Kaon Physics in the New B-era

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Fermilab

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Borrowing some nice material from:

- K. Schubert, Dresden.
- J. Graham, University of Chicago, KTeV.
- The KTeV, CERN-NA48 and CPLEAR collaborations.
Outline of These Two Lectures…

- Relevance: We are entering the era of precision measurements in B-physics….What impact can Kaon physics have??

- Brief review of the CPV and *T-violating* phenomena that have been observed, and some common formalism.

- Review of precision CP, T, and CPT measurements & techniques in the kaon system. (Today)

- Review of rare kaon decay $O(10^{-10} – 10^{-12})!$ physics, which can *quantitatively* probe the CP structure of the CKM matrix.
Relevance I: Baryogenesis Dilemma.

We need more CPV than present in the CKM formalism; But B’s and K’s so far respect this formalism!

Doug Wright’s ICHEP 2002 talk
Relevance II…

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I invented $\rho$ and $\eta$ and I don’t care what there values are so why should you?? The physics here is to determine if the breadth of CPV phenomena are really described by this simple description.’’
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The work of Nir, Isidori, Colangelo, Buras and others have shown that theories beyond (e.g. SUSY) the Standard Model typically contain much more CPV, and often very different manifestations between the B and K systems.

Lincoln Wolfenstein, CMU
Relevance III...

- Kaon Physics is a mature field...Advances in very intense beams and detector technology have staked out the Precision and Sensitivity Frontiers....

Where the holy grail is the $K\rightarrow \pi\nu\bar{\nu}$ process.
Post Cards From the Frontier...

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

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

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

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

(KTeV Preliminary.)
Evolution of the Frontier...

\[ K_L \rightarrow \pi^+ \pi^- \quad 1964, \text{Discovery of CP violation.} \]

\[ K_L \rightarrow e^+ e^- \gamma \quad 1980, \text{Dalitz Decays.} \]

\[ K_L \rightarrow \mu^+ \mu^- \quad 1973, \text{GIM Suppression.} \]

\[ K_L \rightarrow \pi^+ \nu \bar{\nu} \quad 1997, \text{Birth of Quantitative CKM tests.} \]

\[ K_L \rightarrow e^+ e^- \quad 1998, \text{Rarest particle decay ever seen.} \]

The Frontier: \( K_L \rightarrow \mu^+ e^- < 4.7 \times 10^{-12} \) (90% CL)

\[ B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10} \]
Where and how does CPV and T-violation manifest itself in our world?

CP Violation:

1) CPV in Mixing; e.g. $\text{Re}(\varepsilon_K)$, $\text{Re}(\varepsilon_B)$
2) CPV in Mixing-Decay Interference; e.g. $\sin 2\beta$
3) CPV in Decays to one final state (Direct); e.g. $\text{Re}(\varepsilon'/\varepsilon)$

T Violation:

1) Observation of T-Violation in $K^0 \leftrightarrow \overline{K^0}$.
2) Observation of T-odd decay asymmetries in $K_L \rightarrow \pi^+\pi^-e^+e^-$. 
Kaon Phenomenology Review:

Strangeness eigenstates:
\[ K^0 (\bar{s}d) \quad (S = +1) \]
\[ \bar{K}^0 (s\bar{d}) \quad (S = -1) \]

CP eigenstates:
\[ K_1 = (K^0 + \bar{K}^0)/\sqrt{2} \quad (CP = +1) \]
\[ K_2 = (K^0 - \bar{K}^0)/\sqrt{2} \quad (CP = -1) \]
\[ \pi^+\pi^-, \pi^0\pi^0 \quad (CP = +1) \]

Mass and Lifetime eigenstates:
\[ K_S \simeq K_1 + \varepsilon K_2 \quad (c\tau_S = 2.67 \text{ cm}) \]
\[ K_L \simeq K_2 + \varepsilon K_1 \quad (c\tau_L = 15.5 \text{ m}) \]

<table>
<thead>
<tr>
<th></th>
<th>$K_S$</th>
<th>$K_L$</th>
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<tr>
<td>$69 %$</td>
<td>$\pi^+\pi^-$</td>
<td>$21 %$</td>
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<td>$31 %$</td>
<td>$\pi^0\pi^0$</td>
<td>$13 %$</td>
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<td>$27 %$</td>
<td>$\pi\mu\nu$</td>
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<td>$39 %$</td>
<td>$\pi e\nu$</td>
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<tr>
<td></td>
<td>$0.2 %$</td>
<td>$\pi^+\pi^-$</td>
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<tr>
<td></td>
<td>$0.1 %$</td>
<td>$\pi^0\pi^0$</td>
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</table>

\[ \varepsilon = (2.27 \pm 0.02) \times 10^{-3} \]
Re(εₖ) can be related to the p/q formalism, $K_L = pK^0 - q\bar{K}^0$, which leads to:

$$\left| \frac{p}{q} \right| = 1 + \frac{2\text{Re}(\varepsilon_K)}{1 + |\varepsilon_K|^2} = 1 + 2\text{Re}(\varepsilon_K), \quad \text{Re}(\varepsilon_K) \ll 1.$$  

**Experimental results:**

$$\frac{\Gamma(K_L \to \ell^+\nu\pi) - \Gamma(K_L \to \ell^-\nu\pi)}{\Gamma(K_L \to \ell^+\nu\pi) + \Gamma(K_L \to \ell^-\nu\pi)} = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = (0.327 \pm 0.012)\%.$$  

$|p/q| = 1.00327 \pm 0.00012$, $\text{Re}(\varepsilon_K) = (1.64 \pm 0.06) \cdot 10^{-3}$.

**For B⁰ mesons:** $\text{Re}(\varepsilon_B) = (1 \pm 3 \pm 4) \cdot 10^{-3}$.  

[PDG 2000]  

[BABAR 2001]
300M $K_L \rightarrow \pi e\nu$ Decays!

$\text{Re}(\varepsilon_K) = (1.64 \pm 0.06) \times 10^{-3}$ \hspace{1cm} [PDG 2000]

$\text{Re}(\varepsilon_K) = (1.661 \pm 0.037) \times 10^{-3}$ \hspace{1cm} [KTeV 2001]
CPLEAR: CP Physics at a Low Energy Antiproton Ring. Technique is to stop $\bar{p}$’s in $\text{H}_2$, and observe the following reactions:

$$pp \rightarrow K^+\pi^-K^0, \text{ and}$$

$$p\bar{p} \rightarrow K^-\pi^+K^0.$$  

The $K^0/\bar{K}^0$ is tagged by the away-side $K\pi$. Hence one can study the time evolution of CPV in $K^0 \leftrightarrow \bar{K}^0$ mixing.
\( \pi^+ \pi^- \) Results from CPLEAR, CPV in mixing:

\[
a(t) = \frac{N(\bar{K}^0 \rightarrow \pi^+ \pi^-) - N(K^0 \rightarrow \pi^+ \pi^-)}{N(\bar{K}^0 \rightarrow \pi^+ \pi^-) + N(K^0 \rightarrow \pi^+ \pi^-)} = \frac{-2|\eta_{+-}| e^{-(\Gamma_s+\Gamma_t)t/2} \cos (\Delta m \cdot t - \phi_{+-})}{e^{-\Gamma_s t} + |\eta_{+-}|^2 e^{-\Gamma_t t}} \]

\[
\eta_{+-} = (2.27 \pm 0.02) \times 10^{-3} \cdot e^{i(43.3 \pm 0.5)}
\]

\[\eta_{+-} = \varepsilon + \varepsilon'\]
**Measurement of $\mathcal{T}$ violation**

$$ A_T = \frac{R(\bar{K}^0 \to K^0) - R(K^0 \to \bar{K}^0)}{R(\bar{K}^0 \to K^0) + R(K^0 \to \bar{K}^0)} = 4 \Re \varepsilon T $$

**Example** $\tau = 0.5 \tau_s$

CPLEAR measures:

- $N(K^0_{\tau=0} \to e^-\pi^+\nu)|\tau] = 15050$
- $N(\bar{K}^0_{\tau=0} \to e^+\pi^-\bar{\nu})|\tau] = 13559$

**A = 0.0521**

**first correction:**

Different reconstruction efficiency for $e^+\pi^-$ and $e^-\pi^+$. Obtained from unbiased pure electron and pion samples: $\langle \eta \rangle = 1.014 \pm 0.002$

**A = 0.0610**

**second correction:**

Different reconstruction efficiency for $K^+\pi^-$ and $K^-\pi^+$. Obtained from $\pi\pi$ decays: $\langle \alpha \rangle = 1.1275(4) \pm 0.00034$ $A = 0.0098$

(ratio of $K^+\pi^-/K^-\pi^+$ efficiencies) x

$$ [1 + 4 \Re (\varepsilon_T + \delta)]$$

**third correction:**

Assume CPT conservation in semileptonic decay amplitudes, use $A = 0.0036$

$$ \delta = 2 \Re (\varepsilon_T + \delta) = (0.327 \pm 0.012)\% $$

$$ A_T = (6.6 \pm 1.3_{\text{stat.}} \pm 1.0_{\text{syst.}}) \times 10^{-8} $$

**First direct measurement of time reversal non-invariance!**

$K_L \rightarrow \pi^+\pi^-e^+e^-$, Another T-odd laboratory...

$\text{BR}(K_L \rightarrow \pi^+\pi^-e^+e^-) = 3.6 \times 10^{-7}$
\[ K_L^0 \rightarrow \pi^+ \pi^- e^+ e^- \quad \phi \text{ Angle} \]

\[ (K_L^0 \text{ Center of Mass}) \]

\[ \hat{n}_{ee} = \frac{p_{ee} \times \hat{p}_{ee}}{|p_{ee} \times \hat{p}_{ee}|} \]

\[ \hat{n}_{\pi \pi} = \frac{\hat{p}_{\pi^+} \times \hat{p}_{\pi^-}}{|\hat{p}_{\pi^+} \times \hat{p}_{\pi^-}|} \]

\[ \hat{z} = \frac{\hat{p}_{\pi^+} \times \hat{p}_{\pi^-}}{|\hat{p}_{\pi^+} \times \hat{p}_{\pi^-}|} \]

\[ \sin \phi \cos \phi = (\hat{n}_{ee} \times \hat{n}_{\pi \pi}) \cdot \hat{z} (\hat{n}_{ee} \cdot \hat{n}_{\pi \pi}) \]
Discovered at KTeV, confirmed by CERN-NA48…

Asymmetry = (13.6 +/- 2.5 +/- 1.2)%

This T-odd effect is due entirely to mixing, no evidence of direct CPV.
Summary of $K^0 \leftrightarrow \bar{K}^0$ CPV

- Precisely measured in both $K^0 \rightarrow \pi\pi$ and $K^0 \rightarrow \pi\nu\bar{\nu}$ decays.

- Recently, T-violation in $K^0 \leftrightarrow \bar{K}^0$ has been directly measured, and agrees with CPV; thereby testing CPT.
\[ \varepsilon \Rightarrow \text{Indirect CP violation via } K^0/\bar{K}^0 \text{ mixing} \]

Is there also a component of CP violation in the decay process?

\[ K_L = K_2^{-1} + \varepsilon K_1^{+1} \]

Need interference of two decay amplitudes

\( \pi\pi \) from \( K^0 \) can have \( I=0,2 \) \( \Rightarrow \) amplitudes \( A_0, A_2 \)

\[ A(K^0 \rightarrow \pi\pi, I) = A_I \exp(i\delta_I) \]
\[ A(\bar{K}^0 \rightarrow \pi\pi, I) = A_I^* \exp(i\delta_I) \]

\[ \varepsilon' = \frac{i}{\sqrt{2}} \text{Im} \frac{A_2}{A_0} \exp(i(\delta_2 - \delta_0)) \]
\( \varepsilon' \Rightarrow \text{Direct CP violation:} \)

\[
\begin{align*}
\bar{s} & \to W^- \\
K^0 & \to \pi^0 \pi^0 \to \pi^+ \pi^- \\
\bar{d} & \to \bar{u} \\
\end{align*}
\]

\[
\eta_{+-} \equiv \frac{A(K_L \to \pi^+ \pi^-)}{A(K_S \to \pi^+ \pi^-)} \approx \varepsilon + \varepsilon' \\
\eta_{00} \equiv \frac{A(K_L \to \pi^0 \pi^0)}{A(K_S \to \pi^0 \pi^0)} \approx \varepsilon - 2 \varepsilon' \\
R = \frac{\Gamma(K_L \to \pi^0 \pi^0)/\Gamma(K_L \to \pi^+ \pi^-)}{\Gamma(K_S \to \pi^0 \pi^0)/\Gamma(K_S \to \pi^+ \pi^-)} \approx 1 - 6 \text{Re}(\frac{\varepsilon'}{\varepsilon}) \\
\]

**IF** the 4 modes are taken

- simultaneously
- in the same decay region

\[
R = \frac{N(K_L \to \pi^0 \pi^0) \cdot N(K_S \to \pi^+ \pi^-)}{N(K_S \to \pi^0 \pi^0) \cdot N(K_L \to \pi^+ \pi^-)}
\]
Status of $\text{Re}(\varepsilon'/\varepsilon)$…

Experiment:

NA48, Final Result @ Blois 2002: $\text{Re}(\varepsilon'/\varepsilon_0) = (14.7 \pm 2.2) \times 10^{-4}$
KTeV, (1/2 Data) @ Blois 2002: $\text{Re}(\varepsilon'/\varepsilon_0) = (20.7 \pm 2.8) \times 10^{-4}$

World Average: $\text{Re}(\varepsilon'/\varepsilon_0) = (16.6 \pm 1.6) \times 10^{-4}$

Theory: (victim of the brown muck)

Typical range has been $5 \times 10^{-4}$ to $40 \times 10^{-4}$,
However, latest Lattice calculations are
around $-7 \times 10^{-4}$ (!) (CP-PACs, RBC)
The KTeV Detector

“Vacuum” beam $\rightarrow K_L$ beam

“Regenerator” beam $\rightarrow K_L + \rho K_S$ beam
Decay Volume

Magnet

Regenerator

Drift Chambers

CsI Calorimeter

Photon Vetos

Photon Vetos

25 cm

Z = Distance from Target (m)
The KTeV Pure CsI Calorimeter.

Very fast scintillation light, $\tau \sim 20$ nsec, lower light yield requires PMT readout.
The KTeV Detector Performance

**NEUTRAL:**
- CsI energy res: 0.7% at 15 GeV (1.3% at 3 GeV)
- CsI position res: $\sim 1$ mm

![E/P Resolution for Electrons from K→πν](image)

$N_{\text{events}} = 4.24 \times 10^8$

$\sigma_{EP} = 0.72\%$

**CHARGED:**
- Drift Chamber resolution: 100 $\mu$m.
- Momentum resolution:
  $$\frac{\sigma_p}{p} = 0.17\% \oplus 0.0071\% \cdot p \ [\text{GeV}]$$

$$\sigma(M_{\pi^+\pi^-}) \sim \sigma(M_{\pi^0\pi^0}) \sim 1.5 \ \text{MeV}$$
Sample $K \rightarrow \pi^+ \pi^-$ Event

- Magnetic spectrometer to reconstruct kinematics.
- Regenerator/Vacuum beam identification using $x$-vertex position
- Clearance cuts define fiducial volume.
Sample $K \rightarrow \pi^0\pi^0$ Event

- CsI calorimeter to reconstruct photons energies and positions
- $z_\nu$ determined as average of
  \[ z_{\pi^0} = \sqrt{E_1 E_2 R_{12}} / m_{\pi^0} \]
- Regenerator/Vacuum beam identification using $x$-center of energy
- Fiducial volume defined by veto detectors & $z_\nu$
Raw $K^0 \rightarrow \pi\pi$ Statistics: $\sigma(\varepsilon'/\varepsilon) = 1.7 \times 10^{-4}$

CPV first found with 47 $K_L \rightarrow \pi^+\pi^-$ events!
Position and Energy of $K \to \pi \pi$ decays…
Detector Acceptance Issues.

Due to the different lifetimes ($\tau_L \gg \tau_S$), the $K_S$ beam reconstructs upstream of the $K_L$ beam, and hence has a different average acceptance.

Need an analysis technique to put two beams on equal footing.
Monte Carlo Acceptance Correction.

We measure the detector geometry and response, and create a detailed MC prediction of the acceptance in each beam.

Correction to $\text{Re}(\epsilon'/\epsilon)$ is large ($\sim 80 \times 10^{-4}$) → Systematics under control?

- Most of the correction is due to the geometry of the detector ($\sim 90\%$).
- Remaining effort for detailed understanding of detector response.
- Use large statistics modes ($K_{e3}, K_L \rightarrow 3\pi^0$) to cross-check performance of the Monte Carlo.
- Monte Carlo predicts slight acceptance differences between beams, due to accidental activity.
- Can measure kaon parameters ($\tau_S, \Delta m$)
Geometry-Only Monte Carlo Simulation.

Acceptance correction based on Monte Carlo with ideal detector response: \( \Delta \text{Re}(\epsilon' / \epsilon) \approx 12 \times 10^{-4} \), of which \( \sim 10 \times 10^{-4} \) is seen as a \( z \)-slope.

\( \rightarrow \) corrections due to detector simulation \( \sim 10 \times 10^{-4} \).
The "Hard Part" of Detector Simulation.

We measure the response of detector:

- Resolutions.
- Inefficiency profiles.
- DC "maps" of response.
- New DC delayed-hit model.
- GEANT showers in CsI.

For example, measure the inefficiency and delayed-hit probabilities across chamber face, use as input to MC.
How well is the Acceptance Known?

The final check of the acceptance is the vertex $z$ distribution in the vacuum beam.

Acceptance bias on $\text{Re}(\epsilon'/\epsilon) \leftrightarrow$ slope in plot, due to different vertex $z$ distributions in vac/reg beams.

$$1997 \ K \to \pi^+ \pi^- \ & \ K_{e3}$$
From Counting to $\text{Re}(\epsilon'/\epsilon)$….

Naïvely, could take global acceptance, raw number of events, and calculate $\text{Re}(\epsilon'/\epsilon)$.

$$\text{Re}(\epsilon'/\epsilon) \approx \frac{1}{6} \left[ \frac{N(\text{Vac } \pi^+\pi^-)}{A(\text{Vac } \pi^+\pi^-)} / \frac{N(\text{Reg } \pi^+\pi^-)}{A(\text{Reg } \pi^+\pi^-)} \right] - 1$$

Problems:

- Regenerator beam not pure $K_S$.
  $$K_{\text{reg}} = K_L + \rho K_S$$
  Interference
- Requires precise determination of *average* acceptance.
**$K_L$ and $K_S$ in the Regenerator Beam.**

The regenerator beam is a coherent super-position of $K_S$ and $K_L$. Must account for $K_L$ component to extract correct value of $\text{Re}(\varepsilon'/\varepsilon)$.

$K_{\text{Reg}}$ shape depends on:

- $\tau_S$, $\Delta m$, $\phi_\eta$.
- Attenuation in the regenerator.

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Quantum coherence over 30m!
Fitting for $\Delta m$, $\tau_S$, $\phi_{+-}$, $\Delta \phi$ ..

With the interference information in the regenerator beam, KTeV can measure the kaon sector parameters:

- $\Delta m = m_{K_L} - m_{K_S}$
- $\tau_S$
- $\phi_{+-}$, phase of $\eta_{+-}$
- $\Delta \phi = \phi_{00} - \phi_{+-}$ \[CPT\]

$\text{Im}(\epsilon' / \epsilon) = -\frac{1}{3} \Delta \phi$ \[CPT\]

Have made new measurements of the above.
Summary of KTeV $K^0 \rightarrow \pi\pi$ Measurements.

FNAL experiments can measure both $Re(e'/e)$ and $Im(e'/e)$ (with less precision).

$Re(e'/e) = 20.7 +/- 1.5^{(stat)} +/- 2.4^{(sys)} \times 10^{-4}$

$\Delta \phi = 0.41^{o} +/- 0.22^{o}^{(stat)} +/- 0.48^{o}^{(sys)}$

(CPT test)

$\phi_{+/-} = 44.11^{o} +/- 0.72^{o}^{(stat)} +/- 1.1^{o}^{(sys)}$
Sister Experiment to KTeV: CERN-NA48.

\[ \pi^0\pi^0 \text{ detection (} \rightarrow 4 \gamma) \]

LKr calorimeter
\[ \sigma(E)/E=0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042 \]
\[ < 1\% \text{ for } E=25 \text{ GeV} \]

\[ \pi^+\pi^- \text{ detection} \]

magnetic spectrometer
\[ \sigma(p)/p = 0.5\% \oplus 0.9\%*(p/100 \text{ GeV}) \]
The CERN NA48 Technique: Separate $K_L$ and $K_S$ decays in time, and analyze $K_L$ and $K_S$ with the same effective proper time $\rightarrow$ Relative $K_L/K_S$ acceptance cancels!
NA48

Ks tagger:

2 × 12 thin scintillator foils

Proton rate: \( \approx 30 \text{ MHz} \)

→ split the intensity between foils

readout by Flash-ADC 8 bits at 960 MHz

⇒ Time resolution: 140 ps

⇒ Double pulse separation: 4 ns
$K_L / K_S$

Identification:

$K \rightarrow \pi^+ \pi^-$ (vertex selected)

Equalize Acceptance…
Comparison of experimental results

World average \( \varepsilon' / \varepsilon = (16.6 \pm 1.6) \times 10^{-4} \) \( \chi^2 = 6.2/3 \) (prob = 10%)

- NA31: \((23.0 \pm 6.5) \times 10^{-4}\)
- E731: \((7.4 \pm 5.9) \times 10^{-4}\)
- KTeV: \((20.7 \pm 2.8) \times 10^{-4}\) (preliminary)
- NA48: \((14.7 \pm 2.2) \times 10^{-4}\)
Summary of $\text{Re}(\varepsilon'/\varepsilon)$ Measurements.

- Direct CPV into one final state has been clearly established, $(K_L \rightarrow \pi\pi)$.

- This validates a clear prediction of the Standard Model, although the prediction comes with a poor level of precision due to difficulty of the calculation.

- $\text{Re}(\varepsilon'/\varepsilon)$ will stand for quite some time as the most precise measurement of Direct CPV. Lattice based calculation techniques are promising, and could provide a precision test in the future.
Preview for Friday…. 

Tomorrow our discussion will turn to rare kaon decays, where we can leave the brown muck behind and quantitatively challenge the Standard Model.
Spare Slides
Second example for Type-II CPV: $B^0, \bar{B}^0 \rightarrow c\bar{c}K$

\[ \sin 2\beta = 0.755 \pm 0.074 \]

\[ \sin 2\beta = 0.723 \pm 0.158 \]

\[ \sin 2\beta = 0.741 \pm 0.067 \text{ (stat)} \pm 0.033 \text{ (sys)} \]

(BaBar, ICHEP 2002)
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:
  \[
  \begin{align*}
  K^+ \to \pi^+ \nu \bar{\nu} & : \text{BNL787/949, CKM} \\
  K^0 \to \pi^0 \nu \bar{\nu} & : \text{KOPIO, KEK-e391a/JHF} \\
  B_d \to J/\psi K_S & : \text{Babar, Belle, CDF, D0, LHCb, Atlas, CMS, BTeV} \\
  \Delta M_d/\Delta M_s & : \text{CDF, D0, LHCb, Atlas, CMS, BTeV}
  \end{align*}
  \]
The two KTeV beams are shown: Vacuum on left, Regenerator on right.
Neutral-Mode Backgrounds

“Ring Number” is a scaled Center of Energy. Cut at $R = 110$ is the edge of the beam. Scattered events appear outside beam, $R > 110$. $K_L \rightarrow 3\pi^0$ events are inside beam, but identifiable from mass sidebands.

Back/Sign(Vac) $\approx 0.5\%$  
Back/Sign(Reg) $\approx 1.2\%$
## Systematic Uncertainties for 1997

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty (×10⁻⁴) from π⁺π⁻</th>
<th>Uncertainty (×10⁻⁴) from π⁰π⁰</th>
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<tr>
<td><strong>Class 1: Data collection</strong></td>
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<tr>
<td>Trigger and level 3 filter</td>
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<td><strong>0.16</strong></td>
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<td><strong>Class 2: Event reconstruction, selection, backgrounds</strong></td>
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<td>Energy/Resolution scale</td>
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<td>Calorimeter nonlinearity</td>
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<td>Analysis cut variations,</td>
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<td>Reconstruction</td>
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<td>Δm, τS</td>
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<td>Reg phase screening</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>2.32</strong></td>
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</table>
Update of Published Result with Improved Techniques (cont)

\[
\text{Re}(\epsilon'/\epsilon) = (23.2 \pm 3.0 \text{ (stat)}) \\
\pm 3.2 \text{ (syst)} \pm 0.7 \text{ (MC stat)}) \times 10^{-4}
\]

Note: sources of shifts are not correlated