The Final Measurement of $\varepsilon'/\varepsilon$ from KTeV

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For the KTeV Collaboration:
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Overview

- Introduction
- The KTeV Experiment
- Data Analysis
- Monte Carlo Simulation
- Backgrounds
- Systematic Uncertainties
- Results
CP Violation in Kaon System

\[ K_L = K_2 + \varepsilon K_1 \]

\[ \varepsilon' \quad \text{"Direct" in decay process} \]

\[ \pi \pi \quad \text{"Indirect" from asymmetric } K^0 - \bar{K}^0 \text{ mixing} \]

If CPT: \( \phi_\varepsilon \approx \phi_{\varepsilon'} \)

\( \text{Re}(\varepsilon'/\varepsilon) \rightarrow \text{direct CP violation} \)

\( \text{Im}(\varepsilon'/\varepsilon) \rightarrow \text{CPT violation} \)

\[ \eta_{+-} = \frac{A(K_L \rightarrow \pi^+ \pi^-)}{A(K_s \rightarrow \pi^+ \pi^-)} = \varepsilon + \varepsilon' \]

\[ \eta_{00} = \frac{A(K_L \rightarrow \pi^0 \pi^0)}{A(K_s \rightarrow \pi^0 \pi^0)} = \varepsilon - 2\varepsilon' \]

\[ \text{Re}(\varepsilon'/\varepsilon) \approx \frac{1}{6} \left( \left| \frac{\eta_{+-}}{\eta_{00}} \right|^2 - 1 \right) \]
Previous Results

Data from 1996 and 1997

\[
\text{Re}(\varepsilon'/\varepsilon) = [20.7 \pm 1.48\text{(stat)} \pm 2.39\text{(syst)}] \times 10^{-4}
\]
### Re(ε′/ε) Uncertainties (2003)

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$K \rightarrow \pi^+\pi^-$</th>
<th>$K \rightarrow \pi^0\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>0.58</td>
<td>0.18</td>
</tr>
<tr>
<td>CsI energy, position recon</td>
<td>-</td>
<td>1.47</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>0.32</td>
<td>-</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>0.47</td>
<td>0.37</td>
</tr>
<tr>
<td>Apertures</td>
<td>0.30</td>
<td>0.48</td>
</tr>
<tr>
<td>Background</td>
<td>0.20</td>
<td>1.07</td>
</tr>
<tr>
<td>z-dependence of acceptance</td>
<td>0.79</td>
<td>0.39</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.41</td>
<td>0.40</td>
</tr>
<tr>
<td>Fitting</td>
<td></td>
<td>0.30</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>2.39</td>
</tr>
</tbody>
</table>

Statistical Uncertainty: $1.5 \times 10^{-4}$
The KTeV Detector

- Movable active regenerator to provide a coherent mixture of $K_L$ and $K_S$ and to veto scattered kaons
- Charged spectrometer to reconstruct $K \rightarrow \pi^+\pi^-$ decays
- CsI calorimeter to reconstruct $K \rightarrow \pi^0\pi^0$ decays
The KTeV Detector

- Spectrometer
  - 4 drift chambers
    - hexagonal cell geometry
    - 2 planes each in x and y
  - Dipole magnet
    - ~412 MeV/c kick in x
  - Calibrated using data and the known kaon mass
    - position resolution ~80 µm
    - momentum resolution ~0.3%
    - absolute momentum scale ~0.01%

- CsI Calorimeter
  - 3100 CsI crystals
    - small blocks 2.5 × 2.5 × 50 cm³
    - large blocks 5.0 × 5.0 × 50 cm³
  - Calibrated using in-situ laser system and momentum analyzed electrons from Ke3 decays
    - position resolution 1.2 – 2.4 mm
    - energy resolution ~0.6%
    - absolute energy scale ~0.05%
$K \rightarrow \pi^+\pi^-$ Analysis

Reconstructed Mass

Transverse Momentum
Photon Pairing

- Must determine which photons are from the same pion decay
- Pair photons and calculate $z$ for each pair using pion mass as constraint

$$z_{12} \approx \frac{\sqrt{E_1 E_2}}{m_{\pi^0}} r_{12}$$

- Only correct pairing will yield consistent $z$ for both pairs
- Consistency of measured $z$ quantified by pairing chi-squared variable
- Choose incorrect pairing for 0.007% of $2\pi^0$ events
Final Energy Scale

z vertex at regenerator edge

Before

z shift to match data to MC

After

1999:
  z shift = 2.7 cm
  energy scale adjustment = 0.05%
K \rightarrow \pi^0\pi^0 \text{ Analysis}

Reconstructed Mass
Monte Carlo Simulation

- MC used to make acceptance correction and simulate backgrounds to signal modes
  - simulates kaon generation, propagation, and decay
  - simulates detector geometry and response
  - includes the effect of “accidental” activity by overlaying data events from accidental trigger
Improvements to MC

- More complete treatment of particle interactions with matter
  - Ionization energy loss
  - Improved Bremsstrahlung
  - Improved delta rays
  - Hadronic interactions in drift chambers

- Improved electromagnetic shower simulation
  - Shower library binned in incident particle angle
  - Simulate effects of dead material (wrapping and shims) in CsI calorimeter
Improvements: Transverse Shower Shape

2003: Includes transverse energy correction to match data and MC

Current: No transverse energy correction required

Fraction of energy per CsI block

Data/MC Ratio

2003 current

2003: Includes transverse energy correction to match data and MC

Current: No transverse energy correction required
Improvements: Reconstructed Energy

E_{\text{rec}}/E_{\text{gen}} vs Local X

- Small Blocks
- Large Blocks

2003

Current

2003

Current
Improvements: Energy Linearity

Mass vs. Energy

Mass vs. Photon Angle
Improvements: Energy Scale

![Graph showing scale correction vs. energy (GeV)](image)
Backgrounds

- Scattering backgrounds
  - Scattering in defining collimator
  - Diffractive and inelastic scattering in regenerator treated as background
  - Characterized using $\pi^+\pi^-$ events with large $p_T^2$
  - Common to charged and neutral signal modes
  - Level higher in neutral mode because no cut on $p_T^2$
    - Use RING variable instead

- Non $\pi\pi$ backgrounds
  - Semileptonic decays in charged mode
  - $K \rightarrow 3\pi^0$ decays and hadronic production in neutral mode

- Backgrounds simulated by MC, normalized to data sidebands, and subtracted

- Total background levels
  - ~0.1% in charged mode
  - ~1% in neutral mode
Systematic Uncertainties in Re(ɛ'/ɛ)

<table>
<thead>
<tr>
<th>Source</th>
<th>Error on $Re(ɛ'/ɛ)$ ($\times 10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K \rightarrow \pi^+\pi^-$</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.23</td>
</tr>
<tr>
<td>CsI cluster reconstruction</td>
<td>--</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>0.22</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>0.23</td>
</tr>
<tr>
<td>Apertures</td>
<td>0.30</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.57</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.20</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.20</td>
</tr>
<tr>
<td>Total</td>
<td>0.81</td>
</tr>
<tr>
<td>Fitting</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
</tr>
</tbody>
</table>

Reduced from 1.47
Uncertainty from Acceptance

- Quality of MC simulation evaluated by comparing vacuum beam z vertex distributions between data and MC
- Bias on Re(ε'/ε) given by $s\Delta z/6$
  - $s$ is slope of data-MC ratio
  - $\Delta z$ is difference between mean z value for vacuum and regenerator beams
- Use $\pi^+\pi^-$ and $\pi^0\pi^0\pi^0$ slopes to determine systematic uncertainty
Uncertainty from Energy Non-linearity

- Use $M_K$ vs $E_K$ plot to determine distortion which provides best data-MC match
- 0.1%/100 GeV nonlinearity applied to data for 1997 and 1999
- 0.3%/100 GeV nonlinearity for 1996
- Change in $\text{Re}(\varepsilon'/\varepsilon)$
  - 1996: $-0.1 \times 10^{-4}$
  - 1997: $-0.1 \times 10^{-4}$
  - 1999: $+0.2 \times 10^{-4}$
- Systematic error: $\pm 0.15 \times 10^{-4}$
Uncertainty from Energy Scale

Total uncertainty: ±0.65 × 10^{-4}
Results

The final KTeV measurement of $\text{Re}(\varepsilon'/\varepsilon)$ . . .
Results: $\text{Re}(\varepsilon' / \varepsilon)$

$\text{Re}(\varepsilon' / \varepsilon) = [19.2 \pm 1.1\,\text{(stat)} \pm 1.8\,\text{(syst)}] \times 10^{-4}$

$\text{Re}(\varepsilon' / \varepsilon) = (19.2 \pm 2.1) \times 10^{-4}$

Probability = 13%

KTeV 2003: $\text{Re}(\varepsilon' / \varepsilon) = [20.7 \pm 1.5\,\text{(stat)} \pm 2.4\,\text{(syst)}] \times 10^{-4}$
Results: Re(\(\varepsilon' / \varepsilon\)) Crosschecks

- Run Ranges
 across different run ranges.

- Momentum Bins
  showing \(\chi^2/\text{dof} = 12.4/11\) for momentum bins.

- Half Samples
  with intensity, reg position, polarity, and bend data samples.
Kaon Parameters: z-binned fit

- Fit for $\Delta m$, $\tau_S$, $\phi_{\epsilon}$, $\text{Re}(\epsilon'/\epsilon)$, $\text{Im}(\epsilon'/\epsilon)$
- Systematic uncertainties evaluated using same methods as $\text{Re}(\epsilon'/\epsilon)$ analysis
- Significant reduction in systematic uncertainties for $\phi_{\epsilon}$ and $\Delta \phi$
  - Improved measurements of regenerator properties
  - Nuclear screening effects ($\phi_{\epsilon}$)
  - Energy scale ($\Delta \phi$)
- CPT assumption applied a posteriori

$$\Phi_{+-} \approx \Phi_{\epsilon} + \text{Im}(\epsilon'/\epsilon)$$

$$\Phi_{00} \approx \Phi_{\epsilon} - 2\text{Im}(\epsilon'/\epsilon)$$

$$\Delta \Phi = \Phi_{00} - \Phi_{+-} \approx -3\text{Im}(\epsilon'/\epsilon)$$

$$\phi_{SW} = \tan^{-1}\left(\frac{2\Delta m}{\Delta \Gamma}\right)$$
Results: z-binned Fit

No CPT assumption:
\[ \Delta m = (5279.7 \pm 19.5) \times 10^6 \text{ fs}^{-1} \]
\[ \tau_S = (89.589 \pm 0.070) \times 10^{-12} \text{ s} \]

CPT assumption applied:
\[ \Delta m = (5269.9 \pm 12.3) \times 10^6 \text{ fs}^{-1} \]
\[ \tau_S = (89.623 \pm 0.047) \times 10^{-12} \text{ s} \]
Results: $\Delta m$ and $\tau_S$

KTeV 2003: $\Delta m = (5261 \pm 13) \times 10^6 \, \text{fs}^{-1}$

KTeV 2003: $\tau_S = (89.65 \pm 0.07) \times 10^{-12} \, \text{s}$
Results: z-binned fit

\[ \phi_\varepsilon = (43.86 \pm 0.63)^\circ \]
\[ \phi_\varepsilon - \phi_\text{SW} = (0.40 \pm 0.56)^\circ \]
\[ \Delta\phi = (0.30 \pm 0.35)^\circ \]
Results: CPT Tests

KTeV 2003: $\phi_{+-} = (44.1 \pm 1.4)^\circ$

KTeV 2003: $\Delta \phi = (0.39 \pm 0.50)^\circ$

Consistent with CPT symmetry
KTeV Results

- \( \text{Re}(\epsilon'/\epsilon) = (19.2 \pm 2.1) \times 10^{-4} \)
- \( \Delta m = (5269.9 \pm 12.3) \times 10^6 \text{\,fs}^{-1} \)
- \( \tau_S = (89.623 \pm 0.047) \times 10^{-12} \text{\,s} \)
- \( \phi_\epsilon = (43.86 \pm 0.63) \degree \)
- \( \phi_\epsilon - \phi_{SW} = (0.40 \pm 0.56) \degree \)
- \( \Delta \phi = (0.30 \pm 0.35) \degree \)

Assuming CPT

No CPT assumption
Extra Slides
**Backgrounds**

<table>
<thead>
<tr>
<th>Source</th>
<th>Vacuum Beam</th>
<th>Regenerator Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K \rightarrow \pi^+ \pi^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regenerator Scattering</td>
<td>–</td>
<td>0.075%</td>
</tr>
<tr>
<td>Collimator Scattering</td>
<td>0.008%</td>
<td>0.008%</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^\pm e^\mp \nu$</td>
<td>0.032%</td>
<td>0.001%</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^\pm \mu^\mp \nu$</td>
<td>0.030%</td>
<td>0.001%</td>
</tr>
<tr>
<td>Total</td>
<td>0.070%</td>
<td>0.085%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Vacuum Beam</th>
<th>Regenerator Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K \rightarrow \pi^0 \pi^0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inelastic Scattering</td>
<td>0.128%</td>
<td>0.175%</td>
</tr>
<tr>
<td>Diffractive Scattering</td>
<td>0.130%</td>
<td>0.906%</td>
</tr>
<tr>
<td>Collimator Scattering</td>
<td>0.120%</td>
<td>0.091%</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^0 \pi^0 \pi^0$</td>
<td>0.301%</td>
<td>0.012%</td>
</tr>
<tr>
<td>Photon Mispairing</td>
<td>0.008%</td>
<td>0.007%</td>
</tr>
<tr>
<td>Hadronic Production</td>
<td>–</td>
<td>0.007%</td>
</tr>
<tr>
<td>Total</td>
<td>0.678%</td>
<td>1.190%</td>
</tr>
</tbody>
</table>

**1999 backgrounds (other years vary slightly)**
$K \rightarrow \pi^+\pi^-$ Backgrounds
$K \rightarrow \pi^0\pi^0$ Backgrounds

Vacuum Beam

Regenerator Beam
K → π^0\,π^0 Backgrounds

- Vacuum Beam
- Regenerator Beam
PDG: $\phi_{+-}$
Regenerator Transmission

- Transmission measured from data using $K_L \rightarrow \pi^+\pi^-\pi^0$ decays
- Dedicated trigger in 1999 improved statistical precision of measurement

$slope = (-3.47 \pm 0.16) \times 10^{-5} \text{ c/GeV}$
Screening corrections

- Screening corrections use elastic and inelastic screening models
- Check corrections by fitting regeneration amplitude in momentum bins
- Good agreement at low momentum

![Graph showing screening corrections](image)
Screening corrections

- For p binned fit, evaluate regeneration phase using Derivative Analyticity Relation (DAR).
- Perform fit which floats the regeneration phase in p bins, DAR agrees well with data.
- Evaluate systematic uncertainty by comparing inelastic screening correction (nominal) to direct fit to data using DAR for the phase.