Measurement of $K^+ \rightarrow \pi^+ \nu \nu$
at CKM

by Sasha Kushnirenko

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CKM experiment

CKM is a proposed $K^+$ decay-in-flight experiment at Fermilab. The GOAL of CKM experiment is to observe a sample of 100 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events with small background.

- Precise measurement of $|V_{td}|$
- Constrain $\rho - \eta$ plane
- Rare $K^+$ decays

Experimental Feautures

- Decay in flight experiment
- Narrow band search
- Redundancy (BNL experience)
- High resolution
- Control non-gaussian tails
Physics motivation

SM diagrams

100 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events provides 10% theoretically clean measurement of $|V_{td}|$

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \sim |V_{cb}|^4 \cdot ((\bar{\rho} - \rho_0)^2 + \bar{\eta}^2)$$

$$BR(K^0 \rightarrow \pi^0 \nu \bar{\nu}) \sim |V_{cb}|^4 \cdot \bar{\eta}^2$$

Simultaneous measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K^0 \rightarrow \pi^0 \nu \bar{\nu}$ is extremely important
Physics motivation

- In ideal SM world all $\rho - \eta$ measurements should agree
- CKM triangle can be overconstrained within Kaon system only.
- Comparison with $B$ physics can reveal New Physics
- Comparison with $B$ requires knowledge of $|V_{cb}|$
Charged Kaons at the Main Injector

April 2, 2001

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

J. Frank, S. Kettell, R. Strand
Brookhaven National Laboratory, Upton, NY, USA

L. Bellantoni, R. Coleman, P.S. Cooper*, T. R. Kobilarcik, A. Kushnirenko, C. Milstene,
H. Nguyen, A. R. Pastiak†, E. Ramberg, R. S. Tschirhart, H. B. White, J. Y. Wu
Fermi National Accelerator Laboratory, Batavia, IL, USA

G. Britvich, A. V. Inyakin, V. Kurshetsov, L. G. Landsberg, V. Mokhanov,
V. Obraztsov, S. I. Petrenko, V. Polyakov, V. I. Rykalin, A. Soldatov,
M. M. Shapkin, O. G. Tchikilev, D. Vavilov, O. Yushchenko
Institute of High Energy Physics, Serpukhov, Russia

J. Engelfried, A. Morelos
Instituto de Física, Universidad Autonoma de San Luis Potosí, Mexico

M. Campbell, R. Gustafson, M. Longo, H. Park
University of Michigan, Ann Arbor, Michigan 48109

K. Lang
University of Texas at Austin, Austin, Texas 78712

C. Dukes, R. Godang, L. Lu, K. Nelson
University of Virginia, Charlottesville, VA 22901

† Visitor from the Institute for Nuclear Research, Troitsk, Russia

* Spokesman: P.S. Cooper, pcooper@fnal.gov, (630) 840-2629

Web Address: www.fnal.gov/projects/ckm/Welcome.html
Region 1 - Goal to get 100 events
Region 2 - Did not invest in that yet, but will definitely try
Region 3 - Hopeless

\[ K^+ \rightarrow \pi^+ \pi^0 \] is the main background source
Basic orders of magnitude

\[ Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \approx 10^{-10} \]

100 events \rightarrow \quad 10^{12} K^+ decays
\[ \epsilon \sim 1\% \quad \rightarrow \quad 10^{14} K^+ decays \]
\[ \gamma c \tau = 165m, \epsilon = 10\% \quad \rightarrow \quad 10^{15} K^+ \text{ decays} \]

\[ 10^{15} K^+ / 10^7 s = 100 \text{ MHz beam} \]

Resolution to fight \( K^+ \rightarrow \pi^+ \pi^0 \) background:

near \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \quad \rightarrow \quad \sim 10^{13} K^+ \rightarrow \pi^+ \pi^0 \) decays
\[ \epsilon_{\gamma \gamma} \sim 10^{-7} \quad \rightarrow \quad \sim 10^6 K^+ \rightarrow \pi^+ \pi^0 \) decays
\[ \epsilon_{\text{kinem}} \sim 10^{-5} \quad \rightarrow \quad \sim 1 K^+ \rightarrow \pi^+ \pi^0 \) decays

\begin{itemize}
  \item Divide in half available \( M_{\text{miss}}^2 \)
  \item \( \epsilon_{\text{kinem}} \sim 10^{-5} \)
  \item \( 5\sigma M^2 = M_{\pi 0}^2 / 2 \)
  \item \( \sigma M^2 \sim 0.002 \text{ GeV}^2 \)
\end{itemize}

\[ M_{\text{miss}}^2 = M_K^2 (1 - \frac{p_\pi}{p_K}) + m_\pi^2 (1 - \frac{p_K}{p_\pi}) - p_\pi p_K \theta^2 \]

\[ \sigma_{p/p} \sim 1\% \quad \sigma_{\theta} \sim 0.1 \text{ mrad} \]
RF separated $K^+$ beam

Requirements

- 30 MHz $K^+$ rate @ 22 ± 0.4 GeV
- < 50 MHz total charged particle rate.
- Debunched beam

Due to their differing velocities, $\pi^+$, $p^+$ and $K^+$ "slip" in phase by different amount.

$\pi^+$ and $p^+$ arrive 180 degrees out of phase with respect to first RF station and receive no net deflection.

$K^+$ arrive ~93 degrees out of phase with respect to first RF station and receive time-varying deflection.

$L=86\text{m}, f=3.9\text{GHz}$

$\pi^+\quad 0\text{ ps}\quad \phi = 0^\circ$
$p^+\quad 257\text{ ps}\quad \phi = 360^\circ$
$K^+\quad 67\text{ ps}\quad \phi = 94^\circ$
RF separated $K^+$ beam
RF separated $K^+$ beam

- 2 station with 13-cell superconducting RF
- $p_T = 5$ MeV/m
- GEANT/TURTLE simulation
- The design exceeds the requirement
- R&D under extensive study
- Collaboration with TESLA on SCRF design

Our most recent 1-cell test result

Goal is to test a complete cryomodule in 2002 and test it in a beam during 2003
CKM Apparatus

- Kaon Entrance Angle Tracker
- Beam Time Stamp
- Upstream Magnetic Spectrometer
- Kaon RICH 0.7 atm CF$_4$
- Beam Interaction Veto
- 50 MHz Separated K+ Beam 22 GeV/c

- UltraVacuum Veto Plane
- Exit Time Plane
- Forward Veto Plane
- Conversion Veto Plane
- BM109 Magnet
- Hole Veto
- Beam Dump

- Pion RICH 1 atm Neon
- Downstream Magnetic Spectrometer
- Muon Veto
- Forward Veto
- Beam Interaction Veto

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Photon Veto System

Total $\pi^0$ inefficiency $= 1.6 \cdot 10^{-7}$

- $0.3 \cdot 10^{-7}$ low energy $\gamma$ escapes in the gap.
- $0.5 \cdot 10^{-7}$ when $\gamma$ lands within 10 cm from $\pi^+$ in FVS.
- $0.8 \cdot 10^{-7}$ low energy/high energy photon pair is lost. Mostly in VVS.

- VVS - most stringent inefficiency requirements up to $3 \cdot 10^{-5}$
- FVS - only 10% of photons hit it. Inefficiency requirement $\sim 1 \cdot 10^{-4}$
  Fine segmentation to separate $\pi^+$ and $\gamma$.
  Simulated with MC and checked on KTeV data.
- HVS - even more relaxed requirement $2 \cdot 10^{-3}$
Vacuum Veto System

- Low energy inefficiencies due to sampling. Studied with GEANT.
- Middle energy inefficiencies: data exist for the similar Photon Veto system in BNL-E787
- High energy inefficiencies: very important. Background almost proportional to inefficiency.
  - Shower escaping in vacuum - GEANT
  - Photo-Nuclear interactions: Estimates from data
  - Tagged $e$ sample in KTeV data. $1 - \epsilon < 3 \cdot 10^{-5}$. 

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Vacuum Veto System

- 34 annular stations which fill 50%
- $15X_0$: 81 layer 1 mm Pb/5 mm scintillator
- Light collection with WLS fibers
- 10 p.e./MeV (better values achieved in studies)
- Modeled after KTeV and BNL-E787
- Odd/Even layer are mapped to 2 PMT
- Monitoring with LED, muons
Measurement of momenta with RICH

- 5% measurement of radius gives 0.5% momentum resolution
- $K^+$ is well separated from $\pi^+$
- Modeled after successful SELEX RICH

2 RICHs can measure $K$ and $\pi$ track directions and momenta. So they can give an independent measure of $M_{\text{miss}}^2$. Comparison of Tracking and RICH measurements is a critical element of the experiment.

Running RICH in “momentum-measuring” mode limits accessible momentum range.
Kaon RICH

- 11 m long vessel
- $CF_4 @ 0.7$ atm or $N_2 @ 1.2$ atm
- 600 1/2'-PMT
- Excellent $\pi/K$ separation $\sim 50\sigma$
- Rate per tube $< 1.4$ MHz
- $n_{hit} = 10.8$, $\sigma_\Theta = 0.1$ mrad, $\sigma_p/p \simeq 0.5\%$
- Resolution limited by chromatic dispersion $dn/d\lambda$
Pion RICH

- 20 m long vessel, \( d = 2 \) m
- \( N_e \) @ 1 atm
- 3000 1/2'-PMT
- Good \( \pi/\mu \) separation \( \sim 10 - 15\sigma \)
- Rate per tube \( f_\pi < 90 \) kHz, \( f_K < 400 \) kHz
- \( n_{hit} \sim 20, \sigma_\Theta \sim 0.1 \) mrad, \( \sigma_p \sim 0.17 \) GeV, \( \sigma_p/p \sim 1\% \)
- Resolution not limited by one factor.
SELEX RICH performance

Non-gaussian tails in RICH detectors?

Solid histogram already gives acceptable performance

We think we can do better.
Upstream Magnetic Spectrometer

Plan View

Elevation View

- 6 stations, each has 6 views \((x, x', u, u', v, v')\)
- Inter length = 1.7\%, Rad length = 2.1\%
- UMS have to provide excellent resolution in high-intensity beam
- Modeled after HyperCP chambers
HiperCP = 1 mm wire pitch @ 270 kHz/cm² max rate
CKM = 0.8 mm wire pitch @ 750 kHz/cm² max rate

- Maximum rate per wire 610 kHz,
HyperCP tested 640 kHz rate rate per wire
- $\sigma_p/p \simeq 0.2\%$, $\sigma_\Theta \simeq 0.06$ mrad

Kaon Entrance Angle Tracker

- Kaon RICH introduces 10% of the rad length
- 2 UMS chambers separated by 2.6 m. $\sigma_\Theta \simeq 0.08$ mrad
- Another option: Silicon in Vacuum
**Downstream Magnetic Spectrometer**

- 4 straw chambers in **Vacuum**
- 5/8/8/8, 4 views \(0^\circ, 90^\circ, \pm 45^\circ\)
- As thin as possible:
  - 5 layers = 0.21 \(X_0\), 8 layers = 0.34 \(X_0\)
- Active area \(80 \times 80 \text{ cm}^2\), drift time = 25 ns
- Maximum rate per straw 120 kHz
- Deadened in the beam
- Gas leakage in vacuum is tiny compared to scintillator.
- Similar system worked in BNL-871
- MECO also plan to use straws in vacuum
Downstream Magnetic Spectrometer

Non-gaussian tails in DMS? Comparison with BNL-871

BNL-871: CKM:
3-4GeV 14-20GeV
4 chambers 4 chambers
5 straw layers 8 straw layers
100 kHz < 110 kHz

- GEANT simulation: $\sigma_p/p \simeq 1.1\%, \sigma_\Theta \simeq 0.04$ mrad
- Data from BNL-871 shows higher tails
- Resolution tails: we understand some differences with BNL-871
Muon Veto

To control $K^+ \rightarrow \mu^+ \nu_\mu$ background.

- Veto $\mu$, identify $\pi$
- Prototype test on 25 GeV beam in Protvino (Russia)
- 26 layers: 4.1 cm Fe / 1 cm scintillator
- Alternating $X, Y$ projections
- Requirement: $< 1 \times 10^{-5}$ at 95% $\pi$ efficiency
- Test Beam: $< 3 \times 10^{-6}$ at 75% $\pi$ efficiency

Possible improvements:

- Increase length (83%)
- Better plastic and light collection
- Relaxing cuts
- Better algorithms
# Summary of CKM backgrounds

<table>
<thead>
<tr>
<th>Background source</th>
<th>Effective BR $(\times 10^{-12})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu_\mu$</td>
<td>$&lt; 0.04$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0$</td>
<td>3.7</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu_m u \gamma$</td>
<td>$&lt; 0.09$</td>
</tr>
<tr>
<td>$K^+ A \rightarrow K_L X, K_L \rightarrow \pi^+ e^- \bar{\nu}_e$</td>
<td>$&lt; 0.14$</td>
</tr>
<tr>
<td>$K^+ A \rightarrow \pi^+ X$ in trackers</td>
<td>$&lt; 4.0$</td>
</tr>
<tr>
<td>$K^+ A \rightarrow \pi^+ X$ in residual gas</td>
<td>$&lt; 2.1$</td>
</tr>
<tr>
<td>Accidentals (2 $K^+$ decays)</td>
<td>0.51</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$&lt; 10.6$</td>
</tr>
</tbody>
</table>
E787 and Background Factorization

- No photon veto cuts
- Online photon veto cuts
- Full offline photon veto cuts

Shape does not change.
Does not prove that it will work for CKM, but gives us hope.
Comparison of Momentum (Tracking) and Velocity (RICH) Spectrometers

Based on GEANT simulation of $K^+ \rightarrow \pi^+\pi^0$. 
**Selection cuts:**

- Clean event, reasonable number of hits
- Decay angle $\Theta_{K\pi} > 2.5$ mrad - good vertex
- $x$, $y$ on the beam, $z$ inside vacuum veto
- Distance between $K$ and $\pi$ tracks < 1 cm
- $14 < p_{\pi} < p_K - 1$ (GeV)
- $|M^2_{\nu\nu}(\text{RICH}) - M^2_{\nu\nu}(\text{tracking})| < 0.01$
- $-0.005 < |M^2_{\nu\nu}| < 0.008$
Summary

- Rare $K$ decay program has a solid physics case.
- CKM has a potential of robust measurement on $\rho - \eta$ plane.
- CKM got a scientific approval on June 28, 2001