Review of Electric Dipole Moments (EDMs)

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Rencontres de Moriond
“ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES”
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Excuse

I am a little surprised since my talk is in the SM session. The SM predictions of EDMs are hard to reach in near-future experiments except finite QCD theta parameter. I think that it would be boring to discuss only sensitivity to QCD theta parameter. Then, I will also include sensitivities to physics beyond the SM.

EDMs

Magnetic and electric dipole moments (MDM and EDM) with spin **S**

$$H = -\mu\ \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\ \mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

Under time(T) and space(P) reflections, EDM is T, P-odd.

$$P : \mathbf{E} \to -\mathbf{E},\ \mathbf{B} \to +\mathbf{B},\ \mathbf{S} \to +\mathbf{S}$$
$$T : \mathbf{E} \to +\mathbf{E},\ \mathbf{B} \to -\mathbf{B},\ \mathbf{S} \to -\mathbf{S}$$

EDMs are sensitive to CP violation in particle physics models under CPT inv.

EDMs sensitive to TeV-scale physics

Upper bounds on electron and neutron EDMs:

$|d_e| < 8.7 \times 10^{-29}$ e cm (ACME, 13) $|d_n| < 2.9 \times 10^{-26}$ e cm (Baker et al, 06)

Dim. analysis for EDM assuming source of CPV is FC:

$$d_e \sim e\frac{m_e}{M^2} = 10^{-23} e\text{cm}\left(\frac{1\text{TeV}}{M}\right)^2$$

(Renormalizable models give an extra suppression of EDMs by loop factors (~$O(10^{-(2\text{-}4)})$).)

EDM measurements would be important whether LHC finds new physics or not.

EDM measurements

Schiff's theorem:
EDM for neutral syst. which composes of non-rel. point particles is zero.

Neutral particle EDMs:

- paramagnetic atoms (Tl, Fr..) /molecules (YbF, ThO, PbO..)

  Sensitive to electron EDM.

  $|d_e|<1.4\times10^{-27}$ (YbF,2012) $\longrightarrow$ 8.7×10^{-29} e cm (ThO,2013)

  Future prospects: $|d_e|\sim10^{-30}$ e cm
- diamagnetic atoms (Sensitive to T, P-odd nuclear force)

  $|d_{Hg}|<3.1\times10^{-29}$ e cm, $|d_{Xe}|<6.6\times10^{-27}$ e cm
- neutron

  $|d_n|<2.9\times10^{-26}$ e cm

  UCN experiments aim to $|d_n|\sim10^{-(27\text{-}28)}$ e cm.

(Flavor-conserving) CP-violating interactions at parton level

$$-\mathcal{L} = \frac{g_s^2\bar{\theta}}{32\pi^2} G\tilde{G} + \sum_{f=u,d,s,e} d_f \frac{i}{2}\bar{f}(\sigma\cdot F)\gamma_5 f + \sum_{q=u,d,s} d_f^c \frac{i}{2}\bar{q}(\sigma\cdot G)\gamma_5 q$$

QCD theta term

Quark and lepton EDMs

Quark CEDMs

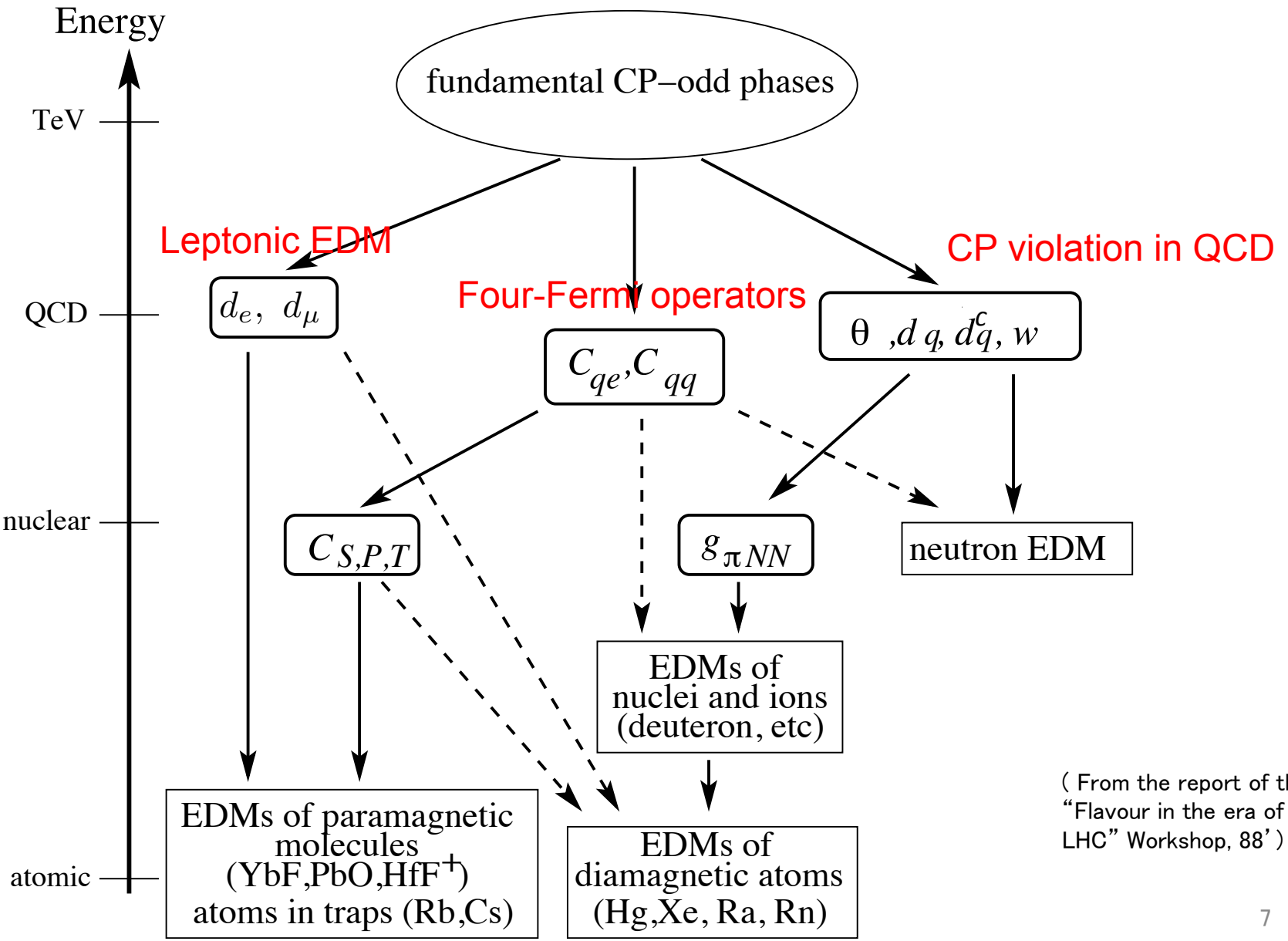
$$+\frac{1}{3}wGG\tilde{G} + \sum_{f,f'=u,d,s,e} (\bar{f}f)(\bar{f}\gamma_5 f)$$

Weinberg op.

4-Fermi

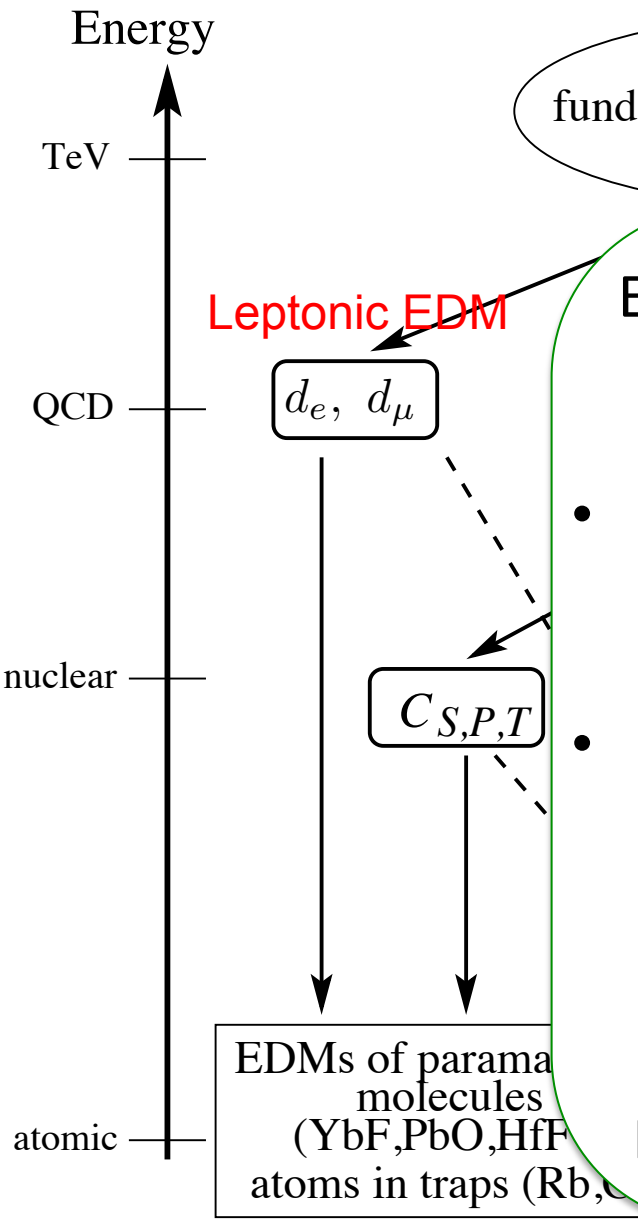
- Wilson coefficients for CP-violating operators depend on CP phases in particle physics models.
- QCD theta is suppressed in Peccei-Quinn mechanism, though it is not zero if CEDMs are non-zero.

Evaluation of EDMs



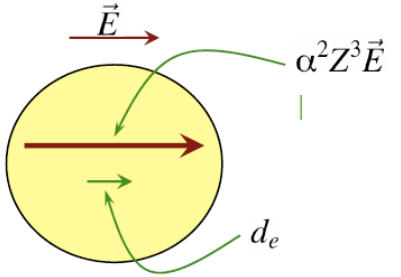
(From the report of the "Flavour in the era of the LHC" Workshop, 88')

Evaluation of EDMs



EDMs for paramagnetic atoms/molecules sensitive to electron EDM

- For high Z atoms, an enhance factor is ~ $\alpha^2 Z^3$ for internal E field.
- Polar molecules, such as ThO and YbF, have larger enhance factors.



4F operators also contribute to them.
Extraction of d_e is talked by Martin Jung.

Evaluation of EDMs

Energy

Neutron EDM

QCD sum rules evaluation

(developed by Pospelov and Ritz)

$$d_n = 1^{+0.5}_{-0.5}(1.4(-0.25d_u + d_d) + 1.1e(0.5d^c_u + d^c_d))$$

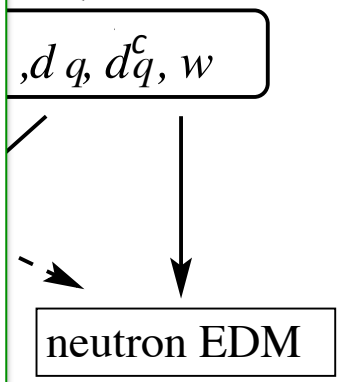
(Pospelov and Ritz)

$$d_n = 1^{+0.8}_{-0.4}(-0.2d_u + 0.8d_d + e(0.3d^c_u + 0.6d^c_d))$$

(JH, Lee, Nagata, Shimizu,
and also JH, Nagata, Fuyuto)

Here, those results are under Peccei-Quinn mechanism for strong CP problem.
We used lattice outputs for LOCs.
We still have factor 2 uncertainties.

CP violation in QCD



atoms in traps (Rb,Cs)

(Hg,Xe, Ra, Rn)

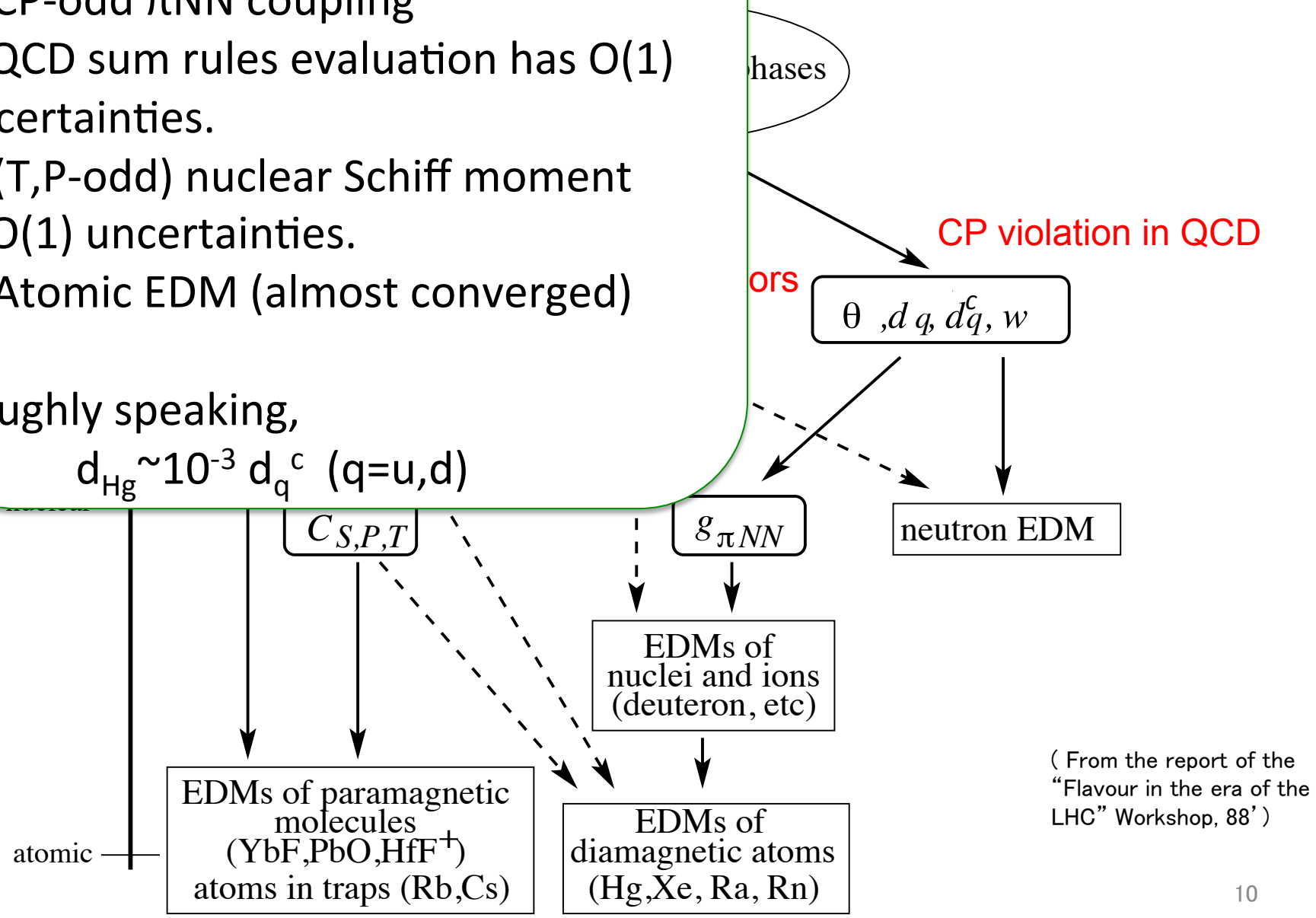
(From the report of the "Flavour in the era of the LHC" Workshop, 88')

Steps to diamagnetic atoms

1. CP-odd πNN coupling
   QCD sum rules evaluation has O(1) uncertainties.
2. (T,P-odd) nuclear Schiff moment
   O(1) uncertainties.
3. Atomic EDM (almost converged)

Roughly speaking,

$d_{Hg} \sim 10^{-3}\, d_q^c$ (q=u,d)

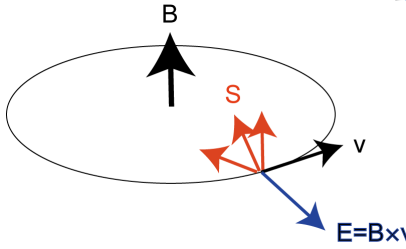


(From the report of the "Flavour in the era of the LHC" Workshop, 88')

New type of EDM measurements

Charged particles in storage rings (new methods):

Strong motional E field for relativistic particles in B field.
Measure of tilt of spin precession plane in E field.



- proton/deuteron

  prospects: $d_p \sim 10^{-29}$ ecm, $d_D \sim 10^{-29}$ ecm.

  Anatomic study of hadronic EDMs would be possible.

  $d_D = (d_p + d_n) + d_D^{NN\pi}$

- muon

  Prospects: $d_\mu \sim 10^{-21}$ ecm (ultimate case, 10^{-24} ecm)

  flavor-blind case: $d_\mu = (m_\mu/m_e) d_e < 2\ 10^{-26}$ ecm

  Larger value may be possible in flavor-violating cases.

SM prediction

The QCD theta parameter contributes to neutron EDM as $d_n \sim 10^{-16}\,\theta$ ecm. Then, $\theta < \sim 10^{-10}$ (called strong CP problem). Peccei-Quinn mechanism?

The CP phase in Kobayashi-Maskawa matrix gives contributions to EDMs, prpto to Jarlskog (rephasing) invariant:

$$J_{\rm CP} = {\rm Im} V_{cs}^{\star} V_{us} V_{cd} V_{ud}^{\star} \sim 10^{-5}$$

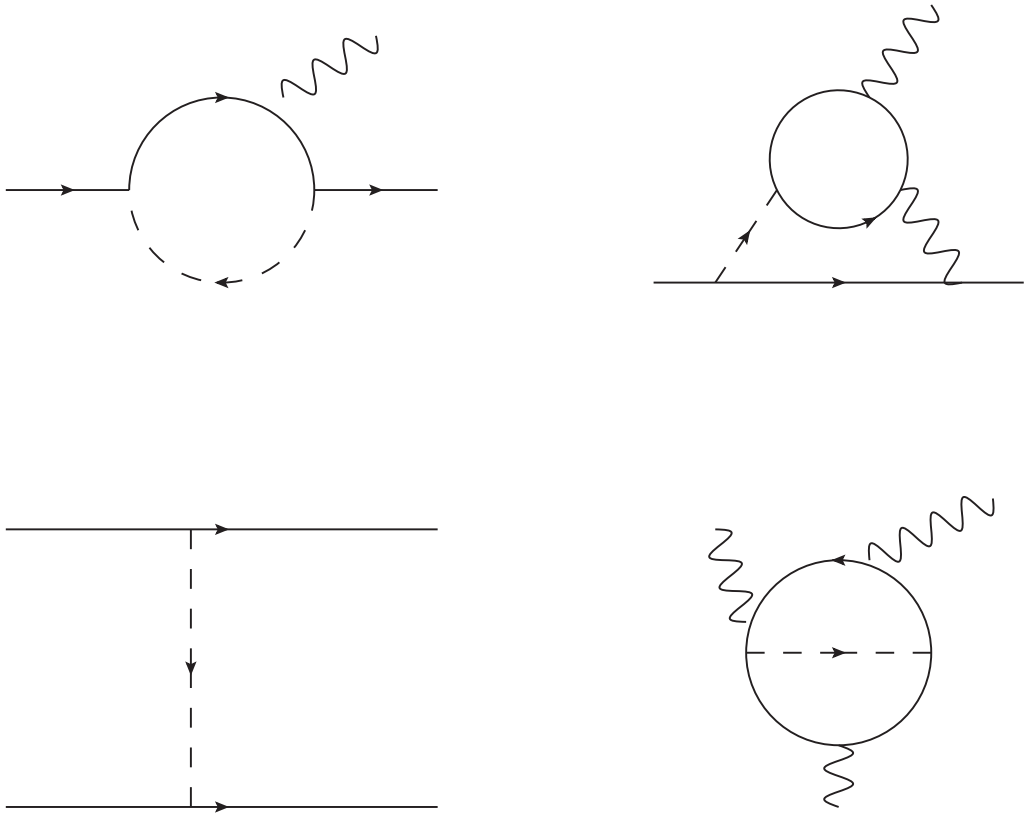
- Quark EDMs

  $d_d \sim 10^{-34}$ e cm (3loops at $O(G_F^2\,\alpha_s)$)
- Neutron EDM

  $d_n \sim 10^{-(31\text{-}32)}$ e cm (long-distance effect at $O(G_F^2)$)
- Electron EDM

  $d_e \sim 10^{-44}$e cm (4loops $O(G_F^3\,\alpha_s)$)

EDMs from BSM



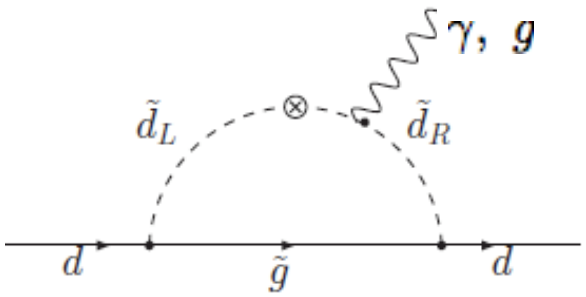
Assuming maximal CP phase, one-loop diagrams for
(C) EDMs give strong constraints to new-physics even above the TeV scale, and even two-loop diagrams can also constrain new physics around TeV scale.

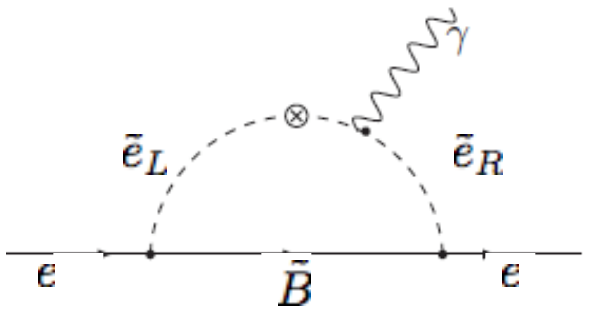
EDMs in supersymmetric standard model

SUSY SM is a leading candidate for BSM. SUSY breaking parameters introduced there are complex so that EDMs are predicted. One-loop diagrams of SUSY particles generate (C)EDMs. Assuming maximal CP violation and degenerate mass spectrum for SUSY particles ,

$$d_e/e \sim 0.6 \times 10^{-26}\mathrm{cm}\left(\frac{M_{SUSY}}{1\mathrm{TeV}}\right)^{-2}\tan\beta$$

$$d_d/e \sim d_d^c \sim 2 \times 10^{-25}\mathrm{cm}\left(\frac{M_{SUSY}}{1\mathrm{TeV}}\right)^{-2}\tan\beta$$



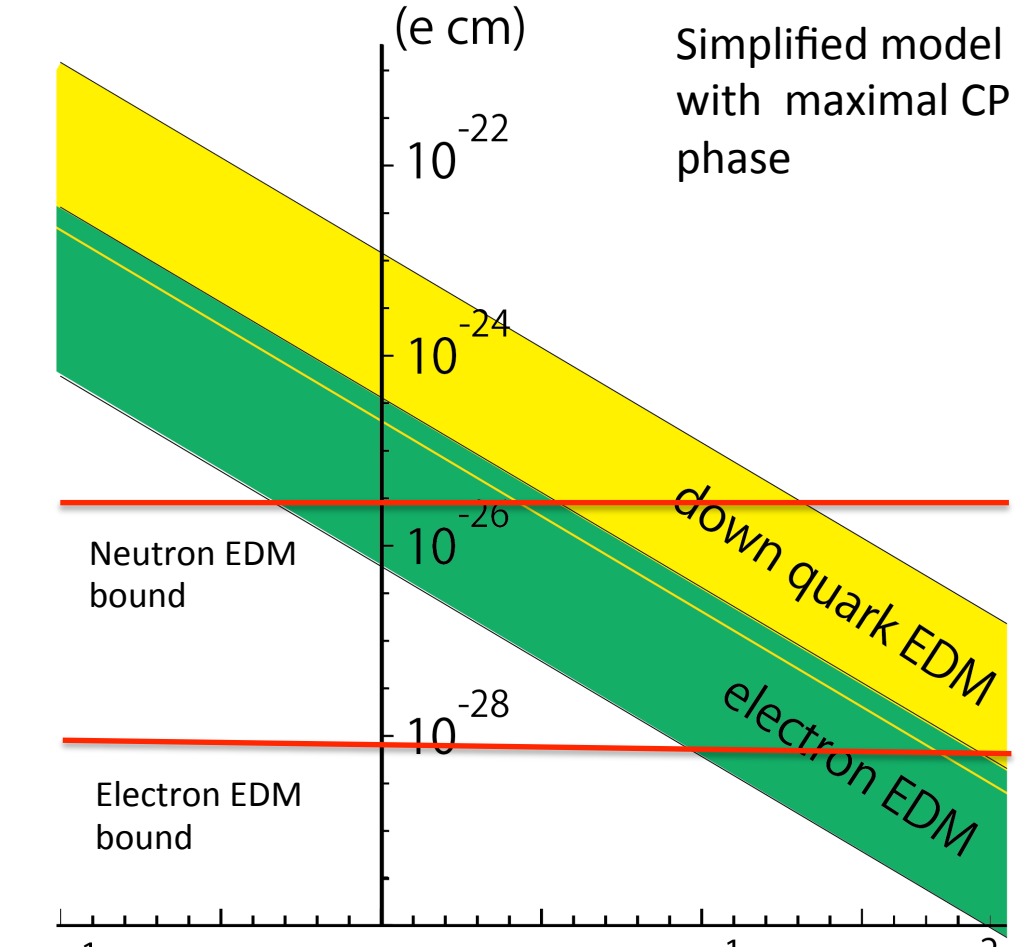


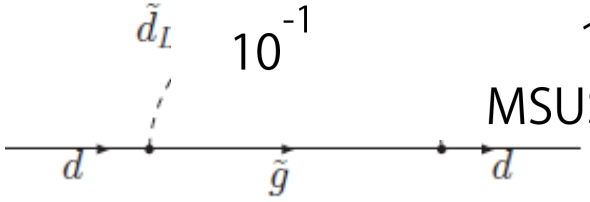
Supersymmetric standard model

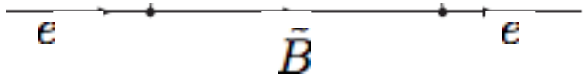
SUSY SM is a … JSY
breaking pa… x so that
EDMs are pr… particles
generate (C… ,

d_e

$d_{d/}$ … 3

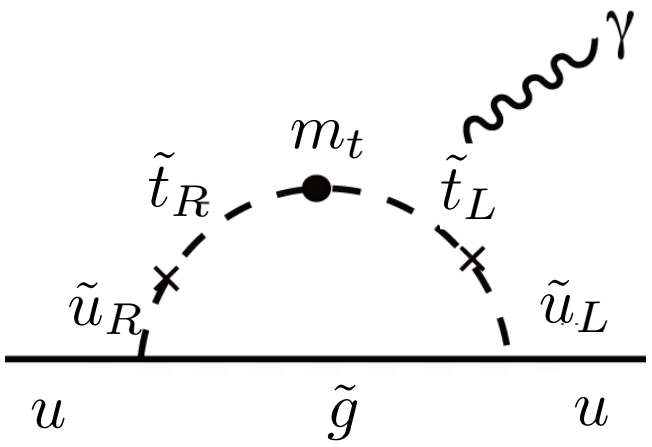


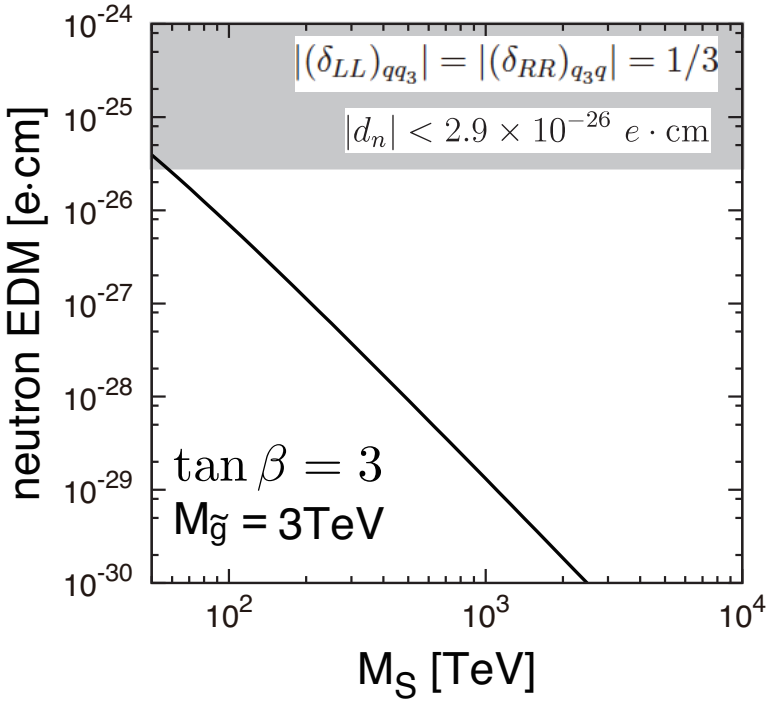




Supersymmetric standard model with flavor violation

When both left-handed and right-handed squarks/sleptons have flavor violation, the relative phases between them contribute to EDMs. EDMs are enhanced by heavier fermion mass.



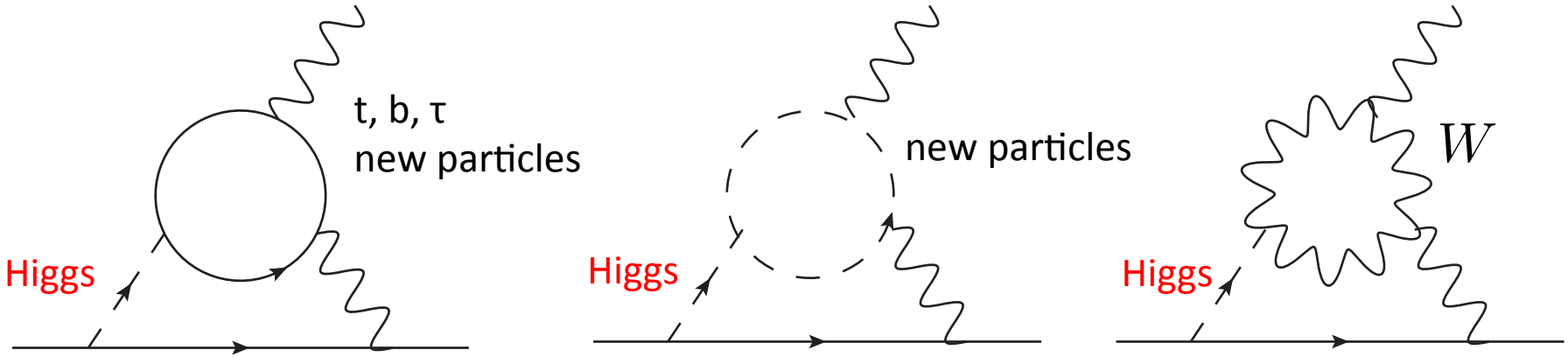


(Fuyuto, JH, Nagata, Tsumura)

Similar recent works:

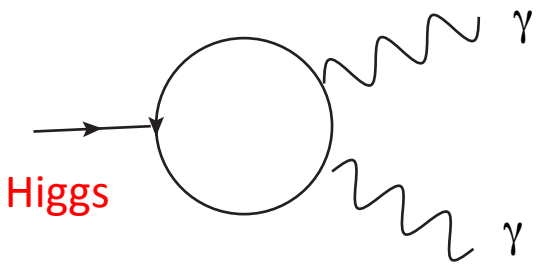
- McKeen, Pospelov, and Ritz
- Moroi and Nagai
- Also talk by Filippo Sala

Higgs-mediated Barr-Zee diagrams



When Higgs boson has CP-violating coupling with SM particles or new particles in BSM, the Barr-Zee diagrams at two-loop level generate (C)EDMs for quarks and leptons.

New (charged) fermions coupled to (discovered) Higgs boson may contribute to both Higgs decay to 2 gammas and also EDMs.

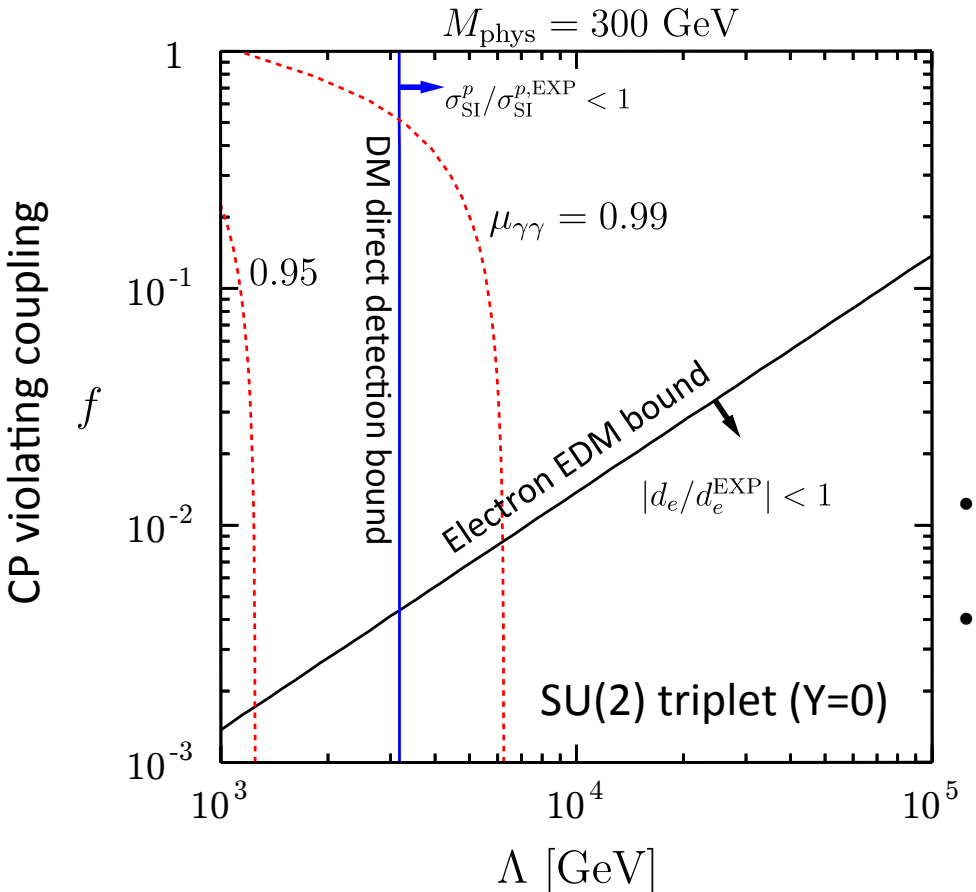


New physics contribution to hγγ and EDMs

SU(2) mutiplet fermions (ψ), whose neutral component is the DM candidate, may have coupling with Higgs boson,

$$\mathcal{L}_H = -\frac{1}{2\Lambda}|H|^2\,\bar{\psi}^c(1+i\gamma_5 f)\psi + h.c..$$

(JH, Kobayashi, Mori, Senaha)



- Gaugino-Higgsino system studied by Giudice and Romanino.
- Recent similar works:
  Fan and Reece.
  McKeen, Pospelov and Ritz.

Summary

- EDMs are sensitive to CP violation in new physics at and beyond TeV scale. The measurements are complimentary to the energy-frontier physics, such as LHC. Due to current null results in new physics searches at LHC, importance of the EDM measurements is increasing.
- Measurements of various EDMs are important to probe source of CP violation.
- Higgs boson properties may be constrained with EDMs induced by Barr-Zee two-loop diagrams.
- Evaluation of hadronic EDMs still has large uncertainties, and more efforts are needed to reduce them.

Thank you very much
for your attention.

Fin.