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3/18/04

CKM Unitarity, Lattice Pseudoscalar Decay Constants and "New Physics"

Outline

I. 3 Generation CKM Unitarity: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$? ($|V_{ud}|^2 \sim 1-\lambda^2$, $|V_{us}|^2 \sim \lambda^2$, $|V_{ub}|^2 \sim 10^{-5}$)

i) $|V_{ud}| = 0.9739(5)$

ii) $|V_{us}| = (0.215 \sim 0.227)$ A Big Mess! ~6% spread!

II. Lattice Pseudoscalar Decay Constants: f_π, f_K, f_D, f_B (MILC Collaboration)

* i) $f_K/f_\pi \rightarrow |V_{us}| = 0.222(3)$ ±1.4%!

III. Possible "New Physics" Effects (No Really Big Effects)

i) Supersymmetry?

ii) Heavy Quark (or Lepton) Mixing

iii) Exotic Muon Decays ~0.2% eg $\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu$ wrong neutrinos

iv) Z' + Extra Dim. loops

v) Charged Higgs ($H^\pm$) + large $\tan\beta \simeq 40$

⋮

IV. Outlook

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I. 3 Generation CKM Unitarity

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\lambda = |V_{us}| = \sin\theta_{Cabibbo}$ = CKM Cornerstone

$J_{CP} = \lambda^6 A^2 \eta \simeq 3\times10^{-5}$ CP Invariant

Value of λ?

Unitarity Test: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

How well is it tested? ~ ±0.15% (25sigma loop determination)

Deviation → "New Physics" (How sensitive?)

$|V_{ub}|^2 = (3.6\pm0.7\times10^{-3})^2 < 2\times10^{-5}$ Negligible

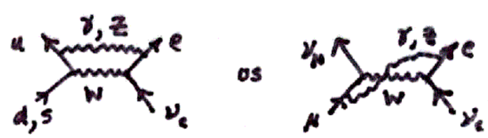
Becomes a Cabibbo angle problem

$|V_{us}| = \sin\theta_c$, $|V_{ud}| \simeq \cos\theta_c$

PDG (2002): $|V_{ud}| = 0.9734(8)$, $|V_{us}| = 0.2196(26)$

$|V_{ud}|^2 + |V_{us}|^2 = 0.9957(16)(11)$ 2.2σ deviation

Without Rad. Corrections $|V_{ud}|^2 + |V_{us}|^2 = 1.04$!



Large R.C. A. Sirlin } SM Success

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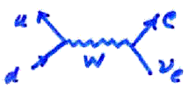
All semileptonic CC reactions renormalized using $G_\mu = 1.16637(1) \times 10^{-5}\,GeV^{-2}$ from the muon lifetime.

$$G_\mu = g_2^2/4\sqrt{2}m_W^2$$

Assumes no exotic μ decays beyond SM, no big tree or loop beyond SM.

i) Status of $|V_{ud}|$



+ R.C. / Muon decay amp.

9 Super-Allowed $0^+ \to 0^+$ Nuclear β-decays $\to |V_{ud}| = 0.9740(3)(4)_{RC}$

*Neutron $\tau_n = 885.7(7)$ sec, $|\bar{g}_A| = 1.2720(18) \to |V_{ud}| = 0.9729(4)(11)(4)_{RC}$

Pion $\pi^+ \to \pi^0 e^+ \nu_e$ (BR$\sim 10^{-8}$!) $\to |V_{ud}| = 0.9737(39)(2)_{RC}$

Ave $|V_{ud}| = 0.9739(5)$ A. Czarnecki, W.M. + A. Sirlin (In progress)

ii) Status of $|V_{us}|$ Clouded + Changing

$\to V_{us}$

EW Rad. Corrections, Hadronic Effects } < ±1% goal (Less Important)

K_{e3} decays $K \to \pi e \nu$ Vector Current

Corrections 2nd Order in SU(3) BR

Should be clean

PDG (2002) uses fits for $\overset{(-)}{K^0} \to \pi^\pm e^\mp \nu$ + $K^+ \to \pi^0 e \nu$ {Old Data}

+ $(m_d - m_u)$ + EW Rad. Corr. (Roos + Leutwyler)

$|V_{us}|_{PDG} = 0.2196(26)$ $\to$ 2.2σ deviation (Unitarity)

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Recent Advances?

E865 at BNL BR($K^+ \to \pi^0 e^+ \nu$) increase ~+5% $\to |V_{us}| \simeq 0.2272(30)$

KLOE (Preliminary) BR($K_{S,L} \to \pi^\pm e^\mp \nu$) unchanged $\to |V_{us}| \simeq 0.2180(24)$

About 4.3% difference

Note $(0.9739)^2 + (0.2272)^2 = 1.0001$ Perfect Unitarity! E865

In fact $|V_{ud}| = 0.9739(5)$ + Unitarity $\to |V_{us}| = 0.2269(22)$

Recent Cirigliano, Neufeld + Pichl (p^6 Chiral Corrections) ~ 1.5% reduction! Large!

E865 $|V_{us}| = 0.2238(30)$

K^0_{e3} $|V_{us}| = 0.2148(24) \to$ 3.8σ deviation from CKM Unit.

Something is wrong: PDG Fits? Ch Pert.? Both?

Test: $$\frac{\Gamma(K_L \to \pi^\pm e^\mp \nu)_{PDG}}{\Gamma(K^+ \to \pi^0 e^+ \nu)_{E865}} = 1.81(2)(3)$$ Expect 2 in isospin limit. 9.5% difference!

$m_{K_L} = 497.67$ MeV, $m_{K^+} = 493.65$ MeV } mainly $m_d - m_u \to \pi^0$-η mixing

$m_{\pi^+} = 139.57$ MeV, $m_{\pi^0} = 134.97$ MeV } mainly em

Isospin Corrections: $\frac{1.034 \times 0.96}{0.9726 \times 1.023}$ $\left\{ \begin{matrix} (m_d - m_u) \\ em \end{matrix} \right\}$ = 0.9982 Almost no isospin corr.! (theorem)

9.5% discrepency $\to$ Exp (Fit) Errors!

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PDG Kaon Properties τ_K, BR May Be "Way" Off

eg. All K_L off but ϕ ! eg $\Delta\tau_{K_L} = \pm 0.8\%$ Last measured 1972 (PPR)

Meanwhile Cabibbo et al Hyperon Lifetimes + Asy.
(Like neutron decay) use V+A

$|V_{us}| = 0.2250(27)$

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9991(16)$ Agrees with Unitarity

Summary Table (Use $|V_{ud}| = 0.9739(5)$)

Input	$\lvert V_{us}\rvert$	$\lvert V_{ud}\rvert^2 + \lvert V_{us}\rvert^2 + \lvert V_{ub}\rvert^2$
Unitarity	0.2269(22)	1
Hyperons	0.2250(27)	0.9991(16)
K^+_{e3}	0.2238(30)	0.9986(17)
K^0_{e3}	0.2148 (24)	0.9946(14) significant deviation

II. Lattice Pseudoscalar Decay Constants: $f_\pi, f_K, f_D, f_B \cdots$

MILC Collaboration C. Aubin, C. Bernard et al..

Staggered Fermions + Ch. Corrections .. (Very Detailed)

Leave Out e.m. + $m_d - m_u$ effects

use m_{π^0}, m_η, $\frac{m_{K_0} + m_{K^+}}{2} = m_K$ (?) as input

predict $f_\pi, f_K, L_i \cdots$ Claim ~2-3% Exp. Agreement

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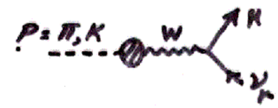
HEP-LAT/0309088 $\langle 0|A_\mu|P\rangle = i f_P P_\mu$

Preliminary: $f_\pi = 129.3 \pm 1.1 \pm 3.5$ MeV
$f_K = 155.0 \pm 1.8 \pm 3.7$ MeV

$f_K/f_\pi = 1.201(8)(15)$ Errors Partially Cancel! ~±1.5% error! Can be improved!



$$\Gamma(K\to\mu\nu(\gamma)) = \frac{G_\mu^2 |V_{us}|^2}{8\pi} f_K^2 m_K m_\mu^2 \left(1 - \frac{m_\mu^2}{m_K^2}\right)^2 \left(1 + \frac{\alpha}{\pi} C_K\right)$$

EW R.C.

$$\Gamma(\pi\to\mu\nu(\gamma)) = \frac{G_\mu^2 |V_{ud}|^2}{8\pi} f_\pi^2 m_\pi m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2 \left(1 + \frac{\alpha}{\pi} C_\pi\right)$$

Exp. $\frac{\Gamma(K\to\mu\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))} = 1.334(4)$ Very Precise (Should be checked)

Rad. Corrections Largely Cancel in ratio $C_K - C_\pi = -3.0 \pm 1.5$

Short-distance ~2.4%

Finkemeier 1996 should be checked

$$\frac{|V_{us}|^2 f_K^2}{|V_{ud}|^2 f_\pi^2} = 0.07602(23)_{exp}(27)_{RC}$$

Tiny Errors!

lattice f_K/f_π → (2003 Preliminary) $\frac{|V_{us}|^2}{|V_{ud}|^2} = 0.05271(16)(19)(149)_{\text{lattice}}$

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Assume Unitarity → $|V_{us}| = 0.2238(30)$
Use $|V_{ud}| = 0.9739(5)$ → $|V_{us}| = 0.2236(30)$
} Agree with E865 + Unitarity

* **Preliminary Revision of Preliminary f_K/f_π Lattice** 3/12/04

$$f_K/f_\pi = 1.201(8)(15) \rightarrow 1.211(6)\binom{15}{13}$$

→ Assume Unitarity $|V_{us}| = 0.2220(30)$

Use $|V_{ud}| = 0.9739(5)$ $|V_{us}| = 0.2218(30)$

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9977(16)$ small deviation

Lattice calculations can be improved (already competitive).

Aim for $\Delta|V_{us}| \simeq \pm 0.0007$ (Phenomenal)

Different than K_{e3} (Vector Current) vs Axial

Not sensitive to G_μ Normalization

Gives relatively pure $\tan\theta_c$ → λ

If other determinations differ → "New Physics"

eg. Lattice → $|V_{ud}| = 0.9750(6)$

β-decays → $|V_{ud}| = 0.9739(5)$

diff = $11 \pm 8 \times 10^{-4}$ "New Physics"? Bound?

Differ by 0.1% Why? Not a big deal?

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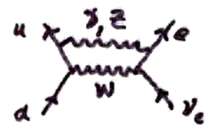
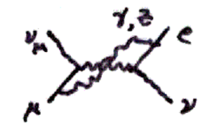
III. Possible "New Physics" Effects (Hint or Constraint?)

What could cause a 0.1% shift in $|V_{ud}|_{exp.}$?

Total R.C. ~ 2% (How Precise?)



vs

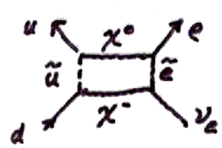


different Hypercharge $Y = \frac{1}{3}$ vs $Y = -1$

$$1 + \frac{\alpha}{\pi} \ln m_Z / E_{max}$$

Other 0.1% sources 2 loop effects, matching .... No!

i) Supersymmetry



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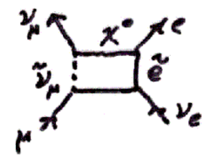

} Constrains SUSY

Tends to give the wrong sign! But can be forced to give −0.1% shift

Tests squark-slepton universality

ii) Heavy Quark Mixing

$|V_{ub'}| = 0.05$ seems large ($|V_{ub}| \simeq 0.0036$)

Heavy Neutrino Mixing - Opposite Sign (Constraint)

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iii) Exotic Muon Decays $BR \simeq 0.2\%$ Beyond SM.

If present $\to G_\mu = 1.16537 \times 10^{-5}\,GeV^{-2}$ not $1.16637(1) \times 10^{-5}\,GeV^{-2}$

Allowed by G_μ vs $\alpha, m_Z, m_W, \sin^2\theta_W, \Gamma_Z \ldots$

(Reduces m_H prediction)

eg $\mu^+ \to e^+ \bar{\nu}_e \bar{\nu}_\mu$ Babu + Pakvasa (Cute idea)

antineutrino

At 0.2% BR responsible for LSND $\bar{\nu}_e$ signal

Mini Boone will not see it $\pi^+ \to \mu^+ \nu_\mu$ source

Marginally Allowed

Predicts new scalars ~ 300 GeV in leptonic sector!

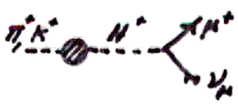
iv) Z' + Extra Dim. Loops eg Z_χ of $SO(10)$

Like SUSY tend to increase unitarity violation

β-decay vs μ decay (Constraint)

v) Charged Higgs $H^\pm$ (2 doublet models)

Affect $K \to \mu\nu$ + $\pi \to \mu\nu$ not β + μ decays Helicity



destructive interference

$(1 - 2\frac{m_P^2}{m_{H^+}^2}\tan^2\beta)$ reduction

$\tan\beta = v_2/v_1$

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To mimic 0.1% shift in $|V_{ud}|$ requires

$$\frac{m_K^2 - m_\pi^2}{m_{H^+}^2}\tan^2\beta = 0.02$$

or $m_{H^+} = 3.4 \tan\beta$ GeV

if $\tan\beta = 40$ requires $\simeq m_{H^+} \simeq 140\,GeV$

Some Sensitivity to m_H
For large $\tan\beta$

Also constrains Leptoquark Interactions

IV Outlook

Lattice Potentially Best $|V_{us}|$ goal factor 4-5 improvement

(Domain Wall Fermions? Very Large Computers)

R.C. Redone, New $\Gamma(K^+ \to \mu\nu(\gamma))_{exp.}$ (Doubts?) τ_{K^+}

* Need Independent $|V_{ud}|$ or $|V_{us}|$ for comparison

Reduce theory errors? $\pi^+ \to \pi^0 e^+ \nu$ Hard 10^{-8} BR

Lattice Calculation of R.C.? $n \to pe\nu$ or K_{e3}^+

Eventually see or constrain "New Physics"

Advance Theory Along The Way

Lattice Has Arrived

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Anticipated and Possible $|V_{ud}|$ + $|V_{us}|$ Advances

$\pi^+ \to \pi^0 e^+ \nu_e$ at PSI $|V_{ud}| \to \pm 0.0025$ Goal

Theory Clean to ± 0.0002

New Experiment Required (Very Hard $BR \sim 10^{-8}$)

* $n \to p e^- \bar{\nu}_e$ Several New Exps. Being Prepared

Measure τ_n + g_A

$$|V_{ud}|^2 = \frac{4908(4)\,sec}{\tau_n(1+3g_A^2)}$$

A. Czarnecki, W.M., A. Sirlin (Preliminary)

will reach ± 0.0004 (R.C. Uncertainty) Lattice?

$K_L \to \pi^\pm e^\mp \nu$ KLOE, KTeV, NA48 Data Exists Analysis Needed

Normalization?

New K_L Lifetime Needed

If no changes → Large Deviation From CKM Unitarity

$K^+ \to \pi^0 e^+ \nu$ New Exp. Needed KLOE?

New τ_{K^+} Needed

Hyperon Decays: Cabibbo et al Approach Needs Study

V+A

FNAL?

Lattice f_K/f_π, $\pi_{\mu 2}$, $K_{\mu 2}$ Best Bet

Domain Wall Fermions?