

# Neutron Electric Dipole Moment from colored scalars

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Presented at: QCD@work, Bari, june 2014

June 13, 2014

To be publ. in PRD 89 (2014)

## Unexplained issues:

- CP-Violation in the Universe: The SM has not enough!
- Observed CPV in  $D \rightarrow P^+P^-$  ( $P = K, \pi$ ) not explained in SM??
- NEDM control SM extensions

## Outline

- CP-violation in  $D \rightarrow P^+P^-$   
Non-pert effect in QCD - or New Physics?
- What is NEDM? - NEDM in SM
- NEDM beyond SM
- NEDM from colored scalar FC coupling

## CP-violation in $D \rightarrow PP$

Measured CP-violating effect:

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

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

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

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

Measurement not compatible with SM ???

Consider Flavor changing colored scalar  $c \rightarrow u$  coupling

Total amplitude

$$A_f = A \left( 1 + r_f e^{i\delta} e^{i\Phi_f} \right)$$

(where  $A$  might be complex). Asymmetry:

$$a_f = 2 r_f \sin\delta \sin\Phi_f$$

Need CP-violating phase  $\Phi_f$  in some coupling  
CPV from (?) operator

$$\sim C_8 m_c \bar{u} \sigma \cdot G P_{L,R} c$$

Need also strong (threshold, unitarity) phase  $\delta_f$

## CP-violation in $D \rightarrow PP$ within SM

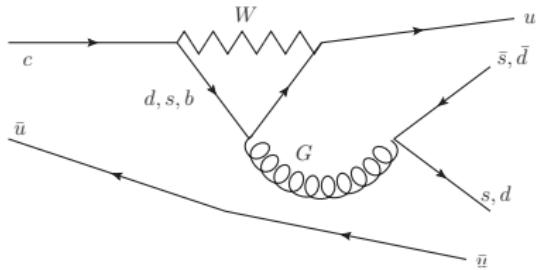


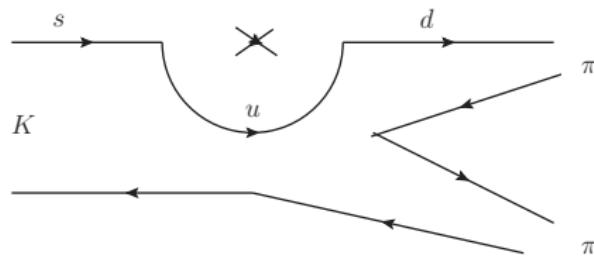
Figure:  $D \rightarrow PP$  with Penguin mech in SM

Doubtful if this diagram can explain the observed CP-Violation  
Small CKM factor and  $m_b^2 \ll m_t^2$

Non-perturbative explanation? (Cheng and Chiang 2012, Brod et al. 2012)

## Lattice theory for $M \rightarrow M_1 M_2$

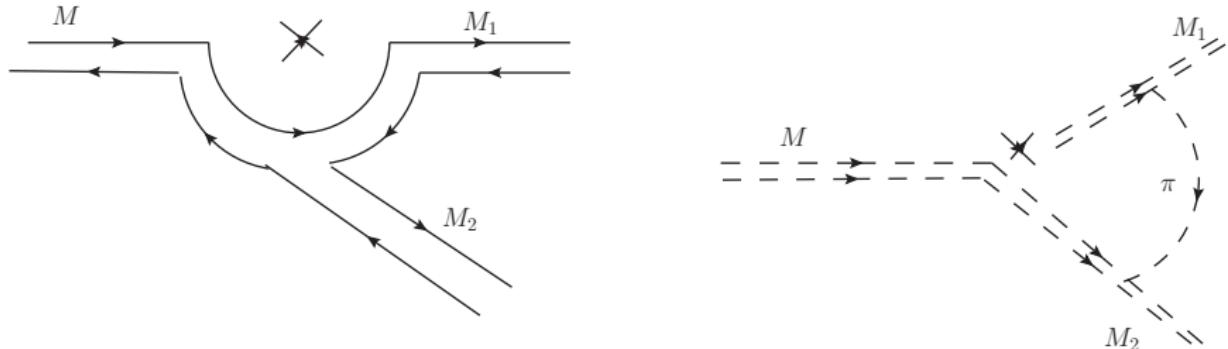
Example (“Eye-diagram” or “Penguin contraction”):



**Figure:** The “Eye-diagram” for  $K \rightarrow 2\pi$ . Relevant for the  $\Delta I = 1/2$  rule.

Similar (?) for:  $D \rightarrow K^+ K^-$  (with  $s \rightarrow c, u \rightarrow s, d \rightarrow u$ )

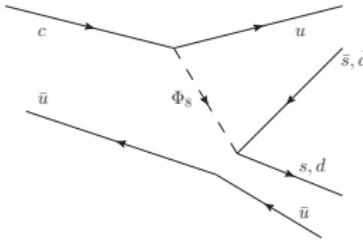
## Unitarity phase from $\chi$ PT (like) diagram



**Figure:** Chiral loop contribution to  $M \rightarrow M_1 M_2$  ( $M$  = heavy meson)

Like HL $\chi$ PT? ; New similar LE $\chi$ PT? (to appear?)

## NP for $D \rightarrow PP$



**Figure:**  $D \rightarrow PP$  with  $c \rightarrow u$  coupling from colored scalars

New Phys. scenario (Altmannshofer et al):

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

couplings  $G(c \rightarrow u)$  and  $X_d$  prop to quark masses ( $t^A$  = color matrices):

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

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

## Other NP models with (say) FC ( $c \rightarrow u$ ) ?

- FC Z or  $Z'$  bosons
- FC Heavy gluon
- 2HDM
- L-R sym ,  $W_R$

...Not so favorable, have more constraints  
(According to Altmannshofer et al)

Asymmetry, assuming max CPV phase  $\Phi_f$ , and strong phase  $\delta_f$  is

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

(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

Assuming New Physics ;- should check NEDM

## What is an 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:

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

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

$$|d_n/e| < 2 \times 10^{-26} \text{ cm}$$

(corresp to  $2 \times 10^{-12}$  in Bohr Magnetons)

## NEDM in SM; - quark EDM

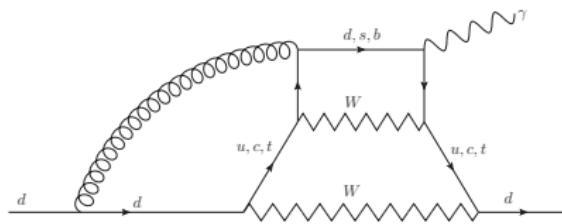


Figure: EDM of quark to lowest order

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

$H(m_q)$ = 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 ( $q = u, d$ ). Shabalin 1980, Czarnecki and Krause 1997  
Result:  $d_n/e \sim 10^{-34} \text{cm}$

## NEDM in SM- Interplay of quarks in N

Pole diagram mechanism (1980's Orsay group, etc )

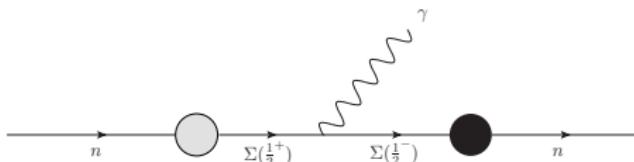


Figure: EDM from pole diagram

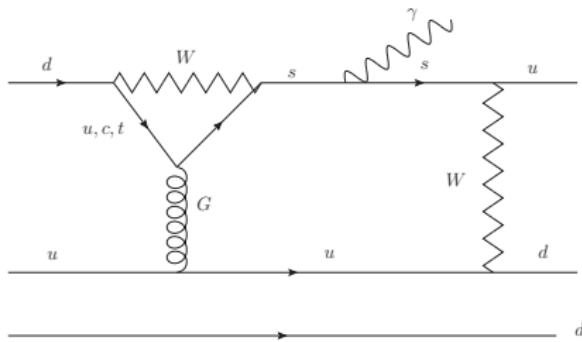
Need quark model at baryonic level..or other assumptions...

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

Also NP in “blobs”...

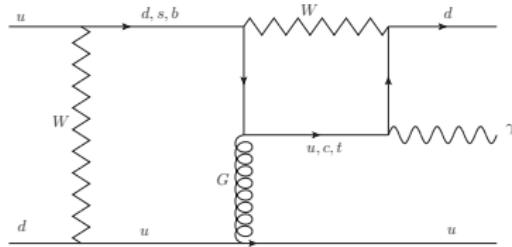
## NEDM as two loop

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 1983)



**Figure:** Pole diagram at quark level. Diquark mechanism

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

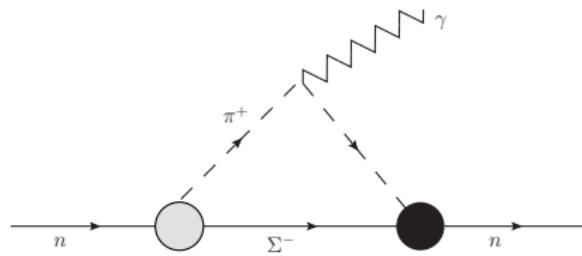


**Figure:** “Photopenguin diagram for “diquark mechanism” for EDM

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

## NEDM from chiral loop

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



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

$d_n/e \sim (10^{-32} - 10^{-31})\text{cm}$  ;- dep on hadr. matrix uncertainty.  
Also NP in “blob”

## Other mechanisms for NEDM

Still within SM: U(1) gluonic anomaly

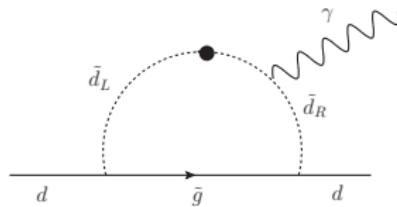
$$\mathcal{L}_{\text{an}} \sim \theta g_s^2 \epsilon^{\mu\nu\alpha\beta} G_{\mu\nu} G_{\alpha\beta}$$

(PQ sym , axions?, rotated away?)

Mechanisms beyond the SM :

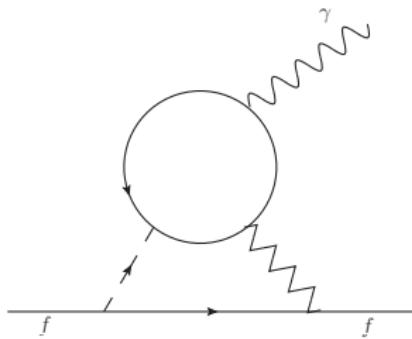
LR-sym. model, SUSY,

Barr-Zee mechanism, Weinberg operator

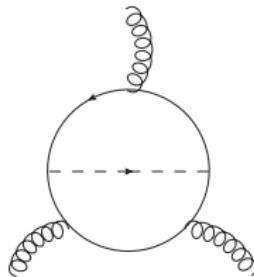


**Figure:** Typical diagram for EDM of  $d$ -quark in SUSY

For SUSY: Cancellations among contributions needed



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



**Figure:** 2-loop diagram generating Weinberg's CPV 3gluon operator

Weinberg operator (gluons attached to quark lines. Dimensional analysis)

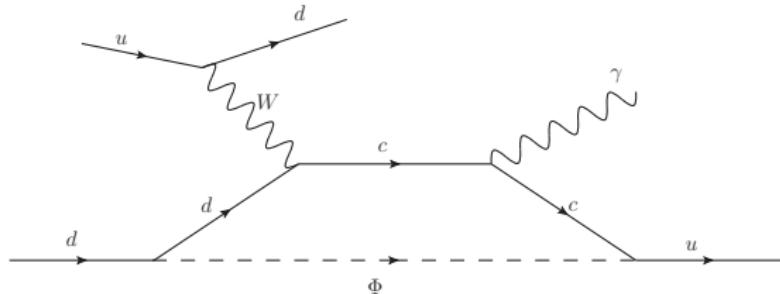
$$\mathcal{L}_{\text{eff}}^W = \frac{C_W}{6} f^{abc} G_{\mu\nu}^a \epsilon^{\nu\beta\rho\sigma} G_{\rho\sigma}^b G_{\beta}^{\mu c}$$

contribute significantly to the NEDM (dimension analysis;- and also like  $\chi$ -loop).

An additional dimension six operator is

$$\mathcal{L}_{\text{eff}}^{ff'} = C_{ff'} (\bar{\psi}_f \psi_f) (\bar{\psi}_{f'} i\gamma_5 \psi_{f'}) ,$$

## NEDM from $ud \rightarrow du\gamma$ with FC $c \rightarrow u$ coupl.



**Figure:** NEDM from  $ud \rightarrow du\gamma$ ; - diquark mechanism

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

## NEDM from EDM of d-quark with FC $c \rightarrow u$ coupl.

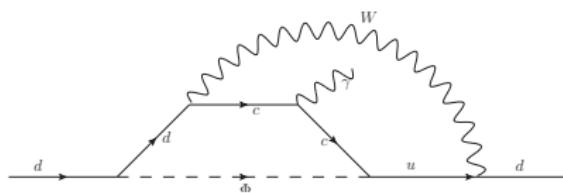
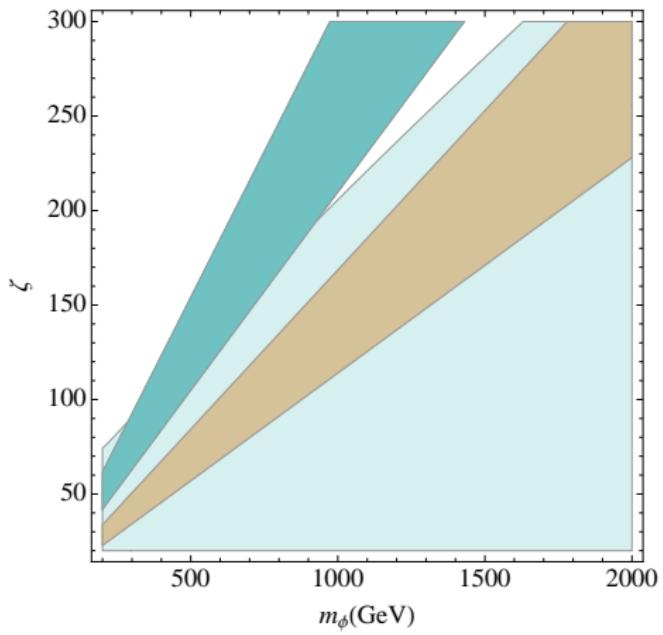


Figure: NEDM from 2-loop diagram with  $c \rightarrow u$  coupling

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

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

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



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

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

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

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

$$(d_n/e)_{2-loop}^\Phi \simeq (1.0 - 2.3) \times 10^{-26} \text{ cm} ,$$

for  $M_\Phi$  in the range 400 GeV to 2 TeV. Pert theor. OK!.

**Maybe in conflict with bound?! (dep. on  $\Phi_f$ )**