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The Fermilab Proposal P996: Precision Measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

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Abstract

The high precision measurement of the ultra-rare $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay at Fermilab would be one of the most incisive probes of quark flavor physics this decade. The dramatic physics reach of a precision measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is due to three factors. 1) The Standard Model prediction for the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ branching fractions are broadly recognized as theoretically robust to the 2-4% level. No other loop-dominated quark process can be predicted with this level of certainty. 2) The $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ branching fraction is highly suppressed in the Standard Model to the level of less than 1 part in 10 billion. This suppression allows physics beyond the Standard Model to contribute noticeably to the branching fraction with enhancements of up to factors of 5 above the Standard Model level. 3) The certainty with which the Standard Model contribution to $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is known permits a 5σ discovery potential for new physics even for enhancements of the branching fraction as small as 20% . This sensitivity is unique in quark flavor physics and probes essentially all models of new physics that couple to quarks within the reach of the LHC. Further, precision measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is sensitive to many models of new physics far beyond the direct mass reach of the LHC. The experimental challenge of measuring $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at the 1 in 10-billion Standard Model rate has been met successfully. Several events of the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ process have been clearly observed at BNL. Operating the Tevatron after Run-II as a 120 GeV high-duty factor synchrotron "Stretcher" offers the opportunity to reach more than two orders of magnitude greater sensitivity yielding a 1000-event experiment based on incremental improvements to the techniques refined and firmly demonstrated at BNL. The Fermilab Stretcher would be a unique facility that would provide ideal properties for such rare-decay experiments, allowing the demonstrated performance of the AGS experiment to be extrapolated with confidence to an experiment driven by the Fermilab Stretcher.

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1. Qaark flavor physics in the modern era

The existence of flavor for quarks and leptons gives the Standard Model its structure of families or generations of elementary particles. Higher order effects related to the family structure has been instrumental in the development of the Standard Model (SM). For example, the absence of neutral currents in kaon decay led to the prediction of the charm quark. Kaon decays also led to the observation of matter anti-matter asymmetries (CP violation), and to the Cabibbo-Kobayashi-Maskawa model, which in turn predicted the existence of a third generation of particles. Mixing of neutral B mesons, in a role like that played by neutral kaon mixing in establishing the mass range for the charm quark, was the first experimental observation that correctly anticipated the large value of the top quark mass. The dramatic discovery of neutrino masses provided the first incontrovertible evidence that the original Standard Model was incomplete, and could provide a window to the unification of forces. Several of the great questions of particle physics have flavor at their core, and flavor physics can play a unique and crucial role in the progress of the field.

Numerous elements directly associate LHC physics with flavor. Without a Higgs or some other mechanism of electroweak symmetry breaking (EWSB), quark flavor effects would not even exist. All flavor phenomena in the Standard Model is encoded by a handful of input parameters that currently lack explanation. But beyond the Standard Model, flavor phenomena can cover a much wider landscape and are even more strongly entangled with the dynamics of symmetry breaking. New particles, such as charged Higgs particles or supersymmetric partners, can mediate flavor-changing processes. New flavors may appear, either in the form of new generations, or as exotic partners of standard quarks (such as composite quark states in "little Higgs" models). New sources of CP violation can arise from couplings of non-minimal Higgs sectors or of super-partners. All of these new sources of flavor effects put the natural suppression of most flavor-violating phenomena in the Standard Model in jeopardy, and physicists expect much larger effects from new Terascale physics at the LHC. In the context of Beyond Standard Model (BSM) theories, this is a fundamental issue called "the flavor problem."

Equally important is that in several BSM frameworks, the parameters of flavor are not just arbitrary inputs but instead are the result of dynamics or symmetries of the underlying theory. Unified theories predict relations between the couplings of quarks and leptons. In supersymmetric models with neutrino masses, a mix of symmetry relations and dynamics connects neutrino mixing and flavor transitions in the charged-lepton sector. In extra-dimensional theories, the family replicas can be understood as different branes on which fermions are bound to live, and mixings are tied to the relative positions of these branes in the extra dimensions. In super-symmetric theories, the large value of the top quark mass can dynamically generate electroweak symmetry breaking, making EWSB, in some sense, a flavor-driven phenomenon. Finally, the numerical coincidence of the top mass value with the scale of EWSB is yet another mysterious hint of a possible direct connection between EWSB and flavor.

These connections between symmetry breaking and flavor, as well as the flavor mysteries of neutrino masses and the matter-antimatter asymmetry of the universe, strongly suggest that flavor will play a key role in exploring the new physics landscapes unveiled by the LHC. Most conceivable new physics manifestations will provide new sources of flavor phenomena, underscoring our need to address the flavor problem. The optimal approach to understanding flavor will depend on the details of the discoveries. It is sensible to expect, on the basis of the history of particle physics and of the explicit models of new physics available today, that experiments at the Energy Frontier and flavor experiments at the Intensity Frontier will provide complementary advances in the coming phases of exploration of the laws of nature.

2. Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$

Advanced rare-decay kaon experiments have probed branching fractions in the 10^{-11} – 10^{-12} range including the rarest particle decay ever observed, $B(K_L \rightarrow e^+e^-) = 9x10^{-12}$ [BNL E871] and the discovery of the long sought after process $B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [BNL E949] . These measurements were achieved with 20-50 kW of “slow extracted” proton beam power from proton synchrotrons, the BNL AGS, Fermilab, and others. Next-generation experiments, aimed at 1000-event Standard Model sensitivity to the $K \rightarrow \pi\nu\bar{\nu}$ process, require branching fraction sensitivities at the 10^{-14} level, which require much higher beam with high-duty-factor beams. High-duty-factor beams have historically been limited to 20-30% duty factor. Configuration of the Fermilab Tevatron as a stretcher ring can deliver 100kW of beam power with a duty factor in excess of 90%

Today in Europe CERN experiment NA62 is pursuing the next step in sensitivity beyond discovery with a promising new technique driven by the SPS proton facility which aims for 100-event sensitivity. The NA62 experiment is described elsewhere in these proceedings. The proven techniques developed at the Brookhaven AGS can be further exploited to reach 1000-event sensitivity with the Fermilab Stretcher which could deliver 7 times the rate of K^+ decays realized at the AGS with essentially the same instantaneous rates due to the high beam duty factor possible with the Fermilab stretcher.

The Fermilab Physics Advisory Committee strongly supports the P996 physics case, but has identified the operational costs of the Tevatron stretcher at about $15M/year to be a significant road block to forward progress. The P996 collaboration continues to work with the Fermilab directorate to develop funding scenarios to mitigate these operational costs and move the proposal forward.