Fundamental Neutron Properties

(A Theory Perspective)

William J. Marciano

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Grenoble, France

BROOKHAVEN NATIONAL LABORATORY

Outline

- **1.** τ_n **,** g_A **,**V_{ud} **& <u>CKM Unitarity</u>**

  (Future Goals: Theory & Experiment)

  <u>Main Topic of this talk</u>

- **2. *Neutron Electric Dipole Moment P & T Viol.***

  (A Higgs Boson➔ϒϒ Connection?}

- **3. *Neutron-Antineutron Oscillations |ΔB|=2***

  (Are Neutrons Majorana Particles?)

  Dark Matter may also be Majorana! (Example)

- **4. *Outlook and Conclusion***

Some References

Refs: ***A. Sirlin RMP 50, 573 (1978)*** + earlier work

WJM & A. Sirlin, PRL 56, 22 (1986); ibid 96, 032002 (2006)

A. Czarnecki, WJM, A. Sirlin, PRD 70, 093006 (2004);

The classic: D. Wilkinson, NP A377, 474 (1982).

Reviews: "*The neutron. Its properties and basic interactions*"

Hartmut Abele Prog.Part.Nucl.Phys. 60 (2008) 1.

"*The Neutron and Its Role in Cosmology and Particle Physics*"

Dirk Dubbers, Michael G. Schmidt RMP. 83 (2011) 1111.

"The Neutron Lifetime"

Fred E. Wietfeldt, Geoffrey Greene RMP. 83 (2011) 1173.

1. τ_n , g_A, V_{ud} & CKM Unitarity

$SU(2)_L x U(1)_Y$ Standard Model Electroweak Loop Corrections to $\mu \rightarrow e\nu_e\nu_\mu$ and $n \rightarrow pe\nu_e$ ***both Infinite*** but renormalized using ($G_F^0 \rightarrow G_\mu$) Quark mixing divergences absorbed in $V^0_{ud} \rightarrow V_{ud}$ maintaining Unitarity

The CKM 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

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

$|V_{ud}|^2+|V_{cd}|^2+|V_{td}|^2=1$ **etc.**

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

Muon Decay $\Gamma_0(\mu \to e\nu\nu) = F(m_e^2/m_\mu^2) G^0{}_F{}^2 m_\mu^5/192\pi^3 = 1/\tau_\mu^0$

Neutron Decay $\Gamma_0(n \to pe\nu) = \mathbf{f} G^0{}_F{}^2 |V^0{}_{ud}|^2 m_e^5 (1+3g_A^2)/2\pi^3 = 1/\tau_n^0$

$F(x)=1-8x+8x^3-x^4-12x^2\ln x$ Phase Space Factor

f=1.6887 phase space factor, including Fermi function proton recoil, finite nucleon size… Uncertainty O(few $\times 10^{-5}$)

Other Effects: Weak Magnetism, **Induced Pseudoscalar** etc. negligible

g_A and τ_n **important for: *CKM Unitarity***, solar neutrino flux, reactor neutrino flux, ***primordial abundances*** ΔN_ν, spin content of proton, Goldberger-Treiman/***Muon Capture***, Bjorken Sum Rule, lattice benchmark $\mathbf{g_A}$ **&** $\mathbf{g_p}$…

Must be precisely determined!

±0.01% Outstanding/Appropriate Goals for τ_n and g_A^2

Muon Capture $\mu p \rightarrow \nu_\mu n$ Example

- MuCap(2012) $\Lambda_S(\mu p \rightarrow \nu_\mu n) = 714.9 \pm 7.4 s^{-1}$ **±1%!**

Extract induced pseudoscalar coupling g_p using

g_A^{PDG}=<u>1.2701±0.0025</u> (probably low by about 2 sigma)

Recent g_A = 1.2755(13) Perkeo II

$g_p^{exp} = 8.06 \pm 0.48_{exp} \pm 0.19_{RC} \pm 0.15_{gA}$ (Perkeo II➔8.37)

g_p^{th} = 8.26±0.23 ChPT Future Lattice Improvement?

Future ΔRC➔Δg_p ±0.05 (or smaller?) Δg_A➔Δg_p ±0.01!

Future Exp. ±? Future Lattice g_p ±?

Is a future precision (±0.1%) "New Physics" Test Possible?

Electroweak Radiative Corrections to Muon Decay

Virtual One Loop Corrections + Inclusive Bremsstrahlung

Absorb Ultraviolet divergences and some finite parts in

$G^0_F = g_0^2/4\sqrt{2}m^2_{W0} \rightarrow G_\mu$

$\boldsymbol{\tau_\mu^{-1} = \Gamma(\mu^+ \rightarrow e^+ \nu_e \nu_\mu(\gamma)) \equiv F(m_e^2/m_\mu^2) G_\mu^2 m_\mu^5 [1+RC]/192\pi^3}$

$RC = \alpha/2\pi(25/4-\pi^2)(1+\alpha/\pi[2/3\ln(m_\mu/m_e)-3.7)\ldots]$ Fermi Th.

Defines G_μ

Other SM and **"New Physics"** radiative corrections absorbed into G_μ. Eg. Top Mass, Higgs Mass, Technicolor, Susy,W*…

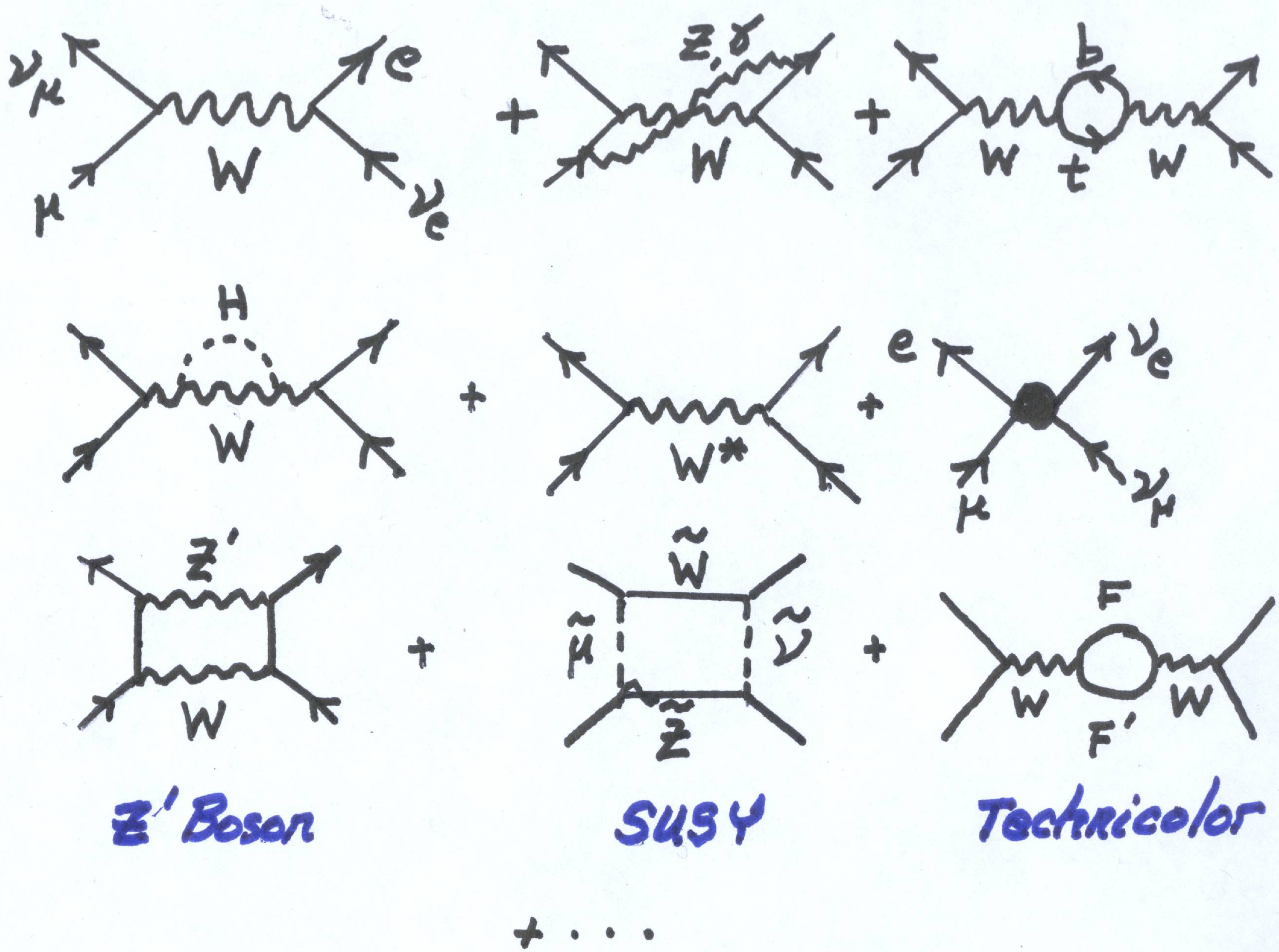
MuLAN experiment at PSI (Complete)

World Ave. $\tau_{\mu+} = 2.1969803(22) \times 10^{-6}$ sec 1ppm!

Most precise lifetime ever measured gives:

$G_\mu = 1.1663787(6) \times 10^{-5}\,\mathrm{GeV}^{-2}$ precise & important

Loop and Tree Level Corrections to Muon Decay



Electroweak Radiative Corrections to Neutron Beta Decay

Include Virtual Corrections + Inclusive Bremsstrahlung

Normalize using G_μ from the muon lifetime

Absorbs Ultraviolet Divergences & some finite parts

$$1/\tau_n = f G_\mu^2 |V_{ud}|^2 m_e^5 (1+3g_A^2)(\underline{1+RC})/2\pi^3$$

f=1.6887 (Includes Fermi Function etc. not Rad. Corr.)

RC calculated for (Conserved) Vector Current since it is not renormalized by strong interaction at zero momentum transfer.

Same RC used to define g_A: $[A(g_A)=(1.001)A^{exp}]$

$$RC = \alpha/2\pi[\langle g(E_m)\rangle + 3\ln(m_Z/m_p) + \ln(m_Z/m_A) + 2C + A_{QCD}]$$

+ higher order $O(\alpha/\pi)^2$

$g(E_e)$=Universal *Sirlin Function* from Vector Current

A. Sirlin, PRD 164, 1767 (1967).

$\alpha/2\pi$ <g(E_m=1.292579MeV)>=0.015056 long distance loops and brem. averaged over the decay spectrum. Independent of Strong Int. up to $O(E_e/m_P)$

$g(E_e)$ also applies to Nuclei A. Sirlin (1967) Uncertainty < 10^{-5}

$3\alpha/2\pi \ln(m_Z/m_p)$ short-distance (Vector) log ***not*** renormalized by strong int.

$[\alpha/2\pi[\ln(m_Z/m_A)+2C+A_{QCD}]$ Induced by axial-current loop

Includes hadronic uncertainty

m_A=1.2GeV long/short distance matching scale (factor 2 m_A unc.)

$C=0.8g_A(\mu_N+\mu_P)=0.891$ (long distance γW Box diagram) WJM&A.Sirlin(1986)

$A_{QCD}= -\alpha_s/\pi(\ln(m_Z/m_A)+\text{cons})=-0.34$ QCD Correction

$[\alpha/\pi \ln(m_Z/m)]^n$ leading logs summed via renormalization group, **(+0.0016)**

Next to leading short distance logs ~ **-0.0001,**

and ***$-\alpha^2 \ln(m_p/m_e)$=-0.00043*** estimated (for neutron decay)

Czarnecki, WJM, Sirlin (2004) 1+RC=1.0390(8) main unc. from m_A

matching short and long distance γW (VA) Box. Unc*. **±8x10^{-4}**

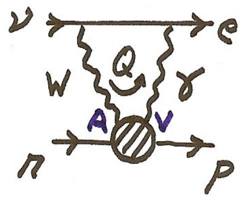
vs future (±0.1sec goal) τ_n **±1.1x10^{-4} goal.**

*** Note, unc. cancels in neutron vs nuclear beta decays eg V_{ud}**

γW Box Diagram

Weak Axial-Vector Induced Radiative Corrections

AV Loop → V → Superallowed β-decays

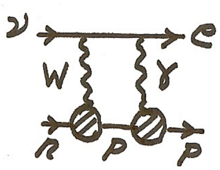


$$\longrightarrow \underbrace{\bar{u}\gamma_\mu d}_{\text{Vector}}\, \bar{e}_L \gamma^\mu \nu_L + QCD$$

$$RC = \frac{\alpha}{4\pi}\int_0^\infty dQ^2 \frac{m_W^2}{Q^2+m_W^2} F(Q^2)$$

Large Q^2 $F(Q^2) = \frac{1}{Q^2}\left[1 - \frac{\alpha_s(Q^2)}{\pi} + \dots\right] + O\left(\frac{1}{Q^4}\right)$

Small Q^2 → Nucleon Form Factors



$$\rightarrow \frac{\alpha}{2\pi}\left(0.8 g_A (\mu_p + \mu_n)\right)$$

$$\frac{\alpha}{2\pi}\left\{ \ln \frac{m_Z}{m_A} + \underbrace{A_g}_{\text{QCD}} + \underbrace{2C}_{\text{Long Distance}} \right\}$$

m_A = matching

2006 Improvement WJM & A. Sirlin

1.) Use large N_{QCD} Interpolator to connect long-short distances

2.) Relate neutron beta decay to Bjorken Sum Rule ($N_F=3$)

$1-\alpha_s/\pi \rightarrow 1-\alpha_s(Q^2)/\pi-3.583(\alpha_s(Q^2)/\pi)^2-20.212(\alpha_s(Q^2)/\pi)^3$
$-175.7\,(\alpha_s(Q^2)/\pi)^4$ (Baikov,Chetyrkin and Kuhn)

Negligible Effect

The extra QCD 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 uncertainties reduced by a factor of 2 (perhaps 3)!

(Both Prescriptions Agree)

1+RC= 1.0390(8)→1.03886(39) for Neutron Beta Decay

Reduction by 1.4×10^{-4} (Same for $0^+\rightarrow0^+$ beta decays)

Unc. Reduced to $\pm3.9\times10^{-4}$ (about 3x τ_n goal).

RC Error Budget

1) Neglected Two Loop Effects: **±0.0001** conservative

2) Long Distance $\alpha/\pi C \sim \alpha/\pi\ (0.75 g_A(\mu_N+\mu_P))=0.0020$

Assumed Uncertainty ±10%→**±0.0002** reasonable?

3) Long-Short Distance Loop Matching: 0.8GeV<Q<1.5GeV

±*100*% → **±0.0003** conservative

Total RC Error **±0.00038** $\rightarrow \Delta V_{ud}$=**±0.00019**

More Aggressive Analysis →ΔV_{ud}=±0.00013

(1/2 conservative)

➔ **only about 2xτ_n goal of ±0.1sec. (well matched)**

Superallowed ($0^+ \rightarrow 0^+$) Beta Decays & V_{ud}

RC same as in Neutron Decay but with <$g(E_m)$> averaged Nuclear decay spectrum, C modified by Nucleon-Nucleon Interactions and $+Z\,\alpha^2 \ln(m_p/m_e)$ corrections (opposite sign from neutron)

$$ft = |V_{ud}|^2 (2984.5\text{s})(1+\text{RC})(1+\text{NP corr.})$$

Nuclear Physics (NP) isospin breaking effects (Hardy & Towner Calculations: See later critique)

ft values + RC for 13 precisely measured nuclei found to be consistent with CVC: Average $\rightarrow V_{ud}$

Superallowed Nuclear Beta Decays

RC Uncertainty-Same as Neutron Decay

Nuclear Unc. - Significantly Reduced (2006-08)

Nuclear Coulomb Corrections Improved

$$|V_{ud}| = \underline{0.97425}(11)_{Nuc}(19)_{RC}$$

(2008 Hardy and Towner Update)

(0.97418((13)(14)(19) in PDG08)

(0.97377(11)(15)(19) in PDG06)

(0.97340(80) in 2004) Factor of 3 worse

The Kaon Revolution of 2004-2005

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

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

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

Now Based on: $\Gamma(K \rightarrow \pi l \nu)_{exp}$ & $\Gamma(K \rightarrow \mu\nu)/\Gamma(\pi \rightarrow \mu\nu)_{exp}$

+ Lattice Matrix Elements $f_+(0)$=0.960(5) & f_K/f_π=1.193(6)

***2010 Flavianet Analysis Currently*:**

$|V_{us}|$=0.2253(13) from $K \rightarrow \pi l \nu$ Vector

$|V_{us}|$=0.2252(13) from $K \rightarrow \mu\nu$ Axial-Vector

$|V_{us}|$=0.2253(9) Kaon Average (was ~0.220 pre 2004)

(Watch for lattice updates)

CURRENT STATUS of CKM Unitarity

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9999(4)_{Vud}(4)_{Vus}$$

$$=0.9999(6)$$

Outstanding Agreement With Unitarity

Confirms CVC & SM Radiative Corrections:

$2\alpha\ln(m_Z/m_p)/\pi+\ldots \approx +3.6\%$ at 60 sigma level!

Naively Fits m_Z=90(7)GeV vs 91.1875GeV (Direct)

Comparison of G_μ with other measurements (normalization) constrains or unveils **"New Physics"**

New Physics Constraints-Implications:

Exotic Muon Decays, W*bosons, SUSY, Technicolor,

Z' Bosons, $H^\pm$, Heavy Quark/Lepton Mixing…

- Exotic Muon Decays:

  $\mu \rightarrow e \nu_e \nu_\mu$ wrong neutrinos!

  BR $\leq$0.001 (95%CL)

  Potential Background Uncertainty For Neutrino Oscillations At Neutrino Factory

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

  $V_{uD} \leq 0.03$ Similar Heavy Lepton Constraint

  Seems unlikely, since $V_{ub}=0.003$

W* Excited KK Bosons or sequential W’ (different μ & β)

$4(m_W/m_{W^*})^2=0.0001(6)$, $m_{W^*}>6$TeV?

Unless Cancellation with muon decay?

(1TeV extra dim. Unlikely?) LHC sequential W’?

- 2 Higgs Doublets→Charged Higgs $H^\pm$

$m_{H^\pm} \geq 5.6\tan\beta$ (From $K \to \mu\nu$)

Superallowed Beta Decay Issue

- Isospin Breaking Coulomb Corrections of Hardy and Towner ***questioned*** by: G. Miller & A. Schwenk

  N. Auerbach

  H. Liang et al.

Hardy and Towner (1-δ_C) correction increases V_{ud}

δ_C~0.2-1.6% Correction

Recent Claims δ_C is smaller due to nuclear radial excitations

smaller V_{ud}=0.97425→0.9730 (Liang, Giai, Meng)

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2$ reduced to (roughly) 0.9975?

Unitarity Lost?

Issue needs "complete" quantitative resolution

(Experimentally Addressed by Hardy & Towner)

Neutron Decay Master Relations

1) $|V_{ud}|^2 = \dfrac{4908.7(1.9)\text{sec}}{\tau_n(1+3g_A^2)}$ Unc. Radiative Corrections Same as in Nuclear β Decay

2) $\tau_n = \dfrac{4908.7(1.9)\text{sec}}{|V_{ud}|^2\,(1+3g_A^2)}$ Radiative Corrections Cancel!

3) $(1+3g_A^2) = \dfrac{4908.7(1.9)\text{sec}}{|V_{ud}|^2\,\tau_n}$ Radiative Corrections Cancel!

Current $\Delta|V_{ud}|^2/|V_{ud}|^2 = \pm 0.02\%$ (NP) $\pm 0.04\%$ (RC) <u>Superallowed β</u>

$\Delta\tau_n/\tau_n = \pm 0.12\%$ $\tau_n^{PDG} = 880.1(1.1)$sec.

$\Delta g_A^2/g_A^2 \approx \pm 0.20\%$ *Recent* $g_A = 1.2755(13)$ *Perkeo II*

±0.01% Outstanding/Appropriate Goals for τ_n *and* g_A^2

Neutron Decay ($n \rightarrow pe\nu$) & V_{ud}

$$|V_{ud}|^2 = \frac{4908.7(1.9)\text{sec}}{\tau_n(1+3g_A^2)}$$ **Master Relation**

Measure τ_n and $g_A \equiv G_A/G_V$ (decay asymmetries)

2008 PDG τ_n^{ave}=**885.7(8)**sec, g_A^{ave}=1.2695(29)

$\rightarrow |V_{ud}|^{ave}=0.9746(4)_{\tau n}(18)_{gA}(2)_{RC}$ reasonable but …

2012 $\tau_n^{PDG} \approx$ **880.1(1.1)**sec? & **$g_A \approx$1.2755(13) Perkeo II**

$\rightarrow |V_{ud}|=0.9739(6)_{\tau n}(8)_{gA}(2)_{RC}$

Agrees with superallowed! $0^+ \rightarrow 0^+$ Nuclear Beta V_{ud}=0.97425(22)

(Are τ_n & g_A both shifting?)

History g_A=1.18→1.23→1.25→1.26→1.27→1.275?

Many New τ_n & g_A Experiments Planned

2. Neutron Electric Dipole Moment P & T Viol.

1950 Purcell & Ramsey Speculate P may be violated

Begin search for neutron edm

T (CP) violation also needed for edms!

P & T Violation ➔ EDMs for all particles with spin

CKM CP Violation ➔ unobservably small edms

EDMs: Window to Early Universe CP Violation!

"New Physics" Source of CP Violation Needed!

Supersymmetry Leading Candidate

(Not observed at LHC yet! Some Tension!)

Some Current Dipole Moments

fermion	a_f^{exp}	$\lvert d_f^{exp}\rvert$ e-cm
e	0.00115965218073(28)	$<1x10^{-27}$ (from TFI)
p	1.792847356(23)	$<8x10^{-25}$ (from d_{Hg})
n	-1.9130427(5)	$<3x10^{-26}$

electron & neutron bounds roughly comparable

(Very Powerful SUSY Constraints)

Griffith, Swallows, Loftus, Romalis, Heckel & Fortson
PRL102, 101601 (2009)

- $\lvert d_{Hg} \rvert < 3.1x10^{-29}$ **e-cm**

Further factor 3-5 Hg Improvement Expected!

Great Future Expectations

- **$d_n \rightarrow 10^{-27}$-10^{-29} e-cm Neutron Spallation/Reactor Sources**
- **$d_e \rightarrow 10^{-29}$ e-cm or better!**
- **d_p & $d_D \rightarrow 10^{-28}$-10^{-29}e-cm Storage Ring Proposal (BNL/COSY)**

Pave the way for a new generation of storage ring experiments d_p, d_D, d(^{3}He), d(radioactive nuclei), d_μ

Several orders of magnitude improvement expected

Higgs (125-126GeV) Discovery & Properties

- ATLAS and CMS Experiments have strong evidence for a
- Higgs like (spin 0) new particle with mass 125-126GeV

Expected Higgs SM Properties

H Decay Channel	Branching Ratio
$b\bar{b}$	0.578
WW^*	0.215
gg	0.086
$\tau^+\tau^-$	0.063
$c\bar{c}$	0.029
ZZ^*	0.026
$\gamma\gamma$	2.3×10^{-3}
$Z\gamma$	1.5×10^{-3}
$H \to ZZ^* \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$	1.2×10^{-4}
$H \to ZZ^* \to \ell^+\ell^-\nu\bar{\nu}$	3.6×10^{-4}

- ***<u>5 sigma SM evidence/experiment presented (July 4, 2012)</u>***

> 1,000,000 H already produced at the LHC!

gluon + gluon ➔ H   through top quark loop

<u>H➔γγ</u>   ≈   ATLAS ***<u>1.65 x SM Expectation (2σ)</u>***

H➔ZZ*(virtual)➔4 leptons

H➔WW*➔4 leptons (includes Neutrinos)

<u>H➔$\tau^+\tau^-$</u> **coming into SM agreement**

H➔bb   (too much background for now)

<u>Early fluctuations</u>?

<u>Other decays e, u, d expected to be unobservabley small</u>

FNAL Tevatron strong hints of HW &HZ (3 sigma)

with H➔bb (as expected or higher)

Vector-like Heavy Leptons Dark Variant
Davoudiasl, Lee &WJM

- Example: A Possible Dark Sector

Two Left Handed Doublets $(N_i^0, E_i^-))_L$ i=1,2

Two Right-Handed Doublets $(N_i^0,E_i^-)_R$

Dark Charges ±1

Four Left Handed Singlets N_{jL}, E_{jL} j=3,4

Four Right Handed Singlets N_{jR}, E_{jR}

Dark Charges ±1

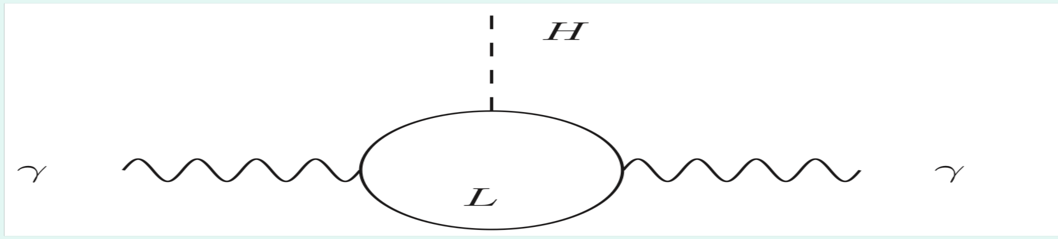
Gauge Invariant Mass Terms + Higgs Couplings ➔ Mixing

All interactions vector-like under $SU(2)_L xU(1)_Y \mathbf{xU(1)_d}$

4 Charged & 3 Neutral Leptons Unstable

Lightest Neutral: Potential Stable Dark Matter?

Charged Leptons: *H➔γγ Loops (sign change)*



Increase Br(H➔γγ) by factor ≈ 1.5

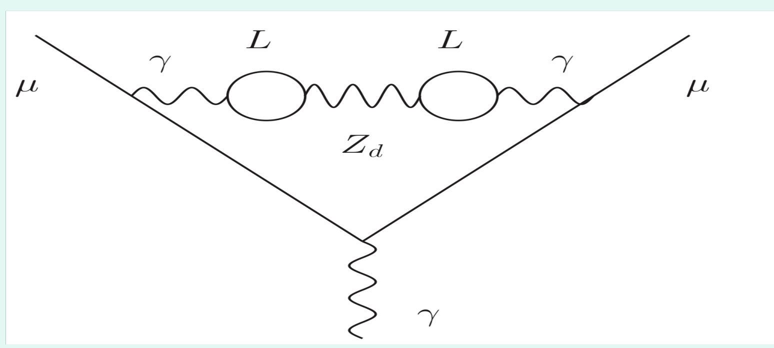
Could Violate CP! (M. Voloshin)

induce edms! (McKeen, Pospelov, Ritz)

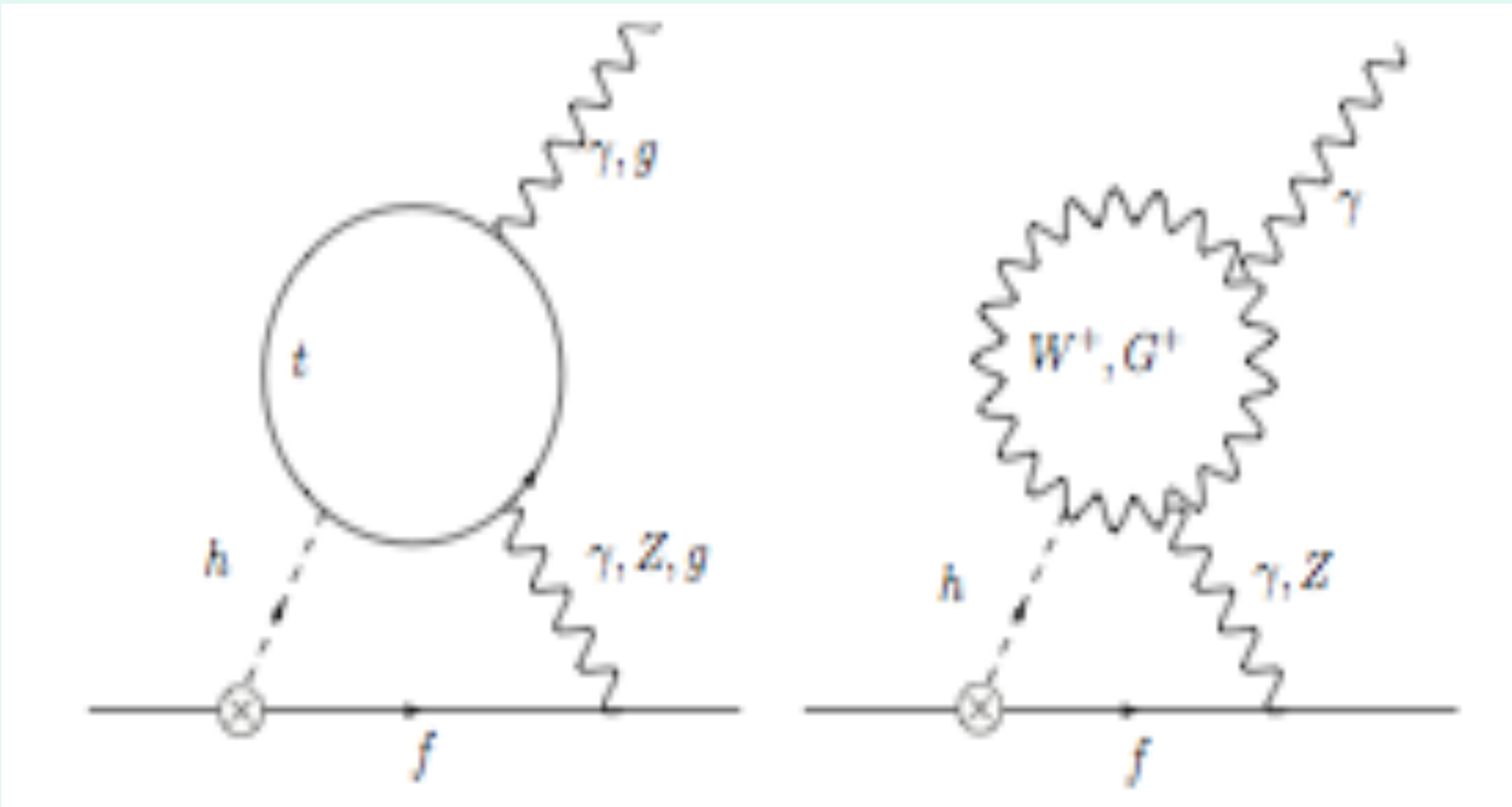
Also give rise to γ–Z_d kinetic mixing

If g_d ≈e ➔ ε≈α/2π≈10-3 solves g_μ -2 problem

for 20MeV<m_{Zd}<50MeV (Experimental Range)



<u>2 loop dipole moment sources</u>: McKeen, Pospelov, Ritz
earlier Huber, Pospelov, Ritz



a_f vs d_f (very roughly)

- Two loop Higgs contribution: $a_\mu(H) \approx \text{few} \times 10^{-11}$
  $a_e(H) \approx 5 \times 10^{-16}$

  Unobservably Small!

  Two Loop Higgs contribution: $d_e(H) \sim 10^{-26} \sin\phi$ e−cm
  $|d_n(H)| \approx |d_p(H)| \sim 5 \times 10^{-26} \sin\phi$ e−cm

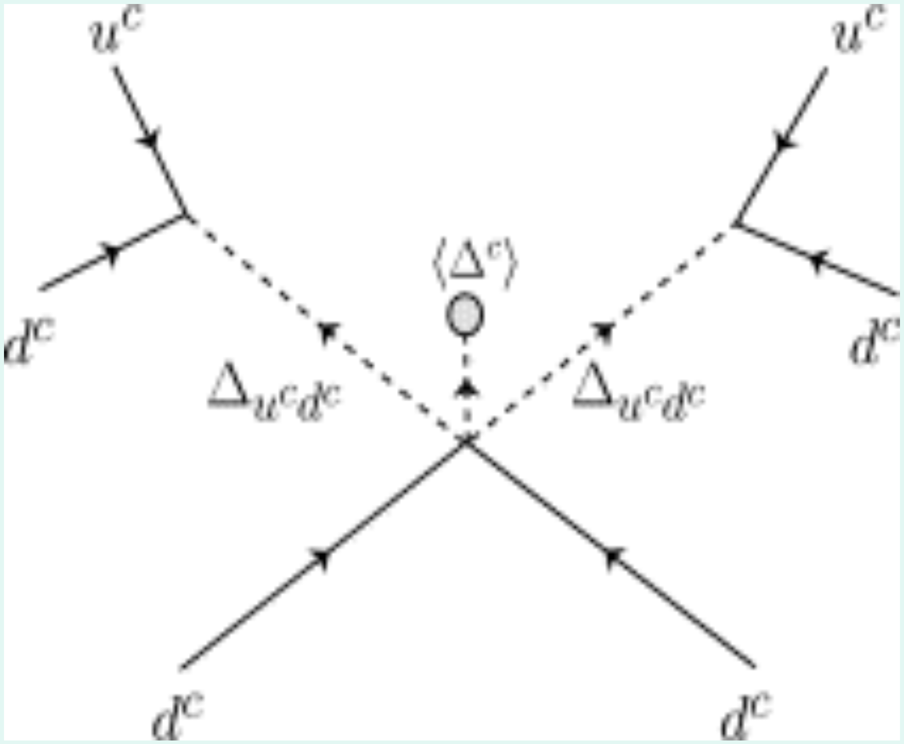
Already d_e bound implies $\sin\phi \leq 0.1$ (smaller?)

CP violation in *H*➔γγ $\sin^2\phi \leq 0.01$

Unlikely to be observable, but edm experiments can
Explore down to $\sin\phi \approx O(10^{-3})$! ***Unique!***

3. Neutron-Antineutron Oscillations |ΔB|=2

see Babu & Mohapatra Papers



- New (Scalar) Interactions quark ➔antiquark
- Color Sextets or Triplets Fractionally Charged
- Masses ~ 1-2TeV Look like dijets at the LHC
- Give rise to neutron-antineutron osc. T_{nn}~10^8-10^9sec

Neutron and antineutron are ***<u>not</u>*** mass eigenstates!

m_n δm ➔ $|n_\pm\rangle = (|\text{neutron}\rangle \pm |\text{antineutron}\rangle)/\sqrt{2}$

δm m_n $m_\pm = m_n \pm \delta m$ $\delta m < 10^{-21}$eV!

$|n_\pm\rangle$ are Majorana states! B=0, neutral, no dipole mom.
No vector interactions etc.

Is the neutron a Majorana state?

Find neutron-antineutron Oscillations (Analog of ΔL=2 Neutrinoless Double beta decay)

Is Dark Matter a Majorana Fermion?

- Dark Matter Candidate Lightest Neutral Lepton Member of Dark Sector N (≥100GeV) Wimp

  Lepton Number Violation $\delta m \approx O(50MeV)$!

Mass Diagonalization➔$N_{\pm}$ Majorana States

N_{-} is stable dark matter (Vector Interactions with ordinary matter suppressed!)

Makes N_{-} difficult to observe in laboratory

4. Outlook and Conclusion

1) ***Current Exps & Th:*** $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9999(4)_{Vud}(4)_{Vus}$

Great Unitarity Test & Sucess→ No New Physics!

Nuclear Isospin Breaking? Needs Further Resolution

Radiative Corrections Stable *(Unchallenged!)*

2) ***Neutron Decay:*** $|V_{ud}|=[4908.7(1.9)s/\tau_n(1+3g_A^2)]^{1/2}$ **clean & precise**

Neutron Lifetime Controversy (6σ discrepancies)

2010 τ_n^{PDG}=885.7(8)s vs τ_n=878.5(8)s Needs Resolution

g_A larger? Perkeo Ave. 1.2755(13) vs 2012 g_A^{PDG}=1.2701(25)

Larger g_A & smaller τ_n → Unitarity, solar neutrino flux, primordial nuclear abundances, proton spin, Goldberger-Treiman/Muon Capture, Bjorken Sum Rule, lattice calculation benchmark…

Goals

1) Extraction of g_A from τ_n **&V_{ud} (nuclear*) independen*t of radiative corrections unc!**

τ_n to±0.1 sec + $|V_{ud}|$ = 0.97425(11)$_{Nuc}$ → Δg_A to ±0.0001!

2) V_{ud} comparison of neutron and nuclear beta decays ($|V_{ud}|$ = 0.97425(11)$_{Nuc}$(19)$_{RC}$) suggests

τ_n should be measured to ±0.1sec → ΔV_{ud} ±0.000055!

±0.01% Outstanding/Appropriate Goals for τ_n and g_A^2

Further Outlook

EDMs may soon be discovered: $d_e, d_n, d_p \ldots d_D$

Magnitudes of ≈ 10^{-27}-10^{-28} expected for Baryogenesis

Atomic, Neutron, ***Storage Ring*** (All should be pursued)

CP violation in ***H➔γγ*** ***(Contemporary topic)***

Uniquely explored by 2 loop edms!

May be our only window to Hee, Huu and Hdd couplings

Guided by experiment: *H➔γγ*

Future Updates Anxiously Anticipated!

In the end, the Higgs may be central to our existence and the matter dominated universe!

Neutron-Antineutron Oscillations

- Very interesting longshot (limited sensitivity 1-2TeV)
- If seen ➔Neutrons are Majorana Fermions!

  Baryon Number is violated!

  Should be pursued as far as possible $T_{nn}>10^9$sec

Similar Physics may imply: Dark Matter Majorana!

You can't discover if you don't look