“Charged Kaon Semi-Leptonic Form Factors from NA48/2”

KAON2019
10.9.2019
Perugia

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On behalf of the NA48/2 collaboration
Outline

- NA48/2 experiment
  - Beam line
  - Detector
- Precise measurement of $K_{l3}$ form factors (FF).
- Conclusions
Kaon physics @ CERN

SPS

LHC

NA48/2 & NA62

1997 NA48: $\epsilon'/\epsilon$

2001 NA48/1: $K_s$ & Hyper.

2002

2003-2004 NA62: RK

2007-2008 NA48/2: $K+K$

2012-2014 NA62: tech

2015-2018 NA62: physics
fixed target experiment at CERN-SPS

60±3 GeV/c kaon momentum (~7x10^{11} ppp)

6.3x10^7 particles per pulse in decay region

Simultaneous, unseparated, focused beams

Similar acceptance for K^+ and K^- decays

Beams superimposed with 1mm for the whole decay region

K^+/K^- ~ 1.8
NA48/2 Detectors

- ~100 m long decay region in vacuum
- Triggers based on LKr peaks, CHOD hits and DCH multiplicity
- Similar acceptance between K+ and K- beams checked reversing magnetics fields
- Pion decay products, from the hadronic beam, remain into the beam pipe

Spectrometer:
- \( \sigma_p/p = 1.02\% + 0.044\% \ p \ [p \text{ in GeV/c}] \)

LKR calorimeter:
- \( \sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\% \ [E \text{ in GeV}] \)
- \( \sigma_x = \sigma_y = 0.42/\sqrt{E} +0.06\text{cm} \ [E \text{ in GeV}] \)

CHOD, HAC,MUV, vetos, Kabes, Beam Monitor
\[ K^\pm \rightarrow \pi^0 e^\pm \nu \ (K_{e3}) \]

and

\[ K^\pm \rightarrow \pi^0 \mu^\pm \nu \ (K_{\mu3}) \]

form factors

[Batley et al. (NA48/2 Collaboration) JHEP 1810 (2018) 150]
Semileptonic Form Factors

\[ A = M_K(2E_lE_\nu - M_K(E_{\pi}^{\text{max}} - E_\pi)) + M_l^2 \left( \frac{E_{\pi}^{\text{max}} - E_\pi}{4} - E_\nu \right) \]

\[ \frac{d^2\Gamma}{dE_l dE_\pi} \propto Af_+^2(t) + B f_+(t)f_-^0(t) + C f_-^2(t) \]

\[ B = M_l^2 \left( E_\nu - \frac{E_{\pi}^{\text{max}} - E_\pi}{2} \right) \quad C = \frac{M_l^2(E_{\pi}^{\text{max}} - E_\pi)}{4} \]

- \( f^+ \) and \( f^- \) are the Form Factors (FF)

\[ f^-(t) = (f^+(t) - f^0(t)) \frac{(m_K^2 - m_\pi^2)}{t} \quad f^0 : \text{«scalar» FF} \]

\[ f^{+,-} : \text{«vector» FF} \]

- The FF can be parametrized in several ways

<table>
<thead>
<tr>
<th>FF Parametrization</th>
<th>( f^+(t) )</th>
<th>( f^0(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadratic</td>
<td>( 1 + \lambda'<em>+ \left( \frac{t}{m</em>\pi^2} \right) + \frac{1}{2} \lambda''<em>+ \left( \frac{t}{m</em>\pi^2} \right)^2 )</td>
<td>( 1 + \lambda'<em>0 \left( \frac{t}{m</em>\pi^2} \right) )</td>
</tr>
<tr>
<td>Pole</td>
<td>( \frac{M_V^2}{M_V^2 - t} )</td>
<td>( \frac{M_S^2}{M_S^2 - t} )</td>
</tr>
<tr>
<td>Dispersive</td>
<td>( e^{(\Lambda_+ + H(t)) \frac{t}{m_\pi^2}} )</td>
<td>( e^{(\ln(C) - G(t)) \frac{t}{M_K^2 - M_\pi^2}} )</td>
</tr>
</tbody>
</table>
Data Selection

Generic cuts

- $\gamma$ isolation: distance $> 15$ cm from charged tracks extrapolation
- $\pi^0$ candidate: 2 gammas on LKr with distance $> 20$ cm and total energy $> 15$ GeV
- Neutral vertex: obtained only with $\gamma$s; compatibility with beam axis and decay region.
- 1 good track in time with the $\pi^0$ ($< 10$ ns), no extra charged tracks in 8 ns
- Reconstructed kaon momentum compatible (in $\pm 7.5$ GeV) with nominal beam momentum (measured on run by run basis with $K \rightarrow \pi\pi\pi$)

- $K_{e3}$ dedicated cuts
  - Track Momentum $> 5$ GeV/c
  - $E/P > 0.9$
  - Cut to remove $\pi^+\pi^0$ with mis-identified pion ($P_{t,\nu} > 0.03$ GeV/c)

- $K_{\mu3}$ dedicated cuts
  - Track Momentum $> 10$ GeV/c
  - $E/P < 0.2$
  - Signal in MUV
  - Cuts to remove $\pi^+\pi^0\pi^0$ and $\pi^+\pi^0$ with $\pi^\pm \rightarrow \mu^\pm \nu$ decay in flight ($m(K - \pi^0) > 0.16 \frac{GeV}{c^2}$ and $m(\pi^\pm \pi^0) + P_{t,\pi^0}/c < 0.6$ GeV/c$^2$)
The vertex position is defined by the two $\pi^0$'s gammas (assuming $\pi^0$ mass).

The transverse position is determined by the charged tracks at the neutral vertex position.

The kaon momentum is obtained by kinematic as solution of a quadratic equation (assuming $m_\nu=0$ and $P_T(\nu)=-P_T$ and with $P_L$, $P_T$ and $E$ as momentum and energy of the $\pi^0l$ system):

\[
 P_K = \frac{\Phi P_L}{E^2 - P_L^2} \pm \sqrt{D}
\]

Where:

\[
 \Phi = \frac{1}{2} \left( m_K^2 + E^2 - P_L^2 - P_T^2 \right)
\]

\[
 D = \Phi^2 \frac{P_L^2}{(E^2 - P_L^2)^2} - \frac{m_K^2 E^2 - \Phi^2}{E^2 - P_L^2}
\]
Selection Cuts

Difficult to simulate the negative tails of the longitudinal neutrino momentum ($>0.014 \text{ GeV}^2/\text{c}^2$)

- Cut on the vertex position ($>-1600 \text{ cm}$) to avoid background from last collimator.
$K_{e3}$ Dedicated cuts

- $P_T(\nu) > 0.03$ GeV/c

To reduce the contamination of the $\pi^+\pi^0$
K_{\mu 3} dedicated cuts

- 2D Cut to avoid $\pi^\pm\pi^0$ background:
  - $m(\mu\nu) > 0.16$ GeV/c^2
  - $m(\pi\pi^0) + P_{\pi^0, T}/c < 0.6$ GeV/c^2
Data Selection

- Special run with dedicated trigger configuration
  - 16 runs, 4 days in 2004
  - Trigger: 1 track (2 hod hits) + LKr(E>10 GeV)

- Events selected:
  - $4.4 \times 10^6 \ K_{e3}$
  - $2.3 \times 10^6 \ K_{\mu3}$

- Small or negligible background contamination

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR (%)</th>
<th>$F_e \ (10^{-3})$</th>
<th>$F_{\mu} \ (10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0 \ (2\pi)$</td>
<td>20.66</td>
<td>0.272</td>
<td>0.392</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \ (3\pi)$</td>
<td>1.761</td>
<td>0.287</td>
<td>2.192</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0_D \ (2\pi D)$</td>
<td>1.174</td>
<td>0.049</td>
<td>0.000</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0 \gamma \ (2\pi \gamma)$</td>
<td>0.0275</td>
<td>0.004</td>
<td>0.044</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \mu^\pm \pi^0 \nu \ (K\mu3)$</td>
<td>0.03353</td>
<td>0.004</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Dalitz plot: Pion and leptons energy in the K rest frame

Bin size chosen to have at least 20 events per bin in the whole allowed region: 5x5 MeV²

Background tails and radiative corrections outside the kinematic limits are not considered in the fit
- Backgrounds surviving to $K_{e3}$ and $K_{\mu3}$ selection
- The simulated backgrounds are normalized to the kaon flux
The MC generated Dalitz Plot (with form factors $\lambda_{gen}$) is reweighted using a different set of form factors parameters $\vec{L}$:

$$ w(\vec{L}) = w_R(E_L, E_\pi) \frac{\rho(\vec{L}, E_L, E_\pi)}{\rho(\lambda_{gen}, E_L, E_\pi)} $$

- $\rho$ is the non radiative density Dalitz formula
- $w_R$ is used for $K_{e3}$ to apply radiative correction in the corresponding Dalitz Plot bin [V. Cirigliano et al. Eur. Phys. J. C23 (2002) 121–133]

The most probable FF ($\vec{L}$) are obtained minimizing

$$ \chi^2 = \sum_{bins} \frac{\left( \omega_{i,data} - N \cdot \omega_{i,MC} - \omega_{i,bkg} \right)^2}{\sigma_{i,data}^2 + N^2 \cdot \sigma_{i,MC}^2 + \sigma_{i,bkg}^2} $$

- $\omega_{i,data}$ and $\omega_{i,MC}$ are the contents of experimental data in the i-th bin and the reweighted bin contents from MC, $\omega_{i,bkg}$ is the background contribution in the i-th bin.
Results $K_{e3}$

<table>
<thead>
<tr>
<th></th>
<th>Quadratic (10^{-3})</th>
<th>Pole (MeV)</th>
<th>Dispersive (10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda'_+$</td>
<td>$\lambda''_+$</td>
<td>$M_V$</td>
</tr>
<tr>
<td><strong>Central value</strong></td>
<td>24.26</td>
<td>1.64</td>
<td>885.2</td>
</tr>
<tr>
<td><strong>$\sigma_{\text{stat}}$</strong></td>
<td>0.78</td>
<td>0.30</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>$\sigma_{\text{syst}}$</strong></td>
<td>1.30</td>
<td>0.39</td>
<td>7.2</td>
</tr>
<tr>
<td><strong>Total error</strong></td>
<td>1.51</td>
<td>0.49</td>
<td>7.9</td>
</tr>
<tr>
<td><strong>$\chi^2/\text{ndf}$</strong></td>
<td>569.1/687</td>
<td>568.9/688</td>
<td>569.0/688</td>
</tr>
<tr>
<td><strong>Correlation</strong></td>
<td>-0.929</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Only results validated by FLAVIANET are quoted, OKA (2018) results not yet included. See next talk by E.Passemar.
## Results $K_{\mu 3}$

<table>
<thead>
<tr>
<th>Quadratic (10^{-3})</th>
<th>Pole (MeV)</th>
<th>Dispersive (10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda'_+$</td>
<td>$\lambda''_+$</td>
<td>$\lambda'_0$</td>
</tr>
<tr>
<td>Central value</td>
<td>24.27</td>
<td>1.83</td>
</tr>
<tr>
<td>$\sigma_{\text{stat}}$</td>
<td>2.88</td>
<td>1.05</td>
</tr>
<tr>
<td>$\sigma_{\text{syst}}$</td>
<td>2.89</td>
<td>1.09</td>
</tr>
<tr>
<td>Total error</td>
<td>4.08</td>
<td>1.52</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>409.9/381</td>
<td></td>
</tr>
<tr>
<td>Correlation</td>
<td>-0.974 ($\lambda'<em>+ / \lambda''</em>+$); 0.551 ($\lambda'_+ / \lambda'<em>0$); -0.513 ($\lambda''</em>+ / \lambda'_0$)</td>
<td>0.029</td>
</tr>
</tbody>
</table>

![Graphs showing fits to $K_{\mu 3}$ data](image-url)
### Combined results

<table>
<thead>
<tr>
<th>Quadratic (10^{-3})</th>
<th>Pole (MeV)</th>
<th>Dispersive (10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda'_+$</td>
<td>$\lambda''_+$</td>
<td>$\lambda'_0$</td>
</tr>
<tr>
<td>Central value</td>
<td>24.24</td>
<td>1.67</td>
</tr>
<tr>
<td>$\sigma_{\text{stat}}$</td>
<td>0.75</td>
<td>0.29</td>
</tr>
<tr>
<td>$\sigma_{\text{syst}}$</td>
<td>1.30</td>
<td>0.41</td>
</tr>
<tr>
<td>Total error</td>
<td>1.50</td>
<td>0.50</td>
</tr>
<tr>
<td>$\chi^2/\text{ndf}$</td>
<td>979.6/1070</td>
<td>979.3/1071</td>
</tr>
</tbody>
</table>

- Joint fits obtained minimizing $\chi^2_{(\text{Ke3})} + \chi^2_{(\text{K}\mu3)}$ with a common set of parameters
Dalitz plot projections assuming the result of the fit (Taylor expansion)

Good data-mc agreement
## Combined results: systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Quadratic (10^{-3})</th>
<th>Pole (MeV)</th>
<th>Dispersive (10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda'_+$</td>
<td>$\lambda''_+$</td>
<td>$\lambda'_0$</td>
</tr>
<tr>
<td>Diverging beam</td>
<td>0.97</td>
<td>0.35</td>
<td>0.55</td>
</tr>
<tr>
<td>Kaon mom. spectrum</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Kaon mean momentum</td>
<td>0.04</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>LKr energy scale</td>
<td>0.66</td>
<td>0.12</td>
<td>0.61</td>
</tr>
<tr>
<td>LKr non-linearity</td>
<td>0.20</td>
<td>0.01</td>
<td>0.55</td>
</tr>
<tr>
<td>Residual Bacground</td>
<td>0.08</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Electron ID</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Event pileup</td>
<td>0.23</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.23</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>Neutrino mom. Resolution</td>
<td>0.16</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Trigger eff.</td>
<td>0.29</td>
<td>0.13</td>
<td>0.20</td>
</tr>
<tr>
<td>Dalitz plot bin.</td>
<td>0.05</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>Dalitz plot res.</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Radiative</td>
<td>0.17</td>
<td>0.01</td>
<td>0.57</td>
</tr>
<tr>
<td>External inputs</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>Syst.error</strong></td>
<td><strong>1.30</strong></td>
<td><strong>0.41</strong></td>
<td><strong>1.17</strong></td>
</tr>
</tbody>
</table>
Beam Profile

- Main systematics: beam diverging component.
- Decays can happen few cm off the beam axis
- This is measured with:
  \[ B = \sqrt{\left(\frac{x - x_0}{\sigma_x}\right)^2 + \left(\frac{y - y_0}{\sigma_y}\right)^2} \]

- Main systematics: beam diverging component.
- Only the core of the beam distribution (B<3) is well simulated.
- Beam divergence added for systematics studies.
- B<11 to minimize correlation between beam direction and momentum

![Graphs showing data and Monte Carlo simulations for Ke3 and Kμ3 decays]
Combined results

- $1\sigma$ ellipse (39.4% CL): to improve visibility
- Compatible with previous results
- Better precision

Only results validated by FLAVIANET are quoted, OKA (2018) results not yet included.
See next talk by E. Passemar
Conclusions

$K_{l3}$ form factors are measured with $\sim 4.4 \cdot 10^6 K_{e3}$ and $\sim 2.3 \cdot 10^6 K_{\mu3}$ events, from the 2004 NA48/2 data taking in a special minimum bias run (3 days).

- For the first time the measurement is done simultaneously in $K^+$ and $K^-$.
- Improved vertex definition with respect to the preliminary result → result less sensitive to beam shape.
- Similar level of precision with other experiments in the $K_{\mu3}$ mode and the smallest error in $K_{e3}$ has been reached.
- The combined result is fully compatible with previous measurement with improved precision.

- NA62 will collect order of $10^7$-$10^8$ semileptonic decays, with better vertex definition (Gigatracker); no dedicated trigger, minimum bias trigger with large downscaling.
\[ \Gamma(K_{l3}(\gamma)) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{\text{EW}} |V_{us}|^2 |f_+(0)|^2 I_K^l \left(1 + 2\delta_{\text{SU(2)}}^l + 2\delta_{\text{EM}}^l\right) \]

- **Theory:**
  - \( S_{\text{EW}} \) = Universal short distance EW correction
  - \( f_+(0) \) = form factor at 0 momentum transfer
  - \( \delta_{\text{SU(2)}}^l \) = Isospin breaking correction
  - \( \delta_{\text{EM}}^l \) = Long distance EM effects

- **Experiment:**
  - \( \Gamma \) = Branching ratios and Lifetime
  - \( I_K \) = Phase space integral
### Neutral Kl3

<table>
<thead>
<tr>
<th>Quadratic ($\times 10^{-3}$)</th>
<th>$\chi'_+$</th>
<th>$\chi''_+$</th>
<th>$\lambda_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu3}^\pm$</td>
<td>26.3 ± 3.0$<em>{\text{stat}}$ ± 2.2$</em>{\text{syst}}$</td>
<td>1.2 ± 1.1$<em>{\text{stat}}$ ± 1.1$</em>{\text{syst}}$</td>
<td>15.7 ± 1.4$<em>{\text{stat}}$ ± 1.0$</em>{\text{syst}}$</td>
</tr>
<tr>
<td>$K_{e3}^\pm$</td>
<td>27.2 ± 0.7$<em>{\text{stat}}$ ± 1.1$</em>{\text{syst}}$</td>
<td>0.7 ± 0.3$<em>{\text{stat}}$ ± 0.4$</em>{\text{syst}}$</td>
<td></td>
</tr>
<tr>
<td>Pole (MeV/c$^2$)</td>
<td>$m_N$</td>
<td>$m_S$</td>
<td></td>
</tr>
<tr>
<td>$K_{\mu3}^\pm$</td>
<td>873 ± 8$<em>{\text{stat}}$ ± 9$</em>{\text{syst}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{e3}^\pm$</td>
<td>879 ± 3$<em>{\text{stat}}$ ± 7$</em>{\text{syst}}$</td>
<td>1183 ± 31$<em>{\text{stat}}$ ± 16$</em>{\text{syst}}$</td>
<td></td>
</tr>
</tbody>
</table>

- 4 millions $K_{e3}$ and 2.5 millions $K_{\mu3}$ analyzed