Aspects of CP violation in electroweak baryogenesis

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Dark side of the Universe

Outline :

1. Introduction

2. Relationship between the BAU and EDMs

3. Numerical results

4. Summary

Introduction

Baryon Asymmetry of the Universe (BAU)

Observational facts indicates that our Universe is baryon-asymmetric.

$$Y_B \equiv \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$$

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One attractive scenario is electroweak baryogenesis (EWBG).

Kuzmin, Rubakov, Shaposhnikov, PLB155,36 (‘85)

Relevant energy scale is ~ O(100) GeV.

$\sim$ Collider experiments can verify it.

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It turns out that the SM EWBG was ruled out.

- CP violation is too small to generate the BAU.

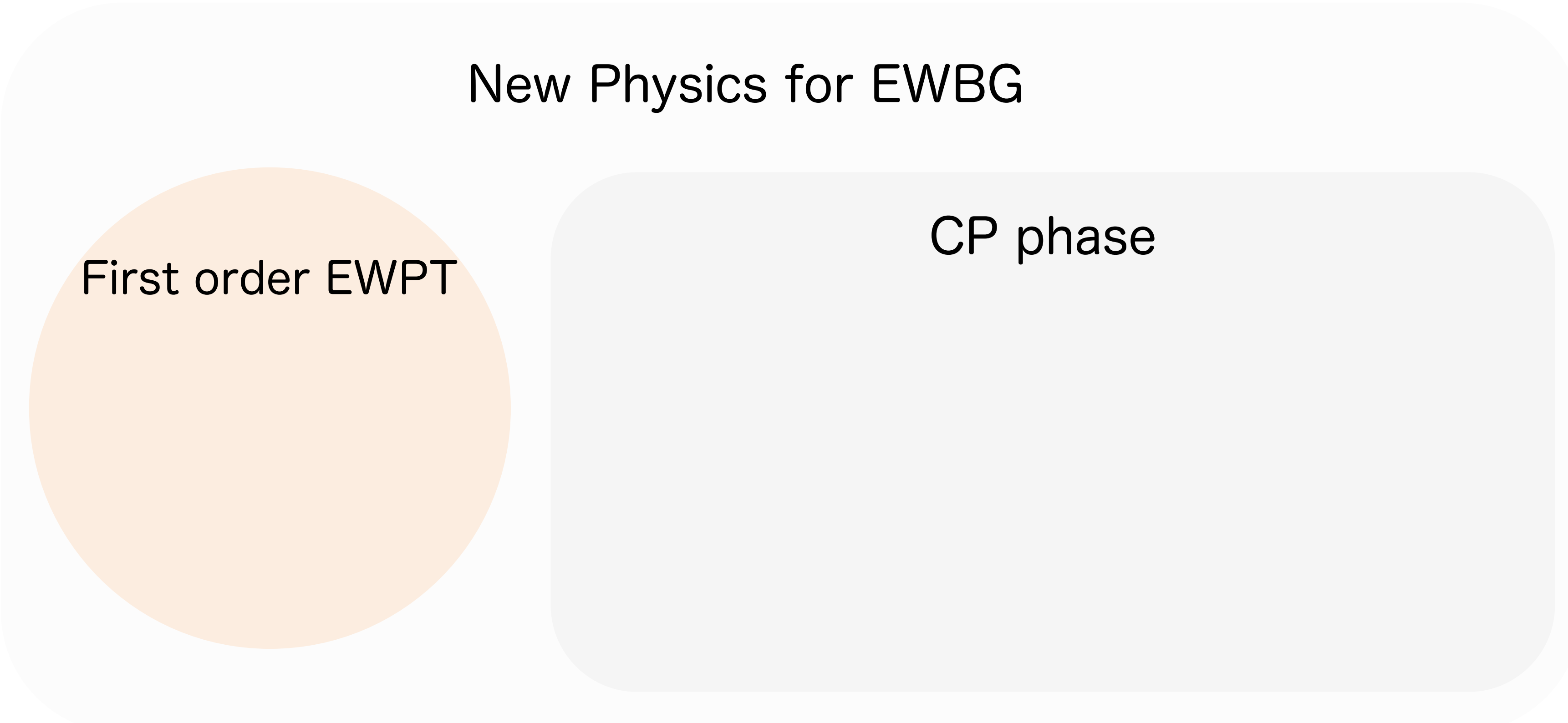
Gavela et al, NPB430, 382 (1994) ; Huet and Nelsen, PRD51, 379 (1995)

- EWPT becomes crossover for $m_h > 73$ GeV.

Kajantie et al, PRL77, 2887 (1996) ; Rummukainen et al, NPB 542, 283 (1998)
Csikor et al, PRL 82, 21 (1999) ; Aoki et al, PRD 60, 013001 (1999)
Laine et al, NPB 73, 180 (1999)

New physics

For the successful EWBG, physics beyond the SM is needed.



New physics

For the successful EWBG, physics beyond the SM is needed.

New Physics for EWBG

First order EWPT

Extended Higgs sector

e.g. Real singlet,

2 Higgs doublets

LHC, ILC

CP phase

New physics

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New Physics for EWBG

First order EWPT

Extended Higgs sector

Real singlet

CP phase

EW-interacting fermions

$$\begin{pmatrix} \psi^+ \\ \psi_i \end{pmatrix} \qquad \psi_j$$

Electric Dipole Moment

* It becomes possible to discuss both the first order EWPT and the CP violation, separately.

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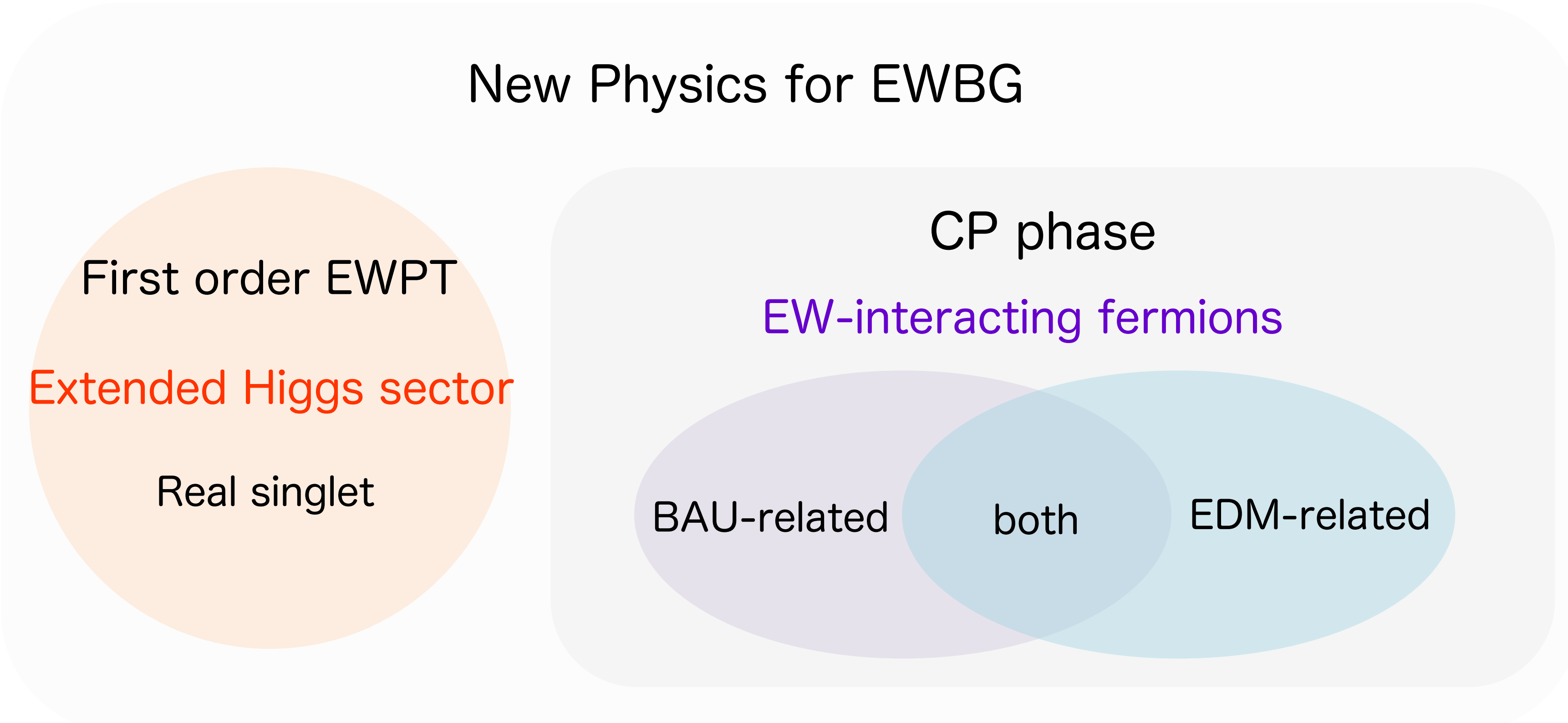

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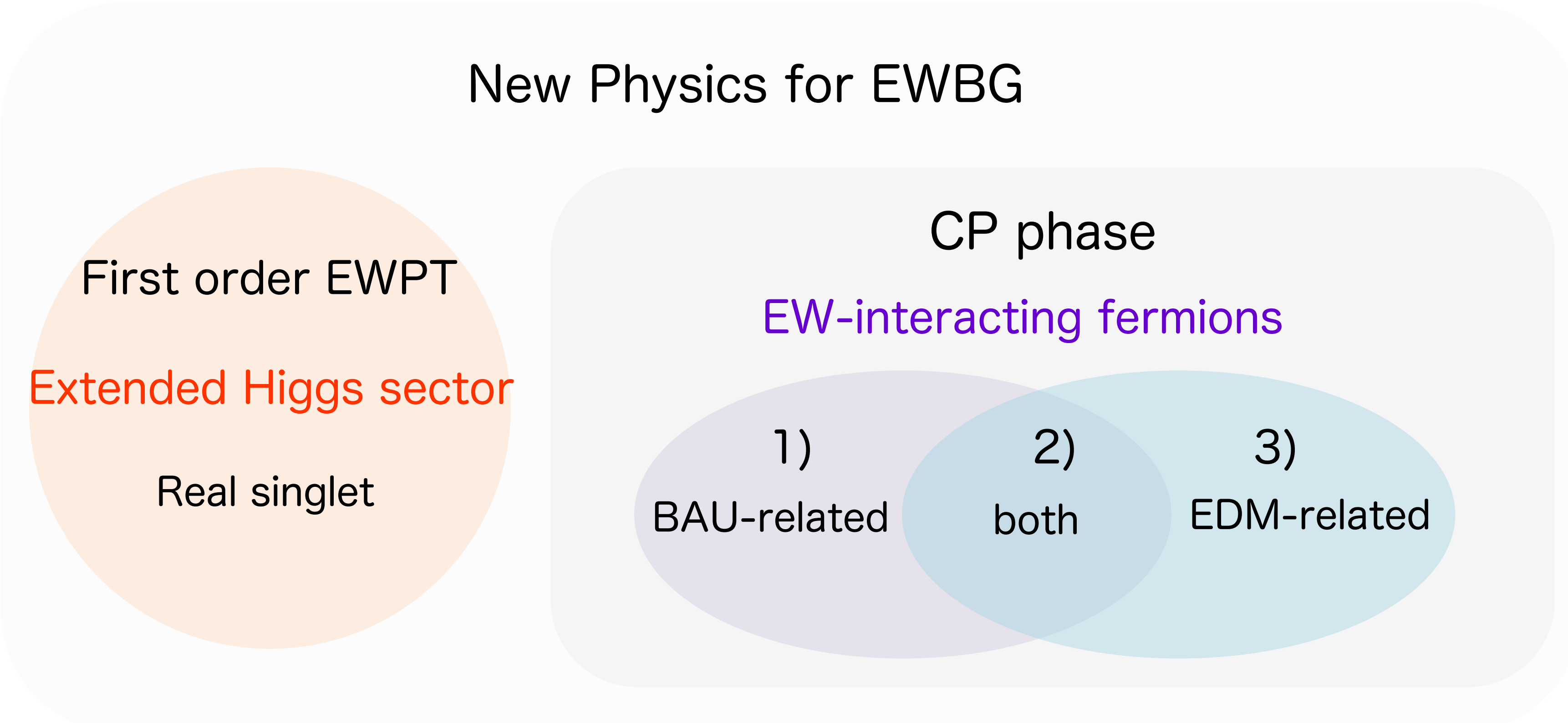

1) BAU-related CP phase
2) Relationship between the BAU and EDMs
3) Situation where the other CP phase exists

Relationship between the BAU and EDMs

BAU

Two fermions $\psi_{i,j}$ have the following interactions.

$$\mathcal{L} = \frac{1}{\sqrt{2}}\bar{\psi}_i \left[c_L v_b(x) P_L + c_R v_a(y) P_R\right] \psi_j + \mathrm{h.c.}$$

$c_{L,R}$: Complex numbers

$v_{a,b}(x)$: Space-dependent VEVs

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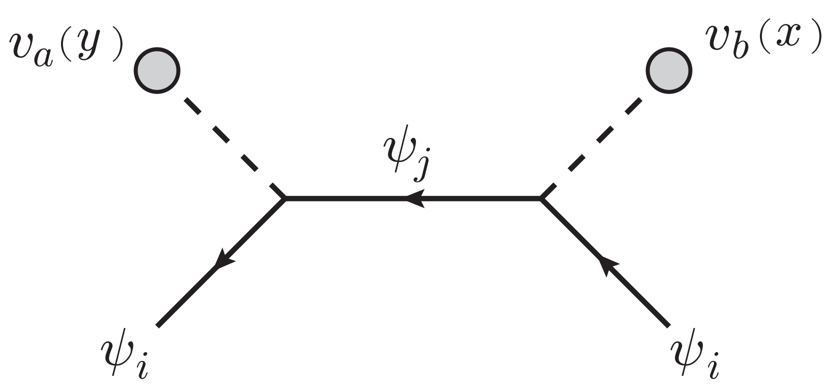
CP-violating source is supplied to the BAU by the following diagram.

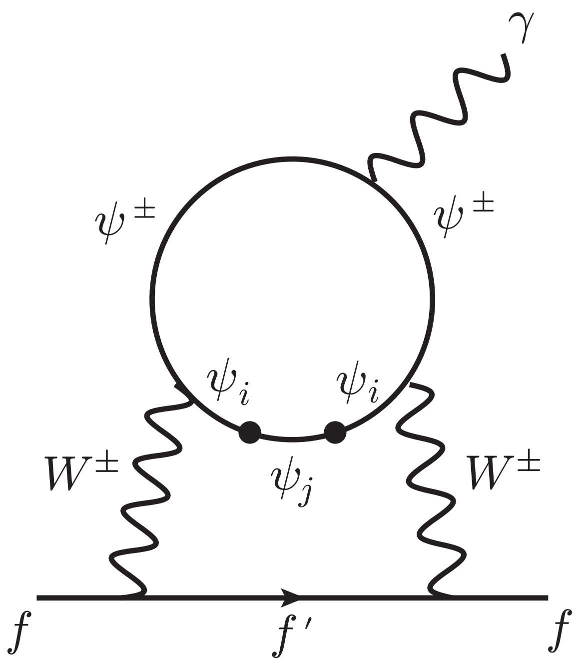


$$\sim \quad S_{\psi_i} \equiv C_{\text{BAU}} \text{Im}[c_L c_R^*]$$

$$(n_B \propto S_{\psi_i})$$

EDM via Barr-Zee diagram

New fermions can induce EDMs via the Barr-Zee diagram.



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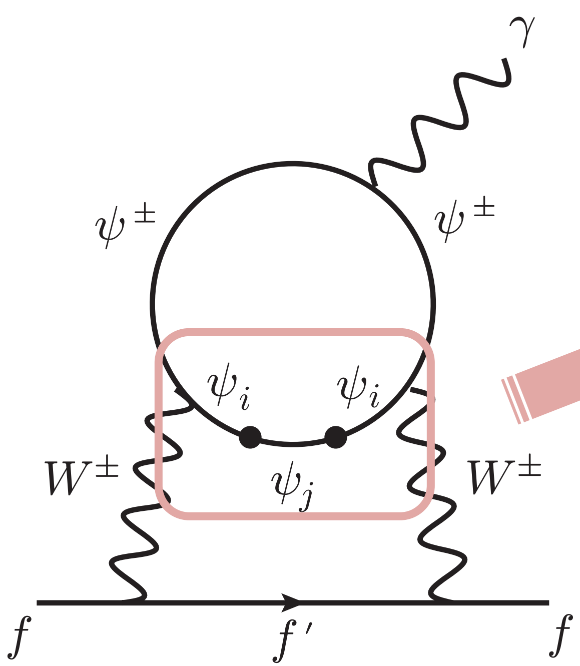

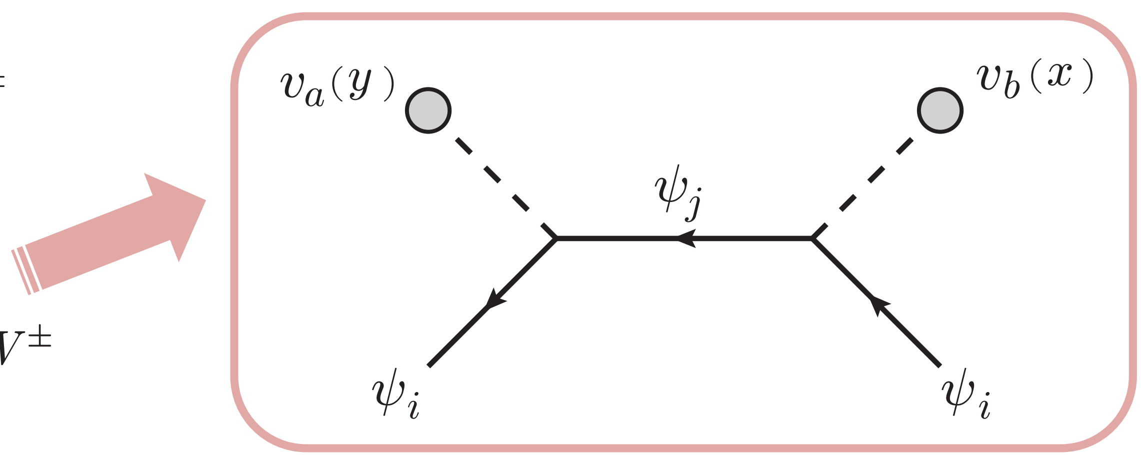

EDMs are directly connected to the CP-violating source.

EDM via Barr-Zee diagram

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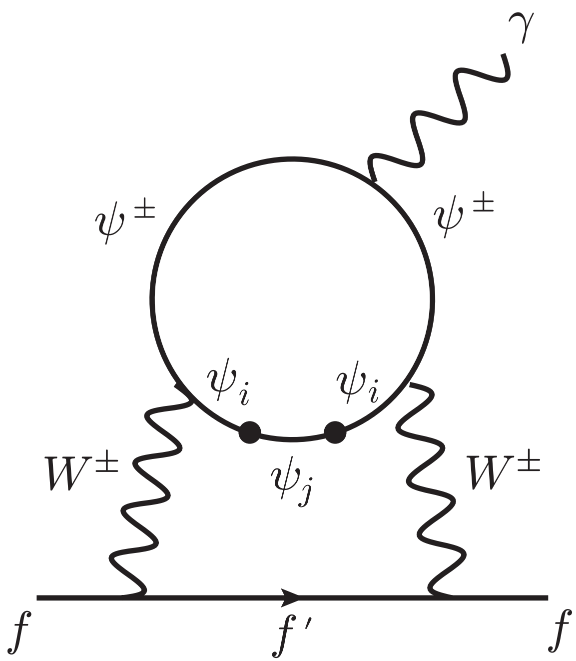

$$\frac{d_f^{WW}}{e} \equiv C_{\rm EDM}^{WW} {\rm Im}[c_L c_R^*]$$

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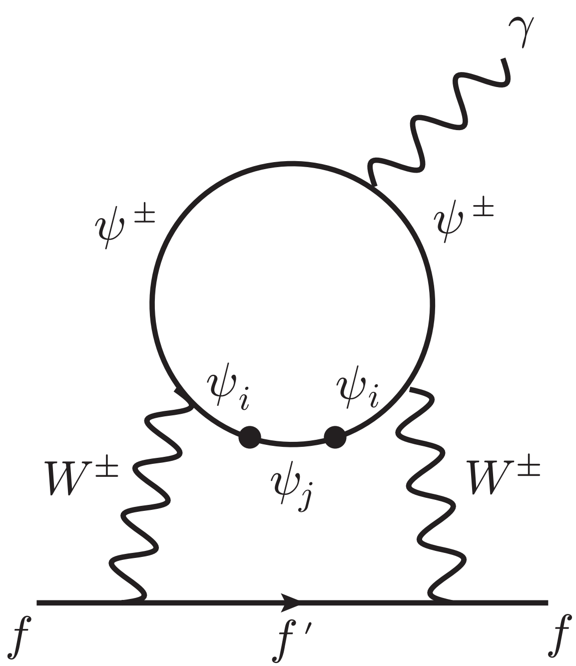

$$\frac{d_f^{WW}}{e} \equiv C_{\rm EDM}^{WW} {\rm Im}[c_L c_R^*]$$

We finally obtain $$S_{\psi_i} = \frac{C_{\rm BAU}}{C_{\rm EDM}^{WW}} \left(\frac{d_f^{WW}}{e} \right)$$

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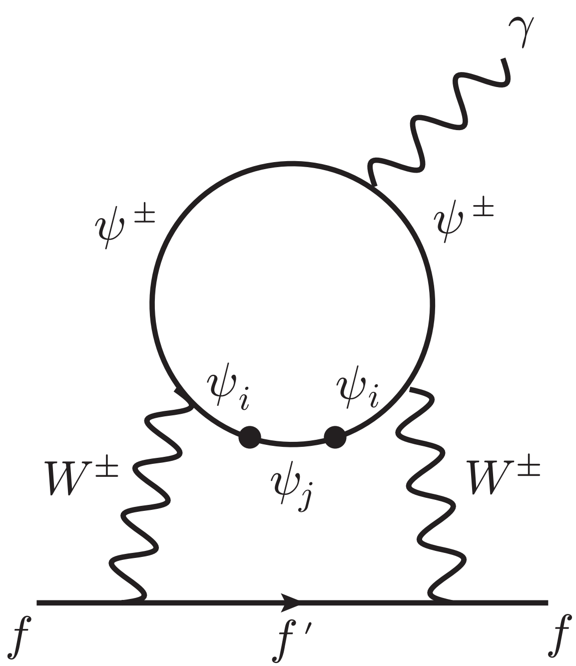


$$\frac{d_f^{WW}}{e} \equiv C_{\mathrm{EDM}}^{WW} \mathrm{Im}[c_L c_R^*]$$

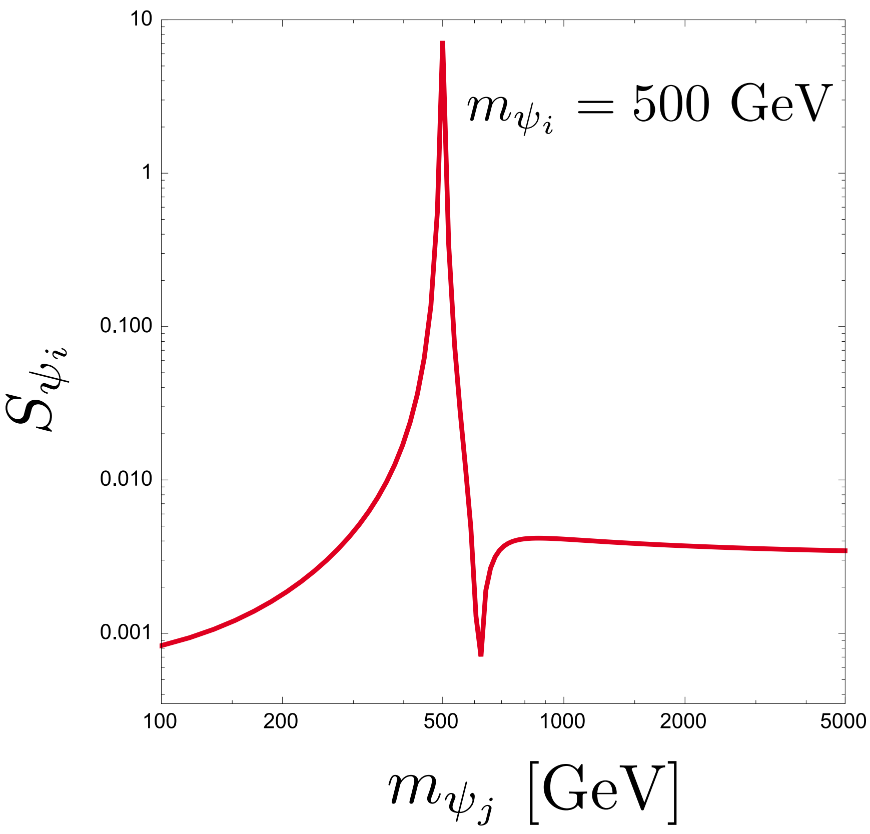
We finally obtain $$S_{\psi_i} = \frac{C_{\mathrm{BAU}}}{C_{\mathrm{EDM}}^{WW}} \left(\frac{d_e^{WW}}{e} \right)_{\mathrm{exp}}$$

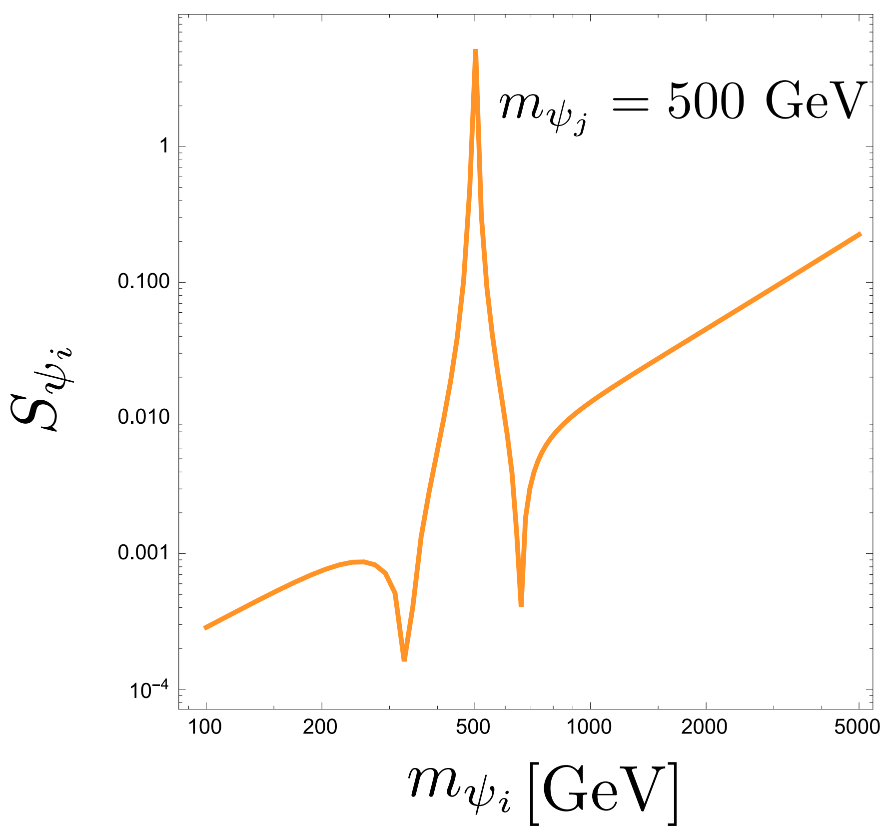
Numerical results

CP-violating source as a function of $m_{\psi_{i,j}}$

For numerical calculations, $|d_e^{\rm exp}| = 8.7 \times 10^{-29}\ e \cdot {\rm cm}$

* We get rid of model-dependent parameters, VEVs and β.





CP-violating source as a function of $m_{\psi_{i,j}}$

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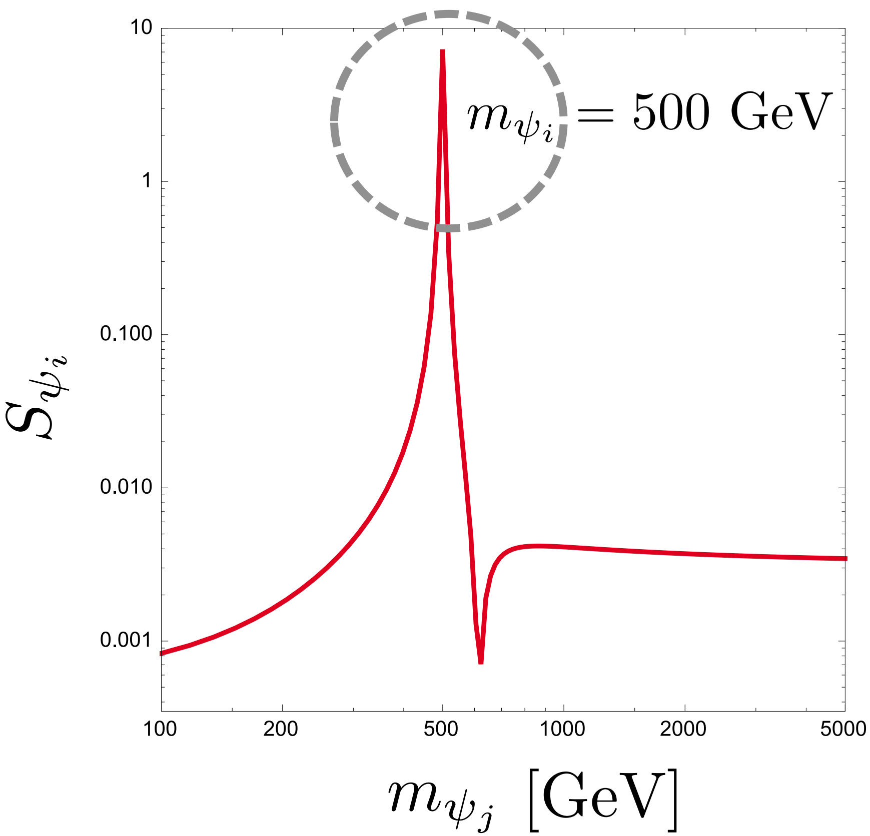
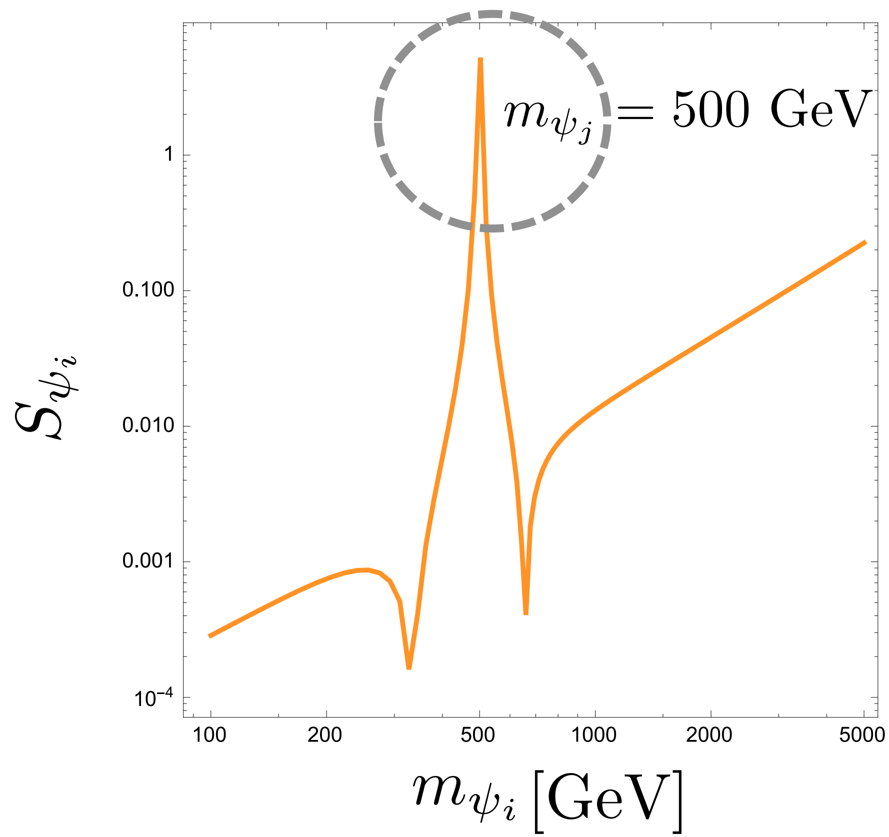
Enhancement shows up due to thermal effect in C_{BAU} .





CP-violating source as a function of $m_{\psi_{i,j}}$

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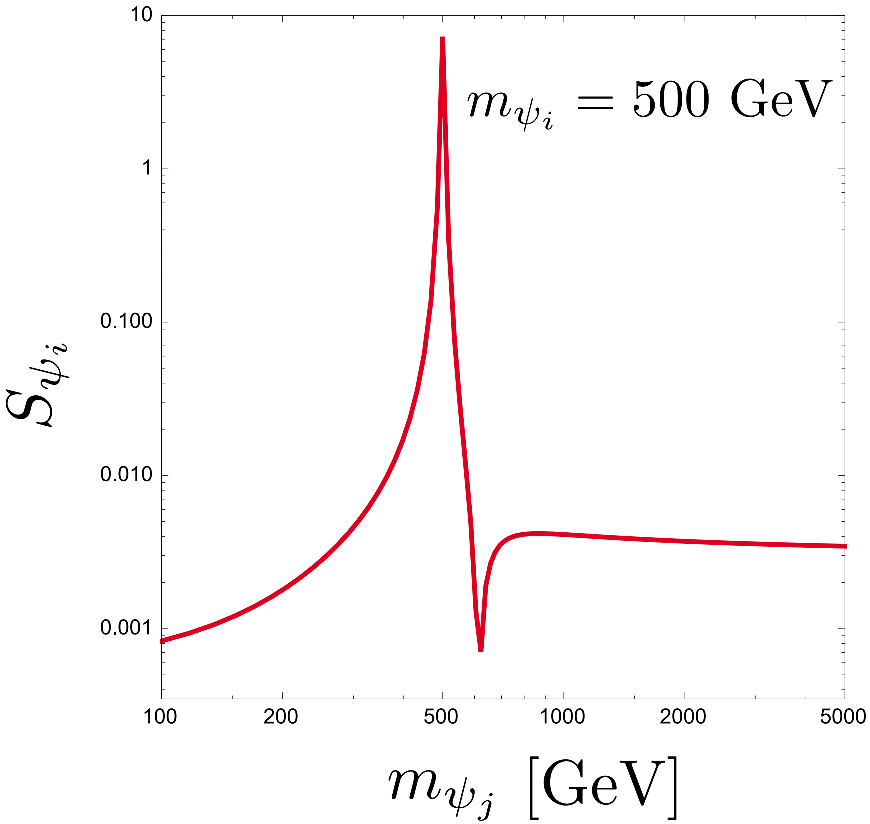
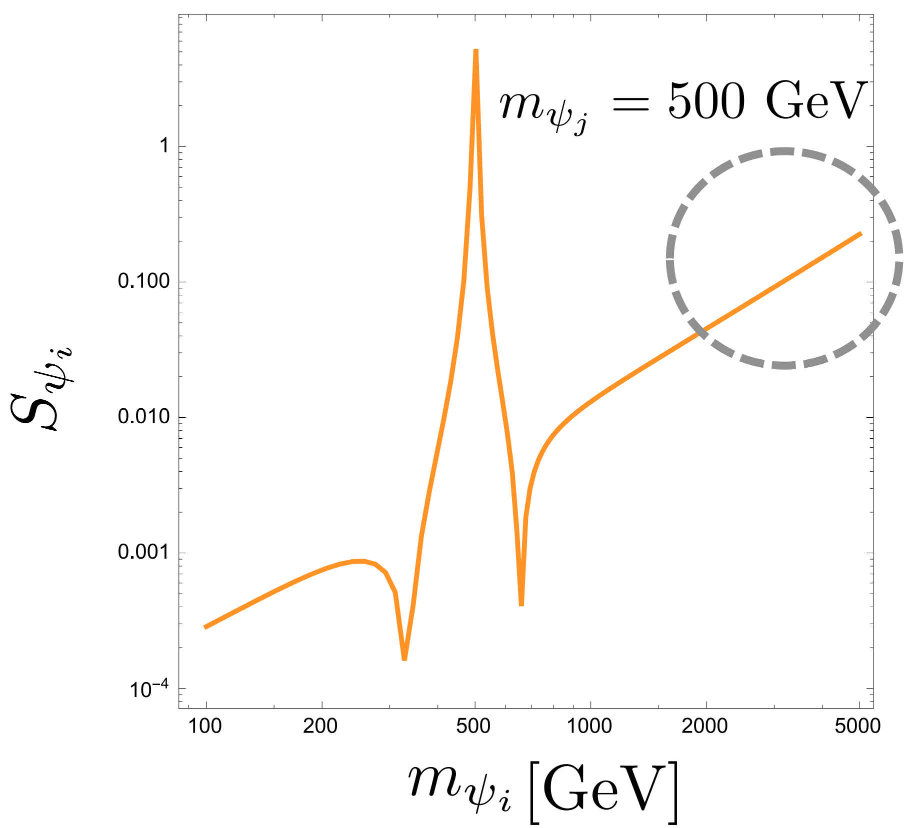
Due to the rapid suppression of $C_{\rm EDM}^{WW} \sim \dfrac{m_e m_j}{m_i^3}$





Particle contents

Particle contents are NMSSM-like.

Scalars	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Z_2
Φ_1	$(\mathbf{1},\ \mathbf{2},\ 1/2)$	$-$
Φ_2	$(\mathbf{1},\ \mathbf{2},\ 1/2)$	$+$
S	$(\mathbf{1},\ \mathbf{1},\ 0)$	$-$

Fermions	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Z_2
$\tilde{\Phi}_1$	$(\mathbf{1},\ \mathbf{2},\ 1/2)$	$-$
$\tilde{\Phi}_2$	$(\mathbf{1},\ \mathbf{2},\ 1/2)$	$+$
$\tilde{S}^0$	$(\mathbf{1},\ \mathbf{1},\ 0)$	$-$

Parameters are set in such a way as to take the limit of the real-singlet model.

BAU vs EDM

$$|c_L| = |c_R| = 0.42,\ \phi = \phi_L - \phi_R = 225^\circ$$

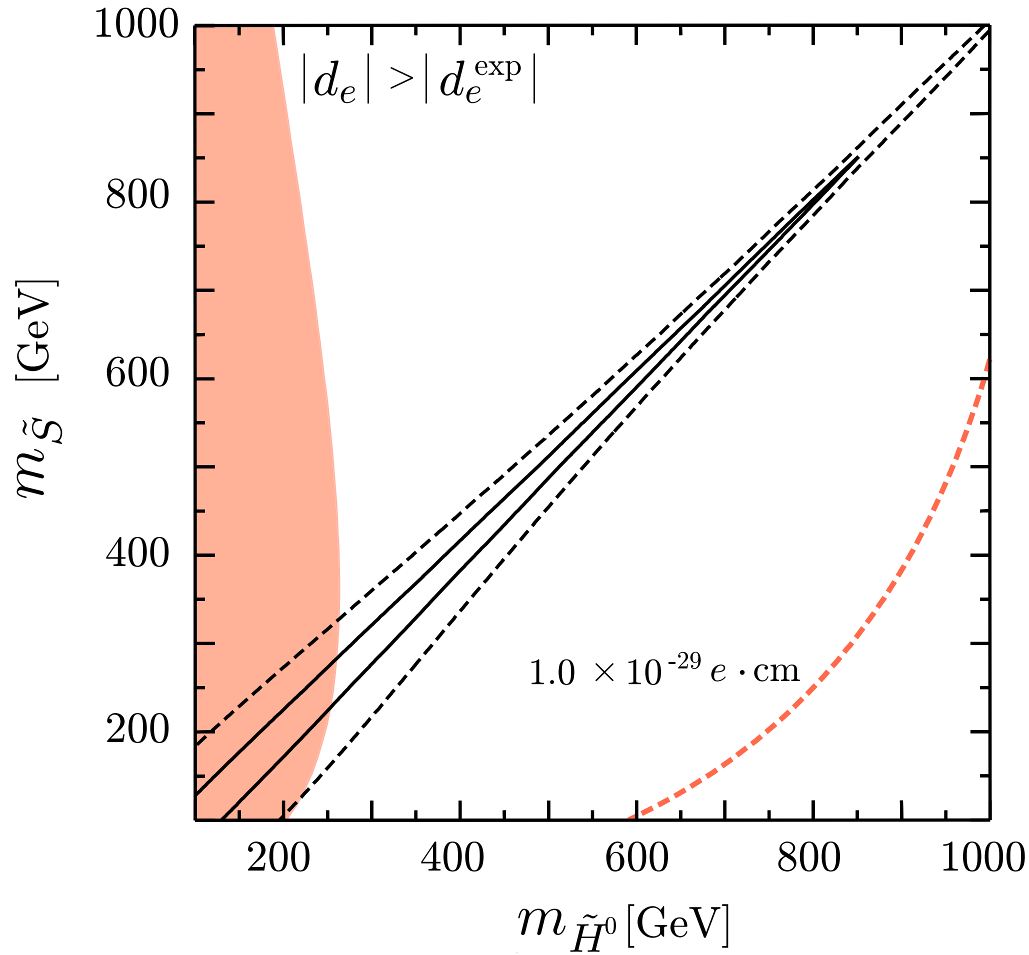
Solid line :

$$Y_B/Y_B^{\rm obs} = 1$$

Dashed line :

$$Y_B/Y_B^{\rm obs} = 0.1$$

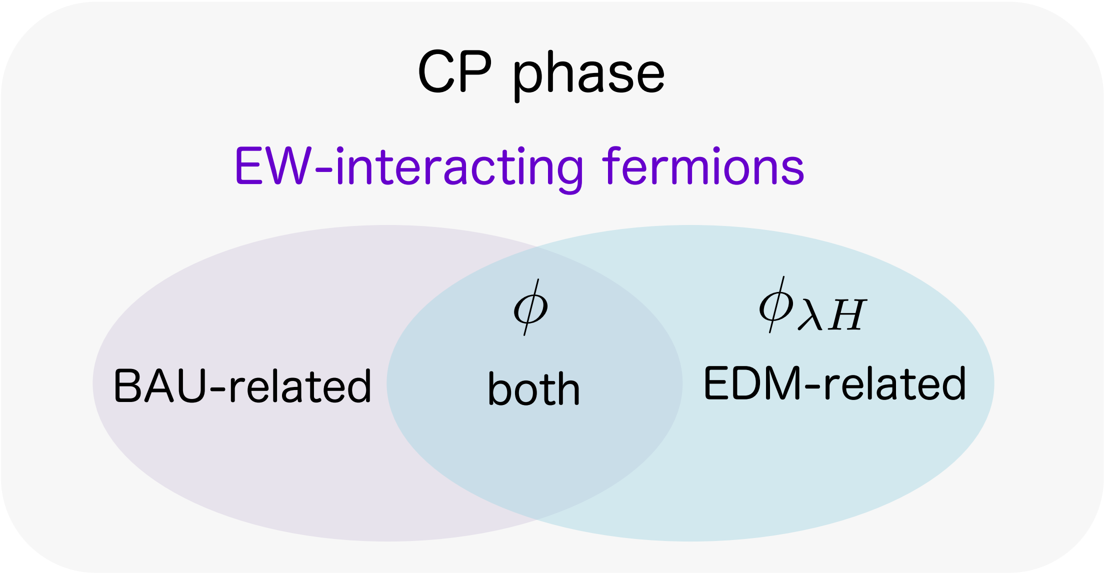
If $d_e=10^{-29}$ e・cm can be achieved, the successful region would be tested !



Other CP phase

Other CP phase

If the other CP phase exists, the situation is different.



The other Barr-Zee diagram can be induced.

The other Barr-Zee diagram

Real singlet h_S has the following interactions.

$$\mathcal{L} \ni h_S \bar{\psi}^+ \left(g^S + i\gamma_5 g^P \right) \psi^+$$

with
$$g^S = |\lambda| \cos \phi_{\lambda H}$$
$$g^P = -|\lambda| \sin \phi_{\lambda H}$$

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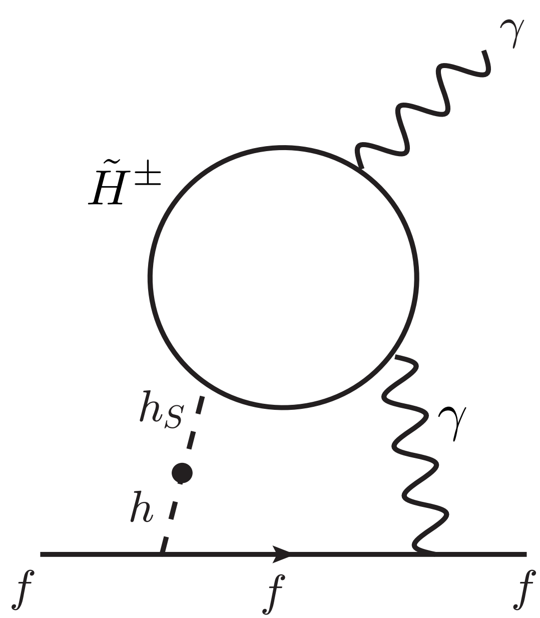
$$\mathcal{L} \ni h_S \bar{\psi}^+ \left(g^S + i\gamma_5 g^P \right) \psi^+$$

This interaction induces the other Barr-Zee diagram, $d_e^{H\gamma}$.



The electron EDM becomes

$$d_e^{\rm sum} = d_e^{WW} + d_e^{H\gamma}$$

It is possible that $d_e^{\rm sum} = 0.$

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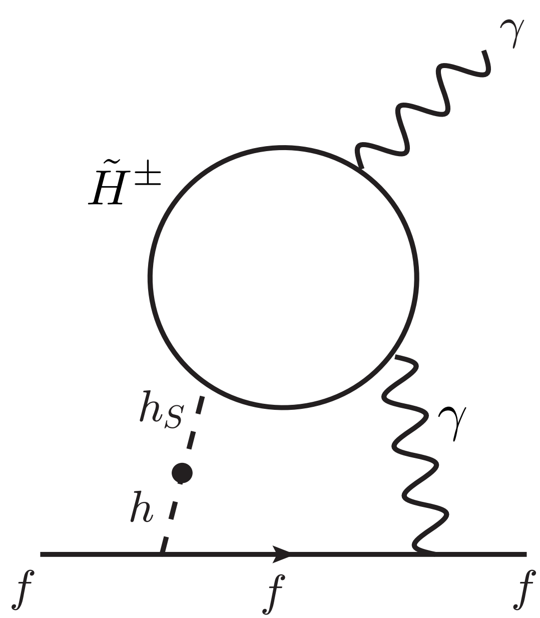

Even if $d_e^{\rm sum} = 0,$

the Higgs physics helps

the verifiability in this model !

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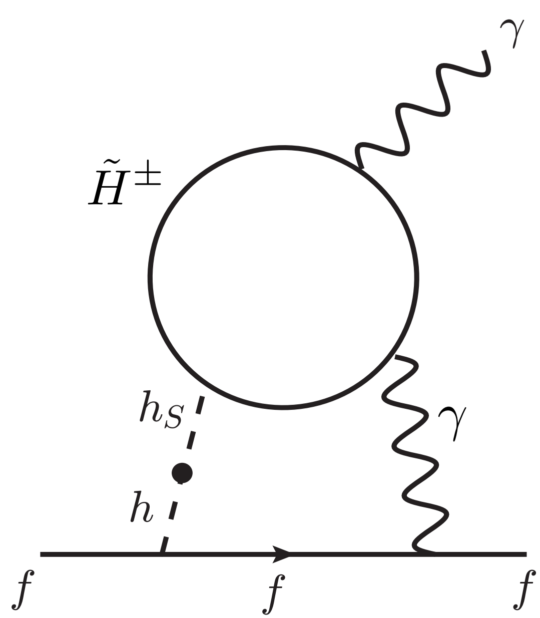

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- Higgs-gamma-gamma loop
- EWPT < Mixing angle < LHC

Electron EDM

$$d_e^{\rm sum} = d_e^{WW} + d_e^{H\gamma}$$ in $(\lambda, \phi_{\lambda H})$ plane.

☐ Parameters

$$m_{\tilde{H}^0} = 300 \text{ GeV}$$

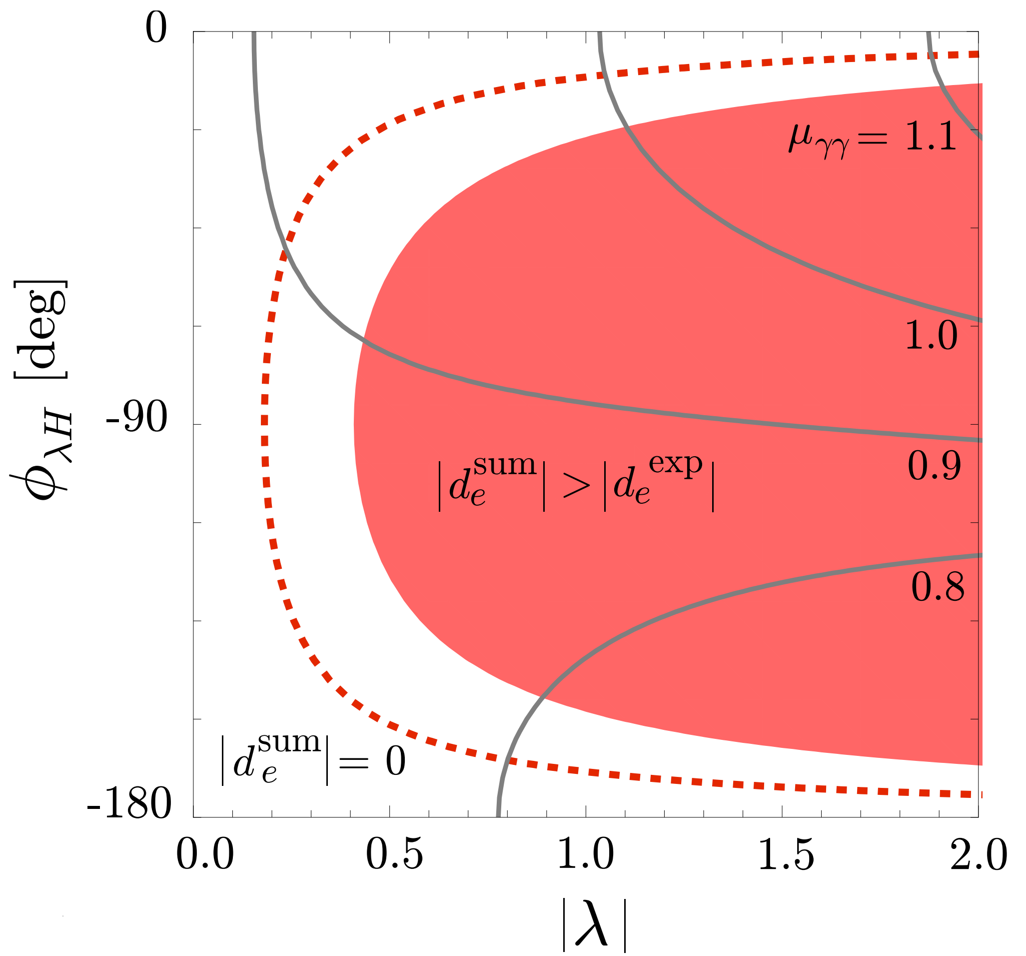
$$m_{\tilde{S}} = 277 \text{ GeV}$$

which leads to

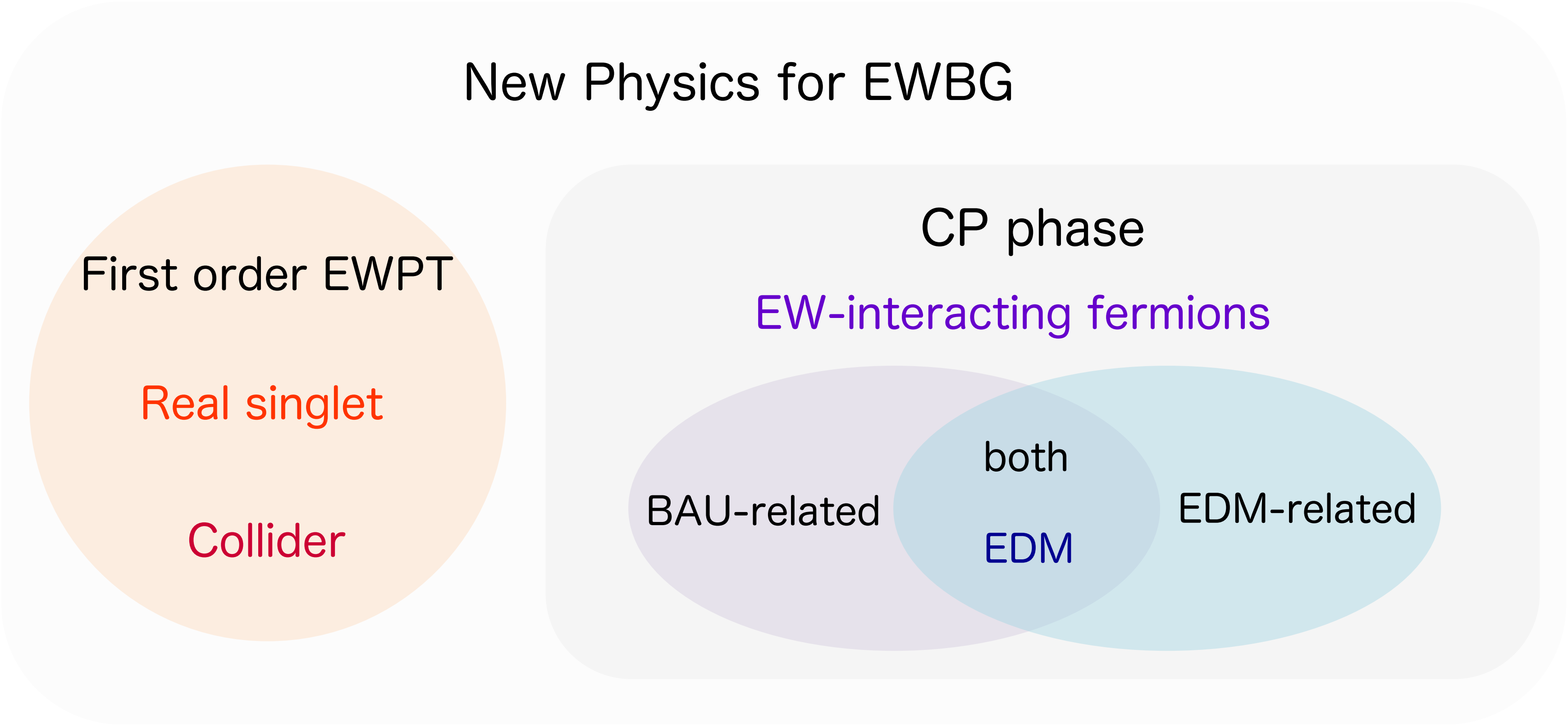
$$Y_B / Y_B^{\rm obs} = 1$$

■ Gray line : $\mu_{\gamma\gamma}$

Signal strength of the Higgs decay to two gammas



Summary



As long as only the BAU-related CP phase exists in the model, it can be verified by the electron EDM.