A $K_{\mathrm{L}} \to \pi^0 \nu\bar{\nu}$ Experiment at Fermilab

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Abstract

A definitive measurement of the rare CP-violating decay $K_{\mathrm{L}} \to \pi^0 \nu\bar{\nu}$ using Fermilab's 8-GeV Booster is discussed. Since calculation of the $K_{\mathrm{L}} \to \pi^0 \nu\bar{\nu}$ branching ratio is extremely well-grounded in the standard model, a precise measurement is a highly sensitive approach to discovery of a wide variety of new physics effects.

1 Introduction

The goal of a new experiment to measure $K_{\rm L} \to \pi^0\nu\bar{\nu}$ at Fermilab is to explore the range of branching ratios down to the level of the SM prediction, B($K_{\rm L} \to \pi^0\nu\bar{\nu}$)$= 3 \times 10^{-11}$, and below so as to discover new physics effects. Achievement of this goal appears to be feasible at Fermilab using techniques similar to those previously proposed for the KOPIO experiment at BNL. In the absence of a clear non-SM result, a precision of ∼10% on the $K_{\rm L} \to \pi^0\nu\bar{\nu}$ branching ratio at the SM level would be achieved, yielding a statistical uncertainty in the measurement of the area of the CKM unitarity triangle of less than 6%.

There are several reasons why the decay $K_{\rm L} \to \pi^0\nu\bar{\nu}$ may play a special role in the discovery of physics beyond the SM with sensitivity to extremely high mass scales.[1] The clean theoretical character of $K_{\rm L} \to \pi^0\nu\bar{\nu}$ remains valid in essentially all extensions of the SM.[1] In $K_{\rm L} \to \pi^0\nu\bar{\nu}$ the contributions from the CP violation in K_0 mixing are several orders of magnitude smaller than the direct CP violation in the decay amplitude and consequently the direct CP violation in the SM and in its extensions can be tested here in a very clean environment. Due to the different structure of the corresponding electroweak amplitudes, new-physics effects could be quite different in direct- and indirect-CP-violating amplitudes which can only be explored by means of $K_{\rm L} \to \pi^0\nu\bar{\nu}$.

One of the most popular scenarios about the flavor structure of physics beyond the SM is the so-called Minimal Flavor Violation (MFV) hypothesis. Within this framework, flavor- and CP-violating interactions are induced only by terms proportional to the SM Yukawa couplings. Theoretically clean quantities such as $a_{\rm CP}(B \to J/\psi K_S)$ and M_{B_d}/M_{B_s}, which measure only ratios of FCNC amplitudes, turn out to be insensitive to new-physics effects. Within this framework, the need for additional clean and precise information on FCNC transitions is therefore even more important[2]. A precise measurement of B($K_{\rm L} \to \pi^0\nu\bar{\nu}$) offers a unique opportunity to discover new physics or for the interpretation of new flavor physics effects that may be revealed at the LHC.

In most SM extensions the new physics contributions in $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L^0 \to \pi^0\nu\overline{\nu}$ can be parameterized in a model-independent manner by two parameters, the magnitude and the phase of the Wilson coefficient of the operator $Q_{sd}^{\nu\nu}$. More explicitly, we can encode all the new-physics effects around and above the electroweak scale into

[1] This is generally not the case for non-leptonic two-body B decays used to determine the CKM parameters through CP asymmetries and/or other strategies. While several mixing induced CP asymmetries in non-leptonic B decays within the SM are essentially free from hadronic uncertainties, as the latter cancel out due to the dominance of a single CKM amplitude, this is often not the case in extensions of the SM in which the amplitudes receive new contributions with different weak phases implying no cancellation of hadronic uncertainties in the relevant observables.

an effective Hamiltonian of the type

$H_{eff}(M_W^2) = \frac{G_F^2 M_W^2}{2\pi^2}\lambda_t X Q_{sd}^{\nu\nu}$ + non-FCNC terms + h.c.

where $\lambda_t = V_{ts}^* V_{td}$ and the short-distance function $X \equiv |X| e^{i\theta_X}$ is such that the SM case corresponds to $|X| = 1.46 \pm 0.03$ and $\theta_X \to 0$. The important virtue of the $K \to \pi\nu\overline{\nu}$ system is that $|X|$ and θ_X can be extracted from $K_L^0 \to \pi^0\nu\overline{\nu}$ and $K^+ \to \pi^+\nu\overline{\nu}$ without hadronic uncertainties, while the function X can be calculated in any extension of the SM within a perturbative framework.

The modulus of X is directly constrained by $\mathrm{B}(K^+ \to \pi^+\nu\overline{\nu})$, which is not very sensitive to θ_X while $\mathrm{B}(K_L^0 \to \pi^0\nu\overline{\nu})$ strongly depends on θ_X. A non-vanishing value of θ_X would signal the presence of extra CP-violating phases in $K_L^0 \to \pi^0\nu\overline{\nu}$ amplitudes in addition to the standard CKM phase.

In general, we can write

$\mathrm{B}(K_L^0 \to \pi^0\nu\overline{\nu})/\mathrm{B}(K_L^0 \to \pi^0\nu\overline{\nu})_{SM} = \left|\frac{X}{X_{SM}}\right|^2 \left[\frac{sin(\beta-\theta_X)}{sin(\beta)}\right]^2$

where $\beta = 23°$ is the standard angle of the unitarity triangle. At present, the first factor on the right-hand side of this equation is constrained by the experimental data on $\mathrm{B}(K^+ \to \pi^+\nu\overline{\nu})$ to be smaller than 7 (at 90% C.L.). However, even with an infinitely precise and completely SM result for $\mathrm{B}(K^+ \to \pi^+\nu\overline{\nu})$, one would still have much room for possible enhancements in $\mathrm{B}(K_L^0 \to \pi^0\nu\overline{\nu})$ due to the second factor, which could be as large as 6. Combining these two possible enhancement factors, reveals the large potential for enhancement of $\mathrm{B}(K_L^0 \to \pi^0\nu\overline{\nu})$ over its SM prediction. The pattern of the two $K \to \pi\nu\overline{\nu}$ branching ratios as a function of θ_X is illustrated in Fig. 1. Note, in particular, that the ratio of the two modes depends very mildly on $|X|$ and provides the ideal tool to extract the non-standard CP-violating phase θ_X.

The X function has been defined assuming the SM normalization (electroweak couplings and CKM factors) for the $Q_{sd}^{\nu\nu}$ operator. In principle, the non-standard effects could actually originate through a very different type of dynamics.

To estimate the new-physics sensitivity of $\mathrm{B}(K_L^0 \to \pi^0\nu\overline{\nu})$ on pure dimensional grounds, we can denote by $\lambda_{sd}/\Lambda_{NP}^2$ the overall coefficient of the extra (non-SM) contribution to the $Q_{sd}^{\nu\nu}$ operator. If the generic dimensionless coupling λ_{sd} is of O(1), it follows that a measurement of $\mathrm{B}(K_L^0 \to \pi^0\nu\overline{\nu})$ with 10%-20% accuracy probes new-physics scales well above 100 TeV. To be more precise, a measurement of $\mathrm{B}(K_L^0 \to \pi^0\nu\overline{\nu})$ with central value equal to the SM prediction and relative precision $p = \sigma_B/B$, allows setting the following 90% CL bound on the scale of the operator:

$\Lambda_{NP}/\sqrt{Im\lambda_{sd}} > \left[\frac{G_F^2 M_W^2}{2\pi^2} Im\lambda_t X\right]^{-1/2} (0.64p)^{-1/2}$

For a measurement at 10% precision ($p = 0.1$), this gives = 1280TeV! This remarkably high scale corresponds to the effective mass of new particles in the scenarios where new physics effects contribute to $K_L^0 \to \pi^0\nu\overline{\nu}$ at the tree level and all the relevant

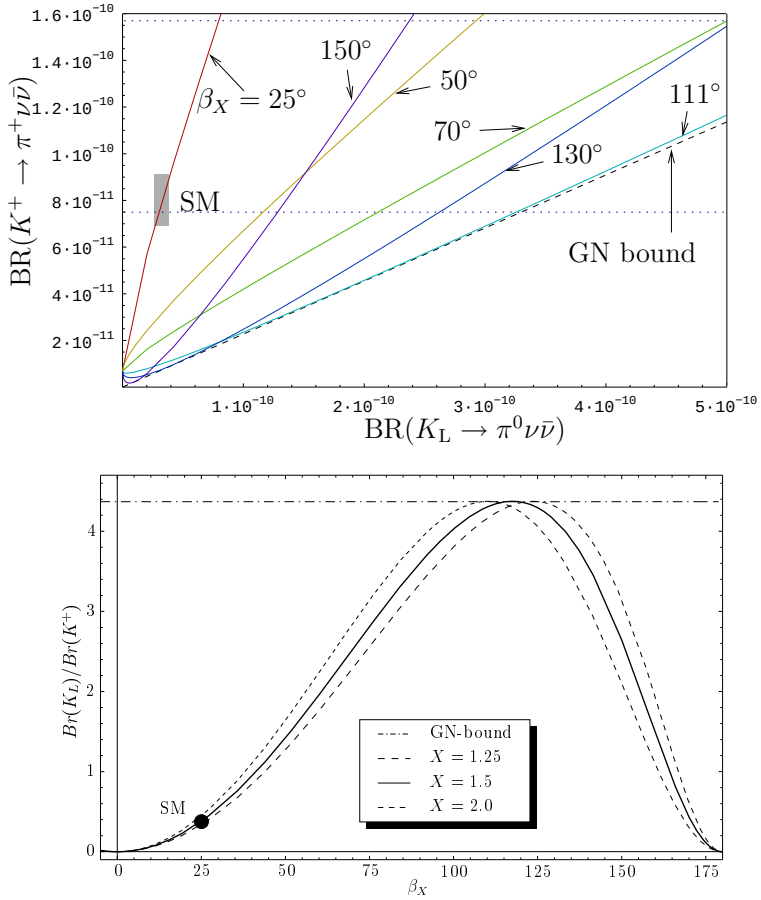

Figure 1: Up: $\mathrm{B}(K^+ \to \pi^+\nu\overline{\nu})$ as a function of $\mathrm{B}(K_L^0 \to \pi^0\nu\overline{\nu})$ for various values of $\beta_X = \beta - \theta_X$ [3]; the dotted horizontal lines indicate the lower part of the experimental range[4]; the SM range and the bound[5]) are also indicated. Down: ratio of charged and neutral branching ratios as a function of β_X for $|X| = 1.25,\ 1.5,\ 2.0$ [6].

couplings are O(1). This analysis (see [1] for more details) puts a 10% measurement of $K_L^0 \to \pi^0\nu\overline{\nu}$ in a comparable class of sensitivity to new high mass scale physics proposed for future generations of lepton flavor violation experiments such as $\mu \to e\gamma$ (10^{-14}) and $\mu \to e$ conversion (10^{-17}). Although effective couplings may be smaller, even in the most pessimistic cases (e.g. minimal flavor violation models) a 10% measurement of $\mathrm{B}(K_L^0 \to \pi^0\nu\overline{\nu})$ probes new physics scales well above the electroweak scale.

Thus, there is strong scientific motivation to consider a $K_L^0 \to \pi^0\nu\overline{\nu}$ experiment at Fermilab. Initial indications are that such an experiment could be mounted at the 8 GeV Booster, without unduly impacting the Main Injector program.

Additional details of the motivation for studying $K_L^0 \to \pi^0\nu\overline{\nu}$ can be found in Ref. [1] and the description of the KOPIO experiment can be found in the KOPIO CDR [7].

2 The Technique

The experimental aspects of measuring $B(K_{\rm L} \rightarrow \pi^0\nu\bar{\nu})$ are quite challenging. The mode is a three-body decay where only a π^0 is observed. There are competing decays which also yield π^0s, but whose branching ratios are millions of times larger. Observing a decay mode with a branching ratio on the order of 3×10^{-11} requires a prodigious number of kaons in order to achieve the desired sensitivity. Because the measurement is so demanding, a detection technique must be adopted that provides maximum possible redundancy for this kinematically unconstrained decay, that has an optimum system for insuring that the observed π^0 is the only observable particle emanating from the K_L^0 decay, and that has multiple handles for identifying possible small backgrounds that might simulate the signal. It is with these issues in mind that the experiment discussed here was designed.

The technique employs a low-energy, time structured K_L^0 beam to allow determination of the incident kaon momentum by the time-of-flight (TOF) technique. Utilizing low momentum also permits a detection system for the π^0 decay photons that yields a fully constrained reconstruction of the π^0 mass, energy, and momentum. The system for vetoing extra particles is also well understood. These features, which are similar to those employed successfully in the BNL AGS E787/E949 measurements of $K^+ \rightarrow \pi^+\nu\bar{\nu}$, provide the necessary redundancy and checks. Fig. 2 is a schematic representation of this technique.

The goal for a new experiment is the study of $K_{\rm L} \rightarrow \pi^0\nu\bar{\nu}$ decay with a statistical sensitivity of a few $\times 10^{-13}$/event, compared to the current best limit (KEK E391a) of 2.1×10^{-7} [8]. To accomplish this goal, an intense flux of protons will be microbunched on extraction to provide 200 ps-wide bunches at an interval of ~40ns. The extracted protons will be directed onto a 10cm-long Pt target. A neutral beam will be taken off at a large angle ($\sim 40^{\rm o}$) so that the $K_{\rm L}$'s will be slow enough for the time-of-flight measurement to determine their velocity within a few percent. After traversing a carefully collimated 10 m beamline, a "pancake" beam of 4 mr $\times$ 90 mr will impinge on a 4 m evacuated decay region in which about 10% of the $K_{\rm L}$'s decay. Forward-going decay photons will be detected in a preradiator consisting of alternating drift chamber and scintillator planes. The preradiator will measure the direction of the photons as well as the portion of their energy that is deposited in the 2.5 radiation lengths comprising this device. The preradiator will be backed up by an 18-X_0 "shashlyk" lead-scintillator sampling calorimeter. Photon directions will be measured with a precision of approximately 25mr (e.g. at E_γ=250 MeV), energies to 2.7% $/\sqrt{E}$ and arrival times to ~200ps. The photon directions can be used to determine the decay vertex and to assure that it is in the beam phase space. The decay region will be surrounded by a cylindrical 18-X_0 thick

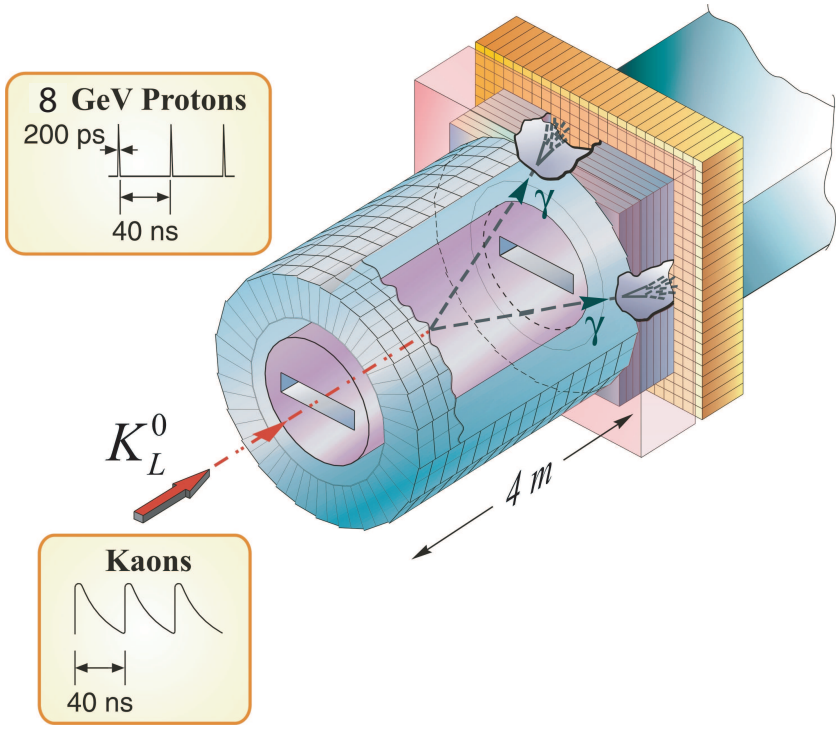

Figure 2: KOPIO technique

photon detector also consisting of shashlyk modules, and the upstream end of the tank will be covered by a circular wall of plate shower counter photon vetoes. Suppression of most backgrounds is provided by a hermetic, high-efficiency, charged-particle and photon detector system surrounding the decay volume. The system includes scintillators inside the evacuated region, decay-volume photon veto detectors, and detectors downstream of the main decay volume. Downstream of the latter will be a large dipole magnet to sweep the remaining charged particles out of the beam so that events containing these can be efficiently vetoed. To complete the hermeticity of photon detection, there will be photon counter stations surrounding the beampipe at several locations downstream of the sweeping magnet, and finally, at the end of the beamline, a neutron-blind lead-aerogel shower counter will detect the residual photons from background processes originating in the decay region that stay within the beam.

With the knowledge of the decay vertex and the time of flight, one can determine the $K_{\rm L}$ momentum and transform into its center of mass. This will allow most of the main backgrounds, such as $K_{\rm L} \to \pi^0\pi^0$ to be kinematically rejected. In combination with very high efficiency photon vetoing (as proven in E949), this will allow all backgrounds to be reduced to acceptable levels.

3 Measuring $K_{\rm L} \to \pi^0 \nu\bar{\nu}$ at FNAL

A preliminary investigation revealed that running at the Fermilab 8 GeV Booster would result in sensitivity per hour comparable to that expected at the 24 GeV BNL AGS. This somewhat surprising conclusion is due to the following factors:

1. The cross-section for kaon production at large angles appears to fall rather slowly with primary proton energy (unlike the case for forward production) [9]. Fig. 3 shows a comparison of K_L production at 8 GeV vs 24 GeV, as a function of angle.

2. The Fermilab Proton Plan envisions $\sim 2 \times 10^{20}$ protons per year available for the Booster program. A cycle of $\sim 2 \times 10^{13}$ protons every 1.5 seconds is therefore possible.

3. An extremely good duty cycle is possible using the Accumulator for storing and rebunching the proton beam.

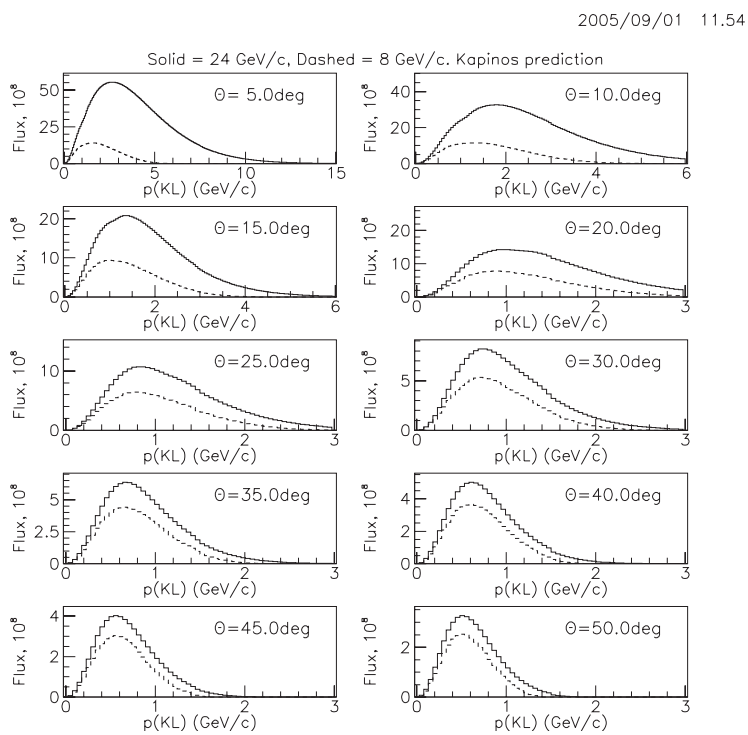

Figure 3: Production of K_L into 500μsr by 5×10^{13} protons for various central lab angles. Solid lines are for 24 GeV protons, dashed lines are for 8 GeV protons.

A possible realization of the Booster scheme [10] would involve using the Accumulator to store four batches of 4.8×10^{12} protons per 1.5 s cycle, debunching them and then

microbunching on extraction as in the AGS scheme [11] [2]. Beam would be spilled out over 1.23 s, yielding a duty factor of $\sim 82\%$. This assumes the Booster cycles at 15Hz, installation of a Booster to Accumulator beamline, beam manipulation and extraction hardware installed in the Accumulator, as well as an external proton beamline originating at that ring. In this scheme the impact on MI neutrino running is a 15% loss of protons. However the sensitivity versus intensity optimization curve for this instantaneous rate limited experiment is very broad, so that the impact can be much reduced without significantly compromising the sensitivity to $K_L \to \pi^0 \nu\bar{\nu}$.

The beamline and detector described in the KOPIO CDR [7] would be viable for running at FNAL, but would benefit from reoptimization for 8 GeV operation. In addition, there are desirable modifications based on the experience of designing and simulating the original BNL apparatus, that could potentially enhance both the sensitivity and robustness of the experiment.

In addition, since the running time available at Fermilab per year is expected to be considerable, the reach of the experiment can be increased significantly. Conservatively, we estimate that twice the sensitivity of the previously proposed BNL experiment can be achieved in a run of 2.5 years.

4 Expected Sensitivity

Since the proposed technique allows for considerable information to be available in each event, simulation and extensive studies of data samples will be employed to achieve a high degree of understanding of the acceptance of the signal and backgrounds. This approach fosters the use of maximum likelihood techniques which were employed in E949 studying $K^+ \to \pi^+ \nu\bar{\nu}$. In the maximum likelihood technique, events are classified by their relative cleanliness (i.e. probability to be due to signal or to background) and weighted accordingly allowing optimal use of the information available. The expected distribution of signal to background (S/B) vs signal in a run of 2.5 years is shown in Fig. 4.

The black curve shows the sum of the contributions of several different categories of events with different geometrical configurations. If the data were analyzed using a traditional "cut" approach, for example, the 50 cleanest events have a signal to background of about 5:1. One can further relax the selection criteria so as to collect 200 events, along with 154 background events. However, the maximum likelihood method

[2] The scheme is actually slightly different - rather than sweeping the beam through empty RF-buckets, the buckets are swept through the beam. In addition the bunching frequency would be 26MHz instead of 25MHz.

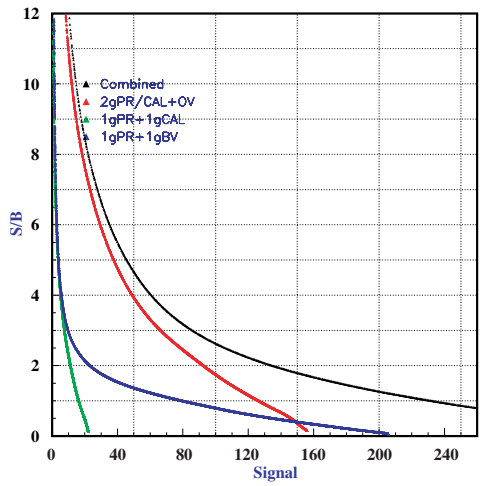

Figure 4: S/B vs S. Black curve is the total of all events. Colored curves show the result for various topologies of events separately.

will be used the obtain the optimum result from the entire data set. In the absence of new physics effects, this results in a 10.5% measurement of the branching ratio at $B(K_L \to \pi^0\nu\bar{\nu}) = 3 \times 10^{-11}$. The small systematic error contribution of $\sim 4\%$ would allow further progress to be made with longer running. For example, a 5-year run would yield an 8% determination of the same branching ratio. This is statistically equivalent to a measurement with 175 signal events and S:B of ∼10:1. Fig. 5 gives the relative precision on $\mathrm{Im}\lambda_t$ as a function of running time[3].

Of course the strongest motivation for pursuing $K_\mathrm{L} \to \pi^0\nu\bar{\nu}$ is its power to reveal new physics. Fig. 6 shows the sensitivity of the experiment as a function of running time for approximately the first two years. The solid lines show the branching ratios that could be distinguished from that of the SM by $5\,\sigma$. Note that after about 1000 hours, the branching ratio is established to be greater than 0 by 5σ. After this, models giving branching ratios that are too low can be ruled out. Branching ratios above or below the dashed lines can be ruled out at 95% confidence.

5 The Flavor Physics Scene and Fermilab

In addition to the great potential of the upcoming programs at the LHC, a focused worldwide program of searches for lepton flavor violation and measurements of the $K \to \pi\nu\bar{\nu}$"dynmamic duo" would provide extraordinary potential for discovery and interpretation of new physics at high mass scales. The imminent MEG experiment at

[3] $\mathrm{Im}\lambda_t = \mathrm{Im}V_u^* sV_u dV_t^* sV_t d \approx \lambda^6(1-\lambda^2/2)A^2\eta^2$.

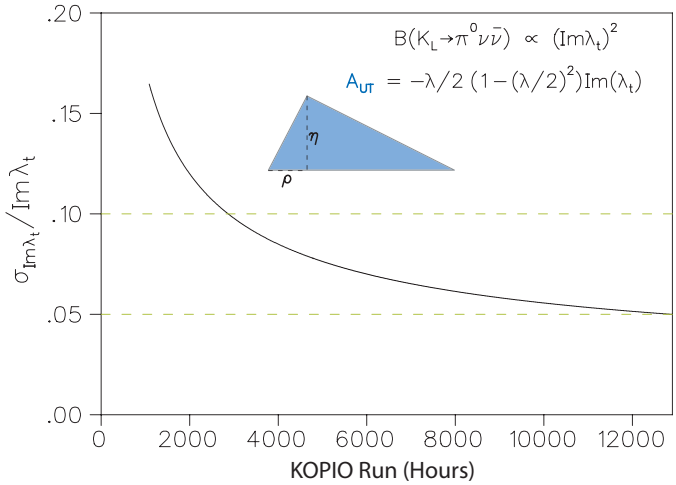

Figure 5: Relative precision on Imλ_t (or equivalently on the area of the unitarity triangles) as a function of running time.

PSI on $\mu \to e\gamma$ could be well complemented by a potential effort on $\mu \to e$ conversion at Fermilab or at JPARC (via PRISM).

At CERN, the proposal P326 which aims for O(100) $K^+ \to \pi^+\nu\overline{\nu}$) events is progressing well with a several months long R&D run occurring this summer using the SPS. If finally approved, P326 may have results in the 2012-2014 time frame. There is also an active $K_L \to \pi^0\nu\bar{\nu}$ program at JPARC, where an experimental approach similar to the previously proposed KAMI technique (relying extensively on the yet-to-be established photo vetoing capability) is being pursued. However,the initial stated objective at JPARC is a sensitivity of only O(7) events with a comparable level of background. Recognizing that their approach which re-uses apparatus from KEK due to scarcity of funding lacks the capability for a discovery-class measurement of $K_L^0 \to \pi^0\nu\overline{\nu}$, the JPARC group anticipates a future unspecified effort.

In the context of these initiatives, initiation of a definitive $K_L^0 \to \pi^0\nu\overline{\nu}$measurement based on the KOPIO technique which is quite distinct from that being pursued elsewhere and which has been extensively reviewed for its capabilities, risks, and costs is worthy of serious consideration at Fermilab. the former KOPIO proposal, a

References

[1] D. Bryman, A. J. Buras, G. Isidori and L. Littenberg, Int.J.Mod.Phys.A21:487-504,2006 (arXiv:hep-ph/0505171).

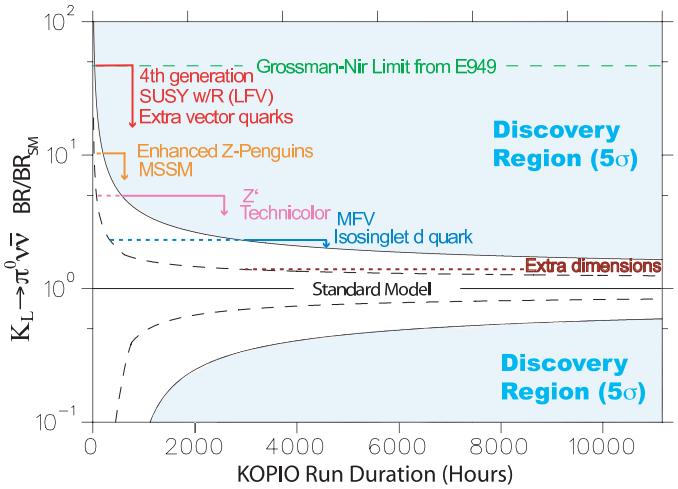

Figure 6: Exclusion limits in terms of observed branching ratio divided by the SM expectation as a function of running time. See text for details. The prediction ranges of various non-SM models are indicated.

[2] C. Bobeth, M. Bona, A. J. Buras, T. Ewerth, M. Pierini, L. Silvestrini and A. Weiler, Nucl. Phys. B **726**, 252 (2005) [arXiv:hep-ph/0505110].

[3] A. J. Buras, R. Fleischer, S. Recksiegel and F. Schwab, Phys. Rev. Lett. **92** (2004) 101804; Nucl. Phys. **B697** (2004) 133. V. V. Anisimovsky *et al.* [E949 Collaboration], Phys. Rev. Lett. **93**, 031801 (2004) [arXiv:hep-ex/0403036].

[4]

[5] Y. Grossman and Y. Nir, Phys. Lett. **B398**, (1997) 163.

[6] A. J. Buras, F. Schwab and S. Uhlig, hep-ph/0405132.

[7] J.R. Comfort et al., "KOPIO Project Conceptual Design Report", April 2005, http://www.kopio.bnl.gov/cdr2005_nsf.pdf.

[8] J.K. Ahn et al., Phys.Rev.D74:051105,2006, Erratum-ibid.D74:079901,2006. (hep-ex/0607016

[9] T. Abbott *et al.* [E-802 Collaboration], Phys. Rev. D **45** (1992) 3906.

[10] D. McGinnis, private communication.

[11] J.W. Glenn et al., "Microbunching the AGS slow external beam, *Proc. of the 1997 Particle Accelerator Conf.*, Vancouver, B.C. Canada, May 1997, IEEE Press. p. 967.