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MEASUREMENT OF THE $K^- \to \pi^0 e^- \bar{\nu}(\gamma)$ BRANCHING RATIO

Protvino 2007

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Abstract

Romanovsky V.I., Akimenko S.A., Britvich G.I. et al Measurement of the $K^- \to \pi^0 e^- \bar{\nu}(\gamma)$ Branching Ratio: IHEP Preprint 2007–5. – Protvino, 2007. – p. 8, figs. 1, refs.: 14.

The branching fraction for the decay $K^- \to \pi^0 e \bar{\nu}$ is measured using in-flight decays detected with **ISTRA+** setup working at the 25 GeV negative secondary beam of the U-70 PS: $Br(K_{e3}) = (5.124 \pm 0.009(stat) \pm 0.029(norm) \pm 0.030(syst))\%$.

From this value the $|V_{us}|$ element of the CKM matrix is extracted, using previously measured $f_+(t)$ form factor: $|V_{us}| = 0.227 \pm 0.002$. The results are in agreement with recent measurements by BNL E865, FNAL KTeV, KLOE .

Аннотация

Романовский В.И., Акименко С.А., Бритвич Г.И. и др. Измерение относительной вероятности распада $K^- \to \pi^0 e^- \bar{\nu}(\gamma)$: Препринт ИФВЭ 2007–5. – Протвино, 2007. – 8 с., 1 рис., библиогр.: 14.

На установке **ИСТРА+**, работающей на ускорителе У-70 на пучке отрицательно заряженных частиц с импульсом 25 ГэВ/с, проведено измерение относительной вероятности распада $K^- \to \pi^0 e \bar{\nu}$: $Br(K_{e3}) = (5.124 \pm 0.009$*(стат)* ± 0.029*(норм)* ± 0.030*(сист)*$)\%$.

Из этой величины, с использованием измеренного ранее формфактора $f_+(t)$ извлекается элемент СКМ-матрицы $|V_{us}|$: $|V_{us}| = 0.227 \pm 0.002$. Результаты находятся в согласии с недавними измерениями коллабораций BNL E865, FNAL KTeV и KLOE.

1. Introduction

The decay $K \to e\nu\pi^0(K_{e3})$ is known to be one of the best sources of information about V_{us} element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The interest in high statistics, low systematics measurement of the K_{e3} branching has raised after the paper by BNL E865 collaboration [1], where 2.5 σ increase of the K_{e3}^{+} branching as compared with PDG02 [2] was reported. This result improved the agreement of the measured V_{ud}, V_{us}, V_{ub} with the unitarity condition:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \ ,$$

which was violated by 2.3 σ with the old value of V_{us}. Since then, a set of new measurements of the K_{e3} branchings for K_L [3,4,5], K_S[6] has appeared, confirming the increase of V_{us} value. In our analysis, we present a new measurement of K_{e3}^{-} branching based on statistics of about 2M events using new approach, which allows to significantly reduce the systematics uncertainties.

2. Experimental setup

The experiment has been performed at the IHEP 70 GeV proton synchrotron U-70. The experimental setup ISTRA+ (Fig. 1) has been described in some details elsewhere [7].

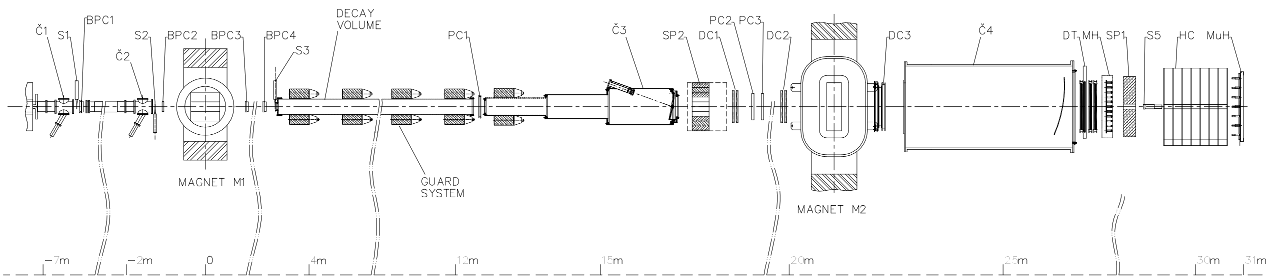

Figure 1. Elevation view of the ISTRA+ detector.

The setup is located in the negative unseparated secondary beam. The beam momentum in the measurements is $\sim$ 25 GeV with $\Delta p/p \sim 1.5\%$. The admixture of K^- in the beam is $\sim 3\%$. The beam intensity is $\sim 3 \cdot 10^6$ per 1.9 sec. U-70 spill. The beam particle deflected by M_1 is measured by $BPC_1 \div BPC_4$ PC's with 1mm wire step, the kaon identification is done by $\check{C}_0 \div \check{C}_2$ threshold $\check{C}$-counters. The 9 meter long vacuumed decay volume is surrounded by 8 lead glass rings $LG_1 \div LG_8$ used to veto low energy photons. SP_2 is a lead glass calorimeter to detect/veto large angle photons. The charged decay products deflected in M2 with 1 Tm field integral are measured with the help of $PC_1 \div PC_3$ — 2 mm step proportional chambers; $DC_1 \div DC_3$ — 1 cm cell drift chambers and finally with 2 cm diameter drift tubes $DT_1 \div DT_4$. Wide aperture threshold Cerenkov counters $\check{C}_3$, $\check{C}_4$ are filled with He and are not used in the present measurements. SP_1 is a 576-cell lead glass calorimeter, followed by HC — a scintillator-iron sampling hadron calorimeter, subdivided into 7 longitudinal sections 7×7 cells each. MH is a 11×11 cell scintillating hodoscope, used to improve the time resolution of the tracking system, MuH is a 7×7 cell muon hodoscope.

The trigger is provided by $S_1 \div S_5$ scintillation counters, $\check{C}_0 \div \check{C}_2$ Cerenkov counters, analog sum of amplitudes from the last dinodes of the SP_1 : $T = S_1 \cdot S_2 \cdot S_3 \cdot \bar{S}_4 \cdot \check{C}_0 \cdot \bar{\check{C}}_1 \cdot \bar{\check{C}}_2 \cdot \bar{S}_5 \cdot \Sigma(SP_1)$, here S_4 is a scintillator counter with a hole to suppress beam halo; S_5 is a counter downstream the setup at the beam focus; $\Sigma(SP_1)$ — a requirement for the analog sum of amplitudes from SP_1 to be larger than ~700 MeV — a MIP signal. The last requirement serves to suppress the $K \to \mu\nu$ decay.

3. General description of the experimental method

Our experimental approach to the K_{e3} branching ratio measurement is based on the following points:

1. K_{e3} is the dominant source of electrons in single track decays of charged kaon. Indeed, $Br(K_{e3}) \sim 5\%; Br(K_{e2}) \sim 1.5 \times 10^{-5}; Br(K_{e2\gamma}) \sim 1.5 \times 10^{-5}; Br(K_{e\nu\pi^0\pi^0}) \sim 2 \times 10^{-5}$. The contribution from the decay chain $K \to \mu\nu$; $\mu \to e\nu\bar{\nu}$ corresponds to effective $Br(K_{\mu 2}) < 10^{-5}$, because of the long lifetime of muon. The background sources do not exceed fraction of % from K_{e3} and can be easily taken into account.
2. The number of electrons is obtained from the fit of the E/p distribution, where E is the energy of the shower, associated with the charged track with momentum p.
3. The decay $K^- \to \pi^-\pi^0 (K_{\pi 2})$, which is used for the normalization is identified by the peak in the distribution over momentum of the charged secondary track in the kaon c.m.s (p_π^{cms}—distribution). The number of $K_{\pi 2}$ events is obtained from the fit of this distribution.
4. This method is based on the reconstruction of the beam and decay track only, i.e does not require a reconstruction of π^0 both in K_{e3} and $K_{\pi 2}$ decays. It uses few selection cuts, thus one can hope for a small systematics in this analysis.

4. Data set and event selection

During physics run in Winter 2001, 332M events were logged on tapes. This information is complemented by about 260M MC events generated with Geant3 [8] Monte Carlo program. MC generation includes a realistic description of the setup including decay volume entrance windows, track chambers windows, gas, sense wires and cathode structure, Cerenkov counters mirrors and gas, shower generation in EM calorimeters, etc.

The data processing starts with the beam particle reconstruction in $BPC_1 \div BPC_4$, then the secondary tracks are looked for in $PC_1 \div PC_3$; $DC_1 \div DC_3$; $DT_1 \div DT_4$ and events with one good negative track are selected. The decay vertex is searched for, and a cut $P > 1\%$ on the probability of the vertex fit is introduced.

The decay vertex is selected to locate in the decay volume region $500 < z < 1500$ cm, z being the coordinate along the beam line.

To suppress undecayed particles(beam electrons, in particular) a cut on the space angle between beam and secondary track is introduced: $\Delta\theta > 2$ mrad.

The next step is to require the total energy in the SP_1 calorimeter to be above one GeV: $E_{SP1} > 1$ GeV. This cut repeats "digitally" the trigger requirement, which is introduced to suppress $K \to \mu\nu$ decays.

The matching of the charged track and a shower in SP_1 is done on the basis of the distance **r** between the track extrapolation to the calorimeter front surface and the shower coordinates ($r \leq 5$ cm). This cut is used for the electron identification only.

5. Verification of the method on Monte-Carlo events.

The cuts described above were applied to the MC-sample which contains a natural mixture of reconstructed six largest kaon decays ($\mu^-\nu$, $\pi^-\pi^0$, $\pi^-\pi^+\pi^-$, $\pi^0 e^-\nu$, $\pi^0\mu^-\nu$, $\pi^-\pi^0\pi^0$), i.e the sample includes both signal and main backgrounds.

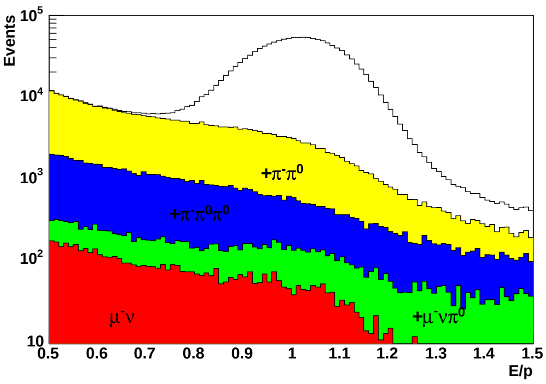

Figure 2: The cumulative distributions over the ratio of the energy of the associated calorimeter cluster to the momentum of the charged track (E/p plot) for four largest background decays and K_{e3} signal events (MC-events).

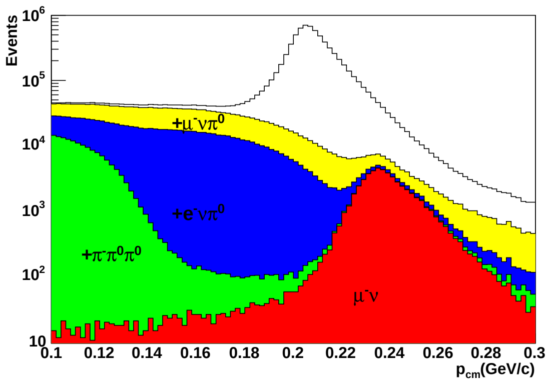

Figure 3: The cumulative distributions over p_π^{cms} — the momentum of the secondary particle in the kaon c.m.s. system, assuming that the particle is π-meson for four largest background decays and K_{e3} signal events (MC-events).

The E/p distribution for these events is presented in Fig. 2. MC shows that the main background to E/p is from $\pi^-\pi^0$ and $\pi^-\pi^0\pi^0$. Background is smooth enough to be described by $A \times e^{-P1 \cdot x}$, signal is described by sum of two Gaussians. Direct test of the fit gives $N_{Ke3}^{fit} = 1.006 \times N_{Ke3}^{true}$, where N^{fit}_{Ke3} — is the number of events in the peak of E/p distribution of Fig. 2 and N^{true}_{Ke3} is the "true" number of K_{e3} events in Fig. 2 known from MC.

The p^{cms}_{π} distribution for the same events is presented in Fig. 3. For the p^{cms}_{π} the main background is $e\nu\pi^0$ and $\mu\nu\pi^0$. Background is smooth enough to be described by 4-th order polynomial. Signal is described by the sum of two Gaussians.

6. Data Analysis

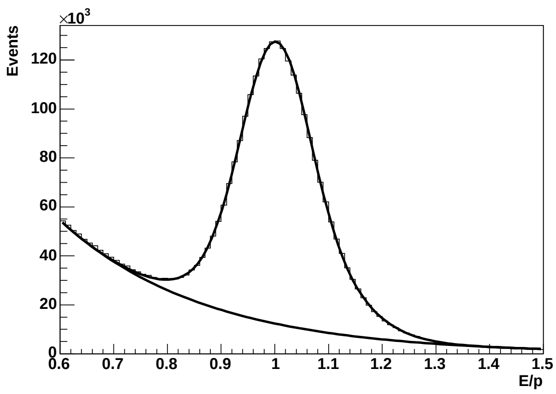

Figure 4: The E/p distribution for the real data.

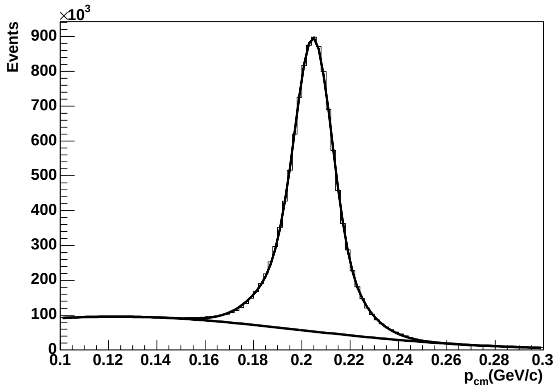

Figure 5: The distributions over the p^{cms}_{π} for the real data.

The application of the procedure described above to the real data results in the E/p and p^{cms}_{π} distributions of Fig. 4, Fig. 5.

The fit of the distributions gives:

$N_{Ke3} = (2.1739 \pm 0.0024) \times 10^6$; $N_{K\pi 2} = (10.2940 \pm 0.0053) \times 10^6$ for the data
$N_{Ke3} = (1.2319 \pm 0.0013) \times 10^6$; $N_{K\pi 2} = (6.2758 \pm 0.0030) \times 10^6$ for the MC.

In Geant3 version which we are using, the following branchings are assumed: $Br_{Ke3} = 4.82\%$; $Br_{K_{\pi 2}} = 21.17\%$. From this we can get:

$$Br_{Ke3}/Br_{K_{\pi 2}} = 0.2449 \pm 0.0004(stat).$$

Using PDG06 [9] value $Br_{K\pi 2} = (20.92 \pm 0.12)\%$:

$$Br_{Ke3} = (5.124 \pm 0.009(stat) \pm 0.029(norm))\%.$$

In fact, the $K_{\pi 2}$ branching of [9] is obtained by the fit, which has many inputs, including $Br_{Ke3}/Br_{K\pi 2}$ ratio. That is, it would be more correct to repeat the fit with our new result on branching ratio. This is done in [14] together with averaging over all recent experimental data. In present paper we however decided to limit ourself to our own results.

7. Study of systematics

The specific feature of our measurements is that the statistical error is much smaller than the systematic one. This allows us to study systematics by subdividing our statistics in parts over different variables. Fig. 6 shows the dependence of the measured $N_{Ke3}/N_{K\pi2}$ ratio versus run number and Fig. 7 versus z — the vertex coordinate along the beam line.

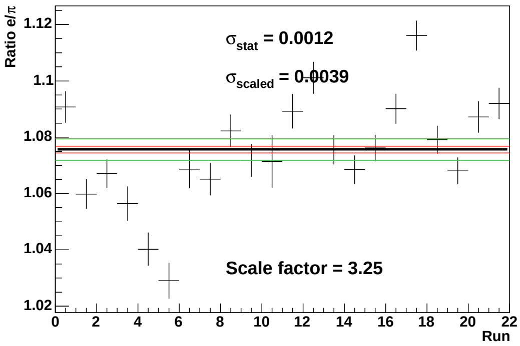

Figure 6: The measured ratio $N_{Ke3}/N_{K_{\pi2}}$ versus run number.

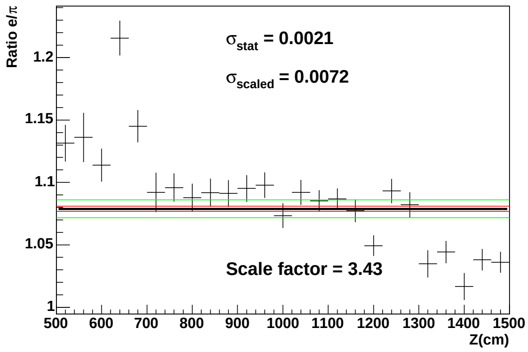

Figure 7: The measured ratio $N_{Ke3}/N_{K\pi2}$ versus z coordinate of the vertex.

The spread of the measured values around average is significantly larger than that expected from gaussian statistics. In extracting the systematics error we used an approach proposed by PDG [9] when calculating average from different experiments: a scale factor is defined $s = [\chi^2/(N-1)]^{1/2}$. If we scale up all the errors by this factor, the χ^2 becomes N-1, as required by ideal Gaussian statistics and the error of the average scales up by the same factor. The systematic error is then defined as $\sigma_{syst} = \sigma_{stat}\sqrt{s^2-1}$. For example, the scale factor for Fig. 6 equals 3.25 and for Fig. 7 it is 3.43. Note, that Fig. 7 demonstrates clear systematics in the region of z before the vacuumed decay volume ($z < 700$ cm) and after it ($z > 1300$ cm). We could cut out this regions, reducing systematics related to z, but it does not reduce significantly the scale factors for other distributions. That is why we decided not to introduce this "a posteriori" cut.

In this way several more distributions were studied, in particular, over azimuthal and polar angles of the secondary track etc. The average scale factor observed is $s \sim 3.5$. This gives estimation for systematic error in $Br_{Ke3}/Br_{K\pi2}$ of 0.0014 or the systematic error in Br_{Ke3} of 0.030%.

A systematics related to a possible admixture of electrons, muons and pions in the beam was separately studied. Fig.8 shows the distribution of events from the E/p peak of Fig. 4 over momentum (p). The histogram corresponds to the selection of the E/p peak region by a simple cut, and the points with errors are the results of the fit of E/p distribution for every bin in momentum. The absence of a bump in the region of the beam momentum (~ 25 GeV) indicates the absence of this type of background. Indeed, beam electrons are suppressed by two $\check{C}$-counters in the beam and by the $\Delta\theta > 2$ mrad cut.

It is easy to show that the amount of electrons from the decay chain $\pi \to \mu \to e$ of the beam pion is negligible as compared with the decay chain $K \to \mu \to e$, which is correctly reproduced in our MC: the number of pions which may pass $\check{C}$-counters "Veto" is at most 0.5%, i.e it is 1/6 of kaons, the lifetime factor($\gamma c\tau$) is 7.5, then taking into account the $K \to \mu\nu$ branching of .63 we get factor of 30 in favour of kaon decays.

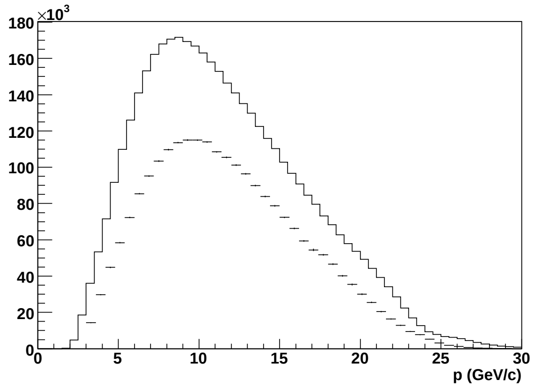

Figure 8: The measured momentum distribution of the tracks, identified as electrons. Histogram corresponds to the "rough" identification by the selection $0.6 < E/p$, the points with errors — results of the fits of the E/p distributions for each bin in p.

The effects on $N_{Ke3}/N_{K\pi2}$ from the cuts variation (vertex fit probability, $\Delta\theta > 2$ mrad, $E_{SP1} >$ 1 GeV) and different parametrization of the signal and background of Fig. 2 – Fig. 5 are less then estimation of systematic error from previous section.
Summing up all the systematics observed leads to our final result:

$$Br_{Ke3}/Br_{K\pi2} = 0.2449 \pm 0.0004(stat) \pm 0.0014(syst) \ ,$$

$$Br_{Ke3} = (5.124 \pm 0.009(stat) \pm 0.029(norm) \pm 0.030(syst))\% \ .$$

The comparison of our results with the E865 [1] shows reasonable agreement.

8. Extraction of $|V_{us}|$

In the Standard Model the Born-level matrix element for the $K^{\pm} \to \pi^0 l^{\pm}\nu$ decay modes is:

$$M = \frac{G_F V_{us}}{2}[f_+^{K^+\pi^0}(p_K + p_\pi)_\alpha + f_-^{K^+\pi^0}(p_K - p_\pi)_\alpha]\bar{u}(p_\nu)(1+\gamma^5)\gamma^\alpha v(p_l) \ ,$$

here $\frac{1}{\sqrt{2}}[f_+^{K^+\pi^0} \cdot (p_K + p_\pi)_\alpha + f_-^{K^+\pi^0} \cdot (p_K - p_\pi)_\alpha] \equiv < \pi^0|\bar{s}\gamma_\alpha(1-\gamma_5)u|K^+ >$; $f_\pm^{K^+\pi^0}(t)$ — form factors, which depend on $t = (p_K - p_\pi)^2 = (p_l + p_\nu)^2$ — the square of the four momentum transfer to the leptons.

The term in the vector part, proportional to f_- is reduced(using the Dirac equation) to an effective scalar term, proportional to m_l. That is why in case of K_{e3} decay one can neglect the term proportional to f_-.

The $K_{e3}^{\pm}$ decay rate can be expressed as:

$$\Gamma(K_{e3}^{\pm}) = \frac{Br(K_{e3}^{\pm})}{\tau(K^{\pm})} = \frac{G_\mu^2}{384\pi^3} M_K^5 |V_{us}|^2 |f_+(0)|^2 I_{K^+}^e S_{EW}(1 + \delta_{SU2} + \delta_+^e)^2 \ .$$

Here $S_{EW} = 1.0232 \pm 0.0003$ is the short-distance radiative correction [10]; $\delta_{SU2} = (2.31 \pm 0.22)\%$ takes into account the difference between $f_+^{K^0\pi^-}(0) \equiv f_+(0)$ and $f_+^{K^+\pi^0}(0)$ [11,14];

$\delta^e_+ = (0.03 \pm 0.1)\%$ is the long distance radiative correction for K^+_{e3}, for the fully inclusive $K_{e3(\gamma)}$ decay [11,14]. The $I^e_{K^+}$ is the dimensionless decay phase space integral [12]:

$$I^e_{K^+} = \int_0^{(M_K - M_\pi)^2} dt \frac{1}{M_K^8} \lambda^{3/2} (f_+(t)/f_+(0))^2 \ .$$

Where $\lambda = (M_K^2 - t - M_\pi^2)^2 - 4tM_\pi^2$.

To extract $|V_{us}|$, we take $Br(K^\pm_{e3})$ from the present experiment, $\tau(K^\pm) = (12.385 \pm 0.025)$ nsec — the charged kaon life-time from PDG06 [9] and calculate $I^e_{K^+}$ from our measurement of $f_+(t)$, where the quadratic non-linearity was observed for the first time [13]:

$$I^e_{K^+} = 0.15912 \pm 0.00084(stat) \pm 0.00114(syst) \ .$$

The systematic error reflects the difference between the quadratic and linear fit of the $f_+(t)$. Putting everything together we get:

$$|V_{us} f_+(0)| = 0.2186 \pm 0.0009_{Br} \pm 0.0012_{th} \ .$$

And finally:

$$|V_{us}| = 0.2275 \pm 0.0009_{Br} \pm 0.0022_{th} \ .$$

If theoretical value $f_+(0) = 0.961 \pm 0.008$ [12] is used.

9. Summary and conclusions

The K^-_{e3} decay has been studied using in-flight decays of 25 GeV K^-, detected by ISTRA+ magnetic spectrometer. Due to the high statistics, adequate resolution of the detector and good sensitivity over all the Dalitz plot space, the errors are significantly reduced as compared with the previous measurements. The K_{e3} branching is measured to be:

$$Br_{Ke3}/Br_{K\pi 2} = 0.2449 \pm 0.00005(stat) \pm 0.00020(syst).$$

$$Br_{Ke3} = (5.124 \pm 0.009(stat) \pm 0.029(norm) \pm 0.030(syst))\%.$$

From that we obtain:

$$|V_{us} f_+(0)| = 0.2186 \pm 0.0009_{Br} \pm 0.0012_{th}.$$

Which leads to:

$$|V_{us}| = 0.2275 \pm 0.0009_{Br} \pm 0.0022_{th}$$

if the theoretical value for $f_+(0)$ is substituted. Our result on $|V_{us}|$ is in reasonable agreement with that from charged [1] and neutral [3],[5],[6] kaon decays.

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References

[1] A.Sher et al.(BNL E865), Phys. Rev. Lett. **91**, 261802 (2003).

[2] K.Hagiwara et al. (PDG), Phys.Rev. **D66** (2002), 1.

[3] T.Alexopoulos et al. (KTeV), Phys.Rev.Lett. **93** (2004), 181802.

[4] A.Lai et al.(NA48), Phys.Lett. **B602** (2004), 41-51.

[5] F.Ambrosino et al. (KLOE), Phys.Lett. **B632** (2006), 43-50.

[6] F.Ambrosino et al. (KLOE), hep-ex/0601026.

[7] V.N.Bolotov et al., IHEP preprint 8-98,1998.

[8] R.Brun et al., CERN-DD/EE/84-1.

[9] A.B.Balantekin J. Phys. G: Nucl. Part. Phys. **33** (2006), 1.

[10] A.Sirlin, Nucl.Phys. **B196** (1982), 83.

[11] V.Cirigliano et al., Eur.Phys. J.**C35** (2004), 53.

[12] H.Leutwyler and M.Roos, Z.Phys. **C25** (1984), 91.

[13] O.P.Yushchenko et al.(ISTRA+), Phys. Lett. **B589** (2004), 111-117.

[14] M.Moulson, hep-ex/0703013.

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