Review of NA48 CP violation measurements with Neutral and Charged Kaons

\[ K^0 \rightarrow \pi^+\pi^- \]
\[ K^+ \rightarrow \mu^+\nu \]
OUTLINE

Kaons and CP Violation

The NA48 experiment at CERN:
  experimental program

**NA48**: CP Violation in $K^0 \rightarrow 2\pi$ decays

**NA48/1**: CP Violation in $K_S \rightarrow 3\pi$ decays

**NA48/2**: CP Violation in $K^\pm \rightarrow 3\pi$ decays

**NA48/2**: CP Violation in $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ **NEW RESULTS**

Conclusions
Kaons and CP Violation

Motivation for Kaon experiments:
- a powerful probe of the flavour structure of the Standard Model and an effective tool to investigate the nature of the physics beyond it
- CP violation represents one of the sectors where a large sensitivity to possible New Physics (NP) effects can be expected.

Kaon meson system is a privileged observatory for flavour physics:
- Simple (minimal) flavour laboratory
- Nicely accessible experimentally
- CP violation of same size as in B

All 3 types of CP Violation can be observed in $K^0$ decays
- in $K^0$–$\bar{K}^0$ mixing ($\Delta S=2$, Indirect CPV: $\text{Re}(\epsilon)$),
- in the decay amplitudes ($\Delta S=1$, Direct CPV: $\text{Re}(\epsilon')$)
- in the Interference between decays with and without mixing ($\text{Im}(\epsilon)$ and $\text{Im}(\epsilon')$)

Only Direct CP Violation occurs in $K^\pm$ decays (no mixing)

Complementary observables to measure CP Violation in Kaons
- $\epsilon'/\epsilon$, $A_g$, asymmetries and other parameters of rare decays, …
The SPS at CERN provides protons at 400 GeV/c using a multi-turn, fast and slow, extraction system. The SPS is used as well as injector for the LHC accelerator. NA48 is a fixed target experiment at the CERN SPS aiming at studying CP violation and rare decays with Kaons.
### Data taking periods:

**NA48 (1997-2001)**
- Direct CP violation in neutral kaon decays:
  \[ \text{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4} \]

**NA48/1 (2000-2002)**
- Rare \( K_S \) decays
  - \( \text{BR} (K_S \rightarrow \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9} \)
  - \( \text{BR} (K_S \rightarrow \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9} \)

**NA48/2 (2003-2004)**
- Search for direct CP violation in \( K^\pm \rightarrow 3\pi \) decays
- Rare \( K^\pm \) decays

**Next: NA62** ⇒ G. Collazuol, this conference

Results shown at this conference: E. Marinova, G. Lamanna
NA48: beam and detector

- split same proton beam ($\sim 10^{12}$ ppp)
- convergent $K_L-K_S$ beams
- $K_S$ from protons on near target
- $K_S$ identification via proton tagging

NA48/1 (2000-02): high intensity $K_S$ beam
- new $K_S$ target region
  - more details in G. Lamanna talk

- non separated, high-intensity, narrow band $K^\pm$ beams
- upgraded detector: beam spectrometer, beam monitor
  - trigger hodoscope, hadron calorimeter, photon and muon veto counters, ...

Magnetic Spectrometer
$\Delta p/p = 1.02\% \oplus 0.044\% \times p$ [GeV/c]

LKr Calorimeter
$\Delta E/E = 3.2\%/\sqrt{E} \oplus 9%/E \oplus 0.42\%$ [GeV]

⇒ NA48:
$\sigma_M(\pi^0\pi^0) \approx \sigma_M(\pi^+\pi^-) \approx 2.5$ MeV

⇒ NA48/2:
$\sigma_M(\pi^\pm\pi^0\pi^0) = 0.9$ MeV
Direct CP Violation in neutral kaons: $\text{Re}(\varepsilon'/\varepsilon) \neq 0$

$\Rightarrow$ measure the Double Ratio $R$ of the 4 observable decay rates $K^0 \rightarrow 2\pi$ (counting experiments)

$$R = \frac{\left| \eta_{00} \right|^2}{\left| \eta_{+-} \right|^2} = \frac{\Gamma(K_L \rightarrow \pi^0\pi^0) \Gamma(K_S \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow \pi^0\pi^0) \Gamma(K_L \rightarrow \pi^+\pi^-)} = 1 - 6\text{Re}(\varepsilon'/\varepsilon) \approx 1 - 6\varepsilon'/\varepsilon$$

The last generation experiments for the $\text{Re}(\varepsilon'/\varepsilon)$ measurement are designed to exploit cancellations of systematic effects at first order:

- High intensity simultaneous $K_L$ and $K_S$ beams
- Simultaneous collection of the 4 decay modes
  - *cancellation of detector inefficiencies*
- Precise magnetic spectrometer and EM calorimeter
  - *reduction of backgrounds due to other K decays*
  - *good control of the decay volume*
Experimental results on $\varepsilon'/\varepsilon$

NA48 Final: $\text{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}$

PDG World Average: $(1.65 \pm 0.26) \times 10^{-3}$

PDG2008 and 2009 partial update for the 2010 edition

(KTeV final result not included)

Measurement compatible with SM

Large hadronic uncertainty in the calculation

 Improvement expected with lattice QCD

$\varepsilon'/\varepsilon$ may become a quantitative test of SM

Physics beyond SM may contribute

Waiting also for KLOE results: different method
The CP violation parameter $|\eta_{+-}|$

The amplitude ratio $\eta_{+-}$ is a fundamental observable of CP violation:

$$\eta_{+-} = \varepsilon + \varepsilon' = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} ightleftharpoons \text{CPV decay}$$

The NA48 measurement method:

- **Measure directly the ratio:**
  $$\text{BR}(K_L \rightarrow \pi^+\pi^-)/\text{BR}(K_L \rightarrow \pi e \nu) \Rightarrow \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_L \rightarrow \pi^+e^+\nu)}$$

- **Compute**
  $$\Rightarrow \text{BR}(K_L \rightarrow \pi^+\pi^-) = \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_L \rightarrow \pi^+e^+\nu)} \cdot \text{BR}(K_L \rightarrow \pi^+ e^+ \nu)$$

- **Extract**
  $$\Rightarrow |\eta_{\pm}| = \sqrt{\frac{\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow \pi^+\pi^-)}} = \sqrt{\frac{\text{BR}(K_L \rightarrow \pi^+\pi^-)}{\text{BR}(K_S \rightarrow \pi^+\pi^-)}} \frac{\tau_{KS}}{\tau_{KL}}$$

Use as external inputs the best single measurements of:

- $\text{BR}(K_L \rightarrow \pi e \nu)$ (NA48’04 + KTeV’04, KLOE’06)
- $\text{BR}(K_S \rightarrow \pi^+\pi^-)$ (KLOE’06)
- $K_S$ (NA48’02) and $K_L$ (KLOE’06) lifetime measurements

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P. Cenci  
EPS-HEP 2009
Dedicated $K_L$ run in 1999 (2-days):
~80 million 2-track events recorded

Final data samples:
- 47,142 $K_L \rightarrow \pi^+\pi^-$ (CP violating);
- 4,999,126. $K_L \rightarrow \pi$ e $\nu$
- small residual background in both modes

**NA48 results** (PL B645, 2007):

- ratio $R$ directly measured:
  $$\frac{\text{BR}(K_L \rightarrow \pi^+\pi^-)}{\text{BR}(K_L \rightarrow \pi e\nu)} = (4.835 \pm 0.022_{\text{stat}} \pm 0.016_{\text{syst}}) \times 10^{-3}$$

- branching fraction: $\text{BR}(K_L \rightarrow \pi^+\pi^-) = (1.941 \pm 0.019) \times 10^{-3}$
  - Inner Bremsstrahlung $\pi^+\pi^-\gamma$ component included
  - Direct Emission (CP conserving) component subtracted

- the CP violation parameter:
  $$|\eta_{+-}| = \sqrt{\frac{\text{BR}(K_L \rightarrow \pi^+\pi^-)}{\text{BR}(K_S \rightarrow \pi^+\pi^-)}} \cdot \frac{\tau_{K_S}}{\tau_{K_L}} = (2.223 \pm 0.012) \times 10^{-3}$$

- agreement among NA48, KTeV and KLOE results
- revision of previous PDG result $\Rightarrow |\eta_{+-}| = 2.233 \pm 0.012$ (PDG 2008)

**Corrections and systematic uncertainties on $R$**

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<th>Uncertainty source</th>
<th>Correction</th>
<th>Uncertainty</th>
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<tr>
<td>Particle ID (E/p)</td>
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<td>$K_{2\pi}$ background</td>
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<td>Muon ID</td>
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<td>Radiative corrections</td>
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<tr>
<td>MC statistics</td>
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<td>0.10%</td>
</tr>
<tr>
<td>Total</td>
<td>+0.04%</td>
<td>0.33%</td>
</tr>
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Uncertainty source corrections and systematic uncertainties on $R$

*P. Cenci  EPS-HEP 2009*
CP Violation in $K_S \rightarrow \pi^0 \pi^0 \pi^0$

$K_S \rightarrow 3\pi^0$ is CP violating: $\text{CP}(K_S) \approx +1$, $\text{CP}(3\pi^0) = -1$

- In the SM: $\text{BR}(K_S \rightarrow 3\pi^0) = 1.9 \times 10^{-9}$

- Can be parametrized with the amplitude ratio $\eta_{000}$:

$$|\eta_{000}| = \frac{A(K_S \rightarrow 3\pi^0)}{A(K_L \rightarrow 3\pi^0)} = \sqrt{\frac{\tau_L}{\tau_S} \frac{\text{BR}(K_S \rightarrow 3\pi^0)}{\text{BR}(K_L \rightarrow 3\pi^0)}} \Rightarrow |\eta_{000}| = \varepsilon + \varepsilon'_{000}$$

  - If CPT is conserved $\Rightarrow \text{Re}(\eta_{000})$: CPV in mixing, $\text{Im}(\eta_{000})$: direct CPV

- Best experimental limit (direct search, KLOE 2005):
  - $\text{BR}(K_S \rightarrow 3\pi^0) < 1.2 \times 10^{-7}$
  - $|\eta_{000}| < 1.8 \cdot 10^{-2}$ at 90% CL

- NA48/1: no direct measurement
  - sensitivity to $|\eta_{000}|$ from $K_S / K_L \rightarrow 3\pi^0$ interference at small decay times near the target
  - aim: $O(1\%)$ error on $\text{Re}(\eta_{000})$ and $\text{Im}(\eta_{000})$
  - results based on $\sim 4.9 \times 10^6$ reconstructed $K_S / K_L \rightarrow 3\pi^0$ (2000 run)
NA48/1: $K_S \to \pi^0\pi^0\pi^0$ and $\eta_{000}$

- Study the time evolution of $K_{L,S} \to 3\pi^0$ close to the production target
  - measure the intensity of ($K \to 3\pi^0$) as a function of proper time
  - sensitivity to $\eta_{000}$ from $K_S$-$K_L$ interference superimposed on a huge flat $K_L \to 3\pi^0$ component

Method: measurement of $K_S$-$K_L$ interference close to the production target

- use $3\pi^0$ events from near-target ("$K_S$") run $\Rightarrow K_S/K_L \to 3\pi^0$
- normalize to $K_L \to 3\pi^0$ from far-target ("$K_L$") run
- use MC to correct for residual acceptance difference and Dalitz decays
- fit double ratio in $E_K$ bins (free parameters: $\text{Re}(\eta_{000})$, $\text{Im}(\eta_{000})$):

$$\frac{3\pi^0 \text{ (Data, } K_S \text{ run)}}{K_L \to 3\pi^0 \text{ (Data, } K_L \text{ run)}} / \frac{K_L \to 3\pi^0 \text{ (MC, } K_S \text{ run)}}{K_L \to 3\pi^0 \text{ (MC, } K_L \text{ run)}}$$

NA48/1 results:

- $\text{Re}(\eta_{000}) = -0.002 \pm 0.011_{\text{stat.}} \pm 0.015_{\text{syst}}$
- $\text{Im}(\eta_{000}) = -0.003 \pm 0.013_{\text{stat.}} \pm 0.017_{\text{syst}}$
- $|\eta_{000}| < 0.045$ at 90% CL
- $\text{Br}(K_S \to 3\pi^0) < 7.4 \times 10^{-7}$ at 90% CL

(PL B610, 2005)
CP Violation in charged K decays $\Rightarrow$ no mixing, any CPV is direct

**Search for Direct CP Violation in $K^{\pm}_{3\pi}$**
- Two decay modes: $\text{BR}(K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0})=5.57\%$; $\text{BR}(K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0})=1.73\%$.
- Rate asymmetry $\Gamma(K^{+})=\Gamma(K^{-})$ experimentally not simple:
  - CPV asymmetry of decay widths strongly suppressed
- Better: measure difference in Dalitz plot slopes

**Method:**
- The $K^{\pm}_{3\pi}$ decay matrix:

$$|M(u,v)|^2 \sim 1 + gu + h u^2 + k v^2$$

$$u = (s_3-s_0)/m_{\pi}^2 \quad \text{and} \quad v = (s_2-s_1)/m_{\pi}^2$$

$$s_i = (P_{K_i}P_{\pi_i})^2, \quad i=1,2,3 \quad (3=\text{odd } \pi); \quad s_0 = (s_1+s_2+s_3)/3;$$

- Direct CP violating asymmetry:

$$A_g = \frac{g_+ - g_-}{g_+ + g_-} = \frac{\Delta g}{g}$$

$$g_+ = g(K^{+}\rightarrow\pi^{+}\pi\pi)$$

$$g_- = g(K^{-}\rightarrow\pi^{-}\pi\pi)$$

- SM $\sim O(10^{-5}-10^{-6})$ (Gamiz, Prades, Scimeni, JHEP 10 (2003))
- New Physics (SUSY) could boost it up to $O(10^{-4})$ (G. D’Ambrosio et al., PLB480 (2000))
- Experimental limit before NA48/2: $\geq O(10^{-3})$
- NA48/2 aim: precision $O(10^{-4})$ $\Rightarrow$ large statistics, simple selection, low background
\( K^{\pm} \rightarrow \pi^{\pm} \pi \pi \) asymmetry: method

The method: exploit maximal cancellations

- **Simmetrization of running conditions:**
  - Simultaneous \( K^+ \) and \( K^- \) beams, superimposed in space, narrow momentum band with similar spectra
  - Equalize averaged \( K^+ \) and \( K^- \) acceptances and achieve cancellation of major systematic effects by combining data collected with opposite polarities in the relevant magnets (beam line and spectrometer);
  - Monitor residual fake instrumental asymmetries with control samples.

- **Measurement:**
  - measure the asymmetry exclusively from the slopes of the ratios of normalized \( u \) distributions for \( K^+ \) and \( K^- \):
    \[
    R(u) = \frac{N^+(u)}{N^-(u)} \propto 1 + \frac{\Delta g \ u}{1 + gu + hu^2}
    \]
  - fit a quadruple ratios of similar data samples taken at different beam line (up-down) and spectrometer (left-right) magnets polarities:
    \[
    R = R_{UR} \times R_{UL} \times R_{DR} \times R_{DL} \sim 1 + 4 \times \Delta g \times u
    \]
Final result with the full NA48/2 data statistics (2003-04 run)

- A factor x20 better precision than the previous measurements
- Result compatible with SM, no evidence for CPV due to NP
- Statistical uncertainties dominate
- Limits improved to one order of magnitude to $O(10^{-4})$
  - NA48/2 design goal reached

\[ \Delta g = (0.6 \pm 0.7_{\text{stat}} \pm 0.4_{\text{trig}} \pm 0.5_{\text{syst}}) \times 10^{-4} = (0.6 \pm 0.9) \times 10^{-4} \]

\[ A_g = (-1.5 \pm 1.5_{\text{stat}} \pm 0.9_{\text{trig}} \pm 1.1_{\text{syst}}) \times 10^{-4} = (-1.5 \pm 2.1) \times 10^{-4} \]
Final result with the full NA48/2 data statistics (2003-04 run)
- Statistical precision in $A_g^0$ similar to $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ mode
- Results compatible with SM: no evidence for CPV due to NP
- Limits improved to one order of magnitude
- NA48/2 design goal reached

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ asymmetry: result

\[
\Delta g^0 = (2.2 \pm 2.1_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} = (2.2 \pm 2.2) \times 10^{-4}
\]

\[
A_g^0 = (1.8 \pm 1.7_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-4} = (1.8 \pm 1.8) \times 10^{-4}
\]
CP violation in \(K^\pm \rightarrow \pi^\pm \pi^0 \gamma\)

- \(K^\pm \rightarrow \pi^\pm \pi^0 \gamma\): sources of \(\gamma\) radiation
  - Inner Bremsstrahlung and Direct Emission
  - Interference component: first evidence in NA48/2

- Kinematic Variable:

\[
W^2 = \frac{(P^*_\pi \cdot P^*_\gamma)(P^*_K \cdot P^*_\gamma)}{(m_K m_\pi)^2}
\]

- A clean observable of direct CP violation is provided by the asymmetry between \(K^+ \rightarrow \pi^+ \pi^0 \gamma\) and \(K^- \rightarrow \pi^- \pi^0 \gamma\) decay widths (rates) and Dalits plots:
  - if \(\phi \neq 0 \Rightarrow \Gamma(K^+) \neq \Gamma(K^-) \Rightarrow CP\) Violation

- SM prediction on asymmetry: \(2 \times 10^{-6} - 10^{-5}\) for \(50 < E^*_\gamma < 170\) MeV.

- Possible SUSY contributions can push the asymmetry up to \(10^{-4}\) in some \(W\) regions.
Summary of NA48/2 results on CP Violation in $K^\pm \rightarrow \pi^\pm \pi^0\gamma$

- **Measurement of rate asymmetry (1.08 million events):**

  $$A_N = \frac{\Gamma(K^+)-\Gamma(K^-)}{\Gamma(K^+)+\Gamma(K^-)} = (0.03 \pm 1_{\text{stat}} \pm 0.6_{\text{sys}}) \cdot 10^{-3}$$

  $$A_N < 1.5 \cdot 10^{-3} \quad 90\% \text{ C.L.}$$

  PDG (2008): $(0.9 \pm 3.3) \cdot 10^{-2}$

- **First limit on $\sin(\phi)$:**

  $$\sin(\phi) = (-0.011 \pm 0.43)$$
  $$|\sin(\phi)| < 0.56 \quad 90\% \text{ C.L.}$$

- **Asymmetry in the $W$ spectrum:**

  $$A_W = (-0.6 \pm 1_{\text{stat}}) \cdot 10^{-3}$$

  compatible with $A_N$

  no evidence for CP asymmetry
Conclusions

Over 10 years, the NA48 experiment at CERN has carried out an extensive physics programme devoted to high precision study of CP violation (and rare decays) with both neutral and charged K

- Direct and Indirect CP Violation in neutral kaon decays (Direct CPV established)
- Precise |\eta_{+-}| measurement (PDG revised)
- Search for direct CP violating charge asymmetry in $K^{\pm} \rightarrow 3\pi$ decays (order of magnitude improvement in precision)
- Search for CPV effects in radiative $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decays
- All results all consistent with SM: no evidence for CPV effects due to NP
- However, matter-antimatter asymmetry of the universe requires additional sources of CP Violation generated by extensions to the Standard Model, to be measured as small deviations from it
- Quantitative tests of CKM mechanism and search for new physics beyond SM are needed and become possible with next generation K experiments:
  - Ultra-rare Kaon decay measurements ($K \rightarrow \pi\nu\nu$) ⇒ G. Collazuol, this conference
  - J. Ocaritz, this conference (CKM): support kaon physics!