Recent Results in Rare and Semileptonic Kaon Decays from NA48.

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Recent results are presented on rare neutral kaon decays from the NA48/1 collaboration, and on semileptonic charged kaon decays from the NA48/2 collaboration.
Using data taken on 2002, NA48/1 has measured the CP conserving component of the decay $K^0 \to \pi^0\pi^+\pi^-$. For the λ parameter describing this decay the values Re(λ)=0.038±0.008$_{stat}$±0.006$_{syst}$ and Im(λ)=-0.013±0.005$_{stat}$±0.004$_{syst}$ have been obtained. This is consistent with previous measurements and with chiral perturbation theory predictions. NA48/1 has also measured the BR($K_S \to \pi^{\pm}e^{\mp}\nu$) = (6.8±0.2$_{stat}$±0.2$_{syst}$)$10^{-4}$, consistent with ΔS=ΔQ.
Using data collected during eight hours minimum bias run on 2003, the NA48/2 collaboration has measured BR($K^{\pm} \to \pi^0 e^{\pm}\nu$)=(5.14±0.02$_{stat}$±0.06$_{syst}$)$10^{-2}$, where the channel $K^{\pm} \to \pi^0\pi^{\pm}$ has been used as normalization. From the same data sample, the ratio of $K^{\pm} \to \pi^0\mu^{\pm}\nu$ to $K^{\pm} \to \pi^0 e^{\pm}\nu$ has been obtained. This results on BR($K^{\pm} \to \pi^0\mu^{\pm}\nu$)=(3.462±0.018$_{stat}$±0.006$_{syst}$±0.011$_{\lambda_+,\lambda_0}$±0.068$_{norm}$). From semileptonic decays the value of the CKM matrix element V_{us} can be extracted. The values of $V_{us}|f_+(0)|$ obtained by NA48/2 from electron and muon channels are compatible.
The result on $K^0 \to \pi^0\pi^+\pi^-$ is final, and all the other results presented here are preliminary.

1. Beamline and Detector Description.

1.1. The NA48/1 experiment.

The main goal of NA48/1 was the measurement of rare decays of $K_S \to \pi^0 l^+ l^-$ with l=e,μ [1]
Data were taken in 2002 at the CERN SPS accelerator. The experiment used a modified version of the NA48 beamline and upgraded detector [2]
The primary beam consisted of 400 GeV protons impinging on a Beryllium target. Its intensity was 5 $\times 10^{10}$ protons per cycle, with a 4.8 s flat spill and 16.2 s cycle. After a sweeping magnet used to deflect charged particles, a 5.1 m collimator defined the neutral beam axis at 4.2 mrad with respect to the incident protons. This collimator was followed by a 89 m vacuum tank terminated by a 0.3% X_0 Kevlar window. Most of the short-lived particles (K_S and hyperons) decayed in this tank, together with an small fraction of long-lived kaons (K_L)
The main components of the NA48 detector are a magnetic spectrometer, a charged hodoscope, a liquid Krypton (LKr) electromagnetic calorimeter, a hadronic calorimeter (HAC) and a muon detection system.
The magnetic spectrometer consisted of a magnet and four drift chambers (DCH). The magnet provided a transverse momentum kick of 265 MeV/c. The spatial resolution was 150 μm and the momentum resolution could be parameterised as $\sigma(p)/p \simeq (0.48 \oplus 0.015\,p)\%$ (p in $[GeV/c]$).
The timing for charged events was given by an hodoscope with a resolution of 250 ps.
The electromagnetic calorimeter was a 27 X_0 liquid Krypton. The energy resolution is given by $\sigma(E)/E = 3.2\%/\sqrt{E} \oplus (9\%)/E \oplus 0.42\%$ (E in GeV). The time resolution is better than 300 ps.
The hadronic calorimeter consisted of two stacks of scintillator slabs separated by iron blocks. It had a total thickness of 7.2 interaction lengths.
The muon counter consisted on three planes of plastic scintillators, each shielded by 80 cm iron walls.

1.2. The NA48/2 experiment.

The main goal of the NA48/2 experiment is the search for direct CP violation on charged kaons decays to three pions, $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ and $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$. Data were collected on 2003 and 2004, using basically the NA48 detector with a changed beamline providing simultaneous and collinear K^{+} and K^{-} beams.

Two sets of achromat units selected charged particles with momentum of (60±3) GeV. After traversing cleaning and final collimators, positive and negative kaon beams travelled through a 114 m vacuum tank superimposed with a precision of about 1 mm. The main change on the detector side was the value of the spectrometer magnetic field, providing now a 120 MeV/c momentum kick and a resolution of $\sigma(p)/p \simeq (1.0 \oplus 0.044\,p)\%$ (p in [GeV/c]).

2. Results from NA48/1

2.1. The CP conserving component of the rare decay $K_S \rightarrow \pi^0\pi^+\pi^-$ [3].

The neutral kaon decay $K^0 \rightarrow \pi^0\pi^+\pi^-$ occurs mainly through two angular momemtum states, l=0 which is CP odd and l=1, which is CP even. As the mass of the three pions is very close to the kaon mass, there is little kinetic energy available in the kaon rest frame, supressing high angular momemtum configurations. The analysis measures the CP conserving component $K_S \rightarrow \pi^0\pi^+\pi^-$ through its interference with the dominant $K_L \rightarrow \pi^0\pi^+\pi^-$, that has l=0, and is therefore kinematically favoured and CP allowed. The amplitudes of kaons into three pions are very conveniently described in terms of the Dalitz plot variables X and Y, defined as:

$$X = \frac{s_{\pi^+} - s_{\pi^-}}{m^2_{\pi^\pm}} \qquad Y = \frac{s_{\pi^0} - s_0}{m^2_{\pi^\pm}} \qquad (1)$$

with $s_\pi = (p_K - p_\pi)^2$,$s_0 = \frac{1}{3}(s_{\pi^+} + s_{\pi^-} + s_{\pi^0})$, and p_K and p_π being the 4-momenta of the kaon and the pion respectively. The l=0 amplitude is even in X, and the l=1 is odd in X, allowig the extraction of the K_S component of the decay by integrating on Y separately for X>0 and X<0 and subtracting one from the other [4,5].

The parameter λ describes the interference of the K_S component with the K_L and it is defined as:

$$\lambda = \frac{\int_{-\infty}^{\infty} dY \int_0^{\infty} dX A_L^{*3\pi(l=0)} A_S^{3\pi(l=1)}}{\int_{-\infty}^{\infty} dY \int_0^{\infty} dX |A_L^{3\pi(l=0)}|^2} \qquad (2)$$

where A$_L$ and A$_S$ are the decay amplitudes for K_L and K_S respectively, functions of X,Y [6].

The trigger required a minimum energy deposition of 30 GeV in the calorimeters. Besides, it incorporated a cut on the difference between the calculated mass of the decaying particle under the assumption of $K_S \rightarrow \pi^+\pi^-$ and $\Lambda \rightarrow p\pi$ and the nominal [7] K_S and Λ masses. A cut was also made on the ratio of momenta of the charged tracks ($p_{larger}/p_{smaller}$<3.5) to further reduce $\Lambda \rightarrow p\pi$ background. The trigger efficiency ranged between (75±4%) and (86±4%), depending on the value of the high voltage at which the drift chambers were operated.

Offline, events were selected with two opposite charge tracks with closest distance of approach less than 3 cm, and at least two electromagnetic clusters. In addition, the photons and the tracks had to be separated more than 15 cm at the LKr calorimeter. Tracks were considered as pions if the energy deposit in the electromagnetic calorimeter was less than 90% of the momentum measured at the spectrometer (E/p<0.9). The trigger cuts were tightened and cuts were applied on the masses reconstructed for $K_S \rightarrow \pi^0\pi^+\pi^-$ ($M^{PDG}_{K^0} \pm$ 10.5 MeV) and $\pi^0 \rightarrow \gamma\gamma$ ($M^{PDG}_{\pi^0} \pm$ 7.8 MeV). The reconstructed kaon energy should be within 30 and 166 GeV.

Experimentally, the number of $K^0 \rightarrow \pi^0\pi^+\pi^-$ decays at a given decay time t was obtained separetly for X>0 ($N_{3\pi}^{X>0}(t)$) and for X<0 ($N_{3\pi}^{X<0}(t)$) The parameter λ can be extracted through the relation [6]:

$$V(t) = \frac{N_{3\pi}^{X>0}(t) - N_{3\pi}^{X<0}(t)}{N_{3\pi}^{X>0}(t) + N_{3\pi}^{X<0}(t)}$$
$$\approx 2D(E)[Re(\lambda)cos(\Delta mt) - Im(\lambda)sin(\Delta mt)] \times \frac{e^{\frac{-t}{2}(\frac{1}{\tau_S} + \frac{1}{\tau_L})}}{e^{\frac{-t}{\tau_L}}} \qquad (3)$$

where Δm is the mass difference between K_L^0 and K_S^0, τ_L and τ_S are the respective lifetimes, and

D(E) is the energy-dependent difference of relative abundances of K^0 and $\overline{K^0}$, called dilution.
The real and imaginary parts of the λ parameter have been obtained by a combined fit in eight kaon energy bins to expression (3) .
Care had to be taken to exclude any detector effect that could fake an asymmetry on the X variable, faking a K_S contribution. A potential bias could be introduced by any mometum dependence difference in the trigger acceptance for positive and negative pions. In order to check and correct for such effects, the spectrometer magnetic field was reversed on weekly basis.
Using Monte Carlo simulation, the acceptance was calculated as a function of $|X|$, kaon decay time and kaon energy, and a weight applied for every data event. To exclude possible additional effects, the already acceptance corrected data was also averaged in positive and negative fields.
Slightly different results were obtained when using either Monte Carlo correction only, or only averaging over magnetic field orientations. Half of the difference was used as contribution to the systematic error (±0.004 for Re λ and ± 0.003 for Im λ) The uncertainty on the $K^0/\overline{K^0}$ dilution, D(E), contributes to the systematic error in ±0.005 for Re λ and ±0.003 Im λ.
The final NA48/1 result is [3]:

$$Re\lambda = +0.038 \pm 0.008_{stat} \pm 0.006_{syst} \quad (4)$$

$$Im\lambda = -0.013 \pm 0.005_{stat} \pm 0.004_{syst} \quad (5)$$

In Fig. 1 the function given by equation (3) is plotted for the values of Re(λ) and Im(λ) obtained from the fit and for 87 GeV kaon energy (mean kaon energy) and superimposed to the experimental V(t) distribution obtained from all reconstructed $K_S \to \pi^0\pi^+\pi^-$ decays at all energies.
From the real part of λ the branching ratio of $K_S \to \pi^0\pi^+\pi^-$ can be obtained:

$$BR(K_S \to \pi^0\pi^+\pi^-) = (4.7^{+2.2}_{-1.7}(stat)^{+1.7}_{-1.5}(syst))10^{-7} \quad (6)$$

This is in agreement with theoretical predictions and previous experiments [6,8].

2.2. The rare decay $K_S \to \pi^\pm e^\mp \nu$ (K^0_{e3})

Assuming CPT invariance and neglecting CP violation, the branching ratio of $K_S \to \pi^\pm e^\mp \nu$ can be expressed as:

$$BR(K_S \to \pi^\pm e^\mp \nu) = |\eta|^2 \frac{\tau_S}{\tau_L} BR(K_L \to \pi^\pm e^\mp \nu) \quad (7)$$

where τ_S and τ_L are the K_S and K_L lifetimes and the parameter η is given by:

$$\eta = |\eta| e^{i\phi} = \frac{1+x}{1-x} \qquad x = \frac{A_W(\Delta S = -\Delta Q)}{A_W(\Delta S = \Delta Q)} \quad (8)$$

with the variable x defined as the ratio of amplitudes of transitions with ΔS=-ΔQ and ΔS=ΔQ.
The analysis procedure consists in producing independent Monte Carlo (MC) samples of K_S and K_L decays, and to fit the data vertex position to a linear combination of both. This is equivalent to a fitting of the exponential time evolution of the $K^0 \to \pi^\pm e^\mp \nu$ decays. The total number of $K^0 \to \pi^\pm e^\mp \nu$ decays as a function of the z vertex position is related to the MC distributions for K_S and K_L decays (F_S^{MC} and F_L^{MC} respectively) by:

$$N_{Ke3}(z) = \alpha_S F_S^{MC}(E, \frac{z}{c\tau_S}) + \alpha_L F_L^{MC}(E, \frac{z}{c\tau_L}) \quad (9)$$

where the values of the coefficients α_S and α_L are extracted from the best fit to the data. In

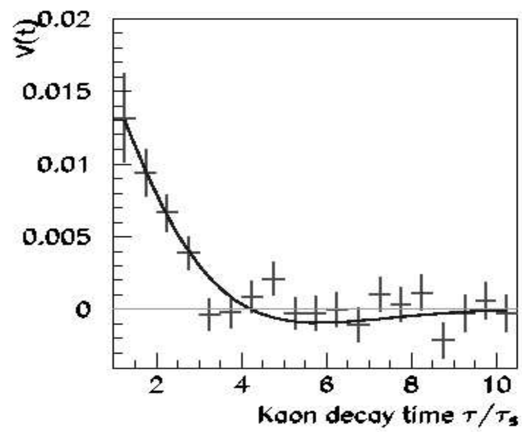

Figure 1. Data distribution of V(t), summed over all kaon energies (error bars) and the function obtained from the fitted values for Re(λ) and Im(λ) for mean kaon energy of 87 GeV (solid curve).

this way, $|\eta|^2$ can be simply calculated as:

$$|\eta|^2 = \frac{\tau_L}{\tau_S}\frac{\alpha_S}{\alpha_L} \quad (10)$$

To perform this analysis a minimum bias trigger has been used. It required at least one hit in the charged hodoscope, more than two hits in at least three views in the drift chambers and a minimum energy deposition in the calorimeters. The event selection required two spectrometer tracks of opposite charge, with a closest distance of approach smaller than 5 cm. The point of intersection of the two tracks along the detector axis defined the z position of the vertex. A track was considered an electron if the energy deposit in the electromagnetic calorimeter was greater than 90% of the momentum measured at the spectrometer (E/p>0.9). This cut excludes background from $K_S \to \pi^+\pi^-$. For the pion E/p<0.8 was required. In addition, the electron energy needed to be bigger than 20 GeV in order to exclude possible trigger effects. To reduce background from $K_S \to \pi^+\pi^-$ and $\Lambda \to p\pi$ the invariant mass of the event was caculated in these two assumptions, requiring that $|m^2_{\pi^+\pi^-} - M^2_K| > 0.13M^2_K$, $m_{\pi^+\pi^-} > 0.35$ GeV and $|m^2_{p\pi} - M^2_\Lambda| > 0.03M^2_\Lambda$. Against Λ decays a further cut on the of the tracks momentum was implemented ($p_{larger}/p_{smaller}$<2.5). For $K_L \to \pi^0\pi^+\pi^-$ rejection $|M_{\pi^0\pi\pi} - M_K|$ >30 MeV was required. The visible energy has been selected between 70 and 130 GeV. Kinematic constrains can be used to retrieve the total kaon energy. A cut at high energies has been applied imposing both solutions of the resulting equations to lie between 70 and 180 GeV. Also it was required that the invariant mass of the two tracks be in the range between (M_e+M_π) and M_K for both combinations. After all these cuts 234000 $K^0 \to \pi^\pm e^\mp\nu$ decays remained in the sample with negligible background. In the Monte Carlo the form factors of the decay have been introduced in the matrix element [9]. Also radiative decays were simulated and Ginsberg's corrections [10] applied. As the analysis method strongly relies on the goodness of the Monte Carlo many important checks have been done regarding specially sensitive items, like the target position and kaon spectrum. The target position has been corrected using $K_S \to \pi^+\pi^-$ decays , and the kaon spectrum has been tuned with $K_S \to \pi^0\pi^0$.

Finally, the vertex distribution of the 234000 K^0_{e3} reconstructed events has been fitted to the K_S and K_L Monte Carlo samples. Out of the 234000 events, from the fit 221000 events were estimated to be K_L decays and 13000 to be K_S decays. The result is shown in Fig. 2, where good agreement can be seen between data and MC.

This result has been normalized to the

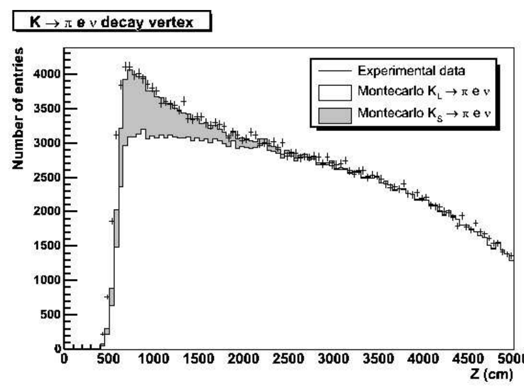

Figure 2. Distribution of vertex position for all $K_L \to \pi^\pm e^\mp\nu$ decays. Contributions of K_S and K_L MC samples are superimposed in proportions given by the fit to the data.

BR($K_L \to \pi^\pm e^\mp\nu$) [13] to obtain:

$$BR(K_S \to \pi^\pm e^\mp\nu) = (6.8\pm0.2_{stat}\pm0.2_{syst})10^{-4} \quad (11)$$

which is in agreement with previous experiments and consistent with the ΔS=ΔQ rule.

3. Results from NA48/2

3.1. The branching ratio of the $K^\pm \to \pi^0 e^\pm\nu$ decay ($K^\pm_{e3}$).

Unsing data from an eight hours low intensity run taken in 2003, the NA48/2 collaboration has measured the branching ratio of $K^\pm \to \pi^0 e^\pm\nu$

using $K^{\pm} \to \pi^0\pi^{\pm}$ as the normalization channel. A minimum bias trigger, based on hodoscope signals with an efficiency greater than 99%, was used. Selection of $K^{\pm} \to \pi^0 e^{\pm}\nu$ and $K^{\pm} \to \pi^0\pi^{\pm}$ events required one charged track only and at least two clusters in the LKr calorimeter. The intersection of the extrapolation of the track line of flight with the beamline provided a charged-vertex. Also a neutal-vertex was calculated assuming the nominal π^0 mass for every combination of clusters. The combination yielding the best agreement between the neutral and charged verteces was retained. For $K^{\pm}_{e3}$, the invariant mass of the event in the $K^{\pm} \to \pi^0\pi^{\pm}$ hypothesis ($m_{\pi^0\pi}$) was calculated, and only events outside of ±16.5 MeV window around the nominal kaon mass were kept. The track momentum was required to be between 5 and 35 GeV, and with a transverse component between 0.01 and 0.2 GeV. For the normalization the invariant mass ($m_{\pi^0\pi}$) was required to be within 477.2 and 510.2 MeV, the track momentum between 10 and 50 GeV with transverse component smaller than 0.215 GeV. To distinguish electrons from pions a cut was imposed on the ratio E/p of the energy deposited in the electromagnetic calorimeter and the track momentum measured on the spectrometer. For $K^{\pm}_{e3}$, the electron was identified requiring this ratio to be greater than 0.95, and for normalization the track was identified as a pion requiring E/p <0.95. The efficiency of this cut as function of the track momentum was studied on separated clean samples, on which the E/p requirement was not applied. For electrons a clean sample of $K^{\pm} \to \pi^0 e^{\pm}\nu$ (from the whole 2003 data) was selected, with a tighter cut on the $m_{\pi^0\pi}$. The global efficiency for E/p>0.95 was found to be 97.37±0.09%. For pions a sample of clean $K^{\pm} \to \pi^0\pi^{\pm}$ was taken and an average efficiency of 99.552±0.001% was obtained. A correction for this effect was applied to MC events. Assuming the decaying kaon to have energy of 60 GeV and direction along the beamline axis, the squared missing mass (m^2_{ν}) can be calculated for every event. For $K^{\pm}_{e3}$ this was required to be within -0.012 and 0.012 GeV^2, and for $K^{\pm} \to \pi^0\pi^{\pm}$ between -0.0025 and 0.001 GeV^2. In addition, for the signal, a cut on the invariant mass of the electron and π^0 candidates ($m_{e\pi^0}$) was implemented, ($m_{e\pi^0}$ <0.425 GeV). After all cuts were applied, about 728000 $K^{\pm} \to \pi^0\pi^{\pm}$ and 92000 $K^{\pm} \to \pi^0 e^{\pm}\nu$ events were selected, practically background free.

In the Monte Carlo simulation the form factor was implemented in the decay matrix element, the value of the λ_+ coefficient taken from the PDG04 [7]. Radiative events were also included and the Ginsberg's corrections [11] applied. This procedure gave good agreement in the comparison of the energy of the electron in the kaon rest frame between data and Monte Carlo.

Taking as input the braching ratio of $K^{\pm} \to \pi^0\pi^{\pm}$ from the PDG04 [7] the calculated branching ratio for $K^{\pm} \to \pi^0 e^{\pm}\nu$ is:

$$BR(K^{\pm} \to \pi^0 e^{\pm}\nu) = (5.14 \pm 0.02_{stat} \pm 0.06_{syst}) \times 10^{-2} \qquad (12)$$

where the systematic error includes the error on the normalization.

The relation between the decay width and the V_{us} CKM matrix element is given by [16]

$$\Gamma(K \to \pi l \nu) = |V_{us}|^2 |f_+(0)|^2 \frac{G_F^2 M_K^5 C_K^2 S_{EW}}{128\pi^2} I_K^l(\lambda_{+,0})(1 + \delta^K_{SU(2)} + \delta^{Kl}_{em})^2 \qquad (13)$$

where $|f_+(0)|$ is the form factor at zero momentum transfer, λ_0 and λ_+ are the coefficients of the expansion in momentum transfer, $\delta^K_{SU(2)}$ is the SU(2) breaking correction and δ^{Kl}_{em} the electromagnetic correction. The rest of the parameters are defined in [16]. Inserting the numerical values for these quantities from table 1, we get:

$$V_{us}|f_+(0)| = 0.2192 \pm 0.0015 \qquad (14)$$

3.2. The branching ratio of the $K^{\pm} \to \pi^0\mu^{\pm}\nu$ decay ($K^{\pm}_{\mu 3}$).

This decay was studied using the same data sample as for the electron channel, that was taken as normalization.

The main characteristics of the selection are common for the two modes and have already been described on the previous section. The most important new element is the muon identification procedure. Two methods were used

Table 1
Inputs for $V_{us}|f_+(0)|$ determination from the branching fractions of $K^\pm \to \pi^0 e^\pm \nu$ and $K^\pm \to \pi^0 \mu^\pm \nu$

	$K^\pm \to \pi^0 e^\pm \nu$	$K^\pm \to \pi^0 \mu^\pm \nu$	Reference
$I^l_K(\lambda_+, \lambda_0)$	0.110528(609)	0.073684(459)	Calculated
$\delta^K_{SU(2)}$	2.31(22)	2.31(22)	[16]
δ^{Kl}_{em}	-0.10(16)	+0.20(20)	[16]

to identify tracks as muons, either by association of hits in the muon detector within 2ns of the hodoscope hit, or by requiring small energy deposition in the electromagnetic and hadronic calorimeters (E_{LKr} < 1.5 GeV and E_{HAC} <5 GeV). The efficiency of both methods was calculated as a function of the track momentum using $K^\pm \to \mu^\pm \nu$ events from the same data sample. The global efficiency of muon identification using the muon detector was measured to be 99.763± 0.002 %, almost flat for every track momentum. Using the signals on the calorimeters the global muon identification efficiency was 96.16 ± 0.01 %. After applying the corresponding corrections, both methods yielded consistent results. For the final result the muon detector was used.

The main potential source of background for $K^\pm \to \pi^0 \mu^\pm \nu$ was $K^\pm \to \pi^\pm \pi^0 \pi^0$ and $K^\pm \to \pi^0 \pi^\pm$ with charged pion decaying in flight to muon. The remaining background after cuts was of the order of 0.2%, and was subtracted from the signal. Finally about 77000 $K^\pm\mu3$ events were reconstructed.

In Monte Carlo the form factor was parametrized with values of λ_+ and λ_0 from [7] and radiative corrections applied [12]. The result for the ratio of the partial width into muon and electron channel was found to be:

$$\frac{\Gamma(K^\pm \to \pi^0 \mu^\pm \nu)}{\Gamma(K^\pm \to \pi^0 e^\pm \nu)} = (67.49 \pm 0.35_{stat} \pm 0.11_{syst} \pm 0.21_{\lambda_+,\lambda_0}) \times 10^{-2} \quad (15)$$

where the index $_{\lambda_+,\lambda_0}$ refers to effetcs of variations of λ_+ and λ_0 within their errors. This result is in good agreement with theory [14]

The branching ratio of $K^\pm \to \pi^0 \mu^\pm \nu$ has been calculated normalizing to the branching ratio from the BNL E865 experiment for $K^\pm_{e3}$ [15]

$$BR(K^\pm \to \pi^0 \mu^\pm \nu) = (3.462 \pm 0.018_{stat} \pm 0.006_{syst} \pm 0.011_{\lambda_+,\lambda_0} \pm 0.068_{normBNL}) \times 10^{-2} \quad (16)$$

Using again the values in table 1, the corresponding result for $V_{us}|f_+(0)|$ is:

$$V_{us}|f_+(0)| = 0.2204 \pm 0.0015 \quad (17)$$

As can be seen from equations (14) and (17), the NA48/2 results on $V_{us}|f_+(0)|$ are compatible for the electron and muon channels.

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