An Intense Road to the Sensitivity Frontier:

Future Kaon Beam Experiments.

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XIVth Recontres De Blois
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Post Cards From the Frontier...

- Link to the high energy frontier: $B(K_L \rightarrow \mu e) < 4.7 \times 10^{-12}(90\% C.L)$, BNL-871. Corresponds to Lepton Flavor Violating X-boson: $m_X > 190 \text{ TeV}/c^2$.

- Rarest particle decay every seen: $B(K_L \rightarrow e^+e^-) = (9^{+6}_{-4}) \times 10^{-12}$, BNL-871.

- The KTeV $K_{\gamma\ast\gamma\ast}$ laboratory: $K_L \rightarrow \mu^+\mu^-e^+e^-$.  

![Invariant Mass Distribution](image)

Branching Fraction = \((2.61 \pm 0.23(stat) \pm 0.18(syst)) \times 10^{-9}\)

(KTeV Preliminary.)
Brookhaven E787 has Detected Two $K^+ \rightarrow \pi^+\nu\bar{\nu}$ Events

$$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

Standard Model prediction: $BR = (0.77 \pm 0.21) \times 10^{-10}$.

FIG. 2: Range vs. energy plot of the final sample. The circles are for the 1998 data and the triangles are for the 1996-97 data set. The group of events around $E = 108$ MeV is due to the $K_{e2}$ background. The simulated distribution of expected events from $K^+ \rightarrow \pi^+\nu\bar{\nu}$ is indicated by dots.
**Measuring $V_{td}$**

- **CKM Goal:** Measure $|V_{td}|$ to the limits of theory.

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = |V_{td}|^2 \times \left( \frac{\text{known stuff}}{\text{stuff}} \right)$$

$$= (0.44 \pm 0.15) \times 10^{-10}[1.4 - \bar{\rho}^2 + \pi^2]$$

- We really measure the branching ratio ratio:

$$\frac{B(K^+ \rightarrow \pi^+ \nu \bar{\nu})}{B(K^+ \rightarrow \pi^0 e^+ \nu)} = \frac{3\alpha^2}{8\pi^2 \sin^4 \theta_W} \frac{|V_{us} V_{cd} D(X_c) + V_{ts} V_{td} D(X_t)|^2}{|V_{us}|^2}$$

- Total theoretical uncertainty of 8% estimated by Buras et al. is dominated by uncertainty in the charmed quark mass.

- With $\sim 100$ events CKM’s measurement of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ translates to an uncertainty in $|V_{td}|$ of about 6% statistical and 8% theoretical.

- With current $|V_{CKM}|$ values:

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.77 \pm 0.21) \times 10^{-10}$$
The Physics Context

- It is *vital* that $\rho$ and $\eta$ of the CKM matrix be precisely measured.
- The *critical question* is not what $\rho$ and $\eta$ are, but whether all CP phenomena can be described with such a compact formalism.
- Four Gold-Plated accessible measurements have sufficient theoretical robustness that a contradiction could call the Standard Model into question:

  - $K^+ \to \pi^+ \nu \bar{\nu}$ : BNL787/949, CKM
  - $K^- \to \pi^- \nu \bar{\nu}$ : KOPIO, KEK-e391a/JHF
  - $B_d \to J/\psi K_S$ : Babar, Belle, CDF, D0, LHCb, Atlas, CMS, BTeV
  - $\Delta M_d/\Delta M_s$ : CDF, D0, LHCb, Atlas, CMS, BTeV
Comparison of Precision from Proposed K and B Measurements

$\sigma(|V_{cb}|) = \pm 0.002(0.001)$

<table>
<thead>
<tr>
<th></th>
<th>$K \rightarrow \pi \nu \bar{\nu}$</th>
<th>B-Factory Era</th>
<th>LHCb/BTEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(</td>
<td>V_{td}</td>
<td>)$</td>
<td>$\pm 10%(9%)$</td>
</tr>
<tr>
<td>$\sigma(\bar{\rho})$</td>
<td>$\pm 0.16(0.12)$</td>
<td>$\pm 0.03$</td>
<td>$\pm 0.01$</td>
</tr>
<tr>
<td>$\sigma(\bar{\eta})$</td>
<td>$\pm 0.04(0.03)$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.01$</td>
</tr>
<tr>
<td>$\sigma(\sin 2\beta)$</td>
<td>$\pm 0.05$</td>
<td>$\pm 0.06$</td>
<td>$\pm 0.02$</td>
</tr>
<tr>
<td>$\sigma(\text{Im } \lambda_t)$</td>
<td>$\pm 5%$</td>
<td>$\pm 14%(11%)$</td>
<td>$\pm 10%(6%)$</td>
</tr>
</tbody>
</table>
Progress toward Measuring $\text{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu})$
CKM: Charged Kaons at the Main Injector

Measuring the CKM matrix element $|V_{td}|$ with a statistical precision of 5% and an overall precision of 10% through a measurement of the branching ratio of:

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

And There is Other Physics Yet...
Charged Kaons at the Main Injector

June 6, 2002

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

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Web Address: www.fnal.gov/projects/clm/Welcome.html
• Decay in flight experiment: 22 GeV/c enriched $K^+$ beam.
• Philosophy: redundant measurements, proven technology.
• Good, redundant measurements of $K^+$ and $\pi^+$ momenta.
• Good, redundant particle ID for signal and backgrounds.
• Very high-rate, low-mass detectors.
Number of Kaons Needed

\[
\text{Branching Ratio} \times \begin{cases} 
0.12 & \text{decay region} \\
0.034 & \text{acceptance/cuts} \\
0.70 & \text{livetime/efficiencies}
\end{cases} = 2.74 \times 10^{-13}
\]

\[3.65 \times 10^{14} \text{ } K^+\text{'s needed for 100 accepted } K^+ \to \pi^+\nu\bar{\nu}\text{ decays.}\]

Assume a 2-year run with a 1-s spill of \(4 \times 10^{12}\) protons every 3-s:

2 yr/run·39 wk/yr·120 hr/wk·3600 s/hr·1 spill/3 s = \(1.12 \times 10^7\) spill/run

\[32.5 \text{ MHz } K^+ \text{ beam needed}\]

* Implications *

1. Protons required are a small fraction of the Main Injector capacity.
2. Unbunched beam *required*.
3. Enriched \(K^+\) beam *required*.

Relative 22 GeV rates from 120 GeV protons:

\[
\begin{cases}
10 & \pi^+ \\
4 & p \\
1 & K^+
\end{cases}
\]
Enriching the Kaon Content of the Beam

Target RF 1

Unitary Transfer Lattice RF 2

Point-to-Parallel optics

Beam stop

$\mathbf{p}$, $^+$, $K^+$

$\mathbf{p}$

$K^+$

$\frac{1}{256}$ ps = 3.91 Ghz

$v/c$

$^+$: 0.99998

$K^+$: 0.99975

$p$: 0.99909

180°

180° + 94°

$p$, $^+$, $K^+$

RF 1

RF 2

net kick

RF 1

RF 2

net kick

v/c

$p$

$K^+$

86.4 m

7.7 cm 2.01 cm 0 cm

256 ps 67 ps 0 ps

360° 94.1° 0°
13-cell transverse field prototype.

Six 13-cell cavities per station: $p_T = 15\text{ MeV}$.

Tesla R&D has been critical to the success of this development.

- One-cell prototype has exceeded surface field requirement by $\times 2$.
- Tuning and optimization of 13-cell cavity underway.
Backgrounds a (the) Problem!

**Signal**
- \( K^+ \)
- Tools
  - momentum
  - direction
  - particle ID
  - 3-body decay

For every 10 billion \( K^+ \) decays we get:
- 1
  - \( (BR = 1 \times 10^{-10}) \)

**Backgrounds**
- \( K^+ \)
- \( K^+ \)
- \( K^+ \)
- \( K^+ \)
- Tools
  - particle ID
  - 2-body decay
  - -veto
  - charged veto
  - low material

- \( 6,350,000,000 \)
  - \( (BR = 0.635) \)

- \( 2,120,000,000 \)
  - \( (BR = 0.212) \)

- lots!
Eliminating Backgrounds

Background rejection must be $\sim 10^{12}$

1. Kinematics

$$M^2_{\text{miss}} = M^2_K (1 - \frac{p_\pi}{p_K}) + m^2_\pi (1 - \frac{p_K}{p_\pi}) - p_\pi p_K \theta^2$$

- Major backgrnds, $K^+ \rightarrow \pi^+\pi^0$, $K^+ \rightarrow \mu^+\nu_\mu$, have well-defined missing masses.
- $\theta$, $p_K$, $p_\pi$, need to be measured to 1% or better.
- Done with momentum and velocity spectrometers.

2. Particle Identification

1. Mass using momentum and velocity spectrometers.

$$m = \frac{p}{\gamma v}$$

Ring Imaging Cherenkov Detector Systems

\[ r = \frac{R}{2} \sqrt{2 - \frac{2}{n} \left[ 1 + \left( \frac{mc}{p} \right)^2 \right]} \]

- Vector velocity spectrometers.
- Provide totally independent measurement of momentum of \( K^+ \) and \( \pi^+ \).
- Provide (with magnetic spectrometers) particle ID for \( K^+ \), \( \pi^+ \), \( \mu \), \( p \) and \( e \).
- Fast: phototube readout.
- Excellent momentum resolution.
- Based on successful SELEX RICH.
SELEX RICH: Particle Id negative tracks

Entries: 53229793

Muon
Pion
Kion
Proton
Sigma
Xi
Omega

Momentum [GeV/c]
Momentum and Velocity Spectrometer Resolutions Well Matched

$$M_{\text{miss}}^2 = M_K^2 (1 - \frac{p_\pi}{p_K}) + m_\pi^2 (1 - \frac{p_K}{p_\pi}) - p_\pi p_K \theta^2$$
SELEX RICH Rings Gaussian over Five Orders of Magnitude
Little Correlation between Magnetic and Velocity Measurements

\[ \left( \frac{M^2_{\text{miss}}}{\text{track}} \right) \]
CKM Sensitivity After Two Years

\[ K^+ \rightarrow \pi^+\pi^0 \text{ 158K events} \]

\[ K^+ \rightarrow \pi^+\nu\bar{\nu} \]

95 events in signal region

\[ M^2_{\text{miss}} [\text{GeV}^2] \]

1.123\times10^7 \text{ spill-s/2 yr run}
× 31\times10^6 \text{ MHz kaon beam} = 3.5\times10^{14} K^+
× 1\times10^{-10} \text{ BR}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 3.5\times10^4 K^+ \rightarrow \pi^+\nu\bar{\nu}
× 0.116 \text{ lifetime acceptance} = 4.0\times10^3 K^+ \rightarrow \pi^+\nu\bar{\nu}
× 0.034 \text{ acceptance/cuts} = 137 K^+ \rightarrow \pi^+\nu\bar{\nu}
× 0.070 \text{ livetime/efficiency} = 96 K^+ \rightarrow \pi^+\nu\bar{\nu}
Use Data to Test Factorization

Two sources of background rejection in CKM:

- Kinematics: \( \sim 5 \times 10^{-6} \) for \( K^+ \rightarrow \pi^+\pi^o \).
- Particle ID: \( \sim 2 \times 10^{-7} \) for \( K^+ \rightarrow \pi^+\pi^o \).

**Important:** We assume these two sources are independent:
Factorization Assumption

Demonstrated for BNL-787: \( \pi^+ \) momentum line shape unchanged after online \( \gamma \) cuts and full offline \( \gamma \) cuts.
## $K_L$ Decay Modes

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Ratio</th>
<th>Additional Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0\pi^0\pi^0$</td>
<td>21.13 %</td>
<td>4$\gamma$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^0$</td>
<td>12.55 %</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\pi^0\mu^-\nu$</td>
<td>27.18 %</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\pi^0\epsilon^-\nu$</td>
<td>38.78 %</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>5.86 $\cdot 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma\gamma$</td>
<td>&lt;2.4 $\cdot 10^{-7}$</td>
<td>1$\gamma$</td>
</tr>
<tr>
<td>$\pi^0\gamma\gamma$</td>
<td>1.68 $\cdot 10^{-6}$</td>
<td>2$\gamma$</td>
</tr>
<tr>
<td>$\pi^0\pi^+\pi^-$</td>
<td>5.18 $\cdot 10^{-5}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\pi^0\pi^-\pi^+$</td>
<td>3.62 $\cdot 10^{-3}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\pi^+\pi^-\gamma$</td>
<td>5.7 $\cdot 10^{-4}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\pi^0\pi^-\gamma$</td>
<td>4.61 $\cdot 10^{-5}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\pi^0\pi^+\gamma$</td>
<td>&lt;5.6 $\cdot 10^{-6}$</td>
<td>3$\gamma$</td>
</tr>
<tr>
<td>$\mu^-\mu^-\gamma$</td>
<td>3.25 $\cdot 10^{-7}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$e^-e^-\gamma$</td>
<td>10.0 $\cdot 10^{-7}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$e^-e^-\gamma$</td>
<td>6.9 $\cdot 10^{-7}$</td>
<td>2Ch</td>
</tr>
</tbody>
</table>

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<tr>
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<th>Branching Ratio</th>
<th>Additional Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0\epsilon^+\epsilon^-$</td>
<td>&lt;7.1 $\cdot 10^{-7}$</td>
<td>1$\gamma$ 2Ch</td>
</tr>
<tr>
<td>$\pi^0\pi^0$</td>
<td>2.06 $\cdot 10^{-3}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\pi^+\pi^-$</td>
<td>9.27 $\cdot 10^{-4}$</td>
<td>2$\gamma$</td>
</tr>
<tr>
<td>$\mu^-\mu^-$</td>
<td>7.15 $\cdot 10^{-9}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$e^-e^-$</td>
<td>9 $\cdot 10^{-9}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\pi^0\epsilon^+\epsilon^-$</td>
<td>3.5 $\cdot 10^{-9}$</td>
<td>4Ch</td>
</tr>
<tr>
<td>$\mu^-\mu^-$</td>
<td>2.9 $\cdot 10^{-9}$</td>
<td>4Ch</td>
</tr>
<tr>
<td>$e^-e^-\epsilon^-$</td>
<td>4.1 $\cdot 10^{-8}$</td>
<td>4Ch</td>
</tr>
<tr>
<td>$\pi^0\nu\nu$</td>
<td>&lt;5.1 $\cdot 10^{-9}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\nu\nu\nu$</td>
<td>&lt;4.3 $\cdot 10^{-9}$</td>
<td></td>
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<tr>
<td>$e^-\mu^-$</td>
<td>&lt;5.9 $\cdot 10^{-9}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$e^-e^-\mu^-\mu^-$</td>
<td>&lt;4.7 $\cdot 10^{-9}$</td>
<td>4Ch</td>
</tr>
<tr>
<td>$\pi^0\epsilon^+\epsilon^-$</td>
<td>&lt;6.1 $\cdot 10^{-9}$</td>
<td>2Ch</td>
</tr>
<tr>
<td>$\pi^0\nu\nu$</td>
<td>&lt;6.2 $\cdot 10^{-9}$</td>
<td></td>
</tr>
</tbody>
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G. Y. Lim
KEK
How far must we go?

G.Y. Lim;
KEK

$BR(K_L \rightarrow \pi^0 e\nu_e, K_{e3}, K_{\mu3})$

$K_{TeV}$ \(\Rightarrow\) Current Exp. Limit

Limit from $K^+ \rightarrow \pi^+ e\nu$ (PRL 84, 3768 (2000))

E391a \(\Rightarrow\) New Physics (?)

S. M. Prediction

JHF KOPIO(BNL)
KEK PS E391a Detector Setup

\[ K_L \rightarrow \pi^0 \nu \nu \]

Features:
* Pencil Beam
* High acceptance
* High \( P_T \) selection

* Pilot Project for JHF
* Test reliance on extreme photon veto efficiency

pure CsI calorimeter

\( 4\pi \) veto system
Beam Profile

Counts per $10^3$ protons

Distance from beam center (mm)

- Neutron
- Photon

G.Y. Lim;
KEK
**KOPIO: Measurement of** $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

**CONCEPTS**

- Measure as much as possible:
  Energy, position and $ANGLE$ of each photon.
- Work in the C.M. system:
  Use TOF to get the $K_L^0$ momentum.
- Maximize Photon Veto Efficiency
- Maximize Intensity of Microbunched Beam
Conclusions

- Kaon Physics has matured to the point where the step from proven $1 \times 10^{-11}$ sensitivity to $1 \times 10^{-12}$ has been sensibly argued. This sensitivity is the key that will unlock the door to $K \rightarrow \pi\nu\bar{\nu}$.

- This step is fueled by ever increasing proton drivers ($7 \times 10^{13}$ protons/pulse with the AGS!), very clean kaon beams, and innovative detector technologies.

- The CKM, KOPIO, and E391-KEK/JHF experiments form a suite of promising experiments that can reach the $1 \times 10^{-12}$ frontier in this decade.

- The scope of these experiments is similar to the Fermilab KTeV and BNL-E787 experiments which have been successfully executed. These mid-size experiments are well within the resources of this field; and the physics compels us to build them.

The Protons Are Here Today—The Frontier Awaits!