Kaon physics at CERN:
recent results

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on behalf of CERN NA48 and NA62 collaborations

Outline:
1) The NA48/NA62 experiments at CERN;
2) Lepton flavour universality test with $K^\pm \rightarrow e^\pm \nu / K^\pm \rightarrow \mu^\pm \nu$ decays;
3) Search for the lepton number violating $K^* \rightarrow \pi^- \mu^+ \mu^+$ decay;
4) Form factors of semileptonic decays;
5) Conclusions.

European Physical Society HEP 2011 conference
Grenoble, France • 22 July 2011
NA48/NA62 experiments

Jura mountains

SPS

NA48/NA62: centre of the LHC

France

LHC

NA48/NA62: discovery of direct CPV

NA48/1

NA48/2

NA62 (R_K phase)

NA62
talk by P. Valente

Earlier: NA31

1997: \( \epsilon'/\epsilon: K_L+K_S \)

1998: \( K_L+K_S \)

1999: \( K_L+K_S \) \( K_S \) HI

2000: \( K_L \) only \( K_S \) HI

2001: \( K_L+K_S \) \( K_S \) HI

2002: \( K_S / \) hyperons

2003: \( K^+/K^- \)

2004: \( K^+/K^- \)

2007: \( K^+/K^- \)

2008: \( K^+_{e2}/K^-_{\mu2} \) tests

2007–2013: design & construction

2012: first data taking

1997–2013: Na48/2, Na62


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Beam: \(~4\times4\text{mm}, \sim10\times10\mu\text{rad (rms)}\). 22\% (18\%) of kaons decay in the 114m long vacuum tank.

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The detector

Data taking

- NA48/2:
  ~six months in 2003-04.
- NA62 (R_K phase):
  ~4 months in 2007;
  ~2 weeks (systematics studies) in 2008

Principal subdetectors for R_K:

- Magnetic spectrometer (4 DCHs):
  4 views/DCH: redundancy \(\Rightarrow\) efficiency;
  \(\Delta p/p = 0.47\% + 0.020\% \times p\) [GeV/c] (in 2007)

- Hodoscope
  fast trigger, precise \(t\) measurement (150ps).

- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  \(\sigma_E/E = 3.2\%/E^{1/2} + 9%/E + 0.42\%\) [GeV];
  \(\sigma_x = \sigma_y = 4.2\text{mm}/E^{1/2} + 0.6\text{mm}\) (1.5mm@10GeV).
Lepton Flavour Universality (LFU): not a fundamental law (violated in $\nu$ sector).

New physics models (2HDM, SUSY, SM4): significant LFU violation.

Observable sensitive to LFU violation:

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

Helicity suppression: $f \sim 10^{-5}$

- **SM prediction**: excellent sub-permille accuracy: free of hadronic uncertainties.
- Measurements of $R_K$ (and $R_\pi$) have long been considered as tests of LFU.
- NP contributions accessible experimentally due to the suppression of the SM value.

$$R_K^{\text{SM}} = (2.477 \pm 0.001) \times 10^{-5}$$

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$R_K = \frac{K_{e2}}{K_{\mu2}}$ beyond the SM

**2HDM - tree level** (including SUSY)

$K_{l2}$ can proceed via exchange of charged Higgs $H^\pm$ instead of $W^\pm$

→ Does not affect the ratio $R_K$

**2HDM - one-loop level**

Dominant contribution to $R_K$: $H^\pm$ mediated LFV (rather than LFC) with emission of $\nu_\tau$

→ $R_K$ enhancement can be experimentally accessible

$$R^{LFV}_K \approx R^{SM}_K \left[ 1 + \left( \frac{m_K^4}{M_{H^\pm}^4} \right) \left( \frac{m_{\tau}^2}{M_{e}^2} \right) |\Delta_{13}|^2 tan^6 \beta \right]$$

uniquely sensitive to slepton mixing

~1% effect in large $\tan\beta$ regime with a massive $H^\pm$

**Example:** $\Delta_{13} = 5 \times 10^{-4}$, $\tan\beta = 40$, $M_H = 500$ GeV/c² lead to $R_{K}^{MSSM} = R_{K}^{SM}(1+0.013)$.

Large effects in $B$ decays due to $(M_B/M_K)^4 \sim 10^4$:

$B_{\mu\nu}/B_{\tau\nu} \rightarrow \sim 50\%$ enhancement;

$B_{e\nu}/B_{\tau\nu} \rightarrow$ enhanced by ~one order of magnitude.

Out of reach: $Br^{SM}(B_{e\nu}) \approx 10^{-11}$
Radiative $K^+ \rightarrow e^+ \nu \gamma$ process

$R_K$ is inclusive of IB radiation by definition. SD radiation is a background. INT is negligible.

**SD**

SD**: positive $\gamma$ helicity

$\nu$, $S_e$, $S_{\nu}$, $S_{\gamma}$

$\nu$, $p_e$, $p_{\gamma}$

SD radiation is not helicity suppressed. KLOE measurement of the form factor leads to $BR(SD^+, \text{full phase space}) = (1.37 \pm 0.06) \times 10^{-5}$. (EPJC64 (2009) 627)

$B/(S+B) = (2.60 \pm 0.11)\%$

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Measurement strategy

(1) $K_{e2}/K_{\mu2}$ candidates are collected **concurrently**:  
\rightarrow no kaon flux measurement; several systematic effects cancel at first order  
(e.g. reconstruction/trigger efficiencies, time-dependent effects).

(2) Counting experiment, independently in **10 lepton momentum bins**  
(owing to strong momentum dependence of backgrounds and event topology)

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

- prescaling of $K_{\mu2}$ trigger  
- numbers of selected $K_{\mu2}$ candidates  
- numbers of background events  
- geometric acceptance correction  
- particle ID eff (measured)  
- trigger eff (measured)  
- LKr readout efficiency (measured)  
- MC simulations used to a limited extent

(3) Data-driven beam halo background subtraction:  
\rightarrow Alternating $K^+/K^-$ beams ($K^+$: 66%, $K^-$: 7%, simultaneous: 27%);  
\rightarrow $K^+$ only sample used to measure background in $K^-$ sample & vice versa.
**Large common part** (topological similarity)
- one reconstructed track (lepton candidate);
- geometrical acceptance cuts;
- K decay vertex: closest approach of lepton track & nominal kaon axis;
- veto extra LKr energy deposition clusters;
- track momentum: $13\text{GeV/c}<p<65\text{GeV/c}$.

**Kinematic identification**
missing mass $M_{miss}^2 = (P_K - P_l)^2$

$P_K$: average measured with $K_{3\pi}$ decays

$\rightarrow$ Sufficient $K_{e2}/K_{\mu2}$ separation at $p_{\text{track}}<30\text{GeV/c}$

**Lepton identification**

$E/p = (\text{LKr energy deposit/track momentum})$.

$(0.90 \text{ to } 0.95)<E/p<1.10$ for electrons,
$E/p<0.85$ for muons.

$\rightarrow$ Powerful $\mu^\pm$ suppression in $e^\pm$ sample ($\sim 10^6$)
**K_{\mu2} background in K_{e2} sample**

**Main background source**
Muons ‘catastrophic’ energy loss in LKr by emission of energetic bremsstrahlung photons.

\[ P_{\mu e} \sim 3 \times 10^{-6} \] (and momentum-dependent).

- **P_{\mu e} / R_K \sim 10\%:** K_{\mu2} decays represent a major background

**Direct measurement of P_{\mu e}**

Pb wall (9.2X_0) in front of LKr: suppression of \( \sim 10^{-4} \) positron contamination due to \( \mu \to e \) decay.

- K_{\mu2} candidates, track traversing Pb, \( p > 30\text{GeV}/c \), \( E/p > 0.95 \): positron contamination <10^{-8}.

- **P_{\mu e}** is modified by the Pb wall:
  - ionization losses in Pb (low p);
  - bremsstrahlung in Pb (high p).

The correction \( f_{Pb} = P_{\mu e}/P_{\mu e}^{Pb} \) is evaluated with a dedicated Geant4-based simulation

**4 data samples with different background conditions:**
- \( K^+(Pb), K^+(noPb) \)
- \( K^-(Pb), K^-(noPb) \).
Muon mis-identification

Result: \( B/(S+B) = (5.64 \pm 0.20)\% \)

Uncertainty is \( \sim 3 \) times smaller than the one obtained solely from simulation

Uncertainties:
- limited control data sample (0.16%),
- MC correction \( \delta f_{Pb} \) (0.12%),
- \( M^2_{miss} \) vs \( P_{track} \) correlation (0.08%).

Stability checks:
- vs lower \( E/p \) cut, upper HOD energy deposit.
145,958 $K^\pm \rightarrow e^\pm \nu$ candidates. 
Background: $B/(S+B) = (10.95 \pm 0.27)\%$. 
Electron ID efficiency: (99.28\% \pm 0.05)\%.

cf. KLOE: 13.8K candidates, 
~90\% electron ID efficiency, 16\% background

# Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>$B/(S+B)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu 2}$</td>
<td>$(5.64 \pm 0.20)%$</td>
</tr>
<tr>
<td>$K_{\mu 2} (\mu \rightarrow e)$</td>
<td>$(0.26 \pm 0.03)%$</td>
</tr>
<tr>
<td>$K_{e2\gamma} (SD^+)$</td>
<td>$(2.60 \pm 0.11)%$</td>
</tr>
<tr>
<td>$K_{e3(D)}$</td>
<td>$(0.18 \pm 0.09)%$</td>
</tr>
<tr>
<td>$K_{2\pi(D)}$</td>
<td>$(0.12 \pm 0.06)%$</td>
</tr>
<tr>
<td>Wrong sign K</td>
<td>$(0.04 \pm 0.02)%$</td>
</tr>
<tr>
<td>Beam halo</td>
<td>$(2.11 \pm 0.09)%$</td>
</tr>
<tr>
<td>Total</td>
<td>$(10.95 \pm 0.27)%$</td>
</tr>
</tbody>
</table>
K$_\mu^2$ sample

K$_\mu^2$ candidates

$\text{Na62}$

Log scale

42.817M candidates (pre-scaled trigger).

$B/(S+B) = (0.50 \pm 0.01)\%$, background dominated by beam halo.
Fit over 40 measurements (4 data samples x 10 momentum bins) including correlations: $\chi^2/\text{ndf}=47/39$.

\[
R_K = (2.488 \pm 0.007_{\text{stat}} \pm 0.007_{\text{syst}}) \times 10^{-5} = (2.488 \pm 0.010) \times 10^{-5}
\]

New result: July 2011

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\delta R_K \times 10^5$</th>
</tr>
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<tbody>
<tr>
<td>Statistical</td>
<td>0.007</td>
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<tr>
<td>$K_{\mu2}$ background</td>
<td>0.004</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^+\nu\gamma$ (SD(^+))</td>
<td>0.002</td>
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<tr>
<td>$K^+ \rightarrow \pi^0e^+\nu$, $K^+ \rightarrow \pi^+\pi^0$</td>
<td>0.003</td>
</tr>
<tr>
<td>Beam halo background</td>
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<td>Helium purity</td>
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<td>Acceptance correction</td>
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<td>DCH alignment</td>
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<tr>
<td>Electron identification</td>
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<tr>
<td>1TRK trigger efficiency</td>
<td>0.001</td>
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<tr>
<td>LKr readout efficiency</td>
<td>0.001</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.010</td>
</tr>
</tbody>
</table>

NA62 partial (40\%) data set result: $R_K = (2.487 \pm 0.013) \times 10^{-5}$ [PLB698 (2011) 105]

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$R_K$ world average

<table>
<thead>
<tr>
<th>World average</th>
<th>$\delta R_K \times 10^5$</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG 2008</td>
<td>2.447 ± 0.109</td>
<td>4.5%</td>
</tr>
<tr>
<td>July 2011</td>
<td>2.488 ± 0.009</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

Other limits on 2HDM-II:
$K^+ \rightarrow \pi^- \mu^+ \mu^+$, $K^- \rightarrow \pi^+ \mu^- \mu^-$

$K^+ \rightarrow \pi^- \mu^+ \mu^+$ proceeds if the neutrino is a Majorana particle:

**Tree diagram (dominating)**

**Box diagram**

\[
\text{BR} \approx 10^{-8} \times (\langle m_{\mu\mu} \rangle / \text{TeV})^2
\]


Analogously, neutrinoless double beta decay rate is $\sim \langle m_{ee} \rangle^2$.

\[
\langle m_{ll} \rangle = |\Sigma m_i U_{li}^2| \text{ is the effective Majorana neutrino mass}
\]

Best upper limits on LFV/LNV decays $K_{\pi ee}$, $K_{\pi \mu \mu}$, $K_{\pi \mu e}$ come from BNL E865.

The E865 $K_{\pi \mu \mu}$ limit, based on a (short) special run, is the weakest: $\text{BR} < 3 \times 10^{-9}$.

→ NA48/2 is competitive for $K_{\pi \mu \mu}$ mode: $\sim 8$ times larger data sample ($K^\pm$ collected in 2003–04).
The NA48/2 limit

PLB 697 (2011) 107

$K^{\pm} \rightarrow \pi^{\pm} \mu^+ \mu^-$ analysis: 3,120 candidates
($\sim$4 times world sample),
(3.3$\pm$0.7)$\%$ background.
BR, CPV and FB asymmetries measured.

Lepton number violating decay:

$N_{\text{data}} = 52$
$N_{\text{bkg}} = 52.6 \pm 19.8_{\text{syst.}}$

$\text{BR} < 1.1 \times 10^{-9}$ (90% CL)

A factor of 3 improvement on the upper limit for $\text{BR}(K^+ \rightarrow \pi^- \mu^+ \mu^+)$. 

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$K^\pm \rightarrow \pi^0 \mu^\pm \nu_\mu$ ($K_{\mu 3}$) form factors

Most precise measurement of $|V_{us}|$: from $K \rightarrow \pi^0 \mu^\pm \nu_\mu$ decays

$$\Gamma_{K_{\mu 3}(\gamma)} = \frac{C_K^2 G_F^2 m_K^5}{192 \pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_{K\mu}(\lambda_0) (1 + \delta_{SU(2)}^\ell + \delta_{EM}^\ell)^2$$

Decay rates

Phase space integrals depend on form factors

Data sample: NA48/2 2004 special run with a minimum bias trigger

$\rightarrow 3.4 \times 10^6 K_{\mu 3}$ candidates with 0.8% background

Missing mass: $M^2 = (P_K - P_\mu - P_\pi)^2$

$K^\pm \rightarrow \pi^0 \mu^\pm \nu_\mu$
**K_{\mu3} form factor fits**

Form-factor parameterizations:

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

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

- **POLE**
  \[
  \tilde{f}_{+,0}(t) = \frac{m_{\nu,s}^2}{m_{\nu,s}^2 - t}
  \]

- **DISPERITIVE**
  \[
  f_0(t) = f_+(t) + f_-(t) = \frac{t}{m_K^2 - m_{\pi}^2} f_-(t)
  \]
  \[
  \tilde{f}_+(t) = \exp \left[ \frac{t}{m_{\pi}^2} (\Lambda_+ + H(t)) \right]
  \]
  \[
  \tilde{f}_0(t) = \exp \left[ \frac{t}{-\Delta_{K\pi}} (\ln C - G(t)) \right]
  \]

---

**K_{\mu3} world data: polynomial parameterization**

- **NA48/2 preliminary results**

<table>
<thead>
<tr>
<th>Quadratic ((\times 10^3))</th>
<th>Dispersive ((\times 10^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda'_+)</td>
<td>30.3±2.7±1.4</td>
</tr>
<tr>
<td>(\lambda'_+)</td>
<td>1.0±1.0±0.7</td>
</tr>
<tr>
<td>(\Lambda_+)</td>
<td>15.6±1.2±0.9</td>
</tr>
<tr>
<td>Pole ((\text{MeV}/c^2))</td>
<td></td>
</tr>
<tr>
<td>(m_\nu)</td>
<td>836±7±9</td>
</tr>
<tr>
<td>(m_s)</td>
<td>1210±25±10</td>
</tr>
<tr>
<td>Dispensive ((\times 10^3))</td>
<td></td>
</tr>
<tr>
<td>(\ln C)</td>
<td>28.5±0.6±0.7±0.5</td>
</tr>
<tr>
<td>(\ln C)</td>
<td>188.8±7.1±3.7±5.0</td>
</tr>
</tbody>
</table>

Further details:

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Summary

• New NA62 measurement of $R_K = \text{BR}(K_{e2})/\text{BR}(K_{\mu2})$ presented. Combined experimental precision has improved by an order of magnitude over the last 3 years, but is still an order of magnitude worse than the SM prediction.

• $R_K$ experiment and SM currently agree at $1.2\sigma$ level.

• NA48/2 upper limit on LNV $\text{BR}(K^+ \rightarrow \pi^- \mu^+ \mu^+)$ is an improvement by a factor of 3: $\text{BR} < 1.1 \times 10^{-9} \rightarrow \langle m_{\mu\mu} \rangle < 300$ GeV at 90% CL.

• NA48/2 precisely measured the $K^\pm_{\mu3}$ form factors: $\rightarrow$ further improvement in the determination of $|V_{us}|$.

Future plans of kaon physics at CERN: talk by Paolo Valente, “Detector R&D and Data Handling” session