Recent Results from the NA48/NA62 CERN Experiments

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on Behalf of the
NA48/2 Collaboration
NA62 Collaboration

Cambridge, Chicago,
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Mainz, Perugia,
Pisa, Torino

Bern ITP, Birmingham,
Fairfax, Frascati, IHEP,
INR, Louvain, Merced,
Napoli, Roma I, Roma II,
San Luis Potosi, SLAC,
Sofia, Triumf

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Experimental Setup

**NA48/2**
- $K^\pm \rightarrow \pi^\pm \gamma\gamma$: Branching Ratio
- $K^\pm \rightarrow \pi^\pm e^+e^-\gamma$: Branching Ratio and Spectrum Shape
- $K^\pm \rightarrow \pi^+\pi^-e^\pm\nu$: Form Factors and $\pi\pi$ Scattering Length

**NA62**
- $K^\pm \rightarrow e^\pm\nu / K^\pm \rightarrow \mu^\pm\nu$: Lepton Universality
Experimental Setup
Direct CP violation in neutral K
\[ \text{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4} \]

**NA48/1 (2002)**
Rare K\(_S\) decays
\[ \text{BR}(K_S \rightarrow \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9} \]
\[ \text{BR}(K_S \rightarrow \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9} \]

**NA48/2 (2003–2004)**
Direct CP violation in charged K
\[ A_g(K^\pm \rightarrow \pi^\pm \pi^+ \pi^-) = (-1.5 \pm 2.1) \times 10^{-4} \]
\[ A_g(K^\pm \rightarrow \pi^\pm \pi^0 \pi^0) = (1.8 \pm 1.8) \times 10^{-4} \]

Lepton universality
Very rare charged K decays

<table>
<thead>
<tr>
<th>Year</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997–1998</td>
<td>K(_L) &amp; K(_S)</td>
</tr>
<tr>
<td>1999–2001</td>
<td>K(_L) &amp; K(_S)</td>
</tr>
<tr>
<td>2000</td>
<td>K(_L) Only</td>
</tr>
<tr>
<td>2002</td>
<td>K(_S) &amp; Hyperons HI</td>
</tr>
<tr>
<td>2003–2004</td>
<td>K(^+) &amp; K(^-)</td>
</tr>
<tr>
<td>2006–2011</td>
<td>Design &amp; Construction</td>
</tr>
<tr>
<td>2007–2008</td>
<td>Ke2/Km2 Tests</td>
</tr>
<tr>
<td>2009</td>
<td>Tests</td>
</tr>
<tr>
<td>2012–2013</td>
<td>K(^+) \rightarrow \pi^+ \nu \nu</td>
</tr>
</tbody>
</table>
**Beam**
> Simultaneous $K^\pm$ ($K^+ / K^- \sim 1.8$)
> $P_K = (60 \pm 3)$ GeV/c

**Magnetic Spectrometer**
> 4 view / DCH -> high efficiency
> $\sigma_p/P = 1.0\% + 0.044\% \cdot P$ [GeV/c]

**Hodoscope**
> Fast trigger
> $\sigma_t = 150$ps

**Electromagnetic Calorimeter**
> High granularity, quasi-homogeneous
> $\sigma_E/E = 3.2\% / \sqrt{E} + 9\% / E + 0.42\%$ [GeV]

**Hadron Calorimeter, Muon and Photon Vetoes**
$K^\pm \rightarrow \pi^\pm \gamma \gamma$ \& $K^\pm \rightarrow \pi^\pm e^+e^-\gamma$
In the Chiral Perturbation Theory framework the differential rate of the \( K^\pm(p) \rightarrow \pi^\pm(p_3) \gamma(q_1) \gamma(q_2) \) process (no \( O(p^2) \) contribution) is

\[
\frac{\partial^2 \Gamma}{\partial y \partial z} = \frac{m_{K^\pm}}{(8\pi)^3} \left[ z^2 \cdot \left( |A + B|^2 + |C|^2 \right) + \left( y^2 - \frac{1}{4} \lambda(1,z,r^2) \right)^2 \left( |B|^2 + |D|^2 \right) \right]
\]

relevant only @ low \( m_{\gamma\gamma} \)

- The leading contribution @ \( O(p^4) \) is given by \( A(z,\zeta) \) (loops) which is responsible for a cusp at \( m_{\gamma\gamma} = m_{2\pi} \)
- \( C \) (WZW) corresponds to \( \sim 10\% \) of \( A @ O(p^4) \)
- \( B, D = 0 @ O(p^4) \)


- \( O(p^6) \) unitarity corrections can increase the BR by \( 30\%-40\% \)

\[D’Ambrosio, Portoles, Nucl. Phys. B386 (1996), 403\]
Both decay spectrum and rate strongly depend on the single \( \hat{c} \) parameter (\( O(1) \))

\[
BR(K^+ \rightarrow \pi^+\gamma\gamma) = (5.26 + 1.64 \cdot \hat{c} + 0.32 \cdot \hat{c}^2 + 0.49) \cdot 10^{-7} \geq 4 \cdot 10^{-7}
\]

\( m_{\gamma\gamma} \) spectrum

\( \hat{c} \) = 0
\( \hat{c} = -2.3 \)

unitarity corrections

cusp-like behaviour at 2\( \pi \) threshold
Previous measurement by E787 based on
31 candidate, 5.1 ± 3.3 background events

$$\text{BR}(\pi^+\gamma\gamma) = (1.10 \pm 0.32) \cdot 10^{-6}$$

Event Sample (~20% of the total statistics)
> $K^\pm \rightarrow \pi^\pm\pi^0$ as normalization
> 1164 candidate events
> 3.3% background/signal ($K^\pm \rightarrow \pi^\pm\pi^0\gamma$)

Shape Analysis
> MC $O(p^6)$ and $\hat{c} = 2$ for comparison
> Data shape follows $\chi$PT prediction
> Possibility of precise $\hat{c}$ measurement but no quantitative result yet

$$\text{BR}(K^\pm \rightarrow \pi^\pm\gamma\gamma) = (1.07 \pm 0.04_{\text{stat}} \pm 0.08_{\text{syst}}) \cdot 10^{-6}$$

assuming $O(p^6)$

trigger cut

First clear observation of the cusp at 2$\pi$ threshold

2$\pi$ threshold
$K^\pm \rightarrow \pi^\pm e^+e^-\gamma$ - I

Never observed before
Naïve estimation of the BR

\[ K^\pm \rightarrow \pi^\pm \gamma^* \rightarrow \pi^\pm e^+e^-\gamma \]

\[ \text{BR}(\pi^+e^+e^-\gamma) = \text{BR}(\pi^+\gamma\gamma) \cdot 2\alpha \sim 1.6 \cdot 10^{-8} \]

Theoretical expectation \cite{Gabbiani, PRL D59, 094022}

\[ \text{BR}(\pi^\pm e^+e^-\gamma) = (0.9\div1.6) \cdot 10^{-8} \]

**Event Sample** (full statistics)

- $K^\pm \rightarrow \pi^\pm \pi^0_\Delta$ as normalization
- 120 candidate events
- 6.1\% background/signal ($K^\pm \rightarrow \pi^\pm \pi^0_\Delta\gamma$)

**Model-Independent BR** ($m_{ee\gamma} > 260$ MeV/c$^2$)

\[ \text{BR}(K^\pm \rightarrow \pi^\pm e^+e^-\gamma) = (1.19 \pm 0.12_{\text{stat}} \pm 0.04_{\text{syst}}) \cdot 10^{-8} \]
Shape Analysis

> $\hat{c}$ has been extracted by fitting data to the absolute $O(p^4)$ $\chi$PT prediction

\[ \chi^2/\text{ndf} = 8.1/17 \]
\[ \text{Prob} = 96.4\% \]

$\hat{c} = (0.90 \pm 0.45)$

1.2σ away from BNL E787 value in $K^+ \to \pi^+\gamma\gamma$: $\hat{c} = 1.8 \pm 0.6$

$K^\pm \rightarrow \pi^+ \pi^- e^\pm \nu$
The $K^\pm \rightarrow \pi^+\pi^-e^{\pm}\nu$ ($K_{e4}$) dynamic is fully described by 5 variables (Cabibbo-Maksymovicz)

\[ M_{\pi\pi}^2, M_{ev}^2, \cos\theta_{\pi}, \cos\theta_{e} \text{ and } \phi \]

The transition amplitude can be written using 2 axial and 1 vector Form Factors that can be developed in a partial wave expansion

\[ F = F_s \cdot e^{i\delta_s} + F_p \cdot e^{i\delta_p} \cdot \cos\theta_{\pi} + \text{terms}_{d\text{-wave}} \]

\[ G = G_p \cdot e^{i\delta_p} + \text{terms}_{d\text{-wave}} \]

\[ H = H_p \cdot e^{i\delta_p} + \text{terms}_{d\text{-wave}} \]

The Form Factors can be expanded as a function of $q^2=(M_{\pi\pi}^2/4m_{\pi}^2-1)$ and $M_{ev}^2$

\[ F_s = f_s + f_s' \cdot q^2 + f_s'' \cdot q^4 + \]
\[ + f_e' \cdot (M_{ev}^2/4m_{\pi}^2) + \ldots \]

\[ F_p = f_p + f_p' \cdot q^2 + \ldots \]

\[ G_p = g_p + g_p' \cdot q^2 + \ldots \]

\[ H_p = h_p + h_p' \cdot q^2 + \ldots \]

$F_s, F_p, G_p, H_p$ and $\delta=\delta_s-\delta_p$ used as fit parameters
**Signal and Background**

**Event Sample (full statistics)**

- 1.13M candidate events
- \( \sim 0.6\% \) background/signal

**Background Sources**

- \( K^\pm \rightarrow \pi^\pm \pi^+\pi^- \) decay with \( \pi \rightarrow e\nu \) (dominant) or \( \pi \) mis-ID as \( e \)

- \( K^\pm \rightarrow \pi^\pm \pi^0(\pi^0) \) decay with \( \pi^0 \rightarrow e^+e^-\gamma \) and \( e \) mis-ID as \( \pi + \gamma \)s undetected

- Background studied using electron “wrong sign” events (assuming \( \Delta Q = \Delta S \) and total charge \( \pm 1 \)) and cross checked with MC
Using iso-populated bins in the 5-D space of the C.M. variables one defines a grid of

\[ 10(M_{\pi\pi}) \times 5(M_{e\nu}) \times 5(\cos \theta_e) \times 5(\cos \theta_\pi) \times 12(\phi) = 15000 \text{ boxes} \]

The set of Form Factor values is used to minimize a log-likelihood estimator well suited for small numbers of data event/bin and taking into account the statistics of the simulation (simulated and expected events/bin)

Assuming constant Form Factors over single boxes, \( K^+ \) and \( K^- \) samples fitted separately in 10 independent \( M_{\pi\pi} \) bins/slices and then combined in each slice according to their statistical error

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Monte-Carlo</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^+ ) Events</td>
<td>726400</td>
<td>17.4 M</td>
</tr>
<tr>
<td>Events/Box</td>
<td>48</td>
<td>1160</td>
</tr>
<tr>
<td>( K^- ) Events</td>
<td>404400</td>
<td>9.7 M</td>
</tr>
<tr>
<td>Events/Box</td>
<td>27</td>
<td>650</td>
</tr>
</tbody>
</table>
**Form Factors - I**

*Quadratic in $q^2$*

*First measurement of $F_p \neq 0$*

*Linear in $q^2$*

*No linear term ($h_p'$)*
All the Form Factors are measured relatively to $f_s$ (no BR measurement)

Systematics mostly from background and acceptance control, but ~ same size as statistical error or smaller

First evidence of $f_e' \neq 0$ and $f_p \neq 0$

<table>
<thead>
<tr>
<th>Form Factor</th>
<th>Value</th>
<th>Statistical Error</th>
<th>Systematic Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_s'/f_s$</td>
<td>0.152 ± 0.007</td>
<td>± 0.005</td>
<td></td>
</tr>
<tr>
<td>$f_s''/f_s$</td>
<td>-0.073 ± 0.007</td>
<td>± 0.006</td>
<td></td>
</tr>
<tr>
<td>$f_e'/f_s$</td>
<td>0.068 ± 0.006</td>
<td>± 0.007</td>
<td></td>
</tr>
<tr>
<td>$f_p/f_s$</td>
<td>-0.048 ± 0.003</td>
<td>± 0.004</td>
<td></td>
</tr>
<tr>
<td>$g_p/f_s$</td>
<td>0.868 ± 0.010</td>
<td>± 0.010</td>
<td></td>
</tr>
<tr>
<td>$g_p'/f_s$</td>
<td>0.089 ± 0.017</td>
<td>± 0.013</td>
<td></td>
</tr>
<tr>
<td>$h_p/f_s$</td>
<td>-0.398 ± 0.015</td>
<td>± 0.008</td>
<td></td>
</tr>
</tbody>
</table>
The extraction of the $\pi\pi$ scattering lengths from the $\delta = \delta_s - \delta_p$ phase shift needs external theoretical and experimental data inputs.

The Roy equations provide this relation between $\delta$ and $(a_0, a_2)$ near threshold, extrapolating from the $M_{\pi\pi} > 0.8$ GeV/c$^2$ region. The precision of these data defines the width of the Universal Band in the $(a_0, a_2)$ plane.

The fit of the experimental points using the Roy equations in the Universal Band allows to extract the $a_0$ and $a_2$ values.
Minimizing the $\chi^2$ in the 2-D fit it’s possible to identify the favoured solution (and the corresponding ellipse)

**Single parameter fit** ($a_2$ constrained to $\chi_{PT}$ prediction)

\[
a_0 \cdot m_{\pi^+} = 0.2206 \pm 0.0049_{\text{stat}}
\]
\[
\pm 0.0018_{\text{syst}}
\]
\[
\pm 0.0064_{\text{theo}}
\]

**Two parameters fit** ($\rho \sim 97\%$)

\[
a_0 \cdot m_{\pi^+} = 0.2220 \pm 0.0128_{\text{stat}}
\]
\[
\pm 0.0050_{\text{syst}}
\]
\[
\pm 0.0037_{\text{theo}}
\]
\[
a_2 \cdot m_{\pi^+} = -0.0432 \pm 0.0086_{\text{stat}}
\]
\[
\pm 0.0034_{\text{syst}}
\]
\[
\pm 0.0028_{\text{theo}}
\]

\[
a_0 \cdot m_{\pi^+} = 0.220 \pm 0.005
\]
\[
a_2 \cdot m_{\pi^+} = -0.0444 \pm 0.0008
\]

[CGL NPB603 (2001), PRL86 (2001)]
Correct the $\delta$ phase before extracting the $\pi\pi$ scattering length

- Correction is $10\div15$ mrad
- Experimental precision $7\div8$ mrad

$K_{e4}$ fit range $285\div390$ MeV

[CGL RPJ C59 (2009) 777]
Two statistical independent measurements by NA48/2, with mostly independent systematic uncertainties and different theoretical inputs

\[ a_0 \cdot m_{\pi^+} = 0.2206 \pm 0.0047_{\text{stat}} \pm 0.0015_{\text{syst}} \pm (0.0049_{\text{theo}}) \]

\[ a_2 \cdot m_{\pi^+} = -0.0429 \pm 0.0044_{\text{stat}} \pm 0.0016_{\text{syst}} \pm (0.0030_{\text{theo}}) \]

\[ (a_0 - a_2) \cdot m_{\pi^+} = 0.2639 \pm 0.0020_{\text{stat}} \pm 0.0004_{\text{syst}} \pm (0.0021_{\text{theo}}) \]

\[ a_2 \cdot m_{\pi^+} = -0.0429 \pm 0.0044_{\text{stat}} \pm 0.0016_{\text{syst}} \pm (0.0030_{\text{theo}}) \]
$K^\pm \rightarrow e^\pm \nu / K^\pm \rightarrow \mu^\pm \nu$
Leptonic decays of light pseudoscalar mesons are the ideal test of SM and search for NP

- Not directly usable due to hadronic uncertainties
- Hadronic uncertainties cancel in the ratio $K_{e2}/K_{\mu2}$
- SM prediction is very accurate ($\delta R_K/R_K \sim 0.04\%$)

$$R_K^{SM} = \frac{\Gamma(K \rightarrow e\nu_e)}{\Gamma(K \rightarrow \mu\nu_\mu)} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1 + \delta R_{QED}\right) =$$

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

The only difference between electron and muon channel is due to the $V-A$ coupling

$K_{e2}$ is strongly helicity suppressed ($V-A$ coupling) $\rightarrow$ Enhanced sensitivity to non-SM effects

A small correction (few %) has to be included due to the IB radiative decay

[Cirigliano, Rosell JHEP 0710:005 (2007)]
In the MSSM large tan$\beta$ scenario, the presence of LFV terms (charged Higgs coupling) introduces extra contribution to the SM amplitude, enhancing the decay rate

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

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

Sizeable effects are predicted for reasonable SUSY parameters

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

Analogous SUSY effects in pion decay are suppressed by a factor

$$\left( \frac{m_\pi}{m_K} \right)^4 \approx 6 \cdot 10^{-3}$$

[Masiero, Paradisi, Petronzio, PRD 76 (2006)]
The **PDG08** value is based on 3 measurements in 70s

\[ R_K = (2.45 \pm 0.11) \cdot 10^{-5} \text{ (4.5% error)} \]

but a better precision is needed when comparing with theoretical predictions

**Preliminary results** by KLOE and NA48/2

\[ R_K = (2.457 \pm 0.032) \cdot 10^{-5} \text{ (1.3% error)} \]

**Final result by KLOE** (LaThuile09)

\[ R_K = (2.493 \pm 0.025 \pm 0.019) \cdot 10^{-5} \]

(1.3% with \(\sim 13.8k\) \(K_{e2}\) candidates, 16% background)

**World average**

\[ R_K = (2.468 \pm 0.025) \cdot 10^{-5} \text{ (1% error)} \]
Measurement Strategy

Beam setup and detector of NA48/2 slightly optimized
  > 75 GeV/c K to better separate $K_{e2}$ and $K_{\mu2}$ events
  > Minimum bias triggers

$K_{e2}$ and $K_{\mu2}$ candidates collected simultaneously
  > Measurement independent of kaon flux
  > Many systematic effects cancel in the ratio (@ first order)

MC simulation used to limited extent
  > Acceptance correction (geometry)
  > Correction for background from catastrophic energy loss of muons in the LKr

Analysis in 10 bins of reconstructed lepton momentum

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

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Event Selection

Similar kinematics and topology -\> Maximize common cuts

Common selection
\> 1 reconstructed track
\> common geometrical acceptance
\> decay vertex defined as the closest distance of approach between track and kaon axis
\> track momentum $[15\div65]$ GeV/c

Kinematical identification
\> 2 body decay $M^2_{\text{miss}} = (P_K - P_l)^2$
\> (kaon momentum measured with $K_{3\pi}$)
\> $|M^2_{\text{miss}}| < 0.015$ GeV$^2$/c$^4$

Particle identification
\> e $(0.95 < E_{LKR}/p_{DCH} < 1.10)$
\> $\mu$ $(E_{LKR}/p_{DCH} < 0.85)$
> The main background in the $K_{e2}$ sample comes from catastrophic energy loss of muons in the LKr
  $(E_{LKr}/p_{DCH} > 0.95 \rightarrow$ tag events as $K_{e2}$)
> It’s important at high momentum where the missing masses are indistinguishable
> To measure directly $P(\mu \rightarrow e)$ a “lead wall” ($\sim 8.9 \times X_0$) has been installed on $\sim 18\%$ LKr surface for $\sim 50\%$ of the run time
> Tracks traversing the lead are pure muon samples (contamination $< 10^{-7}$)
> The reliability of these technique has been studied in special “muon runs”
> The result agrees perfectly with GEANT4 simulation ($P$ dependence)

$$P(\mu \rightarrow e) \sim (3 \div 5) \cdot 10^{-6}$$
**Ke2 background sources**

- $K_{\mu 2}$ (CB) $(6.28 \pm 0.17)\%$
- $K_{\mu 2}$ ($\mu \rightarrow e$) $(0.23 \pm 0.01)\%$
  - measured with MC (including also the contribution of $\mu$ decay in spectrometer)
- $K_{e 2\gamma}$ (SD$^+$) $(1.02 \pm 0.15)\%$
  - BR measurement by KLOE (improvement expected by our new measurement)
- Beam halo $(0.45 \pm 0.04)\%$
  - directly measured on data (special runs)
- $K_{2\pi}$ 0.03\%
- $K_{e 3}$ 0.03\%

**Kµ2 background sources**

- Beam halo $\sim 0.2\%$

> Selection criteria are optimized individually in each momentum bin

> Largest background fraction at high momentum
51089 $K_{e2}$ candidates (B/S = 8.0%)

Estimated total $K_{e2}$ sample: 140k $K^+$ and 20k $K^-$
(K$^+$ statistics ~90% of the total sample due to a larger halo background in $K^-$ beam)
15.56M $K_{\mu 2}$ candidates (B/S ~ 0.25%)
Results - I

Uncertainty

\[ \delta R_K \cdot 10^5 \]

\[ \begin{align*}
  \text{Statistics} & : 0.012 \\
  K_{\mu 2} & : 0.004 \\
  K_{e 2\gamma} (SD^+) & : 0.004 \\
  \text{Beam halo} & : 0.001 \\
  \text{Electron ID} & : 0.001 \\
  K_{e 2\gamma} (IB) \text{ simulation} & : 0.007 \\
  \text{Acceptance} & : 0.002 \\
  \text{Trigger timing} & : 0.007 \\
  \text{Total} & : 0.016 \\
  \end{align*} \]

The total sample of \( \sim 160k \) candidates will allow a statistical error \( \sim 0.3\% \) and total uncertainty (0.4\%\,\text{÷}0.5\%) in agreement with proposal.

\[ R_K = (2.500 \pm 0.012_{\text{stat}} \pm 0.011_{\text{syst}}) \cdot 10^{-5} = (2.500 \pm 0.016) \cdot 10^{-5} \]
Status after KAON 09

$R_K^{SM} = (2.477 \pm 0.001) \cdot 10^{-5}$
Study of radiative kaon decays

- $K^\pm \rightarrow \pi^\pm \gamma \gamma$
  First possibility for shape study
- $K^\pm \rightarrow \pi^\pm e^+ e^- \gamma$
  First observation and measurement of BR and shape

Determination of the $\pi\pi$ scattering length

- Achieved precision ($K_{e4} + $Cusp) is competitive with the best theoretical prediction

$R_K$ measurement

- $K_{e2}$ world sample increased by an order of magnitude
- Excellent $K_{e2}/K_{\mu2}$ separation (>99% electron ID efficiency and ~$10^6$ $\mu$ suppression) leads to a low ~8% background
- Measurement with ~0.5% precision within reach