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A NEW DETERMINATION OF $|V_{us}|$ FROM KTEV

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ABSTRACT

We present a determination of the CKM parameter $|V_{us}|$ based on new measurements of the six largest K_L branching fractions and semileptonic form factors by the KTeV (E832) experiment at Fermilab. Our value of $|V_{us}|$ is consistent with unitarity of the CKM matrix.

1 Introduction

The first row of the Cabibbo-Kobayashi-Maskawa (CKM) matrix provides the most stringent test of the unitarity of the matrix. Current measurements [1] deviate from unitarity at the 2.2 sigma level: $1-(|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2) = 0.0043 \pm 0.0019$. $|V_{us}|$, which contributes an uncertainty of 0.0010 to this unitarity test, has been determined from charged and neutral kaon semileptonic decay rates. This determination is based on the partial width for semileptonic K decay, $\Gamma_{K\ell 3}$:

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1+\delta_K^\ell) C^2 \left|V_{us}\right|^2 f_+^2(0) I_K^\ell, \tag{1}$$

where ℓ refers to either e or μ, G_F is the Fermi constant, M_K is the kaon mass, S_{EW} is the short-distance radiative correction, δ_K^ℓ is the mode-dependent long-distance radiative correction, $f_+(0)$ is the calculated form factor at zero momentum transfer for the $\ell\nu$ system, and I_K^ℓ is the phase-space integral, which depends on measured semileptonic form factors. C^2 is 1 (1/2) for neutral (charged) kaon decays.

In this paper, we present a new determination of $|V_{us}|$ by the KTeV[1] (E832) experiment at Fermilab based on measurements of the $K_L \to \pi^\pm e^\mp \nu$ and $K_L \to \pi^\pm \mu^\mp \nu$ partial widths and form factors. These measurements are described in detail elsewhere [2, 3, 4]; a brief summary is given here.

2 Partial Width Measurements

To determine the $K_L \to \pi^\pm e^\mp \nu$ and $K_L \to \pi^\pm \mu^\mp \nu$ partial widths, we measure the following five ratios:

$$\begin{aligned}
\Gamma_{K\mu 3}/\Gamma_{Ke3} &\equiv \Gamma(K_L \to \pi^\pm \mu^\mp \nu)/\Gamma(K_L \to \pi^\pm e^\mp \nu) && (2)\\
\Gamma_{+-0}/\Gamma_{Ke3} &\equiv \Gamma(K_L \to \pi^+\pi^-\pi^0)/\Gamma(K_L \to \pi^\pm e^\mp \nu) && (3)\\
\Gamma_{000}/\Gamma_{Ke3} &\equiv \Gamma(K_L \to \pi^0\pi^0\pi^0)/\Gamma(K_L \to \pi^\pm e^\mp \nu) && (4)\\
\Gamma_{+-}/\Gamma_{Ke3} &\equiv \Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi^\pm e^\mp \nu) && (5)\\
\Gamma_{00}/\Gamma_{000} &\equiv \Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_L \to \pi^0\pi^0\pi^0), && (6)
\end{aligned}$$

where internal bremsstrahlung contributions are included for all decay modes with charged particles. Since the six decay modes listed above account for more than 99.9% of the total decay rate, the five partial width ratios may be converted into measurements of the branching fractions for the six decay modes. The PDG average K_L lifetime [1] of $\tau_L = (5.15 \pm 0.04) \times 10^{-8}$ s is then used to convert these branching fractions into partial widths.

[1]The KTeV Collaboration includes Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, UCLA, UCSD, Virginia, and Wisconsin.

Table 1: K_L *branching fractions and partial widths* (Γ_i).

Decay Mode	Branching fraction	Γ_i ($10^7 s^{-1}$)
$K_L \to \pi^{\pm} e^{\mp} \nu$	0.4067 ± 0.0011	0.7897 ± 0.0065
$K_L \to \pi^{\pm} \mu^{\mp} \nu$	0.2701 ± 0.0009	0.5244 ± 0.0044
$K_L \to \pi^+ \pi^- \pi^0$	0.1252 ± 0.0007	0.2431 ± 0.0023
$K_L \to \pi^0 \pi^0 \pi^0$	0.1945 ± 0.0018	0.3777 ± 0.0045
$K_L \to \pi^+ \pi^-$	$(1.975 \pm 0.012) \times 10^{-3}$	$(3.835 \pm 0.038) \times 10^{-3}$
$K_L \to \pi^0 \pi^0$	$(0.865 \pm 0.010) \times 10^{-3}$	$(1.679 \pm 0.024) \times 10^{-3}$

Simple event reconstruction and selection may be used to distinguish different kaon decay modes from each other, and to reduce background to a negligible level for all decay modes. A Monte Carlo simulation is used to correct the ratios in Eqs. 2 - 6 for acceptance differences between numerator and denominator.

Table 1 summarizes the measured branching fractions and partial widths. Figure 1 shows a comparison of the KTeV and PDG values for the six branching fractions. The new KTeV measurements are on average a factor of two more precise than the current world average values, but are not in good agreement with these averages. Compared to the PDG fit [1], the KTeV measurement of $B(K_L \to \pi^{\pm} e^{\mp} \nu)$ is higher by 5%, $B(K_L \to \pi^0 \pi^0 \pi^0)$ is lower by 8%, $B(K_L \to \pi^+ \pi^-)$ is lower by 5%, and $B(K_L \to \pi^0 \pi^0)$ is lower by 8%. Our measurements of $B(K_L \to \pi^{\pm} \mu^{\mp} \nu)$ and $B(K_L \to \pi^+ \pi^- \pi^0)$ are consistent with the PDG fit.

3 Semileptonic Form Factor Measurements

The semileptonic form factors describe the distribution of t, the square of the momentum transfer to the $\ell\nu$ system. This t dependence increases the decay phase space integrals, I_K^e and I_K^{μ}, by about 10%. We use the following parametrization for the two independent semileptonic form factors:

$$f_+(t) = f_+(0) \left[1 + \lambda'_+ \frac{t}{M_\pi^2} + \frac{1}{2} \lambda''_+ \frac{t^2}{M_\pi^4} \right], \quad f_0(t) = f_+(0) \left[1 + \lambda_0 \frac{t}{M_\pi^2} \right], \qquad (7)$$

where $f_+(0)$ is obtained from theory, and we measure λ'_+, λ''_+, and λ_0.

The $f_+(t)$ form factor is measured in both semileptonic decay modes; the effect of $f_0(t)$ is proportional to the lepton mass, so it is only measured in

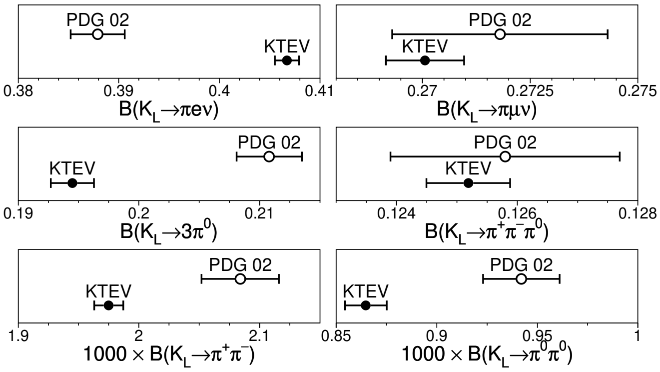

Figure 1: K_L *branching fractions measured by KTeV (dots) and from PDG fit (open circles).*

$K_L \to \pi^\pm\mu^\mp\nu$ decays. The measured parameters for the semileptonic form factors are $\lambda'_+ = (20.64 \pm 1.75) \times 10^{-3}$, $\lambda''_+ = (3.20 \pm 0.69) \times 10^{-3}$, and $\lambda_0 = (13.72 \pm 1.31) \times 10^{-3}$. The corresponding phase space integrals are $I_K^e = 0.15350 \pm 0.00105$ and $I_K^\mu = 0.10165 \pm 0.00080$, where the quoted errors include an additional uncertainty related to the form factor parameterization [4]. Compared to phase space integrals based on PDG form factors, KTeV's I_K^e and I_K^μ integrals are 1.7% and 4.2% lower, respectively. If we fit our data without the λ''_+ term, our I_K^e and I_K^μ integrals are increased by 1%, and are consistent with PDG averages that use only linear terms.

4 Consistency of Branching Fraction and Form Factor Measurements with Lepton Universality

To check the consistency of our branching fraction and form factor measurements with lepton universality, we compare G_F for the two decay modes by taking the ratio of Eq. 1 for $K_L \to \pi^\pm\mu^\mp\nu$ and $K_L \to \pi^\pm e^\mp\nu$:

$$\left(\frac{G_F^\mu}{G_F^e}\right)^2 = \left[\frac{\Gamma(K_L \to \pi^\pm\mu^\mp\nu)}{\Gamma(K_L \to \pi^\pm e^\mp\nu)}\right] \Big/ \left(\frac{1+\delta_K^\mu}{1+\delta_K^e} \cdot \frac{I_K^\mu}{I_K^e}\right). \tag{8}$$

Many common uncertainties cancel in this ratio. The ratio of radiative corrections is calculated to be [5] $(1+\delta_K^\mu)/(1+\delta_K^e) = 1.0058 \pm 0.0010$, the ratio of the phase space integrals is $I_K^\mu/I_K^e = 0.6622 \pm 0.0018$, and $\Gamma_{K\mu3}/\Gamma_{Ke3} = 0.6640 \pm 0.0026$. The resulting ratio of couplings squared is $(G_F^\mu/G_F^e)^2 = 0.9969 \pm 0.0048$, consistent with lepton universality. The same ratio calculated from PDG widths and form factors is $(G_F^\mu/G_F^e)^2 = 1.0270 \pm 0.0182$. Note that the 0.5% uncertainty in our universality test is much smaller than the 5% difference between the KTeV and PDG values of $\Gamma_{K\mu3}/\Gamma_{Ke3}$.

5 Determination of $|V_{us}|$

The measured partial widths and phase space integrals for semileptonic decays can be combined with theoretical corrections to calculate $|V_{us}|$ using Eq. 1. The short-distance radiative correction, $S_{EW} = 1.022$, [6] is evaluated with a cutoff at the proton mass. The long-distance radiative corrections are taken from [5]: $\delta_K^e = 0.013 \pm 0.003$ and $\delta_K^\mu = 0.019 \pm 0.003$. For $f_+(0)$, we use the same value used in the PDG evaluation of $|V_{us}|$ [7]: $f_+(0) = 0.961 \pm 0.008$.

Assuming lepton universality, we average the results for $K_L \to \pi^\pm e^\mp \nu$ and $K_L \to \pi^\pm \mu^\mp \nu$ (accounting for correlations):

$$|V_{us}| = 0.2252 \pm 0.0008_{\mathrm{KTeV}} \pm 0.0021_{\mathrm{ext}}. \tag{9}$$

The KTeV error comes from uncertainties in the KTeV branching fraction and form factor measurements. The external error comes from $f_+(0)$, the K_L lifetime, and radiative corrections.

To compare our result with previous charged and neutral kaon measurements, we use the product of $|V_{us}|$ and $f_+(0)$ rather than $|V_{us}|$ to avoid significant common uncertainties from $f_+(0)$. Figure 2 shows a comparison of our measurement of

$$|V_{us}|f_+(0) = 0.2165 \pm 0.0012 \tag{10}$$

with values from the PDG and Brookhaven E865 [8]. Our value of $|V_{us}|f_+(0)$ is inconsistent with previous K_L determinations, but is consistent with K^+ results. The figure also shows $f_+(0)(1 - |V_{ud}|^2 - |V_{ub}|^2)^{1/2}$, the expectation for $f_+(0)|V_{us}|$ assuming unitarity, based on $|V_{ud}| = 0.9734 \pm 0.0008$, $|V_{ub}| = (3.6 \pm 0.7) \times 10^{-3}$, and several recent calculations of $f_+(0)$. Our value of $|V_{us}|$ (Eq. 9), based the Leutwyler and Roos calculation of $f_+(0)$, is consistent with unitarity: $1-(|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2) = 0.0018 \pm 0.0019$. For other calculations of $f_+(0)$, the consistency with unitarity ranges from 1 to 1.7 sigma, as shown in Fig. 2.

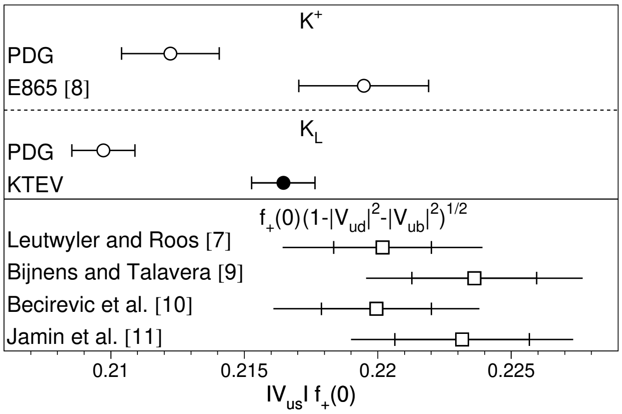

Figure 2: *Comparison of the KTeV measurement of* $|V_{us}|f_+(0)$ *with Brookhaven E865, PDG, and also with determinations of* $f_+(0)(1-|V_{ud}|^2-|V_{ub}|^2)^{1/2}$ *based on different theoretical calculations of* $f_+(0)$*. PDG refers to our evaluation based on PDG partial widths and form factors. For* $f_+(0)(1-|V_{ud}|^2-|V_{ub}|^2)^{1/2}$*, the inner error bars are from* $f_+(0)$ *uncertainty; the total uncertainties include the* $|V_{ud}|$ *and* $|V_{ub}|$ *errors.*

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