Extended Higgs models, Electroweak Baryogenesis and the UV picture

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U. Osaka Dr. Wani (mascot character)

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This talk

- Introduction
- Extended Higgs and BSM phenomena
- Scenarios EW Baryogenesis in 2HDM with/without EDM cancellation
- A UV picture of extended Higgs models
- Summary

Collaborators
Masashi Aiko (Miyakonojo), Motoi Endo (KEK), Kazuki Enomoto (NTU),
Yushi Mura (KEK), Kodai Sakurai(Tsuruoka), Tetsuo Shindou (Kogakuin),
Masanori Tanaka (Peking), Sora Taniguchi (Osaka), Kei Yagyu (TUS), ….

Current Situation

Higgs Discovery 2012

Mass 125 GeV Spin・Parity

Good agreement with SM prediction

No BSM evidence found up to now

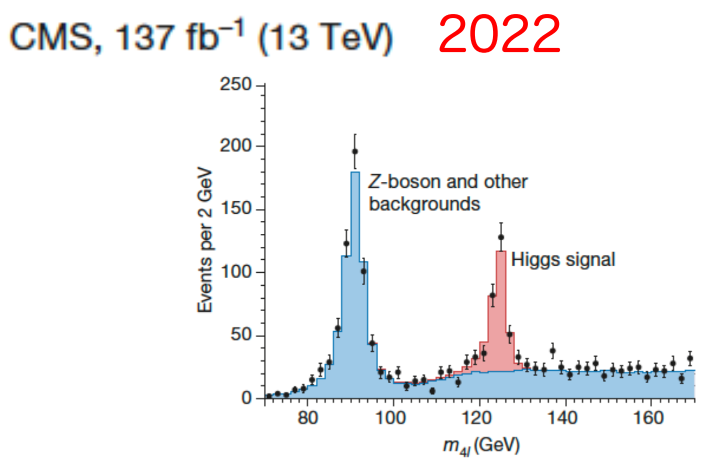
But big questions → New physics

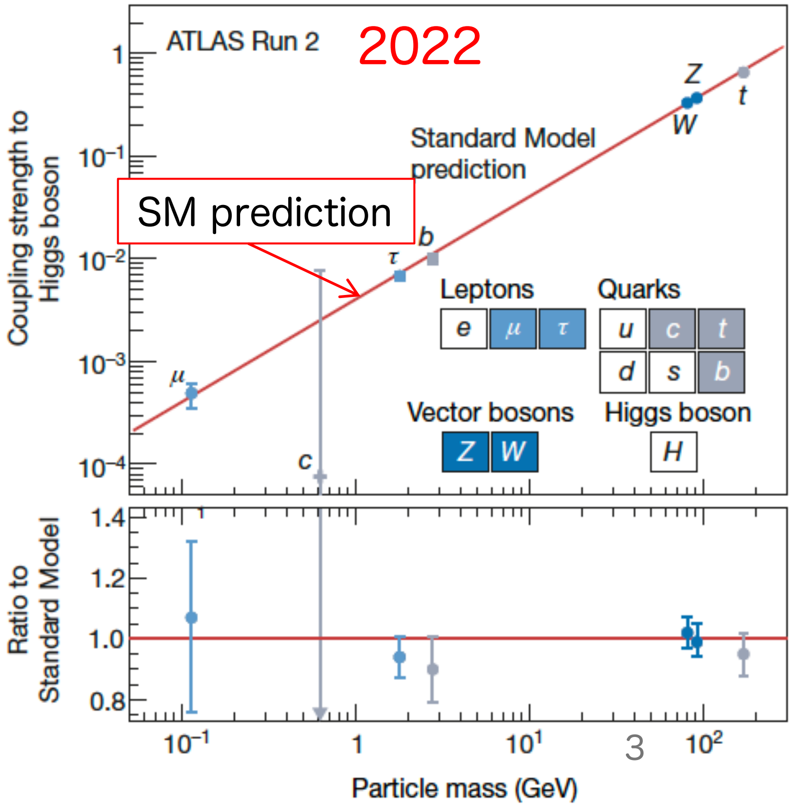
<u>Where is new physics?</u>

Low scale?

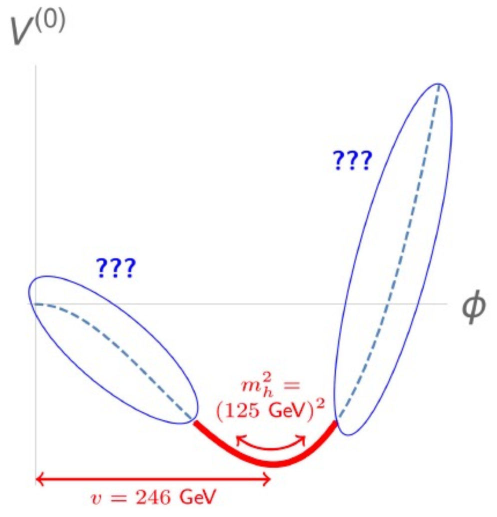
TeV Scale?

High Scale?





Higgs: window to new physics



Braathen

Higgs sector remains unknown

Multi-plet Structure (# of fields, symmetry, couplings, ⋯)
Higgs Potential (dynamics of EWSB, EWPT, ⋯)
Yukawa Structure (flavor, CPV, ⋯)
Elementary or Composite? Hierarchy?

SM Higgs sector: no principle

Extension of the Higgs sector
⇒ BSM phenomena may be explained

Tiny Neutrino mass
Dark Matter
Baryon Asymmetry

TeV scale: testable at current and future experiments

Baryogenesis and Higgs

Kuzmin, Ruvakov, Shaposhnikov (1985)

Sakharov Condition in EW baryogenesis

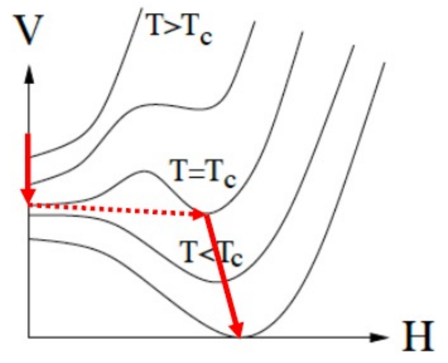
1) B non-conservation ➡ Sphaleron transition at high T

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

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

SM cannot satisfy the condition

Extended Higgs sectors
new sources of CPV and mechanisms of 1st OPT



Studied in 2HDMs, SM+Singlets, Triplets, 2HDM+Singlets, …

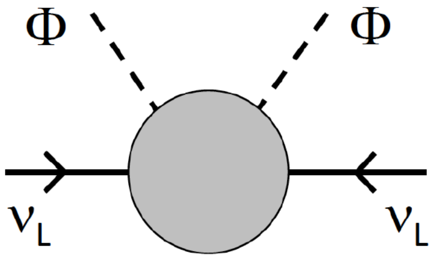
Rich phenomenology: Testable by experiments (colliders, EDM, flavor, GW, …)

Neutrino mass and Higgs

Neutrino Oscillation → Tiny mass (< eV)

Majorana mass

$$\boxed{\mathcal{L} = \frac{c}{\Lambda}(\phi\overline{\nu_L^c})(\nu_L\phi)}$$

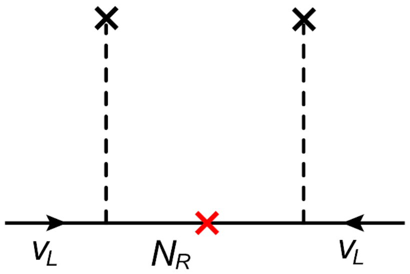


Seesaw Mechanism

$$m_\nu^{ij} = y_i y_j \frac{\langle\phi\rangle^2}{M_R} \leftarrow$$

Tiny mass

Large mass of Right-handed Neutrinos



Seesaw

Mediated by RH neutirnos N_R

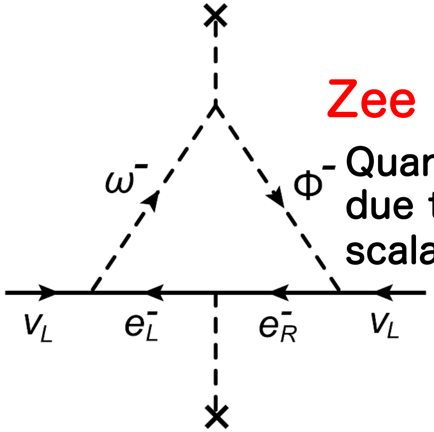
Alternative Scenario by quantum effects

$$m_\nu^{ij} = c_{ij}\left(\frac{1}{16\pi^2}\right)^N \frac{\langle\phi\rangle^2}{M_{\phi^+}}$$

Tiny mass

Quantum suppression

Mass around TeV scale



Zee model

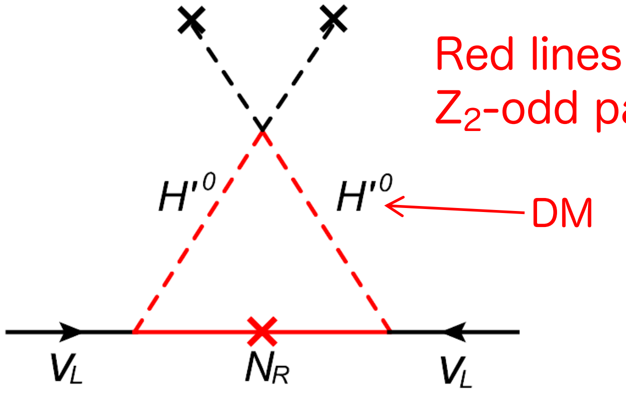
Quantum effect due to additional scalar fields

Physics of specific extended Higgs sectors

Models of neutrino mass with DM

Introducing a discrete Z_2

- Stability of new particle (DM)
- Loop induced masses



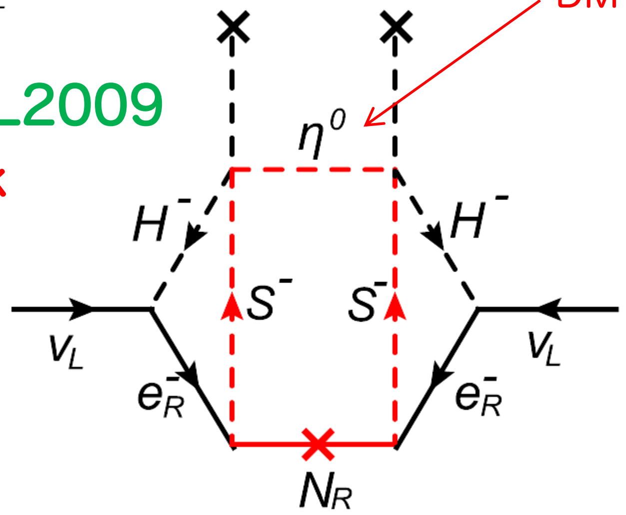
<u>Tao-Ma model</u> Tao 1996, Ma, 2006

SM+ H' + N_R
1-loop induced ν-mass
Dark matter candidate [H']

<u>Model with 3-loop induced mass</u> Aoki, SK, Seto, PRL2009
Sora Taniguchi's Talk

2HDM + η^0 + S^+ + N_R
ν-masses are 3-loop induced
DM candidate [η^0]
EW Baryogenesis possible (CPV, 1stOPT)

3 Problems can be explained by the TeV scale physics



Extended Higgs Zoo

SU(2) doublet extensions

Two Higgs doublet model (2HDM)

Inert doublet model (IDM)

Lee, PRD (1973); Deshpande and Ma, PRD (1978)

Tao-Ma model (w/ RHNs)

Tao, PRD (1996); Ma, PRD (2006)

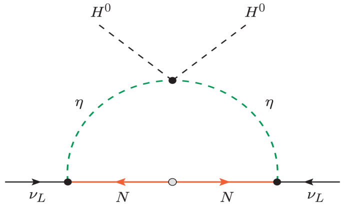


Fig from Sánchez et al. JHEP (2023)

w/ singlet scalars

Zee model Zee, PLB (1980)

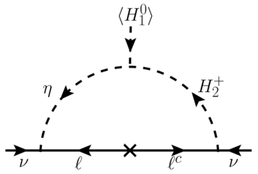
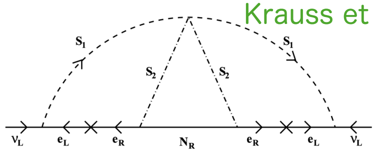


Fig. from Heeck and Thapa, PLB (2023)

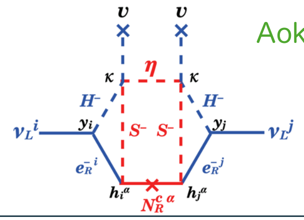
Krauss-Nasri-Trodden (KNT) model

Krauss et al. PRD (2003)



Aoki-Kanemura-Seto (AKS) model

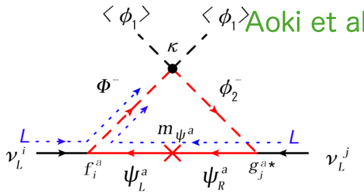
Aoki et al. PRL (2009)



w/ doubly charged scalars

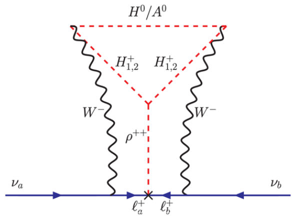
Aoki-Kanemura-Yagyu (AKY) model

Aoki et al. PLB (2011)



Gustafsson-No-Revera (GNR) model

Gustafsson et al. PRL (2013)



w/ triplet scalars

Triplet model (type II seesaw)

Georgi-Machacek model

Georgi and Machacek, NPB (1985)
Chanowitz and Golden, PLB (1985)

w/ combo

N2HDM

Chen, Freid, and Sher, PRD (2014)
Muhlleitner et al., JHEP (2017)

There are many other models with extended Higgs sectors

Slide from Yushi Mura

Extended Higgs sectors

- Variety of extended Higgs models were introduced for many phenomenological purposes

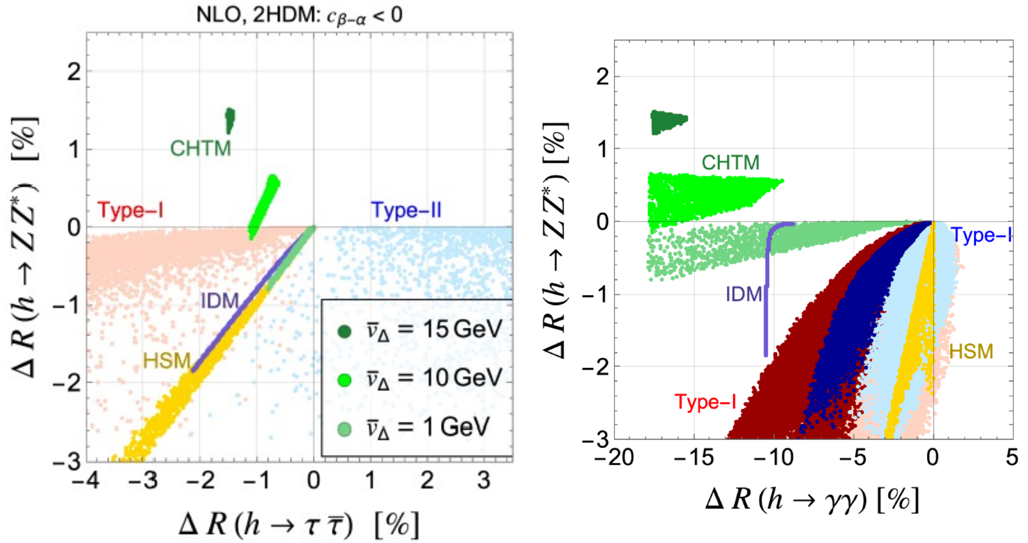
  2HDM, singlets, triplets, their mixtures, …

  Multiplet structures, symmetries, interactions, …

- Tested by precision measurements and the direct searches at future experiments

- Some of such (ad hoc) models may not be UV complete. What is the fundamental theory of such extended Higgs sectors?

Model separation by future precision measurement of Higgs couplings



Aiko, SK, Kikuchi, Sakurai, Taniguchi, Yagyu, 2026
(H-COUP project)

Kodai Sakurai's Talk

EW Baryogenesis

Sakharov Conditions

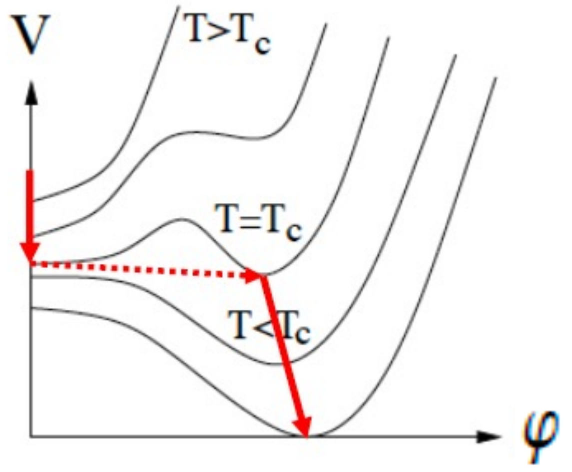
Kuzmin, et al (1985)

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

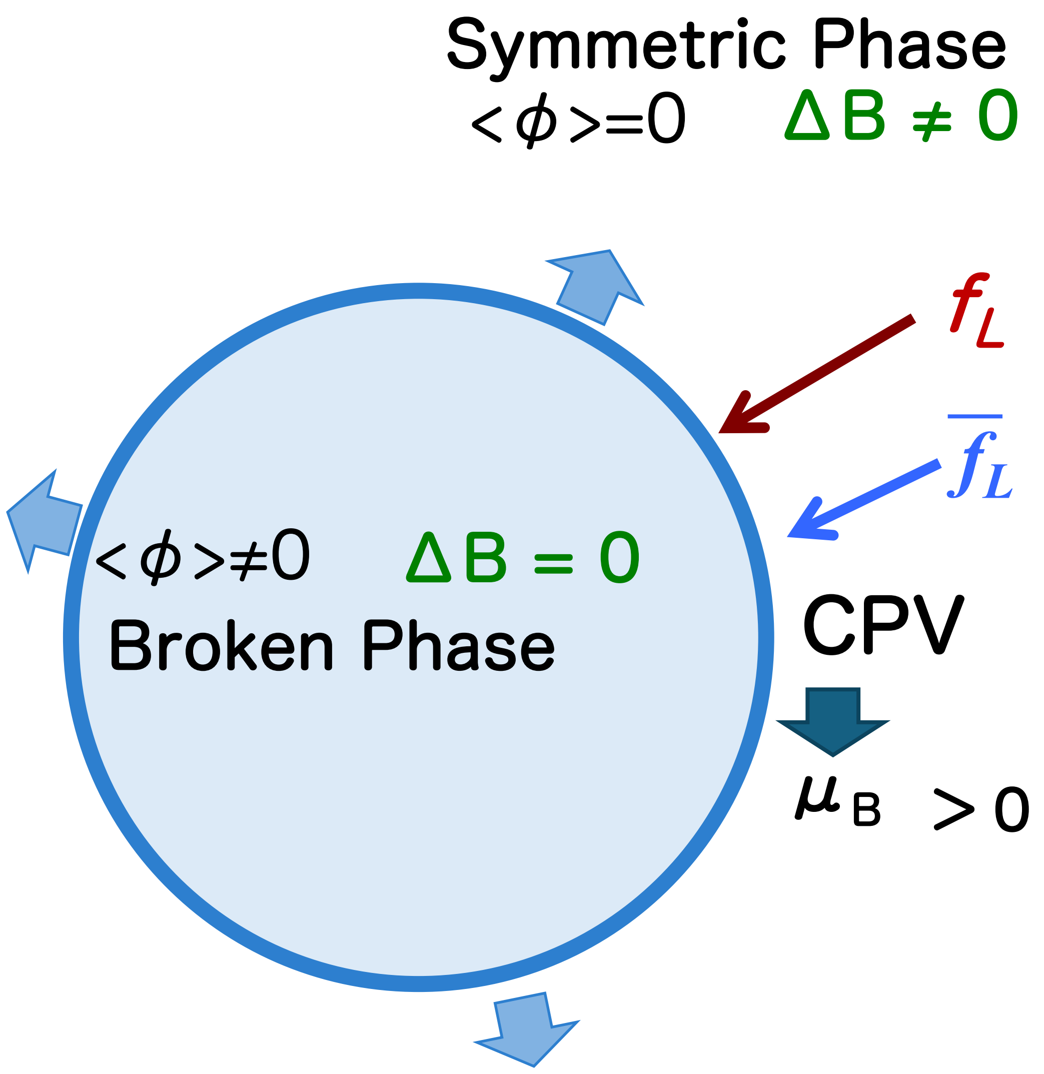
In the broken phase, sphaleron should quickly decouple to avoid wash out

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

Physics of Higgs potential

EW Baryogenesis

- 1^{st} OPT ⇒ bubbles of the broken phase
- CPV ⇒ charge flow around the wall



Dirac equation solved by WKB method
Cline, Joyce, Kainulainen 2000

Boltzmann equation

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

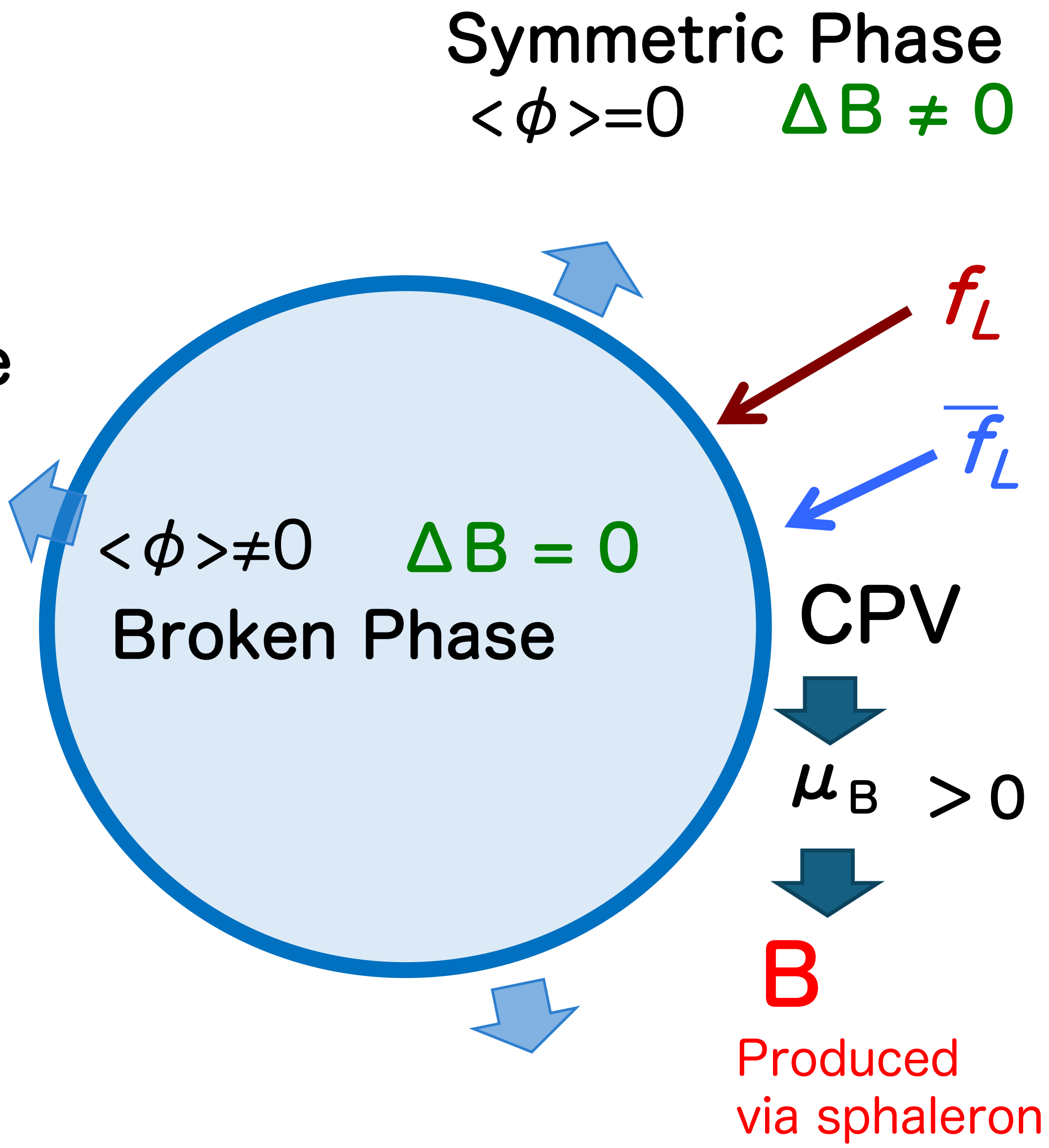
Different sign between particle and anti-particle

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

⇒ $\boxed{\text{Transport eq for } \mu_i}$

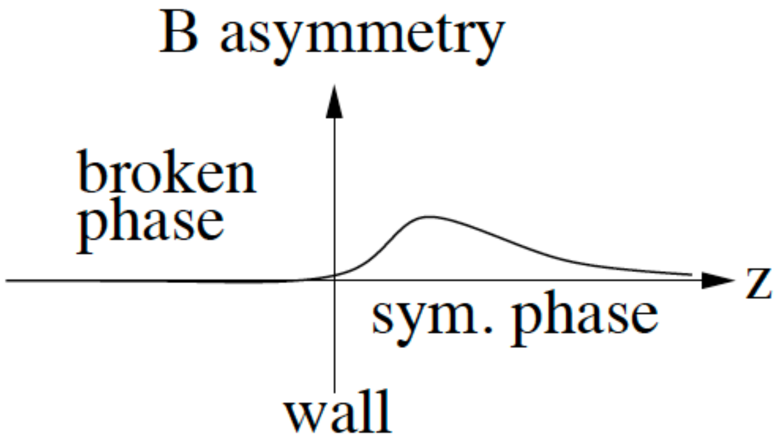
EW Baryogenesis

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



Chemical potential

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



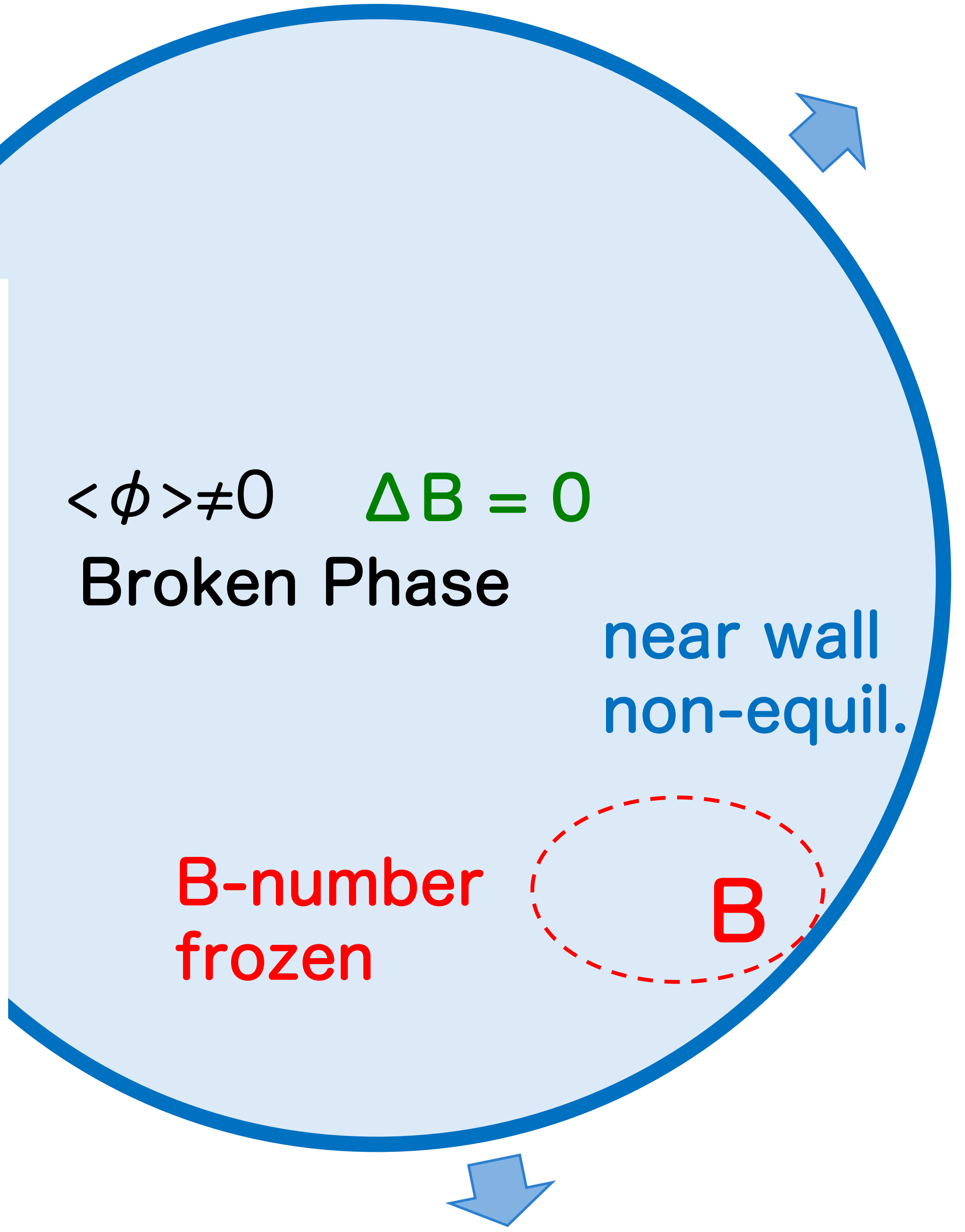
EW Baryogenesis

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

Sphaleron decoupling

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

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



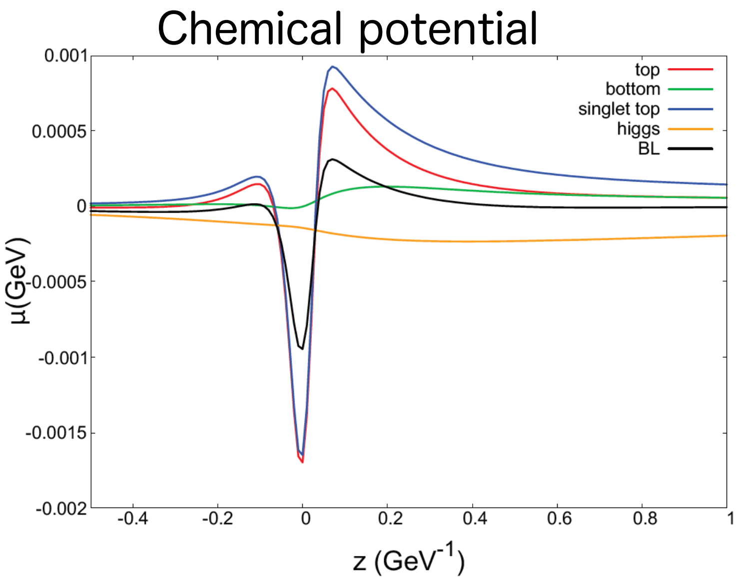
Evaluation of BAU

L_w : wall width
T_n : nucleation temp

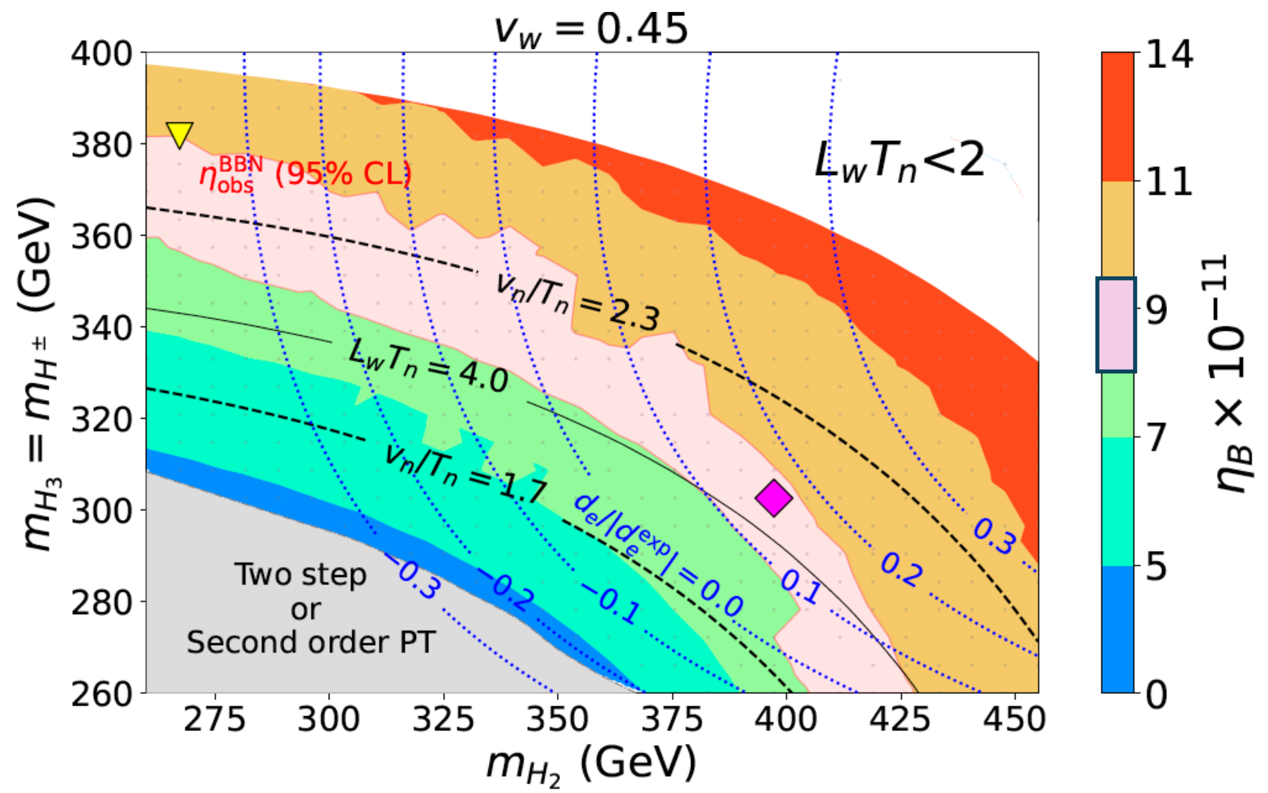
$$M = 30\ \text{GeV},\quad \lambda_2 = 0.1,\quad |\lambda_7| = 0.8,\quad \theta_7 = -0.9,$$
$$|\zeta_u| = |\zeta_d| = |\zeta_e| = 0.18,\quad \theta_u = \theta_d = -2.7,\quad \delta_e = -0.04$$

K. Enomoto, SK, Y. Mura, 2022

Aligned 2HDM



Top transport scenario



In symmetric phase, B is produced by sphaleron

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

Frozen at the Broken phase when $v_n/T_n > 1$

Cline, Joyce, Kainulainen

BAU data reproduced (pink region)

$$\boxed{\eta_{obs}^{\text{BBN}} \equiv \frac{n_B}{s} = 8.2\text{–}9.2 \times 10^{-11}}$$

$$\boxed{s = 0.74 n_\gamma}$$

Test of 1st OPT(1)

Sphaleron decoupling
(Strongly 1st OPT)

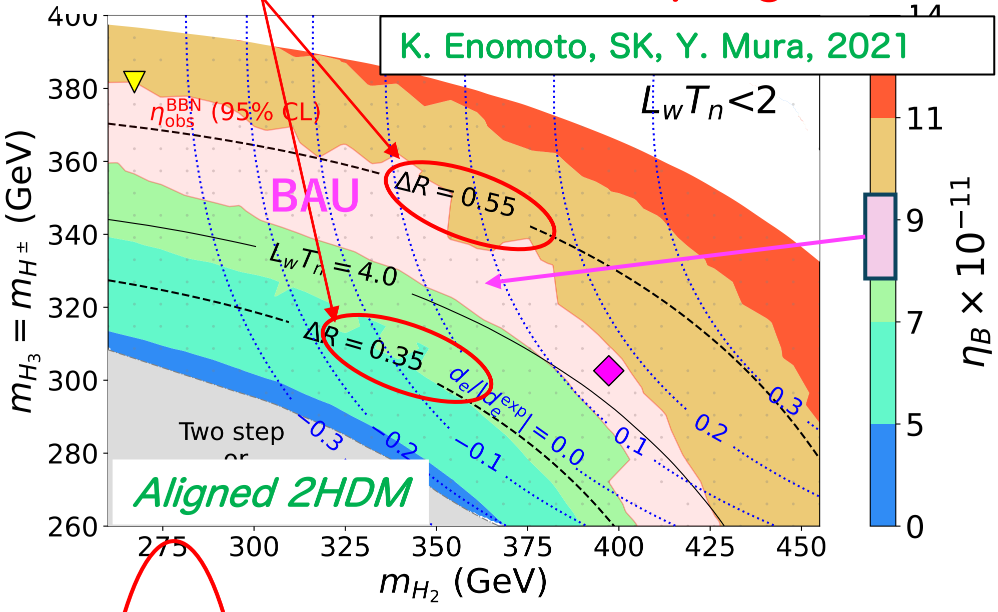
$$\boxed{\frac{\varphi_c}{T_c} \gtrsim 1} \quad \rightleftarrows \quad \boxed{\text{Large deviation in the hhh coupling}}$$

SK, Y. Okada, E. Senaha 2025

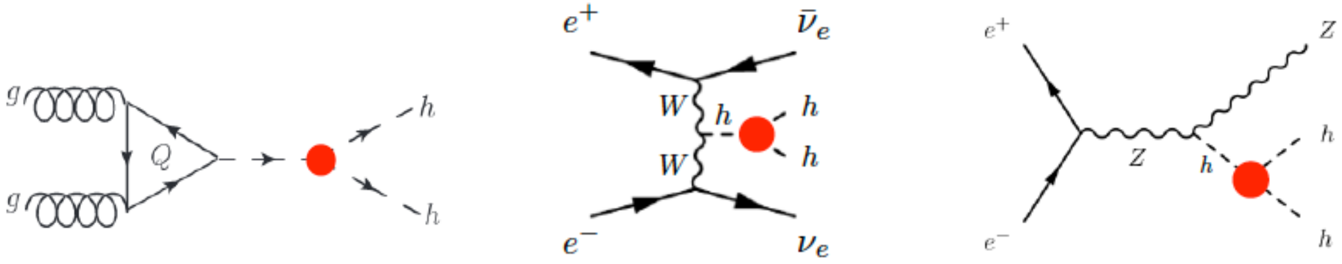
Aligned 2HDM

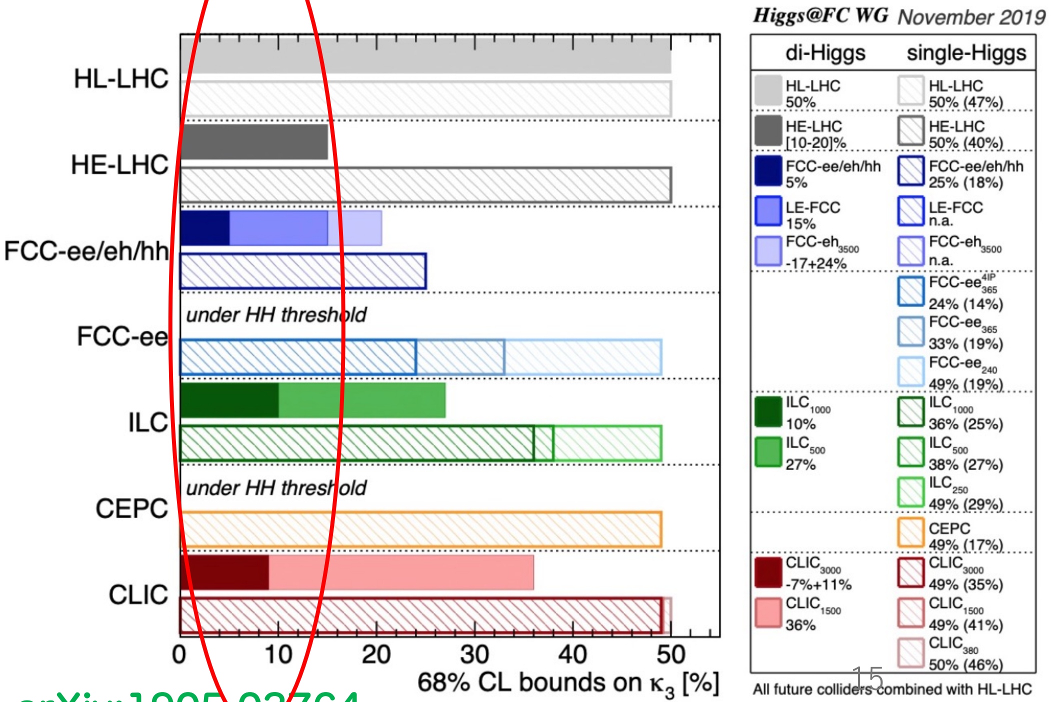
40-60% deviations
in the hhh coupling

Deviation in the hhh coupling (%)



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



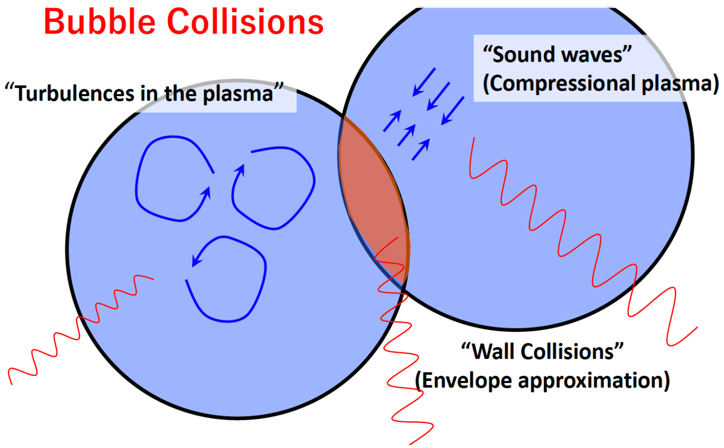


arXiv:1905.03764

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

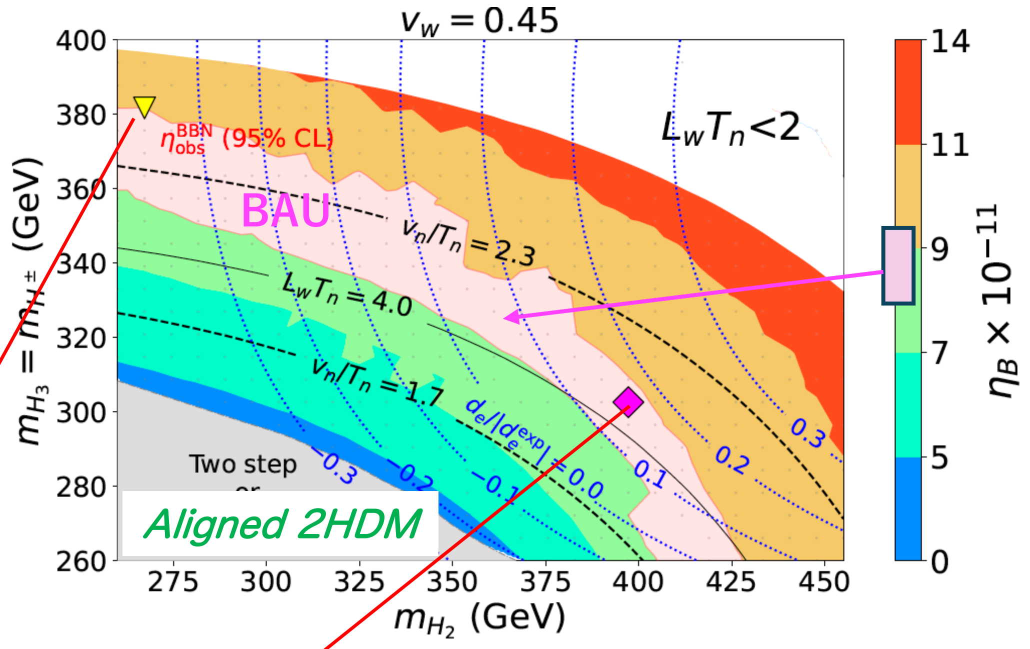
hγγ can also be sensitive to non-decoupling effects

Test of 1stOPT(2)



Example
Aligned 2HDM

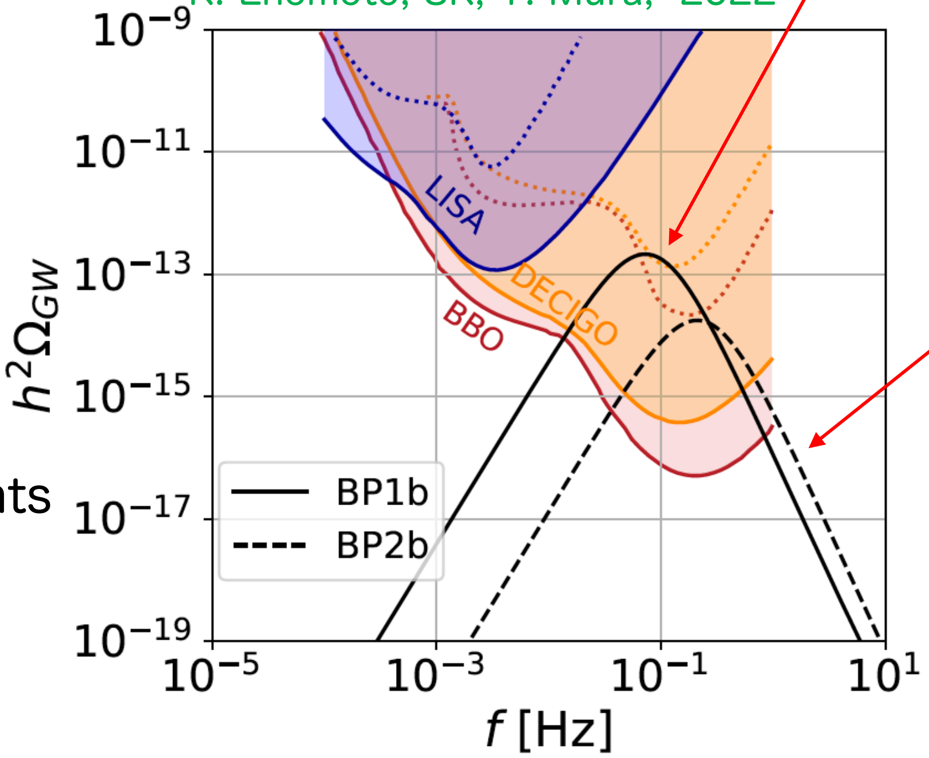
K. Enomoto, SK, Y. Mura, 2022



GWs for benchmark points of BAU

They may be tested by future GW experiments

K. Enomoto, SK, Y. Mura, 2022



Dotted curves: Sensitivity Curve
M. Breitbach et al., arXiv: 1811.11175

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

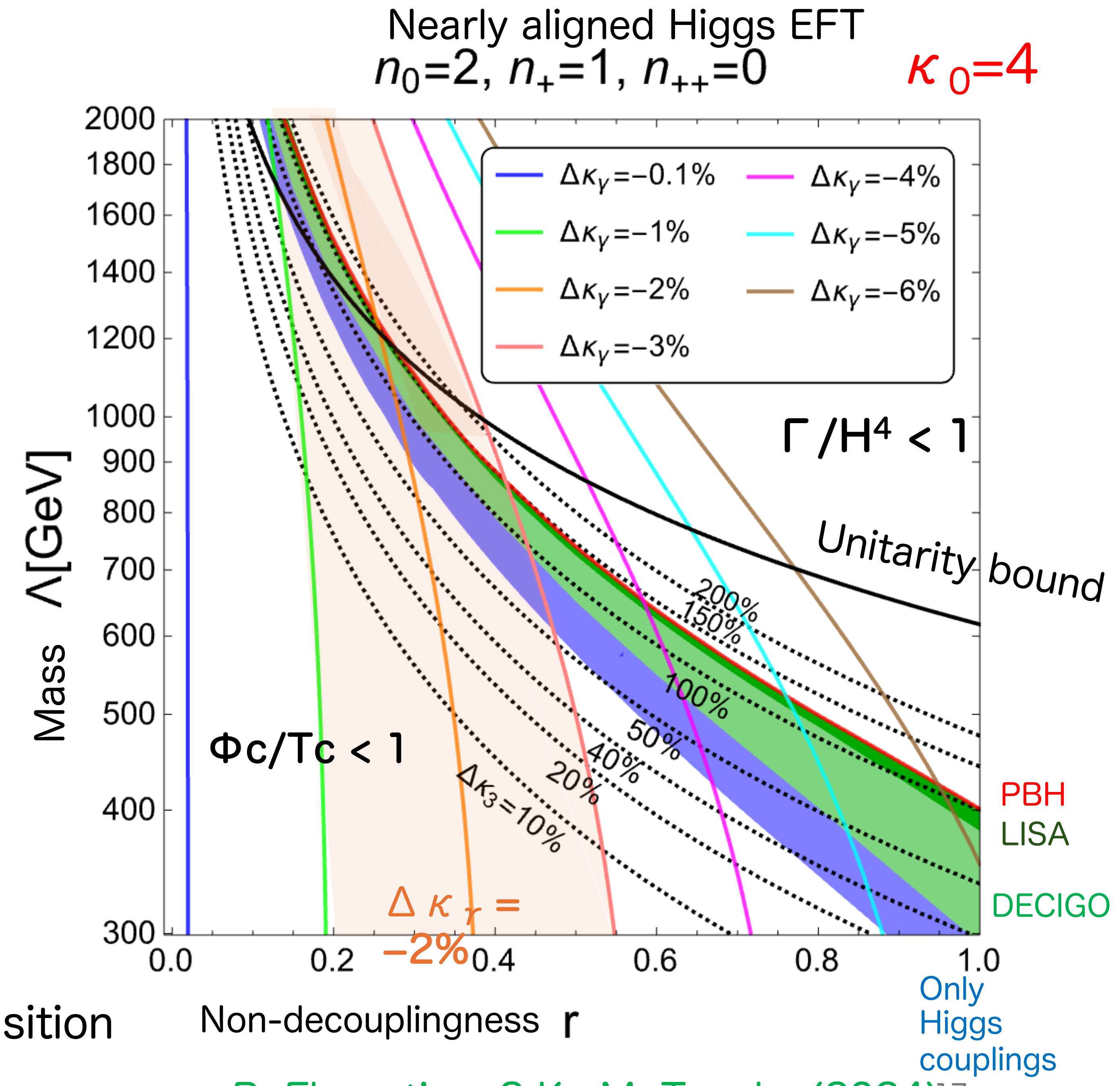
Test of 1st OPT

Colored region satisfies two conditions

- Sphaleron decoupling $\frac{\varphi_c}{T_c} \gtrsim 1$
- Bubble nucleation completion $\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1$

- PBH (RomanTelescope $f_{PBH} > 10^{-4}$)
- GW (LISA detectable)
- GW (DECIGO detectable)
- Only Higgs couplings can test 1st OPT

  ($\Delta\kappa_3$, $\Delta\kappa_\gamma$, …)



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

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

Electric dipole moments

Experimental Bounds on Electric dipole moments (EDMs)

Current bounds

- Electron EDM $|d_e| < 4.1\times10^{-30}\ e$ cm JILA, Science (2023)
- Neutron EDM $|d_n| < 1.8\times10^{-26}\ e$ cm Abel et al. PRL (2020)
- Proton EDM $|d_p| < 2.1\times10^{-25}\ e$ 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 Z2 symmetry (Type I, Type II etc) Fromme, Huber and Seniuchi (2006)

- Suppressed FCNC
- One CP phase
- CP violation for observed BAU $\rightarrow |d_e| = O(10^{-28})\ e\ \mathrm{cm}$

Difficult

Observation

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

Roussy et al. 2022

(2) General 2HDM Viable EWBG in the aligned 2HDM, ⋯

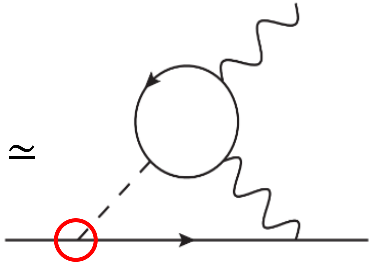
Fuyuto, Hou and Senaha (2019);
SK Kubota and Yagyu (2020);
Enomoto, SK, Mura (2022)

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

Cancellation among multiple CPV phases is used

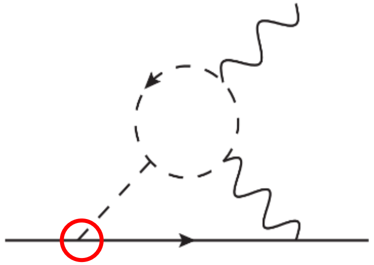
EDM cancellation

$d_e \simeq$



(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 light fermions)

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

Minimal scenario for EWBG without EDM cancellation

Aiko, Endo, SK. Mura (2025)

Most general potential

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

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

Davidson and Haber (2005)

Most general Yukawa sector

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

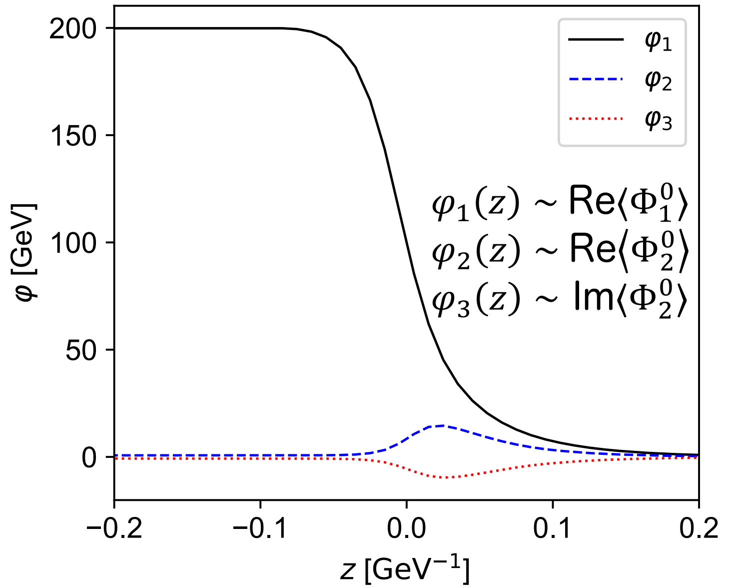
$$Y_{1,u} = \mathrm{diag}(y_u, y_c, y_t) \qquad Y_{1,d} = \mathrm{diag}(y_d, y_s, y_b) \qquad Y_{1,l} = \mathrm{diag}(y_e, y_\mu, y_\tau)$$

$\boldsymbol{Y_2}$ is 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.

Minimal Scenario



Discovered 125GeV Higgs is SM like

$\kappa_Z \simeq 1$ ➡ $|\lambda_6| \ll 1$ ATLAS, Nature (2022); CMS, Nature (2022);

➡ $\mathrm{Im}[\lambda_5^* \lambda_7^2]$, $\mathrm{Im}[\lambda_5 \rho_{tt}^2]$, $\mathrm{Im}[\lambda_7 \rho_{tt}]$

<u>Top transport scenario</u>

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

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$_2$ ($\boldsymbol{\Phi_2} \to -\boldsymbol{\Phi_2}$). → $\varphi_2, \varphi_3 \ll 1$

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)

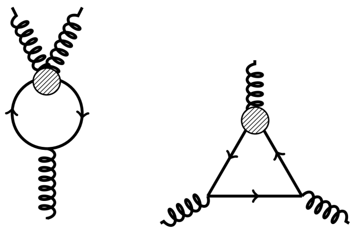
➡ $m_{H_2} = m_{H_3} = m_{H^\pm} \equiv m_\Phi$ One available CP phase: $\arg[\lambda_7\rho_{tt}]$

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

EDMs in the minimal setup

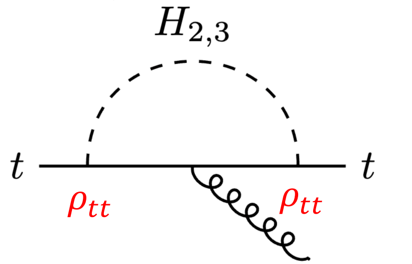
- No Barr-Zee type diagram

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



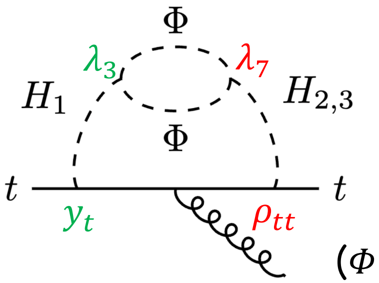
Kamenik et al. (2012);
Hisano, Tsumura and Yang (2012);
and more works

- At 1 loop level



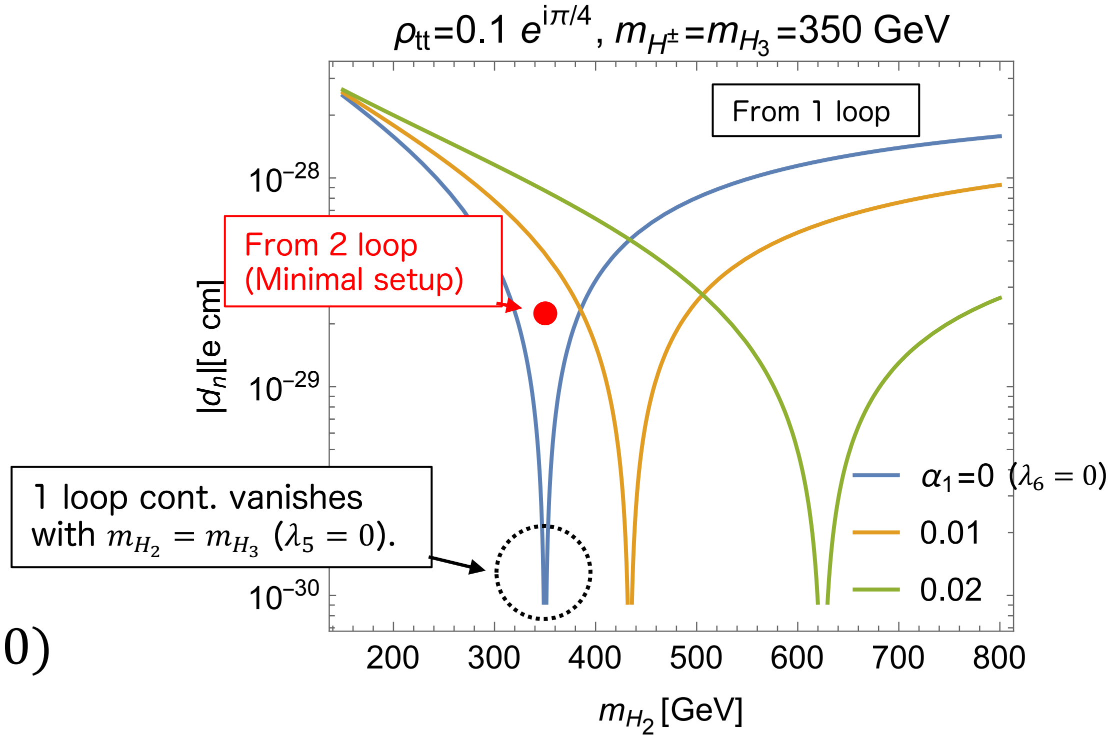
$\propto Im[\lambda_5 \rho_{tt}^2]$ $(= 0)$

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



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

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



M. Aiko, M. Endo, S.K., Y. Mura,
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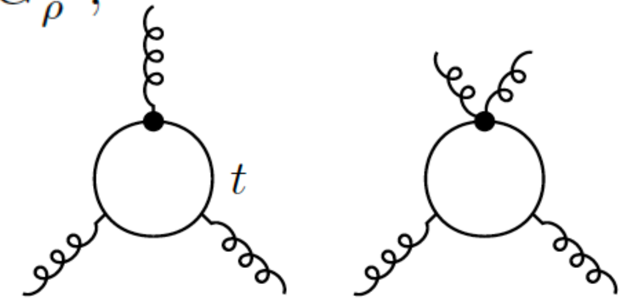
At the red point,
$\lambda_7 = e^{i\pi/4}, -\mu_2^2 = 30^2$ GeV^2 are taken.

EDMs from top (C)EDM from $\mathrm{Im}[\lambda_7 \rho_{tt}]$

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



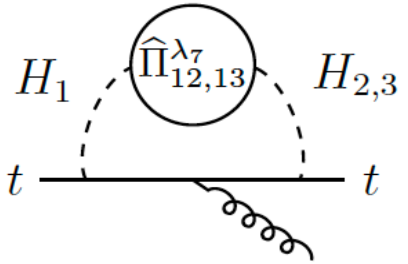
Induced Weinberg operator and EDMs

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

RGE

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

hadronization scale $\mu_H = 2$ GeV



QCD sum rule

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

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>

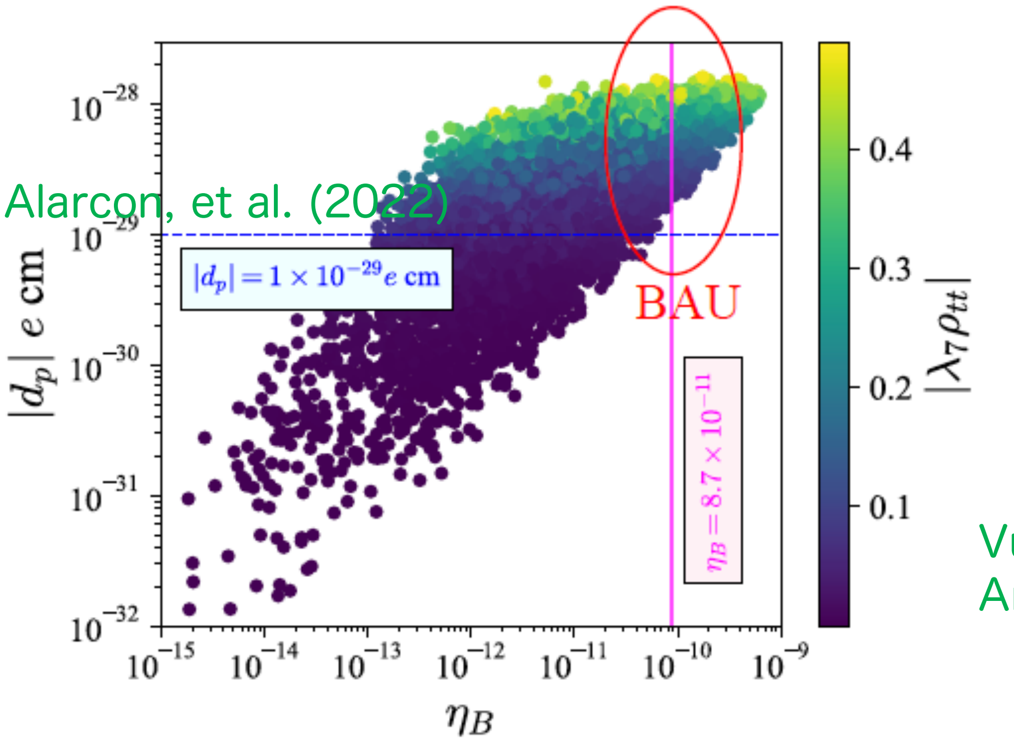
$$m_\Phi = [200{,}500]\ \mathrm{GeV}, \mu_2^2 = \left[-m_\Phi^2, 0\right], |\rho_{tt}| = [0{,}0.5]$$
$$|\lambda_7| = [0{,}1], \lambda_2 = [0{,}1], \arg[\lambda_7\rho_{tt}] = -\pi/2\,, v_w = \left[0.1, 1/\sqrt{3}\right]$$

Neutron EDM

Sahoo, PRD (2017)

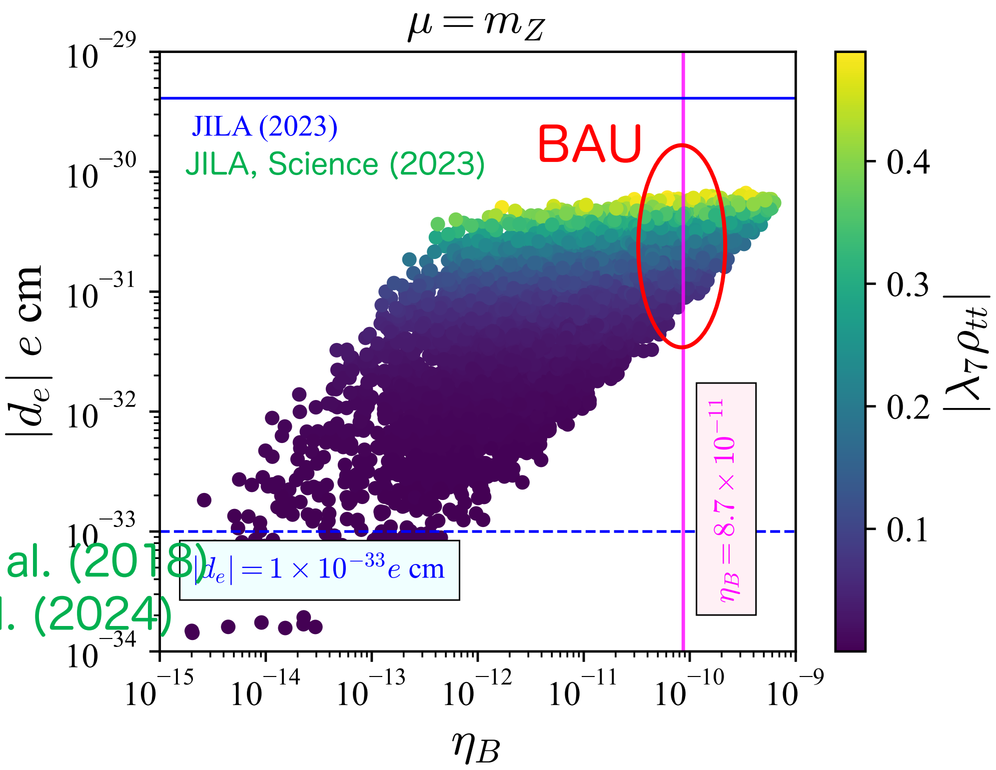
$|d_p| < 2.1\times10^{-25}\ e$ cm (current)

Alarcon, et al. (2022)



Electron EDM

Vutha et al. (2018)
Ardu et al. (2024)



Viable, and testable at future EDM experiments

UV of extended Higgs models

In various TeV models, additional scalars are introduced in an ad-hoc way.

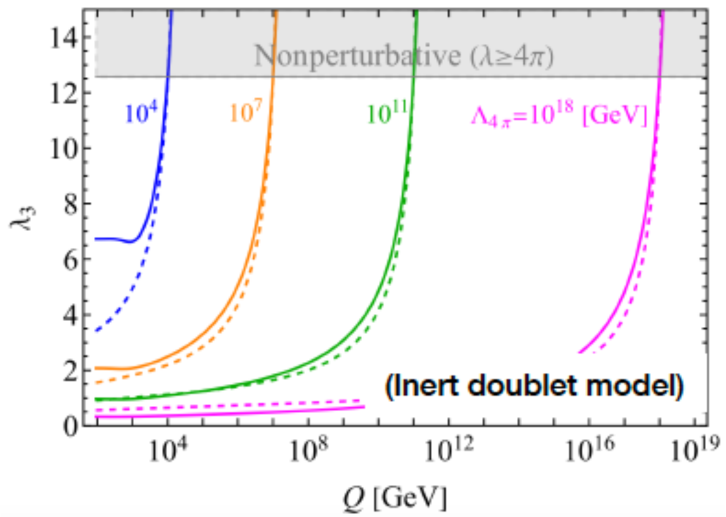
In extended Higgs sectors, λ's may blow up below the Planck scale, causing a landau pole.

$$16\pi^2\mu\frac{d}{d\mu}\lambda = \underbrace{24\lambda^2 - 6y_t^2}_{\text{SM: negative}} + \underbrace{A(\lambda', \lambda'', \ldots)}_{\substack{\text{Extra scalar effect}\\ \text{Positive } (A>0)}}$$

Especially for the strong 1st OPT

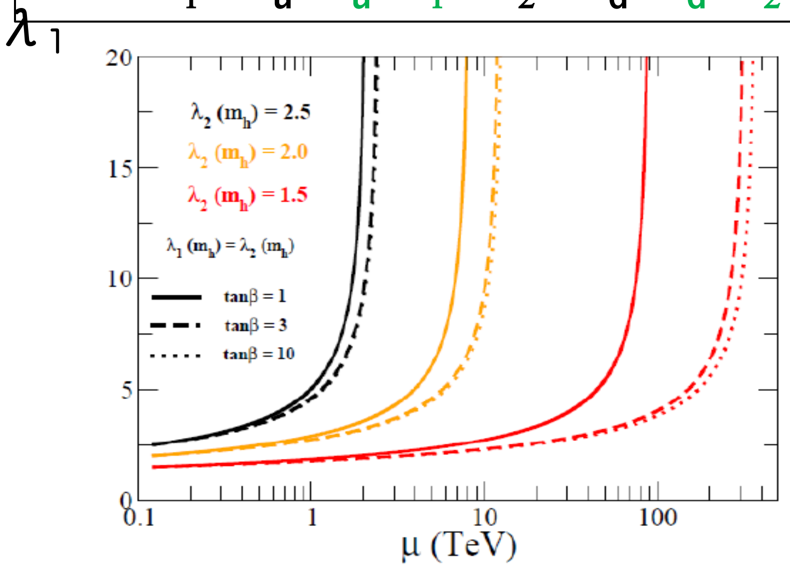
$$\boxed{\phi_c/T_c > 1 \quad \Rightarrow \quad \Lambda < 10\text{-}100\ \mathrm{TeV}}$$

What is the fundamental theory of extended Higgs models?



SK, Mura 2023

$W = \lambda_1\ H_u\ H_u'\Omega_1 + \lambda_2\ H_d\ H_d'\Omega_2$



SK, Senaha, Shindou 2013

A natural picture
Higgs as mesons

$$M_{ij} = T_i T_j$$

Technicolor (EWSB)
Composite Higgs models (pNGB)

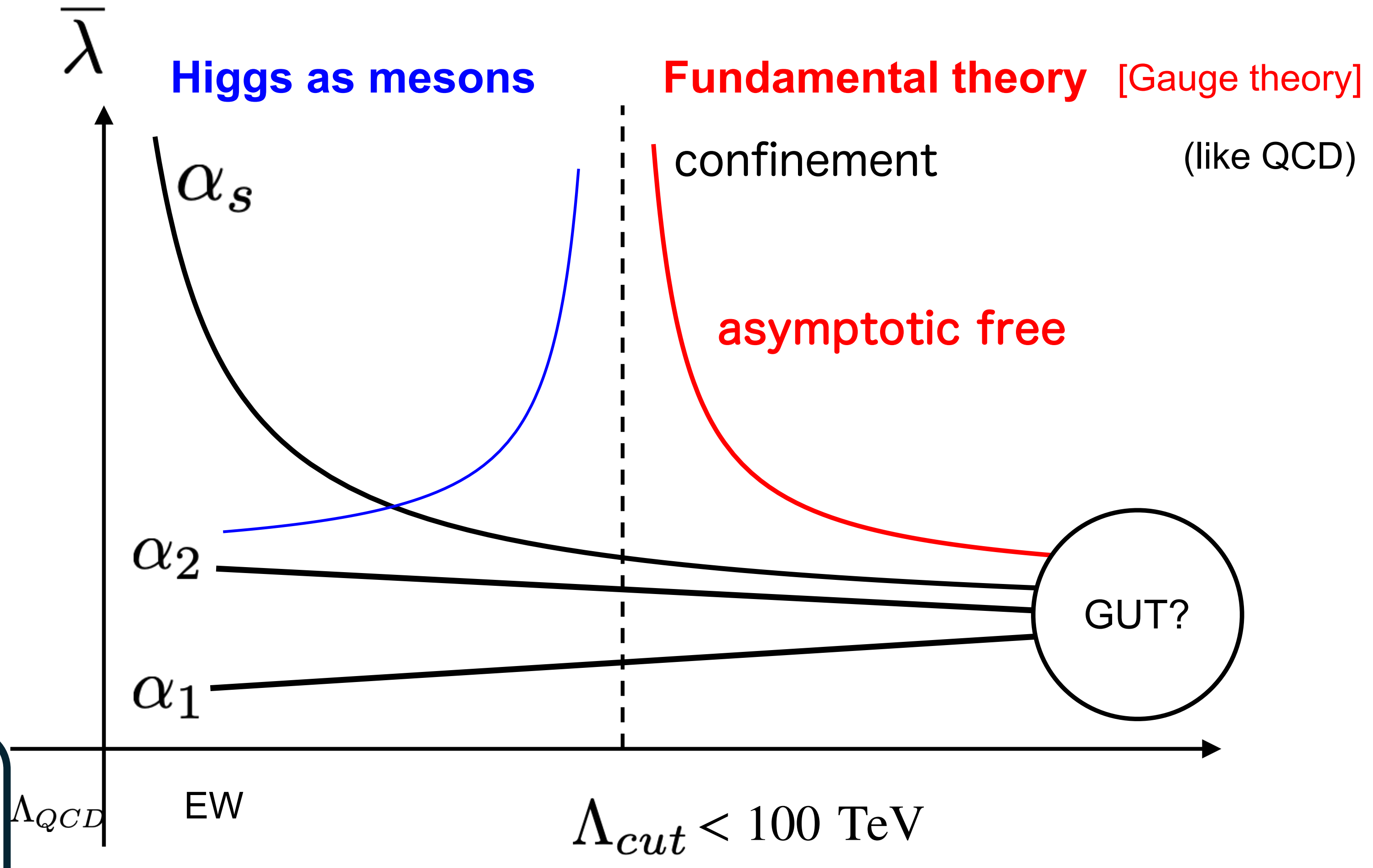
Minimal SUSY Fat Higgs models
by Murayama et al 2004,
and many references

Particle Contents of Higgs sector

⇄ Properties of the UV theory

SK, T. Shindou, T. Yamada 2014

Landau pole and new physics

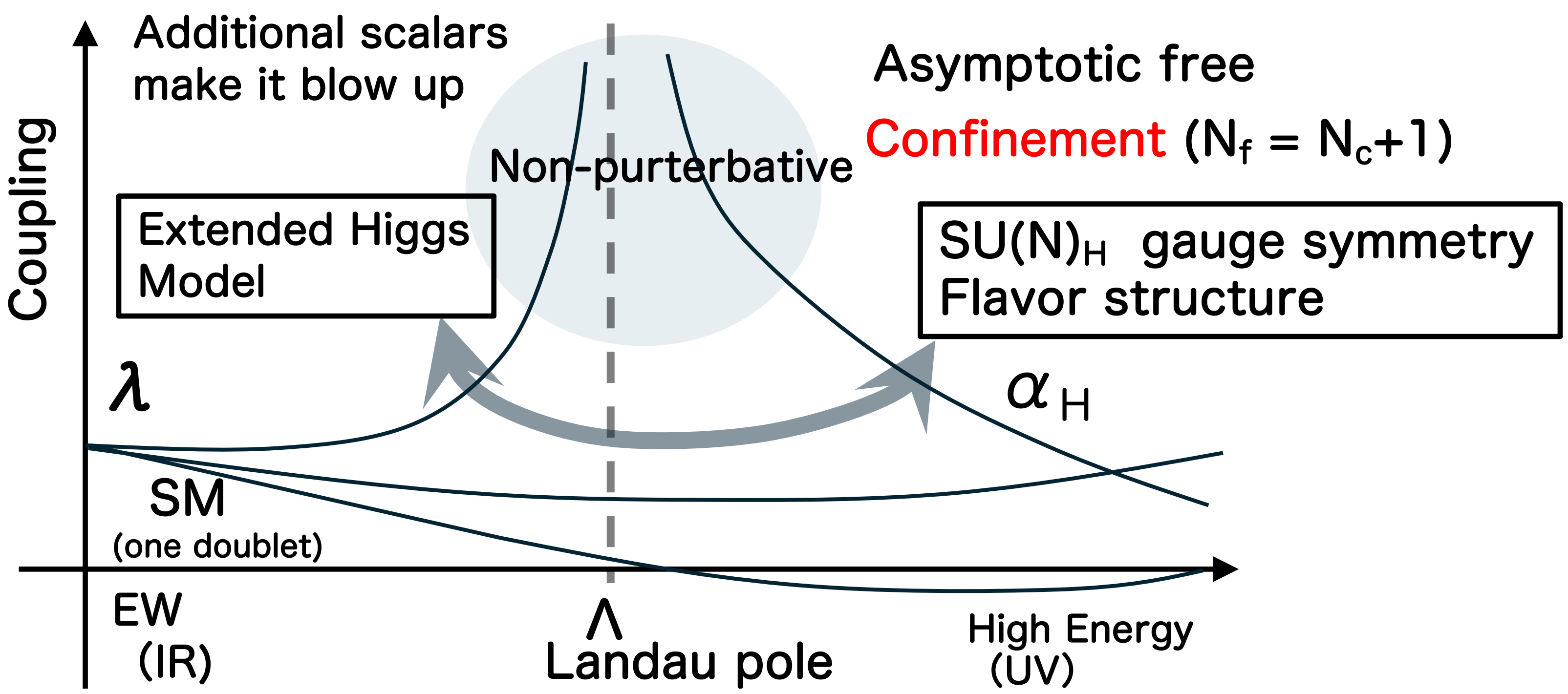


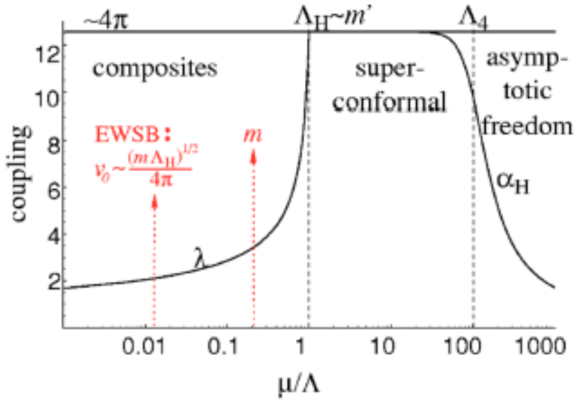
Previous example (in SUSY)

SK, T. Shindo, T. Yamada 2014

SUSY
Intrilligator, Seiberg

Minimal SUSY Fat Higgs models by Murayama et al 2004, and many references





$$\boxed{M_{ij} = T_i T_j}$$

In the SUSY model with N_c=2, N_f=3, adding Z_2 parity and introducing RH Neutrinos, a radiative seesaw scenario is realized at TeV scale

Minimal model for confinement ($N_c=2$, $N_f=3$)

→ 3 pairs of $SU(2)_H$ fundamental rep. T_i (i=1-6)

SK, Shindou, Yamada 2014

Higgs as Mesons

$$M_{ij} = T_i T_j$$

Field	$SU(2)_L$	$U(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	2	0	+
T_3	1	+1/2	+
T_4	1	−1/2	+
T_5	1	+1/2	−
T_6	1	−1/2	−

Additional Super-fields

- MSSM Higgs doublets
- Extra Higgs doublets
- Charged Higgs singlets
- Z_2-even Higgs singlets
- Z_2-odd Higgs singlets

Field	$SU(2)_L$	$U(1)_Y$	Z_2
H_u	2	+1/2	+
H_d	2	−1/2	+
Φ_u	2	+1/2	−
Φ_d	2	−1/2	−
Ω^+	1	+1	−
Ω^-	1	−1	−
$N,\ N_\Phi,\ N_\Omega$	1	0	+
$\zeta,\ \eta$	1	0	−

Superpotential of IR theory

Intrilligator, Seiberg

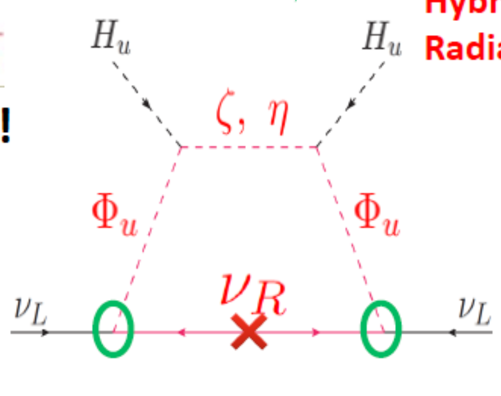
$$W_{eff} = \lambda \{ N(H_u H_d + v_0^2) + N_\Phi(\Phi_u \Phi_d + v_\Phi^2) + N_\Omega(\Omega^+\Omega^- + v_\Omega^2) \\ - N N_\Phi N_\Omega - N_\Omega \zeta\eta + \zeta H_d \Phi_u + \eta H_u \Phi_d - \Omega^+ H_d \Phi_d - \Omega^-$$

The low energy theory is 4HDM+Singlets but with a common λ !

RH neutrinos

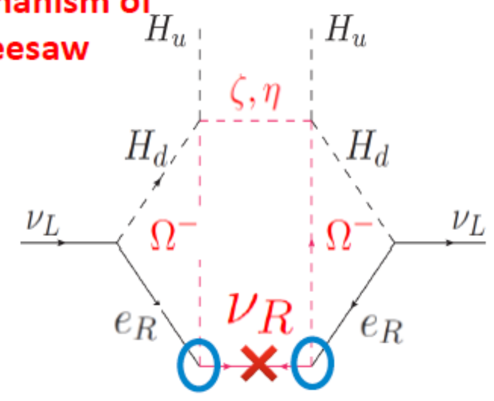
SK, Shindou, Machida, Yamada 2014

$$W_{\rm eff}^N = \frac{\kappa}{2} N \nu_R^c \nu_R^c + y_N^i \nu_R^c L_i \Phi_u + h_N^i \nu_R E_i^c \Omega^- + \frac{M}{2} \nu_R^c \nu$$



Ma Type diagram

Hybrid mechanism of Radiative Seesaw



AKS Type diagram

SK, Shindou, Machida, Yamada 2014

Particle contents of the Tao-Ma/AKS models predicted

Correspondence between the symmetry structure of the UV theory and the Higgs multi-plet structure of the IR theory

SK, Y. Mura, T. Shindou, arXiv: 2509.05934, PRD to appear

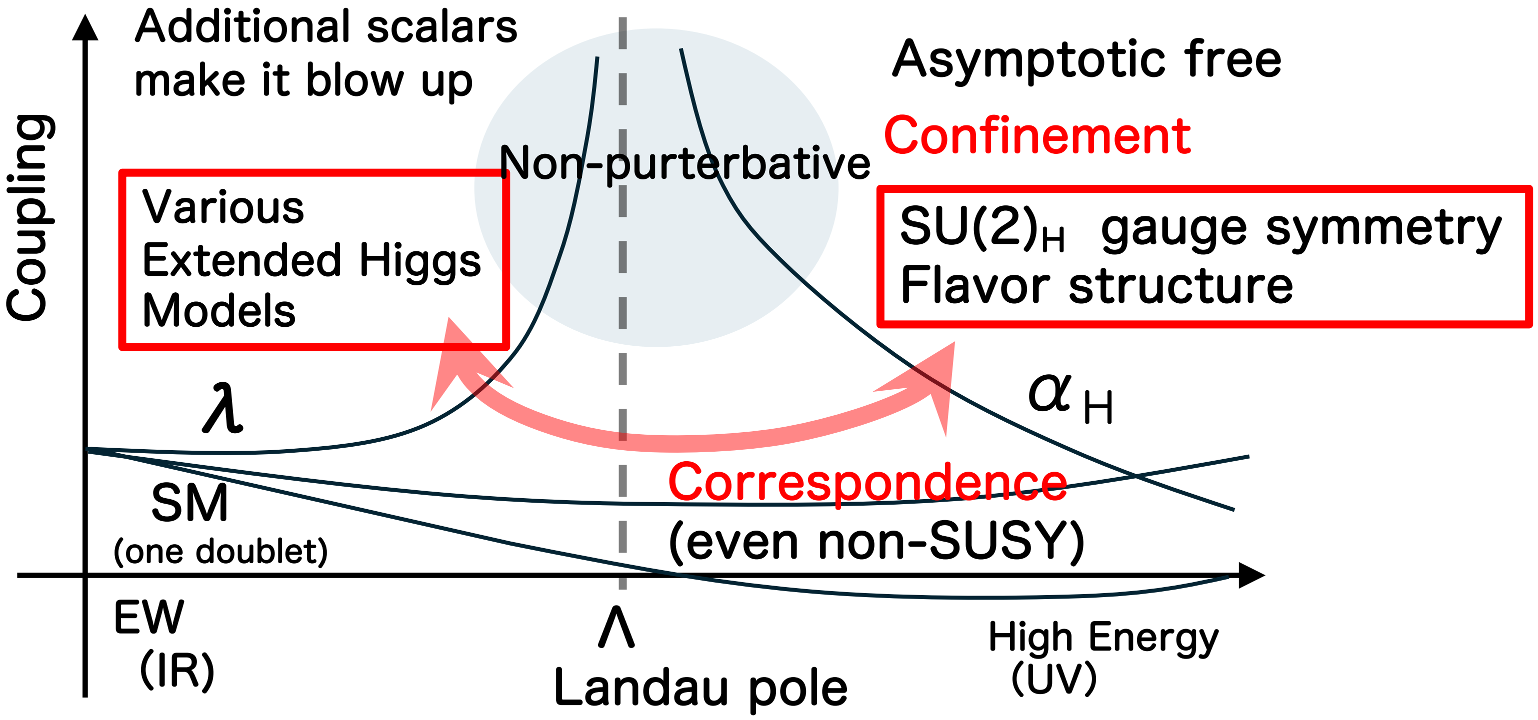
$\boxed{\text{SU(2)}_H \quad \text{Confinement if } N_f < 4.7}$

Appelquist et al (1999)

Classify low energy models by

1. Number of T_i (fundamental Rep)
2. Global symm. (Flavor symm.)
3. Charge of T_i under EW symm.
   Discrete symm.
   ….

The SU (2) x U(1) gauge symmetry is embedded in the global symmetry



$$\boxed{M_{ij} = T_i T_j}$$

Flavor symmetry in SU(2)$_H$ gauge theory

- $\boxed{\text{Letting } T_i = (\chi_i, \eta_i^*)^\intercal \text{ as a fundamental irreps. of SU(2)}_H\ (i = 1, \dots, n)}$, the kinetic term is written by

cf.) In terms of $\psi = (\chi, \eta)^\intercal$, it is $\mathcal{L}_{\rm kin} = \bar{\psi} i D_\mu \gamma^\mu \psi$.

$$\boxed{\mathcal{L}_{\rm kin} = \overline{\boldsymbol{T}}(i\bar{\sigma}^\mu) D_\mu \boldsymbol{T}, \quad \text{where } \boldsymbol{T} = (T_1, \dots, T_n)^\intercal.} \quad \to \quad \text{Invariant under } \boldsymbol{T} \to U\boldsymbol{T},\ U \in \mathrm{SU}(2n).$$

(chiral symmetry)

- The mass term is, in general, $\boxed{\mathcal{L}_{\rm mass} = -\frac{1}{2}\boldsymbol{T}^\intercal\, \boldsymbol{m}\, \boldsymbol{T} - \frac{1}{2}\boldsymbol{T}^\intercal\, \boldsymbol{M}\, \boldsymbol{T} + \mathrm{h.c.}\ ,}$

where $\boldsymbol{m} = \mathrm{diag}(m_1, \dots, m_n) \otimes (-i\sigma^2)$, $\boldsymbol{M} = \begin{pmatrix} 0 & M_{12} & \cdots & \cdots & M_{1n} \\ -M_{12} & 0 & \cdots & \cdots & M_{2n} \\ \vdots & \vdots & \ddots & & \vdots \\ \vdots & \vdots & & 0 & M_{n-1\,n} \\ -M_{1n} & -M_{2n} & \cdots & -M_{n-1\,n} & 0 \end{pmatrix} \otimes \mathbb{I}_2.$

- Various explicit symmetry breaking is realized, depending on the mass term.

e.g.) $M_{ij} = 0$ -> $\otimes_{i=1}^{n} \mathrm{SU}(2)_i$ symmetry

$M_{ij} = 0$ & $m_i = m$ -> $\mathrm{Sp}(2n)$ symmetry

cf.) Symplectic symmetry

$U^\intercal(\mathbb{I}_n \otimes i\sigma^2)U = \mathbb{I}_n \otimes i\sigma^2$, $U \in \mathrm{Sp}(2n)$

Slide from Yushi Mura

Bound states and discrete symmetry

- Scalars are SU(2)$_H$ singlet states denoted by

$$\boxed{S_\pm^{AB} = (\boldsymbol{T})^A(\boldsymbol{T})^B \pm (\boldsymbol{T}^*)^A(\boldsymbol{T}^*)^B \quad \text{: +(-) parity even (odd)}}$$

where A and B are indices of flavor symmetry.

cf.) A “proper” parity transformation commuting to Sp(2n) symmetry

$$\chi_\alpha \to i\eta^{\dot\alpha},\ \eta^{\dot\alpha} \to i\chi_\alpha$$

Drach, Janowski and Pica, EPJWC (2018)

- Totally symmetric (A ↔ B) irreps. cannot be scalars.

e.g.) $V^{\mu AB} = (\boldsymbol{T})^A\sigma^\mu(\boldsymbol{T}^*)^B + (\boldsymbol{T})^B\sigma^\mu(\boldsymbol{T}^*)^A$

- Discrete symmetry commuting to $\otimes_{i=1}^n \mathrm{SU}(2)_i : \boldsymbol{T} \to \begin{pmatrix} \omega_1 & & & & \\ & \omega_1^* & & & \\ & & \ddots & & \\ & & & \omega_n & \\ & & & & \omega_n^* \end{pmatrix} \boldsymbol{T}$ where $\omega_i = \omega_i^* = \pm 1$.

- For simplicity, focusing on Lorentz scalars and neglecting CP violation

Slide from Yushi Mura

SU(2)$_H$ gauge theory (case n=2)

- Massless fermions are confined below $\Lambda \sim \Lambda_H$, when $n \lesssim 4.7$.
- We consider explicit chiral symmetry breaking by $m_i \lesssim \Lambda_H$.

Appelquist, Cohen and Schmaltz, PRD (1999);
Neil, Pos LATTICE2011 (2011);

cf.) Spontaneous breaking of $\mathrm{SU}(4) \to \mathrm{Sp}(4)$ happens via $\langle TT \rangle \sim \Lambda_H^3$.

Lewis, Pica and Sannino, PRD (2012);
Drach, Janowski and Pica, EPJWC (2018); and more

- For $\underline{\boldsymbol{n=2}}$ with $\underline{m_1, m_2 \neq 0, M_{12} = 0}$, there is $\underline{\mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2}$. $\mathcal{L} = \overline{\boldsymbol{T}}(i\bar{\sigma}^\mu) D_\mu \boldsymbol{T} - \frac{1}{2}\boldsymbol{T}^\intercal \boldsymbol{m}\, \boldsymbol{T} + \mathrm{h.c.}$ $\quad \boldsymbol{T} = (T_1, T_2)^\intercal$
- This symmetry can be regarded as $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \supset \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$.

singlets: $\phi_i^\pm = \epsilon_{a_i b_i} (T_i)^{a_i} (T_i)^{b_i} \pm \epsilon_{a_i b_i} (T_i^*)^{a_i} (T_i^*)^{b_i}$

bi-doublet: $\mathbb{M}_\pm^{a_1 a_2} = (\boldsymbol{T})^{a_1} (\boldsymbol{T})^{a_2} \pm (\boldsymbol{T}^*)^{a_1} (\boldsymbol{T}^*)^{a_2}$

Particle contents

	$\mathbb{M}$	$\phi_1^\pm$	$\phi_2^\pm$
Y	$1/2$	0	0
L	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
R	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$

$\mathbb{M}$: bi-linear (2,2) of two SU(2)

$\phi_{1,2}^\pm$: parity even and odd real singlets $\rightarrow$ **Real singlet extension of the SM (xSM)**

(When $m_1 = m_2$, they become 1+5 of Sp(4))

Ramsey-Musolf, and Wise, PRD (2007);

Hermitian fields $i\phi_i^+$ and ϕ_i^- are independent because SO(2) symmetry in $(i\phi_i^+, \phi_i^-)^\intercal$ ($\sim T_i \to e^{i\theta_i} T_i$) is broken by m_i, while each component of $\mathbb{M}$ is complex because of U(1)$_i$ ($\subset$ SU(2)$_i$) which is $T_i \to e^{i\theta_i \sigma_3} T_i$

SU(2)$_H$ gauge (case n=3)

		$\mathbb{M}_{12}$	$\mathbb{M}_{13}$	$\mathbb{M}_{23}$	$\phi_1^\pm$	$\phi_2^\pm$	$\phi_3^\pm$
	Z_2	$+$	ω_3	ω_3	$+$	$+$	$+$
exact	♠ Y	$1/2$	y_3	$1/2+y_3$	0	0	0
	♠ L	**2**	**2**	**1**	**1**	**1**	**1**
approximate	♢ R_1	**2**	**1**	**2**	**1**	**1**	**1**
either	♡ R_2	**1**	**2**	**2**	**1**	**1**	**1**

- For $\mathbf{n=3}$, various extended Higgs models are included.

U(1)$_Y$ Z_2

Ex 1) charge assignment for T$_3$: $(y_3, \omega_3) = (1/2, +1)$ $\rightarrow$ xSM + 2HDM + CxSM + Zee

- 2HDM part $\mathrm{SU}(2)_{R_1} \otimes \mathrm{SU}(2)_{R_2}$ ($\supset$ custodial symmetry)

Pomarol and Vega, PLB (1994);
Haber and O'Neil, PRD (2011)

$$V_{R_1R_2}^{(d\leq 4)} = \mu_1^2\Phi_1^\dagger\Phi_1 + \mu_2^2\Phi_2^\dagger\Phi_2 + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$

suppressed $\Delta V^{(d\leq 4)} = \mu_3^2(\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) + \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \left(\lambda_5\left(\Phi_1^\dagger\Phi_2\right) + \lambda_6|\Phi_1|^2 + \lambda_7|\Phi_2|^2\right)(\Phi_1^\dagger\Phi_2 + \mathrm{h.c.})$

FCNC → minimal flavor violation (Yukawa alignment)
ρ parameter → custodial symmetry in 2HDM
Alignment w/o decoupling → taking $m_2 = m_3$, or assuming $\lambda_1 \sim \lambda_2 \sim \lambda_3$ or small VEV for Φ_1 or Φ_2

Ex 2) charge assignment for T$_3$: $(y_3, \omega_3) = (1/2, -1)$ $\rightarrow$ xSM + IDM (Tao-Ma) + Singlet DM

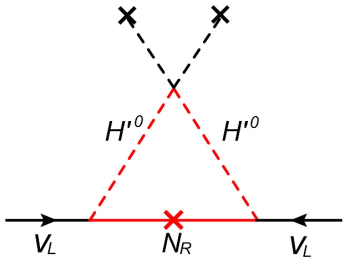
- IDM (Tao-Ma) part $\mathrm{SU}(2)_{R_1} \otimes \mathrm{SU}(2)_{R_2} \otimes Z_2$

$$\mathcal{L}_{\mathrm{TaoMa}} = -\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 - h\,\overline{\ell_L}\Phi_2 N_R + \mathrm{h.c.}$$

$$V_{R_1R_2}^{(d\leq 4)} = \mu_1^2\Phi_1^\dagger\Phi_1 + \mu_2^2\Phi_2^\dagger\Phi_2 + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$

suppressed $\Delta V^{(d\leq 4)} = \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \lambda_5\left(\left(\Phi_1^\dagger\Phi_2\right)^2 + \mathrm{h.c.}\right)$

Tao, PRD (1996);
Ma, PRD (2006)



SU(2)$_H$ gauge theory (case n=4)

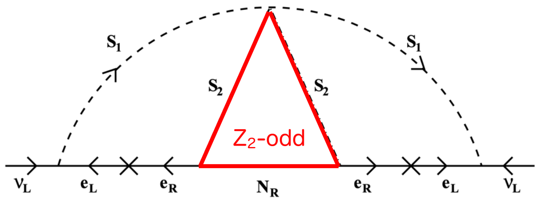
- For $n=4$, particle contents are

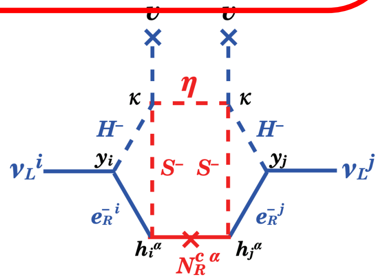
	$\mathbb{M}_{12}$	$\mathbb{M}_{13}$	$\mathbb{M}_{14}$	$\mathbb{M}_{23}$	$\mathbb{M}_{24}$	$\mathbb{M}_{34}$	$\phi_1^\pm$	$\phi_2^\pm$	$\phi_3^\pm$	$\phi_4^\pm$
♠ Z_2	$+$	ω_3	ω_4	ω_3	ω_4	$\omega_3\omega_4$	$+$	$+$	$+$	$+$
♠ Y	$1/2$	y_3	y_4	$1/2+y_3$	$1/2+y_4$	y_3+y_4	0	0	0	0
♠ L	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
♢ R_1	**2**	**1**	**1**	**2**	**2**	**1**	**1**	**1**	**1**	**1**
♡ R_2	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**1**	**1**	**1**
♡ R_3	**1**	**1**	**2**	**1**	**2**	**2**	**1**	**1**	**1**	**1**

e.g., models for three loop neutrino mass is

$$y_3 = y_4 = 1/2,\ \omega_3 = +1, \omega_4 = -1$$

$\rightarrow$ CxSM + Zee + IDM (Tao-Ma) + Singlet DM + Krauss-Nasri-Trodden + Aoki-Kanemura-Seto





- Example of triplet scalar: Georgi-Machacek model ($n=4$)

$$m_1 = m_2 = m_3 \neq 0,\ m_4 \neq 0$$

-> $Sp(6) \otimes SU(2)_{R_1} \supset SU(2)_L \otimes SU(2)_{R_1} \otimes SU(2)_{R_2}$

	$(\mathbb{M}_{\Phi_{3/2}}, \mathbb{M}_{\Phi_{1/2}}, \mathbb{M}_{\Phi_{-1/2}})^\intercal$	$(\chi^*, \zeta, \chi)^\intercal$	$(S^{++}, S^{+}, S^{0}, S^{-}, S^{--})^\intercal$	$\phi_1^\pm$	$\phi_2^\pm$
♠ Y	$3/2, \pm 1/2$	$\pm 1, 0$	$\pm 2, \pm 1, 0$	0	0
♠ L	**2**	**3**	**1**	**1**	**1**
♢ R_1	**2**	**1**	**1**	**1**	**1**
♢ R_2	**3**	**3**	**5**	**1**	**1**

From $(T_1, T_2, T_3)^\intercal \sim (\mathbf{2}, \mathbf{1}, \mathbf{3})$ and $T_4 \sim (\mathbf{1}, \mathbf{2}, \mathbf{1})$, we have

$(\mathbf{2}, \mathbf{2}, \mathbf{3}) \sim \left(\Phi_{3/2}, \Phi_{1/2}, \Phi_{-1/2}\right)^\intercal$, $(\mathbf{3}_S, \mathbf{1}, \mathbf{3}_A) \sim (\chi^*, \zeta, \chi)^\intercal$, $(\mathbf{1}_A, \mathbf{1}, \mathbf{5}_S) \sim (S^{++}, S^{+}, S^{0}, S^{-}, S^{--})^\intercal$, and $(\mathbf{1}_A, \mathbf{1}, \mathbf{1}_S) + (\mathbf{1}, \mathbf{1}_A, \mathbf{1})$.

Due to the custodial symmetry, tree level ρ is 1, even if $\langle \chi^0 \rangle = \langle \zeta^0 \rangle \neq 0$.

Table of IR particle content and UV symmetry structure

SK, Y. Mura, T. Shindou 2025

flavor charge assignment corresponding Higgs models

Class	n	Charge assignment of the UV model	Higgs sectors as a part of the low-energy effective theory
1	2	$y_2 = 1/2$	xSM
2	3	$(y_3, \omega_3) = (1/2, +1)$	xSM, 2HDM, Zee, CxSM
3	3	$(y_3, \omega_3) = (1/2, -1)$	xSM, IDM (Tao–Ma), SDM
4	3	$(y_3, \omega_3) = (3/2, +1)$	xSM, Zee–Babu
5	4	$(y_3, \omega_3, y_4, \omega_4) = (1/2, -1, 3/2, -1)$	xSM, IDM (Tao–Ma), SDM, Zee–Babu, AKY, KNT, GNR
6	4	$(y_3, \omega_3, y_4, \omega_4) = (1/2, +1, 1/2, -1)$	xSM, Zee, CxSM, IDM (Tao–Ma), SDM, KNT, AKS, N2HDM
7	4	$(T_1, T_2, T_3)^\intercal \sim (\mathbf{2}, \mathbf{1}, \mathbf{3})$, $T_4 \sim (\mathbf{1}, \mathbf{2}, \mathbf{1})$	xSM, 2HDM, Zee, Zee–Babu, GM

Models	xSM	2HDM	Zee	CxSM	IDM (Tao–Ma)	SDM	Zee-Babu	AKY
(Y, L, Z_2)	$(0, \mathbf{1}, +) \in \mathbb{R}$	$(1/2, \mathbf{2}, +)$	$(1/2, \mathbf{2}, +)$, $(1, \mathbf{1}, +)$	$(0, \mathbf{1}, +) \in \mathbb{C}$	$(1/2, \mathbf{2}, -)$	$(0, \mathbf{1}, -)$	$(2, \mathbf{1}, +)$, $(1, \mathbf{1}, +)$	$(1/2, \mathbf{2}, -)$, $(3/2, \mathbf{2}, -)$
Class	1,2,3,4,5,6,7	2,6,7	2,6,7	2,6	3,5,6	3,5,6	4,5,7	5

Models	KNT	GNR	AKS	N2HDM	GM
(Y, L, Z_2)	$(1, \mathbf{1}, -)$, $(1, \mathbf{1}, +)$	$(1/2, \mathbf{2}, -)$, $(1, \mathbf{1}, -)$, $(2, \mathbf{1}, +)$	$(1/2, \mathbf{2}, +)$, $(0, \mathbf{1}, -)$, $(1, \mathbf{1}, +)$	$(1/2, \mathbf{2}, +)$, $(0, \mathbf{1}, -)$	$(1, \mathbf{3}, +)$, $(0, \mathbf{3}, +)$
Class	5,6	5	6	6	7

xSM: Real singlet extension of the SM
2HDM: Two Higgs doublet model
CxSM: Complex singlet extension of the SM
IDM: Inert doublet model
SDM: Singlet dark matter model
AKY: Aoki-Kanemura-Yagyu model

KNT: Krauss-Nasri-Trodden model
GNR: Gustafsson-No-Rivera model
AKS: Aoki-Kanemura-Seto model
N2HDM: Next-to-minimal 2HDM
GM: Georgi-Machacek model

UV gauge theory may be the mother of extended Higgs sectors

Summary

- BSM phenomena may be explained by extended Higgs model
- EW baryogenesis in a simple setup
  - Aligned 2HDM
  - 2HDM without EDM cancellation
- UV scenario ($SU(2)_H$ with N_f flavor with confinement)

Particle contents of an extended Higgs model ⇔ Charge and flavor structure of the UV gauge theory

Landau pole

confinement

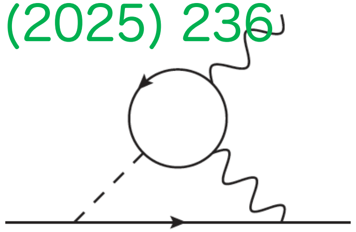
There are many things to do ahead

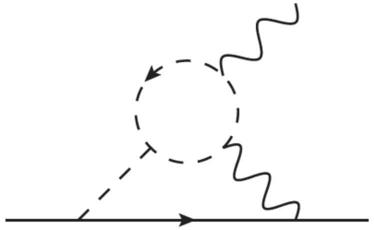
Thank you!

Back up slides

A scenario without EDM cancellation

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





- BZ-type diagrams are 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 theoretical and experimental constraints.
- The scenario is viable under current experimental bounds, and also testable at future EDM experiments as well as other experiments.

Extended Higgs sectors?

Multiplet Structure (with additional scalars)

Φ_{SM} + Isospin Singlet,
Φ_{SM} + Doublet (2HDM),
Φ_{SM} + Triplet,
…

Additional Symmetry

Discrete or Continuous?
Exact or Approximate or Softly broken?

Interaction

Weakly coupled or strongly coupled?

Hint for BSM models

Rho parameter ➡ Multi-doublet (and singlet) structures
FCNC Suppression ➡ Strong constraint on the Yukawa sector
Higgs alignment ➡ Strong constraint on mixing angles

Deviation in couplings

Scaling factors

$$\boxed{\kappa_X = g_{hXX}^{BSM} / g_{hXX}^{SM}}$$

2HDM :

$$\kappa_V = \sin(\beta - \alpha)$$

$$\kappa_f = \sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha)$$

HSM :

$$\kappa_V = \cos\alpha$$

$$\kappa_f = \cos\alpha$$

Deviation comes due to mixing and also quantum corrections of BSM particles

	Mixing factor		
	ξ_u	ξ_d	ξ_e
Type-I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	$\cot\beta$	$-\tan\beta$	$\cot\beta$

$$\frac{\Gamma(h \to VV^*)_{BSM.}}{\Gamma(h \to VV^*)_{SM}} \sim \kappa_V^2$$

$$\frac{\Gamma(h \to ff)_{BSM.}}{\Gamma(h \to ff)_{SM}} \sim \kappa_f^2$$

1^{st} OPT by nondecoupling quantum effect

Effective Potential at finite T (HTE)

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

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

SM: The condition cannot be satisfied

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

$$\frac{\phi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + \underbrace{\sum_\Phi n_\Phi m_\Phi^3\left(1 - \frac{M^2}{m_\Phi^2}\right)^{3/2}}_{\text{Quantum effects of }\Phi(=H,\,A,\,H^+,\,\cdots)}\right\} > 1$$

(when $M \ll m_\Phi$)

Prediction: Large deviation in the hhh coupling

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

SK, Okada, Senaha, Yuan, 04

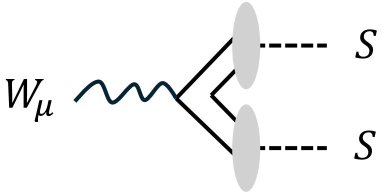
Grojean, Servant, Wells, 2005

SK, Y. Okada, E. Senaha, 2005

Gauge and Yukawa interactions

- Gauge interactions: flavor symmetry is partially gauged. Mrazek et al., NPB (2011), and more

$$\mathcal{L}_{\text{gauge}} = \overline{T}_i (i\bar{\sigma}^\mu)\left(-ig(T^a)_i \cdot W_\mu^a - ig'(2y_i)\frac{\sigma^3}{2} B_\mu\right) T_i$$

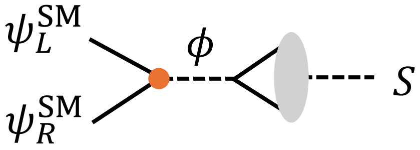


- Yukawa interactions: similar mechanism to partial compositeness Kaplan, NPB (1991); Agashe et al., NPB (2005);

$$\mathcal{L}_{\text{UV}} = -\mathcal{F}\,\overline{\psi_L^{\text{SM}}}\psi_R^{\text{SM}}\phi - \mathcal{G}_S (TT)_S \phi^\dagger + \text{h.c.}$$

-> $\mathcal{L}_{\text{eff}} = -\dfrac{\mathcal{F}\mathcal{G}_S}{M_{\Phi_S}^2}\,\overline{\psi_L^{\text{SM}}}\psi_R^{\text{SM}}(TT)_S$ (integ. out ϕ)

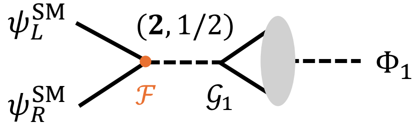
-> $\mathcal{L}_Y = -\mathcal{F}\mathcal{G}_S \dfrac{\Lambda_H^2}{M_{\Phi_S}^2}\,\overline{\psi_L^{\text{SM}}}\psi_R^{\text{SM}} S$ (confinement)



-> minimal flavor violation is naturally realized.

● breaks SM chiral symmetry / quark flavor symmetry

e.g., for 2HDM, Yukawa alignment: S = Φ_1, Φ_2 Pich and Tuzon, PRD (2009)



$$\mathcal{L}_Y = -\mathcal{F}\mathcal{G}_1 \frac{\Lambda_H^2}{M_{\Phi_S}^2}\,\overline{\psi_L^{\text{SM}}}\psi_R^{\text{SM}}\Phi_1 - \mathcal{F}\mathcal{G}_2 \frac{\Lambda_H^2}{M_{\Phi_S}^2}\,\overline{\psi_L^{\text{SM}}}\psi_R^{\text{SM}}\Phi_2$$

$\mathcal{F}$: matrix in flavor space
$\mathcal{G}_{1,2}$: constants