CKM Unitarity
and
"New Physics" Constraints

William J. Marciano, BNL

September 9, 2008

CKM2008

Cabibbo-Kobayashi-Maskawa (CKM) Unitarity And Its Implications For "New Physics"

(Improved R.C. with Alberto Sirlin PRL(2006))

BJ Sum Rule Correspondence (3 Loop QCD!)

& Large N QCD (Low-High Loop Mom. Matching)

The Quark Mixing Matrix:

$$V^{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$ 3x3 Unitary Matrix

When properly renormalized & R.C. Applied:

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

Deviation from 1 Implies "New Physics" at the tree or quantum loop level

Egs. Heavy New Quark or Lepton Mixing, W_R, W*(extra dim.), Leptoquarks, Z', Supersymmetry, Scalars, Exotic Muon Decays….

Probes New Physics Up To ~5TeV! (LHC Domain!)

History (Pre 2004):

- Superallowed $0^+ \rightarrow 0^+$ Nuclear β-Decays $N \rightarrow N' e^+ \nu$
  $|V_{ud}| = 0.9734(8)$

- K_{e3}, $K \rightarrow \pi e \nu$ ($K = K^+$ or K^0)
  $|V_{us}| = 0.2196(26)$ (stood for 20 years in PDG)

  $|V_{ub}| \approx 0.004 \rightarrow |V_{ub}|^2 \approx 0.00002$ Negligible

  $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9957(16)_{Vud}(11)_{Vus}$ 2.2σ

Deviation?

What about V_{ud}? (Theory Improvements)

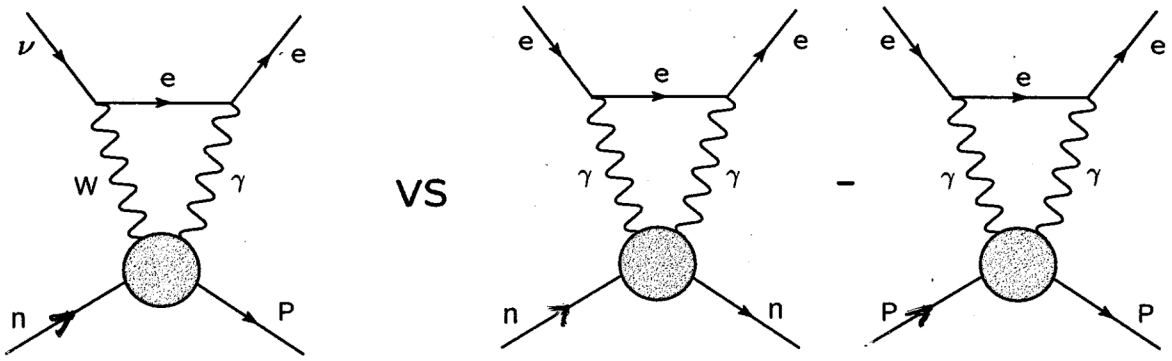
Dominant Uncertainty Electroweak Radiative Corrections(RC) to Nuclear Beta Decays

A. Sirlin and W. Marciano 1986: RC≈3.6±0.08%

2006: QCD Corrections to Nuclear Beta Decays and Bjorken Sum Rule are the same to all orders! Large N QCD Long and Short Distance Loop Matching. Uncertainty reduced by about a factor of 2!

2007: Hardy and Towner Improve Nuclear Isospin Violating Corrections

(see talk by I. Towner)



$AV \to V$ $\qquad$ $VV \to A$

Same QCD Corrections
for $m_q = 0$ Chiral Limit

- So, we learn from the BJ Sum Rule Theory and Experiment that $1/Q^2$ (higher twist) corrections to the beta decay loops are very small and the perturbative amplitude corrections become (for N_F=3 i.e. below charm):

  $1-\alpha_s(Q^2)/\pi-3.583(\alpha_s(Q^2)/\pi)^2-20.212(\alpha_s(Q^2)/\pi)^3$

  The extra corrections lead to a matching between short and long distance corrections at about $Q^2=(0.8\text{GeV})^2$. Very little change in size of RC, but uncertainty reduced by at least a factor of 2!

- **Superallowed $0^+ \rightarrow 0^+$ Nuclear Beta Decays**
  (Includes Updated Hardy and Towner Isospin Corrections)
  (Some new Q and $t_{1/2}$ values)

Nucleus	ft(sec)	$V_{ud}(14)_{Nuc}(19)_{RC}$	2008 PDG (now old)
^{10}C	3042.4(43)	0.97324(74)*	0.97370(80)
^{14}O	3042.5(27)	0.97411(51)	0.97411(51)
^{26}Al	3037.0(11)	0.97400(24)	0.97400(24)
^{34}Cl	3050.0(11)	0.97417(34)	0.97417(34)
^{38}K	3052.1(10)	0.97399(39)*	0.97413(39)
^{42}Sc	3046.4(14)	0.97423(44)	0.97423(44)
^{46}V	3049.6(16)	0.97386(49)	0.97386(49)
^{50}Mn	3048.7(12)	0.97419(45)*	0.97487(45)
^{54}Co	3051.3(15)	0.97431(54)*	0.97490(54)
World Ave.		**0.97405(13)(14)(19)***	**0.97418(13)(14)(19)**

*Updated

Superallowed Nuclear Beta Decays

- $|V_{ud}| = \underline{0.97405}(13)_{exp}(14)_{Nuc}(19)_{RC}$
  (New Preliminary Update)

  (0.97418((13)(14)(19) in PDG08)
  (0.97377(11)(15)(19) in PDG06)
  (0.97340(80) in 2004) Factor of 3 worse

Neutron Decay: $|V_{ud}|^2 = \frac{4908.7(1.9)\text{sec}}{\tau_n(1+3g_A^2)}$

τ_n and g_A exp. Discrepancies

Current PDG Averages → $V_{ud}=0.9746(4)_{\tau n}(18)_{gA}(2)_{RC}$

Future Best Bet

Many New Experiments Planned

(See talk by B. Plaster)

The Kaon Revolution of 2004-2005

(Starting with BNL E865) +FNAL, Frascati & CERN

BR($K \to \pi e \nu$) all increased by ≈6%!

All Major K_L BRs Changed! ε_K changed by 3.7σ!

- Now: $|V_{us}|$=0.22461(48)x[0.9644/$f_+(0)$] **Flavianet**

  $f_+(0)$=1-second order SU(3) corrections

  $f_+(0)$=0.9644(49) RBC-UKQCD DW Lattice

  *(But χ Pert Th. + Large N: $f_+(0)$=0.984(12))

  (V. Cirigliano et al.)

K_{l3} Decays $K \to \pi l \nu_l$ ($l=e,\mu$):

$|V_{us}|=0.21661(47)/f_+(0)$ Flavianet

Lattice DWF: $f_+(0)=0.9644(49)$ RBC-UKQCD

- $\mathbf{|V_{us}|=0.2246(5)_{exp}(11)_{f+(0)}}$

$K_{\mu 2}$ Decays $K \to \mu\nu/\pi \to \mu\nu$

Lattice Stag.: $f_K/f_\pi=1.189(7) \to \mathbf{|V_{us}|=0.2261(5)_{exp}(13)_{lat}}$

Kaon Average: $|V_{us}|=0.2252(9)$ Value I will use

Hyperon Decays $\to |V_{us}| \approx 0.226(5)$ consistent

Future in the hands of lattice?: $f_+(0)$, f_K/f_π, m_s

(but χ Pert, Th. + Large N $\to f_+(0)=0.984(12) \to V_{us}=0.2201(5)(27)$?)

($\Delta S=1$, τ decays $\to 0.2167(26)$ 3 sigma difference!) A. Pich et al
K. Maltman et al.

CURRENT STATUS

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9995(5)_{Vud}(4)_{Vus}$

$=0.9995(7)$

Very Good Agreement With Unitarity

Confirms SM Radiative Corrections:

$2\alpha\ln(m_Z/m_p)/\pi+\ldots \approx +3.6\%$ at 50 sigma level!

Naively Fits $m_Z=83(13)$GeV

New Physics Constraints-Implications:

Exotic Muon Decays, W*bosons, SUSY,

Z' Bosons, Heavy Quark/Lepton Mixing…

- CC and NC Amplitudes Usually Normalized Relative To The Muon Lifetime

$\tau_\mu = 2.197019(21) \times 10^{-6}$ sec (update)

$G_F = G_\mu = 1.166371(6) \times 10^{-5}\,\mathrm{GeV}^{-2}$

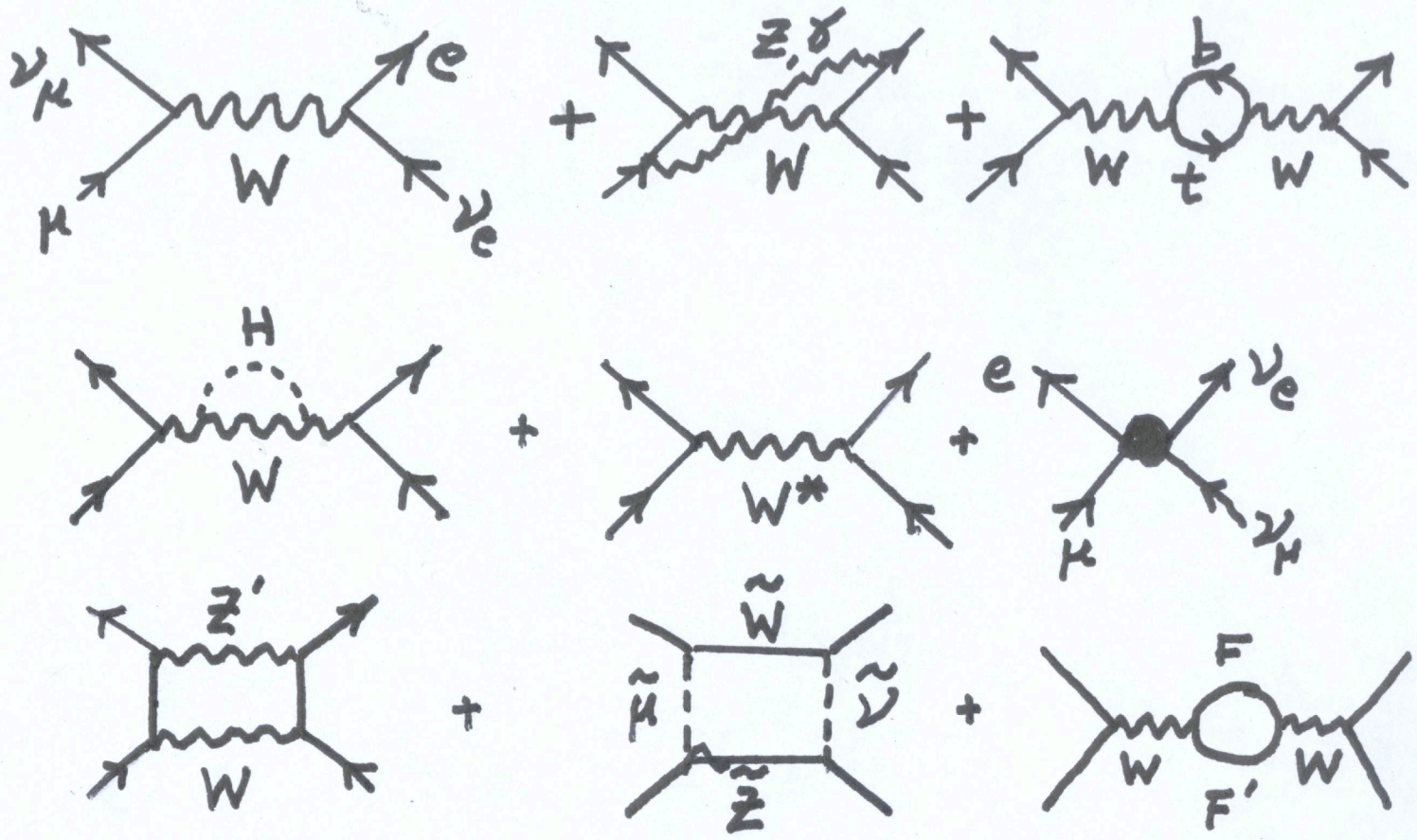
(Will further improve by factor of 10!)

New Physics Effects Absorbed In G_μ:

Top-bottom loop, Higgs loop, W*, WZ' box,
SUSY loops, Technicolor (S), Exotic μ Decays…

Comparison of G_μ with other measurements unveils "New Physics"

Loop and Tree Level Corrections to Muon Decay



Z' Boson SUSY Technicolor

+ . . .

CKM Unitarity: $G_F^{CKM}=1.166079(409)\times10^{-5}GeV^{-2}$

Best After τ_μ! $G_\mu=1.166371(6)\times10^{-5}GeV^{-2}$

Agreement Helps Validate Use of G_μ in Many Precision Tests

Note: $G_F\equiv\pi\alpha/\sqrt{2}m_W^2\sin^2\theta_W(m_Z)_{MS}(1-\Delta r_{MS})$

$=1.165600(1100)\times10^{-5}GeV^{-2}$

$=G_\mu(1-0.0085S)$ S Parameter Sensitivity!

Agreement Among All Such G_F Constrains:

Exotic Muon Decays, Heavy Quark or Lepton Mixing,

W* (extra dim.), SUSY Loops (Squarks vs Sleptons), Z', …

S (technicolor)=0.08(13), T=-0.02(15), Higgs…

Various Fermi Constants

$G_F \times 10^5 GeV^2$	Input
1.166371(6)	Muon Lifetime
1.166079(409)	CKM Unitarity
1.165600(1100)	α, m_W, $\sin^2\theta_W(m_Z)_{MS}$ → S=0.08(11)
1.166202(1400)	$\Gamma(Z \to l^+l^-)$, $\sin^2\theta_W(m_Z)_{MS}$ → T=-0.02(15)
1.167071(2600)	$\Gamma(\tau \to e\nu\nu)$
1.166954(2700)	$\Gamma(\tau \to \mu\nu\nu)$
etc.	

No Deviation

No Sign of "New Physics"

- Exotic Muon Decays(affect G_μ):
  eg $\mu \rightarrow e\nu_e\nu_\mu$ wrong neutrinos!
- BR=0.0005(7) allowed $\leq$0.0015 (90%CL)
  Direct Bound$\leq$0.012 (PDG)
- Potential Background Uncertainty For Neutrino Oscillations At Neutrino Factory
- (LSND Effect? Babu and Pakvasa)
  Unlikely-But Needed Testing

- Heavy Quark Mixing (e.g. E6 D_L singlets)

  $V_{uD} \leq 0.04$, Such large mixing unlikely since $V_{ub}=0.003\text{-}0.004$

  Heavy Neutrino Mixing ≤ 0.02

- W* Excited KK Bosons (Extra Dim.)

  $4(m_W/m_{W^*})^2 = \pm 0.0005(7) \rightarrow m_{W^*} \geq 4\text{-}8\text{TeV}$?

  Unless Cancellation between muon and beta decay?

  Or, compare G_μ or G_F^{CKM} with $\pi\alpha/\sqrt{2}m^2_W \sin^2\theta_W(m_Z)$

  Suggests $m_{W^*} \geq 3\text{TeV}$ (more general)

  (1TeV extra dim. Unlikely, Too Bad)

- SUSY Loops: squarks in beta decay vs sleptons in muon decay loops

  Barbieri et al (1985);

  Hagiwara et al (1995);

  Kurylov & Ramsey-Musolf (2000);

  Ramsey-Musolf & Su (2006)
- Many Possibilities!
- More Likely SUSY Scenario $\rightarrow |V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 \geq 1$

  But large sfermion mixing can cause ≤ 1

  No real sign of supersymmetry in CKM!

  (g_μ-2, $b \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$, $\mu \rightarrow e\gamma$… do better)

- Z' Bosons→WZ' Box Diagrams

(Marciano and Sirlin PRD(1987))

Different For Muon and Beta Decay

$G_\mu = G_F^{CKM}[1-0.002Q_{eL}(Q_{\mu L}-Q_{dL})\ln x_i/(x_i-1)]$

$x_i=(m_{Zi}/m_W)^2$

SO(10) $Z\chi$ Boson: $Q_{eL}=Q_{\mu L}=-3Q_{dL}=1$

$m_{Z\chi} \geq 600$GeV (95%CL-One Sided)

Similar (~1TeV) Bounds From APV & $A_{LR}(e^-e^-)$

Direct Collider Search ≥840GeV

No Sign of Z' Bosons!

- Summary and Conclusion

  CKM Unitarity Tested At The Quantum Loop Level: $\mathbf{|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9995(7)!}$

  Spectacular Standard Model Success

  Constrains "New Physics" in Muon Decay and Beta Decay. Dominated by theory errors.

- Future Improvements: V_{ud} neutron decay exp. & BJSR, V_{us} Lattice, ChPT, tau decays

  Goal: ±0.07%→±0.04%

  Currently No Real Sign of "New Physics! But…

What If V_{us}≈0.218(2) (tau decays, $f_+(0)$ of χ Pert. Th.)?
$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2$=0.9963(11) 3.4sigma deviation

More Interesting-Potential Future 4-5 sigma!

With improvements in $f_+(0)$, f_k/f_π, tau exp.

Then pick your favorite "New Physics"

What if only tau decays show a deviation?

"New Physics" in $\bar{\tau}\nu_\tau\bar{s}u$ amplitude?

Destructive Interference?

Special Charged Higgs? But what about $K\rightarrow\mu\nu$?

Susy Loop Effect?

- Future: Improve & Compare with LHC Discoveries(?)

The End