97-
LA-UR- 3419

Title: Lepton Flavor Violation

CONF-970564--

RECEIVED
OCT 01 1997
OSTI

Author(s): M. D. Cooper, M. Brooks, G. E. Hogan, V. D. Laptev, R. E. Mischke, P. S. Cooper, Y. Chen, M. Dzemidzic, A. Empl, E. V. Hungerford III, K. Stantz, J. Szymanski, C. Gagliardi, R. E. Tribble, D. D. Koetke, R. Manweiler, S. Stanislaus, K. O. H. Ziock, and L. E. Piilonen

Submitted to: *Sixth Conference on the Intersections of Particle and Nuclear Physics*
Big Sky, Montana
May 27 – June 2, 1997

Los Alamos
NATIONAL LABORATORY

Lepton Flavor Violation

M. D. Cooper, M. Brooks, G. E. Hogan, V. D. Laptev, and R. E. Mischke

Los Alamos National Laboratory
Los Alamos NM 87545

P. S. Cooper

Fermi National Accelerator Laboratory
Batavia, IL 60510

Y. Chen, M. Dzemidzic, A. Empl, E. V. Hungerford III, K. Lan, and W. von Witsch

University of Houston
Houston, TX 77004

K. Stantz and J. Szymanski

Indiana University
Bloomington, IN 47405

C. Gagliardi and R. E. Tribble

Texas A&M University
College Station, TX 77843

D. D. Koetke, R. Manweiler, and S. Stanislaus

Valparaiso University
Valparaiso, IN 46383

K. O. H. Ziock

University of Virginia
Charlottesville, VA 22901

L. E. Piilonen

Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Abstract. The connection of rare decays to supersymmetric grand unification is highlighted, and a review of the status of rare decay experiments is given. Plans for future investigations of processes that violate lepton flavor are discussed. A new result from the MEGA experiment, a search for $\mu^+ \rightarrow e^+\gamma$, is reported to be B.R. < 3.8×10^{-11} with 90% confidence.

INTRODUCTION

The Standard Model of electroweak interactions gives a type of periodic table of the elementary fermions, where the periodicity is labeled by the family of the particle. The repetition of families is not understood, and neutral current transitions between the families appear to be forbidden by experiment. The Standard Model of electroweak interactions is a remarkably robust phenomenological theory that encompasses all current measurements and tempts us to look for process outside its sphere of applicability. As it is generally accepted that the Standard Model is not likely to be a complete description of nature, many extensions have been proposed.

Searching for decays that change total lepton family number is an excellent method to explore potential physics beyond the Standard Model because those processes are predicted to be zero except when new physics is present. Even the addition of neutrino oscillations would produce only an immeasurably small rate. Essentially all extensions of the Standard Model that introduce new, heavy particles predict the existence of these rare decays, though the most probable channel is highly model dependent. If a lepton-violating process is observed, measuring many related decays will be important in uncovering the underlying physics. This paper will review the status of searches for rare processes.

There have been many reviews of possible extensions of the Standard Model and their implications for the observation of rare decays, e.g., refer to the one by Melese (1). Recently, the prejudice has grown within the physics community that supersymmetry is an extension that is likely to be related to nature. Barbieri, Hall, and Strumia (2) show that rare decays are signatures for grand unified supersymmetry and calculate the rates for $\mu^+ \to e^+\gamma$ and related processes for a wide range of parameters of these models. They conclude that $\mu^+ \to e^+\gamma$ has the largest rate by more than two orders of magnitude, and it ranges between the current experimental limit and 10^{-14}. Figure 1 was prepared by Barbieri (3) for a minimal SO(10) supersymmetry and plots the predicted branching ratio for $\mu^+ \to e^+\gamma$ and $\mu^-\text{Ti} \to e^-\text{Ti}$ as a function of the top Yukawa coupling at the grand unification scale. These theories have many free parameters, e.g., the mass of the supersymmetric intermediate-vector-boson, for which there is no preferred values, and each point in the figure is the calculated result for sampling these parameters randomly over their reasonable range. The points above the heavy, horizontal line are already excluded by experiment. A tantalizing feature of this plot is that all points appear to be above roughly 10^{-14}, leaving open the possibility that a new generation of experiments might actually push the parameters into an awkward corner of their allowed region. In fact, Hall (4) states that the most natural parameters would lead to values above 10^{-13}.

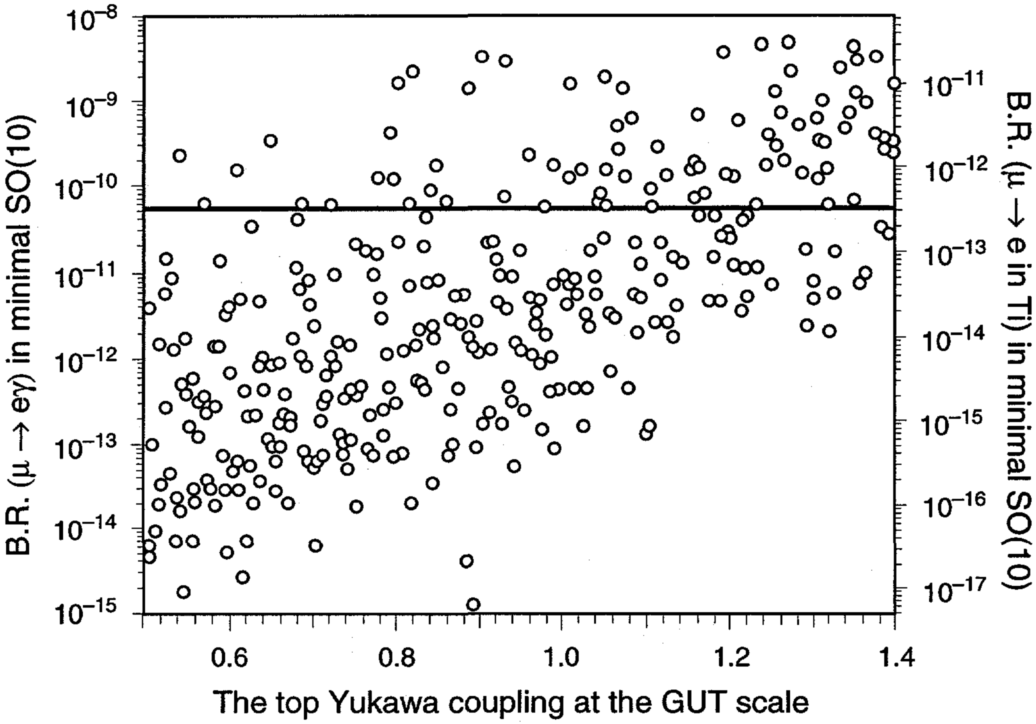

FIGURE 1. Predicted branching ratios for $\mu^+ \to e^+\gamma$ and $\mu^-\text{Ti} \to e^-\text{Ti}$ as a function of the top Yukawa coupling at the grand unification scale of a minimal SO(10) model. Each point is the result when the other parameters of the model are chosen randomly over their likely range.

ONGOING EXPERIMENTS

The smallest limits on branching ratios for rare decays come from muon and kaon decays. However, there are interesting limits from other mesons that can provide useful constraints on specific models. Therefore, this overview will try to touch on all the recent results.

A characteristic aspect of all muon experiments is that the muon lifetime is sufficiently long to require stopping the muons in a detector. A typical detector is that of SINDRUM II, shown in Fig. 2 as it will look after upgrades in 1998. The main features include the pion-muon converter (PMC) (A) designed to provide 10^8 muons to stop in the target (D), a superconducting magnet (L) to analyze the momentum of the decay products, a set of tracking chambers (I,J) to visualize the electron trajectories, and a set of trigger counters (F). The most important upgrade is the PMC, which will pass a very high rate of muons without allowing pions into the detector to very high precision. Decays of pions in the apparatus would produce unacceptable backgrounds. The goal of this detector system is a sensitivity of 2×10^{-14} for the muon-electron conversion process from a nucleus by 1999.

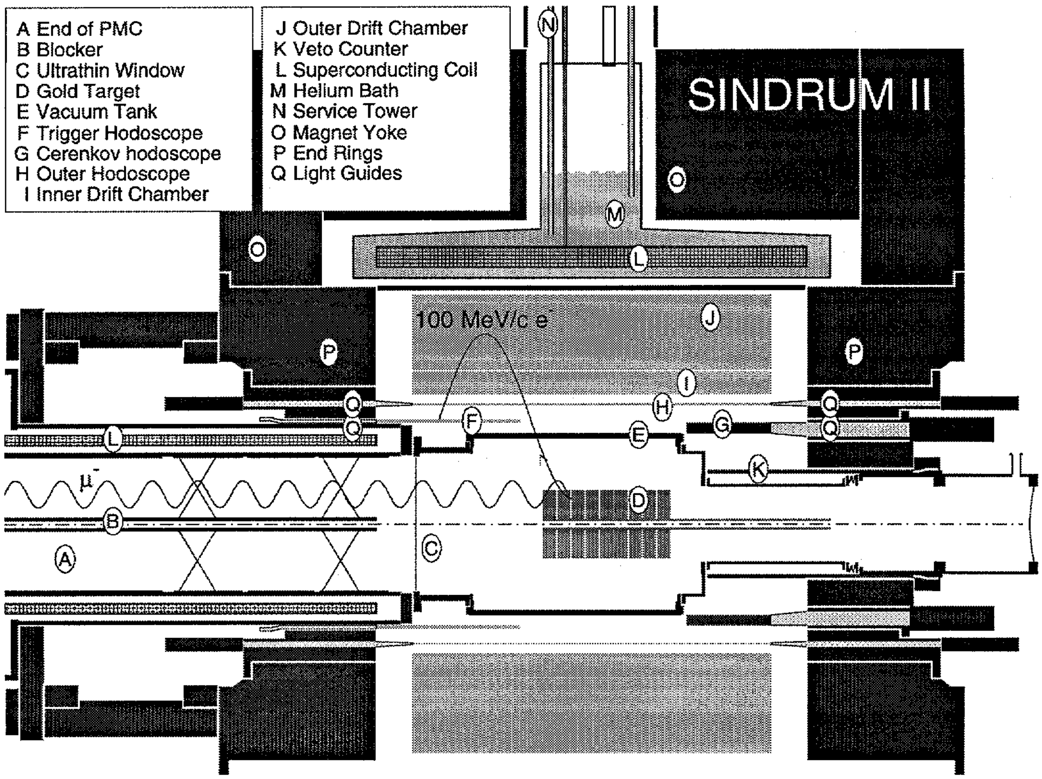

FIGURE 2. The SINDRUM II detector as it will look after addition of the PMC.

Even without the PMC, the SINDRUM II detector has produced the best limits on muon-electron conversion. Figure 3 shows their data when the beam was prepared with degraders and a beam scintillator as a method to eliminate pions. For this data set, the most serious backgrounds are a photon from a cosmic-ray shower that converts to a high-energy electron in the target and prompt decays associated with residual pions. The three curves are the electrons from the target, the spectrum after the

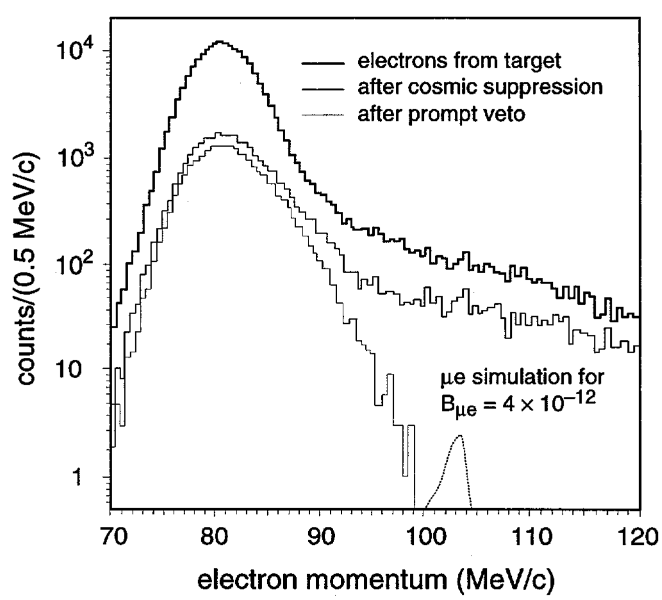

FIGURE 3. Electron spectra from SINDRUM II searching for muon-electron conversion in Ti.

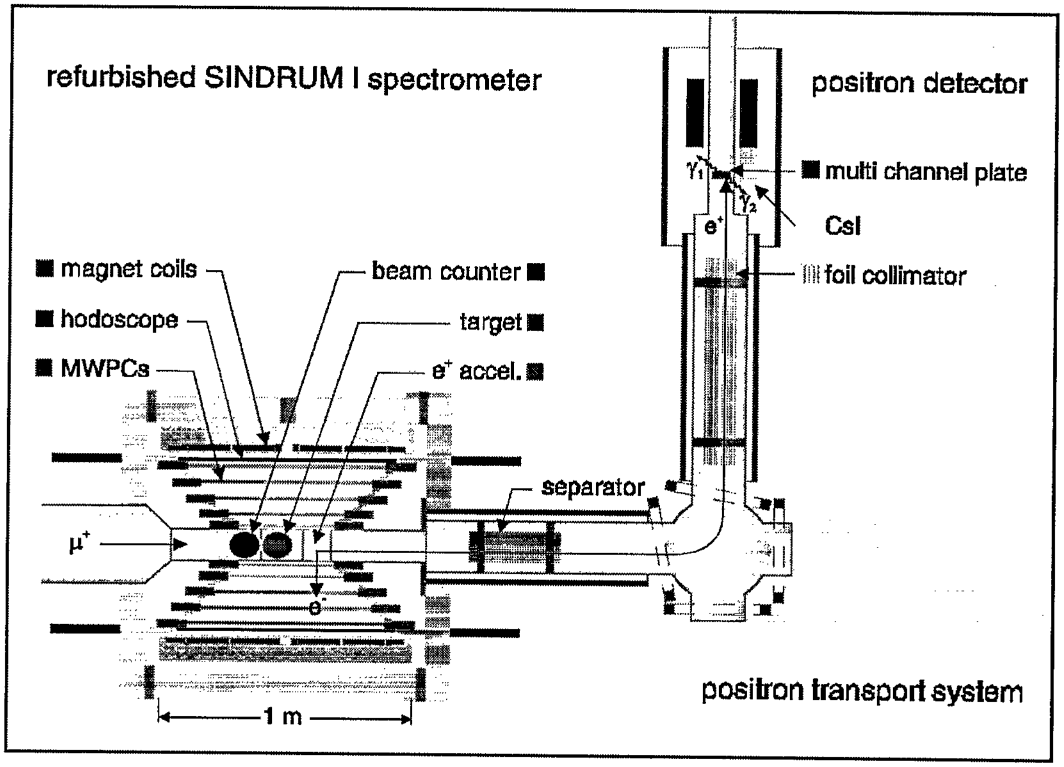

FIGURE 4. The refurbished SINDRUM I detector used to look for muonium, anti-muonium conversion.

suppression of cosmic rays, and the spectrum after the elimination of the prompt signals. Also shown is the expected signal if the branching ration were 4×10^{-12}. They see no signal events and set limits of 7×10^{-13} for $\mu^{-}\text{Ti} \to e^{-}\text{Ti}$ and 1.7×10^{-12} for $\mu^{-}\text{Ti} \to e^{+}\text{Ca(g.s.)}$ (5). The peeling away of backgrounds as more stringent requirements are placed on events is quite typical of how a potential signal is isolated in these types of experiments.

The SINDRUM I spectrometer, originally used to search for $\mu^{+} \to e^{+}e^{+}e^{-}$, has been refurbished to seek the spontaneous conversion of muonium to anti-muonium. The new detector is shown in Fig. 4. It features a target where the muons are brought to atomic velocities to produce muonium that subsequently drifts into a decay region outside the target. If a conversion to anti-muonium were to occur, a high energy electron from μ^{-} decay would be observed in the magnet spectrometer and a very low energy positron would be left behind. To suppress backgrounds, it is necessary to observe the positron. The positron is seen by accelerating it and analyzing it in the transport system. Finally, its position is determined by a multi-channel plate and its sign is verified by observing the annihilation products. Figure 5 shows the events that might be candidates for muonium, anti-muonium conversion. The ordinate is the quality of the vertex

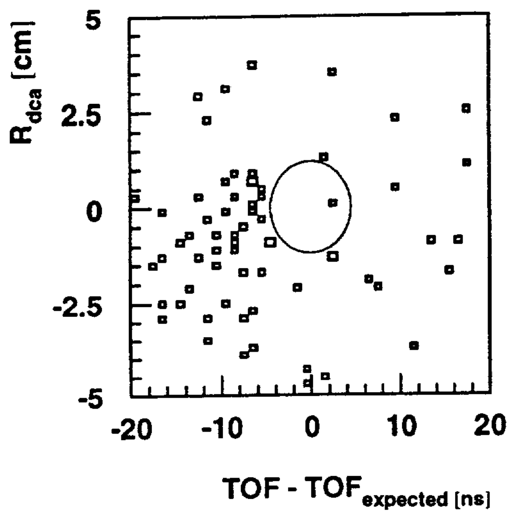

FIGURE 5. Candidate events for muonium, anti-muonium conversion characterized by the quality of their vertex and their relative timing.

between the high-energy electron and the low-energy positron, and the abscissa is their relative time. The circle is a 3σ-ellipse around the signal location. The one event inside is consistent with background, and there are no events in the region of 90% confidence. The result is an upper limit for the size of the coupling constant that could induce such a transition of $< 3 \times 10^{-3}\ G_F$, which is a factor of 2500 better than the previous measurement (6).

Rare decays of the kaon must be handled differently in experiments from those of the muon because of the much shorter lifetime. A typical kaon experiment is Brookhaven experiment 871, a search for $K_L \to \mu e$, whose apparatus is sketched in Fig. 6. The detector system features a decay region and high-rate, position-sensitive elements for tracing the decay products back to a vertex. The decay products are momentum analyzed and then particle-identified in Čerenkov detectors and muon range-finders. Results from this search are expected in the near future. The collaboration has observed more than 5000 $\mu\mu$ events, a remarkable example of the improvement in experimental technique considering that the $K_L \to \mu\mu$ had not been seen convincingly roughly a decade earlier (7). Eventually, their sensitivity for $K_L \to \mu e$ should be a few times 10^{-12}.

A related process is sought after by Brookhaven experiment 865, the decay $K^+ \to \pi^+\mu^+e^-$. The group is reporting a result of B.R. (90% C.L.) $< 2 \times 10^{-10}$, and when combined with their previous value gives B.R. (90% C.L.) $< 1 \times 10^{-10}$ (8). A second related decay is $K_L \to \pi^0\mu e$ that has been studied at Fermilab. The CP-group has a result of B.R. (90% C.L.) $< 3.2 \times 10^{-9}$, but expects the eventual results from KTEV to be better than 10^{-10} (9).

A number of other rare processes have had limits set on them at around the 10^{-6} level. Usually, they are not too restrictive on extensions to the Standard Model, though they can press special models. The new results for τ, D^0, B^0 are summarized in Table 1, which is discussed at the end (10). One somewhat different set of decays are those of the Z^0, where the mass of an external line is more comparable to the masses of the internal lines. Some new limits for purely leptonic processes are B.R. ($Z^0 \to e\mu$, 95% C.L) $< 2 \times 10^{-6}$; B.R. ($Z^0 \to e\tau$, 95% C.L) $< 7.3 \times 10^{-6}$; and B.R. ($Z^0 \to \mu\tau$, 95% C.L) $< 10 \times 10^{-6}$ (11).

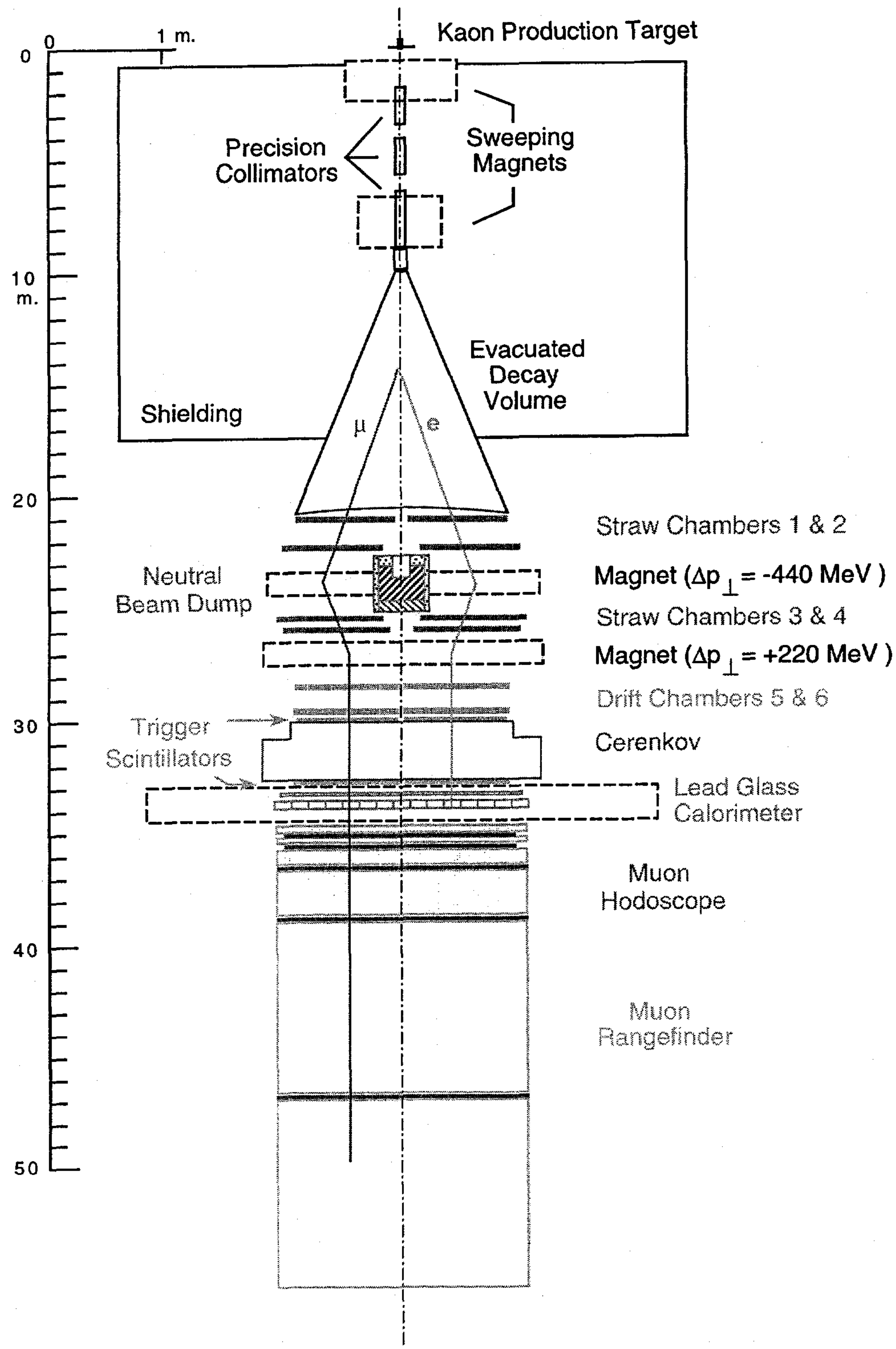

FIGURE 6. A sketch of the apparatus for Brookhaven experiment 871, a search for $K_L \to \mu e$.

TABLE 1. Results on Rare Decays since the last CIPANP Conference

Process	New Limit	Reference
$\mu^+ \rightarrow e^+\gamma$	3.8×10^{-11}	This report
$\mu^-\text{Ti} \rightarrow e^-\text{Ti}$	7.0×10^{-13}	(5)
$\mu^-\text{Ti} \rightarrow e^-\text{Ca}$	1.7×10^{-12}	(5)
$\mu^+e^- \rightarrow \mu^-e^+$	$3.0 \times 10^{-3}\ G_F$	(6)
$K^+ \rightarrow \pi^+\mu^+e^-$	1.0×10^{-10}	(8)
$K_L \rightarrow \pi^0\mu e$	3.2×10^{-9}	(9)
$\tau \rightarrow e\gamma$	2.7×10^{-6}	(10)
$\tau \rightarrow \mu\gamma$	2.9×10^{-6}	(10)
$\tau^- \rightarrow e^-\pi^0$	3.7×10^{-6}	(10)
$\tau^- \rightarrow \mu^-\pi^0$	4.0×10^{-6}	(10)
$D^0 \rightarrow \mu e$	1.9×10^{-5}	(10)
$D^0 \rightarrow \pi^0\mu e$	8.6×10^{-5}	(10)
$D^0 \rightarrow \phi\mu e$	3.4×10^{-5}	(10)
$B^0 \rightarrow K^-\mu e$	1.2×10^{-5}	(10)
$B^0 \rightarrow K^{*0}\mu e$	2.7×10^{-5}	(10)
$Z^0 \rightarrow \mu e$	2.0×10^{-6}	(11)
$Z^0 \rightarrow \tau e$	7.3×10^{-6}	(11)
$Z^0 \rightarrow \tau\mu$	1.0×10^{-5}	(11)

IDEAS FOR NEW EXPERIMENTS

The excitement being generated by the possibility of observing a signal associated with supersymmetry has initiated designs for future experiments that may span the full range of predictions in Fig. 1. The most promising arrangements aim for sensitivities of 10^{-14} and 10^{-16} for $\mu^+ \rightarrow e^+\gamma$ and $\mu^-\text{Ti} \rightarrow e^-\text{Ti}$, respectively. The MECO detector (12) would search for the latter process by utilizing a very intense source of μ^- (10^{11}/s) from a superconducting-solenoid bottle (13). Pion contamination in the beam is suppressed sufficiently by pulsing the proton beam and by the momentum acceptance of the transition region between the source and the detector. The detector, which is designed to see high energy electrons only, is shown in Fig. 7. It has three important regions. To the left is a multi-layer target designed to minimize contributions to the energy resolution due to straggling in the stopping material. The central element is a set of straw tube detectors designed for tracking the high energy positrons with a resolution of about 0.8-MeV FWHM. Finally, there is a cylindrical barrel of scintillators for the trigger. The detection elements have a hole in the center to allow the products of normal muon decay pass harmlessly through the detector. Estimates of background rates in this very high rate environment are under study.

In March of 1997, there was a workshop held at the Paul Scherrer Institute in Switzerland on "A New $\mu^+ \rightarrow e^+\gamma$ Experiment" (14). Many configurations were studied, but a final design is unsettled. In general, the problem is to keep the

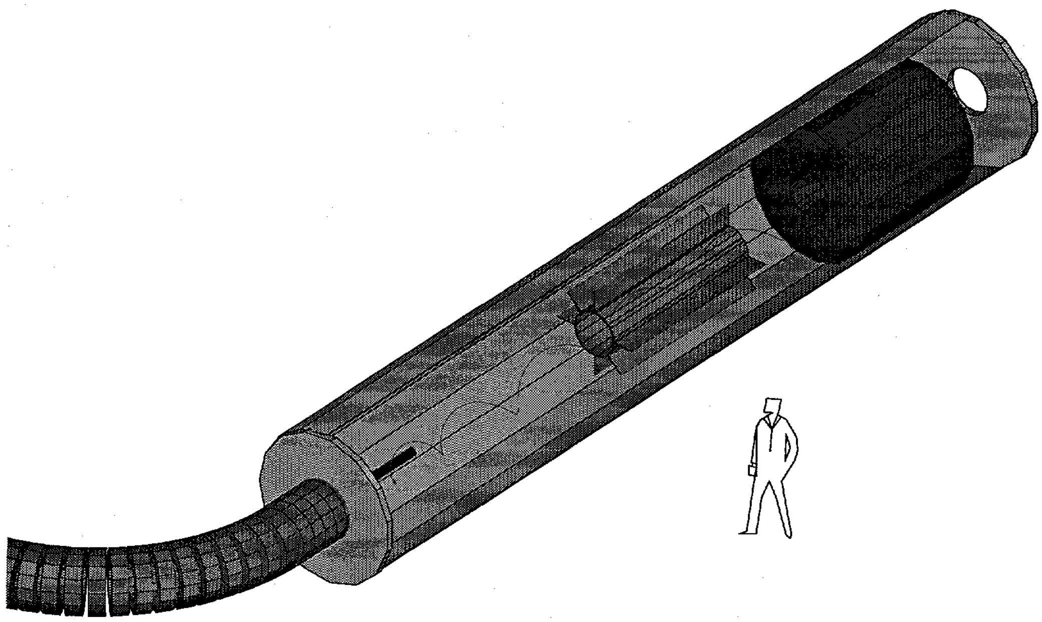

FIGURE 7. The MECO detector under design for a new search for $\mu^- Ti \rightarrow e^- Ti$ with a sensitivity of 10^{-16}.

acceptance high while suppressing accidental coincidences. However, the conclusion of the workshop was that a 10^{-14} experiment looks feasible.

One interesting idea for suppressing accidental backgrounds has been developed for stopped, polarized muons (15). If the muons are polarized along the beam direction, then the angular distribution of the positrons and photons is given by

$$\begin{array}{lll} \mu^+ \rightarrow e^+ \nu\nu & d\Gamma/d\theta_e \sim 1 + P_\mu \bullet k_e & \text{for } E_e \sim 53 \text{ MeV}, \\ \mu^+ \rightarrow e^+ \gamma\nu\nu & d\Gamma/d\theta_\gamma \sim 1 + P_\mu \bullet k_\gamma & \text{for } E_\gamma \sim 53 \text{ MeV}, \\ \mu^+ \rightarrow e^+ \gamma & d\Gamma/d\theta_e \sim \text{unknown} & \text{for } E_e \sim 53 \text{ MeV}. \end{array}$$

As the angular correlation of the $\mu^+ \rightarrow e^+ \gamma$ process is unknown, it is necessary to search in both the forward and backward hemispheres. At backward angles, either the high-energy positron or photon is suppressed. The suppression factor is large and crudely $(1 - \cos\theta)/(1 + \cos\theta) \sim 0.05$ for $\theta \sim 25°$. To realize this factor, two back-to-back apparatuses are needed, one with the photon detector at back angles and the other with the electron detector at back angles. With a large solid angle detector, the suppression factor is considerably worse but still worth incorporating into a design.

A large solid-angle detector is needed for beam intensities of 10^8/s. However, for intensities of 10^{10}/s, a small solid angle detector would be practical and well matched to the use of polarized muons (16). The idea would be to use a beam similar to that planned for MECO. It is unknown whether the rate, about 1/10 of the total possible, can be achieved with a high polarization. The idea is based on the fact that the sensitivity formula depends on the product of the solid angle and the rate:

$$S\,(90\%\ \text{C.L.}) = 2.3/M\,,$$

where

$$M = (\Omega_0/4\pi) \bullet \varepsilon_\gamma \bullet \varepsilon_p \bullet E_c \bullet R \bullet T\ ,$$

and Ω_0 is the overlap solid angle, ε_γ is the gamma-ray detection efficiency, ε_p is the positron detection efficiency, E_c is the cut efficiency, R is the average stop rate, and T is the live time. If the rate is as high as suggested above, then the solid angle can be small. Hence, small solid-angle, special-purpose spectrometers can be used that solve the problems of high singles rates and costs. The sensitivity is estimated to be 10^{-14}, and the result would be free of background.

STATUS REPORT ON MEGA

The experimental signature for an at-rest $\mu^+ \to e^+\gamma$ is a 52.8-MeV positron that is back-to-back and in time coincidence with a 52.8-MeV photon. The MEGA experiment, designed to search for it, has been described several times (17). Briefly, it consists of a magnetic spectrometer for the positron and three pair spectrometers for the photon. The apparatus has been optimized for high rates and for good resolution to suppress backgrounds; the principal background is random coincidences. MEGA had three period when it took beam, one during each of 1993, 1994, and 1995. The data samples have a ratio of sizes of roughly 1:2:3. The apparatus is mothballed and scheduled to be dismantled unless the analysis shows something surprising.

The total number of muons stopped in the apparatus was 1.5×10^{14} in roughly 10^7 s. There are 4.5×10^8 events on magnetic tape awaiting analysis. The analysis is proceeding in three stages. The first reconstructs the kinematic parameters of the particles; the second refines the reconstruction, and the last cuts away kinematically uninteresting events. At the time of this report, the data from 1993, about 1/6 of the total, has been processed through all three steps.

In general, the reconstruction algorithms trade improving the resolution of the particles for maximizing the efficiency and suppressing backgrounds. The three easiest response functions to measure are the photon energy resolution, the positron-photon timing, and the positron energy resolution. Each is done with a different technique.

The primary beam conditions with stopping muons do not contain any sharp photon lines. In order to get a sharp photon line, negative pions are stopped in polyethylene. They charge exchange roughly 50% of the time and produce a slowly moving π^0 that, in turn, decays into two photons. If one selects those photons that happen to be nearly back-to-back, one gets a narrow line at 55 MeV from the lower energy photon, quite near the endpoint of the location of any possible photon from $\mu^+ \rightarrow e^+\gamma$. The spectrum of such events is shown in Fig. 8. The energy resolution is near that predicted.

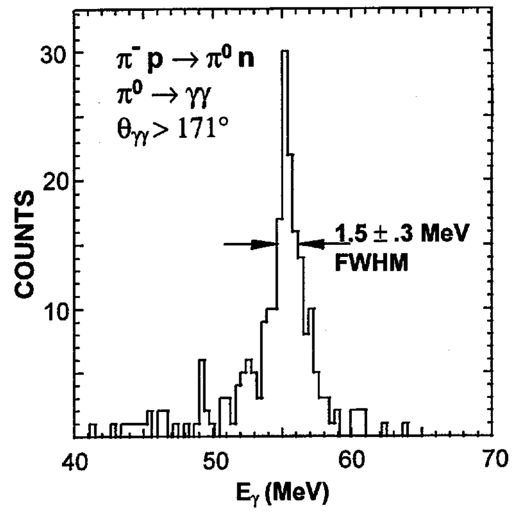

FIGURE 8. Photon energy response for 55-MeV gamma rays from π^0 decays.

The relative time resolution can be measured by looking for the allowed process $\mu^+ \rightarrow e^+\gamma\nu\nu$. This internal bremsstrahlung correction to ordinary muon decay can only be seen easily at low rates where the random backgrounds are greatly reduced. The timing spectrum is shown in Fig. 9. Improvements in calibration constants are expected to improve the timing to be nearly 1 ns FWHM. Observation of this decay is reassuring because it is the proof that the detector sees some events that it should.

The positron energy spectrum has a kinematic edge at 52.8 MeV. The resolution is given accurately by the energy difference between the 10 and 90% points on the edge and is about 500 keV FWHM. At high rates, the positron spectrum acquires a high-energy tail due to the improper reconstruction of unphysical events made from random hits in the detector; these are shown in the upper left panel of Fig. 10.

The panels of Fig. 10 show the shapes of the random backgrounds for the energies, times, and directions of the positron and photon. The Monte-Carlo response to a signal is also shown. The shapes of each curve is quite distinct between signal and background for all the variables even on these expanded scales. The deviation from a constant time spectrum for accidental coincidences is understood in terms of the acceptance of the on-line filtering software. Some of the contribution to the photon spectrum in the unphysical region above 55 MeV has been identified as originating from two separate photons.

Figure 11 is a plot of photon versus positron energy for those events with cuts on all other variables around the signal region. The box shows the signal region. It contains no events. The absence of signal corresponds to a branching-

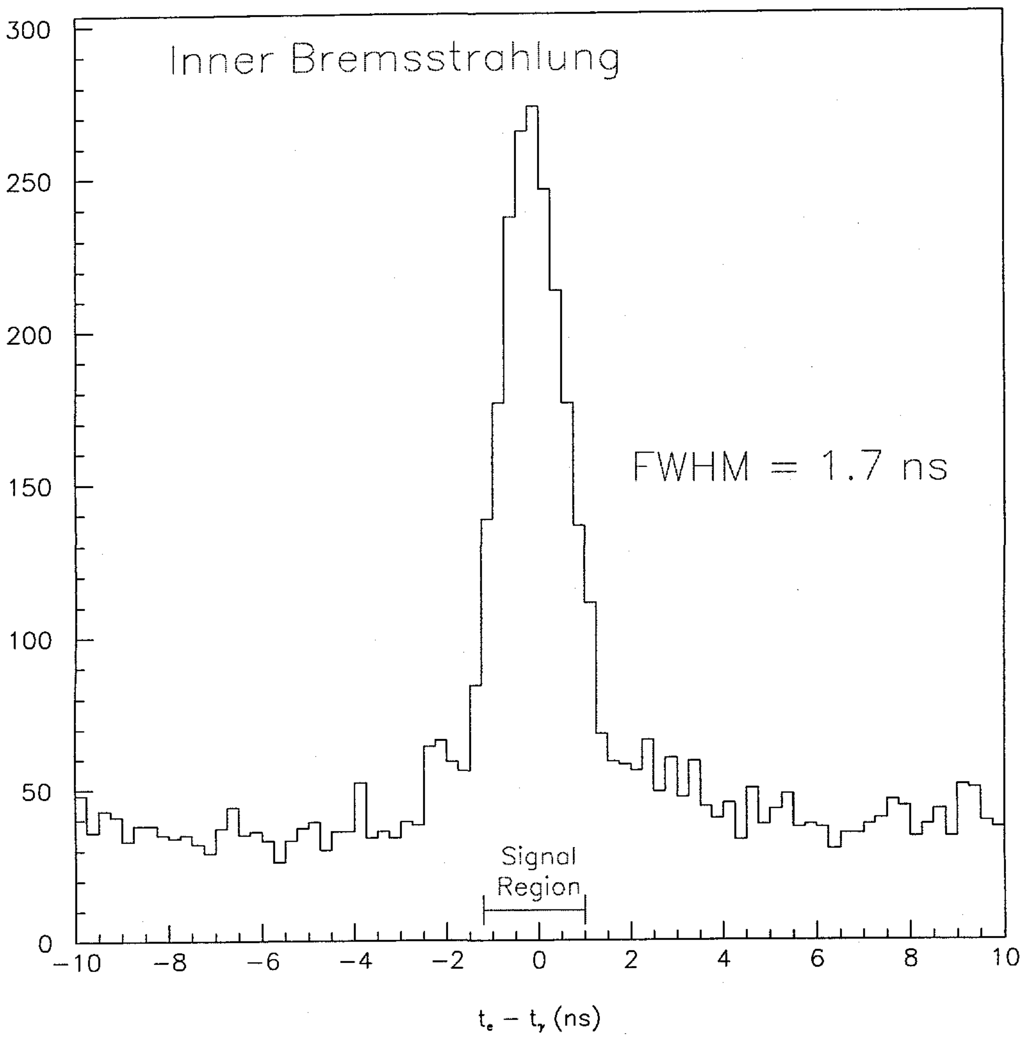

FIGURE 9. Positron-photon timing for the process $\mu^+ \rightarrow e^+\gamma\nu\nu$ process at low rates.

ratio limit (90% C.L.) of $< 3.8 \times 10^{-11}$ for $\mu^+ \rightarrow e^+\gamma$, a small improvement over the published value but background free.

It is to be expected that Fig. 11 contains no events for positrons above 53 MeV because the probability of getting such an unphysical particle is small. However, as noted above, a background from two separate photons has been identified that gives high energy events that are equally probable near 50-MeV positron energy as near 52.8-MeV positron energy. Hence, it would be nice to eliminate the five events with photon energies above 50 MeV. It is work still in progress, but indications are that four of the five photons are dubious; eliminating such events will cost about 10% of the acceptance. Hence, there is a reasonable probability that the box will remain empty if there is no signal as the balance of

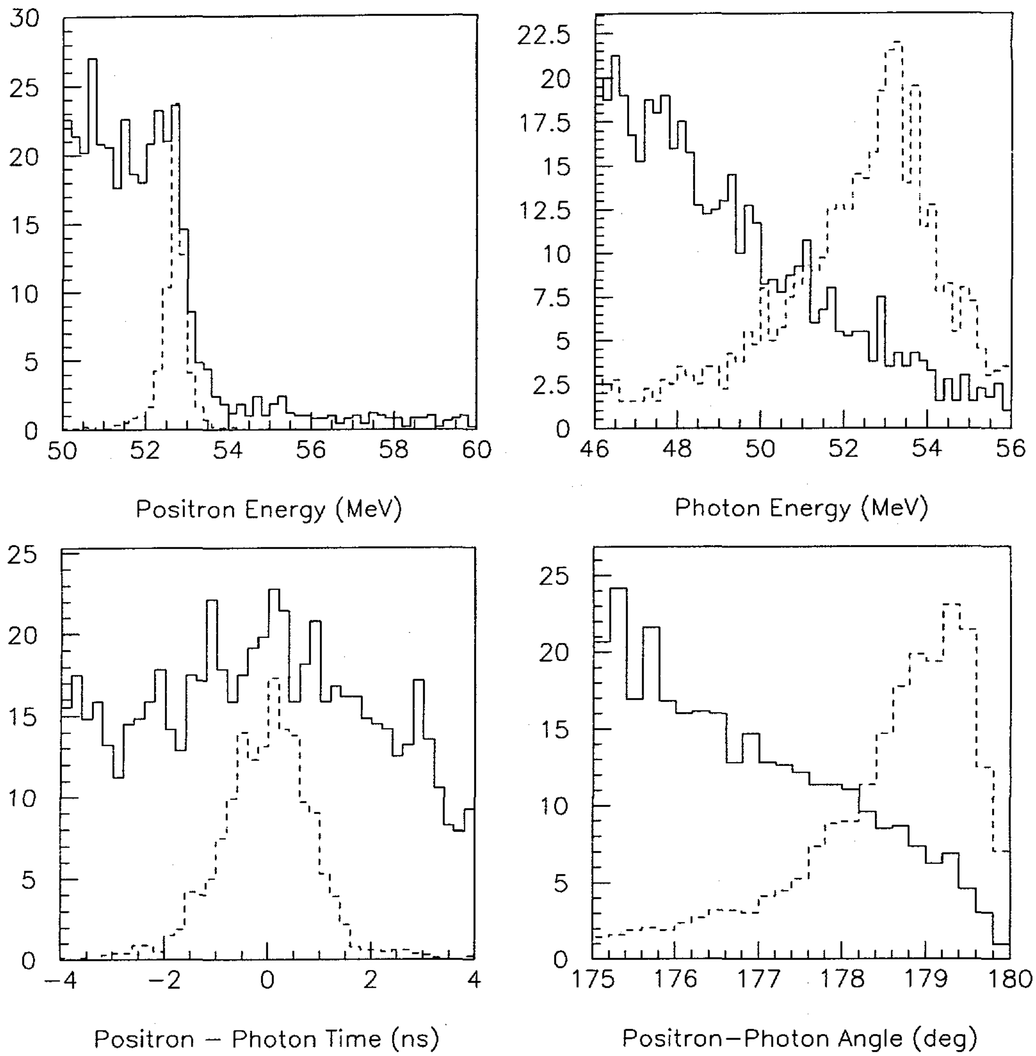

FIGURE 10. Solid curves are the data for random events near the signal region for the positron and photon energies as well as the relative timing and angle. Dashed curves are the Monte-Carlo simulated events for the $\mu^+ \rightarrow e^+\gamma$ signal.

the data are analyzed, and it is expected that a background-free sensitivity can be obtained at a level between 3–5 $\times 10^{-12}$ for the full data set.

SUMMARY

The search for lepton-number violation has been a very active field since the last Conference on the Intersections of Particle and Nuclear Physics in St. Petersburg. Table 1 shows all of the new results since that meeting. Many more

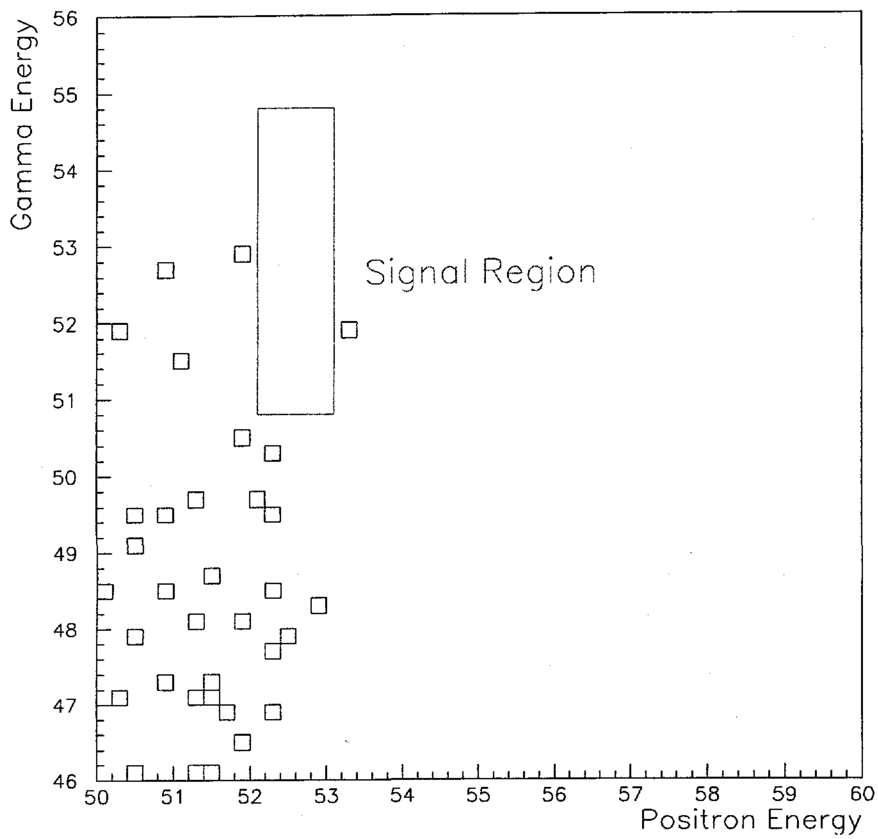

FIGURE 11. Photon energy versus positron energy with cuts on timing and back-to-back angle from high-rate data.

experiments are taking data, and plans are underway for even more ambitious goals. The popularity of supersymmetric extensions to the Standard Model is currently driving this area of research, and rare decays may provide evidence for both supersymmetry and grand unification. The field appears both vibrant and compelling.

REFERENCES

1. Melese, P., *Comments Nucl. Part. Phys.* **19**, 117 (1989).
2. Barbieri, R., Hall, L., and Strumia, A., *Nucl. Phys. B* **449**, 437 (1995).
3. Barbieri, R., in *Workshop on a New $\mu^+ \to e^+\gamma$ Experiment*, Paul Scherrer Institute, 1997.
4. Hall, L., in *Conference on the Intersections of Particle and Nuclear Physics*, Big Sky, Montana, 1997.
5. Riepenhausen, F., in *Conference on the Intersections of Particle and Nuclear Physics*, Big Sky, Montana, 1997.
6. Meyer, V., in *Conference on the Intersections of Particle and Nuclear Physics*, Big Sky, Montana, 1997.

7. Bachman, M., in *Conference on the Intersections of Particle and Nuclear Physics*, Big Sky, Montana, 1997.
8. Eilerts, S., in *Conference on the Intersections of Particle and Nuclear Physics*, Big Sky, Montana, 1997.
9. Ansaka, K. et al., University of Chicago Preprint EFI 95-08; Corcoran, M., in *Conference on the Intersections of Particle and Nuclear Physics*, Big Sky, Montana, 1997.
10. Edwards, K. W. et al., *Phys. Rev. D* **55**, 3919 (1997); hep ex/9704010; Freyberger, A. et al., *Phys. Rev. Lett.* **76**, 3065 (1996); Cornell University CLEO94-4.
11. Adriani, O. et al., *Phys. Lett. B* **316**, 427 (1993); *Lepton-Photon Conference*, Brussels, 1995.,
12. Bachman, M. et al., UC Irvine Phys. Tech. Report 96-30; Molzon, R., in *Conference on the Intersections of Particle and Nuclear Physics*, Big Sky, Montana, 1997.
13. Djilkibaev, R., and Lobashev, V., *Sov. J. Nucl. Phys.* **49(2)**, 384 (1989).
14. Walter, H. K., in *Conference on the Intersections of Particle and Nuclear Physics*, Big Sky, Montana, 1997.
15. Kuno, Y. et al., *Phys. Rev. D* **55**, 2517 (1997); Kuno, Y., and Okada, Y., *Phys. Rev. Lett.* 77, 434 (1996).
16. Cooper, M., in *Conference on Flavor Physics*, Tsukuba, Japan, 1996.
17. Hogan, G. E. et al., in *International Conference on High Energy Physics*, Warsaw, 1996; Los Alamos National Laboratory document LA-UR-96-3749.