Test of Lepton Flavour Universality in Kaon Decays at CERN NA62 experiment

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for the NA62 collaboration

(Bern ITP, Birmingham, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, IHEP Protvino, INR Moscow, Liverpool, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin)

IFAE 2011
Perugia (Italy), 27th - 29th April 2011
**R_K in the SM**
- Ideal test of SM
- Hadronic uncertainties cancel in the ratio $R_K = K_{e2}/K_{\mu2}$
- Helicity suppression: $\sim 10^{-5}$

$R_K =$\[ \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} \]

$R_K =$\[ \frac{m_e^2}{m_\mu^2} \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot \left( 1 + \delta R_K^{\text{rad.corr.}} \right) \]

- Helicity suppression
- Radiative correction (few%)

**R_K beyond SM**
- Indirect search of NP
- MSSM scenario: LFV terms (charged Higgs coupling) introduces extra contributions to the SM amplitude
- Up to 1% variation

$R_K^{\text{LFV}} \approx R_K^{\text{SM}} \left[ 1 + \left( \frac{m_K^4}{m_{H^+}^4} \right) \left( \frac{m_\tau^2}{m_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right]$

**Experimental status:**
- PDG'08 average (1970s measurements): $R_K = (2.45 \pm 0.11) \times 10^{-5}$ ($\delta R_K/R_K = 4.5\%$)
- Recent improvement KLOE (Frascati): $R_K = (2.493 \pm 0.031) \times 10^{-5}$ ($\delta R_K/R_K = 1.3\%$)

**NA62 (phase I) goal:** measurement of $R_K$ with accuracy level below 1% ($\sim 0.5\%$)
Primary SPS protons (400 GeV/c): $1.8 \times 10^{12}$/SPS spill
Un-separated secondary positive beam: p=$(74.0\pm1.6)$ GeV/c

K$^+$ decaying in vacuum tank: 18%
Data Taking and Detector

- Four months in 2007:
  ~ 400K SPS spills, 300TB of raw data
- Two weeks in 2008:
  special data sets allowing reduction of the systematic uncertainties.
- Beam composition: \( K^+(\pi^+) = 5\%(63\%) \)

**Principal subdetectors for \( R_K \):**

- **Magnetic spectrometer (4 DCHs):**
  4 views/DCH \( \rightarrow \) high efficiency; 
  \( \sigma_p/p = 0.47\% + 0.020\%p \) [GeV/c]
- **Hodoscope:**
  fast trigger, precise time measurement (150ps).
- **Liquid Krypton EM calorimeter (LKr):**
  High granularity, quasi-homogeneous;
  \( \sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\% \) [GeV]
  \( \sigma_x = \sigma_y = 0.42/E^{1/2} + 0.6\text{mm} \) (1.5mm@10GeV).
**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;
- Correction for bkg from catastrophic energy loss of muons in the LKr;

(3) PID, trigger, readout efficiencies are **measured directly** from data.

*Analysis in 10 bins of reconstructed lepton momentum:*
(owing to strong momentum dependence of backgrounds and event topology)

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

- $K_{\mu2}$ downscaling
- $K_{e2}$ downscaling
- Signal events
- Background events
- Particle ID eff
- Trigger efficiency
- Global LKr readout eff
**Ke2 vs Kμ2 selection**

Large common part (topological similarity)
- one reconstructed track;
- geometrical acceptance cuts;
- K decay vertex: closest distance of approach between track & kaon axis;
- veto extra LKr energy deposition clusters;

Kinematic identification
- 2 body decay $M^2_{miss} = (P_K - P_l)^2$
  (kaon momentum measured with $K_{3\pi}$ decays)
- sufficient $K_e2/K_\mu2$ separation up to 25GeV/c

Particle Identification
- $E/p = (\text{LKr energy deposit}/\text{track momentum})$
- $(0.9 \text{ to } 0.95) < E/p < 1.10$ for electrons
- $E/p < 0.85$ for muons
  → Powerful $\mu^\pm$ suppression in $e^\pm$ sample: $\sim 10^6$
The main background in the \( K_{e2} \) sample is due to catastrophic energy loss of muons in the LKr \( (E_{\text{LKr}}/p_{\text{DCH}} > 0.95 \rightarrow \text{misID events as } K_{e2}) \).

To measure directly \( P(\mu \rightarrow e) \) a “lead wall” (~9.2 \( x_0 \)) has been installed on ~18% LKr surface for ~50% of the run time:

\[ P(\mu \rightarrow e) \sim (3 \div 5) \cdot 10^{-6} \]


\( K_{\mu 2} \) candidates, track traversing Pb, \( p > 30 \text{GeV/c}, \ E/p > 0.95 \): electron contamination <10\(^{-8}\).

The result agrees with Geant4 simulation. (p dependence)

\( P(\mu \rightarrow e) \) is modified by the Pb wall: the correction \( f_{\text{Pb}} \) is evaluated with a dedicated Geant4-based simulation.

Result: \( B/(S+B) = (6.11 \pm 0.22)\% \)

Uncertainty ~3 times smaller than using only simulation.
**Partial (40%) data set**

- **KE2** background sources:
  - $K_{\mu2}$ (CB) $\rightarrow K_{\mu2}$ (m→e) measured with MC
  - Beam halo directly measured on data (special runs)
  - $K_{e2\gamma}$ (DE$^+$) limited by the error on the measured BR (Ongoing NA62 measurement → 2% precision)
  - $K_{2\pi D}$
  - $K_{e3D}$

- NA62 estimated total $K_{e2}$ sample: ~146k candidates (11% bkg)

- 59,813 $K^+ \rightarrow e^+\nu$ candidates.
  - Positron ID efficiency: (99.27±0.05)%.
  - $B/(S+B) = (8.71±0.24)%$.

- NA62 estimated total $K_{e2}$ sample:
  - ~146k candidates (11% bkg)
NA62 Result (40% data set)

\[ R_K = (2.487 \pm 0.011_{\text{stat}} \pm 0.007_{\text{syst}}) \times 10^{-5} = (2.487 \pm 0.013) \times 10^{-5} \]

Recently published: PLB B698 (2011) 105

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_{\mu 2} )</td>
<td>0.005</td>
</tr>
<tr>
<td>( \text{BR}(K_{\ell 2\gamma} \text{ SD}^+) )</td>
<td>0.001</td>
</tr>
<tr>
<td>Helium purity</td>
<td>0.003</td>
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<tr>
<td>Beam halo</td>
<td>0.001</td>
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<tr>
<td>Acceptance</td>
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<tr>
<td>DCH alignment</td>
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</tr>
<tr>
<td>Positron ID</td>
<td>0.001</td>
</tr>
<tr>
<td>Lkr readout inef</td>
<td>0.001</td>
</tr>
<tr>
<td>1-track trigger</td>
<td>0.002</td>
</tr>
<tr>
<td>Total</td>
<td>0.013</td>
</tr>
</tbody>
</table>

(0.5% precision)

Measurement of \( R_K \times 10^5 \) in lepton momentum bins (systematic errors included, partially correlated)
World average $\delta R_K \times 10^5$ Precision

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG'08</td>
<td>2.447±0.109</td>
<td>4.5%</td>
</tr>
<tr>
<td>January 2011</td>
<td>2.487±0.012</td>
<td>0.48%</td>
</tr>
</tbody>
</table>

Any significant enhancement with respect to the SM would be evidence of new physics.
Conclusions & Future Prospects

- Due to the suppression of the $K_{e2}$ decay in the SM, the measurement of $R_K$ is well-suited for a stringent SM test.

- Preliminary result based on ~40% of the NA62 $K_{e2}$ sample: $R_K = (2.487 \pm 0.013) \times 10^{-5}$, reaching a new level of accuracy of ~0.5%.

- With the full 2007/2008 NA62 data sample, the precision is expected to improve to a level $\delta R_K/R_K = 0.4\%$.

- One of the NA62 (phase-II, see V.Palladino’s talk) goals will be to improve the precision on the $R_K$ measurement by a factor of ~2.
Spares
Leptonic meson decays: $P^+ \rightarrow l^+ \nu$

SM contribution is helicity suppressed:

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

Sizeable tree level charged Higgs ($H^\pm$) contributions in models with two Higgs doublets (2HDM including SUSY)


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

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

(BaBar, Belle: $Br_{\text{exp}}(B \rightarrow \tau \nu)=(1.64 \pm 0.34) \times 10^{-4}$
Standard Model: $Br_{\text{SM}}(B \rightarrow \tau \nu)=(1.20 \pm 0.25) \times 10^{-4}$

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

Challenged by hadronic uncertainties

~3σ discrepancy between $B^\tau \nu$ measurement and expectation from a global CKM fit

[UTfit, CKMfitter, ICHEP2010]
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:

$R_{\mu 23} = \left( \frac{f_{K}/f_{\pi}}{f_+(0)} \right)^{-1} \left( \frac{|V_{us}|}{|V_{ud}|} \frac{f_{K}}{f_{\pi}} \right)_{\mu 2} \frac{|V_{ud}|_{0^+ \rightarrow 0^+}}{[|V_{us}|f_+(0)]_{\ell 3}}$

Lattice QCD input

Measured with $K_{\mu 2}/\pi_{\mu 2}$

Measured with $K \rightarrow \pi \mu \nu$

Charged Higgs mediated contribution:

$R_{\mu 23} \approx 1 - \frac{m_{K^+}^2}{m_{H^+}^2} \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta}$

Experiment: $R_{\mu 23} = 0.999(7)$,

$|V_{us}|^2 + |V_{ud}|^2 - 1 = -0.0001(6)$.

Precision limited by lattice QCD input.

(Flavianet Kaon WG, arXiv:1005.2323)
**R\textsubscript{K} in the SM**

A precise measurement of the ratio of $K \rightarrow l\nu$ leptonic decays provides an ideal 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

$R\textsubscript{K}$ is sensitive to lepton flavour violation and its SM expectation:

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

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

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

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

**Recently understood:** helicity suppression of $R\textsubscript{K}$ might enhance sensitivity to non-SM effects to an experimentally accessible level.

**$R\textsubscript{K}\text{SM} = (2.477\pm0.001) \times 10^{-5}$**

**$R_K$ beyond the SM**

In the MSSM large tan$\beta$ scenario, the presence of LFV terms (charged Higgs coupling) introduces extra contributions to the SM amplitude, enhancing the decay rate.

$$R_{K}^{LFV} = \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma_{LFV}(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$

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

Up to 1% variation is predicted for reasonable SUSY parameters:

$$m_H = 500 \text{ GeV}, \ |\Delta_{13}| = 5 \cdot 10^{-4}, \ \tan \beta = 40 \rightarrow R_{K}^{LFV} \approx R_{K}^{SM} (1 + 0.013)$$
Trigger Logic

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

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

- Efficiency of $K_{e2}$ trigger: monitored with $K_{\mu2}$ & other control triggers.
- $E_{LKr}$ inefficiency for electrons measured to be $(0.05 \pm 0.01)\%$ for $p_{track} > 15$ GeV/c.
- Different trigger conditions for signal and normalization!
Systematic effect: positron ID

LKr energy response is calibrated for every 2×2 cm² cell within acceptance

A typical inefficiency map

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

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

ID inefficiency vs momentum

Positron ID efficiency is measured with K⁺ → πeν and special K_L → πeν samples: integral ε = (99.27 ± 0.05)%

E/p > 0.90
E/p > 0.95

NA62
$K^+ \to e^+ \nu \gamma$ (SD) decay

Decay density:
\[
\frac{d\Gamma(K \to e\nu\gamma)}{dx dy} = \rho_{IB}(x, y) + \rho_{SD}(x, y) + \rho_{INT}(x, y)
\]

Helicity suppressed
Negligible

Kinematic variables (kaon frame):
\[
x = 2E_\gamma/M_K, \quad y = 2E_e/M_K
\]

Two non-interfering contributions $SD^+$ and $SD^-$:
emission of photons with positive and negative helicity

\[
\rho_{SD}(x, y) = \frac{G_F^2 |V_{us}|^2 \alpha}{64\pi^2} M_K^5 ((f_V + f_A)^2 f_{SD^+}(x, y) + (f_V - f_A)^2 f_{SD^-}(x, y))
\]

$f_V(x), f_A(x)$: model-dependent effective
vector and axial couplings

$SD^+$: positive $\gamma$ helicity
$SD^-$: negative $\gamma$ helicity
Radiative $K^+\rightarrow e^+\nu\gamma$ background in $K_{e2}$ sample

$R_K$ 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
$BR(SD^+, \text{full phase space}) = (1.37 \pm 0.06) \times 10^{-5}$. (EPJC64 (2009) 627)

SD background contamination
$B/(S+B) = (1.07 \pm 0.05)\%$

A new $K_{e2\gamma}$ ($SD^+$) measurement is being performed by NA62 (...me!)
**$K_{\mu2}$ with $\mu \to e$ decay in flight**

For NA62 conditions (74 GeV/c beam, ~100 m decay volume),

$$N(K_{\mu2}, \mu \to e \text{ decay})/N(K_{e2}) \sim 10$$

$K_{\mu2}$ (\(\mu \to e\)) naively seems a huge background

Muons from $K_{\mu2}$ 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 $K_{e2}$ candidates

They are naturally suppressed by the muon polarisation

(radiative corrections provide another ~10% suppression)
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 $K_{e2}^-$ (~20%) than for $K_{e2}^+$ (~1%).
- Halo background in the $K_{\mu 2}$ sample is considerably lower.
- ~80% of the data sample is $K^+$ only, ~20% 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.

\[
\frac{B}{S+B} = (1.16 \pm 0.06)\%
\]

Uncertainty:
1) limited size of control sample;
2) $\pi$, $K$ decays upstream vacuum tank.
18.03 M candidates with low background
$B/(S+B) = (0.38\pm0.01\%)$

$K_{\mu 2}$ background source:

- Beam halo $(0.38\pm0.01\%)$
Hermetic veto (large-angle and small-angle veto counters) will strongly
decrease the background.
SD background will not be relevant for a future NA62 precision RK measurement.

Beam spectrometer (beam tracker plus beam Cherenkov) will allow time
correlation between incoming kaons and decay products (improved PID).
Expect beam halo background to be reduced to negligible level.

Only the $K_{\mu2}$ ($\mu \rightarrow e$) background will remain: well known $\sim0.3\%$ contamination.
Expected total uncertainty $<0.2\%$.

Assuming an analysis at low lepton momentum and not using electron ID,
measurement of $R_K$ with 0.1-0.2\% relative precision is feasible.

Required statistical uncertainty is $\sim0.05\% \rightarrow$ few million $K_{e2}$ candidates.
Required kaon decay flux: $N_K \sim 10^{12}$
Expected NA62 flux: $N_K \sim 10^{13}$

$K_{e2}$ trigger $\sim$1 month of data taking sufficient for such $R_K$ measurement.
$K_{e2\gamma}$ (SD), $K_{e3}$ suppression

$K_{e2\gamma}$ (SD$^+$) MC selected as $K_{e2}$

$K_{e2\gamma}$ (SD) MC events

No $\gamma$s in LAV, SAC, IRC

$K_{e2\gamma}$ (SD$^+$) sample reduced by a factor of 35

Rejection provided by the new veto detectors is excellent for $K_{e2}$ analysis

$K_{e3}$ MC selected as $K_{e2}$

$K_{e3}$ MC events

No $\gamma$s in LAV, SAC, IRC

$K_{e3}$ sample reduced by a factor of 500

$K_{e2}$ sample untouched by the veto requirement
KLOE $K_{e2}$ analysis: decays at rest

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

- CM energy $\sim m_\phi = 1019.4$ MeV;
- BR($\phi \rightarrow K^+K^-$) = 49.2%;
- $\phi$ production cross-section $\sigma_\phi = 1.3 \mu$b;
- Data sample (2001-05): 2.5 fb$^{-1}$.

Kaon decay experiment

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

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

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>$\delta R_K/R_K$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>1.0</td>
</tr>
<tr>
<td>$K_{\mu2}$ subtraction</td>
<td>0.3</td>
</tr>
<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><strong>Total</strong></td>
<td><strong>1.3</strong></td>
</tr>
</tbody>
</table>

Full data sample analyzed [EPJ C64 (2009) 627]

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

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

[arXiv:1003.3862]