Loop-Less Nucleon EDM and Charm CP Violation

Nikolai Uraltsev

Synopsis:

- Dipole moments
- CP violation in the Standard Model
- d_n in the SM (historic perspective)

$\Big\}$ Introduction

- Loop-less d_n in the KM
- CP asymmetry in $D^0 \to K^+K^-/\pi^+\pi^-$
- Impact on d_n
- Conclusions

Introduction

EDM: No fuss in classical electrodynamics:

$$\vec{d} = \sum_i q_i \vec{r}_i \qquad U = -\sum_i q_i V(r_i) = -\bar{V}\cdot Q_{\rm tot} + \vec{d}\cdot\vec{E} + \ldots$$

QM: Stationary states of bound systems or elementary particles are characterized by momentum $\vec{P}$ and spin J, canonic pairs to $\vec{x}$ and orientation. Then $\vec{d}$ is proportional to $\vec{J}$, or

$$\text{Energy} \propto d\, \vec{J}\cdot\vec{E}$$

$\vec{J}$ is pseudovector, $\vec{E}$ is vector $\Rightarrow$ d violates Parity

$\vec{J} \xrightarrow{T} -\vec{J}$ $\qquad$ $\vec{E} \xrightarrow{T} \vec{E}$ $\qquad$ d is also T-violating!

CPT: a nonzero EDM means violation of CP as well

Introduction

Studying EDMs we look deep into the origin of CP violation, Baryon Asymmetry, etc.

For neutron, without T-invariance $d_n \sim \mu_n \approx R_N \approx 2\cdot 10^{-14} e\cdot cm$

Experimental bound $|d_n| < 2.9\cdot 10^{-26} e\cdot cm$ (90% C.L.)

A sensitive probe!

CP violation in the Standard Model

$$L_{\rm QCD} = -\frac{1}{4}\mathrm{Tr}\, G_{\mu\nu}^2 + \sum_q \bar{q}(i\not{D} - m_q)q + \vartheta \frac{g_s^2}{16\pi^2}\mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$\vec{E}\cdot\vec{B}$

ϑ-term is P- and T-odd. T-violation in strong interaction, hence naively $d_n \sim \vartheta\cdot 10^{-14}\mathrm{e}\cdot\mathrm{cm}$ (not too wrong)

Upshot of the highly nontrivial story:
In gluodynamics and in QCD ϑ-term is observable; ϑ is not renormalized. Yet with light flavors its effect is proportional to $\bar{m}_q = (1/m_u + 1/m_d + 1/m_s)^{-1}$. We know $m_{u,d} \neq 0$, $m_u + m_d \approx 8\,\mathrm{MeV}$, and

$$d_n \propto \vartheta \bar{m}_q(\ln \bar{m}_q + \mathrm{const}) \approx \vartheta\cdot 2.5\cdot 10^{-16} e\cdot cm$$

Hence $|\vartheta| < \text{few} \times 10^{-10}$ Too small! Exactly zero?
notorious Strong CP problem

One solution – dynamic relaxation like Peccei-Quinn axion mechanism
Assume effective $\vartheta = 0$

CP from electroweak sector

Originate from Yukawa couplings along with quark mixing itself.
When using the unitary gauge CP resides in the $W^{\pm}$ vertices:

$$L_w = \frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu, \quad J_\mu = \sum_{i,j} V_{ij}\, \bar{u}_i \gamma_\mu (1-\gamma_5) d_j, \quad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

T or CP involve complex conjugation, therefore CP-violation requires complexities. Only the amplitudes from (to) the same flavor states can interfere, therefore we always probe products like

$$V_{ud}^* V_{cd} V_{cb}^* V_{ub}, \quad \text{e.g. } \Delta = \mathrm{Im}\, V_{cs}^* V_{us} V_{cd}^* V_{ud} \simeq 3.4 \cdot 10^{-5}$$

Unitarity of V makes them real for 2×2 matrices, yet are described by a single CP-odd phase in the 3×3 KM case.

KM mechanism roots in flavor-nondiagonal transitions and is mostly manifest in the intricate flavor-changing processes: K^0-, B-decays; D?

Successfully confirmed in K and B. KM CP-violation is '$\mathcal{O}(1)$', yet many conditions must be met, hence large statistics are required

d_n from the KM CP-violation

Flavor-diagonal process! Shaped by strong/electromagnetic forces

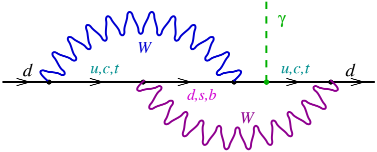
First order in G_F: Hermiticity and $\Delta F = 0$ ensure CP-invariance, hence no effect at $\underbrace{0.2\cdot 10^{-13} e\cdot cm \cdot G_F m_n^2}_{2\cdot 10^{-19} e\cdot cm} \times \Delta \approx 6\cdot 10^{-24} e\cdot cm$

Common argument: CP-violation has to invoke all 3 generations; vanishes if quark masses degenerate. Fair guiding note, yet may be misleading

These are satisfied to order G_F^2, two loop diagrams

Quark EDMs

Historically: quark dipole moments



$$d_n = \frac{4}{3}d_d - \frac{1}{3}d_u \qquad L_{\rm em} = -\frac{d}{2}\bar\psi\sigma_{\mu\nu}F^{\mu\nu}\gamma_5\psi \qquad d_q \sim \underbrace{m_q \frac{G_F^2 m_c^2}{64\pi^4}}_{5\cdot 10^{-30} e\cdot cm} \Delta$$

Sum of all 2-loop diagrams for d_q vanishes — Shabalin, 1978

Effect emerges at 3 loops, need an extra gluon — Khriplovich 1986, Czarnecki, Krause 1997

$$d_d = e\frac{m_d\alpha_s G_F^2 m_c^2}{108\pi^5}\left[\ln^2\frac{m_b^2}{m_c^2}\ln\frac{M_W^2}{m_b^2} + \ldots\right] \approx -0.3\cdot 10^{-34} e\cdot cm$$

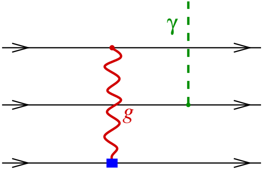
bring a factor $-0.2\ldots$

$m_{u,d}$ cost a factor of $\lesssim 1/50$ inevitable in d_q due to chirality flip

Other operators

CP violation can be passed to strong forces inside or between hadrons
The color EDMs $-\frac{d_c}{2}\bar{q}\sigma_{\mu\nu}G^{\mu\nu}\gamma_5 q$ were earliest considered

The same suppressions apply: 3 loops, $d_q \propto m_q$



Non-diagonal EDMs (color EDMs) for $d \to s$ transitions, they contain m_s, 15 times larger. Right-handed s weakly interacts via Penguins (short diastances) or enters through chiral symmetry breaking, e.g. $\langle \bar{s}s \rangle$ (long distances).

Examples of long-distance effects with strange intermediate states

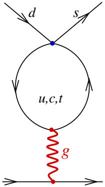
Gavela et al., Khriplovich et al. early 1980s

Still rather small; status was not clear (cancellations; double counting)

Bound-state long-distance effects

A better way to overcome the $\Delta F = 0$ and heavy-flavor sensitivity constraints was long-distance strangeness effects using Penguins

$$\frac{G_F}{\sqrt{2}}\frac{\alpha_s}{3\pi}\left(\bar{s}\Gamma_\mu \frac{\lambda^a}{2} d\right)\left(\bar{q}\gamma_\nu \frac{\lambda^a}{2} q\right)$$



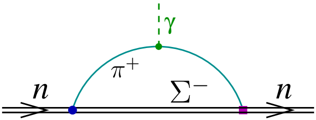


Diagram often quoted as dominating although for no good reason: pion vertex vanishes at small momentum

Estimated to yield $d_n \approx 10^{-32} e \cdot cm$, although the size is always questioned

Suppression beyond $G_F^2 \Delta$ due to perturbative loop factors, for Penguins in particular: numerically small in the perturbative regime

Is it possible to bypass them?

Tree-level d_n

Mannel, N.U. arXiv:1202.627

CP violation appears to the second order in L_w:

$$\mathcal{L}_2 = \frac{G_F^2}{2}\int \mathrm{d}^4x\, \tfrac{1}{2} iT\left\{\mathcal{L}_w(x)\,\mathcal{L}_w(0)\right\} \qquad\qquad \Gamma_\mu = \gamma_\mu(1-\gamma_5)$$

In nucleon t and b are irrelevant – integrate them out. A bit trickier than in meson mixing, but at tree level means simply cross them out!

$$\mathcal{L}_w = J_\mu^\dagger J^\mu, \qquad J_\mu = V_{cs}\,\bar{c}\Gamma_\mu s + V_{cd}\,\bar{c}\Gamma_\mu d + V_{us}\,\bar{u}\Gamma_\mu s + V_{ud}\,\bar{u}\Gamma_\mu d$$

Two-generation Cabibbo case? Not quite, the 2×2 matrix V is not unitary, all phases cannot be removed:

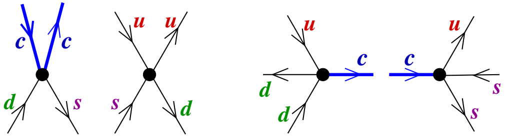
$$\Delta = \mathrm{Im}\, V_{cs}^* V_{cd} V_{ud}^* V_{us} \neq 0$$

$\mathcal{L}_2$ contains 256 terms, but only 64 for $\Delta F = 0$. Most are CP-even like $(\bar{s}u)(\bar{u}s)$. Only a few remain!

Two different 8-quark operators plus their conjugate, both proportional to $V_{cs}^* V_{cd} V_{ud}^* V_{us}$ or to its complex conjugate

Survivors must have both q and $\bar{q}$ for each of four flavors

Differ by which quark pairs, U or D come from the same weak vertex



their eventual effect is different, for in nucleon we need to integrate out charm as well

Where $\bar{c}c$ comes out of $\mathcal{L}_w$ the loop can be closed, this is the conventional Penguin. In another case we do not loop $\bar{d}d$ or $\bar{s}s$, they go into the nucleon wavefunction. It has a single charm propagator, yet highly virtual:

$$\frac{G_F^2}{2} V_{cs}V_{cd}^* V_{ud}V_{us}^* \int \mathrm{d}^4x \; iT\{(\bar{d}\Gamma_\mu c)(\bar{u}\Gamma_\mu d)_0 \cdot (\bar{c}\Gamma_\nu s)(\bar{s}\Gamma_\nu u)_x + \overset{s \leftrightarrow d}{\text{H.c.}}$$

Loopless d_n

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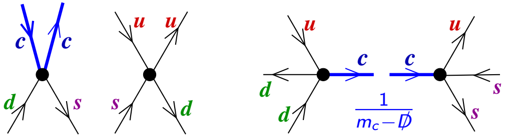

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Results in local OPE in $1/m_c$

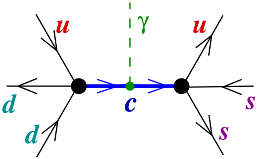
Loopless d_n

$$iT\{c(0)\bar{c}(x)\} = \left(\frac{1}{m_c - i\not{D}}\right)_{0x} = \frac{1}{m_c}\delta^4(x) + \frac{1}{m_c^2}\delta^4(x)\, i\not{D} + \frac{1}{m_c^3}\delta^4(x)\,(i\not{D})^2 + \ldots$$

sandwiched between $\gamma_\mu(1-\gamma_5)$ and $\gamma_\nu(1-\gamma_5)$ only $1/m_c^2$, $1/m_c^4$, ... survive

$$\tilde{\mathcal{L}}_- = -i\frac{G_F^2\Delta}{2m_c^2}\,\tilde{O}_{uds} = -i\frac{G_F^2\Delta}{2m_c^2}\left[(\bar{u}\Gamma^\mu d)\,(\bar{d}\Gamma_\mu i\not{D}\Gamma_\nu s)\,(\bar{s}\Gamma^\nu u) - (s \leftrightarrow d)\right]$$

$i\not{D}$ contains photon field, $i\not{D} = i\not{D}_{\rm QCD} + \frac{2}{3}e\not{A}$ yielding



$$O^\alpha_{uds} = (\bar{u}\gamma^\mu(1-\gamma_5)s)\,(\bar{s}\gamma_\mu i\gamma^\alpha\gamma_\nu(1-\gamma_5)d)\,(\bar{d}\gamma^\nu(1-\gamma_5)u) - (s \leftrightarrow d)$$

$$A_\alpha\mathcal{L}^\alpha_- = -e\, i\Delta\frac{G_F^2}{m_c^2}A_\alpha\left[\frac{2}{3}O^\alpha_{uds} + \int \mathrm{d}^4x\; iT\{O_{uds}(0)\; J^\alpha_{\rm em}(x)\}\right]$$

Contact vertex and non-local T-product reflect different scales, yet for $(V-A)\times(V-A)$ turn out of the same order $1/m_c^2$

Finite in the chiral limit $\Rightarrow$ no m_q-suppresssion

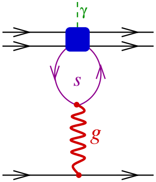
Does not depend on $m_s - m_d$. CKM folklore: CP-odd effects must vanish in the $SU(3)$ approximation. In fact, does not need to!*

d_n vanishes if $m_c = m_t$

CP-odd operator contains $\bar{s}s$ $\Rightarrow$ d_n would vanish in the valence approximation – yet it is not a property of the QCD nucleon

$\langle N|\bar{s}s|N\rangle \approx 1$ vs. $\langle n|\bar{u}u|n\rangle \approx 3$

Does not need to vanish even in the quenched approximation



Becomes explicit in the large-N_c picture of nucleons: quantized states of the soliton of the pion/kaon field

Witten et al., 1983

Role of $\bar{s}s$ operators is given by certain Clebsh-Gordan factors of $SU(3)_{\rm fl}$

*more comments on $m_s = m_d$ later

Nucleon matrix elements

Difficult... Good thing: O_{uds} and O^{α}_{uds} are well defined despite high dimension. Special structure, in particular $s \leftrightarrow d$ antisymmetry, do not mix with lower-dimension operators

$$\langle n(p+q)|\mathcal{L}^{\mu}_{-}|n(p)\rangle = -d_n\, q_\nu\, \bar{u}_n(p+q)\sigma^{\mu\nu}\gamma_5 u_n(p)$$

There are ideas exploiting large N_c, similar to Skyrme/Witten treatment, or its dynamic counterpart in the instanton liquid picture. O^{α}_{uds} is a product of three left-handed flavor currents

Hope in the future to predict not only scale but also sign

At the moment try to estimate the scale, using dimensional arguments

$$\langle n|(\bar{u}_L\gamma^{\alpha}s_L)\,(\bar{s}_L\gamma_\alpha\gamma^\mu\gamma_\beta d_L)\,(\bar{d}_L\gamma^{\beta}u_L) - (d\leftrightarrow s)|n\rangle = -2i\mathcal{K}_{uds}\, q_\nu\, \bar{n}\sigma^{\mu\nu}\gamma_5 n$$

$$|\mathcal{K}_{uds}| \approx \kappa\, \mu^5_{\rm hadr} \qquad\qquad \kappa \;-\; \textit{strangeness suppression, } \sim 1/3$$

Typical momenta in hadrons are $\gtrsim$600 MeV – yet taking $\mu_{\rm hadr} \approx 0.5$ GeV would grossly overestimate $d_n \propto \mu^5_{\rm hadr}$

Matrix elements

$$-\langle\bar{q}q\rangle \approx (250\,\mathrm{MeV})^3 \quad \text{yet} \quad \langle\bar{q}(iD)^2 q\rangle \approx (0.65\,\mathrm{GeV})^2\langle\bar{q}q\rangle$$

Each $\bar{q}q$ intrinsically contains $N_c/8\pi^2$ on top of $k_{\rm max}^3$. $1/8\pi^2$ comes from Fourier when converting momentum into coordinates, this reduces the apparent scale. These factors are explicit in f_π, μ_N, $\langle r^2\rangle$, etc.

We have three $\bar{q}q$ in the operator, hence the factors are significant

Rules:

- $\langle n|\bar{q}q|n\rangle = 1$
- Each additional $\bar{q}q$ adds $\mu_\psi^3 = (0.25\,\mathrm{GeV})^3$
- The remaining dimension is made up of $\mu_{\rm hadr} \approx 0.5\,\mathrm{GeV}$

Matrix elements

Applying this to d_n, the contact photon operator yields

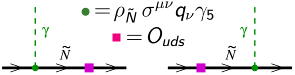
$$|d_n| = \frac{32}{3} e \, \frac{G_F^2 \Delta}{m_c^2} |\mathcal{K}_{uds}| \approx 3.3 \cdot 10^{-31} e{\cdot}\mathrm{cm} \times \kappa \left(\frac{\mu_\psi}{0.25\,\mathrm{GeV}}\right)^6 \left(\frac{0.5\,\mathrm{GeV}}{\mu_{\rm hadr}}\right)$$

Non-local T-product: dimension is the same, the naive estimate would be the same (less factor 2/3). Different once do more accurately:

$$|d_n|^{(T)} \approx 32 e \, \frac{G_F^2 \Delta}{m_c^2} \kappa \, \mu_\psi^9 \, \mu_{\rm hadr}^{-4} \approx 1.2 \cdot 10^{-31} e{\cdot}\mathrm{cm} \times \kappa \left(\frac{\mu_\psi}{0.25\,\mathrm{GeV}}\right)^9 \left(\frac{0.5\,\mathrm{GeV}}{\mu_{\rm hadr}}\right)^4$$

numerically not too far away

Alternatively, the contribution of the $\frac{1}{2}^-$ excited nucleon $\tilde{N}$, $N(1535)$



From $\Gamma(\tilde{N} \to n\gamma) \approx 0.38\,\mathrm{MeV}$ $\quad \rho_{\tilde{N}} \approx 0.34\,\mathrm{GeV}^{-1}$

$$|d_n|^{(\tilde{N})} \approx 32 e \, \frac{G_F^2 \Delta}{m_c^2} \kappa \, \mu_\psi^6 \, \mu_{\rm hadr} \, \frac{\rho_{\tilde{N}}}{M_{\tilde{N}} - M_n} \approx 1.4 \cdot 10^{-31} e{\cdot}\mathrm{cm} \times \kappa$$

Quite consistent!

d_n, summary

With $\kappa = 1/3$ the loop-less estimate would be around

$$|d_n| \approx 10^{-31} \mathrm{e{\cdot}cm}$$

with the local photon contribution dominating
Even 5 to 10 times larger d_n may not be excluded

All short-distance loops have been neglected. They exist inducing different color flow and renormalizing strength, $c_\pm$. The structure is the same, most notably $s \leftrightarrow d$ antisymmetry

Penguins: no qualitative change either in spite of right-handed currents (mostly affect the conventional contribution). All potential effects have counterparts in renormalization of O_{uds} and O^{α}_{uds} themselves

Possibly, moderate enhancement due to $c_- > 1$

The main features: no chiral suppression & independence of $SU(3)$ mass breaking

d_n summary

The principal difference with conventional long-distance effects: no hard loops involved. This is the reason they may dominate

Descending below m_b charm quarks have to show up for CP violation to be seen

No charm in nucleon... If we avoid $\bar{c}c$ loops, a price have to be paid in $1/m_c$ suppressions for nonperturbative charm. But it is mild, $p/m_c \gtrsim 0.5$

We encountered similar effects, 'Intrinsic Charm', in inclusive B decays; these were small, mattered only at the highest precision

Bigi et al., 2003; Zwicky et al., 2005; Mannel et al., 2010

Here we sense 'tree nonperturbative charm' vs. virtual charm in the loops. Expansion in $1/m_c$ vs. $1/2m_c$, no loop factors like $\alpha_s(2m_c)$

Left-handed vertices $\Rightarrow$ $1/m_c^2$ suppression

d_n summary

$$d_n \propto \Delta\, G_F^2\, \mu_{\rm hadr}^3 \quad - \quad \text{the top benchmark for the SM}$$

With the loop-less contribution we have

$$d_n \propto \Delta\, G_F^2\, \mu_{\rm hadr}^3 \cdot \frac{\mu_{\rm hadr}^2}{m_c^2} \cdot \kappa$$

unavoidable in one form or another;
in nucleon wavefunction is the softest

Mild overall suppression specific to the SM and its left-handed implementation. No chiral log $\mu_{\rm hadr}^2/m_\pi^2$, no scalar matrix elements – potential loss of a factor of a few

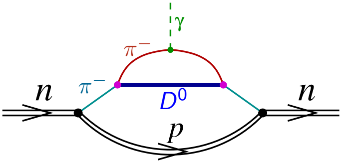
Can be recovered beyond the Standard Model

LHCb: direct CP asymmetry

$$\Delta a_{\rm CP} = a_{\rm CP}(D^0 \to K^+K^-) - a_{\rm CP}(D^0 \to \pi^+\pi^-) \approx -8\cdot 10^{-3}$$ too large?

Connection to d_n: the considered effect came from the product of two $\Delta C=1$, $\Delta S=0$ amplitudes $(\bar{c}u)(\bar{s}s)$ and $(\bar{c}u)(\bar{d}d)$ with different weak phases. This is precisely what drives the 'direct' D-decay asymmetry

Increasing the CP-odd amplitude must boost d_n



Meson diagrams are the worst way to trace the link

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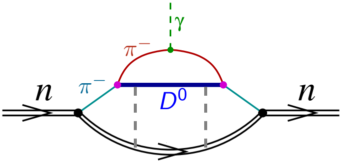

Meson diagrams are the worst way to trace the link; would need extra hadron exchanges...

$D^0 \to K^+K^-/\pi^+\pi^-$ in the SM

$$\mathcal{L} = -\frac{G_F}{\sqrt{2}}\left[\frac{V_{cs}^*V_{us}-V_{cd}^*V_{ud}}{2}\left([\bar{c}\Gamma^\mu u][\bar{s}\Gamma_\mu s] - [\bar{c}\Gamma^\mu u][\bar{d}\Gamma_\mu d]\right) - \right.$$
$$\left.\frac{1}{2}\,V_{cb}^*V_{ub}\left([\bar{c}\Gamma^\mu u][\bar{s}\Gamma_\mu s] + [\bar{c}\Gamma^\mu u][\bar{d}\Gamma_\mu d] - 2[\bar{c}\Gamma^\mu u][\bar{b}\Gamma_\mu b]\right)\right] + \text{H.c.}$$
$$= -\frac{G_F}{\sqrt{2}}\sin\theta_C\cos\theta_C\left[o_1 + \frac{1}{2}re^{-i\gamma}o_2\right] + \text{H.c.} \qquad r\sin\gamma = \tilde{\Delta} = \frac{\Delta}{\sin^2\theta_C\cos^2\theta_C}$$

$o_{1,2}$ are U-spin triplet and singlet, respectively (symmetry $s \leftrightarrow d$)

$$A(D^0 \to f) = -i\frac{G_F}{\sqrt{2}}\sin\theta_C\cos\theta_C\left[m_1^{(f)} + \frac{1}{2}re^{-i\gamma}m_2^{(f)}\right] \quad \text{and} \quad (r \ll 1)$$

$$a_{\rm CP}^{(f)} = \tilde{\Delta}\frac{m_2^{(f)}}{m_1^{(f)}}\sin\delta_{21}^{(f)} \leftarrow \text{FSI} \qquad \tilde{\Delta} \simeq 0.73\cdot 10^{-3}$$

Typically each $a_{\rm CP} \lesssim 0.7\cdot 10^{-3}$, the sum of the two $\lesssim 1.5\cdot 10^{-3}$ vs. $8\cdot 10^{-3}$ from LHCb $\Rightarrow$ must have $m_2 > 5m_1$

m_1 is not suppressed: $|m_1^{K^+K^-}| = 0.464\ \text{GeV}^3$, $|m_1^{\pi^+\pi^-}| = 0.256\ \text{GeV}^3$

Agree with the simple-minded factorization

Another point: in a valence approximation the same piece in o_1 and in o_2, $\bar{s}s$ or $\bar{d}d$, contributes a given final state. Hence FSI phase is the same, $\delta_{21}=0$ regardless of factorization double shield

Not a proof, yet a consideration

Adopt the viewpoint: the enhanced CP asymmetry comes from New Physics

NP would bring in many effects: renormalization of ϑ, quark EDM, CEDM, FCNC and CP-odd flavor-diagonal local operators, ... – all at the NP scale

Depend on arbitrary details at high scale. Strongly constrained by EDMs

May be suppressed by the CKM-like origin; probably flavor-antisymmetric structure, at least for CP-odd mediators

We do not speculate on the underlying details Giudice et al., arXiv:1201.6204

Contributions at different scales are physically distinct, cannot cancel other than accidentally

Consider what is generated around the charm scale

Assume: a CP-odd NP amplitude with $\Delta C = 1$, $\Delta S = 0$
its CP-even part is much smaller than $|A_1|$
neglect the SM contribution to $a_{\rm CP}$ altogether

$$a_{\rm CP}(D^0 \to f) = -2 \left| \frac{\mathrm{Im}\, g_{\rm np}\, m_{\rm np}^{(f)}}{m_1^{(f)}} \right| \sin \delta_{\rm np}^{(f)}$$

Do not stretch uncertainties, discard extreme parameter ranges

with 'natural' normalization $m_{\rm np}^{(f)} \approx m_1^{(f)}$ would need $|\mathrm{Im}\, g_{\rm np}| \sim (2 \div 5) \cdot 10^{-3}$

$$-1.9 \frac{\mathrm{Im}\, g_{\rm np}\, m_{\rm np}^{K^+K^-}}{10^{-3}\,\mathrm{GeV}^3} \sin\delta_{\rm np}^{K^+K^-} + 1.05 \frac{\mathrm{Im}\, g_{\rm np}\, m_{\rm np}^{\pi^+\pi^-}}{10^{-3}\,\mathrm{GeV}^3} \sin\delta_{\rm np}^{\pi^+\pi^-} = \frac{-\Delta a_{\rm CP}}{8.2 \cdot 10^{-3}}$$

Roughly, $A_{\rm np}^{(-)} \approx 10 A_2^{\rm SM}$ hence a $\gtrsim 10$-fold enhancement of d_n

In fact, rather a factor of 20 to 200

Plenty of $\Delta C = 1$ operators, even with $D \le 6$ – chiral, color, flavor content

Scalar operators do not induce KK or $\pi\pi$ decays $\Rightarrow$ can be large. Must be checked in other modes like $\rho^+\pi^-$

New Physics

$$O_1 = e m_c \bar{c}\, \sigma_{\alpha\beta} F^{\alpha\beta} \gamma_5 u \qquad O_2 = g_s m_c \bar{c}\, \sigma_{\alpha\beta} G^{\alpha\beta} \gamma_5 u$$

$$O_3 = [\bar{c}\Gamma_\mu u]([\bar{s}\Gamma^\mu s] + [\bar{d}\Gamma^\mu d]) \qquad O_4 = (\bar{c}\gamma_\mu(1+\gamma_5)u)\,(\bar{d}\gamma^\mu(1-\gamma_5)d)$$

$$\mathcal{L}_{\rm np} = \frac{G_F}{\sqrt{2}} \sin\theta_C \cos\theta_C \sum_k c_k O_k$$

O_3 is the simplest case: $\mathrm{Im}\, c_3 \simeq 10\frac{\tilde{\Delta}}{2}$ and $d_n^{(3)} \sim 10\, d_n^{\rm SM}$

For others need $\langle \pi^+\pi^- | O_k | D^0 \rangle$ – assume $\sin\delta_{\rm FSI} \approx 1/2$ and need $\langle n | \int d^4x\, iT\{O_k(x) o_1(0)\} | n \rangle_{CP=-1}$

$$d_n \propto \langle n | \int d^4x\, iT\{O_k(x) o_1(0)\} | n \rangle \; / \; \langle \pi^+\pi^- | O_k | D^0 \rangle$$

T-product again reduces $c(0)\bar{c}(x)$ via local OPE. Either odd or even powers of $1/m_c$ survive depending on charm chirality in O_k
Both contact and non-local photon vertices

Have elaborated reasonable estimates for D decays, use factorization for $O_{3,4}$ The above dimensional estimates for d_n

	$-i\langle\pi^+\pi^-\vert O_k\vert D^0\rangle$	$\vert\sin\delta_{\rm FSI}{\rm Im}\, c_k\vert$	$d_n,\; e\cdot cm$
O_1	$8\pi\alpha\, q_d\, f_\pi f_+^{D\to\pi}(0) M_D^2$	$6.8\cdot 10^{-2}$	$2\cdot 10^{-27}$
O_2	$4\pi g_s\sqrt{3}\, f_\pi f_+^{D\to\pi}(0) M_D^2$	$1.7\cdot 10^{-4}$	$8\cdot 10^{-30}$ | $2\cdot 10^{-30}$
O_3	$-f_\pi f_+^{D\to\pi}(0) M_D^2$	$2\;\;\cdot 10^{-3}$	10^{-30}
O_4	$f_\pi f_+^{D\to\pi}(0) M_D^2\, \frac{1}{N_c}\, \frac{m_\pi^2}{2(m_u+m_d)m_c}$	$1.2\cdot 10^{-2}$	$2\cdot 10^{-29}$

$\bar{c}\sigma G u$: $20\, d_n^{(\rm SM)}$ (right-handed charm), $80\, d_n^{(\rm SM)}$ (left-handed charm)

$\bar{c}\sigma F u$: $10^4\, d_n^{(\rm SM)}$

Scaled up o_2: $10\, d_n^{(\rm SM)}$

$(\bar{c}_R u_R)(\bar{d}_L d_L)$: $200\, d_n^{(\rm SM)}$

In all non-$(V{-}A)$ scenarios d_n appears to be typically enhanced

Standard CKM *minimizes* d_n

Direct EDM constraints are safe for the CP asymmetry in D^0

Conclusions

The SM KM mechanism of breaking CP is instructive as an example where the dominant effect in neutron EDM comes not from the effective operators of the lowest dimension

It remains to understand if anything similar is possible in the new physics scenarios

We argue that even in the highly constrained KM mechanism the contribution not requiring short-distance quantum loop corrections plausibly dominates, owing to a relatively light charm quark mass. Rough estimate $d_n \approx 10^{-31}\mathrm{e{\cdot}cm}$ will hopefully be improved providing the prediction for the sign

Observation of an enhanced direct CP asymmetry in D decays would suggests boosting the contribution to d_n from the charm scale. The increase is from 20 to 200 or even larger, depending on details


RECYCLE

On $m_s \to m_d$

CKM *CP* violation: the case of $m_s \to m_d$

General fact: if any quark pair of the same charge becomes degenerate complexities in V_{ij} become unobservable due to an extra $U(2)$ freedom: one can pass from d and s to the combinations d' and s' such that, for instance, $V_{cd}=0$ which is a *CP*-invariant scenario if V is unitary

Would this mean that EDMs must vanish as $m_s \to m_d$? Not necessarily where the external hadronic state has definite D and S flavor

For quarks running in loops there is GIM cancellation indeed, like $\ln m_i^2/m_k^2$ or $(m_i^2 - m_k^2)/M_{\rm ext}^2$. Induced ϑ-term, $GG\tilde{G}$, etc. would vanish. Yet if the external state has d and no s one cannot apply the $U(2)$ symmetry

Physically: the answer is different for $|m_s - m_d| \gg G_F m_c^2\, m_d$ and for $|m_s - m_d| \ll G_F m_c^2\, m_d$

Alternatively, dipole moments *per se* are `not` forbidden in a T-invariant theory. They must vanish for eigenstates of the Hamiltonian, but at $|m_s - m_d| < G_F m_d m_c^2$ these are not the states with definite strangeness, rather the mixtures diagonalizing weak interaction