Neutron Electric Dipole Moment from flavor changing scalars

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based (partially) on J.O.E. & S.F. : *Phys. Rev.* **89** 095030 (2014)

How to undertand CP-violation in nature ?

- Look for New Physics (more CP-viol phases)
- NEDM control SM extensions

Outline

- CP-violation in $D \to P^+ P^-$. Is the "Δa_{CP} saga" still relevant?
- Mechanisms for NEDM in SM and beyond
- NEDM from colored scalar FC coupling
  New mechanism (new type diagrams) for EDM's
- NEDM from hypothetical FC Higgs-coupling

The Electric dipole moment

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

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

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

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

$$|d_n/e| \;<\; 2\times 10^{-26}\mathrm{c}m$$

(corresp to 2×10^{-12} in Bohr Magnetons)

CP-violation in $D \to P^+P^-$

Old world average: $\Delta a_{CP} = (-0.329 \pm 0.121)\%$,

with $\Delta a_{CP} = a_{K^+K^-} - a_{\pi^+\pi^-}$ and the definition

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} .$$

where $f = K^+ K^-$ or $f = \pi^+ \pi^-$

Recent LHCb measurement $\Delta a_{CP} = (+0.14 \pm 0.16 \pm 0.008)\%$

New world average (HFAG): $\Delta a_{CP} = (-0.256 \pm 0.10....)\%$

CP-violation in $D \to P^+P^-$ within SM

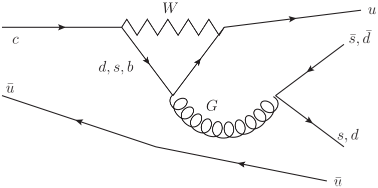

Figure: $D \to P^+P^-$ with Penguin mech in SM

Small CP-violating contribution (small CKM and Wilson coeff.)
(Maybe Non-pert explanation for Δa_{CP} ?)

NP for $D \to P^+ P^-$

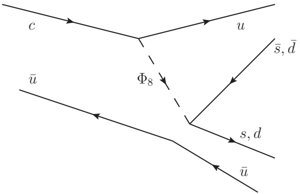

Figure: $D \to P^+ P^-$ with $c \to u$ coupling

Assuming FC color octet scalar (Altmannshofer et al. JHEP,2012):

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

couplings $G(c \to u)$ and X_d prop to quark masses:

$$G(c \to u) \equiv [X_u]_{12} = \zeta_u \, y_c \, X_{cu} \; ; \quad X_{cu} \sim V_{cs} V_{us}^* \quad ; \quad X_d = \zeta_d \, y_d \; ,$$

$\zeta_{u,d}$ to be determined by CP-violation in $D \to PP$ and $y_q = m_q / v$,
v= VEV of Higgs, m_q mass of quark q

- Color octet might be motivated by GUTs

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

$$\Delta a_{CP} = \frac{2}{9} \frac{\zeta_u \zeta_d}{M_\Phi^2} m_K^2 C_{RGE} C_H$$

(Have used color matrix relations,Fierz transf and Naive Factorization) coefficient $C_{RGE} = 0.85$, for the running from the scale $M_\Phi \sim 1$ TeV down to the scale equal m_c, C_H = hadronic factor
Adjust Δa_{CP} by adjusting $\zeta_u \zeta_d \equiv \zeta^2$

Assuming New Physics ;- should check NEDM

NEDM within SM

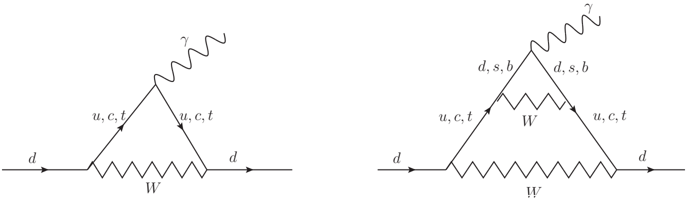

Figure: Diagrams giving zero EDM

No net CP-viol. from one and 2 loop diagrams.

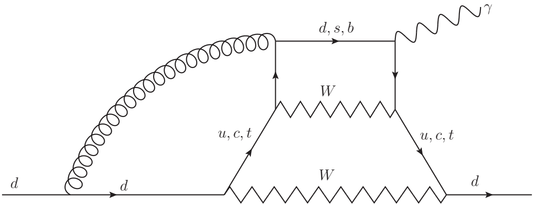

Figure: EDM of quark to lowest order

$$d_n/e \ \sim \ \frac{\alpha_s}{\pi}(G_F)^2 Im(V_{ub}^{\dagger}V_{tb}V_{td}^{\dagger}V_{ud})\, H(m_q)$$

$H(m_q)$= funct. of quark masses (and M_W)
Valence quark approximation: $d_n = \frac{4}{3}d_d - \frac{1}{3}d_u$, where d_q is the quark EDM ($q = u, d$)
Result: $d_n/e \sim 10^{-34}$cm

NEDM in SM- Pole mechanism

Pole diagram mechanism (Orsay group, 1980's)

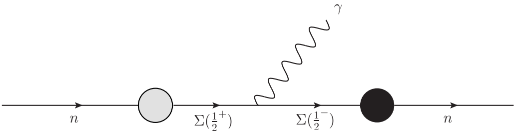

Figure: EDM from pole diagram

Need quark model at baryonic level..or other assumptions...
$d_n/e \sim (10^{-32} - 10^{-31})$cm ;- dep on hadr. matrix elem.

NEDM as two loop

The same pole diagrams at quark level as two loop diagrams . Also d, b in loop. Now: Sizeable 4-momenta in second(-non-penguin) loop - gives a two-fold GIM cancellations due to unitary CKM matrix ($\Rightarrow$ "Relics of SD effects"). (JOE and I.Picek, Nucl Phys.B 1983)

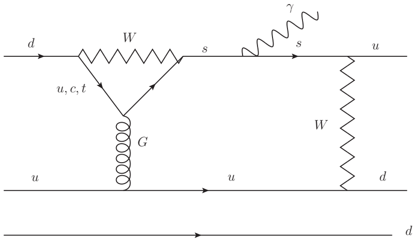

Figure: Pole diagram at quark level

Consider all diagrams to same order $\Rightarrow$
Effective lagrangian for $u\,d \to d\,u\,\gamma$

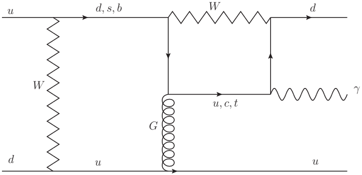

Figure: "Photopenguin diagram for "diquark mechanism" for EDM

$\mathcal{L}_{eff} \sim F_{CKM}\, G_F^2\, I(m_q)\, \epsilon^{\mu\nu\alpha\beta}\, F_{\mu\nu}\, j_\alpha^L(u \to d)\, j_\beta^L(d \to u)$
$I(m_q)$ = loop funct. dep on quark masses and M_W, and j_α^L = left-handed quark current.
Result: $d_n/e \sim 10^{-32}$cm

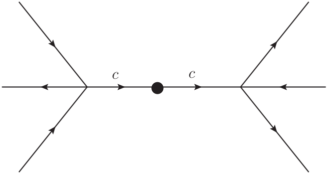

Figure: Nonperturbative mechanism for NEDM in SM (soft γ added)

Contribution from higher dimensional operator in SM (Mannel and Uraltsev, PRD 2012)

NEDM from chiral loop

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

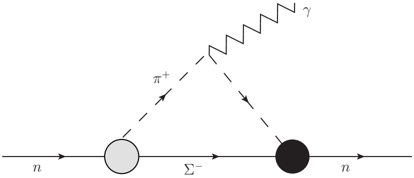

Figure: Hadronic diagram for NEDM. One of the blobs is a Penguin interaction, and one W-exchange.

$d_n/e \sim (10^{-32} - 10^{-31})$cm ;- dep. on hadr. uncertainty.

Other mechanisms for NEDM

- Mechanisms beyond the SM - often bigger than in SM (more phases) Examples:
- LR-symmetric model(s) (many authors...recent: Maiezza and Nevemšek)
- SUSY (many authors...)
- Barr-Zee mechanism (many authors),

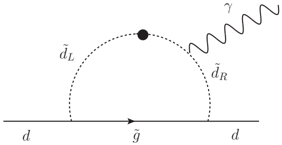

Figure: Typical diagram for EDM of *d*-quark in SUSY

For SUSY: Cancellations among contributions needed

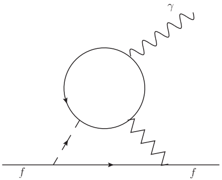

Figure: EDM for a fermion *f* within the Barr-Zee mechanism

No contribution from FC scalars in Barr-Zee mechanism

NEDM from $ud \to du\gamma$ (new type diagr)

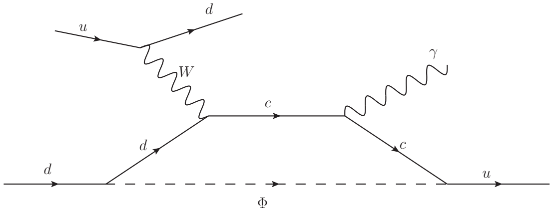

Figure: NEDM from $ud \to du\gamma$

Result compatible with 2-loop diquark mech. of SM (JOE and IP)
Hadronic matrix element uncertain

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

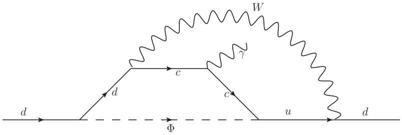

Figure: NEDM from 2-loop diagram with $c \to u$ coupling

In leading log. approximation ($M_\Phi^2 >> M_W^2 >> m_c^2$): $d_n/e =$

$$\frac{16}{9} Im[g_W^2 V_{ud} V_{cd}^* G(c \to u) X_d] \frac{m_c}{(16\pi^2 M_\Phi)^2} \left(\left[ln \frac{M_\Phi^2}{m_c^2} \right]^2 - \left[ln \frac{M_W^2}{m_c^2} \right]^2 \right)$$

To explain CPV in $D \to PP$: $G(c \to u)\, X_d/(M_\Phi)^2$ related to Δa_{CP}

Have $d_n \sim (lnM_\Phi)^2/M_\Phi^2$, BUT: For fixed asymmetry - i.e. $\frac{\zeta^2}{M_\Phi^2}$ fixed - we obtain the relation

$$(d_n/e)^\Phi_{2-loop} \simeq \left(\frac{\lambda^2\, m_d}{8\pi^4}\right) \frac{M_W^2 m_c^2}{v^4\, m_K^2} \frac{\Delta a_{CP}}{C_{RGE}\, C_H} \left(\left[ln \frac{M_\Phi^2}{m_c^2}\right]^2 - \left[ln \frac{M_W^2}{m_c^2}\right]^2 \right) \, .$$

Numerically, we obtain the range (for $C_H \sim 3,\ \lambda \simeq V_{us} \simeq 0.2$):

$$(d_n/e)^\Phi_{2-loop} \simeq (0.8 - 1.7) \times 10^{-26}\,\mathrm{cm} \, ,$$

for M_Φ in the range 400 GeV to 2 TeV, (and: New world average)

- Generalization from c-quark to t-quark in loop (Preliminary!). $G(t \to u) \equiv [X_u]_{13} = \zeta_u\, y_t\, X_{tu}$; $X_{tu} \sim V_{tb} V_{ub}^*$ (with $\zeta \sim 30$ as in charm case:) $d_n/e \sim 4 \times 10^{-28}$cm

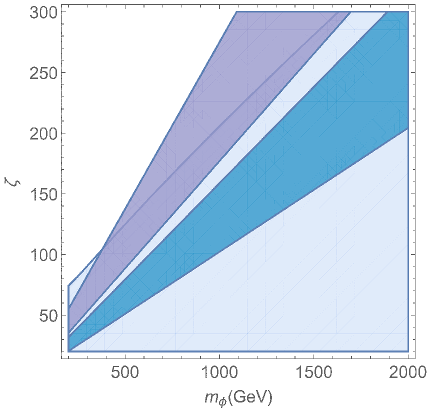

Figure: Regions in the $\zeta - M_\Phi$ plane compatible with the data on Δa_{CP} (violet for $C_H = 1$ and blue for $C_H \simeq 3$) and on the current experimental lower bound on *NEDM* (pale blue).

Flavor changing Higgs coupling?

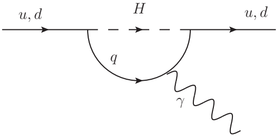

Figure: One loop diagrams with FC Higgs coupling

FC Coupling (in quark and lepton cases):

$Y_L(f_1 \to f_2)\, P_L \;+\; Y_R(f_1 \to f_2)\, P_R$

where

$Y_L(f_2 \to f_1) \;=\; Y_R(f_1 \to f_2)^*$ and $Y_L(f_2 \to f_1) \;=\; Y_R(f_1 \to f_2)^*$

Bounds on such FC Yukawa's from various processes, see for inst:

Harnik,Kopp and Zupan, JHEP (2012)

Same diagrams as for colored scalar are possible for FC coupling for the phys. Higgs. PRELIMINARY !!!

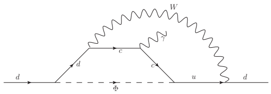

Figure: NEDM from 2-loop diagram with $c \to u$ coupling

$$d_n/e \sim 10^{-27}\text{cm} \times \text{Im}\left(Y_R(c \to u)\right)$$

- One magnitude smaller for top-quark in loop

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

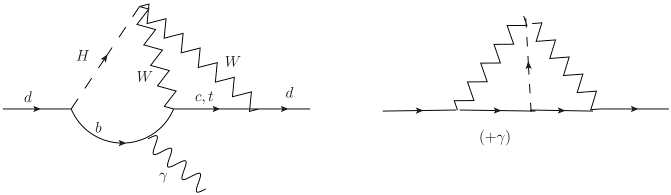

Figure: Diagrams with FC Higgs coupling

For b-quark and t-quark in loop (PRELIMINARY !):

$$d_n/e \sim 2 \times 10^{-25}\mathrm{cm} \times \ \mathrm{Im}\left(Y_R(d \to b)\frac{V_{tb}^* V_{td}}{|V_{tb}|\cdot|V_{td}|}\right)$$

Diquark mechanism with FC Higgs ?

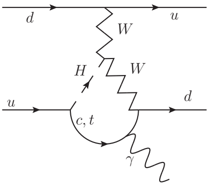

Figure: Diagrams with FC Higgs coupling

with c-quark in loop (PRELIMINARY !):

$d_n/e \;\sim\; 10^{-24}\text{cm} \times \; \text{Im}\left(Y_L(u \to c)\right)$

-but hadronic uncertainty

Technical remark

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

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

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

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

Conclusions

- For Δa_{CP} in $D \to P^+ P^-$ close to world average $\Rightarrow d_n/e$ from colored FC scalar (still) close to exp. bound
- Pointed out new mechanisms (new type of diagrams) for EDMs
- Remind: Estimates for FC couplings of physical Higgs are preliminary
- Contributions with FC Higgs few orders below experimental bound for nEDM ?. But our contrib. prop. to one Yukawa only.
- Some of the diagrams also relevant for eEDM
- More work to do on EDM's....