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

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- Introduction to $\epsilon'/\epsilon$
- The KTeV Experiment
- Overview of Analysis
- Measurements of $\epsilon'/\epsilon$ and other $K^0$ parameters
- Summary

KTeV Collaboration: Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Sao Paolo, UCLA, Virginia, Wisconsin
Kaons and the CKM Matrix

• 1964 observation of $K_L \rightarrow \pi^+ \pi^-$ demonstrated CP violation and presented problem for the electroweak theory with 2 generations

• Kobayashi and Maskawa recognized that 3 generation theory allowed CP violation, with a single CP-violating quantity

• For decades, however, there was only one measured CP-violating parameter, $\varepsilon$, describing an asymmetry between $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$ mixing – “indirect” CP violation

• Search for “direct” CP violation ($\varepsilon'$) motivated many of the kaon experiments done during the 40 years following discovery of CPV
\[ \varepsilon' / \varepsilon : \text{Indirect vs. Direct CP Violation} \]

\[ K_L \sim K_{\text{odd}} + \varepsilon K_{\text{even}} \]

"Direct" \[ \varepsilon' \]

in decay process \[ \pi\pi \]

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

To distinguish between direct and indirect CP violation, compare \[ K_{L,S} \rightarrow \pi^+\pi^-, \pi^0\pi^0 : \]

\[ \text{Re}(\varepsilon'/\varepsilon) \approx \frac{1}{6} \left[ \frac{\Gamma(K_L \rightarrow \pi^+\pi^-) / \Gamma(K_s \rightarrow \pi^+\pi^-)}{\Gamma(K_L \rightarrow \pi^0\pi^0) / \Gamma(K_s \rightarrow \pi^0\pi^0)} - 1 \right] \]

\[ \text{Re}(\varepsilon'/\varepsilon) \neq 0 \quad \text{direct CP violation} \]

\[ \Gamma(K^0 \rightarrow \pi^+\pi^-) \neq \Gamma(\bar{K}^0 \rightarrow \pi^+\pi^-) \]
KTeV 2003 result (based on half of KTeV data sample):

\[
\text{Re}(\varepsilon' / \varepsilon) = (20.7 \pm 1.5\text{(stat)} \pm 2.4\text{(syst)}) \times 10^{-4}
\]

\[
= (20.7 \pm 2.8) \times 10^{-4}
\]
Improvement in systematics needed to take advantage of increase in statistics.

### Re(ε'/ε) Systematics (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>

2008 analysis of full data sample includes many improvements in charged and neutral event reconstruction and simulation.
• Charged particle momentum resolution < 1% for p>8 GeV/c; Momentum scale known to 0.01% from K→π^+π^−
• CsI energy resolution < 1% for E_\gamma > 3 GeV; energy scale known to 0.05% from K→πeν.

For E_K ~ 70 GeV, K_L: γβcτ ~ 2.2 km
K_S: γβcτ ~ 3.5 m
CsI Calorimeter Performance

Full calibration sample includes 1.5 billion electrons from $K \to \pi e \nu$. 

![Graphs showing (a) the distribution of events per 0.001 with $N_e = 1.5 \times 10^9$ and (b) the resolution with $\sigma_{E/E} = 2\%/\sqrt{E} \pm 0.4\%$.](image)
• 2003 result included $\sim$3 million $K_L \to \pi^0\pi^0$ decays from 1996 and 1997
  - $\sigma_{\text{stat}} = 1.5 \times 10^{-4}$
• 1999 dataset contains $\sim$3 million $K_L \to \pi^0\pi^0$ decays
  - $\sigma_{\text{stat}} = 1.5 \times 10^{-4}$
• Today: results from full data sample: $\sigma_{\text{stat}} = 1.1 \times 10^{-4}$
\[ K_L \rightarrow \pi^0\pi^0 \]
Mass resolution is \( \sim 1.5 \text{ MeV/c}^2 \) for both decay modes.
Backgrounds and event yields

Main classes of background:
• Misidentified kaon decays
  – For $K \rightarrow \pi^+\pi^-$: $K_L \rightarrow \pi\nu$, $K_L \rightarrow \mu\nu$
  – For $K \rightarrow \pi^0\pi^0$: $K_L \rightarrow \pi^0\pi^0\pi^0$
• Scattered $K \rightarrow \pi\pi$ events
  – From regenerator and final collimator
• Backgrounds are simulated with MC, normalized to data sidebands, and subtracted
• Background level is $\sim 0.1\%$ for charged mode and $\sim 1\%$ for neutral mode.

After background subtraction:

<table>
<thead>
<tr>
<th></th>
<th>$K_L$</th>
<th>“$K_S$”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Beam</td>
<td>$K \rightarrow \pi^+\pi^-$</td>
<td>25,107,242</td>
</tr>
<tr>
<td></td>
<td>$K \rightarrow \pi^0\pi^0$</td>
<td>5,968,198</td>
</tr>
</tbody>
</table>
Reconstructed Vertex z Distributions

\[ K_L \rightarrow \pi^+ \pi^- \]

\[ K_S \rightarrow \pi^+ \pi^- \]

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

\[ K_S \rightarrow \pi^0 \pi^0 \]
0.1% shift in E scale: $\sim 3$ cm shift in vertex; $\sim 1 \times 10^{-4}$ shift in $\varepsilon^\prime/\varepsilon$
Acceptance Correction

- A detailed Monte Carlo simulation based on measured detector geometry and response is used to calculate acceptance as a function of $p,z$, and beam (reg or vac).
- Includes effects of accidental activity.

Many improvements compared to 2003 analysis:

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
Monte Carlo Improvements: Simulation of photon angles

Fraction of energy in 49 crystals for electron shower

2003 data / MC

Current data / MC

20-30 mrad incident angles used
Improved Modeling of Energy Nonlinearities

Mass vs. Energy

2003 Current

Mass vs. Photon Angle

2003 Current
## Systematic Uncertainties in Re(ε'/ε)

<table>
<thead>
<tr>
<th>Source</th>
<th>Error on Re(ε'/ε) (×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>
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<td>0.22</td>
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</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
• Use $M_K$ vs $E_K$ plot to determine distortion that 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 $\text{Re}(e'/e)$
  – 1996: $-0.1 \times 10^{-4}$
  – 1997: $-0.1 \times 10^{-4}$
  – 1999: $+0.2 \times 10^{-4}$
• Systematic error: $\pm 0.15 \times 10^{-4}$
Calorimeter Energy Scale

- Calorimeter calibrated with momentum-analyzed electrons from $K\rightarrow\pi\nu$
- Final energy scale adjustment based on $K^0\rightarrow\pi^0\pi^0$ at regenerator edge

1999:
$z$ shift = 2.7 cm
energy scale adjustment = 0.05%
Improvement in Energy Scale Correction
Energy scale fixed at regenerator edge \(\rightarrow\) check scale at vacuum window.

Uncertainty in \(\text{Re}(\varepsilon'/\varepsilon)\):
\(\pm 0.65 \times 10^{-4}\)

\(~\times 2\) improvement compared to previous analysis.
Data – MC comparisons of z vertex distributions

Difference between mean z vertex in reg and vac beams is about 6 m

⇒

\[ \delta \text{Re}(\varepsilon' / \varepsilon) \approx \text{data/mc slope} \]
Calculating \( \text{Re}(\varepsilon'/\varepsilon) \)

Naively,

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

but regenerator beam is not purely \( K_S \).
$K_L - K_S$ Interference Downstream of Regenerator

\[ N(p, z) \propto \eta^2 e^{-\Gamma_L t} + \rho^2 e^{-\Gamma_S t} + 2\eta|\rho| e^{-(\Gamma_S + \Gamma_L)t/2} \cos(\Delta mt + \Phi_\rho - \Phi_\eta) \]
Fit to Extract Re(ε'/ε)

• Acceptance applied to prediction function in 2 m z bins and 10 GeV/c momentum bins

• Data are fit in 10 GeV/c momentum bins and a single z bin for each beam

• $K_L$ fluxes are floated in 10 GeV/c $p$ bins separately for charged and neutral mode

• Regenerator beam attenuation measured directly from data using $K_L \rightarrow \pi^+ \pi^- \pi^0$ decays (special trigger in 99 gave 9-fold increase in sample):

![Graph showing $N^{+0}/N^{+0}_{\text{vac}}$ vs. $p$, GeV/c]

$slope = (-3.47 \pm 0.16) \times 10^{-5} \text{ c/GeV}$
KTeV Result: \[ \text{Re}(\varepsilon'/\varepsilon) = [19.2 \pm 1.1\text{(stat)} \pm 1.8\text{(syst)}] \times 10^{-4} \]
\[ = (19.2 \pm 2.1) \times 10^{-4} \]

World average:
\[ \text{Re}(\varepsilon'/\varepsilon) = (16.8 \pm 1.4) \times 10^{-4} \]
(confidence level = 13%)

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

Momentum Bins

\[ \chi^2/\text{dof} = 12.4/11 \]

Run Ranges

\[ \chi^2/\text{dof} = 12.3/10 \]
Fit Strategy for z-binned Fits

• In contrast with Re(\(\varepsilon'/\varepsilon\)) fit, in which a single ~50 m z bin is considered, we now fit the regenerator beam data in 2 m z bins.

• Float \(\Delta m=m_L-m_S\), \(\tau_S\), \(\phi_\varepsilon\), Re(\(\varepsilon'/\varepsilon\)), Im(\(\varepsilon'/\varepsilon\)) with no CPT assumption.

• CPT constraint (\(\phi_\varepsilon=\phi_{SW}\) and Im(\(\varepsilon'/\varepsilon\)=0) then applied \textit{a posteriori} to find best values \(\tau, \Delta m\).

\[
\eta_{++} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} = \varepsilon + \varepsilon' \\
\eta_{00} = \frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} = \varepsilon - 2\varepsilon' \\
\phi_{SW} = \tan^{-1}\left(\frac{2\Delta m}{\Delta \Gamma}\right) \\
\phi_{++} \approx \phi_\varepsilon + \text{Im}(\varepsilon'/\varepsilon) \\
\phi_{00} \approx \phi_\varepsilon - 2\text{Im}(\varepsilon'/\varepsilon) \\
\Delta \phi \equiv \phi_{00} - \phi_{++} \approx -3 \text{Im}(\varepsilon'/\varepsilon)
\]
**z-binned Fit Results**

\[ \phi_\varepsilon = (43.86 \pm 0.63)\degree \]

\[ \phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)\degree \]

\[ \text{Im}(\varepsilon'/\varepsilon) = (-17.2 \pm 20.2) \times 10^{-4} \Rightarrow \Delta \phi = (0.30 \pm 0.35)\degree \]

All results consistent with CPT symmetry
### $\phi_{+-}$ and $\Delta \phi$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\phi_{+-}$ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEC 74</td>
<td>43.3 ± 1.1</td>
</tr>
<tr>
<td>NA31 90</td>
<td>44.4 ± 1.7</td>
</tr>
<tr>
<td>E731 93</td>
<td>41.4 ± 1.0</td>
</tr>
<tr>
<td>E773 95</td>
<td>43.0 ± 0.8</td>
</tr>
<tr>
<td>CPLR 99</td>
<td>42.9 ± 0.6</td>
</tr>
<tr>
<td><strong>KTEV 08</strong></td>
<td>43.8 ± 0.6</td>
</tr>
<tr>
<td>PDG 2006</td>
<td>43.4 ± 0.7</td>
</tr>
</tbody>
</table>

**KTEV 2008:** $\phi_{+-} = (43.8 \pm 0.6)^\circ$

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

**Improvement:** better treatment of reg. transmission, screening

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<th>Experiment</th>
<th>$\Delta \phi$ (degrees)</th>
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<tbody>
<tr>
<td>E731, E773 95</td>
<td>-0.30 ± 0.88</td>
</tr>
<tr>
<td><strong>KTEV 08</strong></td>
<td>0.30 ± 0.35</td>
</tr>
<tr>
<td>New World Ave.</td>
<td>0.22 ± 0.33</td>
</tr>
<tr>
<td>PDG 2006</td>
<td>0.20 ± 0.40</td>
</tr>
</tbody>
</table>

**KTEV 2008:** $\Delta \phi = (0.30 \pm 0.35)^\circ$

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

**Improvement:** neutral energy scale
z-binned Fit Results (cont)

No CPT constraint:

\[ \Delta m = (5279.7 \pm 19.5) \times 10^6 \text{ hs}^{-1} \]
\[ \tau_s = (89.589 \pm 0.070) \times 10^{-12} \text{ s} \]

CPT constraint applied:

\[ \Delta m = (5269.9 \pm 12.3) \times 10^6 \text{ hs}^{-1} \]
\[ \tau_s = (89.623 \pm 0.047) \times 10^{-12} \text{ s} \]
Δm and τ_S

KTeV 2008: Δm = (5270 ± 12) × 10^6 hs^{-1}
(KTeV 2003: Δm = (5261 ± 13) × 10^6 hs^{-1})

KTeV 2008: τ_S = (89.62 ± 0.05) × 10^{-12} s
(KTeV 2003: τ_S = (89.65 ± 0.07) × 10^{-12} s)
Summary

KTeV Results:

- \( \text{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.1) \times 10^{-4} \)
- \( \Delta m = (5269.9 \pm 12.3) \times 10^6 \text{hs}^{-1} \) \{ Assuming CPT \}
- \( \tau_S = (89.623 \pm 0.047) \times 10^{-12} \text{s} \)
- \( \phi_{\varepsilon} = (43.86 \pm 0.63)° \)
- \( \phi_{\varepsilon} - \phi_{\text{SW}} = (0.40 \pm 0.56)° \) \{ No CPT assumption \}
- \( \Delta \phi = (0.30 \pm 0.35)° \)

- Direct CP violation measured precisely:
  \[
  \frac{\text{Rate}(K^0 \rightarrow \pi^+\pi^-) - \text{Rate}(\bar{K}^0 \rightarrow \pi^+\pi^-)}{\text{Rate}(K^0 \rightarrow \pi^+\pi^-) + \text{Rate}(\bar{K}^0 \rightarrow \pi^+\pi^-)} = (5.5 \pm 0.5) \times 10^{-5}
  \]
- Future lattice calculations may make these precise experimental measurements equally precise tests of the Standard Model.
- All measurements are consistent with CPT symmetry.
Screening Corrections

- Determine regeneration amplitude in 10 GeV kaon momentum bins. Agrees with screening correction calculations for low P.
- Calculate phase at each P using Derivative Analyticity Relation using the 12 amplitudes
- Compare variation of the phase vs P from DAR to direct fit to data – good agreement.
$K_L \rightarrow \pi^0 \pi^0$ Distributions

Vac ($K_L$)

Reg ($K_S$)