Aligned CP-violating Higgs sector canceling the electric dipole moment

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Introduction

[Sakharov (1967)]
[Kuzmin, Rubakov, Shaposhnikov (1985)]
[Huet and Sather (1995)]
[Kajantie, Laine, Rummukainen, Shaposhnikov (1996)]

- Baryon asymmetry of the Universe requires the Sakharov's conditions:

  1. B violation 2. C and CP violation 3. departure from equilibrium.

- Standard model cannot satisfy them:
  - Kobayashi-Maskawa phase is numerically not sufficient.
  - Phase transition is not first-order getting out of equilibrium.

- Extended Higgs model with extra CP-phases and modifications to Higgs potential can realize electroweak baryogenesis.

- However, such a CP-phase is normally strongly constrained by the current data for the electric dipole moment (EDM).

- We investigate a scenario with O(1) CP-phase but avoiding the EDM constraint.

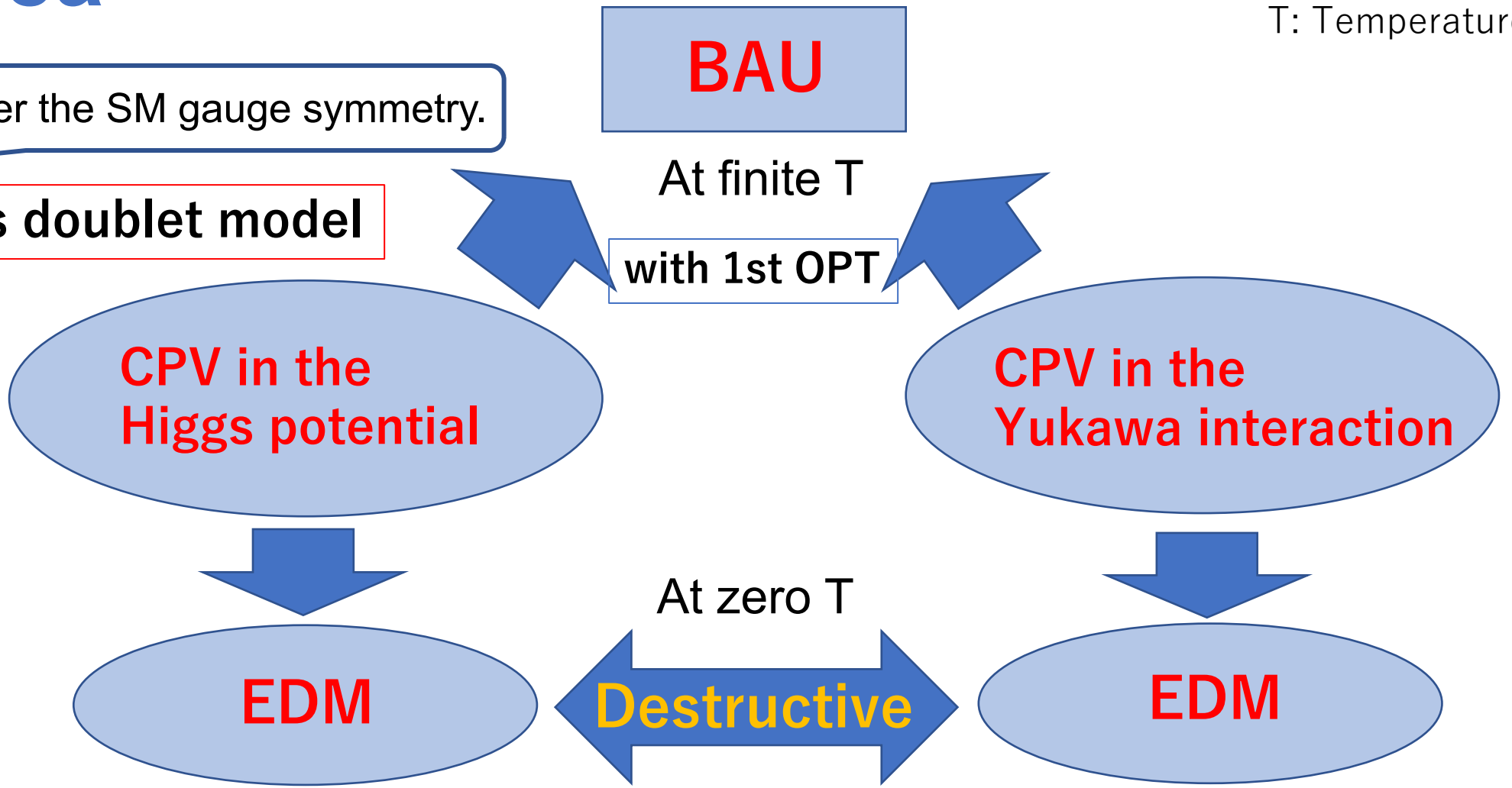
Our idea

BAU: Baryon number asymmetry of the Universe

T: Temperature

It is general under the SM gauge symmetry.

Two Higgs doublet model



Model (1/3) -Higgs potential-

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix}$$
$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

(Higgs basis)
[Davidson, Haber, PRD72, 035004 (2005)]

- Potential: $V = -\mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 - \left\{\boxed{\mu_3^2}(\Phi_1{}^\dagger\Phi_2) + h.c.\right\}$

$$+\frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_2{}^\dagger\Phi_1|^2$$
$$+\left\{\left[\frac{1}{2}\boxed{\lambda_5}(\Phi_1{}^\dagger\Phi_2) + \boxed{\lambda_6}|\Phi_1|^2 + \boxed{\lambda_7}|\Phi_2|^2\right](\Phi_1{}^\dagger\Phi_2) + h.c.\right\}$$

Stationary condition:

$$0 = \left.\frac{\partial V}{\partial h_j}\right|_{\Phi_{1,2}=\langle\Phi_{1,2}\rangle} \quad \text{-->} \quad \begin{cases} \mu_1^2 = \frac{1}{2}v^2\lambda_1 \\ \boxed{\mu_3^2} = \frac{1}{2}v^2\boxed{\lambda_6} \end{cases}$$

Three complexes: $\boxed{\lambda_{5\text{-}7} = |\lambda_{5\text{-}7}|e^{i\theta_{5\text{-}7}}}$

Model (2/3) -Higgs potential-

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix}$$
$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

- Mass matrix: $\mathcal{M}^2 = v^2 \begin{pmatrix} \lambda_1 & \cancel{|\lambda_6|\cos\theta_6} & \cancel{-|\lambda_6|\sin\theta_6} \\ & \mathcal{M}_{22} & \cancel{-\frac{1}{2}|\lambda_5|\sin\theta_5} \\ & & \mathcal{M}_{33} \end{pmatrix}$ $\quad h_1 = H_1^0,\ h_2 = H_2^0,\ h_3 = H_3^0$

Mass eigenstate

We can take the phase redefinition so that $\theta_5 = 0$.

We assume $\lambda_6 = 0$, then h_1 does not mix with the others.

Mixing matrix: $R = \delta^{ij}$ -> At tree level, $\boxed{\dfrac{g^{\rm 2HDM}_{H_1^0 XX}}{g^{\rm SM}_{hXX}} = 1}$

$\begin{cases} X & \text{: SM particle} \\ H_1^0 & \text{: 125 GeV Higgs} \end{cases}$

-> In the potential, one CP-violating phase, θ_7 of λ_7 remains.

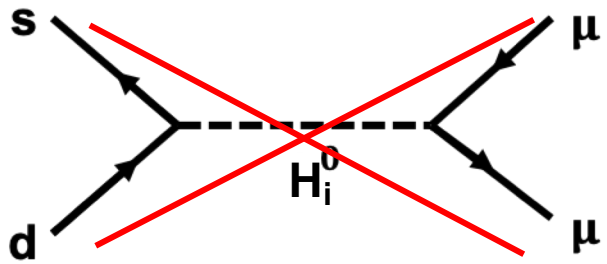
Model (3/3) -Yukawa int.-

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix}$$
$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

- Yukawa: $\mathcal{L}_Y \supset -\frac{\sqrt{2}}{v}\bar{Q}_L^i\left(M_d^{ij}\Phi_1 + \boxed{Y_d^{ij}}\Phi_2\right)d_R^j + h.c.$

FCNC should be suppressed.

FCNC: Flavor changing neutral current



We assume $Y_d^{ij} = \zeta_d M_d^{ij}$ -> No FCNC

[A. Pich, P. Tuzon, PRD80, 091702 (2009)]

$$\boxed{\zeta_d = |\zeta_d| e^{i\theta_d}}$$

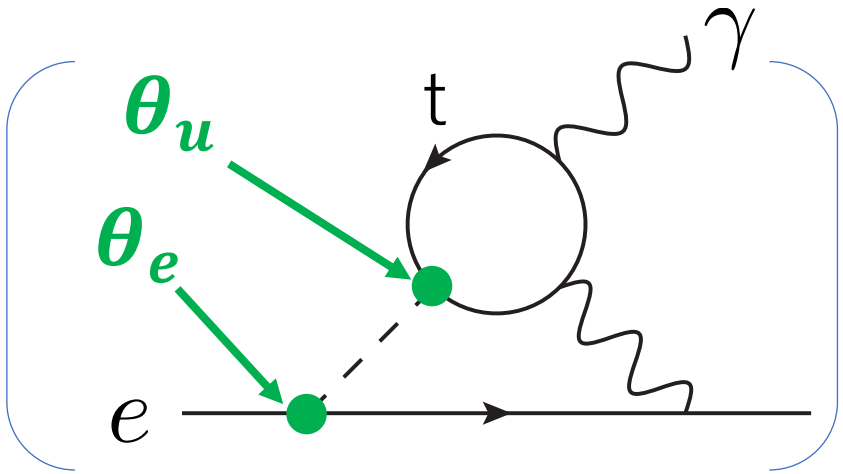
Y_u and Y_e are in a similar way.

-> Three CP-violating phases, $\boldsymbol{\theta_f}$ (f = u,d,e) arise from Yukawa term.

Contribution to the EDM

- Barr-Zee diagram is the leading contribution to electron EDM
  [Barr, Zee, PRL (1990)]

$d_e =$



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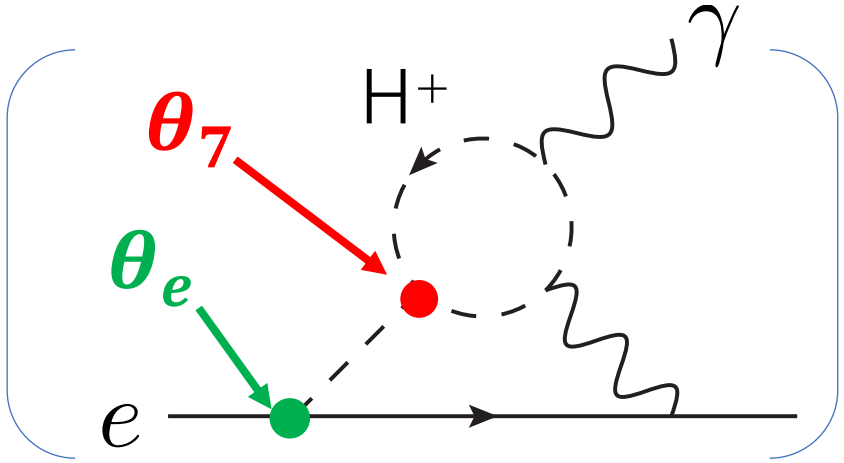


$< d_e^{(\mathrm{exp.})}$

$\zeta_f = |\zeta_f| e^{i\theta_f}$

$f = u, d, e$

$\lambda_7 = |\lambda_7| e^{i\theta_7}$

Destructive interference

[S. Kanemura, MK and K. Yagyu]

Numerical result: Electron EDM

- Input:

$$m_{H^+} = 230[\mathrm{GeV}]$$

$$|\zeta_u| = 0.01, |\zeta_d| = 0.1, \quad m_{H_2^0} = 280[\mathrm{GeV}]$$

$$|\zeta_e| = 0.5, |\lambda_7| = 0.3 \quad m_{H_3^0} = 230[\mathrm{GeV}]$$

- Output:

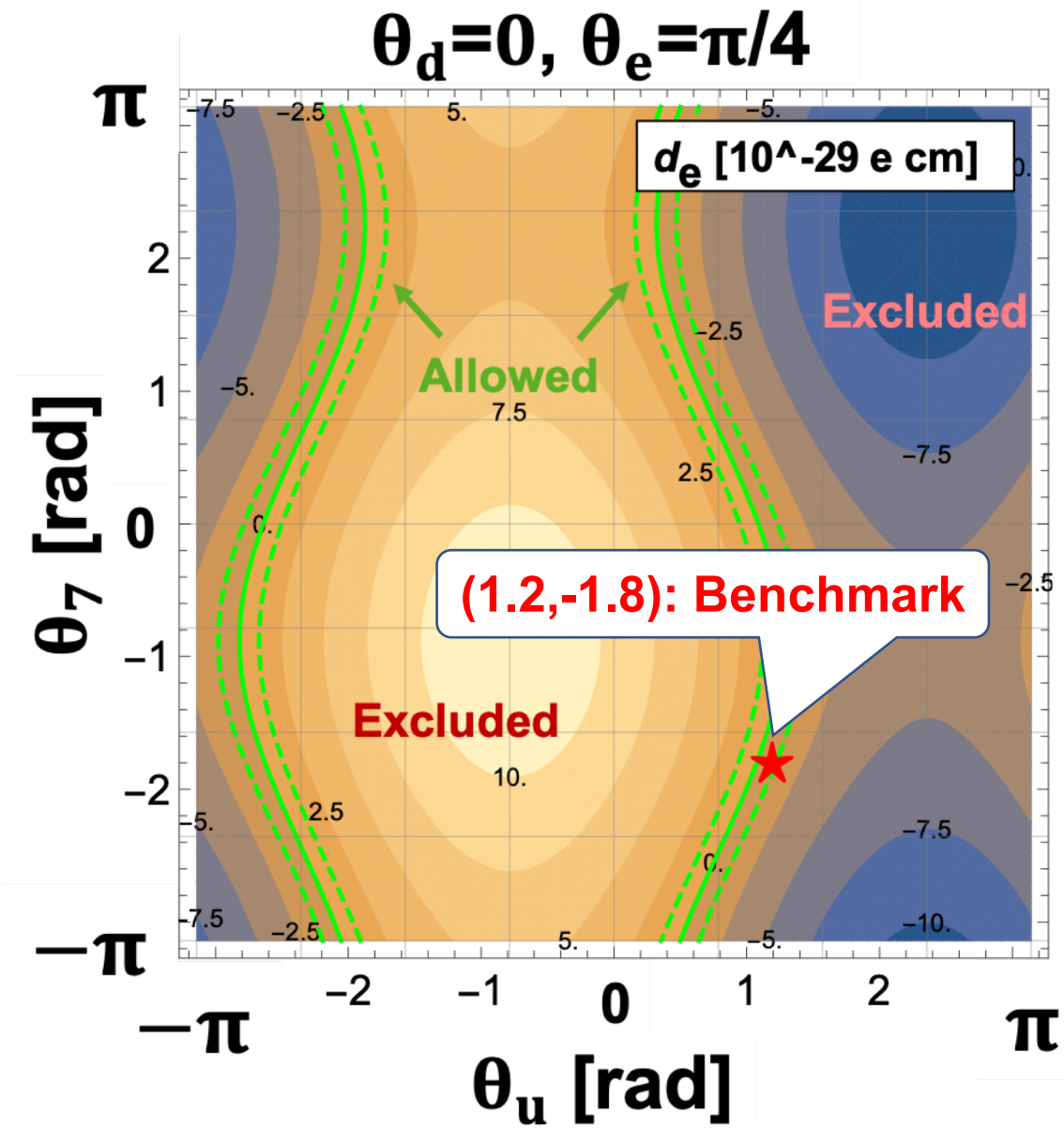
— : $d_e = 0$
- - -: Latest EDM bound

At the Benchmark point (1.2, -1.8):

$$d_e = -0.95\,[10^{-29}\ \mathrm{e\ cm}]$$

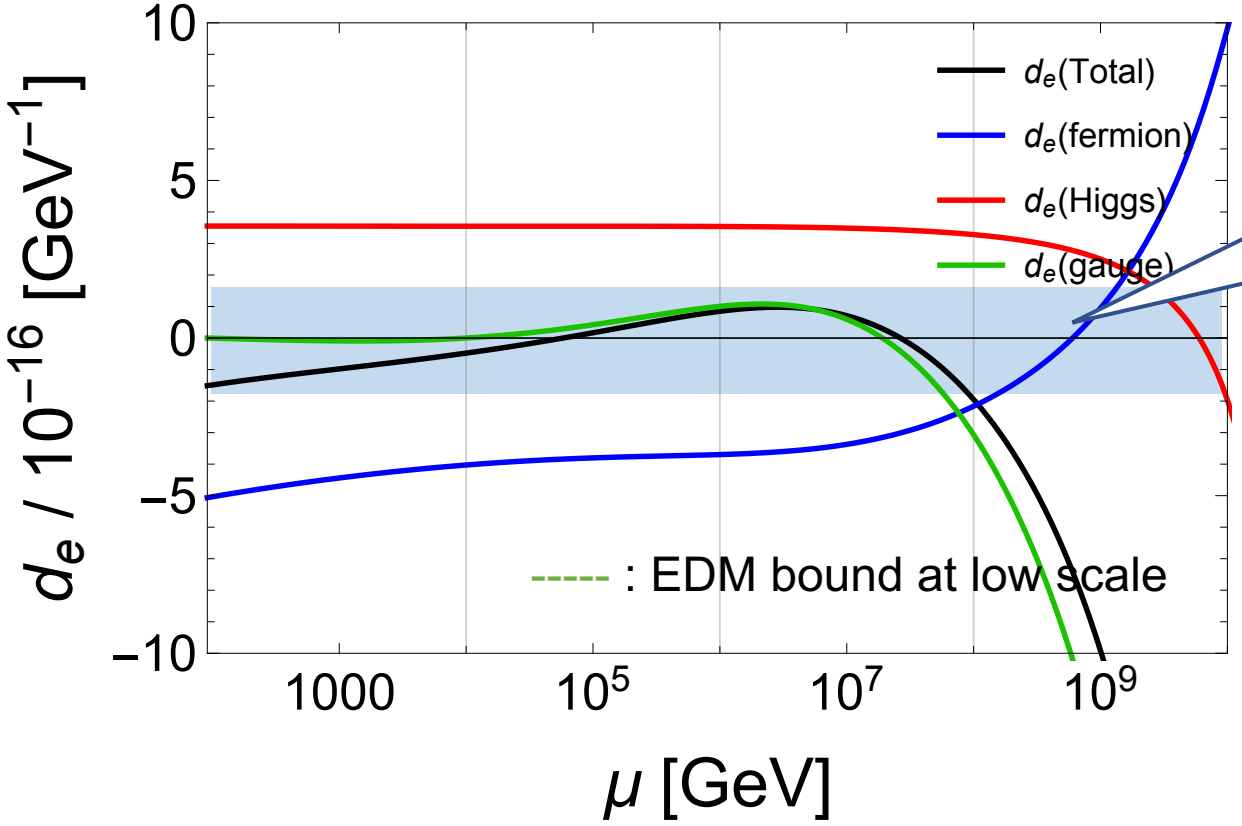
$$|d_e^{\mathrm{exp.}}| < 1.1 \quad [10^{-29}\ \mathrm{e\ cm}]$$

[ACME collaboration, Nature (2018)]



CP-phases can be O(1) without large electron EDM.

RGE analysis:
Scale dependence of the EDM



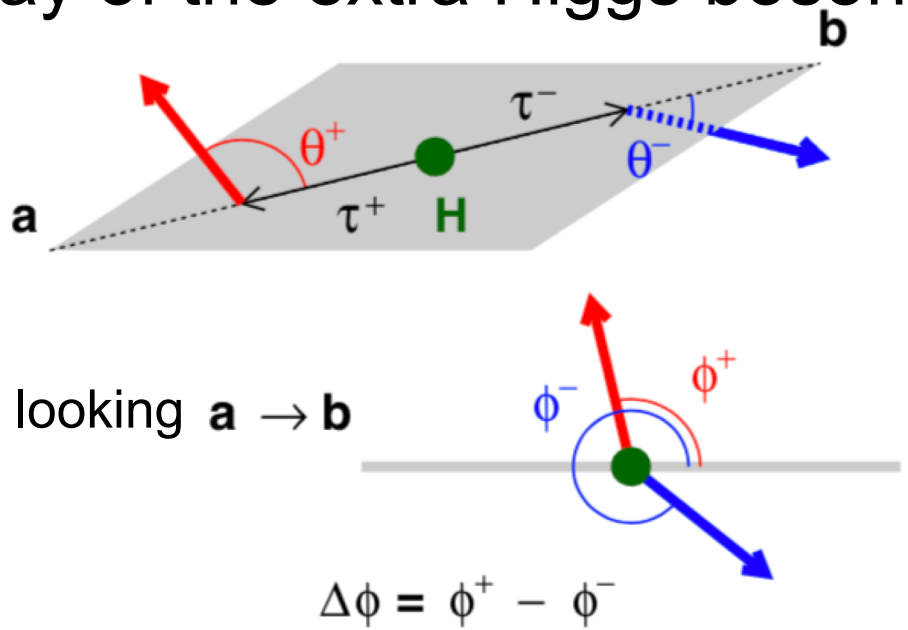
Until 10^8 GeV, the EDM is kept within the constraint imposed at low scale.

That might imply the existence of a symmetry, theory or something realizing the destructive interference below 10^8 GeV.

Beta functions: the general 2HDM at 1-loop level

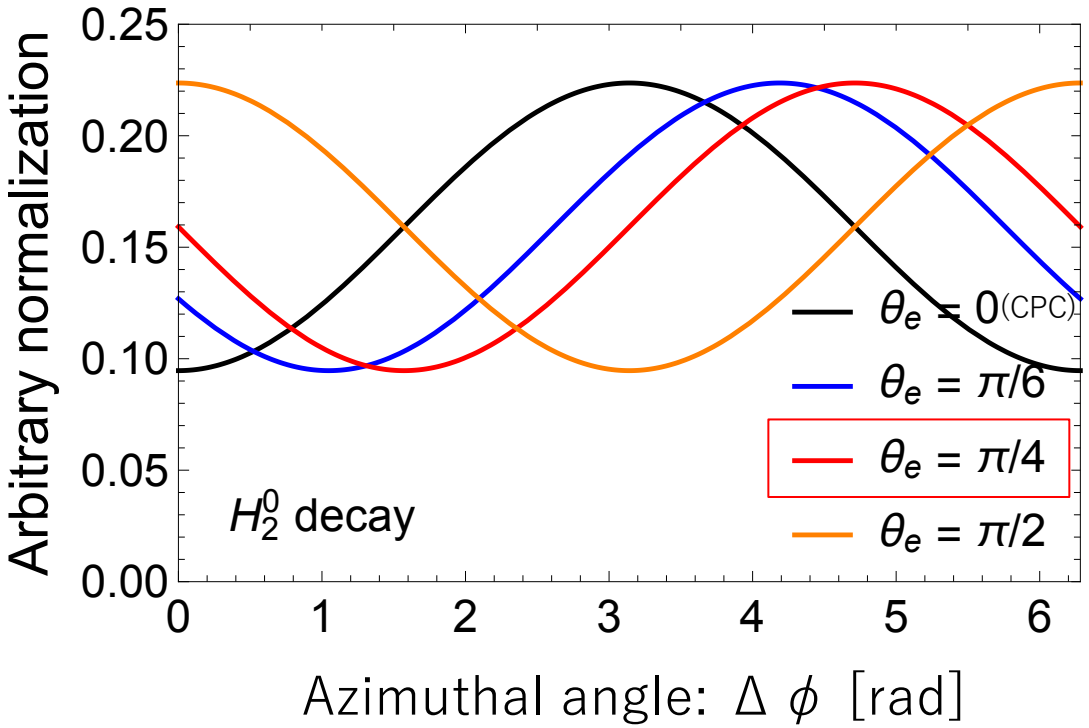
Angular distribution

Decay of the extra Higgs boson



Picture by [Jeans, Wilson, PRD98, 013007 (2018)]

[S. Kanemura, MK and K. Yagyu]



The distribution depends on θ_e.

Such a CP-phase may be measured by ILC 250 (2 /ab) with an accuracy of 0.075 rad. [Jeans, Wilson (2018)]
But it simply cannot be adapted for our scenario. Promising process: $e^- e^+ \to H_2 H_3$ (work in progress)

Summary

1. We have considered the two Higgs doublet model with CPV in the Yukawa interaction and in the Higgs potential.
2. EDM can be satisfied by the destructive interference between multiple O(1) CP-violating phases.
3. Destructive interference can be conserved until the high scales.
4. CP-violating phases can be tested by the angular distributions of the decays of extra Higgs bosons. ILC will be useful then.
5. Such O(1) CP-violating phases might be the source of the baryon number asymmetry of the Universe.

Back up

[S. Kanemura, MK and K. Yagyu]

Numerical result: Electron EDM

- Input: $(\theta_u, \theta_d, \theta_e, \theta_7) = (2, 0, \pi/2, 1)$

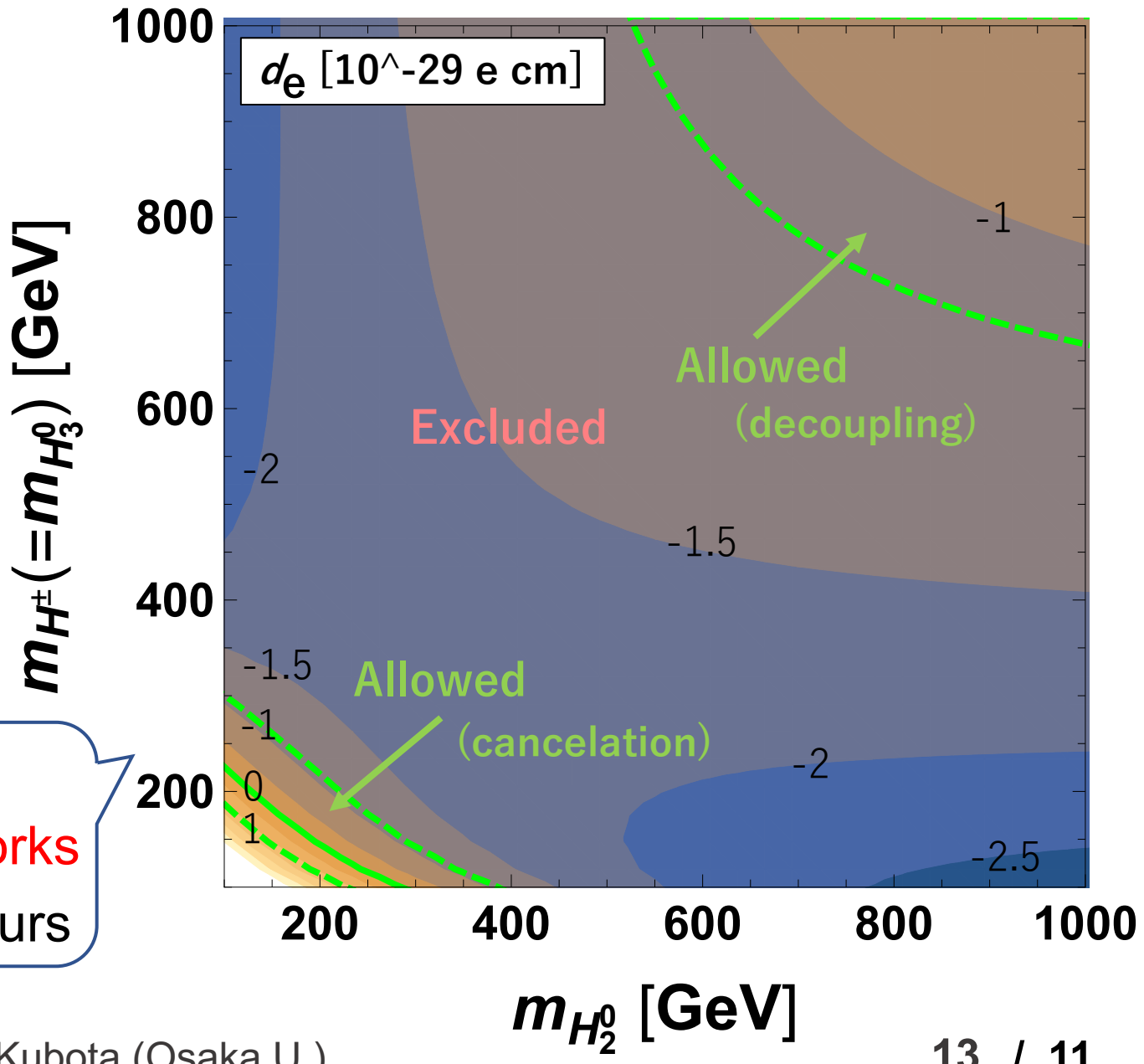
  $|\zeta_u| = 0.01, |\zeta_d| = 0.1,$

  $|\zeta_e| = 0.5, |\lambda_7| = 0.3$

- Output:

— : $d_e = 0$

- - -: Latest EDM bound



EDM is getting the small value:

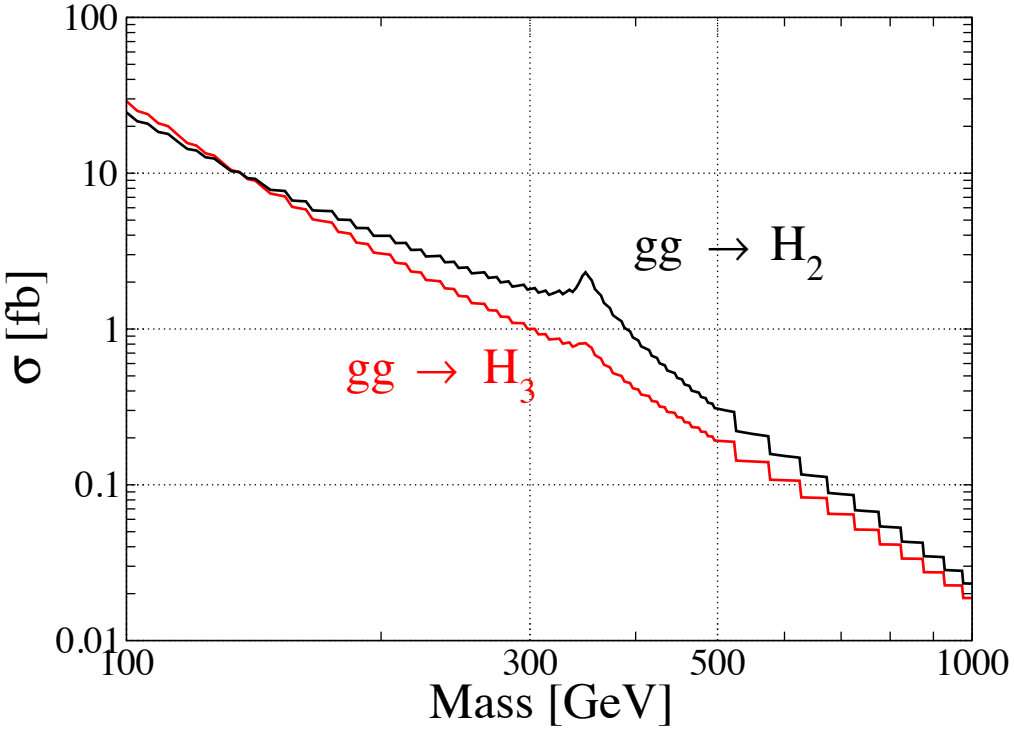
Masses ~ 200 GeV -> Cancellation works

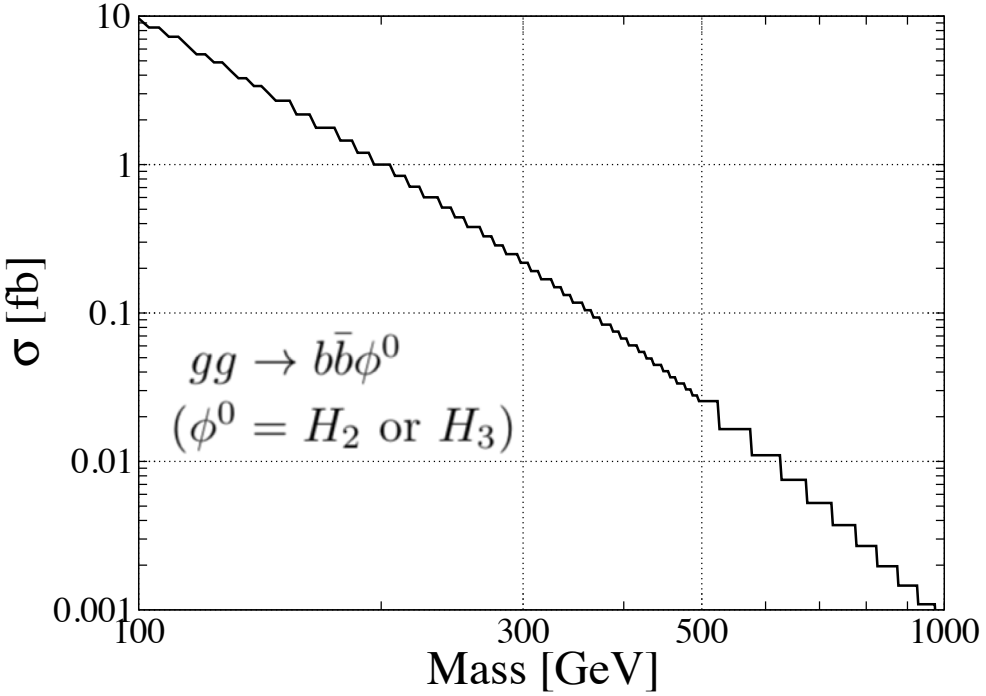
Masses ~1000 GeV -> Decoupling occurs

[S. Kanemura, MK and K. Yagyu]

Productions

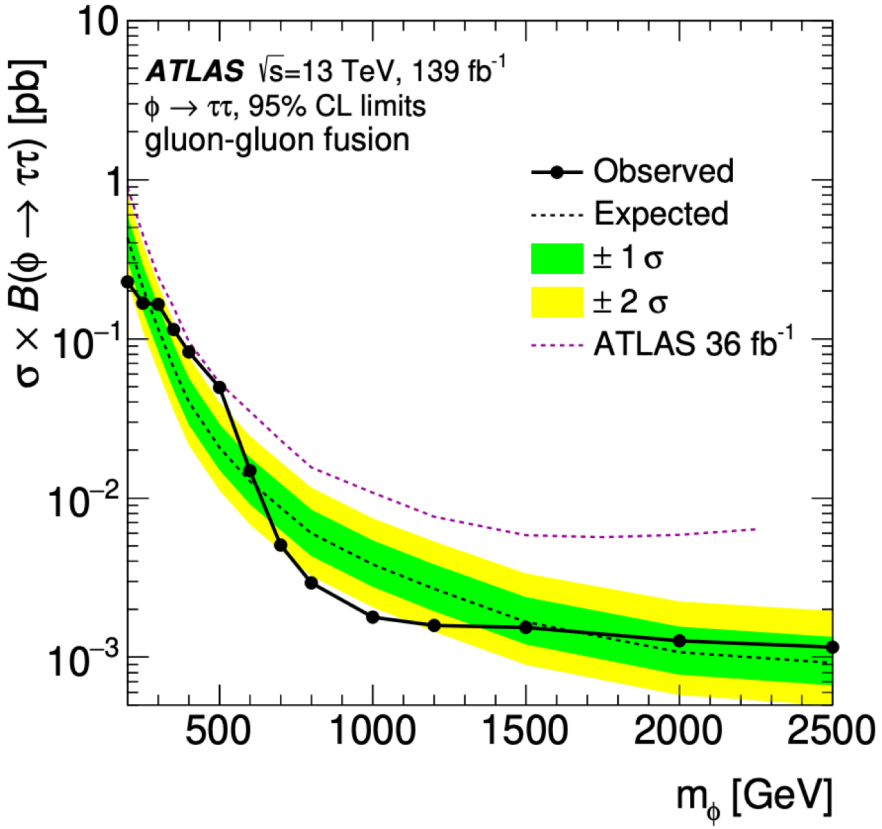
at $\sqrt{s} = 13$ TeV

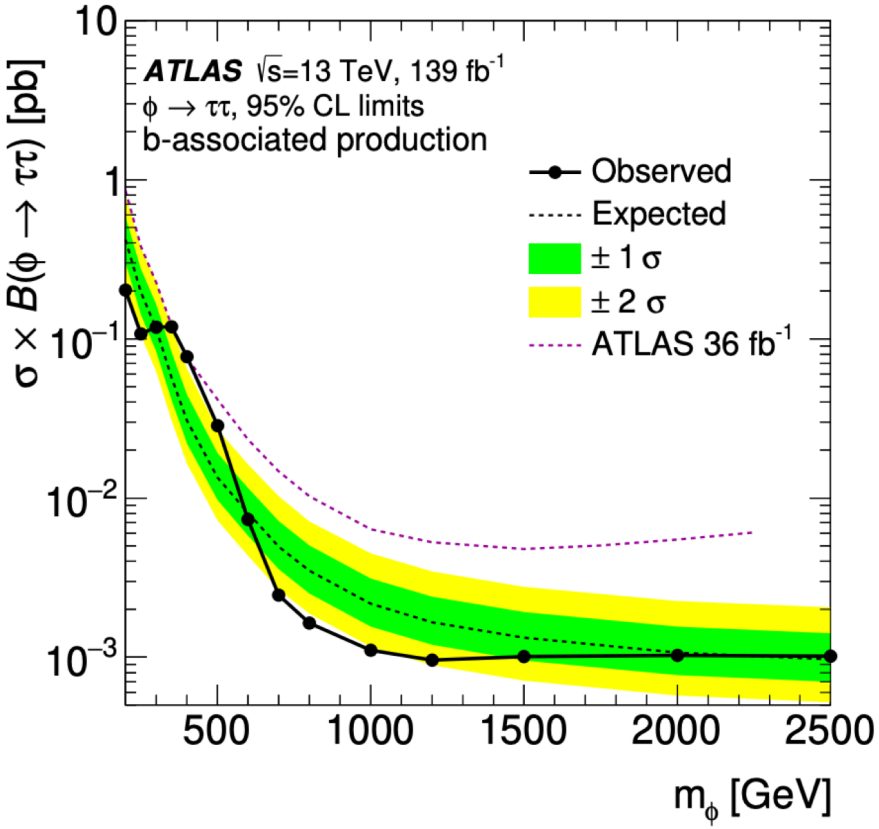




Productions

[arXiv:2002.12223]



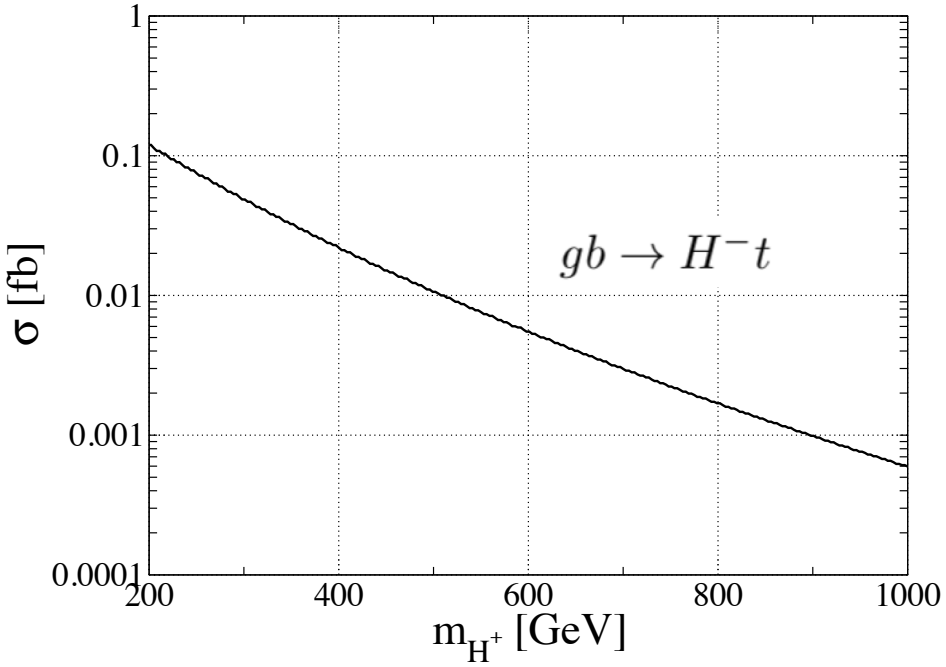


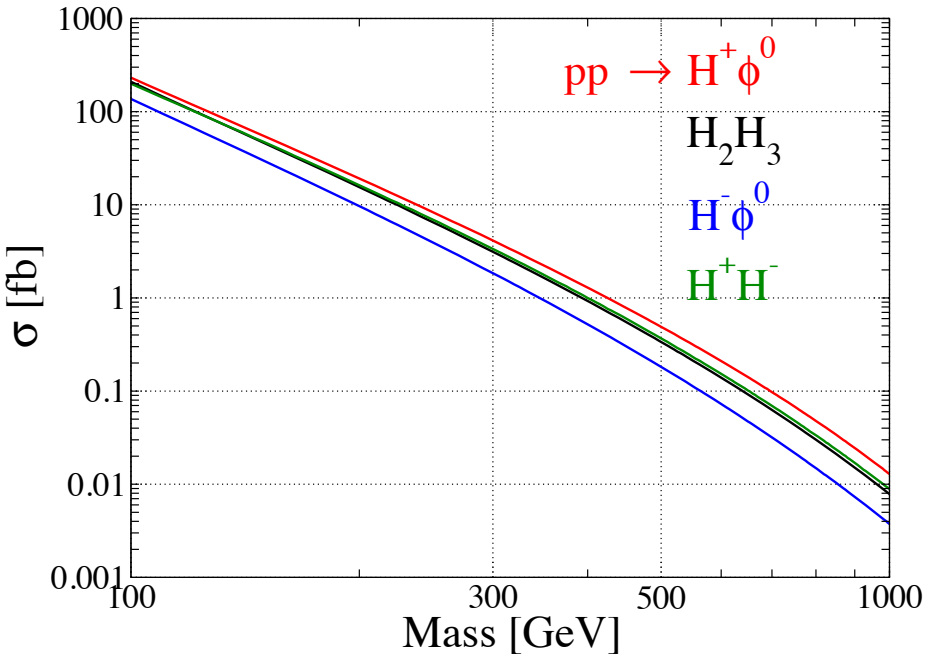
The observed and expected 95% CL upper limits on the production cross section times branching fraction for a scalar boson (φ) produced via (left) ggF and (right) b-associated production.

[S. Kanemura, MK and K. Yagyu]

Productions

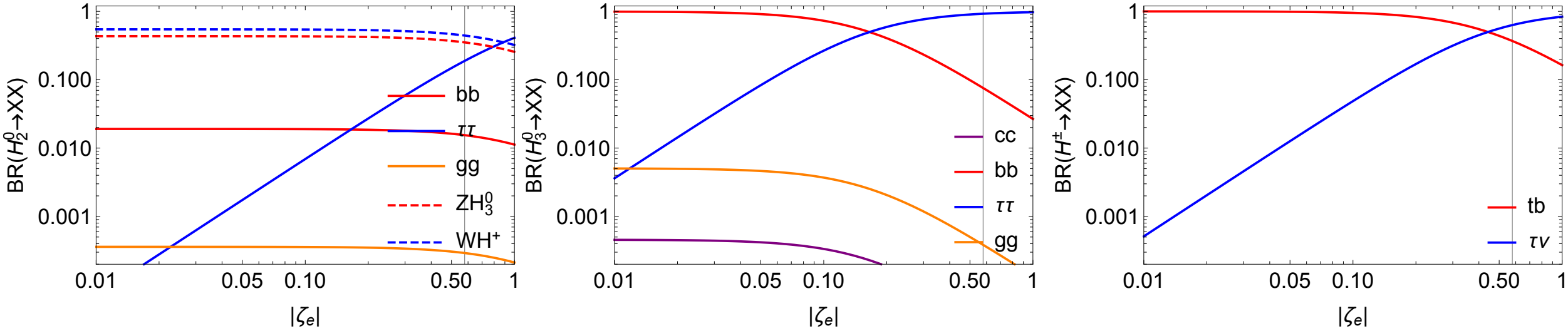
at $\sqrt{s} = 13$ TeV



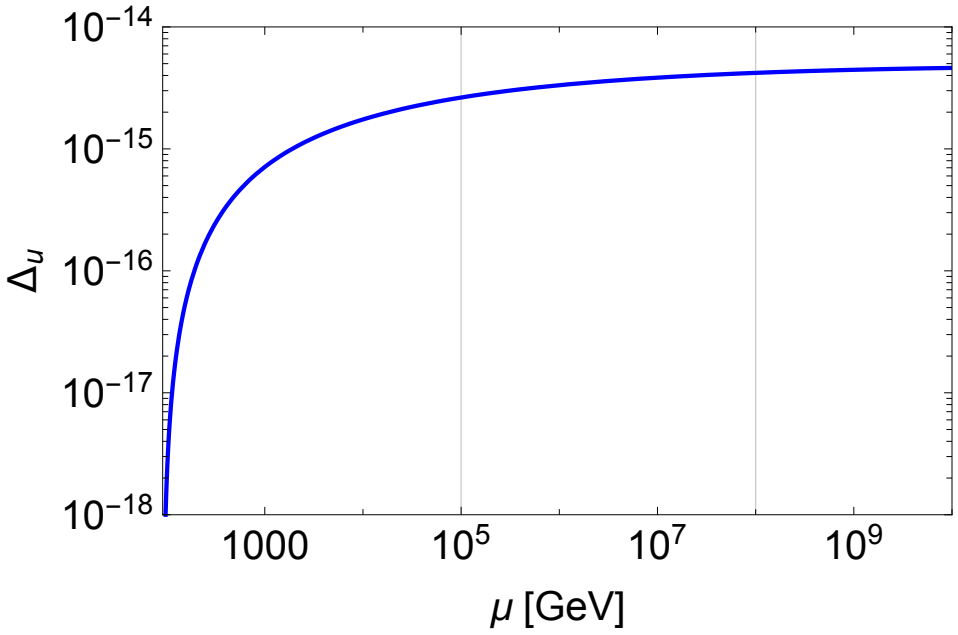


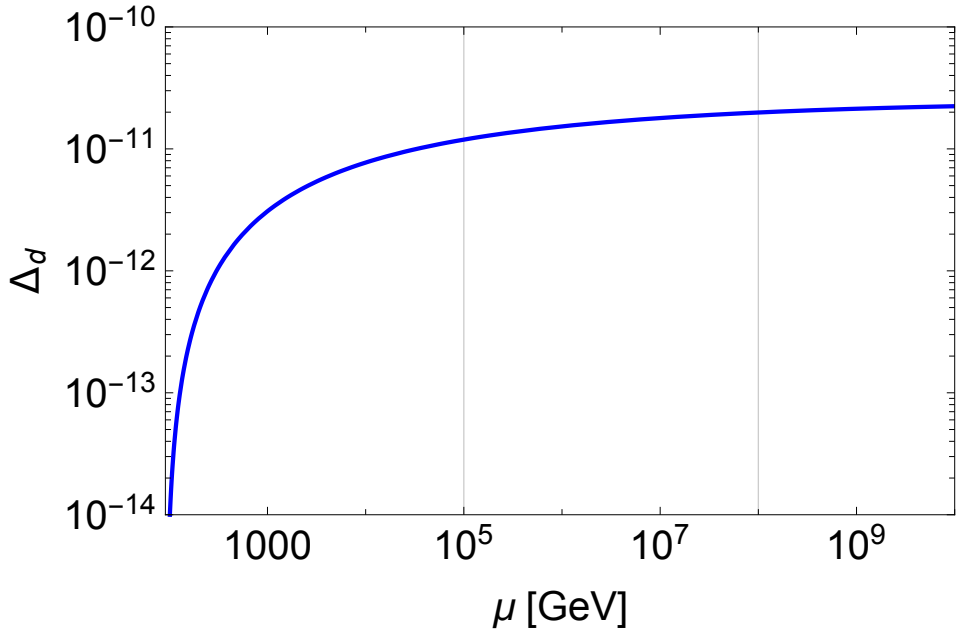
[S. Kanemura, MK and K. Yagyu]

Branching ratios



RGE -Yukawa couplings-

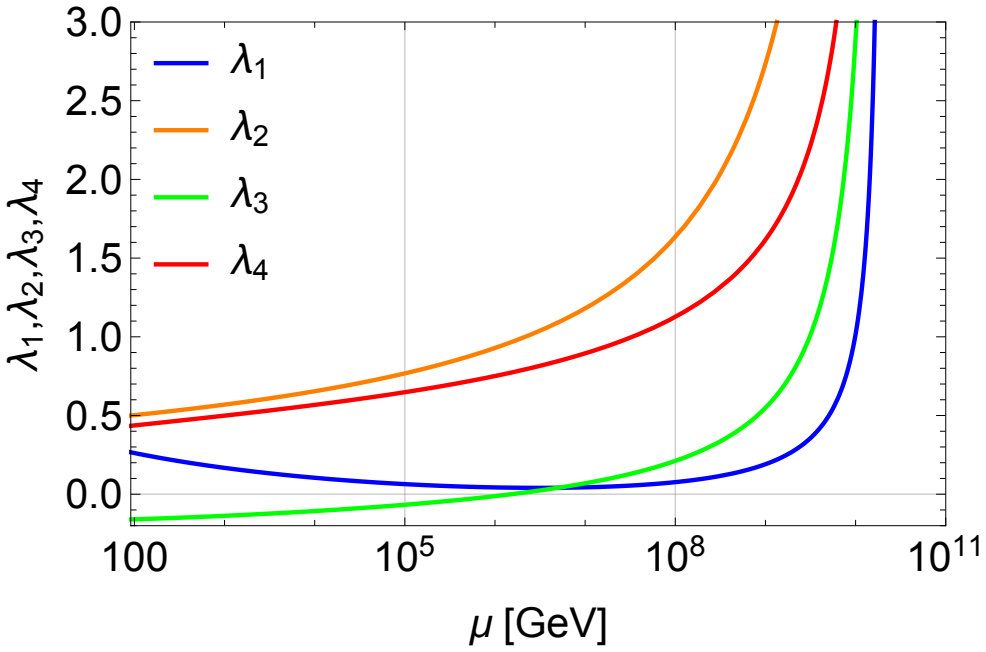


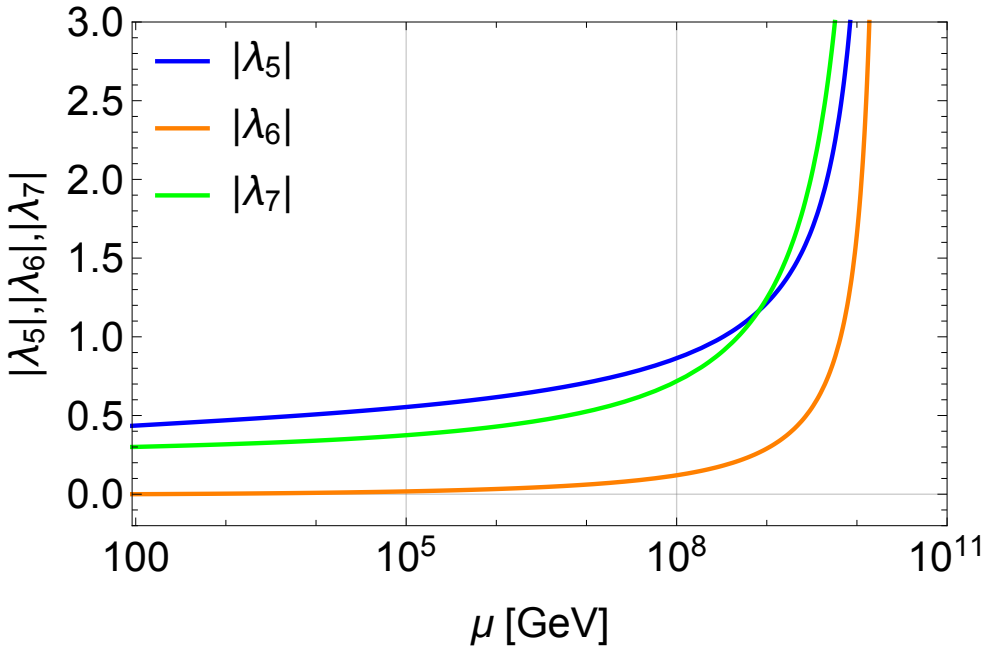


$$\Delta_q \equiv \mathrm{Tr}\left[\delta y_q^\dagger \delta y_q\right], \quad \text{where} \quad \delta y_q \equiv \hat{\rho}_q - \left\{ \frac{\hat{\rho}_q^{33}}{\hat{M}_q^{33}} \right\} \hat{M}_q, \quad (q = u, d)$$

[S. Kanemura, MK and K. Yagyu]

RGE -Higgs couplings-



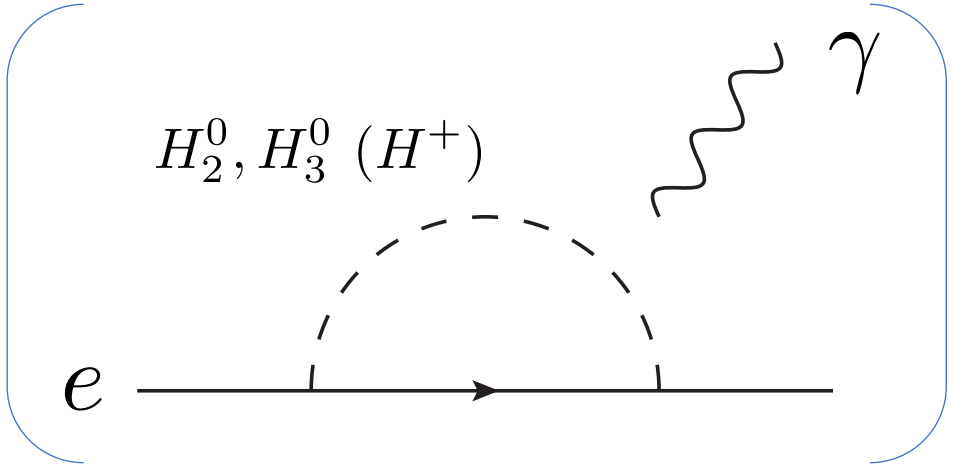


$$\mathcal{L}_{EDM} = -i\frac{d}{2}\,\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi\;F_{\mu\nu}$$

Barr-Zee diagram

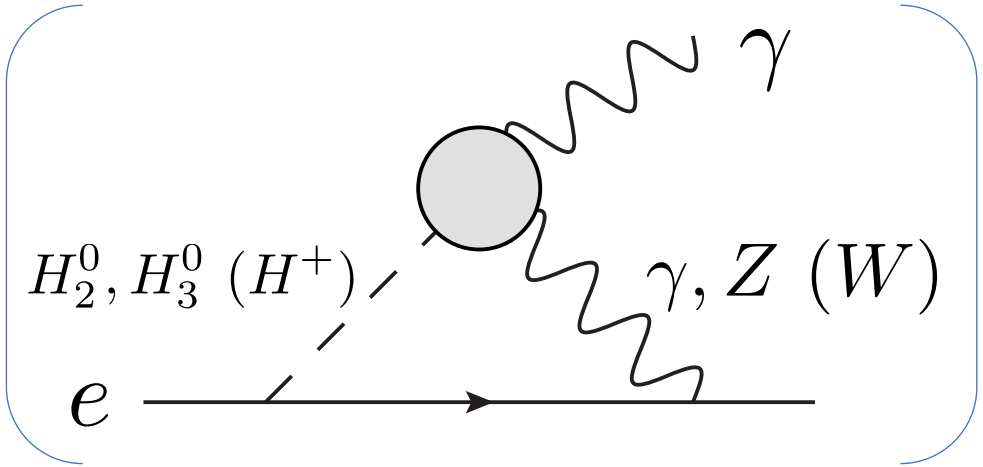
[S. M. Barr, A. Zee, PRL (1990)]

- BZ diagrams (2-loop) give a larger contribution.



$$\propto \frac{1}{(4\pi)^2} y_e^3$$

$<$

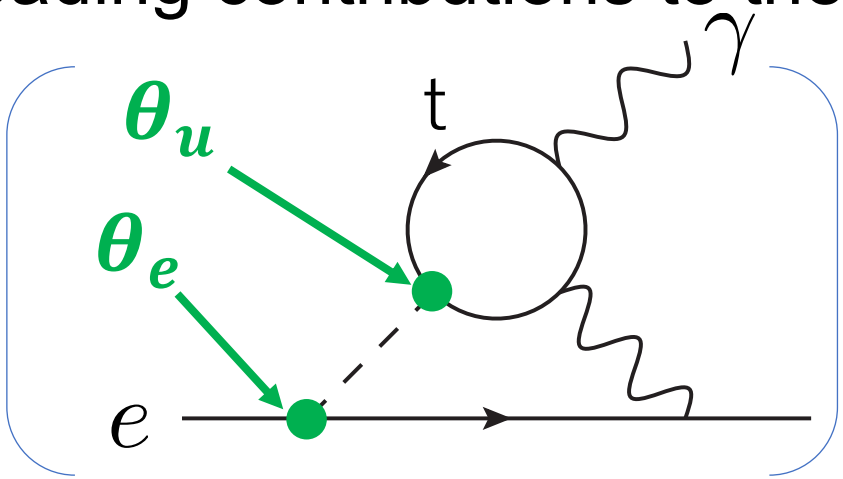


$$\propto \frac{1}{(4\pi)^4} y_e$$

Destructive interference of the EDM

- Leading contributions to the electron EDM are decomposed as

$d_e =$



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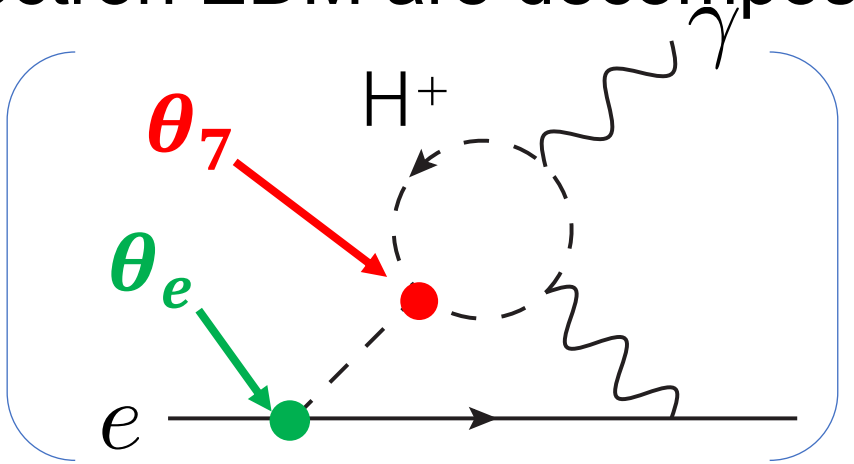


$< d_e^{(\mathrm{exp.})}$

$$d_e = \left(A^\gamma I^\gamma + A^Z I^Z + A^W I^W\right) |\zeta_u| \sin(\theta_u - \theta_e) \quad + \quad \left(B^\gamma J^\gamma + B^Z J^Z + B^W J^W\right) |\lambda_7| \sin(\theta_7 - \theta_e),$$

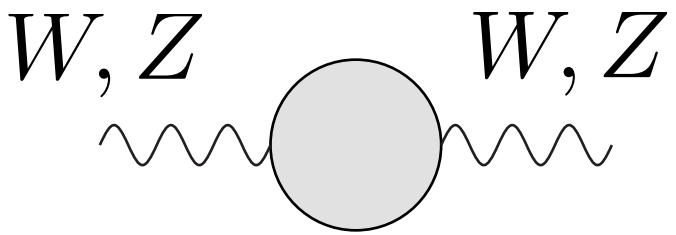
A, B: constant factors

I, J: loop functions

rho parameter

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$ (at tree level)

- When CP symmetry is broken, the custodial symmetry is not respected and the rho parameter deviates from the SM value.



Corrections to the rho parameter do not contain the Higgs self couplings at 1-loop level.

$$\boxed{V \supset \lambda_7'(\Phi_2'^\dagger \Phi_2')(\Phi_1'^\dagger \Phi_2')}$$

-> λ_7' does not change the rho parameter at 1-loop level.