Lepton Universality Test
with $K^+ \rightarrow l^+ \nu$ Decays at CERN NA62

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Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin)

Outline:
1) Motivation & experimental status;
2) Beam, detector and data taking;
3) Backgrounds & systematic effects;
4) Preliminary results and prospects.

Rencontres de Moriond (EW session)
La Thuile, Italy • 10 March 2010
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 $M_H=500\text{GeV}/c^2$, $\tan\beta = 40$)

- $\pi^+ \rightarrow l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_{\pi}/m_H)^2 m_d/(m_u+m_d) \tan^2\beta \approx 2 \times 10^{-4}$
- $K^+ \rightarrow l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_K/m_H)^2 \tan^2\beta \approx 0.3\%$
- $D_{s}^+ \rightarrow l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_{D}/m_H)^2 (m_s/m_c) \tan^2\beta \approx 0.4\%$
- $B^+ \rightarrow l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_{B}/m_H)^2 \tan^2\beta \approx 30\%$

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

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

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

$\Delta\Gamma/\Gamma_{SM} = 1.07 \pm 0.37$

(4$\sigma$ discrepancy + new data: PRD79 (2009) 052001)

$R = \text{Br}(K \rightarrow \mu\nu)/\text{Br}(K_{e3})$:

$\delta R/R_{\text{exp}} = 1.0\%$, challenging by not hopeless

$\text{PRL100 (2008) 241802}$

$f_{D_s}(QCD) = (241 \pm 3)\text{MeV}$

$f_{D_s}(\text{exp}) = (277 \pm 9)\text{MeV}$

Obstructed by hadronic uncertainties
$R_K = \frac{K_{e2}}{K_{\mu2}}$ in the SM

Observable sensitive to lepton flavour violation and its SM expectation:

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

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

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

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

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

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

*Phys. Lett. 99 (2007) 231801*
\[ R_K = \frac{K_{e2}}{K_{\mu2}} \text{ beyond the SM} \]

**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  
LFV (rather than 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 \( R_K^{\text{MSSM}} = R_K^{\text{SM}}(1 + 0.013) \).
RK & Rπ: experimental status

Kaon experiments:
- PDG’08 average (1970s measurements):
  \[ R_K = (2.45 \pm 0.11) \times 10^{-5} \quad (\delta R_K/R_K = 4.5\%) \]
- Recent improvement: KLOE (Frascati).
  Data collected in 2001–2005,
  13.8K Ke2 candidates, 16% background.
  \[ R_K = (2.493 \pm 0.031) \times 10^{-5} \quad (\delta R_K/R_K = 1.3\%) \]
  (EPJ C64 (2009) 627)
- NA62 (phase I) goal:
  dedicated data taking strategy,
  ~150K Ke2 candidates, <10% background,
  \( \delta R_K/R_K < 0.5\% \): a stringent SM test.

Pion experiments:
- PDG’08 average (1980s, 90s measurements):
  \[ R_\pi = (12.30 \pm 0.04) \times 10^{-5} \quad (\delta R_\pi/R_\pi = 0.3\%) \]
- Current projects: PEN@PSI (stopped \( \pi \)) running (arXiv:0909.4358)
  PIENU@TRIUMF (in-flight) proposed (T. Numao, PANIC’08 proceedings, p.874)
  \( \delta R_\pi/R_\pi \sim 0.05\% \) foreseen (similar to SM precision)
NA48/NA62: 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: $K^\pm_e/K^\pm\mu_2$ tests
2008: $K^\pm_{e_2}/K^\pm_{\mu_2}$ tests
2007–2012: design & construction
2013–2015: $K^+\to\pi^+\nu\bar{\nu}$ data taking


NA62 (phase II): $K^\pm_{e_2}/K^\pm_{\mu_2}$ tests
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 $\Rightarrow$ efficiency; $\Delta p/p = 0.47\% + 0.020\%p$ [GeV/c]
- Hodoscope
  fast trigger, precise t measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ [GeV];
  $\sigma_x = \sigma_y = 0.42/E^{1/2} + 0.6mm$ (1.5mm@10GeV).
Trigger logic

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

\( K_{e2} \) condition: \( Q_1 \times E_{LKr} \times 1TRK \).
Purity \( \sim 10^{-5} \).

\( K_{\mu2} \) condition: \( Q_1 \times 1TRK/D \),
downscaling (D) 50 to 150.
Purity \( \sim 2\% \).

- 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 \( p_{\text{track}} > 15 \) GeV/c.
- Different trigger conditions for signal and normalization!
Measurement strategy

(1) $K_{e2}/K_{\mu2}$ candidates are collected **simultaneously**:
- the result 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 **10 lepton momentum bins**
(owing to strong momentum dependence of backgrounds and event topology)

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

- $N(K_{e2})$, $N(K_{\mu2})$: 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.

(3) **MC simulations** used to a limited extent only:
- Geometrical part of the acceptance correction (not for particle ID);
- simulation of “catastrophic” bremsstrahlung by muons.
**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;
- track momentum: $15\text{GeV/c}<p<65\text{GeV/c}$.

**Kinematic separation**

$\text{missing mass } M_{miss}^2 = (P_K - P_l)^2$

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

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

**Separation by particle ID**

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

$0.95<E/p<1.10$ for electrons,
$E/p<0.85$ for muons.

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

\[
P(\mu \rightarrow e)/R_K \sim 10\%:
\]
\( K_{\mu 2} \) decays represent a major background

Theoretical bremsstrahlung cross-section
must be validated in the region \( (E_\gamma/E_\mu) > 0.9 \)
by a direct measurement of \( P(\mu \rightarrow e) \)
to \( \sim 10^{-2} \) relative precision.

Obtaining pure muon samples
Electron contamination due to \( \mu \rightarrow e \) decay: \( \sim 10^{-4} \).
Pb wall (~10\( X_0 \)) placed between the HOD planes:
tracks traversing the wall and having \( E/p > 0.95 \)
are sufficiently pure muon samples (electron contamination <10\(^{-7}\)).
**K_{\mu2} background (2)**

**P(\mu \to e):** measurement (2007 special muon run) vs Geant4-based simulation


Good data/MC agreement for the Pb wall installed

P(\mu \to e) is modified by the Pb wall via two competing mechanisms:

1) ionization losses in Pb (low p);
2) bremsstrahlung in Pb (high p).

\[ \to \text{a significant MC correction} \]

**Result:** \[ B/(S+B) = (6.28 \pm 0.17)\% \]

(uncertainty is due to the limited size of the data sample used to validate the cross-section model)

**Improvements:**
- Muons from regular K_{\mu2} decays from kaon runs with the Pb wall installed.
Only energetic forward electrons (passing $M_{\text{miss}}$, $E/p$, vertex CDA cuts) are selected as $K_{e2}$ candidates: (high $x$, low $\cos\Theta$). They are naturally suppressed by the muon polarisation.

Important but not dominant background

For NA62 conditions (74 GeV/c beam, ~100 m decay volume), $N(K_{\mu2}, \mu\rightarrow e \text{ decay})/N(K_{e2}) \sim 10$

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

Muons from $K_{\mu2}$ decay are fully polarized: Michel electron distribution

$$d^2\Gamma/dx d(\cos\Theta) \sim x^2[(3-2x) - \cos\Theta(1-2x)]$$

$$x = E_e/E_{\text{max}} \approx 2E_e/M_\mu,$$

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

Result: $B/(S+B) = (0.23\pm0.01)\%$
**K^+ → e^+ νγ (SD) background**

- Background by definition of $R_{K^r}$, no helicity suppression.
- Rate similar to that of $K_{e2}$, limited precision: $\text{BR} = (1.52 \pm 0.23) \times 10^{-5}$.

**ChPT $O(p^6)$, form factor with measured kinematic dependence (EPJC64 627)**

**SD background contamination**

$\frac{B}{S+B} = (1.02 \pm 0.15)\%$

(uncertainty due to PDG BR, will be improved using a recent KLOE measurement, EPJC64 627)

Only energetic electrons ($E_e^* > 230 \text{MeV}$) are compatible to $K_{e2}$ kinematic ID and contribute to the background.

This region of phase space is accessible for direct BR and form-factor measurement (being above the $E_e^* = 227 \text{MeV}$ endpoint of the $K_{e3}$ spectrum).

**Ke2γ (SD) Dalitz plot distribution**

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SD background contamination

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(uncertainty due to PDG BR, will be improved using a recent KLOE measurement, EPJC64 627)
Electrons produced by beam halo muons via $\mu \to e$ 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.
- $\sim 90\%$ 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.

$$B/(S+B) = (0.45 \pm 0.04)\%$$

Uncertainty is due to the limited size of the control sample.
$K_{e2}$: partial (40%) data set

51,089 $K^+\rightarrow e^+\nu$ candidates, 99.2% electron ID efficiency, $B/(S+B) = (8.0\pm0.2)\%$

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

NA62 estimated total $K_{e2}$ sample: ~120K $K^+$ & ~15K $K^-$ candidates.
Proposal (CERN-SPSC-2006-033): 150K candidates
Backgrounds: summary

**Backgrounds**

<table>
<thead>
<tr>
<th>Source</th>
<th>(\text{B/(S+B)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_{\mu 2})</td>
<td>((6.28 \pm 0.17))%</td>
</tr>
<tr>
<td>(K_{\mu 2} (\mu \rightarrow e))</td>
<td>((0.23 \pm 0.01))%</td>
</tr>
<tr>
<td>(K_{e 2\gamma} (SD^+))</td>
<td>((1.02 \pm 0.15))%</td>
</tr>
<tr>
<td>Beam halo</td>
<td>((0.45 \pm 0.04))%</td>
</tr>
<tr>
<td>(K_{e3})</td>
<td>(0.03)%</td>
</tr>
<tr>
<td>(K_{2\pi})</td>
<td>(0.03)%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>((8.03 \pm 0.23))%</td>
</tr>
</tbody>
</table>

**Record \(K_{e2}\) sample:**
51,089 candidates with low background

\(\text{B/(S+B)} = (8.0 \pm 0.2)\)%

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

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Statistics in lepton momentum bins

(selection criteria, e.g. \(Z_{\text{vertex}}\) and \(M_{\text{miss}}^2\), are optimised individually in each \(P_{\text{track}}\) bin)
The only significant background source is the beam halo.

15.56M candidates with low background $B/(S+B) = 0.25\%$

(K$_\mu$2 trigger was pre-scaled by D=150)
Preliminary result (40% data set)

\[ R_K = (2.500 \pm 0.012_{\text{stat}} \pm 0.011_{\text{syst}}) \times 10^{-5} \]
\[ = (2.500 \pm 0.016) \times 10^{-5} \]

Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta R_K \times 10^5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>0.012</td>
</tr>
<tr>
<td>( K_{\mu2} )</td>
<td>0.004</td>
</tr>
<tr>
<td>Beam halo</td>
<td>0.001</td>
</tr>
<tr>
<td>( K_{e2}\gamma ) (SD(^+))</td>
<td>0.004</td>
</tr>
<tr>
<td>Electron ID</td>
<td>0.001</td>
</tr>
<tr>
<td>IB simulation</td>
<td>0.007</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.002</td>
</tr>
<tr>
<td>Trigger timing</td>
<td>0.007</td>
</tr>
<tr>
<td>Total</td>
<td>0.016</td>
</tr>
</tbody>
</table>

(0.64% precision)

The whole 2007 sample will allow statistical uncertainty \( \sim 0.3\% \), total uncertainty of 0.4–0.5%. 19
Comparison to world data

March 2009

<table>
<thead>
<tr>
<th>World average</th>
<th>$\delta R_K \times 10^5$</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 2009</td>
<td>$2.467 \pm 0.024$</td>
<td>0.97%</td>
</tr>
<tr>
<td>June 2009</td>
<td>$2.498 \pm 0.014$</td>
<td>0.56%</td>
</tr>
</tbody>
</table>

(NA48/2 preliminary results excluded from the new average: they are superseded by NA62)
\(R_K\): sensitivity to new physics

\(R_K\) measurements are currently in agreement with the SM expectation at \(\sim 1.5\sigma\). Any significant enhancement with respect to the SM value would be an evidence of new physics.

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 \(B \rightarrow \tau \nu\).

"Maybe NA62 will find the first evidence for a charged Higgs exchange?"
-- John Ellis (arXiv:0901.1120)
Conclusions & prospects

• Due to the helicity suppression of the $K_{e2}$ decay, the measurement of $R_K$ is well-suited for a stringent test of the Standard Model.

• NA62 data taking in 2007/08 was optimised for $R_K$ measurement. The NA62 $K_{e2}$ sample is $\sim 10$ times the world sample. Powerful $K_{e2}/K_{\mu 2}$ separation ($>99\%$ electron ID efficiency and $\sim 10^6$ muon suppression) leads to a low $8\%$ background.

• Preliminary result based on $\sim 40\%$ of the NA62 $K_{e2}$ sample: $R_K = (2.500 \pm 0.016) \times 10^{-5}$, reaching a record $0.7\%$ accuracy and compatible to the SM prediction. A timely result, as direct searches for New Physics at the LHC are approaching.

• With the full NA62 data sample of 2007/08, the precision is expected to be improved to better than $\delta R_K/R_K = 0.5\%$.

• $R_K$ measurement with $\sim 0.1\%$ precision has been proposed in the framework of the NA62 (phase II) experiment.