Electric Dipole Moments
A Theoretical Perspective

Lecture 3

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Baryogenesis: $N_B/N_\gamma \approx 10^{-10}$

1957 - Parity Violation in Weak Interactions (Maximal!)

Lee & Yang Why is nature left-handed (Chiral)?

1964- CP Violation Discovered in Kaon Decays

1967 Sakharov Conditions:

1) Baryon Number Violation

2) CP Violation (strong source)

3) Non-Equilibrium 1st Order Phase Transition

***(Leptogenesis – Very Early Universe Alternative)**

Harvard Homework (edm 101)

<u>1950</u> <u>Purcell & Ramsey</u> 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

<u>EDMs</u>: Window to Early Universe CP Violation!

<u>"New Physics" Source of CP Violation Needed!</u>

<u>Supersymmetry Leading Candidate</u>

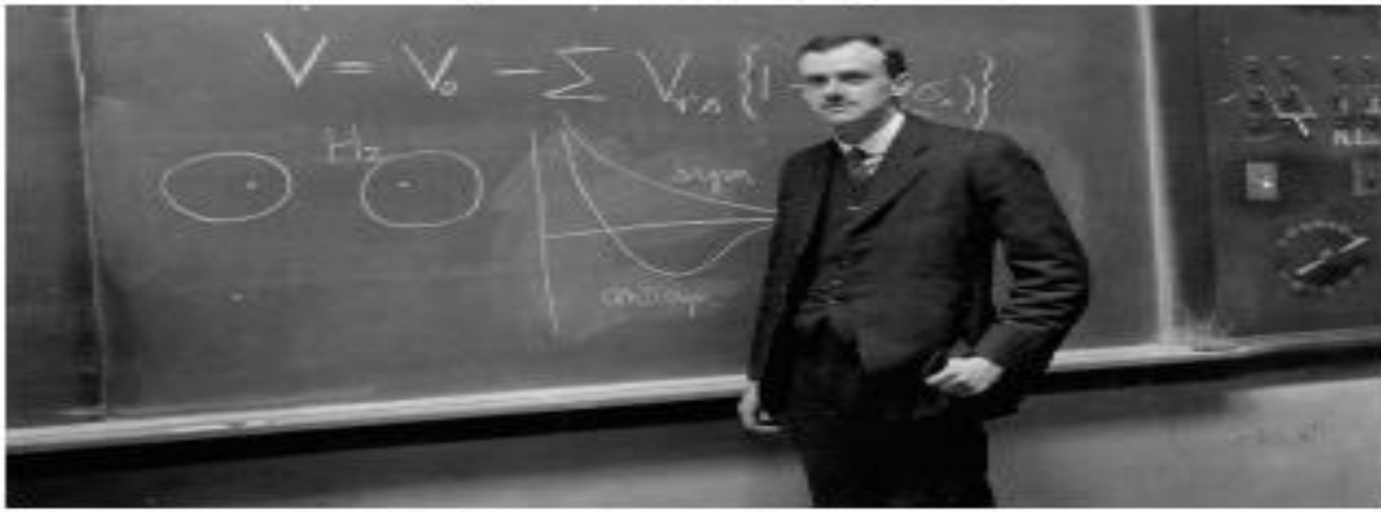
<u>(Not observed at LHC yet! Some MSSM Tension!)</u>

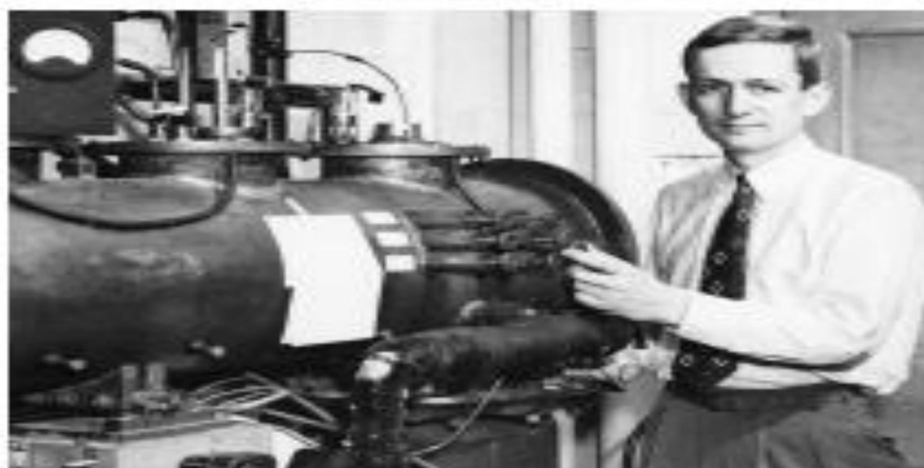
<u>Recent Interest in Higgs CP Violation in</u> $H \rightarrow \tau\tau$

Clockwise:

Julian Schwinger,
Polykarp Kusch,
Paul Dirac,
Norman Ramsey and
Edward Purcell

Courtesy AIP Emilio Segrè Visual Archives (full credits overleaf)





General Formalism (Spin1/2 Form Factors)

$<f(p')|J_\mu^{em}|f(p)> = u_f(p')\Gamma_\mu u_f(p)$

$\Gamma_\mu = F_1(q^2)\gamma_\mu + iF_2(q^2)\sigma_{\mu\nu}q^\nu - F_3(q^2)\gamma_5\sigma_{\mu\nu}q^\nu \ldots$

$F_1(0)=Q_f e$	electric charge
$F_2(0)=a_f Q_f e/2m_f$	anom. mag. mom.
$F_3(0)=d_f Q_f$	el. dipole mom.
	P & T violating

Some Current Dipole Moments

fermion	a_f^{exp}	$\lvert d_f^{exp}\rvert$ e-cm
e	0.00115965218073(28)	$<1 \times 10^{-27}$ (from TFl)
p	1.792847356(23)	$<8 \times 10^{-25}$ (from d_{Hg})
n	-1.9130427(5)	$<3 \times 10^{-26}$

electron & neutron bounds roughly comparable

(Very Powerful SUSY Constraints)

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

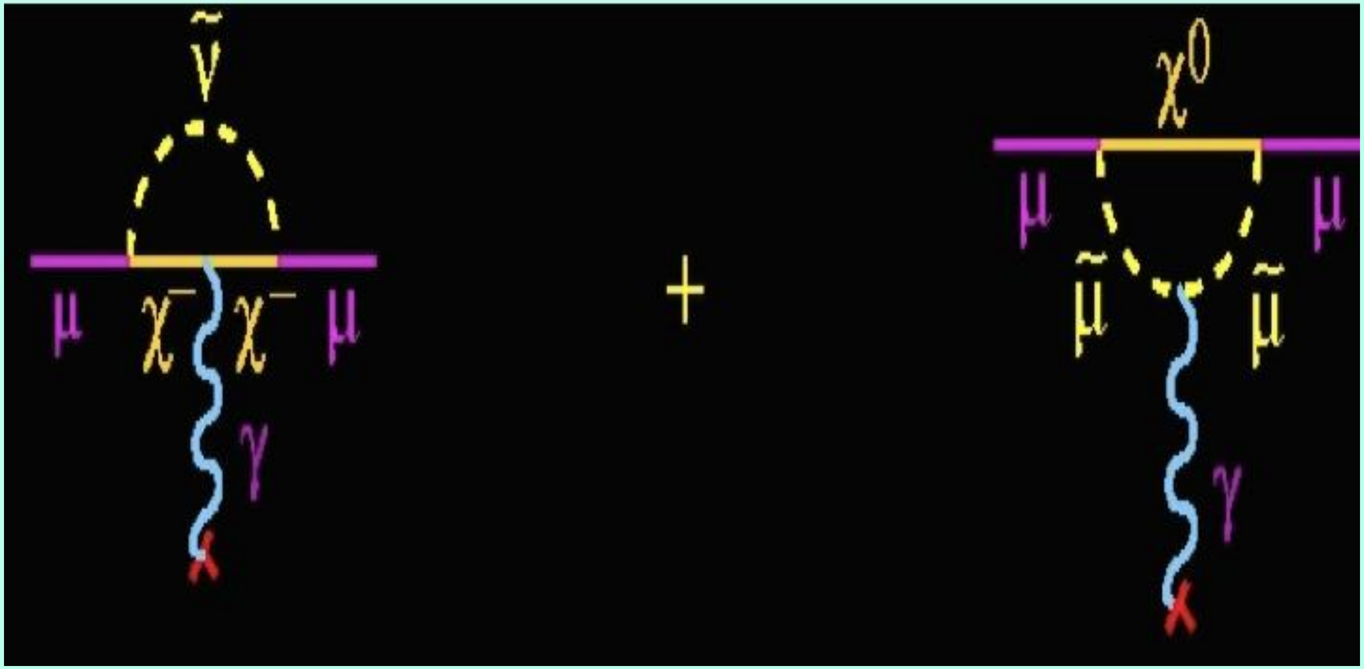
- $\mathbf{\lvert d_{Hg}\rvert < 3.1 \times 10^{-29}}$ **e-cm**

Further factor 3-5 Hg Improvement Expected!

<u>3.2 "New Physics" Effects</u>

_SUSY 1 loop a_μ Corrections

(Most Likely Scenario)



Great Future Expectations

- **$d_n \rightarrow 10^{-27}$-10^{-28} 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

d_p not "just" complementary to d_n

Window to **"New Physics"**

Baryogenesis! (**why do we exist?**)

Potential sensitivity an order of magnitude **better** than d_n!

Probes New Physics(NP) at **$(1\text{TeV}/\Lambda_{NP})^2 \tan\phi_{NP} \leq 10^{-7}$!**

or for ϕ_{NP}~O(1) → Λ_{NP}~3000TeV! (**well beyond LHC**)

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

Baryogenesis & New Physics CP Violation

Examples of New Physics Models with potentially large CP Violation: Supersymmetry, Multi-Higgs,
L-R Models, 4th Generation, Extra Dimensions…

"Standard Higgs"?

- Generic Manifestation - **Electric Dipole Moments**

What is the "New Physics"?

Look for EDMs!

No Standard Model Background (too small)

General (complex) Moment Formalism

$$\langle f(p')|J_\mu^{em}|f(p)\rangle = u_f(p')\Gamma_\mu u_f(p)$$

$$\Gamma_\mu = F_1(q^2)\gamma_\mu + iF_2(q^2)\sigma_{\mu\nu}q^\nu - F_3(q^2)\gamma_5\sigma_{\mu\nu}q^\nu \ldots$$

$F_1(0)=Q_f e$ electric charge

$F_2(0)=a_f Q_f e/2m_f$ anom. mag. mom.

$F_3(0)=d_f Q_f$ el. dipole mom.

Effective Dim. 5 Dipole Operators

$$H_{dipole}=-1/2[F_2 f(x)\sigma_{\mu\nu}f(x)+iF_3 f(x)\sigma_{\mu\nu}\gamma_5 f(x)]F^{\mu\nu}(x)$$

F_2 & F_3 Real, Finite & Calculable in Ren. QFT

***(No Arbitrary Counterterms**!)*

Effective Dim. 5 Dipole Operators

$H_{dipole} = -1/2[F_2 f(x)\sigma_{\mu\nu} f(x) + iF_3 f(x)\sigma_{\mu\nu}\gamma_5 f(x)]F^{\mu\nu}(x)$

F_2&F_3 Real, Finite & Calculable in Ren. QFT

Complex Formalism: $F_D = F_2 + iF_3$

$H_{dipole} = -1/2[F_D f_L \sigma_{\mu\nu} f_R + F_D^* f_R \sigma_{\mu\nu} f_L]F^{\mu\nu}$

$F_D = |F_D| e^{i\phi}$ (Relative to m_f)

$|F_D| = (F_2^2 + F_3^2)^{1/2}$, $\tan\phi = F_3/F_2$

$\tan\phi$ = Relative Degree of CP Violation

$|\tan\phi_e|^{SM}$ & $|\tan\phi_n|^{SM}$ very small

Anomalous Dipole Moments

fermion	a_f^{exp}	$\lvert d_f(e/2m_f)^{exp}\rvert$
e	0.00115965218073(28)	$<1\times10^{-16}$
μ	0.00116592089(63)	$<3\times10^{-6}$
p	1.792158142(28)	$<3\times10^{-12}$ (d_{Hg})
n	-1.9130427(5)	$<1\times10^{-13}$

"New Physics" expected to scale as $(m_f/\Lambda)^2$

$(m_\mu/m_e)^2 \approx 43000$ Muon only a_f sensitive to high Λ~2TeV!

All d_f sensitive to "New Physics" if $\tan\phi^{NP}$ not too small

Nucleon edms Isovector or isoscalar? Mixed?

Both d_n and d_p need to be measured!

$\frac{1}{2}\,\theta_{QCD}\varepsilon^{\mu\nu\alpha\beta}G^{a}{}_{\mu\nu}G^{a}{}_{\alpha\beta}$ total divergence but ➔ $d_n \sim 10^{-16}\theta_{QCD}$e-cm

Currently: $d_n \rightarrow \theta_{QCD} < 10^{-10}$! Future: 10^{-12}

d_p at 10^{-29}e-cm explores $\theta_{QCD} < 10^{-13}$

If a non-zero d_n is discovered, the first thing we want to do is know d_p

Opposite sign? Isovector, θ_{QCD} Interpretation

Same Sign? θ_{QCD} Unlikely

More Likely: strangeness, gluonic, susy…

Both d_n & d_p needed!

Complex Formalism: $F_D=F_2+iF_3$

$$H_{dipole}=-1/2[F_D f_L \sigma_{\mu\nu} f_R + F_D^* f_R \sigma_{\mu\nu} f_L]F^{\mu\nu}$$

$F_D=|F_D|e^{i\phi}$ $\quad f_{R,L}=(1\pm\gamma_5)/2f$

$|F_D|=(F_2^2+F_3^2)^{1/2}$, $\tan\phi=F_3/F_2$

$\tan\phi$= Relative Degree of CP Violation

egs. $|\tan\phi_e|^{SM}\approx 10^{-24}$ $\quad |\tan\phi_n|^{SM}\approx 10^{-20}$

Can ϕ be removed by a chiral rotation?

$f\rightarrow \exp(i\gamma_5\phi/2)\, f$ (Dirac Confusion)

No, not if it makes the mass m_f complex

(EDM = relative phase!)

- If the same "New Physics" responsible for Δa_μ is also giving edms, we expect:

$|d_\mu^{NP}| \sim 3x10^{-22} \tan\phi_\mu^{NP}$ e-cm

$|d_e^{NP}| \sim 2x10^{-24} \tan\phi_e^{NP}$ e-cm

$|d_n^{NP}| \sim 4x10^{-23} \tan\phi_n^{NP}$ e-cm

$|d_p^{NP}| \sim 4x10^{-23} \tan\phi_p^{NP}$ e-cm

<u>Future Experiments will have sensitivity:</u>

$\phi_\mu^{NP} \sim 10^{-2}-10^{-3}$

$\phi_e^{NP} \sim \phi_n^{NP} \sim \phi_p^{NP} \sim 10^{-6}-10^{-7}$

<u>Hadronic edms theoretically more complicated (richer)?</u>

d_p & d_n Relationship

Constituent Quark Model: $d_n = 4/3 d_d - 1/3 d_u$

$d_p = 4/3 d_u - 1/3 d_d$

Roughly $1/4 < |d_p/d_n| < 4$ Similar Magnitudes

Isovector $(d_p - d_n)/2$ or Isoscalar $(d_p + d_n)/2$?

Need both d_n & $d_p \rightarrow d_d$ & d_u (Relationship?)

(Deuteron edm more sensitive to isoscalar)

θ_{QCD} leading effect (roughly) isovector (χPT)

$d_n = -d_p \sim 3.6 \times 10^{-16} \theta_{QCD}$ e-cm

Currently: $d_n \rightarrow |\theta_{QCD}| < 10^{-10}$! Future: 10^{-12}

d_p at 10^{-29}e-cm explores $\theta_{QCD} < 10^{-13}$

If a non-zero d_n is discovered, the first thing we want to do is know d_p

Opposite sign? Isovector, θ_{QCD} Interpretation

or ***Higgs (2 loop) Example: naïve $d_p = -d_n$***

Same Sign? Isoscalar, θ_{QCD} Unlikely Primary Source

More Likely: strangeness, gluonic, susy…

d_n, d_p, d_D…d_e all needed!

6. Outlook

Precision a_e and a_μ test SM and Probe "New Physics"

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(63)(49)\times 10^{-11}$ (3.6 σ)

$\Delta a_e = a_e^{exp} - a_e^{SM} = -105(82) \times 10^{-14}$ *(Note Sign)*

Both a_e and a_μ should be pushed as far as possible

Harbinger of Supersymmetry, Dark Photon, Heavy Leptons…

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

Or significantly constrain "New Physics"

Eg CP violation in $H($[illegible] ***(Contemporary topic)***

CP violation better explored by 2 loop edms

than all diboson (*γγ, ZZ, WW…)* modes at the LHC!

Atomic, Neutron, ***Storage Ring*** (All Complementary)

LHC Results and Low Energy Physics 125-126GeV Higgs & No SUSY Yet

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May 21, 2013

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Electroweak Unification and the Higgs Boson

Following up on the work of his advisor (J. Schwinger)

1961 Glashow $SU(2)_L xU(1)_Y$ Gauge Symmetry

$W^{\pm}$, Z (massive) & γ (massless) gauge bosons

(chiral) fermions massless left-right asymmetric

All masses put in by hand

Explicitly Break Symmetry

$\sin^2\theta_W=(e/g)^2$

γ-Z weak mixing angle introduced

Weak Neutral Currents Alluded To

Largely Ignored

1967 Weinberg Introduces Higgs Mechanism

- Weinberg (following the work of P. Higgs) adds a scalar $SU(2)_L$ doublet (ϕ^+,ϕ^0) with tachyonic mass to the model that breaks $SU(2)_L xU(1)_Y \rightarrow U(1)_{em}$ at the vacuum level
- $<\Phi>\approx 250$GeV gives masses to $W^{\pm}$,Z and all fermions

Source of Quadratic Divergences - Unnaturalness

$\sin^2\theta^0_W=1-(m^0_W/m^0_Z)^2=(e^0/g^0)^2$ Natural Relations…

Predicts weak neutral currents… & ***Higgs Boson***

1971 Renormalizability proved by "tHooft

Is the Higgs Mechanism Fundamental or Dynamical?

Is there just a single Higgs doublet? Several?

$H=0^{++}$ Remnant Predicted – Higgs Boson, Others h, A, $H^{\pm}$…

H coupling to particles proportional to their masses

W, Z, t, b ***large***… *e, u, d* ***very small (undetectable?)***

Today

Elementary Particle Physics ***(Many Particles!)***

$SU(3)_C x SU(2)_L x U(1)_Y$ Standard Model

8 gluons + $W^{\pm}$, Z, γ ***gauge bosons*** ***(spin 1)***

3 generations of ***quarks & leptons (mix->CP violation)***

e, ν_e, u, d μ, ν_μ, c, s τ, ν_τ, t, b (m_t/m_ν >10^{13}!!) ***(spin ½)***

Scalar Doublet: $S^{\pm}$, S^0, H still source of all mass

Strong (Growing) Evidence for m_H≈125-126GeV

What Else Is There? New Particles? Interactions?

Supersymmetry - Something Else

****Recent Paradigm Heavy Leptons (Vector-like)***

What is the role of the Higgs Boson?

a) Break electroweak gauge symmetry

b) Provide elementary particle masses

c) Responsible for our existence

d) All of the above

The Higgs Boson

Now Dominates Elementary Particle Physics

Where will it lead us?

Early LHC "Lessons"

- ***SM Higgs Scalar Discovered!***: m_H=125-126GeV

  After 45 years Weinberg was right.

  Great Discovery but reopens old Issues.

$\lambda\Phi^4$ theory: Trivial, Quadratic Divergences, Vacuum stability…

Higgs Properties become a primary goal

Branching Ratios (Couplings), - Precision! Anomalies!

ATLAS

$BR(H\rightarrow\gamma\gamma) \approx 1.5\, BR(H\rightarrow\gamma\gamma)_{SM}$ Anomalous? Maybe?

New CP Violation Source?

1) Implications for edms! d_e, d_n, d_p

No Sign of Supersymmetry (yet)
LHC, MEG, g-2, Theory Tension

Early LHC tension $m_{susy} \geq 1, 3, 10\ldots$TeV Naturalness?

Recent BR($\mu \rightarrow e\gamma$)$\leq 5.7\times10^{-13}$ MEG (Motivated by SUSY)

Muon Anomalous Magnetic Moment **(3.6 sigma deviation)**

What about SUSY GUT Unification?

What if $m_{susy} \geq 10$TeV?

Muon g-2, (Dark Photon Alternative Solution?)

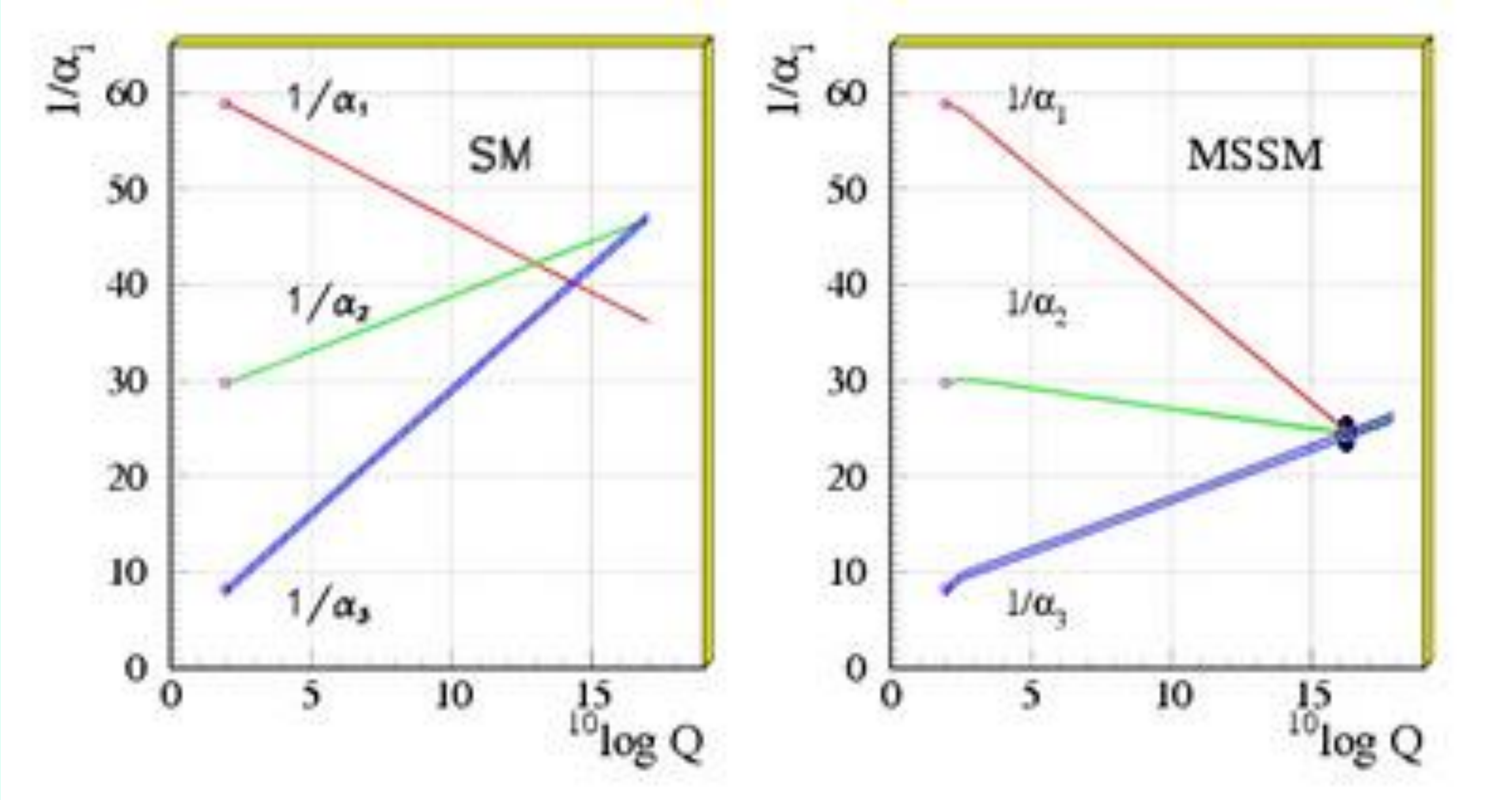
Electron Scattering, Rare K, π, μ, B… Decays

Proton Decay ($p \rightarrow e^+\pi^0$ easier discovery?)

Major Goal of LBNE! Window to Unification!

$\sin^2\theta_W(m_Z)^{exp}=0.23125$ better agreement with GUTS!

SUSY GUT Unification
S. Raby PDG (2010)



Properties of the Higgs Boson?

The Higgs Boson

Now the Center of Attention

Where will it lead us?

Higgs (125-126GeV) Discovery & Properties

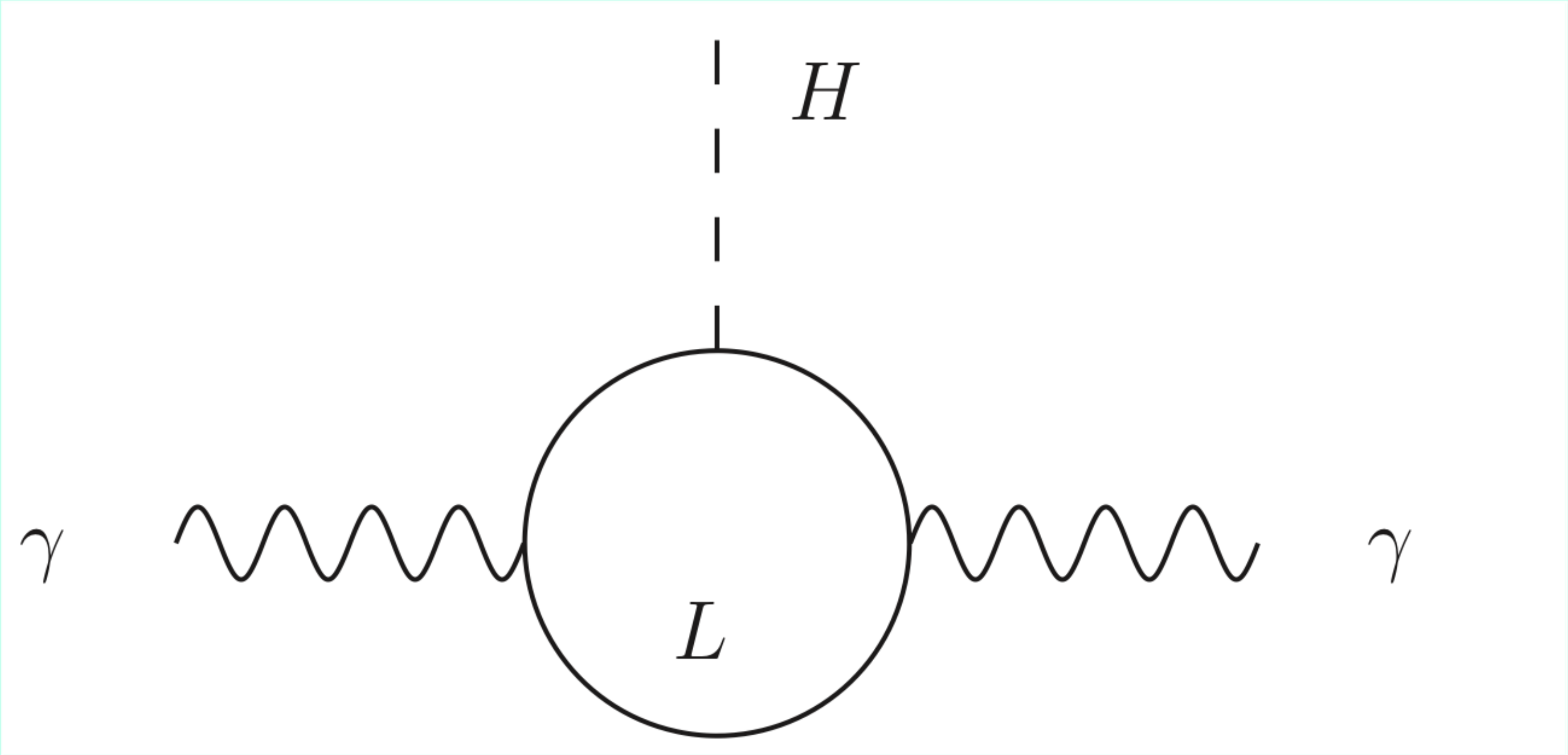
- ATLAS and CMS Experiments have strong evidence for a
- Higgs like (spin 0) new particle with mass 125-126GeV

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}

New Physics Loops or Pseuoscalar Mixing etc.
New CP Violation Source (eg. Voloshin)

$aHF^{\mu\nu}F_{\mu\nu} + b\tfrac{1}{2}\varepsilon^{\mu\nu\alpha\beta}HF_{\mu\nu}F_{\alpha\beta}$ **(CP odd)**



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

  Expect > 2,000,000 H already produced at the LHC!

  gluon + gluon ➔ H through top quark loop

  <u>H➔⇖⇖</u> ☝***<u>1.5 x SM Expectation (2σ)</u>***

  H➔ZZ*(virtual)➔4 leptons

  H➔WW*➔4 leptons (includes Neutrinos)

  <u>H➔⇳⇳</u> Seen

  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)

W Loop Contribution to H→γγ

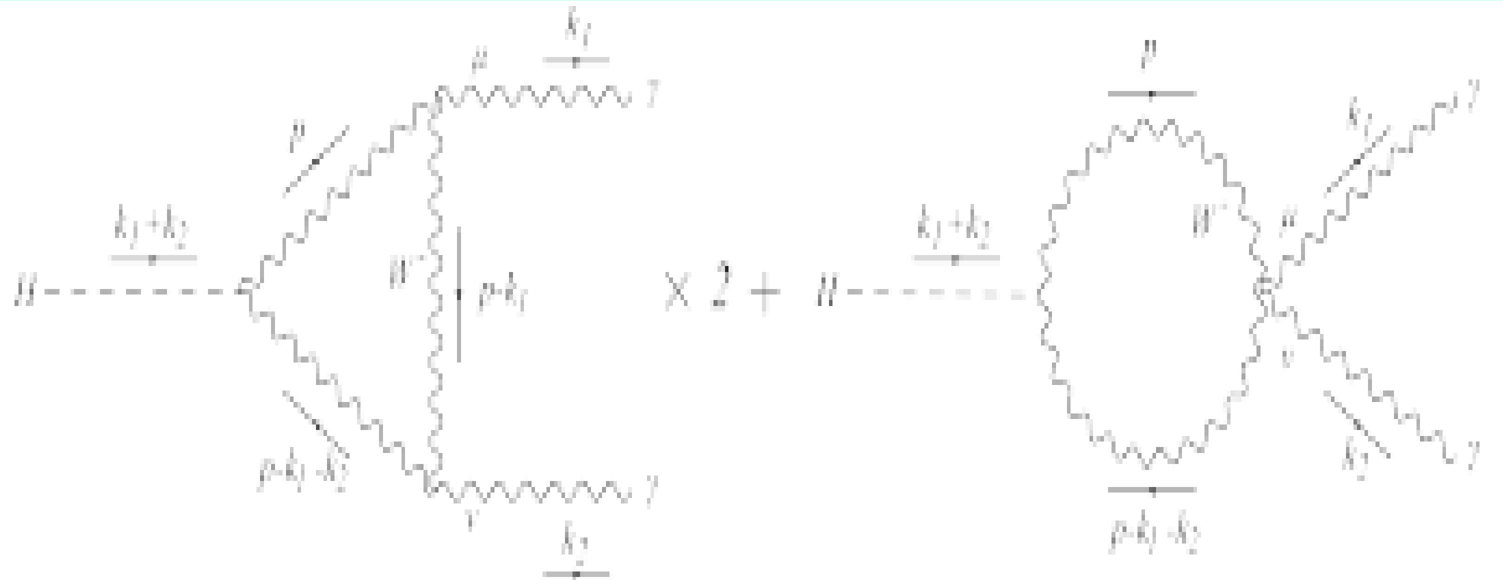


Figure 1: Feynman diagrams for $H \rightarrow \gamma\gamma$ in unitary gauge.

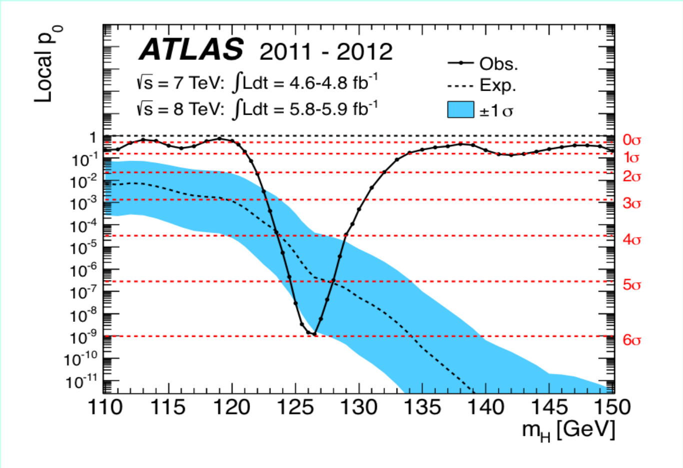


Figure 9: The observed (solid) local p_0 as a function of m_H in the low mass range. The dashed curve shows the expected local p_0 under the hypothesis of a SM Higgs boson signal at that mass with its $\pm 1\sigma$ band. The horizontal dashed lines indicate the p-values corresponding to significances of 1 to 6 σ.

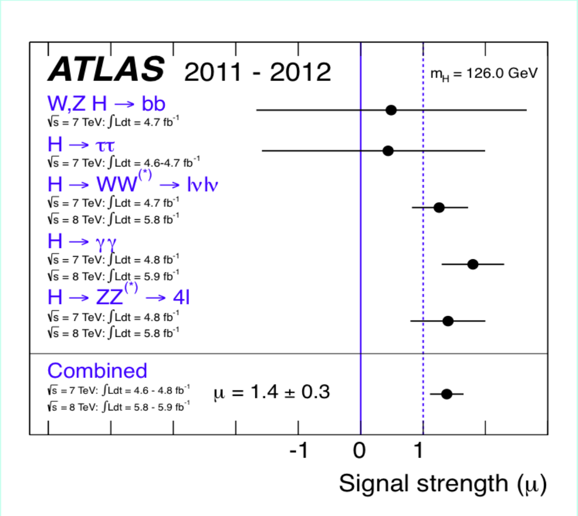


Figure 10: Measurements of the signal strength parameter μ for m_H=126 GeV for the individual channels and their combination.

9.3. Characterising the excess

The mass of the observed new particle is estimated using the profile likelihood ratio $\lambda(m_H)$ for $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$, the two channels with the highest mass resolution. The signal strength is allowed to vary independently in the two channels, although the result is essentially unchanged when restricted to the SM hypothesis $\mu = 1$. The leading sources of systematic uncertainty come from the electron and photon energy scales and resolutions. The resulting estimate for the mass of the observed particle is 126.0 $\pm$ 0.4 (stat) $\pm$ 0.4 (sys) GeV.

The best-fit signal strength $\hat{\mu}$ is shown in Fig. 7(c) as

Fig. 11, where the asymptotic approximations have been validated with ensembles of pseudo-experiments. Similar contours for the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel are also shown in Fig. 11, although they are only approximate confidence intervals due to the smaller number of candidates in this channel. These contours in the (μ, m_H) plane take into account uncertainties in the energy scale and resolution.

The probability for a single Higgs boson-like particle to produce resonant mass peaks in the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels separated by more than the observed mass difference, allowing the signal strengths to vary independently, is about 20%.

The contributions from the different production modes in the $H \rightarrow \gamma\gamma$ channel have been studied in order

Br($H \to \gamma\gamma$) ≈ 1.5 x expectations (early)

How can you enhance $H \to \gamma\gamma$? Beyond SM

Leave SM glue +glue → H at SM Rate (top loop)

Multi-Higgs mixing, SUSY Loops,… Scenarios

<u>New Heavy Fermion Loops (Not Colored)→Leptons</u>

Problem: if SM like HD_LS_R → Br($H \to \gamma\gamma$) reduction!

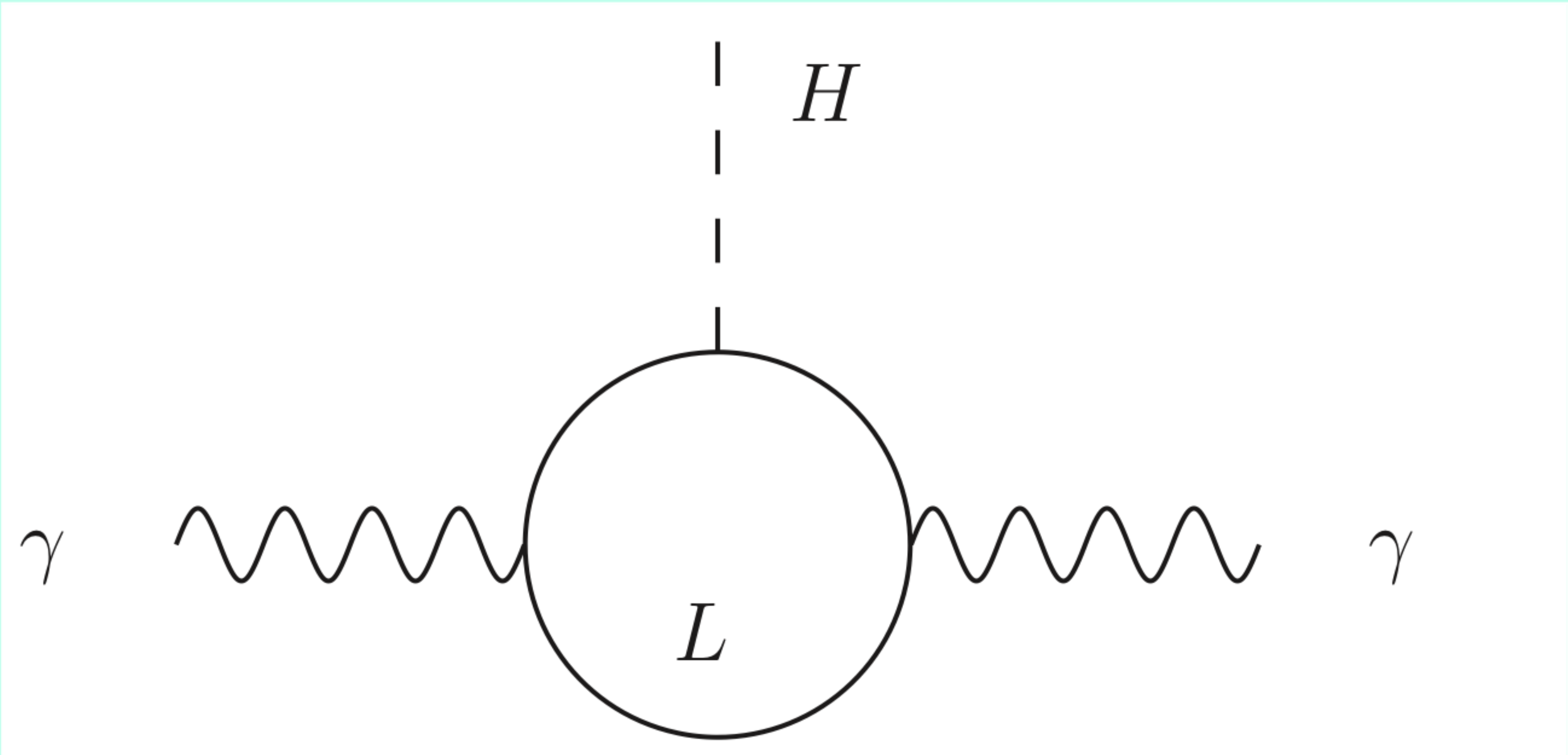
W & top loops have opposite sign

****<u>Popular Solution</u> – New Heavy (O(125GeV)) Vector-Like***

Leptons L-R Doublets & Singlets $SU(2)_L x U(1)_Y$

Invariant Masses + HDS couplings → Mixing

Potential opposite sign contribution to $H \to \gamma\gamma$


H
γ
L
γ

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 $SU(2)_L x U(1)_Y$ **$x U(1)_d$**

4 Charged & 3 Neutral Leptons Unstable

Lightest Neutral: Potential Stable Dark Matter?

Recent Example H→γγ vs edms
McKeen, Pospelov & Ritz

H→γγ Dim. 5 Operator (Scalar Analog of Dipole Moments)

$aHF_{\mu\nu}F^{\mu\nu} + bH{}^*F_{\mu\nu}F^{\mu\nu}$ $\quad ({}^*F_{\mu\nu}=F_{\mu\nu}$ dual $=1/2\,\varepsilon_{\mu\nu\alpha\beta}F^{\alpha\beta})$

second term violates P & T (much like edm)

New Source of CP Violation!

Higgs ***pseudoscalar*** Coupling

$\tan\phi_{H\rightarrow\gamma\gamma} = b/a$ $\qquad \Gamma(H\rightarrow\gamma\gamma) \propto a^2 + b^2$

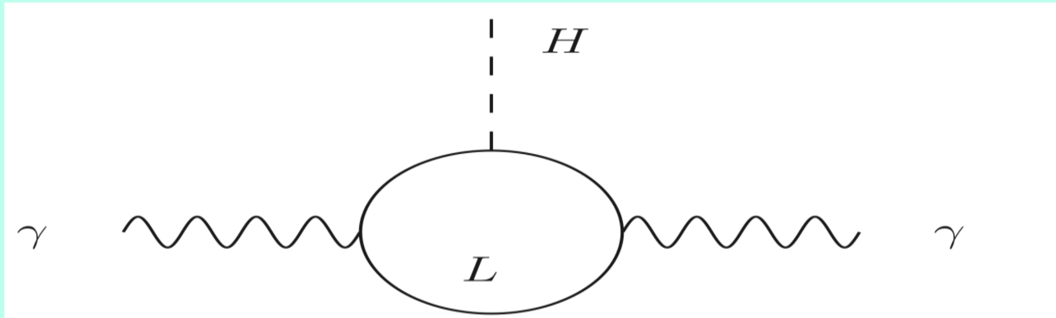
Could the Higgs violate CP? Source of Baryogenesis?

Measure γγ planes of polarizaton (Voloshin)

Max. at $\theta=\phi_{H\rightarrow\gamma\gamma} = b/a$ (instead of 0)

Very Difficult, particularly for b<<a

Charged Leptons: $H \to \gamma\gamma$ *Loops (sign change)*



Increase Br($H \to \gamma\gamma$) by factor ≈ 1.5

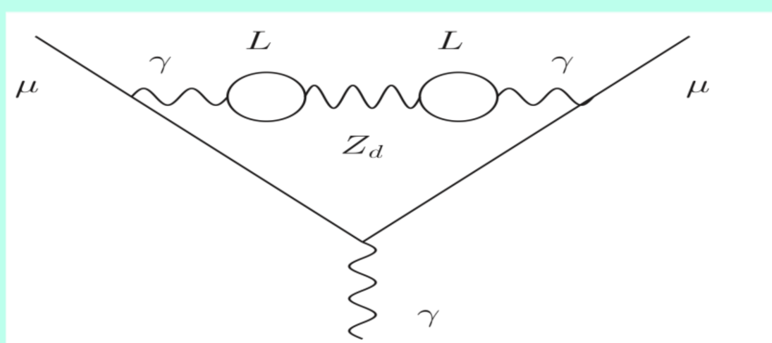
Could Violate CP! (M. Voloshin)

induce edms! (McKeen, Pospelov, Ritz)

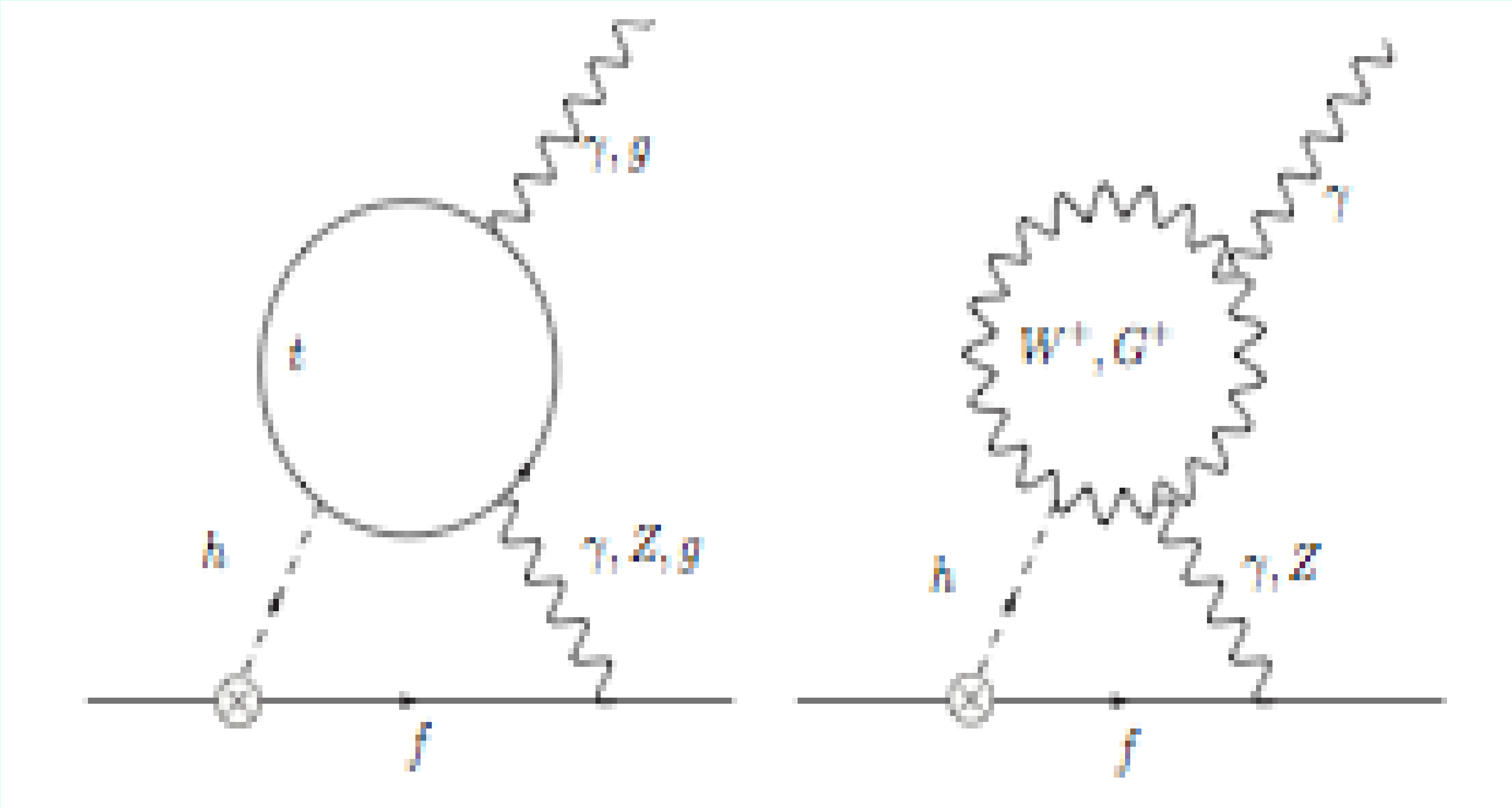
Also give rise to γ-Z_d kinetic mixing

If $g_d \approx e \Rightarrow \varepsilon \approx \alpha/2\pi \approx 10^{-3}$ solves g_μ-2 problem

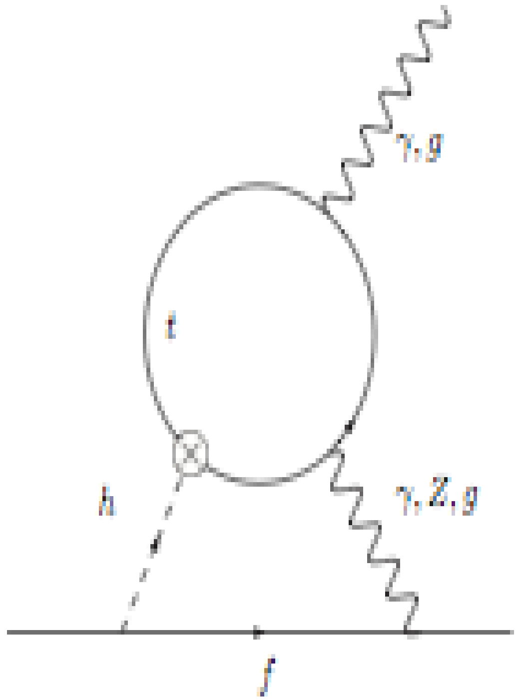
for 20MeV< m_{Zd} <50MeV (Experimental Range)



2 loop dipole moment sources: McKeen, Pospelov, Ritz
earlier Huber, Pospelov, Ritz



Two Loop Higgs Contribution to fermion Dipole Moments



a_f vs d_f (very roughly)

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

  $a_e(H) \approx 5 \times 10^{-16}$

  <u>Unobservably Small!</u>

  Two Loop Higgs contribution: $d_e(H) \approx 10^{-26} \sin\phi$ e-cm

  $|d_n(H)| \approx |d_p(H)| \approx 3 \times 10^{-26} \sin\phi$ e-cm

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

<u>CP violation in *H*(ττ</u> $\sin^2\phi \leq 0.01$

Unlikely to be observable, but edm experiments can

Explore down to $\sin\phi \approx O(10^{-3})$! ***<u>Unique!</u>***

Very Rough d_e, d_p & d_n Relationship

<u>Constituent Quark Model</u>: $d_n = 4/3 d_d - 1/3 d_u$

$d_p = 4/3 d_u - 1/3 d_d$

2 loop Higgs induced edms: $H \nwarrow$ ***couplings*** $\boldsymbol{m_f Q_f}$

$\boldsymbol{d_u \approx -d_d}$ $\boldsymbol{d_u = -\tfrac{2}{3}(m_u/m_e) d_e}$

$d_p \approx -d_n \approx -(10 m_u / 9 m_e) d_e \approx -3 d_e$

<u>Lattice Calculation Would Be Useful</u>

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 ***$H \rightarrow \gamma\gamma$*** ***(Contemporary topic)***

Uniquely explored by 2 loop edms!

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

Guided by experiment: *$H \rightarrow \gamma\gamma$* ***($H \rightarrow \tau^+\tau^-$) upcoming***

Updates Anxiously Anticipated!

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

Truly the God Particle

Fundamental Neutron Properties

(A Theory Perspective)

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May 22, 2013

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BROOKHAVEN
NATIONAL LABORATORY

Outline

- τ_n, g_A, V_{ud} & CKM Unitarity

  (Future Goals: Theory & Experiment)

  Neutron-Antineutron Oscillations **$|\Delta B|=2$**

  (Are Neutrons Majorana Particles?)

  Dark Matter may also be Majorana! (Example)

- ***Outlook and Conclusion***

1. τ_n , g_A, V_{ud} & CKM Unitarity

$SU(2)_L \times U(1)_Y$ Standard Model Electroweak Loop Corrections to $\mu \to e \nu_e \nu_\mu$ and $n \to p e \nu_e$ ***both Infinite*** but renormalized using ($G_F^0 \to G_\mu$) Quark mixing divergences absorbed in $V^0_{ud} \to V_{ud}$ 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 $\to |V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1$

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

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

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

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

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

<u>f=1.6887</u> phase space factor, including Fermi function proton recoil, finite nucleon size… Uncertainty O(few x10^{-5})

<u>Other Effects</u>: Weak Magnetism, **<u>Induced Pseudoscalar</u>** 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/***<u>Muon Capture</u>***, Bjorken Sum Rule, lattice benchmark **g_A & g_p**…

<u>Must be precisely determined!</u>

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

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*…

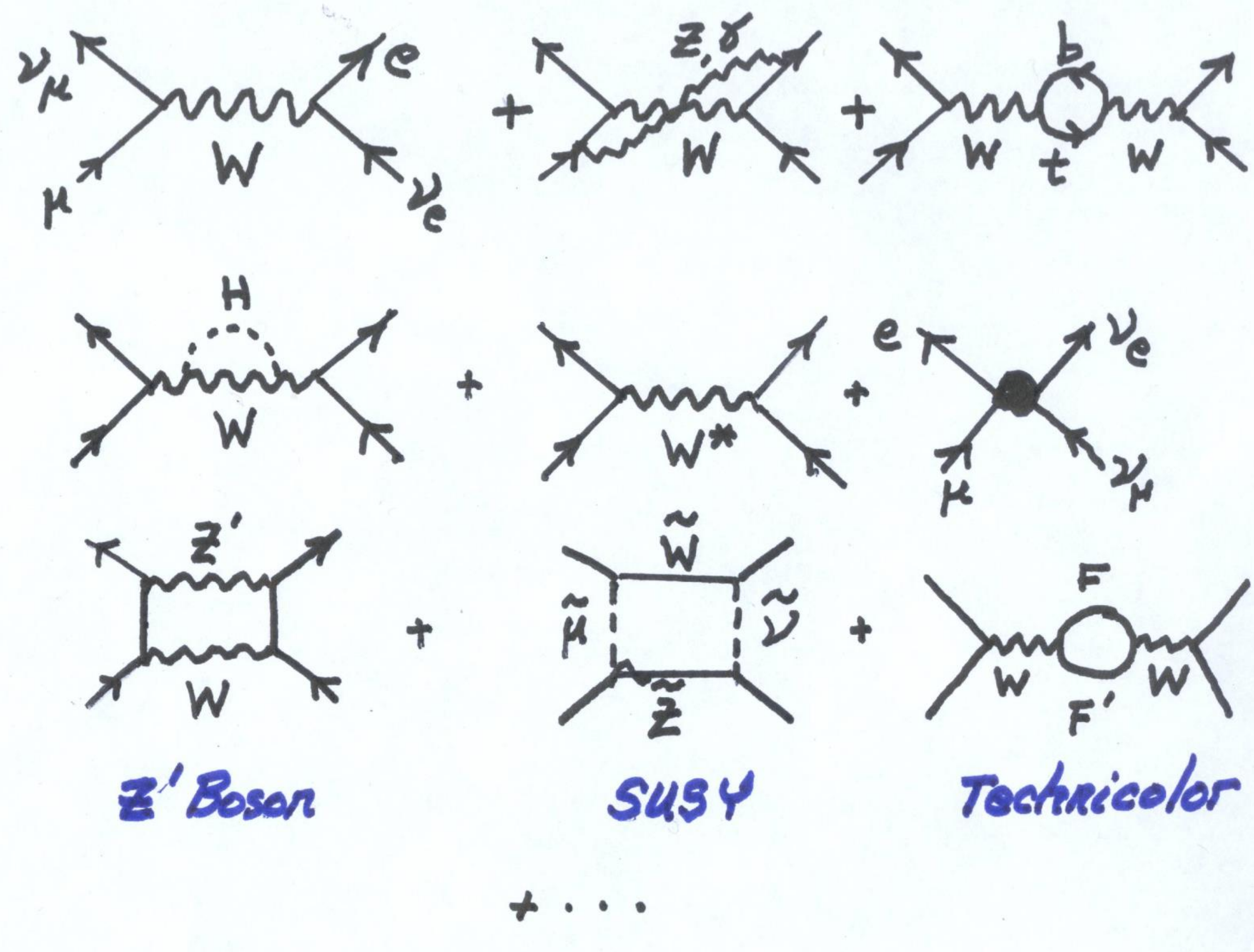
MuLAN experiment at PSI (Complete)

World Ave. $\tau_{\mu+}$ =2.1969803(22)x10^{-6}sec 1ppm!

Most precise lifetime ever measured gives:

G_μ=1.1663787(6)x10^{-5}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*. **$\pm 8\times10^{-4}$**

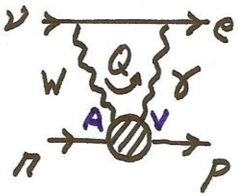
vs future ($\pm$0.1sec goal) τ_n **$\pm 1.1\times10^{-4}$ goal.**

*** 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

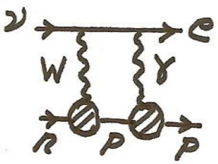


$\longrightarrow \underbrace{\bar{u}\gamma_\mu d}_{\text{Vector}}\, \bar{e}_L \gamma^\mu \nu_L + QCD$

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

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

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

<u>2006 Improvement WJM & A. Sirlin</u>

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)!

<u>(Both Prescriptions Agree)</u>

1+RC= 1.0390(8)→<u>1.03886(39)</u> for Neutron Beta Decay

Reduction by $1.4\text{x}10^{-4}$ (Same for $0^+ \rightarrow 0^+$ beta decays)

Unc. Reduced to ±$3.9\text{x}10^{-4}$ (about 3x τ_n goal).

RC Error Budget

1) Neglected Two Loop Effects: **$\pm$0.0001** conservative

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

Assumed Uncertainty $\pm$10%$\rightarrow$**$\pm$0.0002** reasonable?

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

$\pm$*100*% $\rightarrow$ **$\pm$0.0003** conservative

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

More Aggressive Analysis $\rightarrow \Delta V_{ud} = \pm 0.00013$

(1/2 conservative)

only about 2xτ_n goal of $\pm$0.1sec. (well matched)

Superallowed ($0^+ \to 0^+$) 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 $\to$ 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 $f_+(0)=0.960(5)$ & $f_K/f_\pi=1.193(6)$

***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 $K\to\mu\nu$)

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) Superallowed β

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

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

$\pm 0.01\%$ Outstanding/Appropriate Goals for τ_n and g_A^2

Neutron Decay ($n \to pe\nu$) & 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 τ_n^{PDG}≈ **880.1(1.1)**sec? & **g_A≈1.2755(13) Perkeo II**

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

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

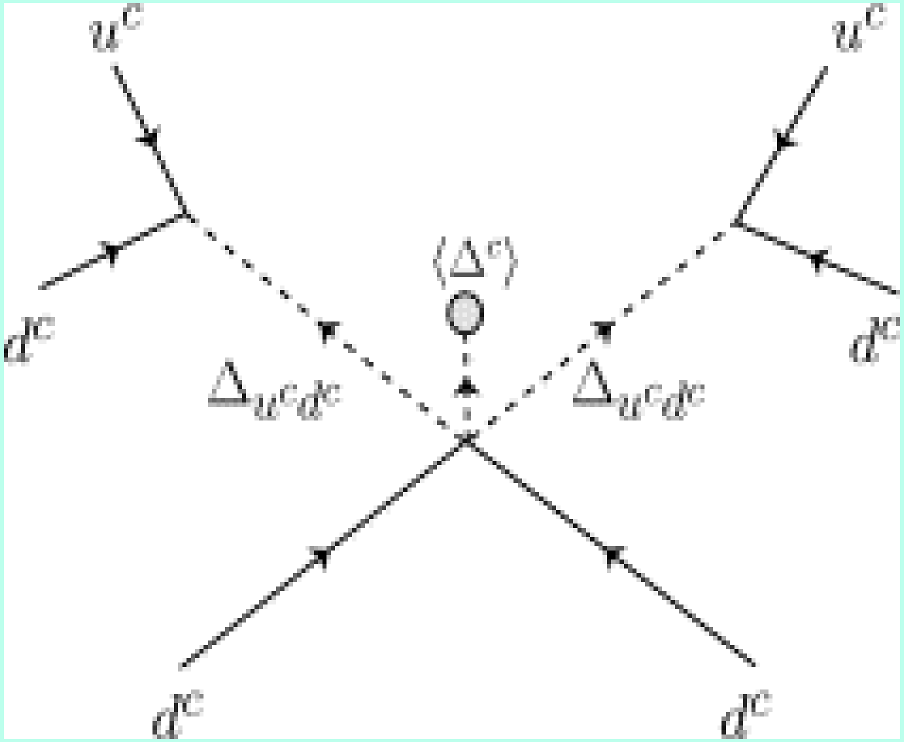
(Are τ_n & g_A both shifting?)

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

Many New τ_n & g_A Experiments Planned

. *Neutron-Antineutron Oscillations* $|\Delta B|=2$

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. $T_{nn} \sim 10^8 - 10^9$sec

Neutron and antineutron are ***not*** mass eigenstates!

$m_n \;\; \delta m \quad \rightarrow \; |n_\pm\rangle = (|\text{neutron}\rangle \pm |\text{antineutron}\rangle)/\sqrt{2}$

$\delta m \;\; m_n \qquad m_\pm = m_n \pm \delta m \qquad \delta m < 10^{-21}$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 $\Delta L=2$ 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 $\delta m \approx O(50\text{MeV})$!

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 $\tau_n^{PDG}=885.7(8)$s vs $\tau_n=878.5(8)$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…

<u>Goals</u>

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

τ_n to ±0.1 sec + $|V_{ud}|$ = <u>0.97425</u>(11)$_{Nuc}$ ➔ Δg_A to ±0.0001!

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

τ_n should be measured to ±0.1sec ➔ V_{ud} ±0.000055!

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

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