CP violation in Top Physics

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AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

K, Fuyuto and M. Ramsey-Musolf, 1706.08548
K. Fuyuto, WS. Hou, and E. Senaha, PLB 776 (2018) 402

March 30th 2018
Testing CP-Violation
for Baryogenesis

Outline :

1. Introduction

2. Top-driven Electroweak Baryogenesis

3. Top-quark dipole operator

4. Conclusion

Introduction

Top quark physics

Top quark is expected to be the most sensitive to New Physics due to the large Yukawa couplings.

Experimentally, top quarks can be copiously produced in high-energy proton-proton collisions.

Precise measurements of top-quark couplings are key searches for New Physics.

This talk : CP-violating coupling

CP-violating top quark coupling

1) CP-violating top-Higgs coupling

$$\mathcal{L}_Y = -\frac{y_t}{\sqrt{2}}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) h$$

J. Brod, et al, JHEP11(2013)180
J. Ellis, et al JHEP1404(2014)004
C. Englert, et al, PRD95(2017)015018

✔ Application in electroweak baryogenesis

2) Top-quark electric dipole operator

$$\mathcal{L}_{\mathrm{EDM}} = -\frac{i}{2} d_t \bar{t}\sigma^{\mu\nu}\gamma_5 t F_{\mu\nu}$$

Sensitivities at LHC:
PRD92 014006(2015),
PRD88 033003(2013),
PRD87 074015,
PRD71 054013(2005)

✔ Implication from electron EDM

Top-driven Electroweak Baryogenesis

Electroweak Baryogenesis

Kuzmin, Rubakov, Shaposhnikov, PLB155 36(1985)
For review, see; A. Cohen, D. Kaplan, A. Nelson, NPS43(1993)27
D.E. Morrissey, M. Ramsey-Musolf, New J Phys 14(2012)125003

Sakharov's conditions can be satisfied as follows:

(1) Baryon number violation

Sphaleron process

(2) C and CP violation

Chiral gauge theory and CP phase

(3) Out of equilibrium

First order EW phase transition
with expansion of bubble wall

Electroweak Baryogenesis

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Sakharov's conditions can be satisfied as follows:

(1) Baryon number violation

Sphaleron process

(2) C and CP violation

* SM fails ✔ Chiral gauge theory and CP phase

(3) Out of equilibrium

✔ First order EW phase transition with expansion of bubble wall

Possibility of EWBG in New Physics

- Successful scenario for EWBG needs

  1) New Scalar for the 1st order PT

  2) New CP violation

Possibility of EWBG in New Physics

✦ General Two Higgs Doublet Model

1) New Scalar for the 1st order PT

Two Higgs doublet : $\Phi_{1,2}$

Sensitivity at LHC and EDMs
Haolin's talk (1708.00435)

* Two doublets couple to fermions.

2) New CP violation

T. Liu, et al, PRL108(2012)221301
KF, et al, PLB762(2016)315,
HK Guo, et al, PRD96(2017)115034
KF, et al, PLB 776 (2018) 402

✔ Complex Yukawa couplings

General Two Higgs Doublet Model

General Two Higgs Doublet Model

Yukawa interactions : $i,\ j$: Flavor indices

$$-\mathcal{L}_Y = \bar{q}_{iL}\left(Y_{1ij}\tilde{\Phi}_1 + Y_{2ij}\tilde{\Phi}_2\right)u_{jR} + \text{h.c.}$$

$$\Phi_{i=1,2} = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + ia_i) \end{pmatrix} \qquad \tilde{\Phi}_a = i\tau_2\Phi_a^*$$

$$v_1 = v\cos\beta \qquad v_2 = v\sin\beta$$

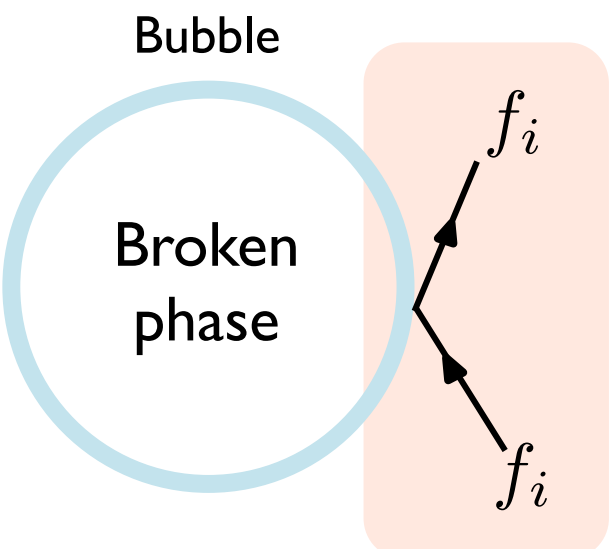
We take $t_\beta = 1\,.$

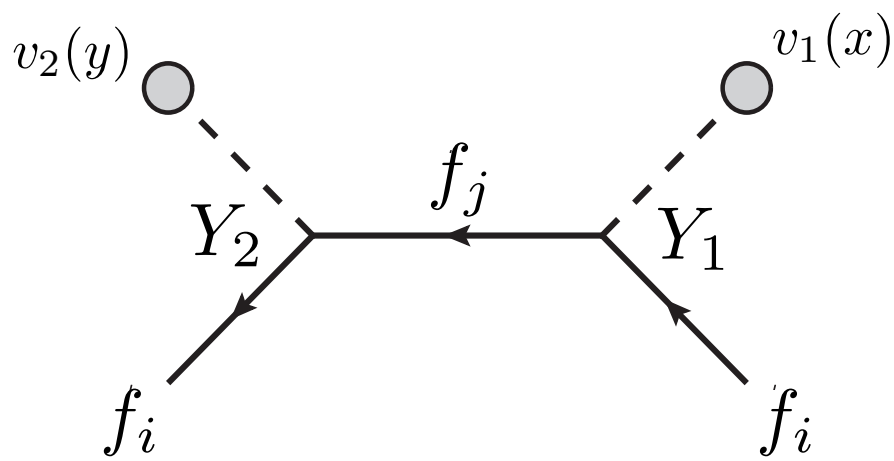
$Y_1,\ Y_2$: Complex numbers ✦ Important couplings!

General Two Higgs Doublet Model

CP-violating interaction with expanding bubble:

$$-\mathcal{L}_Y = \bar{q}_{iL}\left(Y_{1ij}\, v_1 + Y_{2ij}\, v_2\right) u_{jR} + \text{h.c.}$$





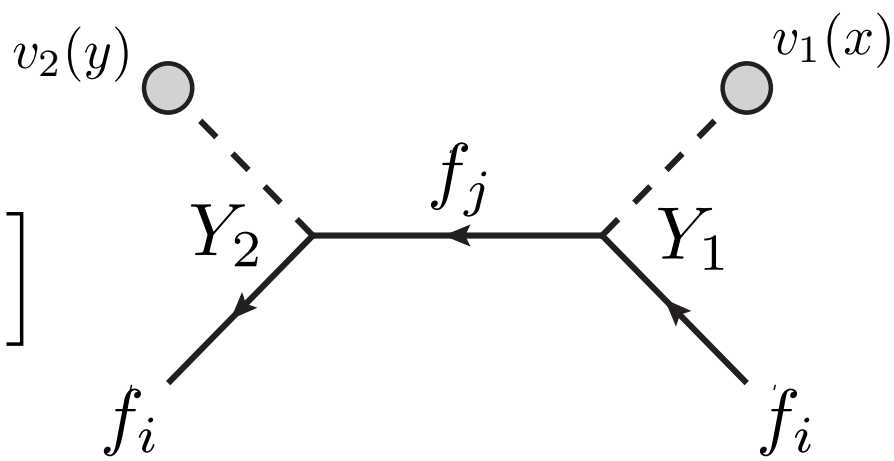
General Two Higgs Doublet Model

CP-violating interaction with expanding bubble:

$$-\mathcal{L}_Y = \bar{q}_{iL}\left(Y_{1ij}\, v_1 + Y_{2ij}\, v_2\right) u_{jR} + \text{h.c.}$$

Sakharov's 2nd condition:

$$n_B \propto \text{Im}\left[(Y_1)_{ij}\,(Y_2)^*_{ij}\right]$$



Im $[Y_1 Y_2^*]$ leads to the BAU.

General Two Higgs Doublet Model

After diagonalizing mass matrices

$$-\mathcal{L}_Y = \bar{u}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho^u_{ij}c_{\beta-\alpha}\right]u_{jR}h \quad +\text{h.c.}$$

Yukawa : $\dfrac{m_u}{v}$ Complex : $|\rho_{ij}|e^{\phi_{ij}}$

$s_{\beta-\alpha} = \sin(\beta-\alpha)$ * SM limit is $s_{\beta-\alpha} = 1$

α : Mixing angle between h and H

with 125 GeV

General Two Higgs Doublet Model

After diagonalizing mass matrices

$$-\mathcal{L}_Y = \bar{u}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho^u_{ij}c_{\beta-\alpha}\right]u_{jR}h \quad +\text{h.c.}$$

$$= -\frac{y_t}{\sqrt{2}}\left(\kappa_t\bar{t}t + i\tilde{\kappa}_t\bar{t}\gamma_5 t\right)h$$

where $\kappa_t = s_{\beta-\alpha} + \frac{|\rho_{33}|}{y_t}c_{\beta-\alpha}c_{\phi_{33}}$

$\tilde{\kappa}_t = \frac{|\rho_{33}|}{y_t}c_{\beta-\alpha}s_{\phi_{33}}$ We take $c_{\beta-\alpha} = 0.1$.

General Two Higgs Doublet Model

After diagonalizing mass matrices

$$-\mathcal{L}_Y = \bar{u}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho^u_{ij}c_{\beta-\alpha}\right]u_{jR}h \quad +\text{h.c.}$$

Relationship :

$$Y_1 = V_L^\dagger\left[c_\beta y - s_\beta \rho\right]V_R^\dagger \qquad u_L \to V_L^\dagger u_L$$

$$Y_2 = V_L^\dagger\left[s_\beta y + c_\beta \rho\right]V_R^\dagger \qquad u_R \to V_R u_R$$

Nonzero ρ can be induced by the nonzero Y_1 and Y_2.

Approximate diagonalization

T. Liu, et al, PRL108(2012)221301
HK Guo, et al, PRD96(2017)115034
KF, et al, PLB 776 (2018) 402

Assumption: $i = 1, 2$

$$Y_i = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & (Y_i)_{32} & (Y_i)_{33} \end{pmatrix} \quad \text{and} \quad (Y_1)_{33} = (Y_2)_{33}$$

In this case,

$$V_L \left(Y_1 c_\beta + Y_2 s_\beta\right) V_R = \mathrm{dia}\left(0, 0, y_t\right) \quad \text{with } V_L = 1$$

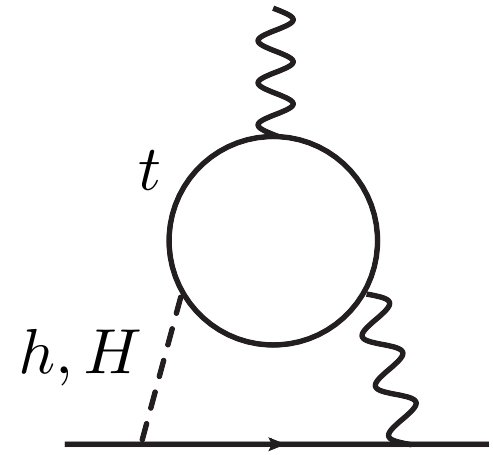
$$\underbrace{\mathrm{Im}\left[(Y_1)_{32}(Y_2)^*_{32}\right]}_{\text{BAU}} = -y_t \underbrace{\mathrm{Im}\left(\rho_{33}\right)}_{\text{Low energy}}$$

* Our numerical analysis take a nonzero $(Y_i)_{22}$ such that charm Yukawa is achieved.

Phenomenology

- Electron EDM:

$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}\ \ (90\%\ \mathrm{CL})$$



- Signal strength of $h \to 2\gamma$:

  * Top quark and charged scalars can contribute

$$\mu_{\gamma\gamma} = 1.14^{+0.19}_{-0.18}$$

Combined Run 1 limit from ATLAS and CMS
JHEP08(2016)045

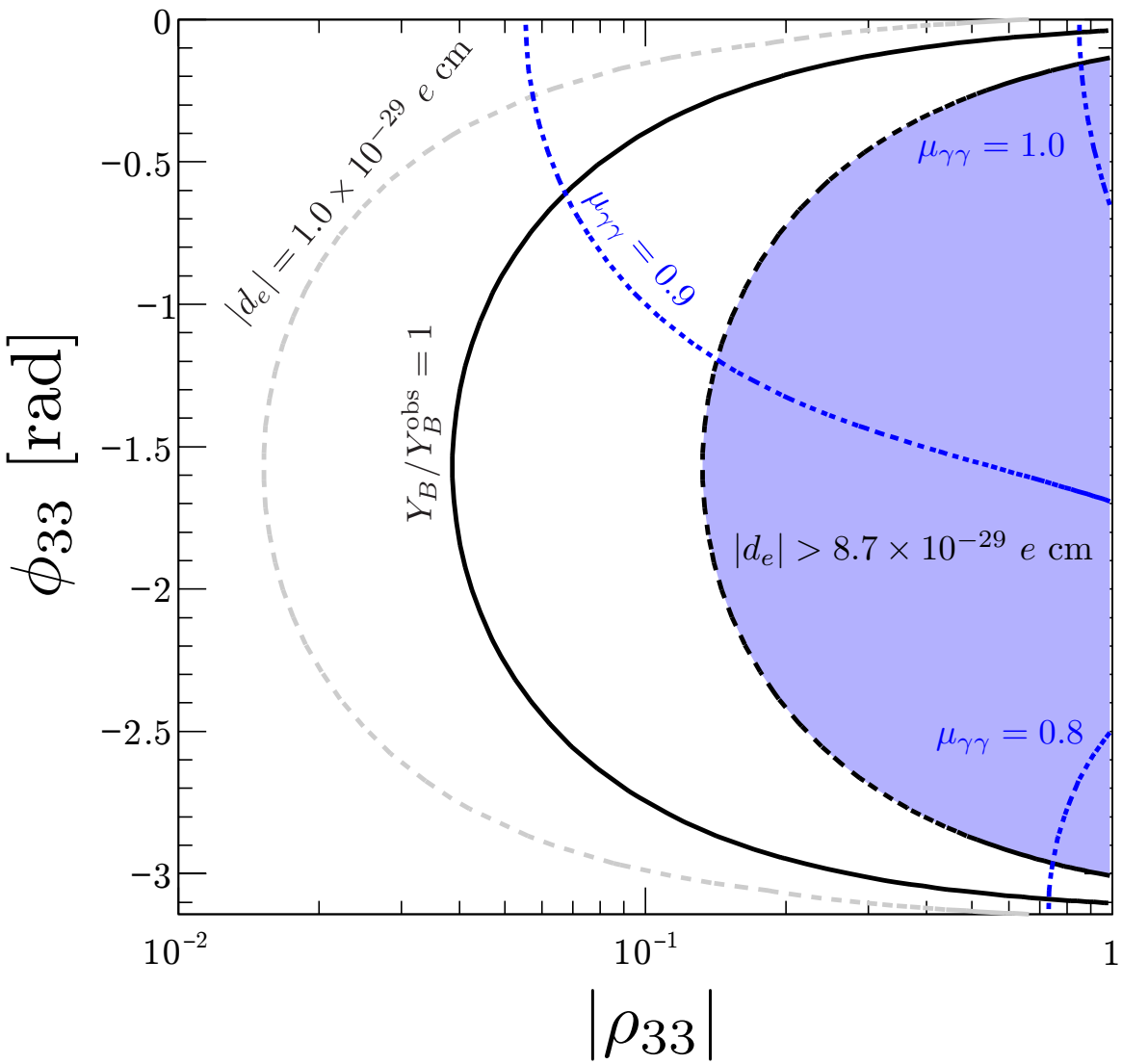
- B physics constraint : $|\rho_{33}| < 1$ at $m_H = 500\ \mathrm{GeV}$

B. Altunkaynak, et al PLB751(2015)135

For estimate of the BAU, we use CTP formalism with VEV insertion.

Results

Black line satisfies the observed BAU.



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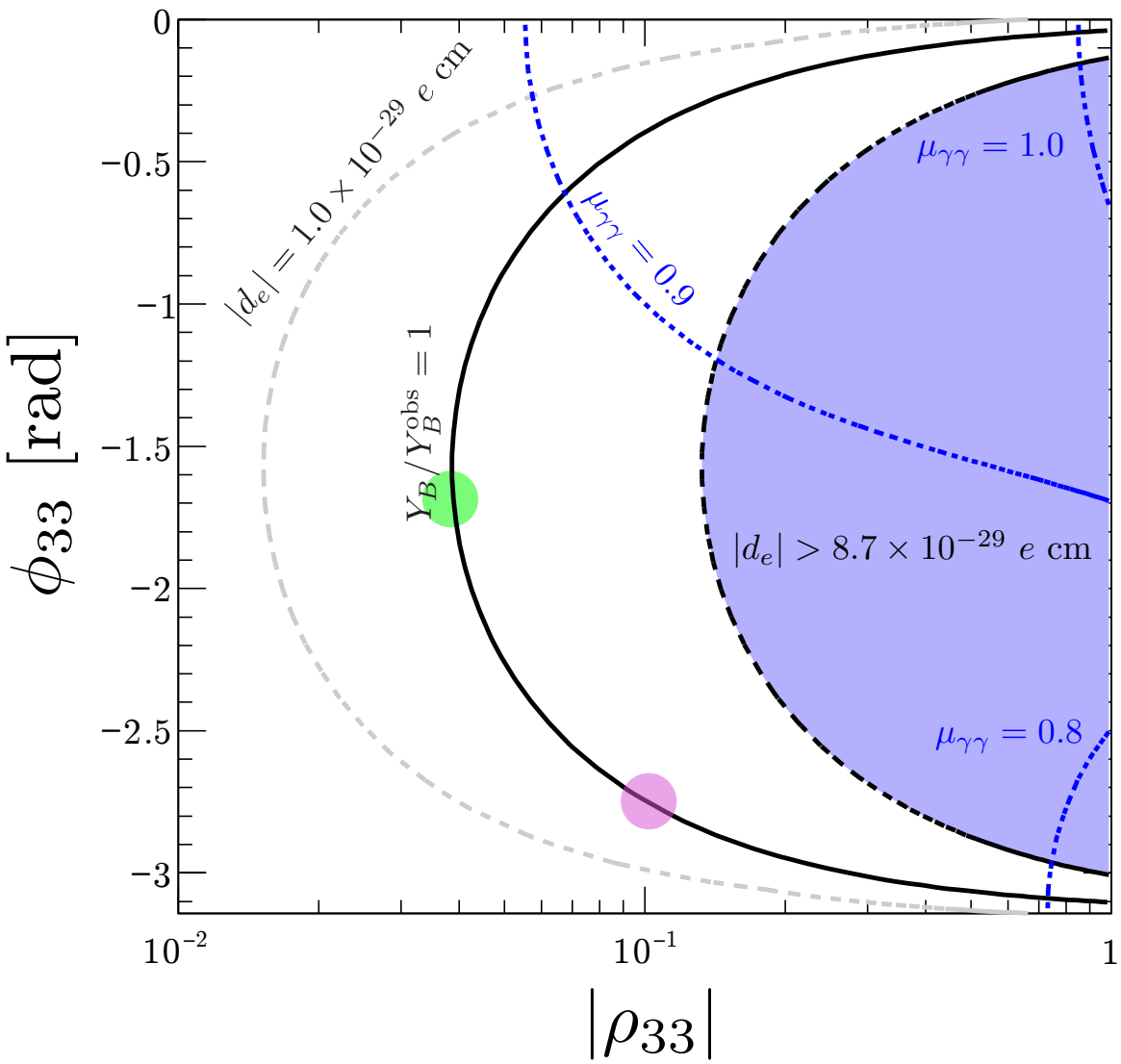


$(|\rho_{33}|, \phi_{33})$
$= (0.1, -2.8)$

$\kappa_t = 0.98$

$\tilde{\kappa}_t = -3.4 \times 10^{-3}$

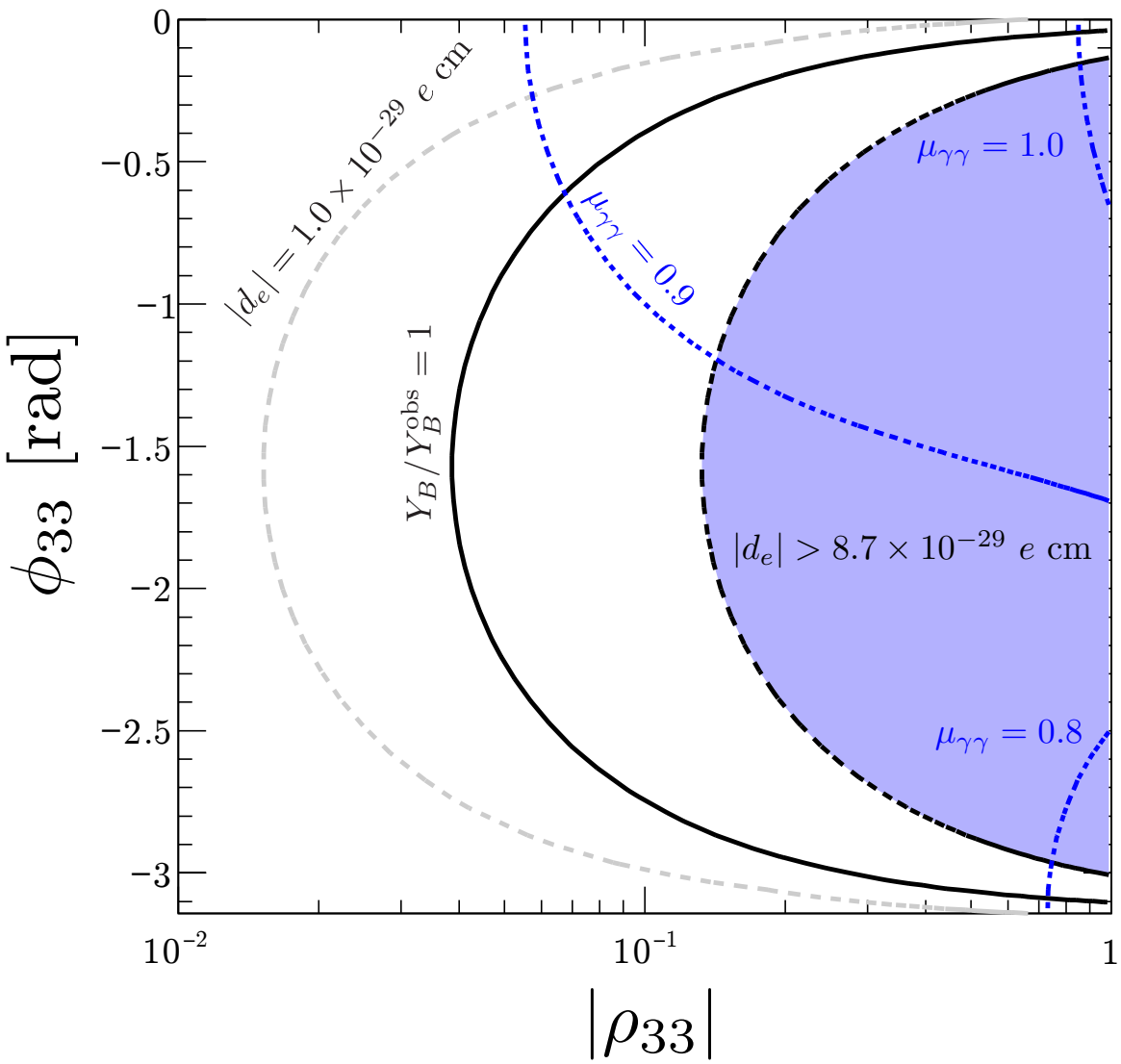
$(|\rho_{33}|, \phi_{33})$
$= (4 \times 10^{-2}, 1.57)$

$\kappa_t = 0.99$

$\tilde{\kappa}_t = 4 \times 10^{-3}$

Results

Black line satisfies the observed BAU.



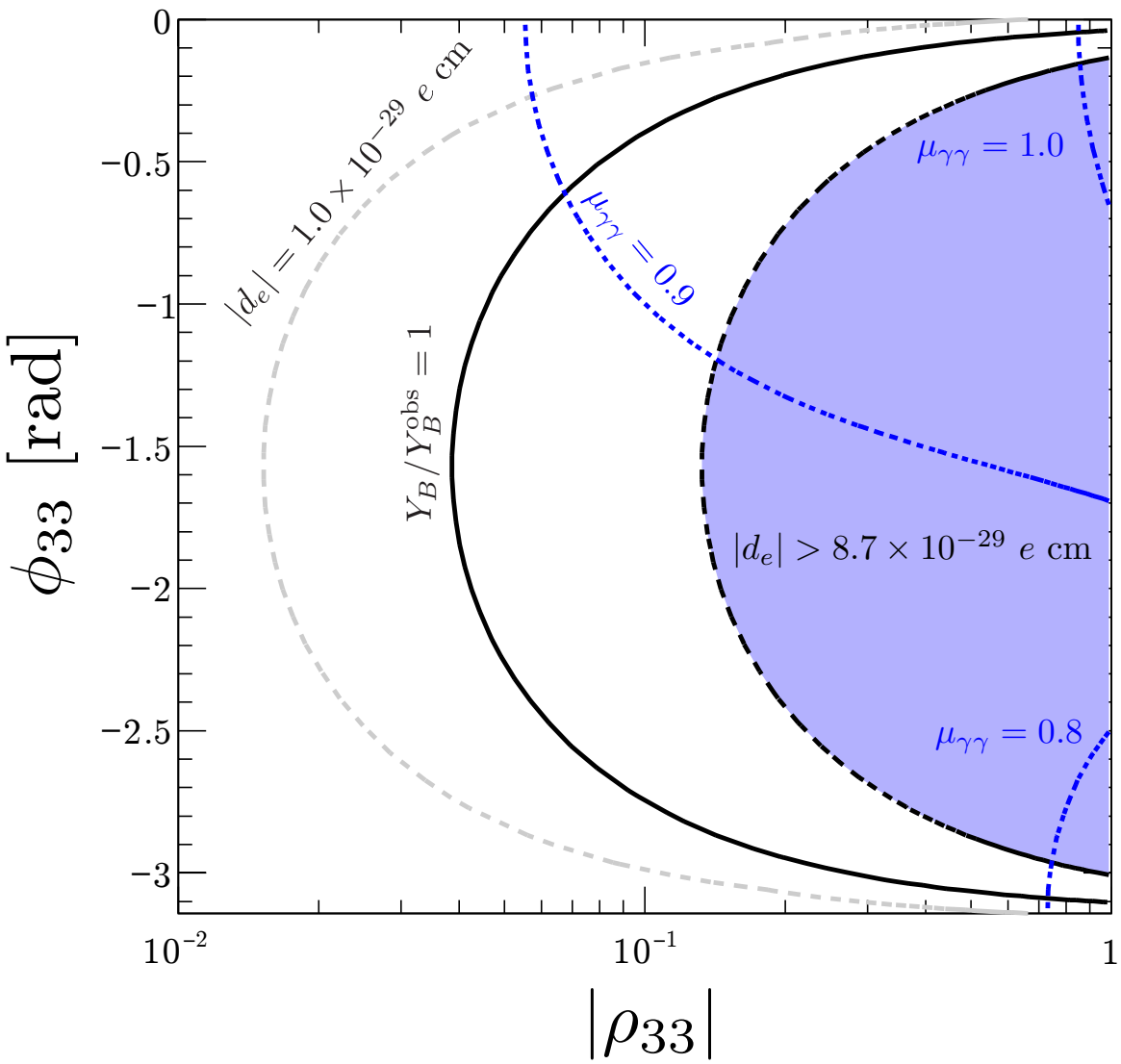
✔ Electron EDM

Blue region is excluded.

Gray line is $d_e = 10^{-29}$ e cm

Results

Black line satisfies the observed BAU.



✔ Electron EDM

Blue region is excluded.
Gray line is $d_e = 10^{-29}$ e cm

✔ Signal strength

Blue dotted line

$\mu_{\gamma\gamma} = 1.0,\ 0.9,\ 0.8$

Top quark EDM

Top-quark dipole operators

Another key to CPV effects on top quark might be dipole operator:

$$\mathcal{O}_{tB} = \bar{Q}\sigma^{\mu\nu} t_R \tilde{H} B_{\mu\nu}$$

$$\mathcal{O}_{tW} = \bar{Q}\sigma^{\mu\nu} t_R \tau^A \tilde{H} W^A_{\mu\nu}$$

* LHC attempts to give constraints on their Wilson coefficients.

JHEP01(2016)096, 1711.02547

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After EW symmetry breaking, these operators induce

Top-quark EDM: $\mathcal{L}_{\rm EDM} = -\frac{i}{2} d_t \bar{t}\sigma^{\mu\nu}\gamma_5 t F_{\mu\nu}$

with

$$d_t = \frac{e}{v}\left(\frac{v}{\Lambda}\right)^2 \{\mathrm{Im}(C_{tB}) + \mathrm{Im}(C_{tW})\}$$

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Naively, X 10^5

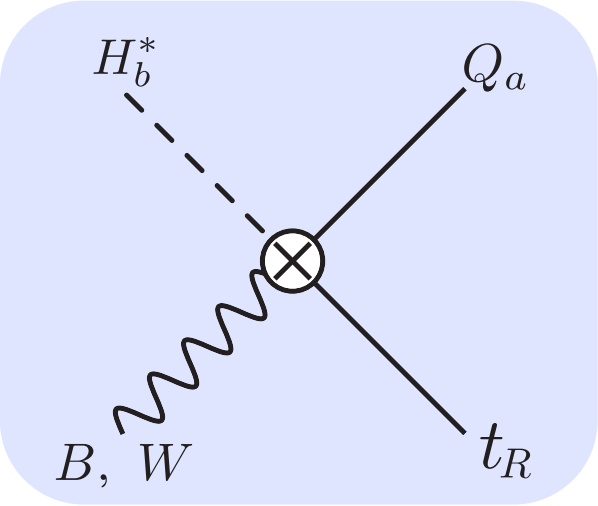
$$d_e \sim \frac{m_e}{\Lambda^2} \ll d_t \sim \frac{m_t}{\Lambda^2}$$

Much enhanced

Operator mixing

Suppose that the two dipole operators appear at Λ .

Top dipole operator



$$\mathcal{O}_{tB} = \bar{Q}\sigma^{\mu\nu} t_R \tilde{H} B_{\mu\nu}$$

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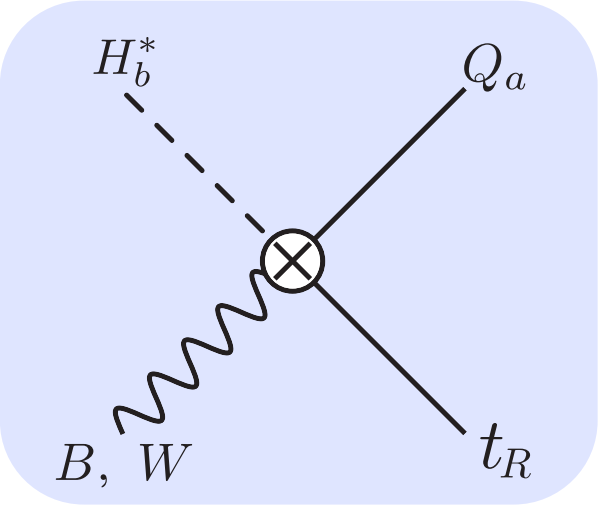
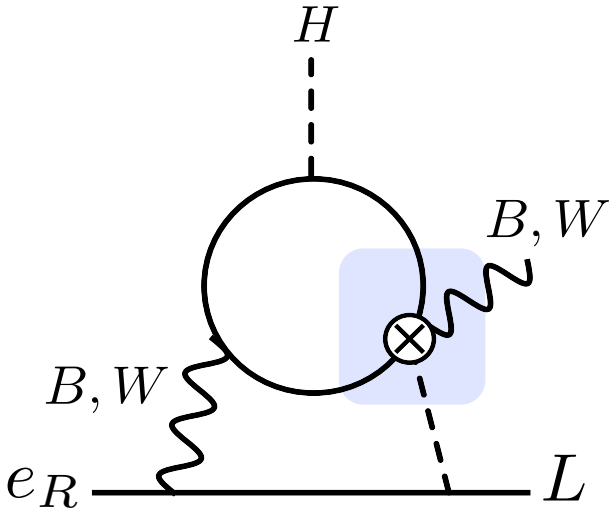


Two-loop Barr-Zee diagram

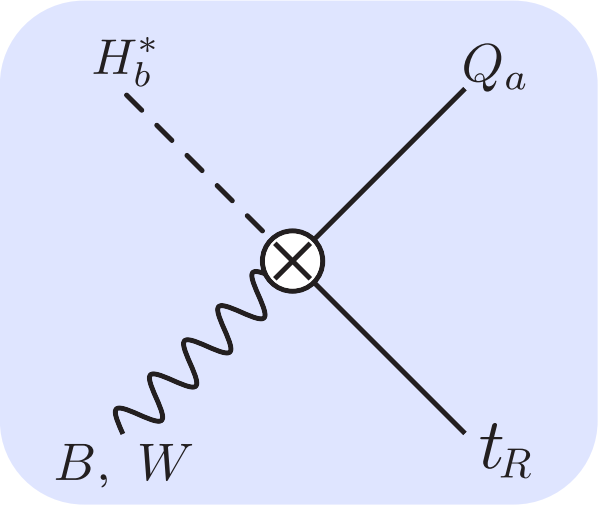


The top dipole operators can induce electron dipole operators through the two-loop Barr-Zee diagrams.

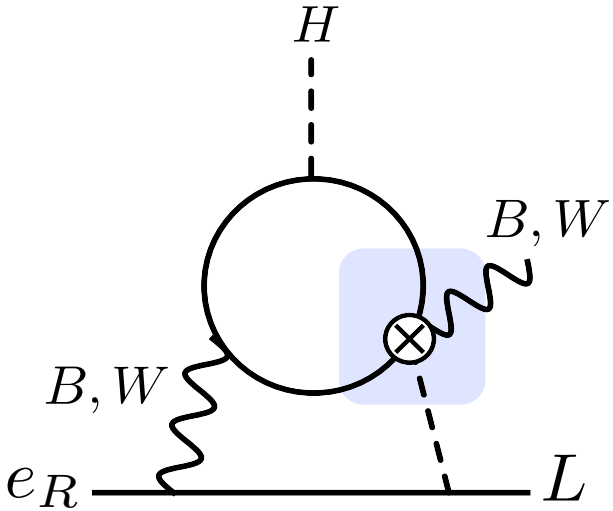
Operator mixing

Suppose that the two dipole operators appear at Λ .

Top dipole operator



Two-loop Barr-Zee diagram



This implies operator mixing between the electron and top quark through the EW running.

Translation from limit on d_e to d_t

Once the electron dipole operators are induced, they yield the electron EDM as in the top EDM.

$$d_e = \frac{e}{v}\left(\frac{v}{\Lambda}\right)^2 \{\mathrm{Im}(C_{eB}) - \mathrm{Im}(C_{eW})\}$$

where $$C_{eB} \sim A \times C_{tB} + B \times C_{tW}$$

$$C_{eW} \sim D \times C_{tB} + E \times C_{tW}$$

⟺ Experimental limit : $|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$

The top dipole operators can be restricted.

Translation from limit on d_e to d_t

Once the electron dipole operators are induced, they yield the electron EDM as in the top EDM.

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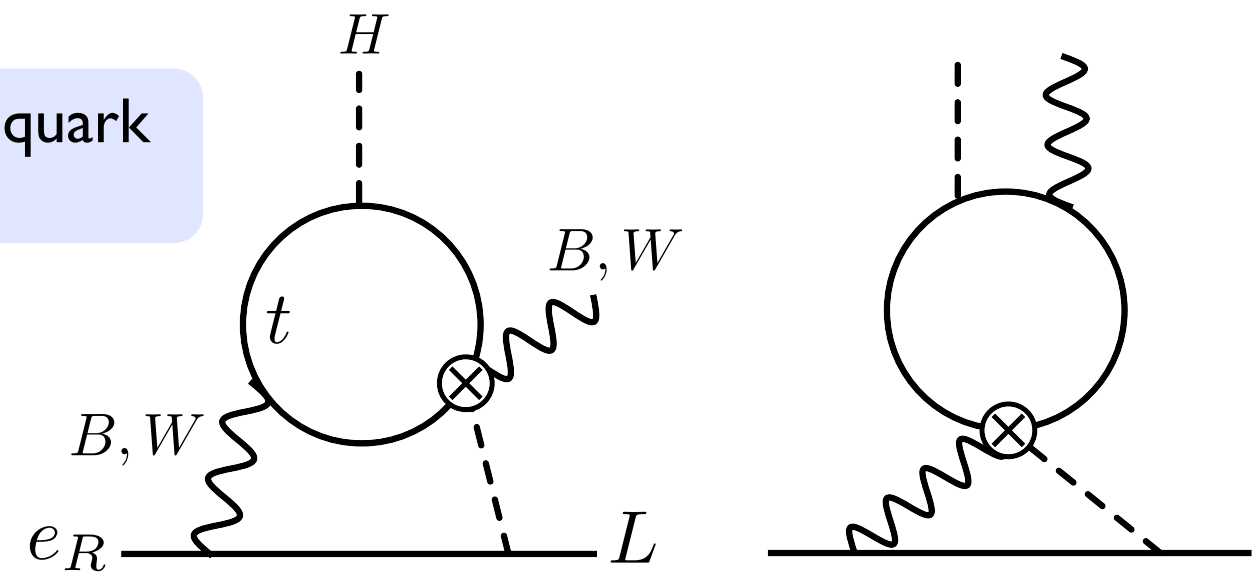
Experimental limit : $|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$

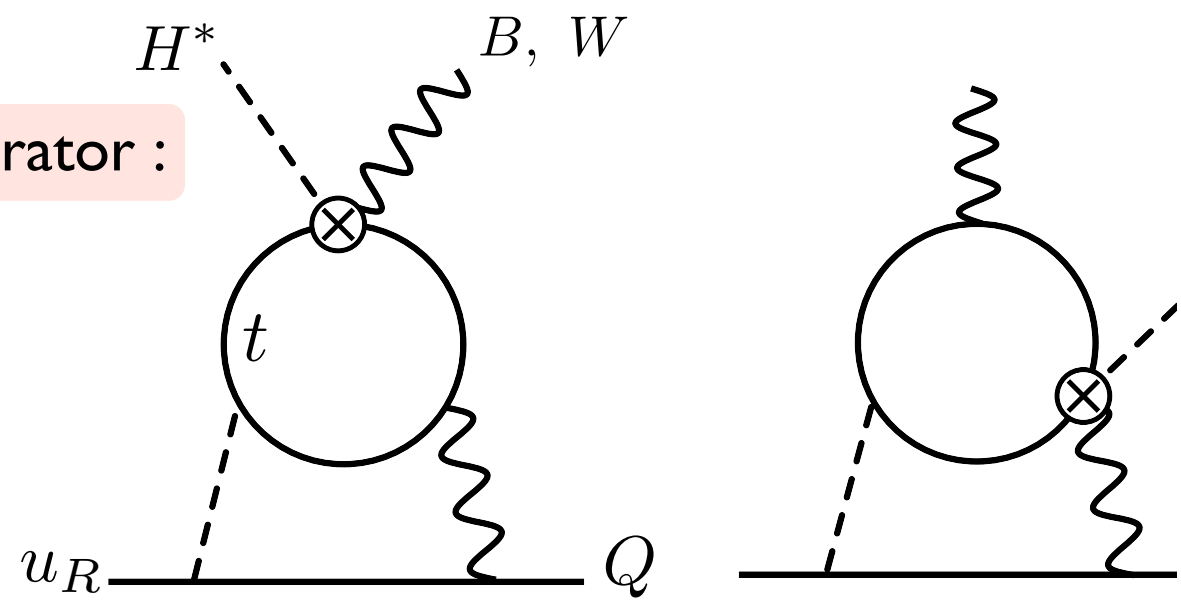
We show the limit on $\mathrm{Im}(C_{tB,tW})$ and d_t from d_e and d_n.

Two-loop Barr-Zee diagrams

Electron and down quark dipole operators :

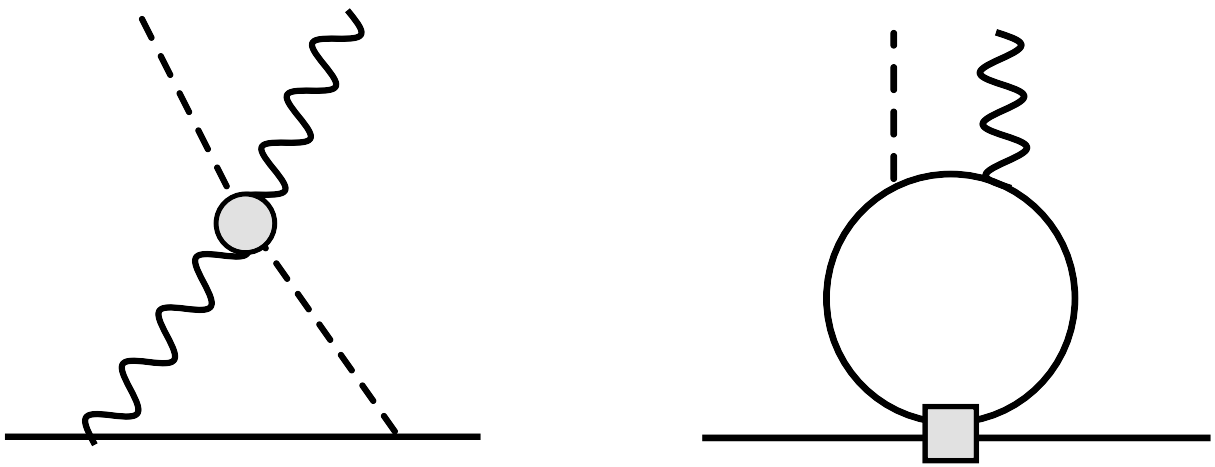


Up quark dipole operator :



1-loop diagrams

1-loop diagrams with counter terms for the upper and lower loops are also included.



The calculations of all diagrams lead to $f = e, u, d$

$$\mathcal{M}_f \sim \frac{1}{\epsilon^2}\Big[(A_f C_{tB} + B_f C_{tW})\mathcal{O}_{fB} + (D_f C_{tB} + E_f C_{tW})\mathcal{O}_{fW}\Big]$$

Divergence : $4 - d = \epsilon$

(A,B,C and D : Coefficients)

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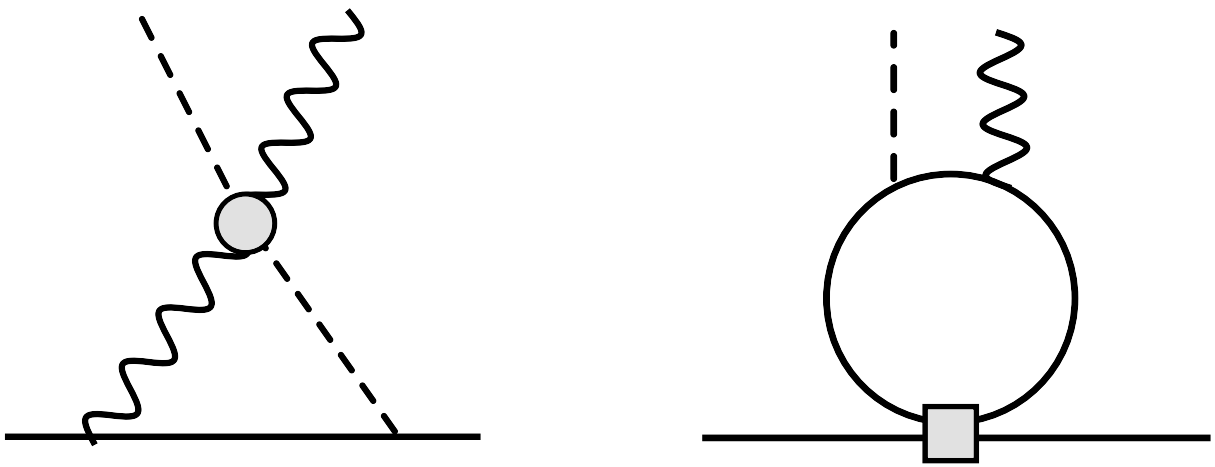

The calculations of all diagrams lead to $f = e, u, d$

$$\mathcal{M}_f \sim \frac{1}{\epsilon^2}\left[(A_f C_{tB} + B_f C_{tW})\mathcal{O}_{fB} + (D_f C_{tB} + E_f C_{tW})\mathcal{O}_{fW}\right]$$

$$= C_{fB}\mathcal{O}_{fB} + C_{fW}\mathcal{O}_{fW}$$

(A,B,C and D : Coefficients)

Electroweak running

Using the leading-logarithmic approximation, we obtain the Wilson coefficients at EW scale. $(f = e, u, d)$

$$C_{fB}(v) = -\frac{1}{2}(A_f C_{tB} + B_f C_{tW}) \log\left(\frac{\Lambda}{v}\right)^2$$

$$C_{fW}(v) = -\frac{1}{2}(D_f C_{tB} + E_f C_{tW}) \log\left(\frac{\Lambda}{v}\right)^2$$

Enhancement

Electroweak running

Using the leading-logarithmic approximation, we obtain the Wilson coefficients at EW scale. $(f = e, u, d)$

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$$C_{fW}(v) = -\frac{1}{2}(D_f C_{tB} + E_f C_{tW}) \log\left(\frac{\Lambda}{v}\right)^2$$

Finally, the EDMs are given by $-(+)$ for $e(u)$

$$d_f = -\frac{e}{2v}\left(\frac{v}{\Lambda}\right)^2 \log\left(\frac{\Lambda}{v}\right)^2$$

$$\times\left[(A_f \mp D_f)\mathrm{Im}(C_{tB}) + (B_f \mp E_f)\mathrm{Im}(C_{tW})\right]$$

Electroweak running

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$$C_{fB}(v) = -\frac{1}{2}(A_f C_{tB} + B_f C_{tW}) \log\left(\frac{\Lambda}{v}\right)^2$$

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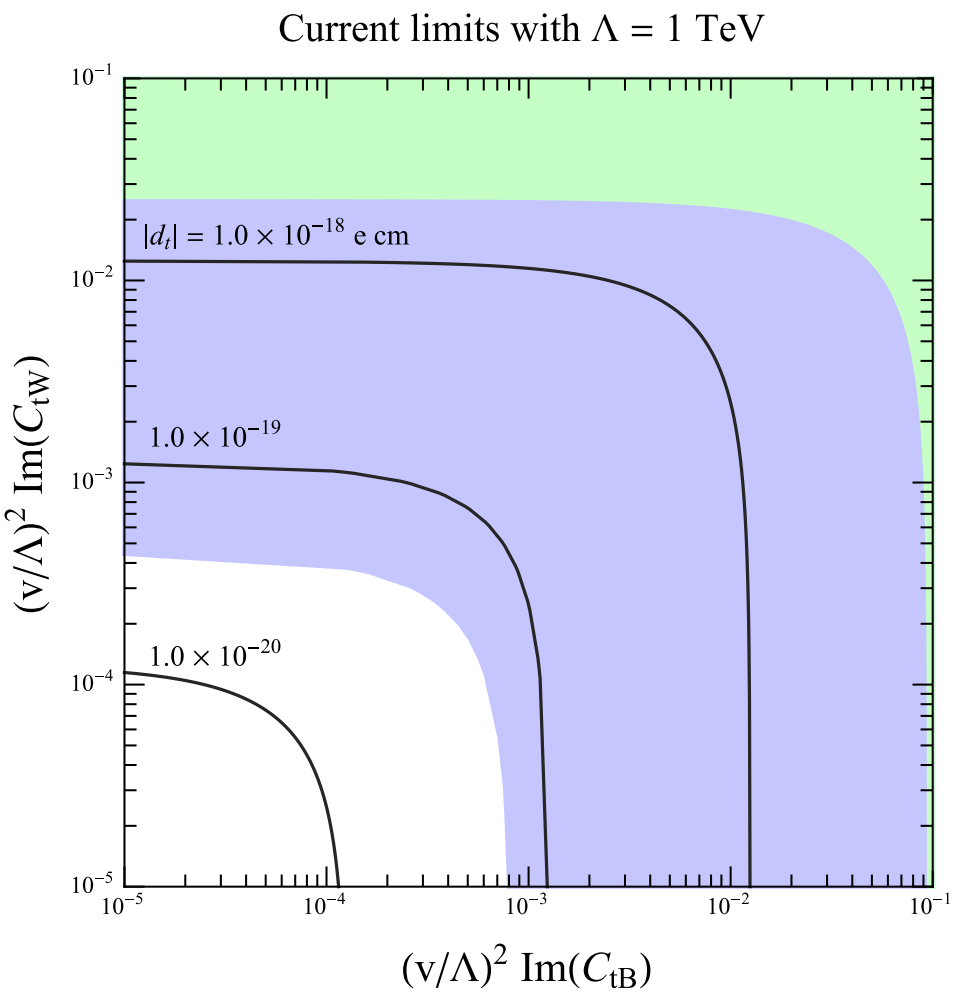
$$\times\left[(A_f \mp D_f)\mathrm{Im}(C_{tB}) + (B_f \mp E_f)\mathrm{Im}(C_{tW})\right]$$

$$\text{(i) } \mathrm{Im}(C_{tW}) > 0$$

$$\text{(ii) } \mathrm{Im}(C_{tW}) < 0$$

Positive case



Green :

Excluded by the neutron EDM

$$|d_n| < 3.0 \times 10^{-29}\ e\ \mathrm{cm}$$

Blue :

Excluded by the electron EDM

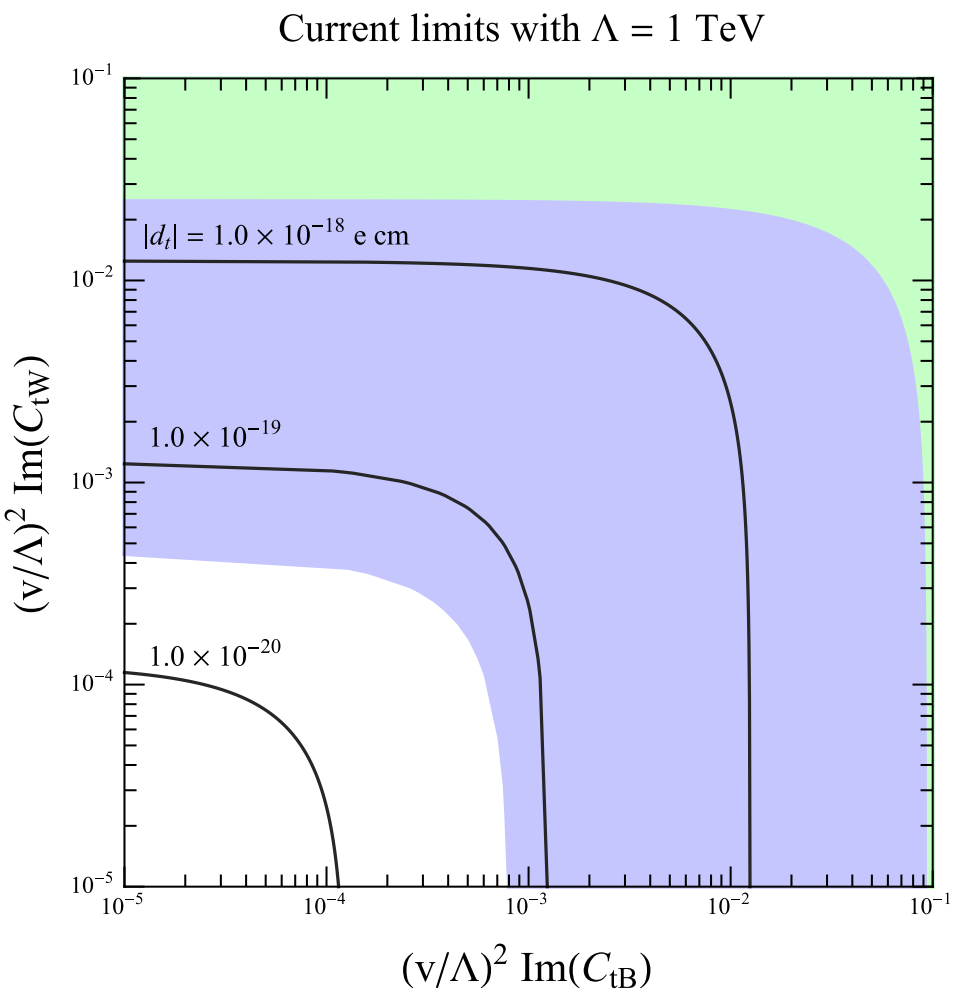
$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$$

Black lines : top EDM

$$|d_t| = 10^{-(18-20)}\ e\ \mathrm{cm}$$

Current limit : $|d_t| \lesssim 6.5 \times 10^{-20}\ e\ \mathrm{cm}$

Positive case



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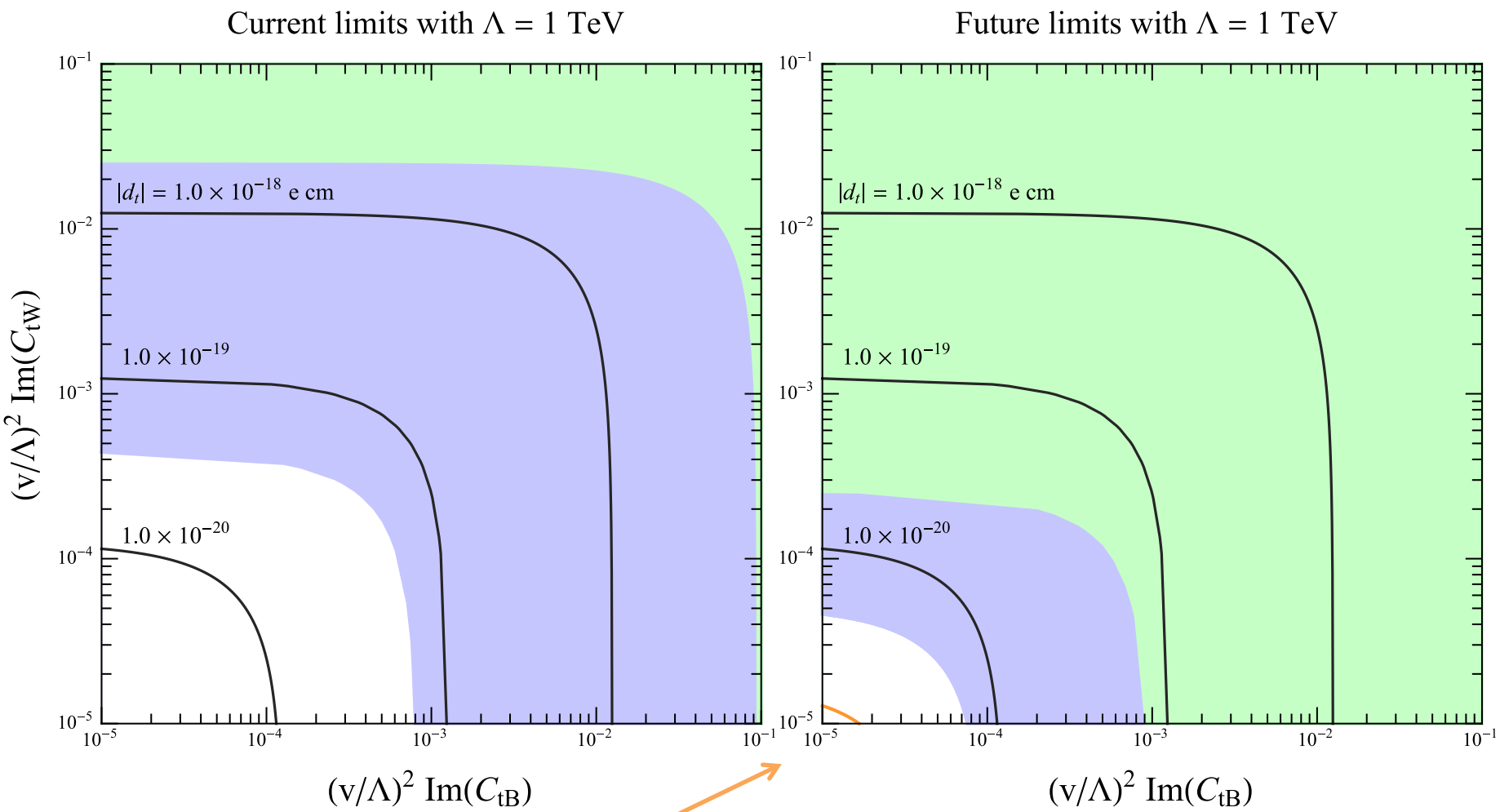
$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$$

Excluded region:

$$\left(\frac{v}{\Lambda}\right)^2 \mathrm{Im}\left(C_{tB}\right) \gtrsim 8 \times 10^{-4}$$

$$\left(\frac{v}{\Lambda}\right)^2 \mathrm{Im}\left(C_{tW}\right) \gtrsim 4 \times 10^{-4}$$

Positive case with future sensitivities



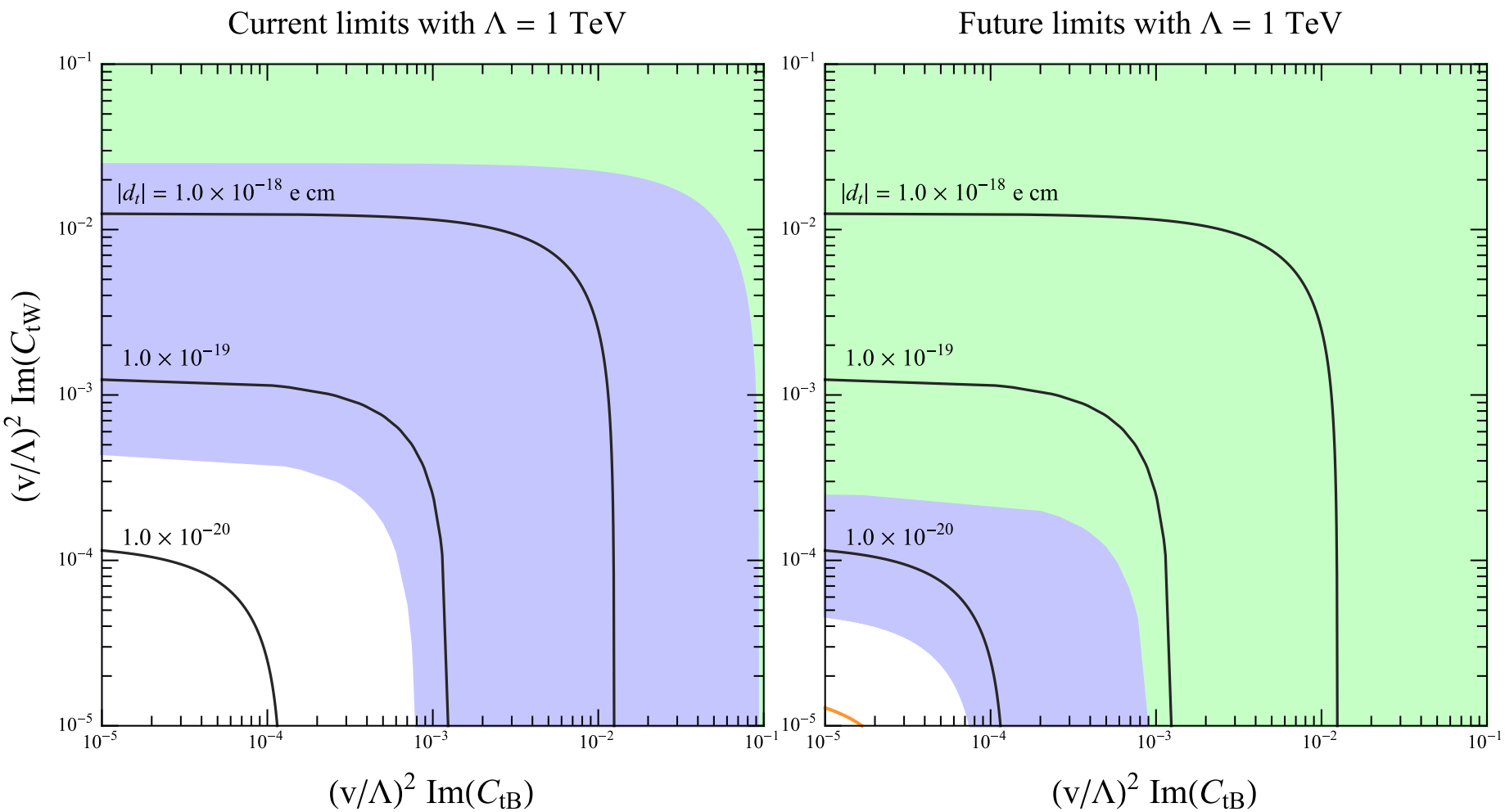
Orange line

$$d_p = 1.0 \times 10^{-29}\ e\ \mathrm{cm}$$

$$d_e = 1.0 \times 10^{-29}\ e\ \mathrm{cm}$$

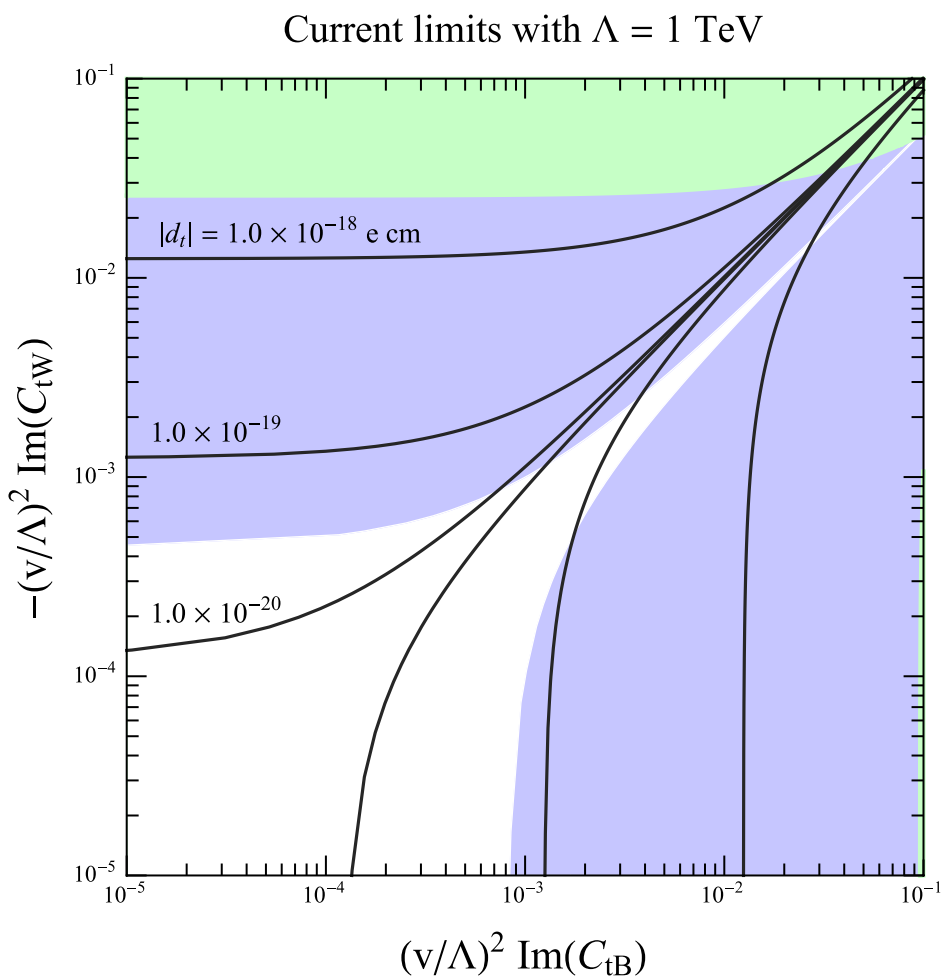
$$d_n = 3.0 \times 10^{-28}\ e\ \mathrm{cm}$$

Positive case with future sensitivities



Future limit : $|d_t| \lesssim 3.2 \times 10^{-21}\ e\ \mathrm{cm}$

Negative case



Green :

Excluded by the neutron EDM

$$|d_n| < 3.0 \times 10^{-29}\ e\ \mathrm{cm}$$

Blue :

Excluded by the electron EDM

$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$$

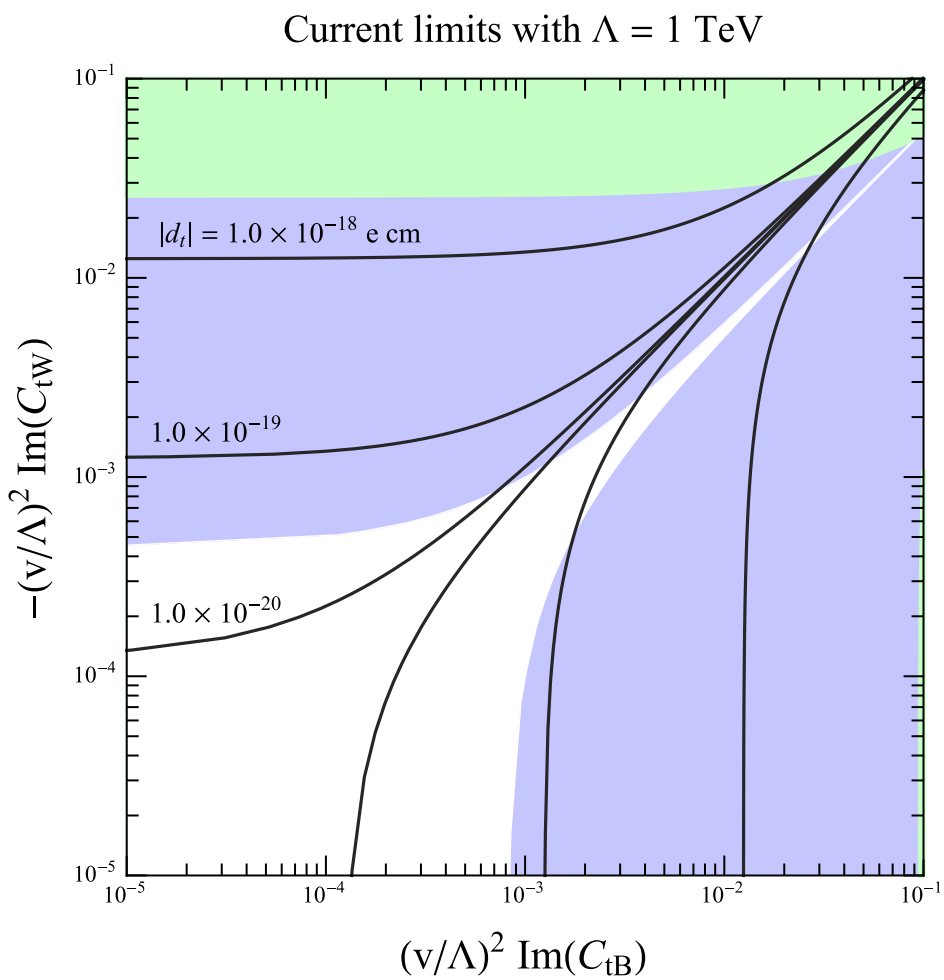
Black lines : top EDM

$$|d_t| = 10^{-(18-20)}\ e\ \mathrm{cm}$$

Allowed

Cancellation region of the electron EDM exists.

Negative case



Green :

Excluded by the neutron EDM

$$|d_n| < 3.0 \times 10^{-29}\ e\ \mathrm{cm}$$

Blue :

Excluded by the electron EDM

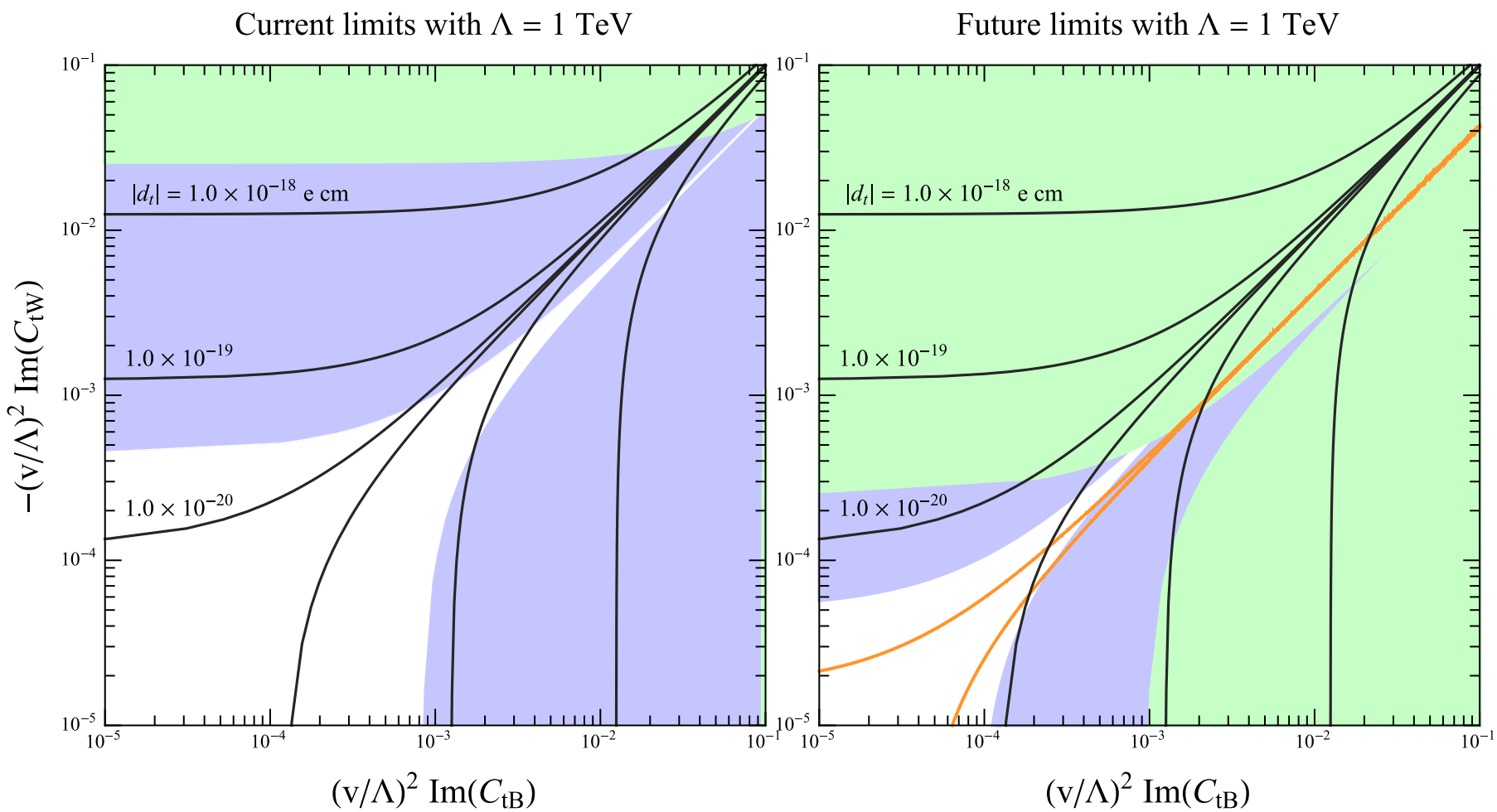
$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$$

Black lines : top EDM

$$|d_t| = 10^{-(18-20)}\ e\ \mathrm{cm}$$

Current limit : $|d_t| \lesssim 3.5 \times 10^{-18}\ e\ \mathrm{cm}$

Negative case with future sensitivities



Future limit : $|d_t| \lesssim 2.5 \times 10^{-20}\ e\ \mathrm{cm}$

Conclusion

- Top quark might a key particle to look for New Physics due to its large Yukawa coupling.

  Two CP-violating couplings :

  Top-Higgs $\tilde{\kappa}_t \bar{t} i \gamma_5 t h$

  Top EDM $d_t \bar{t} \sigma^{\mu\nu} \gamma_5 t F_{\mu\nu}$

- G2HDM is one successful scenario for EWBG.
  It is important to examine possible parameter regions with several experiments.

- Current electron EDM limit implies $d_t \lesssim 6.5 \times 10^{-20}\ e\ \mathrm{cm}$.

Thank you very much for your attention :)