FERMILAB-CONF-10-048-E

A New Proposal to Measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

D. A. Jensen

Fermi National Laboratory PO Box 510, Batavia IL, 60510

Abstract. For an experimentalist in high energy physics, the most interesting experiments that one should pursue is often well known. The very rare CP violating decay of the kaon into a pion and two neutrinos (both the charged and neutral modes) is such an experiment. We have recently proposed the charged kaon experiment to Fermilab as proposal P966. We present her a general overview of that proposal. The goal is to obtain of order 1000 events in order to confront the expected theoretical calculations and to search for physics beyond the standard model.

Keywords: K decay, CP violation.
PACS: 10.14.40.Dx, 20.29.30.Aj, 20.29.40.Gx

INTRODUCTION

It is often the case that very interesting questions in physics are well known by the community. This is particularly the case in high energy physics. A very nice example is in chapter 19 of Okun's[1] first book on particle physics: there is a list of experiments that he suggests should be done, which includes, among others:
- "Check of CP invariance."
- "Check the hypothesis that the muon neutrino and electron neutrino are different particles"
- "Search for the intermediate vector W-boson."

These were, in the 60's, what one might refer to as 'textbook questions'. There was little doubt that these questions should be addressed experimentally. As will be recognized, most of these questions were addressed in succeeding years, gaining considerable accolades from the particle physics community. It is usually the case that these experiments became possible through improvements in experimental and / or accelerator techniques.

The measurement of the branching ratio of the decay $K \rightarrow \pi \nu \bar{\nu}$, where the K and π can be either + or neutral, are currently such experiments. Considerable theoretical and experimental work has been done to understand these processes. The recommendation of recent panels[2] emphasizes that the goal of the experiments should be to confront theory at the level of accuracy of the theory. As will be discussed below such an experiment would need to obtain of order 1000 events, as the theory is expected to approach an accuracy of order 3% within the next few years.

In proposal P996[3] as submitted to Fermi National Accelerator Laboratory, we propose to carry out this experiment for the K^+ decay. The technological innovation that makes it possible to better previous experimental efforts by of order 1000 is the idea of using the Tevatron superconducting synchrotron as a stretcher ring for main injector beam. This makes it possible to obtain a large number of K^+'s stopping in a target with minimal instantaneous rate. The detector to be used is an upgrade of a previous detector – the detector used in the Brookhaven National Laboratory Experiment E 987[3].

In the following sections, a broad overview of the proposed experiment is presented. Many details are not included here, but may be found the in the proposal. In particular, cost and schedule, where the experiment might be located and exactly which magnet might be used are not discussed. Accelerator operation and details of the detector upgrades are only briefly sketched.

Theory of $K^+ \to \pi^+ \nu \bar{\nu}$

The K decays to pions plus neutrinos are particularly interesting because decays proceed at lowest order through loop diagrams, usually highly suppressed with respect to other channels. The lowest order diagrams for the K^+ decay are shown in figure 1. The basic interaction is simple: $\bar{s} \to d$ through $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$.

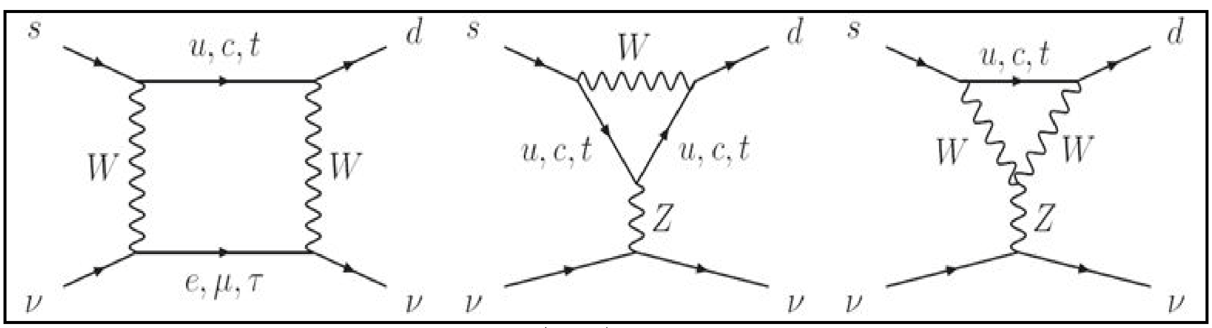

Figure 1 Feynman diagrams for lowest order $K^+ \to \pi^+ \nu \bar{\nu}$

The branching ratio can then be calculated as[4]:

$$BR(K^+ \to \pi^+ \upsilon \bar{\upsilon}) = \frac{\tau_{K^+} M^5_{K^+}}{32\pi^3}(1+\Delta_{EM}) \,|\, f_+^{K^+\pi^+}(0) \,|\, I_\upsilon^+ \,|\, \frac{G_F \alpha(M_Z)}{2\pi\sqrt{2}\sin^2\theta_W} Y|^2 \qquad (1)$$

Where the matrix element Y is

$$Y = V_{td}^* V_{ts} X(x_t) + V_{cd}^* V_{cx}[\, X(x_c) + |V_{us}|^4 \delta P_{cu} \,] \qquad (2)$$

$$X(x_q) = \frac{1}{3}\sum_{l} X(x_q, x_l) \quad (3)$$

Where V denotes the CKM matrix, $x_q = m_q^2/M_W^2$ and . $x_l = m_l^2/M_W^2$ The functions X are calculated in perturbation theory.

There are of course many higher order diagrams. Currently, the predicted branching ratio for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is $(8.5 \pm 0.7) \times 10^{-13}$. The theory is expected to improve to an accuracy of order 5% in the next few years. The figure 2 shows the current contributions to the errors in the theoretical calculations. Clearly, this is a very complex subject, and there are many contributions the error on the BR calculation.

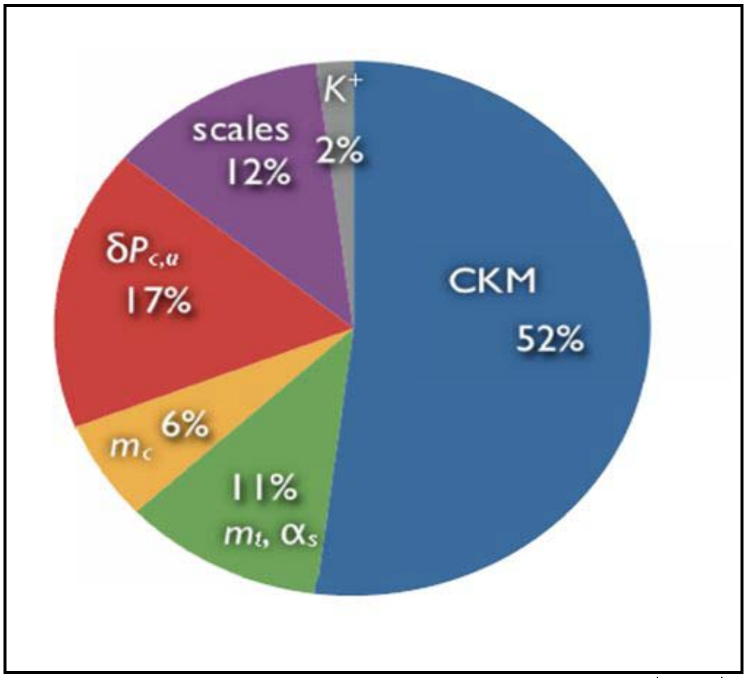

Figure 2 Contributions to the current error on the calculation of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio. The theory as well as the accuracy of the CKM parameters are expect to improve by the time P996 would have results.

It is interesting to note that the theoretical estimation of the branching ration for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is currently, and is expected to remain, more accurate than the calculation of the branching ration for $K^0 \rightarrow \pi^0 \nu \bar{\nu}$.

This sets the level of experimental determination that is of interest. A 3% accuracy requires of order 1000 events. The Fermilab proposal P996 proposes the study of the K^+ mode at this 1000 event level

In addition to the best measurement of the Vts matrix element in the standard model, a precise measurement of . $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in the standard model is sensitive to physics beyond the standard model in loops. For example, new non-standard model particles that might be observed at the LHC might be included by adding terms as $C_{new}X_{new}$ to the matrix element used in calculating the branching fraction above.

There are many studies of for example Minimal Flavor Violation models that would be constrained by P996. A much more detailed discussion of these models is discussed in the proposal and references cited therein.

THE SIGNAL

As already discussed, the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ has a very small branching fraction. When trying to measure this process, other decay channels provide many sources of possible backgrounds. Figure 3 show schematically the decay modes of the K^+, including the mode of interest. In order to observe the signal, all other modes must be rejected. This is effected partly by requiring a very positive signature, and partly be rejecting unwanted modes. A positive signature is generated through the requirement that the K^+ be observed to stop in the target, and then the π^+ be observed leaving from the same region of the target followed by observing the π^+ to decay into a μ^+ and the μ^+ into an e^+ (the π-μ-e sequence). The properties of the π^+ are further constrained by measuring its momentum in the magnetic spectrometer and by its range in the range stack (see Figure 5) A trigger may be rejected if there is for example a photon signal in the veto counters at the entrance or exit of the solenoid, or if there are signals in the surrounding counters without an incoming track.

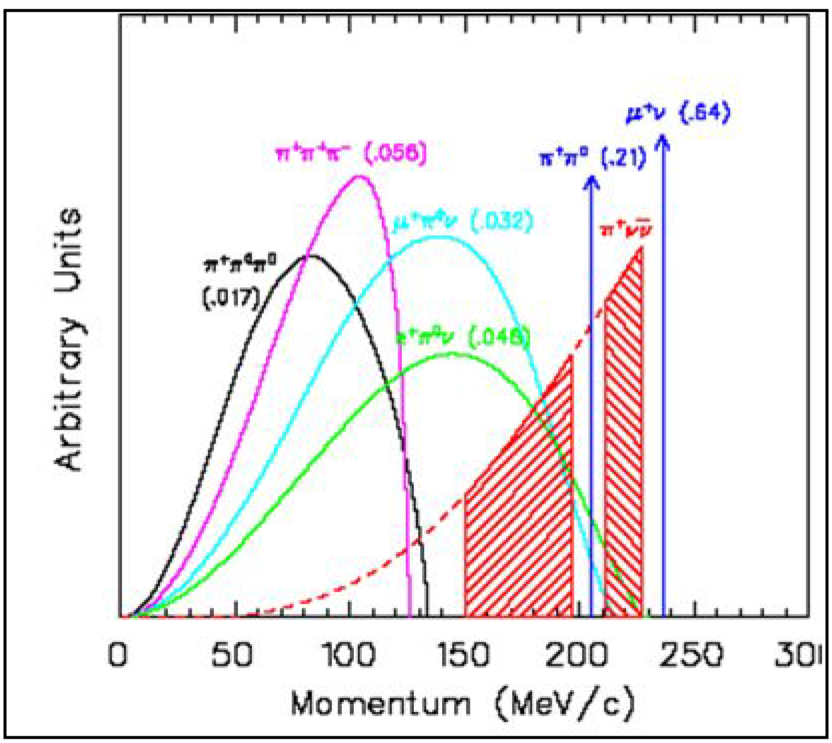

Figure 3 K+ decay modes. The vertical scale is clearly not the same for the different modes. Note that there are two possible signal regions for the K+ decay to two neutrinos. Those areas are shaded in red. The momentum scale is for the charged decay product. Numbers in parentheses are the branching ratios. The red shaded area represents areas where the measurement can be carried out.

THE EXPERIMENT

The first and primary concern in planning an experiment is of course the rate. This concern is of course paramount when addressing a measurement where the branching fraction is so low. As noted in Figure 3, selecting signal events in this decay mode is particularly challenging.
The design of the P996 experiment follows very closely the design of the successful set of experiments carried out at Brookhaven National Laboratory - E787 and E949[5]. The discussion of the experiment P996 is a discussion of how that set of experiments can be improved upon.
There are three aspects of the experiment, each critical to the success if the experiment: the accelerator complex, the secondary K^+ beam and the detector. In each case, significant improvements are proposed. These improvements make it possible to obtain the proposed 1000 events.

Accelerator

The most dramatic improvement in the design of P996 compared to BNL-E987 is the accelerator. We have proposed to use the Fermilab Tevatron, scheduled to stop running as a collider after 2011, as a stretcher ring for the Fermilab Main Injector (MI). The MI currently provides 120 to 150 GeV proton beams to produce anti-protons and protons for the collider and proton beams to the neutrino program and a 4 second slow spill to the test beam. Typically, the MI provides a fast extracted beam to experiments every 2.3 seconds. Slow extracted beam to the test beam facility is provided once per minute. The MI will be upgraded over the next few years to decrease the cycle time so that 150 GeV protons can be delivers once per 1.667 seconds. The proposal is then to use two MI cycles to fill the Tevatron ring with 150 GeV protons (the Tevatron has twice the circumference of the MI). The beam of 96 Tp (teraprotons) would then be slowly extracted over the next 34 seconds. This scheme provides 150 GeV protons to the experiment with a duty cycle of order 95% !
Using the Tevatron ring as a stretcher ring has been tried. At the end of fixed target Tevatron running at the end of 1999 and the beginning of 2000, a test run was carried out to test the technique. 150 GeV beam was delivered to the KTeV experiment as a test run for the proposed KAMI (KAons at the Main Injector) experiment. Slow extracted beam was delivered for about one week. The test was very successful. For P996, the intensity will have to be significantly increased compared to that test run.

The K^+ Beam

The 150 GeV protons are brought to a platinum target of approximately one interaction length. The Brookhaven experiments used a 6 cm Pt target, P996 proposed a 8 cm Pt target. Because of the higher beam energy, K^+ production is improved. The overall improvement in K^+ production is expected to be improved by as much as a factor of (7 ± 2). K^+'s in the forward direction are collected, momentum selected,

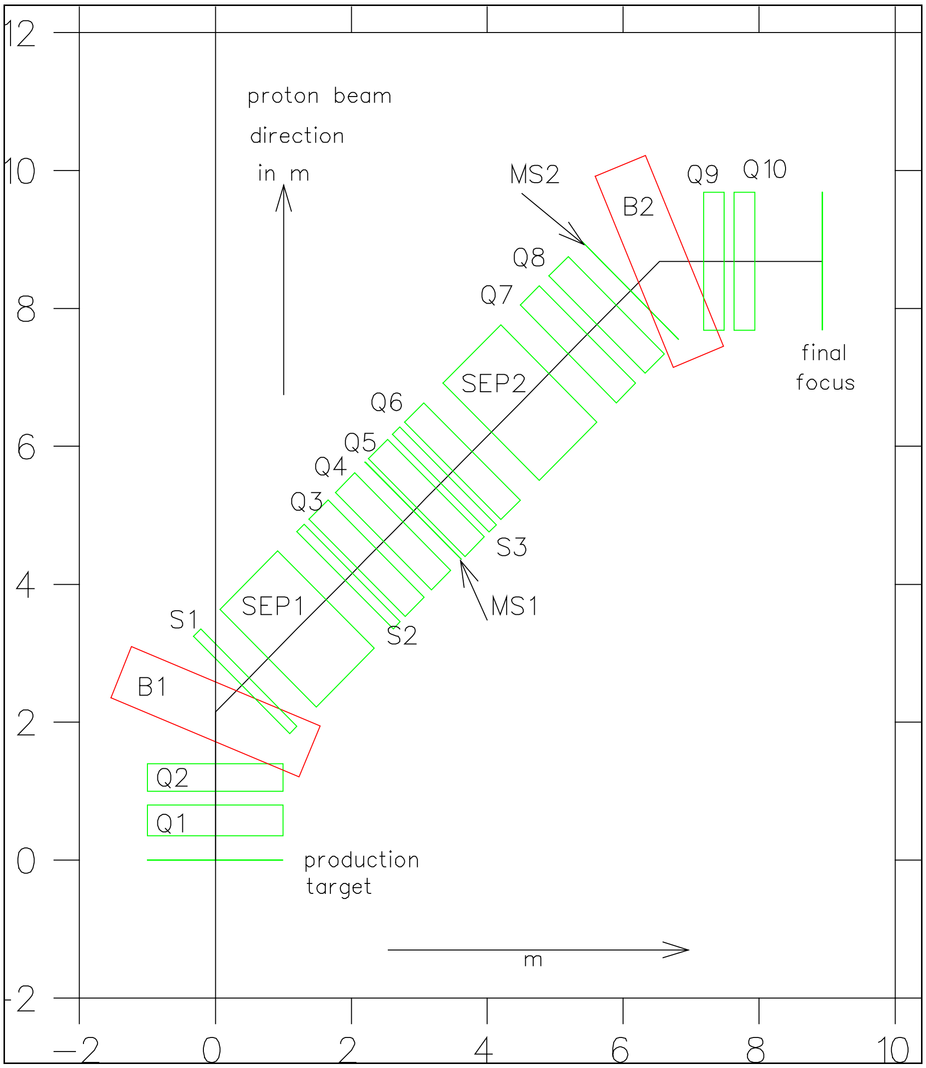

Figure 4 K+ beam design

separated, and focused onto the production target. In the BNL experiment, the secondary K+ beam was 750 MeV/c and was 19.6 meters long. Jaap Dornbos has designed a new beam[6] for this experiment. The new beam is 550 Mev/c and is 13.74 meters long. The layout of the beam is shown in Figure 4. The advantage of the lower beam momentum is that one can achieve better K/π separation, and a larger fraction of the incoming K^+ beam stops in the target. The net result is that with a somewhat higher stopping K^+ rate in the detector, the incoming flux is comparable to that in the Brookhaven experiments. As backgrounds are due primarily to the flux of incoming particles, the background is no worse than the previous experiments– even before improvements to the detector.

The Detector

The P996 detector is very similar to the detector used in the BNL experiments. The detector is shown in Figure 5. The detector is placed in a large solenoid – for example the CDF solenoid, though there are other possibilities. The K^+ beam passes through tracking, hodoscopes, and a Fitch type Cerenkov counter, and enters along the axis of the solenoid, passing through an active degrader on the way to the target where the K^+'s stop. The highly segmented active target consists of scintillator bars. The target is followed by a veto system that is used to define the stopping K+. When the K+ decays, the resulting π^+ is also detected in the target.

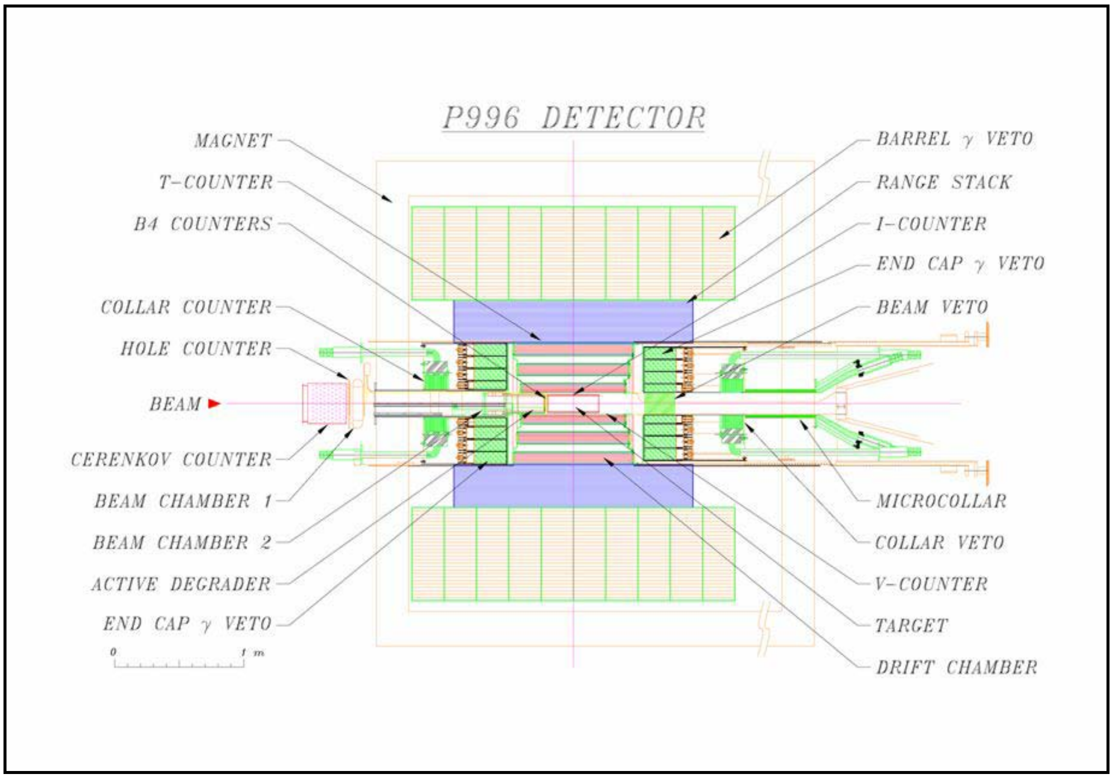

Figure 5 The P996 detector

The momentum of the π^+ is measured in the drift chamber. The π^+ stops in the range stack, which provides validation of the momentum measurement. The π^+ decay is observed within the range stack. The decay μ^+ is also observed and its range measured. The μ^+ decay to an electron is then observed.

The whole detector is surrounded by veto counters providing a full 4π coverage. The veto system is clearly critical to the suppression of background processes.

The data acquisition system will of course also be upgraded to a deadtimeless system. This will significantly improve the dead time, effectively increasing the acceptance of the detector. Timing and signal heights from all of the detectors will be saved for each event.

CONCLUSIONS

The measurement of the branching ratio of $K^+ \to \pi^+ \nu \bar{\nu}$ at the few percent level is now one of the experiments that the high energy physics community recognizes as one of the 'must be done' experiments. Proposal P996 demonstrates how this experiment might be carried out. Comparing the accelerator, beam and detector performance expected in P996 compared to BNL experiment E949, one may obtain an estimate of the $K^+ \to \pi^+ \nu \bar{\nu}$ event rate. As there have been careful calculations of the ratios of improvements in each stage, it is even possible to assign errors to the improvements and thus to the final estimate of the event rate. The number of stopping K^+ is 7.6 MHz, the running time is 5000 hours per year (approximately 60% of wall clock time), with an acceptance of about 4%, and a branching ratio of 0.85×10^{-10}, one obtains an event rate of 194^{+89}_{-79} events per year. The errors are not discussed in this document, but are discussed in detail in the full proposal. With the number of events expected in P998, the predictions based on the Standard Model will be confronted and the window will be open to the observations of new physics beyond the Standard Model.

ACKNOWLEDGMENTS

This paper is presented in memoriam of Agusto Garcia Gonzalez, a colleague who contributed in many ways to our efforts to understand the weak interaction. This talk is based on the Fermilab proposal P996 and the presentations made by R. Tschirhart, J. Ritchie and J Comfort. This work was supported by Fermilab: operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

REFERENCES

1. L. B. Okun, *Weak Interactions of Elementary Particles*, Reading, Massachusetts; Pergamon Press 1965
2. P5 report to DOE at http://www.er.doe.gov/hep/panels/reports/hepap_reports.shtml
3. F. Mescia and C. Smith, Phys. Rev **D 76**, 034017 (2007) [arXiv:0705.2025 [hep-ph]], and other papers referenced in the P996 proposal
4. Joseph Comfort et. al Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ Decay at Fermilab, Fermilab Proposal P996, October 14, 2009 see also references cited therein
5. A. V. Artamonov et al., *Phys Rev* **79**, 092004 (2009).
6. Jaap Dornboss "A 550 MeV/c kaon beam" TRIUMPH, September 16, 2009, unpublished