniques being considered now are a new optimized beam line extracted at 5 degrees from a new target station to increase the kaon yield, and increasing the size of the decay volume and the calorimeter.

Evolution of the Fermilab accelerator complex:

The existing Fermilab accelerator complex has sufficient beam power to take an important step forward in $K^+ \to \pi^+ \nu\bar{\nu}$ sensitivity. A next-generation of the successful BNL E787/E949 experiments has been proposed [33] employing Fermilab accelerators in a post-collider era to produce a proton source suitable for low energy kaon decay experiments. The centerpiece of the long term future Fermilab plan is a very high power 3-MW 3-GeV continuous beam proton source with 100% duty factor referred to as Project-X [21] which can simultaneously provide multi-megawatt beam power to long-baseline neutrino experiments and a campus of rare process experiments.

The high sensitivity kaon programs at the BNL AGS and underway now at JPARC and CERN are driven with relatively high energy proton beams which optimize kaon yields with high-Z thick targets (e.g. Pt) where secondary interactions increase kaon yields by up to 30%. Next generation experiments driven with Project-X (T_p= 3.0 GeV) beams are suited to low-Z targets, such as carbon which has high kaon transparency, low spallation neutron yield, and excellent thermal properties for high beam power management. The LAQGSM/MARS (MARS15) simulation framework for particle production has recently improved modeling of the challenging T_p region of 1-4 GeV [34,35,36] . Kaon production in this simulation is treated as a sum of well measured exclusive channels with little tuning. The simulations have been benchmarked against high quality data sets from the COSY facility [37] and one such benchmark in excellent agreement is shown in figure 6.

The estimated kaon yield at constant beam power (yield/T_p) is shown in figure 7. The yield on carbon saturates at about 5 GeV, and the T_p = 3.0 GeV yield is about a factor of about x2 less than the peak yield in the experimentally optimal angular region of 17-23 degrees chosen to mitigate the high forward flux of pions and neutrons. The 3 MW beam power of Project-X more than compensates for the unsaturated yield point which is a compromise between accelerator cost and particle yield. Future $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ experiments at Project-X could be served from the same production target, similar to the strategy employed in the JPARC hadron hall.

Considerations for a Project-X $K^+ \to \pi^+ \nu\bar{\nu}$ Experiment

The BNL E787/E949 [22] program previously discussed was the culmination of a series of experiments where high flux low-energy K^+ beams were transported to a target, stopped, and subsequently decay. The beam that impinges on the stopping target must be primarily kaons in order to control detector rates. Achieving high beam purity requires a separator system to remove the overwhelming pion component. Balancing the lifetime of K^+ ($\beta\gamma c\tau \sim 3.5$ m) with the practical minimal length of a separator system (~14m) optimizes the separated beam momentum in the 400-600 MeV/c range which is maximally produced on carbon at Project-X energies as illustrated in 6.

Recent studies [33,38] suggest that the rate capability and acceptance of stopped K^+ technique can be further improved over BNL E787/E949 with straightforward detector upgrades and by lowering the kaon momentum on the stopping target from 710 MeV/c used at BNL to about 500 MeV/c. This stopping K^+ source at Project-X would be 100 times brighter than the BNL E949 experiment enabling a very high statistics (>1000 SM events) experiment which can precisely determine both the rate and form-factor of the $K^+ \to \pi^+ \nu\bar{\nu}$ process. Although the useful kaon rate is significantly greater than at BNL, the ideal timing and energy aspects of the Project-X beam results in comparable instantaneous rate in the detector thereby maintaining an acceptable level accidental activity. The Project-X experiment requires a proton beam pulse train frequency of 20 MHz or greater which is comfortably within the bandwidth of the proposed proton linac. The excellent timing of proton pulses (< 50 psec) within the pulse train may be exploited to improve the pion rejection from the beamline, which will be required to contend with the estimated 4 time higher pion flux per kaon from the production target.

Considerations for a Project-X $K_L \to \pi^0 \nu\bar{\nu}$ Experiment.

The KOPIO initiative at the BNL AGS [39] (which was not realized) proposed to measure the

$K_L \to \pi^0 \nu\bar{\nu}$ process with a SM sensitivity of 100 events which required about 10,000 hours of upgraded BNL AGS proton beam (100 x 10^{12} 24 GeV protons every 5 seconds on target). In the KOPIO technique, the kaon momentum is determined by Time-Of-Flight in the 300-1200 MeV/c momentum range, to suppress dominant backgrounds from $K_L^0 \to \pi^0\pi^0$ decays in which two photons are unobserved. The neutral beam incident on the KOPIO detector was designed with a large targeting angle ($\theta = 42^0$) from the production target in order to produce the low momentum neutral kaons critical to the TOF strategy of the experiment illustrated in figure 8. The KOPIO K_L beam had an average kaon momentum of 800 MeV/c with ~1000 neutrons (E_n>10 MeV) for every K_L in the beam acceptance which requires that the beam propagate through an excellent vacuum.

This approach is well matched to the Project-X kaon momentum spectrum shown in figure 6. The high-precision timing properties of Project-X continuous wave (CW) proton linac technology provide experimental tools (time-of-flight (TOF) techniques) to strengthen the experimental signature and reject background processes to the required level. The projected TOF performance of KOPIO at the AGS was limited by achievable proton beam bunching of the AGS of about 250 psec. The Project-X beam pulse timing, including target time slewing, is expected to be less than 50 psec which would substantially improve the momentum resolution and background rejection capability of the $K_L \to \pi^0 \nu\bar{\nu}$ experiment driven with Project-X beam illustrated in figure 8.

The AGS K_L/p yield from 24 GeV protons is 20 times the Project-X K_L/p yield for 3.0 GeV protons. Project-X compensates this relative yield with a proton flux that is x150 the AGS KOPIO goal of 100x10^{12} protons every 5 seconds. Hence the Project-X neutral kaon flux into the nominal KOPIO beam acceptance is x8 the AGS kaon flux. A nominal five-year Project-X run is x2.5 the duration of the KOPIO AGS initiative and hence the reach of a Project-X $K_L \to \pi^0 \nu\bar{\nu}$ experiment is 20 times the reach of the KOPIO goals.

A TOF-based $K_L \to \pi^0 \nu\bar{\nu}$ experiment driven by Project-X would need to be re-optimized for the Project-X K_L momentum spectrum, TOF resolution, and corresponding background rejection. It is probable that this optimization would be based on a much smaller neutral beam solid angle which greatly simplifies the detector design, increases the acceptance, and relaxes the requirement to tag photons in the fierce rate environment of the neutral beam. Optimizing the TOF performance will likely require a proton pulse train frequency of 20-50 MHz and an individual proton pulse timing < 50 psec. The very high K_L beam flux, the potential of break-through TOF performance, and improvements in calorimeter detector technology support the plausibility of a $K_L \to \pi^0 \nu\bar{\nu}$ experiment with ~1000 SM event sensitivity.

Testing electron-muon universality with precision π and K decay measurements

Electron-muon universality, within the content of the SM, refers to the fact that charged leptons have identical electroweak gauge interactions. They differ only in their masses and coupling to the Higgs mechanism, including the yet to be discovered neutral physical Higgs scalar remnant of electroweak symmetry breaking. Of course, there could be additional "New Physics" effects, such as non-universal gauge interactions or scalar (pseudoscalar) bosons with couplings not simply proportional to the lepton masses. If so, they might unveil themselves as deviations from SM expectations in high precision universality tests and help explain the large disparity, $m_\mu \approx 206 m_e$, in lepton masses. Perhaps, they may even answer Rabi's famous question regarding the muon "Who ordered that?" A question that can be similarly posed for the entire second and third generations of fermions.

One of the most precise tests of charged-current electron-muon universality is the pion leptonic rate ratio in equation (6), where the decay ratio is fully radiative inclusive, i.e. including all hard and soft bremsstrahlung (and in principle e^+e^- pairs). In lowest order this ratio is

$$R_0^\pi \equiv \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 = 1.28336(2)\times 10^{-4} \qquad (8)$$

where the PDG value $m_{\pi^+} = 139.57018(35) MeV/c^2$ is used. (Note, that a more current pion mass has reduced R_0^π compared to earlier studies which used $R_0^\pi = 1.28347\times 10^{-4}$) The small size of R_0^π is a result of pseudoscalar decay amplitudes being helicity suppressed.

Electroweak radiative corrections to $\Gamma(\pi \to l\bar{v}_l)$, $l = e, \mu$ are finite and calculable when expressed in terms of renormalized SM parameters; but they have some degree of hadronic uncertainty, much of which cancels in the ratio $R_{e/\mu}^\pi$. Indeed, one finds

$$R_{e/\mu}^\pi = R_0^\pi\left[1 + \frac{\alpha}{\pi}\left\{F\left(\frac{m_e}{m_\pi}\right) - F\left(\frac{m_\mu}{m_\pi}\right) + \frac{m_\mu^2}{m_\rho^2}\left(3.1\ln\frac{m_\rho^2}{m_\mu^2} + C_3\right) + 3.4\frac{m_\pi^6}{m_e^2 m_\rho^4}\right\} + \frac{7}{2}\left(\frac{\alpha}{\pi}\ln\frac{m_\mu}{m_e}\right)^2 + \ldots\right] \qquad (9)$$

where the rho mass, $m_\rho = 768\ MeV/c^2$, parameterizes hadronic structure effects not cancelled in the ratio.

The $O(\alpha)$ $F(x)$ function was calculated in the pioneering work of Kinoshita [11]. It corresponds to the full one loop corrections for a point (structureless) pion and is relatively large, giving rise to a -3.929% correction to R_0^π. The leading structure dependent virtual contributions $3.1\frac{\alpha}{\pi}\frac{m_\mu^2}{m_\rho^2}\ln\frac{m_\rho^2}{m_\mu^2} \cong 5.4\times 10^{-4}$ was first calculated by Terentev [40] using PCAC techniques and confirmed in [12]. The model dependent C_3 was most recently computed by Cirigliano and Rosell [13] using Chiral Perturbation Theory. The calculation corresponds to $C_3 = -0.9 \pm 2.5$ which leads to a $-0.004(11)\%$ correction. The effect is small but the uncertainty estimate is important. The final $O(\alpha)$ correction enhanced by m_e^{-2} comes from structure dependent hard bremsstrahlung corrections to $\Gamma(\pi \to e\bar{\upsilon}_e\gamma)$ which are not helicity suppressed. They amount to a $+0.064\%$ correction. Finally, the leading log 2 loop, $O\left(\alpha^2\ln^2\left(\frac{m_\mu}{m_e}\right)\right)$ term in equation (8) was computed in [12]. It gives a $+0.054(10)\%$ shift in R_0^π. A $\pm 0.01\%$ uncertainty coming from uncalculated two loops $O\left(\alpha^2\ln\left(\frac{m_\mu}{m_e}\right)\right)$ effects is included in the error. Combining the above corrections with (eq. 3) (adding errors in quadrature), one finds

$$R_{e/\mu}^{\pi} = 1.2351(2)\times 10^{-4} \qquad (10)$$

a very precise theoretical prediction. It is to be compared with the current experimental average [41]:

$$R_{\mathrm{exp.}}^{\pi} = 1.230(4)\times 10^{-4} \qquad (11)$$

which is consistent with the SM but has a 20 times larger uncertainty than theory.
Current experiments at TRIUMF and PSI, discussed below, aim to reduce the experimental errors in equation (11) by a factor of 5 or more, bringing it below $\pm 0.1\%$ and thereby approaching the theoretical precision.

Measurements (equation (11)) clearly enforce $e-\mu$ universality and limit longitudinal W boson couplings at about the $\pm 0.16\%$ level, strongly constraining extensions of the SM. To illustrate the reach of this measurement compared to other precision tests, we consider the effect of the following effective 4-fermion V, A, S, and P interactions, presumably coming from short-distance "New Physics" at scale Λ.

$$\mathcal{L}_{NP} = \left[\pm\frac{\pi}{2\Lambda_V^{2}}\bar{u}\gamma_\alpha d \pm \frac{\pi}{2\Lambda_A^{2}}\bar{u}\gamma_\alpha\gamma_5 d\right]\bar{e}\gamma^\alpha(1-\gamma_5)\nu + \left[\pm\frac{\pi}{2\Lambda_S^{2}}\bar{u}d \pm \frac{\pi}{2\Lambda_P^{2}}\bar{u}\gamma_5 d\right]\bar{e}\gamma^\alpha(1-\gamma_5)\nu \qquad (12)$$

Unitarity of the CKM matrix (a test of lepton-quark universality) and measurement [41] of super-allowed nuclear β-decays currently constrains $\Lambda_V \geq 20 TeV$ and $\Lambda_S \geq 10 TeV$; which are indeed outstanding constraints. The current program of experiments at TRIUMF and PSI with a target sensitivity on $R_{\mathrm{exp.}}^{\pi}$ of $\pm 0.1\%$ will probe scales of $\Lambda_P \leq 1000 TeV$ and $\Lambda_A \leq 20 TeV$. Scalar interactions are not directly probed by $R^{\pi}{}_{e/\mu}$; however, new scalar interactions can induce pseudoscalar amplitudes through loop effects. Hence, one finds indirect sensitivity to $\Lambda_S \leq 60 TeV$, well beyond nuclear beta decay capabilities.

Most impressive is the "New Physics" pseudoscalar scale probed, O(1000 TeV) which is well beyond present and foreseeable collider capabilities. That sensitivity comes largely from an enhancement factor of $\frac{m_\pi^{2}}{m_e(m_u+m_d)}$ relative to the SM amplitude with which it interferes. Of course, the actual particle masses probed could be considerably smaller than Λ_P if the "New Physics" amplitude is suppressed by cancellations or small Yukawa couplings. For example, consider the case of a charged physical Higgs boson with couplings $\frac{g}{2\sqrt{2}}\lambda_{ud}$ to the $\bar{u}\gamma_5 d$ pseudoscalar current and $\frac{g}{2\sqrt{2}}\lambda_{l\nu}$ to $\bar{l}(1-\gamma_s)\nu_l$, $l = e, \mu$ where g is the $\mathrm{SU(2)_L}$ gauge coupling and λ represents chiral breaking suppression factors. One then finds

$$R^{\pi}_{e/\mu}(New) = R^{\pi}_{e/\mu}\left[1 - \frac{2m_{\pi}^{2}}{\mathrm{m_e}(\mathrm{m_u}+\mathrm{m_d})}\frac{m_W^{2}}{m_{H^{\pm}}^{2}}\lambda_{ud}(\lambda_{e\nu} - \frac{m_e}{m_{\mu}}\lambda_{\mu\nu})\right] \tag{13}$$

and a $\pm 0.1\%$ measurement of $R^{\pi}_{e/\mu}$ probes

$$\mathrm{m}_{H^{\pm}} \cong 200TeV \times \lambda_{ud}^{1/2}(\lambda_{\mathrm{ev}} - \frac{m_e}{m_u}\lambda_{\mu\nu})^{1/2} \tag{14}$$

If $\frac{\lambda_{\mathrm{ev}}}{\lambda_{\mu\nu}} = \frac{m_e}{m_{\mu}}$, as in the minimal 2-Higgs doublet model, there is no sensitivity to $m_{H^{\pm}}$. In fact, that scenario just corresponds to a sample extended definition of $e-\mu$ universality in the enlarged scalar sector. However, in more general multi-Higgs model such a chiral relationship is not necessary and the λ may not be too suppressed. For example, in the case of loop induced charged Higgs couplings $\lambda_{e\nu} \cong \lambda_{\mu\nu} \cong \lambda_{ud} \cong \frac{\alpha}{\pi}$, one finds $m_{H^{\pm}} \approx 400GeV$ is probed for $R^{\pi}_{e/\mu}$ sensitivity of $\pm 0.1\%$. If a discrepancy between theory and experiment is found in $R^{\pi}_{e/\mu}$, some type of charged Higgs explanation would be quite natural; however, it could also point to additional charged axial-vector interactions or loop effects due to "New Physics." It could also be interpreted as an effect of heavy neutrino mixing damping one of the π_{l2} decay modes.

In the case of $K^{\pm}$ decays, a theoretical study K_{l2} decay rates analogous to the pion study outlined above, recently compiled by Cirigliano and Roswell [13] found

$$R^{K}_{e/\mu} \equiv \frac{\Gamma\left(K^{+} \to e^{+}\nu_e(\gamma)\right)}{\Gamma\left(K^{+} \to \mu^{+}\nu_{\mu}(\gamma)\right)} = 2.477(1) \times 10^{-5} \tag{15}$$

after including virtual hadronic structure effects in the framework of chiral perturbation theory but leaving out structure dependent bremsstrahlung because it is large but relatively insensitive to "New Physics". The latter omission differentiates the inclusive nature of $R^{K}_{e/\mu}$ and $R^{\pi}_{e/\mu}$.

The theoretical uncertainty in $R^{K}_{e/\mu}$ is fractionally larger than $R^{\pi}_{e/\mu}$ but still quite good. It is considerably better than the error on the current experimental average

$$R^{K}_{e/\mu}(\mathrm{exp}) = 2.487(12) \times 10^{-5} \tag{16}$$

which is based on recent results from KLOE [42] and NA62 [43] as discussed below; previous measurements were reported in [44,45,46]. One can use this measurement to obtain bounds on the scale of "New Physics" allowed in strangeness changing 4-fermion amplitudes (similar to equation (12) with d→s).

A strong additional incentive to improve the measurement of $R^K_{e/\mu}(\exp)$ comes from the possibility of lepton number violating loop contributions to the charged Higgs coupling to $e\nu_\tau$ in some super-symmetry scenarios. The added decay mode $K^+ \to e^+\nu_\tau$ would effectively increase the observed $R^K_{e/\mu}(\exp)$ by a fractional amount [10]

$$\frac{\Delta R^K}{R^K_{e/\mu}} \cong \left(\frac{m_{K^+}}{m_{H^+}}\right)^4 \left(\frac{m_\tau}{m_e}\right)^2 |\Delta_3|^2 \tan^6\beta \tag{17}$$

Where Δ_3 is an effective $\tau - e$ coupling and $\tan\beta$ is the potentially large ratio of vacuum expectation values in the super-symmetric 2-Higgs doublet model. That deviation from SM electron-muon universality could be in the $10^{-2} - 10^{-3}$ range and thus observable in future $R^K_{e/\mu}(\exp)$ studies. In fact, even the recent result in (16) is approaching an interesting level of sensitivity. For $R^\pi_{e/\mu}$, the above lepton flavor violating scenario gives rise to $\pi^+ \to e^+\nu_\tau$ and a fractional increase in $R^\pi_{e/\mu}(\exp)$ given by eq. (17) under the replacement $m_{K^+} \to m_{\pi^+}$. Hence, it is expected to be smaller by $\left(\frac{m_{\pi^+}}{m_{K^+}}\right)^4 \approx \frac{1}{150}$; this makes $R^K_{e/\mu}$ a favorable searching ground for such an effect although the higher experimental precision achievable in $R^\pi_{e/\mu}$ is potentially competitive.

Precision measurement of the rare leptonic decay modes: K$^+$→e$^+$ν and π$^+$→e$^+$ν

The most recent π$^+$→e$^+$ν (π_{e2}) branching ratio measurements and subsequent determination of the ratio R (equation (6)) were done at TRIUMF [47]and PSI [48] in the 1990s. The results from the two experiments were consistent and in agreement with the SM expectation previously discussed:

$$\mathrm{R}^{\pi-TRIUMF}{}_{\mathrm{e}/\mu} = 1.2265(34)(44)x10^{-4} \;;\; \mathrm{R}^{\pi\text{-PSI}}_{\mathrm{e}/\mu} = 1.2346(35)(36)x10^{-4} \tag{18}$$

for TRIUMF and PSI respectively, where the first and second uncertainties were due to statistical and systematic effects. The PDG average value is $R^{\pi-\exp t}{}_{e/\mu} = 1.230(4)\times10^{-4}$ [41] including results from [49]; earlier measurements were reported in [48,49,50,51]. Two new experiments are underway at TRIUMF [54] and PSI [55] which aim to improve the precision of $\mathrm{R}^{\exp\pi}_{e/\mu}$ by a factor of 5 or more, thereby confronting the SM prediction to better than ±0.1%. At that level, new physics effects could appear as a deviation from expectations or in the absence of a deviation strong new constraints on new physics hypotheses will be placed. There has been considerable recent activity in measurements of the K_{e2} branching ratio. KLOE at DAΦNE and the ongoing NA48/62 experiment at CERN have both reported new results which are now in the 0.5-1.0% range of precision for $\mathrm{R}^{\exp K}_{e/\mu}$. In the following, we discuss the current experiments measuring $\mathrm{R}^{\exp\pi}_{e/\mu}$ and $\mathrm{R}^{\exp K}_{e/\mu}$.

The TRIUMF *PIENU* Experiment

The new PIENU experiment is a refinement of the technique used in the previous TRIUMF experiment. The branching ratio will be obtained from the ratio of positron yields from the $\pi \rightarrow e\nu$ decay and from the $\pi \rightarrow \mu \rightarrow e$ decay chain. By measuring positrons from the decays $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu \rightarrow e$ in a non-magnetic spectrometer many normalization factors, such as the solid angle of positron detection, cancel to first order and only small energy-dependent effects, such as those for multiple Coulomb scattering (MCS) and positron annihilation, need to be corrected for. Major improvements in precision stem from the use of an improved geometry, a superior calorimeter, high speed digitizing of all pulses, Si strip tracking, and higher statistics.

Figure 9 shows the PIENU experimental setup in which B and T indicate beam pion and positron telescope plastic scintillation counters, respectively. A 75 MeV/c π^+ beam from the improved TRIUMF M13 beam line [54] is tracked in wire chambers (WC), identified by plastic scintillators, and stopped in a 0.8-cm thick scintillator target. Fine tracking near the target is provided by two sets of single-sided (X,Y) silicon-strip counters located immediately upstream and downstream of the target assembly. The positrons from decays $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu\nu$ followed by $\mu \rightarrow e\nu\bar{\nu}$ decay ($\pi \rightarrow \mu \rightarrow e$ decay) are measured in the positron telescope which consists of a silicon-strip counter, two thin plastic counters, and an acceptance defining wire chamber covering the front of the crystal calorimeter described below. The solid angle acceptance of the telescope counters is 20% of 4π.

The primary energy measurement is done using a 48 cm diameter x 48 cm (19 X_0) cylindrical single crystal NaI(Tl) detector (BINA) [56]. In beam tests, BINA has shown excellent energy resolution, approximately 2.2% (FWHM), for incident positrons at 70 MeV [57] which is about a factor of two better resolution than observed in [47]. The detailed shape of the BINA resolution function was also studied and found to contain additional small bumps at low energy due to photonuclear interactions (see [57]). Two layers consisting of 97 pure CsI crystals 8.5-cm-thick, 2x25-cm-long [58] surround the NaI(Tl) crystal to capture shower leakage from BINA.

Analog signals from plastic scintillators (Si-strip, NaI and CsI detectors) are recorded by 500 MHz “Copper” [59] (60 MHz VF48 [60]) digitizers. In order to suppress background levels arising from ‘old’ muon decay signals in the target region and to minimize potential distortions in the time spectrum due to pile-up, the beam rate is kept low at 60KHz incident pions. The branching ratio will be obtained by determining the numbers of events due to $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu \rightarrow e$ decays by simultaneous fitting the time distributions shown in figure 10 in the low-energy (E< 55 MeV) and high-energy (E> 55 MeV) regions.

A potentially dominant source of systematic uncertainty is related to knowledge of the low-energy tail of events due to $\pi \rightarrow e\nu$ decays which hide under the larger $\pi \rightarrow \mu \rightarrow e$ distribution. Suppression of the $\pi \rightarrow \mu \rightarrow e$ events [47] using timing, target energy, and target pulse shape is used to reveal the low-energy tail so that a correction (~1%) can be accurately determined. The majority of remaining low-energy events in the background-suppressed spectrum come from in-flight decays of pions near the target. High precision pion tracking near the target provides additional background suppression. Figure 11 shows a $\pi \rightarrow e\nu$ spectrum with the $\pi \rightarrow \mu \rightarrow e$ component largely suppressed.

A total of $2\mathrm{x}10^7$ or more $\pi \to e\nu$ events will be accumulated in PIENU which is scheduled to run through 2012. With the detailed pulse shape information and reduced background due to pile-up compared to previous experiments, an improvement factor of 30 or more is expected, resulting in a statistical uncertainty of <0.05 % in the branching ratio. The improvements lead to an expected precision on the $\mathrm{R}_{e/\mu}^{\exp\pi}$ branching ratio <0.06 %, which corresponds to a 0.03 % uncertainty in the ratio of the gauge boson-lepton coupling constants g_e/g_μ testing electron-muon universality.

The PSI *PEN* Experiment

At PSI, the PIBETA CsI spectrometer [61] built for a determination of the $\pi^+ \to \pi^0 e\nu$ branching ratio and other measurements [62] has been upgraded and enhanced for the PEN [55] measurement of the $\pi \to e\nu$ branching ratio. The PEN technique is similar to that employed in the previous PSI experiment which used a nearly 4π-sr BGO spectrometer. The principal component of the PEN apparatus shown schematically in figure 12 is a 3π–sr 12 X_0 electromagnetic calorimeter made of 240 pure CsI crystals which has an energy resolution of 12.8% (FWHM) at 66 MeV.

Tracking of outgoing positrons is performed with cylindrical multi-wire proportional chambers (MWPC) and plastic scintillator hodoscope (PH), surrounding a plastic scintillator active target (AT). Beam pions pass through an upstream detector (BC), a position-sensitive wedge active degrader (AD), and stop in the target. A small time projection chamber (mTPC) with position resolution 1-2 mm was added for the 2009-10 run to improve tracking for observing pion decay-in-flight events. Signals from the beam detectors (BC, AD, and AT) are digitized by 2 GS/s waveform digitizers. As described above for PIENU, PEN separates $\pi\to e\nu$ and $\pi\to\mu\to e$ decays with a high threshold calorimeter energy trigger. Positron signals are accepted within a 250 ns gate which starts about 40 ns before the pion stop time. The beam counter waveform digitizer data allows separation of $\pi\to e\nu$ events with two pulses in the target (pion stop and decay positron), from the sequential decay events with three pulses in the target (pion, 4 MeV muon, and positron).

PEN has been in operation since 2007 and has observed $>10^7$ $\pi \to e\nu$ decays. PEN completed data acquisition 2010 and expects to obtain an improved precision measurement of $\mathrm{R}_{e/\mu}^{\exp\pi}$ at the level <0.05%.

Precision measurement of $K \to e\nu / K \to \mu\nu$:

KLOE at DAΦNE

The KLOE group working at DAΦNE have recently reported a measurement of $\mathrm{R}_{e/\mu}^{\exp K}$ [42]. KLOE collected a data set of 3.3 billion K^+K^- pairs, observing decay products in a drift chamber in a 0.52 T axial magnetic filed surrounded by an electromagnetic calorimeter. The momentum resolution for tracks at large polar angle was $\sigma(p_\perp/p_\perp) \leq 0.4\%$ and the energy and time resolutions were $\sigma_E/E \sim 5.7\%/\sqrt{E(\mathrm{GeV})}$ and $\sigma_T = 54\ \mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 140\ \mathrm{ps}$, respectively. In the measurement of $\mathrm{R}_{e/\mu}^{\exp K}$ including radiative decays (IB), KLOE included gammas from $K \to e\nu\gamma$ decays with $E_\gamma > 10 MeV$. The measurement of $\mathrm{R}_{e/\mu}^{\exp K}$ consisted of comparing the corrected numbers of decays observed from the $K \to e\nu(\gamma)$ and $K \to \mu\nu(\gamma)$ channels.

By determining the momenta of the kaon and decay particle, the mass squared m_l^2 of the lepton in $K \to e\nu$ or $K \to \mu\nu$ decay was determined. Background rejection necessary to observe $K \to e\nu$ at the 10^{-5} level was achieved through kinematic cuts, tracking cuts, shower analysis, and comparisons between measured energy and momentum. Based on approximately $5.6x10^8$ kaons ($K^+$and K^-) the result found was $\mathrm{R}_{e/\mu}^{\exp K-KLOE}$ = (2.493±0.025(stat) ±0.019(syst)×10^{-5} [42] in agreement with the SM prediction at the 1% level.

The NA62 experiment at CERN:

NA62 at CERN using the setup from NA48/2 has embarked on a series of $K_{e2}/K_{\mu 2}$ measurements [43]. A K^+ beam is produced by the 400 GeV/c SPS. Positively charged particles within a narrow momentum band of (74.0 ± 1.6) GeV/c are selected by an achromatic system of four dipole magnets and a muon sweeping system, enter a fiducial decay volume contained in a 114 m long cylindrical vacuum tank producing a secondary beam flux of $2.5x10^7$ particles per 4.8 s pulse of which 5% are kaons; a kaon decay fraction of 18% in the beamline results. The $K \to e\nu(\gamma)$ and $K \to \mu\nu(\gamma)$ detection system includes a magnetic spectrometer, a plastic scintillator hodoscope (HOD) and a 27 X_0 liquid krypton electromagnetic calorimeter (LKr).

As in KLOE, the experimental strategy is based on counting the numbers of reconstructed $K \to e\nu(\gamma)$ and $K \to \mu\nu(\gamma)$ events concurrently eliminating dependence on the absolute beam flux and other potential systematic uncertainties. The measurement was performed in 10 bins of lepton momentum covering a range from 13 to 65 GeV/c. Acceptance corrections for signal and background processes were derived from detailed Monte Carlo (MC) simulations. Reconstructed events were used to calculate the missing mass squared $\mathrm{M}_{\mathrm{miss}}^2(l) = (\mathrm{P}_{\mathrm{K}} - \mathrm{P}_l)^2$ where P_K and P_ℓ are the four-momenta of the kaon and lepton. Lepton identification was based on determining the ratio E/p of track energy deposition in the LKr to momentum measured by the spectrometer in the region p<30GeV/c. The $K \to \mu\nu$ background contamination to the $K \to e\nu$ signal has been determined to be about 6% and the overall background level was $(8.78 \pm 2.9)\%$. The $\mathrm{M}_{\mathrm{miss}}^2(e)$ distributions of signal events and backgrounds are shown in figure 13.

Independent measurements of R_K in ten lepton momentum bins were used to extract the branching ratio. The result was $\mathrm{R}_{e/\mu}^{\exp K-NA62}$ = (2.487 ± 0.011stat. ± 0.007syst.) × 10^{-5}= (2.487 ± 0.013) × 10^{-5} [43] in agreement with the SM prediction. This result is based on 40% of the data sample acquired in 2007. The full data sample may allow a statistical uncertainty of 0.3% and a total uncertainty of 0.4-0.5% .

Conclusion

The rare decays of K and π mesons play an important role in the search for the underlying mechanism of flavor dynamics. Among many π, K and B rare processes that can be studied, the ratios $\mathrm{R}_{e/\mu}^{\pi/K} \equiv \frac{\Gamma(\pi/\mathrm{K} \to \mathrm{e}\nu(\gamma))}{\Gamma(\pi/\mathrm{K} \to \mu\nu(\gamma))}$ and the decay rates for $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L^0 \to \pi^0\nu\bar{\nu}$ are worthy of special attention because they can be calculated to an unusually high degree of precision in the context of the SM, not matched by any comparable flavor-changing processes involving quarks, and are also among the most sensitive to the presence of new physics effects at mass scales up to O(1000 TeV). Not only are these processes theoretically attractive to pursue but they have also been shown to be experimentally accessible at extraordinarily high levels of sensitivity which could result in observations that are not compatible with SM expectations at high levels of significance.

The branching ratio $R^{\pi}_{e/\mu} \equiv \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$ provides unique access to physics beyond the SM due to the extraordinary precision of its SM prediction and the potential for highly accurate measurements; strong helicity-suppression in the SM $\pi / K \to e\nu$ decays make them extremely sensitive to helicity-unsuppressed couplings due to pseudoscalar and scalar interactions. Recent reports on $R^{K}_{e/\mu} \equiv \frac{\Gamma(K \to e\nu(\gamma))}{\Gamma(K \to \mu\nu(\gamma))}$ by KLOE and NA48 groups have so far provided substantial improvements in precision facilitating new tests for non-SM physics related to lepton flavor violation. The best test of the SM hypothesis of charged current universality comes from the decay ratio $R^{\pi}_{e/\mu} \equiv \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$ which has been measured to a precision of 0.4%, in comparison with calculations that are an order of magnitude more precise. Current experiments PIENU at TRIUMF and PEN at PSI are aiming to increase the experimental precision by an order of magnitude.

The highly suppressed rare decays $K^{+} \to \pi^{+}\nu\bar{\nu}$ and $K_{L} \to \pi^{0}\nu\bar{\nu}$ are exceptionally clean theoretically in the SM and in most of its extensions. These processes play key roles in the search for physics beyond the SM by offering potential insights into the CP violation and flavor breaking structure of hypothetical SM extensions. Although most of the theoretical virtues are shared by both processes, $K^{+} \to \pi^{+}\nu\bar{\nu}$ involves CP-conserving and CP-violating interactions whereas $K_{L} \to \pi^{0}\nu\bar{\nu}$ is sensitive purely to CP violation (if the unobserved particles in the final state are neutrinos). Since each is dominated by one-loop electroweak dynamics, the two $K \to \pi\nu\bar{\nu}$ rates may be greatly affected by new-physics contributions in complementary ways making the comparison of the decay rates another incisive test of new physics scenarios. Experimentally, the prospects for achieving high precision measurements of $K^{+} \to \pi^{+}\nu\bar{\nu}$ are excellent. E787/E49 at BNL discovered the decay $K^{+} \to \pi^{+}\nu\bar{\nu}$ based on observations of 7 events. NA62 at CERN is now gearing up to seek an order of magnitude increase in sensitivity and a proposal at Fermilab aims for sensitivity of 1000 events at the SM level. At J-PARC the KOTO experiment is pursuing $K_{L} \to \pi^{0}\nu\bar{\nu}$ with the sensitivity goal of a few events at the SM level. Future experiments at J-PARC and at Fermilab's proposed Project-X high intensity proton source could reach the ultimate levels which have SM sensitivities comparable to the small theoretical uncertainties, allowing extremely incisive probing of hypothetical new physics scenarios including new physics effects of the form $K \to \pi X(X')$ where $X(X')$ are light weakly interacting particles.

References

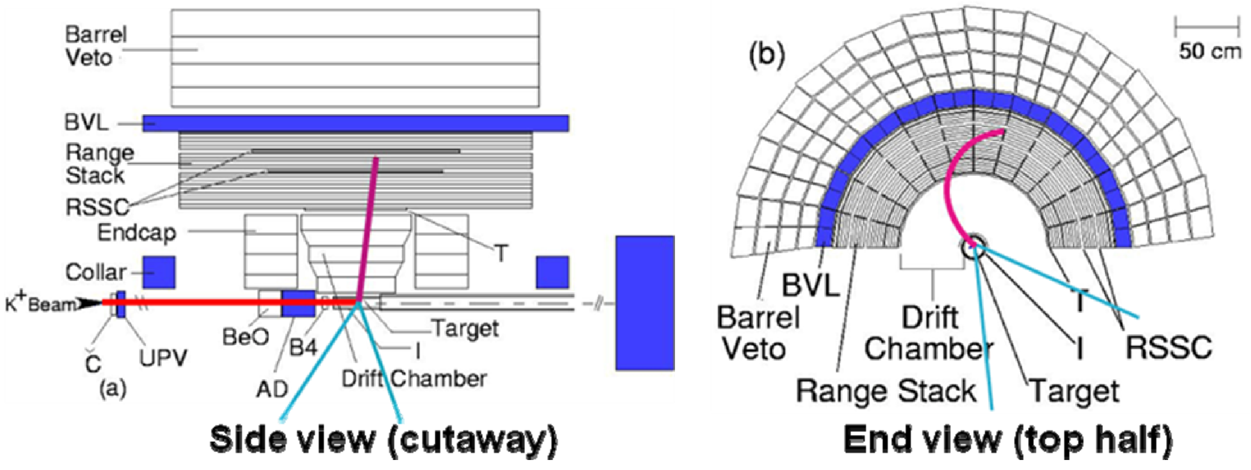

Figure 1: Elevation side-view and end-view of schematic of the BNL E787 and E949 technique [22] . The 700 MeV/c K^+ beam enters from the left in (a). The stopped K^+ decays in the stopping target and the subsequent decay π^+ track is momentum analyzed by the tracker in (b). The decay π^+ then stops in the Range Stack where the range and energy are measured.

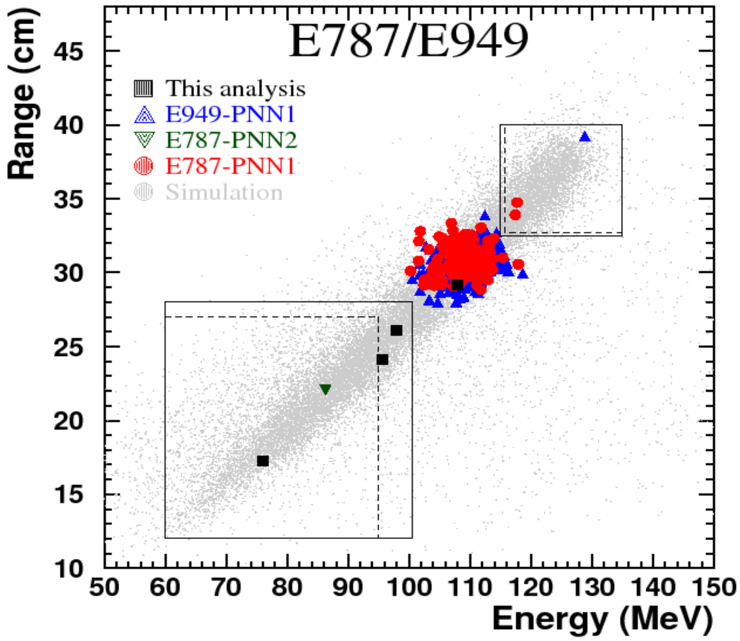

Figure 2: The seven candidate events of the BNL E787 and BNL E949 experiments [22]. The background population from $K^+ \to \pi^+\pi^0$ is evident at (E=110 MeV, R=32 cm), and the simulated signal population is indicated along the diagonal as small grey dots. “PNN1” refers to the signal region indicated as the box in the upper right, and “PNN2” refers to the signal region indicated as a box in the lower left.

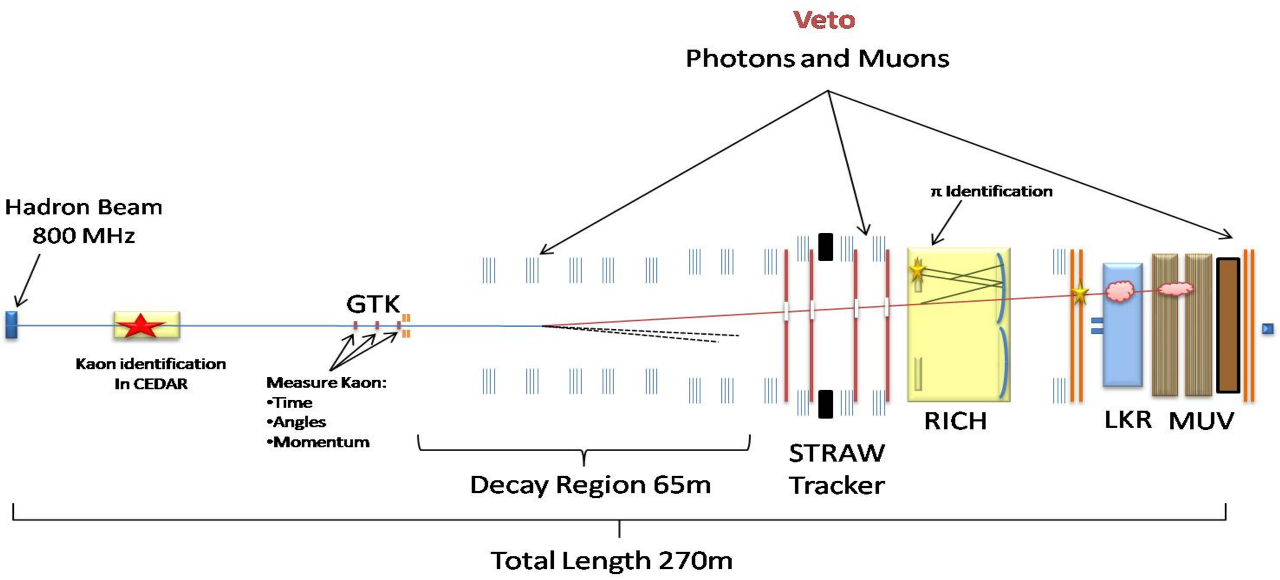

Figure 3: The CERN NA62 detector configured to search for and measure $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ **[29].**

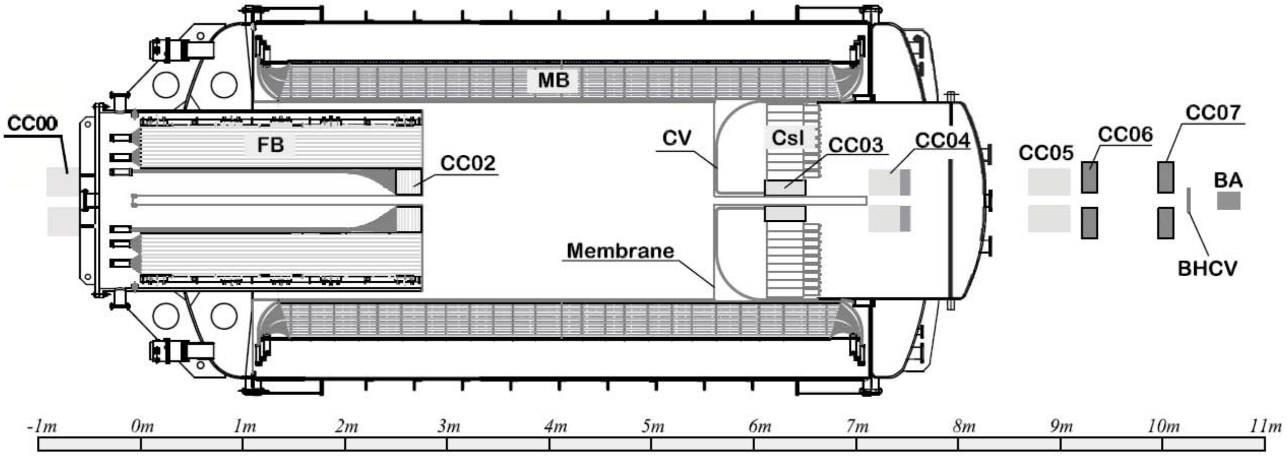

Figure 4: The KEK PS E391a Experiment Detector System to search for $K_L \rightarrow \pi^0 \nu\bar{\nu}$ [9]. The neutral kaon beam enters from the left and the decay $\pi^0 \rightarrow \gamma\gamma$ occurs within the central decay volume which is completely surrounded by veto systems to tag the presence of extra photons from background processes such as $K_L \rightarrow \pi^0\pi^0$.

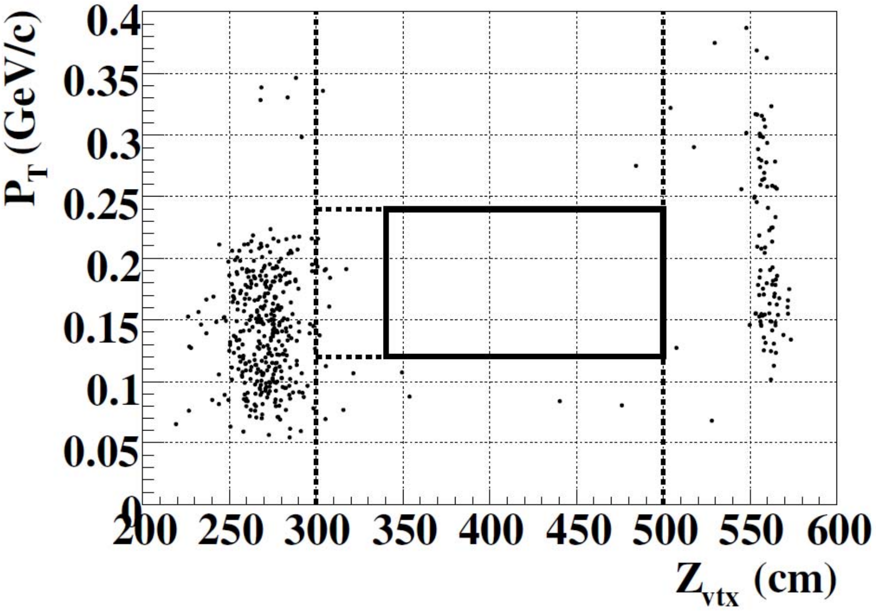

Figure 5: Scatter plot of KEK E391a reconstructed P_T vs the reconstructed *Z*-vertex (Z_{vtx}) position for the events with all other selection criteria imposed. The box indicates the signal region for $K_L \rightarrow \pi^0 \nu\bar{\nu}$ decays [9].

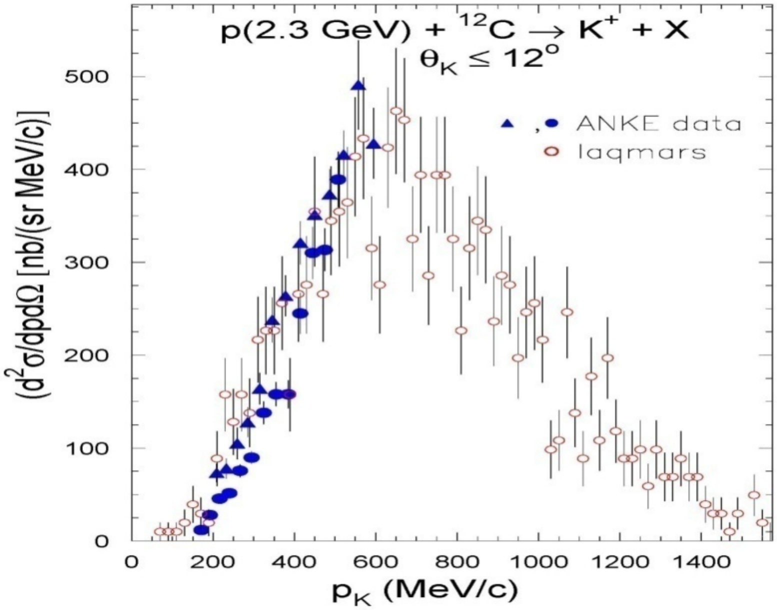

Figure 6: Absolute simulation (dots) of the K^+ momentum spectrum from 2.3 GeV protons (T_p, kinetic) incident on a thin carbon target [31]. Data from the ANKE experiment at COSY are overlaid as triangles.

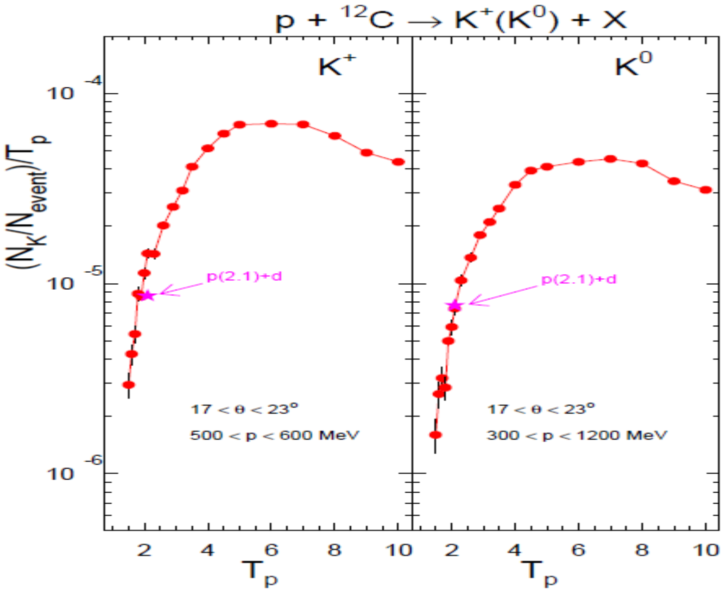

Figure 7: The simulated (LAQGSM/MARS15) kaon yield at constant beam power (yield/T_p) for experimentally optimal angular and energy regions as a function of T_p (GeV) [31].

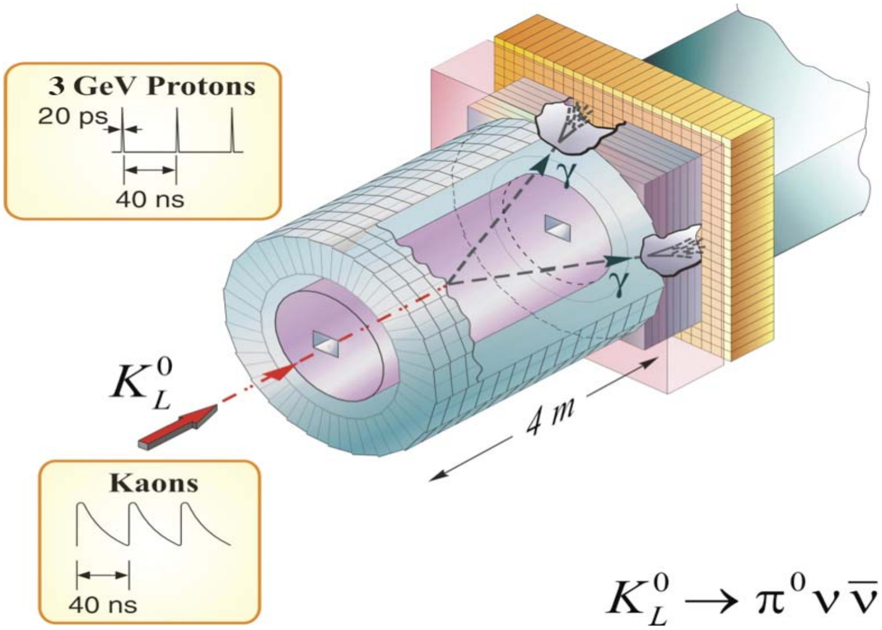

Figure 8: Illustration of the key elements of the KOPIO [39] technique implemented in a Project-X $K_L \rightarrow \pi^0 \nu\bar{\nu}$ experiment: TOF measurement of the K_L momentum, measurement of ($\pi^0 \rightarrow \gamma\gamma$) and veto of all other background process particles.

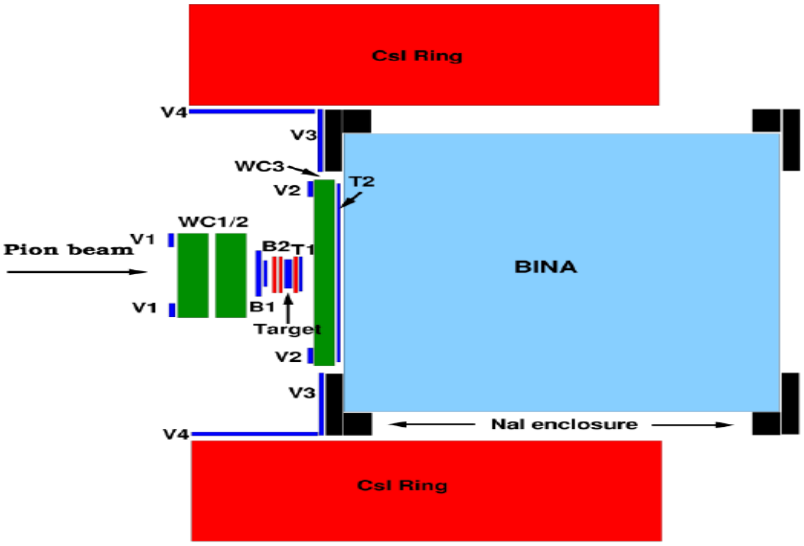

Figure 9: The TRIUMF PIENU experiment setup described in the text. Beam enters from the left.

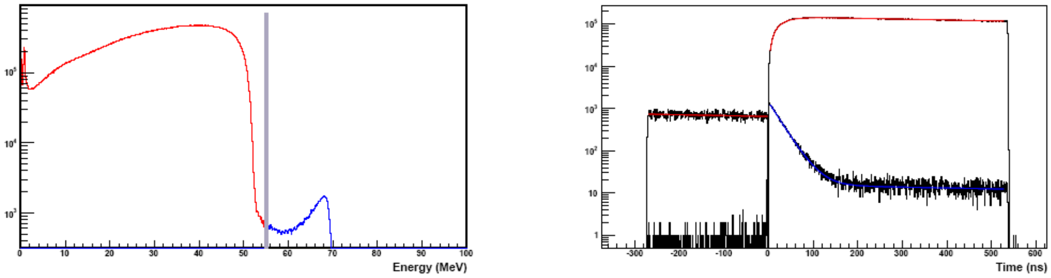

Figure 10: Left: The e^+ energy spectrum. The grey line shows the point of division between the $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu \rightarrow e$ regions. Right: Fitted time spectra of both energy regions; blue for $\pi \rightarrow e\nu$ and red for $\pi \rightarrow \mu \rightarrow e$.

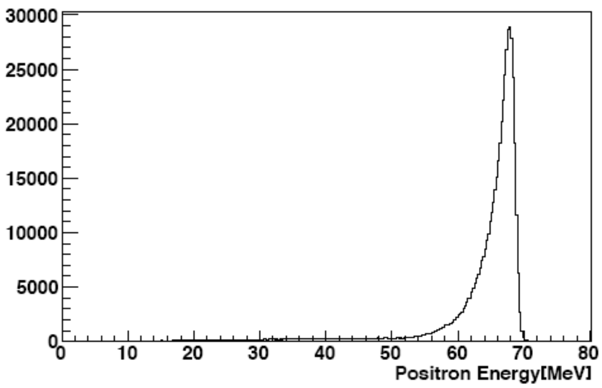

Figure 11: $\pi \rightarrow e\nu$ spectrum with $\pi \rightarrow \mu \rightarrow e$ decays suppressed using timing and target energy cuts; no background has been subtracted. The time window used was 2-26 nsec. The tail fraction below 55 MeV is 7% including components from the intrinsic response, radiative pion decay, and residual $\pi \rightarrow \mu \rightarrow e$ decays

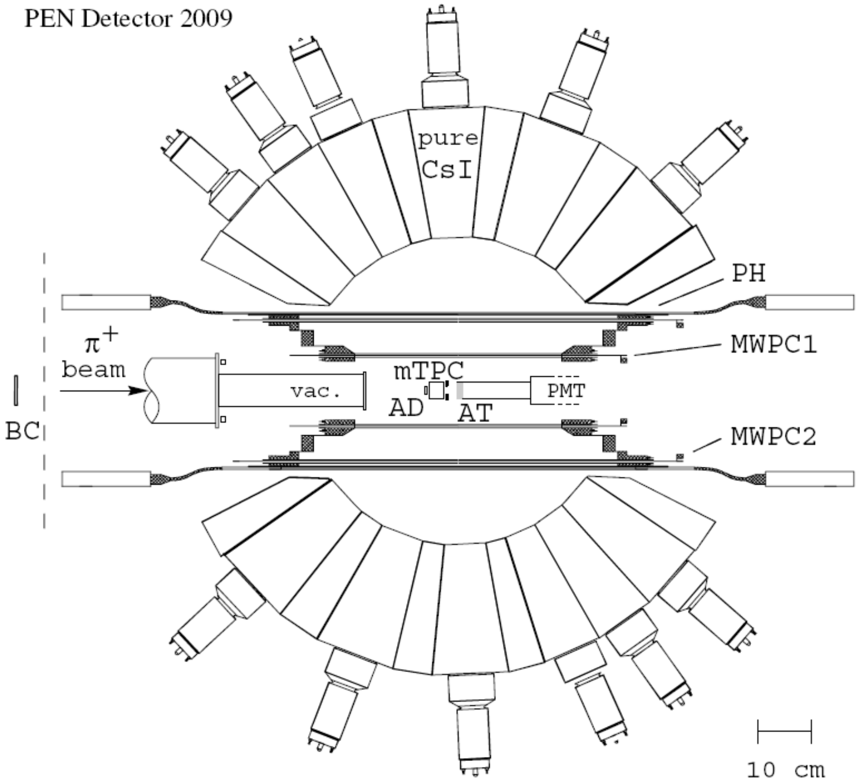

Figure 12: PEN detector cross-sectional view showing the major detector sub-systems.

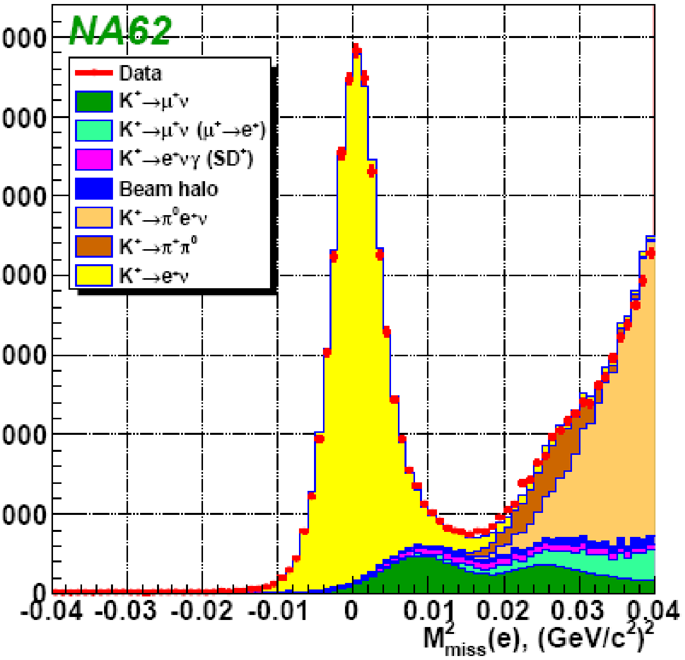

Figure 13: The NA62 reconstructed squared missing mass M^2miss(e) distribution of $K^+ \rightarrow e^+\nu$ candidates compared with the sum of normalized MC signal and background components.

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