Recent results from NA48 and NA62 experiments at CERN

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on behalf of the NA48 and NA62 collaborations
Outline:

- The NA48 experiment
  - The beam and the detector, data taking periods
  - Recent results on $K\mu3$ and $Ke3$ Form Factors
- The NA62 experiment
  - First phase: $R_K$ measurement from 2007 data
- Summary and outlook
The NA48 experiment

K\(^+\) and K\(^-\) superimposed in space
Flux ratio: K\(^+\)/K\(^-\) \(~\) 1.8

Kaon momentum:
60\(\pm\)3 GeV/c

Data taking:
2003 – 50 days
2004 – 60 days

Beams coincide within 1 mm

Width \(~\) 5 mm
The NA48 Detector

Magnetic spectrometer (4 DCHs):
4 views: redundancy ⇒ efficiency
\( \sigma(p)/p = 1.0\% + 0.044\% \, p \) [GeV/c]

Charged hodoscope (scintillators):
Fast trigger and precise time measurement (~200 ps on single track)

Liquid Krypton E.M. Calorimeter (LKr):
10 m\(^3\) (~22 t), 1.25 m (27 \(X_0\)), 13212 cells
granularity: 2x2 cm\(^2\), quasi-homogeneous
\( \sigma(E)/E = 3.2%/\sqrt{E} + 9%/E + 0.42% \) [E in GeV]

Then hadronic calorimeter, large angle vetos and muon counter (scintillators)

**Trigger:**
- **L1:** Hodoscope, DCH multiplicity, \( E_{LKr} \), LKr projections
- **L2:** ON-line processing of DCH information

**Min Bias Trigger:** Coincidence of two Hodoscope hits \( \times E_{LKr} > 10 \text{ GeV} \)
The $K^+$ semileptonic decays

- $K \to \pi l \nu(K_{l3})$ decays provide the **most accurate** and **theoretically cleanest** way to access $|V_{us}|$:

\[
\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^l(\lambda_0)(1 + \delta^l_{SU(2)} + \delta^l_{EM})^2
\]

**Experimental Inputs:**
- $\Gamma(K_{l3(\gamma)})$ Branching ratios and kaon lifetimes
- $I_K^l(\lambda_0)$ Phase space integral depends on the form factors

**Theory Inputs:**
- $S_{EW}$ Universal short distance EW corrections ($1.0232\pm0.0003$)
- $f_+(0)$ Form factor at zero momentum transfer
- $\delta^l_{SU(2)}$ Form factor correction for isospin breaking (ch. mode only)
- $\delta^l_{EM}$ Long distance EM effects
K_{13} decays are described by \textbf{two form factors} \( f_{\pm}(t) \), and the \textbf{matrix element} can be written as:

\[
M = \frac{G_F}{2} V_{us} (f_+(t)(P_K + P_\pi) + \mu \bar{u}_l \gamma_\mu (1 + \gamma_5) u_\nu + f_-(t)m_l \bar{u}_l (1 + \gamma_5) u_\nu)
\]

\( t = q^2 \) is the square of the four-momentum transfer to the lepton neutrino system

\( f_-(t) \) can only be measured in \( K_{\mu 3} \) decays because of \( m_e << m_K \)

\( f_+(t) \) is the \textbf{vector form factor} and \( f_0(t) \) the \textbf{scalar form factor} with:

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

\( f_+(0) \) cannot be measured directly, therefore the form factors are normalised to \( f_+(0) \):

\[
\bar{f}_+(t) = \frac{f_+(t)}{f_+(0)} \quad \bar{f}_0(t) = \frac{f_0(t)}{f_+(0)}
\]
Form Factor Parametrizations

Parametrizations using **physical quantities** are called **class 1** parametrizations. They depend on free parameters with a physical meaning.

**Pole parametrization:**
Assumes the exchange of vector and scalar resonances $K^*$ with spin-parity $1^-/0^+$ and masses $m_V/m_S$, $f_+(t)$ can be described by $K^*(892)$, for $f_0(t)$ no obvious dominance is seen:

$$\bar{f}_{+,0}(t) = \frac{m_{V,S}^2}{m_{V,S}^2 - t}$$

Parametrizations without a **physical meaning** are called **class 2** parametrizations. They require more free parameters and are expansions in the momentum transfer.

**Linear and quadratic parametrization:**

$$\bar{f}_{+,0}(t) = 1 + \lambda_{+,0} \frac{t}{m^2_\pi}$$  \hspace{1cm} \text{Linear}$$

$$\bar{f}_{+,0}(t) = 1 + \lambda'_{+,0} \frac{t}{m^2_\pi} + \frac{1}{2} \lambda''_{+,0} \left( \frac{t}{m^2_\pi} \right)^2$$  \hspace{1cm} \text{Quadratic}$$

**Correlations!**
No sensitivity to $\lambda''_0$
Event selection:

- **1 good track**
  - Muon identified by muon veto and E/p
  - Electron identified by E/p
- **1 good $\pi^0 \rightarrow \gamma\gamma$**
  - Pion mass cut: $|m_{\gamma\gamma} - m_{\text{PDG}}(\pi^0)| > 10$ MeV

Event reconstruction:

- LKr clusters and muon track consistent in time
- Missing mass cut using $K^\pm$ hypothesis
  $$M^2_{KL3} = (P_K - P_\gamma - P_{\pi^0})^2 < 10 \text{ MeV}^2$$
- Kaon energy reconstructed under the assumption of a missing undetected neutrino within the range of:
  $$55 \text{ GeV} < E \pm < 65 \text{ GeV}$$

$$2.5 \times 10^6 \ K^\pm_{\mu3} \text{ events selected}$$
$$4.0 \times 10^6 \ K^\pm_{e3} \text{ events selected}$$

- DIS2012 - University of Bonn - Bonn (Germany)
To $K^\pm_{\mu3}$:

$K^\pm \rightarrow \pi^\pm \pi^0$ with $\pi \rightarrow \mu$ can fake the signal

Without suppression, $K^\pm \rightarrow \pi^\pm \pi^0$ background at the level of 20%

Cut in the invariant $\pi^\pm \pi^0$ mass and the transverse momentum of the pion:

→ Background contamination reduced to 0.5%

→ about 24% of $K^\pm_{\mu3}$ events are lost

Background is well localized in the Dalitz plot

To $K^\pm_{e3}$:

Pion with $E/P > 0.95$ can fake a $K^\pm_{e3}$ decay

Cut in the transverse momentum of the event:

$p_T^{\text{event}} > 0.02$ GeV/c

→ Background contamination reduced to < 0.1%

→ about 3% of $K^\pm_{e3}$ events are lost
Radiative corrections

The $K_{l3}$ decay rate including first order radiative corrections can be written as:

$$\Gamma_{K_{l3}} = \Gamma_{K_{l3}}^0 + \Gamma_{K_{l3}}^1 = \Gamma_{K_{l3}}^0 (1 + 2\delta_{EM}^{Kl})$$

Simulation code provided by KLOE
author C. Gatti, *EPJ C45 (2006) 417*

Parameters used for the normalization:

*(JHEP 11 (2008) 006)*

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\delta_{EM}^{Kl3}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu3}^{\pm}$</td>
<td>$0.008 \pm 0.125$</td>
</tr>
<tr>
<td>$K_{e3}^{\pm}$</td>
<td>$0.050 \pm 0.125$</td>
</tr>
</tbody>
</table>

For $K_{e3}^{\pm}$ the effects on the acceptance are bigger with respect to $K_{\mu3}^{\pm}$

• ~10% effect on the Dalitz plot slope for $K_{e3}^{\pm}$
• Percent effect on slope for $K_{\mu3}^{\pm}$
Data – MC comparison

- Pion energy in the kaon rest frame: $K_{\mu 3}^{\pm}$

- Pion energy in the kaon rest frame: $K_{e 3}^{\pm}$

**Dis2012 - University of Bonn - Bonn (Germany)** 27/03/12 11
Form factors fitting procedure

To extract the form factors, a fit to the Dalitz plot density is performed:

$$\rho(E_\ell^*, E_{\pi}^*) = \frac{d^2 N(E_\ell^*, E_{\pi}^*)}{dE_\mu^* dE_{\pi}^*} \propto Af_+^2(t) + Bf_+(t)(f_0 - f_+) \frac{m_K^2 - m_{\pi}^2}{t} + C \left[ (f_0 - f_+) \frac{m_K^2 - m_{\pi}^2}{t} \right]^2$$

- $E_\ell^*$ and $E_{\pi}^*$ are the energy of the lepton and of the pion in the kaon rest frame
- $A$, $B$ and $C$ are kinematical terms

Cells which are outside or crossing the border of the physical region of the Dalitz plot are not used in the fit.

Applied corrections:
- Background subtraction
- Acceptance
- Radiative corrections

DIS2012 - University of Bonn - Bonn (Germany)
## Systematic checks

<table>
<thead>
<tr>
<th>$K_{\mu 3}^\pm$</th>
<th>$\Delta \lambda'_+ \times 10^{-3}$</th>
<th>$\Delta \lambda''_+$</th>
<th>$\Delta \lambda_0$</th>
<th>$\Delta m_V$</th>
<th>$\Delta m_S$ MeV/$c^2$</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>$K_{2\pi}$</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>

<table>
<thead>
<tr>
<th>$K_{e 3}^\pm$</th>
<th>$\Delta \lambda'_+ \times 10^{-3}$</th>
<th>$\Delta \lambda''_+$</th>
<th>$\Delta m_V$ MeV/$c^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaon Energy</td>
<td>±0.3</td>
<td>±0.1</td>
<td>±6</td>
</tr>
<tr>
<td>Vertex</td>
<td>±0.2</td>
<td>±0.1</td>
<td>±0</td>
</tr>
<tr>
<td>Bin size</td>
<td>±0.0</td>
<td>±0.1</td>
<td>±2</td>
</tr>
<tr>
<td>Energy scale</td>
<td>±0.1</td>
<td>±0.0</td>
<td>±0</td>
</tr>
<tr>
<td>Acceptance</td>
<td>±0.2</td>
<td>±0.0</td>
<td>±3</td>
</tr>
<tr>
<td>2nd Ana</td>
<td>±0.9</td>
<td>±0.4</td>
<td>±1</td>
</tr>
<tr>
<td>FF input</td>
<td>±0.4</td>
<td>±0.0</td>
<td>±1</td>
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<tr>
<td>Systematic</td>
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<td>±0.4</td>
<td>±7</td>
</tr>
<tr>
<td>Statistical</td>
<td>±0.7</td>
<td>±0.3</td>
<td>±3</td>
</tr>
</tbody>
</table>

$K_{\mu 3}^\pm$ is dominated by statistics, $K_{e 3}^\pm$ is dominated by the systematics.
Preliminary results

<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_{\mu^3}^\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_{e^3}^\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_{\mu^3}^\pm )</td>
<td>873 ( \pm ) 8_{\text{stat}} ( \pm ) 9_{\text{syst}}</td>
<td>1183 ( \pm ) 31_{\text{stat}} ( \pm ) 16_{\text{syst}}</td>
</tr>
<tr>
<td>( K_{e^3}^\pm )</td>
<td>879 ( \pm ) 3_{\text{stat}} ( \pm ) 7_{\text{syst}}</td>
<td></td>
</tr>
</tbody>
</table>

68% Confidence level contours
Experimental situation: \( K^{0}_{l3} \) results from KLOE, KTeV and NA48, \( K^{-}_{l3} \) from ISTRA+

NA48/2 is the first measurement with both \( K^{\pm}_{e3} \) and \( K^{\pm}_{\mu3} \).

NA48/2 preliminary result with high precision - very competitive with the other results. Offers the smallest error with the combined result.

The results for \( K e_3 \) and \( K \mu_3 \) from NA48/2 are in good agreement.

<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_{\mu3}^{\pm}K_{e3}^{\pm} ) combined</td>
<td>26.98 ± 1.11</td>
<td>0.81 ± 0.46</td>
<td>16.23 ± 0.95</td>
</tr>
<tr>
<td>Pole ((\text{MeV}/c^2))</td>
<td>( m_{V} )</td>
<td>( m_{S} )</td>
<td></td>
</tr>
<tr>
<td>( K_{\mu3}^{\pm}K_{e3}^{\pm} ) combined</td>
<td>877 ± 6</td>
<td>1176 ± 31</td>
<td></td>
</tr>
</tbody>
</table>

68% Confidence level contours

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DIS2012 - University of Bonn - Bonn (Germany)
A precise measurement of the ratio $R_K$ of $K^\pm\rightarrow l^\pm\nu_l$ ($K_{l2}$) leptonic decays provides a stringent test of SM and indirect search for New Physics.

- Hadronic uncertainties cancel in the ratio $K_{e2}/K_{\mu2}$
- SM prediction: excellent sub-permille accuracy

$R_K$ is sensitive to lepton flavour violation and its SM expectation:

$$R_K = \frac{\Gamma(K^\pm \rightarrow e^\pm\nu)\Gamma(K^\pm \rightarrow \mu^\pm\nu)}{\Gamma(K^\pm \rightarrow e^\pm\nu)\Gamma(K^\pm \rightarrow \mu^\pm\nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\text{rad.corr.}})$$

Helicity suppression: $f\sim10^{-5}$

Radiative correction (few %) due to $K^+\rightarrow e^+\nu\gamma$ (IB) process, by definition included into $R_K$

$[V.Cirigliano, I.Rosell JHEP 0710:005 (2007)]$

$R_K^{\text{SM}} = (2.477\pm0.001)\times10^{-5}$


Helicity suppression of $R_K$ might enhance sensitivity to non-SM effects to an experimentally accessible level.
Measurement strategy

(1) $K_{e2}/K_{\mu2}$ candidates are collected **concurrently**:
- analysis does not rely on kaon flux measurement;
- several systematic effects cancel in the ratio (at first order);

(2) MC simulations used **to a limited extent**:
- Geometrical part of the acceptance correction and bkg estimation;

(3) PID, trigger, readout efficiencies and beam halo bkg **measured directly** from data;

**Counting experiment - analysis in 10 lepton momentum bins**: (due to strong momentum dependence of backgrounds and event topology)

$$R_K = \frac{1}{D} \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \cdot \frac{f_\mu \cdot A(K_{\mu2}) \cdot \varepsilon(K_{\mu2})}{f_e \cdot A(K_{e2}) \cdot \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKR}}$$

<table>
<thead>
<tr>
<th>Signal events</th>
<th>Particle ID eff</th>
<th>Trigger efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(K_{e2})$</td>
<td>$f_\mu \cdot A(K_{\mu2}) \cdot \varepsilon(K_{\mu2})$</td>
<td>$1$</td>
</tr>
<tr>
<td>$N_B(K_{e2})$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N(K_{\mu2})$</td>
<td>$f_e \cdot A(K_{e2}) \cdot \varepsilon(K_{e2})$</td>
<td></td>
</tr>
<tr>
<td>$N_B(K_{\mu2})$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$K_{\mu2}$ downscaling
**\( K_{e2}: \text{NA62 full data set} \)**

145,958 \( K^+ \rightarrow e^+ \nu \) candidates.
Positron ID efficiency: \((99.28\pm0.05)\%\).
\( B/(S+B) = (10.95\pm0.27)\% \).

**Proposal (CERN-SPSC-2006-033):**
~150k candidates

cf. KLOE: 13.8K candidates (\( K^+ \) and \( K^- \)), ~90% electron ID efficiency, 16% bkg
NA62 result

\[ R_K = (2.488 \pm 0.010) \times 10^{-5} \]

Fit over 40 measurements (4 data samples x 10 momentum bins) including correlations: \( \chi^2/\text{ndf}=47/39 \).

Uncertainties 0.4% tot precision

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta R_K \times 10^5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>0.007</td>
</tr>
<tr>
<td>( K_{\mu2} )</td>
<td>0.004</td>
</tr>
<tr>
<td>( \text{BR}(K_{e2\gamma} \text{SD}^+) )</td>
<td>0.002</td>
</tr>
<tr>
<td>Beam halo</td>
<td>0.002</td>
</tr>
<tr>
<td>( K^\pm \to \pi^0 e^\pm \nu, )</td>
<td>0.003</td>
</tr>
<tr>
<td>( K^\pm \to \pi^\pm \pi^0 )</td>
<td>0.003</td>
</tr>
<tr>
<td>Matter</td>
<td>0.003</td>
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<td>Composition</td>
<td>0.002</td>
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<tr>
<td>Acceptance</td>
<td>0.001</td>
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<tr>
<td>DCH alignment</td>
<td>0.001</td>
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<tr>
<td>Electron ID</td>
<td>0.001</td>
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<tr>
<td>LKr readout inef</td>
<td>0.001</td>
</tr>
<tr>
<td>1-track trigger</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.010</strong></td>
</tr>
</tbody>
</table>

Independent measurements in lepton momentum bins

(\text{systematic errors included, partially correlated})

NA62 result (40% data set): \( R_K=(2.487\pm0.013)\times10^{-5} \) [PLB698 (2011) 105]
NA48/2 provides new preliminary results on the $K_{l3}$ form factors in the quadratic and Pole parametrization.

For the first time a result is presented studying both $K^+$ and $K^-$ decays

- Very competitive with the other results in $K_{\mu3}$ and smallest error in $K_{e3}$
- Offers the combined result with the smallest error.

In the year 2007 NA62 collected data for a dedicated measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$, the final result has been shown here.

4 months of data taking in 2007 with $K^+$ and $K^-$ beams (mostly $K^+$) with a beam momentum of $P_K = (74 \pm 1.6)$ GeV/c, trigger very similar to the 2004 special run. Transverse momentum kick of the magnetic spectrometer was doubled wrt 2003/2004 → improvement in the track momentum resolution.

Huge statistics in $K_{\mu3}$ and $K_{e3}$ of $O(10^7)$ events, also a special (15 h) $K^0_L$ run collected

So $K_{l3}$ Form Factors can be studied on NA62 2007 run with different/larger data sets

Moreover the construction of the new NA62 detector is on-going. Foreseen to start the data taking for the second phase in 2014 to measure the Branching Ratio of the very rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$