Aspects of CP violation in electroweak baryogenesis

Kaori Fuyuto

Saga University

In collaboration with Junji Hisano and Eibun Senaha

10 May, 2016

At Pheno 2016

K. Fuyuto and E. Senaha, Phys. Rev. D90, 015015(2014)
K. Fuyuto, J. Hisano and E. Senaha, Physics Letters B 755 (2016)

Outline :

1. Introduction of Electroweak Baryogenesis

2. Relationship between the BAU and EDMs

3. Situation where BAU-unrelated CP phase exists

4. Conclusion

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

One attractive scenario is

Electroweak Baryogenesis (EWBG).

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

Collider experiments and Electric Dipole Moments (EDM) can verify this scenario.

* Since LHC is running, it is urgent issue to clarify its possibility.

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

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)

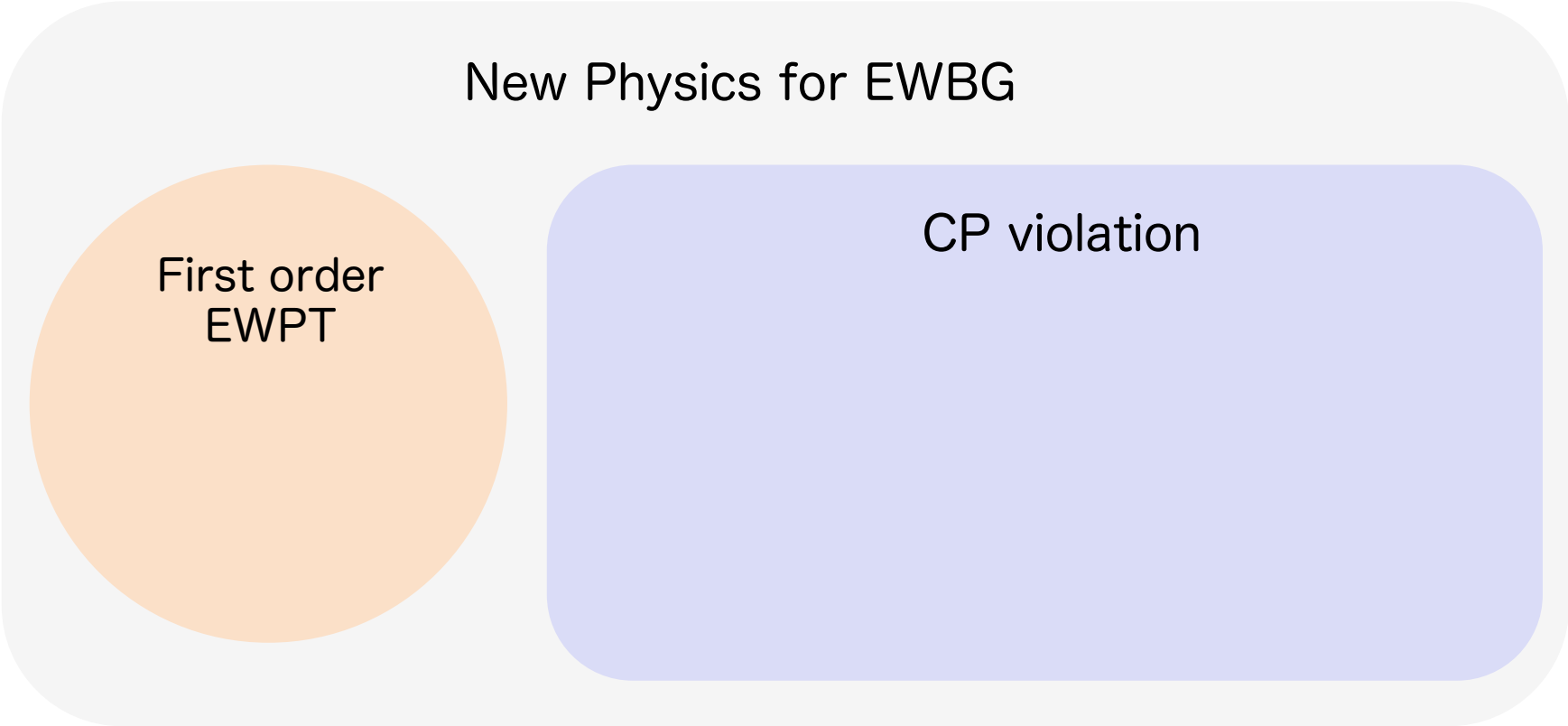
- EWPT becomes crossover for $m_h > 73$ GeV.

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

K. Fuyuto, J. Hisano and E. Senaha, Physics Letters B 755 (2016)

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



New physics

K. Fuyuto, J. Hisano and E. Senaha, Physics Letters B 755 (2016)

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

New Physics for EWBG

First order EWPT

Real singlet

S

CP violation : $\phi_{\rm BAU}$

Two new fermions

Dirac : $\begin{pmatrix} \psi^+ \\ \psi_i \end{pmatrix}$ Majorana : ψ_j

SU(2) doublet

- Scalar for EWPT
- Fermion for CP violation

New physics

K. Fuyuto, J. Hisano and E. Senaha, Physics Letters B 755 (2016)

Particle contents

New Physics for EWBG

First order EWPT

Real singlet

S

CP violation : $\phi_{\rm BAU}$

Two new fermions

Dirac : $\begin{pmatrix} \psi^+ \\ \psi_i \end{pmatrix}$ Majorana : ψ_j

SU(2) doublet

Two Higgs doublet :

$\Phi_1, \quad \Phi_2$

UV complete model : NMSSM, U(1)' MSSM etc.

- Relationship between the BAU and EDM
- Possibility of EWBG

BAU and EDMs

CP violating process

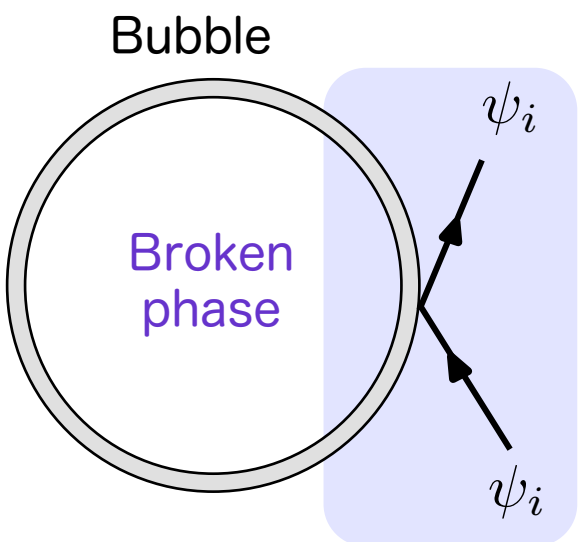
Interactions between bubble wall and new fermions :

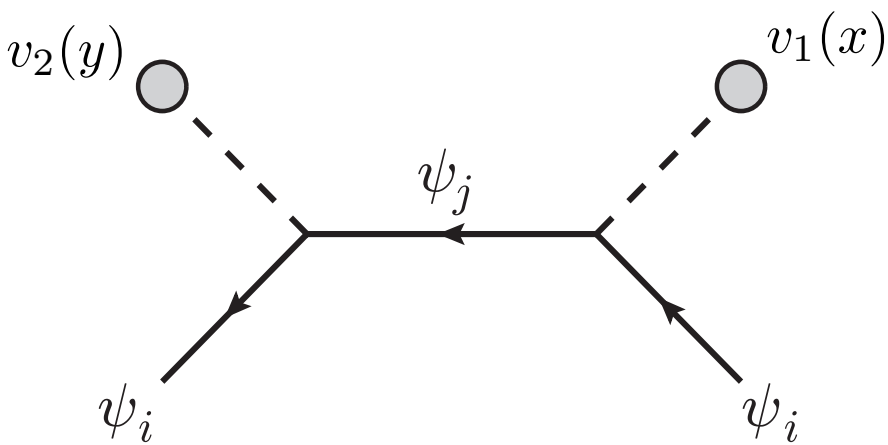
$$\mathcal{L} = \frac{1}{\sqrt{2}} \bar{\psi}_i \left(c_L v_2 P_L + c_R v_1 P_R \right) \psi_j + \text{h.c.}$$

$c_{L,R}$: Complex number

(BAU-related physical CP phase : $\mathrm{Im}[c_L c_R^*]$)

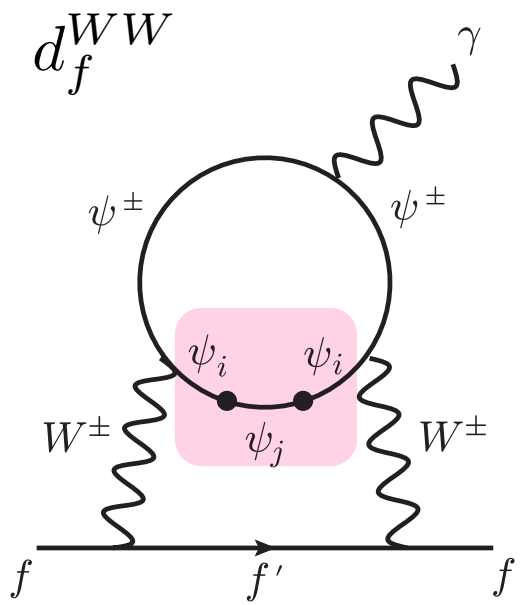
$v_{1,2}$: Space-dependent Higgs VEV

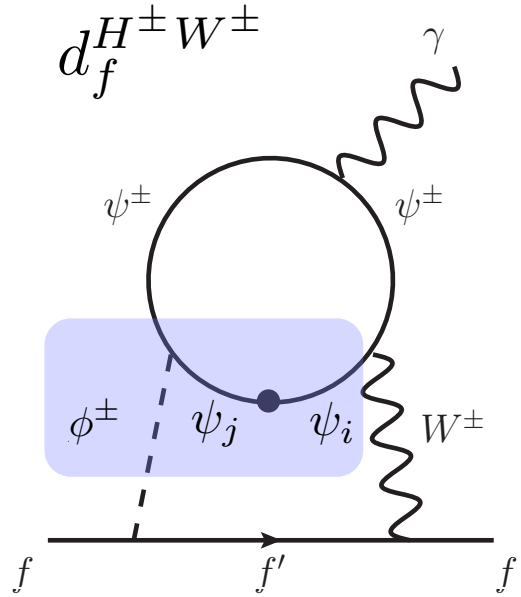




CP violating process and EDM

BAU-related CP phase can induce two Barr-Zee diagrams.





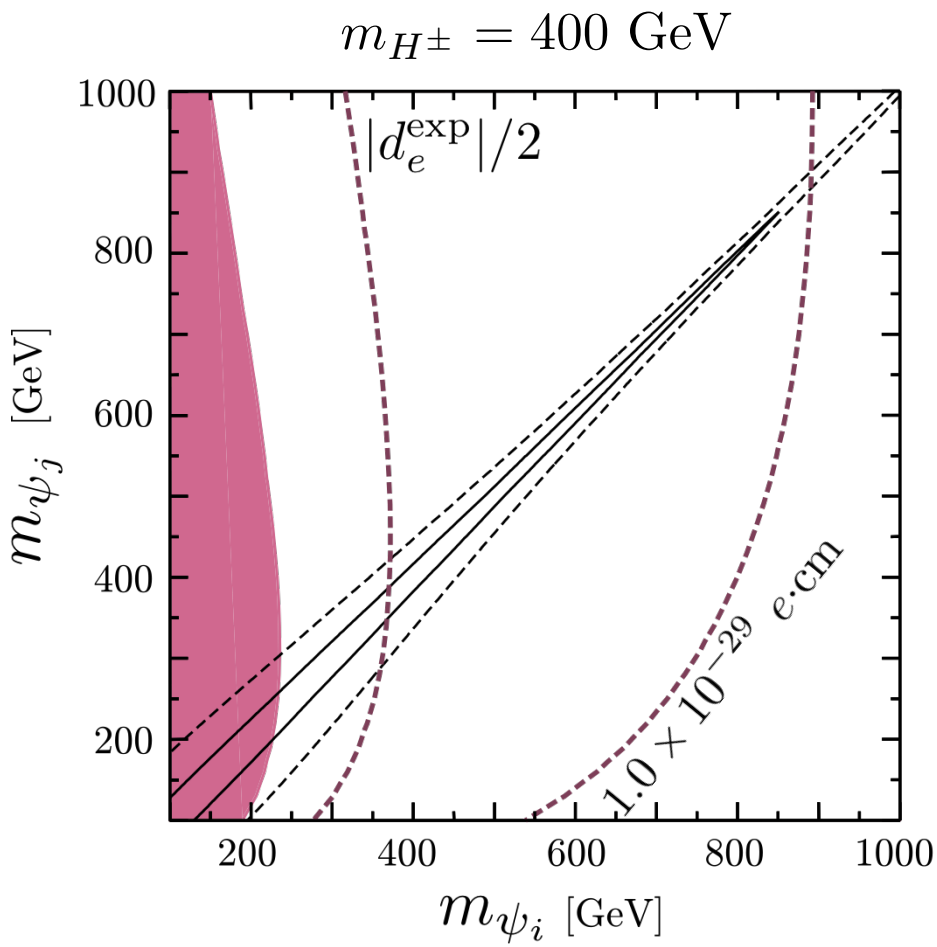
$$\mathcal{L} = \frac{1}{\sqrt{2}}\bar{\psi}_i\left(c_L v_2 P_L + c_R v_1 P_R\right)\psi_j + \frac{1}{\sqrt{2}}\bar{\psi}^+\left(c_L^+ \phi_2^+ P_L + c_R^+ \phi_1^+ P_R\right)\psi_j$$

$c^+_{L(R)}$ is related to $c_{L(R)}$ in SU(2), $c^+_{L(R)} = -c_{L(R)}$.

BAU and electron EDM

Input parameter : $|c_L| = |c_R| = 0.42, \quad \phi_{\rm BAU} \equiv \phi_L - \phi_R = 225^\circ$

Electron EDM constraint (Pink region) : $|d_e^{\rm exp}| < 8.7 \times 10^{-29}\ e \cdot {\rm cm}$



Black solid : $Y_B/Y_B^{\rm obs} = 1$

Black dashed : $Y_B/Y_B^{\rm obs} = 0.1$

- Degenerate masses lead to the successful BAU.
- If $d_e = 1.0 \times 10^{-29}\ e \cdot {\rm cm}$ is achieved, this scenario can be verified.

New physics

K. Fuyuto, J. Hisano and E. Senaha, Physics Letters B 755 (2016)

Concrete model

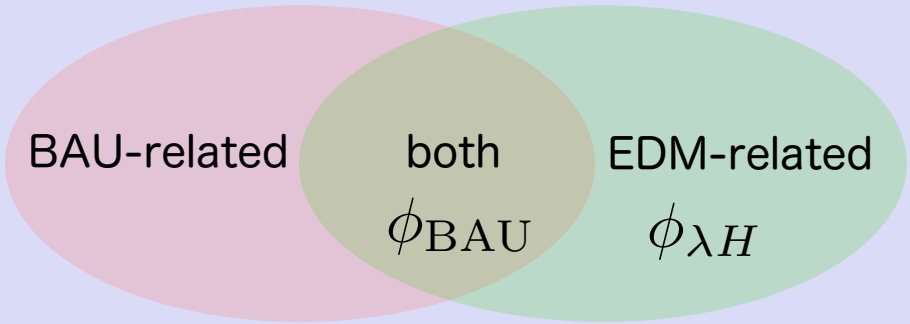
New Physics for EWBG

First order EWPT

Real singlet

S

CP phase： $\phi_{\rm BAU}$ $\phi_{\lambda H}$



The other CP phase comes from the interaction between singlet and charged fermions.

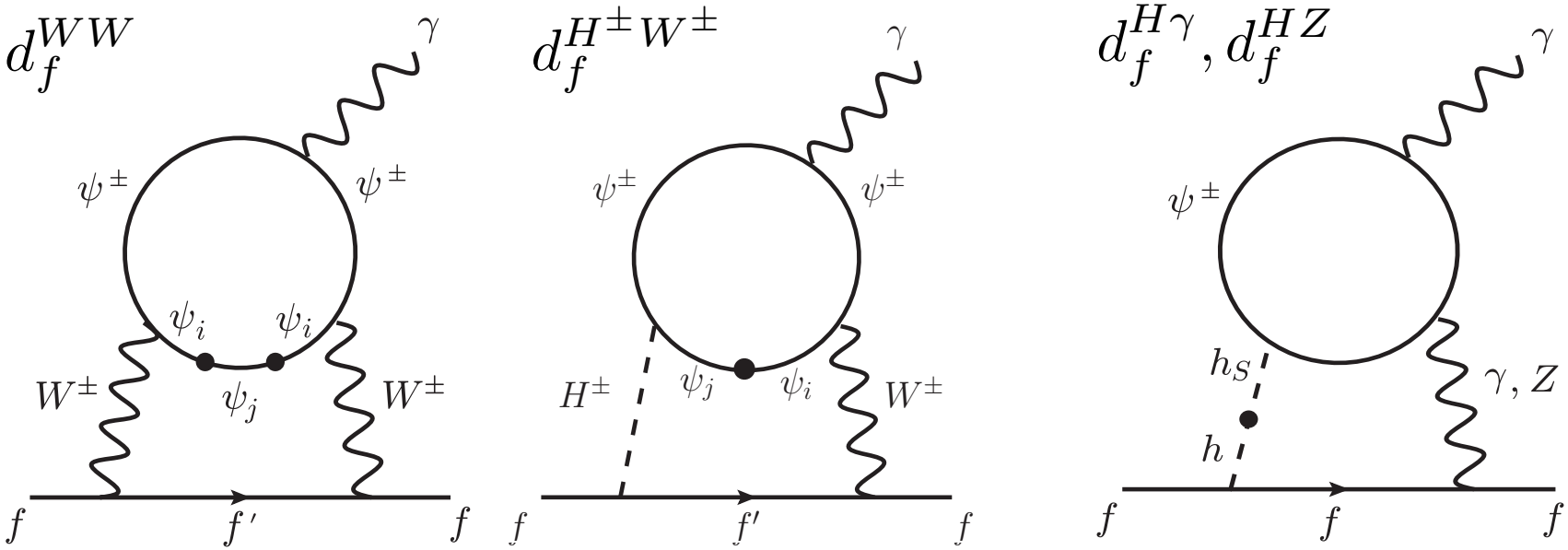
$$\mathcal{L} \ni h_S \bar{\psi}^+ (g^S + i\gamma_5 g^P)\psi^+$$

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

BAU-unrelated CP phase

The total number of Barr-Zee diagrams are four.

BAU-unrelated CP phase



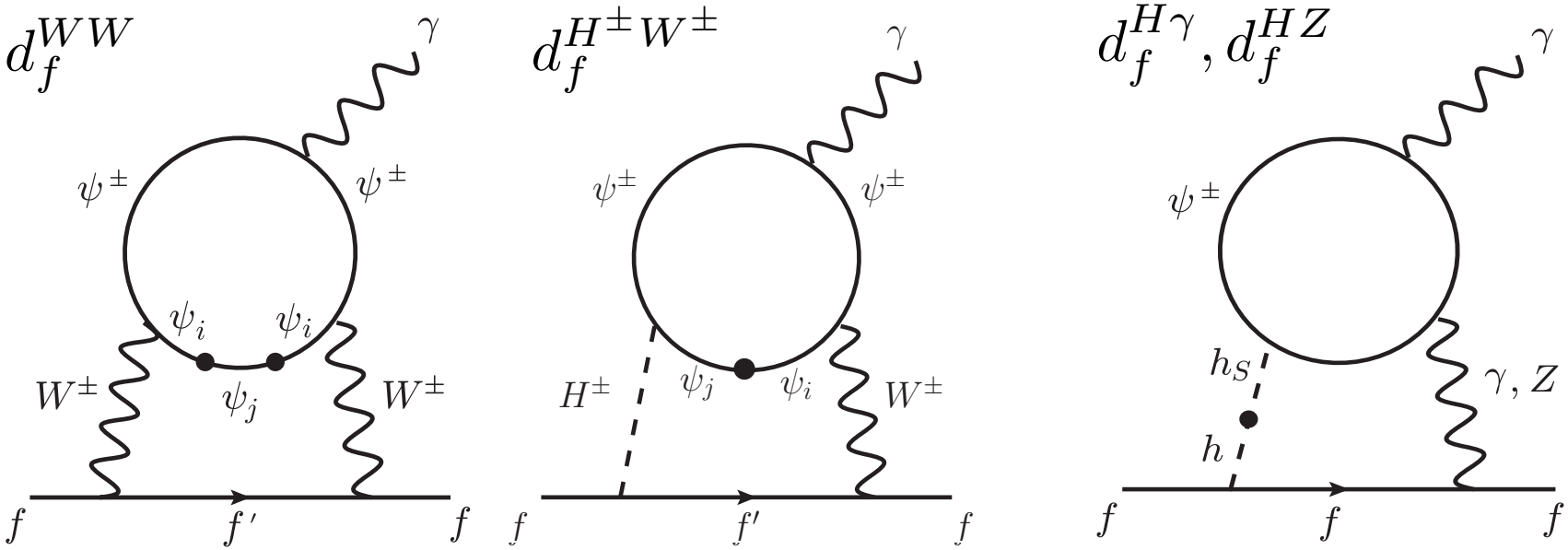
EDM : $d_f^{\rm sum} = d_f^{WW} + d_f^{H^\pm W^\pm} + d_f^{H\gamma} + d_f^{HZ}$

Cancellation between CP phases exists, which leads to $d_e^{\rm sum} = 0$.

BAU-unrelated CP phase

The total number of Barr-Zee diagrams are four.

BAU-unrelated CP phase



Even if $d_e^{\rm sum} = 0$, this scenario can be verified by

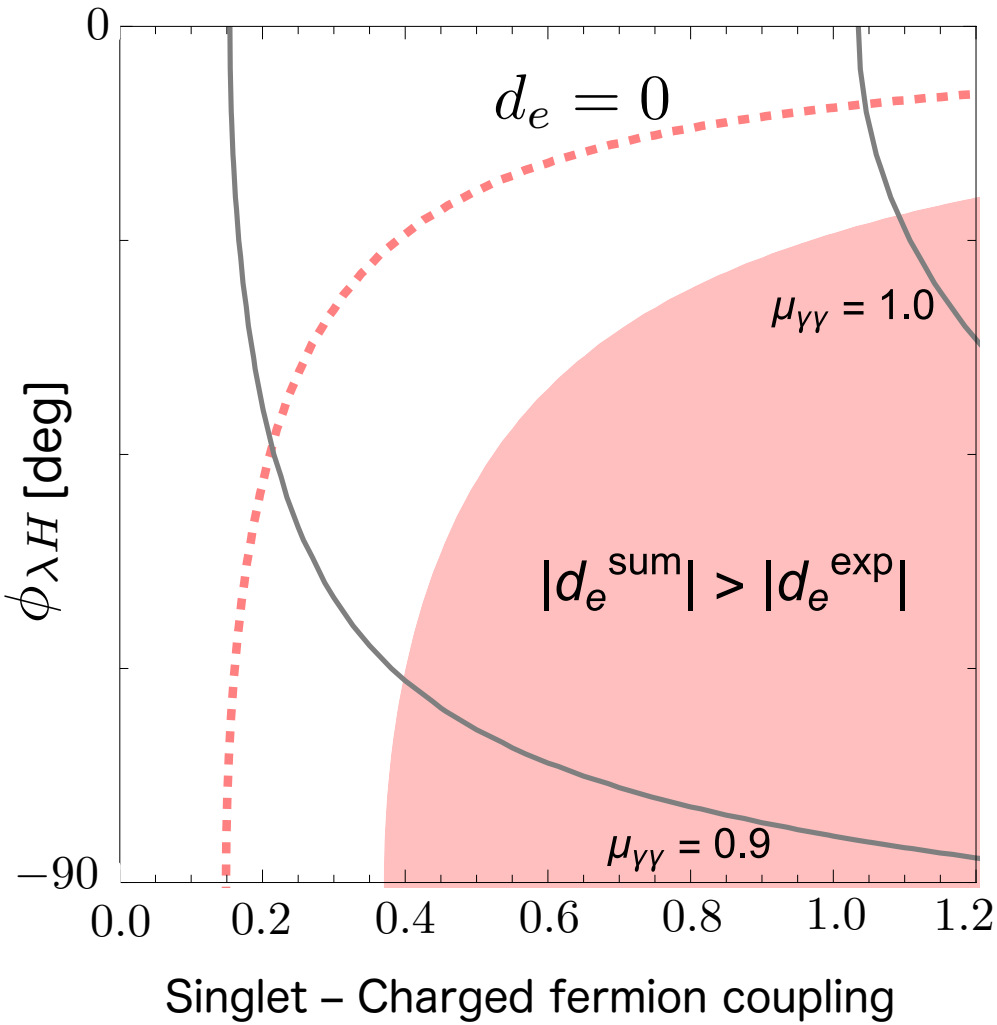
- Signal strength of the Higgs decay to two gammas, $\mu_{\gamma\gamma}$
- Other EDMs such as neutron and proton

Numerical results

K. Fuyuto, J. Hisano and E. Senaha, Physics Letters B 755 (2016)

Verifiability by EDMs and signal strength

Electron EDM : $d_e^{\rm sum} = d_e^{WW} + d_e^{H^\pm W^\pm} + d_e^{H\gamma} + d_e^{HZ}$



Input parameters :

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

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

* BAU can be explained.

Pink region :

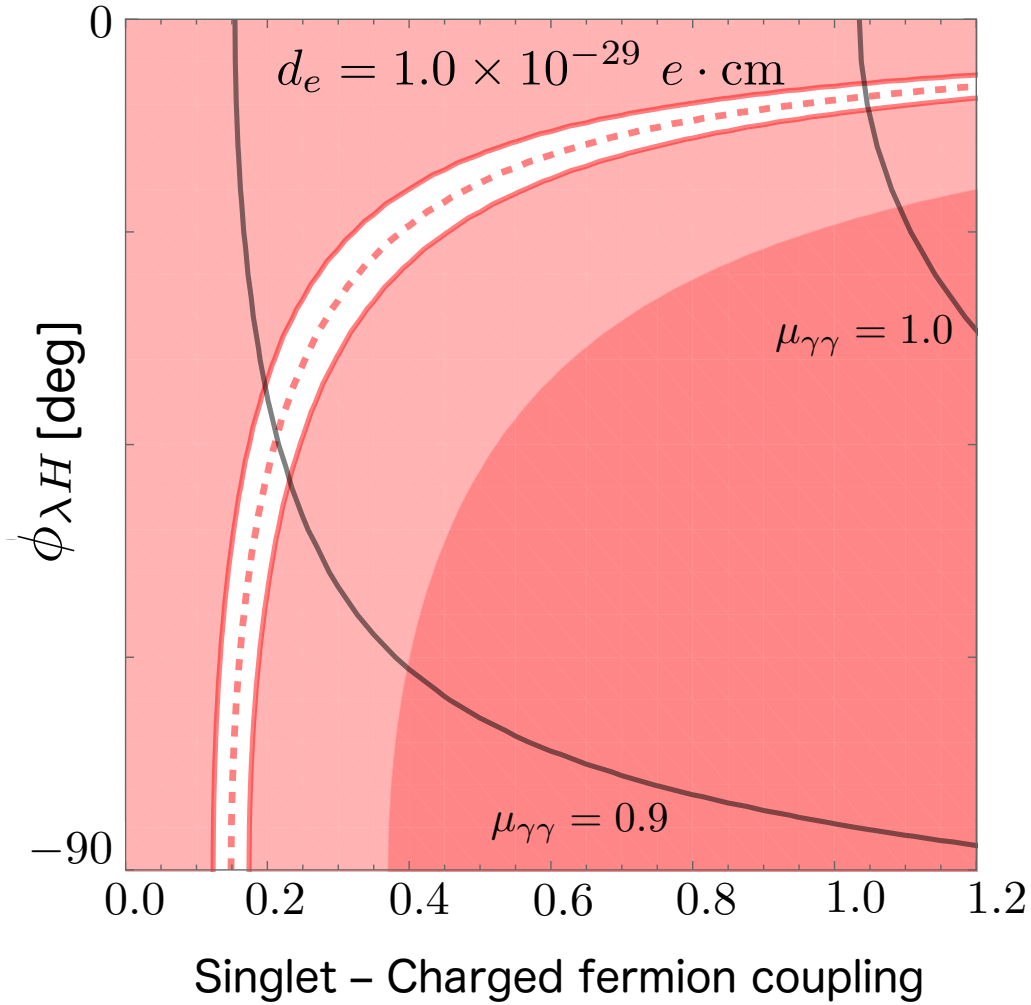
Excluded by electron EDM

Grey line : $\mu_{\gamma\gamma}$

$H_1 \to 2\gamma$ Signal strength

Verifiability by EDMs and signal strength

Electron EDM : $d_e^{\rm sum} = d_e^{WW} + d_e^{H^\pm W^\pm} + d_e^{H\gamma} + d_e^{HZ}$



Light pink region :

Excluded if electron EDM reaches

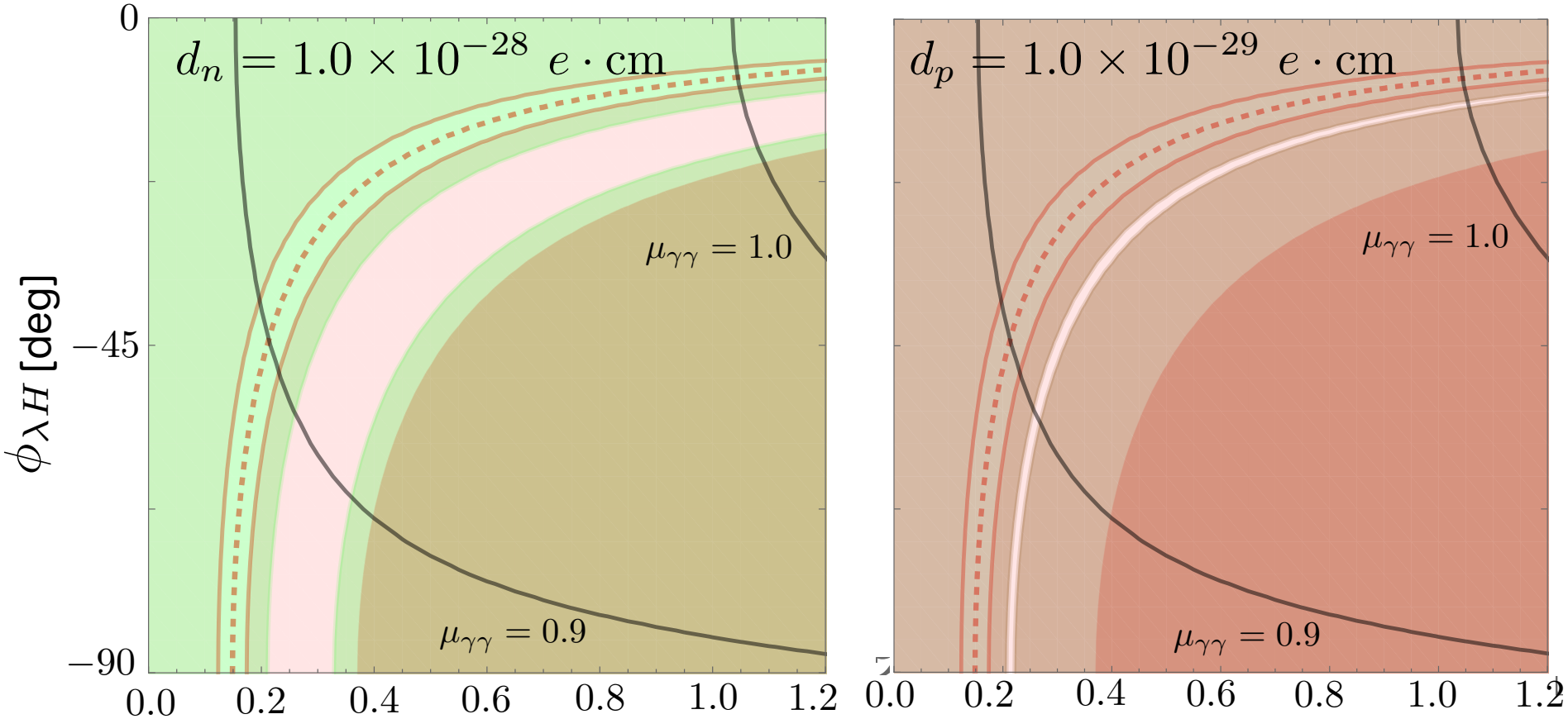
$d_e = 1.0 \times 10^{-29}\ e \cdot \mathrm{cm}$

White region : Still allowed

Neutron and Proton EDMs

Green : Excluded by neutron EDM

Brown : Excluded by proton EDM



Singlet – Charged fermion coupling

The cancellation region can be covered by neutron and proton EDMs.

Conclusion

- EWBG can be verified by the collider experiments.

  Current situation is ripe for verification of EWBG.

- New Physics is needed for successful EWBG.

  We consider

First order EWPT	New CP violation
Singlet scalar	Two EW-interacting fermions
Higgs physics	EDMs + Higgs physics

- The degenerate masses of fermions lead to the successful BAU.
- The EDMs and Higgs physics can verify it in near future.

BACKUP

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	$(\mathbf{1},\ \mathbf{1},\ 0)$	$-$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

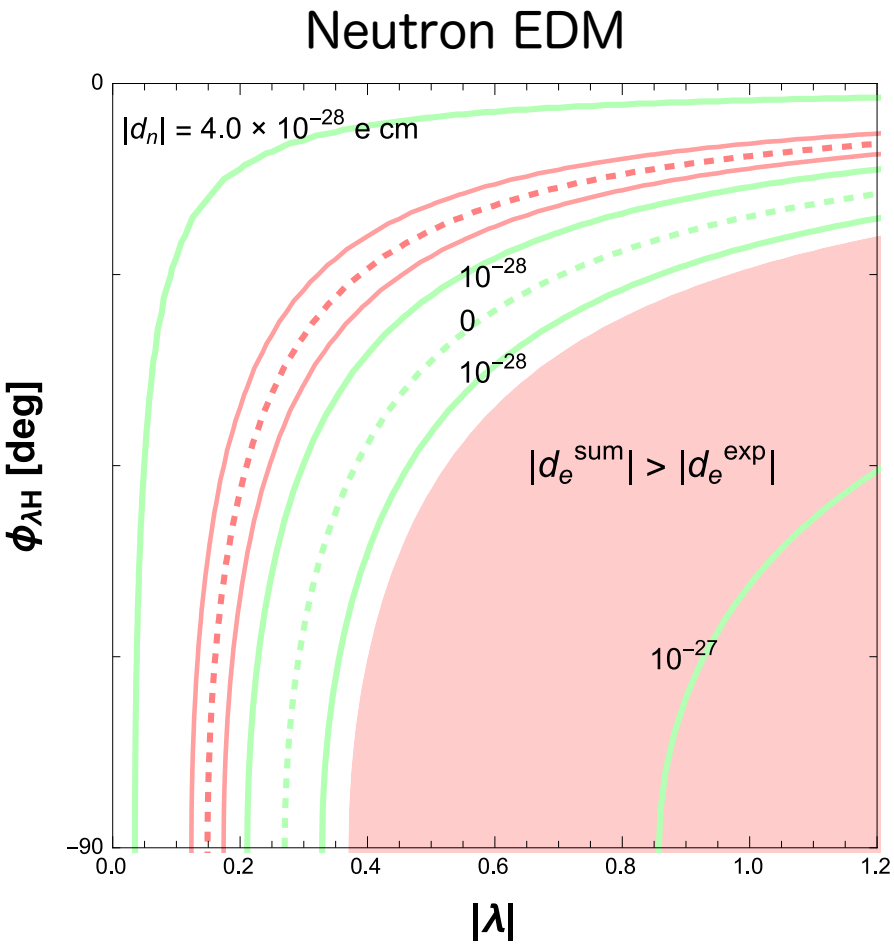
Fermions	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Z_2
$\tilde{\Phi}_1$	$(\mathbf{1},\ \mathbf{2},\ -1/2)$	$-$
$\tilde{\Phi}_2$	$(\mathbf{1},\ \mathbf{2},\ 1/2)$	$+$
$\tilde{S}^0$	$(\mathbf{1},\ \mathbf{1},\ 0)$	$-$

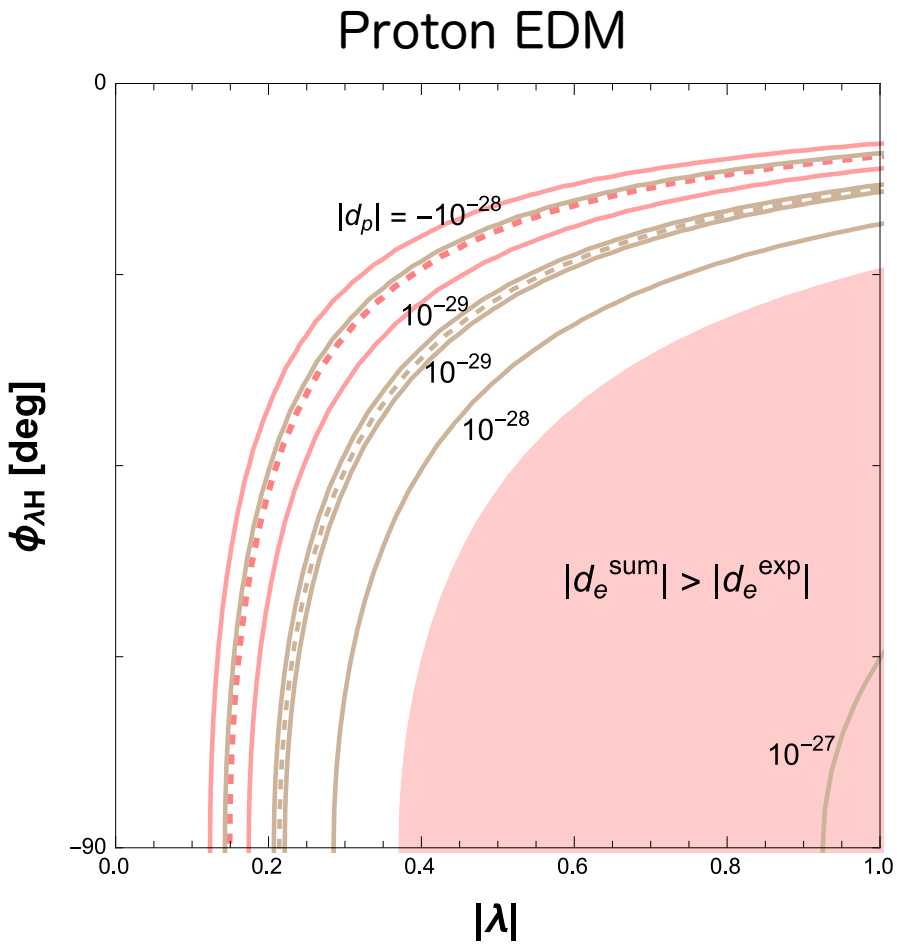
$$\tilde{\Phi}_1 = \begin{pmatrix} \tilde{\phi}_1^0 \\ \tilde{\phi}_1^+ \end{pmatrix}$$

$$\tilde{\Phi}_2 = \begin{pmatrix} \tilde{\phi}_2^+ \\ \tilde{\phi}_2^0 \end{pmatrix}$$

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

Neutron EDM と Proton EDM



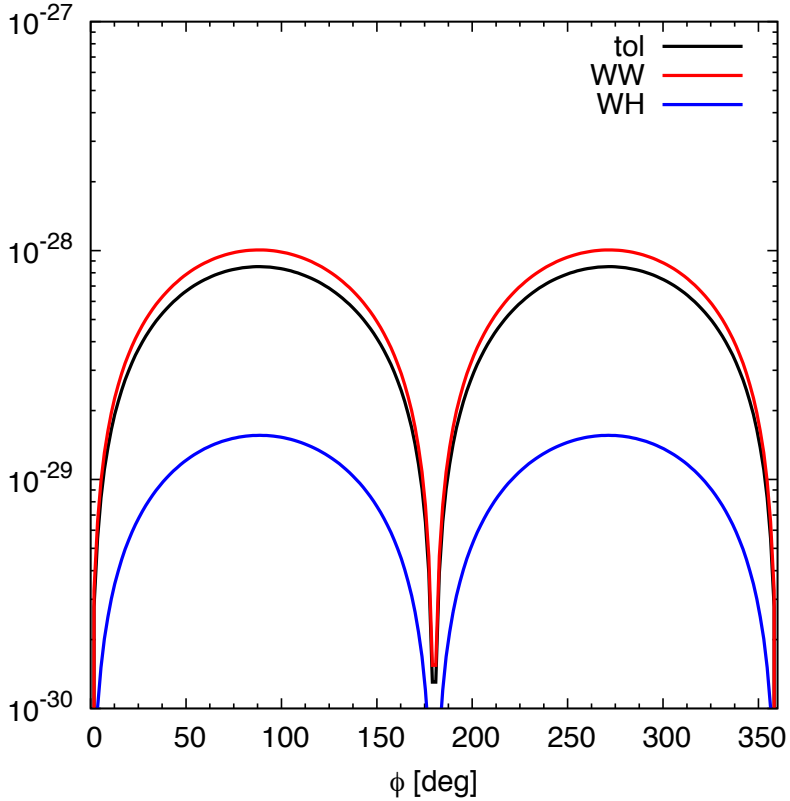


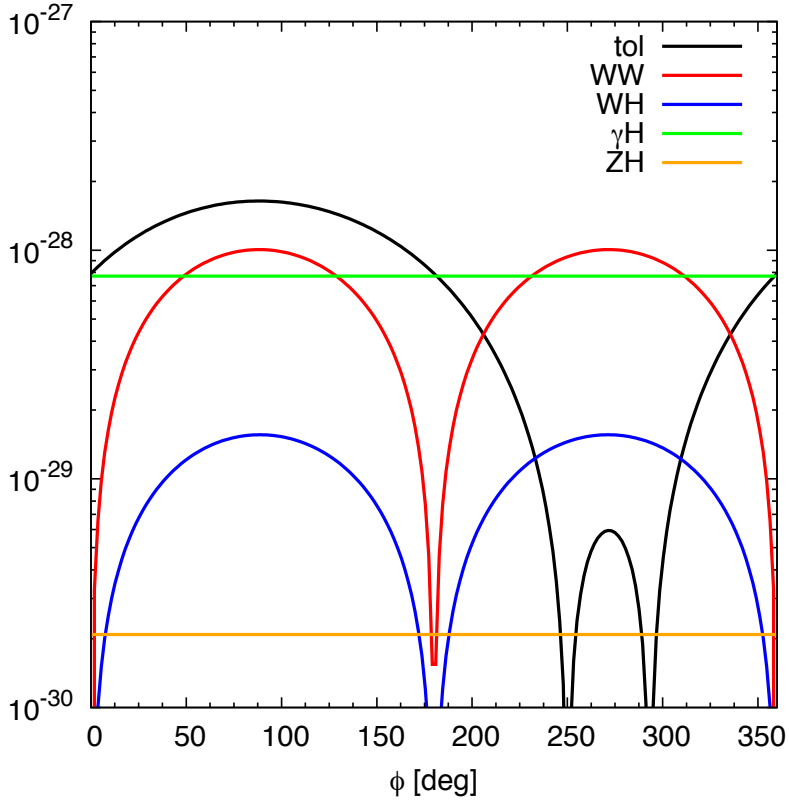
$\lambda = 0$

$|d_n| = 4.6 \times 10^{-28}\ e \cdot \mathrm{cm}$

$|d_p| = 3.0 \times 10^{-28}\ e \cdot \mathrm{cm}$

Electron EDM





$$\lambda = 0.2 \quad \phi_{\lambda H} = -90^\circ$$