Measurement of FCNC decays
$K^\pm \rightarrow \pi^\pm l^+l^-$ by NA48/2 at CERN

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(University of Birmingham)
on behalf of the NA48/2 collaboration
(Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Florence, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Turin, Vienna)

Outline:
1) Beams, detector and data taking in 2003/04;
2) $K^\pm \rightarrow \pi^\pm e^+e^-$ analysis: NA48/2 final results;
3) $K^\pm \rightarrow \pi^\pm \mu^+\mu^-$ analysis: analysis status and prospects;
4) Summary.

Kaon 2009 conference
Tsukuba, Japan • June 9, 2008
NA48/NA62 experiments

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>$\varepsilon'/\varepsilon$ run $K_L + K_S$</td>
</tr>
<tr>
<td>1998</td>
<td>$K_L + K_S$</td>
</tr>
<tr>
<td>1999</td>
<td>$K_L + K_S$, $K_S$ HI</td>
</tr>
<tr>
<td>2000</td>
<td>$K_L$ only, $K_S$ HI</td>
</tr>
<tr>
<td>2001</td>
<td>$K_L + K_S$, $K_S$ HI</td>
</tr>
<tr>
<td>2002</td>
<td>$K_S$ / hyperons HI</td>
</tr>
<tr>
<td>2003</td>
<td>$K^+ / K^-$</td>
</tr>
<tr>
<td>2004</td>
<td>$K^+ / K^-$</td>
</tr>
<tr>
<td>2007</td>
<td>$K^e_2 / K^\mu_2$, tests</td>
</tr>
<tr>
<td>2008</td>
<td>$K^e_2 / K^\mu_2$, tests</td>
</tr>
<tr>
<td>2006–2010</td>
<td>Design &amp; construction</td>
</tr>
<tr>
<td>2011</td>
<td>Start of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ run</td>
</tr>
</tbody>
</table>

NA48/NA62: a series of experiments, present-day CERN kaon physics programme

The presented results are based on 2003/04 data.

NA48/NA62: a series of experiments, present-day CERN kaon physics programme

The presented results are based on 2003/04 data.
NA48/2: kaon beam line

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

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

Front-end achromat
- Momentum selection

Quadrupole quadruplet
- Focusing
- $\mu$ sweeping

Beams coincide within ~1mm all along 114m decay volume

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$P_K$ spectra, $60\pm3$ GeV/c
$\approx 7 \cdot 10^{11}$ ppp, 400 GeV

$\sim 7 \cdot 10^{11}$ ppp, 400 GeV
Main detector components:

- Magnetic spectrometer (4 DCHs):
  4 views/DCH: redundancy \(\Rightarrow\) efficiency; used in trigger logic; \(\Delta p/p = 1.0\% + 0.044\% p\) [GeV/c].

- Hodoscope
  fast trigger;
  precise track time measurement (150ps).

- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogenous;
  \(\sigma_E/E = 3.2\%/E^{1/2} + 9%/E + 0.42\%\) [GeV];
  \(\sigma_x = \sigma_y = 0.42/E^{1/2} + 0.6\text{mm (1.5mm@10GeV)}\).
  Used for \(\gamma\) detection and particle ID.

- Hadron calorimeter, muon veto counters, photon vetoes.

E. Goudzovski / Kaon09, 9 June 2009
NA48/2 data taking: completed

2003 run: ~ 50 days
2004 run: ~ 60 days

$K_{3\pi}$ statistics in 2 years:
$K^\pm \rightarrow \pi^-\pi^+\pi^\pm$: $\sim 4 \cdot 10^9$
$K^\pm \rightarrow \pi^0\pi^0\pi^\pm$: $\sim 1 \cdot 10^8$

Rare $K^\pm$ decays:
BRs down to $10^{-9}$
can be measured

$>$200 TB of data recorded
K_{\pi ll}: motivation & theory

\[ K^\pm \to \pi^\pm \gamma^* \to \pi^\pm l^+ l^- : \text{suppressed FCNC process proceeding through single virtual photon exchange.} \]

Information on weak interactions at low energy.

\[ d\Gamma_{\pi ee}/dz \sim P(z) \cdot |W(z)|^2 \]

\[ z=(M_{ee}/M_K)^2, \text{ P(z) is a phase space factor} \]

Considered models for the form factor:

1) polynomial:
   \[ W(z) = G_F M_K^2 \cdot f_0 \cdot (1+\delta z) \]

2) ChPT O(p^6):
   \[ W(z) = G_F M_K^2 \cdot (a_+ + b_+ z) + W_{\pi\pi}(z) \]
   G. D’Ambrosio et al., JHEP 9808 (1998) 4

3) ChPT, large-\(N_c\) QCD:
   \[ W(z) = W(w, \beta, z) \]
   S. Friot, D. Greynat, E. de Rafael, PLB 595 (2004) 301

4) “Mesonic” ChPT:
   \[ W(z) = W(M_a, M_\rho, z) \]

Goals:

1) \(d\Gamma/dz\) and model-independent BR in kinematic range \(z>0.08\);
2) parameters of the models + BRs in the full kinematic range;
3) upper limit for CPV charge asymmetry of decay rates.
Principal selection criteria

The $K^{\pm}\rightarrow\pi^{\pm}e^{+}e^{-}$ is measured normalizing to $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}_{D}\rightarrow\pi^{\pm}e^{+}e^{-}\gamma$. Thus particle ID efficiencies cancel in the first order.

**Common selection criteria:**
3-track vertex [consistent in space/time], one $\pi$ candidate, two opposite sign electron candidates.
Electron (pion) ID based on E deposition: $E/p>0.95$ ($E/p<0.85$).

**Signal selection:**
Kinematic suppression of $\pi^{\pm}\pi^{0}_{D}$ background: $M_{ee}>140\text{MeV}/c^{2}$.
Limitations on reconstructed $\pi^{\pm}e^{+}e^{-}$ invariant mass, total & transverse momentum

**Normalization selection:**
Selection of good $\gamma$ candidate.
Limitations on reconstructed $e^{+}e^{-}\gamma$ and $\pi^{\pm}e^{+}e^{-}\gamma$ masses, total & transverse momentum.
Signal & normalisation samples

Total kaon decays in fiducial volume (2003+2004): \( N_K = 1.7 \times 10^{11} \)

- \( K^\pm \to \pi^\pm e^+e^- \)
- \( K^\pm \to \pi^\pm \pi^0_D \)

### Background/Signal

- \( K^\pm \to \pi^\pm \pi^0_D, K^\pm \to \pi^0_D e^+\nu + \) particle misID, two \( e^+e^- \) pairs: \( \pi^0_{D(D)}, \gamma \) conversions.
- Subtracted with same-sign lepton candidates.

7253 candidates

Background/Signal = 1.0%

12.12 mln candidates

Background/Signal = 0.15%

(Subtracted with simulation)
The accessible $M_{ee}$ region

All analysis cuts except the $M_{ee}$ cut are applied

- The region $M_{ee} < 140\text{MeV}/c^2$ is dominated by background and not accessible;
- Subtraction of the $K^\pm \rightarrow \pi^\pm \pi^0_{DD}$ reveals the $\pi^0 \rightarrow e^+e^-$ signal ($\sim 500$ events).

E. Goudzovski / Kaon09, 9 June 2009
Kinematic variables: $(z, \cos\theta_{e\pi})$

$z = (M_{ee}/M_K)^2$

Decay via one photon exchange:

$$d\Gamma/d\theta \sim \sin^2\theta = (1 - \cos^2\theta),$$

$\theta = \text{angle between } (e^+,\pi) \text{ in } (e^+,e^-) \text{ frame.}$

No dynamical information in this projection.

$z$ distribution is sensitive to the form-factor and contains the dynamical information:

$$d\Gamma/dz \sim P(z) \times |W(z)|^2.$$
Fit results (1)

Model parameters with their statistical errors and correlation coefficients:

\[
\begin{align*}
(1) \quad & f_0 = 0.531 \pm 0.012 \\
& \delta = 2.32 \pm 0.15 \\
& \rho(\delta, f_0) = -0.962 \\

(2) \quad & a_+ = -0.578 \pm 0.012 \\
& b_+ = -0.779 \pm 0.053 \\
& \rho(a_+, b_+) = -0.913 \\

(3) \quad & w = 0.057 \pm 0.005 \\
& \beta = 3.45 \pm 0.24 \\
& \rho(w, \beta) = 0.999 \\

(4) \quad & M_a = (0.951 \pm 0.028) \text{ GeV} \\
& M_p = (0.705 \pm 0.010) \text{ GeV} \\
& \rho(M_a, M_p) = 0.998
\end{align*}
\]

Model-independent BR (integral of \(d\Gamma/dz\)):

\[
\text{BR}_{\text{mi}}(z>0.08) = (2.28 \pm 0.03) \times 10^{-7}
\]

The models cannot be distinguished with the available data set.
Squared form factors normalised by $|W(0)|^2 = 1$
Fit results (3)

68% CL contours

- \(|f_0|, \delta\)
- \((a_+, b_+)\)
- \((w, \beta)\)
- \((M_a, M_\rho)\)
### Fit results (4)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}_{\text{mI}} \times 10^7$</td>
<td>$2.28 \pm 0.03_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.06_{\text{ext}}$</td>
<td>= $2.28 \pm 0.08$</td>
</tr>
<tr>
<td>$f_0$</td>
<td>$0.531 \pm 0.012_{\text{stat}} \pm 0.008_{\text{syst}} \pm 0.007_{\text{ext}}$</td>
<td>= $0.531 \pm 0.016$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>$2.32 \pm 0.15_{\text{stat}} \pm 0.09_{\text{syst}}$</td>
<td>= $2.32 \pm 0.18$</td>
</tr>
<tr>
<td>$\text{BR}_{1} \times 10^7$</td>
<td>$3.05 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}} \pm 0.08_{\text{ext}}$</td>
<td>= $3.05 \pm 0.10$</td>
</tr>
<tr>
<td>$a_+ = -0.578 \pm 0.012_{\text{stat}} \pm 0.008_{\text{syst}} \pm 0.007_{\text{ext}}$</td>
<td>= $-0.578 \pm 0.016$</td>
<td></td>
</tr>
<tr>
<td>$b_+ = -0.779 \pm 0.053_{\text{stat}} \pm 0.036_{\text{syst}} \pm 0.017_{\text{ext}}$</td>
<td>= $-0.779 \pm 0.066$</td>
<td></td>
</tr>
<tr>
<td>$\text{BR}_{2} \times 10^7$</td>
<td>$3.14 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}} \pm 0.08_{\text{ext}}$</td>
<td>= $3.14 \pm 0.10$</td>
</tr>
<tr>
<td>$w$</td>
<td>$0.057 \pm 0.005_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.001_{\text{ext}}$</td>
<td>= $0.057 \pm 0.007$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$3.45 \pm 0.24_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.05_{\text{ext}}$</td>
<td>= $3.45 \pm 0.30$</td>
</tr>
<tr>
<td>$\text{BR}_{3} \times 10^7$</td>
<td>$3.13 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}} \pm 0.08_{\text{ext}}$</td>
<td>= $3.13 \pm 0.10$</td>
</tr>
<tr>
<td>$M_a$</td>
<td>$0.974 \pm 0.030_{\text{stat}} \pm 0.019_{\text{syst}} \pm 0.002_{\text{ext}}$</td>
<td>= $0.974 \pm 0.035$ [GeV/c]</td>
</tr>
<tr>
<td>$M_\rho$</td>
<td>$0.716 \pm 0.011_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.002_{\text{ext}}$</td>
<td>= $0.716 \pm 0.014$ [GeV/c]</td>
</tr>
<tr>
<td>$\text{BR}_{4} \times 10^7$</td>
<td>$3.18 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}} \pm 0.08_{\text{ext}}$</td>
<td>= $3.18 \pm 0.10$</td>
</tr>
</tbody>
</table>

Including uncertainty due to the model dependence,

$$\text{BR} = (3.11 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}} \pm 0.08_{\text{ext}} \pm 0.07_{\text{model}}) \times 10^{-7} = (3.11 \pm 0.12) \times 10^{-7}$$

**CPV parameter (first measurement; only uncorrelated $K^+/K^-$ uncertainties):**

$$\Delta(K^\pm_{\text{nee}}) = (\text{BR}^+ - \text{BR}^-) / (\text{BR}^+ + \text{BR}^-) = (-2.1 \pm 1.5_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-2}$$
**Comparison: FF slope $\delta$**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Process</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alliegro et al., PRL 68 (1992) 278</td>
<td>$K^+ \rightarrow \pi^+ e^+ e^-$</td>
<td>1.31 ± 0.48</td>
</tr>
<tr>
<td>Appel et al. [E865], PRL 83 (1999) 4482</td>
<td>$K^+ \rightarrow \pi^+ e^+ e^-$</td>
<td>2.14 ± 0.20</td>
</tr>
<tr>
<td>Ma et al. [E865], PRL 84 (2000) 2580</td>
<td>$K^+ \rightarrow \pi^+ \mu^+ \mu^-$</td>
<td>2.45 ± 1.30 ± 0.95</td>
</tr>
<tr>
<td>NA48/2, arXiv:0903:3130 (2009)</td>
<td>$K^\pm \rightarrow \pi^\pm e^+ e^-$</td>
<td>2.32 ± 0.18</td>
</tr>
</tbody>
</table>

$\chi^2 / \text{ndf} = 4.288 / 3$

- NA48/2 measurement of $\delta$ is compatible with the earlier results, has good precision;
- A contradiction of the data to the meson dominance models observed earlier is further confirmed;
- NA48/2 values of $(f_0, a_+, b_+, \omega, \beta)$ are in agreement with BNL E865 ones.

E. Goudzovski / Kaon09, 9 June 2009
Comparison: BR in full z range

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sample</th>
<th>BR × 10^7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bloch et al., PL 56 (1975) B201</td>
<td>41 (K^+)</td>
<td>2.70±0.50</td>
</tr>
<tr>
<td>Alliegro et al., PRL 68 (1992) 278</td>
<td>500 (K^+)</td>
<td>2.75±0.26</td>
</tr>
<tr>
<td>Appel et al. [E865], PRL 83 (1999) 4482</td>
<td>10,300 (K^+)</td>
<td>2.94±0.15</td>
</tr>
</tbody>
</table>

Comparison of E865 vs NA48/2 results taking into account correlated uncertainties (normalization and model dependence): 1.6σ difference.

**K^± → π^±μ^+μ^− analysis (1)**

NA48/2: N=3,100 $K^± → π^±μ^+μ^−$ candidates with 3% background.

Background well described by both $K_{3\pi}$ MC and same-sign muon samples.

*Cf.* total world sample is ~700 events.
$K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ analysis (2)

$$z = (M_{ee}/M_K)^2$$

Analysis is well advanced, we aim to present the preliminary results in 2009.
Summary

- Precise study of the $K^{\pm}\rightarrow\pi^{\pm}e^+e^-$ decay ($BR\sim3\times10^{-7}$):
  - sample & precision comparable to world’s best ones;
  - $(BR, FF)$ agree to theory and earlier measurements;
  - first limit on the CPV charge asymmetry obtained;
  - final results published recently.

- Precise study of the $K^{\pm}\rightarrow\pi^{\pm}\mu^+\mu^-$ decay ($BR\sim0.8\times10^{-7}$):
  - NA48/2 sample $\sim4$ times larger than total world sample;
  - background is low and under control;
  - aim at preliminary results in 2009 – stay tuned!