Participation of the Experimental High Energy Physics Group at the University of South Alabama in the Fermilab CKM Experiment (Charged Kaons at the Main Injector)

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For the CKM Collaboration

Abstract

The Experimental High Energy Physics group at the University of South Alabama has joined the Fermilab (Fermi National Accelerator Laboratory, near Chicago, Illinois) CKM (Charged Kaons at the Main Injector) collaboration. This collaboration has received scientific approval (as of June 28, 2001) and is seeking final approval to collect data sufficient to observe 100 rare $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ decays with a background of 10 events. This sample may be used to extract the CKM (Cabbibo-Maskawa-Kobayashi) matrix element $|V_{td}|$ to a precision of 10%. Two K^+decays in this decay mode has been observed in the Brookhaven National Laboratory Experiment E-787 resulting in a branching ratio of $(1.57\,^{+1.75}_{-0.82}) \times 10^{-10}$. A branching ratio is the fraction a particular decay mode is observed to the total decays of a particular type of particle (the K^+in this case). This implies that the CKM experiment must keep background rejection to the 10^{-11} level to achieve its planned sensitivity. The CKM matrix relates the weak quark states to the quark mass states. This matrix has two complex elements (V_{ub} and V_{td}). In the Standard Model, one parameter controls the complex phases of these matrix elements that lead to CP violation, which is used to explain the observed excess of matter over anti-matter in the present Universe. The CKM experiment will use a superconducting RF separated 22 GeV/c K^+beam to observe their time-of-flight decays. The spectrometer will use two magnetic spectrometers to measure the incident K^+momentum and the outgoing π^+momentum. A redundant system of ring imaging Cherenkov counters will simultaneously measure the velocity vectors of the $K^+$and π^+. Both systems will be used to reconstruct independently the missing mass, which should agree to help in background rejection. The spectrometer will also have a hermetic system of calorimeters for photon detection (used for background rejection) and a muon detector (also used for background rejection). A brief description of the experiment will be presented. The High Energy Physics Group at the University of South Alabama is currently writing the single event display for the experiment. This event display is written in C++ and will run on PC running the Linux.

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Charged Kaons at the Main Injector

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A Proposal for a Precision Measurement of the Decay $K^+ \to \pi^+ \nu \overline{\nu}$ and Other Rare K^+ Processes at Fermilab Using the Main Injector

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Participation of the Experimental High Energy Physics Group at the University of South Alabama in the Fermilab CKM Experiment (Charged Kaons at the Main Injector)

1 Introduction

The Experimental High Energy Physics Group at the University of South Alabama has been working on high energy physics fixed target experiments at the Fermi National Accelerator Laboratory (Fermilab) since 1988. Fermilab is the site of the most powerful proton accelrator in the world and is located about 35 mile west of Chicago, Illnois. The Fermilab complex has five proton accelerators that run in tandem: the Crockoff-Walton (accelerates H^- to 850 keV/c), the Linac (accelerates H^- then strips off the electrons and accelerates protons to a final momentum of 850 MeV/c), the 8 GeV booster ring, the **main injector** which accelerates protons to 125 GeV/c, and the Tevatron which accelerates protons and anti-protons to 0.912 TeV/c. The main-injector is used to supply protons that produce anti-protons which are accumulated and sent into the Tevatron for proton-anti-proton collisions.

Figure 1: Arial View of Fermilab with the main injector in the background. Courtesy of Fermilab

Figure 2: Arial view of the main injector. Courtesy of Fermilab

The Tevatron, the source of 800 GeV/c protons for the 1999 fixed target run, will not be used as a source for fixed target beam in the future. Instead, the new **main injector**, is the source of 120 GeV/c protons for the next generation of fixed target experiments at Fermilab. The University of South Alabama high energy physics group is a member of one of the next generation fixed target experiments: Fermilab CKM experiment (Charged Kaons at the Main Injector).[1] The CKM experiment has received stage I (scientific approval) and is seeking final approval to collect data sufficient to observe 100 rare $K^+ \to \pi^+ \nu\overline{\nu}$ decays with a background of 10 events. CKM will use the Fermilab main injector to produce a 22 GeV/c RF separated K^+ beam whose decays-in-flight will be observed in a spectrometer. This experiment will make a precision measurement of the rare kaon decay branching ratio: $K^+ \to \pi^+ \nu\overline{\nu}$. A branching ratio is the fraction a particular decay mode is observed to the total decays of a particular type of particle (the K^+in this case). The CKM experiment is designed to detect 100 clean signal events with an anticipated 10 background events. A sample of this size can be used to measure the value of the $|V_{td}|$ element of the Cabbibo Kobayashi Maskawa matrix (CKM matrix) to a 5% statistical uncertainty.[2][3]

Two events in this decay mode has been observed by the Brookhaven National Laboratory experiment E-787.[4] This experiment used a stopping K^+ beam. The resulting branching ratio reported was computed to be $(1.57\ ^{+1.75}_{-0.82}) \times 10^{-10}$ which is consistent with current theoretical predictions of $0.77 \pm 0.21 \times 10^{-10}$.[5] A precision measurement of the CKM matrix $|V_{td}|$ element requires the observation of many more $K^+ \to \pi^+ \nu\overline{\nu}$ decays in order to make a better measurement of the branching ratio which is used to extract the value of $|V_{td}|$. The CKM experiment will accomplish this by a much higher rate experiment using a **time of flight** technique. Additionally, the CKM experiment will search for other rare charged kaon decay modes.

2 Physics

The $K^+ \rightarrow \pi^+\nu\overline{\nu}$ decay mode is theoretically well understood.[6] The decay process is through Flavor Changing Neutral Currents (FCNC). These processes proceed via penguin diagrams or a box diagram. The salient characteristic is that the main contribution to FCNC is at small distances ($\frac{1}{m_t}$ or $\frac{1}{m_Z}$) so perturbative QCD works well. The small distance nature of these processes allows this decay to be sensitive to heavier particles that may exist but have not been observed yet (such as from SUSY).[7] The hadronic part of the calculation ($<\pi|H_w|K>$) can be normalized to the branching ratio $K^+ \rightarrow \pi^o e^+\nu$ because of isospin symmetries.[8] This cancels the hadronic matrix element when the $K^+ \rightarrow \pi^+\nu\overline{\nu}$ branching ratio is normalized to the $K^+ \rightarrow \pi^o e^+\nu$ branching ratio. Ultimately, the BR($K^+ \rightarrow \pi^+\nu\overline{\nu}$) has a form of:[5]

$$\mathrm{Br}(K^+ \rightarrow \pi^+\nu\overline{\nu}) = R_+ \frac{|\lambda_c F(x_c) + \lambda_t F(x_t)|^2}{|V_{us}|^2} \tag{1}$$

Where the factor $R_+ = 3\left(\frac{\alpha}{2\pi\sin^2(\theta_2)}\right)^2 2r_+\mathrm{Br}(K^+ \rightarrow \pi^0 e^+\nu)$. The value of $\alpha = 1/129$, $sin^2(\theta_w) = 0.23$ and $\mathrm{Br}(K^+ \rightarrow \pi^0 e^+\nu) = 4.82 \times 10^{-2}$. The quantities $F(x_c)$ and $F(x_t)$ are loop functions for the penguin diagrams and box diagrams, with $x_c = (m_c/m_W)^2$ and $x_t = (m_t/m_W)^2$.[9] Equation 1 also include factors $\lambda_c = V^*_{cs}V_{cd}$ and $\lambda_t = V^*_{ts}V_{td}$, where V_{cs}, V_{cd}, V_{ts}, V_{td} and V_{us} are elements of the CKM matrix. The largest theoretical uncertainty in this calculation is the mass of the charm quark.[10]

The CKM matrix (V) relates the six quark mass eigenstates to the quark weak eigenstates (i.e. the two eigenbases are different).[11] The weak quark eigenstates ($d^{'}$, $s^{'}$ and $b^{'}$) are related to the mass quark eigenstates (d, s, b) via the matrix relation:

$$\begin{bmatrix} d^{'} \\ s^{'} \\ b^{'} \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} \tag{2}$$

The CKM matrix may written in the Wolfenstein parameterization:[12]

$$V = \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4) \quad (3)$$

This matrix is parameterized in four free parameters (A, λ, ρ and η). Expanding the Wolfenstein parameterization of the CKM matrix to higher orders in λ allows the calculation of the parameters λ_c and λ_t found in Equation 1:[13]

$$\begin{array}{ll} \mathrm{Re}\lambda_c = -\lambda(1-\frac{\lambda^2}{2}) & \mathrm{Re}\lambda_t = -A^2\lambda^5(1-\overline{\rho}) \\ \mathrm{Im}\lambda_c = -A^2\lambda^5\eta & \mathrm{Im}\lambda_t = A^2\lambda^5\eta \end{array} \quad (4)$$

The result is a theoretical prediction for the branching ratio of $BR(K^+ \rightarrow \pi^+\nu\overline{\nu})$ of $(0.77 \pm 0.21) \times 10^{-10}$.[5]

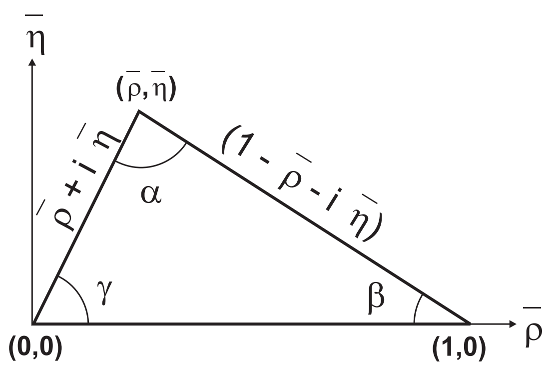

Figure 3: An idealized unitarity triangle resulting from the CKM matrix.

One of the advantages, according to reference [13] of the Wolfenstein parameterization is that it leads to a unitarity triangle that gives a clear geometric representation of the CKM matrix which can be related to the phenomenology of rare decays. The unitarity triangle is obtained by treating each column of the unitary matrix in Equation 2 as a vector. Since this 3×3 matrix is unitary, each vector is orthogonal to the other two vectors. Taking the inner product of the vector represented by column 1 with the complex conjugate of the vector represented by column 2 of the CKM matrix in Equation 2 results in zero. As reference [13] points out, Equation 3 needs to be expanded to higher orders when addressing CP violation. The resulting expression for the unitarity triangle is:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (5)$$

The result, using the expansion of the Wolfenstein parameterization in reference [13] is:

$$A\lambda^3(\overline{\rho} + i\overline{\eta}) + A\lambda^3(1 - \overline{\rho} - i\overline{\eta}) = A\lambda^3 \quad (6)$$

Where $\overline{\rho} = \rho\left(1 - \frac{\lambda^2}{2}\right)$ and $\overline{\eta} = \eta\left(1 - \frac{\lambda^2}{2}\right)$. Canceling out the factor of $A\lambda^3$ and treating each term as a vector in the complex $\overline{\rho} - \overline{\eta}$ plane yields the unitarity triangle. Figure 3 illustrates an ideal unitarity triangle and how it relates to the terms of Equation 6. Figure 4 illustrates the current constraints on the unitarity triangle.

The CKM experiment will include physics goals other than the main goal of observing 100 $K^+ \to \pi^+\nu\overline{\nu}$ events. However, no compromises on the sensitivity or background rejection of the main physics goal will be tolerated. The CKM spectrometer has excellent rate capability and time resolution along with the RICH's that provide particle identification from the velocity measurements. The power of the CKM spectrometer to collect a large quantity of kaon decays is shown in Table 1.

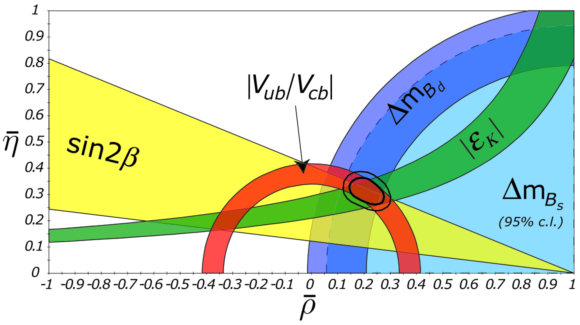

Figure 4: The current situation on the constraints of the unitarity triangle. Taken from reference [16] which used reference[14].

Table 1: Interesting Kaon decay modes

Decay Mode	Branching Ratio [15]	Events/Week
$K^+ \to \pi^o\mu^+\nu\gamma$	$< 6.1 \times 10^{-5}$	5.8×10^4
$K^+ \to \pi^o e^+\nu\gamma$	$(2.62 \pm 0.20) \times 10^{-5}$	2.1×10^6
$K^+ \to \pi^+\pi^+\pi^-$	$(5.59 \pm 0.05) \times 10^{-2}$	4.0×10^9
$K^+ \to \pi^+\pi^o\pi^o$	$(1.73 \pm 0.04) \times 10^{-2}$	2.5×10^7
$K^+ \to \pi^+\pi^o\gamma$	$(2.75 \pm 0.15) \times 10^{-4}$	1.1×10^6
$K^+ \to \pi^+e^+e-$	$(2.88 \pm 0.13) \times 10^{-7}$	1.2×10^3
$K^+ \to \pi^+\mu^+\mu^-$	$(7.6 \pm 2.1) \times 10^{-8}$	2.3×10^3
$K^+ \to \mu^+\nu\gamma$	$(5.50 \pm 0.28) \times 10^{-3}$	1.0×10^8
$K^+ \to \pi^+\pi^-e^+\nu$	$(3.91 \pm 0.17) \times 10^{-5}$	9.4×10^5
$K^+ \to \pi^0\pi^o e^+\nu$	$(2.1 \pm 0.4) \times 10^{-5}$	7.2×10^4
$K^+ \to \pi^+\pi^-\mu^+\nu$	$(1.4 \pm 0.9) \times 10^{-5}$	1.4×10^6

There are many other Physics topics that can be addressed by the CKM experiment. A search for lepton flavor conservation in decays such as $K^+ \to \pi^+\mu^\pm e^\mp$, $K^+ \to \pi^-\mu^+e^+$, $K^+ \to \pi^-\mu^+\mu^+$ and $K^+ \to \pi^-e^+e^+$. T_{odd} asymmetries may be searched for in $K^+ \to \pi^o\mu\nu\gamma$ decays by studying the T_{odd} parameter $T_{\mu\nu\gamma} = \frac{\vec{p}_\gamma\cdot(\vec{p}_\pi\times\vec{p}_\mu)}{|\vec{p}\gamma|\,|\vec{p}_\pi\times\vec{p}_\mu|}$.

A search for direct CP violation in the decay $\mathrm{K}^{\pm} \rightarrow \pi^{+}\pi^{-}\pi^{\pm}$. This search will be limited by the ability of the CKM experiment to control its systematic uncertainties. No serious evaluation of the systematics involved with the experimental apparatus and this decay has been done yet. The decay modes $\mathrm{K}^{+} \rightarrow \pi^{+}\mathrm{e}^{+}\mathrm{e}^{-}$, $\mathrm{K}^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$ and $\mathrm{K}^{+} \rightarrow \mu^{+}\nu\gamma$ may be used to test chiral perturbation theory.

3 Description of the CKM Experimental Method

The CKM experiment plans to observe 100 $K^{+} \rightarrow \pi^{+}\nu\overline{\nu}$ decays with a 10% background. Since BR($K^{+} \rightarrow \pi^{+}\nu\overline{\nu}$) $\approx$ 10^{-10}, the background must be kept at the 10^{-11} level. Adding to the difficulty of the experiment, the $K^{+} \rightarrow \pi^{+}\nu\overline{\nu}$ events will not be signaled by something as obvious as a mass peak. The $K^{+} \rightarrow \pi^{+}\nu\overline{\nu}$ signal will be a region of missing mass phase space (see Figure 5 on page 10). An essential element to the viability of this experiment (or any rare kaon decay experiment) is **redundancy**. For the CKM experiment, the redundancy of the spectrometer is 1) the measurement of the **momentum vectors** of in going and outgoing charged particle with two conventional magnetic spectrometers and 2) the measurement of the **velocity vectors** of the in going and outgoing charged particle(s) with two ring imaging Cherenkov counters (RICH). These totally independent measurements produce **independent measurements of the missing mass** which will be required to agree.

Obviously, the rejection of background is an important aspect of the CKM experiment. Any K^{+} that enters the spectrometer and has a π^{+} and neutrals in the final state is a candidate for background. A quick perusal of the Particle Data Group tables reveals the decay modes with the largest branching ratios that fit this description which is summarized in Table 2.

The two decay modes with the largest branching ratios, $K^{+} \rightarrow \mu^{+}\nu_{\mu}$ and $K^{+} \rightarrow \pi^{+}\pi^{o}$, are potentially the largest contributors to the background. This background is rejected if the μ is identified or if a γ's from the π^{o} decay are detected in the spectrometer. The rejection is increased by exploiting the kinematics of these decays. Both of these decay modes are two-body decays, so that in the center of mass frame, the momentum of the charged

Table 2: Background K$^+$ Decay Modes[17]

Decay Mode	Branching Ratio	Decay Mode	Branching Ratio
$K^+ \to \mu\nu_\mu$	63.51 %	$K^+ \to \mu^+\nu_\mu\gamma$	$(5.50 \pm 0.28) \times 10^{-3}$
$K^+ \to \pi^+\pi^o$	21.16 %	$K^+ \to \pi^+\pi^o\gamma$	$(2.75 \pm 0.15) \times 10^{-4}$
$K^+ \to \pi^o e^+\nu_e$	4.82 %	$K^+ \to \pi^+\pi^o\pi^o\gamma$	$(7.5^{+5.5}_{-3.0}) \times 10^{-6}$
$K^+ \to \pi^o\mu\nu$	3.18 %	$K^+ \to \pi^+\gamma\gamma$	$(1.10 \pm 0.32) \times 10^{-6}$
$K^+ \to \pi^+\pi^o\pi^o$	1.73 %		

daughter particle is a sharp peak (with some spread due to the momentum resolution). The background from these modes is reduced by rejecting single charged particles with center of mass momenta values near these momentum peaks.

The decay mode the CKM experiment wishes to observe is $K^+ \to \pi^+\nu\overline{\nu}$. Because the mode has a single charged particle initial state and only one charged particle in the final state, the neutral, undetected $\nu\overline{\nu}$ pair is treated as missing mass. The background modes $K^+ \to \mu^+\nu_\mu$ will have a missing mass of zero, and $K^+ \to \pi^+\pi^o$ will have a missing mass of m_{π^o}. Again, rejection of these background decay modes can be increased by rejecting on missing mass near these values. Of course, to exploit this method, the missing mass resolution must be good. The missing mass squared may be approximated as:

$$M^2_{mm} = m_k^2\left(1 - \frac{p}{p_k}\right) + m^2\left(1 - \frac{p_k}{p}\right) - pp_k\theta^2 \qquad (7)$$

Where p_k is the magnitude of the (parent) kaon momentum, p is the magnitude of the charged daughter particle's momentum and θ is the angle (in radians) between the incident kaon and the charged daughter particle's momentum. If the momentum of the kaon is fixed, as it is in a fixed target experiment like CKM, then the missing mass squared is a function of p and θ. Figure 5 shows the missing mass distribution plotted as decay angle vs. momentum of the charged daughter particle for 22.0 GeV/c incident Kaons. If the missing mass is a single particle, such as an unobserved π^o, the recoiling π^+ forms a curve on the missing mass distribution, which is labeled on Figure 5 as $K^+ \to \pi^+\pi^o$. However, if the K^+ decays into a three body decay, the missing mass distribution falls below a line determined by the minimum value of the missing mass. The blue region of Figure 5 represents the region populated by $K^+ \rightarrow \pi^+\pi^+\pi^-$. Figure 5 is split up into three regions. Region I is the signal region. This is the typical search region for $K^+ \rightarrow \pi^+\nu\overline{\nu}$ events. Region III is the region populated by $K^+ \rightarrow \pi^+\pi^+\pi^-$ decay mode. Because there are no particles in the final state that can be used for rejection and no kinematical methods to guaranteed rejection to the 10^{-11} level, this region cannot be used as a signal region for $K^+ \rightarrow \pi^+\nu\overline{\nu}$ events. However, there is hope for Region II which is between Region I and Region III. The CKM experiment will concentrate on understanding background in Region I to extract the $K^+ \rightarrow \pi^+\nu\overline{\nu}$ signal, but the experiment will study Region II in an attempt to extract a $K^+ \rightarrow \pi^+\nu\overline{\nu}$ signal as acceptance is increased.

As previously mentioned, rejection of the two-body decay requires excellent missing mass resolution. A missing mass squared resolution of 1.82×10^{-3} $(\mathrm{GeV/c}^2)^2$ requires that the momentum of the incident kaon (p_k), the daughter charged particle momentum (p) and the decay angle (θ) be measured to 1.0 %. Figure 6 (on page 11) is a monte carlo simulation of the missing mass distribution that was produced by the CKM_GEANT based monte-carlo using all rejection cuts including the kinematic cuts on two-body decay, agreement between the magnetic spectrometer missing mass and RICH measured missing mass plus other background rejection cuts.

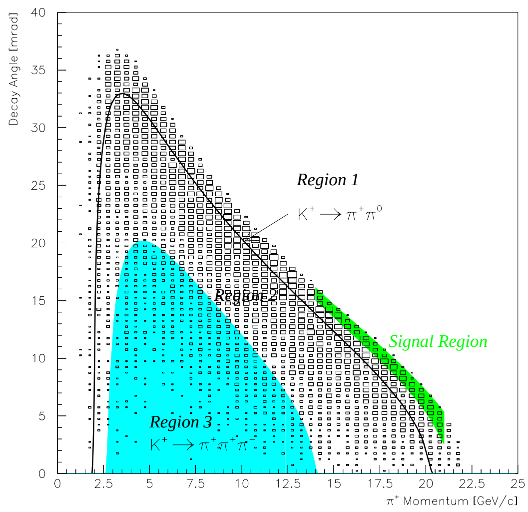

Figure 5: The missing mass as a function of p and θ for monte carlo generated 22 GeV/c incident Kaons.

Other background reductions are achieved by muon identification for background decay modes that contain muons and photon rejection for background decay modes that contain π^o's or γ's. The photon rejection requires a nearly hermetic calorimeter system to detect at least one final state γ from these modes.

There are other exotic background sources, such as when an incident K^+ interacts in spectrometer material to produce a K^o which decays via the mode $K^o \rightarrow \pi^+e^-\overline{\nu}_e$ and with the e^- having a low enough energy that it is swept out of the CKM spectrometer. Another source of exotic background is a π^+ from beam contamination that scatters in spectrometer material and is mismeasured as K^+ then appears as a π^+ for the charged daughter particle measurement. These backgrounds can be rejected by the Beam Interaction Veto System and by requiring the K^+ decay be confined to the decay volume (i.e. the decay vertex with in the decay vacuum volume) sufficiently separated from spectrometer material.

4 Description of the CKM Apparatus

The CKM experiment will use a 22.0 GeV/c RF separated K^+ beam to search for 100 $K^+ \to \pi^+\nu\overline{\nu}$ decays with a background of 10. The experiment needs 5×10^6 K^+ decays per spill to reach a single event sensitivity of 10^{-12} in two years of Main Injector run time. This results in a requirement of approximately 3×10^7 debunched K^+ per spill to keep the detector rates uniform. To achieve the desired sensitivity, the CKM experiment requires a 30 MHz K$^+$ beam. Using RF separation techniques, 50 MHz beam with a 30 MHz K$^+$ content can be achieved. This experiment requires a a spectrometer that can tolerate very high rates. Because of the high beam rates, most detectors in the CKM experiment will be instrumented to a TDC to supply a time reading as well. The beam will be debunched to keep the beam rate uniform and RF separation will be required. The separator will be constructed from two RF stations each containing six 13 cell superconducting RF cavities. The beam particles entering the two RF separation stations have the same momentum, but different velocities. The RF separation technique exploits the time of flight difference between the different species types to deflect the desired species (the K$^+$) and leave the undesired species undeflected where it will hit a beam stop. Tests have been completed with one cavity and five

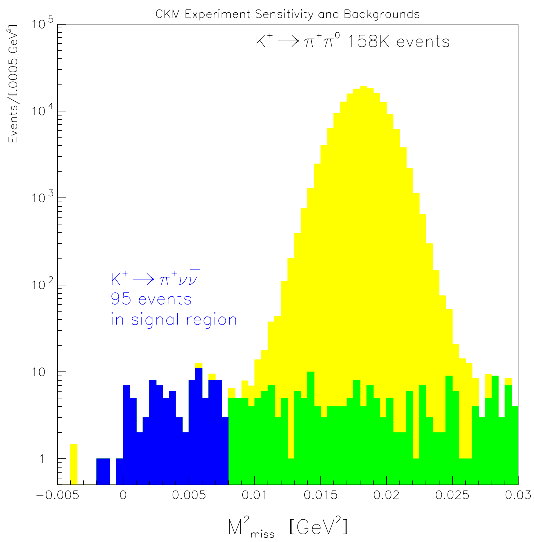

Figure 6: The missing mass distribution for monte carlo generated 22 GeV/c incident Kaons.

cavity separators for field strength and quality. These limited cavities have exceeded the CKM specifications. External reviews of this project found the design feasible and on track for testing in 2003.

The CKM experiment spectrometer is shown in Figure 7. The CKM spectrometer consists of two magnetic spectrometers, two ring imaging Cherenkov counters, photon calorimetry and muon identification.

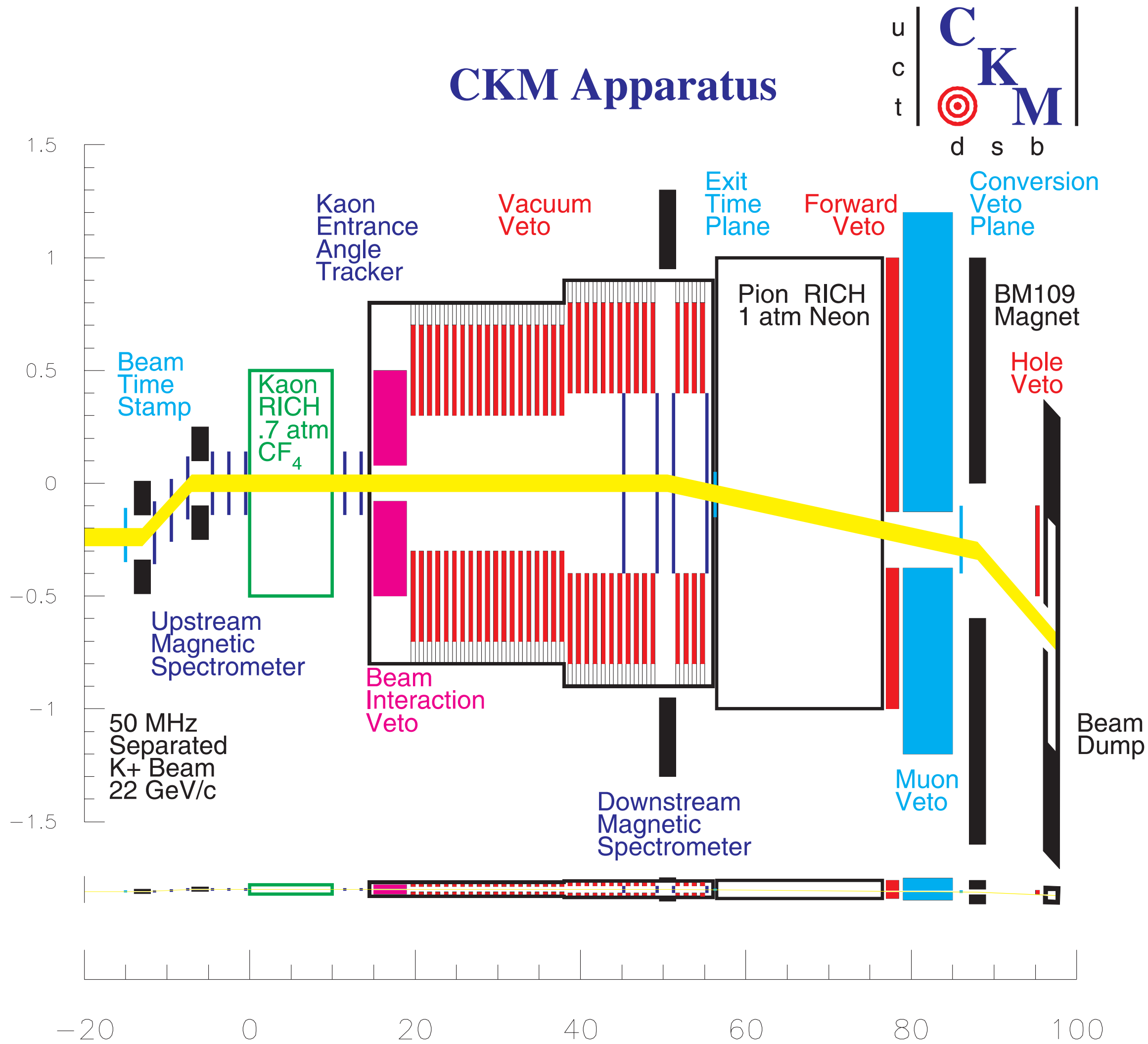

Figure 7: The CKM experiment's spectrometer. An incident beam of 22 GeV/c Kaons are allowed to decay in the vacuum region. The spectrometer consist of two magnetic momentum spectrometers, two ring imaging Cherenkov counters, photon calorimetry and muon identification.

The upstream magnetic spectrometer (UMS) measures the incident K^+ momentum. This system consist of and analysis magnetic and six high-rate multi-wire proportional chambers (PWC) similar in design to the upstream

PWC's used in the Fermilab HyperCP experiment. The other element of the magnetic spectrometer system is the Kaon Entry Angle Tracker (KEAT), consisting of two multi-wire proportional chambers, similar to the UMS tracking chambers. The KEAT measures the angle of the beam track from the UMS just before the track enters the vacuum decay region. The downstream momentum spectrometer (DMS) measures the charged daughter particle(s) momentum. The DMS tracking measurement planes are constructed of 0.5 cm diameter straw tubes that are located inside the decay vacuum region. Two straw planes are upstream and downstream of the DMS analysis magnet. To achieve a ± 1 ns time resolution in the magnetic spectromet an Exit Time Plane and the Beam Time Stamp Module.

The velocity spectrometer is a unique system that is critical for background control. This system makes a velocity measurement of the incident Kaon track and the daughter decay product tracks. Using a hypothesis of a Kaon for the incident track and a pion for the decay product track, a missing mass is calculated. The velocity spectrometer is composed of two ring imaging Cherenkov counters. The upstream ring imaging Cherenkov counters (RICH) measures incident K^+ **velocity vector** and the downstream Cherenkov counter measures the charged daughter particle's **velocity vector**. An essential feature of the CKM spectrometer is the **redundancy** in measuring the incident particle and the charged daughter particles to give a **redundant missing mass measurement**. The momentum vector measurement is totally independent of the velocity vector measurement.

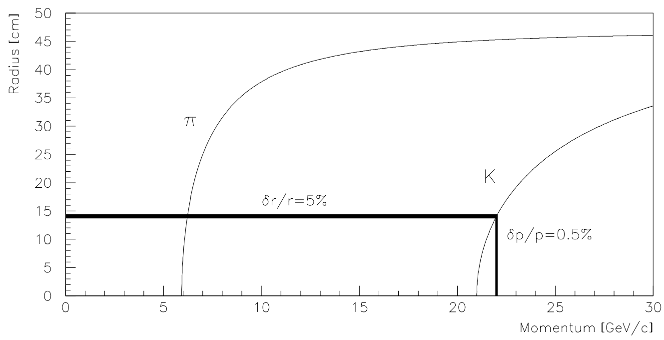

Figure 8: The ring radius vs. momentum for K^+ and π^+ tracks in the Kaon rich.

Typically, RICH's are operated well above "turn-on" (i.e. where the rings radii saturate as a function of particle momentum) and serve as a particle identifier. Instead, the CKM RICHS will be operated in the region that is centered in the "turn-on" threshold. Figure 8 illustrates the relationship the anticipated operation region for the Kaon RICH. As can be seen in Figure 8 the radius of the Cherenkov ring is very sensitive to the momentum of the Kaon.

Also apparent in Figure 8 the Cherenkov ring radii for Kaons vs. π are well separated in value. The velocity resolution is dependent on the ring size, with larger rings yielding better momentum resolution. However as can be seen from Figure 8, the slope of the curve ($\frac{\mathrm{dR}}{\mathrm{dp}}$) flattens out as the ring radii increase, which also degrades the momentum resolution. Also, chromatic dispersion (the dependence on the index of refraction in a media on the wavelength of light, $\mathrm{n}(\lambda)$) degrades the velocity spectrometer's momentum resolution. The momentum spectrometer and velocity spectrometer have comparable momentum resolution as deduced from `SPEC_RES` calculations.[18] The redundancy in the missing mass calculation results from the fact the mechanisms for misreconstruction for one spectrometer are different for the other spectrometer.

The photon calorimetry is used to reject K^+ decay modes that have final state γ's. The most important background decay modes are listed in Table 2 on page 9. The photon veto system must reject K^+ decays that have γ's with great efficiency. Given this requirement, the CKM veto system must be nearly hermetic in its coverage. Extensive monte carlo studies using the GEANT based monte carlo show that the veto system only has to be efficient from about 10-20 MeV (in the cylindrical region around the vacuum decay volume) up to about 8 GeV in all regions. In addition, the photon veto system must have sufficient energy and position resolution to measure all final state particles for some fraction of the $K^+ \rightarrow \pi^+\pi^o$ decays so as to record a sufficiently large sample of γ's from this decay mode for γ efficiency measurements and monitoring purposes. The photon veto system must be able to tag minimum ionizing particles produced by beam interaction of material used to build the spectrometer. The photon veto system is composed of the following elements: Vacuum Veto System (VVS), Forward Veto System (FVS) and the Hole Veto System (HVS).

The VVS is essentially an annular calorimeter that lines the inner volume of the vacuum decay region. The basic VVS component is a Pb/scintillator calorimeter constructed in a wedge-line 22.5^o annular sector. Sixteen of the sectors are pieced together to produce a annulus. This module is composed longitudinally of 81 layers of 1 mm Pb and 5 mm scintillator laminate. The scintillators are segmented in the azimuthal direction and are read out by wave shifting fibers that are bundled and sent to the inside surface of a window in the vacuum vessel wall. Photomultiplier tubes are grease fitted to the outside of the window. Alternating layers of the 81 planes of scintillator are sent to one of two different sets of photomultiplier tubes. The other layers are sent to the other photomultiplier tube so that successive scintillator planes are not instrumented by the same photomultiplier tube. The VVS is split up into two regions. The VVS in the upstream region has 34 annular modules with an inner radius of 27 cm and an outer radius of 135 cm. The second region is constructed with 4 annular modules with an inner radius of 40 cm and an outer radius of 192 cm. The entire VVS system will be approximately 38 m long. The efficiency of the VVS will be monitored by $K^+ \to \pi^+\pi^o$ events where one γ is observed in the Forward Veto System. Pile-up from energy deposited before the trigger event will be monitored by the large trigger time window as any activity in the spectrometer for several hundred nanoseconds prior to the trigger will be recorded. Other potential sources of inefficiency may result from the read out. This is monitored by redundant readout of successive VVS layers in a given sector-module (i.e. half of the scintillator planes go to a single photomultipliers tube, with the other interleaving planes going to a second photomultiplier tube). In addition, each photomultiplier tube will be read out with both a TDC and ADC. The scintillators of the entire VVS system will be exposed to light from an LED that is pulsed at a rate of 1 Hz. Other mean of monitoring the VVS will be accomplished by the high fluence of μ's from $K^+ \to \mu^+\nu_\mu$ decay and γ's from $K^+ \to \pi^+\pi^o$ decays.

The FVS is positioned downstream of the vacuum decay volume and VVS. The FVS is constructed from CsI crystals and has a 15 $\times$ 15 cm^2 hole for the 50 MHz channeled beam to pass through. Such a calorimeter is totally active, has high resolution, excellent linearity for a large dynamic range of γ energies and is radiation hard. The CKM CsI crystal array will be composed of an array of 5$\times$5 cm^2 blocks with an 18 X_o (radiation lengths) in depth. There are cracks between the blocks, so the calorimeter will have to be tilted. The FVS is designed to detect forward, high energy γ's that can result from the 22 GeV K^+ decay (primarily $K^+ \to \pi^+\pi^o$ and $K^+ \to \mu^+\nu_\mu\gamma$). Photons from the decay mode $K^+ \to \pi^+\pi^o$ that intercept the FVS have energies in excess of 1 GeV. It has been found in monte carlo studies that if a γ with an energy of > 1 GeV from $K^+ \to \pi^+\pi^o$ decay lands in the FVS, the other γ from the π^o decay must land in the VVS.

The HVS is located downstream of the FVS, Muon Veto System and the BM-109 sweeping magnet aligned with the 15 $\times$ 15 cm beam hole in these detectors that the 50 MHz beam travels through. The BM-109 magnet sweeps out the charged beam leaving neutrals to impact the HVS which is similar in design to the FVS calorimeter. The purpose of this detector is to veto K^+ decays with very forward γ's.

Currently, there are two designs under consideration for the HVS. Both designs are hermetic to less than 10^{-4} and can distinguish $\pi^+ - \gamma$ coalescence from a single γ for separations of greater than 10 cm. The first design is a Pb/scintillator calorimeter and the second design is a CsI crystal calorimeter. The Pb/scintillator calorimeter is similar to the PHEONIX shashlik calorimeter. It is composed of sheets of Pb interleaved with scintillator sheets. Wave shifting fibers penetrate perpendicular through the Pb/scintillator planes towards the back of the calorimeter where these fibers are bundled into a photomultiplier tube. The scintillator sheets are segmented by grooves cut into the plastic sheets to form optically isolated 5×5 cm^2 tiles. The calorimeter may be constructed from four supermodules that are overlapped with a 15×15 cm^2 hole in the middle. A prototype shashlik has been built and successfully tested at CERN.[19] If the CKM experiment employs the shashlik design, we will use a lower wave shifting fiber density which will reduce the light yield and therefore the energy resolution. However, this reduces particle channeling. Also, a shashlik calorimeter will have to tilted about 50 mrad so that holes for the wavelength shifting fibers do not project back to the target. The second design is a CsI array.

Muon identification or rejection depends upon the fact that muons are electrically charged and are highly penetrating whereas pions do not penetrate a lot of material. Muon identification must reject π's that mimic μ's from hadronic punch through and decay in flight pions ($\pi^+ \rightarrow \mu^+\nu_\mu$). For muon identification, the misidentifications of a π as a μ is a source of background. The CKM experiment will use muon rejection. Here the π's that are misidentified as μ's are a small source of inefficiency and are not a background. Backgrounds in muon rejection result from π's that mimic μ's. The Muon Veto System (MVS) will provide this rejection.

The CKM experiment requires a muon rejection efficiency of less than 1×10^{-5} for muons with a momentum $14 < p_\mu < 22$ GeV/c. CKM used monte carlo generated $K^+ \rightarrow \mu^+\nu_\mu$ and $K^+ \rightarrow \mu^+\nu_\mu\gamma$ decays to study the rejection efficiency of the muon veto calorimeter. A MVS prototype has been constructed and tested at IHEP Protovino. The prototype was constructed out of 27 planes of $600 \times 600 \times 41$ mm^3 steel plates sandwiching 26 scintillator planes that had dimensions of $500 \times 400 \times 10$ mm^3. All of these planes were perpendicular to the beam and each scintillator plane was constructed out of 12 $500 \times 40 \times 10$ mm^3 counters that were connected via light guides to Russian FEU-84 photomultiplier tubes. The prototype was constructed with a plane of horizontal scintillator counters, steel plate and vertical plane of scintillator counters. The cracks between successive horizontal or vertical planes were staggered so that they did not line up.

This prototype was placed in the ISTRA spectrometer as part of the U-70 run at IHEP Protovino. The prototype was subjected to a 25 GeV/c π^+ beam, a high intensity muon beam (closed collimators) and a low intensity muon beam. Analysis of the data collected in the prototype MVS used transverse and longitudinal information for hadron identification. A misidentification rate of 4×10^{-6} was achieved (better than the specifications).

In the CKM spectrometer, the 50 MHz beam that is transported through the hole of the FVS and MVS is inside an atmospheric pressure He bag. Just downstream of the MVS and spanning the cross section of the beam is the Conversion Veto Plane (CVP). The CVP will be constructed out of a plane of scintillating fibers. This device is use to reject events where photons have converted in the pion RICH or other material upstream. The CVP will be instrumented with multi-anode photomultiplier tubes and read out by TDC's. The time resolution required for the CVP is $\pm$ 1 nsec. The beam 50 MHz beam remnant is bent subsequently by a BM-109 magnet (1 GeV/c p_t kick) into a borated reentrant cavity 20 meters downstream (and offset to) the HVS.

5 Contributions from the University of South Alabama High Energy Physics Group

The University of South Alabama High Energy Physics Group is writing the single event display program for the CKM experiment. The High Energy Physics Group will also install and support the computer controlled high voltage system for the photomultiplier tubes of the CsI crystals of the FVS. A single event display is a program that takes the event record recorded by the spectrometers data acquisition system and draws a picture of the spectrometer, all hits in detection devices and superimposes the results of analysis (such as tracks from pattern recognition, decay vertecies and track momenta). The single event displays are being developed on Linux based PCs.

The complexity of the CKM spectrometer requires a single event display program that has the ability to simultaneously display multiple windows that displays different views and spectrometer subsystems (for examples the pion RICH, UMS or DMS, elevation or plan views). This capability is the motivation to developing a C++ based single event display. The first version of the C++ single event display was developed using `glade--` which is a C++ graphics resource editor to produce the graphical user interface (GUI), `gtk--` which is a C++ graphics library, `CLHEP` which is a CERN product that interfaces `Fortran` and C++. The `Fortran`/C++ interface is needed as most of the analysis code is written in `Fortran`. An undergraduate student, Jacob Harris, wrote a GUI user interface and and a graphics interface wrapper for `gtk--`. The faculty member in the USA High Energy Physics group has written the interfaces to the CKM event record reader and the code to draw the spectrometer, event and analysis results. Figure 9 on page 19 shows an image captured on the screen of a PC for this version of the CKM single event display.

The `glade--` and `gtk--` packages have demonstrated many weakness, particularly when additional features such as saving graphics output were attempted. These packages are a C++ wrapper to C libraries and they are still under development. In addition, these packages are poorly documented and the packages often do not work as the documentation says it should. Consequently, a C++ graphics package, called Qt, is currently being explored for use in the C++ single event display. This package is open-source, a true C++ graphics library, well documented and the library works as the documentation says it should. Currently, a wrapper from the CKM single event display to the Qt graphics library has been written and a GUI has been written. A GUI shell with all the functionality of the earlier C++ version of the single event display is nearly ready to be integrated with the Fortran based CKM event record reading and analysis programs. The University of South Alabama Experimental High Energy Physics group expects to build a fully functional Qt CKM single event display program in the near future.

The high voltage power supply system that will be used with the CsI array is a computer controlled system. The faculty member at the University of South Alabama has extensive experience setting this system up and supporting it. Part of the setup is suppling a computer program that will communicate with the microprocessor inside the high voltage power supply system. The University of South Alabama Experimental High Energy Physics group anticipates updating this program from terminal emulation line based user interface to a graphical user interface to make control of the high voltage power supply more user friendly.

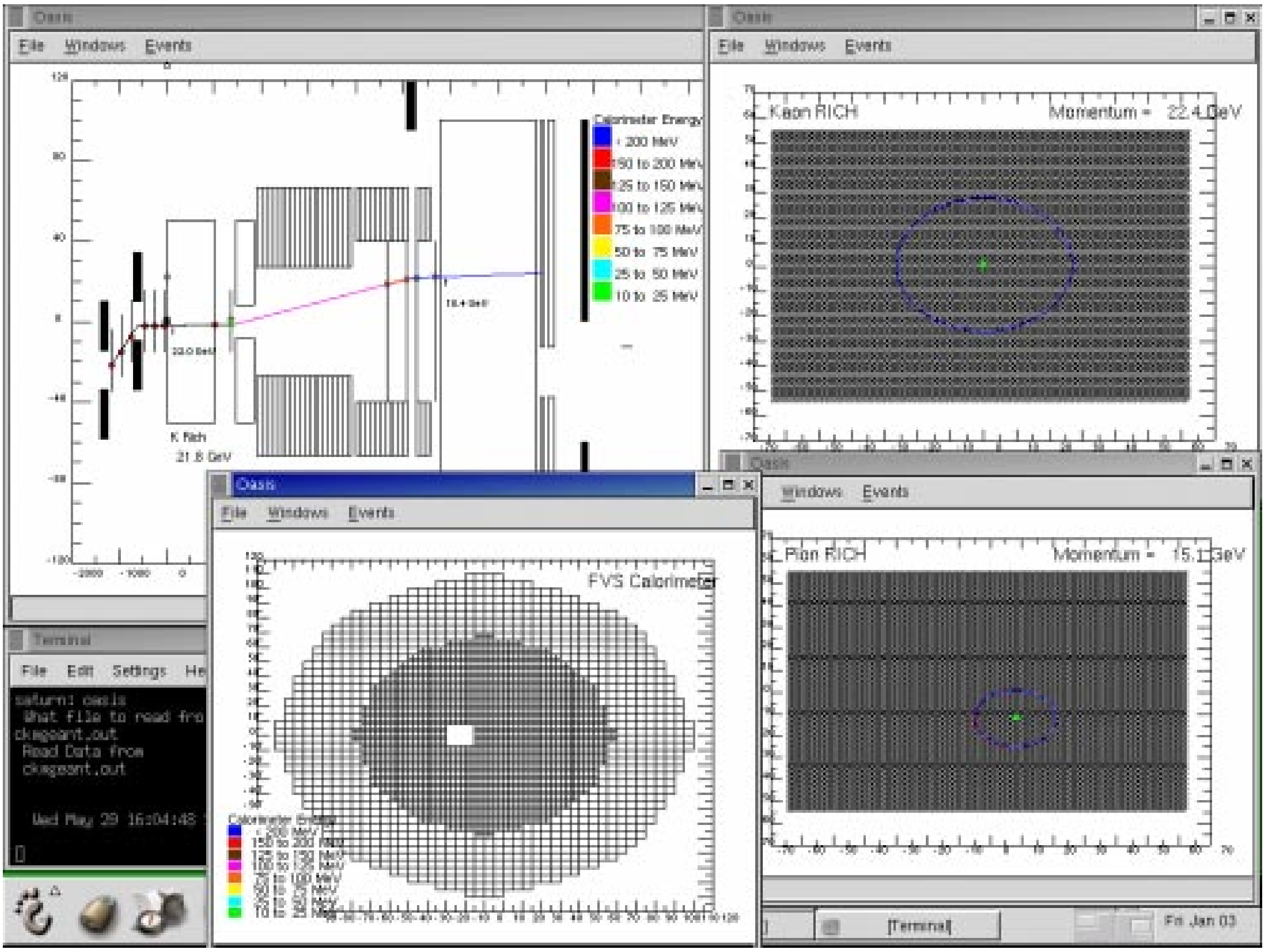

Figure 9: A version of the CKM C++ single event display.

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References

[1] L. Bellantoni et al., “Charged Kaons at the Main Injector”, Fermilab Experiment Proposal, April 2, 2001.

[2] N. Cabibbo, “Unitarity Symmetry and Lepton Decays”, Phys. Rev. Lett **10** (1963) 531.

[3] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652.

[4] S. Adler et al., “Evidence for the Decay $K^+ \to \pi^+\nu\overline{\nu}$”, Phys. Rev. Lett. **79** (1997) 2204, S. Adler et al., “Further Search for the Decay $K^+ \to \pi^+\nu\overline{\nu}$, Phys. Rev. Lett. **84** (2001) 3768., S. Adler et al., “Further evidence for the Decay $K^+ \to \pi^+\mu^+\mu^-$”, Phys. Rev. Lett. **88** (2002) 041803.

[5] L. Bellantoni et al., “Charged Kaons at the Main Injector”, Fermilab Experiment Proposal, April 2, 2001, page 25.

[6] G. Buchalla and Andrzej J. Buras, “$K \to \pi\nu\overline{\nu}$ and a high precision determinations of the CKM matrix”, Phys. Rev. **54D** (1996) 6782.

[7] L. Bellantoni et al., “Charged Kaons at the Main Injector”, Fermilab Experiment Proposal, April 2, 2001, page 23.

[8] L. Bellantoni et al., “Charged Kaons at the Main Injector”, Fermilab Experiment Proposal, April 2, 2001, page 23., T. Inami and Cs. Lim, Prog. Theor. Phys. **65** (1981) 297.

[9] L. Bellantoni et al., “Charged Kaons at the Main Injector”, Fermilab Experiment Proposal, April 2, 2001, pages 22-23.

[10] L. Bellantoni et al., “Charged Kaons at the Main Injector”, Fermilab Experiment Proposal, April 2, 2001, page 25., A. Falk, A. Lewandowski, A Petrov, “Effects from the charm scale in $K^+ \to \pi^+\nu\overline{\nu}$ ”, hep-ph/0010299, Dec 2000.

[11] Particle Data Group, The European Physical Journal **C15**(2000)110.

[12] L. Wolfenstein, “Parameterization of the Kobayashi Maskawa Matrix”, Phys. Rev. Lett **51** (1983) 1945.

[13] Andrzej J. Buras et al., “Waiting for the top quark mass, $K^+ \to \pi^+\nu\overline{\nu}$, $B_s^o - \overline{B}_s^o$ mixing and CP asymmetries in B decays”, Phys. Rev. **50D** (1994) 3433.

[14] P. Faccioli, “CKM matrix ‘over consistent’ picture of the unitarity triangle”, Nucl. Inst. and Meth. **A462** (2001) 313.

[15] Particle Data Group, The European Physical Journal **C15** (2000) 498.

[16] L. Bellantoni et al., “Charged Kaons at the Main Injector”, Fermilab Experiment Proposal, April 2, 2001, page 26.

[17] Particle Data Group, European Physical Journal **C15** (2000) 498.

[18] L. Bellantoni et al., "Charged Kaons at the Main Injector", Fermilab Experiment Proposal, April 2, 2001, page 55. Specres, an analytical calculation of the magnetic spectrometer resolution, Peter Cooper, CKM internal memo.

[19] L. Bellantoni et al., "Charged Kaons at the Main Injector", Fermilab Experiment Proposal, April 2, 2001, page 167.