The Final Result on Direct CP Violation from the NA48 Experiment

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on behalf of the NA48 collaboration

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Outline

- Short history of direct CP violation in the Neutral Kaon System
- The peculiar NA48 method
- The 2001 data and the FINAL result
- Not only $\varepsilon'/\varepsilon$ ...
**CP Violation in the Neutral Kaon System**

CP conserved \( \implies K_L = K_2 \equiv \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0) \) (CP=-1) \( \implies K_L \not\to \pi\pi \)

**1964**: \( K_L \) decay to \( \pi^+\pi^- \) observed with B.R. = \( 2 \cdot 10^{-3} \)

**Indirect CP Violation**

![Diagram of CP Violation]

\[ K_L = K_2 + \varepsilon K_1 \]

\[ \pi^+ \pi^-, \pi^0 \pi^0 \]

**Direct CP Violation**

\[ \langle I, 0 | T | K^0 \rangle = A_I e^{i\delta_I} \]
\[ \langle I, 0 | T | \bar{K}^0 \rangle = A_I^* e^{i\delta_I} \]

\[ \varepsilon' \equiv \frac{i}{\sqrt{2}} \text{Im} \left( \frac{A_2}{A_0} \right) e^{i(\delta_2 - \delta_0)} \quad (\text{Im}(A_0) \equiv 0) \]

**Superweak Model by Wolfenstein**: CP violation due to a new force in \( \Delta S = 2 \) transitions \( \implies \varepsilon' = 0 \)

**1973**: Kobayashi and Maskawa show that CP violation can be accommodated in the **Standard Model** by increasing the number of quark generations.
Direct CP Violation in the Standard Model

- within the Standard Model $\varepsilon'$ can be computed as a function of the CKM matrix elements...

$$\frac{\varepsilon'}{\varepsilon} = \frac{Im(\lambda_t)}{0.074} \left( \frac{110 \text{ MeV}}{m_s(2\text{GeV})} \right)^2 \left[ 0.75 \ B_6 - 0.4 \ B_8 \left( \frac{m_t}{165 \text{ GeV}} \right)^{2.5} \right] \frac{\Lambda_{MS}}{340 \text{ MeV}}$$

("pedagogical" formula by A.Buras)

- but errors are dominated by long distance contributions to the penguin diagram terms $B_6$ and $B_8$

Current theoretical predictions:
$\varepsilon'/\varepsilon$ in the range $-10$ to $30 \times 10^{-4}$

Breakthrough from Lattice QCD computations?

- A precision measurement of $\varepsilon'/\varepsilon$ can test SM predictions against other possibilities, as the Superweak Model ($\varepsilon' = 0$) or SUSY contributions
**Measurements of $\varepsilon'/\varepsilon$**

So far all experiments used the **Double Ratio method**:

$$R = \frac{\Gamma(K_L^0 \rightarrow \pi^0\pi^0)}{\Gamma(K_L^0 \rightarrow \pi^+\pi^-)} \frac{\Gamma(K_S^0 \rightarrow \pi^+\pi^-)}{\Gamma(K_S^0 \rightarrow \pi^0\pi^0)} \approx 1 - 6 \times \text{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

**Evolution of World Average:**

<table>
<thead>
<tr>
<th>Year</th>
<th>Average $(10^{-4})$</th>
<th>$\chi^2/ndf$</th>
<th>$\chi^2$ prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>14.4 ± 4.4</td>
<td>3.2/1</td>
<td>7%</td>
</tr>
<tr>
<td>1999</td>
<td>19.2 ± 2.5</td>
<td>10.4/3</td>
<td>2%</td>
</tr>
<tr>
<td>2001</td>
<td>17.3 ± 1.7</td>
<td>5.6/3</td>
<td>13%</td>
</tr>
</tbody>
</table>
Minimize systematic errors on the double ratio

\[
R = \frac{\Gamma(K^0_L \to \pi^0\pi^0) \Gamma(K^0_S \to \pi^+\pi^-)}{\Gamma(K^0_L \to \pi^+\pi^-) \Gamma(K^0_S \to \pi^0\pi^0)} \approx 1 - 6 \text{Re}(\varepsilon'/\varepsilon)
\]

through

- simultaneous acquisition of the 4 decay modes
- in the same fiducial region
- from two high-intensity quasi-collinear beams
The Central Detector

\( \pi^0 \pi^0 \)

**LKr electromagnetic calorimeter:**
- quasi-homogeneous detector based on 9 m^3 LKr
- Cu Be electrodes
- 13212 2 x 2 x 127 cm^3
- \( \pm 48 \) mrad accordion geometry
- projective geometry
- geometry machined with 0.2 mm/m accuracy
- redundant time measurement by scintillating fiber neutral hodoscope

**Magnetic Spectrometer:**
- 4 chambers with 4 views each, 2 staggered planes per view
- 90 \( \mu \)m spacepoint resolution
- wire position known better than 100 \( \mu \)m/m
- magnet providing 265 MeV/c \( p_T \) kick

**Hodoscope:**
- 2 planes of scintillators for precise measurement of event time

G. Graziani – The Final Result of NA48
**Event Reconstruction**

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

Imposing $K^0$ mass to $K \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$

$$D = \sqrt{\sum E_i E_j \times (r_{ij})^2} / M_K$$

→ Longitudinal vertex resolution: $\sim 55$ cm
→ $\pi^0$ mass resolution:

$\sigma_+ \sim 0.42$ MeV
$\sigma_- \sim 0.83$ MeV

**$\pi^+ \pi^-$**

→ Momentum resolution:

$\sigma(P)/P = 0.45\% \oplus 0.009 \ P[\text{GeV/c}]\%$

→ Vertex resolution:

- longitudinal $\sim 50$ cm
- transverse $\sim 2$ mm

→ $\pi^+ \pi^-$ invariant mass resolution:

![Invariant mass distribution](image)

$\sigma = 2.5$ MeV

**Backgrounds** ($3\pi^0, K_{e3}, K_{\mu3}$ decays from $K_L$) reduced to $< 0.2\%$!!
Telling $K_S$ from $K_L$

Vertex Identification for $\pi^+\pi^-$

Tagger Identification

$K \to \pi^+\pi^-$ vertex selected (2001 data)

- Tagging Window
- $K_L$
- Mistagged $K_L$ ($\alpha_{LS}=8\%$)
- Untagged $K_S$ ($\alpha_{SL}=0.01\%$)
**KL Weighting and Acceptance Correction**

70 < Kaon Energy < 170 GeV

![Graph showing MC Double Ratio vs Kaon Energy](image)

**Residual acceptance difference after weighting is < 3 × 10⁻³**
Analysis Strategy

→ identify $K_S$ and $K_L$ by tagging in time the $K_S$ beam protons (correct event counts for mistagging using vertex identification for $\pi^+\pi^-$)

→ the main $K_S / K_L$ differences are minimized offline:
  energy spectra: perform analysis in 20 energy bins from 70 to 170 GeV
  lifetime: weight $K_L$ events according to the theoretical $K_S$ to $K_L$ ratio of proper time distributions: $w(t) \sim e^{-t\left(\frac{1}{\tau_S} - \frac{1}{\tau_L}\right)}$

→ compute the double ratio in each energy bin
→ apply small ($< 0.3 \%$ by first principles) corrections for remaining biases (backgrounds, mistagging, reconstruction and intensity effects...)

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Published results:

1997 data: \( Re(\varepsilon'/\varepsilon) = (18.5 \pm 4.5 \pm 5.8) \times 10^{-4} \)  

1998/1999 data: \( Re(\varepsilon'/\varepsilon) = (15.0 \pm 1.7 \pm 2.1) \times 10^{-4} \)  

All four chambers damaged after beam pipe implosion in Nov. 1999

2000 run only for neutral events (cross-checks and rare \( K_S \) decays)

Chambers rebuilt in time for the 2001 data-taking

**FINAL RESULT (INCLUDING 2001) TODAY**
**The 1998+1999 Result**

<table>
<thead>
<tr>
<th>Event Statistics (millions) 1998+1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \pi^0\pi^0$</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^0\pi^0$</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^+\pi^-$</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^+\pi^-$</td>
</tr>
</tbody>
</table>

$R$ before correction = $0.98739 \pm 0.00101$ (stat.)

**Corrections and systematic errors on $R$**

<table>
<thead>
<tr>
<th>Correction</th>
<th>$\Delta R$</th>
<th>Error</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0\pi^0$ reconstruction</td>
<td>$-$</td>
<td>$\pm 0.00058$</td>
<td></td>
</tr>
<tr>
<td>Acceptance</td>
<td>$+0.00267$</td>
<td>$\pm 0.00057$</td>
<td></td>
</tr>
<tr>
<td>$\pi^+\pi^-$ trigger inefficiency</td>
<td>$-0.00036$</td>
<td>$\pm 0.00052$</td>
<td>$\leftarrow$ rate effects</td>
</tr>
<tr>
<td>Accidental activity</td>
<td>$-$</td>
<td>$\pm 0.00044$</td>
<td>$\leftarrow$ rate effects</td>
</tr>
<tr>
<td>Accidental tagging</td>
<td>$+0.00083$</td>
<td>$\pm 0.00034$</td>
<td>$\leftarrow$ rate effects</td>
</tr>
<tr>
<td>Tagging inefficiency</td>
<td>$-$</td>
<td>$\pm 0.00030$</td>
<td>$\leftarrow$ rate effects</td>
</tr>
<tr>
<td>Background to $\pi^+\pi^-$</td>
<td>$+0.00169$</td>
<td>$\pm 0.00030$</td>
<td></td>
</tr>
<tr>
<td>$\pi^+\pi^-$ reconstruction</td>
<td>$+0.00020$</td>
<td>$\pm 0.00028$</td>
<td></td>
</tr>
<tr>
<td>Beam scattering</td>
<td>$-0.00096$</td>
<td>$\pm 0.00020$</td>
<td></td>
</tr>
<tr>
<td>Background to $\pi^0\pi^0$</td>
<td>$-0.00059$</td>
<td>$\pm 0.00020$</td>
<td></td>
</tr>
<tr>
<td>Long term $K_S/KL$ variations</td>
<td>$-$</td>
<td>$\pm 0.00006$</td>
<td></td>
</tr>
<tr>
<td><strong>Total Systematic</strong></td>
<td>$+0.00359$</td>
<td>$\pm 0.000126$</td>
<td></td>
</tr>
</tbody>
</table>

\[ \text{Re}(\epsilon'/\epsilon) = (1-R)/6 = (15.0 \pm 1.7 \text{ (stat.)} \pm 2.1 \text{ (syst.)}) \times 10^{-4} \]
The 2001 Run

Different Beam conditions:

- duty cycle: 2.4/14.4 s → 5.2/16.8 s
- proton energy: 450 GeV → 400 GeV
- instantaneous intensity: ~ 30% lower

New spectrometer's drift chambers

![Graph of Good K<sub>L</sub> Events / 100 ms over time within burst(s)]

![Graph of M(π<sup>+</sup>π<sup>−</sup>) (GeV/c<sup>2</sup>) distribution with peak at σ = 2.5 MeV]
## Comparing 2001 with 1998/1999

<table>
<thead>
<tr>
<th></th>
<th>1998+1999</th>
<th>2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>#K_L \rightarrow \pi^0\pi^0</td>
<td>$3.29 \times 10^6$</td>
<td>$1.54 \times 10^6$</td>
</tr>
<tr>
<td>Statistical error on R</td>
<td>$10.1 \times 10^{-4}$</td>
<td>$14.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>DCH overflow rate</td>
<td>21.5 %</td>
<td>11.7 %</td>
</tr>
<tr>
<td>Mistagging prob. $\alpha_{LS}$</td>
<td>10.6 %</td>
<td>8.1 %</td>
</tr>
<tr>
<td>L2 charged trigger efficiency</td>
<td>98.3 %</td>
<td>99.2 %</td>
</tr>
</tbody>
</table>

- lower average intensity
- but wider intensity range...
- better monitors of instantaneous rate

⇒ lower systematic uncertainty related to rate effects
The Result

Corrections and uncertainties on $R$ (Units = $10^{-4}$) errors are pure stat or pure syst

<table>
<thead>
<tr>
<th></th>
<th>2001</th>
<th>1998/1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical error</td>
<td>± 14.7</td>
<td>± 10.1</td>
</tr>
<tr>
<td>$\pi^0\pi^0$ reconstruction</td>
<td>± 5.3</td>
<td>± 5.8</td>
</tr>
<tr>
<td>Acceptance</td>
<td>21.9 ± 3.5 ± 4.0</td>
<td>26.7 ± 4.1 ± 4.0</td>
</tr>
<tr>
<td>$\pi^+\pi^-$ trigger inefficiency</td>
<td>5.2 ± 3.6</td>
<td>-3.6 ± 5.2</td>
</tr>
<tr>
<td>Accidentals: intensity diff.</td>
<td>± 1.1</td>
<td>± 3.0</td>
</tr>
<tr>
<td>illumination diff.</td>
<td>± 3.0</td>
<td>± 3.0</td>
</tr>
<tr>
<td>$K_S$ in-time activity</td>
<td>± 1.0</td>
<td>± 1.0</td>
</tr>
<tr>
<td>Accidental tagging</td>
<td>6.9 ± 2.8</td>
<td>8.3 ± 3.4</td>
</tr>
<tr>
<td>Tagging inefficiency</td>
<td>± 3.0</td>
<td>± 3.0</td>
</tr>
<tr>
<td>$\pi^+\pi^-$ background</td>
<td>14.2</td>
<td>16.9</td>
</tr>
<tr>
<td>$\pi^+\pi^-$ reconstruction</td>
<td>± 2.8</td>
<td>± 2.8</td>
</tr>
<tr>
<td>beam scattering</td>
<td>-8.8</td>
<td>-9.6</td>
</tr>
<tr>
<td>$\pi^0\pi^0$ background</td>
<td>-5.6</td>
<td>-5.9</td>
</tr>
<tr>
<td>AKS inefficiency</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Total systematic</td>
<td>+35.0 ± 6.5 ± 9.0</td>
<td>+35.9 ± 8.1 ± 9.6</td>
</tr>
</tbody>
</table>

$R = 0.99181 ± 0.00147_{stat} ± 0.00110_{syst}$
2001 RESULT: \[ \text{Re}(\varepsilon'/\varepsilon) = (13.7 \pm 3.1) \times 10^{-4} \]

different beam conditions and new drift chambers

very good agreement with previous years
The Final Result

combining the 2001 result with the 97+98+99 one
\[ (15.3 \pm 2.6) \times 10^{-4} \]
we get the final result

\[ \text{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4} \]

\[ \rightarrow \text{5 years of data-taking} \]
\[ \rightarrow 5.3 \times 10^6 K_L \rightarrow \pi^0\pi^0 \text{ collected} \]
\[ \rightarrow \text{proposal goal successfully reached} \]
Not only $\varepsilon'/\varepsilon$ . . .

NA48 is producing many other physics results on $K_L$, $K_S$ and hyperon rare decays to study indirect CPV and low energy hadron dynamics (tests of $\chi$PT)

Notably:

- $K_S \to \gamma\gamma$  
  \[ BR = (2.78 \pm 0.06 \text{ (stat)} \pm 0.02 \text{ (MC stat)} \pm 0.04 \text{ (syst)}) \times 10^{-6} \]  
  \text{(preliminary)}

- $K_L \to \pi^0\gamma\gamma$  
  \[ BR = (1.36 \pm 0.03 \text{ (stat)} \pm 0.03 \text{ (syst)} \pm 0.03 \text{ (norm)}) \times 10^{-6} \]
  \[ a_V = -0.46 \pm 0.03 \text{ (stat)} \pm 0.04 \text{ (syst)} \]

- $K_S \to \pi^0\gamma\gamma$  
  \[ BR(m_{\gamma\gamma}^2/m_K^2 > 0.2) < 4.4 \times 10^{-7} \text{ (90 \% conf. level)} \]  
  \text{(preliminary)}

- $K_S \to \pi^0e^+e^-$  
  \[ BR < 1.4 \times 10^{-7} \text{ (90 \% conf. level)} \]  

- $K_L \to \pi^+\pi^-e^+e^-$  
  \[ BR = (3.1 \pm 0.1 \text{ (stat)} \pm 0.2 \text{ (syst)}) \times 10^{-7} \]
  \text{CPV Asymmetry} = (13.9 \pm 2.7 \text{ (stat)} \pm 2.0 \text{ (syst)})\%  
  \text{(preliminary)}

- $K_S \to \pi^+\pi^-e^+e^-$  
  \[ BR = (4.3 \pm 0.2 \text{ (stat)} \pm 0.3 \text{ (syst)}) \times 10^{-5} \text{ first observation!} \]
  \text{CPV Asymmetry} = (-0.2 \pm 3.4 \text{ (stat)} \pm 1.4 \text{ (syst)})\%  
  \text{(preliminary)}
The $\varepsilon'$ program is finished, but not NA48

**NA48/1**  
*PRESENTLY RUNNING!*  
High-Intensity $K_S$ run: $2 \times 10^{10} ppp$ ($\varepsilon'$ intensity $\times 600$)  
→ minor modifications of the beam line  
→ new DCH read–out (higher rate capability)

**Physics goal:** reach unprecedented sensitivity for  
- $K_S \rightarrow \pi^0 e^+ e^-$ ($\sim 2 \times 10^{-10}$)  
- other rare $K_S$ and hyperon decays  
- CPV in $K_S \rightarrow 3\pi$

**NA48/2**  
*STARTING IN 2003*  
Simultaneous $K^+/K^-$ beam  
→ new beam line for an unseparated $K^+/K^-$ beam  
→ new beam spectrometer (KABES)

**Physics goal:** search for direct CPV in $K^\pm \rightarrow 3\pi$ decays  
(measure $A_g$ with $10^{-4}$ accuracy),  
look for QCD vacuum condensate in $K_{e4}$ decays
after the succesfull 2001 run, NA48 presented the final result on $\text{Re}(\varepsilon'/\varepsilon)$:

$$\text{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}$$

*NA48 establishes direct CP violation by more than 6 $\sigma$!!*

Results of similar accuracy expected from KTEV (FNAL) final sample and possibly from KLOE (at DAPHNE $\phi$ factory)

**THEORY** is expected to improve its predictive power for $\text{Re}(\varepsilon'/\varepsilon)$ in the Standard Model, mainly through **Lattice QCD** calculations.

Example of recent results (systematic errors not finalized...):

- CP–PACS group (*hep-lat/0108013*): $\text{Re}(\varepsilon'/\varepsilon) = (-8 \div 0) \times 10^{-4}$
- RBC group (*hep-lat/0110075*): $\text{Re}(\varepsilon'/\varepsilon) = (-9 \div -1) \times 10^{-4}$

*too early to claim for new physics...*

Many new interesting results on Kaon Physics are coming out from the collected data...

...and many more quantitative tests of CPV in the Standard Model (complementary to B physics) and of low–energy hadron dynamics to come in the next futures