Lepton Universality tests with Leptonic Kaon decays in NA62

Cristina Lazzeroni
(University of Birmingham, UK)

for the NA62 collaboration
(Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, IHEP Protvino, INR Moscow, Liverpool, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, Sofia, TRIUMF, Turin)

PANIC 2011 Conference
MIT, Cambridge, US • 23-29 July 2011
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
Composition: $K^+ (\pi^+) = 5\% (63\%)$.
$K^+$ decaying in vacuum tank: 18\%.
Leptonic meson decays: $P^+ \rightarrow l^+ \nu$

SM contribution is helicity suppressed:

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

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

$R=\text{Br}(K\rightarrow \mu\nu)/\text{Br}(K_{e3})$: ($\delta R/R)_{\text{exp}}=1.0\%$, challenging but not hopeless

Subject to hadronic uncertainties
$R_K = \frac{K_{e^2}}{K_{\mu^2}}$ in the SM

Observable sensitive to lepton flavour and its SM expectation:

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

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

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

- **SM prediction:** excellent sub-per mille 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.

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

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

R_K = K_{e2}/K_{\mu2} beyond the SM

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

K_{l2} can proceed via exchange of charged Higgs H^{\pm} (in place of W^{\pm})

→ Does not affect the ratio R_K

**2HDM – one-loop level**

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

→ $R_K$ enhancement can be experimentally accessible

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

Up to \( \approx 1\% \) effect:

- slepton mixing $\Delta_{13}=5\times10^{-4}$,
- $\tan\beta=40$, $M_H=500$ GeV/c$^2$

lead to $R_K^{MSSM} = R_K^{SM}(1+0.013)$

(see also PRD76 (007) 095017)

Analogous SUSY effect in pion decay is suppressed by a factor $(M_\pi/M_K)^4 \approx 6\times10^{-3}$
Measurement strategy

(1) $K_{e2}/K_{\mu2}$ candidates are collected 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, measured independently in 10 lepton momentum bins
    (owing to strong momentum dependence of backgrounds and event topology)

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

$N(K_{e2}), N(K_{\mu2})$: numbers of selected $K_{l2}$ candidates;

$N_B(K_{e2}), N_B(K_{\mu2})$: numbers of background events;

$A(K_{e2}), A(K_{\mu2})$: MC geometric acceptances (no ID);

$f_e, f_\mu$: directly measured particle ID efficiencies;

$\varepsilon(K_{e2})/\varepsilon(K_{\mu2})>99.9\%$: $E_{LKr}$ trigger condition efficiency;

$f_{LKr}=0.9980(3)$: global LKr readout efficiency;

$D=50-150$ downscaling factor of the $K_{\mu2}$ trigger.

(3) MC simulations use minimised:
   • Geometrical part of the acceptance correction comes from simulation;
   • PID, trigger, readout efficiencies are measured directly.
**Ke2 vs K_µ2 selection**

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

**Kinematic separation**

missing mass $M^2_{miss} = (P_K - P_l)^2$

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

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

**Separation by particle ID**

$E/p = (LKr$ energy deposit/track momentum).

(0.9 to 0.95)<E/p<1.10 for electrons,
E/p<0.85 for muons.

→ Powerful $\mu^\pm$ suppression in e$^\pm$ sample: $\sim10^6$
Main background source
Muon “catastrophic” energy loss in LKr by emission of energetic bremsstrahlung photons. \( P_{\mu e} \sim 3 \times 10^{-6} \) (and momentum-dependent).

\[
P_{\mu e} / R_K \sim 10%:
K_{\mu 2} \text{ decays represent a major background}
\]

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

\( K_{\mu 2} \) 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:
\( \rightarrow \) ionization losses in Pb (low p);
\( \rightarrow \) bremsstrahlung in Pb (high p).

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

Muon mis-identification

Uncertainties
- Limited data sample (0.16%);
- MC correction (0.12%);
- \(M^2_{\text{miss}} \text{ vs } P_{\text{track}}\) correlation (0.08%).

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

Uncertainty is \(\sim 3\) times smaller than the one obtained solely from simulation.
**K_{\mu 2} with \( \mu \to e \) decay in flight**

For NA62 conditions (74 GeV/c beam, \( \sim 100 \) m decay volume),
\[
\frac{N(K_{\mu 2}, \mu \to e \text{ decay})}{N(K_{e2})} \sim 10
\]

\( K_{\mu 2} (\mu \to e) \) naively seems a huge background.

Muons from \( K_{\mu 2} \) decay are fully polarized:
Michel electron distribution
\[
d^2\Gamma/dx d(\cos \Theta) \sim x^2[(3-2x) - \cos \Theta(1-2x)]
\]

\[
x = \frac{E_e}{E_{\text{max}}} \approx 2\frac{E_e}{M_\mu},
\]
\( \Theta \) is the angle between \( p_e \) and the muon spin
(all quantities are defined in muon rest frame).

**Result:** \( B/(S+B) = (0.26 \pm 0.03)\% \)

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 \( \sim 10\% \) suppression).
Radiative $K^+\to e^+\nu\gamma$ 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 $BR(SD^+, \text{full phase space}) = (1.37\pm0.06)\times10^{-5}$. (EPJC64 (2009) 627)

SD background contamination

$B/(S+B) = (2.60\pm0.11)\%$

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

INT = interference; IB = inner bremsstrahlung

Photon energy: IB and DE

IB (soft collinear photons)

SD (structure dependent)
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 $K_{\mu 2}$ sample is considerably lower.
- $\sim 66\%$ of the data sample is $K^+$ only, $\sim 7\%$ is $K^-$ only, $\sim 27\%$ has both.
- $K^+$ halo component is measured directly with the $K^-$ sample and vice versa.

1-7\% background in $K^+/ K^- \text{Pb/no Pb}$. The background is measured 0.1-0.2\% 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.

$$B/(S+B) = (2.11 \pm 0.09)\%$$

Uncertainty:
1) limited size of control sample;
2) $\pi, K$ decays upstream vacuum tank.
NA62 data set

145,958 $K^+\rightarrow e^+\nu$ candidates.
Positron ID efficiency: $(99.28\pm 0.05)\%$.
$B/(S+B) = (10.95\pm 0.27)\%$.

42.817M candidates with low background
$B/(S+B) = (0.50\pm 0.01)\%$. 
Backgrounds and Uncertainty

### Backgrounds

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

Lepton momentum bins are differently affected by backgrounds and thus the systematic uncertainties.

### Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta R_K \times 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>0.0007</td>
</tr>
<tr>
<td>$K_{\mu 2}$</td>
<td>0.004</td>
</tr>
<tr>
<td>BR($K_{e2\gamma} SD^+$)</td>
<td>0.002</td>
</tr>
<tr>
<td>$K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$, $K^{\pm} \rightarrow \pi^\pm \pi^0$</td>
<td>0.003</td>
</tr>
<tr>
<td>Beam halo</td>
<td>0.002</td>
</tr>
<tr>
<td>Helium purity</td>
<td>0.003</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.002</td>
</tr>
<tr>
<td>DCH alignment</td>
<td>0.001</td>
</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>0.001</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.010</strong></td>
</tr>
</tbody>
</table>

(40% data set: PLB 698 (2011), 105)
NA62 result

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

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

Independent measurements in lepton momentum bins

(40 measurements (4 data samples x 10 momentum bins) including correlations: \( \chi^2/\text{ndf}=47/39 \))
$R_K$: world average

$(M_H, \tan\beta)$ 95% exclusion limits

Other limits on 2HDM-II:

SM with 4 generations:
• 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

• Result based on total NA62 $K_{e2}$ sample: $R_K = (2.488 \pm 0.010) \times 10^{-5}$, reaching a record $\sim 0.4\%$ accuracy

• After recent precise $R_K$ measurements, the $R_K$ world average has a $0.4\%$ precision
Spares
H$^\pm$ exchange in K$^+\rightarrow\mu^+\nu$

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:

$R_{\mu23} = \left(\frac{f_K/f_\pi}{f_+(0)}\right)^{-1} \left(\frac{|V_{us}|}{|V_{ud}|}\right) \left(\frac{f_K}{f_\pi}\right)_{\mu2} \left|\frac{|V_{ud}|_{0^+\rightarrow0^+}}{|V_{us}|_{f+(0)}}\right|\ell_3$

Lattice QCD input

Measured with K$\mu_2/\pi_{\mu2}$

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

Charged Higgs mediated contribution:

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

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

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

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

**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:**

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

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

The sensitivity in kaon sector approaches those obtained in the other fields.
KLOE $K_{e2}$ analysis: decays at rest

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

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

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

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

$$\chi^2/\text{ndf} = 113/112.$$  
Projection shown here: $\text{NN}_{\text{out}} > 0.96$.

<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>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: expect to start in 2010, $\delta R_K/R_K = 0.4$%.  
[arXiv:1003.3862]
**NA62 data taking 2007/08**

**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 $R_K$:**
- Magnetic spectrometer (4 DCHs):
  4 views/DCH: redundancy ⇒ efficiency;
  $\Delta p/p = 0.47\% + 0.020\%*p \ [\text{GeV/c}]$
- Hodoscope
  fast trigger, precise $t$ measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} + 9%/E + 0.42\% \ [\text{GeV}];$
  $\sigma_x=\sigma_y=4.2\text{mm}/E^{1/2} + 0.6\text{mm} (1.5\text{mm}@10\text{GeV}).$
Minimum bias trigger configuration used

- Efficiency of $K_{e2}$ trigger: monitored with $K_{\mu 2}$ & other control triggers.
- $E_{LKr}$ inefficiency for electrons measured to be $(0.05\pm0.01)\%$ for $p_{track}>15$ GeV/c.
- Different trigger conditions for signal and normalization!
$K^+ \rightarrow e^+ \nu \gamma$ (SD) decay

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

Kinematic variables (kaon frame):
\[x = \frac{2E_\gamma}{M_K}, \quad y = \frac{2E_e}{M_K}\]
\[
\rho_{SD}(x, y) = \frac{G_F^2 |V_{us}|^2 2\alpha}{64\pi^2} M_K^5 \left( (f_V + f_A)^2 f_{SD+}(x, y) + (f_V - f_A)^2 f_{SD-}(x, y) \right)
\]

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

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

$SD^+$: positive $\gamma$ helicity

\[p_\gamma \rightarrow p_\nu \rightarrow S_\nu \rightarrow p_e \rightarrow S_e \rightarrow p_e\]

$SD^-$: negative $\gamma$ helicity

\[p_\gamma \rightarrow p_\nu \rightarrow S_\nu \rightarrow p_e \rightarrow S_e \rightarrow p_e\]
Systematic effect: positron ID

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

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

A typical inefficiency map

ID inefficiency vs momentum

Positron ID efficiency is measured with $K^+ \rightarrow \pi^+ e^+ \nu$ and special $K_L \rightarrow \pi^+ e^+ \nu$ samples:

Integral $\epsilon = (99.28 \pm 0.05)\%$
**R_K: experimental status**

**Kaon experiments:**

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

→ Recent improvement: KLOE (Frascati).
  Data collected in 2001–2005,
  13.8K \( K_{e2} \) candidates, 16% background.
  \[ R_K = (2.493 \pm 0.031) \times 10^{-5} \] (\[ \delta R_K / R_K = 1.3\% \])
  (EPJ C64 (2009) 627)

→ NA62 (\( R_K \)) goal:
  dedicated data taking strategy,
  51.1K \( K_{e2} \) candidates, <9% background,
  \( \delta R_K / R_K < 0.7\% \) (preliminary)

**Data taking:**

• Four months in 2007:
  \( \sim 400K \) SPS spills, 300TB of raw data

• Two weeks in 2008:
  special data sets allowing reduction of the systematic uncertainties.