Letter of Intent for a JHF Experiment

Precise Measurement of the $K^+ \to \pi^0 e^+ \nu$ (K_{e3}) Branching Ratio

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Abstract

In this Letter of Intent, we propose to measure one of the CKM matrix elements, V_{us}, with a precision of 10^{-3} in the kaon decay $K^+ \to \pi^0 e^+ \nu$ at JHF. Precise determination of V_{us} is of importance in testing the unitarity condition of the CKM matrix and in searching for 4th quark generation or new physics beyond the standard model. The experiment can be performed with reasonable up-grading of the KEK-PS E246 setup and the K_{e3} branching ratio will be measured with an accuracy of 0.5%.

1 Physics motivation

V_{us} is one of the most precise entry in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which has been intensively studied so far. Although V_{us} is one of the basic parameters in the standard model, this quantity cannot be theoretically predicted and has to be determined from the decay width of the $K^+ \to \pi^0 e^+ \nu$ decay (K_{e3}). The current V_{us} value recommended by the PDG is [1]

$$|V_{us}| = 0.2196 \pm 0.0023. \tag{1}$$

One of the most interesting motivations for the precise V_{us} determination is a test of the unitarity condition of the CKM matrix. Combining with other CKM elements [2]

$$\begin{aligned} |V_{ud}| &= 0.9740 \pm 0.0005, & (2) \\ |V_{ub}| &= 0.0036 \pm 0.0010, & (3) \end{aligned}$$

the unitarity condition can be tested as [2],

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9968 \pm 0.0014, \tag{4}$$

which should be unity if the CKM matrix is unitary. The total uncertainty in Eq. (4) is decomposed into 50% from V_{ud} and 50% from V_{us}, on the other hand, contribution from the V_{ub} value and its error is negligible in this test. The present experimental results therefore indicate that the CKM matrix does not satisfy the unitarity condition by 2.2 standard deviation, which implies the existence of 4th quark generation or new physics beyond the standard model. In order to settle this problem, further experimental studies are necessary for both V_{ud} and V_{us} at the level of 10^{-4} and 10^{-3}, respectively.

The value quoted for V_{ud} in Eq. (2) is extracted from superallowed Fermi decays in nuclei and from free neutron beta decay [2]. The determination of V_{ud} from neutron beta decay will be reaching the 10^{-4} accuracy from recent experiments for the neutron life time and the ratio of vector and axial vector couplings by putting careful attention to theoretical uncertainties [3]. Therefore, it is highly desirable to improve the accuracy of V_{us} to the level of 10^{-3} for the CKM unitarity test.

2 V_{us} determination from the K_{e3} branching ratio

Under the assumption of pure V$-$A form, the most general Lorentz invariant form of the matrix element of the K^+_{l3} decay is given by

$$\mathcal{M} = \frac{G_F}{2} V_{us}[f_+(q^2)(P_K + P_{\pi^0}) + f_-(q^2)(P_K - P_{\pi^0})][\bar{u}_l \gamma_\lambda (1-\gamma_5) u_\nu] \tag{5}$$

where P_K and P_π are the four-momenta of the K^+ and π^0, respectively. G_F is the effective coupling constant at the tree-level. $f_\pm(q^2)$ are the vector form factors, which are functions of the momentum transfer squared $q^2{=}(P_K - P_{\pi^0})^2$ to the leptons. It has been found the vector form factors can be described with a linearly parameterization in q^2 as $f_\pm(q^2) = f_\pm(0)[1 + \lambda_\pm (q/m_\pi)^2]$. In the case of K_{e3} decay, the quantity $f_-(q^2)$

appearing in $\mathcal{M}$ is proportional to the small e^+ mass and is negligible. The decay width of the K_{e3} decay can be written as,

$$\Gamma(K_{e3}) = \frac{G_F^2 m_K^5}{192\pi^3} |f_+(0) V_{us}|^2 I_K (1+\delta), \tag{6}$$

where I_k and δ correspond to the dimensionless integrated spectrum and the radiative correction [4], respectively. The theoretical calculation for the K_{e3} decay is highly reliable comparing with that for the $K_{\mu 3}$ decay, because the K_{e3} decay depends essentially only on the form factor $f_+(q^2)$. We can deduce the V_{us} value from the experimental K_{e3} decay width and the theoretical $f_+(0)$ calculation using Eq. (6). The uncertainty of V_{us} can be written as,

$$\Delta V_{us} = |V_{us}| \sqrt{[0.5 \frac{\Delta\Gamma(K_{e3})}{\Gamma}]^2 + [\frac{\Delta f_+(0)}{f_+(0)}]^2} \tag{7}$$

where $\Delta\Gamma(K_{e3})$ and $\Delta f_+(0)$ are the experimental error of the K_{e3} decay width and the theoretical $f_+(0)$ uncertainty, respectively.

The first determination of the V_{us} was carried out using charged and neutral K_{e3} decays by Shrock and Wang [5], in which leading flavor symmetry breaking effects were included in the $|f_+(0)|$ calculation by Leutwyler and Roos [6]. Recently, lattice QCD technique is applied for the $|f_+(0)|$ determination [7]. The current theoretical uncertainty of the $|f_+(0)|$ value is ~0.8%. On the other hand, the K_{e3} decay width can be expressed as,

$$\Gamma(K_{e3}) = \frac{Br(K_{e3})}{\tau_{K^+}}, \tag{8}$$

where τ_{K^+} is the mean K^+ life time and $Br(K_{e3})$ is the K_{e3} branching ratio. The world average values quoted by PDG are $\tau_{K^+} = 12.384 \pm 0.024$ ns and $Br(K_{e3}) = 4.87 \pm 0.06\%$. Therefore, the uncertainty of the K_{e3} branching ratio dominates that of the K_{e3} decay width. The most accurate measurement of the K_{e3} branching ratio was performed about 30 years ago using in-flight K^+ beam, and obtained to be $Br(K_{e3}) = 4.86 \pm 0.10\%$ [8]. It can be concluded that, taking into account the theoretical uncertainty in Eq. (7), it is necessary to determine the K_{e3} branching ratio with an accuracy better than 1% to improve the V_{us} accuracy.

3 Recent experimental situation

Recently, K_{e3} measurement was performed at the Brookhaven Alternating Gradient Synchrotron (AGS) using the E865 detector system [9, 12]. In-flight K_{e3} events were identified by detecting e^+ and e^+, e^-, γ from a π^0 Dalitz decay. They reported the preliminary result of the K_{e3} branching ratio to be

$$Br(K_{e3}) = 5.13 \pm 0.02 \pm 0.08 \pm 0.04\%, \tag{9}$$

which was rather amazing quantity to introduce a significant change for the CKM unitarity test so far. This preliminary result corresponds to approximately 3% increase of the V_{us} value, and deviation from unity in the unitarity condition of Eq. (4) disappear. Another experiment performed at DAϕNE reported on the preliminary result as [10],

$$Br(K_{e3}) = 5.33 \pm 0.13\%, \tag{10}$$

which was also inconsistent with the current world average. However, the error size of these experiments are too large (1.8% for former and 2.4% for latter) to rule out the previous experiment. Also, it should be noted that the V_{us} value obtained from the $K_L \rightarrow e^{\pm}\pi^{\mp}\nu$ decay is consistent with that from the previous K_{e3}^{+} experiment and inconsistent with that from these preliminary results [11]. Therefore, the current situation for the V_{us} determination is very confusing, and further experimental studies are necessary.

4 Description of the proposed K_{e3} experiment

4.1 KEK-E246 experiment

Before describing the K_{e3} experiment at JHF, it is worth writing the KEK-E246 experiment in which the K_{e3} form factors were successfully measured [13]. The experiment was performed at 12 GeV proton synchrotron by using a stopped K^+ beam in conjunction with a 12-sector iron-core superconducting toroidal spectrometer. Separated kaons were stopped in an active target, which consist of 256 5×5 mm^2 scintillating fibers, located at the center of the detector system. K_{e3} events were identified by analyzing the e^+ momentum with the spectrometer and detecting the two photon in CsI(Tl) calorimeter. The λ_+ parameter was determined to be

$$\lambda_+ = 0.0278 \pm 0.0026(\mathrm{stat}) \pm 0.0030(\mathrm{syst}) \tag{11}$$

by minimizing the difference between the observed Dalitz plot and the Monte Carlo simulation based on a GEANT.

There are several advantages to use stopped kaons. Because of the rotational symmetry of 12 identical gaps in the spectrometer and the large directional acceptance of the π^0 detector, distortions due to detector misalignment are canceled and systematic errors are greatly suppressed. In addition, the kinematical resolution in the C.M. frame is better for stopped kaons. On the other hand, in contrast to the in-flight experiment, the decay particles can be affected by interactions such as the bremsstrahlung and photon conversion with the target material. These interactions were taken into account in the simulation, however their ambiguity limited the experimental accuracy. As a result, the systematic error became slightly larger than the statistical one for the λ_+ determination. Therefore, it is very difficult to use the E246 detector without any modifications for the K_{e3} experiment at JHF. However, it must be possible to perform the K_{e3} experiment with reasonable up-grading of the E246 detector. The merit of the up-grading is a well-understood detector system and we can start data taking without long-time detector tuning. Also, it is meaningful to say that we can perform the experiment with minimum costs when we use the E246 setup with reasonable modifications.

Here, it is to be noted that an experiment aimed to determine the K_{e3} branching ratio with an accuracy better than 0.5% using a stopped K^+ beam was proposed at KEK in 1993 [14]. This proposal was accepted, however the experiment was not performed for some reasons.

4.2 Experiment at JHF

The purpose of the K_{e3} experiment at JHF is to determine the K_{e3} branching ratio with an accuracy of 0.5%. Since the K_{e3} branching ratio is relatively large, it can be considered that a statistical error does not dominate a total experimental error. Therefore, the essential point for the new experiment is how we reduce a systematic error down to 0.5%. In order to do this, we would like to propose a new experimental method "In-flight K^+ Measurement with Low Energy K^+ Beam", which must combine advantages of the stopped-K^+ and in-flight-K^+ techniques. Fig. 1 shows a schematic view of the detector system. Comparing with the KEK-E246 experiment, two plates of silicon vertex detectors (SVD1 and SVD2) are newly installed, while the active target system is removed.

Kaons are slowed down by a degrader and tracked by the SVDs. The K^+ momentum is obtained from dE/dx in the SVDs and/or time-of-flight between the SVDs. The e^+ and π^0 momentum vectors are determined by using the toroidal spectrometer and the CsI(Tl) calorimeter, respectively. The K^+ decay vertex defined as the intersection point of the K^+ and e^+ tracks is used to determine the fiducial volume. The K_{e3} branching ratio can be calculated as,

$$Br(K_{e3}) = \frac{N(K_{e3})}{N(K^+)} \cdot \frac{1}{\alpha\Omega} \tag{12}$$

where $N(K_{e3})$ and $N(K^+)$ are the numbers of accepted K_{e3} events and K^+ events counted by the SVDs, respectively. Ω is the detector acceptance and α is the fraction of K^+ decays in the fiducial volume. It is needless to say, in order to achieve $\Delta Br(K_{e3}) \sim 0.5\%$, the acceptance correction factor, $\alpha\Omega$, have to be estimated with an accuracy better than 0.5%.

4.3 Monte Carlo Simulation

A simple Monte Carlo simulation using K_{e3} and $K_{\pi 2}$ decays was carried out in order to roughly estimate the Ω and α values. In this simulation, hadronic and electro-magnetic interactions for K^+ were taken into account, although an electro-magnetic shower in the CsI(Tl) calorimeter and a scattering in the spectrometer were neglected.

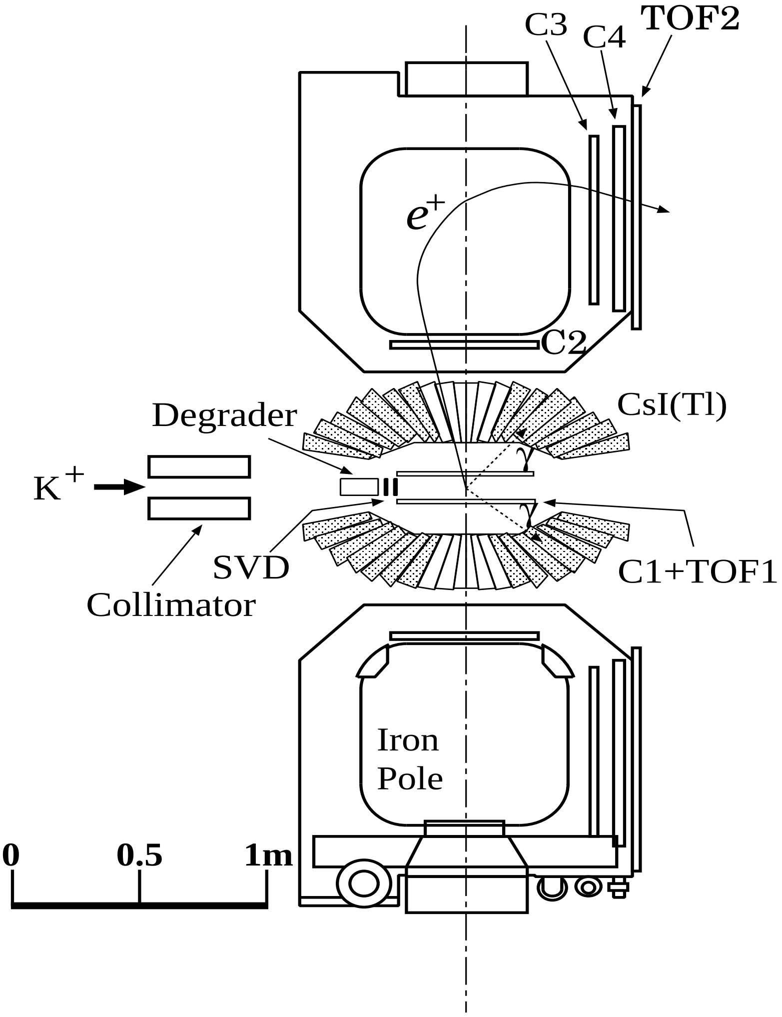

Figure 1: Cross sectional side view of the experimental setup. Two plates of silicon vertex detectors (SVD1 and SVD2) are newly installed, while the active target system is removed.

Table 1: Parameters assumed in the simulation.

Parameter	Value
K^+ momentum	660 MeV/c
K^+ beam diameter	10 mm (σ)
K^+ beam divergence	2°
Momentum byte	±1%
Position resolution of SVD	0.1 mm (σ)
Energy resolution of SVD	100 keV (σ)
Position resolution of MWPC1 and MWPC2	0.3 mm (σ)
Momentum resolution of spectrometer	2.5 MeV/c (σ)

Fig. 2 shows a schematic view of the detector system used in the simulation. The BeO degrader and SVDs were installed, while CsI(Tl) cylinders substituted the CsI(Tl) calorimeter and the magnetic field in the spectrometer was not taken into account. The detector resolutions obtained in the E246 experiment were assumed for the charged particle and π^0 measurements. All parameters used in the simulation are listed in Table 1.

$K_{\pi 2}$ events were identified by analyzing the π^+ momentum in the spectrometer and detecting the two photons in the calorimeter. K^+ and π^+ tracks were obtained from the hit positions in the SVDs and the multi-wire proportional chambers (MWPC1, MWPC2), respectively. The K^+ decay position defined as an intersection point of the K^+ and π^+ tracks was used to select the K^+ decay volume. Fig. 3 shows the correlation plot for the K^+ momentum and energy loss in the SVD2 (Es). The K^+ momentum was calculated from Es using this correlation. The π^+ momentum in C.M. frame was converted from that in Lab. frame using the K^+ momentum vector. Fig. 4(a),(b) show the π^+ momentum spectra of the $K_{\pi 2}$ decay in Lab. and C.M. frames, respectively.

Using K_{e3} events, the Ω and α values were calculated as,

$$\Omega = \frac{N(K_{e3})}{N(\mathrm{dec})} \quad \text{and} \quad \alpha = \frac{N(\mathrm{dec})}{N(K^+)} \tag{13}$$

where $N(K_{e3})$, $N(\mathrm{dec})$, and $N(K^+)$ are the numbers of observed K_{e3} events, K^+ decays in the fiducial volume, and generated K^+ in the simulation, respectively. The α and Ω values were estimated to be 0.12 and 0.005, respectively.

5 Request for a K^+ beam

Since it is considered that the systematic error due to the $\alpha\Omega$ ambiguity dominates the total experimental error, full intensity of the JHF facility is certainly not necessary.

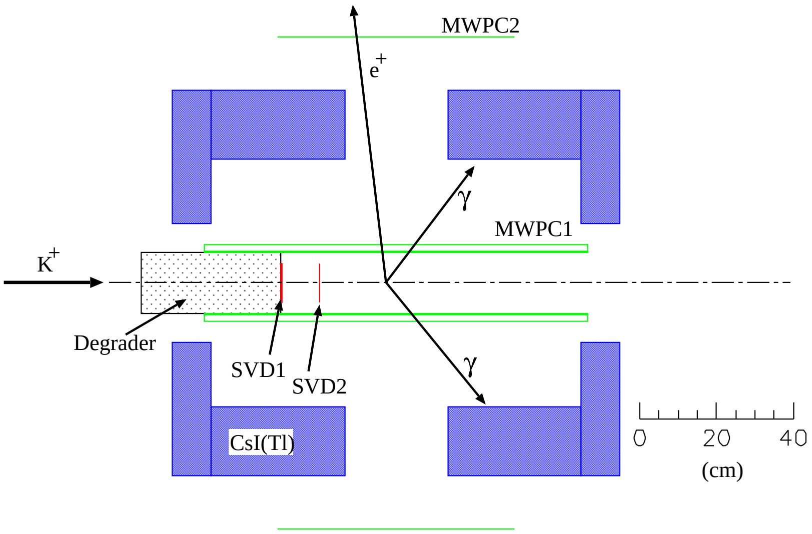

Figure 2: Schematic view of the detector system assumed in the simulation. The BeO degrader and the SVDs were installed, while CsI(Tl) cylinders substituted the CsI(Tl) calorimeter and the magnetic field in the spectrometer was not installed.

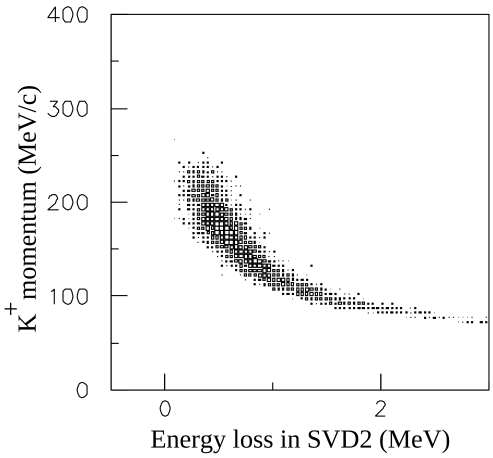

Figure 3: Correlation plot for the K^+ momentum and energy loss in the SVD2. The K^+ momentum was calculated using this correlation from the energy loss in the SVD.

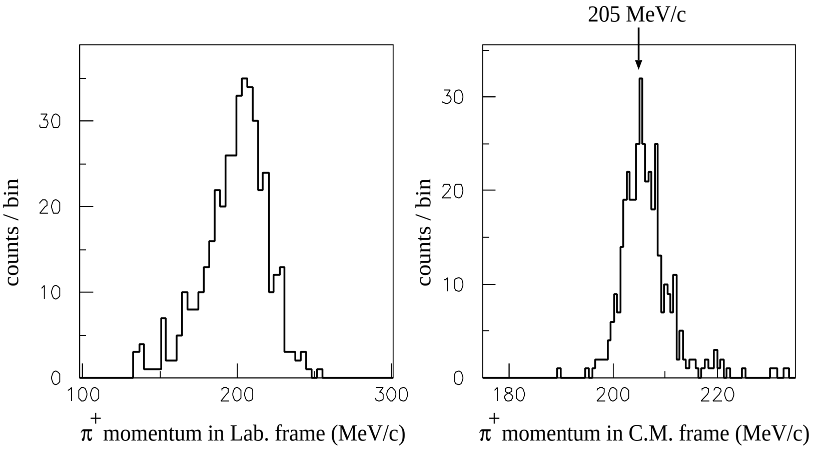

Figure 4: π^+ momentum spectra of $K_{\pi 2}$ decay in Lab. (a) and C.M. (b) frames. The π^+ momentum in C.M. frame was converted from that in Lab. frame using the K^+ momentum vector.

Table 2: Request for a K^+ beam.

K^+ momentum	600−700 MeV/c
K^+ intensity	10^5/s
K^+/π^+ ratio	>1
K^+ momentum byte	2−3 %
K^+ beam size	2cm in diameter (σ)

Also, it is to be noted that the E246 detector system essentially cannot work under high intensity beam environment (Max. 10^5 K^+/s). On the other hand, good beam quality is very important: (1) good K^+/π^+ ratio (at least $K^+/\pi^+ = 1$), (2) negligible π^+ halo, (3) small beam size, are the minimum requirements for the π^0 detection by the CsI(Tl) calorimeter. To realize these conditions, two stages DC separator must be indispensable. According to the Monte Carlo simulation, the maximum fraction of in-flight K^+ decay in the fiducial volume was achieved for the beam momentum between 600−700 MeV/c taking into account production cross section, emittance degradation by the degrader material, and so on. In Table 2, request for a K^+ beam is summarized.

In the initial plan of the experimental hall, a low momentum separate kaon beam line is planned at the second target T2. However, we seek for a possibility to perform the proposed experiment in PhaseI because full intensity of the JHF facility is not necessary. We would like to request to install a low momentum separate line at the T1 target.

6 Detector preparation

6.1 Cost and funding

Since the E246 experimental setup will be used with reasonable up-grading, the cost for the new element should not be high. It is estimated to be approximately 0.4−0.5 M$. We expect a Grant-in-Aid from the Ministry of Education, Culture, Sports, and Technology to carry out the proposed experiment.

6.2 Collaboration forming

There is an experienced group which built the E246 detector, executed the experiment, and succeeded in extracting physics outputs. Some people of this group will form a core of the new collaboration. It is now under discussion about the collaboration forming.

6.3 Schedule

We will finished detailed design of the experimental setup using the Monte Carlo simulation by the end of 2004. The up-grading of the E246 detector system is expected to take 2 years after accepting a proposal. It should be desirable to perform this experiment in the early stage of the experimental programs, because full intensity beam is not necessary.

7 Long-range plan of kaon decay spectroscopy at JHF

In this LoI, we concentrated to discuss the K_{e3} experiment, however this is just the first step of our experimental programs. The spectroscopic studies of various K^+ decay modes are well-recognized to be of importance both in studying low energy properties of the strong interaction in terms of effective theories and in studying fundamental interaction. We have successfully measured $K_{\mu 3}$, $K_{\pi 3}$, $K_{\pi 2\gamma}$, and K_{e4} decays using stopped kaons in the E246/E470 experiments [13, 15, 16, 17, 18, 19]. In these experiments, the decay particles were affected by interactions with the target material and the experimental spectra were slightly deformed. As a consequence, this effect dominated the total experimental error. Therefore, we would like to continue these experiments using the proposed method in this LoI, and we are quite sure that much more precise data of various K^+ decay modes can be obtained at JHF.

References

[1] Particle Data Group, Phys. Rev. **D66** (2002)

[2] J.C Hardy and I.S. Towner, Eur. Phys. J. **A15** (2002) 223.

[3] A. Garcia, J.L. Garcia-Luna, and G. Lopez Castro, Phys. Lett. **B500** (2001) 66.

[4] V. Cirigliano *et al.*, Eur. Phys. J. **C23** (2002) 121.

[5] Robert E. Shrock and Ling-Lie Wang, Phys. Rev. Lett. **41** (1978) 1692.

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

[7] S. Hashimoto, N. Tsutsui, and T. Kaneko (private communication).

[8] I-H. Chiang *et al.*, Phys. Rev. **D6** (1972) 1254.

[9] DPF2002, division of particle and fields of the American physical society, May 24-28 (2002).

[10] M. Martemianov, LNF Spring School, Frascati 20-24 May, 2002.

[11] G. Calderon and Lopez Castro, Phys. Rev. **D65** (2002) 073032.

[12] R. Appel *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **479** (2002) 349.

[13] S. Shimizu *et al.*, Phys. Lett. **B495** (2000) 33.

[14] T. Ohshima *et al.*, KEK experimental proposal (1993).

[15] M. Abe *et al.*, Phys. Rev. Lett. **83** (1999) 4253.

[16] K. Horie *et al.*, Phys. Lett. **B513** (2001) 311.

[17] Y.-H. Shin *et al.*, Eur. Phys. J. **C12** (2000) 627.

[18] M.A. Aliev *et al.*, Phys. Lett. **B** (in press).

[19] C. Rangacharyulu *et al.*, Letter of Intent for a JHF experiment.