Precision Measurements of Charged Kaon Decays with the NA48/2-NA62 Experiments

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for the NA48/2-NA62 Collaborations:
The NA48 detector

\[ R_K = \frac{K_{e2}}{K_{\mu2}} \] - NA62 (RK)

\[ K^\pm \rightarrow \pi^\pm \gamma \gamma \] - min bias data of NA48/2 (2004), NA62 (RK, 2007)

\[ K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^- \] - first observation, NA48/2 (2003-2004)

\[ K^\pm \rightarrow e^\pm \nu \gamma \] - min bias data of NA62 (RK, 2007)

\[ K^\pm \rightarrow \pi^\pm \nu \nu \] – NA62

Summary
Main detector components:

- Hodoscope: fast trigger (150ps).
- Liquid Krypton EM cal. (LKr):
  high granularity, quasi-homogeneous;
  $\sigma_{E}/E = 3.2%/E^{1/2} + 9%/E + 0.42%$ [GeV];
  $\sigma_{x} = \sigma_{y} = 4.2/E^{1/2} + 0.6$mm
  ($E$ in GeV, 1.5mm@10GeV)
- Magnetic spectrometer:
  4 DCHs (4 views each)
  $\Delta p/p = 1.0% + 0.044%*p$ [GeV/c] - NA48/2
  $\Delta p/p = 0.48% + 0.009%*p$ [GeV/c] - NA62(RK)
- Hadron cal.
- Muon veto
- Photon vetoes

K± beams
2-3M K/spill ($\pi$/K~10),
$\pi$ decay products stay in pipe;
$$R_K = \frac{K_{e2}}{K_{\mu2}}$$

**SM:**

$$R_K^{\text{SM}} = \frac{\Gamma(K^\pm \rightarrow e^\pm \nu)}{\Gamma(K^\pm \rightarrow \mu^\pm \nu)}$$

$$= \left(\frac{m_e^2}{m_\mu^2}\right) \times \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \times (1 + \delta R_K^{\text{rad}})$$

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

[*Cirigliano, Rosell, PRL 99 (2007) 231801*

- hadronic uncertainties cancel in the ratio
- excellent test of SM ($\mu$-e universality)

**beyond SM:**

2HDM → presence of extra charged Higgs

introduces LFV at one-loop level

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


**MSSM:** 1% effect

*[Girrbach, Nierste, arXiv: 1202.4906]*
\[ R_K = \frac{K_{e2}}{K_{\mu2}} \]

**NA62***(**RK**): the measurement is based on \(~150~000\) reconstructed \(K^{\pm} \to e^{\pm} \nu\) \((K_{e2})\) decays (helicity suppressed)

the measured parameters:

\[ R_K = \frac{1}{D} \times \left[ N(K_{e2}) - N_{bgr}(K_{e2}) \right] / \left[ N(K_{\mu2}) - N_{bgr}(K_{\mu2}) \right] \times \left[ A(K_{\mu2}) \times \text{id}(e) \times \text{tr}(K_{e2}) \right] / \left[ A(K_{e2}) \times \text{id}(\mu) \times \text{tr}(K_{\mu2}) \right] \times \left( \frac{1}{\varepsilon_{LKr}} \right) \]

- **D=150** – downscaling factor for \((K_{\mu2})\) trigger
- **N** – number of selected events
- **N_{bgr}** – number of background events
- **A** – acceptances (MC)
- **id** – particle \((e, \mu)\) identification efficiencies
- **tr** – trigger efficiencies
- **\varepsilon_{LKr} = (0.9980 \pm 0.0003)\)** - LKr global readout efficiency
**$K_{e2}$ and $K_{\mu2}$ selection**

**Kinematic separation:**

missing mass: \( M_{\text{miss}}^2 = (p_K - p_l)^2 \)

\( P_K \): average monitored from $K3\pi$ decays as a function of time

good separation at $p_{\text{track}} < 30 \text{ GeV/c}$

**Lepton identification:**

- \( E/p = LKr \text{ energy deposition} / p_{\text{track}} \)
  
  \( 0.95 < E/p < 1.1 \) for electrons

  \( E/p < 0.85 \) for muons

- \( \mu \) suppression in the $e$ sample \( \sim 10^6 \)
\[ R_K = (2.488 \pm 0.007_{\text{stat}} \pm 0.007_{\text{syst}}) \times 10^5 = (2.488 \pm 0.010) \times 10^5 \]

**averaged over 10 momentum bins**

**systematic uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta R_K \times 10^5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{\mu2} ) background</td>
<td>0.004</td>
</tr>
<tr>
<td>( K^\pm \rightarrow e^\pm \nu \gamma ) ((SD+))</td>
<td>0.002</td>
</tr>
<tr>
<td>( K_{e3} , K_{2\pi} )</td>
<td>0.003</td>
</tr>
<tr>
<td>beam halo background</td>
<td>0.002</td>
</tr>
<tr>
<td>Matter composition</td>
<td>0.003</td>
</tr>
<tr>
<td>Acceptance correction</td>
<td>0.002</td>
</tr>
<tr>
<td>DCH alignment</td>
<td>0.001</td>
</tr>
<tr>
<td>Electron identification</td>
<td>0.001</td>
</tr>
<tr>
<td>1TRK trigger efficiency</td>
<td>0.001</td>
</tr>
<tr>
<td>LKR readout efficiency</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>0.007</strong></td>
</tr>
</tbody>
</table>

**Integrated over data samples**

**Lepton momentum, GeV/c**

**NA62**
$R_K$ world average & limits for 2HDM

<table>
<thead>
<tr>
<th>PDG 2008</th>
<th>$2.447 \pm 0.109$</th>
<th>4.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG 2010</td>
<td>$2.493 \pm 0.031$</td>
<td>1.3%</td>
</tr>
<tr>
<td>now</td>
<td>$2.488 \pm 0.009$</td>
<td>0.4%</td>
</tr>
<tr>
<td>SM</td>
<td>$2.477 \pm 0.001$</td>
<td>0.04%</td>
</tr>
</tbody>
</table>
\( \mathbf{K}^\pm \rightarrow \pi^\pm \gamma \gamma \)

*minimum bias data samples:*

$K^\pm \to \pi^\pm \gamma \gamma$: ChPT description

*Loop diagrams:*
- Cusp at $2m_\pi$ threshold: $z = 0.32$

[$\text{Ecker, Pich, de Rafael, NPB303 (1988) 665}$]

$O(p^4)$

- ChPT description

$O(p^6)$

- 'Unitarity corrections'
  - Increase BR at low $\hat{c}$
  - Result in a non-zero rate at $m_{\gamma\gamma} \to 0$

[$\text{D'Ambrosio, Portoles, PLB386(1996)403}$]

**BNL E787:** 31 candidates with 5 bkg. events;

$BR = (1.10 \pm 0.32) \times 10^{-6}$

[$\text{PRL79 (1997) 4079}$]
$K^\pm \rightarrow \pi^\pm \gamma \gamma$: the signal versus the background

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \gamma \gamma$ candidates</td>
<td>$147$</td>
<td>$175$</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0(\gamma)$ backgr</td>
<td>$11.0 \pm 0.8$</td>
<td>$11.1 \pm 1.8$</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ backgr</td>
<td>$5.9 \pm 0.7$</td>
<td>$1.3 \pm 0.3$</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \gamma \gamma$ signal</td>
<td>$130 \pm 12$</td>
<td>$163 \pm 13$</td>
</tr>
</tbody>
</table>
\[ K^\pm \rightarrow \pi^\pm \gamma \gamma: \text{ z-spectra ChPT fits} \]

**NA48/2 (2004)**

- Visible region is above the \( K^\pm \rightarrow \pi^\pm \gamma \gamma \) peak with \( m_{\gamma\gamma} = m_{\pi^0} \):
  - \( z > 0.2 \) or \( m_{\gamma\gamma} > 220 \text{ MeV}/c^2 \).
- Cusp-like behavior at \( 2m_\pi \) is clearly observed.
\( K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma \) – fit results \((\text{preliminary})\)

<table>
<thead>
<tr>
<th>( \hat{C} = )</th>
<th>O (p4)</th>
<th>O (p6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA48/2 (2004)</td>
<td>1.36(\pm 0.33_{\text{stat}}\pm 0.07_{\text{syst}})</td>
<td>1.67(\pm 0.39_{\text{stat}}\pm 0.09_{\text{syst}})</td>
</tr>
<tr>
<td></td>
<td>( = 1.36 \pm 0.34)</td>
<td>( = 1.67 \pm 0.40)</td>
</tr>
<tr>
<td>NA62 (2007)</td>
<td>1.71(\pm 0.29_{\text{stat}}\pm 0.06_{\text{syst}})</td>
<td>2.21(\pm 0.31_{\text{stat}}\pm 0.08_{\text{syst}})</td>
</tr>
<tr>
<td></td>
<td>( = 1.71 \pm 0.30)</td>
<td>( = 2.21 \pm 0.32)</td>
</tr>
<tr>
<td>combined</td>
<td>1.56(\pm 0.22_{\text{stat}}\pm 0.07_{\text{syst}})</td>
<td>2.00(\pm 0.24_{\text{stat}}\pm 0.09_{\text{syst}})</td>
</tr>
<tr>
<td></td>
<td>( = 1.56 \pm 0.23)</td>
<td>( = 2.00 \pm 0.26)</td>
</tr>
</tbody>
</table>

ChPT O(p6) combined BR fit: \( BR = (1.01 \pm 0.06) \times 10^{-6} \)

- the combined 2004+2007 results contain correlated uncertainties
- PDG (= BNL E787): \( BR = (1.10 \pm 0.32) \times 10^{-6} \)
First observation of $K^\pm \rightarrow \pi^\pm \pi^0 e^+e^-$


Preliminary; analysis is in progress
**first observation:** \( K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^- \)

with internal \( \gamma \) conversion

[Cappiello, Cata, D’Ambrosio, Gao, EPJ C72 (2012) 1872]

the decay is sensitive to **CPV & New Physics**

more than 4 000
\( K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^- \) - events are observed in the signal region

major background sources:
- \( K^\pm \rightarrow \pi^\pm \pi^0_D \rightarrow \pi^\pm e^+ e^- \gamma \) (+ \( \gamma \) acc)
- \( K^\pm \rightarrow \pi^\pm \pi^0 \pi^0_D \rightarrow \pi^\pm \pi^0 e^+ e^- \gamma \) (\( \gamma \) lost)

the normalization channel for the \( Br \) evaluation:
\( K^\pm \rightarrow \pi^\pm \pi^0_D \rightarrow \pi^\pm e^+ e^- \gamma \)
$K^\pm \rightarrow e^\pm \nu \gamma$

minimum bias data sample: NA62 (RK, 2007)

Preliminary; analysis is in progress
Decay formalism

the decay matrix element is described by two terms:

- **IB** (Inner Bremsstrahlung term) - *could be reliably evaluated* (Low theorem)

- **SD** (Structure Dependent term) – *should be parameterized with*
  vector $F_V(p^2)$ and axial-vector $F_A(p^2)$ *Form Factors*

  dependent on momentum transferred to the leptonic pair: \[ p^2 = (p_K - p_\gamma)^2 \]

two variables define the kinematics: \[ x = \frac{(2p_K \times p_\gamma)}{m_K^2}, \quad y = \frac{(2p_K \times p_e)}{m_K^2} \]

\[
d2\Gamma/dxdy (SD) = (1/64\pi^2) \times (m_K^5 G_F^2 |V_{us}|^2) \times [(F_V + F_A)^2 f^+_{SD}(x; y) + (F_V - F_A)^2 f^-_{SD}(x; y)]
\]

**SD**+ sensitive to $(F_V + F_A)$ \quad **SD**- sensitive to $(F_V - F_A)$
\[ K^+ \rightarrow e^+ \nu \gamma \ (SD^+) \]

NA62(RK) partial (40\%) data set: 2007

- \( \approx 10000 \) signal candidates (normalization mode \( K^+ \rightarrow \pi^0 e^+ \nu \))
- acceptance for the signal \( \approx 7\% \) at the background level of \( \approx 5\% \)
- systematic uncertainties dominated by background subtraction
- \( K^+ \) sample analysed first, then \( K^- \) sample will be added
NA62:

the ultra-rare decay $K^\pm \rightarrow \pi^\pm \nu\nu$

in preparation

The major goal: detection of ~100 decays with a 10% background

Experimental status:
Few decays observed (E787/E949 at BNL) =>

$$BR_{SM}(K^\pm \rightarrow \pi^\pm \nu\nu) = (17.3 \pm^{10.5}_{11.5}) \times 10^{-11}$$

SM prediction:
$$BR(K^\pm \rightarrow \pi^\pm \nu\nu) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$$
SM prediction for the decay $K^\pm \rightarrow \pi^\pm \nu \nu$

FCNC processes described with penguin and box diagrams

With the highest CKM suppression:

$|V^*_{tb} V_{ts}| \sim \lambda^2$

$|V_{tb}^* V_{td}| \sim \lambda^3$

$|V_{ts}^* V_{td}| \sim \lambda^5$

$Kl3$ can be used to compute the hadronic matrix element

SM predictions with a 10% precision

error dominated by CKM parameterization

$$BR_{SM}(K^\pm \rightarrow \pi^\pm \nu \nu) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$$

the measurement of $BR(K^+ \rightarrow \pi^+ \nu \nu)$ with 10% precision

will give a direct (7% precision) determination of the CKM element $V_{td}$
the signal event selection & background suppression are based on:

- **kinematical cuts** - to suppress 92% of background \((A)\) (suppressed by kin. cuts)
- **high efficiency of particle ID & veto’s for \(\gamma\)'s and \(\mu\)
  - to suppress 8% of background \((B)\) (not suppressed by kin. cuts)

\[
m^2_{\text{miss}} = (P_\pi - P_K)^2 \approx m_K^2 \times (1 - |p_\pi|/|p_K|) + m_\pi^2 \times (1 - |p_K|/|p_\pi|) - |p_K| \times |p_\pi| \times \theta^2_{\pi K}
\]

- **kinematical rejection**: \(O(10^5)\)
- **precise timing**: \(O(100 \text{ ps})\)
- **associate decayed and incoming \(K\)**
- **two spectrometers**: \(GTK\) for \(K\) and \(Straw\) for \(pions\)

\(-\) 2 regions of \(m^2_{\text{miss}}\) for signal selection
The NA62 detector for $K^\pm \rightarrow \pi^\pm \nu\nu$

- SPS primary protons @ 400GeV/c
- 75GeV/c unseparated hadron beam ($p/\pi/K$), ($\delta p/p \sim 1\%$)
- 750MHz $\rightarrow$ 50MHz kaons (6%) $\rightarrow$ 6MHz decays
- $4.8 \times 10^{12}$ kaon decays per year

NA62 timeline:
- first technical run in autumn 2012 including many parts of the experiment
- 2013: complete detector installation
- 2014-?: data taking with full detector (driven by CERN accelerator schedule)
Summary

- A high precision measurement of charged kaon decay rates ratio \( RK = \frac{Br(Ke^2)}{Br(K\mu^2)} \) is fulfilled, confirming the \( \mu-e \) universality and giving a new constrain to the 2HDM.

- A study of a large sample of decay \( K^\pm \rightarrow \pi^\pm \gamma \gamma \), collected in NA48/2 and NA62(RK) experiments with min bias trigger, led to a high precision test of the ChPT.

- The largest samples of rare and very rare charged kaon decays \( K^\pm \rightarrow e^\pm \nu \gamma \) and \( K^\pm \rightarrow \pi^\pm \pi^0 e^+e^- \) respectively, are collected in the experiment with min bias trigger.
  /analyses are in progress/

- Preparation of the NA62 experiment dedicated to study of very rare charged kaon decays is well progressing; the main goal is to measure the \( BR(K^0 \rightarrow \pi^0 \nu \bar{\nu}) \) with 10% precision, obtaining a strong test of the SM or indicating to a new physics.
Thank you!