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CKM - Charged Kaons at the Main Injector

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The CKM experiment is a proposal to measure the branching ratio of the rare decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ at the Main Injector at Fermilab using a decay in flight technique. The goal is to observe $\simeq 100$ events, for a Standard Model branching ratio of $1\times\ 10^{-10}$ with a background of less than 10 events.

1. Physics

The branching ratio for the decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ was first calculated by Inami and Lim [1] as an isospin rotation from $K^+ \rightarrow \pi^0 e^+\nu$. The measurement of the branching ratio of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ alone will allow one to obtain the magnitude of V_{td}, the element in the Cabbibo Kobayashi Maskawa matrix, which controls CP violation in the Standard Model. In conjunction with the neutral channel decay $K^0 \rightarrow \pi^0\nu\bar{\nu}$ and measurements in the B sector, this will provide an over-constrained measurement of both the real (ρ) and the imaginary (η) parts of V_{td}. Figure 1 illustrates the proposed sensitivity of experiments that will measure ρ and η.

The critical question is: *Are all CP phenomena described by just ρ and η?* Lincoln Wolfenstein, who invented ρ and η, says he doesn't care what their actual values are - we shouldn't either. The four observables of Figure 1 are the only ones with sufficiently robust theoretical predictions that an inconsistency among them would require contributions to CP violation beyond the Standard Model.

The present Standard Model branching ratio prediction for the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay is $[0.8 \pm 0.3] \times 10^{-10}$ [2]. One event, corresponding to a branching ratio of $1.5^{+3.4}_{-1.2} \times 10^{-10}$, has been observed by the BNL experiment E787 using stopped K^+ [3]. We propose [4] to measure the decay in flight of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and obtain >70 events in two years of data taking . This will match the precision suggested by the theoretical uncertainty. An intermediate stage, the observation of 5-10 events, is the goal of an approved BNL experiment E949, which is the continuation of E787. Some members of the CKM and E949 are now working in collaboration with each other as two stages of a physics program.

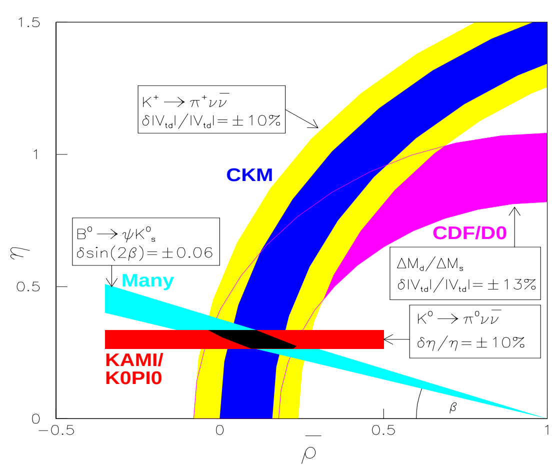

Figure 1. Experiments proposed sensitivity in the measurement of the CP violating parameters of the Standard Model.

2. Backgrounds

The major challenge for the experiment is to maintain signal sensitivity while suppressing backgrounds which are 9 orders of magnitude larger than the expected signal. The philosophy is to make redundant independent measurements of all quantities so that no background event can survive a single detector inefficiency or mis-measurement. This redundancy also allows the imperfections and limitation of each measurement to be carefully studied by using one detector to select background events whose behavior can then be studied in the other detector.

2.1. $K^+ \to \pi^+\pi^0$ background

This decay, with branching ratio $\simeq$ 21%, can mimic the signal if both γs from the decay of the π^0 are undetected. It will be controlled by a combination of kinematic rejection and a photon veto system. The CKM detector must veto photons with a very high efficiency and measure the π^0 missing mass from the charged tracks with high resolution and low non-Gaussian tails to the missing mass squared resolution function.

2.2. $K^+ \to \mu^+\nu$ background

In this decay , with a branching ratio $\simeq$63.5%, the μ^+ can be misidentified as a π^+. This is controlled by a muon veto and by measuring both vector velocity and momenta using both RICH and magnetic spectrometer systems. These events reconstruct in an unphysical region (the neutral missing mass squared is negative) by more than 10 standard deviations when the μ^+ is assigned a π^+ mass.

2.3. Interaction Backgrounds

The interactions of the beam Kaons or daughter π^+s contribute to the background. In order to minimize this contribution, as little material as possible should be encountered by the particles. This dictates the choice of the various detector elements. By adding material at critical points in the beam the contributions of these backgrounds can be enhanced sufficiently to be directly measurable in a run of relatively short duration.

3. Separated K^+ Beam

A critical component of the experiment is an intense and relatively pure K^+ beam. In order to get 6 MHz of K^+ decays in the fiducial volume we need a 30 MHz K^+ beam. In order to suppress the $\simeq$1000 MHz of π^+ and protons which are produced along with this kaon flux we will construct a new RF separated beam based upon 3.9 GHz transverse mode superconducting RF cavities, being developed at Fermilab for this purpose. The goal is to suppress π^+ by a factor of $\simeq$100 to increase the purity of the beam to a K/π ratio of > 2 in the decay volume.

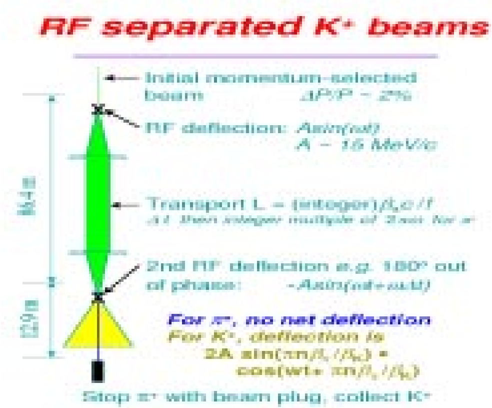

Figure 2. Schematic of the SCRF separated beam operation.

The separator operates by using a set of 2 properly spaced RF cavities operating in a mode which deflects the beam transversely. All charged particles are deflected by the first cavity. The inter-cavity separation and phase is adjusted to deflect both π^+ and protons back onto the optical axis where they are absorbed by a beam stopper. K^+s arrive at the second cavity 180° in RF phase behind π^+s, and 180° ahead of protons. Most of them are deflected around the beam stopper. A cartoon of the operation is shown in Figure 2. In Figure 3 and Figure 4 we show the behavior of the π^+ and K^+ components of the beam respectively from a full GEANT simulation including daughters from decays in the beam.

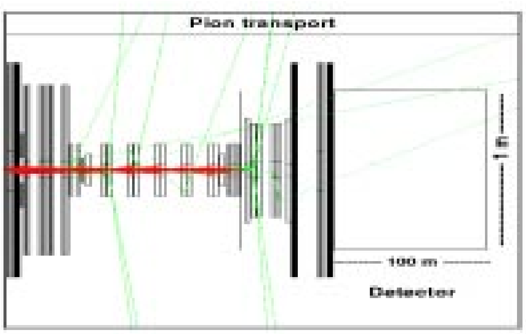

Figure 3. The π^+ component of the beam.

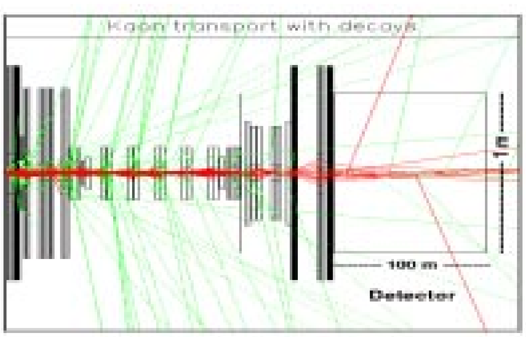

Figure 4. The K^+ component of the beam.

4. Apparatus

In Figure 5 are shown the detector elements which will be detailed below. Note that the bottom portion of Figure 5 shows the apparatus in

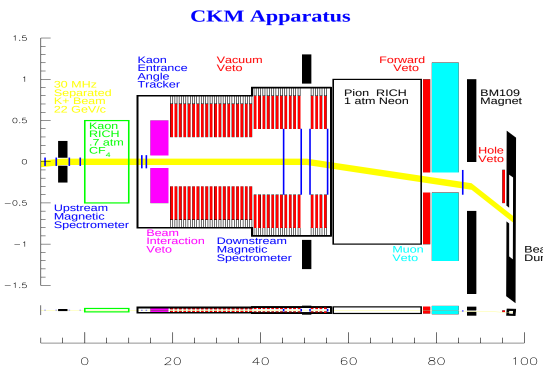

Figure 5. The Detector. The lower section show true proportions of the apparatus.

true proportion; it is a very long and thin instrumented beam pipe.

4.1. Charged Particle Spectrometers

The charged particles in the reaction, the K^+ and π^+, are both measured by vector velocity spectrometers consisting of a pair of Ring Imaging Cerenkov counters (RICH) and independently as vector momenta in upstream and downstream magnetic spectrometers.

The gas in the pion RICH is chosen as neon at one atmosphere in order to meet the low optical dispersion required for good resolution and to minimize the material in the beam by allowing the use of thin windows. The kaon RICH is tuned to operate just above kaon threshold with a folded optical path so that there is only a thin flat mirror in the beam. These considerations have contributed to the choice of the K beam to be 22 GeV energy. The RICH detectors are based on our experience with the Selex RICH [5]. The CKM pion RICH is a copy of the Selex RICH with twice the length and therefore twice the resolution. The photodetectors are an array of 15 mm photomultiplier tubes counting single Cerenkov photons. They provide excellent resolution with very small non-Gaussian tails and extremely fast time resolution. Typical PMT signals are 10 nsec wide at the base with leading edge timing of 1 nsec easily achievable. With signals from particles 10 nsec apart in time clearly resolved these detectors aren't afraid of a 50 MHz beam. As a demonstration of this technique, data from the Selex RICH detector are shown in Figure 6 from a calibration run at ~25 GeV/c. The equivalent π^+ momentum resolution achieved by the RICH is better than 1% for this configuration.

The K^+ and π^+ magnetic spectrometers use conventional trackers, silicon strips or MWPCs and straw tubes respectively. The upstream (kaon) magnetic spectrometer must handle the total 50 MHz rate of the beam and provide excellent momentum resolution ($\leq 0.5\%$) and low non-Gaussian tails. A major concern is pattern recognition errors since, unlike the RICHes, no tracking plane is fast enough to resolve one particle at a time. Two potential solutions are under study with simulations, fast MWPCs and silicon strips. For the downstream (pion) magnetic spectrometer straw tubes have been chosen as the tracking technology to minimize the material transversed by the decay pions and the exiting beam. They are 5mm in diameter with a 20 μm sense wires, 5 or 8 straw layers per station in 4 views. The expected hit resolution is 150 μm per layer while the material in the beam per layer is only 4×10^{-4} X_0. The straws are located in the vacuum decay volume. They are deadened in the beam region so they only record charged tracks from upstream decays. The maximum rates seen are a modest $\leq$ 200 KHz/straw.

4.2. Photon Vetos

As already mentioned, control of the background from the $K^+ \rightarrow \pi^+\pi^0$ decays are critical. This points to the extreme importance of the γ veto system. The goal is an inefficiency for vetoing either photon from a π^0 of $\leq 1 \times 10^{-7}$. The veto system has a component surrounding the decay volume, where the decay takes place and a forward component, after the π^+ RICH to detect forward, mostly high energy γ's. The component surrounding the decay volume will be located inside the vacuum vessel (the Vacuum Veto System - VVS) with a vacuum of $\simeq 10^{-6}$ torr. This solution maintains good efficiency for photons as low

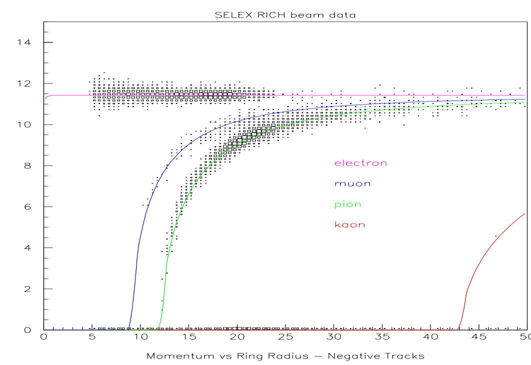

Figure 6. Ring radius data from the Selex RICH with a 25 GeV/c beam

in energy as 10 MeV. The VVS is made of a sandwich of plastic scintillator and lead 5 mm/1 mm each, stacked in modules 50 cm long and 40 cm radially. There are over 80 such sandwich layers per module and 34 such modules in the VVS. There is a void of 50cm between each module which corresponds to a photon angle of $>$ 40 degrees. Photons coming from $K^+ \rightarrow \pi^+\pi^0 \rightarrow \gamma\gamma$ decay at angles this large are below 10 MeV. This allows us to reduce the active volume of the VVS, and thus its cost, by a factor two.

The required VVS detection inefficiency is given in Figure 7. In the intermediate region of energies the requirements have been achieved by E787 with a comparable veto system.

For the Forward Veto System (FVS) a choice of various techniques are avaliable, and are still under study. We are assuming, for the moment, a setup of Sc/Pb 5 mm/1 mm sandwiches with wavelength shift fibers in a shashlik geometry for this calorimeter. Crystals, like CsI, are also possible, but at a significant increase in cost.

4.3. Muon Veto

A muon veto follows the FVS to control the $K^+ \rightarrow \mu^+\nu$ and $K^+ \rightarrow \mu^+\nu\gamma$ backgrounds. This device is planned as 2m of iron absorber with embedded crossed scintillator hodoscopes. The de-

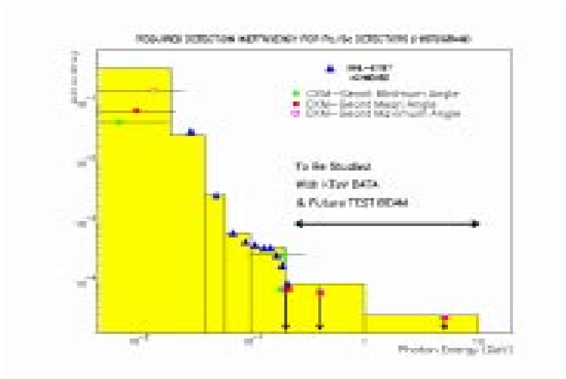

Figure 7. VVS Required inefficiencies. The triangles were measurements achieved by E787. The circles represent the inefficiencies reached by GEANT simulations studies at low and high energies.

tector plays the opposite role to what is usual; a pion which punches through is vetoed and therefore a small signal inefficiency, a muon which does not punch through is a potential un-vetoed background. The goal is a muon inefficiency of 1×10^{-5}. The non-interacting beam goes through a hole in the FVS and muon veto system and is dumped afterward by a magnetic field into the beam dump.

4.4. Interaction Veto

To detect K^+ hadronic interactions before the decay volume entrance, a hadron calorimeter surrounding the beam (Beam Interaction Veto) is used. The backgrounds from interactions are dominated by K^+ scatters in the last material just before the decay volume and π^+ scatters in the first material just after the decay volume. The BIV suppresses the first class of backgrounds by rejecting events with detectable secondaries associated with a K^+ interaction. In addition the requirement that the K^+ and π^+ tracks form a good spatial vertex suppresses both classes of interactions.

5. Present Status

The Fermilab Main Injector is now in commissioned operation for more than one year. The beam line upgrades necessary to transport 120 GeV slow spill protons to the Meson Laboratory are now underway. It is planned that this beam will be available for slow spill test beams in early 2002. CKM requires 5×10^{12} protons per one second spill; $< 20\%$ of the total design intensity of the Main Injector. We will need this beam to be de-bunched so that only a small ripple of the 53 MHz accelerating frequency remains in order to minimize the instantaneous rate in the detector. The exact details of how the accelerator complex can be operated to meet the needs of the Collider, Neutrino and Slow Spill programs is presently under study in the Fermilab Beams Division.

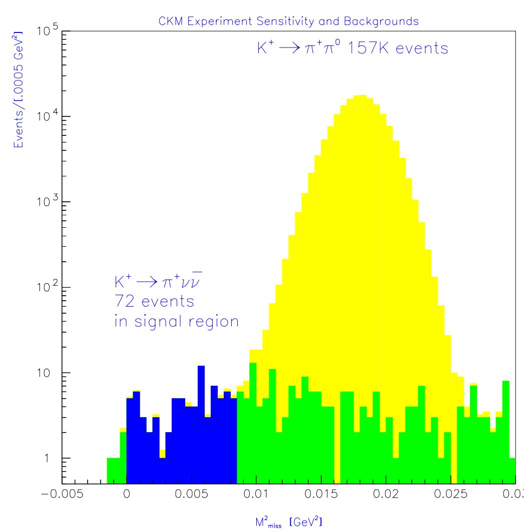

Figure 8. The Missing Mass Square of the generated signal and backgrounds corresponding to the whole experiment.

CKM is presently approved as an R&D project to demonstrate the feasibility of the of proposed technique. We have received strong encouragement from the laboratory; ".. *CKM and KAMI,* *if proven technically feasible, would form the core of a 120 GeV fixed target program"*, Fermilab PAC May 1999. We have been asked to submit a full physics proposal in April 2001 with the intention of a decision on scientific approval of the experiment in June 2001.

As part of the R&D project we are in the process of building prototypes for the photon veto system, the straw tubes and the super-conducting RF cavities. A test beam effort is underway at IHEP Protvino to test a prototype of the muon veto system. Simulations are being done in parallel for both the tracking and the veto systems as well as for the beam line design.

We are now preparing the second edition of our April 1998 physics proposal, based upon our results from the R&D project.

6. Conclusion

Figure 8 shows the expected signal and $K^+ \to \pi^+\pi^0$ background after the photon vetos have been applied from two years of running as a function of the missing mass squared of the neutral system recoiling against the π^+. 72 events survive in a signal region with 3 un-vetoed and mis-measured $K^+ \to \pi^+\pi^0$ event. The total background estimate for this sample, including $K^+ \to \mu^+\nu$, interactions and accidentals is < 8 events. Work is now underway to refine and improve our proposal with the intention of seeking approval in the spring 2001.

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