NA48 Results on Kaon and Hyperon Decays Relevant to $|V_{us}|$

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On behalf of the NA48 Collaboration
Outline

The NA48 detector

Charged Kaons

- $BR(K^\pm \rightarrow \pi^0 e^\pm \nu)$
- $BR(K^\pm \rightarrow \pi^0 \mu^\pm \nu)$

Neutral Kaons

- $BR(K_L \rightarrow \pi^+ \pi^-)$
- $K_L \rightarrow \pi^\pm \mu^\mp \nu$ Form Factors

Hyperons

- $\Xi_0$ Beta Decay

Summary

NA48

1997  $\varepsilon'/\varepsilon$ run  $K_L + K_S$
1998  $\varepsilon'/\varepsilon$ run  $K_L + K_S$
1999  $\varepsilon'/\varepsilon$ run  $K_L + K_S$
2000  $K_L$ only  $K_S$ High Intensity
       NO Spectrometer
2001  $\varepsilon'/\varepsilon$ run  $K_L + K_S$
2002  $K_S$ High Intensity
2003  $K^\pm$ High Intensity
2004  $K^\pm$ High Intensity

NA48/1

NA48/2
The NA48 Detector

Magnetic Spectrometer
4 drift chambers
\[ \frac{\sigma_p}{p} (\%) = 0.48 \pm 0.009 \quad (\text{GeV/c}) \]
Dipole magnet with 265(120) MeV/c
\[ p_T \text{ kick} \]

Hodoscope
Fast trigger
Precise time measurement
\[ \sigma_t \simeq 150 \text{ ps} \]

Liquid Krypton EM Calorimeter
\[ \frac{\sigma_E}{E} (\%) = \frac{3.2}{\sqrt{E}} \pm \frac{9.0}{E} \pm 0.42 \quad (\text{GeV}) \]

Muon Counter
25cm \times 25cm cells
\[ \sigma_t \simeq 350 \text{ ps} \]
$K_{\ell 3}$ decays ⇒ the most accurate and theoretically cleanest way to extract $|V_{us}|$

The master formula for the $K_{\ell 3}$ decay rates:

$$
\frac{BR(K_{\ell 3})}{\tau_K} = C_K^2 G_F^2 m_K^5 S_{EW} |V_{us}|^2 |f_+ (0)|^2 I_K^\ell (\lambda +_0) (1 + \delta_{SU(2)}^\ell + \delta_{EM}^\ell)
$$

- $C_{K0}^2 = 1$
- $C_{K\pm}^2 = 1/2$
- Short Distance Corrections
- Calculated f.f. @ t=0
- $2^{nd}$ order SU(3)
- $\delta_{EM}^\ell \approx 0$ for $K^\pm$
- $\delta_{SU(2)}^\ell = 0$ for $K^0$

Measured BR and Lifetime

Phase Space integral depends on f.f.

Experiments supply BR, $\tau$ and Form Factor measurements
\( BR(K_{e3}^\pm) \) and \( BR(K_{\mu3}^\pm) \)

- \( K^\pm \) collected during 2003 data taking
- (Main purpose search for direct CP violation in \( K^\pm \rightarrow 3\pi \) decays)
- Special low intensity (\( \times 1/8 \)) minimum bias run
- Simultaneous \( K^+ \) and \( K^- \) beams
- \( K^+ \) flux \( \sim 3.2 \times 10^6 \); \( K^+/K^- \approx 1.78 \) (production rate @target)

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We measured the ratios of these decay rates:

\[
\frac{R_{K^3e/K2\pi}}{R_{K\mu3/K2\pi}} = \frac{\Gamma(K^\pm \rightarrow \pi^0 e^{\pm} \nu)}{\Gamma(K^\pm \rightarrow \pi^0 \pi^\pm \pi^0)} \quad \frac{R_{K\mu3/K2\pi}}{R_{K\mu3/Ke3}} = \frac{\Gamma(K^\pm \rightarrow \pi^0 \mu^{\pm} \nu)}{\Gamma(K^\pm \rightarrow \pi^0 e^{\pm} \nu)}
\]

Same event signature in the ratio: 1 charged track and 2 $\gamma$ from a $\pi^0$ decay

→ Cancellation of uncertainties

Selected Events

<table>
<thead>
<tr>
<th>$K_{e3}^+$</th>
<th>$K_{e3}^-$</th>
<th>$K_{\mu3}^+$</th>
<th>$K_{\mu3}^-$</th>
<th>$K_{2\pi}^+$</th>
<th>$K_{2\pi}^+$</th>
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<tbody>
<tr>
<td>56196</td>
<td>30898</td>
<td>49364</td>
<td>27525</td>
<td>461837</td>
<td>256619</td>
</tr>
</tbody>
</table>

Background < 1%
BR($K_{e3}^\pm$) and BR($K_{\mu3}^\pm$)

\[ R_{K_{e3}/K2\pi} = 0.2496 \pm 0.0009_{stat} \pm 0.0004_{syst} \]
\[ R_{K_{\mu3}/K2\pi} = 0.1637 \pm 0.0006_{stat} \pm 0.0003_{syst} \]
\[ R_{K_{\mu3}/K_{e3}} = 0.656 \pm 0.003_{stat} \pm 0.001_{syst} \]

**Systematics**

- Detector Acceptance
- Account for Radiative Corrections
- Trigger Efficiency
- Form Factors
- Input values and Model

Taking BR($K_{2\pi}$) from PDG we evaluate:

\[ \text{BR}(K_{e3}^\pm) = 0.05221 \pm 0.00019_{stat} \pm 0.00008_{syst} \pm 0.00030_{norm} \]
\[ \text{BR}(K_{\mu3}^\pm) = 0.03425 \pm 0.00013_{stat} \pm 0.00006_{syst} \pm 0.00020_{norm} \]

Error dominated by BR($K_{2\pi}$) uncertainty

BNL–E865 result is confirmed
Results for $f_+(0) \mid V_{us} \mid$ from $K_{e3}^\pm$ and $K_{\mu3}^\pm$

With the BR($K_{e3}^\pm$) and BR($K_{\mu3}^\pm$) we can derive $f_+(0) \mid V_{us} \mid$

\[
\begin{align*}
 f_+(0) \mid V_{us} \mid & = 0.2204 \pm 0.0012 & K_{e3}^\pm \\
 f_+(0) \mid V_{us} \mid & = 0.2177 \pm 0.0013 & K_{\mu3}^\pm \\
 f_+(0) \mid V_{us} \mid & = 0.2197 \pm 0.0012 & K_{\ell3}^\pm \\
\end{align*}
\]

External Input Used

- $M_{K^+}$ and $\tau_{K^+}$ from PDG
  - $G_F = (1.16637 \pm 0.00001) \times 10^{-5}$ GeV$^{-2}$
  - $S_{EW} = (1.0230 \pm 0.0003)$
  - $\delta^{e,\mu}_{SU2} = (2.31 \pm 0.22)\%$
  - $\delta^{e}_{EM} = (0.03 \pm 0.10)\%$
  - $\delta^{\mu}_{EM} = (0.20 \pm 0.20)\%$
  - $I_{K}^{e} = 0.1591 \pm 0.0012$
  - $I_{K}^{\mu} = 0.1066 \pm 0.0008$

In good agreement with CKM unitarity
\[ \text{BR}(K_L \rightarrow \pi^+ \pi^-) \]

- \( K_L \) collected during 1999 \( \epsilon' / \epsilon \) data taking
- Special minimum bias run, \( K_L \) beam only

We measured the following ratio:

\[ R_{K2\pi/Ke3} = \frac{\Gamma(K_L \rightarrow \pi^+ \pi^-)}{\Gamma(K_L \rightarrow \pi^+ e^+ \nu)} \]

Event Selection:

- \( \pi^+ \pi^- \) \( K_{e3} \)
- 2 tracks \( \pm \)
- \( E/p < 0.93 \)
- \( E/p > 0.93 \)
- Good vertex
- No \( \mu \)
- \( m_{\pi\pi} \)

Selected events: 47k \( 5 \times 10^6 \)

Determine from data \( W(\pi \rightarrow e) = 0.592 \pm 0.006_{\text{stat}} \)\% and
\( W(e \rightarrow \pi) = 0.478 \pm 0.004_{\text{stat}} \)\%
\[ \frac{\Gamma(K_L \rightarrow \pi^+ \pi^-)}{\Gamma(K_L \rightarrow \pi^\pm e^\mp \nu)} = \left(4.835 \pm 0.022_{\text{stat}} \pm 0.020_{\text{syst}}\right) \times 10^{-3} \] (hep-ex/0611052)

Using updated NA48 measurement
\[ \text{BR}(K_{e3}) = 0.4022 \pm 0.0031 \]

\[ \text{BR}(K_L \rightarrow \pi^+ \pi^-) = \left(1.941 \pm 0.019\right) \times 10^{-3} \text{ (no DE)} \]

In agreement with KTeV and KLOE and contradicting former PDG averages
Two form factors, \( f_\pm(t) \), describe the \( K_{\ell 3} \) decay

\[
\mathcal{M} = G_F / \sqrt{2} V_{us} \left[ f_+(t) \left( P_K + P_\pi \right)^\mu \bar{u}_\ell \gamma_\mu (1 + \gamma_5) u_\nu + f_-(t) \ m_\ell \bar{u}_\ell (1 + \gamma_5) u_\nu \right]
\]

\( t \) is the square of the four–momentum transfer to the lepton system

\[
f_- \Rightarrow m_\ell^2 / M_K^2
\]

Can be measured only in \( K_{\mu 3} \) decays

\( f_0(t) \) is a combination of the two:

\[
f_0(t) = f_+(t) + \frac{t}{(m_K^2 - m_\pi^2)} f_-(t)
\]

\( f_{+,0}(t) \) are the vector and scalar form factor and are related to the angular momentum of the lepton pair
Well known parametrizations of the form factors are: Linear, Quadratic and Pole

\[
\begin{align*}
    f_{+,0}(t) &= f_{+,0}(0) \left(1 + \lambda_{+,0} \frac{t}{m_\pi^2}\right) \quad \text{LINEAR} \\
    f_{+,0}(t) &= f_{+,0}(0) \left[1 + \lambda'_{+,0} \frac{t}{m_\pi^2} + \frac{1}{2} \lambda''_{+,0} \left(\frac{t}{m_\pi^2}\right)^2\right] \quad \text{QUADRATIC} \\
    f_+(t) &= f_{+}(0) \frac{m_V^2}{m_V^2 - t} \quad \text{POLE} \\
    f_0(t) &= f_{+}(0) \frac{m_S^2}{m_S^2 - t}
\end{align*}
\]

In the pole model the f.f. acquire a physical meaning: they are related to the exchange of $K^*$ resonances with spin–parity $1^-/0^+$ and mass $m_V/m_S$

Experiments measure the normalized f.f.: $\tilde{f}(t) = f_{+,0}(t)/f_{+}(0)$
New Parametrizations of the $K_{\mu 3}^0$ Form Factors

Recently new parametrizations of the $K_{\mu 3}^0$ Form Factors have been proposed [Phys. Lett. B 638(2006) 480] (hep–ph/0603202)

$$f_+(t) = \exp\left[\frac{t}{m_\pi^2}\left(\Lambda_+ + H(t)\right)\right] \quad f_0(t) = \exp\left[\frac{t}{(m_K^2 - m_\pi^2)}(\ln C - G(t))\right]$$

- Based on dispersion techniques
- Describe simultaneously the slope and the curvature of the f.f.
- For the dispersive integrals $H(t)$ and $G(t)$ accurate polynomial approximations have been derived
- Key parameter is $\ln C = \ln[f_0(m_K^2 - m_\pi^2)]$ the value of the scalar f.f. at the Callan–Treiman point
- The value of $\ln C$ can provide a test of Right Handed quark Currents coupled to the standard W boson

$$\ln C = 0.2151 \pm 0.0045 + \tilde{\Delta}_{CT} + \Delta(\epsilon)$$

$\Delta(\epsilon)$ is the RHC contribution and $\tilde{\Delta}_{CT} \approx 10^{-3}$ is the Callan–Treiman discrepancy
$K_L \rightarrow \pi^\pm \mu^m p \nu_\mu$ Form Factors Analysis

- $K_L$ collected during 1999 $\epsilon'/\epsilon$ data taking
- Special minimum bias run, $K_L$ beam only
- Dalitz Plot analysis: to extract the f.f. fit the DP density

$$\rho(E^*_\mu, E^*_\pi) = \frac{dN^2(E^*_\mu, E^*_\pi)}{dE^*_\mu dE^*_\pi} \propto A f^2_+(t) + B f_+(t) f_-(t) + C f^2_-(t)$$

**Event Selection**

- $\mu$ id. (Hit in time in MUC)
- $\pi$ id. ($E/p < 0.9$)
- no $e$ (against $K_{e3}$)
- no $K_{3\pi}$ ($P_0' < -0.004 \ (GeV/c)^2$)

Radiative Corrections with KLOR

use the LOW energy corrections (true 61%)

Selected $2.3 \times 10^6$ events
Like other exp. we observe a quadratic term in the expansion of $f_+(t)$

- $\lambda_0$ is smaller than what recently reported

- According to the model of Stern and Coll. the value of $\ln C$ from the dispersive fit gives: $\Delta(\epsilon) + \tilde{\Delta}_{CT} = -0.062 \pm 0.014_{NA48} \pm 0.002_{theo} \pm 0.005_{ext}$
\[ \Xi^0 \text{ BR and Lifetime} \]

- \( \Xi^0 \) collected during 2002 data taking
- **Purpose:** Measurement of very rare \( K_S \) decays and neutral hyperon decays
- Neutral beam with target close to the decay region
- Same \( K_S \) target from \( \epsilon'/\epsilon \) measurement but \( 200 \times \) intensity

\( \Xi^0, \Lambda \) lifetime \( \approx K_S \) lifetime

→ Kaon experiments can provide large samples of neutral hyperons

 Flux in the decay region

\[ K_S \quad \sim \quad 3.5 \times 10^{10} \]
\[ \Xi^0 \quad \sim \quad 2.4 \times 10^9 \]
\( \Xi^0 \) Beta Decay

\( \Xi^0 \) (uss): strange partner of the \( n(\text{uud}) \)

- Under interchange of \( d \) and \( s \) quark the
  \( \Xi^0 \rightarrow \Sigma^+ \ e^- \ \bar{\nu}_e \) decay is analog to neutron \( \beta \)–decay

Test of \( SU(3) \) symmetry

- In exact \( SU(3) \) the ratio between \( g_1 / f_1 \)
  is equal to the neutron \( \beta \)–decay

Possible measurement of \( |V_{us}| \) complementary to the one obtained with \( K \) decays

\[
\Gamma = \frac{BR_{\Xi^0 \rightarrow \Sigma e\bar{\nu}}}{\tau_{\Xi^0}} \approx G_F^2 |V_{us}|^2 \frac{2 \Delta m^5}{60 \pi^3} (1 - \frac{3}{2} \beta) (|f_1^2| + 3|g_1^2|)
\]

\( \Delta m = m_{\Xi^0} - m_{\Sigma^+} = 0.12546 \pm 0.00021 \) GeV/c\(^2\) and \( \beta = \frac{\Delta m}{m_{\Xi^0}} = 0.09542 \pm 0.00011 \)

So far only one BR measurement by KTeV with 176 events
**Ξ⁰ Beta Decay: Event Selection**

**Σ⁺** is a unique signature of Ξ⁰ β–decay

Two body mode forbidden by energy conservation

Reconstruct the Σ⁺ by its decay to \( p \pi^0 \)

Require the presence of an electron

NA48/1 has 6316 candidates

Background \( \approx 215 \) events (3.4%)

Estimated from mass side bands

Use \( \Xi^0 \rightarrow \Lambda \pi^0 \) as normalization channel (59K events)
The NA48/1 result is:

$$\text{BR}(\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}_e) = (2.51 \pm 0.03_{\text{stat}} \pm 0.09_{\text{syst}}) \times 10^{-4}$$

Apply charge inversion to get $\Xi^0$:

$$\Xi^0 \rightarrow \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \pi^0 \rightarrow \bar{p} \pi^0 e^- \nu_e$$

Systematics:

- Trigger efficiency $\pm 2.2\%$
- Form factors $\pm 1.6\%$
- Acceptance $\pm 1.0\%$
- $\Xi^0$ polarization $\pm 1.0\%$
- Normalization $\pm 1.0\%$
- Others (bkg, $\tau_{\Xi^0}$) $\pm 1.0\%$
- Total $\pm 3.4\%$

Measured also: $\text{BR}(\Xi^0 \rightarrow \Sigma^+ e^+ \nu_e)$ (555 events)

$$\text{BR}(\Xi^0 \rightarrow \Sigma^+ e^+ \nu_e) = (2.55 \pm 0.14_{\text{stat}} \pm 0.10_{\text{syst}}) \times 10^{-4}$$
\[ |V_{us}| \text{ from } \Xi^0 \text{ Beta Decay} \]

- Use \( \Xi^0 \) lifetime from PDG06 and the combined result of \( \Xi^0 \) and \( \Xi^0 \) branching ratios to evaluate the decay rate:

\[
\Gamma(\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e) = (8.66 \pm 0.31_{\text{exp}} \pm 0.27_{\Xi^0_{\text{lifetime}}}) \times 10^5 \text{s}^{-1}
\]

- With KTeV form factors and neglecting SU(3) breaking for \( f_1 \) we obtain

\[
|V_{us}| = 0.209 \pm 0.005_{\text{exp}}^{+0.022}_{-0.028} \text{ form factors}
\]

Good agreement with \( |V_{us}| \) from K decay but large uncertainty from form factors

Use \( |V_{us}| \) from Kaon decay to determine \( g_1/f_1 \) instead

\[
g_1/f_1 = 1.20 \pm 0.04_{BR} \pm 0.03_{ext}
\]

→ To be compared with \( g_1/f_1 = 1.267 \) of neutron decay
Summary

New results relevant for $|V_{us}|$ from the NA48 experiment:

\[
\begin{align*}
\text{BR}(K^\pm \to \pi^0 e^\pm \nu) &= 0.05221 \pm 0.00019_{\text{stat}} \pm 0.00008_{\text{syst}} \pm 0.00030_{\text{norm}} \\
\text{BR}(K^\pm \to \pi^0 \mu^\pm \nu) &= 0.03425 \pm 0.00013_{\text{stat}} \pm 0.00006_{\text{syst}} \pm 0.00020_{\text{norm}} \\
\text{PRELIMINARY } K_L \to \pi^\pm \mu^m p \nu \mu & \quad \text{Form Factors} \\
\text{BR}(\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e) &= (2.51 \pm 0.03_{\text{stat}} \pm 0.09_{\text{syst}}) \times 10^{-4}
\end{align*}
\]

And others not shown:

\[\Xi^0 \text{ Lifetime} \quad \tau_{\Xi^0} = (3.082 \pm 0.013 \pm 0.012) \times 10^{-10} \text{s} \]

About 2$\sigma$ above PDG2004 average and 5 times more precise \textbf{PRELIMINARY}

Using the new lifetime value:

\[|V_{us}| = 0.203 \pm 0.004_{\text{exp}}^{+0.022}_{-0.027} \text{ form factors} \]

\textbf{Semi–muonic $\Xi^0$ decay (from 99 events)} \textbf{PRELIMINARY}

\[\text{BR}(\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu) = (2.2 \pm 0.3_{\text{stat}} \pm 0.2_{\text{syst}}) \times 10^{-6} \]