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

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New results from the NA48 experiment on kaon and hyperon decays relevant to $|V_{us}|$ are reported here. For charged kaons we present measurements of $BR(K^{\pm} \to \pi^0 e^{\pm}\nu)$ and $BR(K^{\pm} \to \pi^0 \mu^{\pm}\nu)$. On neutral kaon decays we report the measurements of BR($K_L \to \pi^+\pi^-$) and of $K_L \to \pi^{\pm}\mu^{\mp}\nu$ form factors slopes. For hyperons we present results on the BR($\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$).

I. INTRODUCTION

The NA48 experiment at the CERN SPS has been taking data from 1997 to 2004. During its first phase (ended in 2001) employed simultaneous K_L/K_S beams and was devoted to the precision measurement of direct CP violation in the neutral kaon system. Also several semileptonic and rare K_L decays could be studied.
The second phase (NA48/1) was active in the year 2002. Using only the K_S beam at an increased intensity the experiment measured rare K_S and neutral hyperon decays.
In the third phase (NA48/2) the beam set–up was changed again in order to simultaneously collect K^+ and K^- decays. The data taking was in progress during the years 2003–2004 with the purpose to search for direct CP violation in the $K^{\pm}$ decays to three pions together with the high statistics measurements of semileptonic and rare charged kaon decays.
A detailed description of the NA48 detector can be found elsewhere [1]. The most relevant components are a high resolution liquid–krypton electromagnetic calorimeter (LKr) and a magnetic spectrometer consisting of 4 drift chambers and a dipole magnet located inside a helium tank. Other components are a hodoscope for precise track time determination, a hadronic calorimeter and a muon counter (MUC). Reported here are the results from kaon and hyperon decays relevant to the determination of $|V_{us}|$.

A. $K_{\ell 3}$ decays

The semileptonic kaon decays ($K_{\ell 3}, \ell = e, \mu$), being pure vector transitions, provide the most accurate and theoretically cleanest way to measure $|V_{us}|$. The matrix element of the decay can be written in terms of two dimensionless form factors $f_{\pm}(t)$:

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

where G_F is the Fermi coupling constant, $P_{K/\pi}$ are the kaon/pion four–momenta, $u_{\ell,\nu}$ the lepton spinors and $t = (P_K - P_\pi)^2$. Being proportional to the lepton mass squared, the contribution of f_- can be neglected in K_{e3} decays. The $K_{\mu 3}$ decays are usually described in terms of the scalar form factor defined as $f_0(t) = f_+(t) + t/(m_K^2 - m_\pi^2) f_-(t)$; f_+ and f_0 are related to the vector (1^-) and scalar (0^+) exchange to the lepton system, respectively. The master formula for the $K_{\ell 3}$ decay rates (fully inclusive of radiation) is:

$$\Gamma(K_{\ell 3}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 \, I_K^\ell \left[f_+(t), f_0(t) \right] (1 + \delta_{SU(2)}^{\ell K} + \delta_{EM}^{\ell K}) \qquad (2)$$

where the index K stands for $K^{\pm}, K^0$, m_K is the appropriate kaon mass, C^2 is 1 for K^0 and 1/2 for $K^{\pm}$ decays, S_{EW} is the short–distance electroweak correction, $f_+(0)$ is the calculated form factor at zero momentum transfer. For vector transitions [2] the SU(3) breaking appears only to second order, as consequence $f_+(0)$ is close to unity. This term is calculated for K^0 transitions. The quantity $\delta_{SU(2)}^{\ell K}$, (which is 0 for K^0 decays) is common for e and μ channels and accounts for the SU(2) breaking corrections to $f_+(0)$ in $K^{\pm}$ decays. The $\delta_{EM}^{\ell K}$ term represents the long–distance radiative corrections, these are important only for the K^0 case and especially for the μ channel. $I_K^\ell \left[f_+(t), f_0(t) \right]$ is the phase space integral which depends on the two form factors which describe the decays.

II. THE BRANCHING RATIO OF $K^{\pm}_{e3}$ AND $K^{\pm}_{\mu 3}$ DECAYS

NA48/2 has measured [3] the branching ratios of $K^{\pm} \to \pi^0 e^{\pm}\nu$ ($K^{\pm}_{e3}$) and $K^{\pm} \to \pi^0 \mu^{\pm}\nu$ ($K^{\pm}_{\mu 3}$) decays studying data collected in a dedicated minimum bias run. As normalization channel the decay $K^{\pm} \to \pi^{\pm}\pi^0$ ($K^{\pm}_{2\pi}$) was used. The basic selection of all the three modes was common and was based on the presence of only one track in the spectrometer and at least two clusters (photons) in the LKr that were consistent with a π^0 decay. Further kinematical and particle id requirements were applied to separate the three decays. The invariant mass for $K^{\pm}_{2\pi}$ candidates was required to be within three sigma of the reconstructed kaon mass, that is: 472.2 MeV/c^2 $< m_{\pi^{\pm}\pi^0} <$ 510.2 MeV/c^2 while for

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$K^{\pm}_{\ell 3}$ candidates it had to be outside this range. In order to separate two from three body decays cuts were applied to the squared missing mass (m^2_ν), assuming the decaying kaon to have an energy of 60 GeV and direction along the beam line axis. To distinguish electrons from pions a cut was imposed on the ratio E/p, between the energy deposited by the track in the LKr and its momentum measured by the spectrometer. $K^{\pm}_{e3}$ ($K^{\pm}_{2\pi}$) events were identified requiring this ratio to be greater (smaller) than 0.95. The identificaton of $K^{\pm}_{\mu 3}$ events instead was based on the association, in space and time, of the extrapolation of the track and a hit in the MUC. The selected samples were practically background free and amounted to about 87000 $K^{\pm}_{e3}$, 77000 $K^{\pm}_{\mu 3}$ and 718000 $K^{\pm}_{2\pi}$ events. After correcting for acceptance, trigger and particle id efficiences, radiative effects and taking the current PDG value for the $K^{\pm}_{2\pi}$ branching fraction [4] we obtained (results $\times 10^{-2}$):

$$BR(K^{\pm}_{e3}) = 5.221 \pm 0.019_{stat} \pm 0.008_{syst} \pm 0.030_{norm} \quad (3)$$
$$BR(K^{\pm}_{\mu 3}) = 3.425 \pm 0.013_{stat} \pm 0.006_{syst} \pm 0.020_{norm} \quad (4)$$

The uncertainty is dominated by the existing data for the BR($K^{\pm}_{2\pi}$). Higher branching fractions with respect to PDG ones are found for both $K^{\pm}_{e3}$ and $K^{\pm}_{\mu 3}$ confirming the results reported by the BNL–E865 collaboration [5]. Using the newly measured BRs we determined, through Eq. 2 (see [3] for details on the values used for the phase space integrals and radiative corrections), the following values for the product of the $|V_{us}|$ matrix element and $f_+(0)$:

$$\begin{aligned} |V_{us}| f_+(0) &= 0.2204 \pm 0.0012 \quad [K^{\pm}_{e3}] \\ &= 0.2177 \pm 0.0013 \quad [K^{\pm}_{\mu 3}] \end{aligned}$$

Combining these values by assuming $\mu - e$ universality, we obtained:

$$|V_{us}| f_+(0) = 0.2197 \pm 0.0012 \qquad [K^{\pm}_{\ell 3}] \qquad (5)$$

We can compare the above result to the prediction obtained by imposing the unitarity condition on the CKM matrix. Assuming that $f_+(0) = 0.961 \pm 0.008$ [6] and using the latest values of $|V_{ud}|$ and $|V_{ub}|$ from [4] we have $|V_{us}|_{unitarity} f_+(0) = 0.2185 \pm 0.0022$ in good agreement with our result.

III. THE BRANCHING RATIO OF $K_L \to \pi^+\pi^-$ DECAY

This measurement [7] of the branching ratio of the $K_L \to \pi^+\pi^-$ ($K_{2\pi}$) decay is based on data taken during a dedicated two–days run in 1999 by the NA48 experiment. Throughout this run only the K_L beam was present. The event acquisition was triggered by the presence of two particles in the charged hodoscope system and of a vertex of two tracks in the spectrometer. As normalization channel the $K_L \to \pi^{\pm} e^{\mp} \nu_e$ (K_{e3}) decay was used. The majority of the event selection was common to both decay modes requiring the tracks to have opposite charge and imposing cuts for the definiton of the vertex. To select $K_{2\pi}$ events a cut on the two track invariant mass was applied. The abundant semileptonic background was removed by requiring both tracks to have E/p<0.93 (against e) and rejecting events with an associated signal in the muon counter ($K_{\mu 3}$ events with π decay). The K_{e3} events used for normalization, being the only relevant K_L decay channel with an electron in the final state, were selected by only further demanding a track with E/p>0.93. The final samples

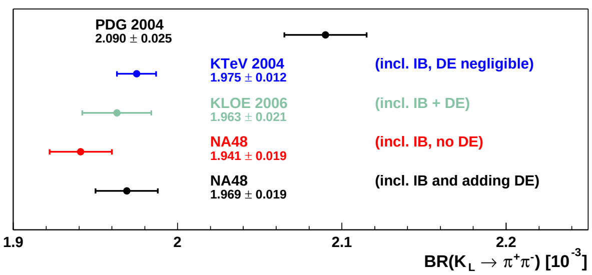

FIG. 1: Comparison of results for $BR(K_L \to \pi^+\pi^-)$.

had a statistics of about 47000 $K_{2\pi}$ and five million K_{e3} events. Since the $\pi^+\pi^-$ event selection did not imply any requirement for or against photons, the radiative $K_L \to \pi^+\pi^-\gamma$ decays were also accepted. To calculate the branching ratio we chose to exclude the CP conserving contribution from radiative decays with the γ coming from direct emission (DE), considering only the CP violating contribution from inner bremsstrahlung (IB). Using the MC the DE contribution was determined and subtracted from the signal. To extract BR($K_{2\pi}$) the value of BR(K_{e3})=0.4022±0.0031 was used. This value is the NA48 measurement [8] updated following the improved knowledge of $BR(K_L \to 3\pi^0)$. Finally we obtained:

$$BR(K_L \to \pi^+\pi^- + \pi^+\pi^-\gamma_{IB}) = (1.942 \pm 0.019) \times 10^{-3} \quad (6)$$

Our result is in good agreement with the measurements done by KTeV [9] and KLOE [10]. All results contradict the values reported by PDG 2004 [11].

IV. $K_L \to \pi^{\pm}\mu^{\mp}\nu$ ($K_{\mu 3}$) FORM FACTORS

As shown in eq. 2 the form factors of the $K_{\ell 3}$ decays are an input (through the phase space integrals) for the evaluation of $|V_{us}|$. It is customary to expand the form factors up to a linear or a quadratic term in t:

$$f_{+,0}(t) = f_+(0) \left[1 + \lambda'_{+,0}\, t/m^2_\pi + \frac{1}{2}\, \lambda''_{+,0}\, (t/m^2_\pi)^2 \right]. \quad (7)$$

According to the pole model instead, the t dependence can be related to the exchange of K^* resonances:

$$f_{+,0}(t) = f_+(0)\, \frac{m^2_{V,S}}{m^2_{V,S} - t} \quad (8)$$

Recently new parametrizations, based on dispersion techniques, have been proposed [12]:

$$f_+(t) = f_+(0)\exp\Big[\frac{t}{m_\pi^2}(\Lambda_+ + H(t))\Big], \qquad (9)$$

$$f_0(t) = f_+(0)\exp\Big[\frac{t}{(m_K^2 - m_\pi^2)}(\ln C - G(t))\Big].$$

The parameter $\ln C = \ln[f_0(m_K^2 - m_\pi^2)]$ is the logarithm of the value of the scalar form factor at the Callan–Treiman point. This value can be used to test the existence of right handed quark currents (RHCs) coupled to the standard W boson.

Using the same data sample utilized for the $K_{2\pi}$ analysis (Sec. III) the $K_{\mu 3}$ events were selected [13] by demanding a vertex of two tracks of opposite charge. The muon track was identified by a coinciding hit in the MUC. The K_{e3} background was rejected imposing E/p<0.9 to both tracks and $K_{3\pi}$ background was suppressed applying a cut on the kinematical variable $P_0^{'2}$. The undetected neutrino in $K_{\ell 3}$ decays is responsible for the quadratic ambiguity in the determination of the K_L energy. A cut was imposed requiring that the two kaon energies (called low and high) had to be greater than 70 GeV. Finally a cut was applied on the variable $p_\nu^* - p_{\nu T}$, where p_ν^* is the total neutrino momentum in the kaon CMS. This quantity, clearly positive for good $K_{\mu 3}$ events, is highly sensitive to resolution effects which give rise to a moderate negative tail. We set a cut at $p_\nu^* - p_{\nu T} > 7$ MeV/c, selecting a region where the MC simulation accurately reproduces the data behaviour. The final data sample consisted of about 2.3×10^6 $K_{\mu 3}$ events. The determination of the form factor parameters is done studying the Dalitz plot density. The low energy solution was used to evaluate the muon and pion energies (in the kaon center of mass) needed to build the Dalitz plot. According to the MC simulation this corresponds to the most probable solution, being in 61% of cases the correct one. The Dalitz plot was divided into cells with a dimension of about 4×4 MeV^2. With this choice, about 39% of the events are reconstructed exactly in the same cell where they were generated. To extract the form factors we fit the data Dalitz plot corrected for acceptance, migration of events due to the wrong choice of the kaon energy, backgrounds and radiative effects. The acceptance and the radiative corrections depend slightly on the form factor values used in the simulation. In order to reduce possible biases due to this dependence, the MC samples were generated, after an iterative procedure, with form factor values close to the fitted ones. Various t dependences of the form factors were considered: linear, quadratic, pole and dispersive. The fit results are listed in Table I. Our results indicate the presence of a quadratic term in the expansion of the vector form factor in agreement with other recent analyses of kaon semileptonic decays. Fig. 2 shows the comparison between the results of the quadratic fits as reported by the recent experiments [14, 15, 16, 17, 18]. The 1 σ contour plots are shown, both for K_{e3} and $K_{\mu 3}$ decays; the ISTRA+ results

TABLE I: Form factors fit results for linear, quadratic pole and dispersive parametrizations. The first error is the statistical one, the second the systematic one.

Linear ($\times 10^{-3}$)			
λ_+	λ_0		χ^2/ndf
26.7±0.6±0.8	11.7±0.7±1.0		604.0/582
Quadratic ($\times 10^{-3}$)			
λ_+'	λ_+''	λ_0	χ^2/ndf
20.5±2.2±2.4	2.6±0.9±1.0	9.5±1.1±0.8	595.9/581
Pole (MeV/c^2)			
m_V	m_S		χ^2/ndf
905±9±17	1400±46±53		596.7/582
Dispersive ($\times 10^{-3}$)			
Λ_+	$\ln C$		χ^2/ndf
23.3±0.5±0.8	143.8±8.0±11.2		595.0/582

have been multiplied by the ratio $(m_{\pi^+}/m_{\pi^0})^2$. The results are higly correlated, those from this measurement and from KTeV have a larger quadratic term and appear only in partial agreement with the other K_{e3} experiments. While the result for λ_+ is well compatible with the recent (and most precise) KTeV measurement, the value of λ_0 appears to be shifted towards lower values. According

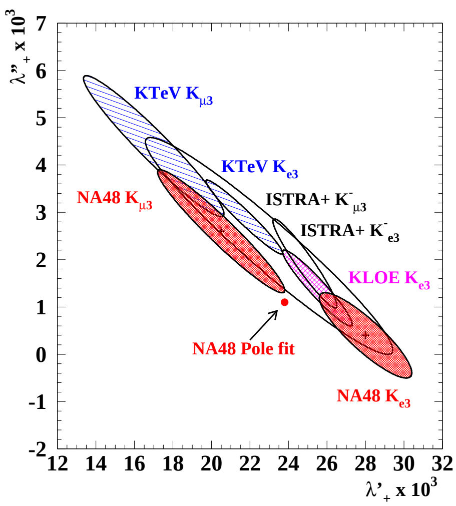

FIG. 2: 1 σ contour plots in the plane λ_+'–λ_+'' showing the NA48 results together with those of [14, 15, 16, 17, 18] for the quadratic fits of the $K_{\mu 3}$ and K_{e3} decays.

to the model proposed in [12] the value of $\ln C$ can be used to test the existence of RHCs by comparing it with the Standard Model predictions. We obtain for a combination of the RHCs couplings and the Callan–Treiman discrepancy ($\tilde{\Delta}_{CT}$) the value: $2(\epsilon_S - \epsilon_{NS}) + \tilde{\Delta}_{CT} = -0.071 \pm 0.014_{NA48} \pm 0.002_{theo} \pm 0.005_{ext}$, where the first error is the combination in quadrature of the to the uncertainties related to the approximations used to replace the dispersion integrals and the last one is due to the external experimental input.

V. THE BRANCHING RATIO OF Ξ^0 β–DECAY

In analogy with kaons, the semileptonic Ξ^0 β–decay ($\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}_e$) can provide a determination of $|V_{us}|$ via the measurements of BR and lifetimes. Furthermore this decay allows a test of SU(3) breaking effects. In exact SU(3) symmetry approximation the form factors describing the Ξ^0 β–decay are the same of the well known neutron β–decay. The NA48/1 experiment collected a sample of 6316 $\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}_e$ events [19]. The identification of the decay was performed using the subsequent $\Sigma^+ \rightarrow p\pi^0$ decay with $\pi^0 \rightarrow \gamma\gamma$. The final state consisted of a proton and an electron, leaving tracks in the spectrometer, in addition to two photons being detected as clusters in the LKr calorimeter, and one unobserved anti–neutrino. The event signature was given by the presence of a Σ^+ since the Ξ^0 β–decay is the only source of of this kind of particles in the neutral beam given that the two–body decay ($\Xi^0 \rightarrow \Sigma^+\pi^-$) is forbidden by energy conservation. Thus signal events were identified by requiring an invariant $p\pi^0$ mass consistent with the nominal Σ^+ mass value. With a background of about 3.4% and using as normalization channel the $\Xi^0 \rightarrow \Lambda\pi^0$ decay, a value for the branching ratio was determined:

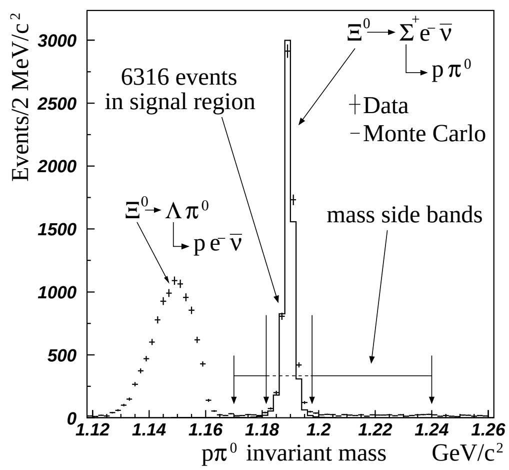

FIG. 3: Reconstructed $p\pi^0$ invariant mass distribution far all $\Sigma^+ \rightarrow p\pi^0$ candidates after all selection criteria were applied. The solid line shows the MC prediciton for the signal.

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

where the systematic error is dominated by the trigger efficiency determination, the geometrical acceptance and the experimental knowledge of the form factors. This value is consistent with the KTeV measurement based on 625 events [20]. Since the trigger did not distinguish between particle charges with respect to the event hypotheses, the recorded data sample also contained decays of anti–hyperons allowing the first measurement of the $\overline{\Xi^0} \rightarrow \overline{\Sigma^+} e^+ \nu_e$ branching ratio to be performed. A sample of 555 candidates was found in the signal region with a background of 136±8 events allowing the determination of:

$$BR(\overline{\Xi^0} \rightarrow \overline{\Sigma^+} e^+ \nu_e) = (2.55 \pm 0.14_{stat} \pm 0.10_{syst}) \times 10^{-4} \quad (11)$$

Using the combined result of the measured Ξ^0 and $\bar{\Xi}^0$ branching ratios together with the current values of form factors and neglecting SU(3) breaking corrections we evaluated $|V_{us}| = 0.209^{+0.023}_{-0.028}$ consistent with the present value obtained from kaon semileptonic decays [4]. The uncertainty on $|V_{us}|$ is largely dominated by the error on the form factors. Alternatively, the form factors ratio g_1/f_1 could be extracted using the current $|V_{us}|$ value determined from kaon decays obtaining: $g_1/f_1 = 1.20 \pm 0.04_{BR} \pm 0.03_{ext}$, where the last uncertainty includes contributions from $|V_{us}|$, Ξ^0 lifetime and form factors. The agreement with the prediction for exact SU(3) symmetry ($f_1 = 1.0$; $g_1 = 1.27$) favours SU(3) breaking models that do not modify significantly g_1/f_1.

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[1] A. Lai *et al.*, *Eur. Phys. J.* C **22**, 231 (2001), A. Lai *et al.*, Nucl. Instr. and Meth. A, in preparation.
[2] Ademollo M., Gatto R., *Phys. Rev. Lett.* **13**, 264 (1964).
[3] J. R. Batley *et al.*, hep-ex/0702015, accepted for pubbl. in *Eur. Phys. J.* C.
[4] W.-M. Yao *et al.*, *Journ. Phys. G* **33**, 1 (2006).
[5] A. Sher *et al.*, *Phys. Rev. Lett.* **91**, 261802 (2003).
[6] H. Leutwyler and M. Roos, *Z. Phys.* C **25**, 91 (1984).
[7] A. Lai *et al.*, *Phys. Lett.* B **645**, 26 (2007) (hep-ex/0611052).
[8] A. Lai *et al.*, *Phys. Lett.* B **602**, 41 (2004).
[9] T. Alexopoulos *et al.*, *Phys. Rev.* D **70**, 092006 (2004).
[10] F. Ambrosino *et al.*, *Phys. Lett.* B **638**, 140 (2006).
[11] S. Eidelman *et al.*, *Phys. Lett.* B **592**, 1 (2004).
[12] V. Bernard *et al.*, *Phys. Lett.* B **638**, 480 (2006).
[13] A. Lai *et al.*, *Phys. Lett B* in press, (hep-ex/0703002),
[14] F. Ambrosino *et al.*, *Phys. Lett.* B **636**, 166 (2006).
[15] A. Lai *et al.*, *Phys. Lett.* B **604**, 1 (2004).
[16] T. Alexopoulos *et al.*, *Phys. Rev.* D **70**, 092007 (2004).
[17] O.P. Yushchenko *et al.*, *Phys. Lett.* B **589**, 111 (2004).
[18] O.P. Yushchenko *et al.*, *Phys. Lett.* B **581**, 31 (2004).
[19] J. R. Batley *et al.*, *Phys. Lett.* B **645**, 36 (2007) (hep-ex/0612043).
[20] A. Alavi–Harati, Proc. of DPF99 (hep–ex/9903031).