Recent Results From NA48/2 Experiment @ CERN-SPS

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on Behalf of the NA48/2 Collaboration
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NA48/2 Experimental Setup

CP Violating Charge Asymmetry in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ Decay

"Cusp" Effect in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ Decay

Rare $K^\pm$ Decays
NA48/2 Experimental Setup
Some History

**NA48 (1997-2001):** Direct CP-Violation in neutral K

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

**NA48/1 (2002):** Rare K<sub>S</sub> decays

\[ \text{BR}(K_S \rightarrow \pi^0 e^+e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8) \cdot 10^{-9} \]
\[ \text{BR}(K_S \rightarrow \pi^0 \mu^+\mu^-) = (2.8^{+1.5}_{-1.2} \pm 0.2) \cdot 10^{-9} \]

**NA48/2 (2003-2004):** Direct CP-Violation in charged K

**P326 (2009-2010):** Very Rare K Decays

\[ K^+ \rightarrow \pi^+ \nu \nu \]

…and many other results on kaon and hyperon decays

**1997** \( \epsilon' / \epsilon \) run \( K_L + K_S \)

**1998** \( \epsilon' / \epsilon \) run \( K_L + K_S \)

**1999** \( \epsilon' / \epsilon \) run \( K_L + K_S \)

**2000** \( K_L \) only \( K_S \) High Intensity

**2001** \( \epsilon' / \epsilon \) run \( K_L + K_S \)

**2002** \( K_S \) High Intensity

**2003** \( K^\pm \) High Intensity

**2004** \( K^\pm \) High Intensity
Simultaneous Beam

2-3M K/spill ($\pi/K \sim 10$) 
$\pi$ decay products stay in pipe
Flux ratio: $K^+/K^- \sim 1.8$

Simultaneous $K^+$ and $K^-$ beams: 
large charge symmetrization of experimental conditions

Beams coincide within 
$\sim 1$mm all along 114m decay volume

$\sim 7 \times 10^{11}$ 
p/spill
400 GeV/c

Front-end achromat: 
Momentum selection

$P_K = (60 \pm 3)$ GeV/c

Quadrupole, Quadruplet: 
Focusing $\mu$ sweeping

Second achromat: 
Cleaning Beam spectrometer

$\delta P_K / P_K = 0.7$
$\delta_{x,y} \sim 100 \mu$m
Magnetic spectrometer (4 DCHs):
  > 4 view / DCH -> high efficiency
  > $\sigma_P/P = 1.0\% + 0.044\% \cdot P$ [GeV/c]

Hodoscope:
  > Fast trigger
  > $\sigma_t = 150$ps

Electromagnetic calorimeter (LKr):
  > High granularity, quasi-homogeneous
  > $\sigma_E/E = 3.2\%/\sqrt{E} + 9%/E + 0.42%$ [GeV]

Hadron calorimeter, muon and photon vetoes

Trigger:
  > Fast hardware trigger (L1): hodoscope & DCHs multiplicity
  > Level 2 trigger (L2): on-line processing of DCHs & LKr information
Data Taking

Run periods:
- 2003: ~ 50 days
- 2004: ~ 60 days

Total statistics in 2 years:
- \( K^\pm \rightarrow \pi^\pm \pi^+ \pi^- \): ~ \(4 \cdot 10^9\)
- \( K^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \): ~ \(1 \cdot 10^8\)

\( \rightarrow \) > 200 TB of data recorded

Rare \( K^\pm \) decays can be measured down to BR ~ \(10^{-9}\)
CP Violating Charge Asymmetry in $K^\pm \to \pi^\pm \pi^+ \pi^-$ Decay
Major milestones in CP-Violation history:


> 1988, 1999: Direct CP-Violation in $K^0$ (NA31, E731, NA48, KTeV)

> 2001: Indirect CP-Violation in $B^0$ (BaBar, Belle)

> 2004: Direct CP-Violation in $B^0$ (Belle, BaBar)

Look for CP-Violation in $K^\pm$
(no mixing $\rightarrow$ only Direct CPV is possible)
**Introduction (I)**

The best two $K^\pm$ decay modes:

- $\mathrm{BR}(K^\pm \to \pi^\pm \pi^+ \pi^-) = 5.57\%$ "Charged"
- $\mathrm{BR}(K^\pm \to \pi^\pm \pi^0 \pi^0) = 1.73\%$ "Neutral"

**Kinematics:**

$s_i = (P_K - P_{\pi_i})^2, \ i = 1, 2, 3 \ (3 = \pi_{\text{odd}})$
$s_0 = (s_1 + s_2 + s_3) / 3$
$u = (s_3 - s_0) / m_{\pi}^2$
$v = (s_2 - s_1) / m_{\pi}^2$

**Matrix element:**

$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$

"Charged" mode

$g = -0.2154 \pm 0.0035$

$|h|, |k| \sim 10^{-2}$

**Kaon rest frame:**

$u = 2m_K \cdot (m_K/3 - E_{\text{odd}}) / m_{\pi}^2$
$v = 2m_K \cdot (E_1 - E_2) / m_{\pi}^2$

**Direct CP violating quantity:**

slope asymmetry

$A_g = (g^+ - g^-) / (g^+ + g^-) \neq 0$
**Theoretical predictions:**

- **Standard Model:**
  \[ A_g = 10^{-6} \pm 5 \cdot 10^{-5} \]

- **Models Beyond the SM:**
  enhancement of the \( A_g \) value

**Experimental results:**

- **“Charged” mode:**
  \[ A_g = (22 \pm 15_{\text{stat}} \pm 37_{\text{syst}}) \cdot 10^{-4} \]
  (HyperCP - 54 \cdot 10^6 \text{ evt.})

- **“Neutral” mode:**
  \[ A_g = (2 \pm 19) \cdot 10^{-4} \]
  (TNF - 620 \cdot 10^3 \text{ evt.})
Introduction (III)

What’s new in NA48/2 measurement?

› Simultaneous $K^+$ and $K^-$ beams, superimposed in space, with momentum spectra $(60\pm3)$ GeV/c

› Equalize $K^+$ and $K^-$ acceptances by frequently alternating polarities of relevant magnets

› Detect asymmetry exclusively considering slopes of ratios of normalized $u$ distributions
In the 2003+2004 data sample $3.11 \cdot 10^9$ $K^\pm \rightarrow \pi^+\pi^+\pi^-$ have been selected:

- $K^+ : 2.00 \cdot 10^9$ events
- $K^- : 1.11 \cdot 10^9$ events
### Results In SuperSamples

<table>
<thead>
<tr>
<th>Run</th>
<th>SuperSample</th>
<th>$\Delta g \cdot 10^4$</th>
<th>$X^2$ of the R(u) fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>0</td>
<td>$-0.8\pm1.8$</td>
<td>30/26</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>$-0.5\pm1.8$</td>
<td>24/26</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>$-1.4\pm2.0$</td>
<td>28/26</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>$1.0\pm3.3$</td>
<td>19/26</td>
</tr>
<tr>
<td>2004</td>
<td>4</td>
<td>$-2.0\pm2.2$</td>
<td>18/26</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>$4.4\pm2.6$</td>
<td>20/26</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>$5.0\pm2.2$</td>
<td>26/26</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>$1.5\pm2.1$</td>
<td>10/26</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>$0.4\pm2.3$</td>
<td>23/26</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td><strong>0.6\pm0.7</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results

- A factor ~20 better precision than the previous measurements
- Uncertainties dominated by those of statistical nature
- Design goal reached. There is still some room to improve the systematic uncertainty
- Result compatible with the Standard Model predictions

Based on the full 2003+2004 data sample

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

\[ = (0.6 \pm 1.0) \cdot 10^{-4} \]

\[ A_g = (-1.3 \pm 1.5_{\text{stat}} \pm 0.9_{\text{trig}} \pm 1.4_{\text{syst}}) \cdot 10^{-4} \]

\[ = (-1.3 \pm 2.3) \cdot 10^{-4} \]

Final 2003 result published: PLB634 (2006) 474-482

Measurements of \( A_g \)
"Cusp" Effect in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ Decay
A "Cusp"

- From $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ decay we observed an anomaly in the $M_{00}^2$ invariant mass distribution in the region around $M_{00}^2 = (2m_{\pi^+})^2 = 0.07792 \text{ (GeV/c}^2\text{)}^2$

- This anomaly has been interpreted as a final state charge exchange scattering process of $K^\pm \rightarrow \pi^\pm\pi^+\pi^-(\pi^+\pi^- \rightarrow \pi^0\pi^0)$

- The parameter $a_0-a_2$ (difference between the $S$-wave $\pi\pi$ scattering lengths in the isospin $I=0$ and $I=2$ states) can be precisely measured using this sudden anomaly ("cusp")
Standard Dalitz plot parameterization shows deficit in data before "cusp":

**Event Selection**

![Graph showing Event Selection](image)

**Standard parametrization**

- Whole region: $X^2/\text{ndf}=9225/149$
- Above cusp: $X^2/\text{ndf}=133/110$

**Equation**

$\Delta = \frac{(\text{Data-Fit})}{\text{Data}}$

**Variables**

- $M_{00}^2$ [(GeV/c$^2$)$^2$]
- Events / 0.00015 [(GeV/c$^2$)$^2$]

![Graph showing Standard parametrization](image)
Re-scattering model: two amplitudes contribute to $K^\pm \to \pi^\pm \pi^0 \pi^0$

$M(K^\pm \to \pi^\pm \pi^0 \pi^0) = M_0 + M_1$

- $M_0$: Direct Emission
- $M_1$: Charge Exchange in final state of $K^\pm \to \pi^\pm \pi^+ \pi^- (\pi^+ \pi^- \to \pi^0 \pi^0)$

The singularity in the invariant mass spectrum at $\pi^+ \pi^-$ threshold is mainly caused by the destructive interference of $M_0$ and $M_1$

The effect is present below the threshold and not above it (re-scattering model at one-loop (N. Cabibbo: PRL 93 (2004) 121801))
More complete formulation of the model including all re-scattering processes at one-loop and two-loop level (N. Cabibbo and G. Isidori: JHEP 0503 (2005) 21) has been used to extract NA48/2 results (systematics: acceptance, trigger efficiency and fitting interval):

- \( g_0 = 0.645 \pm 0.004_{\text{stat}} \pm 0.009_{\text{syst}} \)
- \( h' = -0.047 \pm 0.012_{\text{stat}} \pm 0.011_{\text{syst}} \)
- \( (a_0-a_2) \cdot m_{\pi^+} = 0.268 \pm 0.010_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.013_{\text{ext}} \)
- \( a_2 \cdot m_{\pi^+} = -0.041 \pm 0.022_{\text{stat}} \pm 0.014_{\text{syst}} \)

Based on partial sample of 2003 data

2003 results published:

Measurements of \((a_0-a_2) \cdot m_{\pi^+}\):

- a) NA48 result
  - PLB 633 (2006)
- b) DIRAC result
  - PRL 619 (2005)
- c) G.Colangelo et al.
  - NPB 603 (2001)
- d) J.R.Pelaez et al.
  - PRD 71 (2005)
Rare $K^\pm$ Decays
**Rare $K^\pm$ Decays**

Statistics usually at least one order of magnitude above previous experiments. Several channels not yet observed.

\[ K^\pm \rightarrow \pi^+\pi^-e^\pm\nu \quad (4.09 \pm 0.09) \cdot 10^{-5} \]
\[ K^\pm \rightarrow \pi^0\pi^0e^\pm\nu \quad (2.2 \pm 0.4) \cdot 10^{-5} \]
\[ K^\pm \rightarrow \pi^+\pi^-\mu^\pm\nu \quad (1.4 \pm 0.9) \cdot 10^{-5} \]
\[ K^\pm \rightarrow \pi^\pm\pi^0\gamma \quad (2.75 \pm 0.15) \cdot 10^{-4} \quad \text{Silvia Goy Lopez} \]
\[ K^\pm \rightarrow \pi^\pm\gamma\gamma \quad (1.10 \pm 0.32) \cdot 10^{-6} \quad \text{Simone Bifani} \]
\[ K^\pm \rightarrow \pi^\pm e^+e^-\gamma \]
\[ K^\pm \rightarrow \pi^\pm\pi^0\gamma\gamma \]
\[ K^\pm \rightarrow \pi^\pm e^+e^- \quad (2.88 \pm 0.13) \cdot 10^{-7} \]
$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$

**Two amplitudes:**
- Inner Bremsstrahlung (IB)
- Direct Emission (DE)

Interference (INT) is possible between IB and electric part of DE

Frac(DE) = $(3.35 \pm 0.35_{\text{stat}} \pm 0.25_{\text{syst}})\%$
Frac(INT) = $(-2.67 \pm 0.81_{\text{stat}} \pm 0.73_{\text{syst}})\%$

Based on a partial sample of 2003 data
Summary

> The preliminary result on the Direct CP violating charge asymmetry in \( K^\pm \rightarrow \pi^\pm \pi^+ \pi^- \) based on the whole statistics is:

\[
A_g = (-1.3 \pm 1.5_{\text{stat}} \pm 0.9_{\text{trig}} \pm 1.4_{\text{syst}}) \cdot 10^{-4}
= (-1.3 \pm 2.3) \cdot 10^{-4}
\]

> A new “cusp” structure in \( K^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \) was observed (\( \pi\pi \) final state charge exchange process of \( K^\pm \rightarrow \pi^\pm \pi^+ \pi^- \)) which provides a new method for the extraction of the \( \pi\pi \) scattering lengths:

\[
(a_0-a_2) \cdot m_{\pi^+} = 0.268 \pm 0.010_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.013_{\text{theor}}
\]

> The first measurement of Direct Emission and Interference terms in \( K^\pm \rightarrow \pi^\pm \pi^0 \gamma \) based on \(~30\%\) of the total statistics has been performed:

\[
\text{Frac(DE)} = (3.35 \pm 0.35_{\text{stat}} \pm 0.25_{\text{syst}}) \%
\]
\[
\text{Frac(INT)} = (-2.67 \pm 0.81_{\text{stat}} \pm 0.73_{\text{syst}}) \%
\]