Aspects of CP violation in electroweak baryogenesis

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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.

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

P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5076

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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.

Electroweak Baryogenesis

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

Sakharov's criteria are satisfied as follows:

☐ Baryon number violation : Sphaleron process

☐ C and CP violation : Chiral gauge theory and CP phase

☐ Out of equilibrium : First order electroweak phase transition

Electroweak Baryogenesis

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

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☐ Baryon number violation : Sphaleron process

☐ C and CP violation : Chiral gauge theory and CP phase

(SM) CP violation is too small to generate the BAU.

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

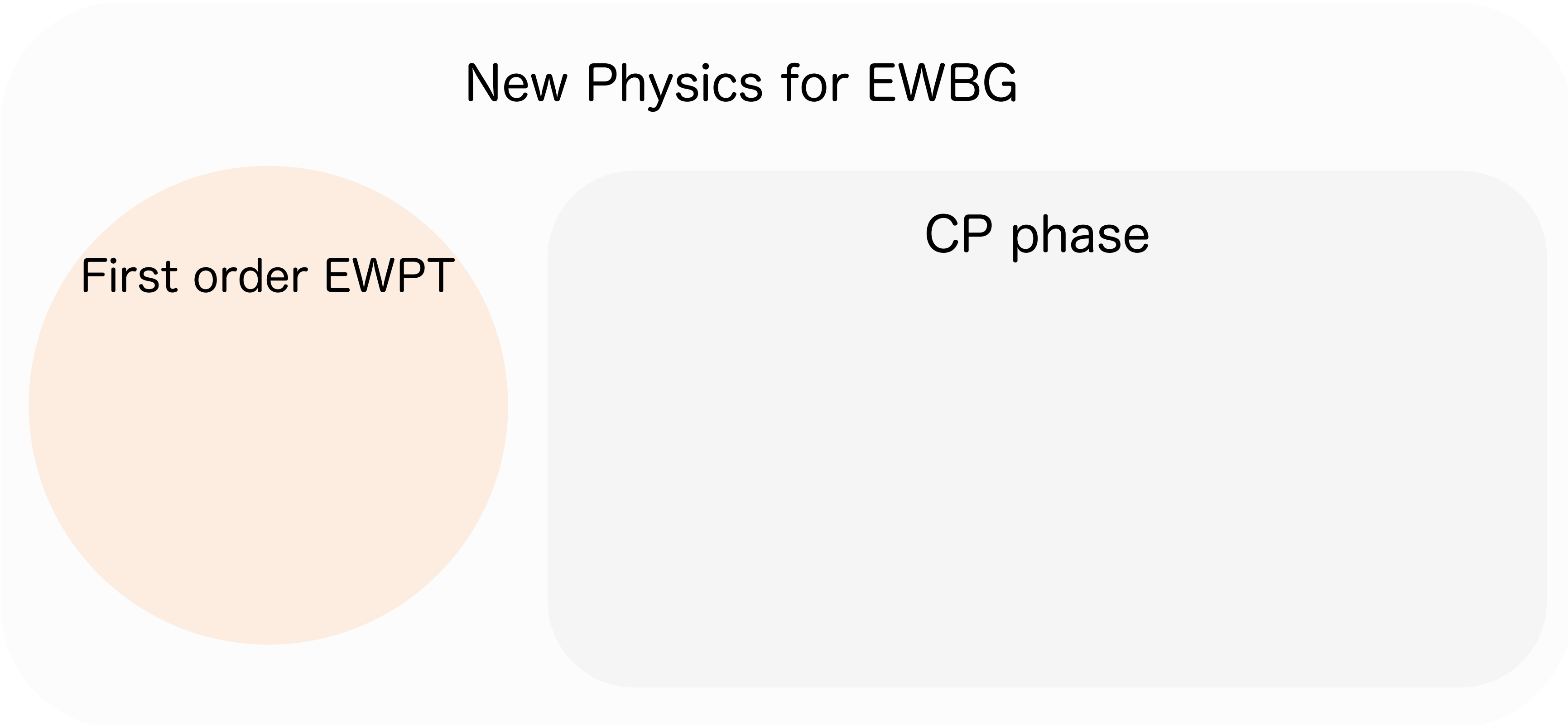
☐ Out of equilibrium : First order electroweak phase transition

(SM) 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

Collider

CP phase

* Given the current situation in the LHC, the colored particles may not play a role in acheving EWBG.

New physics

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

New Physics for EWBG

First order EWPT

Extended Higgs sector

Real singlet

CP phase

EW-interacting fermions

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

EDMs

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

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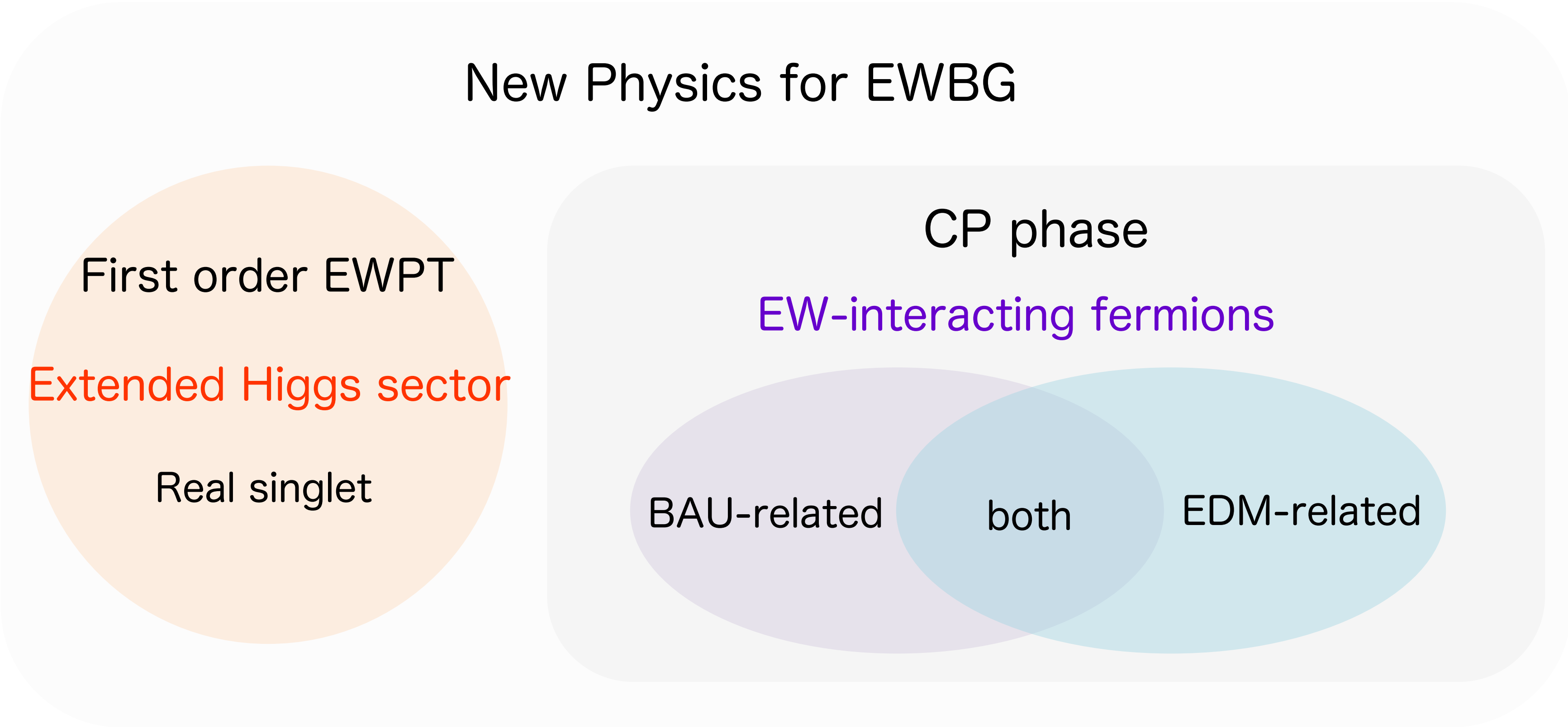

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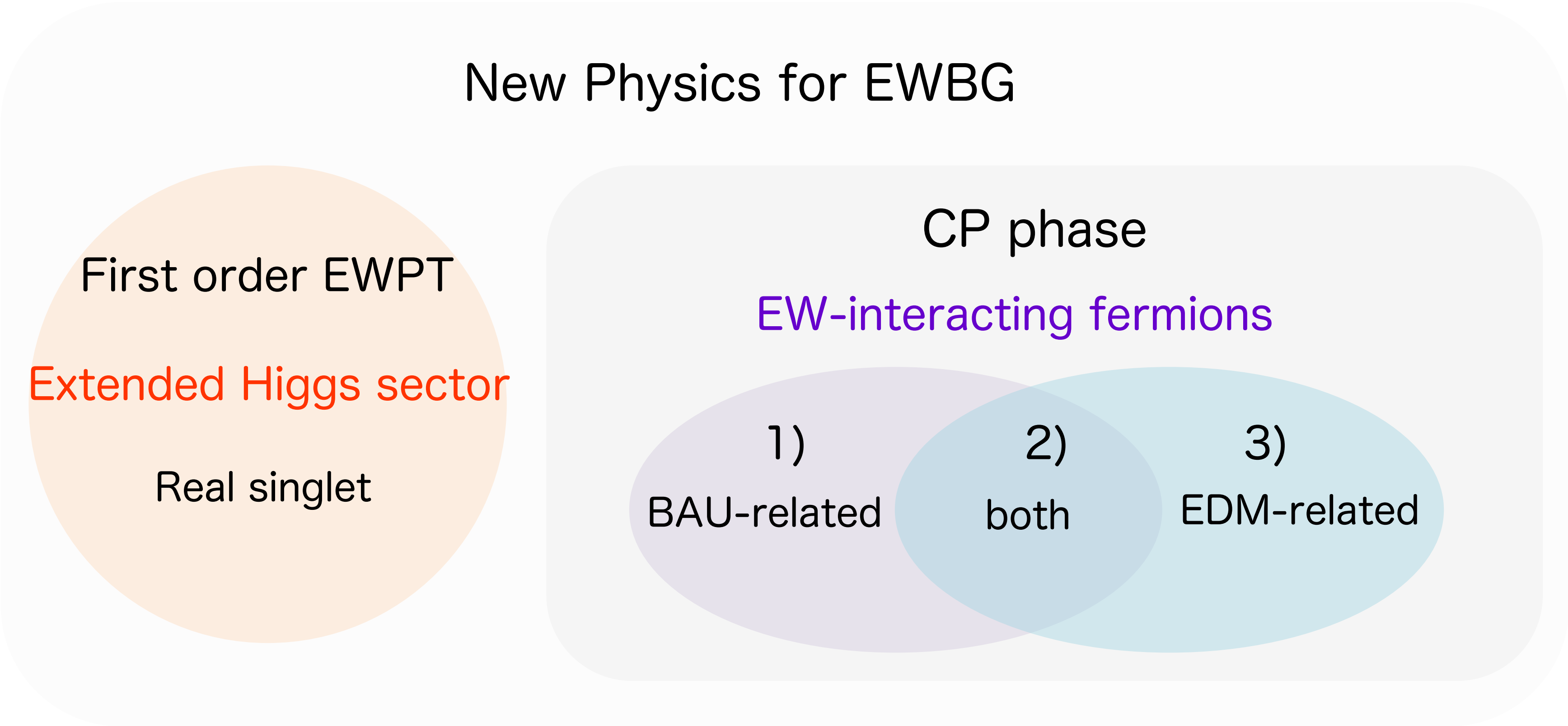

1) What kind of CP phase is the BAU-related one ?
2) Clarify the relationship between the BAU and EDMs
3) Consider the situation where the other CP phase exists

Relationship
between the BAU and EDMs

BAU

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

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

$c_{L,R}$: Complex numbers

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

BAU

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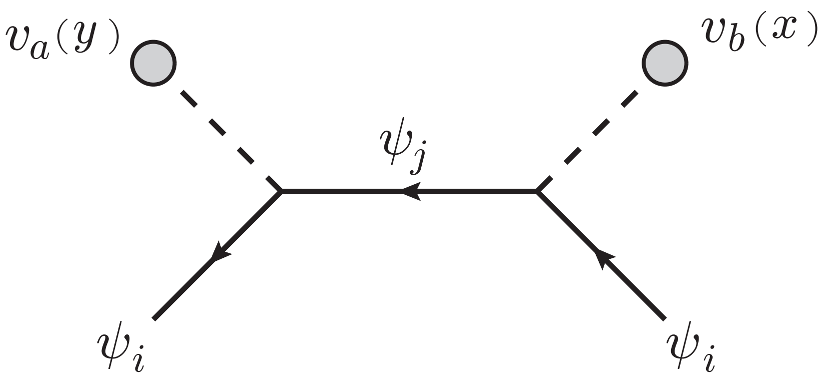
CP-violating source is supplied to the BAU by the following diagram.

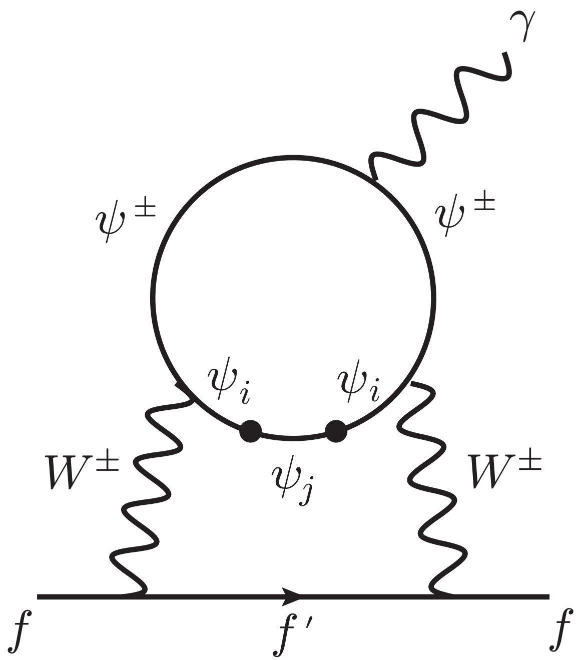


$$\sim \quad S_{\psi_i} \equiv C_{\rm BAU} {\rm Im}[c_L c_R^*]$$

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

EDM via Barr-Zee diagram

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



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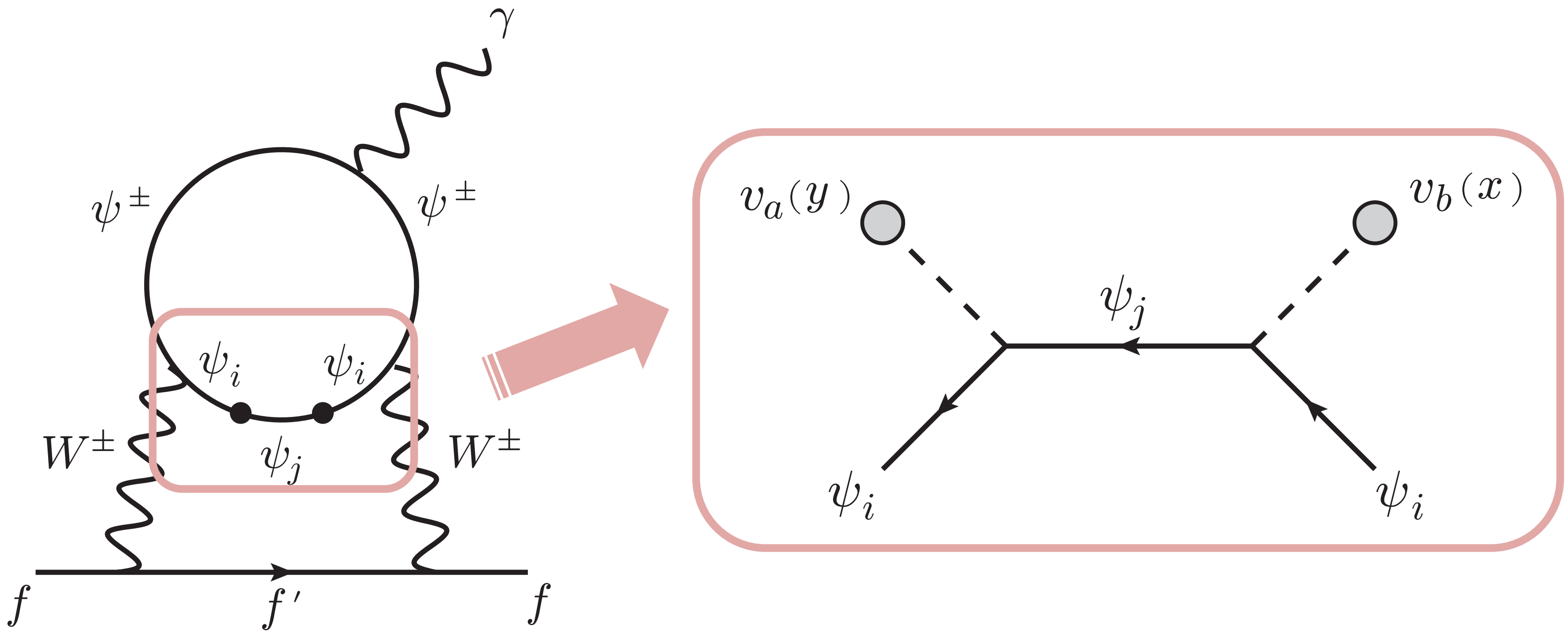

EDMs are directly connected to the CP-violating source.

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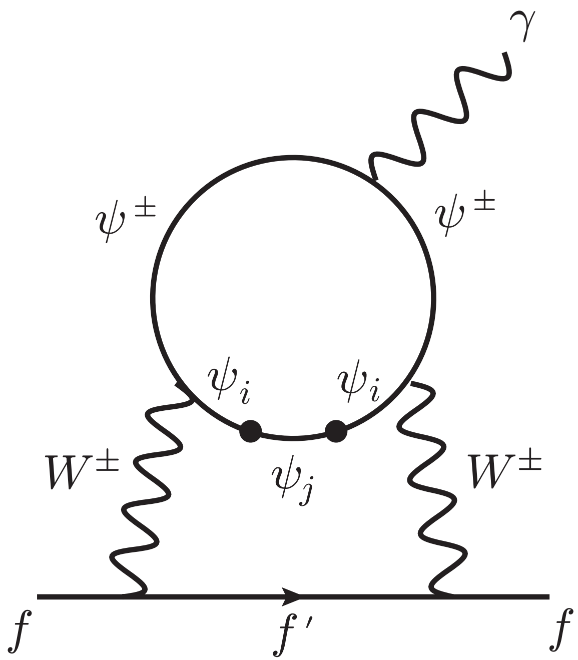

$$\frac{d_f^{WW}}{e} \equiv C_{\mathrm{EDM}}^{WW} \mathrm{Im}[c_L c_R^*]$$

EDM via Barr-Zee diagram

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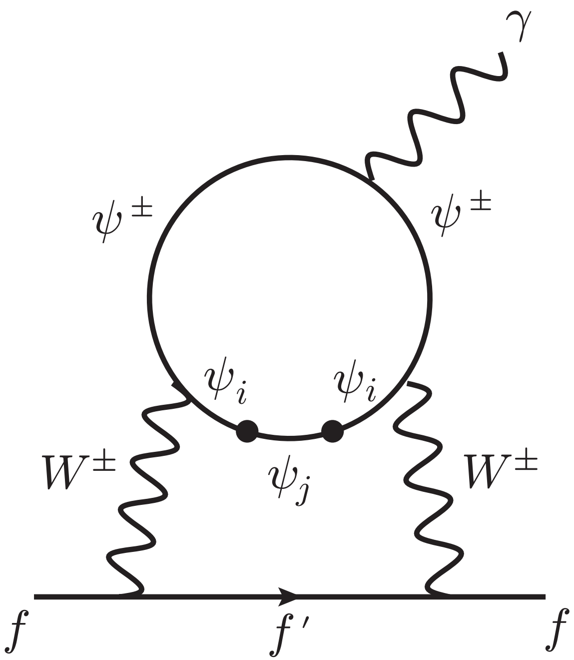

$$\frac{d_f^{WW}}{e} \equiv C_{\mathrm{EDM}}^{WW} \mathrm{Im}[c_L c_R^*]$$

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

EDM via Barr-Zee diagram

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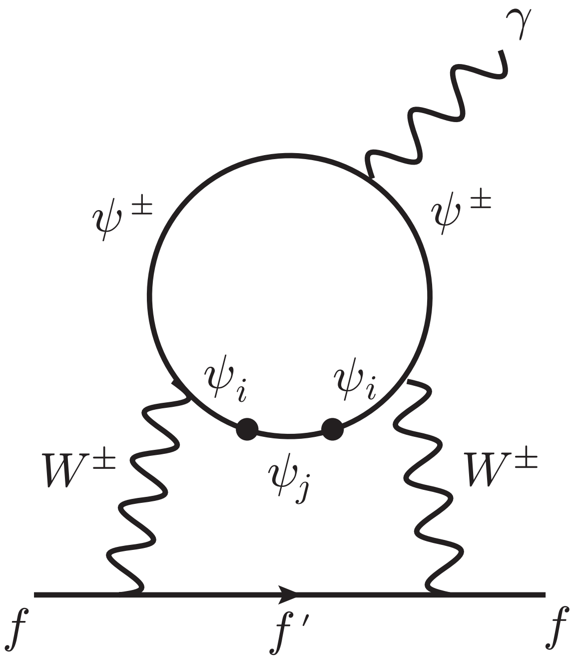


$$\frac{d_f^{WW}}{e} \equiv C_{\rm EDM}^{WW} {\rm Im}[c_L c_R^*]$$

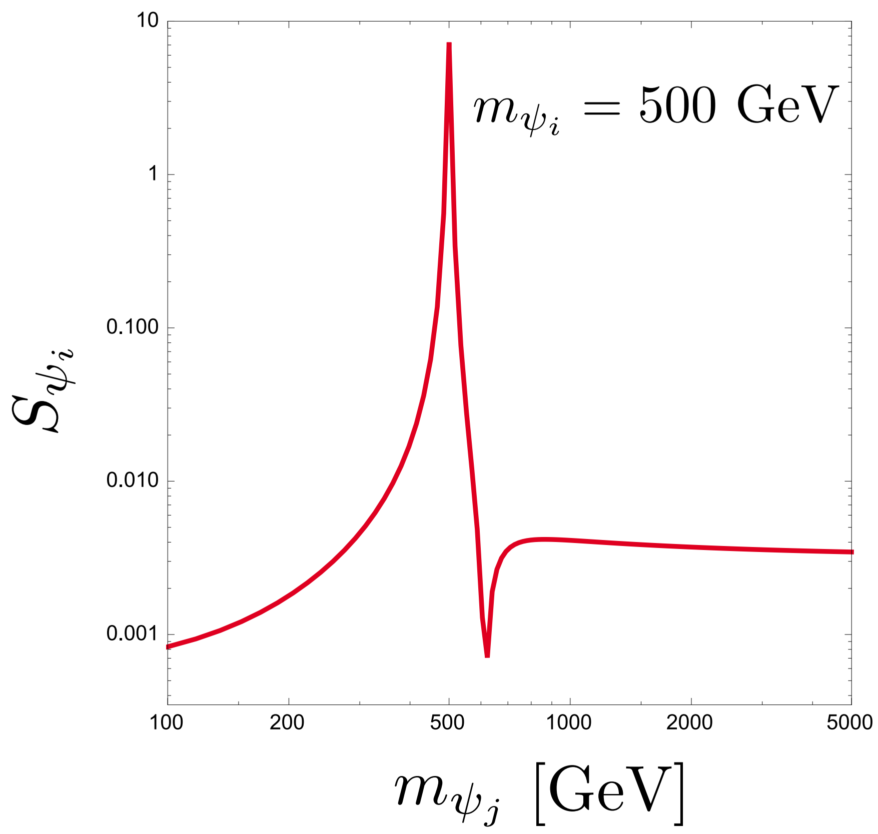
We finally obtain $S_{\psi_i} = \frac{C_{\rm BAU}}{C_{\rm EDM}^{WW}} \left(\frac{d_e^{WW}}{e} \right)_{\rm exp}$

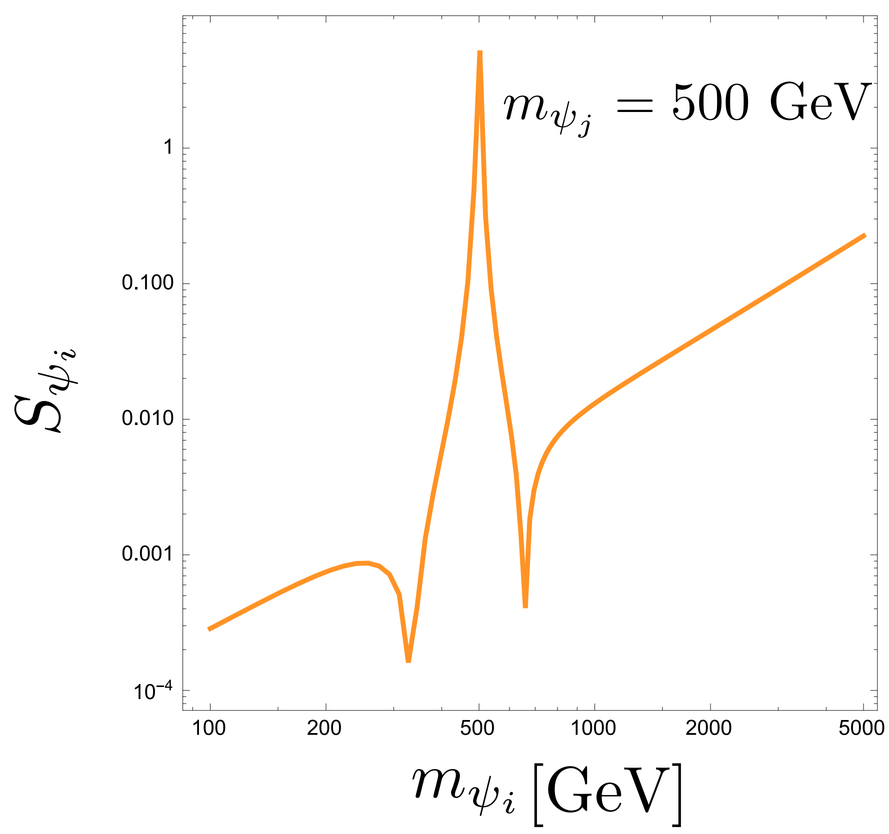
Numerical results

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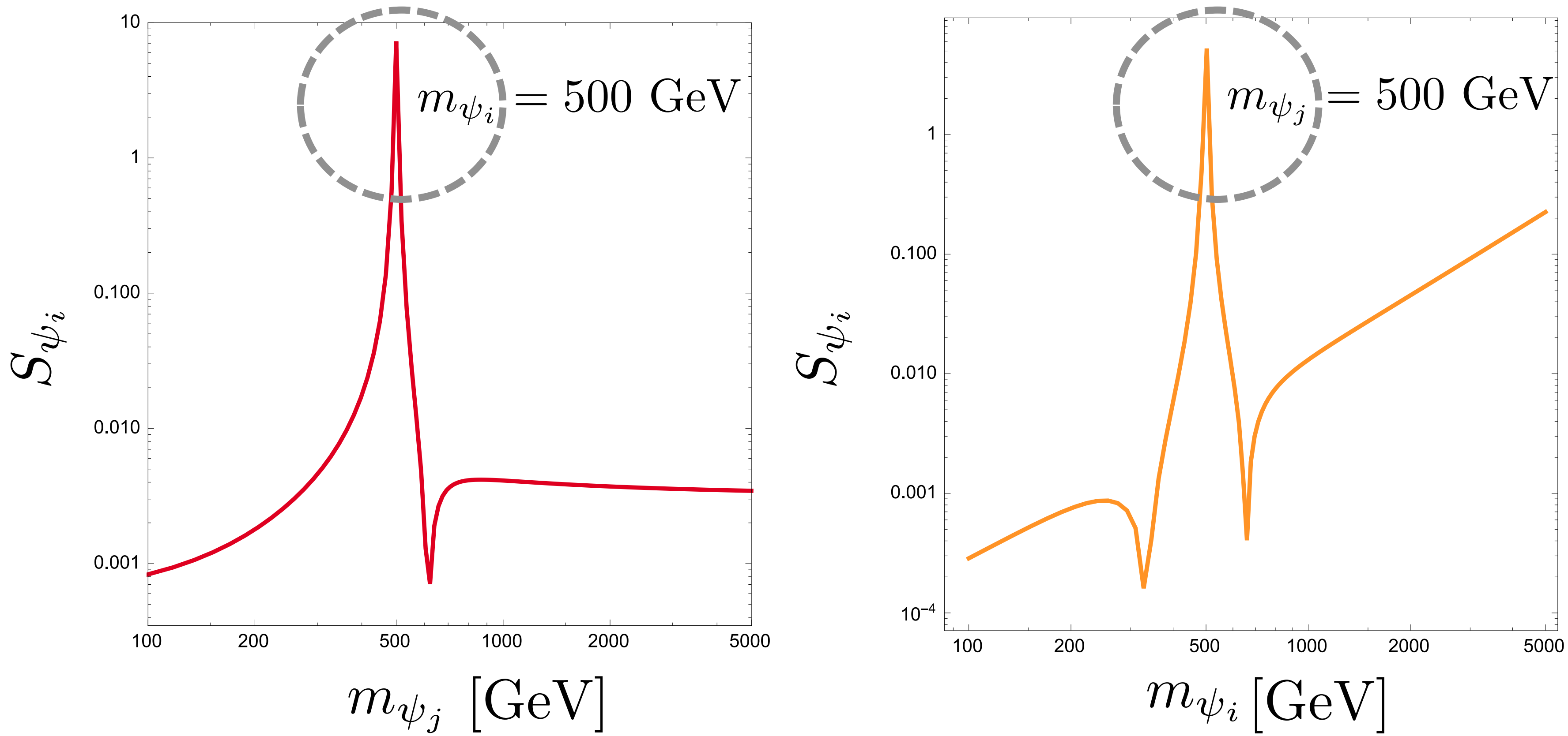
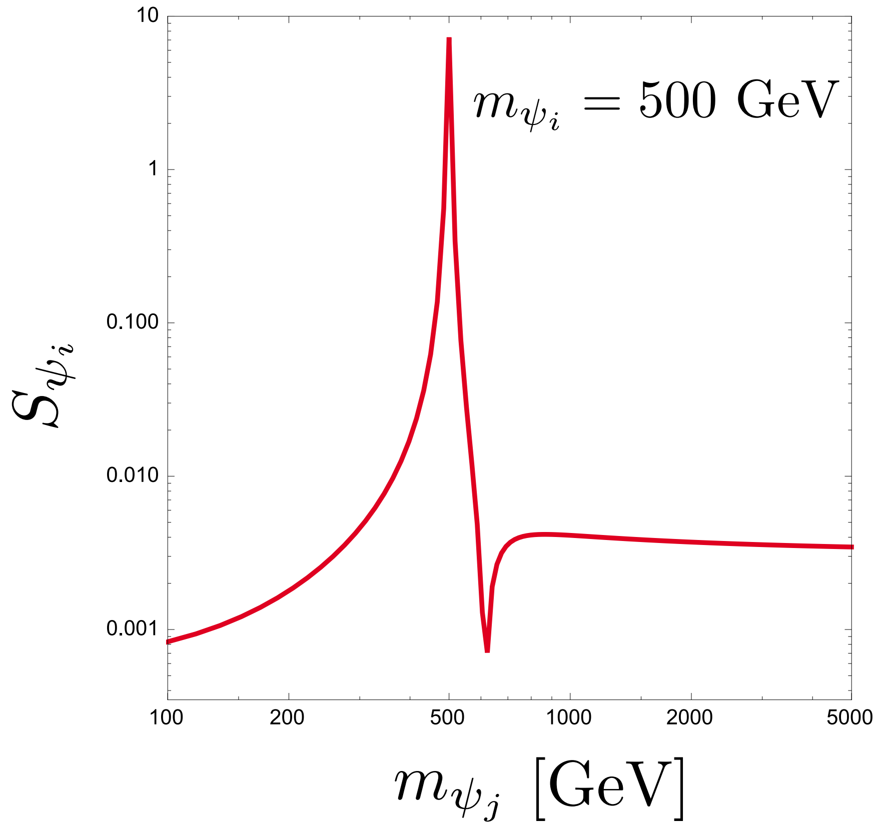
Enhancement shows up due to thermal effect in C_{BAU} .

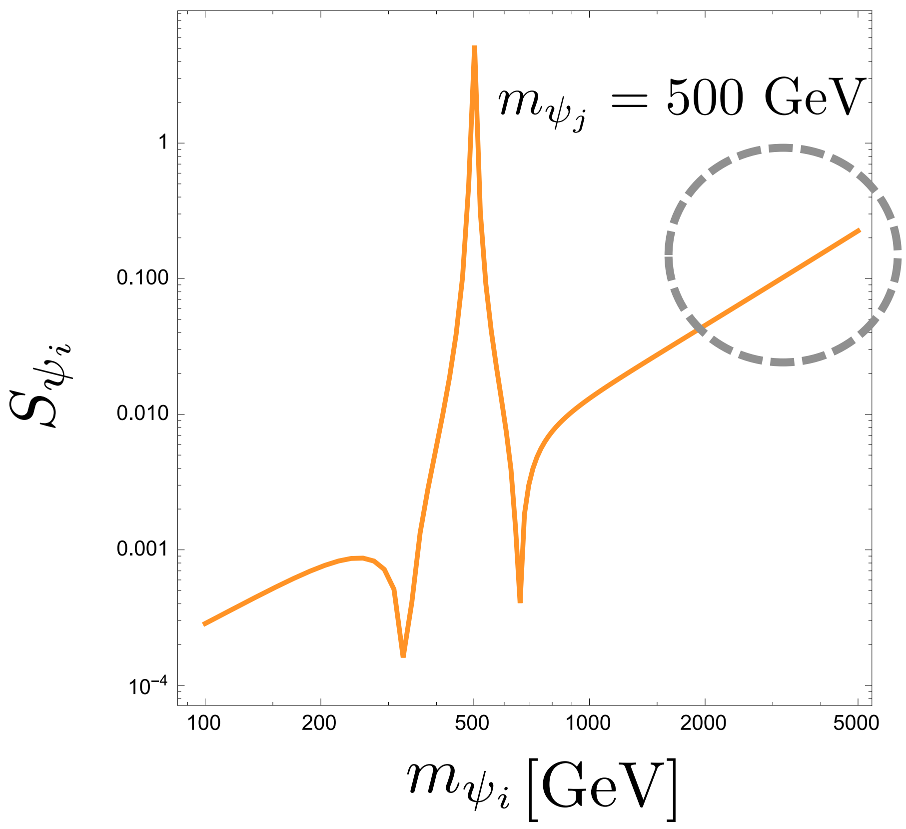


CP-violating source as a function of $m_{\psi_{i,j}}$

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

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





Particle contents

Particle contents are NMSSM-like.

Scalars	$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$	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	$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$	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

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

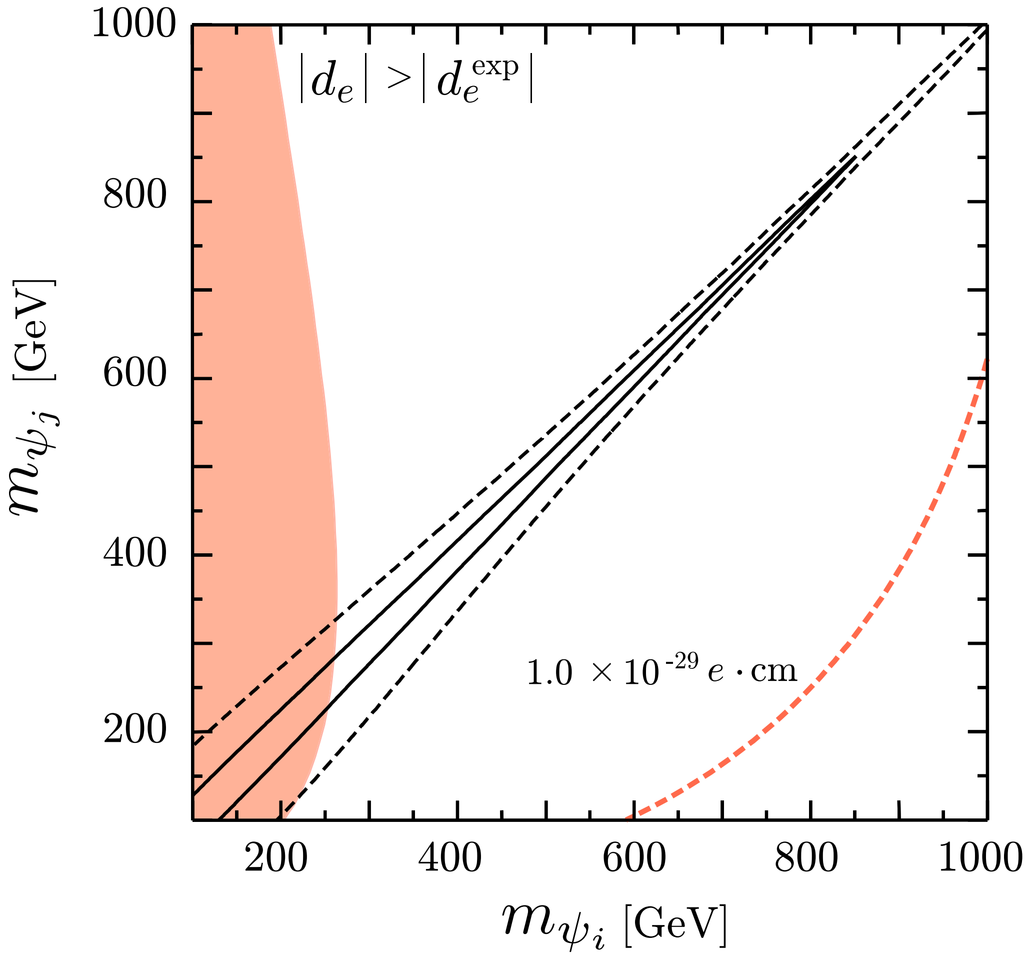
Solid line :

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

Dashed line :

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

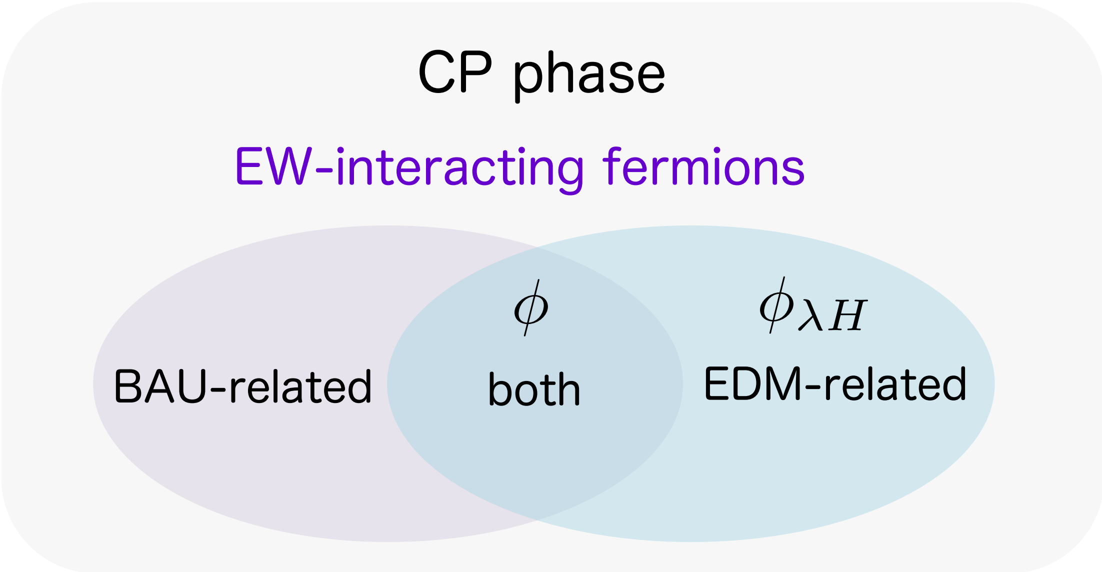
If $d_e = 10^{-29}$ e・cm can be achieved, the successful region would be tested !



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

The other Barr-Zee diagram

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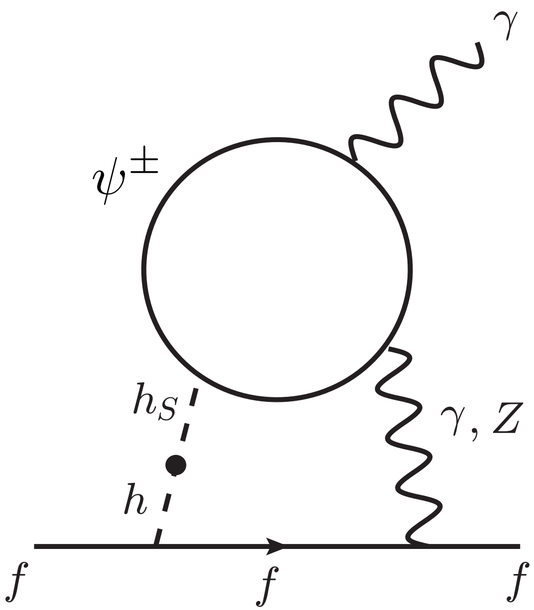
$$\mathcal{L} \ni h_S \bar{\psi}^+ \left(g^S + i\gamma_5 g^P\right) \psi^+$$

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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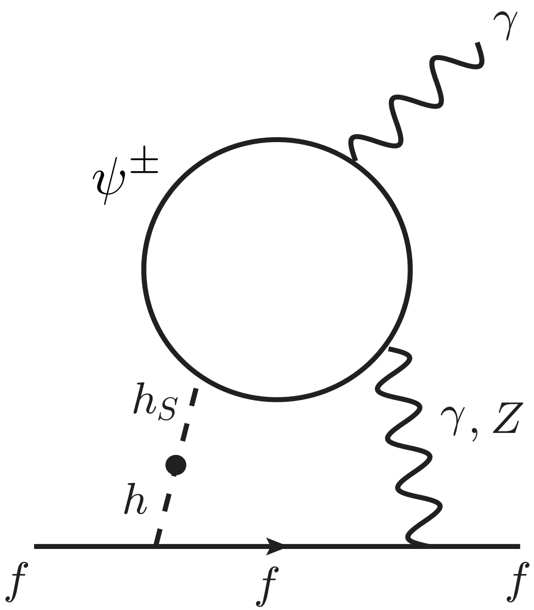

Even if $d_e^{\rm sum} = 0,$

the Higgs physics helps

the verifiability in this model.

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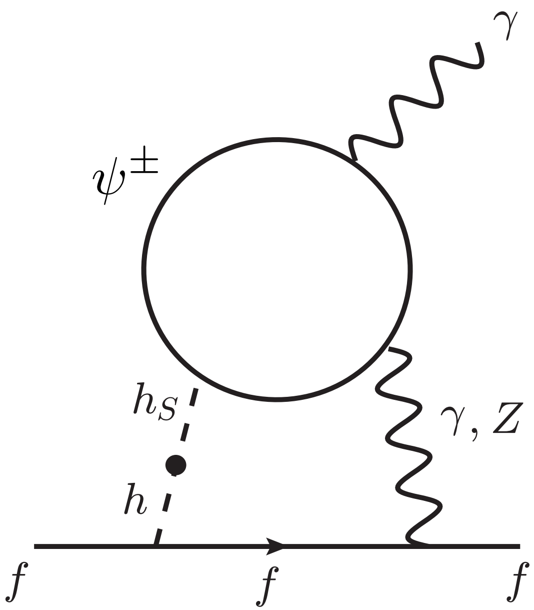

The first loop contributes to the signal strength of the Higgs to two gammas $\mu_{\gamma\gamma}$.

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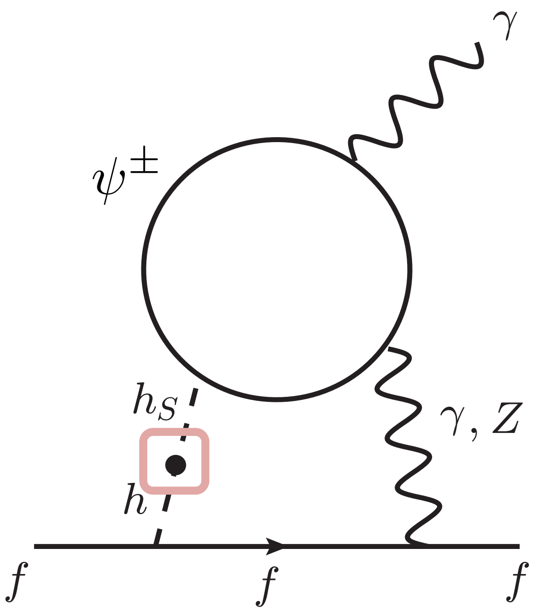


The mixing angle γ is required to be a certain size for EWPT.

Mixing < LHC constraint

Electron EDM

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

☐ Parameters

$$m_{\psi_i} = 300 \text{ GeV}$$

$$m_{\psi_j} = 277 \text{ GeV}$$

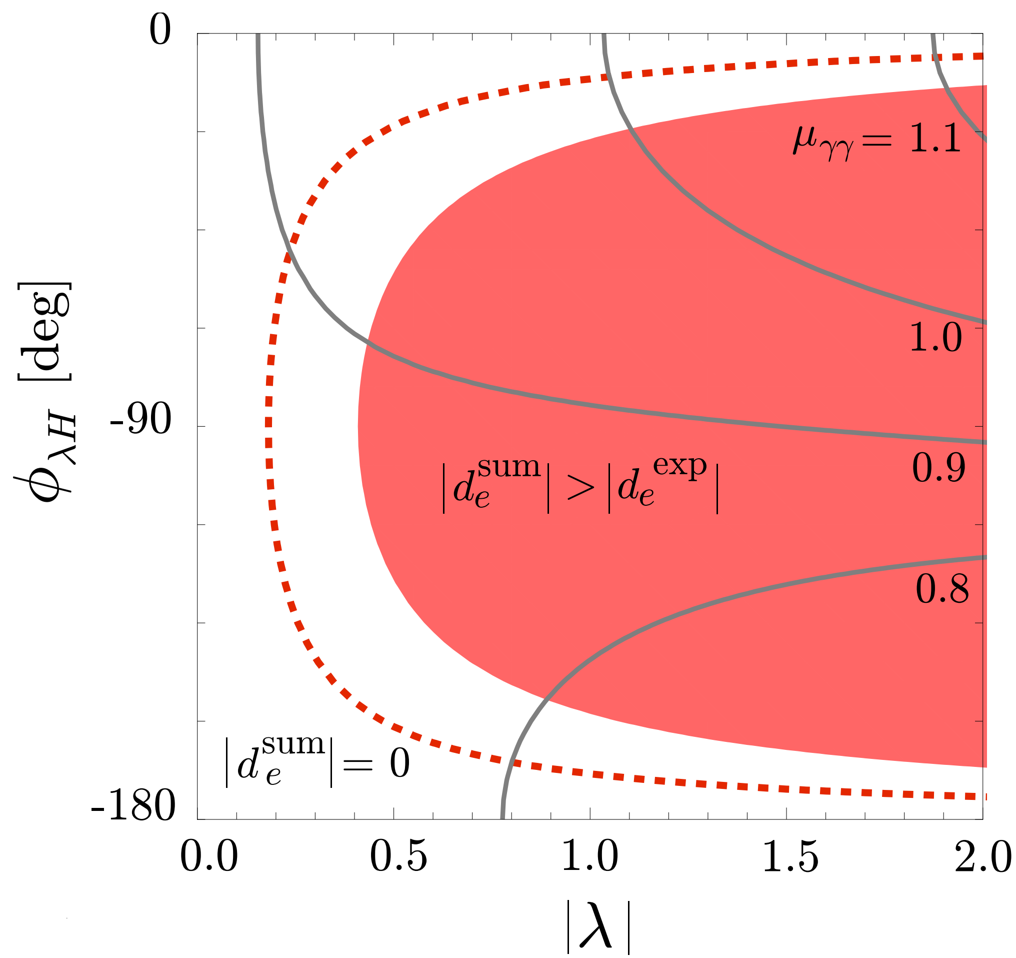
$$\gamma = -20^\circ$$

which leads to

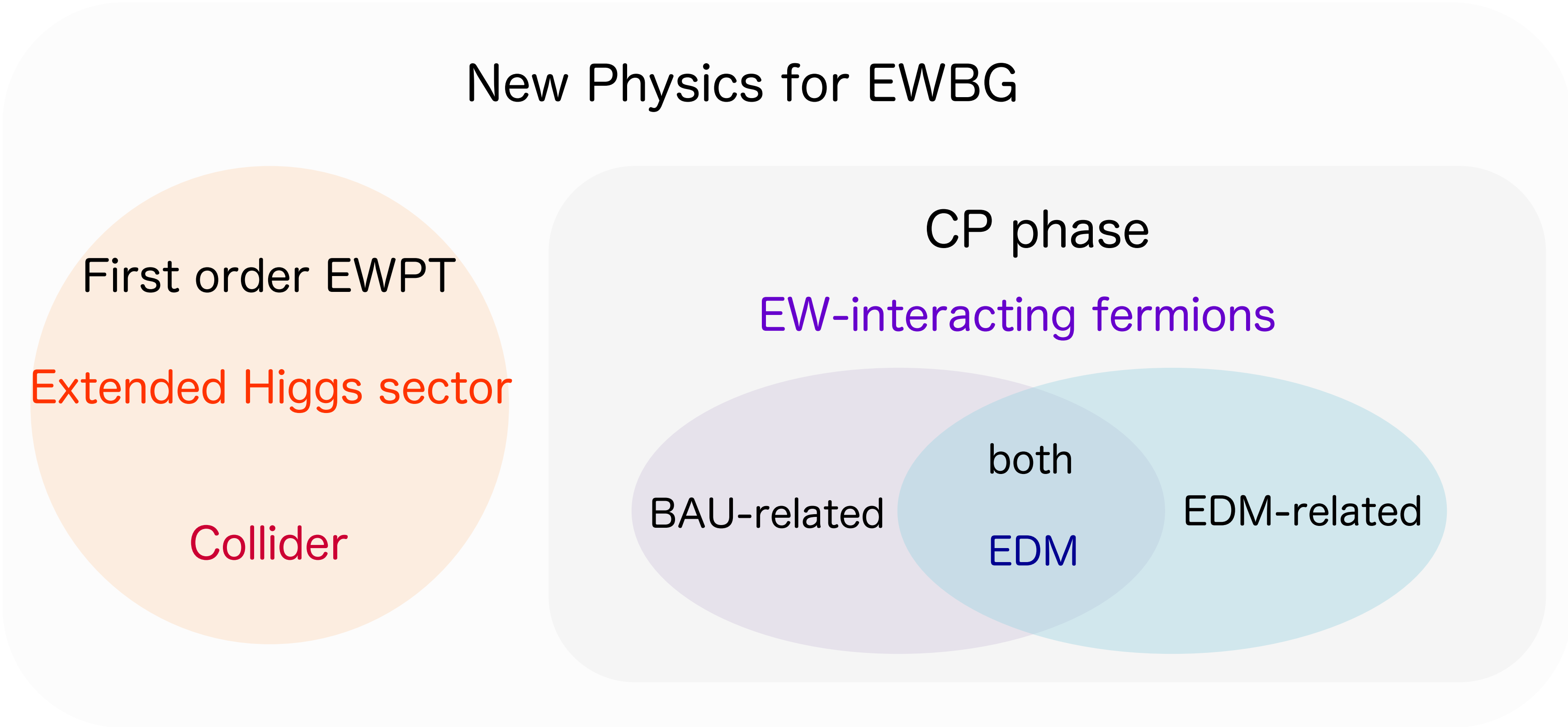
$$Y_B / Y_B^{\rm obs} = 1$$

■ Gray line : $\mu_{\gamma\gamma}$

Signal strength of the Higgs decay to two gammas



Summary

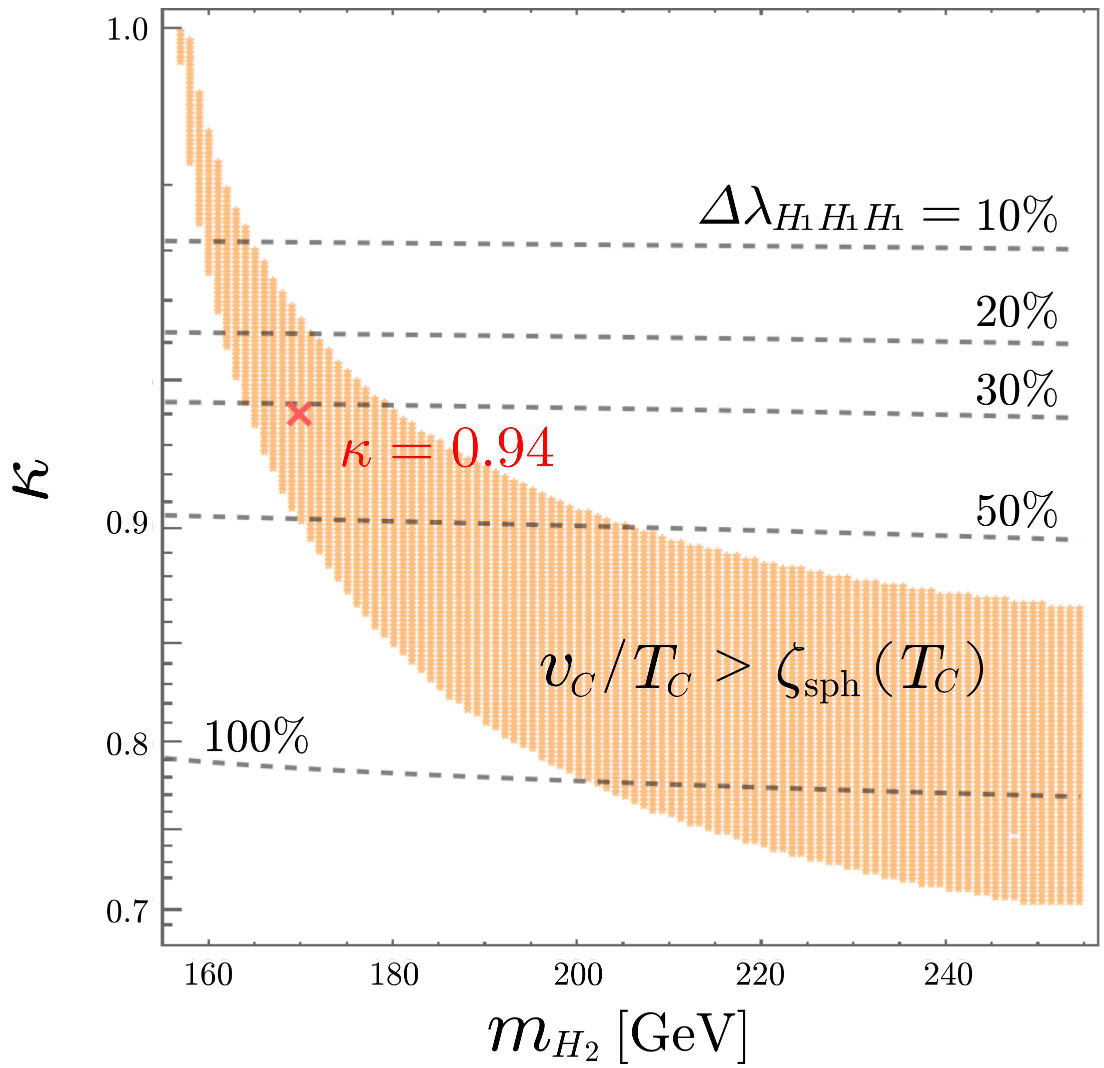


As long as only the BAU-related CP phase exists in the model,

it can be verified by the electron EDM.

Buckup

EWPT in the real-singlet model



Coupling measurements

Higgs couplings :

$$\kappa_V = 1.09 \pm 0.07(\mathrm{ATLAS}), \qquad \kappa_V = 1.11 \pm 0.16(\mathrm{ATLAS}),$$

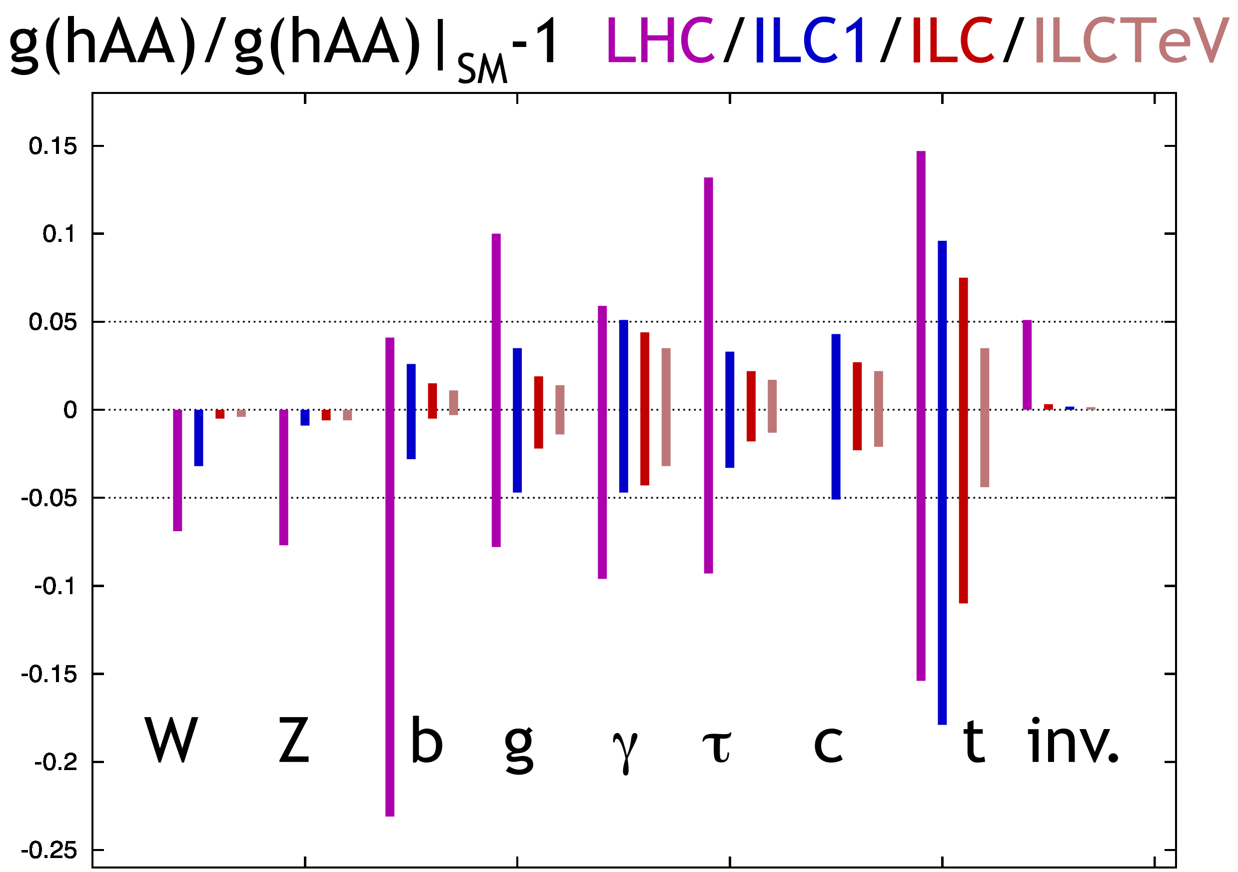
$$\kappa_V = 1.01^{+0.07}_{-0.07}(\mathrm{CMS}), \qquad \kappa_F = 0.89^{+0.14}_{-0.13}(\mathrm{CMS}),$$

Signal strength : $\mu_{\gamma\gamma} = 1.17 \pm 0.27(\mathrm{ATLAS}),$

$$\mu_{\gamma\gamma} = 1.14^{+0.26}_{-0.23}(\mathrm{CMS}),$$

Coupling measurements

M. Peskin, 1207.2516



Coupling measurements

	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.8 %	1.1 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.1 %	1.9 %
$b\bar{b}$	5.3 %	1.6 %	1.3 %	0.7 %
$\tau^+\tau^-$	5.7 %	2.3 %	1.6 %	0.9 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.0 %
$\mu^+\mu^-$	91%	91%	16 %	10 %
$\Gamma_T(h)$	12 %	4.9 %	4.5 %	2.3 %
hhh	–	83 %	21 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.9 %	< 0.4 %