A scenario of Electroweak Baryogenesis without EDM cancellation

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U. Osaka
Dr. Wani
(mascot character)

This talk

- Introduction
    - EW Baryogenesis
    - A viable Model (aligned 2HDM) with EDM cancellation

- Alternative Scenario (Minimal 2HDM for EWBG)
    - Set up
    - EWBG without EDM cancellation
    - Results

- Summary

Introduction

BAU and Baryogenesis

Particle Data Group

Baryon Number of the Universe

$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} (= (5-7) \times 10^{-10})$$

Baryogenesis

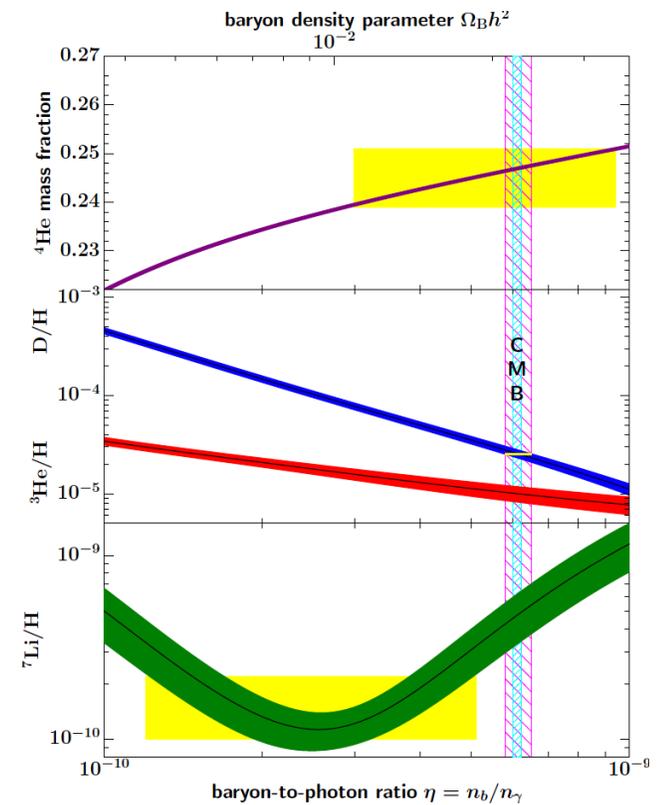What is the mechanism to generate the baryon asymmetric Universe from the symmetric one?

Sakharov's Condition

Sakharov 1967

1. ΔB ≠ 0

2. C and CP violation

3. Departure from thermal equilibrium

SM cannot satisfy these conditions

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Various scenarios of baryogenesis

- GUT （High scales）

  CPV decays of heavy gauge bosons   Y. Yoshimura (1979), S. Weinberg (1979)

- Afleck Dine mechanism （High scales）

  VEV of scalar field with baryon number   I. Affleck and M. Dine (1985)

- Leptogenesis （mainly High scales）

  Generating L number by the decay of RH neutrinos   M. Fukugita and T. Yanagida (1986)
  transfered B+L by sphaleron keeping B-L

- EW baryogenesis （EW-TeV scales）

  B+L is generated by sphaleron   V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov(1986)
  Then, decouple after 1st order EWPT

  Physics to be done NOW
  (testable at experiments)

EW Baryogenesis

Sakharov Conditions   Kuzmin, et al (1985)

１）B non-conservation ➡ Sphaleron transition at high T

２）C and CP violation ➡ C violation (SM is a chiral theory)
CP in BSM sectors

３）Departure from
thermal equilibrium ➡ EWPT is strongly 1st OPT

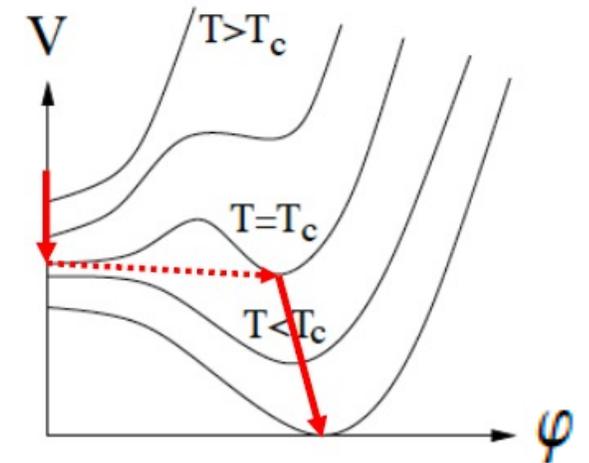Extension of the Higgs sector is required

Condition of Strongly First OPT
In the broken phase, sphaleron should quickly decouple to avoid wash out

$$\Gamma_{sph} < H$$ ➡ $$\frac{\varphi_c}{T_c} \gtrsim 1$$

Physics of Higgs potential

EDM

Experimental Bounds on Electric dipole moments (EDMs)

Current bounds

- Electron EDM $|d_e| < 4.1 \times 10^{-30}\ e$ cm JILA, Science (2023)

- Neutron EDM $|d_n| < 1.8 \times 10^{-26}\ e$ cm Abel et al. PRL (2020)

- Proton EDM $|d_p| < 2.1 \times 10^{-25}\ e$ cm Sahoo, PRD (2017)

Expected sensitivities in the future

$|d_e| \sim 10^{-33}\ e$ cm Vutha et al. (2018) Ardu et al. (2024)

$|d_n| \sim 10^{-28}\ e$ cm nEDM (2019)

$|d_p| \sim 10^{-29}\ e$ cm Alarcon, et al. (2022)

Give very strong constraints on the CPV models at TeV scales

EW Baryogenesis and EDM in 2HDM

(1) 2HDM with softly-broken Z_2 symmetry (Type I, Type II etc) Fromme, Huber and Seniuchi (2006)

- Suppressed FCNC
- <u>One</u> CP phase
- CP violation for observed BAU $\to |d_e| = O(10^{-28})\ e$ cm **Difficult**

Observation

$|d_e| < 4.1 \times 10^{-30}\ e$ cm

Roussy et al. 2022

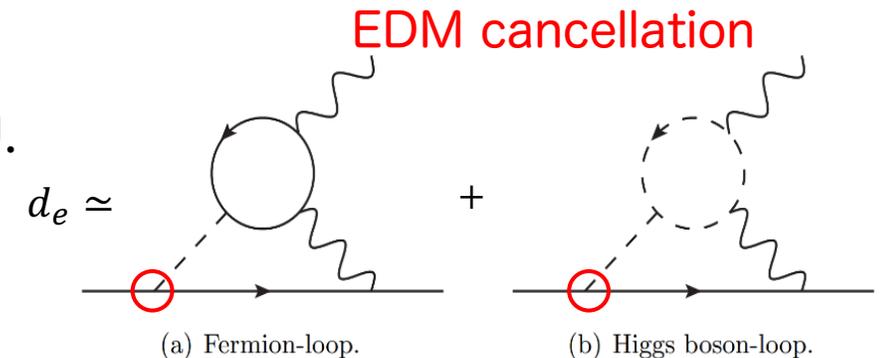**(2) General 2HDM** Viable EWBG in <u>the aligned 2HDM</u>, ⋯

Fuyuto, Hou and Senaha (2019);
SK Kubota and Yagyu (2020);
Enomoto, SK, Mura (2022)

- Assuming Yukawa alignment for avoiding FCNC
- <u>Multiple</u> CP phases
- EDM depends on the parameters not related to BAU.

EDM cancellation

Cancellation among multiple CPV phases is used

$d_e \simeq$

(a) Fermion-loop.   (b) Higgs boson-loop.

(3) Minimal EWBG scenario in the 2HDM without EDM cancellation

$$Y_{2,u} = \begin{pmatrix} \rho_{uu} & \rho_{cu} & \rho_{tu} \\ \rho_{uc} & \rho_{cc} & \rho_{tc} \\ \rho_{ut} & \rho_{ct} & \rho_{tt} \end{pmatrix} \longrightarrow \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \rho_{tt} \end{pmatrix}$$

(switch off Yukawa of the light fermions)

M. Endo, M. Aiko, SK, Y. Mura, JHEP 07 (2025) 236

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Aligned 2HDM (a viable scenario)

General Higgs potential in the 2HDM

$$V = -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - \left(\mu_3^2(\Phi_1^\dagger\Phi_2) + h.c.\right)$$
$$+ \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)$$
$$+ \left\{\left(\frac{1}{2}\lambda_5\Phi_1^\dagger\Phi_2 + \lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_2^\dagger\Phi_2\right)\Phi_1^\dagger\Phi_2 + h.c.\right\}, \quad (\mu_3, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C})$$

Higgs basis

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

Davidson and Haber (2005)

$$m_{H^\pm}^2 = M^2 + \frac{1}{2}\lambda_3 v^2$$

To satisfy LHC data   Avoiding mixing between h and heavy Higgs bosons: $\lambda_6 \sim 0$

Mass matrix of neutral scalar bosons

$$\mathcal{M}^2 = v^2 \begin{pmatrix} \lambda_1 & \text{Re}[\lambda_6] & -\text{Im}[\lambda_6] \\ \text{Re}[\lambda_6] & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 + \text{Re}[\lambda_5]) & -\frac{1}{2}\text{Im}[\lambda_5] \\ -\text{Im}[\lambda_6] & -\frac{1}{2}\text{Im}[\lambda_5] & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 - \text{Re}[\lambda_5]) \end{pmatrix} = \begin{pmatrix} m_h^2 & 0 & 0 \\ 0 & m_{H_2}^2 & 0 \\ 0 & 0 & m_{H_3}^2 \end{pmatrix}$$

rephasing

Higgs alignment

$\arg[\lambda_7] \equiv \theta_7$

Avoiding FCNC: Yukawa alignment is imposed

$$y_f^2 = \zeta_f y_f^1 \quad (f = u, d, e)$$

$$\mathcal{L}_y = -\overline{Q}_L \frac{\sqrt{2}M_u}{v}\left(\tilde{\Phi}_1 + \zeta_u^*\tilde{\Phi}_2\right)u_R - \overline{Q}_L \frac{\sqrt{2}M_d}{v}\left(\Phi_1 + \zeta_d\Phi_2\right)d_R - \overline{L}_L \frac{\sqrt{2}M_e}{v}\left(\Phi_1 + \zeta_e\Phi_2\right)e_R + h.c.$$

Yukawa alignment

Pich and Tuzon (2009)

Multiple CPV phases

Higgs potential
Yukawa couplings

$\arg[\lambda_7] \equiv \theta_7$
$\arg[\zeta_u] \equiv \theta_u, \; \arg[\zeta_d] \equiv \theta_d, \; \arg[\zeta_e] \equiv \theta_e$

Constraint from eEDM

$$\mathcal{L}_{\mathrm{EDM}} = -\frac{d_f}{2} \bar{f} \sigma^{\mu\nu}(i\gamma^5) f F_{\mu\nu}$$

Barr-Zee type diagrams

T violation if ≠ 0 ⇄ CPV   (CPT theorem)

$|d_e| < 4.1 \times 10^{-30}\ e$ cm

Roussy et al.
arXiv:2212.11841

$d_e \simeq$

$\theta_{u,d}$
θ_e
$|\zeta_u||\zeta_e|\sin(\theta_u - \theta_e)$

θ_7
θ_e
$|\lambda_7||\zeta_e|\sin(\theta_7 - \theta_e)$

Aligned 2HDM

when $\zeta_e = \zeta_u = \zeta_d$ 10^{-29} e cm

Higgs potential $\arg[\lambda_7] \equiv \theta_7$
Yukawa couplings $\arg[\zeta_u] \equiv \theta_u,\ \arg[\zeta_d] \equiv \theta_d,\ \arg[\zeta_e] \equiv \theta_e$
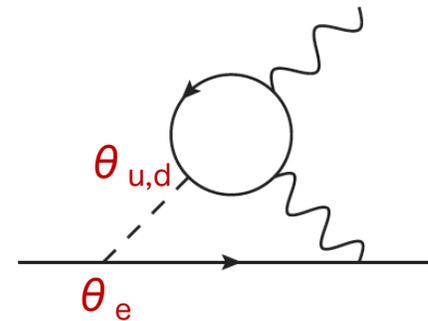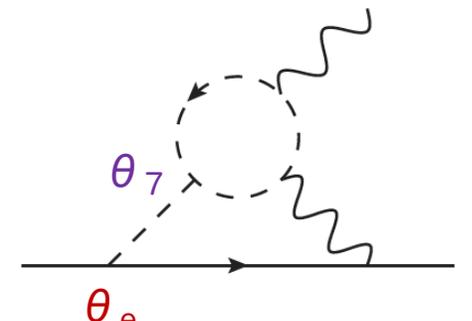
eEDM data can be satisfied by destructive interference (cancellation) among multiple CPV phases

$$d_f = d_f(\text{fermion}) + d_f(\text{Higgs}) + d_f(\text{gauge})$$

Fuyuto, Hou and Senaha (2019); SK Kubota and Yagyu (2020);
Enomoto, SK and Mura (2021), (2022); Idegawa and Senaha (2023); and more

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We evaluate BAU using the semiclassical force method with WKB approximation.

Transport equation for chemical potential

$$C_1\,\mu''(z) + C_2\,\mu'(z) + C_3\,\mu(z) = S_{\mathrm{CPV}}$$

where, $\mu(z) = \mu_\psi - \mu_{\bar{\psi}}$

CPV source term

$$S_{fl} = -\gamma v_w \left(m_{fl}^2 \theta'_{fl}\right)' Q_{fl}^8 + \gamma v_w m_{fl}^2 \theta'_{fl} \left(m_{fl}^2\right)' Q_{fl}^9$$
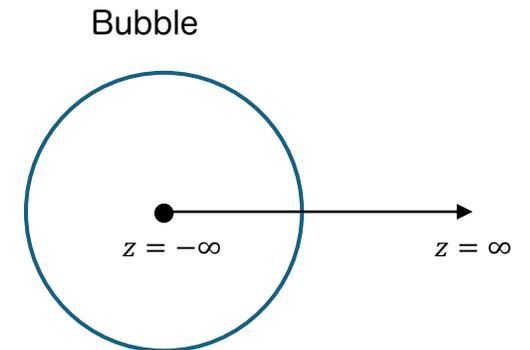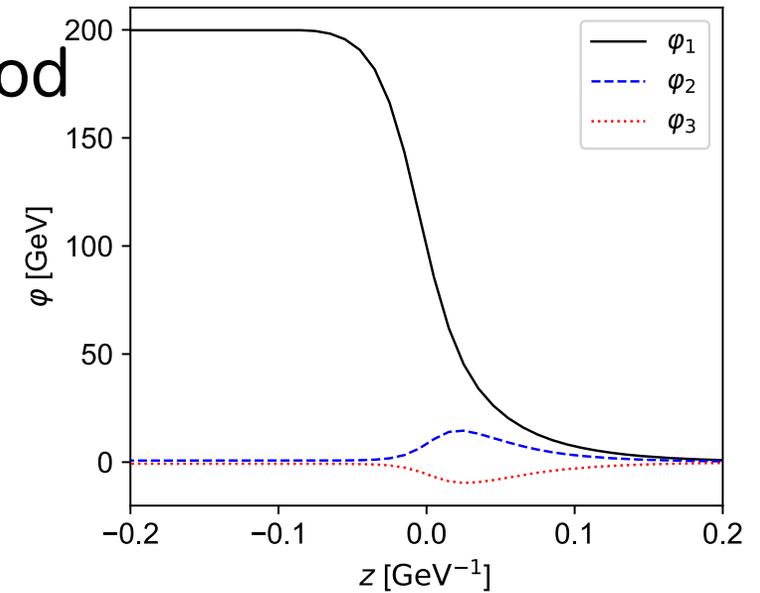
$$\gamma = 1/\sqrt{1 - v_w^2}$$

Top transport scenario

In the minimal setup, the local mass and phase for the top quark are given

Cline, Joyce, and Kainulainen (2000);
Fromme and Huber (2007); and more

$$m_t^2 = \frac{1}{2}\left(y_t^2 \varphi_1^2 + |\rho_{tt}|^2(\varphi_2^2 + \varphi_3^2) + 2y_t|\rho_{tt}|\varphi_1\left(\varphi_2 \cos\theta_{tt} + \varphi_3 \sin\theta_{tt}\right)\right),$$

$$m_t^2 \theta'_t = \frac{1}{2}\left\{y_t|\rho_{tt}|\left((\varphi_3\varphi'_1 - \varphi_1\varphi'_3)\cos\theta_{tt} + (\varphi_1\varphi'_2 - \varphi_2\varphi'_1)\sin\theta_{tt}\right)\right.$$
$$\left. + |\rho_{tt}|^2(\varphi_3\varphi'_2 - \varphi_2\varphi'_3)\right\} + \frac{m_t^2}{\varphi_1^2 + \varphi_2^2 + \varphi_3^2}(\varphi_3\varphi'_2 - \varphi_2\varphi'_3),$$
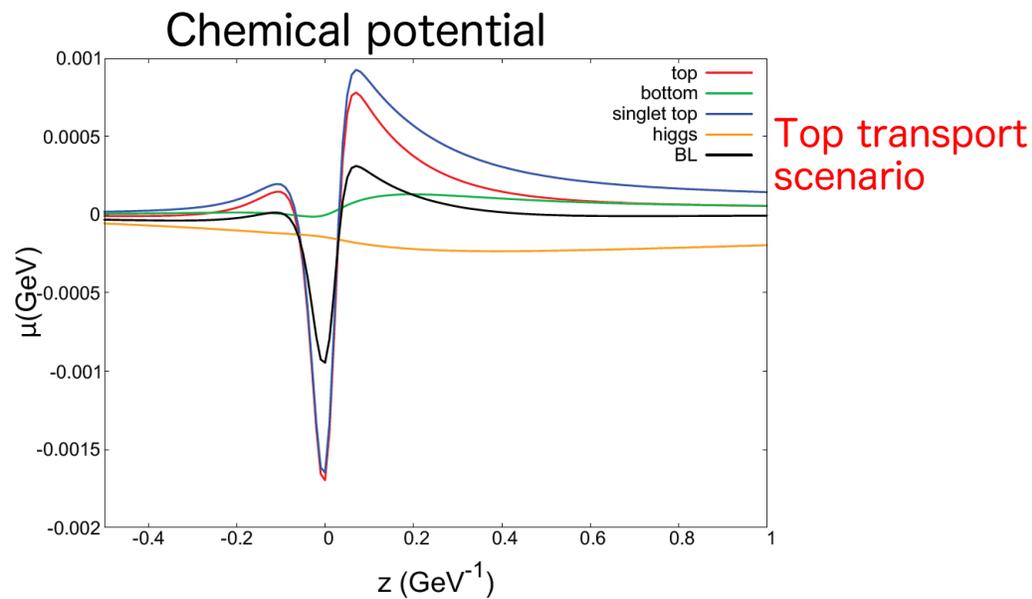
Bubble

Evaluation of BAU

L_w : wall width
T_n : nucleation temp

$$M = 30 \text{ GeV}, \quad \lambda_2 = 0.1, \quad |\lambda_7| = 0.8, \quad \theta_7 = -0.9,$$
$$|\zeta_u| = |\zeta_d| = |\zeta_e| = 0.18, \quad \theta_u = \theta_d = -2.7, \quad \delta_e = -0.04$$

Aligned 2HDM

K. Enomoto, SK, Y. Mura, 2022

Chemical potential

Top transport scenario

$v_w = 0.45$

In symmetric phase, B is produced by sphaleron

$$\eta_B = \frac{405\Gamma_{\mathrm{sph}}}{4\pi^2 v_w g_* T} \int_0^\infty dz \; \mu_{B_L} f_{\mathrm{sph}} e^{-45\Gamma_{\mathrm{sph}} z/(4v_w)}$$

Frozen at the Broken phase when $v_n/T_n > 1$
Cline, Joyce, Kainulainen
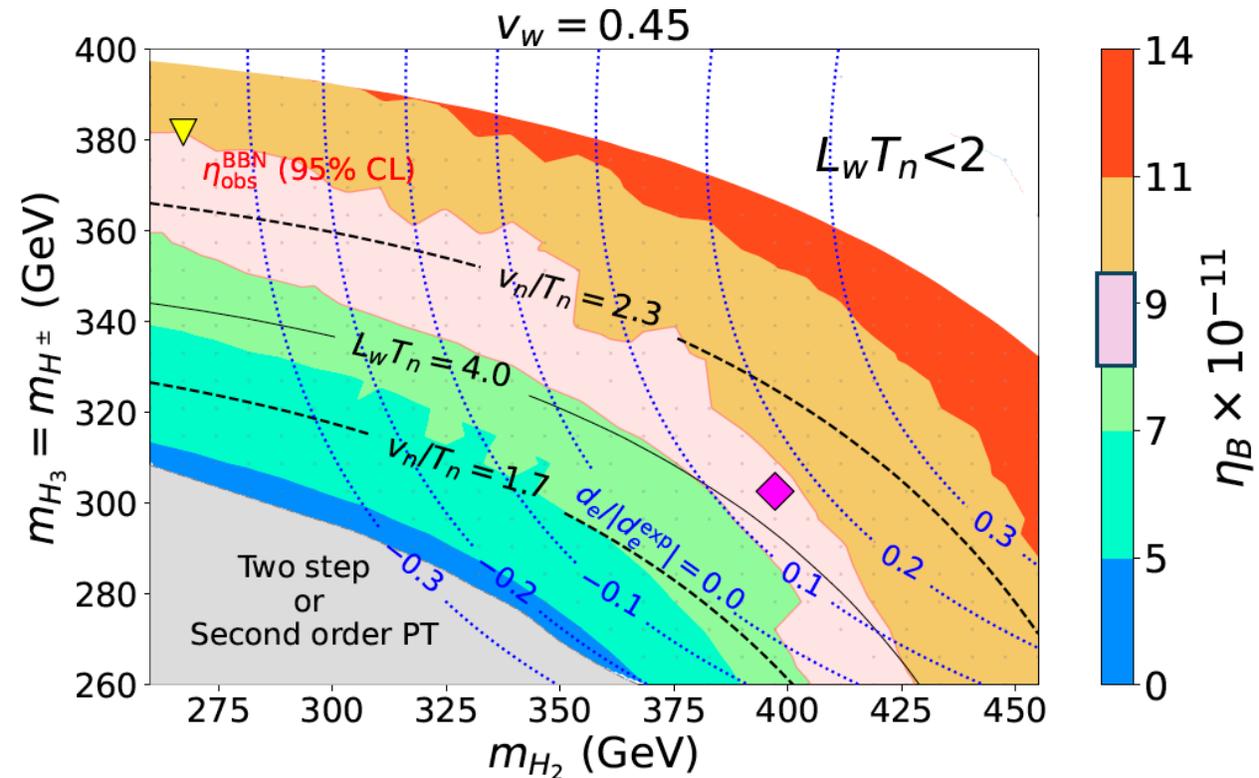
BAU data (pink area)

$$\eta_{obs}^{\mathrm{BBN}} \equiv \frac{n_B}{s} = 8.2\text{--}9.2 \times 10^{-11} \qquad s = 0.74 n_\gamma$$

Test of 1st OPT(1)

Sphaleron decoupling
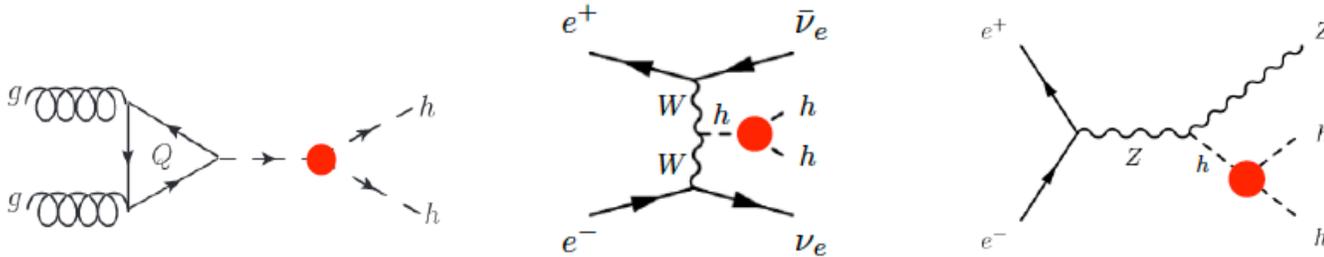**(Strongly 1st OPT)**

$$\frac{\varphi_c}{T_c} \gtrsim 1 \quad \rightleftarrows \quad$$

Large deviation
in the hhh coupling

SK, Y. Okada, E. Senaha 2005

Aligned 2HDM

40-60% deviations
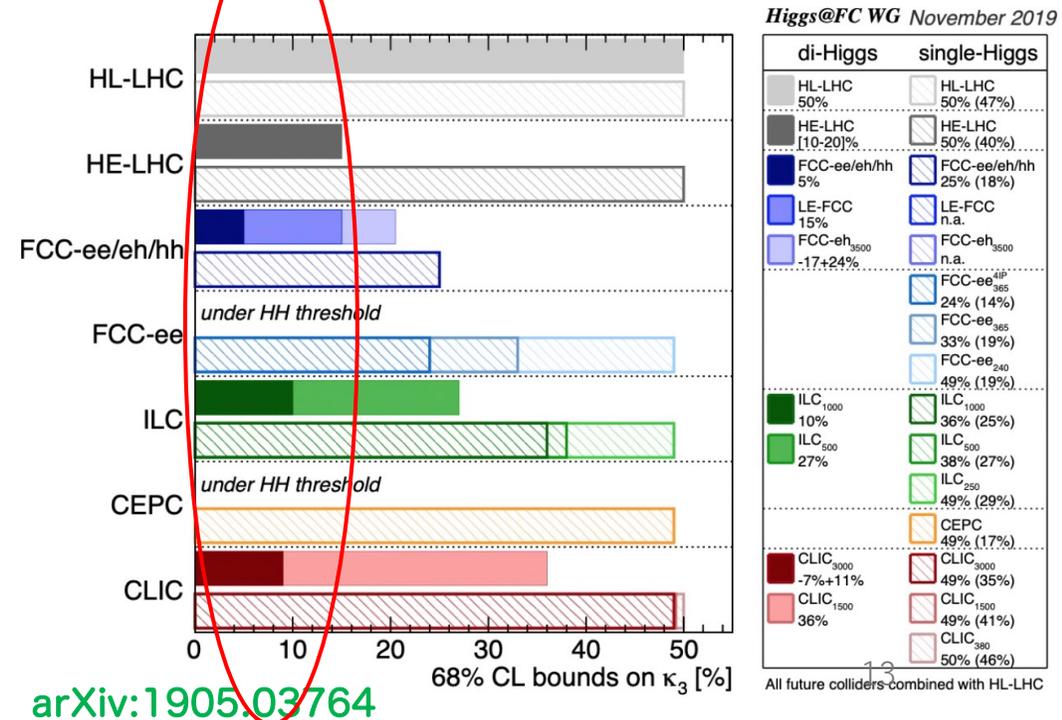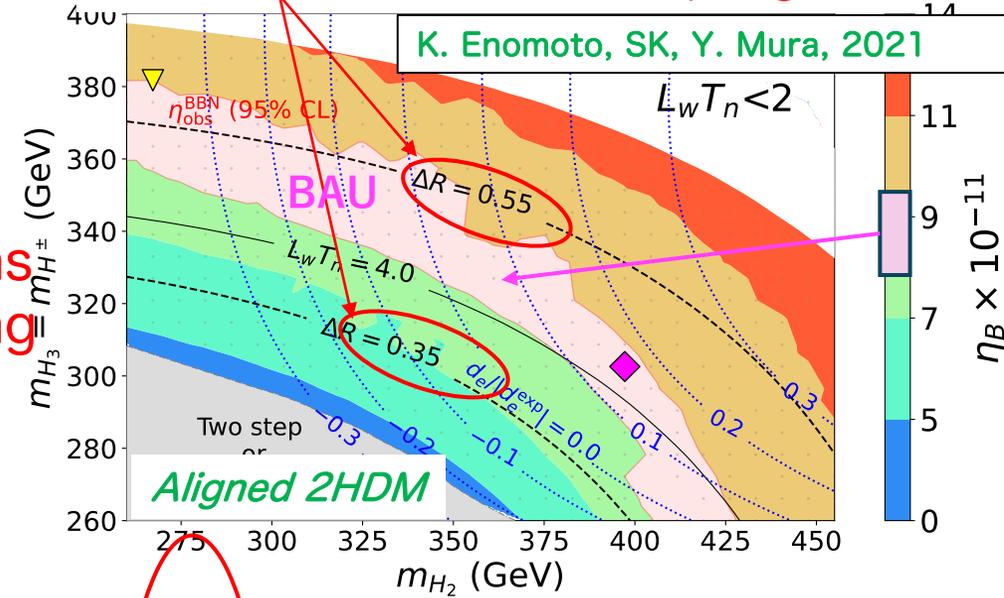in the hhh coupling

K. Enomoto, SK, Y. Mura, 2021

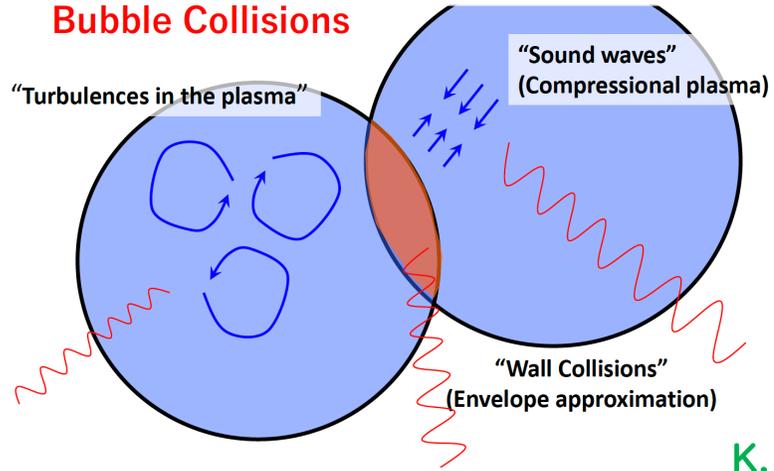The hhh coupling can be measured at
HL-LHC, or future lepton colliders

1st OPT can be directly tested
if hhh is measured by 10% level

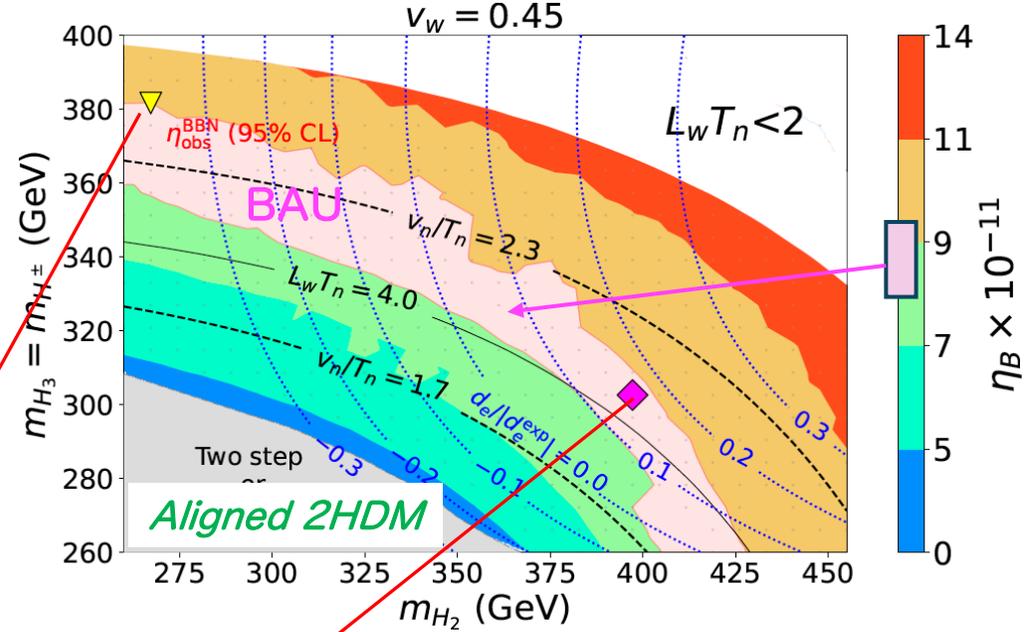$h\gamma\gamma$ can also be sensitive to non-decoupling effects

arXiv:1905.03764

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Test of 1stOPT(2)

Bubble Collisions

"Turbulences in the plasma"

"Sound waves"
(Compressional plasma)

"Wall Collisions"
(Envelope approximation)

Example
Aligned 2HDM

K. Enomoto, SK, Y. Mura, 2022

$v_w = 0.45$

$m_{H_3} = m_{H^\pm}$ (GeV)

η_{obs}^{BBN} (95% CL)

BAU

$L_w T_n < 2$

$v_n/T_n = 2.3$

$L_w T_n = 4.0$

$v_n/T_n = 1.7$

$d_e/|d_e^{exp}| = 0.0$

Two step

Aligned 2HDM

m_{H_2} (GeV)

$\eta_B \times 10^{-11}$

GWs for the benchmark
points of **BAU**

They may be tested
by future GW experiments

K. Enomoto, SK, Y. Mura, 2022

$h^2\Omega_{GW}$

LISA

DECIGO

BBO

BP1b

BP2b

f [Hz]
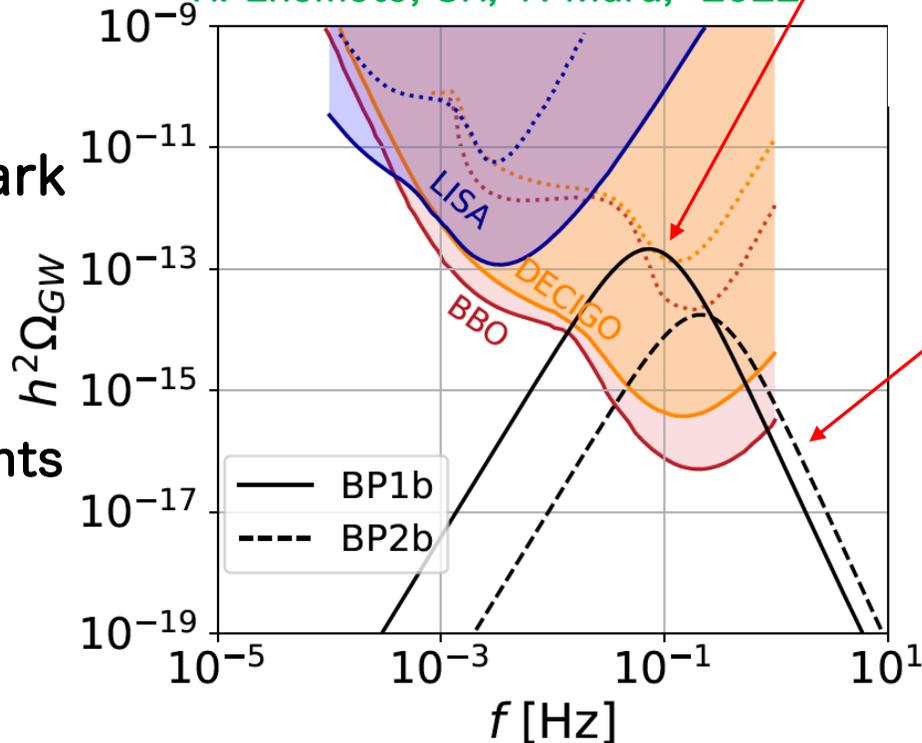
Dotted curves: Sensitivity Curve
M. Breitbach et al., arXiv: 1811.11175

Solid curves: $h^2\Omega_{PISC}$ [SNR criterion]
J. Cline et al., arXiv: 2102.12490

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Minimal 2HDM Scenario for EWBG

M. Endo, M. Aiko, S.K., Y. Mura, JHEP 07 (2025) 236
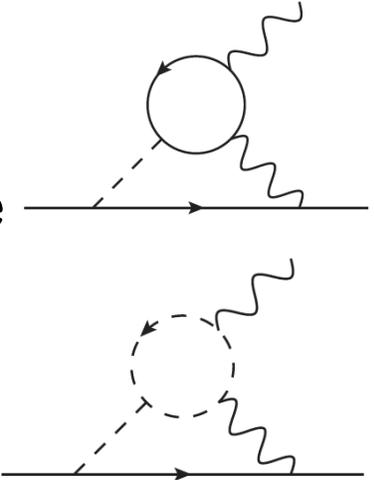
A scenario without EDM cancellation

- BZ diagrams given by light fermion couplings with Higgs bosons.

  If we just switch off them, EDMs via the BZ diagrams vanish, while the CPV phase in top Yukawa can generate BAU.

- Still, the CPV phase of the top coupling for EWBG can lead the top-quark (C)EDM, which causes n, p, eEDMs.

- We examine whether this scenario works or not under current theoretical and experimental constraints.

- The scenario is viable under current experimental bounds, and also testable at future EDM experiments as well as other experiments.

Minimal scenario for EWBG without EDM cancellation

Most general potential

Higgs basis

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

$$V = -\mu_1^2 \Phi_1^\dagger \Phi_1 + M^2 \Phi_2^\dagger \Phi_2 - \left(\mu_3^2 \Phi_1^\dagger \Phi_2 + h.c.\right)$$

Davidson and Haber (2005)

$$+ \frac{1}{2}\lambda_1\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4\left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$

$$+ \left\{\left(\frac{1}{2}\lambda_5 \Phi_1^\dagger \Phi_2 + \lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2\right)\Phi_1^\dagger \Phi_2 + h.c.\right\} \qquad (\mu_3^2, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C})$$

Most general Yukawa sector

$$\mathcal{L}_Y = -\sum_{k=1,2}\left(\overline{Q_L}Y_{k,u}^\dagger \widetilde{\Phi}_k u_R + \overline{Q_L}Y_{k,d}\Phi_k d_R + \overline{L_L}Y_{k,l}\Phi_k e_R + h.c.\right)$$

$$Y_{1,u} = \mathrm{diag}(y_u, y_c, y_t) \qquad Y_{1,d} = \mathrm{diag}(y_d, y_s, y_b) \qquad Y_{1,l} = \mathrm{diag}(y_e, y_\mu, y_\tau)$$

Y_2 **is a general complex matrix**

$$Y_{2,u} = \begin{pmatrix} \rho_{uu} & \rho_{cu} & \rho_{tu} \\ \rho_{uc} & \rho_{cc} & \rho_{tc} \\ \rho_{ut} & \rho_{ct} & \rho_{tt} \end{pmatrix}$$

Off diagonal elements are taken to be small to satisfy FCNC data.

General two Higgs doublet model

- Stationary conditions and mass spectra

$$\frac{\partial V}{\partial h_i} = 0 \Leftrightarrow \mu_1^2 = \frac{1}{2}\lambda_1 v^2, \ \mu_3^2 = \frac{1}{2}\lambda_6 v^2$$

$$\frac{\partial^2 V}{\partial h_i \partial h_j} = \mathcal{M}_{ij}^n = \begin{pmatrix} \lambda_1 v^2 & \mathrm{Re}[\lambda_6]v^2 & -\mathrm{Im}[\lambda_6]v^2 \\ \mathrm{Re}[\lambda_6]v^2 & M^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2 & -\frac{1}{2}\mathrm{Im}[\lambda_5] \\ -\mathrm{Im}[\lambda_6]v^2 & -\frac{1}{2}\mathrm{Im}[\lambda_5] & M^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2 \end{pmatrix}$$

$$m_{H^\pm}^2 = M^2 + \frac{1}{2}\lambda_3 v^2$$

- Mass eigenstate for neutral scalar bosons

Orthogonal matrix R

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}, \qquad R^T \mathcal{M}^n R = \mathrm{diag}(m_{H_1}, m_{H_2}, m_{H_3})$$

125 GeV Higgs

- CPV rephasing invariants in the model $\quad \Phi_2 \to e^{i\theta}\Phi_2$

Potential: $\mathrm{Im}[\lambda_5^* \lambda_6^2], \ \mathrm{Im}[\lambda_5^* \lambda_7^2], \ \mathrm{Im}[\lambda_6^* \lambda_7]$

Yukawa: $\mathrm{Im}[\lambda_5 \rho_{tt}^2], \ \mathrm{Im}[\lambda_6 \rho_{tt}], \ \mathrm{Im}[\lambda_7 \rho_{tt}]$ (and other ρ_{ij} related invariants)

Minimal Scenario

The discovered 125GeV Higgs is SM-like

$$\kappa_Z \simeq 1 \quad \blacktriangleright \quad |\lambda_6| \ll 1$$
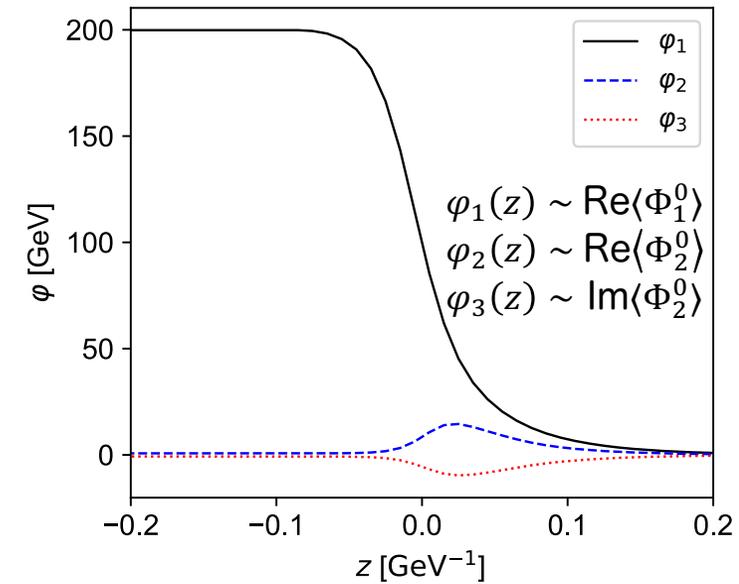
$\blacktriangleright \quad \mathrm{Im}[\lambda_5^* \lambda_7^2], \ \mathrm{Im}[\lambda_5 \rho_{tt}^2], \ \mathrm{Im}[\lambda_7 \rho_{tt}]$

<u>Top transport scenario</u>

$$\varphi_1(z) \sim \mathrm{Re}\langle \Phi_1^0 \rangle$$
$$\varphi_2(z) \sim \mathrm{Re}\langle \Phi_2^0 \rangle$$
$$\varphi_3(z) \sim \mathrm{Im}\langle \Phi_2^0 \rangle$$

$$m_t^2 \theta_t' \sim \frac{y_t |\rho_{tt}|}{2} \{ (\varphi_1 \varphi_2' - \varphi_2 \varphi_1') \sin(\arg[\rho_{tt}]) + (\varphi_3 \varphi_1' - \varphi_1 \varphi_3') \cos(\arg[\rho_{tt}]) \}$$

BAU evaluated by the semi-classical method (with WKB)

For sufficient BAU, $\mathrm{Im}[\lambda_7 \rho_{tt}]$ is necessary.

If $\lambda_6 \simeq \lambda_7 \simeq 0$, the tree potential approximately has Z_2 ($\Phi_2 \to -\Phi_2$). $\to \varphi_2, \varphi_3 \ll 1$

Neglect all irrelevant components to baryogenesis

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \rho_{tt} \end{pmatrix}$$
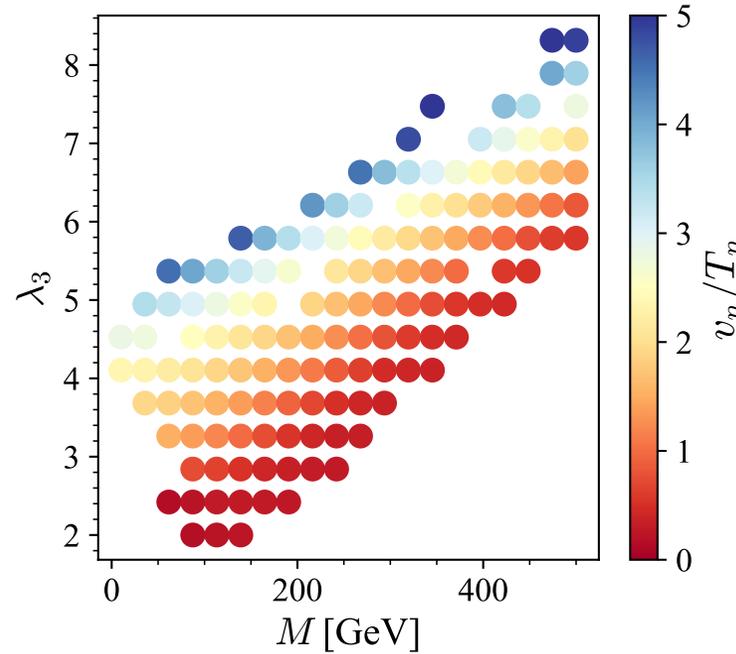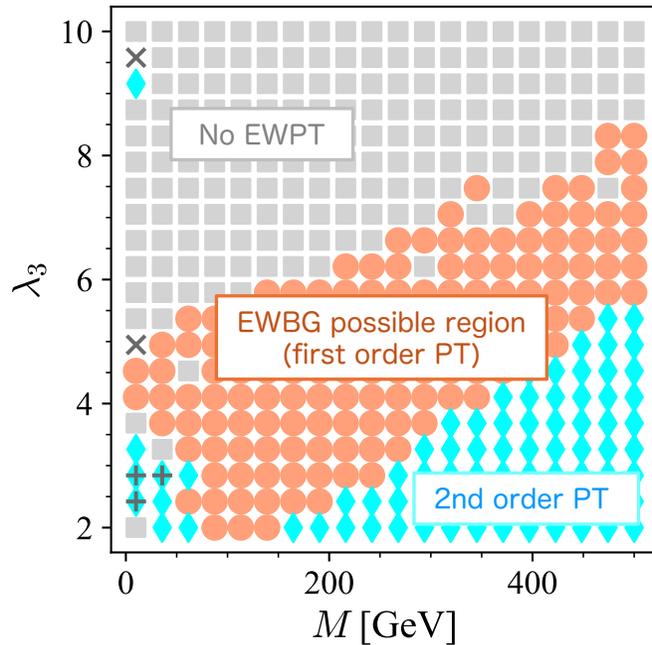
Minimal Scenario for EWBG

$\rho_{ij} = 0$ (except for ρ_{tt}) and $\lambda_4 = \lambda_5 = \lambda_6 = 0$ ($\lambda_4 = \lambda_5$ is for T parameter)

$\blacktriangleright \quad m_{H_2} = m_{H_3} = m_{H^\pm} \equiv m_\Phi$ One available CP phase: $\arg[\lambda_7 \rho_{tt}]$

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Electroweak phase transition
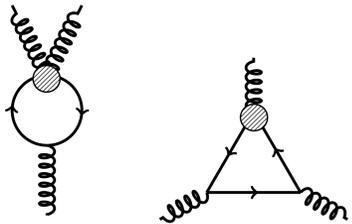
· Several fates of the vacuum

$$m_{H^\pm}^2 = M^2 + \frac{1}{2}\lambda_3 v^2$$

$$m_{H_2} = m_{H_3} = m_{H^\pm}$$

· For successful EWBG, at least,

   · O(1) large λ_3 coupling

   · Satisfying $v_n/T_n > 1$ are required.
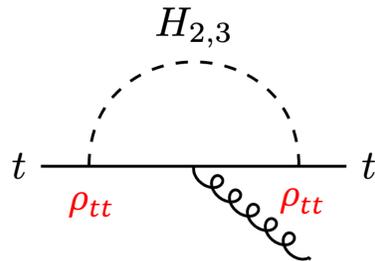
M. Endo, M. Aiko, S.K., Y. Mura, arXiv: JHEP 07 (2025) 236

EDMs in the minimal setup

・No Barr-Zee diagrams

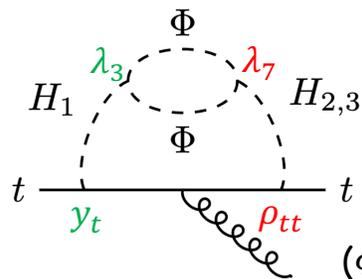・Top chromo EDM induces Weinberg op. and light fermion EDMs by RGE running.

Kamenik et al. (2012);
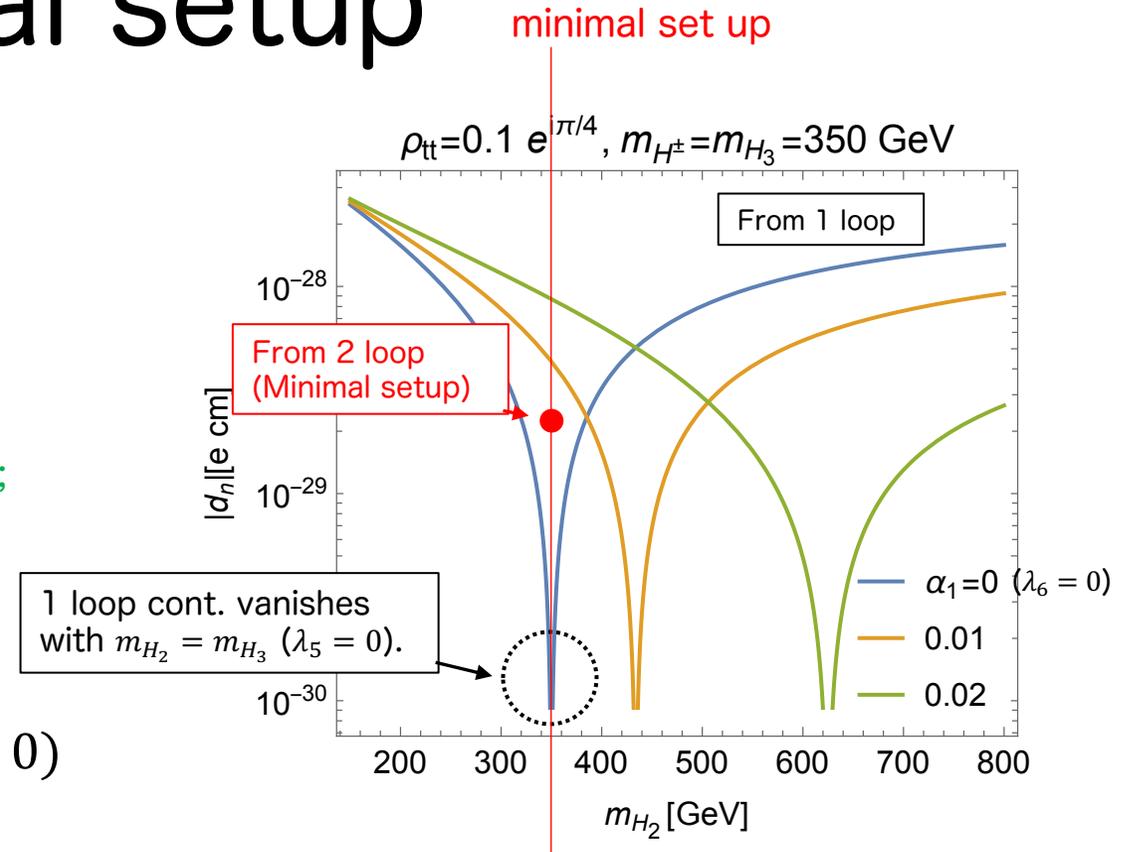Hisano, Tsumura and Yang (2012);
and more works

・At 1 loop level

$$\propto Im[\lambda_5 \rho_{tt}^2] \quad (= 0)$$

$H_{2,3}$

$t \quad \rho_{tt} \quad \rho_{tt} \quad t$

・With the minimal setup, 2 loop diagrams are leading.

Φ

$H_1 \quad \lambda_3 \quad \lambda_7 \quad H_{2,3}$

Φ

$t \quad y_t \quad \rho_{tt} \quad t$

$$\propto Im[\lambda_7 \rho_{tt}]$$

$(\Phi = H_2, H_3, H^{\pm})$

$\rho_{tt}=0.1\ e^{i\pi/4},\ m_{H^{\pm}}=m_{H_3}=350$ GeV

From 1 loop

From 2 loop
(Minimal setup)

1 loop cont. vanishes with $m_{H_2} = m_{H_3}$ ($\lambda_5 = 0$).

$|d_n|$[e cm]

10^{-28}

10^{-29}

10^{-30}

200 300 400 500 600 700 800
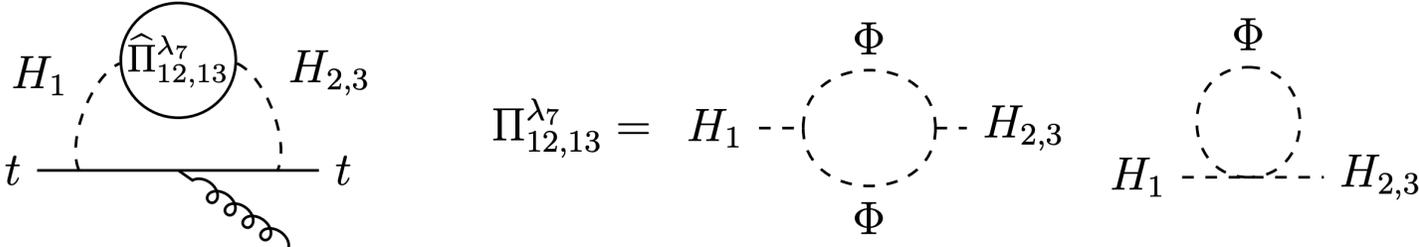
m_{H_2}[GeV]

α_1=0 ($\lambda_6 = 0$)
0.01
0.02

M. Aiko, M. Endo, S.K., Y. Mura,
JHEP 07 (2025) 236

At the red point,
$\lambda_7 = e^{i\pi/4}, -\mu_2^2 = 30^2$ GeV^2 are taken.

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Renormalization

- UV divergence in mixing-self-energy diagrams
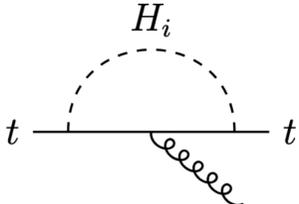

- Effective potential renormalization scheme

$$\left.\frac{\partial V}{\partial \varphi_i}\right|_{\varphi=v_{EW}} = 0, \quad \left.\frac{\partial^2 V}{\partial \varphi_i \partial \varphi_j}\right|_{\varphi=v_{EW}} = \mathcal{M}_{ij}$$

$$\Gamma_i^{(1)}(p^2 = 0) + \delta\Gamma_i^{(1)} = 0$$

$$\Gamma_{ij}^{(2)}(p^2 = 0) + \delta\Gamma_{ij}^{(2)} = 0$$

- Other renormalization schemes?

e.g.) $\overline{\text{MS}}$ scheme $\quad d_t^{\overline{MS}} = d_t^{EP} + \Delta d_t$ $\qquad$ · Scheme conversion $\quad \lambda_6^{\overline{MS}} = \lambda_6^{EP} + \Delta\lambda_6^{EP}$

$\lambda_6^{EP} = 0$ does not mean $\lambda_6^{\overline{MS}} = 0$. $\quad d_t^{\overline{MS}} = d_t^{EP} + \Delta d_t - \underline{\Delta d_t} + O(\hbar^3)$
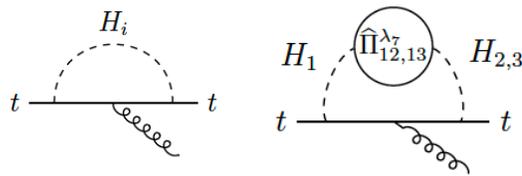
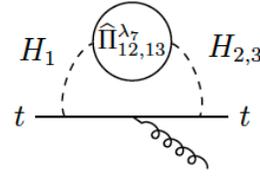from one-loop

22

Other scheme (MS bar)

$$\lambda_6^{\overline{\text{MS}}} = \lambda_6 - \frac{3}{16\pi^2}\lambda_3\lambda_7 \log\frac{\mu^2}{m_\Phi^2} + \cdots \bigg|_{\text{EP}}$$

$\lambda_6^{EP} = 0$ does not mean $\lambda_6^{\overline{MS}} = 0$.

$$\Pi_{12,13}^{\lambda_7} = \quad H_1 \mathrel{-\!\!-} \bigcirc \mathrel{-\!\!-} H_{2,3}$$

In the on-shell scheme, we also confirmed the similar relation

$$\tilde{d}_t^{(1),\overline{\text{MS}}} + \tilde{d}_t^{(2),\overline{\text{MS}}} = \tilde{d}_t^{(2)} + \mathcal{O}(\hbar^3)\bigg|_{\text{EP}}$$

MS bar   EP scheme

$$\tilde{d}_t^{(2),\overline{\text{MS}}} = \tilde{d}_t^{(2)} + \Delta\tilde{d}_t^{(2),\overline{\text{MS}}},$$

$$\Delta\tilde{d}_t^{(2),\overline{\text{MS}}} = \frac{\text{Im}[\lambda_7\rho_{tt}]}{\sqrt{2}}\frac{3\lambda_3 v}{(16\pi^2)^2}\frac{2m_t^2}{m_\Phi^2 - m_{H_1}^2}\left(C_{11}[\Phi,t,t] - C_{11}[H_1,t,t]\right)\log\frac{\mu^2}{m_\Phi^2}\bigg|_{\overline{\text{MS}}}$$

$$\tilde{d}_t^{(1),\overline{\text{MS}}} = \frac{\text{Im}[\lambda_6\rho_{tt}]}{\sqrt{2}}\frac{v}{16\pi^2}\frac{2m_t^2}{m_\Phi^2 - m_{H_1}^2}\left(C_{11}[\Phi,t,t] - C_{11}[H_1,t,t]\right)\bigg|_{\overline{\text{MS}}}$$

EDMs from top CEDM from $\mathrm{Im}[\lambda_7 \rho_{tt}]$

$$\mathcal{L}_{\mathrm{CPV}} = -\frac{1}{2} d_\psi \overline{\psi} \sigma_{\mu\nu} i\gamma^5 \psi F^{\mu\nu} - \frac{1}{2} g_S \tilde{d}_q \bar{q} \sigma_{\mu\nu} i\gamma^5 T^a q G^{a\mu\nu} + \frac{1}{3} w f_{abc} G^a_{\mu\nu} \tilde{G}^{b\nu\rho} G^{c\mu}_\rho,$$

Induced Weinberg operator and EDMs

$$\delta w^{(t)}/g_S = \frac{g_S^2}{32\pi^2} \frac{\tilde{d}_t}{m_t}$$

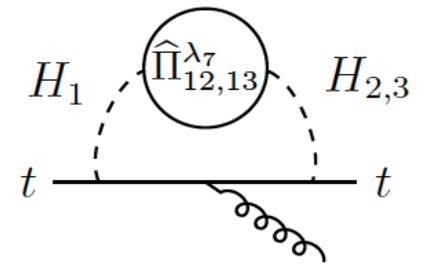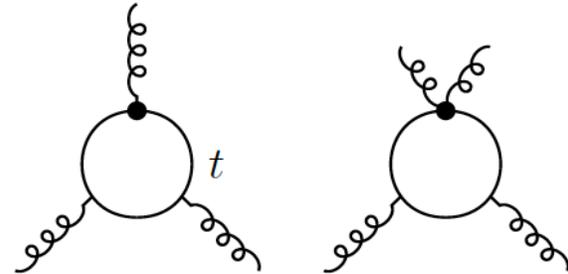$\Rightarrow$

$$d_u = 1.8 \times 10^{-9} \, e \, \tilde{d}_t, \quad d_d = -2.0 \times 10^{-9} \, e \, \tilde{d}_t,$$
$$\tilde{d}_u = -8.0 \times 10^{-9} \, \tilde{d}_t, \quad \tilde{d}_d = -1.7 \times 10^{-8} \, \tilde{d}_t,$$
$$w = -1.4 \times 10^{-5} \, \mathrm{GeV}^{-1} \, \tilde{d}_t,$$

RGE
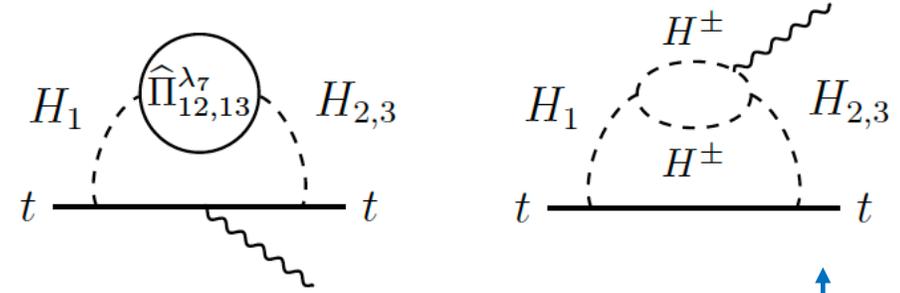
hadronization scale $\mu_H = 2 \ \mathrm{GeV}$

QCD sum rule

$$d_n = 0.73 d_d - 0.18 d_u + e(0.20\tilde{d}_d + 0.10\tilde{d}_u) + 23 \times 10^{-3} \, \mathrm{GeV} \, ew,$$
$$d_p = 0.73 d_u - 0.18 d_d - e(0.40\tilde{d}_u + 0.049\tilde{d}_d) - 33 \times 10^{-3} \, \mathrm{GeV} \, ew,$$

eEDM from the top EDM from $\text{Im}[\lambda_7 \rho_{tt}]$

Effective operators below the scale Λ (= m$_\Phi$)

$$\mathcal{L}_{\text{eff}} = -\frac{1}{\Lambda^2}\left(\frac{g'}{\sqrt{2}}C_{tB}\overline{Q_L}\sigma^{\mu\nu}t_R\tilde{\Phi}_1 B_{\mu\nu} + \frac{g}{\sqrt{2}}C_{tW}\overline{Q_L}\sigma^{\mu\nu}t_R\tau^a\tilde{\Phi}_1 W^a_{\mu\nu} + \text{h.c.}\right)$$

$$\Lambda = m\Phi$$

$$d_t^{B\mu} = \frac{g_1 v}{\Lambda^2}\text{Im}[C_{tB}], \quad d_t^{W^3_\mu} = \frac{g_2 v}{\Lambda^2}\text{Im}[C_{tW}]$$

After RGE flow, by integrating out t, W, and Z at the scale μ, eEDM is obtained

$$d_e = -\frac{e}{2v}\left(\frac{v}{\Lambda}\right)^2\left(\log\frac{\Lambda}{\mu}\right)^2\left[(A_e - D_e)\text{Im}[C_{tB}] + (B_e - E_e)\text{Im}[C_{tW}]\right]$$

$$\mu = mt, mh, mZ$$

$$A_e = \mathcal{Y}_e(15g_1^2 + 3g_2^2), \quad B_e = 10\mathcal{Y}_e g_2^2,$$

$$D_e = -6\mathcal{Y}_e g_1^2, \qquad E_e = -5\mathcal{Y}_e(g_1^2 + g_2^2), \qquad \mathcal{Y}_e = N_c y_e y_t/(4\pi)^4$$

Correlation between EDM and BAU in the minimal set up

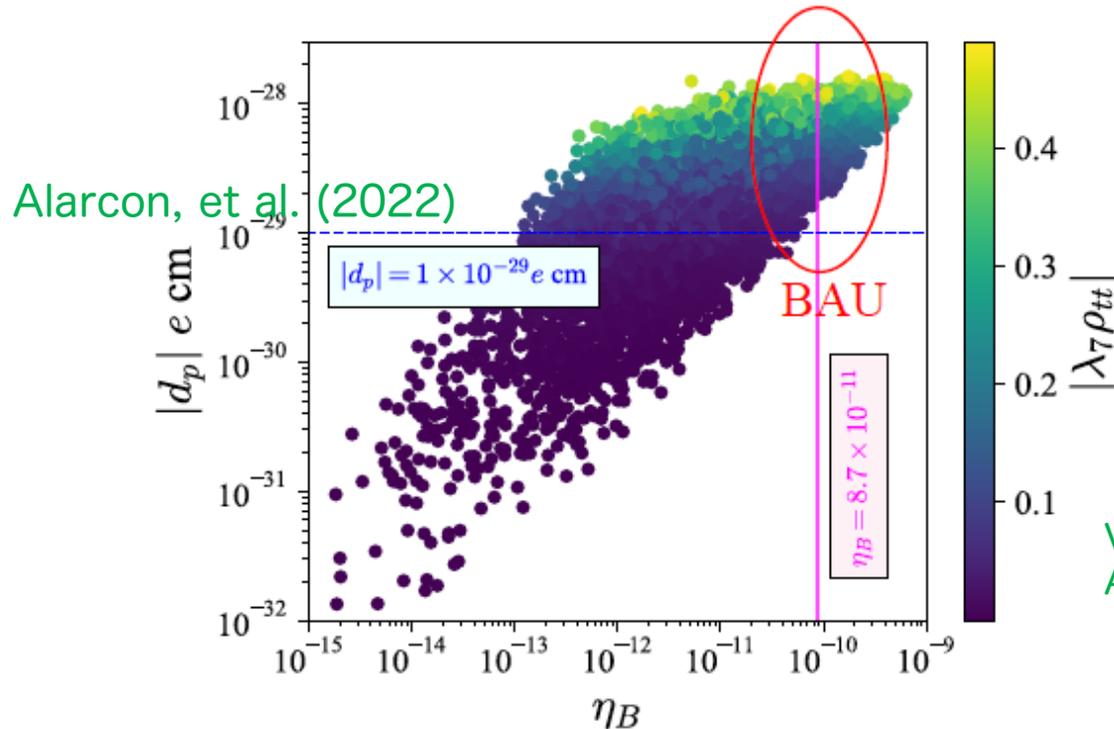M. Endo, M. Aiko, S.K., Y. Mura, JHEP 07 (2025) 236

<u>Parameter scan</u>

$$m_\Phi = [200,500] \text{ GeV}, \mu_2^2 = \left[-m_\Phi^2, 0\right], |\rho_{tt}| = [0,0.5]$$
$$|\lambda_7| = [0,1], \lambda_2 = [0,1], \arg[\lambda_7 \rho_{tt}] = -\pi/2, v_w = \left[0.1, 1/\sqrt{3}\right]$$
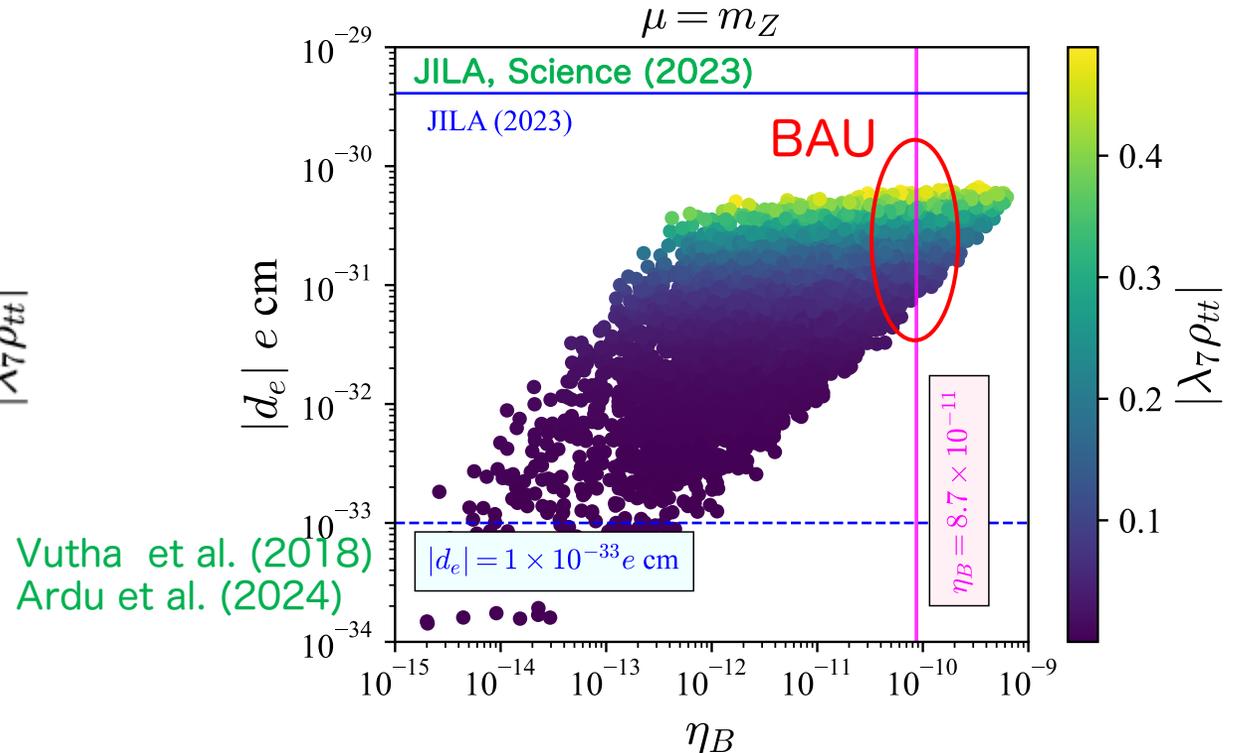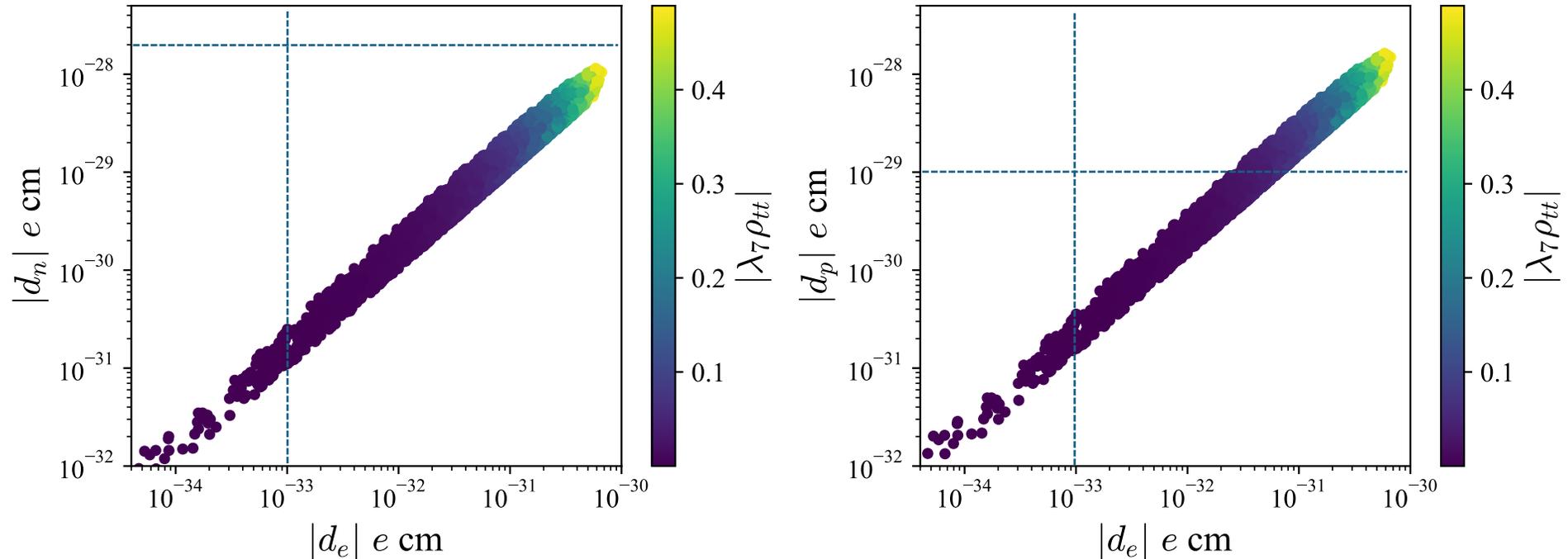
Proton EDM

Electron EDM

Viable, and testable at future EDM experiments

Correlation among EDMs

· Strong correlation among EDMs (dashed: future prospect bounds)

· All of CPV quantities are correlated by $\mathrm{Im}[\lambda_7 \rho_{tt}]$.
  → Characteristic prediction of our scenario

· Null results of EDM in the future experiment
  → We need to start to consider scenario with a cancellation mechanism.

Phenomenology

$$\mu^{\gamma\gamma}_{\mathrm{exp}} = 1.04^{+0.10}_{-0.09}$$

1st OPT
Deviation in the di-photon decay and in the hhh coupling,
Higgs to Higgs decays,
gravitational waves, primordial black holes, ⋯

$$\mu^{\gamma\gamma} = (\sigma \mathrm{Br}_{\gamma\gamma})_{\mathrm{2HDM}}/(\sigma \mathrm{Br}_{\gamma\gamma})_{\mathrm{SM}} \simeq \Gamma^{\gamma\gamma}_{\mathrm{2HDM}}/\Gamma^{\gamma\gamma}_{\mathrm{SM}} = 0.9$$

$$m_{H^\pm} = 500 \text{ GeV}$$

$$M = 0$$

CPV
eEDM, nEDM, pEDM,
Colliders (gg → H$_2$/H$_3$ → tt, H⁺→W⁻Z, ⋯)
Flavor physics (B decays, K decays, etc)

Shape of the 2HDM
Deviation pattern in decays of h(125) via the quantum effect
Detect heavy Higgs bosons   H$_{2,3}$ → tt, H$^\pm$ → tb

Summary

For BAU, additional CP violation is necessary, strongly 1st OPT is realized

- In the SM, insufficient CP violation,   Smooth Cross Over
- In 2HDM,   additional CP violation can be introduced,   and 1st OPT is realized
  Rich predictions, but severely constrained by eEDM data (B-Z type)

We have considered a Minimal scenario for EWBG in general 2HDM

- take ρ_{ij} = 0 except for ρ_{tt} to avoid constraints from B-Z type eEDM.
- $\mathrm{Im}[\lambda_7 \rho_{tt}]$ is the most important rephasing invariant for EWBG.
- In the minimal setup, only $\mathrm{Im}[\lambda_7 \rho_{tt}]$ causes EDM and BAU.

Two loop EDMs and BAU with the minimal setup   No EDM cancellation necessary

- We evaluated leading 2 loop top EDMs in the minimal setup.
- Correlation between EDMs (n, p, e) and BAU.
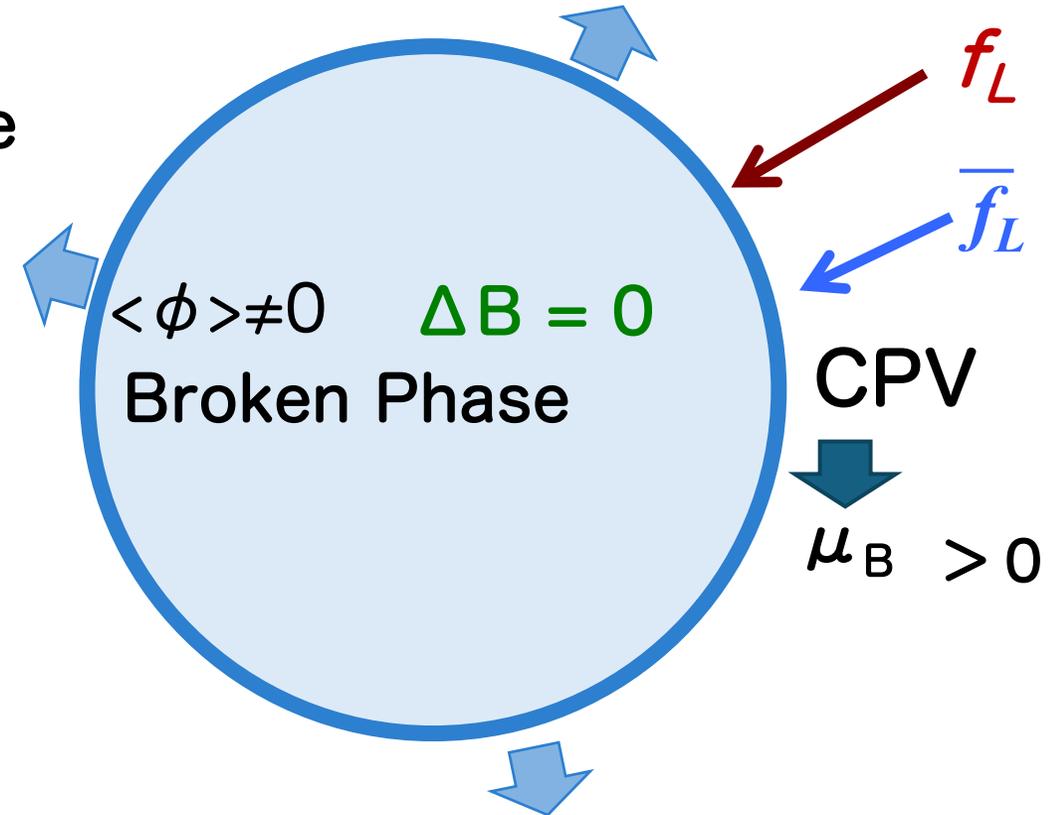- Our scenario is viable under current bounds, and would be testable in future.

Thank you

U. Osaka
Dr. Wani

Back up slides

EW Baryogenesis

Symmetric Phase
$<\phi>=0$ $\Delta B \neq 0$

- **1st OPT** $\Rightarrow$ bubbles of the broken phase
- **CPV** $\Rightarrow$ charge flow around the wall

f_L

$\overline{f_L}$

$<\phi>\neq 0$ $\Delta B = 0$
Broken Phase

CPV

$\mu_B > 0$

Dirac equation solved by WKB method

Cline, Joyce, Kainulainen 2000

Boltzmann equation

$$(\partial_t + \boldsymbol{v}_g \cdot \partial_{\boldsymbol{x}} + \boldsymbol{F} \cdot \partial_{\boldsymbol{p}}) f_i = C[f_i, f_j, \ldots]$$

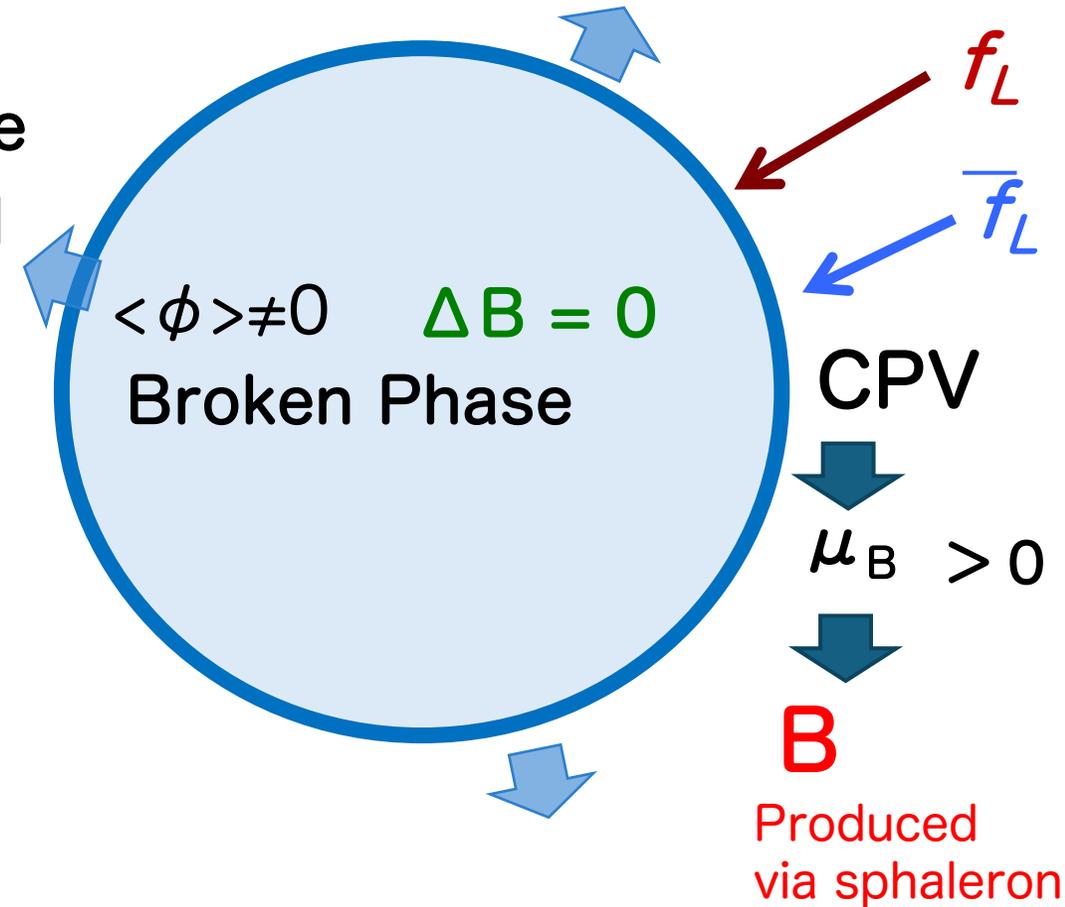Different sign between particle and anti-particle $\Rightarrow$ Transport eq for μ_i

$$f_i = \frac{1}{e^{\beta[\gamma_w(E_i + v_w p_z) - \mu_i]} \pm 1} + \delta f_i$$
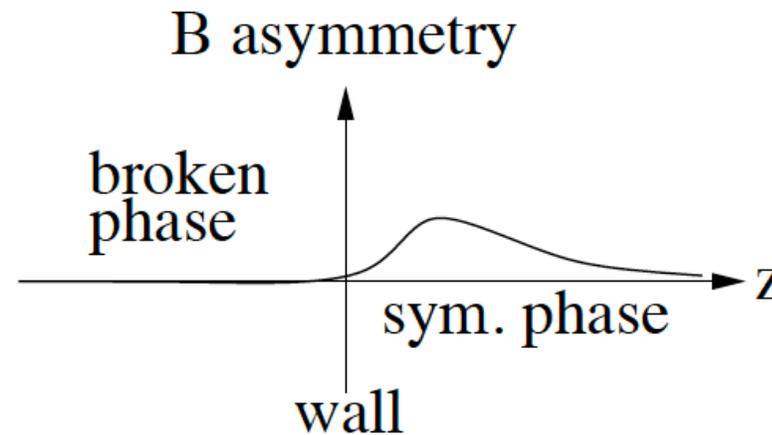
32

EW Baryogenesis

- **1st OPT** $\Rightarrow$ bubbles of the broken phase
- **CPV** $\Rightarrow$ charge flow around the wall
- In symmetric phase, B is generated via sphaleron

Symmetric Phase
$<\phi>=0$ $\Delta B \neq 0$

f_L

$\overline{f_L}$

$<\phi>\neq 0$ $\Delta B = 0$
Broken Phase

CPV

$\mu_B > 0$

B
Produced via sphaleron

Chemical potential

$$\dot{n}_B \simeq -\frac{\mu_B \Gamma_{\text{sph}}}{T}$$

B asymmetry

broken phase

sym. phase

z

wall

EW Baryogenesis

- 1st OPT ⟹ bubbles of the broken phase
- CPV ⟹ charge flow around the wall
- In symmetric phase B is generated via sphaleron
- In broken phase, produced B number is frozen, if sphaleron decouples
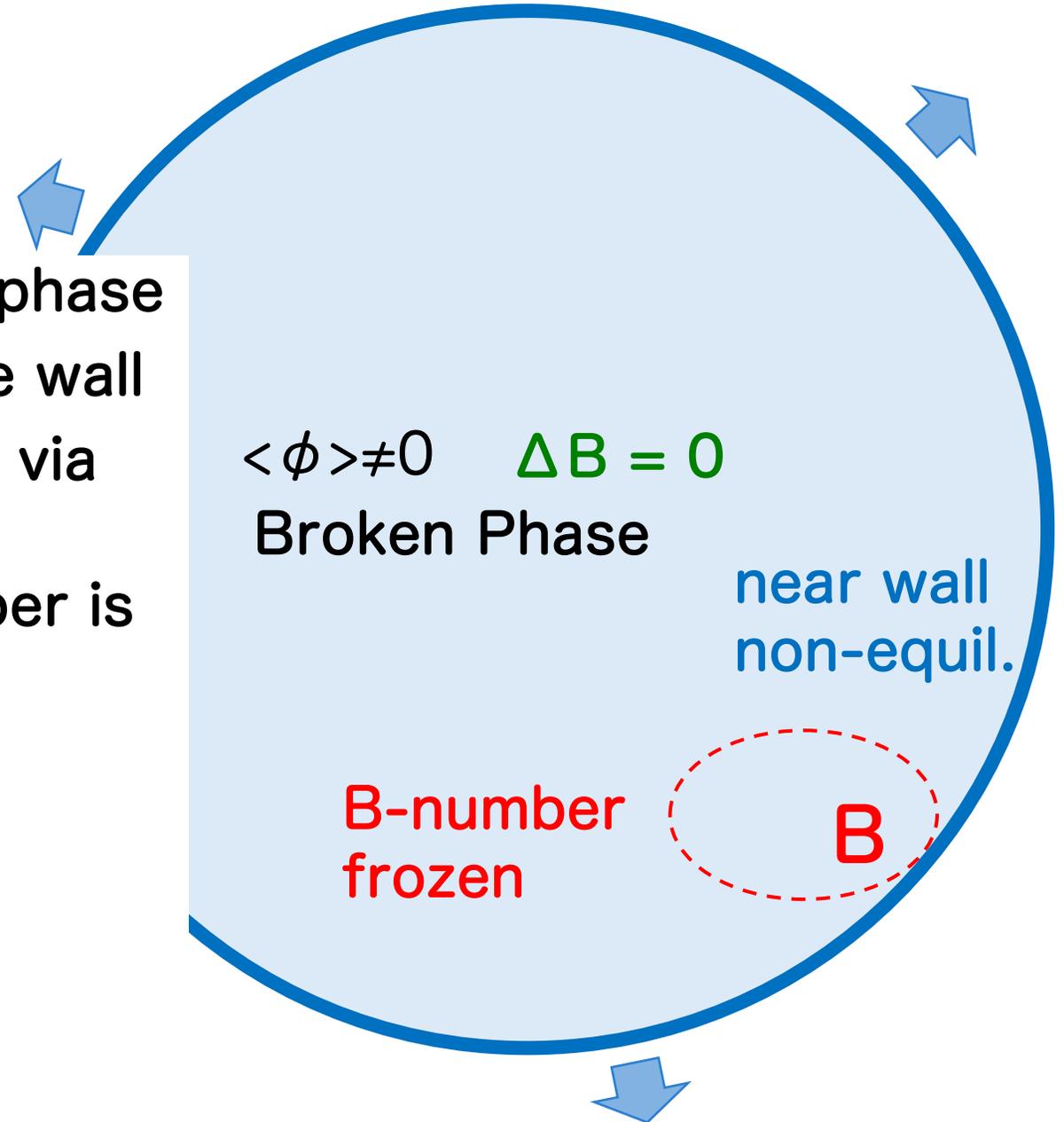
Sphaleron decoupling

$$\Gamma_{sph} < H$$

⟹

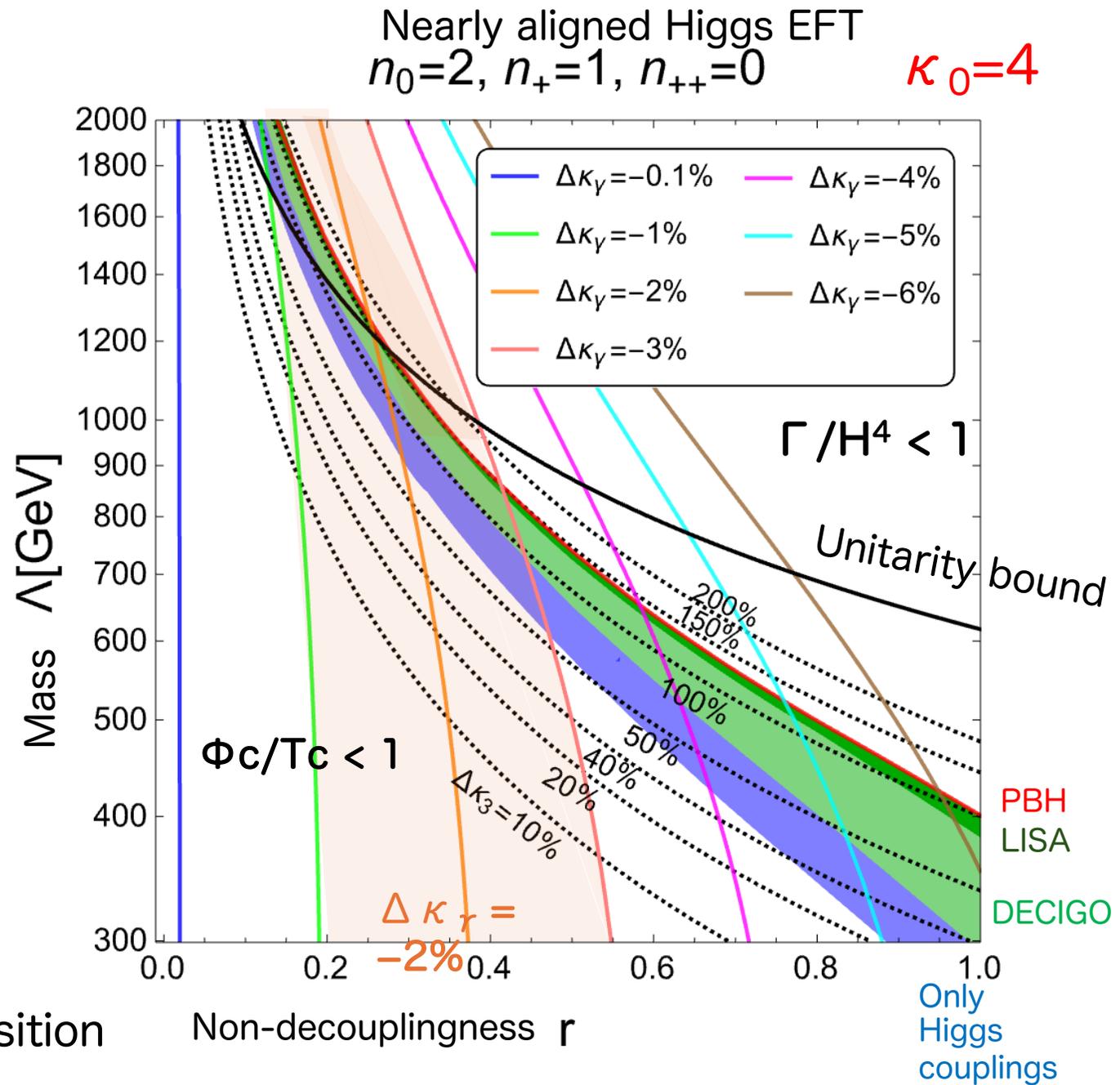$$\frac{\varphi_c}{T_c} \gtrsim 1$$

$$\eta \sim 10^{-10}$$

BAU

$\langle \phi \rangle \neq 0$ $\Delta B = 0$
Broken Phase

near wall non-equil.

B-number frozen

B

Test of 1ˢᵗ OPT

Colored region satisfies two conditions

- Sphaleron decoupling $\quad \dfrac{\varphi_c}{T_c} \gtrsim 1$

- Bubble nucleation completion $\quad \left.\dfrac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1$

- PBH (RomanTelescope $f_{PBH} > 10^{-4}$)
- GW (LISA detectable)
- GW (DECIGO detectable)
- Only Higgs couplings can test 1ˢᵗ OPT
  ($\Delta\kappa_3,\ \Delta\kappa_\gamma,\ \cdots$)

We can examine aspect of EW phase transition by using various future experiments.

Nearly aligned Higgs EFT
$n_0=2,\ n_+=1,\ n_{++}=0$ $\qquad \kappa_0=4$

Legend:
- $\Delta\kappa_\gamma=-0.1\%$
- $\Delta\kappa_\gamma=-1\%$
- $\Delta\kappa_\gamma=-2\%$
- $\Delta\kappa_\gamma=-3\%$
- $\Delta\kappa_\gamma=-4\%$
- $\Delta\kappa_\gamma=-5\%$
- $\Delta\kappa_\gamma=-6\%$

$\Gamma/H^4 < 1$

Unitarity bound

$\Phi_c/T_c < 1$

$\Delta\kappa_3 = 10\%$, 20%, 40%, 50%, 100%, 150%, 200%

$\Delta\kappa_\gamma = -2\%$

Mass Λ[GeV] vs Non-decouplingness r

PBH, LISA, DECIGO, Only Higgs couplings

R. Florentino, S.K., M. Tanaka (2024) 35

1st OPT by nondecoupling quantum effect

Effective Potential at finite T (HTE)

$$V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

$$\frac{\varphi_c}{T_c} \gtrsim 1$$

SM: The condition cannot be satisfied

Non-minimal Higgs can satisfy it due to non-decoupling quantum effects

$$\frac{\phi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{ 6m_W^2 + 3m_Z^3 + \sum_\Phi n_\Phi m_\Phi^3 \left(1 - \frac{M^2}{m_\Phi^2}\right)^{3/2} \right\} > 1 \quad \text{(when } M \ll m_\Phi\text{)}$$

Quantum effects of Φ (= H, A, H+, ···)

Prediction: Large deviation in the hhh coupling

$$\lambda_{hhh} \simeq \frac{3m_h^2}{v}\left\{ 1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \sum_\Phi n_\Phi \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3 \right\} > \lambda_{hhh}^{SM}$$

SK, Okada, Senaha, Yuan, 04

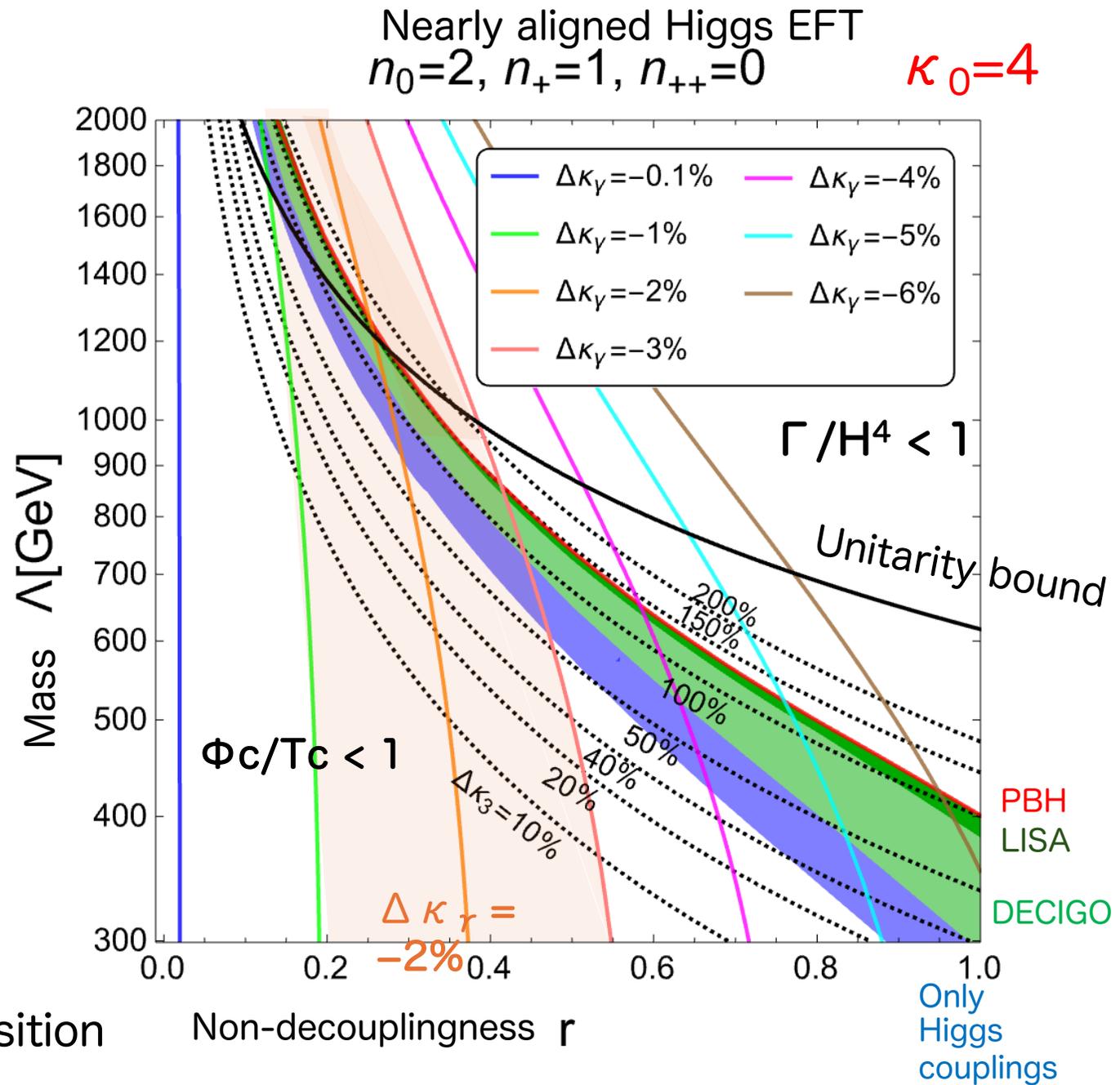Grojean, Servant, Wells, 2005
SK, Y. Okada, E. Senaha, 2005

Test of 1ˢᵗ OPT

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Bubble nucleation completion $\left.\dfrac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1$

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- Only Higgs couplings can test 1ˢᵗ OPT
  ($\Delta\kappa_3$, $\Delta\kappa_\gamma$, $\cdots$)

We can examine aspect of EW phase transition by using various future experiments.

Nearly aligned Higgs EFT
$n_0=2$, $n_+=1$, $n_{++}=0$ $\kappa_0=4$

$\Delta\kappa_\gamma=-0.1\%$ $\Delta\kappa_\gamma=-4\%$
$\Delta\kappa_\gamma=-1\%$ $\Delta\kappa_\gamma=-5\%$
$\Delta\kappa_\gamma=-2\%$ $\Delta\kappa_\gamma=-6\%$
$\Delta\kappa_\gamma=-3\%$

$\Gamma/H^4 < 1$

Unitarity bound

Mass Λ[GeV]

$\Phi c/Tc < 1$

200%
150%
100%
50%
$\Delta\kappa_3=10\%$ 20%   40%

PBH
LISA
DECIGO

$\Delta\kappa_\gamma = -2\%$

Non-decouplingness r

Only Higgs couplings

R. Florentino, S.K., M. Tanaka (2024)

Test of CPV

cEDM

EDM experiments
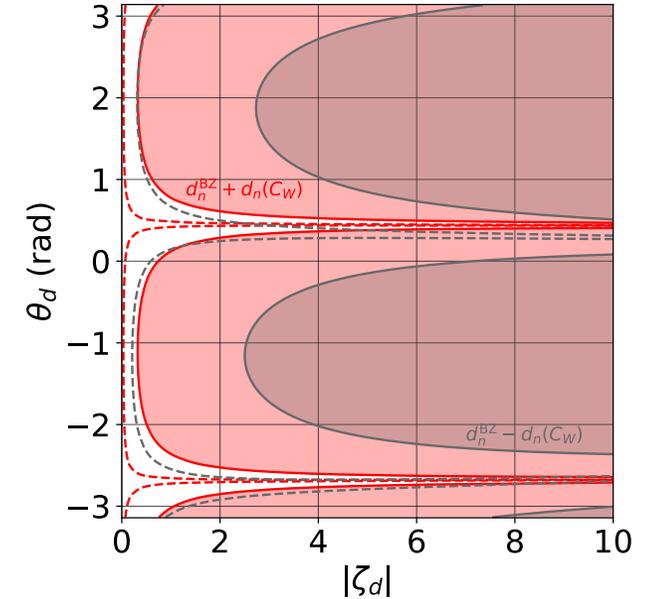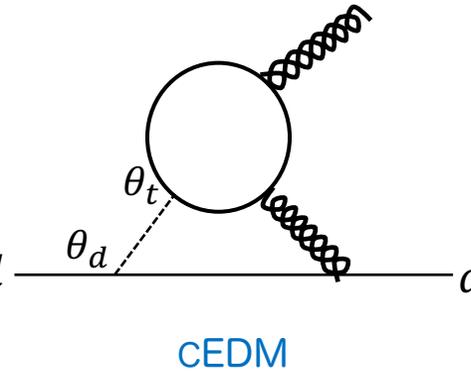
eEDM $|d_e| <$ 4.3 x 10^{-30} e cm

nEDM $|d_n| < 1.8 \times 10^{-26} e$cm

Future 1,2 order improvent can test our scenario of aligned 2HDM

Various flavor experiments

CPV from various mesons

B （Belle II）, K （KOTO）, ⋯ etc

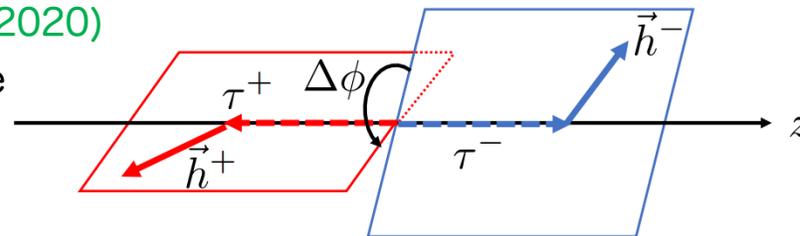Can discriminate various scenarios of charge transportation tt, tc, ⋯
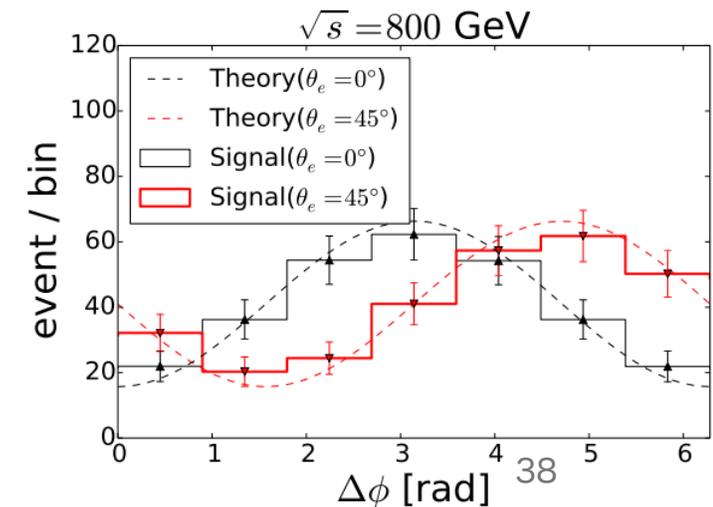
Future collider experiments
（Heavy Higgs decays）

Azimuth angle dependence
in $H_{2,3} \to \tau^+\tau^- \to X^+\bar{\nu}X^-\nu$

ILC800GeV
L=3 ab^{-1}

Decay of
$H_{2,3} \to \tau\tau$

$\sqrt{s} = 800$ GeV

The CPV in this scenario can be tested

Test of extended Higgs models itself

New physical degree of freedom in extended Higgs models

H_2, H_3, H^+, H^-, ...
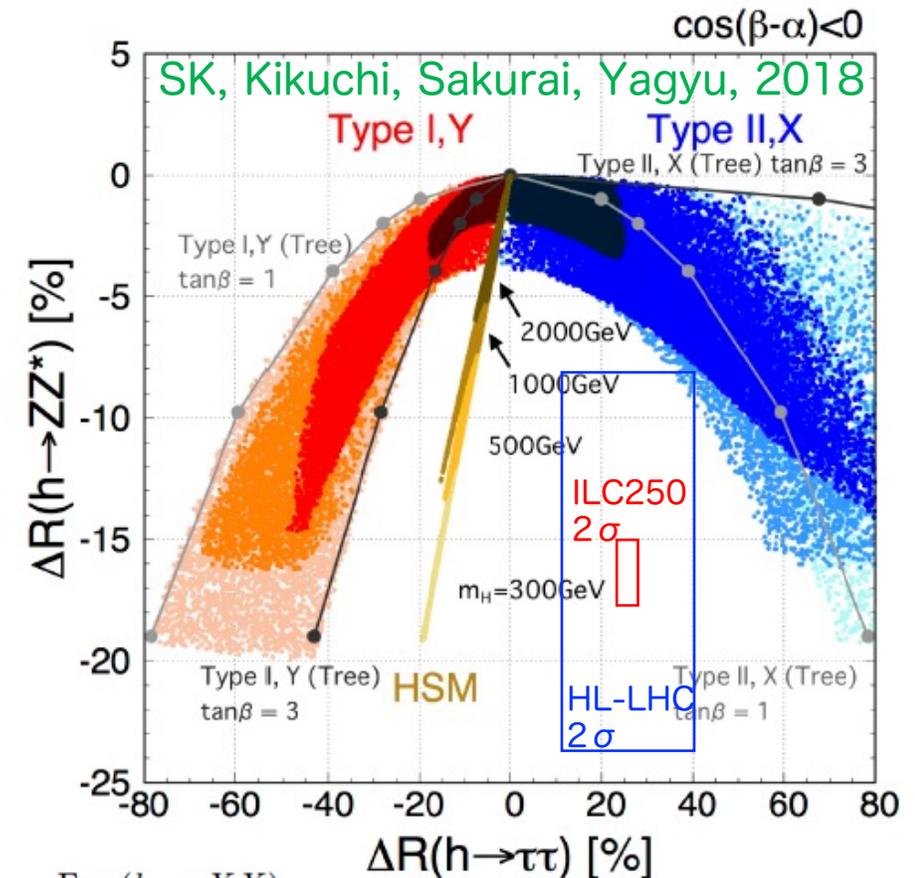
- Direct searches at HL-LHC

$H_{2,3}^0 \to \tau\tau$, $H^\pm \to tb$, ...

- Flavor experiments

$B \to X_s \gamma$, $B_s \to \mu\mu$, ...

- Search of deviations from the SM

We need Higgs factories

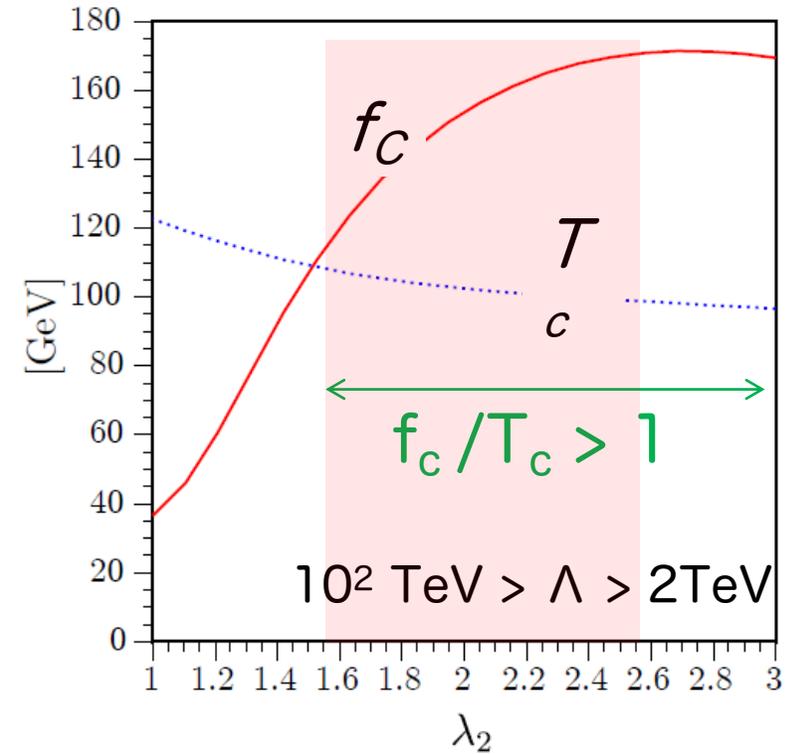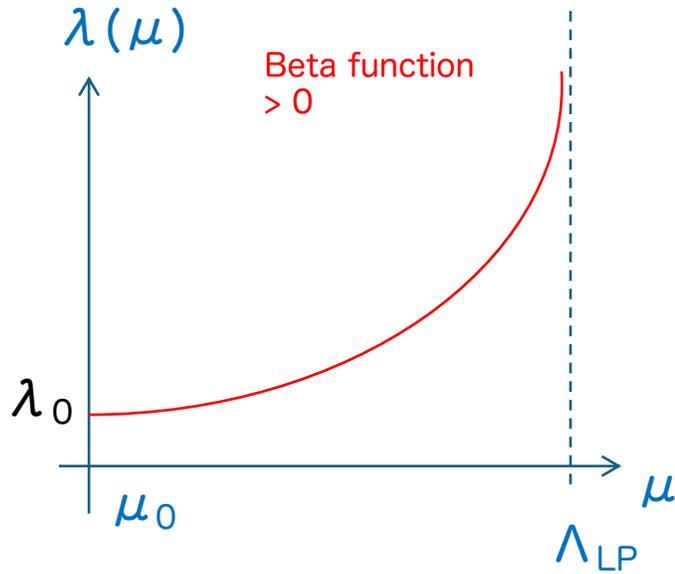$$\Delta R(h \to XX) = \frac{\Gamma_{NP}(h \to XX)}{\Gamma_{SM}(h \to XX)} - 1$$

Landau pole and above

1st OPT → Landau pole

$$\frac{\varphi_c}{T_c} > 1 \Leftrightarrow \Lambda_{LP} = \mathcal{O}(10)\,\text{TeV}$$

$\lambda(\mu)$

Beta function > 0

λ_0

μ_0

Λ_{LP}

μ

f_C

T_c

$f_c / T_c > 1$

10^2 TeV > Λ > 2TeV

What is above ?

Higgs interaction
→ SU(N) gauge interaction

$$H_{ij} = T_i T_j$$

Higgs coupling

New gauge coupling

UV thepry

Asymmptotic free SU(2)$_H$ Theory

Higgs as "Meson"

T_i Fundamental Rep.
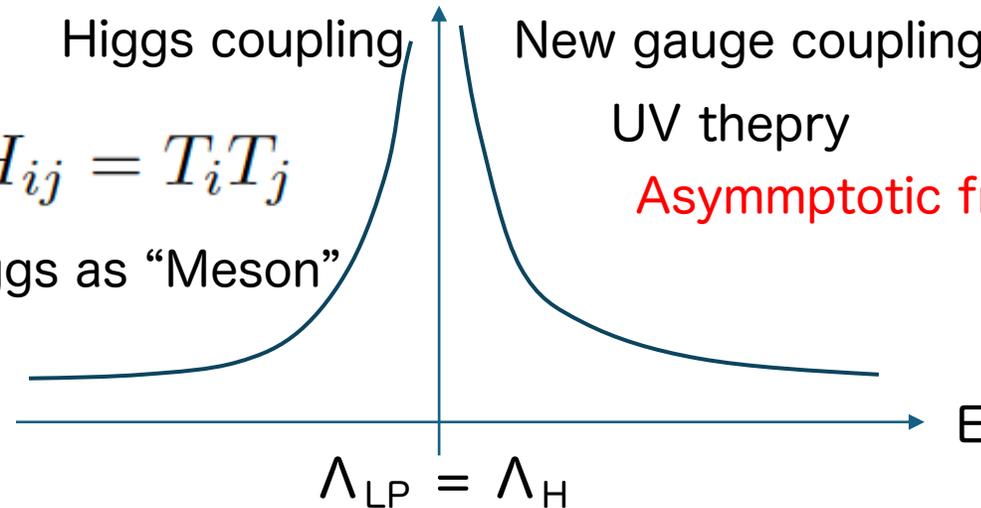
Harnik, Kribs, Larson, Murayama (2004)

SK, T. Shindou, T. Yamada (2012)

SK, T. Shindou, Y. Muar (2025)

$\Lambda_{LP} = \Lambda_H$

E

40