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V_{us} determination from hyperon semileptonic decays

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Abstract: We analyze the numerical determination of the quark mixing factor V_{us} from hyperon semileptonic decays. The discrepancies between the results obtained in two previous studies are clarified. Our fits indicate sizeable SU(3) breaking corrections, which unfortunately can only be fully determined from the data at the first order. The lack of a reliable theoretical calculation of second-order symmetry breaking effects translates into a large systematic uncertainty, which has not been taken into account previously. Our final result, $|V_{us}| = 0.226 \pm 0.005$, is not competitive with the existing determinations from K_{l3}, K_{l2} and τ decays.

Keywords: QCD, Quark Masses and SM Parameters, Chiral Lagrangians, 1/N Expansion.

Contents

1. Introduction

Accurate determinations of the quark mixing parameters are of fundamental importance to test the flavour structure of the Standard Model. In particular, the unitarity of the CKM matrix [1, 2] has been tested to the 0.2% level [3, 4] with the precise measurement of its first-row entries $|V_{ud}|$ and $|V_{us}|$ [5]. At that level of precision, a good control of systematic uncertainties becomes mandatory. In fact, the existence of small deviations from unitarity has been a long-standing question for many years [6].

Recently, there have been many relevant changes to this unitarity test, which have motivated a very alive discussion. While the standard $|V_{ud}|$ determination from superallowed nuclear beta decays remains stable, $|V_{ud}| = 0.9740 \pm 0.0005$ [4], the information from neutron decay is suffering strong fluctuations, due to conflicting data on the axial coupling g_A measured through decay asymmetries [7] and the large decrease of the neutron lifetime by more than $6\,\sigma$ obtained in the most recent precision measurement [8].

On the other side, the $K \to \pi l \nu$ branching ratios have been found to be significantly larger than the previously quoted world averages. Taking into account the recently improved calculation of radiative and isospin-breaking corrections [9 − 11], the new experimental data from BNL-E865 [12], KTeV [13], NA48 [14] and KLOE [15] imply [16]

$$|V_{us}\, f_+^{K^0\pi^-}(0)| = 0.2175 \pm 0.0005\,. \tag{1.1}$$

In the SU(3) limit, vector current conservation guarantees that the K_{l3} form factor $f_+^{K^0\pi^-}(0)$ is equal to one. Moreover, the Ademollo-Gatto theorem [17, 18] states that corrections to this result are at least of second order in SU(3) breaking. They were calculated long-time ago, at $O(p^4)$ in Chiral Perturbation Theory, by Leutwyler and Roos [19] with the result $f_+^{K^0\pi^-}(0) = 0.961 \pm 0.008$. Using the calculated two-loop chiral corrections [20, 21], two recent estimates of the $O(p^6)$ contributions obtain the updated values $f_+^{K^0\pi^-}(0) = 0.974 \pm 0.011$ [22] and $f_+^{K^0\pi^-}(0) = 0.984 \pm 0.012$ [23], while a lattice simulation in the quenched approximation gives the result $f_+^{K^0\pi^-}(0) = 0.960 \pm 0.005_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}$ [24] (the quoted lattice systematic error does not account for quenching effects, which are unfortunately unknown). Taking $f_+^{K^0\pi^-}(0) = 0.974 \pm 0.012$, one derives from K_{l3}:

$$|V_{us}| = 0.2233 \pm 0.0028\,. \tag{1.2}$$

An independent determination of $|V_{us}|$ can be obtained from the Cabibbo-suppressed hadronic decays of the τ lepton [25]. The present data implies [26] $|V_{us}| = 0.2208 \pm 0.0034$. The uncertainty is dominated by experimental errors in the τ decay distribution and it is expected to be significantly improved at the B factories. $|V_{us}|$ can be also determined from $\Gamma(K^+ \to \mu^+\nu_\mu)/\Gamma(\pi^+ \to \mu^+\nu_\mu)$ [27], using the lattice evaluation of the ratio of decay constants f_K/f_π [28]; one gets $|V_{us}| = 0.2219 \pm 0.0025$.

The $|V_{us}|$ determination from hyperon decays is supposed to be affected by larger theoretical uncertainties, because the axial-vector form factors contributing to the relevant baryonic matrix elements are not protected by the Ademollo-Gatto theorem. Thus, it suffers from first-order SU(3) breaking corrections. Moreover, the second-order corrections to the leading vector-current contribution are badly known. In spite of that, two recent analyses of the hyperon decay data claim accuracies which, surprisingly, are competitive with the previous determinations:

$$|V_{us}| = 0.2250 \pm 0.0027\,, \qquad \text{ref.[29]}, \tag{1.3}$$

$$|V_{us}| = 0.2199 \pm 0.0026\,, \qquad \text{ref.[30]}. \tag{1.4}$$

Although they use basically the same data, the two analyses result in rather different central values for $|V_{us}|$ and obtain a qualitatively different conclusion on the pattern of SU(3) violations. While the fit of ref. [29] finds no indication of SU(3) breaking effects in the data, ref. [30] claims sizeable second-order symmetry breaking contributions which increase the vector form factors over their SU(3) predictions. Clearly, systematic uncertainties seem to be underestimated.

In order to clarify the situation, we have performed a new numerical analysis of the semileptonic hyperon decay data, trying to understand the differences between the results (1.3) and (1.4). The theoretical description of the relevant decay amplitudes is briefly summarized in section 2. The simplest phenomenological fit in terms of the total decay rates and the experimental g_1/f_1 ratios is presented in section 3, which roughly reproduces the numerical results of ref. [29]. Section 4 analyzes the sensitivity to SU(3) breaking, following the same $1/N_C$ framework as refs. [30, 31], while a discussion of systematic uncertainties is given in section 5. For completeness, we discuss in section 6 the neutron-decay determination of V_{ud}. Our conclusions are finally given in section 7.

2. Theoretical description of hyperon semileptonic decays

The semileptonic decay of a spin-$\frac{1}{2}$ hyperon, $B_1 \to B_2\, l^- \bar{\nu}_l$, involves the hadronic matrix

$B_1 \to B_2$	$n \to p$	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^- \to \Lambda$	$\Xi^- \to \Sigma^0$	$\Xi^0 \to \Sigma^+$
$C_F^{B_2 B_1}$	1	$-\sqrt{3/2}$	-1	$\sqrt{3/2}$	$1/\sqrt{2}$	1
$C_D^{B_2 B_1}$	1	$-1/\sqrt{6}$	1	$-1/\sqrt{6}$	$1/\sqrt{2}$	1

Table 1: Clebsh-Gordan coefficients for octet baryon decays.

elements of the vector and axial-vector currents:

$$\begin{aligned} \langle B_2(p_2)| \, V^\mu \, |B_1(p_1)\rangle &= \bar{u}(p_2) \left[f_1(q^2)\, \gamma^\mu + i \, \frac{f_2(q^2)}{M_{B_1}} \, \sigma^{\mu\nu} q_\nu + \frac{f_3(q^2)}{M_{B_1}} \, q^\mu \right] u(p_1) \,, \\ \langle B_2(p_2)| \, A^\mu \, |B_1(p_1)\rangle &= \bar{u}(p_2) \left[g_1(q^2)\, \gamma^\mu + i \, \frac{g_2(q^2)}{M_{B_1}} \, \sigma^{\mu\nu} q_\nu + \frac{g_3(q^2)}{M_{B_1}} \, q^\mu \right] \gamma_5 \, u(p_1) \,, \end{aligned} \tag{2.1}$$

where $q = p_1 - p_2$ is the four-momentum transfer. Since the corresponding $V - A$ leptonic current satisfies $q^\mu L_\mu \sim m_l$, the contribution of the form factors $f_3(q^2)$ and $g_3(q^2)$ to the decay amplitude is suppressed by the charged lepton mass m_l. Therefore, these two form factors can be safely neglected in the electronic decays which we are going to consider.

In the limit of exact SU(3) symmetry, the current matrix elements among the different members of the baryon octet are related [31]:

$$\begin{aligned} f_k^{\rm sym}(q^2) &= C_F^{B_2 B_1} \, F_k(q^2) \, + \, C_D^{B_2 B_1} \, D_k(q^2) \,, \\ g_k^{\rm sym}(q^2) &= C_F^{B_2 B_1} \, F_{k+3}(q^2) \, + \, C_D^{B_2 B_1} \, D_{k+3}(q^2) \,, \end{aligned} \tag{2.2}$$

where $F_k(q^2)$ and $D_k(q^2)$ are reduced form factors and $C_F^{B_2 B_1}$ and $C_D^{B_2 B_1}$ are well-known Clebsh-Gordan coefficients. The conservation of the vector current implies $F_3(q^2) = D_3(q^2) = 0$. Moreover, since the electromagnetic current belongs to the same octet of vector currents, the values at $q^2 = 0$ of the vector form factors are determined by the electric charges and the anomalous magnetic moments of the two nucleons, $\mu_p = 1.792847351\,(28)$ and $\mu_n = -1.9130427\,(5)$ [7]:

$$F_1(0) = 1 \,, \qquad D_1(0) = 0 \,, \qquad F_2(0) = -\left(\mu_p + \frac{1}{2} \, \mu_n \right) \,, \qquad D_2(0) = \frac{3}{2} \, \mu_n \,. \tag{2.3}$$

The values at $q^2 = 0$ of the two reduced form factors determining $g_1(q^2)$ are the usual F and D parameters: $F_4(0) = F$, $D_4(0) = D$. SU(3) symmetry also implies a vanishing "weak-electricity" form factor $g_2(q^2)$, because charge conjugation does not allow a C–odd g_2 term in the matrix elements of the neutral axial-vector currents A_μ^3 and A_μ^8, which are C–even.

The available kinematic phase space is bounded by $m_e^2 \le q^2 \le (M_{B_1} - M_{B_2})^2$. Thus, q^2 is a parametrically small SU(3) breaking effect. Since the form factor $f_2(q^2)$ appears multiplied by a factor q_ν, it gives a small contribution to the decay rate. To $O(q^2)$ accuracy, which seems sufficient to analyze the current data, the only momentum dependence which needs to be taken into account is the one of the leading form factors $f_1(q^2)$ and $g_1(q^2)$:

$$f_1(q^2) \approx f_1(0) \left(1 + \lambda_1^f \, \frac{q^2}{M_{B_1}^2} \right) \,, \qquad g_1(q^2) \approx g_1(0) \left(1 + \lambda_1^g \, \frac{q^2}{M_{B_1}^2} \right) \,. \tag{2.4}$$

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	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^- \to \Lambda$	$\Xi^- \to \Sigma^0$	$\Xi^0 \to \Sigma^+$
R	3.161 ± 0.058	6.88 ± 0.24	3.44 ± 0.19	0.53 ± 0.10	0.93 ± 0.14
$\alpha_{e\nu}$	-0.019 ± 0.013	0.347 ± 0.024	0.53 ± 0.10		
α_e	0.125 ± 0.066	-0.519 ± 0.104			
α_ν	0.821 ± 0.060	-0.230 ± 0.061			
α_B	-0.508 ± 0.065	0.509 ± 0.102			
A			0.62 ± 0.10		
g_1/f_1	0.718 ± 0.015	-0.340 ± 0.017	0.25 ± 0.05		1.32 ± 0.22

Table 2: Experimental data on $|\Delta S| = 1$ hyperon semileptonic decays [7]. R is given in units of $10^6\,\mathrm{s}^{-1}$.

Moreover, $f_2(0)$ and $g_2(0)$ can be fixed to their SU(3) values, because any deviations from the symmetry limit would give a second-order symmetry breaking effect. Therefore, the form factor $g_2(q^2)$ can be neglected.

The slopes λ_1^f and λ_1^g are usually fixed assuming a dipole form regulated by the mesonic resonance with the appropriate quantum numbers [32, 33]: $f_1(q^2) = f_1(0)/(1-q^2/M_V^2)^2$ and $g_1(q^2) = g_1(0)/(1-q^2/M_A^2)^2$; i.e., $\lambda_1^f = 2M_{B_1}^2/M_V^2$ and $\lambda_1^g = 2M_{B_1}^2/M_A^2$. Previous analyses have adopted the mass values $M_V = 0.97\,\mathrm{GeV}$ [29−33] and $M_A = 1.25\,\mathrm{GeV}$ [29, 32] or $M_A = 1.11\,\mathrm{GeV}$ [30, 31, 33]. We will analyze in section 5 the systematic uncertainties associated with these inputs.

It is useful to define the ratio of the physical value of $f_1(0)$ over the SU(3) prediction $C_F^{B_2B_1}$:

$$\tilde{f}_1 = \frac{f_1(0)}{C_F^{B_2B_1}} = 1 + \mathcal{O}(\epsilon^2)\,. \tag{2.5}$$

Due to the Ademollo-Gatto theorem [17, 18], $\tilde{f}_1$ is equal to one up to second-order SU(3) breaking effects.

The transition amplitudes for hyperon semileptonic decays have been extensively studied, using standard techniques. We will not repeat the detailed expressions of the different observables, which can be found in refs. [30, 32−34]. In order to make a precision determination of $|V_{us}|$, one needs to include the effect of radiative corrections [33, 35−37]. To the present level of experimental precision, the measured angular correlation and angular spin-asymmetry coefficients are unaffected by higher-order electroweak contributions. However, these corrections are sizeable in the total decay rates. To a very good approximation, their effect can be taken into account as a global correction to the partial decay widths: $\Gamma \sim G_F^2|V_{us}|^2(1+\delta_{\mathrm{RC}})$. The Fermi coupling measured in μ decay, $G_F = 1.16637\,(1)\cdot 10^{-5}\,\mathrm{GeV}^{-2}$ [7], absorbs some common radiative contributions. The numerical values of the remaining corrections δ_{RC} can be obtained from ref. [33].

3. g_1/f_1 analysis

The experimentally measured observables in hyperon semileptonic decays [7] are given in table 2, which collects the total decay rate R, the angular correlation coefficient $\alpha_{e\nu}$ and

	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^- \to \Lambda$	$\Xi^0 \to \Sigma^+$
$\lvert\tilde{f}_1\, V_{us}\rvert$	0.2221 (33)	0.2274 (49)	0.2367 (97)	0.216 (33)

Table 3: Results for $|\tilde{f}_1\, V_{us}|$ obtained from the measured rates and $g_1(0)/f_1(0)$ ratios. The quoted errors only reflect the statistical uncertainties.

the angular-asymmetry coefficients α_e, α_ν, α_B, A and B. The precise definition of these quantities can be found in refs. [32, 33]. Also given is the ratio $g_1(0)/f_1(0)$, which is determined from the measured asymmetries.

The simplest way to analyze [29] these experimental results is to use the measured values of the rates and the ratios $g_1(0)/f_1(0)$. Taking for $f_2(0)$ the SU(3) predictions, this determines the product $|\tilde{f}_1\, V_{us}|$. table 3 shows the results obtained from the four available decay modes. The differences with the values given in ref. [29] are very small; the largest one is due to the slightly different value of the $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ branching ratio [38]. The four decays give consistent results ($\chi^2/\text{d.o.f.} = 2.52/3$), which allows one (assuming a common value for $\tilde{f}_1$) to derive a combined average

$$|\tilde{f}_1\, V_{us}| = 0.2247 \pm 0.0026\,. \tag{3.1}$$

This number agrees (assuming $\tilde{f}_1 = 1$) with the value in eq. (1.3).

The quoted uncertainty only reflects the statistical errors and does not account for the unknown SU(3) breaking contributions to $\tilde{f}_1 - 1$, and other sources of theoretical uncertainties such as the values of $f_2(0)$ and $g_2(0)$ [SU(3) has been assumed], or the momentum dependence of $f_1(q^2)$ and $g_1(q^2)$. We will estimate later on the size of all these effects. For the moment, let us just mention that changing the dipole ansatz for $f_1(q^2)$ and $g_1(q^2)$ to a monopole form, the central value in (3.1) increases to 0.2278, with a $\chi^2/\text{d.o.f.} = 3.24/3$.

The agreement among the four determinations in table 3 has been claimed to be a strong indication that SU(3) breaking effects are indeed small [29]. Note, however, that first-order symmetry breaking corrections in the ratio $g_1(0)/f_1(0)$ are effectively taken into account, since we have used the experimental measurements. What table 3 shows is that the fitted results are consistent, within errors, with a common $\tilde{f}_1$ value for the four hyperon decays. The deviations of $\tilde{f}_1$ from one are of second order in symmetry breaking, but unfortunately even their sign seems controversial [39 – 42].

4. $1/N_C$ analysis of SU(3) breaking effects

The limit of an infinite number of quark colours provides useful simplifications of the strong interacting dynamics [43, 44], both in the meson [45, 46] and baryon sectors [46]. The $1/N_C$ expansion of QCD provides a framework to analyze the spin-flavour structure of baryons [47, 48], which can be used to investigate the size of SU(3) breaking effects through a combined expansion in $1/N_C$ and SU(3) symmetry breaking. A detailed analysis, within this framework, of SU(3) breaking in hyperon semileptonic decays was performed in ref. [31, 30], where all relevant formulae can be found. To avoid unnecessary repetition

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Decay	$g_1(0)$	$\tilde{f}_1$
$n \to p$	$\frac{5}{3}\,\tilde{a} + \tilde{b} + \rho$	1
$\Lambda \to p$	$-\sqrt{\frac{3}{2}}\,\left(\tilde{a} + \tilde{b} + c_3 + c_4\right)$	$1 + v_1 + v_2$
$\Sigma^- \to n$	$\frac{1}{3}\,(\tilde{a} + c_3 + c_4) - \tilde{b}$	$1 + v_1 + v_2 - 2v_3$
$\Xi^- \to \Lambda$	$\frac{1}{\sqrt{6}}\,(\tilde{a} + 7\,c_4) + \sqrt{\frac{3}{2}}\,\left(\tilde{b} + c_3\right)$	$1 + v_1 + 3\,v_2 + 2\,v_3$
$\Xi^- \to \Sigma^0$	$\frac{5}{3\sqrt{2}}\,(\tilde{a} + 3\,c_3) + \frac{1}{\sqrt{2}}\,\left(\tilde{b} + c_4\right)$	$1 + v_1 + 3\,v_2$
$\Xi^0 \to \Sigma^+$	$\frac{5}{3}\,\tilde{a} + \tilde{b} + 5\,c_3 + c_4$	$1 + v_1 + 3\,v_2$

Table 4: Parameterization of $g_1(0)$ and $\tilde{f}_1$ to first and second order, respectively, in symmetry breaking [31]. The neutron decay involves an additional parameter ρ, not included in (4.2).

we will only show explicitly the most important ingredients which have been used in the recent $|V_{us}|$ determination of ref. [30].

At $q^2 = 0$ the hadronic matrix elements of the vector current are governed by the associated charge or SU(3) generator. In the limit of exact SU(3) flavour symmetry, $V^{0a} = T^a$ to all orders in the $1/N_C$ expansion, where T^a are the baryon flavour generators. The SU(3) symmetry breaking corrections to V^{0a} have been computed to second order [31, 49]. For the hyperon $|\Delta S| = 1$ decays that we are considering, the final result can be written in the form [31]

$$V^{0a} = (1 + v_1)\,T^a + v_2\,\{T^a, N_s\} + v_3\,\left\{T^a, -I^2 + J_s^2\right\}, \tag{4.1}$$

where N_s counts the number of strange quarks, I denotes the isospin and J_s the strange quark spin. The parameters v_i constitute a second-order effect in agreement with the Ademollo-Gatto theorem [17, 18].

The $1/N_C$ expansion for the axial-vector current was studied in refs. [48, 50]. For the hyperon $|\Delta S| = 1$ decay modes, one can write the result in a simplified form which accounts for first-order symmetry breaking effects [31, 30]:

$$\frac{1}{2}\,A^{ia} = \tilde{a}\,G^{ia} + \tilde{b}\,J^i T^a + c_3\,\left\{G^{ia}, N_s\right\} + c_4\,\left\{T^a, J_s^i\right\}. \tag{4.2}$$

Here, $G^{ia} = q^\dagger(\sigma^i/2 \otimes \lambda^a/2)q$ is a one-body quark operator acting on the spin and flavour spaces. The coefficients $\tilde{a} \equiv a + c_1$ and $\tilde{b} \equiv b + c_2$ reabsorb the effect of two additional operators considered in ref. [31]. These operators generate an additional contribution to neutron decay, which we parameterize as $\rho = -\left(\frac{5}{3}\,c_1 + c_2\right)$. Table 4 shows the resulting values of $g_1(0)$ and $\tilde{f}_1$ for the relevant decay modes, in terms of the parameters $\tilde{a}$, $\tilde{b}$, c_3, c_4, ρ, v_1, v_2 and v_3.

In the strict SU(3) symmetry limit, $c_i = v_i = 0$, i.e. $\tilde{f}_1 = 1$ while the values of $g_1(0)$ are determined by two parameters a and b, or equivalently by the more usual quantities $D = a$ and $F = \frac{2}{3}\,a + b$. A 3-parameter fit to the hyperon decay data gives the results shown in table 5. Column 2 uses directly the measured values of the different rates and asymmetries, while in column 3 the asymmetries have been substituted by the derived $g_1(0)/f_1(0)$ values

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	SU(3) symmetric fit		$1^{\rm st}$-order symmetry breaking	
	Asymmetries	$g_1(0)/f_1(0)$	Asymmetries	$g_1(0)/f_1(0)$
$\lvert V_{us}\rvert$	0.2214 ± 0.0017	0.2216 ± 0.0017	0.2266 ± 0.0027	0.2239 ± 0.0027
$\tilde{a}$	0.805 ± 0.006	0.810 ± 0.006	0.69 ± 0.03	0.72 ± 0.03
$\tilde{b}$	-0.072 ± 0.010	-0.081 ± 0.010	-0.071 ± 0.010	-0.081 ± 0.011
c_3			0.026 ± 0.024	0.022 ± 0.023
c_4			0.047 ± 0.018	0.049 ± 0.018
χ^2/d.o.f.	40.23/13	14.15/6	18.09/11	2.15/4

Table 5: Results of different fits to the semileptonic hyperon decay data.

in table 2. Both procedures give consistent results, but the direct fit to the asymmetries has a worse $\chi^2/\text{d.o.f.} = 3.09$ (2.36 for the $g_1(0)/f_1(0)$ fit). These χ^2 values indicate the need for SU(3) breaking corrections. The fitted parameters agree within errors with the ones obtained in ref. [30], although our central value for $|V_{us}|$ is $1\,\sigma$ smaller. For the F and D parameters, we obtain:

$$F = 0.462 \pm 0.011\,, \qquad D = 0.808 \pm 0.006\,, \qquad F + D = 1.270 \pm 0.015\,. \tag{4.3}$$

The last number, can be compared with the value of $g_1(0)/f_1(0)$ measured in neutron decay: $[g_1(0)/f_1(0)]_{n\to p} = D + F = 1.2695 \pm 0.0029$ [7]. Using the $|V_{ud}|$ value determined from superallowed nuclear beta decays and the neutron lifetime quoted by the Particle Data Group [7], a more precise value, $[g_1(0)/f_1(0)]_{n\to p} = 1.2703 \pm 0.0008$, has been derived in ref. [4].

Including first-order SU(3) breaking effects in $g_1(0)$, the fit has two more free parameters. The fitted values are given in the last two columns of table 5. The effect of SU(3) breaking manifests through a value of $\tilde{a}$ lower than a (i.e. $c_1 = -0.10 \pm 0.03 \neq 0$, taking a from the SU(3) fits), and the non-zero value of c_4. The fit to the asymmetries has again a worse $\chi^2/\text{d.o.f.} = 1.64$ than the $g_1(0)/f_1(0)$ fit ($\chi^2/\text{d.o.f.} = 0.54$) and gives a $1\,\sigma$ higher value of $|V_{us}|$. Taking $|V_{us}|$ from the best fit, its central value is about $1\,\sigma$ higher than the value obtained with exact SU(3) symmetry. These results agree within errors with the corresponding fits in ref. [30].

One can repeat the fits including also the neutron decay, which introduces the additional parameter ρ. Taking $V_{ud} = 0.9740 \pm 0.0005$ [4], this gives a sizeable measure of SU(3) breaking, $\rho = 0.16 \pm 0.05$. The other parameters remain unchanged.

Ref. [30] presents the results of another fit, including second-order SU(3) breaking effects in $\tilde{f}_1$ through the parameters v_i. The final value quoted for $|V_{us}|$ comes in fact from this fit, where $|V_{us}|$, v_1, v_2 and v_3 are fitted simultaneously (together with $\tilde{a}$, $\tilde{b}$, c_3 and c_4), obtaining a very good $\chi^2/\text{d.o.f.} = 0.72/2 = 0.36$. We cannot understand the meaning of this numerical exercise. While it is indeed possible to fit the data with the parameters given in ref. [30], one can obtain an infinite amount of different parameter sets giving fits of acceptable quality, because there is a flat χ^2 distribution in this case. This can be easily understood looking to the last column in table 4. From the four analyzed $|\Delta S| = 1$ hyperon semileptonic decays, one could only determine the global factor $|V_{us}\,(1 + v_1 + v_2)\,|$, v_2 and

	$2^{\rm nd}$-order symmetry breaking	
	Asymmetries	$g_1(0)/f_1(0)$
$\vert\,(1+v_1+v_2)\ V_{us}\vert$	0.2280 ± 0.0034	0.2220 ± 0.0038
$\tilde{a}$	0.69 ± 0.03	0.74 ± 0.04
$\tilde{b}$	-0.075 ± 0.010	-0.083 ± 0.011
c_3	0.03 ± 0.03	0.02 ± 0.03
c_4	0.04 ± 0.02	0.04 ± 0.02
v_2	0.01 ± 0.03	0.04 ± 0.03
v_3	-0.004 ± 0.013	-0.013 ± 0.014
χ^2/d.o.f.	16.5/9	0.53/2

Table 6: Second order fits to the semileptonic hyperon decay data.

v_3. It is not possible to perform separate determinations of $|V_{us}|$ and v_1 because, as shown in eq. (4.1), the contribution to the vector current of the flavour generator T^a is always multiplied by the same global factor $(1 + v_1)$.

To assess the possible size of these second-order effects, we have also performed a 7-parameter fit to the data. The results are shown in table 6. Once more, the fit to the asymmetries has a worse χ^2/d.o.f. and gives a larger value for $|V_{us}\,(1 + v_1 + v_2)\,|$. The fitted values are consistent with the results in table 5 from the first-order fit. Within the present experimental uncertainties, the 7-parameter fit is not able to clearly identify any non-zero effect from second-order SU(3) breaking. Notice, that in this numerical exercise one is only considering second-order contributions to $\tilde{f}_1$, while $g_1(0)$ is still kept at first order. Unfortunately, it is not possible at present to perform a complete second-order analysis, owing to the large number of operators contributing to the axial current at this order.

Comparing the results from all fits, it seems safe to conclude that the $g_1(0)/f_1(0)$ ratios are less sensitive to SU(3) breaking than the asymmetries. Therefore, we will take as our best estimate the corresponding first-order result in table 5,

$$|\tilde{f}_1\, V_{us}| = 0.2239 \pm 0.0027\,. \tag{4.4}$$

This number is in good agreement with the simplest phenomenological fit in eq. (3.1) and could give a very adequate estimate of $|V_{us}|$, once the systematic uncertainties are properly included.

5. Systematic uncertainties

In our analysis the lepton masses, and therefore the form factors $f_3(q^2)$ and $g_3(q^2)$, have been neglected. This approximation does not introduce any relevant uncertainty at the present level of experimental accuracy. The errors associated with radiative corrections have been already taken into account in the fits, together with the experimental uncertainties. At first order in symmetry breaking, the main source of parametric uncertainties

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Parameter	SU(3) symmetric fit		1st-order symmetry breaking	
	Asymmetries	$g_1(0)/f_1(0)$	Asymmetries	$g_1(0)/f_1(0)$
$f_2^{\Lambda\to p} = 2.40 \pm 0.20$	$^{-0.0001}_{+0.0001}$	$^{-0.0001}_{+0.0001}$	$^{+0.0001}_{-0.0000}$	$^{-0.0002}_{+0.0001}$
$f_2^{\Sigma^-\to n} = -2.32 \pm 0.28$	$^{-0.0001}_{+0.0000}$	$^{+0.0001}_{-0.0000}$	$^{+0.0000}_{-0.0000}$	$^{-0.0001}_{+0.0000}$
$f_2^{\Xi^-\to\Lambda} = 0.178 \pm 0.030$	$^{+0.0000}_{-0.0000}$	$^{+0.0000}_{-0.0000}$	$^{+0.0000}_{-0.0000}$	$^{+0.0000}_{-0.0000}$
$f_2^{\Xi^-\to\Sigma^0} = -3.2 \pm 0.6$	$^{+0.0000}_{-0.0000}$	$^{+0.0000}_{-0.0000}$	$^{+0.0000}_{-0.0000}$	$^{+0.0000}_{-0.0000}$
$f_2^{\Xi^0\to\Sigma^+} = -4.4 \pm 0.8$	$^{+0.0000}_{-0.0000}$	$^{+0.0000}_{-0.0000}$	$^{+0.0000}_{-0.0000}$	$^{+0.0000}_{-0.0000}$
$M_A = 1.10 \pm 0.09$	$^{+0.0001}_{-0.0001}$	$^{+0.0001}_{-0.0001}$	$^{+0.0001}_{-0.0001}$	$^{+0.0001}_{-0.0001}$
$M_V = 0.91 \pm 0.07$	$^{+0.0005}_{-0.0006}$	$^{+0.0004}_{-0.0005}$	$^{+0.0002}_{-0.0002}$	$^{+0.0005}_{-0.0006}$
Total systematic error	0.0006	0.0004	0.0002	0.0006

Table 7: Parametric uncertainties of the V_{us} determination from hyperon decays.

comes from the numerical values of $f_2(0)$ and the slopes λ_1^f and λ_1^g governing the low-q^2 behaviour of the form factors $f_1(0)$ and $g_1(0)$.

Since the $f_2(q^2)$ contribution to the decay amplitude appears multiplied by q_ν, which is already a parametrically small SU(3) breaking effect, at $\mathcal{O}(\epsilon)$ the value of $f_2(0)$ can be fixed in the SU(3) limit from the proton and neutron magnetic moments [see eq. (2.3)]. However, what appears in the vector matrix elements (2.1) are the ratios $f_2(q^2)/M_{B_1}$. The SU(3) limit can either be applied to $f_2(0)$ or $f_2(0)/M_{B_1}$, because the baryon masses are the same for the whole octet multiplet in the limit of exact SU(3) symmetry. Taking the physical baryon masses, the numerical results would be obviously different. In order to estimate the associated uncertainty in $f_2(0)$ we will vary its value within the range obtained with these two possibilities.

The slopes λ_1^f and λ_1^g are determined from electroproduction and neutrino scattering data with nucleons, which are sensitive to the flavour-diagonal vector and axial-vector form factors in the $Q^2 = -q^2 > 0$ region. The obtained distributions are well fitted with dipole parameterizations $G_{V,A}(Q^2) = G_{V,A}(0)/\left(1 + Q^2/M_{V,A}^2\right)^2$, with $M_V^0 = (0.84 \pm 0.04)$ GeV and $M_A^0 = (1.08 \pm 0.08)$ GeV [32]. Extrapolating these functional forms to $q^2 > 0$, one gets a rough estimate of the needed hyperon form factor slopes in the SU(3) limit. To account for SU(3) breaking, one usually modifies the parameters M_V and M_A in a rather naive way, adopting the values $M_V = M_V^0\,(m_{K^*}/m_\rho) = 0.98\,\mathrm{GeV}$ and $M_A = M_A^0\,(m_{K_1}/m_{a_1}) = 1.12\,\mathrm{GeV}$. To estimate the systematic uncertainty associated with λ_1^f and λ_1^g, we adopt these dipole parameterizations, varying the values of the vector and axial-vector mass parameters between $M_{V,A}^0$ and $M_{V,A}$. As mentioned in section 3, a monopole parameterization could lead to a significative shift of the fitted V_{us} value; however, in this case one should take different values for the parameters $M_{V,A}$, in order to fit the $q^2 < 0$ data.

Reference	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^- \to \Lambda$	$\Xi^- \to \Sigma^0$	$\Xi^0 \to \Sigma^+$
DHK'87 [39] (quark model)	0.987	0.987	0.987	0.987	0.987
Sch'95 [40] (quark model)	0.976	0.975	0.976	0.976	
Kr'90 [41] (chiral loops)	0.943	0.987	0.957	0.943	
AL'93 [42] (chiral loops)	1.024	1.100	1.059	1.011	

Table 8: Theoretical predictions for $\tilde{f}_1$.

In table 7 we show the sensitivity of the resulting V_{us} value to these parametric uncertainties. Columns 2 and 3 give the induced systematic errors in the 3-parameter [SU(3) symmetric] fits, while columns 4 and 5 contain the corresponding numbers for the 5-parameter fits including first-order SU(3) breaking in $g_1(0)$. In both cases, we indicate separately the estimates obtained for the fits to the asymmetries and the $g_1(0)/f_1(0)$ fits. The numbers in the table show that the vector slope λ_1^f is the dominant source of parametric uncertainty. In any case, these uncertainties are much smaller than the statistical errors of the corresponding fits.

At second order, one should take into account the unknown value of $g_2(0)$ and the $\mathcal{O}(\epsilon^2)$ corrections to $f_1(0)$ and $g_1(0)$. There exist a few estimates of $f_1(0)$ using quark models and baryon chiral lagrangians. Unfortunately, they give rather different results as shown in table 8. The quark-model calculations agree with the naive expectation that SU(3) corrections should be negative, i.e. $\tilde{f}_1 < 1$ [39, 40]. In contrast, the chiral-loop estimates obtain large corrections with opposite signs: while ref. [42] finds values for $\tilde{f}_1$ which are larger than one for all analyzed decays, ref. [41] gets results more consistent with the quark-model evaluations. The two references use slightly different chiral techniques, and are probably taking into account different sets of Feynman diagram contributions. Clearly, a new and more complete calculation is needed.

Nothing useful is known about $g_2(0)$ and the needed $\mathcal{O}(\epsilon^2)$ corrections to $g_1(0)$. However, $g_2(0)$ is not expected to give a sizeable contribution, while $g_1(0)/f_1(0)$ can be directly taken from experiment using the phenomenological fit of section 3. In fact, the experimental $g_1(0)/f_1(0)$ ratios given in table 2 assume already $g_2(0) = 0$. Thus, the value of $\tilde{f}_1$ constitute the main theoretical problem for an accurate determination of V_{us} from hyperon decays. Although corrections to the SU(3) symmetric value are of $\mathcal{O}(\epsilon^2)$, it has been argued that they are numerically enhanced by infrared-sensitive denominators [42, 31]. In the absence of a reliable theoretical calculation, and in view of the estimates shown in table 8, we adopt the common value

$$\tilde{f}_1 = 0.99 \pm 0.02 \tag{5.1}$$

for the five decay modes we have studied. While the two quark model estimates are in the range $\tilde{f}_1 = 0.98 \pm 0.01$, the disagreement between the two chiral calculations expands the interval of published results to $\tilde{f}_1 = 1.02 \pm 0.08$. However, for some decay modes such as $\Sigma^- \to n e^- \bar{\nu}_e$ one can show that $\tilde{f}_1$ should indeed be smaller than one, as naively expected [29, 51]. This disagrees with the results obtained in ref. [42]. Our educated guess in (5.1) spans the whole interval of quark model results, allowing also for higher values of $\tilde{f}_1$ within a reasonable range. Applying this correction to our best estimate in eq. (4.4), gives the final result:

$$|V_{us}| = 0.226 \pm 0.005\,. \tag{5.2}$$

6. V_{ud} from neutron decay

A recent reanalysis of radiative corrections to the neutron decay amplitude has given the updated relation [4, 52]:

$$|V_{ud}| = \left(\frac{4908\,(4)\,\mathrm{sec}}{\tau_n\,(1+3\,g_A^2)} \right)^{1/2}\,. \tag{6.1}$$

Using $V_{ud} = 0.9740 \pm 0.0005$, ref. [4] derives the Standard Model prediction for the axial coupling

$$g_A \equiv \frac{g_1(0)}{f_1(0)} = 1.2703 \pm 0.0008\,, \tag{6.2}$$

which is more precise than the direct measurements through neutron decay asymmetries.

In order to extract V_{ud} from (6.1), using as inputs the measured values of the neutron lifetime and g_A, one would need to clarify the present experimental situation. The Particle Data Group [7] quotes the world averages

$$\tau_n = (885.7 \pm 0.8)\,\mathrm{s}\,, \qquad g_A = 1.2695 \pm 0.0029\,, \tag{6.3}$$

which imply

$$|V_{ud}| = 0.9745 \pm 0.0019\,. \tag{6.4}$$

However, the most recent measurement of the neutron lifetime [8] has lead to a very precise value which is lower than the world average by $6.5\,\sigma$,

$$\tau_n = (878.5 \pm 0.7 \pm 0.3)\,\mathrm{s}\,. \tag{6.5}$$

Taking g_A from (6.3), this would imply a $2\,\sigma$ higher $|V_{ud}|$:

$$|V_{ud}| = 0.9785 \pm 0.0019\,. \tag{6.6}$$

Actually, the PDG value of g_A in (6.3) comes from an average of five measurements which do not agree among them ($\chi^2 = 15.5$, confidence level $= 0.004$). If one adopts the value obtained in the most recent and precise experiment [53],

$$g_A = 1.2739 \pm 0.0019\,, \tag{6.7}$$

one gets the results:

$$|V_{ud}| = \begin{cases} 0.9717 \pm 0.0013 & (\tau_n \text{ from [7]})\,, \\ 0.9757 \pm 0.0013 & (\tau_n \text{ from [8]})\,. \end{cases} \tag{6.8}$$

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Source	K_{l3} [9–15, 19–24]	K_{l2} [27, 28]	τ [25, 26]	Hyperons
$\lvert V_{us}\rvert$	0.2233 ± 0.0028	0.2219 ± 0.0025	0.2208 ± 0.0034	0.226 ± 0.005

Table 9: Determinations of V_{us}.

7. Summary

At present, the determinations of $|V_{ud}|$ and $|V_{us}|$ from baryon semileptonic decays have large uncertainties and cannot compete with the more precise information obtained from other sources. As shown in eq. (6.1), radiative corrections to the neutron decay amplitude are known precisely enough to allow for an accurate measurement of $|V_{ud}|$, once the existing experimental discrepancies will be resolved. It looks surprising that two basic properties (lifetime and decay asymmetry) of the neutron, one of the most stable particles, are still so badly known. New precision experiments are urgently needed to clarify the situation.

Hyperon semileptonic decays could provide an independent determination of $|V_{us}|$, to be compared with the ones obtained from kaon decays or from the Cabibbo-suppressed τ decay width. However, our theoretical understanding of SU(3) breaking effects constitutes a severe limitation to the achievable precision. We have presented a new numerical analysis of the available data, trying to understand the discrepancies between the results previously obtained in refs. [29] and [30], and the systematic uncertainties entering the calculation.

The $1/N_C$ expansion of QCD is a convenient theoretical framework to study the baryon decay amplitudes and estimate the size of SU(3) breaking effects. From the comparison of fits done at different orders in symmetry breaking, one can clearly identify the presence of a sizeable SU(3) breaking at first order. However, the present uncertainties are too large to pin down these effects at second order.

One can use the measured decay rates and $g_1(0)/f_1(0)$ ratios to perform a rather clean determination of $|\tilde{f}_1\, V_{us}|$. However it is impossible to disentangle V_{us} from $\tilde{f}_1$ without additional theoretical input. The Ademollo-Gatto theorem guarantees that $\tilde{f}_1 = 1 + \mathcal{O}(\epsilon^2)$, but it has been argued that the second-order SU(3) corrections to $\tilde{f}_1 = 1$ are numerically enhanced by infrared-sensitive denominators [42, 31]. The existing calculations, using quark models or baryon chiral perturbation theory, give contradictory results and signal the possible presence of sizable corrections. Adopting as an educated guess the value $\tilde{f}_1 = 0.99 \pm 0.02$, we find our final result in eq. (5.2).

Table 9 compares the hyperon determination of V_{us}, with the results obtained from other sources. The present hyperon value has the largest uncertainty. To get a competitive determination one would need more precise experimental information and a better theoretical understanding of $\tilde{f}_1$, beyond its symmetric value. The average of all determinations is

$$|V_{us}| = 0.2225 \pm 0.0016\,. \tag{7.1}$$

Without the information from hyperon semileptonic decays, the average would be 0.2221 ± 0.0016. Taking $|V_{ud}| = 0.9740 \pm 0.0005$, from superallowed nuclear beta decays [4], the resulting first-row unitarity test gives (the $|V_{ub}|$ contribution is negligible):

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9982 \pm 0.0012\,. \tag{7.2}$$

Thus, the unitarity of the quark mixing matrix is satisfied at the $1.5\,\sigma$ level.

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