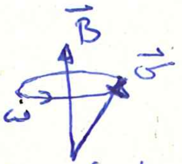
EDM motivation   permanent electric dipole moment

- we would naively expect "large" EDMs in the SM → puzzle
- BSM, hard not to induce large EDMs
- good experiments (precise, complementary)

$$H = -\mu(\vec{\sigma}\cdot\vec{B}) - d(\vec{\sigma}\cdot\vec{E})$$

MDM



$\vec{E}$

$\uparrow\downarrow$

Multipole order	$\not{P}\not{T}$?
E0	M0
E1	M1
E2	M2
E3	M3

spin-1/2 (neutron/electron)

$$\left.\begin{aligned}\Delta E_{MDM} &= 2\mu B\\ \Delta E_{EDM} &= 2\mu E\end{aligned}\right\}\quad d = \frac{\hbar}{4E}(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})$$

MDM from Dirac/QED: $g = 2\left(1 + \frac{\alpha}{2\pi} + \ldots\right)$

~12 digits QED

EDM: $\not{P}\not{T}$, CPT → $\not{CP}$

$P: \vec{\sigma} \to \vec{\sigma}$ but $\vec{E} \sim \partial_0 A_i = \partial_t \vec{A} \to -\vec{E}$

$\vec{B} \sim \epsilon^{ijk}\partial_j A_k \to \vec{B}$

key question: if $\exists$ large $\not{CP}$ then why don't we see EDMs?

electron, muon, neutron, ..., atoms, molecules

QFT Lagrangian: $\mathcal{L} = -\frac{1}{2} C\, \bar{\psi}_L \sigma^{\mu\nu} \psi_R F_{\mu\nu} + \text{h.c.}$

like mass, couples $\psi_{L,R} = \frac{1}{2}(1 \pm \gamma^5)\psi$

non-relativistic limit:

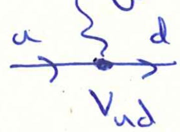
$\mu = \mathrm{Re}\,C$, $d = \mathrm{Im}\,C$ ⇒ need phase to get EDM

constraints on Im C come much more powerfully from precision low-E measurements than from colliders

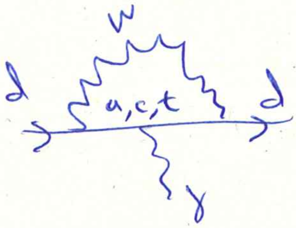
Naively, $[c] = 4 - 2\cdot\frac{3}{2} - 2 = -1$, cf. $\mu_e \sim \frac{1}{m_e}$ ✓ $\frac{eg}{2m_e}$

BSM: soon, cf. scale hierarchy w/ SM

Goal: compute c in SM, start from CKM



EDM of d quark?



one loop

$$M \sim \frac{m_d G_F}{(4\pi)^2} V_{Qd} V^*_{Qd} \qquad Q \sim u,c,t$$

$$\sim \frac{m_d}{m_W^2}$$

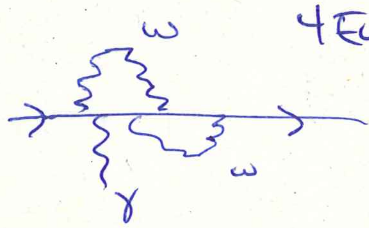
also no interference

m_d external mass from chirality flip

no phase ⇒ no EDM

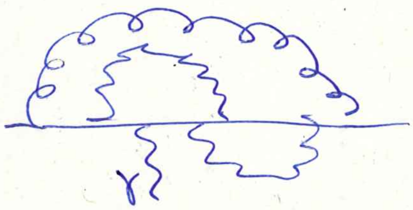
(correction to MDM!)

two loops?



4EW/ all 3 generations... but calculates to zero (not obvious)

three loops?



add gluon

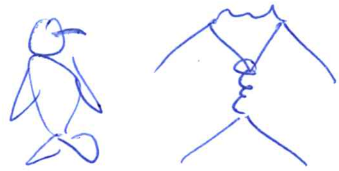
$$d_d \sim \frac{e G_F^2}{(4\pi)^4} \frac{\alpha_s}{4\pi} m_d m_c^2 J_{CP} \sim 10^{-34} \text{ e·cm}$$

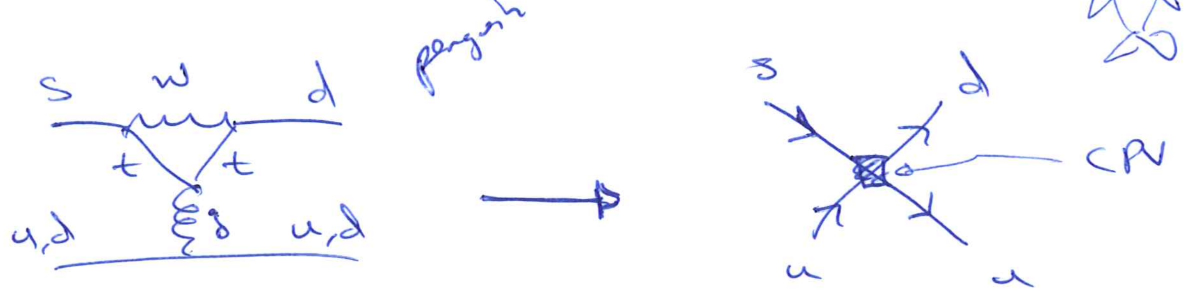
Don't measure d_d directly... measure $|d_n| \leq 10^{-26}$ e·cm

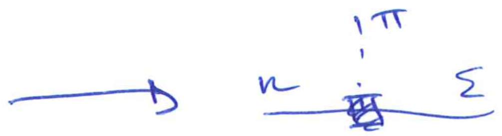
→ d_d is not the right estimate for d_n

Electron: even worse! (Need another loop to go from e^- to quarks)

SM <u>CKM</u> contribution to d_n

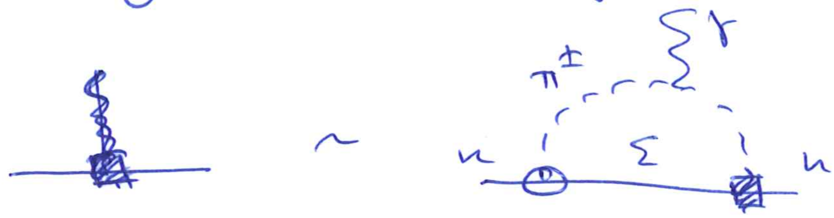






So d_n comes from a strangeness-changing CPV vertex in diagrams with a pion loop:

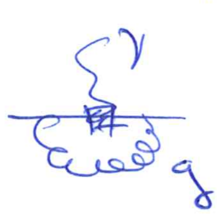
$d_n \sim$



sum to get 4 EW vertices (cf. Jarlskog)

Pion loop enhances $d_{d_\mu} \sim 10^{-34}\ e\cdot\text{cm} \rightarrow d_n(\text{CKM}) \sim 10^{-32\pm1}\ e\cdot\text{cm}$

note also due to running, $d_d(\text{GeV}) \sim 0.3\, d_d(m_W)$



theory w/ quarks $\xrightarrow{\text{(complicated)}}$ theory w/ hadrons

$$\Rightarrow d_n = \underbrace{(\text{a number})}_{\langle N\gamma|\bar{q}\sigma^{\mu\nu}F_{\mu\nu}|N\rangle} \times d_d(1\,\text{GeV})$$

QCD: $\mathcal{L}_\theta = \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} G^a_{\alpha\beta} \epsilon^{\mu\nu\alpha\beta}$

$\mathcal{L}_{QED} \sim F_{\mu\nu} F_{\alpha\beta} \epsilon^{\mu\nu\alpha\beta} \sim \vec{E}\cdot\vec{B}$ is $\cancel{P}\cancel{T}$

<u>but</u> $= \partial_\mu (\epsilon^{\mu\nu\alpha\beta} A_\nu F_{\alpha\beta}) \to 0$

total derivative (boundary term))

in QCD can also write $\mathcal{L}_\theta = \partial_\mu [K^\mu]$ as a total derivative, <u>but</u> in this case it does affect physics

black box $\begin{cases} \text{topological structure QCD} \\ \text{instanton sol'n} \end{cases}$

EW sector: accidental B+L symmetry (U(1)) of SM can be used to rotate ~~θ~~ away phase

EM: Abelian → not here

EW: non-Abelian, but vanishing due to B+L

QCD: non-Abelian, and <u>remains</u>

w/in same framework, $q \to e^{i\alpha\gamma_5} q$

$\mathcal{L} \supset \mathcal{L}_{QCD} - m^* \bar{\theta} \bar{q} i\gamma_5 q \qquad m^* = \frac{m_u m_d}{m_u + m_d}$

$d_n(\bar{\theta}) \sim \frac{e\bar{\theta} m^*}{m_N^2} \sim 10^{-3} \bar{\theta}\ e\text{-fm} = 10^{-16} \bar{\theta}\ e\text{-cm}$

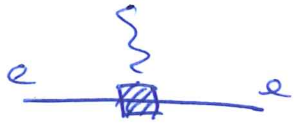
$|d_n| < 10^{-26}\ e\text{-cm} \Rightarrow \bar{\theta} < 10^{-10}$

non other way CKM $\Rightarrow \bar{\theta} \sim 10^{-18}$

Note $\theta > 0.1$
$\Rightarrow$ deuteron binding energy modified
$\Rightarrow$ BBN messed up

BSM :

$\longrightarrow$



at scale Λ at $m_W \sim 100$ GeV

$$\mathcal{L} = C\, \bar{\psi}_L \sigma^{\mu\nu} \psi_R F_{\mu\nu} \qquad [C] = -1$$

$\bar{\psi}_L$: charged under $SU(2)_L$; ψ_R: not

need Higgs to make higher-energy $\mathcal{L}$ gauge-invariant!

$$\mathcal{L} = C\, \bar{\psi}_L \sigma_{\mu\nu} \psi_R B_{\mu\nu} H \qquad [C] = -2$$

Higgs field "turns on" vev at low energy

$$\Rightarrow \quad d \sim \frac{v}{\Lambda^2} \qquad v \sim 246 \text{ GeV}$$

$\hbar c = 200$ MeV·fm

Experimentally, $|d_e| \leq 5 \times 10^{-30}\ e\cdot\text{cm} \sim \dfrac{v}{\Lambda^2}$

$$\Rightarrow \quad \Lambda > 10^6 \text{ TeV} = 1 \text{ EeV}$$

... but we need to be more careful in general!
(details can be important)

$$1 \text{ fm} = 10^{-13} \text{ cm} = \frac{1}{200 \text{ MeV}}$$

$$5\times10^{-30} \, e.\text{cm} = 5\times10^{-17} \, e.\text{fm}$$

$$= 5\times10^{-17} \, e \cdot \frac{1}{200} \text{ MeV}^{-1}$$

$$= 2.5\times10^{-16} \, e \cdot \text{GeV}^{-1}$$

$$\Lambda \sim \sqrt{\frac{v}{d}} > 10^{9} \text{ GeV} = 10^{6} \text{ TeV} = 1 \text{ EeV}$$