The CKM Experiment

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I describe the CKM experiment, a new initiative using the Fermilab Main Injector to obtain $\approx$ 100 events of the ultra-rare decay mode $K^+ \to \pi^+\nu\bar{\nu}$. The branching ratio will be used to extract $|V_{ts}^* V_{td}|$. Due to the decay mode's theoretical cleanliness, it plays a key role in over-constraining the Standard Model description of CP violation.

1. INTRODUCTION

A new initiative at Fermilab called "Charged Kaons at the Main Injector" (CKM) has been proposed to observe $\approx$ 100 events of the decay mode $K^+ \to \pi^+\nu\bar{\nu}$ with about 10 background events[1]. The Standard Model branching ratio for this mode is $O(10^{-10})$.

Along with $B \to J/\Psi - K$, B_s/B_d mixing, and $K_L \to \pi^0\nu\bar{\nu}$, $K^+ \to \pi^+\nu\bar{\nu}$ is one of the four "golden" modes that play a critical role in over-constraining the Standard Model description of CP violation. The leading contributions to this process are short-distance W and Z exchange, with neglibible long-distance contributions (fig. 1).

Since both $K^+ \to \pi^+\nu\bar{\nu}$ and $K^+ \to e^+\pi^0\nu$ involve a single pion in the final state, Inami and Lim[2] noticed that the latter decay mode could be used to understand the $K^+ \to \pi^+$ transition modulo an isospin-breaking correction. Fundamentally, a measurement of the branching ratio allows for a clean extraction of $|V_{ts}^* V_{td}|$[3]:

$$\frac{BR(K^+ \to \pi^+\nu\bar{\nu})}{BR(K^+ \to \pi^0 e^+\nu)} = \frac{3\alpha^2 r_+}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \times |V_{cs}^* V_{cd} F(\frac{m_c}{m_W}) + V_{ts}^* V_{td} F(\frac{m_t}{m_W})|^2 \quad (1)$$

The factor $r_+ = 0.901$ corrects for phase space and isospin-breaking[4]. The F terms are the Inami-Lim functions of the top and charm quark loops. In terms of the Wolfenstein parameterization $A, \lambda, \bar{\rho}, \bar{\eta}$:

$$\frac{BR(K^+ \to \pi^+\nu\bar{\nu})}{BR(K^+ \to \pi^0 e^+\nu)} = \frac{3\alpha^2 r_+}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \times A^4\lambda^8 F^2(\frac{m_t}{m_W}) \times \frac{1}{\sigma}[(\rho_0 - \bar{\rho})^2 + (\sigma\bar{\eta})^2] \quad (2)$$

where $\sigma = 1/(1-\lambda^2/2)^2 = 1.050$, and $\rho_0 = 1 + \Delta$. $\Delta = 0.42 \pm 0.06$, and expresses the charm quark contribution. To fully realize the bounds on $(\bar{\rho}, \bar{\eta})$, one must also deal with the uncertainty

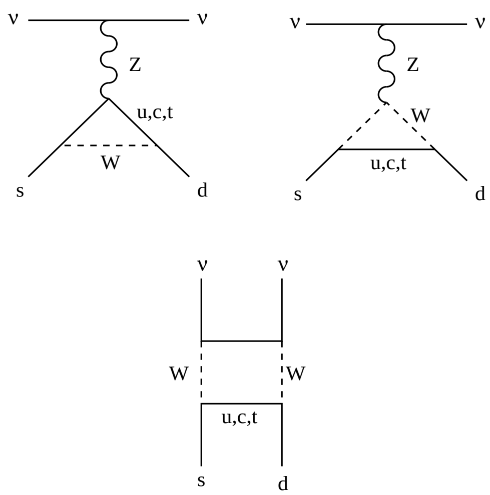

Figure 1. Leading contributions to $K^+ \to \pi^+\nu\bar{\nu}$.

*On behalf of the CKM Collaboration: BNL, Fermilab, IHEP, INR, San Luis Potosi, U. of Colorado, U. of Michigan, U. of South Alabama, U. of Texas at Austin, U. of Virginia in $A^4\lambda^8$, which is currently in the range 16-20%.

The first, and currently the only, observation of this decay mode was made by the BNL-787 collaboration. They observed 2 events with an estimated background of 0.15 ± 0.05 events, leading to a branching ratio of $1.57^{+1.75}_{-0.82} \times 10^{-10}$[5]. This is somewhat higher, but still consistent with the Standard Model prediction of $0.75 \pm 0.29 \times 10^{-10}$[6]. Isidori and D'Ambrosio[7] have performed a thorough analysis of the comparison, and discussed new physics scenarios that are permitted within the data. Recently the BNL-787 apparatus has been upgraded to be BNL-949. Their goal is to observe O(10) $K^+ \to \pi^+\nu\bar{\nu}$ events. A more thorough discussion of the other $K \to \pi\nu\bar{\nu}$ efforts can be found within these proceedings[8].

2. Measurement Technique

The goal of CKM is to observe 100 events with a background of order 10 events using a decay-in-flight technique. The dominant background will be the 2-body decay modes $K^+ \to \pi^+\pi^0$ (Kπ2) and $K^+ \to \mu^+\nu$ (Kμ2), which occur with branching ratios of 21% and 64% respectively. Another source of background will be inelastic collisions with the detector material of the form $K^+ + A \to \pi^+ + X$.

Our requirement is a clean and debunched 33 MHz 22 GeV/c K^+ beam. We will need O(10^5) kinematic rejection of the 2-body finalstate, a robust and redundant particle identification, and a veto system to achieve O(10^7) rejection of the multiparticle final state.

The recoil (or missing) mass X of the reaction $K^+ \to \pi^+ + X$ is:

$$\begin{aligned} M^2_{miss} &= M^2_K(1 - p_\pi/p_K) + \\ &\quad M^2_\pi(1 - p_K/p_\pi) - p_\pi p_K \theta^2 \end{aligned} \qquad (3)$$

where p_π and p_K are the momentum magnitudes, and θ is the relative angle of the K^+ and π^+ trajectories in the lab frame. We will reject the copious 2-body background by identifying its distinct missing mass signatures. The Kπ2 background will have M^2_{miss} of ${m^2}_{\pi^0}$. The Kμ2 background will also have a distinct M^2_{miss}, but will be unphysical (negative) due to the assignment of the pion mass to the muon. Crucial components in the missing mass reconstruction are robust, redundant, and independent measurements of the K^+ and π^+ kinematics.

Another handle to reject Kμ2 will be a muon veto system. Finally, a crucial component in the rejection of Kπ2 and other multiparticle final-states will performed by a highly hermetic veto system. The system is designed to be sensitive to the accompanying $\pi^0 \to \gamma\gamma$ decay and interaction products in the detector material.

2.1. Beam

Our 33 MHz 22 GeV/c debunched K^+ beam will be produced by 120 GeV protons from the Main Injector (MI). The time structure of the beam cycle will be a 1 second pulse (debunched), followed by a 2 second rest. The MI flux needed is estimated to be $5{\times}10^{12}$ protons-per-pulse. The conventional beam optics is described in [1].

It is crucial to reduce the non-K^+ content of the beam to managable levels. We will perform this using a set of superconducting RF (SCRF) cavities that will impart a time-varying transverse kick to the particles. The principles of this technique (RF separation), relies on the time-of-flight differences for protons, π, and K^+. The key ideas are summarized in figure 2. The two SCRF stations, each consisting of 78 Nb cells, will each impart a 15 MeV/c p_t kick. The mode is $\mathrm{TM}_{110}\pi$ with a frequency of about 3.9 GHz. Several prototypes have been made: 1-cell, 3-cell, 5-cell, and 13-cell cavitites. Key research issues include minimizing the Nb surface imperfections, machining tolerance, cavity tuning, and cryostatic cooling. We achieved 9 MV/meter for the 1-cell cavity, out of a requirement of 5 MV/meter. Our simulation of the resultant beam purity is 33 MHz of K^+, 7.5 MHz of π^+ and protons, 7.4 μ^+, and 1 MHz of photons.

2.2. Detector

The detector layout is shown in figure 3. The charged beam passes through a large instrumented 40 meter vacuum volume of $\approx 1\mu$Torr, which contains the fiducial volume for accepted decays. The design is driven by the desire for redundancy in the kinematic measurements. The

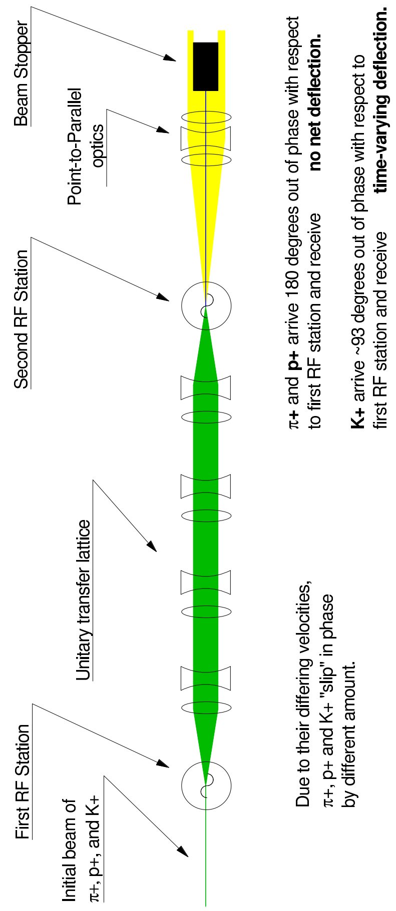

Figure 2. Principle of RF separation.

charged K^+ beam is tracked by the Upstream Magnetic Spectrometer (UMS) and the Kaon Entrance Angle Tracker (KEAT), which consists of several fine-pitched MWPCs and a dipole magnet. The construction of these chambers is based on the experience of the HyperCP (FNAL-E871) chambers. They must operate up to 600 kHz per wire. We've simulated the momentum and angular resolution to be 0.3% and 75μrad respectively. The decay products are momentum-analyzed by the Downstream Magnetic Spectrometer (DMS), a set of thin-walled straw drift tubes that must operate inside the vacuum volume. This is necessary so as to minimize the particle interaction with material. The challenge here is to construct thin-wall chambers that will survive the vacuum without spoiling it. The UMS, KEAT, and DMS form the tracking spectrometers. In addition to being used to calculate M^2_{miss}, the track segments will determine the decay vertex.

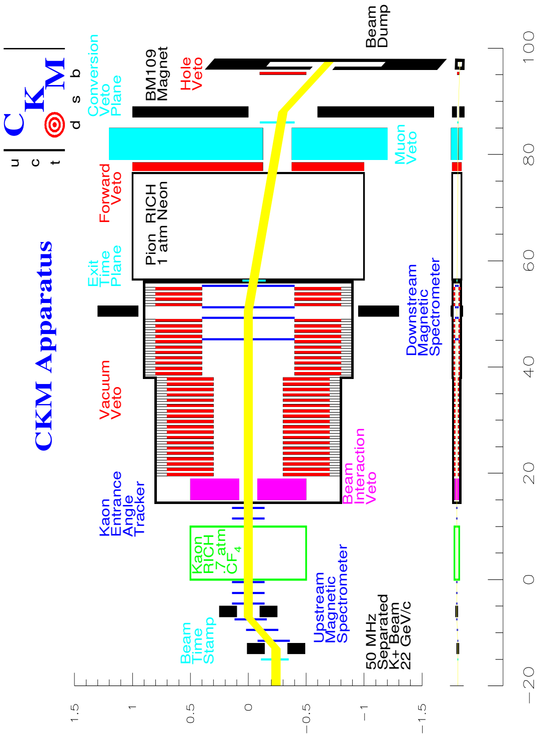

Figure 3. Layout of the CKM Detector.

A particularly novel CKM technique is the RICH detectors. These are gaseous RICH detectors operated near threshold such that the ring radius will be a strong function of the velocity magnitude. And the ring center locations are used to reconstruct the track angles. The readout will be done with 3/4" PMTs to minimize deadtime. The Kaon RICH (K-RICH), used to measure the K^+ vector velocity, is located immediately downstream of the UMS and will contain CF_4 at $\approx$ 0.7 atm. The Pion RICH (π-RICH), used to measure the π^+ vector velocity, is located behind the vacuum window. It will contain N_2 at 1 atm, for which the charged K^+ beam will be below threshold. The ring radius separation will be greater than $40(10)\sigma$ for the K(π) RICH. The RICH detectors will give an independent measurement of M^2_{miss}, with similar resolution to that of the tracking detectors. A large sample GEANT simulation of Kπ2, thus far, indicates no correllation between the non-gaussian tails of the M^2_{miss} reconstruction measured by the tracking and RICH detectors (see fig. 4).

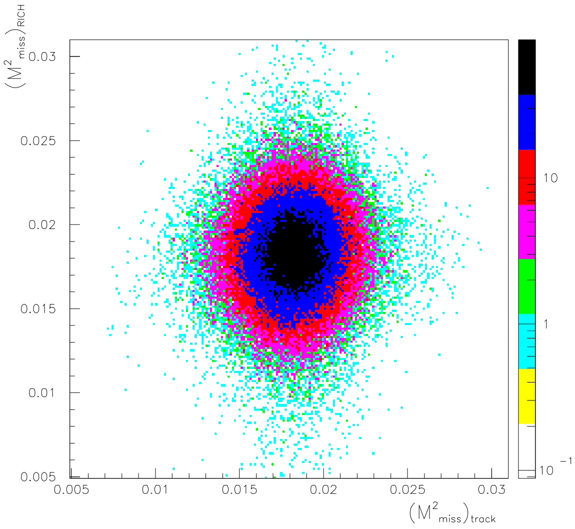

Figure 4. Reconstruction of M^2_{miss} for Kπ2 events using the tracking (horizontal axis) and RICH detectors (vertical axis). Note that the non-gaussian tails of these two measurements are uncorrellated.

The largest component of the CKM apparatus is the highly hermetic veto system, which performs the single most powerful rejection for Kπ2. The dominant component is the Vacuum Veto System (VVS), which consists of a large number of Pb-scintillator "sandwich" calorimeter modules residing inside the vacuum volume. The arrangement of 1 mm Pb and 5 mm scintillator sheets will give a 30% energy sampling. Altogether, the amount of scintillator in the vacuum volume will be about 25 tons. In addition to the nontrivial mechanical engineering requirements, the device must have very low veto inefficiency for high energy (> 1 GeV) photons and must be monitored continuously for liveliness. That is, we must know that the $K \to \pi\nu\bar{\nu}$ events are collected during a period when the veto system is known to be live. A goal for our photon veto inefficiency is given in figure 5.

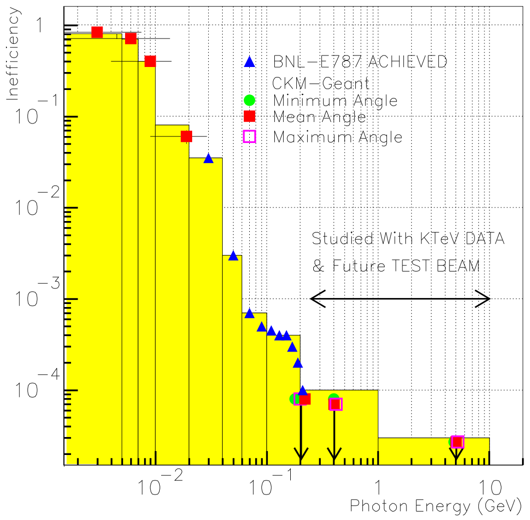

Figure 5. Photon veto inefficiency requirements for the VVS.

2.3. Data Collection

It is envisioned that CKM will use software-only triggers based on a PC-farm. This is a promising concept, given the current (and expected improvement in) power, flexibility, reliability, and price of commercial electronics. Given a 33 MHz event rate, an event size of 1 kbyte, the online processing must handle an input rate of 33 Gbyte/sec, or an average rate of 11 Gbyte/sec.

Given 2 years of data-taking consisting of 10^7 live spills per year, a $K^+ \to \pi^+\nu\bar{\nu}$ signal at the Standard Model prediction would be as shown in figure 6. A possible experimental outcome for CKM and other CP probes are shown in figure 7.

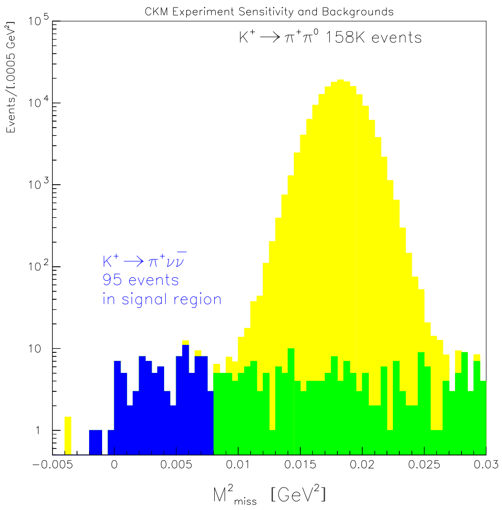

Figure 6. The sensitivity of the CKM apparatus for 2 years of data-taking assuming the Standard Model expectation for $K^+ \to \pi^+\nu\bar{\nu}$.

3. Conclusion

The decay mode $K^+ \to \pi^+\nu\bar{\nu}$ has finally been detected by the observation of 2 golden events by BNL-787. BNL-949 hopes to observe 10 events. Given the compelling physics case and the demonstrated observation by BNL-787, the CKM experiment was reviewed by the Fermilab PAC in June 2001 and given Stage-I approval by the lab directorate. The detector hall will reside in the MP9 building in the Meson East beamline at Fermilab. The time-scale for data-taking is 2007-8. The CKM collaboration is currently engaged in building small-scale prototypes of many of the detector subsystems. An important milestone is an tagged electron testbeam of a small VVS section at JLAB.

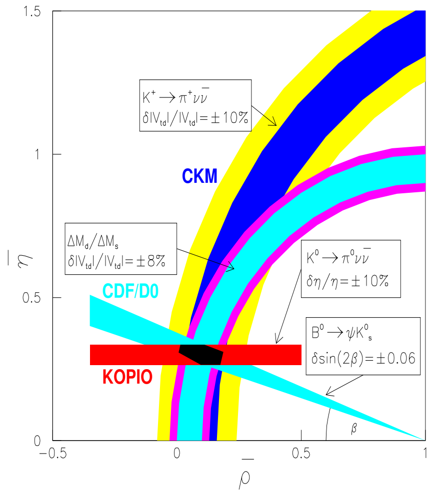

Figure 7. A possible outcome for 2-years of data-taking by CKM and for other CP probes.

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