Neutron Electric Dipole Moment from flavor changing Higgs couplings

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- CP-Violation in the Universe: The SM has not enough!
- nEDM tiny but important: Control SM extensions !

Outline

- What is an EDM?
- CPV in SM
- NEDM in SM
- NEDM beyond SM
- NEDM from colored scalar flavor changing coupling
- NEDM from flavor changing Higgs coupling
- Results and Conclusion

What is an Electric dipole moment?

$$\mathcal{L}_{\text{eff}} \;=\; \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \ldots$$

$$\mathcal{L}_{5EDMf} \;=\; i\frac{d}{2}\,\bar{\psi}_f\,\sigma_{\mu\nu}\,\gamma_5\,F^{\mu\nu}\,\psi_f$$

Non-relativistic limit;- interaction between EM field and spin:

$$\sim d\,\vec{S}\cdot\vec{E} \qquad \sim \mu\,\vec{S}\cdot\vec{B}$$

Magnetic interaction conserve P, T-sym, EDM violate P *and* T-sym.
i.e. NEDM violates CP-sym (-assuming CPT-sym)
Present experimental bound

$$|d_n/e| \;<\; 2.9\times 10^{-26}\text{c}m$$

(corresp to $\sim 3\times 10^{-12}$ in Bohr Magnetons)

How to measure d_n ?

Slow neutrons (velocity $v_n < 7$ m/s) in paralell- and antiparallell $\vec{B}$- and $\vec{E}$- fields.
Larmor precession of neutron spin $\vec{S}$
Measure frequences ν

$$h\,\nu \;=\; 2\,\mu_n\,B \;\pm\; 2\,d_n\,E$$

Electric dipole moment

$$d_n \;=\; \frac{h\,\Delta\nu}{4E}$$

Challenge: Keep constant $\vec{B}$ during experiment
Ref: Baker et al, Nucl. Instr. Meth. A736 (2014) 184.
arXiv: 1305.7336

Energy scales

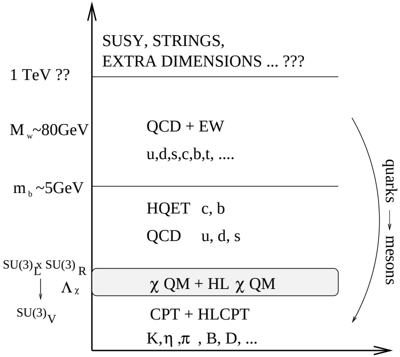

Figure: Energy levels in particle (flavor) physics

Quantum fluctuations (loop effects) at high scales penetrate down to hadronic scales ~ 1 GeV

2014: 50 year annivers. of CP-violation!

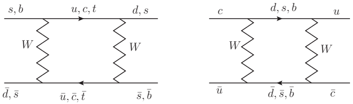

Figure: Fig.1 : $K\bar{K}$, $B\bar{B}$ and $D\bar{D}$ mixing in SM

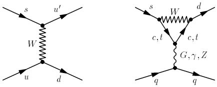

Figure: CP-cons and CP-viol quark diagrams, (“Penguin diagram”)

Difference of $K_L \to \pi^+\pi^-$ and $K_L \to \pi^0\pi^0$ (ϵ'/ϵ- effect).
Later CP-violation in B-decays.... Further?

NEDM in SM -small but non-zero

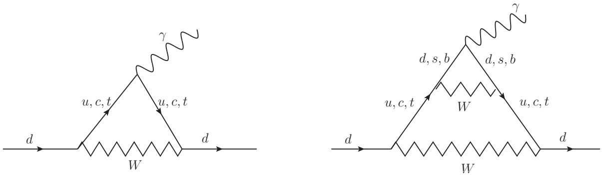

Figure: Loop diagrams for d_d giving zero EDM

SM estimates from 1980's ($\rightarrow$ 1990s)
NEDM-interaction not in SM Lagrangian. Must be loop generated.
Must contain Imaginary parts of CKM. $\Rightarrow$ Must be non-diagonal!
-cannot be one-loop diagram. BUT: 2-loop zero if summed!

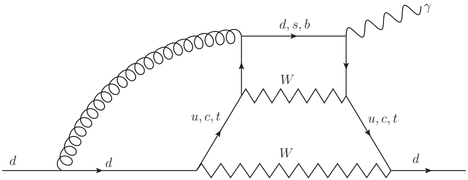

Figure: Typical diagram for EDM of d-quark to lowest order

$$d_n/e \sim \frac{\alpha_s}{4\pi}(G_F)^2 Im(V^\dagger_{ub}V_{tb}V^\dagger_{td}V_{ud})\cdot F(m_q, M_W)$$

Valence quark approximation: $d_n = \frac{4}{3}d_d - \frac{1}{3}d_u$,
(Recent lattice calculation : $d_n = 0.74 d_d - 0.22 d_u + 0.008 d_s$)
Result (Czarnecki and Krause 1997): $d_n/e \sim 10^{-34}$cm

NEDM in SM- Pole mechanism

Pole diagram mechanism (Orsay group, 1980's)

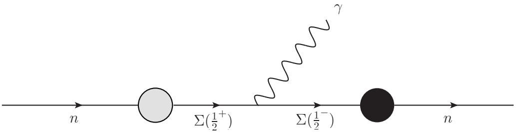

Figure: EDM from pole diagram

Need quark model at baryonic level..or other assumptions...
$d_n/e \sim (10^{-32} - 10^{-31})$ cm ;-
depend on products of three (model dep.) hadronic matrix elements

NEDM as two loop

The same pole diagrams at quark level as two loop diagrams . Also d, b in loop. NB! : two-fold GIM cancellations due to unitary CKM matrix ($\Rightarrow$ Relics of SD effects). (JOE and I.Picek, Nucl Phys.B 1983)

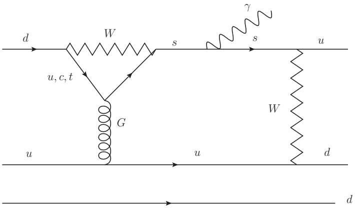

Figure: Pole diagram at quark level $\rightarrow$ 2-loop diagr. More diagrams of same order!

Result (eff. Lagrangian. Only one hadronic matrix element!) :
$d_n/e \sim 10^{-32}$cm

NEDM from chiral loop

SM: Considered Diagrams at hadronic level with chiral loop (Khriplovich and Zhitnitsky, 1982)

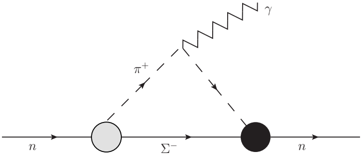

Figure: Hadronic diagram for NEDM. One of the blobs is a Penguin interaction, and one W-exchange.

$d_n/e \sim (10^{-32} - 10^{-31})$cm ;- dep on hadr. matrix uncertainty.
Anyway: SM predicts nEDM $\neq$ 0

Other mechanisms for NEDM

- Mechanisms beyond the SM - often bigger than in SM (more complex phases) Examples:
- LR-symmetric model(s) (many authors... in 1980's...
  Recent: Maiezza and Nemevšek (2014)
- SUSY (many authors...)
- Barr-Zee mechanism (many authors),
- Still within SM: U(1) gluonic anomaly (θ term. Axions?)

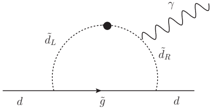

Figure: Typical diagram for EDM of d-quark in SUSY

For SUSY: Cancellations among contributions needed

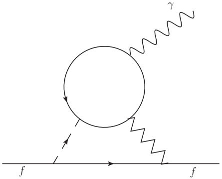

Figure: EDM for a fermion f within the Barr-Zee mechanism

In addition *Weinberg operator*... ....And of course the QCD θ-term....(axions?)

Recent example: CPV in D-decays ?

CP-violation in $D \to PP$ within SM ??

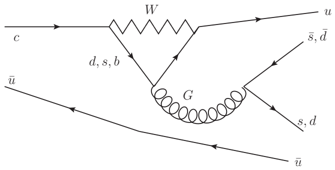

Figure: Fig.12: $D \to PP$ with Penguin mechanism in SM

Small CKM factor and $m_b^2 << m_t^2$
2011 ..."Δa_{CP}-Saga". New Physics (2011) (Now $\to$ 0 ?)

NP for $D \to PP$

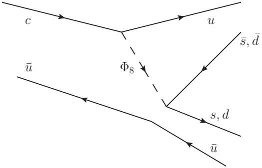

Figure: Fig. 13: $D \to PP$ with $c \to u$ coupling

New Physics ?. Assumption by Altmannshofer et al:

$$\mathcal{L}_{\text{eff}} = G(c \to u)\bar{u}_L\, t^A\, \Phi^A\, c_R + X_d \bar{d}_L\, t^A d_R\, \Phi^A + h.c. \; ,$$

Asymmetry,assuming max CPV phase Φ_f,and strong phase δ_f is

$$\Delta a_{CP} \sim M_\Phi^2\, m_K^2 \cdot G(c \to u) \cdot X_d$$

Assuming New Physics ;- should check NEDM

NEDM from EDM of d-quark (New type diagr.)

EDM of light (u, d) quarks (With Svjetlana Fajfer) :

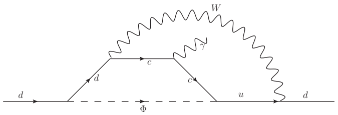

Figure: NEDM from 2-loop diagram with $c \to u$ coupling

$(M_\Phi \sim 0.4$ to 2 TeV).
Expression for loop calculation ($M_\Phi \sim 0.4$ to 2 TeV) connected to parameters in Δa_{CP} for $D \to PP$. Obtain:

$$(d_n/e)^{\Phi}_{2-loop} \simeq (0.8 - 1.7) \times 10^{-26}\,\text{cm} \;,$$

Flavor changing Higgs coupling?

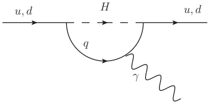

Figure: One loop diagrams with FC Higgs coupling. Quadratic in $(Y_{l,R})$s

FC coupling for fermions: $f_1 \to f_2 + H$ in quark and lepton cases: (f_1 and f_2 has same el. charge !). Example: $b \to d\,H$ coupling:

$$\mathcal{L}_{\text{eff}} = Y_R(d \to b) \cdot \overline{b_L}\,H\,d_R + Y_L(d \to b) \cdot \overline{b_R}\,H\,d_L + h.c.$$

Note: Not $SU(2)_L \times U(1)_Y$ invariant alone (-incomplete).
$Y_L(b \to d) = Y_R(d \to b)^*$ and $Y_L(b \to d) = Y_R(d \to b)^*$
Similar for other quarks, and for leptons (say $e \to \mu\,H$). Note: SM has $f_1 \to f_2 + H$ at one loop, BUT: Small !!

FC Higgs studied by various authors:

Guodelis, Lebedev and Park, Phys Lett B (2012)
Blankenburg, Ellis and Isidori, Phys Lett B (2012)
Harnik,Kopp and Zupan, JHEP (2012)
Greljo, Kamenik and Kopp, JHEP (2014)
Gorbahn and Haisch, JHEP (2014).

Bounds on such FC Yukawa's from various processes,
$K - \overline{K}$ - and $D - \overline{D}$- , and $B - \overline{B}$-mixing, (Tree-level and one-loop box diagrams)
In leptonic sector $\mu \to e\,\gamma$ and $\tau \to \mu\,\gamma$ (up to 2-loop)
Bounds on Y's of order 10^{-3} to 10^{-6}.

This study : nEDM from FC Higgs extended to two loop !

Two loop diagr. for EDM from FC Higgs

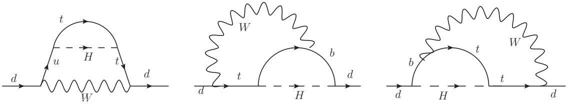

Figure: Three diagrams with FC Higgs coupling for EDMs of a d-quark. Soft photon emission from one of the charged particles is assumed to be added. Left diagram gives contributions suppressed by $m_{u,d}/M_W$. Crossed diagrams in the center or to the right, give contributions not suppressed by light quark masses. The diagram to the right is the complex conjugate of the diagram in the center.

NB ! : Only one FC Yukawa and ttH-coupling. t-quark in loop dominates!

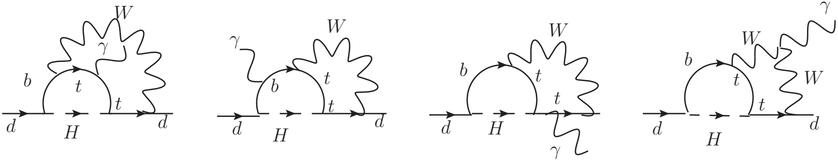

Figure: Fig. 17: Four diagrams for an EDM of a *d* quark obtained by adding a soft photon to the diagram to the right of Fig. 3. The left diagram is the same as in Fig. 1, with obvious particle replacements. For the first three diagrams, there are also corresponding diagrams where the *W*-boson is replaced by an unphysical Higgs-boson within Feynman gauge. The first two diagrams are finite. The third and fourth are log. divergent

NB : First order in Y's. Big SM H-coupling to t-quark !

EDM for the d-quark (e_i= charge of γ emitting part.)

$$(\frac{d_d}{e})_i \; = \hat{e}_i \, F \, S_i \, Im[Y_R(d \to b) \, V_{td}^* \, V_{tb}]$$

$$F \; = \; \frac{g_W^3}{M_W \sqrt{2}} \left(\frac{1}{16\pi^2} \right)^2 \; = \; \frac{2M_W^2}{v^3} \left(\frac{1}{16\pi^2} \right)^2 \; \simeq \; 6.94 \times 10^{-22} \, \mathrm{cm} \; ,$$

$v \simeq 246$ GeV. (Conversion: 1/(200 MeV) = 10^{-13} cm) Recall $|Y_R(d \to b)| < 1.5 \times 10^{-4}$ from other authors ($B_d - \overline{B_d}$-mixing,). Some terms log. divergent $\sim ln(\Lambda^2)$, some S_i finite of order one. Interaction of unphysical Higgs field ϕ for $t \leftrightarrow d$ transitions

$$\mathcal{L}_{\phi \mathrm{td}} \; = \; -\frac{g_W}{M_W} \, V_{td}^* \bar{d} \, \phi_- (m_d P_L \; - \; m_t P_R) t \; + \; h.c. \; ,$$

and similar for $t \leftrightarrow b$ transitions Terms with top quark dominate!

$$m_t^2 >> m_b^2 \Rightarrow d_u \text{ small !}$$

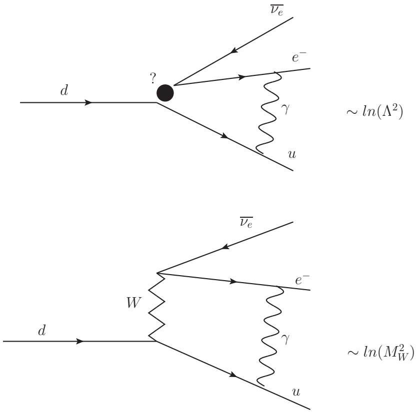

Figure: Fig.18. QED correction to beta-decay within Fermi-theory. -and with W-exchange

Old example with cut-off: Non-renormalizable Fermi theory

There are terms $\sim m_t^2$ and even $\sim m_t^4$ for unphys Higgs terms.
Logarithmic divergence parametrized in terms of

$$C_\Lambda \equiv ln(\frac{\Lambda^2}{M_W^2}) + \frac{1}{2} \sim 5 \text{ to } 8$$

for $\Lambda \sim 1$ to 3 TeV.
Total contribution from Fig. 17 :

$$(\frac{d_d}{e})_{Fig.17} = (1.65 + 1.37\, C_\Lambda) \cdot F \cdot Im[Y_R(d \to b)\, V_{td}^*\, V_{tb}]$$

Log. div. easy to fold into next subloop. Finite terms more complicated.
End up with integrals over one feynman parameter,- numerically.

Numerical integration

$$S_1 \;=\; -\,u\,\int_0^1 \frac{dx\;\left[(1-3x)-\frac{u}{2}(1-x)\right]}{(u-1)\,(1-x)}\;\{ln\frac{C_1}{C_0}$$

$$-\frac{H}{C_1-H}ln(\frac{C_1}{H})\;+\;\frac{H}{C_0-H}ln(\frac{C_0}{H})\}\;.$$

$$C_0\equiv C_0(x)\;=\frac{u}{x(1-x)}\;\;,\;\;C_1\equiv C_1(x)\;=\frac{1+x(u-1)}{x(1-x)}\;.$$

Mass ratios: $u\equiv\frac{m_t^2}{M_W^2}\;\;,\;H\equiv\frac{M_H^2}{M_W^2}\quad;$

$$S_2\;=\;\frac{u\,(1+\frac{u}{2})}{2(u-1)}\int_0^1 dx\,(1-2x)\;\{-dilog(\frac{C_1}{H})\;+\;dilog(\frac{C_0}{H})\}\;,$$

$$dilog(z)\;=\;\int_1^z dt\frac{ln(t)}{(1-t)}\;=\;Li_2(1-z)$$

Diagrams 3,4 are log. divergent in left subloop

$$Log(r^2, x, y, masses)_\Lambda \; = 2 \int_0^1 dx \int_0^{(1-x)} dy \left(ln(\Lambda^2) - \frac{3}{2} - ln(R) \right) \; ,$$

$$R \equiv Q - x(1-x)r^2 \; ; \quad Q \equiv m_b^2 + x(M_W^2 - m_b^2) + y(M_H^2 - m_b^2) \; .$$

r^2 = loop momentum squared for other sub-loop.
$Log(r^2, x, y, masses)_\Lambda$

$$\sim \left[C_\Lambda - 2 \int_0^1 dx \int_0^{(1-x)} dy \, L_Z(r^2, x, y, masses)) \right] \; ,$$

$$C_\Lambda \; = \; ln(\frac{\Lambda^2}{M_W^2}) \; + \; \frac{1}{2} \; \simeq 5.5 \;\; \text{to} \;\; 7.7 \;\; \text{for} \;\; \Lambda \; = 1 \;\; \text{Tev} \;\; \text{to 3 TeV}$$

$$L_Z(r^2, x, y, masses) \; = \; ln \left[-r^2 \; + \; \frac{Q}{x(1-x)} \right] \; - \; ln(M_W^2) \; .$$

$$Fin(r^2, x, y, masses) \; = \; \frac{i}{16\pi^2} \cdot 2 \int_0^1 dx \int_0^{(1-x} dy \left(\frac{r^2\, p(x)}{Q - (1-x)r^2} \right) \quad ,$$

$p(x)$ is a second order polynomial in x. Fold into:

$$J \; = \; \int \frac{\bar{d}\, r}{(r^2 - M_W^2)(r^2 - m_t^2)^2} \; \cdot \; Func(r^2, x, y, masses) \quad ,$$

For Log- divergent term x, y integration trivial.
In general y-integration easy. Left with complicated integration over remaining Feynman parameter x.

$$S_3^W = \frac{u}{2(H-b)} \int_0^1 dx\, x \; \left(K(1,u;B_1) - K(1,u;B_0)\right)$$

where the functions K are in general given by

$$K(A,a;B) \equiv -\frac{a}{(A-a)} ln(B) + \frac{a^2}{(A-a)(B-a)} ln(\frac{B}{a})$$
$$-\left(\frac{A}{A-a}\right)^2 dilog(\frac{B}{A}) + [\left(\frac{A}{A-a}\right)^2 - 1]\, dilog(\frac{B}{a})$$

$$B_0 \equiv B_0(x) \equiv \frac{b+x(u-b)}{x(1-x)} \; ; \; B_1 \equiv B_1(x) \equiv \frac{H+x(u-H)}{x(1-x)} \; .$$

where $b \equiv \frac{m_b^2}{M_W^2}$, $u \equiv \frac{m_t^2}{M_W^2}$, and $H \equiv \frac{M_H^2}{M_W^2}$

$$S^{\phi}_{3Z} = -\frac{u^2}{(H-b)}\int_0^1 dx\, x(1-x)[Z(1,u;B_1) - Z(1,u;B_0)]$$

where the Z-function is in general given by:

$$Z(C,A;B) \equiv \frac{(A^2-AB)}{C-A}\left(\frac{ln(B)}{A} + \frac{ln(\frac{B}{A})}{(B-A)}\right)$$
$$+\frac{C(C-B)}{(C-A)^2}\{\frac{1}{2}[ln(B-C)]^2 + dilog(\frac{B}{B-C}) - ln(C)\cdot ln(B-C)\}$$
$$+\frac{[BC-A(2C-A)]}{(C-A)^2}\{\frac{1}{2}[ln(B-A)]^2 + dilog(\frac{B}{B-A}) - ln(A)\cdot ln(B-A)\}$$

Only one FC Yukawa coupling -and W W H-coupling

Big WWH coupling compensates for loop suppression

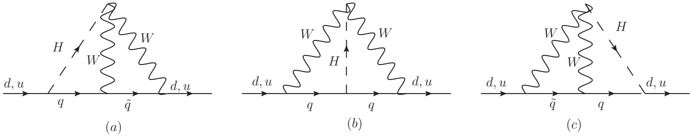

Figure: Fig. 19. The three classes of with FC Higgs coupling. The (b) diagrams are zero (-or proportional to very small current quark masses) due to chirality , and the (c) diagrams are complex conjugates of the (a) diagrams. Here $q = s, b$ and $\tilde{q} = u, c, t$ (with GIM-cancellations) for EDM of a d-quark, and $q = c, t$ and $\tilde{q} = d, s, b$ (with GIM) for EDM of a u-quark. Soft photon emission from charged particles should be added

The relevant Higgs-W-coupling is then given by

$$\mathcal{L}_{\rm WWH} \;=\; g_W \, M_W \, \sqrt{2} \, H \, W^{(-)\,\mu} \, W_\mu^{(+)}$$

For W-boson in Feynman gauge, must add unphys. Higgs.
Relevant Higgs-W-ϕ coupling

$$\mathcal{L}_{\phi\rm HW} \;=\; \frac{g_W}{\sqrt{2}} \left\{ H \, (i\partial^\mu \phi^{(-)}) \;-\; (i\partial^\mu \, H)\phi^{(-)}) \right\} W_\mu^{(+)} + h.c.$$

Derivative coupling implies momentum dependent vertex which create logarithmic divercences.
Need as before the relevant ϕ-d-t coupling

$$\mathcal{L}_{\phi\rm dt} \;=\; -\frac{g_W}{M_W} \, V_{td}^* \, \bar{d} \, \phi^{(-)} \, (m_d P_L \; - m_t P_R)t \; + \; h.c$$

EDMs for u, d-quarks generated by FC Higgs

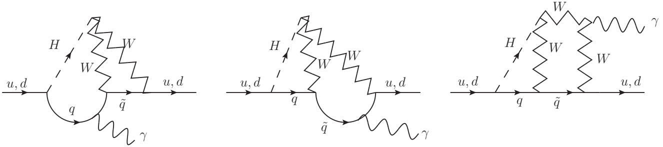

Figure: Fig. 20: Emission of a soft photon from (a)-type diagrams from previous Fig. There is also a diagram with emission from the W in center of the diagram, and in addition additional graphs with the W replaced by an unphysical Higgs

NB! : First order in FC Y couplings. Big WWH-couplings. Consider all quarks in loops.

EDM of d-quark for γ-emission from $q = s, b$ (Left diagram, finite!):

$$
\begin{aligned}
(d_d/e)_q \quad &= \\
2 \cdot \hat{e}_s \cdot \quad F \quad &\cdot \mathrm{Im}\{Y_R(d \to s)\,[\lambda_u\,(f(s,u) - f(s,c)) + \lambda_t\,(f(s,t) - f(s,c))]\} \\
+2 \cdot \hat{e}_b \cdot \quad F \quad &\cdot \mathrm{Im}\{Y_R(d \to b)\,[\xi_u\,(f(b,u) - f(b,c)) + \xi_t\,(f(b,t) - f(b,c))]\}
\end{aligned}
$$

$$
\lambda_{\tilde{q}} = V^*_{\tilde{q}d} V_{\tilde{q}s}\ , \qquad \xi_{\tilde{q}} = V^*_{\tilde{q}d} V_{\tilde{q}b} \qquad , \tilde{q} = u, c, t
$$

The $f(q, \tilde{q})$'s are finite integrals of order one. (Also with unphys Higgs ϕ included). GIM-cancellation among light quarks only: terms almost killed ! But $(c - t)$-case survives! ($\Rightarrow$ c-quark term needed)

$$
\Delta f_d(b; t - c) \equiv f(b,t) - f(b,c) \;\simeq -0.34
$$

Dominating term (NB! d_u small also in this case)

$$
(d_d/e)_q \;\simeq\; -2 \cdot \;\hat{e}_b \cdot F \cdot \mathrm{Im}\{Y_R(d \to b) V^*_{td} V_{tb}\}\; \Delta f_d(b; t - c)
$$

For the u-quark the EDMs are suppressed by a factor of order 10^{-3} compared to the$d$-quark EDM.
The two next diagrams have the same GIM and CKM structure as the left.
BUT: they have divergent terms when $W \to \phi$.
Total contribution from Fig. 20 :

$$(\frac{d_d}{e})_{Fig.20} \simeq (3.46\, C_\Lambda - 9.35)\, F \;\; Im[Y_R(d \to b)\, V_{td}^*\, V_{tb}]$$

For the u-quark the EDM is suppressed by a factor of order 10^{-3} compared to the$d$-quark EDM.

Result/Conclusion for nEDM for FC Higgs

$$(\frac{d_d}{e})_{Tot} \;=\; (4.83\, C_\Lambda \,-\, 7.70)\, F\;\, Im[Y_R(d \to b)\, V_{td}^*\, V_{tb}]$$

Using experimental bound on nEDM ; For $\Lambda \sim 1$ to 3 TeV

$$|\mathrm{Im}\left[Y_R(d \to b) \cdot \frac{V_{td}^*\, V_{tb}}{|V_{td}^*\, V_{tb}|}\right]| \leq (2.0 \;\text{ to }\; 3.2) \times 10^{-4}\;.$$

to be compared to prev. authors (from $B_d - \overline{B_d}$-mixing):

$$|Y_R(d \to b)| \leq 1.5 \times 10^{-4} \equiv |Y_R(d \to b)|_{Bound}$$

Scale with this bound

$$d_n/e \simeq N_\Lambda \times \left\{ \frac{|Y_R(b \to d)|}{|Y_R(b \to d)|_{Bound}} \cdot \mathrm{Im}\left[\frac{Y_R(d \to b)}{|Y_R(b \to d)|} \cdot \frac{V_{td}^*\, V_{tb}}{|V_{td}^*\, V_{tb}|}\right]\right\} \times 10^{-26}\,\mathrm{cm}$$

where $N_\Lambda = 0.31 \cdot (ln(\Lambda^2/m_W^2) - 1.59)$.

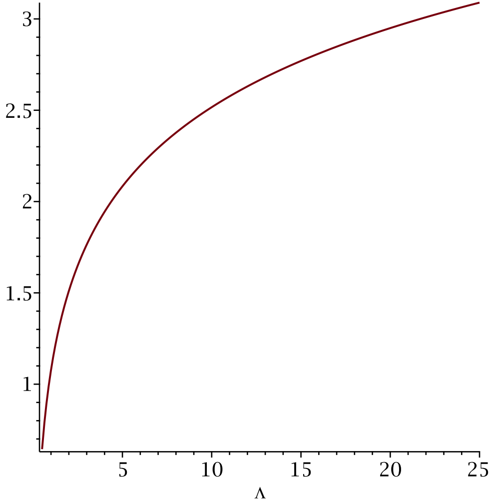

Figure: The quantity N_Λ as a function of cut-off Lambda (in TeV)

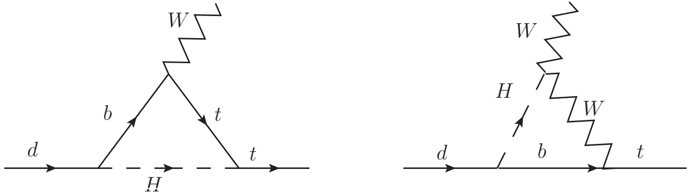

Figure: Fig.20.The divergent effective W-loop vertex correction diagram relevant for diagrams of section III (left), and the (finite) effective vertex correction relevant for diagrams in section IV (right).

- FCH hypothesis extended to two loop case for EDM.
- divergent sub-loops right-handed current) imply non-renorm. Only effective theory;- incomplete.
- Need at the end $SU(2)_L \times U(1)_Y$ symmetric Lagrangian. FC Higgs effective Lagrangian needs additional couplings and (probably) additional higher mass states.

- Found bound for the imaginary part of $Y_R(d \to b)$ of the same order of magnitude as previously by other authors. (Note: Not coherent relative signs from the different diagrams)
- Turned around, using the bound for $Y_R(d \to b)$ found in previous papers, - a value for nEDM not too far below the experimental bound cannot be excluded.
- However, effective theory, imply unprecise predictions.

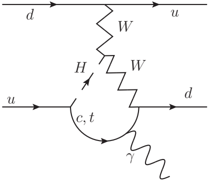

Figure: Diagrams with FC Higgs coupling

Technical remark

May often use effective propagator in soft el.-magn. field $F_{\mu\nu}$:

$S_{eff}(p,F) \; = \; (-\frac{e_q}{4}) \, \frac{(2m\sigma\cdot F + \{\gamma\cdot p,\sigma\cdot F\})}{(p^2-m^2)^2}$

Similarly for emission from a W:

$$(D_1(k,F))^{\alpha\beta} \; = \; (-\frac{e_W}{4}) \; \frac{3\,i\;\left\{g^{\mu\alpha}g^{\nu\beta} - g^{\mu\beta}g^{\nu\alpha}\right\}\;F_{\mu\nu}}{(k^2-M_W^2)^2} \qquad (1)$$

Many loop diagrams suppressed because of chirality ($P_L\,P_R \; = \; 0$) , or symmetric momentum integration:

$\int \frac{d^4p}{(4\pi)^4} f(p^2;\text{masses})\,p^\mu \; = \; 0$