High precision measurement of Kl3 decays form factors at NA48/2

Stefano Venditti - University of Pisa & INFN
On behalf of the NA48/2 collaboration

QCD12
Montpellier, 2-6/7/2012
Outline of the talk

- The NA48/2 experiment
- Kl3 form factors: theory
- Kl3 selection and BG reduction
- Form factors extraction
- Results and outlook

MAIN ACHIEVEMENTS:
- $\varepsilon'/\varepsilon$ measurement
- Limit on CPV in $K^\pm$ decays
- Cusp effect in $K^- \to 3\pi$ decay
- Pion scattering lengths measurement ($Ke4$ analysis)
The NA48/2 beam line

- 400 GeV/c SPS protons
- 6.3 x 10^7 protons/pulse

+/- beams coincide within 1 mm (to minimise systematics)

**K^+ / K^- flux ~ 1.8**

**DETECTORS**
The NA48/2 detectors

- **SPECTROMETER:**
  - 4 DCHs → redundancy.
  - $\sigma_p/p = 1.0\% + 0.044\% \times p(\text{GeV})$;

- **Liquid Krypton EM calorimeter (LKr):**
  - 13248 cells → high granularity.
  - $\sigma_E/E = 3.2\% / \sqrt{E} + 9\% / E + 0.42\%$;
  - $\sigma_x = \sigma_y \sim 1.5 \text{ mm} @ E=10 \text{ GeV}$

- **Hodoscopes:** charged (CHOD) for fast trigger ($\sigma_t \sim 150 \text{ ps}$), neutral as control trigger

- **Muon veto (MUV):** 3 scintillator planes+iron, ($\sigma_t \sim 700 \text{ ps}$)

**Data samples and trigger**

**DATATAKING PERIODS:**
- **2003:** ~ 50 days
- **2004:** ~ 60 days

~ $2.5 \cdot 10^{10}$ triggers

**This analysis:** minimum bias run (3 days) used

**Trigger:** $E_{\text{LKr}} > 10 \text{ GeV} + \text{CHOD coincidence}$
\( K^\pm \rightarrow e(\mu)^\pm \nu \pi^0 \) (Kl3) decay: physical motivations

The Kl3 decay rate can be written as:

\[
\Gamma(Ke3(\gamma)) = \frac{G_F^2 m_K^5}{192 \pi^3} C_K^2 S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^l (1 + 2\delta_{SU(2)}^l + 2\delta_{EM}^l)
\]

- \( C_K^2 = \frac{1}{2} \) for \( K^\pm \)
- \( S_{EW} = 1.0232 \pm 0.0003 \): Universal short distance EW corrections

**MEASURED BY EXPERIMENTS**
- \( \Gamma \): BR estimation (number of total events)
- \( I_K^l \): Integral of form factors over phase space

**MEASURED BY THEORY**
- \( f_+(0) \): Hadronic matrix element @ \( q^2=0 \)
- \( \delta_{SU(2)}, \delta_{EM} \): isospin-breaking and long distance EM corrections

**WHY FORM FACTORS?**
- Knowledge of \( I_K \) allows for Vus extraction
- Knowledge of detector acceptance for Kl3 decays
- Search for new physics in K\( \mu 3 \) decays

Bernard, Passemear, Oertel, Stern, PLB 638 (2006) 480
Kl$^3$ Form factors

The matrix element of the Kl$^3$ decay is:

$$M = \frac{G_F}{2} V_{us} (f_+(t)(P_K + P_\pi)\mu \bar{u} \gamma_\mu (1 + \gamma_5)u_v + f_-(t)m_\ell \bar{u}_\ell (1 + \gamma_5)u_v)$$

- $M$ depends on two dimensionless form factors $f_+(t)$ and $f_-(t)$
- $t = (P_K - P_\pi)^2$ = momentum transferred to the lepton system
- $f_-(t)$ negligible in Ke$^3$ ($m^2_\ell$ dependence of the BR)

The ME is usually expressed in terms of $f_+$ and $f_0$ (scalar and vector form factors):

$$f_0(t) = f_+(t) + \frac{t}{m_K^2 - m_\pi^2} f_-(t)$$

$f_+(0)$ cannot be accessed directly by experiments

- Input from theory (Lattice QCD, ChPT) required
- Only relative form factors are accessible by experiments:
Form factors parametrization

Two f.f. parametrisations have been used in this analysis:

- **Pole parametrisation**: a single resonance (vector or scalar) is assumed as responsible for the process. The value of its mass is to be estimated:

\[
\tilde{f}_{+,0}(t) = \frac{m_{V,S}^2}{m_{V,S}^2 - t}
\]

- **Taylor expansion**: the form factors are expanded up to linear or quadratic terms, whose coefficients are estimated

**LINEAR PARAMETRISATION**

\[
\tilde{f}_{+,0}(t) = \left[1 + \lambda_{+,0} \frac{t}{m_\pi^2}\right]
\]

**QUADRATIC PARAMETRISATION**

\[
\tilde{f}_{+,0}(t) = \left[1 + \lambda_{+,0}' \frac{t}{m_\pi^2} + \lambda_{+,0}'' \left(\frac{t}{m_\pi^2}\right)^2\right]
\]

Not enough sensitivity to \(\lambda''_{+,0}\), linear parametrisation for \(f_0\) used in this analysis.

**PROS**
- Widely used in the past

**CONS**
- Large correlation between parameters
- Absence of a physical meaning
Kl3 analysis

- 1 charged track, 2 γs in the final state
- Electron tag: $0.9 < E/p < 1.1$
- Muon tag: $E/p < 0.2$ and MUV signal

- Cut on $M_{γγ}$ (assuming charged vertex for $π^0$ decay): $|M_{γγ} - M_{PDG}| < 10$ MeV/c$^2$

ADDITIONAL CUTS

- in-time tracks and γs
- $M_{2\text{MISS}}^2 < 10$ MeV$^2$/c$^4$
- $55 < E_K < 65$ GeV

$M_{2\text{MISS}}^2 = (P_K - P_1 - P_π)^2$
Ke3 background suppression

Main Ke3 BG: $K^+ \rightarrow \pi^+\pi^0$ with the $\pi^+$ faking an electron

- Cut on **transverse momentum** of the event:
  \[ P_t > 0.02 \text{ GeV/c} \]
- BG contamination < 0.1%
- After the cut
- Acceptance loss ~ 3%

4.0 x 10^6 Ke3 events selected
**Kµ3 background suppression**

**Main Kµ3 BG:** $K^\pm \rightarrow \pi^\pm \pi^0$ with $\pi \rightarrow \mu$ decay or mis-ID:

- BG at the 20% level before suppression
- 2-dim. cut on Kaon mass (charged track is given the pion mass) and transverse momentum ($\pi^0$ $p_T$ higher than in signal) applied

**AFTER THE CUT:**
- BG contamination $\sim 0.5$
- Signal loss $\sim 24$

$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0 : \pi \rightarrow \mu$ decay or mis-ID, photons lost:

- Small but more scattered on the Dalitz plot
- No dedicated cut applied
- Correction applied to data

2.5 x 10^6 Kµ3 events selected
Radiative effects

- First-order radiative corrections to $K_e3$ and $K_\mu3$ applied:

$$\Gamma_{KL3} = \Gamma_{KL3}^0 + \Gamma_{KL3}^{RAD} = \Gamma_{KL3}^0 (1 + \delta_{RAD}^{l3})$$

- Code provided by KLOE: C. Gatti, EPJ C45 (2006) 417

- Parameters used for normalization: JHEP 11 (2008) 06

<table>
<thead>
<tr>
<th>MODE</th>
<th>$\delta_{EM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_e3$</td>
<td>$0.050 \pm 0.125%$</td>
</tr>
<tr>
<td>$K_\mu3$</td>
<td>$0.008 \pm 0.125%$</td>
</tr>
</tbody>
</table>

- About 10% (1%) effect on $K_e3$ ($K_\mu3$) Dalitz plot slope
Dalitz plot fit

Dalitz plot density, with form factors as free parameters, is fitted on data:

\[ \rho(E_l^*, E_{\pi}^*) = \frac{d^2(E_l^*, E_{\pi}^*)}{dE_l^* dE_{\pi}^*} \propto A f_+(t) + B f_+(t) (f_0 - f_+) \frac{m_K^2 - m_{\pi}^2}{t} + C [(f_0 - f_+) \frac{m_K^2 - m_{\pi}^2}{t}]^2 \]

\[ A, B, C = \text{known kinematical terms} \]
\[ E_{l}^*, E_{\pi}^* = \text{lepton and pion energies in } K^\pm \text{ rest frame} \]

- Fit performed in 5 x 5 MeV^2 bins in (E_l^*, E_{\pi}^*)
- Cells outside physical region (resolution effect) not fitted
- BG subtraction, acceptance and radiative corrections applied
- Form factors from the first fit are the input of a second iteration

**NATIVE DALITZ PLOT (K\mu3)**

**CORRECTED DALITZ PLOT (K\mu3)**
### Excellent Data/MC agreement, residual differences included in systematics

<table>
<thead>
<tr>
<th>K_{\mu3}^+</th>
<th>\Delta \lambda_+</th>
<th>\Delta \lambda''</th>
<th>\Delta \lambda_0</th>
<th>\Delta m_V</th>
<th>\Delta m_S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaon Energy</td>
<td>±0.1</td>
<td>±0.0</td>
<td>±0.3</td>
<td>±1</td>
<td>±8</td>
</tr>
<tr>
<td>Vertex</td>
<td>±1.0</td>
<td>±0.5</td>
<td>±0.1</td>
<td>±2</td>
<td>±7</td>
</tr>
<tr>
<td>Bin size</td>
<td>±0.8</td>
<td>±0.4</td>
<td>±0.7</td>
<td>±3</td>
<td>±10</td>
</tr>
<tr>
<td>Energy scale</td>
<td>±0.3</td>
<td>±0.1</td>
<td>±0.1</td>
<td>±0</td>
<td>±1</td>
</tr>
<tr>
<td>Acceptance</td>
<td>±0.2</td>
<td>±0.1</td>
<td>±0.3</td>
<td>±2</td>
<td>±5</td>
</tr>
<tr>
<td>K_{2\pi} background</td>
<td>±1.7</td>
<td>±0.5</td>
<td>±0.6</td>
<td>±3</td>
<td>±0</td>
</tr>
<tr>
<td>2nd Analysis</td>
<td>±0.1</td>
<td>±0.1</td>
<td>±0.2</td>
<td>±2</td>
<td>±5</td>
</tr>
<tr>
<td>FF input</td>
<td>±0.3</td>
<td>±0.8</td>
<td>±0.1</td>
<td>±7</td>
<td>±3</td>
</tr>
<tr>
<td>Systematic</td>
<td>±2.2</td>
<td>±1.1</td>
<td>±1.0</td>
<td>±9</td>
<td>±16</td>
</tr>
<tr>
<td>Statistical</td>
<td>±3.0</td>
<td>±1.1</td>
<td>±1.4</td>
<td>±8</td>
<td>±31</td>
</tr>
</tbody>
</table>

### Ke3 error dominated by systematics

### K\mu3 error dominated by statistics

![Ke3 distribution](image1.png)

![K\mu3 distribution](image2.png)
### NA48/2 results (preliminary)

<table>
<thead>
<tr>
<th>Quadratic ($\times 10^{-3}$)</th>
<th>$\chi_+^\prime$</th>
<th>$\chi_+''$</th>
<th>$\lambda_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu3}^\pm$</td>
<td>$26.3 \pm 3.0_{\text{stat}} \pm 2.2_{\text{syst}}$</td>
<td>$1.2 \pm 1.1_{\text{stat}} \pm 1.1_{\text{syst}}$</td>
<td>$15.7 \pm 1.4_{\text{stat}} \pm 1.0_{\text{syst}}$</td>
</tr>
<tr>
<td>$K_{e3}^\pm$</td>
<td>$27.2 \pm 0.7_{\text{stat}} \pm 1.1_{\text{syst}}$</td>
<td>$0.7 \pm 0.3_{\text{stat}} \pm 0.4_{\text{syst}}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pole (MeV/c$^2$)</th>
<th>$m_V$</th>
<th>$m_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu3}^\pm$</td>
<td>$873 \pm 8_{\text{stat}} \pm 9_{\text{syst}}$</td>
<td></td>
</tr>
<tr>
<td>$K_{e3}^\pm$</td>
<td>$879 \pm 3_{\text{stat}} \pm 7_{\text{syst}}$</td>
<td>$1183 \pm 31_{\text{stat}} \pm 16_{\text{syst}}$</td>
</tr>
</tbody>
</table>

**68% confidence level contours**

- KTeV $K^0$
- KLOE $K^0$
- Istra+ $K^+${
- NA48 $K^0$
- NA48/2 $K^\pm$
- preliminary

**FlaviaNet Fit $K_{e3}$ 2010**

**FlaviaNet Fit $K_{\mu3}$ 2010**
NA48/2 combined results (preliminary)

<table>
<thead>
<tr>
<th>Quadratic ($\times 10^{-3}$)</th>
<th>$\lambda'_+$</th>
<th>$\lambda''_+$</th>
<th>$\lambda_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{\pm}<em>{\mu3}K^{\pm}</em>{e3}$ combined</td>
<td>26.98 ± 1.11</td>
<td>0.81 ± 0.46</td>
<td>16.23 ± 0.95</td>
</tr>
<tr>
<td>Pole (MeV/c²)</td>
<td>$m_V$</td>
<td></td>
<td>$m_S$</td>
</tr>
<tr>
<td>$K^{\pm}<em>{\mu3}K^{\pm}</em>{e3}$ combined</td>
<td>877 ± 6</td>
<td></td>
<td>1176 ± 31</td>
</tr>
</tbody>
</table>

68% confidence level contours

- In agreement with $K^0_{\mu3}$ results ($KLOE$, $KTeV$) and $K^-_{\mu3}$ ($ISTRA+$)
- Good agreement between $Ke3$ and $K_{\mu3}$ results
- The combined result is the one with the smallest error
Conclusions

- Very precise measurement of Kl3 form factor in the quadratic and pole parametrisation
- First measurement ever using K+ and K-
- Very high statistics, the Ke3+K\mu3 combined result is competitive with the world’s present average

Outlook

- Data collected by NA62 in 2007 (Γ(K_{e2})/Γ(K_{\mu2}) measurement) would allow to select $O(10^7)$ events in both $K^{\pm}_{e3}$ and $K^{\pm}_{\mu3}$ channels
- A special $K_L$ run (~15h) would allow to select $\sim10^6$ $K^0_{e3}$ and $K^0_{\mu3}$ events