A New Measurement of $\text{Re}(\varepsilon'/\varepsilon)$ from KTeV at Fermilab

1) Introduction to CP Violation in the Kaon System
2) The KTeV Experiment at Fermilab
3) Analysis of $\text{Re}(\varepsilon'/\varepsilon)$
4) New 1997 Result, and Re-analysis of 1996 Result
The Neutral Kaon System

- $K^0$ (sd), $\bar{K}^0$ (sd) are quark flavor eigenstates
- Mixing via ElectroWeak interaction:

\[ \begin{align*}
\bar{s} & \quad \text{W}^- & \quad \bar{d} \\
K^0 & \quad \text{W}^+ & \quad \bar{K}^0 \\
d & \quad \text{W}^- & \quad s
\end{align*} \]

- In CP conserving limit, mass eigenstates=CP eigenstates: $K_1 \propto K^0 + \bar{K}^0 \ (\text{CP}+1)$, $K_2 \propto K^0 - \bar{K}^0 \ (\text{CP}-1)$
  
  Expect $K_1$ to be much shorter lived than $K_2$,

\[ M_K - 3M_{\pi_0} \ll M_K - 2M_{\pi_0} \]
CP Violation in Kaons

• 1\textsuperscript{st} Observation of CP Violation was $K_L \to \pi\pi$ (1964):

$$A(K_L \to \pi\pi)/A(K_S \to \pi\pi) \equiv \varepsilon \approx 2 \times 10^{-3}$$

• Bulk of effect is from mixing asymmetry:

$$A(K^0 \to \bar{K}^0) \neq A(\bar{K}^0 \to K^0)$$

• Mass Eigenstates: $K_S \propto K_1 + \varepsilon K_2$, $K_L \propto \varepsilon K_1 + K_2$

$$\tau_L \approx 580 \, \tau_S, \quad \Delta m \approx 1/2 \tau_S$$
CP Violation in the Standard Model

• CP Violation is accommodated in imaginary part of quark mixing parameters:

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
d \\
s \\
b
\end{pmatrix}
\]

\[
V \equiv 
\begin{pmatrix}
1-\frac{\lambda^2}{2} & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3 (1-\rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]
Direct CP Violation

- Direct CP Violation: $K_L \propto \varepsilon K_1 + K_2$

- CP Violation in Decay Amplitudes: EW and Strong Penguins

- Small effect on CP violating $K_L$ Amplitudes:

\[
\frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} \approx \varepsilon + \varepsilon' \\
\frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} \approx \varepsilon - 2\varepsilon'
\]
ε’/ε in the Standard Model

- ε’ ∝ Im(A_2/A_0) : A_{0,2} – I=0,2 Final State
- ε’/ε = Im(λ_t) x [ c_0 + R_s(c_6 B_6^{(1/2)} + c_8 B_8^{(3/2)})]
  - c_{0,6,8} – Wilson Coefficients, NLO (~ ±10%)
  - Im(λ_t) – Im(V_{td} V_{ts}^*) (~ ±40%)
  - B_{6,8}^{(1/2)} – Hadronic matrix elements of effective 4 quark operators – non perturbative, difficult to calculate.

- ε’/ε calculations vary…

Buras, et al., 99 { (4.6±3.0)x10^{-4} -Ciuchini, et al. 97
(5.7±3.6)x10^{-4} -m_s=130 ±20 MeV
(9.1±5.7)x10^{-4} -m_s=110 ±20 MeV
(17^{+14}_{-10})x10^{-4} -Bertolino, et al., 98

P. Shanahan – FNAL
SLAC - July 26, 2001
• Pre-June, 2001: World Average $\varepsilon'/\varepsilon = (18.0 \pm 2.0) \times 10^{-4}$, poor agreement among experiments.
KTeV at Fermilab

- Kaons at the TeVatron

- Three Physics Programs:
  - Rare K decays: E799
  - Hyperon Physics: E799/E832
  - \( \frac{\varepsilon'}{\varepsilon} \): E832

- \( \delta (\varepsilon'/\varepsilon) = O(10^{-4}) \)

University of Arizona, UCLA, UCSD, Universidade Estadual de Campinas, University of Chicago, University of Colorado, Elmhurst College, Fermilab, Osaka University, Rice University, Universidade de São Paulo, University of Virginia, University of Wisconsin
Measuring $\varepsilon'/\varepsilon$

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

- Simultaneous $K_L$ and $K_S$ beams: 20-200 GeV
  - Produce 2 $K_L$ beams 160 m upstream of the detector
  - Coherent regeneration of $K_S$ in 1.8m of plastic scintillator 35 m upstream of detector

- Detector
  - Spectrometer for $\pi^+\pi^-$
  - CsI EM Calorimeter for $\pi^0\pi^0 \to 4\gamma$
KTeV Detector
Coherent Regeneration

- Difference in $K^0$ and $\bar{K}^0$ forward scattering amplitude in matter
- $\rho \approx 0.02 - 0.04$, with power law dependence in $P_K$
- Coherent effect
  - Distinguish from inelastic $K_S$ production via scintillation light from recoil in interactions
  - Subtract diffractive and remaining inelastic and background offline
Cesium Iodide Calorimeter

- 3100 Crystals of 27 X₀ Pure CsI (50cm)
- High Linearity Phototubes
- 8 Range, Deadtimeless, Pipelined ADC
CsI Performance

- CsI Calibrated with $e^\pm$ from 420 Million $K \to \pi e\nu$

Energy Resolution

\[ \sigma_{E/E} = 0.72\% \]

E/P Resolution for Electrons from $K \to \pi e\nu$

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

\[ \sigma_{E/p} = 0.72\% \]
K → ππ Trigger

- High Rate Environment
  - ~ few 100 KHz Kaon decay rate
  - CP violating BR’s $\mathcal{O}(10^{-3})$

<table>
<thead>
<tr>
<th>Trigger Element</th>
<th>Charged inefficiency</th>
<th>Neutral inefficiency</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 (deadtimeless)</td>
<td>0.3%</td>
<td>0.6%</td>
<td>50 KHz</td>
</tr>
<tr>
<td>Level 2 (2μs deadtime)</td>
<td>0.1%</td>
<td>1.0%</td>
<td>10 KHz</td>
</tr>
<tr>
<td>Level 3 (software filter)</td>
<td>0.08%</td>
<td>0.04%</td>
<td>2 KHz</td>
</tr>
</tbody>
</table>

- L1+L2 Live time: 65%
- L3 Live time: 99.9%
ε′/ε Standard Analysis

- Count $K_{L,S}$ to $\pi^+\pi^-$ and $\pi^0\pi^0$
- Background Subtraction – non $\pi\pi$ and non-coherent $K\rightarrow\pi\pi$
- Very different $K_L$ and $K_S$ lifetimes:
  - Need acceptance correction from Monte Carlo simulation of detector + overlay of accidental activity
- Fit for $\varepsilon'/\varepsilon$
  - Account for full kaon wave function in each beam
KTeV Data Taking

1996

1997

1999

2000

E799  E832  1st KTeV result, and re-analysis

New result

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# Event Sample

<table>
<thead>
<tr>
<th>Year</th>
<th>$K_L \pi^+\pi^-$ $(10^6)$</th>
<th>$K_L \pi^0\pi^0$ $(10^6)$</th>
<th>$K_S \pi^+\pi^-$ $(10^6)$</th>
<th>$K_S \pi^0\pi^0$ $(10^6)$</th>
<th>Statistical error $(10^{-4})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>96/97a (PRL)</td>
<td>2.6</td>
<td>0.9</td>
<td>4.5</td>
<td>1.4</td>
<td>3.0</td>
</tr>
<tr>
<td>97</td>
<td>8.6</td>
<td>2.5</td>
<td>14.9</td>
<td>4.2</td>
<td>1.73</td>
</tr>
<tr>
<td>Combined</td>
<td>11.2</td>
<td>3.4</td>
<td>19.4</td>
<td>5.6</td>
<td>~1.5</td>
</tr>
</tbody>
</table>
Reconstructed Invariant Masses

\[ K_L \rightarrow \pi^+\pi^- : 8.6 \text{ M} \]

\[ K_S \rightarrow \pi^+\pi^- : 14.9 \text{ M} \]

\[ K_L \rightarrow \pi^0\pi^0 : 2.5 \text{ M} \]

\[ K_S \rightarrow \pi^0\pi^0 : 4.2 \text{ M} \]
**π⁺π⁻ Reconstruction**

- 2 good tracks, forming a good vertex

**Cuts**

- Track Quality
- Vertex $\chi^2$
- Muon Veto
- $E/p$
- “$p\pi$” Mass
- Regenerator Veto
- $P_T^2$

- reject $K\rightarrow\pi\mu\nu$
- reject $K\rightarrow\pi e\nu$
- reject $\Lambda\rightarrow p\pi$
- noncoherent KS
- nocoherent KS, non $\pi\pi$

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Interference in $K \rightarrow \pi\pi$

Regenerator Vertex $Z$ distribution

- Data
- Prediction
- Prediction without interference

$40 \text{ GeV} < P_K < 50 \text{ GeV}$

Events per 0.5 m

Distance from target (m)

Regenerator Vertex $Z$ distribution
Backgrounds to $\pi^+\pi^-$

- Non-coherent KS regeneration
  - Scattering in regenerator
  - Scattering in collimators
- $K \rightarrow \pi\ell\nu$
- Beam interactions in REG Pb

Total: .098% VAC  .081% REG
Monte Carlo Simulation

- Detector apertures/ performance
- Overlay real random activity
- E.g.: Delayed hit problem
  - Worst for tracks near Drift Chamber sense wires
Simulation Results

Vac beam $\pi^+\pi^- P_T^2$

- Data
- Monte Carlo
- MC, no maps or accid

Events per 25 MeV$^2$/c$^2$

0 50 100 150 200 250 300 350

0 50 100 150 200 250 300 350

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Acceptance

Data-MC comparison of $\pi$ track illumination at CsI

MC tuned with 10s of millions of CP conserving decays

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Acceptance Test

- Comparison of Data and MC Z vertex Distributions
  - Test of acceptance in variable most relevant to $K_L - K_S$ difference
- Set systematic uncertainty based on $\pi^+\pi^-$:
  - $\delta(\varepsilon'/\varepsilon) = 0.53 \times 10^{-4}$

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**$\pi^0\pi^0$ Reconstruction**

- Vertex for each pair of photons found assuming $\pi^0$ mass
- Choose pairing with most consistent $\pi^0$ vertices
- Calculate $\pi^0\pi^0$ mass
  - No direction information – use energy centroids

**Cuts:**
- Photon Veto
- Cluster Shape $\chi^2$
- Vertex Pairing $\chi^2$
- Regenerator Activity
- $(X,Y)_{CE}$
- $M_{\pi^0\pi^0}, E_K, Z_{vtx}$
- Extra intime photons in CsI

- Non-coherents
- Non-coherents
- “Fused” $\gamma s (3\pi^0)$
- Mispairs, $3\pi^0$
- $3\pi^0$
\[ \pi^0 \pi^0 \text{ Center of Energy} \]

- Cut on center of energy
  - In 1 cm\(^2\) square rings
- Simulate Regenerator scattering spectrum using \( p_t^2 \) shape from \( \pi^+ \pi^- \)
Backgrounds to $\pi^0\pi^0$

- Dominant BG: Regenerator Scatters
  - Modeled from $K \rightarrow \pi^+\pi^-$ $p_T^2$ Spectrum
  - Separate normalization of diffractive and inelastic $K_S$ production

REG Beam: 1.27%
VAC Beam: 0.50%
Energy Scale

- Energy Scale:
\[ \Delta Z \equiv Z_{CSI} - Z_{vtx} = \frac{\sqrt{E_1 E_2 r_{12}}}{m_{\pi^0}} \]
\[ E \rightarrow E(1 + \delta) \Rightarrow \Delta Z \rightarrow \Delta Z(1 + \delta) \]

- Apply correction \((1 + \delta)^{-1}\)
  - Relative Data-MC energy scale correction:
    Make data and MC regenerator edge line up.
Energy Scale Cross Check

- Beam interactions
  - Regenerator Pb
  - Vacuum window
- $K \rightarrow \pi^+ \pi^- \pi^0$
- For systematic:
  - Apply extra energy scale, varying linearly from Regenerator, to fix $Z_{\text{VACWIN}}$
- $\delta(\varepsilon'/\varepsilon) = 1.37 \times 10^{-4}$
Acceptance Test

- Set systematic uncertainty from $3\pi^0$

- $\delta(\varepsilon'/\varepsilon)=0.26 \times 10^{-4}$
# Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty $(\times 10^{-4})$ from $\pi^+\pi^-$</th>
<th>Uncertainty $(\times 10^{-4})$ from $\pi^0\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1: Data collection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger and level 3 filter</td>
<td>0.62</td>
<td>0.16</td>
</tr>
<tr>
<td>Class 2: Event reconstruction, selection, backgrounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy/Resolution scale</td>
<td>0.16</td>
<td>1.37</td>
</tr>
<tr>
<td>Calorimeter nonlinearity</td>
<td>—</td>
<td>0.66</td>
</tr>
<tr>
<td>Detector calibration, alignment</td>
<td>0.28</td>
<td>0.38</td>
</tr>
<tr>
<td>Analysis cut variations, Reconstruction</td>
<td>0.25</td>
<td>0.37</td>
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<tr>
<td>Background subtraction</td>
<td>0.2</td>
<td>1.06</td>
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<tr>
<td>Class 3: Detector acceptance</td>
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<td></td>
</tr>
<tr>
<td>Limiting apertures</td>
<td>0.33</td>
<td>0.48</td>
</tr>
<tr>
<td>Detector resolution</td>
<td>0.15</td>
<td>0.08</td>
</tr>
<tr>
<td>Drift chamber simulation</td>
<td>0.37</td>
<td>—</td>
</tr>
<tr>
<td>$z$ dependence</td>
<td>0.53</td>
<td>0.26</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>0.33</td>
<td>0.49</td>
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<tr>
<td>Class 4: Kaon flux and physics parameters</td>
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<td></td>
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<tr>
<td>Regenerator-beam attenuation:</td>
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<td></td>
</tr>
<tr>
<td>Energy dependence</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>$\Delta m$, $\tau_S$, regeneration phase, screening</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>2.39</td>
<td></td>
</tr>
</tbody>
</table>

Table 9: Table of systematics on $Re(\epsilon'/\epsilon)$ in the format of the PRL, updated for the 1997B analysis.
KTeV 1997 $\varepsilon'/\varepsilon$ Result

$\chi^2$/DoF = 9.382 / 11

$\text{Re}(\varepsilon'/\varepsilon) = (19.8 \pm 1.7\,\text{(stat)} \pm 2.3\,\text{(syst)} \pm 0.6\,\text{(mc stat)}) \times 10^{-4}$
Reweighting Analysis

• MC acceptance correction is only ~5% on the double ratio
  – … but this is ~90x10^{-4} on \( \varepsilon'/\varepsilon \)

• We have strong cross checks on our acceptance calculation
  – E.g., purely geometrical MC accounts for about 90% of the acceptance correction

• However, an “MC independent” measurement is desirable:

• Reweighting:
  – reweight VAC beam to have same p,Z distribution as REG
  – Similar to NA48 method (CERN), but more complicated due to substantial interference of \( K_L \) and \( K_S \)

\[
w(p, z) = \frac{\text{prob}(\text{REG}; p, z)}{\text{prob}(\text{VAC}; p, z)}
\]
Pros and Cons of Reweighting

- Reweighting completely removes biases from lifetimes and geometry
- Reweighting de-emphasizes tracks near beam regions
  - Less susceptibility to rate and accidental effects

\[
\delta(\varepsilon'/\varepsilon) : 1.7 \times 10^{-4} \rightarrow 3.0 \times 10^{-4}
\]
Examples of Reweighting

Data vs. Data

Y Track Illum at DC 1

Vac Events
Reg Events

Y Track Illum at DC 1 after rewgt

Vac Events
Reg Events

X Cls Illum at CsI ($\pi^0\pi^0$) m

Vac Events
Reg Events

X Cls Illum at CsI ($\pi^0\pi^0$) after rewgt

Reweighted Vac Events
Reg Events
Reweighting Result

With preliminary understanding of correlated uncertainties,\
\[ \Delta(\varepsilon'/\varepsilon) = (1.5 \pm 2.1 \text{(stat)} \pm 3 \text{ (syst)}) \times 10^{-4} \]

- Preliminary reweighting results (NOT the official KTeV Number….)
  - \[ \text{Re}(\varepsilon'/\varepsilon) = 21.3 \pm 2.9 \text{(stat)} \pm 4.0 \text{(syst)} \]
  - *Hope to reduce systematic…*
Other Cross Checks

Cross Checks on $\text{Re}(\varepsilon'/\varepsilon)$ Measurement

Comparision to Full Result
Comparision to 1997 Result

$\text{Re}(\varepsilon'/\varepsilon) \times 10^4$

- 96/97a
- 97b
- 97c
- 97d
- 97e

- re-weight
- reg-left
- reg-right
- Mag +
- Mag -
Re-Analysis of 1996/97a Result

- Miscellaneous improvements
  - e.g. recalibration, Mask Anti, DC Simulation

- Mistake found in $\pi^0\pi^0$ scattering background

- External parameters
  - $\Delta m$, $\tau_S$ from KTeV (was PDG98)
Updated 1996/97a Results

New 1996 Result:
\[ \frac{\epsilon'}{\epsilon} = (23.2 \pm 3.0 \text{ (stat)} \pm 3.2 \text{ (syst)} \pm 0.7 \text{ (MC st)}) \times 10^{-4} \]

Old Result: (superceded)
\[ \frac{\epsilon'}{\epsilon} = (28.0 \pm 3.0 \text{ (stat)} \pm 2.7 \text{ (syst)} \pm 1.0 \text{ (MC st)}) \times 10^{-4} \]

Note: sources of shifts are not correlated
### Shifts in Updated Analysis

*Each consistent with quoted systematic uncertainty*

![Graph showing shifts in $\Delta \text{Re}(\varepsilon'/\varepsilon) / \sigma_{\text{syst}}$ relative to PRL 83, 22 (1999)](image)

<table>
<thead>
<tr>
<th>Comment</th>
<th>$\Delta \text{Re}(\varepsilon'/\varepsilon)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\pi^0$ background</td>
<td>$(-1.7 \times 10^{-4})$</td>
</tr>
<tr>
<td>reg screening</td>
<td>$(-0.3 \times 10^{-4})$</td>
</tr>
<tr>
<td>reg attenuation</td>
<td>$(-0.3 \times 10^{-4})$</td>
</tr>
<tr>
<td>$\pi^+\pi^-$ reg edge</td>
<td>$(-0.2 \times 10^{-4})$</td>
</tr>
<tr>
<td>collimator scatter</td>
<td>$(-0.2 \times 10^{-4})$</td>
</tr>
<tr>
<td>$2\pi^0$ analysis</td>
<td>$(0.1 \times 10^{-4})$</td>
</tr>
<tr>
<td>Mask Anti geometry</td>
<td>$(0.26 \times 10^{-4})$</td>
</tr>
<tr>
<td>Absorber scatter</td>
<td>$(-0.6 \times 10^{-4})$</td>
</tr>
<tr>
<td>$2\pi^0$ reg edge</td>
<td>$(-0.2 \times 10^{-4})$</td>
</tr>
</tbody>
</table>
Combined 1996 and 1997 Results

\[ \text{Re}(\varepsilon'/\varepsilon) = \left(20.7 \pm 1.5\text{(stat)} \pm 2.4\text{(syst)} \pm 0.5\text{(MC Stat)}\right) \times 10^{-4} \]

\[ \text{Re}(e'/e) = \left(20.7 \pm 2.8\right) \times 10^{-4} \]

**Systematic Uncertainties for Combined Result**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty ((\times 10^{-4})) from (\pi^+\pi^-)</th>
<th>Uncertainty ((\times 10^{-4})) from (\pi^0\pi^0)</th>
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<tr>
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<td></td>
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<tr>
<td>Trigger and level 3 filter</td>
<td>0.56</td>
<td>0.18</td>
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<tr>
<td>Class 2: Event reconstruction, selection, backgrounds</td>
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<td>0.37</td>
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<td>Background subtraction</td>
<td>0.20</td>
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<td>Class 3: Detector acceptance</td>
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<tr>
<td>(\Delta m, \tau_s)</td>
<td>0.24</td>
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<tr>
<td>Reg phase screening</td>
<td>0.31</td>
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<tr>
<td>TOTAL</td>
<td>2.36</td>
<td></td>
</tr>
</tbody>
</table>
World Data on $\text{Re}(\varepsilon'/\varepsilon)$

- World Average:
  - $(17.2 \pm 1.8) \times 10^{-4}$
  - Probability = 13%

![Graph showing World Data on $\text{Re}(\varepsilon'/\varepsilon)$]

- E731 93: $7.4 \pm 5.9$
- NA31 93: $23.0 \pm 6.5$
- NA48 01 (prel): $15.3 \pm 2.6$
- KTEV 01 (prel): $20.7 \pm 2.8$
- New World Ave.: $17.2 \pm 1.8$
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]

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

Have made new measurements of the above. Re($\epsilon'/\epsilon$) fit uses our best values.
**Preliminary:**

\[
\begin{align*}
\Delta m &= (5262 \pm 7.7 \text{ (exp)} \pm 13 \text{ (th.)}) \times 10^6 \text{fs}^{-1} \\
\tau_S &= (8967.1 \pm 3.5 \text{ (exp)} \pm 4 \text{ (th.)}) \times 10^{-14} \\
\phi_{+\pm} &= 44.11 \pm 0.72 \text{ (stat)} \pm 1.1 \text{ (syst)} \\
\Delta\phi &= 0.41^\circ \pm 0.22^\circ \text{ (stat)} \pm 0.53^\circ \text{ (syst)}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(\tau_S) (psec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBC 72</td>
<td>89.58 ± 0.45</td>
</tr>
<tr>
<td>ASPK 74</td>
<td>89.37 ± 0.48</td>
</tr>
<tr>
<td>SPEC 75</td>
<td>89.24 ± 0.32</td>
</tr>
<tr>
<td>SPEC 76</td>
<td>88.10 ± 0.90</td>
</tr>
<tr>
<td>SPEC 87</td>
<td>89.20 ± 0.44</td>
</tr>
<tr>
<td>E731 93</td>
<td>89.29 ± 0.16</td>
</tr>
<tr>
<td>E773 95</td>
<td>89.41 ± 0.14 ± 0.09</td>
</tr>
<tr>
<td>NA31 97</td>
<td>89.71 ± 0.21</td>
</tr>
<tr>
<td>KTEV 01 (prel)</td>
<td>89.65 ± 0.03 ± 0.04</td>
</tr>
<tr>
<td>New World Ave.</td>
<td>89.59 ± 0.04</td>
</tr>
<tr>
<td>PDG 2000</td>
<td>89.40 ± 0.09</td>
</tr>
</tbody>
</table>
Conclusions

• KTeV has new Re(ε’/ε) result with improved error
• Re-analysis of 1996 result
• Combined KTeV Result:
  – Re(e’/e) = (20.7 ± 2.8) \times 10^{-4}
• World data now in significantly better agreement
  – World Average: (17.2 ± 1.8) \times 10^{-4}
  – 13% CL
  – ε’/ε now known to ~10%
• More data from 1999 run!