Results on CP Violation from the NA48 experiment at CERN

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Main goal of NA48 experiment

Precise measurement of Direct CP Violation in the Neutral Kaon System: parameter \( \text{Re}(\varepsilon'/\varepsilon) \).

- Data taking in 97, 98 and 99
- 1999: published result on 97 data
  \[ \text{Phys.Lett.B 465, 335-348 (1999)} \]
- May 2001: announced result on 98+99 data \( \Leftarrow \) Today

also

Study of a wide range of \( K_L \) and \( K_S \) rare decays, collected in parallel or in special runs.
# RARE KAON DECAYS in NA48

Allow study of $\chi$PT theory, CP Violation, SM checks etc

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \pi^0 \gamma \gamma$</td>
<td>$(1.36\pm0.05)\times10^{-6}$</td>
<td>2588</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^0 e^+ e^-$</td>
<td>$&lt; 1.4\times10^{-7}$ (90% CL)</td>
<td></td>
</tr>
<tr>
<td>$K_S \rightarrow \gamma \gamma$</td>
<td>$(2.58\pm0.42)\times10^{-6}$</td>
<td>149</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^+ \pi^- e^+ e^-$</td>
<td>$(4.3\pm0.4)\times10^{-5}$</td>
<td>921</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^+ \pi^- e^+ e^-$</td>
<td>$(3.1\pm0.2)\times10^{-7}$</td>
<td>1337</td>
</tr>
<tr>
<td>$K_L \rightarrow e^+ e^- e^+ e^-$</td>
<td>$(3.7\pm0.4)\times10^{-8}$</td>
<td>139</td>
</tr>
<tr>
<td>$K_L \rightarrow e^+ e^- \gamma$</td>
<td>$(1.06\pm0.05)\times10^{-5}$</td>
<td>6864</td>
</tr>
<tr>
<td>$K_L \rightarrow e^+ e^- \gamma \gamma$</td>
<td>$(6.3\pm0.5)\times10^{-7}$</td>
<td>1543</td>
</tr>
</tbody>
</table>
NEW RESULT: $K_L \rightarrow \pi^0 \gamma\gamma$

- $\chi$PT: Needs to include $O(p^6)$ and Vector meson contribution to reproduce the observed rate.
- Gives constraints to the CP-Conserving amplitude to $K_L \rightarrow \pi^0 e^+e^-$. $\chi_P^2/n.d.f = 31.1/30$
- Low $m_{\gamma\gamma}$: sensitive to the amount of VM $\propto a_V$
- 2588 events with 3.3% background

$$Br = (1.36 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.03_{\text{norm}}) \times 10^{-6}$$
$$a_V = -0.46 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.02_{\text{the}}$$
• Direct CP Violation

• Presentation of NA48

• Analysis for $\text{Re}(\varepsilon'/\varepsilon)$ measurement

• The new result

• Conclusions
**DIRECT CP VIOLATION**

In the Kaon System, CP Violation manifests in the observation of the CP-forbidden $K_L \rightarrow 2\pi$ decay.

- In the Standard Model, an irreducible phase in CKM matrix is the source of CP Violation.
- Two components: Indirect CP Violation ($\varepsilon$), due to CP-states mixing, and Direct CP Violation ($\varepsilon'$) acting in the decay and depending on decay channel.

\[
K_S = K_1 + \varepsilon K_2 \\
K_L = K_2 + \varepsilon K_1
\]
DIRECT CP VIOLATION (cntd)

- Indirect CP Violation ($\varepsilon$) known since '64 ($\approx 2 \times 10^{-3}$).

- Direct CP Violation ($\varepsilon'$) is small wrt Indirect
  $\Rightarrow$ convenient to measure $\text{Re}(\varepsilon'/\varepsilon)$.

- The measurable quantity $\text{Re}(\varepsilon'/\varepsilon)$ is connected to the ratio $R$ of four observable decay rates:

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

- From theory: $\text{Re}(\varepsilon'/\varepsilon)$ in the range $5 - 30 \times 10^{-4}$
PAUSE: large effects of CP Violation in the Kaon System ⇒ the decay $K_L \rightarrow \pi^+\pi^-e^+e^-$

- $K_L$ decays to $\pi^+\pi^-e^+e^-$ through two diagrams
- CP-Viol./CP-Cons. $\approx \eta \times (2M_K/E_\gamma)^2 \sim 1$
- Interference visible in $\sin(\phi)\cos(\phi)$ where $\phi$ is the angle between the $\pi^+\pi^-$ and $e^+e^-$ planes in Kaon rest frame.
PAUSE: the decay $K_L \rightarrow \pi^+\pi^- e^+ e^-$ (cntd)

\(~1300\) observed events

\[ \text{BR}(K_L \rightarrow \pi^+\pi^- e^+ e^-) = (3.1 \pm 0.1_{\text{stat}} \pm 0.2_{\text{syst}}) \times 10^{-7} \]

CPV Asymmetry =

\[ (13.9 \pm 2.7_{\text{stat}} \pm 2.0_{\text{syst}})\% \]

Theory: $A \sim 14\%$

P. Heiliger and L. M. Sehgal

KTeV:

\[ A = (13.6 \pm 2.5_{\text{stat}} \pm 1.2_{\text{syst}})\% \]
RESUME: DIRECT CP VIOLATION (cntd)

The formula:

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

becomes in the experiment:

\[ R_{\text{meas}} = \frac{N_{b}(K_L \rightarrow \pi^0 \pi^0)}{N_{b}(K_S \rightarrow \pi^0 \pi^0)} / \frac{N_{b}(K_L \rightarrow \pi^+ \pi^-)}{N_{b}(K_S \rightarrow \pi^+ \pi^-)} \approx 1 - 6 \times \text{Re}(\varepsilon' / \varepsilon)_{\text{meas}} \]

where \( N_{b}(K_{L,S} \rightarrow \text{final state}) \) = counted \( N_{b} \) of events within the acceptance.

\[ \implies R = R_{\text{meas}} + A_{\text{corr}} \]

To measure precisely \( \text{Re}(\varepsilon' / \varepsilon) \) \( \implies \) Measure precisely \( A_{\text{corr}} \)
PRESENTATION of NA48

- The Beams

- The Detector

- The Analysis Method
Simultaneous $K_S$ and $K_L$ beams.
Slightly converging, to hit the same detector region.
PRESENTATION of NA48: The Detector

High resolution detectors to identify 3body background

- $\pi^+\pi^-$: Magnetic Spectrometer with $P_T$ kick=265MeV/c
- $\pi^0\pi^0$: Liquid Krypton Calorimeter leading to $\sigma(\pi^0) \sim 1$MeV
- Decay time known to $\sim 200$ps allows an accurate $K_S-K_L$ identification
PRESENTATION of NA48: The Method

\[ R = R_{\text{meas}} + A_{\text{corr}} = \frac{Nb(K_L \rightarrow \pi^0 \pi^0)}{Nb(K_S \rightarrow \pi^0 \pi^0)} \cdot \frac{Nb(K_L \rightarrow \pi^+ \pi^-)}{Nb(K_S \rightarrow \pi^+ \pi^-)} + A_{\text{corr}} \]

• Fully exploit the double ratio technique
  ⇒ Do such that all effects are common either to \( K_S \) and \( K_L \) or to \( \pi^0 \pi^0 \) and \( \pi^+ \pi^- \), to obtain cancellation in \( R \).
  ⇒⇒ Simultaneous data taking of four modes: Variation of fluxes, trigger inefficiencies, detector instabilities etc, vanish at first order

• Minimise the amount of residual corrections (\( A_{\text{corr}} \))
  ⇒ Weight \( K_L \) decay distribution to obtain \( \sim \) similar \( K_S \) and \( K_L \) acceptances ⇒ small correction on \( R \)
ANALYSIS for $\text{Re}(\varepsilon'/\varepsilon)$

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays.
- Disentangle $K_S$ from $K_L$ using Tagging.
- Subtract the remaining background from $K_L$ samples.
- Evaluate $A_{corr}$
- Study systematics and stability of the result.

!!! All given effects are on the double ratio $R$ !!!

$$\text{Re}(\varepsilon'/\varepsilon) = (1-R)/6$$
ANALYSIS for Re(\(\varepsilon'/\varepsilon\))

- Reconstruct and count \(\pi^+\pi^-\) and \(\pi^0\pi^0\) decays.
- Disentangle \(K_S\) from \(K_L\) using Tagging
- Subtract the remaining background from \(K_L\) samples
- Evaluate \(A_{corr}\)
- Study systematics and stability of the result
ANALYSIS for \( \text{Re}(\varepsilon'/\varepsilon) \): \( 2\pi \) counting

\[ K_S, K_L \rightarrow \pi^+ \pi^- \] sample

- Decay vertex and \( M(\pi^+ \pi^-) \) reconstructed by the spectrometer
- Decay time from hodoscope (\( \sigma \approx 140 \text{ps} \))

\[ K_S, K_L \rightarrow \pi^0 \pi^0 \] sample

- \( E_i, x_i \) and \( y_i \) of the four photons in LKr \( \Rightarrow \) two \( M(\gamma\gamma) \) and decay vertex
- Decay time from LKr calorimeter (\( \sigma \approx 200 \text{ps} \))

\[ \sigma = 2.5 \text{MeV} \]

\[ M(\pi^+ \pi^-) \]
ANALYSIS for $\text{Re}(\varepsilon'/\varepsilon)$: $2\pi$ counting (cndt)

- Common decay region for $\pi^0\pi^0$ and $\pi^+\pi^-$ (beam flux variations cancel) $70 \leq E_K \leq 170\text{GeV}$ and $\tau \leq 3.5 \tau_S$

- $\pi^0\pi^0$: Both energy and decay vertex given by LKr $\Rightarrow$ Check energy scale looking at the reconstructed AKS position ($\pm10^{-4}$ on energy $\Leftrightarrow \pm1\text{cm on } Z \Leftrightarrow \pm10^{-4}$ on the double ratio $R$)

- $\pi^+\pi^-$: Decay vertex given by the geometry of chambers 1 and 2. Also checked by the reconstructed AKS position ($\pm1\text{cm on } Z \Leftrightarrow \pm10^{-4}$ on $R$)

- Dead time conditions are recorded and applied to all events (similar intensity conditions to all four samples)
ANALYSIS for Re(ε′/ε): 2π counting (cndt)

Uncertainty for K→ π⁺π⁻:

⇒ ΔR = (2.0±2.8)×10⁻⁴

In K→ π⁰π⁰ all uncertainties contributing to the energy definition (energy scale, distance scale, non-linearities, sharing, tails etc) lead to:

⇒ ΔR = ±5.8×10⁻⁴
**ANALYSIS for Re(\(\varepsilon'/\varepsilon\))**

- Reconstruct and count \(\pi^+\pi^-\) and \(\pi^0\pi^0\) decays.
- Disentangle \(K_S\) from \(K_L\) using Tagging
- Subtract the remaining background from \(K_L\) samples
- Evaluate \(A_{corr}\)
- Study systematics and stability of the result
ANALYSIS for \( \text{Re}(\varepsilon'/\varepsilon) \): Disentangle \( K_S \) from \( K_L \)

\[ K_S \text{ and } K_L \text{ beams hit the same detector region} \Rightarrow \]

Identify \( K_S \) decays:

- Compare event time with the closest proton time in tagger.
- If compatible \( \Rightarrow \) event comes from \( K_S \) beam

Tagging applied to both, \( \pi^+\pi^- \) and \( \pi^0\pi^0 \).

In \( \pi^+\pi^- \Rightarrow \) beam also known from vertical vertex position
ANALYSIS: Disentangle $K_S$ from $K_L$ (cntd)

Tagging window $\pm 2\text{ns}$

Two kinds of misidentification:

- $K_S$ identified as $K_L$: called $\alpha_{SL}$, due to misreconstruction
- $K_L$ identified as $K_S$: called $\alpha_{LS}$, due to accidental coincidence of a $K_L$ decay with a proton in tagger
ANALYSIS: Disentangle $K_S$ from $K_L : \alpha_{SL}$

\[
\alpha_{SL}^{+-} = (1.64 \pm 0.03) \times 10^{-4}
\]

measured in $K_S \rightarrow \pi^+ \pi^-$ identified from vertex.

Dominated by proton time misreconstruction $\Rightarrow \pi^+ \pi^-$ and $\pi^0 \pi^0$ symmetric

\[
\Delta \alpha_{SL} = \alpha_{SL}^{00} - \alpha_{SL}^{+-}
\]

\[
\Delta \alpha_{SL} = (0 \pm 0.5) \times 10^{-4}
\]

comparing charged and neutral times in $2\pi^0$ and $3\pi^0$ events with conversions

$\Rightarrow \quad \Delta R = (0 \pm 3) \times 10^{-4}$
ANALYSIS: Disentangle $K_S$ from $K_L$ : $\alpha_{LS}$

$\alpha_{LS}^{+-} = (10.649 \pm 0.008)\%$

measured in $K_L \to \pi^+ \pi^-$ identified from vertex.

Small difference between $\alpha_{LS}^{+-}$ and $\alpha_{LS}^{00}$ because of different sensitivities of $\pi^+ \pi^-$ and $\pi^0 \pi^0$ to the intensity.

$\Delta \alpha_{LS} = (4.3 \pm 1.8) \times 10^{-4}$

$\Rightarrow \Delta R = (8.3 \pm 3.4) \times 10^{-4}$
ANALYSIS for Re(\(\varepsilon'/\varepsilon\))

- Reconstruct and count \(\pi^+\pi^-\) and \(\pi^0\pi^0\) decays.
- Disentangle \(K_S\) from \(K_L\) using Tagging
- Subtract the remaining background from \(K_L\) samples
- Evaluate \(A_{corr}\)
- Study systematics and stability of the result
ANALYSIS: Background subtraction

$K_L$ decays dominated by the CP-conserving 3-body decays

- $K_L \rightarrow \pi e \nu$ (39%)
- $K_L \rightarrow \pi \mu \nu$ (27%)
- $K_L \rightarrow 3\pi^0$ (21%)
- $K_L \rightarrow \pi^+ \pi^- \pi^0$ (13%)

Can mimic $\pi^+ \pi^-$ and $2\pi^0$

Hunted $K_L$ CP-violating modes: $2\pi^0 (0.1\%)$ and $\pi^+ \pi^- (0.2\%)$

Also check for scattered events with modified acceptance
ANALYSIS: Background in $\pi^+\pi^-$

CP-conserving decays, $K_L \to \pi\mu\nu$ and $\pi e\nu$, are strongly suppressed by muon Vetoes and E/P respectively.

The remaining misidentified events are studied in the $P_T'^2$ vs $M_{\pi^+\pi^-}$ and subtracted statistically under the signal.

$$\Delta R = (16.9 \pm 3.0) \times 10^{-4}$$
ANALYSIS: Background in $\pi^0\pi^0$

CP-conserving $K_L \rightarrow 3\pi^0$ with lost or fused $\gamma(s)$. Compatibility of the two $\gamma\gamma$ pair masses with $m(\pi^0)$ described by a $\chi^2$ function. Events with extra clusters within 3ns are rejected. Remaining background studied in control region and subtracted under the signal.

$\Delta R = (-5.9 \pm 2.0) \times 10^{-4}$
ANALYSIS: Scattering effects

\( K_S \) target

\( K_S \) beam

AKS

Final Collimator

\( K_L \) target

\( K_L \) beam

Collimators

Scattered kaons and neutrons in collimator with possible regeneration

Scattered kaons in AKS and collimator

Detector

Results on CP Violation from NA48 experiment
ANALYSIS: Scattering effects (cntd)

In $K_S$, scattered events are symmetrically rejected in $\pi^+\pi^-$ and $\pi^0\pi^0$.

In $K_L$ case, $P_T^{2'}$ cut (in $\pi^+\pi^-$) is stronger than CoG cut (in $\pi^0\pi^0$).

This resulting asymmetry in the halos in $K_L \rightarrow \pi^+\pi^-$ and $K_L \rightarrow 2\pi^0$ leads to a correction on $R$:

$$\Delta R = (-9.6 \pm 2.0) \times 10^{-4}$$
ANALYSIS for Re($\varepsilon'/\varepsilon$)

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays.
- Disentangle $K_S$ from $K_L$ using Tagging
- Subtract the remaining background from $K_L$ samples
- Evaluate $A_{corr}$
- Study systematics and stability of the result
Because $\tau_L \neq \tau_S$, $K_L$ and $K_S$ decays illuminate differently the detector.

This would lead to an acceptance correction on $R$ up to $\pm 10\%$ depending on the kaon energy.

Weighting $K_L$ events by the $K_S / K_L$ $2\pi$-decay ratio $\Rightarrow$ $K_S$ and $K_L$ decay distributions become identical and illuminations similar.
Small remaining acceptance correction

Slightly converging beams ⇒

For $\pi^+ \pi^-$ events small acceptance difference in first chamber close to the beam tube.

$$\Delta R = (26.7 \pm 5.7) \times 10^{-4}$$
### ANALYSIS: Summary of $A_{corr}$

<table>
<thead>
<tr>
<th>Source of Correction</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-$ trigger inefficiency</td>
<td>$-3.6 \pm 5.2$</td>
</tr>
<tr>
<td>AKS inefficiency</td>
<td>$+1.1 \pm 0.4$</td>
</tr>
<tr>
<td>Reconstruction of $\pi^0\pi^0$</td>
<td>$-5.9 \pm 2.0$</td>
</tr>
<tr>
<td>Reconstruction of $\pi^+\pi^-$</td>
<td>$+2.0 \pm 2.8$</td>
</tr>
<tr>
<td>Background to $\pi^0\pi^0$</td>
<td>$+16.9 \pm 3.0$</td>
</tr>
<tr>
<td>Background to $\pi^+\pi^-$</td>
<td>$-9.6 \pm 2.0$</td>
</tr>
<tr>
<td>Scattering</td>
<td>$+8.3 \pm 3.4$</td>
</tr>
<tr>
<td>Tagging: $\Delta \alpha_{LS}$</td>
<td>$-5.9 \pm 2.0$</td>
</tr>
<tr>
<td>Tagging: $\Delta \alpha_{SL}$</td>
<td>$+16.9 \pm 3.0$</td>
</tr>
<tr>
<td>Acceptance statistical</td>
<td>$+26.7 \pm 4.1$</td>
</tr>
<tr>
<td>Acceptance systematic</td>
<td>$-9.6 \pm 2.0$</td>
</tr>
<tr>
<td>Accidental activity</td>
<td>$+8.3 \pm 3.4$</td>
</tr>
<tr>
<td>Long term variations of $K_S/K_L$</td>
<td>$-5.9 \pm 2.0$</td>
</tr>
<tr>
<td>Total correction on $R$</td>
<td>$+35.9 \pm 12.6$</td>
</tr>
</tbody>
</table>

Total correction on $\text{Re}(\varepsilon'/\varepsilon) = -A_{corr}/6 = (-6.0 \pm 2.1) \times 10^{-4}$
ANALYSIS for $\text{Re}(\varepsilon'/\varepsilon)$

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays.
- Disentangle $K_S$ from $K_L$ using Tagging
- Subtract the remaining background from $K_L$ samples
- Evaluate $A_{corr}$
- Study systematics and stability of the result
ANALYSIS: Stability of the result

\[ \chi^2/\text{ndf} = 13.2/19 \]

\( R \) computed in 5GeV bins

- Total systematic error
- Beam Halo
- Charg. Backg.
- Neut. Backg.
- Energy scale
- Tagging
- Accidentals
- Acceptance

- Tagging window ± 2.5 ns
- Tagging window ± 1.5 ns
- Accept QX dead time
- Accept MBX dead time
- Accept 1 view DCH-ovfl
- Reject DCH-ovfl ± 281 ns
- Reject DCH-ovfl ± 344 ns
- Reject extra tracks
- No Ks/Kl intensity weighting
- γ radius > 18 cm
- Track radius > 18 cm
- Mom. asym. < 0.2
- No mom. asym. cut
- Ingoing tracks
- Outgoing tracks

- Estimated systematic for correction under test

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THE RESULT

$$R = 0.99098 \pm 0.00101_{\text{stat}} \pm 0.00126_{\text{syst}}$$

$$\text{Re}(\varepsilon'/\varepsilon) = (1 - R)/6$$

$$\text{Re}(\varepsilon'/\varepsilon) = (15.0 \pm 1.7_{\text{stat}} \pm 2.1_{\text{syst}}) \times 10^{-4}$$

extracted from the analysis of the 98+99 statistics of:

$$K_L \rightarrow \pi^0\pi^0 : 3290000$$
$$K_L \rightarrow \pi^+\pi^- : 5209000$$
$$K_S \rightarrow \pi^0\pi^0 : 14453000$$
$$K_S \rightarrow \pi^+\pi^- : 22221000$$
CONCLUSIONS

Combined NA48 result:

\[ \text{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4} \]

World average of NA31, E731, KTeV and NA48:

\[ \text{Re}(\varepsilon'/\varepsilon) = (17.2 \pm 1.8) \times 10^{-4} \]

Both Indirect and Direct CP Violation components discovered, measured and confirmed in the kaon system

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Spares
LKr Performances and energy scale

$(E+45\text{MeV})/\rho$

Electron Energy (GeV)

- $0.1\%$

- $K_s \rightarrow \pi^0\pi^0$

- $\Delta E/E = 5 \times 10^{-4}$

Resolution

- $\sigma(E/P)$

- $\sigma(E/E)$

Energy (GeV)

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Scattering in $K_L$ collimators

$K_L \rightarrow \pi^+\pi^-$

$P_T^2 > 0.0002\,(\text{GeV}/c)^2$
$K_L \rightarrow \pi^0 \gamma\gamma$

a: $30\text{MeV} \leq m_{\gamma\gamma} \leq 110\text{MeV}$
b: $160\text{MeV} \leq m_{\gamma\gamma} \leq 240\text{MeV}$
c: $240\text{MeV} \leq m_{\gamma\gamma} \leq 260\text{MeV}$
$K_S \rightarrow \pi^+\pi^-e^+e^-$

- **Dominant inner bremsstr. contribution**
- 921 events observed
- $A_S = (-0.2 \pm 3.4 \pm 1.4)\%$
- $\Rightarrow$ No CP-Asymmetry

$\text{BR} = (4.3 \pm 0.2_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-5} \Rightarrow \text{BR}(K_L \rightarrow \pi^+\pi^-e^+e^-)_{IB}$

First Observation!!!!