Testing lepton universality and the flavor structure of the SM with $K \rightarrow \ell \nu$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decays

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for the NA62 Collaboration:


P-326/NA62
Outline

- General motivation
- Measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$
  - Why $R_K$?
  - The NA48/2 experiment at CERN SPS
  - Results from 2003 and 2004 data taking
  - Dedicated 2007 run
- The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay
  - Introduction
  - Principle of the experiment
  - Detector layout
- Conclusions
**K12 and K→πνν: motivation**

**New Physics effects in Flavour Physics**

- **Two main roads**
  - **MFV**
    - Weakly coupled and SM Higgs sector [≈ MSSM small tanβ]
    - Most of the (present) flavour constraints naturally satisfied after imposing EWPO
    - Only notable exception provided by B→Xsγ
  - Strongly coupled or weakly coupled and large tanβ
    - Helicity suppressed, observ particularly interesting: B→ll, K→lν
    - Charged currents as interesting as FCNCs, precision tests of CC both in K and B

- **non-MFV**
  - Long list of useful observables (B and K physics: leptonic, radiative & non-leptonic channels), mainly FCNCs
  - The absence of significant deviations from the SM in any of these, makes generic non-MFV scenarios highly contrived / fine-tuned
  - In several realistic cases (GUT scenarios, new couplings only for the 3rd family, etc...) the most significant constraints are derived from Kaon physics (λ^5 suppression in the SM, because of 1↔3↔2).
Why $R_K$?

The ratio $R_K$ accurately predicted within the SM:

$$R_K = \frac{\Gamma(K^{\pm} \to e^\pm\nu_e)}{\Gamma(K^{\pm} \to \mu^\pm\nu_\mu)} = \frac{m_e^2}{m_\mu^2} \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \left( 1 + \delta R_{QED} \right) = (2.477 \pm 0.001) \cdot 10^{-5}$$

- Helicity suppression
- Radiative (IB) correction

- Cancellation of hadronic uncertainties (no $f_K$)

$$\Delta R_K/R_K \big|_{SM} \sim 0.04\%$$

- A precise measurement probes $\mu - e$ universality and provides a stringent test of the SM

[V. Cirigliano and I Rosell, JHEP 0710:005 (2007)]
MSSM with R-parity allows new contributions to the decays:

\[
\Gamma(K^+ \rightarrow \ell \nu)_{\text{exp}} = \Gamma(K^+ \rightarrow \ell \nu_\ell) + \Gamma(K^+ \rightarrow \ell \nu_\tau)
\]

What about SUSY?

Effective coupling (HRS mechanism):

\[
\ell H^\pm \nu_\tau \rightarrow \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta R^3 \tan^2 \beta \quad \ell = e, \mu
\]
**Prediction and sensitivity**

\[
R_K^{LFV} \approx R_K^{SM} \left[1 + \left(\frac{m_K^4}{m_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)\left|\Delta_{31}\right|^2 \tan^6 \beta\right]
\]

[Masiero, Paradisi, Petronzio]

- **1.3% effect** for \( \tan \beta = 40 \)
- \( M_H = 500 \text{ GeV/c}^2 \)
- \( \Delta_{31} = 5 \times 10^{-4} \)

Exclusion plots for \( \Delta R_K/R_K = 0.3 \% \)
The state of the art

- Poor experimental knowledge of $R_K$ so far
  - PDG 2006 average based on 3 experiments from the 70’s

\[
R_K^{PDG} = (2.45 \pm 0.11) \cdot 10^{-5} \quad \delta R_K / R_K = 4.5\%
\]

- Experimental error $\sim 10^2$ larger than theoretical one
- Preliminary results on $R_K$ from NA48/2 Collaboration
  - 2003 data taking
  - 2004 data taking
- KLOE also presented a preliminary result
- NA62 2007 run dedicated to a sub-percent precision measurement of $R_K$
Where do Kaons come from…

- NA48/2 designed for the search of direct CPV in $K^{\pm} \rightarrow 3\pi$
- Simultaneous, almost collinear $K^+/K^-$ beams ($K^+/K^- \approx 1.8$)
  - $60\pm3$ GeV/c momentum
  - beams coincide within 1 mm along the 114 m decay region

SPS protons @ 400 GeV/c
...and how do NA48 looks at them

- **Spectrometer:**
  \[
  \frac{\sigma(p)}{p} = 1.02\% \oplus (0.044 \cdot p[GeV/c])\%
  \]

- **LKR calorimeter**
  \[
  \frac{\sigma(E)}{E} = \frac{0.09}{E[GeV]} \oplus \frac{0.032}{\sqrt{E[GeV]}} \oplus 0.0042
  \]
  \[
  \sigma(t) < 300\text{ps}
  \]

- **Hodo**, AKL
- **MUV**, HAC
- **Kabes**
2003 and 2004 runs

- 2003 sample (1 month)
  - Trigger:
    - $K\mu_2$: downscaled 1 track trigger (downscaling D)
    - $Ke_2$: 1 track trigger + $E_{LKR}$ + **Online kinematics cut**

- 2004 sample (56 hours dedicated)
  - reduced beam intensity
  - minimum bias trigger

- Analysis strategy: counting number of $Ke_2$ / $K\mu_2$ candidates collected simultaneously
  - Result is independent of the knowledge of kaon flux
  - Several systematic effects cancel in the ratio

\[
R_K = \frac{N(K_{e2}) - N_{BACK}(K_{e2})}{N(K_{\mu2}) - N_{BACK}(K_{\mu2})} \cdot \frac{1}{D} \cdot \frac{Acc(K_{\mu2})Eff_{TR}(K_{\mu2})Eff_{PID}(K_{\mu2})}{Acc(K_{e2})Eff_{TR}(K_{e2})Eff_{PID}(K_{e2})}
\]
Event selection

- Geometry
  - 1 track topology
  - $15 < p < 50$ [GeV/c]
  - Good reconstructed vertex
  - Geometrical acceptance cut
- Particle ID ($E_{LKR}/p_{spectr}$)
  - $e$ ($E/p > 0.95$)
  - $\mu$ ($E/p < 0.2$)
- Kinematics
  - Missing mass: $M_{\text{miss}}^2 = (P_K - P_l)^2$
  - $-0.015 < M_{\text{miss}}^2 < 0.015$ [GeV$^2$/c$^4$]
Dominant background source in the $K_{e2}$ sample is due to $K_{\mu2}$
- Kinematically undistinguishable at high momenta
- The $\mu$ (with a probability of $\sim$ few $\times 10^{-6}$) can undergo a catastrophic energy loss in LKR $\rightarrow (E/p \sim 1)$ thus faking an electron
- This background is measured from data in momentum bins

Contribution from $K_{e3}$ obtained by Monte Carlo

$\pi^\pm \pi^0$ background in $K_{\mu2}$ sample is negligible
Preliminary results

● 2003 data
  ○ (4670 ± 77_{stat}^{+29}_{-8}_{syst}) events
  ○ trigger efficiency is the largest systematic effect

● 2004 data
  ○ (3407 ± 63_{stat}^{+54}_{syst}) events
  ○ systematics dominated by the K_{\mu 2} background subtraction

● KLOE
  ○ \( R_K = (2.55 \pm 0.05 \pm 0.05) \cdot 10^{-5} \)
  ○ ~ 8000 events based on 1.7 fb^{-1} with different systematics [arXiv:0707.4623]

● Combining results
  \[
  R_K = (2.457 \pm 0.032) \cdot 10^{-5}
  \]
  \[
  \left( \chi^2 / ndf = 2.44 / 3 \right)
  \]
Constraints on SUSY parameters

95% CL Exclusion plot

$\Delta R_K/R_K \approx 1.3\%$
The **NA62 experiment** (former NA48) was approved for a dedicated measurement of $R_K$ in 2007
- 4 months of data taking
- Collected $\sim 1 \times 10^5$ Ke2 events (world’s largest)
- Aims to $\delta R_K/R_K$ better than 0.5 %
NA62: resolution

- $p_K$ from 60 $\rightarrow$ 75 GeV/c
- $\delta p_K/p_K$ from 3.8% $\rightarrow$ 2.5%
- $p_\perp$ kick from 120 $\rightarrow$ 263 MeV/c

Improved MM$^2$ resolution!
Measure from data the $\mu$ mis-id probability due to catastrophic energy losses in LKR

Put a $9X_0$ thick lead wall between the HODO planes, in front of the LKR for a subsample of data
NA62: summary

- **Backgrounds to $K_{\mu 2}$:**
  - **Beam halo** $\sim 0.1\%$
  - $K^+ \rightarrow \pi^+\pi^0 < 0.5\%$

- **Backgrounds to $Ke2$:**
  - $K_{\mu 2}$: Evaluated with the direct measurement of $P(\mu \rightarrow e)$
  - **Beam halo** $(1.3 \pm 0.1)\%$
    - estimated with K-less runs
  - $Ke_{2\gamma}$ (SD): Evaluated from MC:
    - $(0.7 \pm 0.1)\%$
  - $Ke_{3}$: Evaluated with MC: $< 1\%$
  - $K^+ \rightarrow \pi^+\pi^0$: Evaluated with MC: $< 1\%$
Kl2 and $K \rightarrow \pi \nu \nu$ : motivation

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  - **non-MFV**

- **Weakly coupled and SM Higgs sector**
  - Weakly coupled or weakly coupled and large $\tan\beta$
  - Helicity suppressed observables particularly interesting: $B \rightarrow \ell\ell$, $K \rightarrow j\nu$
  - Charged currents as interesting as FCNCs → precision tests of CC both in $K$ and $B$

- **Strongly coupled or weakly coupled and large $\tan\beta$**

- Long list of useful observables ($B$ and $K$ physics: leptonic, radiative & non-leptonic channels), mainly FCNCs

- The absence of significant deviations from the SM in any of these, makes generic non-MFV scenarios highly constrained/fine-tuned

- In several realistic cases (GUT scenarios, new couplings only for the $3^{rd}$ family, etc...) the most significant constraints are derived from Kaon physics ($\lambda^5$ suppression in the SM, because of $1 \leftrightarrow 3 \leftrightarrow 2$).
The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay

- SM suppression due to $V_{ts} \ast V_{td} \cong 1^5$
- Precise prediction:
  - $\text{BR} = (8.22 \pm 0.84) \times 10^{-11}$
- Theoretical uncertainty will be further reduced to 5% (better knowledge of $V_{td}$, $m_c$)
- Sensitivity to new physics
New physics scenarios (1)

G. Isidori, Flavianet Kaon workshop

E.g.: MSSM with non-MFV $A_U$ terms

$A_U$ = up-squarks left-right mixing term

$\text{BR}_{\text{SUSY}} / \text{BR}_{\text{SM}}$

$B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$

$B(B_d \rightarrow \mu\mu)$

$B(B_d \rightarrow X_s l^+ l^-)$

$\Delta M_{\text{Bd}}$

G.I., Mescia, Paradisi, Smith, S. Trine, '06
New physics scenarios (2)
**Principle of the experiment**

- **Kinematical Rejection**
  \[ m_{\text{miss}}^2 \approx m_K^2 \left( 1 - \frac{|P_\pi|}{|P_K|} \right) + m_\pi^2 \left( 1 - \frac{|P_K|}{|P_\pi|} \right) - |P_K||P_\pi| \eta^2 \]

- Photon vetoes to reject \( K^+ \rightarrow \pi^+\pi^0 \)
  \( p(\pi^+) < 35 \text{ GeV/c} \rightarrow p(\pi^0) > 40 \text{ GeV/c} \)
  \( \eta(\pi^0) \sim 10^{-8} \)

- PID for \( K^+ \rightarrow \mu^+\nu \) rejection

- Target: \( \mathcal{O}(100) \) events with 10% background in 2y data taking

**Signature:**
- Incoming **high** momentum \( K^+ \)
- Outgoing **low** momentum \( \pi^+ \)
SPS primary p: 400 GeV/c
Unseparated beam:
• 75 GeV/c
• 800 MHz
• π/K/p (~6% K⁺)

νν

ν

～11 MHz of K⁺ decays
Non-gaussian tails can be induced, for instance, by the wrong association between the incoming kaon and the pion.  

200 ps time resolution in gigatracker is required.
Gigatracker (Silicon $\mu$-pixel)

**Requirements:**
- Time resolution: 200 ps / station
- Material Budget: < 0.5 % $X_0$ / station

Driven by the experience with the thin hybrids of the ALICE SPD
Large Angle Vetoes

The design is based on the reuse of the Lead glass blocks that formed the barrel calorimeter of OPAL calorimeter.

Our request on the efficiency is reached rearranging the LGs in a configuration formed by 5 staggered layers so to have at least three modules involved in detection, in order to have at least $20 \times X_0$ needed for the inefficiency requests.
Straw chamber design

Straw prototype successfully operated in vacuum (Summer 2007)
The RICH: $\mu$ suppression (MC)

Muon contamination in $\pi$ sample ($15<p<35$ GeV/c): $1.3 \times 10^{-3}$
The experiment schedule

- September 2005: presented at CERN SPSC
- December 2005: R&D endorsed by CERN Research Board
- Start of the Gigatracker project
- Start of test beams at CERN in 2006
- 2007-2008: prototypes construction and test beams at CERN and Frascati
- 2009 – 2010: Technical design and construction
- Start of data taking 2011
K_{12} decays provide a very challenging opportunity to test physics beyond the Standard Model.

NA48/2 has presented two preliminary measurements of R_K, with data collected in 2003 and 2004, both compatible with SM predictions.

The NA62 experiment took data in 2007 with the aim of measuring R_K with an accuracy better than 0.5%, in order to provide a stringent SM test and has collected the largest world sample of Ke2 decays.

- Expect new results at SUSY 2009!

The NA62 Collaboration proposed a new experiment for the measurement of Br(K^+ \rightarrow \pi^+ \nu\nu) with a ~10% accuracy.

The R&D program is well advanced: during the 2007 run the Collaboration tested successfully a full length (18 m) RICH counter prototype and a full-length straw prototype in the actual vacuum tube, a first prototype of the veto system has been tested on beam in 2008.
Radiative corrections

- Radiative decays receive 2 types of contribution: inner bremsstrahlung (IB) and structure-dependent (SD)
- SD gives the dominant contribution to $K_{e2}$ decay rate
- All experiments measure inclusive $\Gamma(K_{e2(\gamma)})/\Gamma(K_{\mu2(\gamma)})$ and subtract SD contribution
- There are more than one model for SD process, which lead to quite different $E_\gamma$ spectra
- Effects on acceptance
### P-326/NA62 Sensitivity

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal: K⁺→π⁺νν [flux = 4.8×10¹² decay/year]</strong></td>
<td>55 evt/year</td>
</tr>
<tr>
<td>K⁺→π⁺π⁰ [ηπ⁰ = 2×10⁻⁸ (3.5×10⁻⁸)]</td>
<td>4.3% (7.5%)</td>
</tr>
<tr>
<td>K⁺→μ⁺ν</td>
<td>2.2%</td>
</tr>
<tr>
<td>K⁺→e⁺π⁺π⁻ν</td>
<td>≤3%</td>
</tr>
<tr>
<td>Other 3 – track decays</td>
<td>≤1.5%</td>
</tr>
<tr>
<td>K⁺→π⁺π⁰γ</td>
<td>~2%</td>
</tr>
<tr>
<td>K⁺→μ⁺νγ</td>
<td>~0.7%</td>
</tr>
<tr>
<td>K⁺→e⁺(μ⁺)π⁰ν, others</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Expected background</strong></td>
<td>≤13.5% (≤17%)</td>
</tr>
</tbody>
</table>

**Definition of “year” and running efficiencies based on NA48 experience**
$K^+ \rightarrow \pi^+ \nu\nu$: State of the art

$\text{BR}(K^+ \rightarrow \pi^+ \nu\nu) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$
$K_L \rightarrow \pi^0 \nu \nu$ Long Time Prospects

CERN is competitive if the E391A technique is established

CERN is competitive if the E391A technique is established