Probing the TeV scale and beyond with EDMs

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Contents

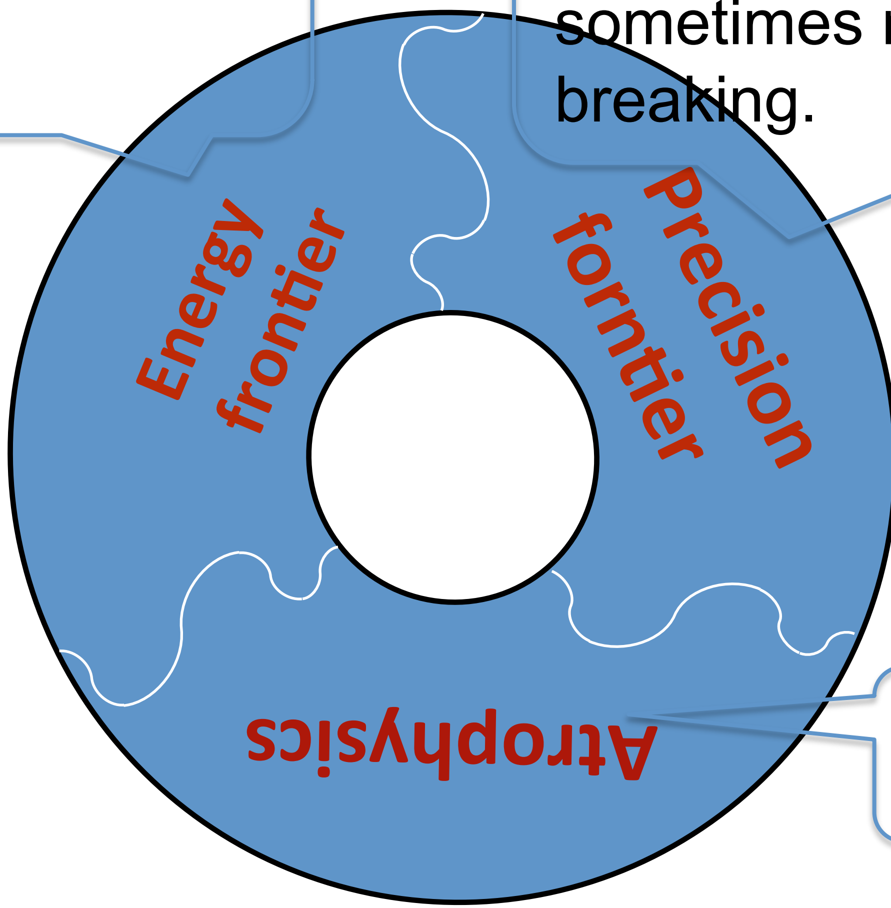
Big issues in particle physics now

1. Is the discovered Higgs particle the SM one?
2. Where is BSM ? TeV scale or higher energy scale?

Tools to probe new physics

Direct search for TeV-scale physics
- LHC
- ILC

- High statistical experiment
- High precise theoretical prediction, sometimes related to symmetry breaking.



- Underground exp.
- Cosmology

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 under CPT inv.

EDMs are good probes to CP violation in particle physics models.

EDMs sensitive to TeV-scale and beyond

Upper bounds on electron and neutron EDMs:

$|d_e| < 8.7\times10^{-29}$ e cm (ACME, 13) $|d_n| < 2.9\times10^{-26}$ e cm (Baker et al, 06)

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

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

$$d_d \sim e\frac{m_d}{M^2} = 10^{-22} e\mathrm{cm}\left(\frac{1\mathrm{TeV}}{M}\right)^2$$

(Renormalizable models give extra suppressions to EDMs by loop factors ($\sim O(10^{-(2\text{-}4)})$).)

EDM measurements would be important even if LHC finds new physics.

Searches for symmetry breaking

Global symmetries in SM are not exact in nature.

- **CP violation (CKM in the SM）**

  EDMs

- **Lepton-flavor violation（neutrino oscillation）**

  Charged lepton flavor-violating decay

- **Lepton and/or baryon number violation (Baryon asymmetry in the universe)**

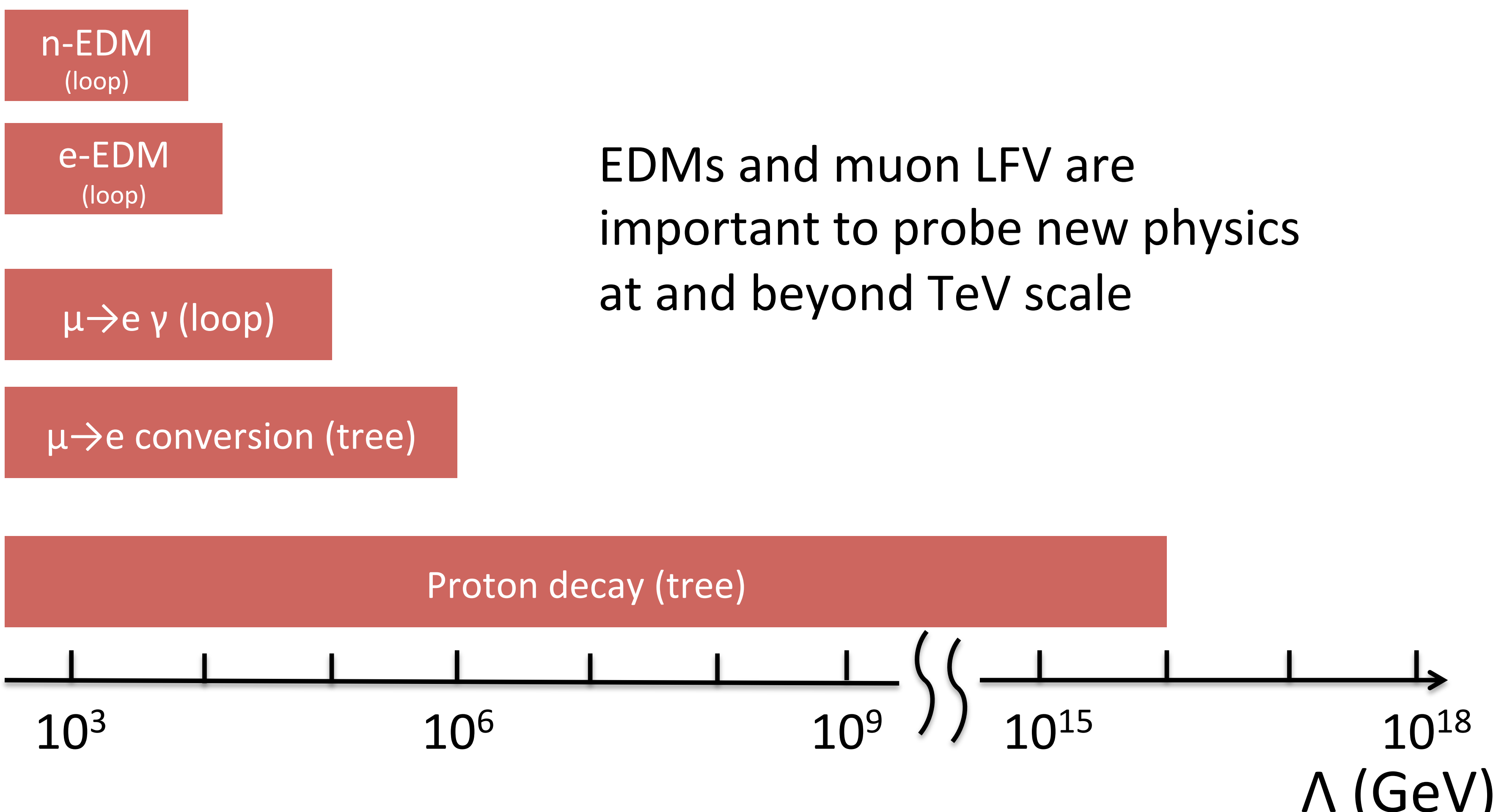
  $0\nu\beta\beta$decay

  Proton decay

Searches for symmetry breaking

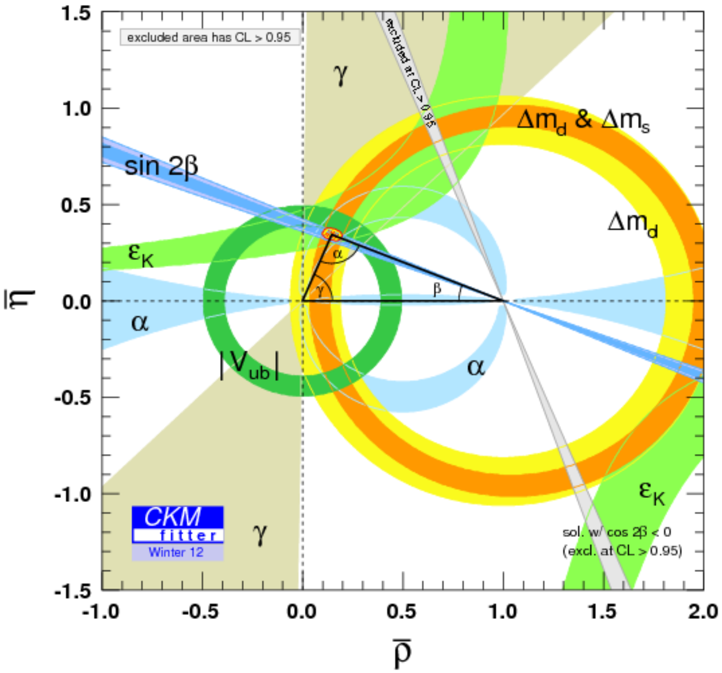
Sensitivities of current experimental bounds on new physics scale (Λ).
Only one loop factors are included for the loop processes.
Small symmetry breaking parameters suppress the sensitivities.

EDMs and muon LFV are
important to probe new physics
at and beyond TeV scale

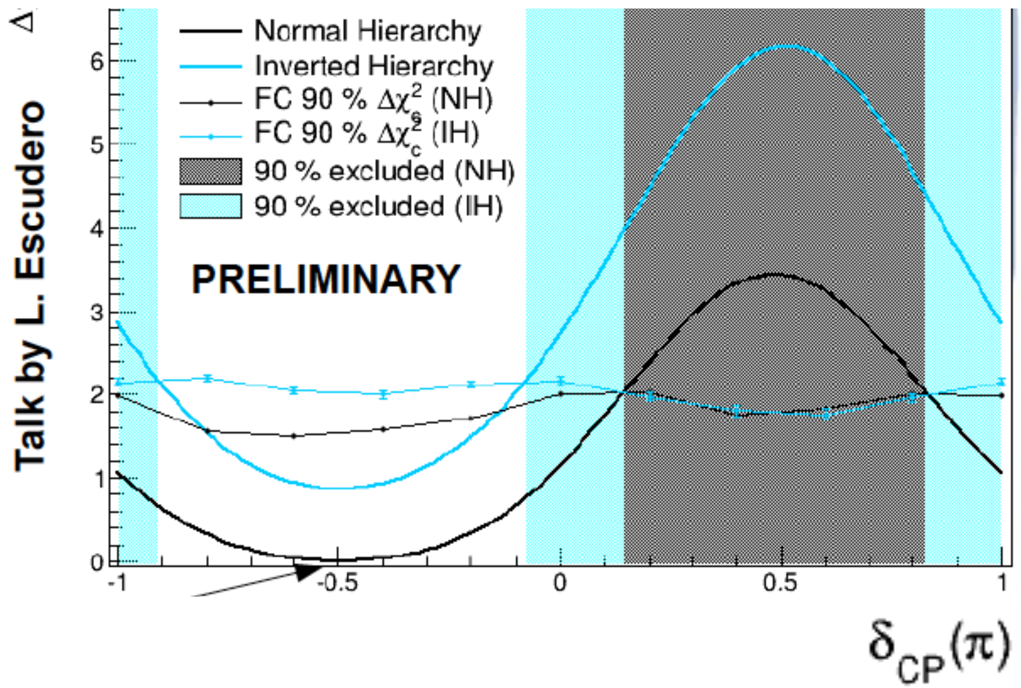


CP phases are naturally O(1) ?

CKM



PMNS



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 $|d_n|\sim10^{-(27-28)}$ e cm.

(Flavor-conserving) CP-violating interactions at parton level up to D=6

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

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.

(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 EDM CEDM

Strong-CP problem: $d_n \sim e\bar{\theta} \times 10^{-(16-17)} e\mathrm{cm}$

The most promising solution is Peccei-Quinn mechanism.

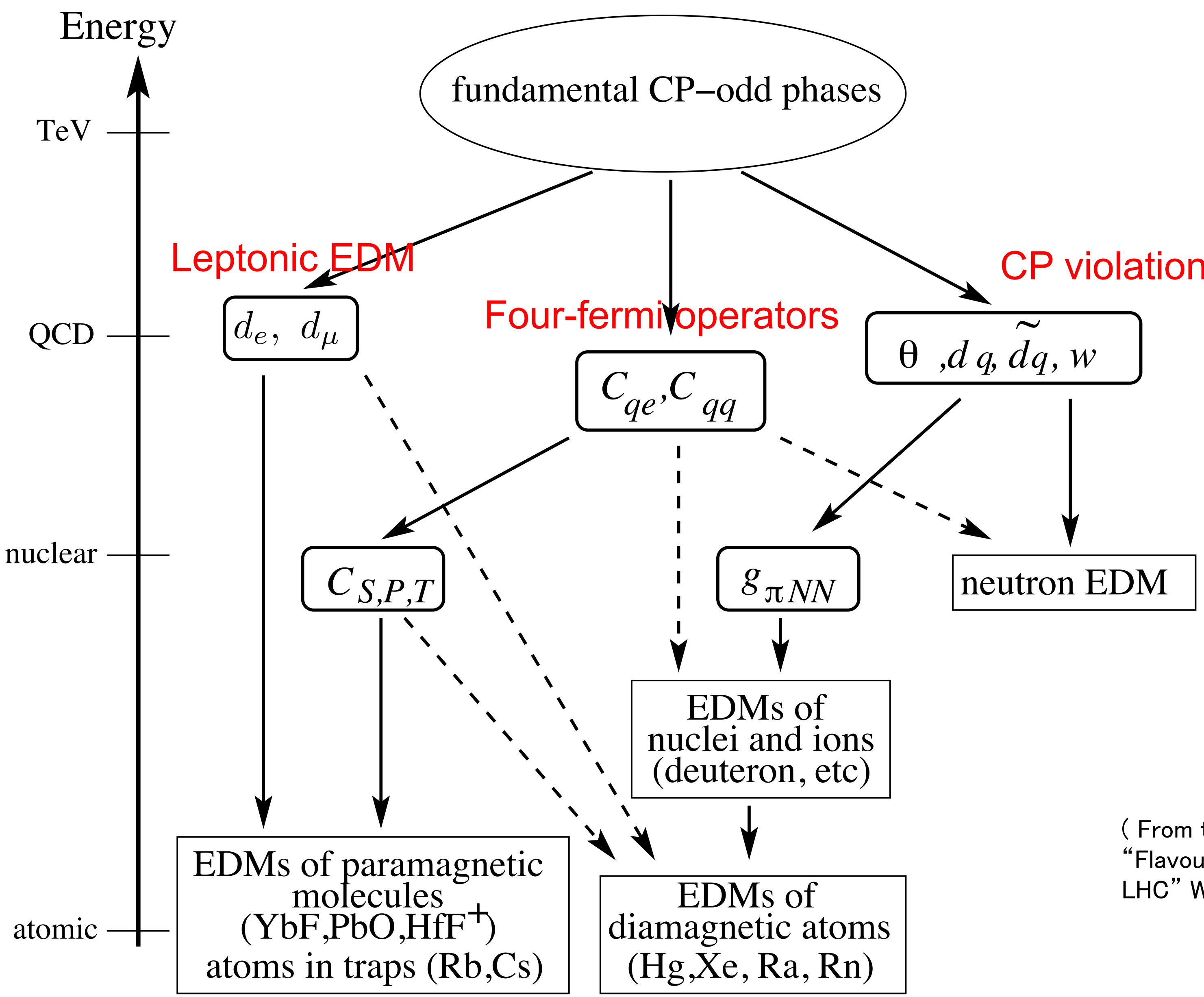
$$\bar{\theta} = \langle S \rangle \simeq 0 \quad (S : \mathrm{axion})$$

Though, the effective theta is generated if there is CP violation in QCD, since the tad pole term for S is generated. (Bigi&Uraltsev)

For example, $\bar{\theta}^{\mathrm{eff}} = m_0^2/2 \sum_q d_q^c/m_q$. $(m_0^2 = 0.8\mathrm{GeV}^2)$

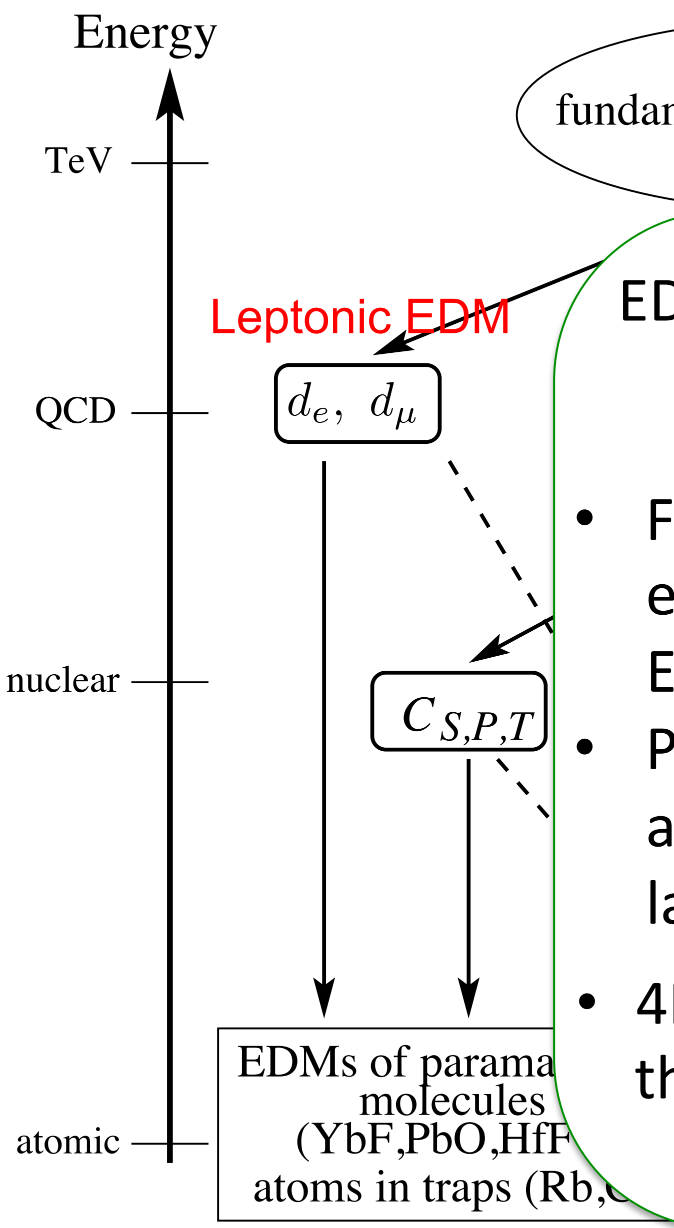
Other proposal: spontaneous CPV, vanishing quark mass.

Evaluation of EDMs



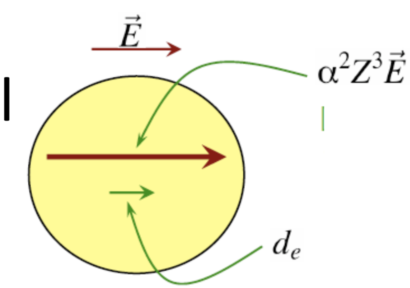
(From the report of the "Flavour in the era of the LHC" Workshop, 88')

Evaluation of EDMs



EDMs for paramagnetic atoms/molecules sensitive to electron EDM

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



- 4F operators (eeqq) also contribute to them.

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

$,d\ q,\ d^c_q,\ w$

neutron EDM

atoms in traps (Rb,Cs)

...atoms
(Hg,Xe, Ra, Rn)

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

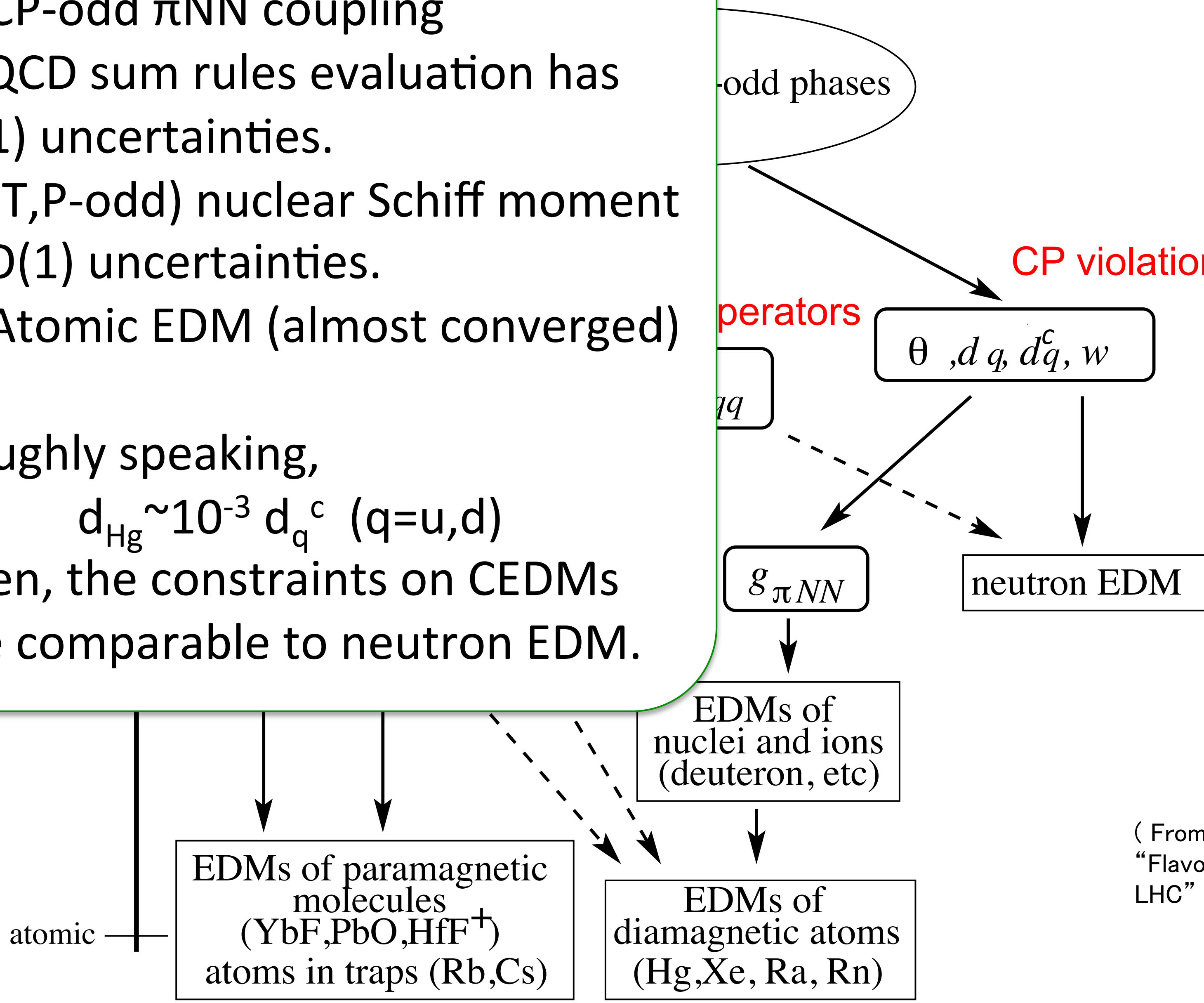
Steps to diamagnetic atoms

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,

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

Then, the constraints on CEDMs are comparable to neutron EDM.



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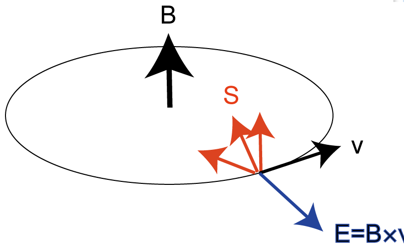
New type of EDM measurements

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 might be possible in flavor-violating cases.

SM prediction

In the SM, origin of CP violation is a phase in Kobayashi-Maskawa matrix (except for QCD theta term). CPV obs. are 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

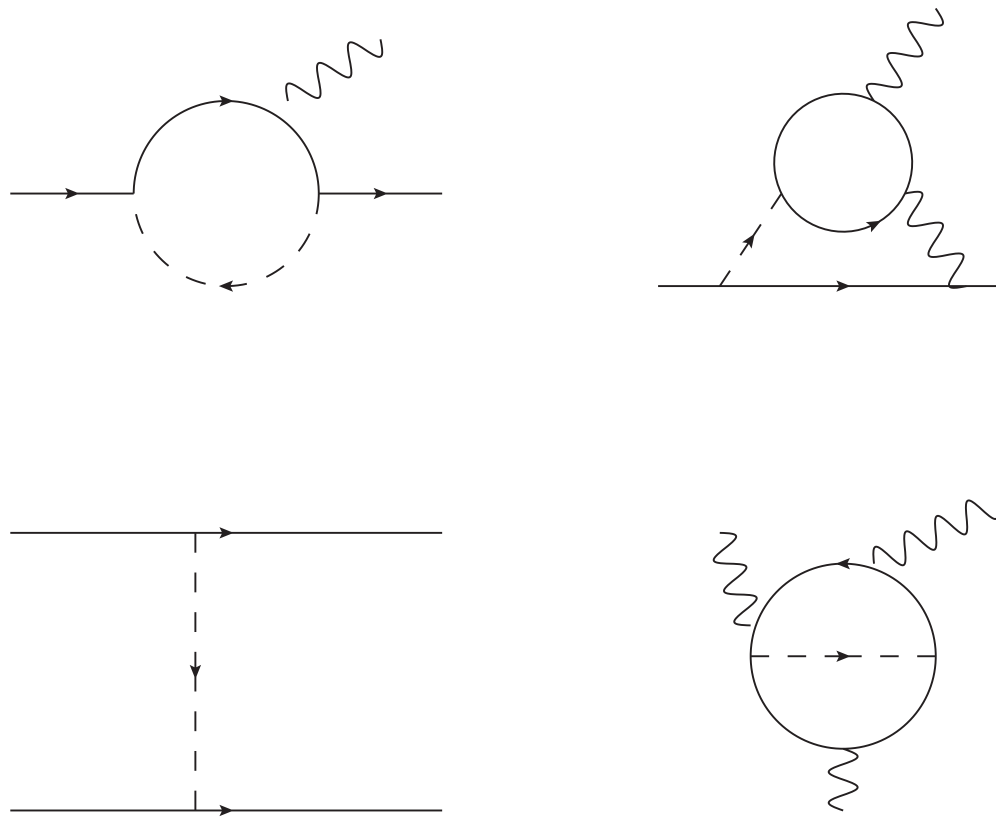
  $d_n \sim 10^{-(31\text{-}32)}$ e cm (long-distance effect at $O(G_F^2)$)

- Electron EDM

  $d_e \sim 10^{-40}$ e cm (4loops $O(G_F^3\,\alpha_s)$)

Discovery of non-zero EDM means beyond the SM.

EDMs from BSM



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

CP phases in the supersymmetric standard model

SUSY breaking terms:

- Gaugino mass terms $M_a\ \lambda_a\lambda_a\ (a=1,2,3)$
- Higgsino mass term $\mu\ \tilde{H}_u\tilde{H}_d$
- Sfermion/Higgs mass terms

$$(m^2_{\tilde{f}})_{ij}\tilde{f}_i^\dagger\tilde{f}_j\ (\tilde{f}=\tilde{q}_L,\tilde{u}_R,\tilde{d}_R,\tilde{l}_L,\tilde{e}_R,\ i,j=1,2,3)$$

- Higgs mixing mass term（B term） $B\mu\ H_uH_d$
- Trilinear coupling（A terms） $(m_fA_f)_{ij}\ \tilde{f}_{Li}\tilde{f}_{Ri}\ (f=u,d,e)$

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- Higgs mixing mass term（B term） $B\mu H_u H_d$
- Left-right mixing mass（A terms） $(m_f A_f)_{ij} \; \tilde{f}_{Li} \tilde{f}_{Ri} \;\; (f = u, d, e)$

$\boxed{\text{F term SUSY breaking parameters are generically complex.}}$

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- Left-right mixing mass（A terms） $(m_f A_f)_{ij} \ \tilde{f}_{Li} \tilde{f}_{Ri} \ (f = u, d, e)$

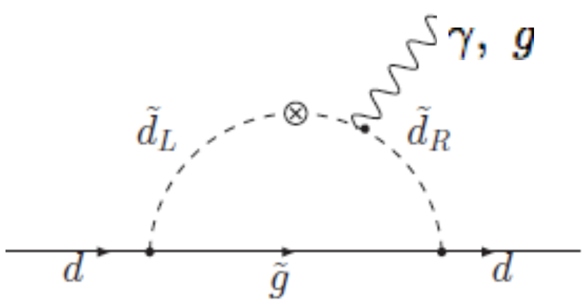
Off-diagonal terms in sfermion mass matrices are generically complex.

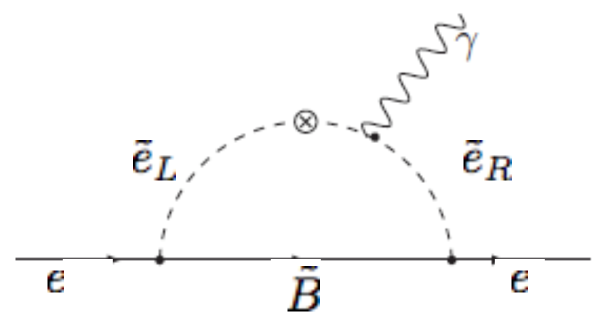
EDMs in supersymmetric standard model

In cMSSM, A and B parameters may have phases even after removing phases in gaugino and Higgsino masses, and they contribute to (C)EDMs at one-loop level. Assuming maximal CP violation and degenerate mass spectrum for SUSY particles , the mu term phase contributions are

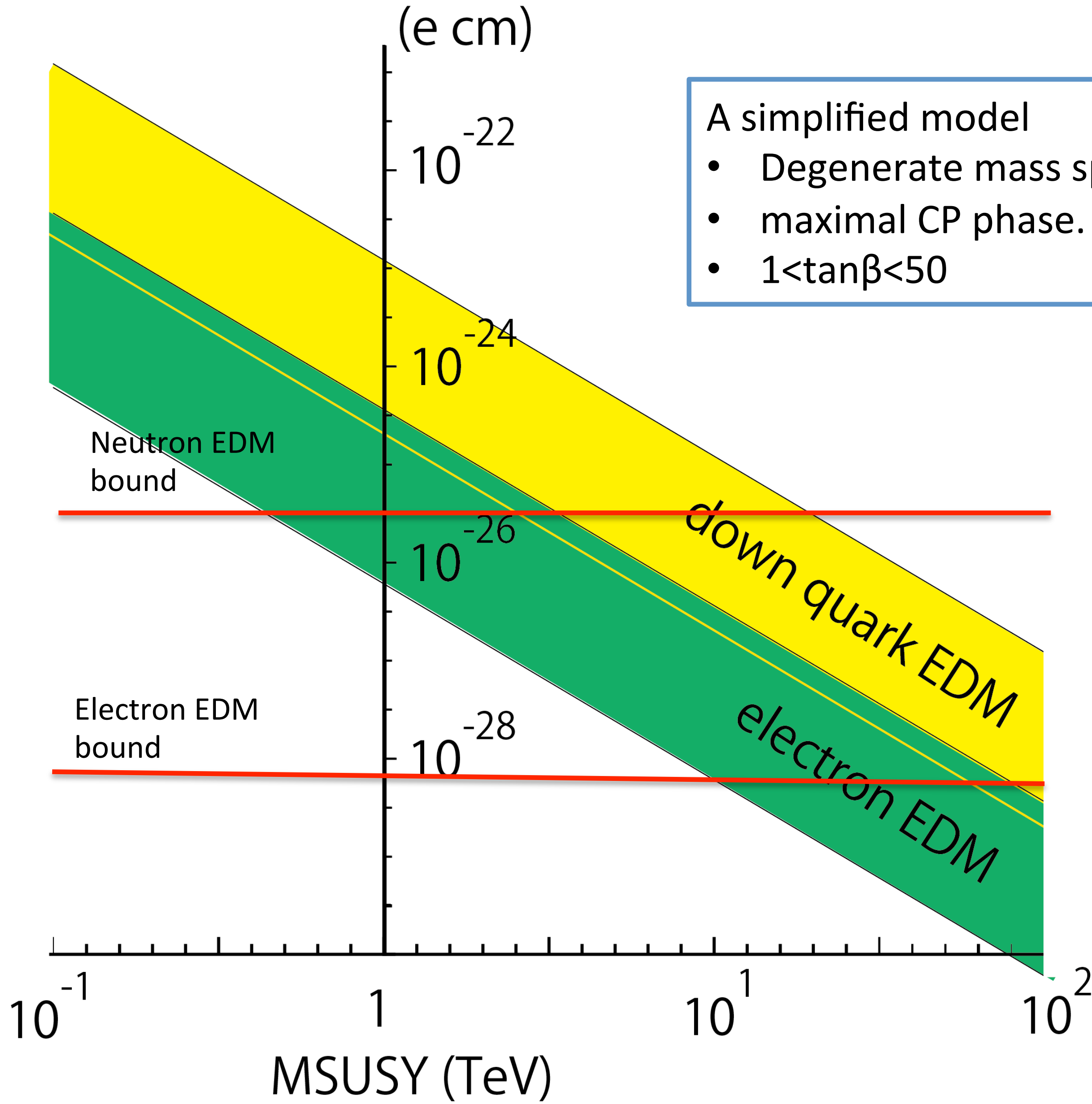
$$d_e/e \sim 0.6 \times 10^{-26}\text{cm} \left(\frac{M_{SUSY}}{1\text{TeV}} \right)^{-2} \tan\beta$$

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





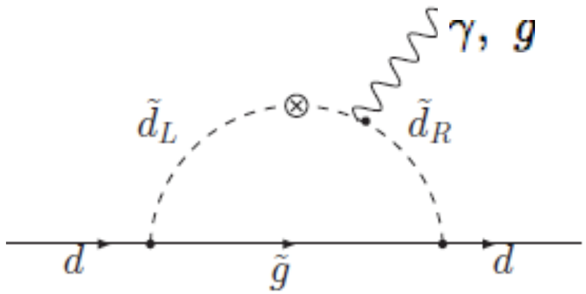
EDMs in Supersymmetric standard model



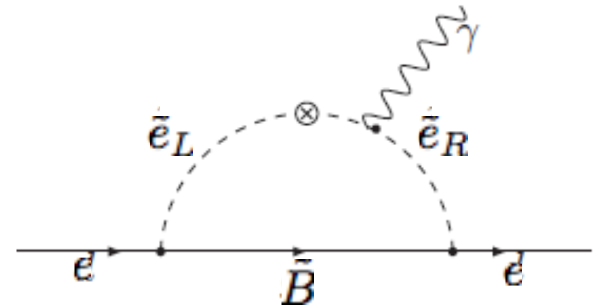
A simplified model

- Degenerate mass spectrum
- maximal CP phase.
- 1<tanβ<50

EDMs in supersymmetric standard model



$$d_d/e,\ d_d^c \propto \frac{M_{\tilde{g}}(\mu \tan\beta - A_d)}{M_{\tilde{s}}^2}$$

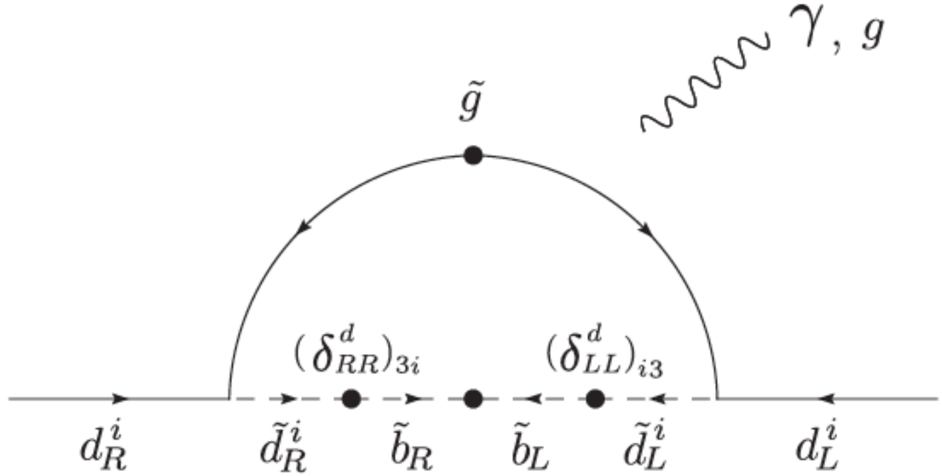


$$d_e/e \propto \frac{M_{\tilde{B}}(\mu \tan\beta - A_d)}{M_{\tilde{e}}^2}$$

Light gauginos and/or Higgsino suppress EDMs, while it seems difficult to have SUSY SM below TeVs if CP phases are maximal.

Flavor-violation and EDM in SUSY SM (1)

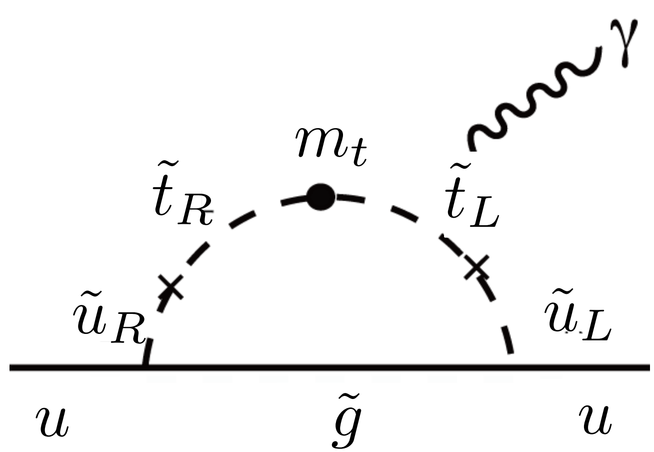
- In SUSY SM, new flavor violations are introduced in squark and slepton mass matrices. When both left- and right-handed squark mass matrices have off-diagonal (flavor-violating) terms, the relative phase contributes to EDM

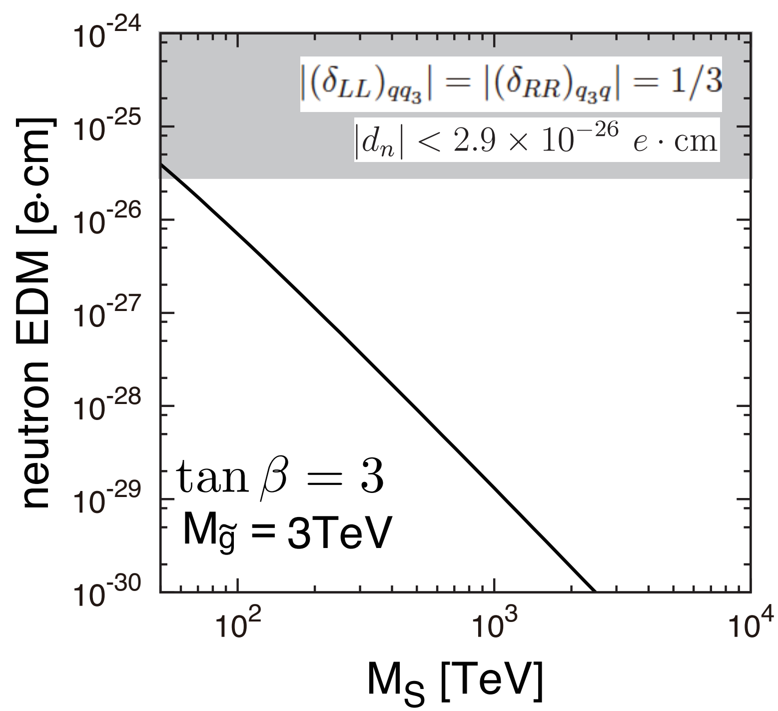


$$d^c_d \simeq 10^{-25}\mathrm{cm} \times \left(\frac{m_{\mathrm{SUSY}}}{500\mathrm{GeV}}\right)^{-2} \left(\frac{(\delta^d_{LL})_{13}}{8\times 10^{-3}}\right) \left(\frac{(\delta^d_{RR})_{31}}{0.1}\right) \tan\beta$$

High-scale SUSY with generic flavor violation

In High-scale SUSY/miniSplit-SUSY model, sfermion masses are O(100)TeV while gaugino masses are around TeV. tanβ~1. Those suppresses EDMs. Even in the case, neutron EDM may be accessible to the model if generic flavor violation is assumed.





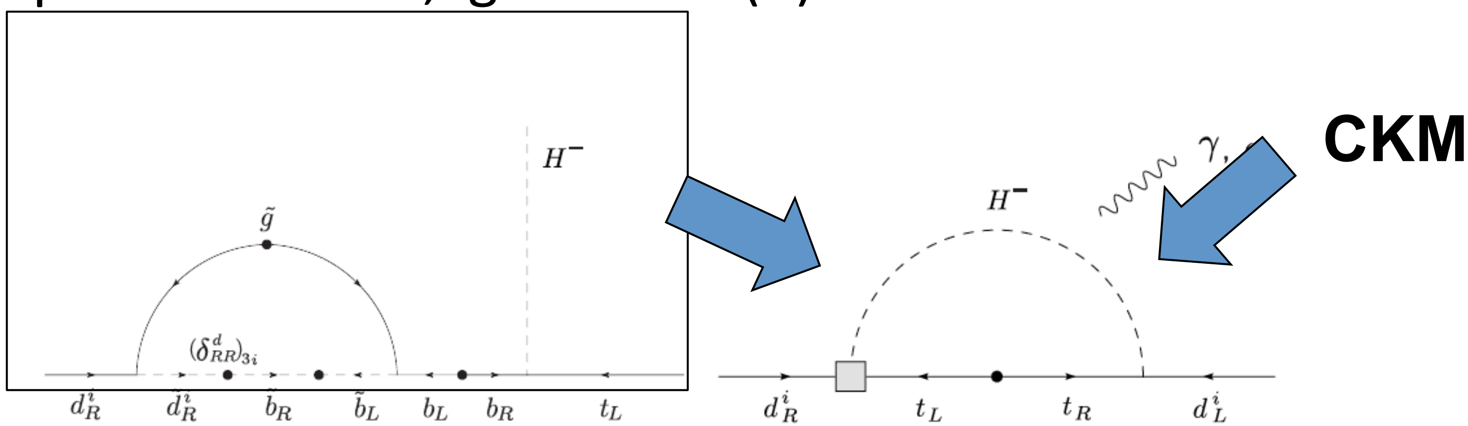
Similar recent works:

- McKeen, Pospelov, and Ritz
- Moroi and Nagai
- Altmannshofer, Harnik, Zupan
- …

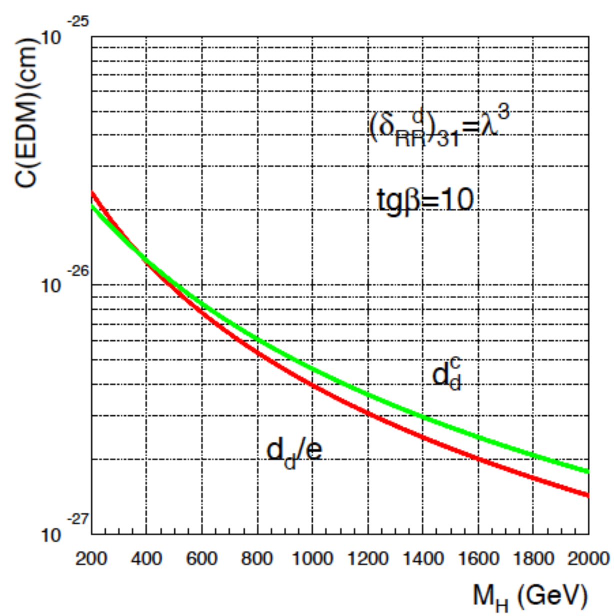
(Fuyuto, JH, Nagata, Tsumura. Anomalous dimension for CPV operators are evaluated in this paper.)

Flavor-violation and EDM in SUSY SM (2)

Even when only right-handed squarks have mixing, anomalous flavor-changing charged Higgs interaction, induced by due to non-holomorphic correction, generates (C)EDMs.



Even if SUSY particles are much heavier than the weak scale, the charged Higgs may generate sizable EDM.



(JH, Nagai, Paradisi)

Higgs studies with EDMs

The discovered Higgs boson is the SM one ?

1, Higgs couplings to fermions and bosons are proportional to their masses?

2, Higgs boson is only one ?

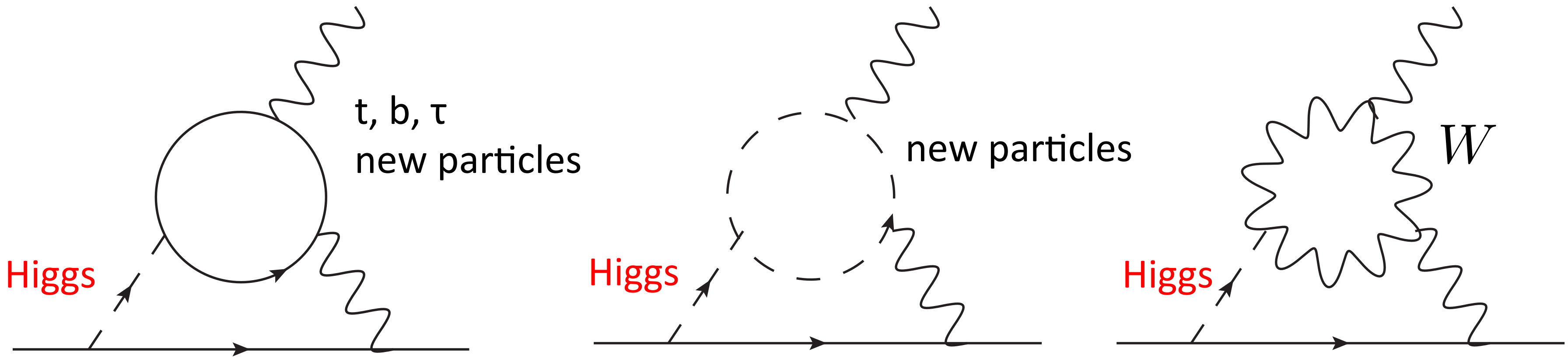
3, Higgs boson is CP even ?

4, Higgs boson interaction is flavor-conserving?

5, Higgs boson has new particles ?

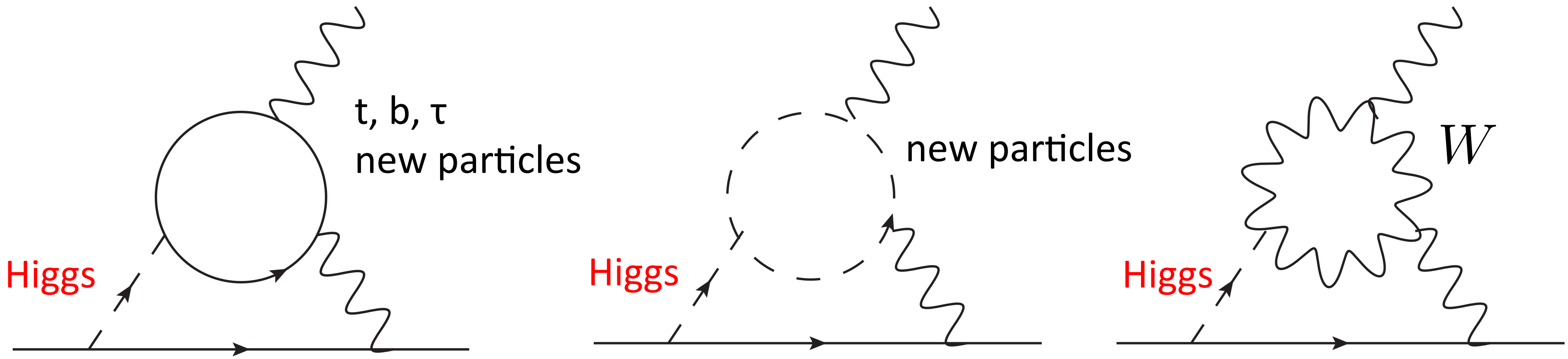
EDM measurements give hints for some of these questions.

Higgs-mediated Barr-Zee diagrams



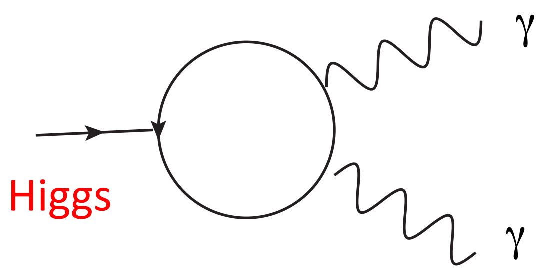
When Higgs boson has CP-violating coupling with SM particles or new particles in BSM, the Barr-Zee diagrams at two-loop level generate (C)EDMs for quarks and leptons.

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.

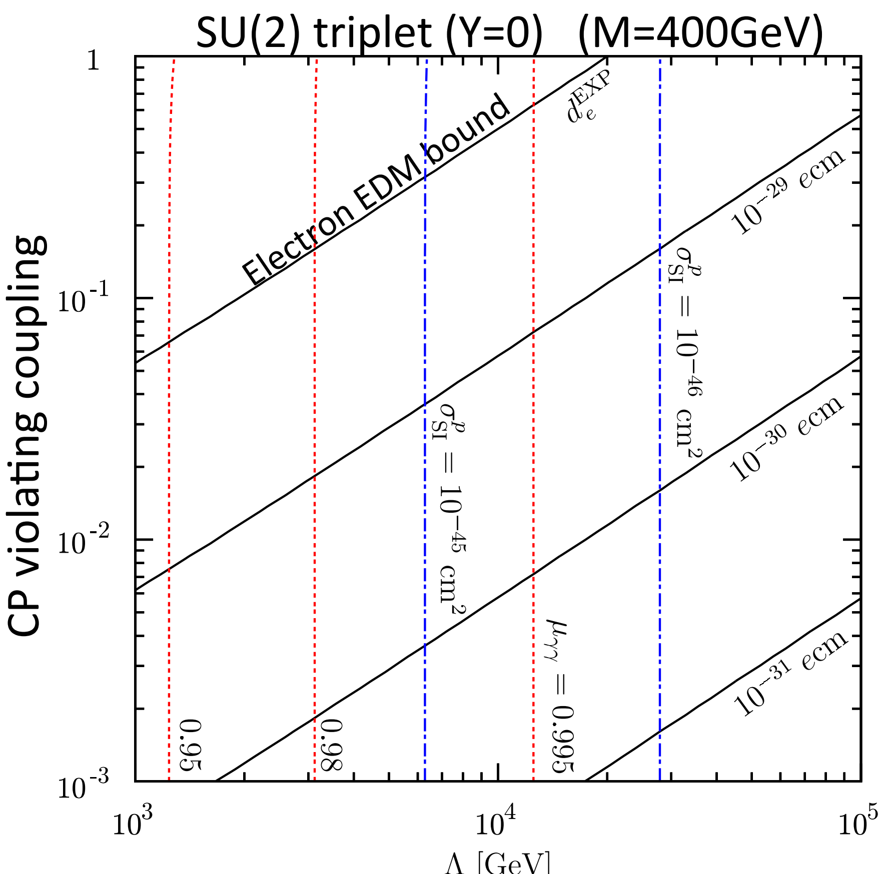


New physics contribution to EDM and h→γγ

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)



Blue lines: SI Cross section For DM direct Detection
Red lines: Signal strength for h→γγ

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

Two-Higgs doublet models

Two-Higgs doublet models have CP phase in the potential, and Barr-Zee diagrams generate (C)EDMs.

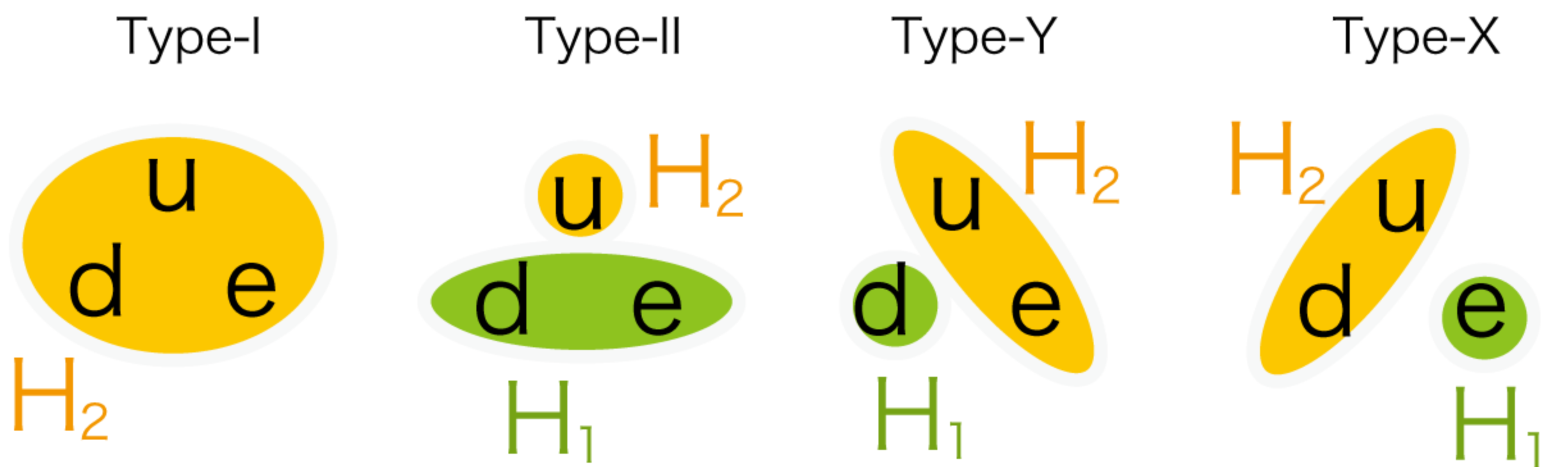
In Two-Higgs doublet models Z_2 symmetry is introduced to suppress FCNC processes.

Scalar potential in softly broken Z_2 symmetry has one CP phase.

$$\begin{aligned} V =& m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - \Big((\mathrm{Re} m_3^2 + i \mathrm{Im} m_3^2) H_1^\dagger H_2 + (h.c.) \Big) \\ & + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \Big(\lambda_5 e^{i2\phi} (H_1^\dagger H_2)^2 + (h.c.) \Big) . \end{aligned}$$

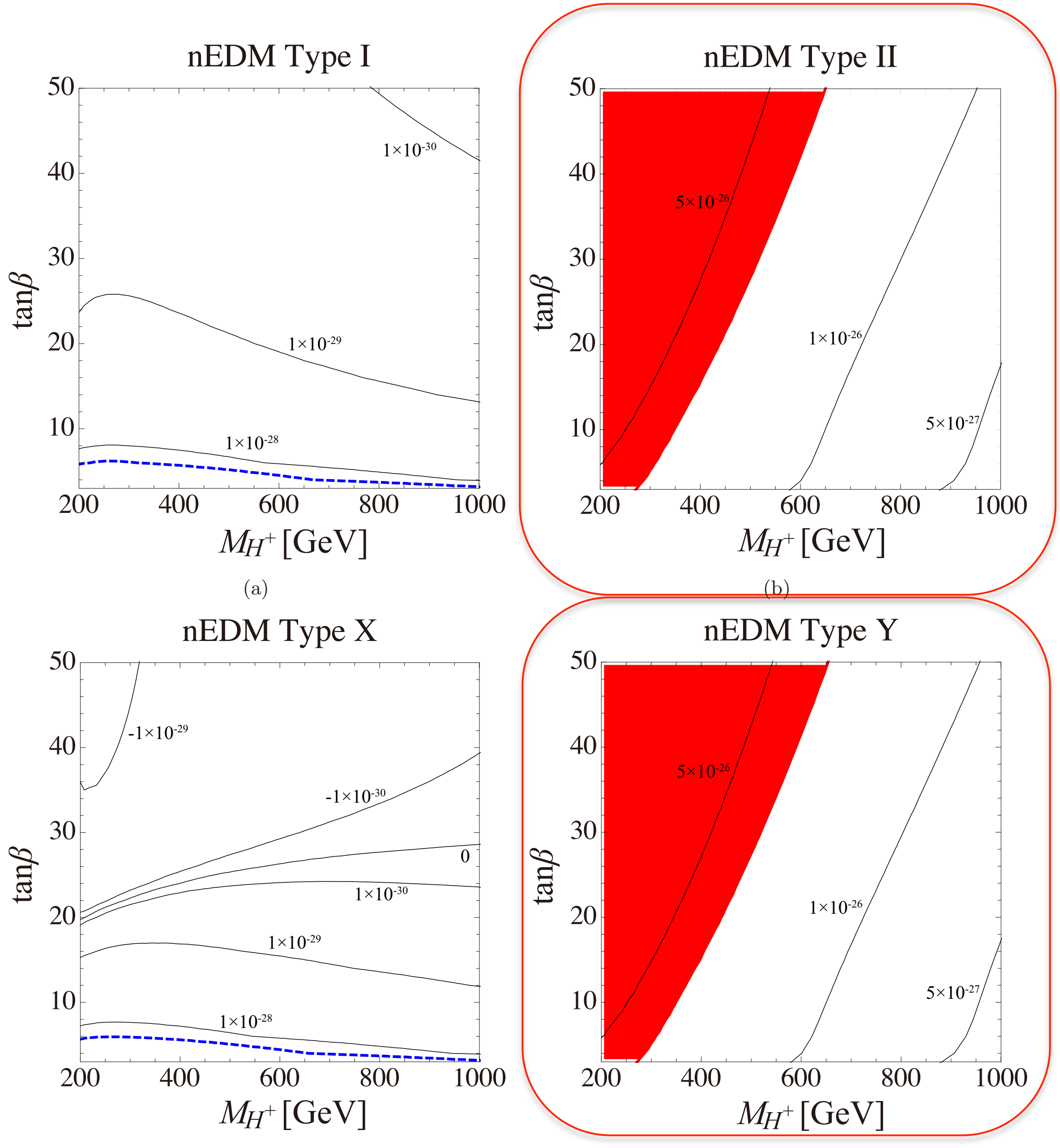
Two-Higgs doublet models

In Two-Higgs doublet models Z_2 symmetry is introduced to suppress FCNC processes. The 4 types of assignments are posiible



In typical cases, Yukawa coupling constants of H1 are larger than the SM ones, since $\langle H_2\rangle >> \langle H_1\rangle$ is expected. In the case, we may discriminate models with correlation among EDMs.

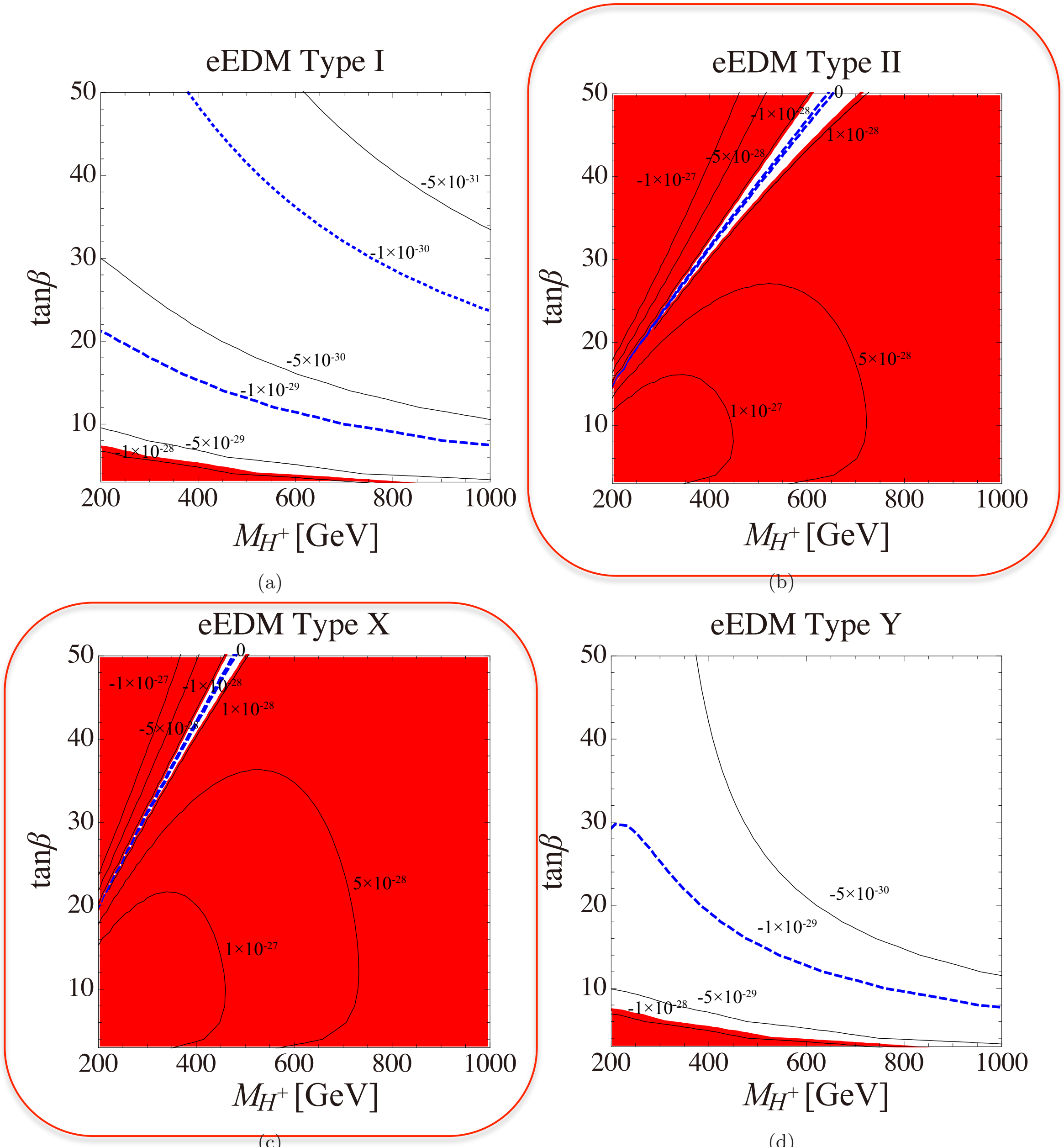
Neutron EDM in Two-Higgs doublet models



- Neutron EDM comes from CEDMs.
- For large tanβ, nEDM is suppressed in type I and X while it has the moderate dependence in type II and Y.
- Red region is excluded.

(Abe, JH, Kitahara, Tobioka)

Electron EDM in Two-Higgs doublet models



- For large tanβ, nEDM is suppressed in type I and Y while it has the moderate dependence in type II and X.
- Accidental cancellation appears in type II and X due to tau/bottom loops.
- Red region is excluded though we need to take care for large tanβ region. (4F contribution is not negligible in molecular EDM).

（Abe, JH, Kitahara, Tobioka)

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 particles are important to probe different CP violating terms.
- Higgs boson properties can be constrained with EDMs induced by Barr-Zee two-loop diagrams.
- Evaluation of hadronic EDMs has large uncertainties, and more efforts are needed to reduce them.