Lepton Universality Tests with Leptonic Kaon Decays

Evgueni Goudzovski

on behalf of the CERN NA62 collaboration

(Birmingham, Bratislava, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Liverpool, Louvain, Mainz, Merced, INR Moscow, Napoli, Perugia, Pisa, IHEP Protvino, Roma I, Roma II, Saclay, San Luis Potosí, SLAC, Sofia, Torino, TRIUMF)

Outline:

1) Purely leptonic meson decays as a SM testing ground
2) New $R_K = \text{BR}(K \rightarrow e\nu)/\text{BR}(K \rightarrow \mu\nu)$ measurement by CERN NA62
3) The KLOE $R_K$ measurement and the world average
4) Conclusions

BEACH 2010
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Leptonic meson decays: a SM testing ground
Leptonic meson decays: $P^+ \rightarrow l^+ \nu$

Angular momentum conservation $\rightarrow$ SM contribution is suppressed

$$\Gamma(P^+ \rightarrow l^+ \nu) = \frac{G_F^2 M_P M_l^2}{8\pi} \left(1 - \frac{M_l^2}{M_P^2}\right)^2 f_P^2 |V_{qq'}|^2$$

Models with 2 Higgs doublets (2HDM-II including SUSY): sizeable charged Higgs ($H^\pm$) exchange contributions


(numerical examples for $M_H=500\text{GeV}/c^2$, $\tan\beta = 40$)

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\Delta\Gamma/\Gamma_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \rightarrow l\nu$</td>
<td>$\approx -2(m_\pi/m_H)^2 m_d/(m_u+m_d) \tan^2\beta \approx -2 \times 10^{-4}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow l\nu$</td>
<td>$\approx -2(m_K/m_H)^2 \tan^2\beta \approx -0.3%$</td>
</tr>
<tr>
<td>$D^+_s \rightarrow l\nu$</td>
<td>$\approx -2(m_D/m_H)^2 (m_s/m_c) \tan^2\beta \approx -0.4%$</td>
</tr>
<tr>
<td>$B^+ \rightarrow l\nu$</td>
<td>$\approx -2(m_B/m_H)^2 \tan^2\beta \approx -30%$</td>
</tr>
</tbody>
</table>

**H$^\pm$ exchange in $B^+ \rightarrow \tau^+ \nu$:**

BaBar+Belle: $\text{Br}_{exp}(B \rightarrow \tau\nu) = (1.42 \pm 0.43) \times 10^{-4}$

Standard Model: $\text{Br}_{SM}(B \rightarrow \tau\nu) = (1.33 \pm 0.23) \times 10^{-4}$

$$(\text{SM uncertainties: } \delta (f_B^2)/f_B^2 = 10\%, \delta |V_{ub}|^2/|V_{ub}|^2 = 13\%)$$

Search for new physics is obstructed by hadronic uncertainties ($f_P$)
Comparison of $|V_{us}|$ determined from helicity suppressed $K^+ \rightarrow \mu^+ \nu$ decays vs helicity allowed $K^+ \rightarrow \pi^0 \mu^+ \nu$ decays

To reduce the uncertainties of hadronic and EM corrections:

$R_{\mu23} = \left( \frac{f_K/f_\pi}{f_+(0)} \right)^{-1} \left( \frac{|V_{us}|}{|V_{ud}|} \frac{f_K}{f_\pi} \right)_{\mu^2} \frac{|V_{ud}|_{0^+ \rightarrow 0^+}}{|V_{us}| f_+(0) \ell_3}$

Charged Higgs mediated contribution:

$R_{\mu23} \approx 1 - \frac{m^2_{K^+}}{m^2_{H^+}} \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta}$

Experiment: $R_{\mu23} = 0.999(7)$, $|V_{us}|^2 + |V_{ud}|^2 - 1 = -0.0001(6)$.

Precision limited by lattice ICQ input.

(Flavianet Kaon WG, arXiv:1005.2323)
\[ R_K = \frac{K_{e2}/K_{\mu2}} \text{in the SM} \]

Observable sensitive to lepton flavour violation and its SM expectation:

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

(similarly, \( R_\pi \) in the pion sector)

**Helicity suppression:** \( f \sim 10^{-5} \)

- **SM prediction:** excellent sub-permille accuracy due to cancellation of hadronic uncertainties.
- Measurements of \( R_K \) and \( R_\pi \) have long been considered as tests of lepton universality.
- **Recently understood:** helicity suppression of \( R_K \) might enhance sensitivity to non-SM effects to an experimentally accessible level.

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

\[
R_\pi^{\text{SM}} = (12.352 \pm 0.001) \times 10^{-5}
\]


E. Goudovski / Perugia, 24 June 2010
\[ R_K = \frac{K_{e2}}{K_{\mu2}} \text{ beyond the SM} \]

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

- \( K_{l2} \) can proceed via exchange of charged Higgs \( H^\pm \) instead of \( W^\pm \)
- \( \rightarrow \) Does not affect the ratio \( R_K \)

**2HDM - one-loop level**

- Dominant contribution to \( \Delta R_K \): \( H^\pm \) mediated \( \text{LFV} \) (rather than \( \text{LFC} \)) with emission of \( \nu_\tau \)
- \( \rightarrow R_K \) enhancement can be experimentally accessible

\[ R_{K}^{\text{LFV}} \approx R_{K}^{\text{SM}} \left[ 1 + \left( \frac{m_K^4}{M_{H^\pm}^4} \right) \left( \frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right] \]

- Up to \( \sim 1\% \) effect in large (but not extreme) \( \tan \beta \) regime with a massive \( H^\pm \)

**Example:**

\( (\Delta_{13} = 5 \times 10^{-4}, \tan \beta = 40, M_H = 500 \text{ GeV/c}^2) \)

lead to \( R_K^{\text{MSSM}} = R_K^{\text{SM}} (1+0.013) \).

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

- \( B_{\mu\nu}/B_{\tau\nu} \rightarrow \sim 50\% \) enhancement;
- \( B_{e\nu}/B_{\tau\nu} \rightarrow \) enhanced by \( \sim \) one order of magnitude.

Out of reach: \( Br^{\text{SM}}(B_e\nu) \approx 10^{-11} \)

**Notes:**

- Analogous SUSY effect in pion decay is suppressed by a factor \( (M_\pi/M_K)^4 \approx 6 \times 10^{-3} \)

(see also PRD76 (007) 095017)

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$R_K$ & $R_\pi$: experimental status

Kaon experiments:

- PDG’08 average (1970s measurements):
  \[ R_K = (2.45 \pm 0.11) \times 10^{-5} \ (\delta R_K / R_K = 4.5\%) \]

  \[ 13.8K K_{e2} \text{ candidates, 16\% background.} \]
  \[ R_K = (2.493 \pm 0.031) \times 10^{-5} \ (\delta R_K / R_K = 1.3\%). \]
  (EPJ C64 (2009) 627)

  preliminary result presented at Kaon’09:
  \[ 51.1K K_{e2} \text{ candidates, } \delta R_K / R_K = 0.7\%. \]
  (arXiv:0908.3858, 1005.1192)

- Now: NA62 final result, same data set:
  \[ 60.0K K_{e2} \text{ candidates, } \delta R_K / R_K = 0.5\%. \ (new!) \]

Pion experiments:

- PDG’08 average (1980s, 90s measurements):
  \[ R_\pi = (12.30 \pm 0.04) \times 10^{-5} \ (\delta R_\pi / R_\pi = 0.3\%) \]

- Current projects: PEN@PSI (stopped \( \pi \)) running (CIPANP 2009; arXiv:0909.4358)
  PIENU@TRIUMF (in-flight) proposed (T. Numao, PANIC’08 proceedings, p.874)
  \[ \delta R_\pi / R_\pi \sim 0.05\% \text{ foreseen (similar to SM precision)} \]

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\[ R_K \text{ world average (June 2009)} \]
The new $R_K$ measurement by CERN NA62
NA48/NA62 at CERN

NA48/NA62: centre of the LHC

SPS

NA48:
discovery of direct CPV

1997: $\varepsilon'/\varepsilon: K_L+K_S$

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: $K^e_2/K^\mu_2$ tests

2008: $K^e_2/K^\mu_2$ tests

2007–2012: design & construction

2013–2015: $K^+\to\pi^+\nu\bar{\nu}$ data taking

NA62 (phase I):
Bern ITP, Birmingham, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Mainz, Merced, Moscow INR, Napoli, Perugia, Pisa, IHEP Protvino Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, Torino, TRIUMF

NA62 (phase II):
G. Ruggiero's talk

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Data taking conditions optimized for a precision $K_{e2}/K_{\mu2}$ measurement: a low intensity run with a minimum bias trigger.

Primary SPS protons (400 GeV/c): $1.8 \times 10^{12}$/SPS spill

Unseparated secondary positive beam: $p = (74.0 \pm 1.6)$ GeV/c.

Entrance to the 114m long vacuum decay volume:
$2.5 \times 10^7$ particles/SPS spill

Composition: $K^+(\pi^+) = 5\% (63\%)$.
$K^+$ decaying in vacuum tank: 18\%.
**Data taking:**

- Four months in 2007 (23/06–22/10): ~400K SPS spills, 300TB of raw data (90TB recorded); reprocessing & data preparation finished.
- Two weeks in 2008 (11/09–24/09): special data sets allowing reduction of the systematic uncertainties.

**Principal subdetectors for R_{K^0}**:

- Magnetic spectrometer (4 DCHs):
  4 views/DCH: redundancy \(\Rightarrow\) efficiency; \(\Delta p/p = 0.47\% + 0.020\% \times p\) \([GeV/c]\)
- Hodoscope
  fast trigger, precise time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  \(\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%\) \([GeV]\);
  \(\sigma_x = \sigma_y = 0.42/E^{1/2} + 0.6\text{mm} (1.5\text{mm}@10\text{GeV}).\)
Measurement strategy

(1) \( K_{e2}/K_{μ2} \) candidates are collected \textit{concurrently}:
- analysis does not rely on kaon flux measurement;
- several systematic effects cancel at first order (e.g. reconstruction/trigger efficiencies, time-dependent effects).

(2) counting experiment, independently in \textbf{10 lepton momentum bins} (owing to strong momentum dependence of backgrounds and event topology)

\[
R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{μ2}) - N_B(K_{μ2})} \cdot \frac{A(K_{μ2}) \times f_μ \times ε(K_{μ2})}{A(K_{e2}) \times f_e \times ε(K_{e2})} \cdot \frac{1}{f_{LKr}}
\]

- \( N(K_{e2}), N(K_{μ2}) \): numbers of selected \( K_{l2} \) candidates;
- \( N_B(K_{e2}), N_B(K_{μ2}) \): numbers of background events;
- \( A(K_{e2}), A(K_{μ2}) \): MC geometric acceptances (no ID);
- \( f_e, f_μ \): directly measured particle ID efficiencies;
- \( ε(K_{e2})/ε(K_{μ2})>99.9\% \): \( E_{LKr} \) trigger condition efficiency;
- \( f_{LKr}=0.9980(3) \): global LKr readout efficiency;
- \( D=150 \): downscaling factor of the \( K_{μ2} \) trigger.

(3) \textbf{MC simulations used to a limited extent}:
- Geometrical part of the acceptance correction comes from simulation;
- PID, trigger, readout efficiencies are \textit{measured directly}.
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

→ Sufficient $K_{e2}/K_{\mu2}$ separation at $p_{\text{track}} < 25 \text{ GeV/c}$

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.

→ Powerful $\mu^\pm$ suppression in $e^\pm$ sample ($\sim 10^6$)

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**K_{μ2} background in K_{e2} sample**

**Main background source**
Muons “catastrophic” energy loss in LKr by emission of energetic bremsstrahlung photons. $P_{μe} \sim 3 \times 10^{-6}$ (and momentum-dependent).

$$P_{μe} / R_K \sim 10\%:$$
$K_{μ2}$ decays represent a major background

**Direct measurement of $P_{μe}$**
Pb wall ($9.2X_0$) in front of LKr: suppression of $\sim 10^{-4}$ positron contamination due to $μ→e$ decay.

$K_{μ2}$ candidates, track traversing Pb, $p>30$GeV/c, $E/p>0.95$: positron contamination $<10^{-8}$.

$P_{μe}$ is modified by the Pb wall:
→ ionization losses in Pb (low p);
→ bremsstrahlung in Pb (high p).

The correction $f_{Pb} = P_{μe}/P_{μe}^{Pb}$ is evaluated with a dedicated Geant4-based simulation

Muon mis-identification

Result: \( B/(S+B) = (6.10 \pm 0.22)\% \)

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

Uncertainties
Limited data sample (0.16\%);
MC correction (0.12\%);
\( \mathcal{M}^2_{\text{miss}} \) vs \( P_{\text{track}} \) correlation (0.08\%).
**$K_{\mu 2}$ with $\mu \rightarrow e$ decay in flight**

For NA62 conditions (74 GeV/c beam, ~100 m decay volume),
\[ N(K_{\mu 2}, \mu \rightarrow e \text{ decay})/N(K_{e 2}) \sim 10 \]

$K_{\mu 2}$ ($\mu \rightarrow e$) naively seems a huge background

Muons from $K_{\mu 2}$ decay are fully polarized:
Michel electron distribution

\[
d^2\Gamma/dxd(cos\theta) \sim x^2[(3-2x) - cos\theta(1-2x)]
\]

\[ x = E_e/E_{\max} \approx 2E_e/M_{\mu}, \]

$\theta$ is the angle between $p_e$ and the muon spin
(all quantities are defined in muon rest frame).

Result: \[ B/(S+B) = (0.27 \pm 0.04)\% \]

Important but not dominant background

Only energetic forward positrons are selected as $K_{e 2}$ candidates
They are naturally suppressed by the muon polarisation
(radiative corrections provide another ~10% suppression)
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 radiation is not helicity suppressed. KLOE measurement of the form factor leads to $\text{BR}(SD^+, \text{full phase space}) = (1.37\pm0.06)\times10^{-5}$. (EPJC64 (2009) 627)

SD background contamination $B/(S+B) = (1.15\pm0.17)\%$

Conservative uncertainty $(3\times\delta \text{BR}_{\text{KLOE}})$ to accommodate the observed $R_K$ variation w.r.t. the LKr veto selection condition.

A new $K_{e2\gamma}$ (SD$^+$) measurement is being performed by NA62.

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Electrons produced by beam halo muons via $\mu \rightarrow e$ decay can be kinematically and geometrically compatible to genuine $K_{e2}$ decays.

**Background measurement:**
- Halo background much higher for $K_{e2}^-$ ($\sim 20\%$) than for $K_{e2}^+$ ($\sim 1\%$).
- Halo background in the $K_{\mu2}$ sample is considerably lower.
- $\sim 90\%$ of the data sample is $K^+$ only, $\sim 10\%$ is $K^-$ only.
- $K^+$ halo component is measured directly with the $K^-$ sample and vice versa.

The background is measured to sub-permille precision, and strongly depends on decay vertex position and track momentum.

The selection criteria (esp. $Z_{\text{vertex}}$) are optimized to minimize the halo background.

$B/(S+B) = (1.14 \pm 0.06)\%$

**Uncertainty:**
1) limited size of control sample;
2) $\pi$, $K$ decays upstream vacuum tank.
NA62 estimated total $K_{e2}$ sample:

~130K $K^+$ & ~20K $K^-$ candidates.

Positron ID efficiency: $(99.27 \pm 0.05)\%$.

$B/(S+B) = (8.8 \pm 0.3)\%$.

$K_{e2}$ candidates

59,963 $K^+ \rightarrow e^+\nu$ candidates.

cf. KLOE: 13.8K candidates ($K^+$ and $K^-$), ~90% electron ID efficiency, 16% background

NA62 estimated total $K_{e2}$ sample:

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# Backgrounds: summary

<table>
<thead>
<tr>
<th>Source</th>
<th>B/(S+B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu 2}$</td>
<td>(6.10±0.22)%</td>
</tr>
<tr>
<td>$K_{\mu 2} (\mu \rightarrow e)$</td>
<td>(0.27±0.04)%</td>
</tr>
<tr>
<td>$K_{e 2\gamma} (SD^+)$</td>
<td>(1.15±0.17)%</td>
</tr>
<tr>
<td>Beam halo</td>
<td>(1.14±0.06)%</td>
</tr>
<tr>
<td>$K_{e 3(D)}$</td>
<td>(0.06±0.01)%</td>
</tr>
<tr>
<td>$K_{2\pi(D)}$</td>
<td>(0.06±0.01)%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>(8.78±0.29)%</td>
</tr>
</tbody>
</table>

**Record $K_{e 2}$ sample:**
59,963 candidates with low background
B/(S+B) = (8.8±0.3)%

Lepton momentum bins are differently affected by backgrounds and thus the systematic uncertainties.
**K_{\mu 2}: partial (40%) data set**

**Backgrounds**

<table>
<thead>
<tr>
<th>Source</th>
<th>B/(S+B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam halo</td>
<td>(0.38±0.01)%</td>
</tr>
<tr>
<td>Total</td>
<td>(0.38±0.01)%</td>
</tr>
</tbody>
</table>

18.030 M candidates with low background $B/(S+B) = 0.38\%$

(The $K_{\mu 2}$ trigger was pre-scaled by $D=150$)
Positron ID efficiency is measured with $K^+ \rightarrow \pi e
$ and special $K_L \rightarrow \pi e
$ samples: integral $\varepsilon = (99.27 \pm 0.05)\%$

LKr energy response is calibrated for every $2\times2\,\text{cm}^2$ cell within acceptance

A typical inefficiency map

(an effect of a loose cable is visible in this map)

### Colour code
- Ineff $< 1.2\%$
- Ineff $= (1.2 - 2)\%$
- Ineff $= (2.0 - 4.0)\%$
- Ineff $= (4.0 - 10)\%$
- Ineff $> 10\%$

ID inefficiency vs momentum

E/p $> 0.90$

E/p $> 0.95$

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NA62 final result (40% data set)

\[ R_K = (2.486 \pm 0.011_{\text{stat}} \pm 0.007_{\text{syst}}) \times 10^{-5} = (2.486 \pm 0.013) \times 10^{-5} \]

(new: June 2010)

Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta R_K \times 10^5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>0.011</td>
</tr>
<tr>
<td>( K_{\mu2} )</td>
<td>0.005</td>
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<tr>
<td>( \text{BR}(K_{e2\gamma} SD^+) )</td>
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<td>Beam halo</td>
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<td>Acceptance corr.</td>
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<td>DCH alignment</td>
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<tr>
<td>1-track trigger</td>
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<tr>
<td><strong>Total</strong></td>
<td>0.013</td>
</tr>
</tbody>
</table>

(0.52% precision)

Preliminary result: \( R_K = 2.500(16) \times 10^{-5} \).

Shift due to multi-photon corrections to the \( K_{e2\gamma} \) (IB) decay.
The KLOE $R_K$ measurement and the world average
KLOE: $\sim$100 MeV kaons

DAΦNE: $e^+e^-$ collider at LNF Frascati

- CM energy $\sim m_\phi = 1.02$ GeV;
- BR($\phi \rightarrow K^+K^-$) = 49.2%;
- $\phi$ production cross-section $\sigma_\phi = 1.3 \mu$b;
- Data sample (2001–05): 2.5 fb$^{-1}$.

$K_{e2}/K_{\mu2}$ selection technique (vs NA62):

- Kinematics: by $M^2_{\text{lep}}$ (equivalent to $M_{\text{miss}}^2$);
- PID: neural network with 12 input parameters (vs E/p for NA62).
KLOE $K_{e2}$ analysis

NN output vs $M^2_{lep}$

2D fit in ($NN_{out}$ vs $M^2_{lep}$) plane.
$\chi^2/ndf = 113/112$.
Projection shown here: $NN_{out}>0.96$.

Identification efficiency: $\sim 90\%$

Uncertainties $\delta R_K/R_K$ (%)

<table>
<thead>
<tr>
<th></th>
<th>(\delta R_K/R_K) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
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<tr>
<td>$K_{\mu 2}$ subtraction</td>
<td>0.3</td>
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<tr>
<td>$K_{e2\gamma}$ (SD$^+$)</td>
<td>0.2</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>0.6</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Full data sample analyzed

[EPJ C64 (2009) 627]

13.8K $K_{e2}$ candidates, 16% background

KLOE-2: starting in 2010, expect $\delta R_K/R_K=0.4\%$

[arXiv:1003.3862]
For non-tiny values of the LFV slepton mixing \( \Delta_{13} \), sensitivity to \( H^\pm \) in \( R_K = K_{e2}/K_{\mu2} \) is better than in \( B \to \tau \nu \).
Conclusions & prospects

• Leptonic meson decays and their ratios are well-suited for stringent tests of the Standard Model. In particular, \( R_K = \frac{K_e^2}{K_{\mu}^2} \) is sensitive to lepton flavour violation in multi-Higgs models.

• NA62 data taking in 2007/08 was optimised for \( R_K \) measurement. NA62 \( K_e^2 \) sample is \(~10\) times the world sample, with excellent \( K_e^2/K_{\mu}^2 \) separation (99.3% electron ID efficiency, 6% \( K_{\mu}^2 \) background).

• Final result based on \(~40\)% of the NA62 \( K_e^2 \) sample \( R_K = (2.486 \pm 0.013) \times 10^{-5} \) reached a record 0.5% accuracy. A timely result, as searches for New Physics at the LHC are starting.

• Future experimental improvements on \( R_K \):
  1) the full NA62 data sample of 2007/08: \( \delta R_K/R_K < 0.4\% \);
  2) NA62 phase II (2012–2015) and KLOE-2 (2010–) aim at \(~0.2\)% and \(~0.4\)% precision.
Spare slides
Trigger logic

Minimum bias (high efficiency, but low purity) trigger configuration used

- $K_{e2}$ condition: $Q_1 \times E_{\text{LKr}} \times 1\text{TRK}$. Purity $\sim 10^{-5}$.
- $K_{\mu2}$ condition: $Q_1 \times 1\text{TRK}/D$, downscaling (D) 50 to 150. Purity $\sim 2\%$.

- Efficiency of $K_{e2}$ trigger: monitored with $K_{\mu2}$ & other control triggers.
- Different trigger conditions for signal and normalization!

NA62 trigger in 2007/08

- $E_{\text{LKr}}$: energy deposit of at least 10 GeV
- $Q_1$: coincidence in the two planes
- $1\text{TRK}$: very loose condition on activity in DCHs against high multiplicity events

HOD: coincidence in the two planes
LKr: energy deposit of at least 10 GeV
DCHs: very loose condition on activity in DCHs against high multiplicity events

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**K_{l3}**: lepton universality test

Comparison of $|V_{us}|$ determined from $K_{e3}$ vs $K_{\mu3}$ decays

$$r_{\mu e} = \frac{[|V_{us}|f^+(0)]_{\mu3, \text{exp}}^2}{[|V_{us}|f^+(0)]_{e3, \text{exp}}^2} = \frac{\Gamma_{K\mu3} I_{e3} (1 + 2\delta_{EM}^{Ke})}{\Gamma_{Ke3} I_{\mu3} (1 + 2\delta_{EM}^{K\mu})} = (g_\mu/g_e)^2 = 1$$

Experimental results

$K^\pm$: $r_{\mu e} = 0.998(9)$

$K^0$: $r_{\mu e} = 1.003(5)$

$\rightarrow r_{\mu e} = 1.002(4)$

Non-kaon measurements:

$\pi \rightarrow l\nu$: $r_{\mu e} = 1.0042(33)$ (PRD 76 (2007) 095017)

$\tau \rightarrow l
\nu\nu$: $r_{\mu e} = 1.000(4)$ (Rev.Mod.Phys. 78 (2006) 1043)

The sensitivity in kaon sector approaches those obtained in the other fields.

SM lepton coupling at the $W \rightarrow l\nu$ vertex

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