An extended Higgs model as the common origin of ν mass, dark matter and baryon asymmetry

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Based on

- Mayumi Aoki[1], KE, Shinya Kanemura[2], arXiv: 2212.14786
  to be published by PRD

1 Kanazawa University, 2. Osaka University

Introduction

The extended Higgs sector play an important role
to explain the unexplained phenomena in the SM

ν mass ⋯ radiative seesaw models

Dark matter (DM) ⋯ New scalar as WIMP

Baryon asymmetry ⋯ Electroweak baryogenesis (EWBG)

A new physics model with the extended Higgs sector
for these 3 problems Aoki, Kanemura, Seto (2009)

- Tiny ν masses : Quantum correction via **3-loop diagrams**
- DM : Z_2 **symmetry** (New Z_2-odd neutral particles)
- BAU : **Electroweak baryogenesis** by extended Higgs sector
- Masses of new particles are $O(100)$ GeV -> **Testable!**

EWBG in this model had not been evaluated
We evaluated it and find one benchmark scenario where
all 3 problems can be explained

<u>The model</u> Aoki, Kanemura, Seto (2009)
Aoki, KE, Kanemura (2022)

Scalar Bosons

Z_2-even) $\Phi_1,\ \Phi_2 : (\mathbf{2},\ +1/2)$

Z_2-odd) $S^+ : (\mathbf{1},\ +1),\quad \eta : (\mathbf{1},\ 0)$ real scalar

Extension of 2-Higgs doublet model

Type-III 2HDM

$$\mathscr{V} = V_\Phi(\Phi_1,\Phi_2) + V_{S\eta}(\Phi_1,\Phi_2,S^+,\eta)$$

CP-violation

Φ_2

$$\mathscr{V}_{CPV} = \mathbf{Im}\Big[\mu_{12}^2\Phi_1^\dagger\Phi_2 + (\Phi_1^\dagger\Phi_2)\Big\{\cancel{\frac{\lambda_5}{2}\Phi_1^\dagger\Phi_2} + \lambda_6|\Phi_1|^2 + \lambda_7|\Phi_2|^2\Big\}$$

$$+\rho_{12}(\Phi_1^\dagger\Phi_2)|S^+|^2 + \frac{\sigma_{12}}{2}(\Phi_1^\dagger\Phi_2)\eta^2 + \cancel{2\kappa(\Phi_1^\dagger\Phi_2)S^-\eta}\Big]$$

$S^\pm$

6 CP-violating couplings

Aoki, Kanemura, Seto (2009)
Aoki, KE, Kanemura (2022)

Mass of Neutral Higgs Bosons

Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + H_1 + iG^0) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_2 + iH_3) \end{pmatrix}$$

$$M_{\mathrm{neutral}} \propto \begin{array}{c c} \begin{array}{ccc} H_1 & H_2 & H_3 \end{array} & \\ \begin{pmatrix} M_{11} & \mathrm{Re}[\lambda_6] & -\mathrm{Im}[\lambda_6] \\ & M_{22} & \cancel{-\mathrm{Im}[\lambda_5]/2} \\ & & M_{33} \end{pmatrix} & \begin{array}{c} H_1 \\ H_2 \\ H_3 \end{array} \end{array}$$

Φ_2

In the limit

$\lambda_6 \to 0$ ➡ Mixings vanish [Higgs alignment].

(Higgs couplings coincide with SM ones)

The model

Aoki, Kanemura, Seto (2009)

Aoki, KE, Kanemura (2022)

Higgs alignment scenario

Simple scenario $\lambda_6 = 0$

Kanemura, Kubota, Yagyu (2020); (2021)

KE, Kanemura, Mura (2022); (2022)

Kanemura, Takeuchi, Yagyu (2022)

- H_1, H_2, H_3 are mass eigenstates w/o mixing

(H_1 is 125GeV Higgs boson)

- 3 CPV couplings in the Higgs potential

$\lambda_6 = 0$ (+ Stationary condition)

Φ_2

$\lambda_6 = 0$

$$\mathscr{V}_{CPV} = \mathbf{Im}\Big[\cancel{\mu_{12}^2\Phi_1^\dagger\Phi_2} + (\Phi_1^\dagger\Phi_2)\{\cancel{\frac{\lambda_5}{2}\Phi_1^\dagger\Phi_2} + \cancel{\lambda_6|\Phi_1|^2} + \lambda_7|\Phi_2|^2\}$$

$$+\rho_{12}(\Phi_1^\dagger\Phi_2)|S^+|^2 + \frac{\sigma_{12}}{2}(\Phi_1^\dagger\Phi_2)\eta^2 + \cancel{2\kappa(\Phi_1^\dagger\Phi_2)S^-\eta}\Big]$$

$S^\pm$

The model

Aoki, Kanemura, Seto (2009)

Aoki, KE, Kanemura (2022)

Yukawa interaction

Both Higgs doublets couple with the SM fermions.

$$\mathscr{L}_Y = \underbrace{-\frac{m_{fi}}{v}\overline{f_L^i}\, f_R^i H_1}_{\text{SM Yukawa}} + \underbrace{(y_2^f)_{ij}\overline{f_L^i}\, f_R^j (H_2 + iH_3)}_{} + \mathrm{h.c.}$$

$(i, j = 1,2,3)$

SM Yukawa

Non-diagonal y_2^f ➡ *FCNC!*

To avoid FCNC,

(FCNC = Flavor Changing Neutral Current)

- In AKS(2009): Softly broken Z_2 Glashow, Weinberg (1977)
- **Current Work: Flavor Alignment**

$$y_2^f = \underbrace{\frac{1}{v}\begin{pmatrix} m_{f^1} & 0 & 0 \\ 0 & m_{f^2} & 0 \\ 0 & 0 & m_{f^3} \end{pmatrix}}_{\text{SM Yukawa}} \begin{pmatrix} \zeta_{f^1} & 0 & 0 \\ 0 & \zeta_{f^2} & 0 \\ 0 & 0 & \zeta_{f^3} \end{pmatrix}$$

$\zeta_f^i \in \mathbb{C}$

For quarks,

$$\zeta_{u^1} = \zeta_{u^2} = \zeta_{u^3} \equiv \zeta_u$$

$$\zeta_{d^1} = \zeta_{d^2} = \zeta_{d^3} \equiv \zeta_d$$

Pich, Tuzon (2009)

The model

Aoki, Kanemura, Seto (2009)

Aoki, KE, Kanemura (2022)

Yukawa interaction

Z_2-odd Majorana fermions: N_R^a $(a = 1,2,3)$

$$\frac{1}{2} m_{N^\alpha} \overline{(N_R^\alpha)^c} N_R^\alpha$$

Lepton # violating

$$\mathscr{L}_Y = - h_i^\alpha \overline{(N_R^\alpha)^c} \ell_R^i S^+ + \mathrm{h.c.}$$

Lepton flavor violating

$\boxed{\text{Summary of the model}}$

New particles: (Z_2-even) $H^\pm$, H_2, H_3 (Z_2-odd) $S^\pm$, η, N_R^a

Alignment: $\lambda_6 = 0$ & $(y_2^f)_{ij} \propto m_{f^i} \zeta_{f^i} \delta_{ij}$

(H_1 is the SM Higgs) (No FCNC)

CP-violation: λ_7, ρ_{12}, σ_{12} & ζ_u, ζ_d, ζ_τ, ζ_μ, ζ_e, h_i^α

Benchmark scenario (BS) Aoki, KE, Kanemura (2022)

Masses of New particle

Z_2 even: $m_{H^+} = 250$ GeV, $m_{H_2} = 420$ GeV, $m_{H_3} = 250$ GeV

Z_2 odd: $m_S = 400$ GeV, $m_\eta = 63$ GeV

$(m_{N_1}, m_{N_2}, m_{N_3}) = (3000, 3500, 4000)$ GeV

Scalar couplings

$$\mu_2^2 = (50\ \text{GeV})^2, \quad \mu_s^2 = (320\ \text{GeV})^2, \quad \mu_{12}^2 = 0$$

$$\lambda_2 = 0.1, \quad \lambda_3 \simeq 1.98, \quad \lambda_4 \simeq 1.88, \quad \lambda_5 \simeq 1.88, \quad \lambda_6 = 0, \quad |\lambda_7| = 0.82,$$

$$\rho_1 \simeq 1.90, \quad \sigma_1 = |\sigma_{12}| = 1.1 \times 10^{-3}, \quad \kappa = 2.0, \quad \theta_7 = -0.73, \quad \cdots$$

New Yukawa interactions

$$y_t|\zeta_u| = 0.17, \quad y_b|\zeta_d| = 4.2 \times 10^{-3}, \quad y_e|\zeta_e| = y_\mu|\zeta_\mu| = 2.5 \times 10^{-4},$$

$$y_\tau|\zeta_\tau| - 2.5 \times 10^{-3}, \quad \theta_e = \theta_\mu = \theta_\tau = -2.94, \quad \theta_u = \theta_d = 0.245$$

$$h_i^\alpha \simeq \begin{pmatrix} 1.0\,e^{-0.31i} & 0.2\,e^{0.30i} & 1.0\,e^{-2.4i} \\ 1.1\,e^{-1.9i} & 0.21\,e^{-1.8i} & 1.1\,e^{2.3i} \\ 0.45\,e^{2.7i} & 1.3\,e^{-0.033i} & 0.10\,e^{0.63i} \end{pmatrix}, \quad \cdots$$

Constraints

Experimental constraints

$H^{\pm}$: (Direct) $H^{\pm} \to tb$ ATLAS (2021)

(Flavor) $B_d \to \mu^+\mu^-$ J. Haller, et al EPJC (2018)

$H_{2,3}$: (Direct) $H_{2,3} \to \tau\bar{\tau}$ ATLAS (2020)

$H_{2,3} \to t\bar{t}$ ATLAS (2018)

$S^{\pm}$: (Direct) $S^{\pm} \to H^{\pm}\eta \to tb\eta$ (from $Z^*, \gamma^* \to S^+S^-$) Weak constraints

(Flavor) Lepton flavor violating processes (Next slides)

N_R^{α} : (Direct) too heavy and weak constraints ($m_{N^\alpha} =$ 3-4 TeV)

(Flavor) Lepton flavor violating processes (Next slides)

η : Dark matter in the model

(DM searches) 3 Pages later

CP-violating phases : (EDM) 2 Pages later

We checked that all of these constraints can be avoided in the BS

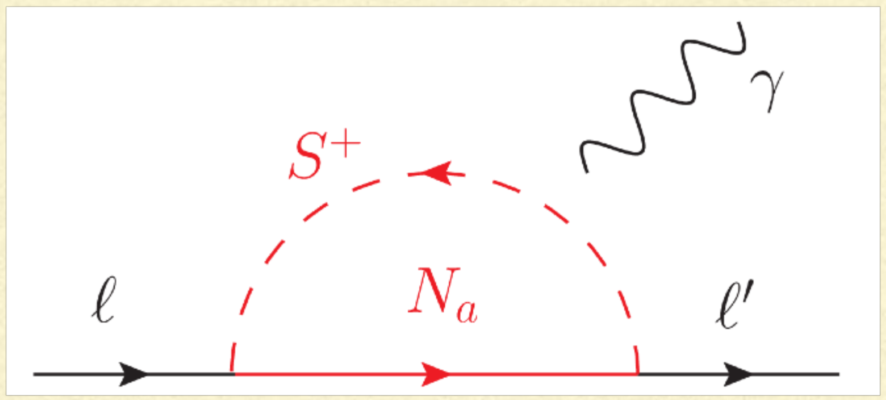
Lepton flavor violation

$m_S = 400$ GeV,

$M_N = \{3000, 3500, 4000\}$ GeV

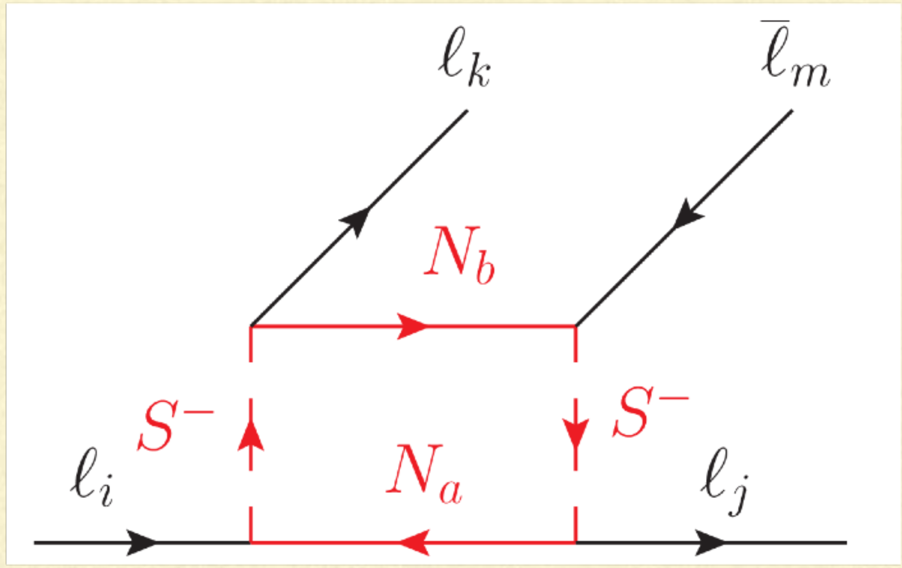
$$h_i^\alpha \simeq \begin{pmatrix} 1.0\,e^{-0.31i} & 0.2\,e^{0.30i} & 1.0\,e^{-2.4i} \\ 1.1\,e^{-1.9i} & 0.21\,e^{-1.8i} & 1.1\,e^{2.3i} \\ 0.45\,e^{2.7i} & 1.3\,e^{-0.033i} & 0.10\,e^{0.63i} \end{pmatrix}$$

■ $\ell \to \ell'\gamma$



Processes	BR	Upper limits
$\mu \to e\gamma$	1.4×10^{-14}	4.2×10^{-13}
$\tau \to e\gamma$	5.3×10^{-10}	3.3×10^{-8}
$\tau \to \mu\gamma$	1.1×10^{-11}	4.4×10^{-8}

■ $\ell_i \to \ell_j \ell_k \overline{\ell}_m$



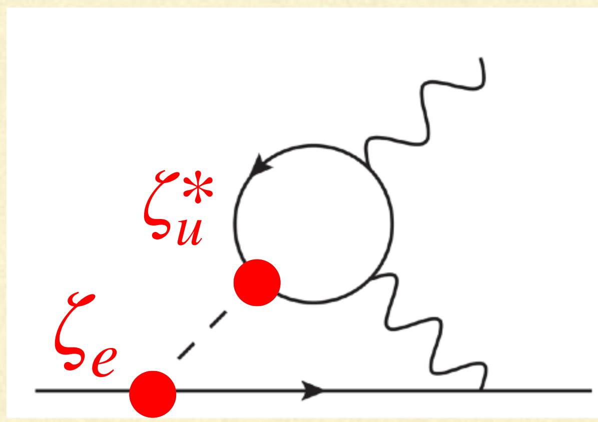
Processes	BR	Upper limits
$\mu \to 3e$	1.0×10^{-13}	1.0×10^{-12}
$\tau \to 3e$	6.2×10^{-10}	2.7×10^{-8}
$\tau \to 3\mu$	2.4×10^{-11}	2.1×10^{-8}
$\tau \to e\mu\bar{e}$	5.1×10^{-12}	1.8×10^{-8}
$\tau \to \mu\mu\bar{e}$	1.1×10^{-12}	1.7×10^{-8}
$\tau \to ee\bar{\mu}$	4.5×10^{-13}	1.5×10^{-8}
$\tau \to e\mu\bar{\mu}$	9.6×10^{-11}	2.7×10^{-8}

Electric dipole moment (EDM)

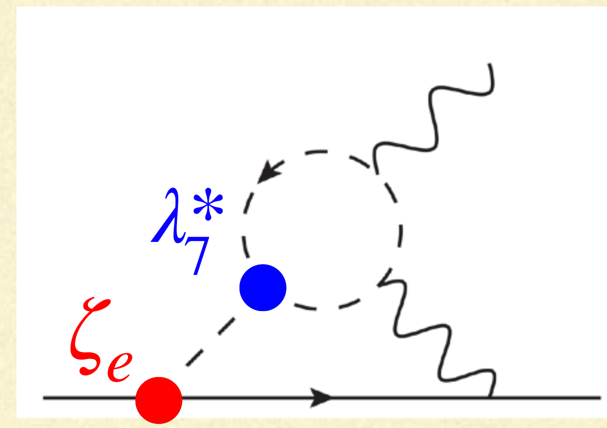
electron EDM (eEDM) $|d_e| < 4.0 \times 10^{-30}$ e cm Roussy, et al (2022)

eEDM can be small by **destructive interference**

Kanemura, Kubota, Yagyu (2020)



$+$



$\propto \sin(\theta_u - \theta_e)$ $\propto \sin(\theta_7 - \theta_e)$

$$m_{H_2} = 420 \text{ GeV}, \quad m_{H_3} = m_{H^\pm} = 250 \text{ GeV}$$
$$\theta_7 = -2.34, \quad \theta_u = 0.245, \quad \theta_e = -2.94$$

$\Rightarrow$ $\boxed{|d_e| = 0.22 \times 10^{-30} \text{ e cm}}$

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

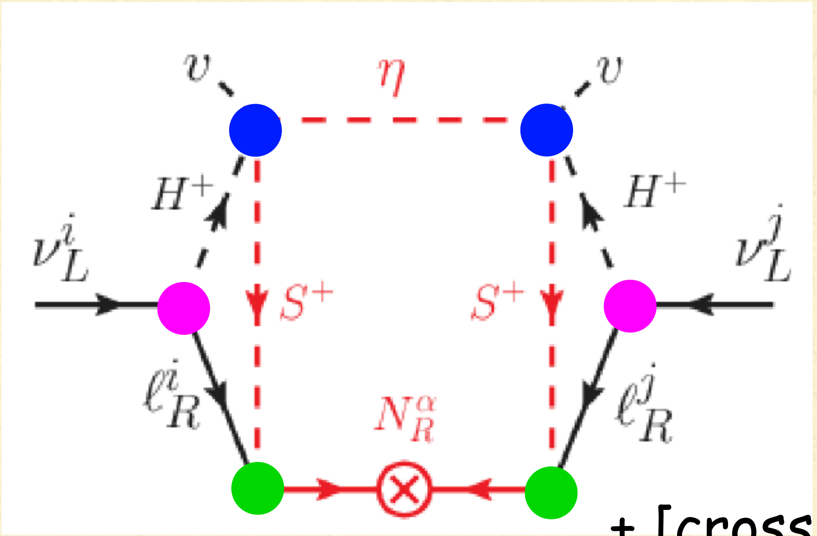
chromo EDM Barr, Zee (1990)

Weinberg ope. Weinberg (1989)

4 fermi interaction Khatsimovsky, Khriplovich, Yelkhovsky (1988)

In the BS, $\boxed{|d_n| \sim 10^{-30} \text{ e cm}}$

ν mass



+ [crossing $S^\pm$ lines]

$\kappa\, \tilde{\Phi}_1 \Phi_2\, S^- \eta$ $\quad h_i^\alpha\, \overline{(N_R^\alpha)^c}\, \ell_{iR}\, S^+$ $\quad \zeta_{\ell^i} y_{\ell^i}\, \overline{\ell_R^i} \nu_L^i H^-$

$$\left(y_e|\zeta_e|,\, y_\mu|\zeta_\mu|,\, y_\tau|\zeta_\tau|\right) = (0.25, 0.25, 2.5) \times 10^{-3}$$

$\theta_{\ell^i} = -2.94$

$\kappa = 2.0$

$$h_i^\alpha \simeq \begin{pmatrix} 1.0\, e^{-0.31i} & 0.2\, e^{0.30i} & 1.0\, e^{-2.4i} \\ 1.1\, e^{-1.9i} & 0.21\, e^{-1.8i} & 1.1\, e^{2.3i} \\ 0.45\, e^{2.7i} & 1.3\, e^{-0.033i} & 0.10\, e^{0.63i} \end{pmatrix}$$

Normal ordering m_ν w/ $\quad m_{\nu^1} \simeq 0.006$ eV

$\delta \simeq 1.36\pi, \quad \alpha_1 \simeq 0, \quad \alpha_2 \simeq -\pi/2$

$m_{\beta\beta} \simeq 1$ meV, $\quad \Sigma\, m_{\nu^i} = 0.067$ eV

$m_{\beta\beta} < 35$ meV KamLAND-Zen (2023) $\quad \Sigma\, m_{\nu^i} < 0.12$ eV Planck (2018)

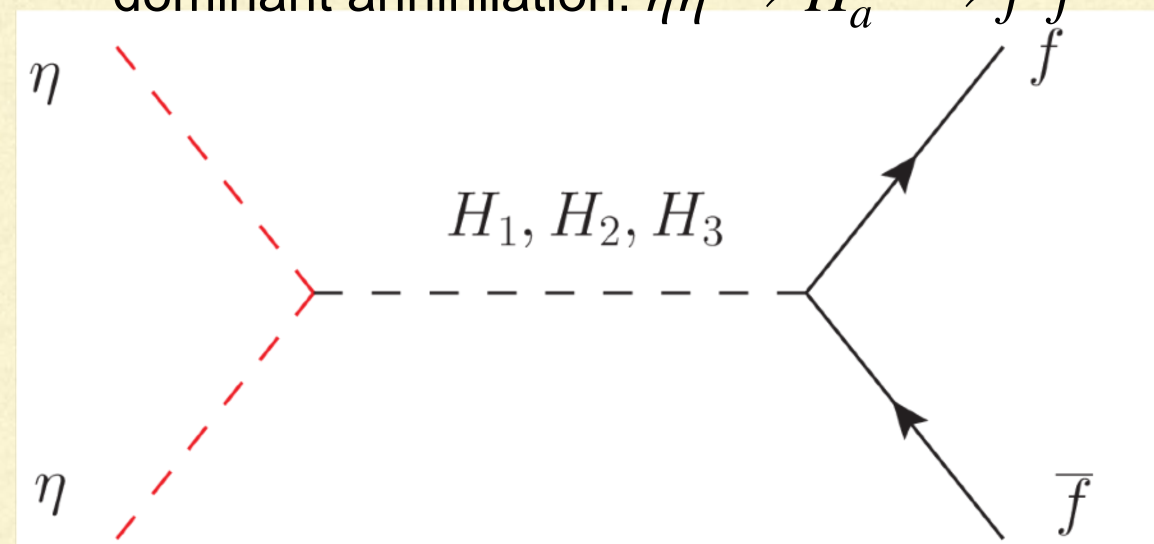
Dark matter (DM)

$m_\eta = 63$ GeV

$(M_{N_1}, M_{N_2}, M_{N_3}) = (3000, 3500, 4000)$ GeV

η: real scalar DM

dominant annihilation: $\eta\eta \to H_a^{(*)} \to f^i f^i$



$m_\eta = 63$ GeV, $m_{H_2} = 420$ GeV, $m_{H_3} = 250$ GeV

$\sigma_1 = |\sigma_{12}| = 1.1 \times 10^{-3}, \quad \theta_\rho = -2.94$

$$\Omega_\eta h^2 \simeq 0.12, \quad \sigma_{\rm SI} = 2.3 \times 10^{-48}\ {\rm cm}^2$$

$\Omega_{\rm DM} h^2 = 0.120(01)$ Planck (2018) $\quad \sigma_{\rm SI} \lesssim 10^{-47}$ LZ (2022)

Electroweak baryogenesis (EWBG)

The Sakharov conditions Sakharov (1967)

1. B-violation ← - - - - - - Sphaleron transition
2. C and CP violation ← - - - - - - CPV phases : $\lambda_7, \rho_{12}, \sigma_{12}, \zeta_u, \zeta_d, \zeta_\ell$
3. Departure from thermal equilibrium ← - - - - - - Strongly 1st order electroweak phase transition

Strongly 1st EWPT (EWPT = ElectroWeak Phase Transition)

Non-decoupling effect by $H_{2,3}$, $H^\pm$, $S^\pm$

$$m_{H^+}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2, \quad m_{H_{2,3}}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5)v^2, \quad m_S^2 = \mu_S^2 + \frac{1}{2}\rho_1 v^2$$

$$m_{H^+} = 250 \text{ GeV}, \quad m_{H_2} = 420 \text{ GeV}, \quad m_{H_3} = 250 \text{ GeV}, \quad m_S = 400 \text{ GeV}$$

$$\lambda_3 \simeq 1.98, \quad \lambda_4 \simeq 1.88, \quad \lambda_5 \simeq 1.88, \quad \rho_1 \simeq 1.90$$

We evaluated one-loop effective potential in Landau gauge Coleman, Weinberg (1973) Dolan, Jackiw (1974)

$(T = 0)$ Kanemura, et al (2003) Kanemura, et al (2004)

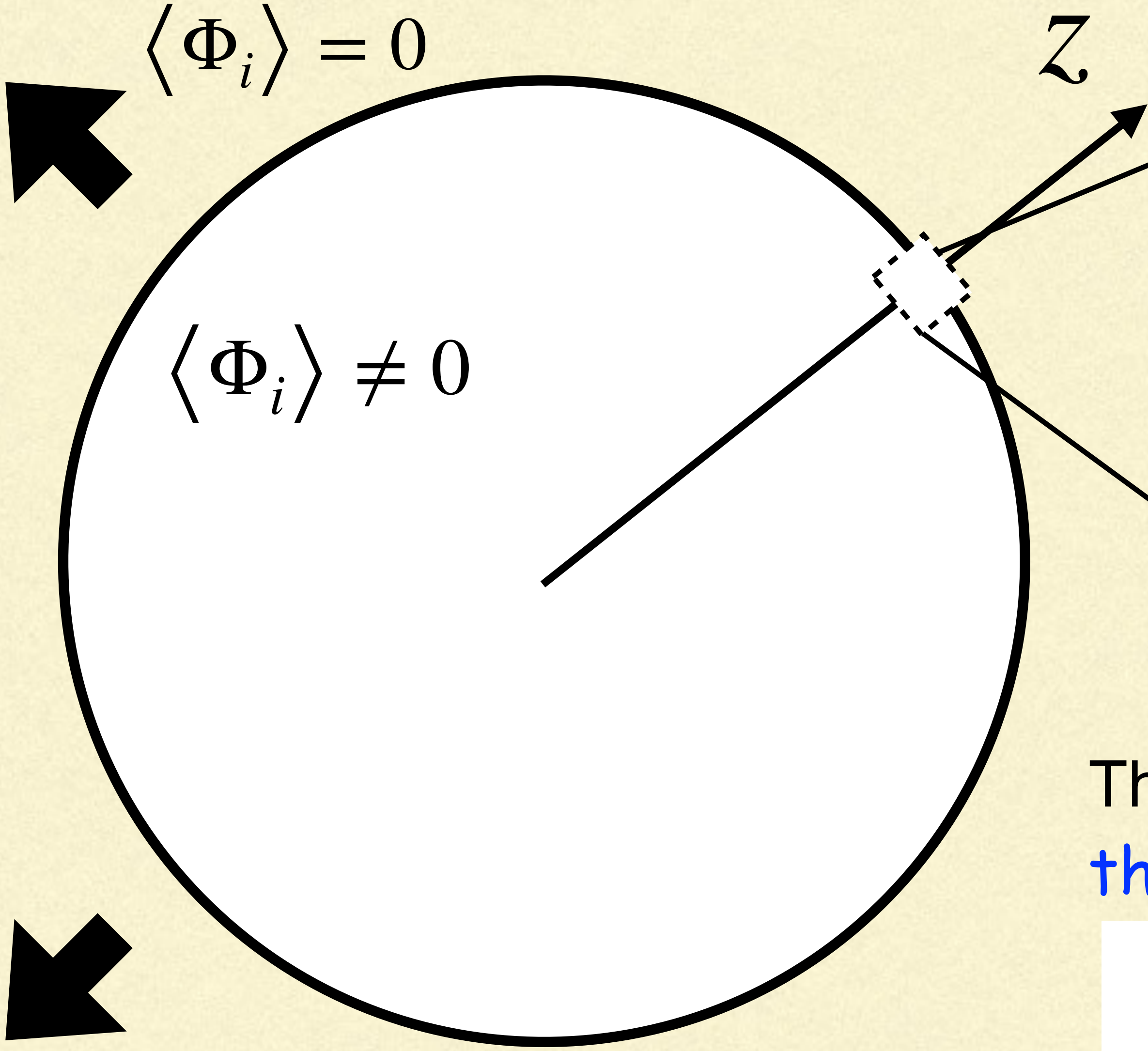
$$\Delta R \equiv \lambda_{hhh}/\lambda_{hhh}^{SM} - 1 = 38\ \%$$

$(T \neq 0)$ thermal resummation Parwani (1992)

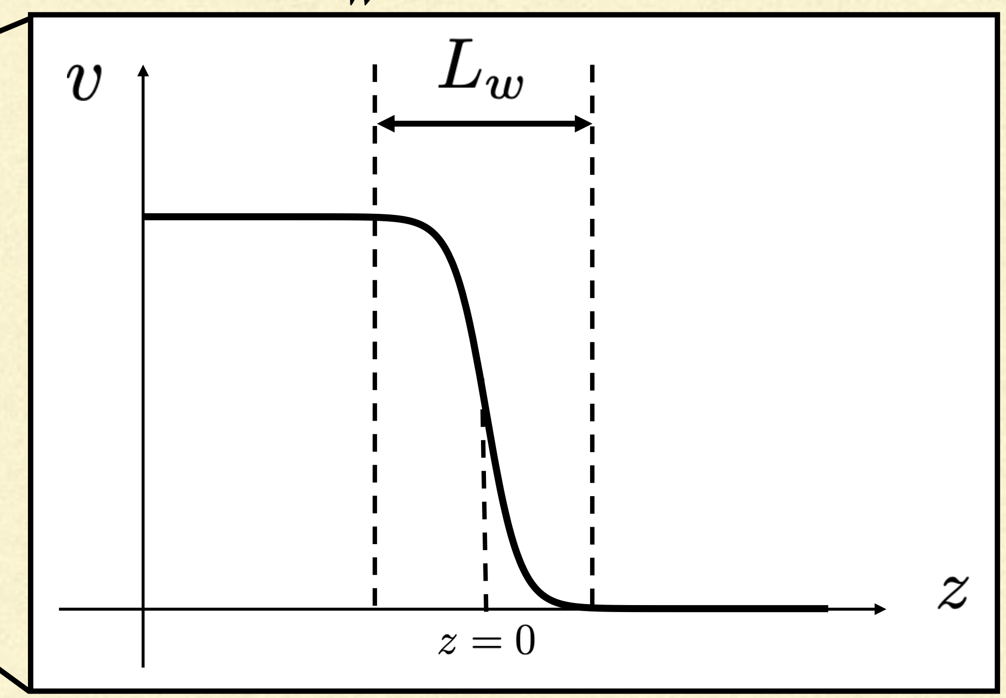
$$v_n/T_n = 1.74 > 1$$

Kuzmin, Rubakov, Shaposhnikov (1985)

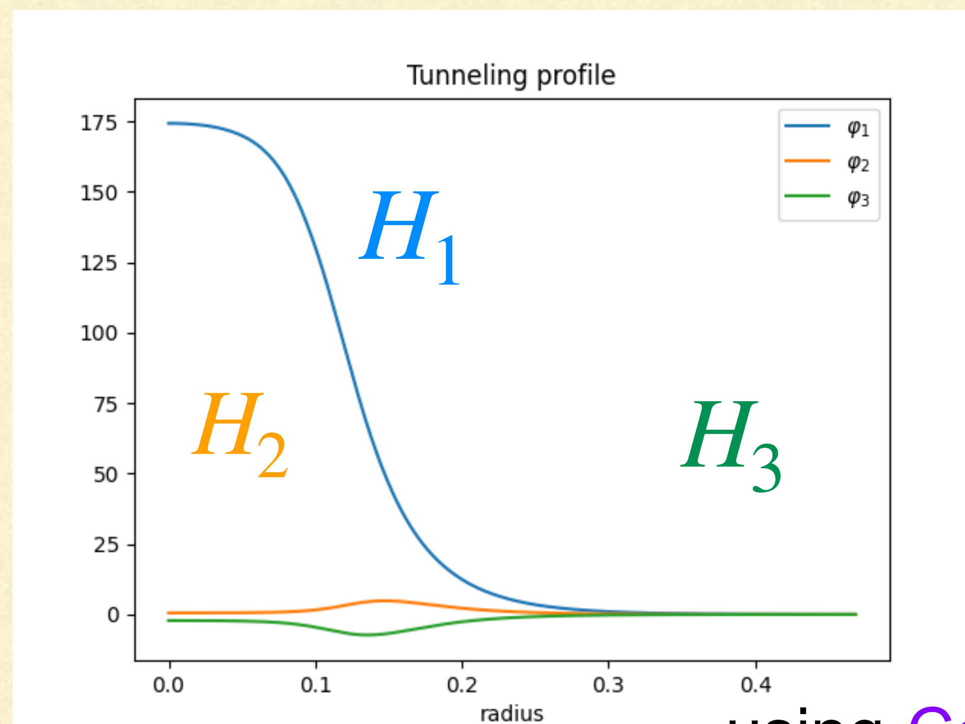
Electroweak baryogenesis



L_w: Wall width



The bubble wall profile is given by
the bounce solution of the effective potential



using CosmoTransition

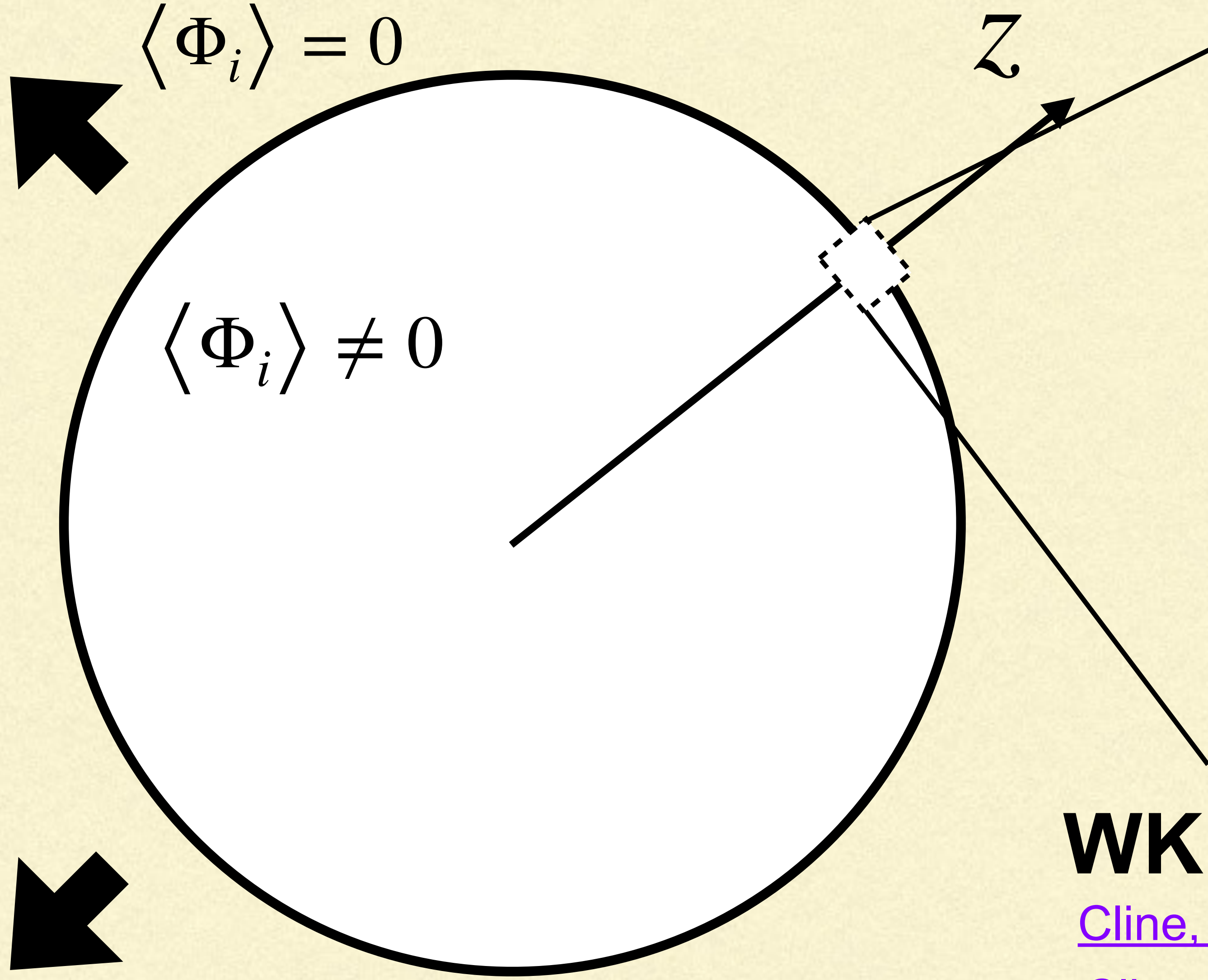
v_w: wall velocity

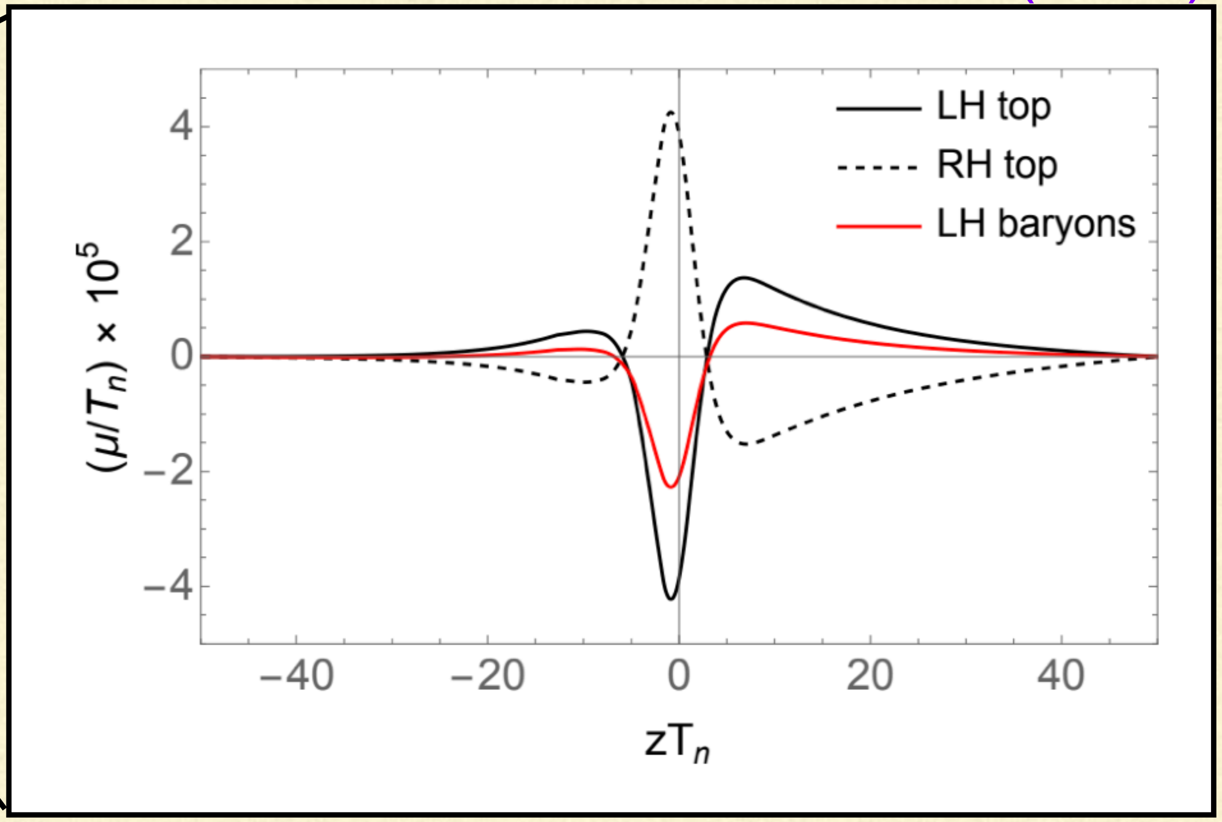
$v_w = 0.1$ is assumed

(In the case of the SM plasma, $v_w = O(0.1)$)

Electroweak baryogenesis

Aoki, KE, Kanemura (2022)





WKB approximation $(L_w T_n \gg 1)$

Cline, Joyce, Kainulainen (2000) Fromme, Huber (2007)

Cline, Kainulainen (2020)

v_w: wall velocity

$v_w = 0.1$ is assumed

Baryon-to-photon ratio

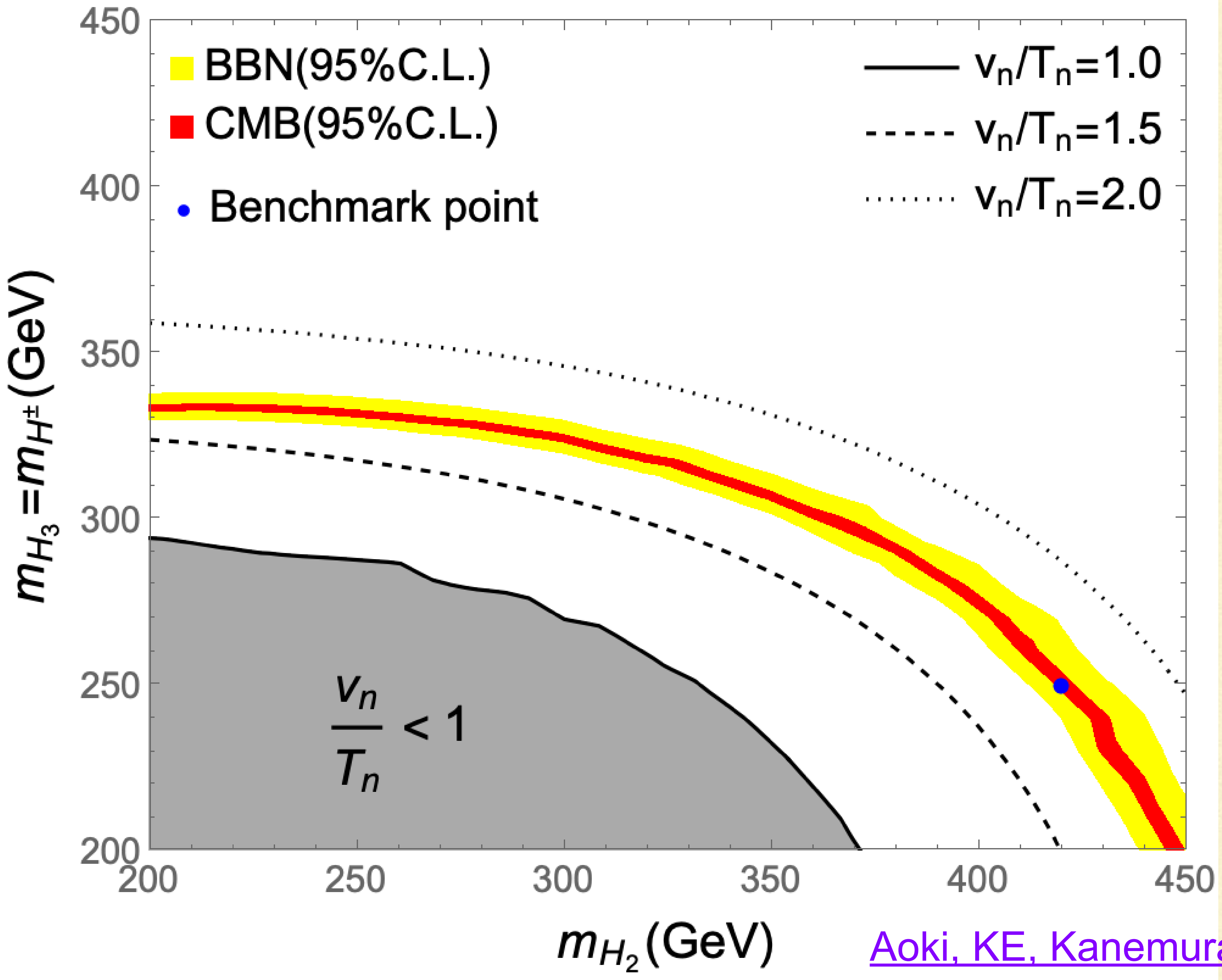
$$\boxed{\eta_B = \frac{n_B}{n_\gamma} \sim \Gamma_{ws} \int_0^\infty \mathrm{d}z\, \mu_{q_L} e^{-kz}}$$

BBN) $5.8 \times 10^{-10} \leq \eta_B \leq 6.5 \times 10^{-10}$ Fields, et al (2020)

CMB) $6.04 \times 10^{-10} \leq \eta_B \leq 6.20 \times 10^{-10}$ Planck (2018)

$\eta_B = 6.17 \times 10^{-10}$

Electroweak baryogenesis



Aoki, KE, Kanemura (2022)

Other parameters are the same with those in the BS

How to test the BS

EDM measurements

- One order improvement is expected in future ACME experiment ACME(2018)

Flavor experiments

- $B \to X_s\gamma$ or $B_d^0 \to \mu^+\mu^-$ in Belle-II experiments E. Kou, et al [Bell-II], arXiv:1808.10567 [hep-ex]
- CP violation in $B \to X_s\gamma$ (ΔA_{CP}) Benz, Lee, Neubert, Paz (2011); Watanuki et al [Belle] (2019)
- Lepton flavor violating decays $\mu \to e\gamma$ MEG-II $\mu \to 3e$, $\tau \to 3e$ Belle-II

Collider experiments

- $gg \to H_2, H_3;\ gg \to H^\pm tb;\ q\bar{q} \to H_{2,3}H^\pm$ Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu (2021); S. Kanemura, M. Takeuchi, K. Yagyu (2021)
- $q\bar{q} \to S^+S^-;\ e^+e^- \to S^+S^-;\ e^+e^- \to NN$ M. Aoki, S. Kanemura, O. Seto (2009)
- Higgs triple coupling $\Delta R = \dfrac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{SM}} = 38\ \%$

  Sensitivity @ ILC ($\sqrt{s} = 500$ GeV)
  $\Delta R = 27\ \%$ K. Fujii, et al, arXiv:1506.05992 [hep-ph]
- Azimuthal angle distribution of $H_{2,3} \to \tau\bar{\tau}$ at e^+e^- collider

  S. Kanemura, M. Kubota, K. Yagyu, JHEP (2021)

Dark matter direct detection

Observation of gravitational waves

The detailed study is a work in progress.

Summary

- The SM cannot explain some observed phenomena (tiny ν masses, DM, BAU), therefore, we need physics beyond the SM.

- In the previous work, the authors proposed a model where tiny ν masses, DM, and BAU can be explained simultaneously at TeV-scale.
  However, they neglected CPV phases for simplicity.

- We have revisited the model and found a new benchmark scenario including CPV phases, where tiny ν masses, dark matter, and BAU can be explained under the constraints from the current experiments. (LFV, EDM, …) .

- This benchmark scenario includes some new particles at a few hundred GeV scale, and they would be testable at various future experiments.

Thank you for listening!

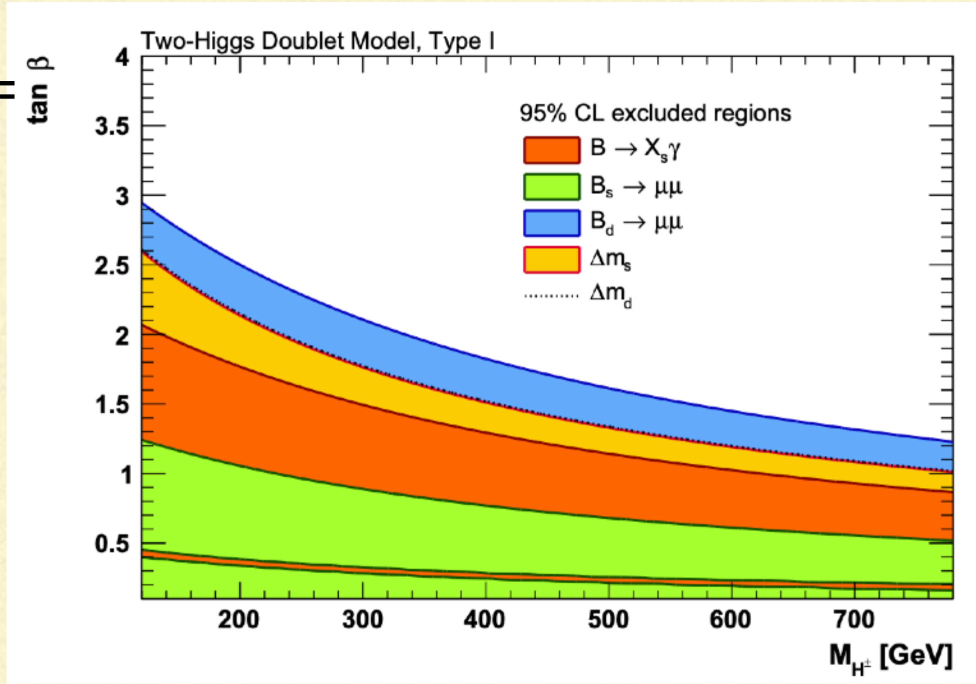
Backup Slides

Constraint from flavor experiments

Figures from [Haller, Hoecker, Kogler, Mooing, Peiffer, Stelzer, EPJC (2018)]

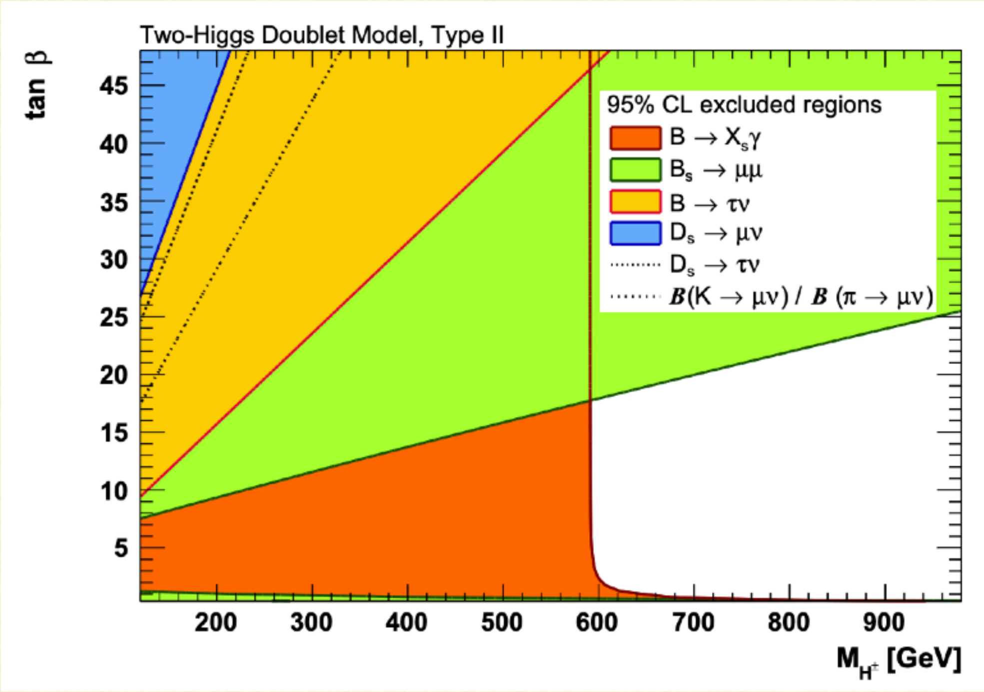
$|\zeta_u| = |\zeta_d| = |\zeta_{\ell^i}|$

$\frac{1}{|\zeta_u|} =$



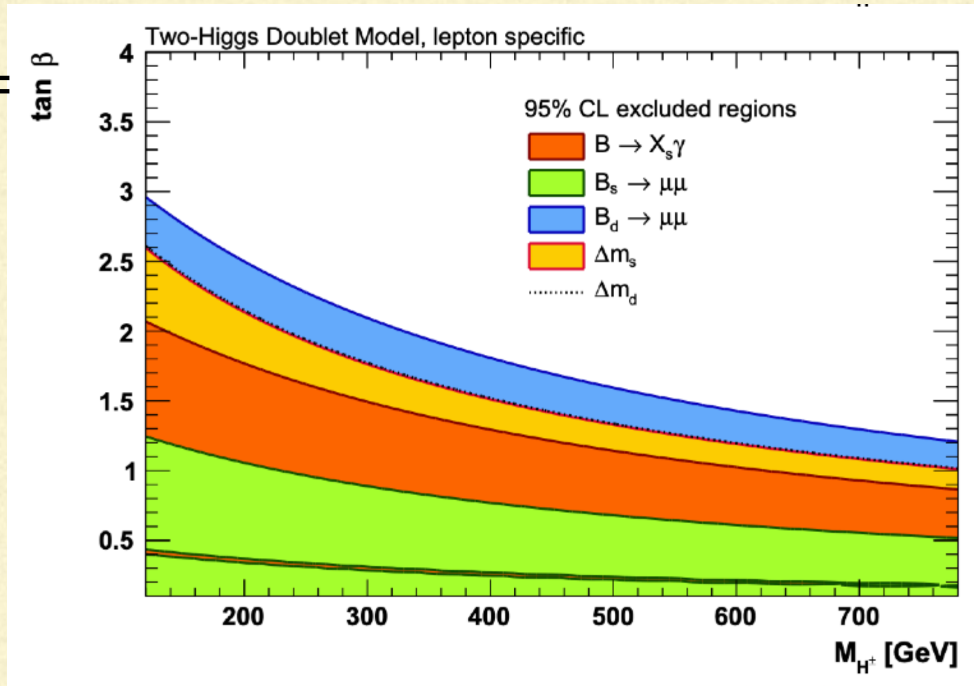
$|\zeta_u| = 1/|\zeta_d| = 1/|\zeta_{\ell^i}|$

$\frac{1}{|\zeta_u|} =$



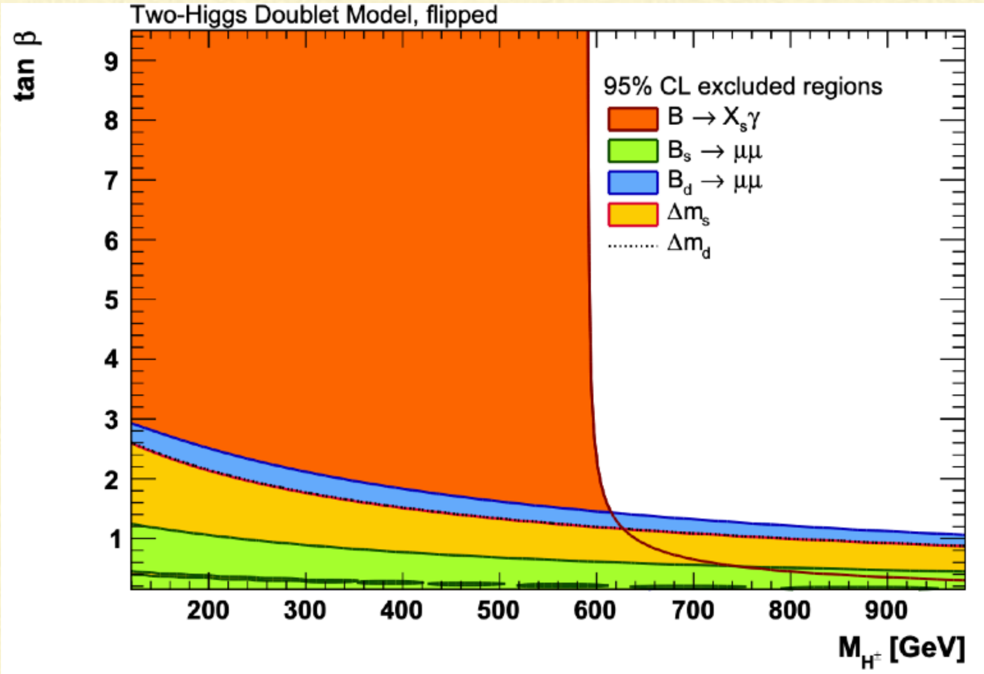
$|\zeta_u| = |\zeta_d| = 1/|\zeta_{\ell^i}|$

$\frac{1}{|\zeta_u|} =$



$|\zeta_u| = 1/|\zeta_d| = |\zeta_{\ell^i}|$

$\frac{1}{|\zeta_u|} =$

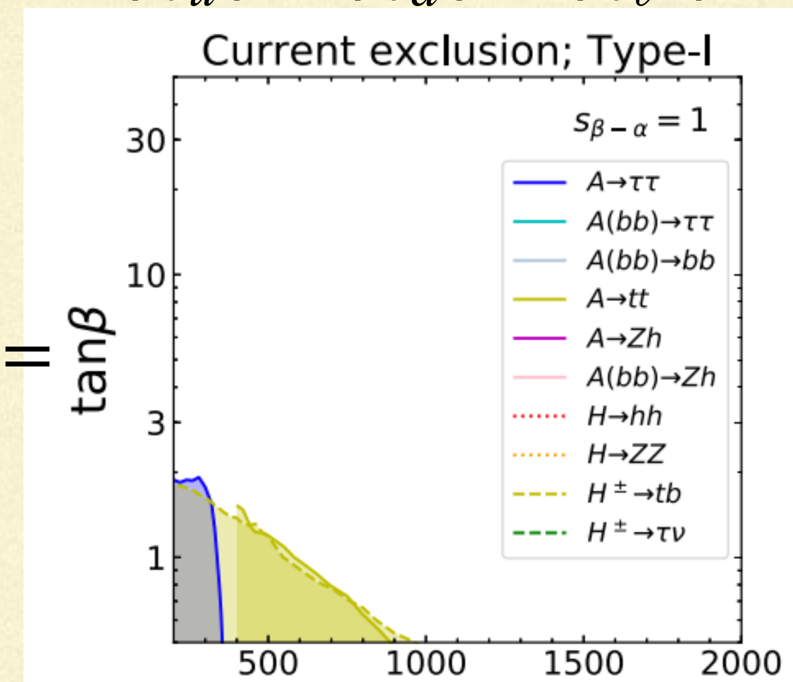


Constraint from flavor experiments

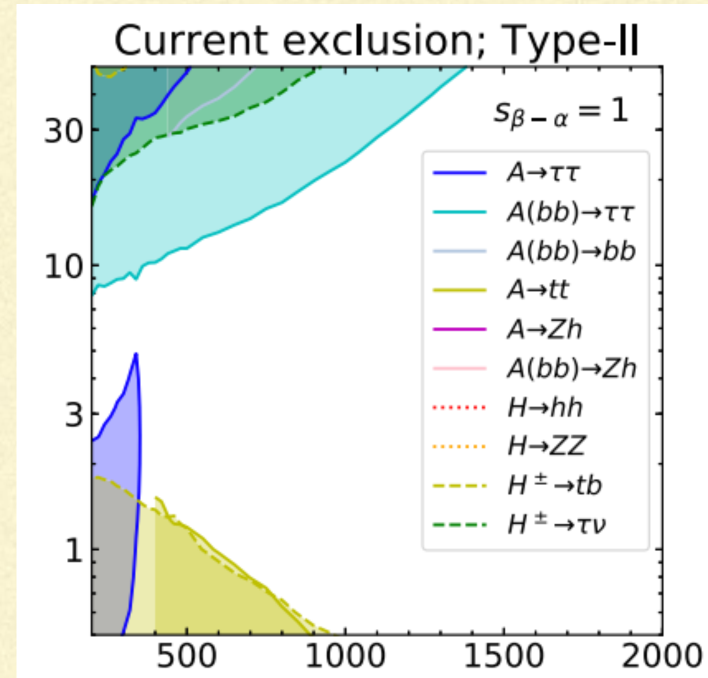
Figures from Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, NPB (2021)

$|\zeta_u| = |\zeta_d| = |\zeta_{\ell^i}|$

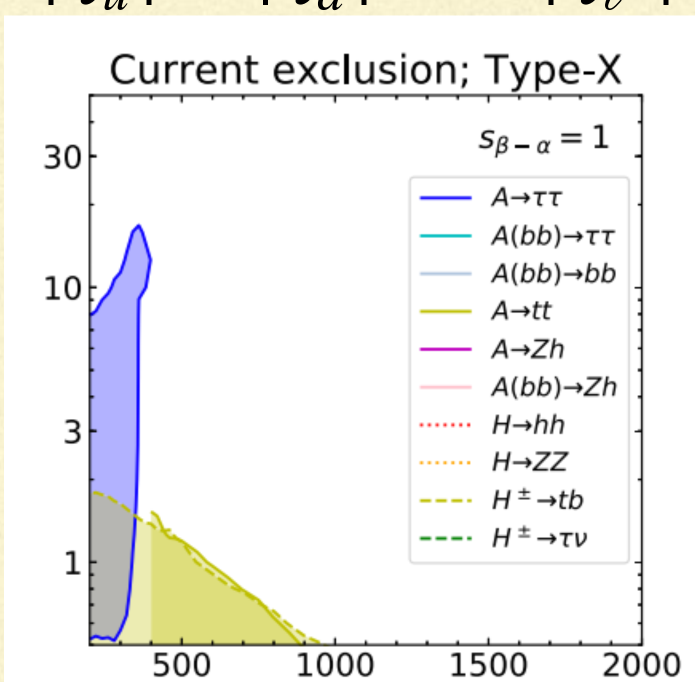
$\frac{1}{|\zeta_u|} =$



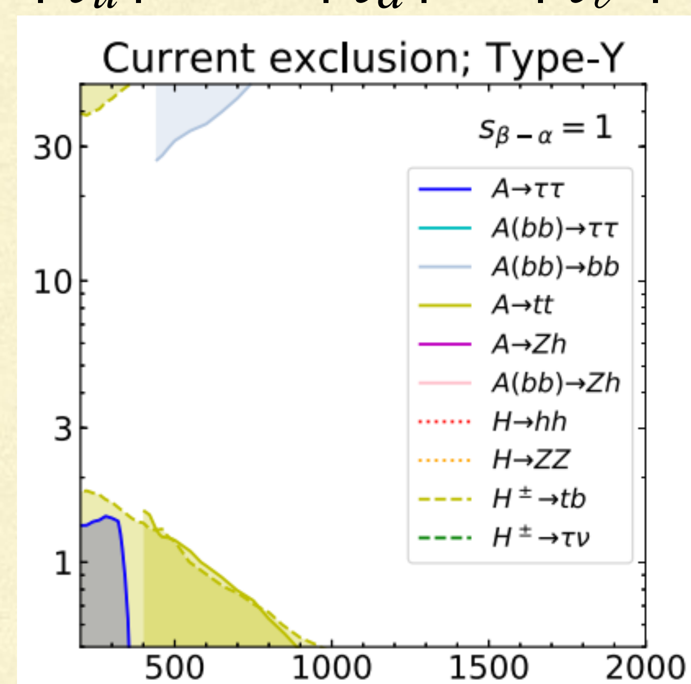
$|\zeta_u| = 1/|\zeta_d| = 1/|\zeta_{\ell^i}|$



$|\zeta_u| = |\zeta_d| = 1/|\zeta_{\ell^i}|$



$|\zeta_u| = 1/|\zeta_d| = |\zeta_{\ell^i}|$

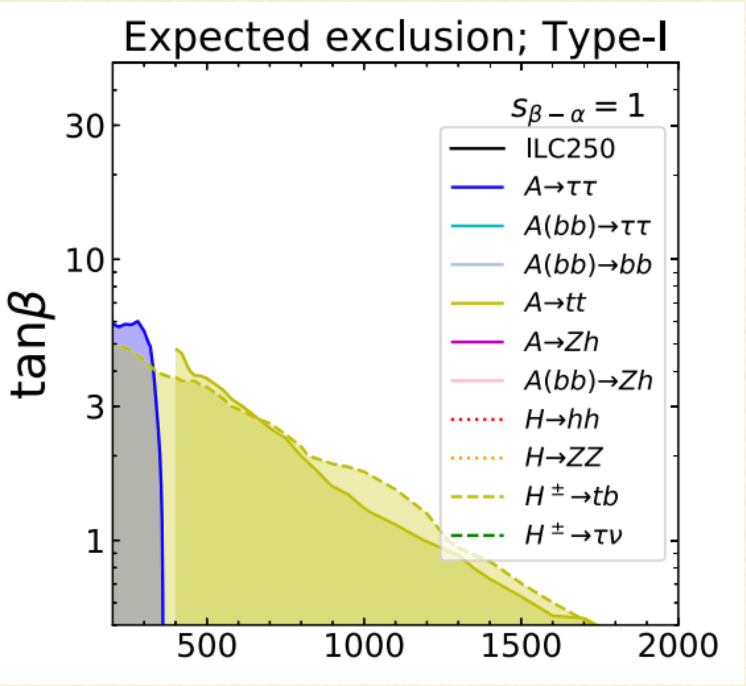


Future direct search at HL-LHC

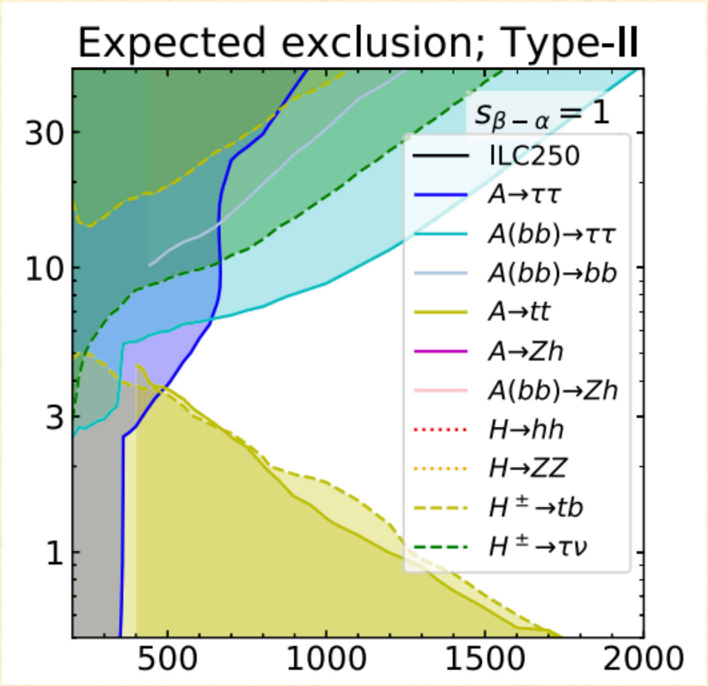
Figures from Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, NPB (2021)

$\frac{1}{|\zeta_u|} =$

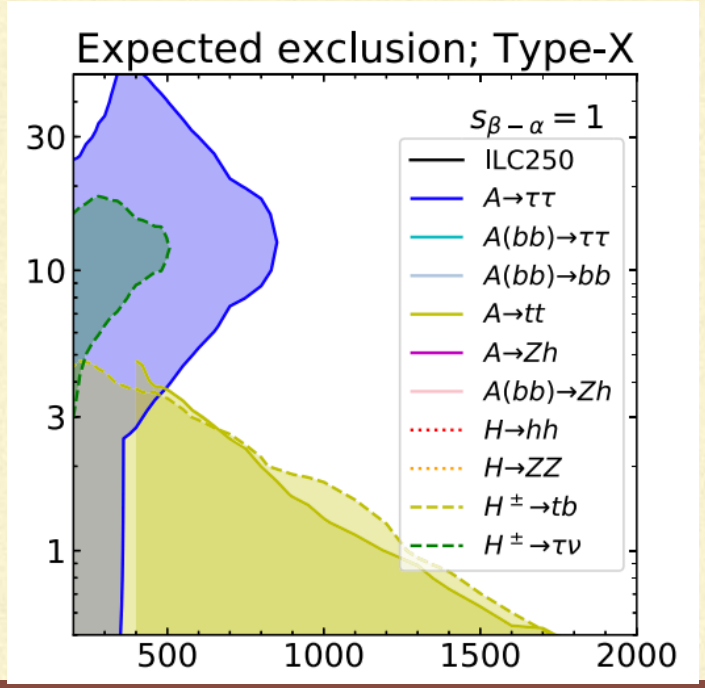
$|\zeta_u| = |\zeta_d| = |\zeta_{\ell^i}|$



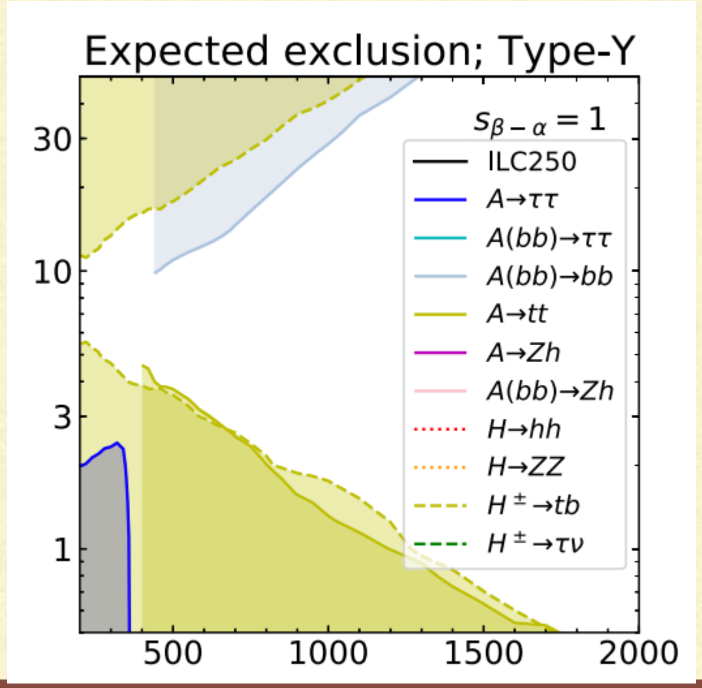
$|\zeta_u| = 1/|\zeta_d| = 1/|\zeta_{\ell^i}|$



$|\zeta_u| = |\zeta_d| = 1/|\zeta_{\ell^i}|$



$|\zeta_u| = 1/|\zeta_d| = |\zeta_{\ell^i}|$

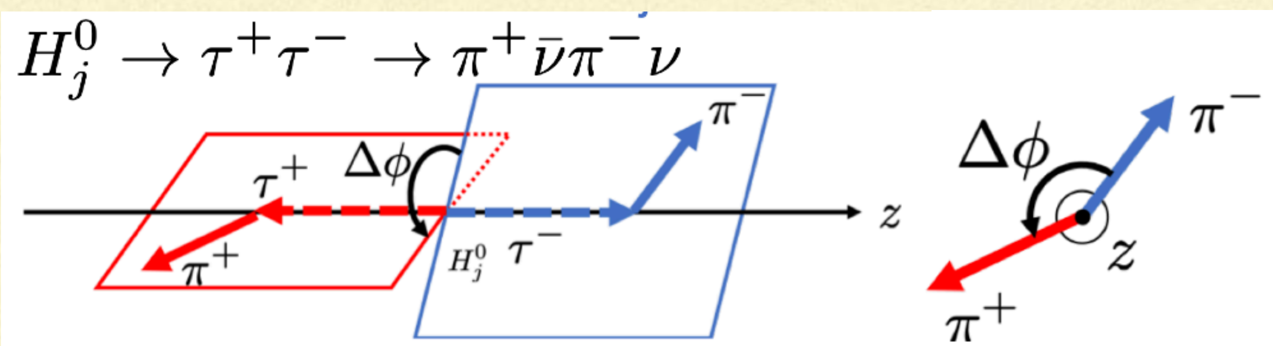


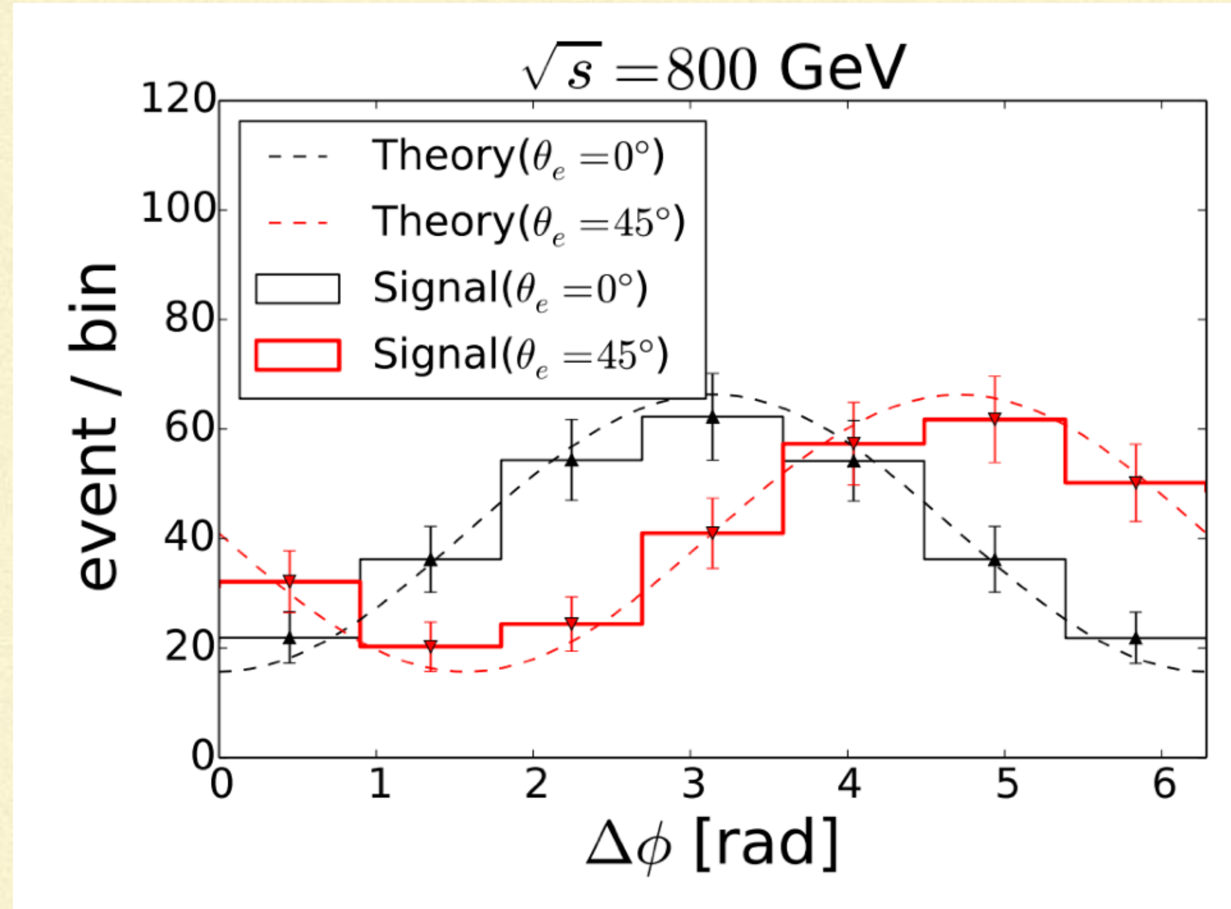
Future test of CP-violation in ζ_τ

At e^+e^- collider

[Kanemura, Kubota, Yagyu, JHEP (2021)]

$$e^+e^- \to H_2H_3 \to \tau^+\tau^-b\bar{b}$$





$M = 240,$	$m_{H_2^0} = 280,$	$m_{H_3^0} = 230,$	$m_{H^\pm} = 230$	(in GeV)
$\lvert\zeta_u\rvert = 0.01,$	$\lvert\zeta_d\rvert = 0.1,$	$\lvert\zeta_e\rvert = 0.5,$	$\lvert\lambda_7\rvert = 0.3,$	$\lambda_2 = 0.5$
$\theta_u = 1.2,$	$\theta_d = 0,$	$\theta_e = \pi/4,$	$\theta_7 = -1.8$	(in radian)

Bubble profiles and nucleation temperature

Euclidean action : $S_E = \int \mathrm{d}^d x \left\{ \frac{1}{2}(\partial_\mu \varphi)^2 + V_{eff}(\varphi) \right\}$ Finite temperature $d = 3$

Rate of the nucleation per volume : $\Gamma/V = \omega T^4 e^{-S_E/T} \ \big(\omega = \mathcal{O}(1)\big)$

Probability of the bubble nucleation per one Hubble volume is $\mathcal{O}(1)$ ➡ $\boxed{\frac{S_E}{T_n} \sim 140}$ T_n: Nucleation temperature

Bubble profile is given by the bounce solution

$$\frac{\mathrm{d}^2\varphi}{\mathrm{d}\rho^2} + \frac{2}{\rho}\frac{\mathrm{d}\varphi}{\mathrm{d}\rho} = \nabla V_{eff}$$

(Boundary)

$$\varphi(\infty) = \varphi_F \qquad \left.\frac{\mathrm{d}\varphi}{\mathrm{d}\rho}\right|_{\rho=0} = 0$$

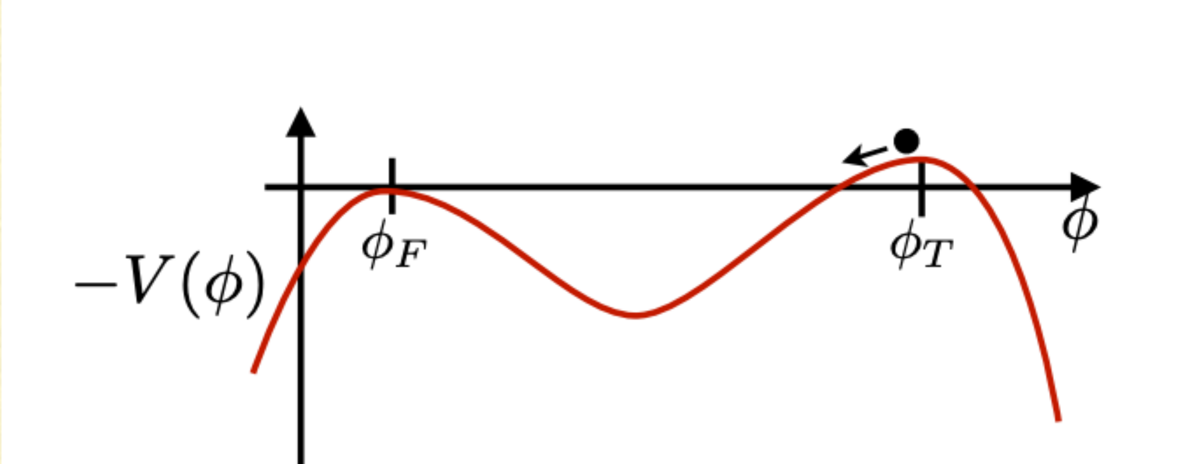


Figure from 1109.4189

Wall width dependence of BAU

In the WKB method, generated baryon asymmetry is roughly estimated as

$$\eta_B \sim \int_0^\infty dz\, \frac{S(z)}{T^3} - A \int_{-\infty}^\infty dz \frac{S(z)}{T^3}$$

Cline, Laurent, PRD (2021)

A is a function of v_w and L_w

v_w : wall velocity

L_w : wall width

When A has a certain value, the first and second terms are canceled.

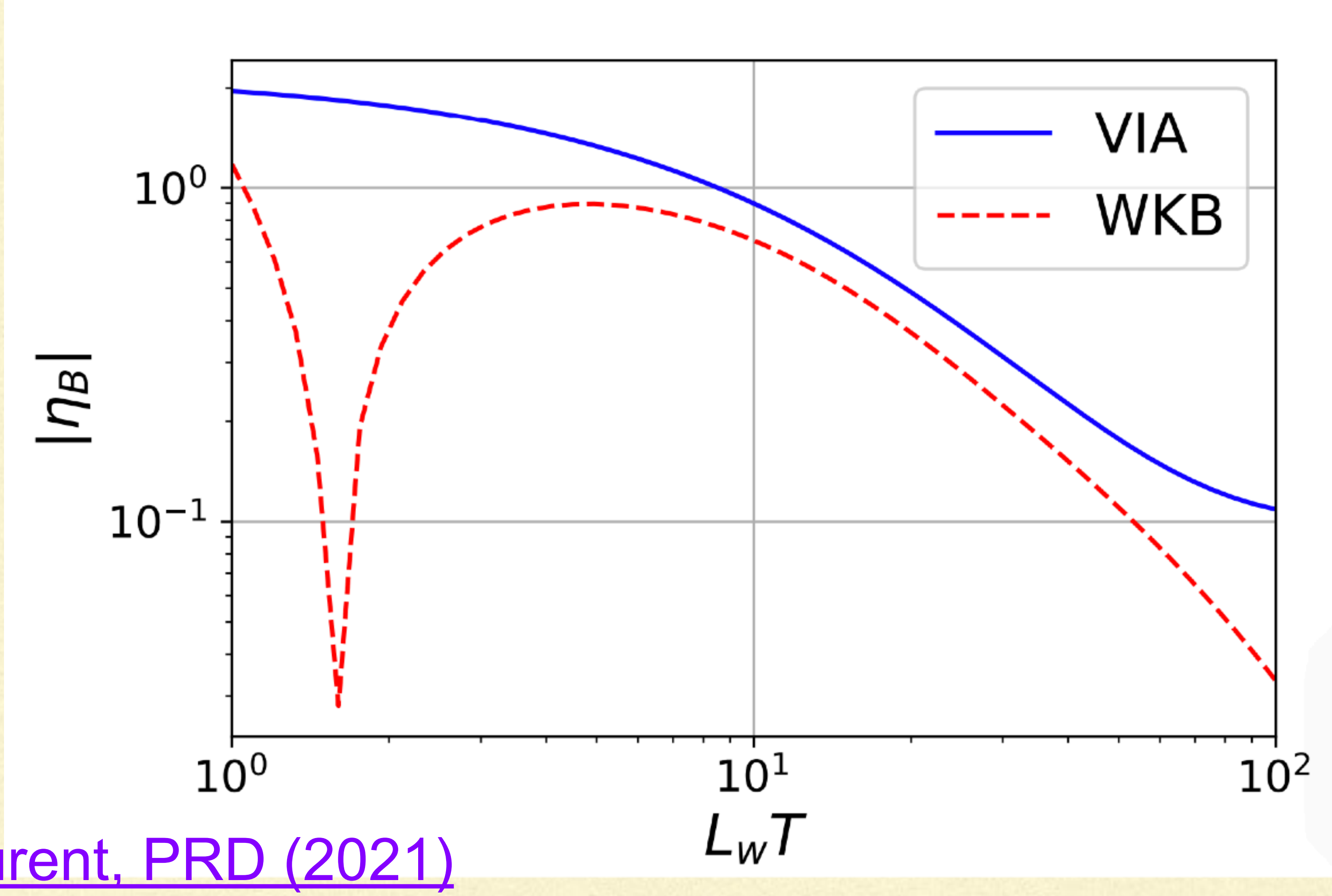


Figure from Cline, Laurent, PRD (2021)

Relativistic effect in BAU

We used the linear expansion by the wall velocity v_w

Effects of higher order terms : Cline, Kainulainen, PRD (2020)

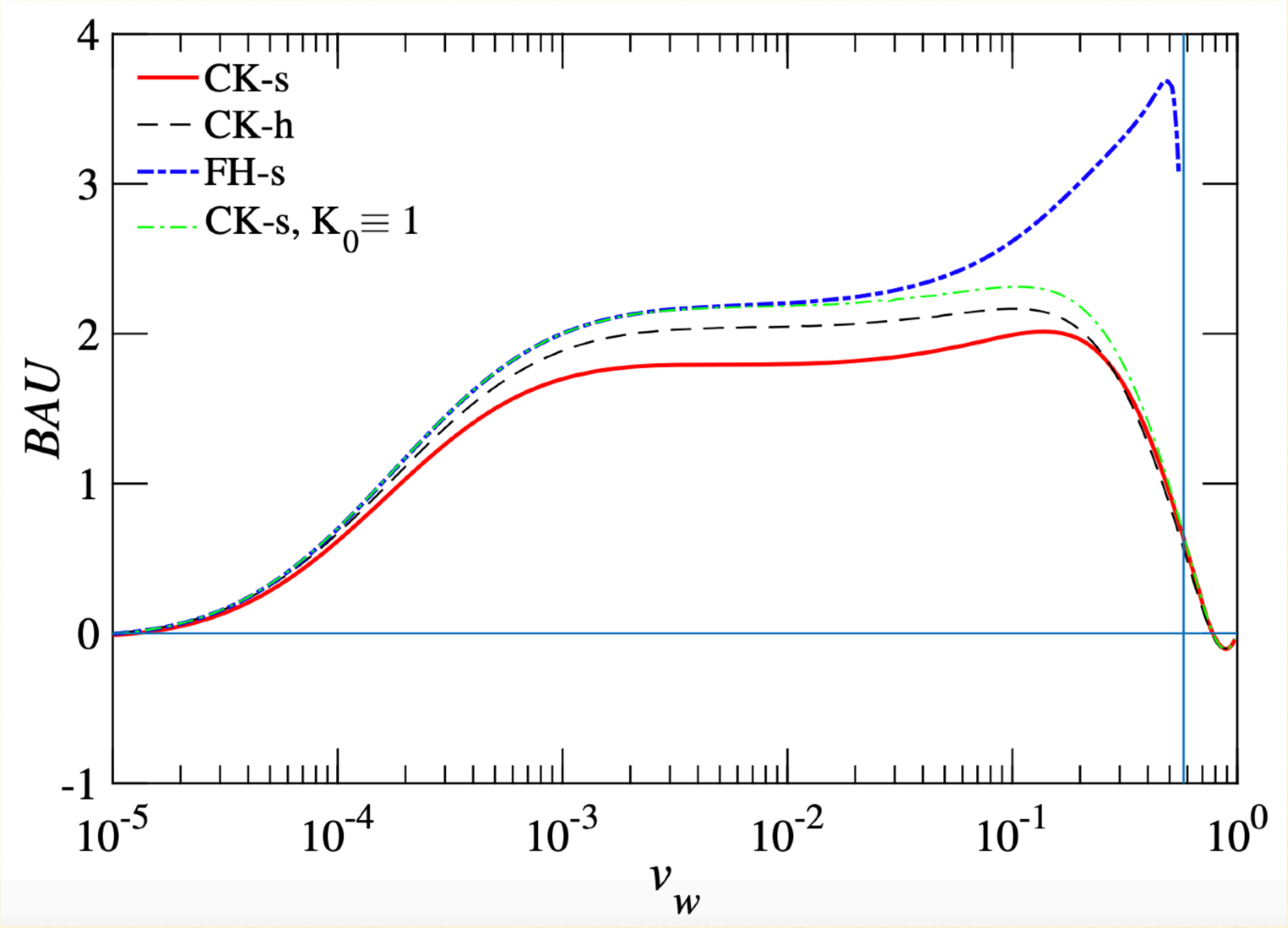


Figure from Cline, Kainulainen, PRD (2020)

Velocity dependence of η_B

$\ell \sim \dfrac{1}{T}$: Mean free path

Charge is accumulated within ℓ (Gray region)

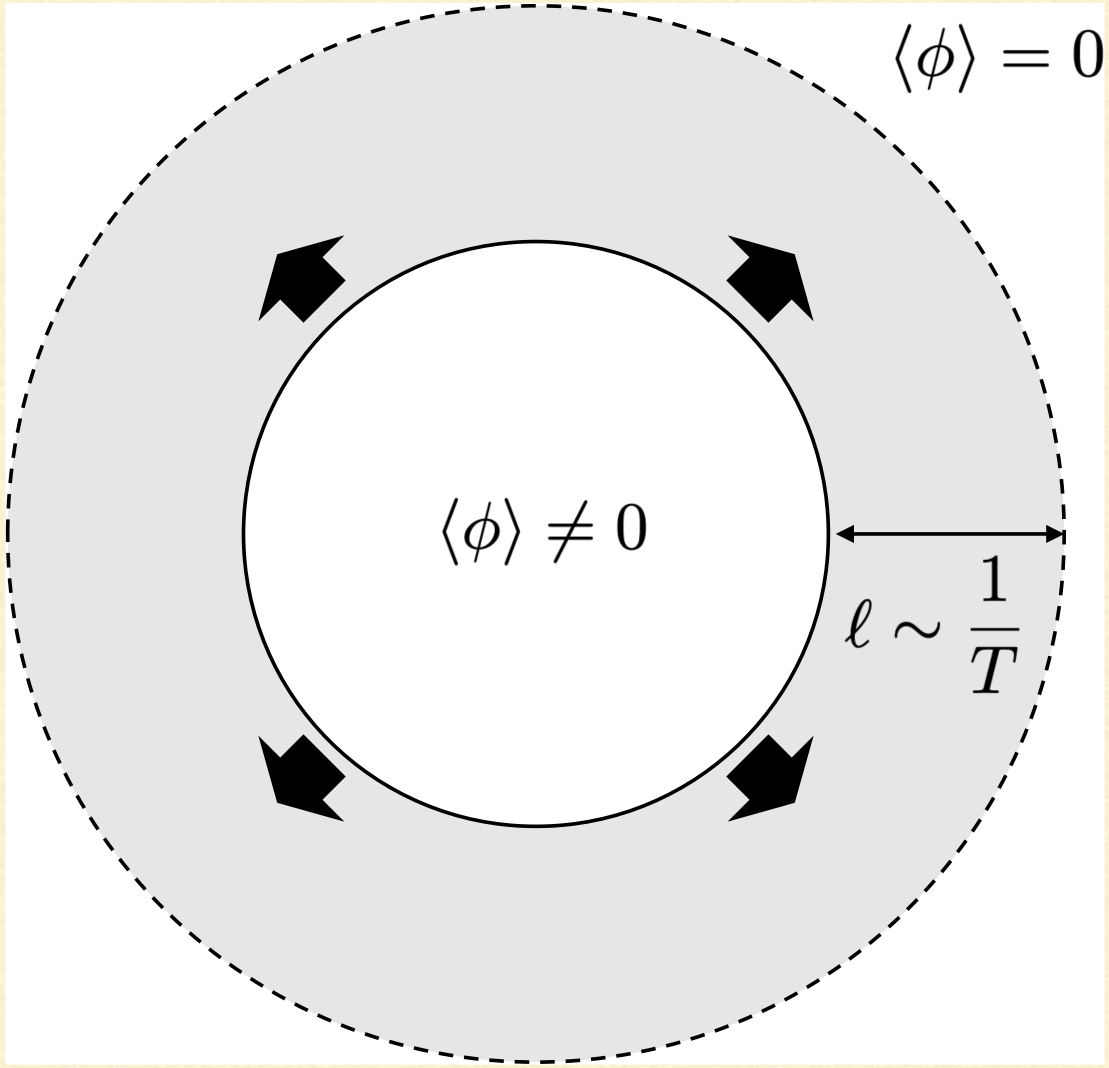
Time for accumulation to enter the bubble

$$t = \frac{\ell}{v_w} \sim \frac{1}{v_w T}$$

# of sphaleron tran.

before the charge enters the bubble

$$N = \Gamma_{sph}^{sym} \times t \sim \frac{\Gamma_{sph}^{sym}}{v_w T}$$



N is too large (small v_w)

➡ washed-out

N is too small (large v_w)

➡ too short time

$$\frac{n_B}{s} \propto \boxed{\frac{\Gamma_{sph}^{sym}}{v_w T}} \int d\hat{z}\, \frac{\mu_{q_L}(\hat{z})}{T} \exp\left(-\boxed{\frac{\Gamma_{sph}^{sym}}{v_w T}}\hat{z}\right)$$

$\hat{z} = zT$

The benchmark scenario

Masses of New particle

Z_2 even: $m_{H^+} = 250$ GeV, $m_{H_2} = 420$ GeV, $m_{H_3} = 250$ GeV

Z_2 odd: $m_S = 400$ GeV, $m_\eta = 63$ GeV

$$(M_{N_1}, M_{N_2}, M_{N_3}) = (3000,\ 3500,\ 4000)\ \text{GeV}$$

Higgs potential

$$\mu_2^2 = (50\ \text{GeV})^2, \quad \mu_s^2 = (320\ \text{GeV})^2, \quad \mu_\eta^2 \simeq (62.7\ \text{GeV})^2, \quad \mu_{12}^2 = 0$$

$$\lambda_2 = 0.1, \quad \lambda_3 \simeq 1.98, \quad \lambda_4 \simeq 1.88, \quad \lambda_5 \simeq 1.88, \quad \lambda_6 = 0,$$

$$|\lambda_7| = 0.821, \quad \rho_1 \simeq 1.90, \quad |\rho_{12}| = 0.1, \quad \rho_2 = 0.1,$$

$$\sigma_1 = |\sigma_{12}| = 1.1 \times 10^{-3}, \kappa = 2.0, \quad \lambda_S = \lambda_\eta = \xi = 1$$

$$\theta_7 = -2.34, \quad \theta_\rho = -2.94, \quad \theta_\sigma = 0$$

The benchmark scenario

Yukawa interactions

$$y_u|\zeta_u| \simeq 2.2\times 10^{-6},\quad y_c|\zeta_u| \simeq 1.3\times 10^{-3},\quad y_t|\zeta_u| \simeq 0.17,$$

$$y_d|\zeta_d| \simeq 4.7\times 10^{-6},\quad y_s|\zeta_d| \simeq 9.3\times 10^{-5},\quad y_b|\zeta_d| \simeq 4.2\times 10^{-3},$$

$$y_e|\zeta_e| \simeq 2.5\times 10^{-4},\quad y_\mu|\zeta_\mu| \simeq 2.5\times 10^{-4},\quad y_\tau|\zeta_\tau| \simeq 2.5\times 10^{-3},$$

$$\theta_u = \theta_d = 0.245,\quad \theta_e = \theta_\mu = \theta_\tau = -2.94$$

$$h_i^\alpha \simeq \begin{pmatrix} 1.0\,e^{-0.31i} & 0.2\,e^{0.30i} & 1.0\,e^{-2.4i} \\ 1.1\,e^{-1.9i} & 0.21\,e^{-1.8i} & 1.1\,e^{2.3i} \\ 0.45\,e^{2.7i} & 1.3\,e^{-0.033i} & 0.10\,e^{0.63i} \end{pmatrix}$$

Messes of the scalar bosons

$$m_{H^+}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2, \quad m_{H_2}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2,$$

$$m_{H_3}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2,$$

$$m_{S^+}^2 = \mu_s^2 + \frac{1}{2}\rho_1 v^2, \quad m_\eta^2 = \mu_\eta^2 + \frac{1}{2}\sigma_1 v^2$$

$$m_{H^+} = 250\ \text{GeV}, \quad m_{H_2} = 420\ \text{GeV}, \quad m_{H_3} = 250\ \text{GeV}$$

$$m_S = 400\ \text{GeV}, \quad m_\eta = 63\ \text{GeV}$$

$$\mu_2^2 = (50\ \text{GeV})^2, \quad \mu_s^2 = (330\ \text{GeV})^2, \quad \mu_\eta^2 \simeq (62.7\ \text{GeV})^2,$$

$$\lambda_3 \simeq 1.98, \quad \lambda_4 \simeq 1.88, \quad \lambda_5 \simeq 1.88, \quad \rho_1 \simeq 1.90, \quad \sigma_1 = 1.1 \times 10^{-3}$$

CPV phases in the Yukawa matrix h

$h_i^\alpha \, \overline{(N_R^\alpha)^c} \, \ell_R^i \, S^+$

The Yukawa matrix h includes nine phases.

Three of them can be zero by rephasing lepton fields.

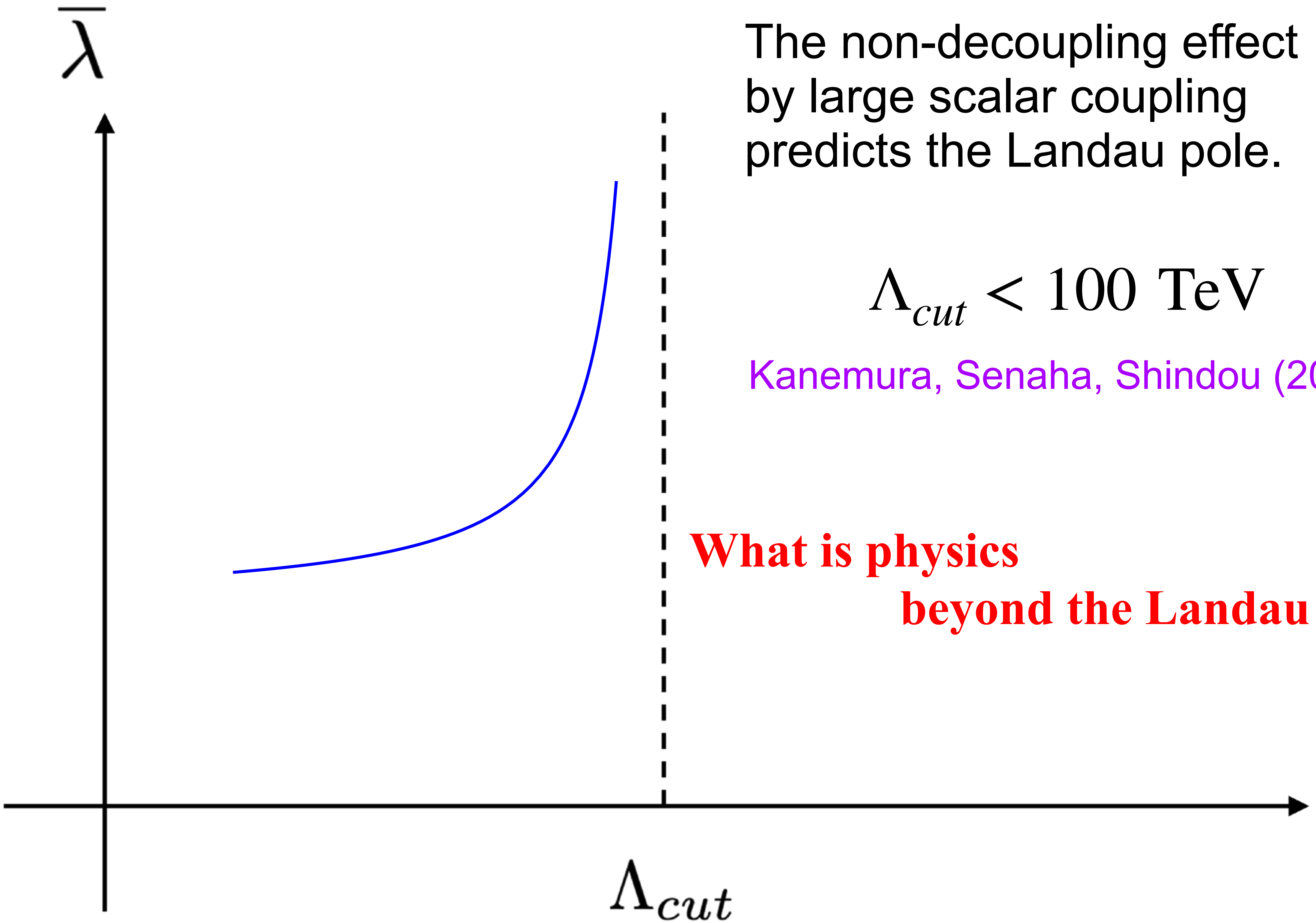
$$\begin{pmatrix} e_{L,R} \\ \mu_{L,R} \\ \tau_{L,R} \end{pmatrix} \to P_\phi \begin{pmatrix} e_{L,R} \\ \mu_{L,R} \\ \tau_{L,R} \end{pmatrix} \quad \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \to P_\phi \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \quad P_\phi \equiv \begin{pmatrix} e^{i\phi_e} & 0 & 0 \\ 0 & e^{i\phi_\mu} & 0 \\ 0 & 0 & e^{i\phi_\tau} \end{pmatrix}$$

This rephasing can eliminate 3 phases from the PMNS matrix.

$$\begin{pmatrix} \nu'_{eL} \\ \nu'_{\mu L} \\ \nu'_{\tau L} \end{pmatrix} = P_\phi \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \qquad U_{\mathrm{PMNS}} = P_\phi U'_{\mathrm{PMNS}}$$

U_{PMNS} includes only 3 CPV phases: δ_{CP}, α_1, α_2

Landau pole and new physics



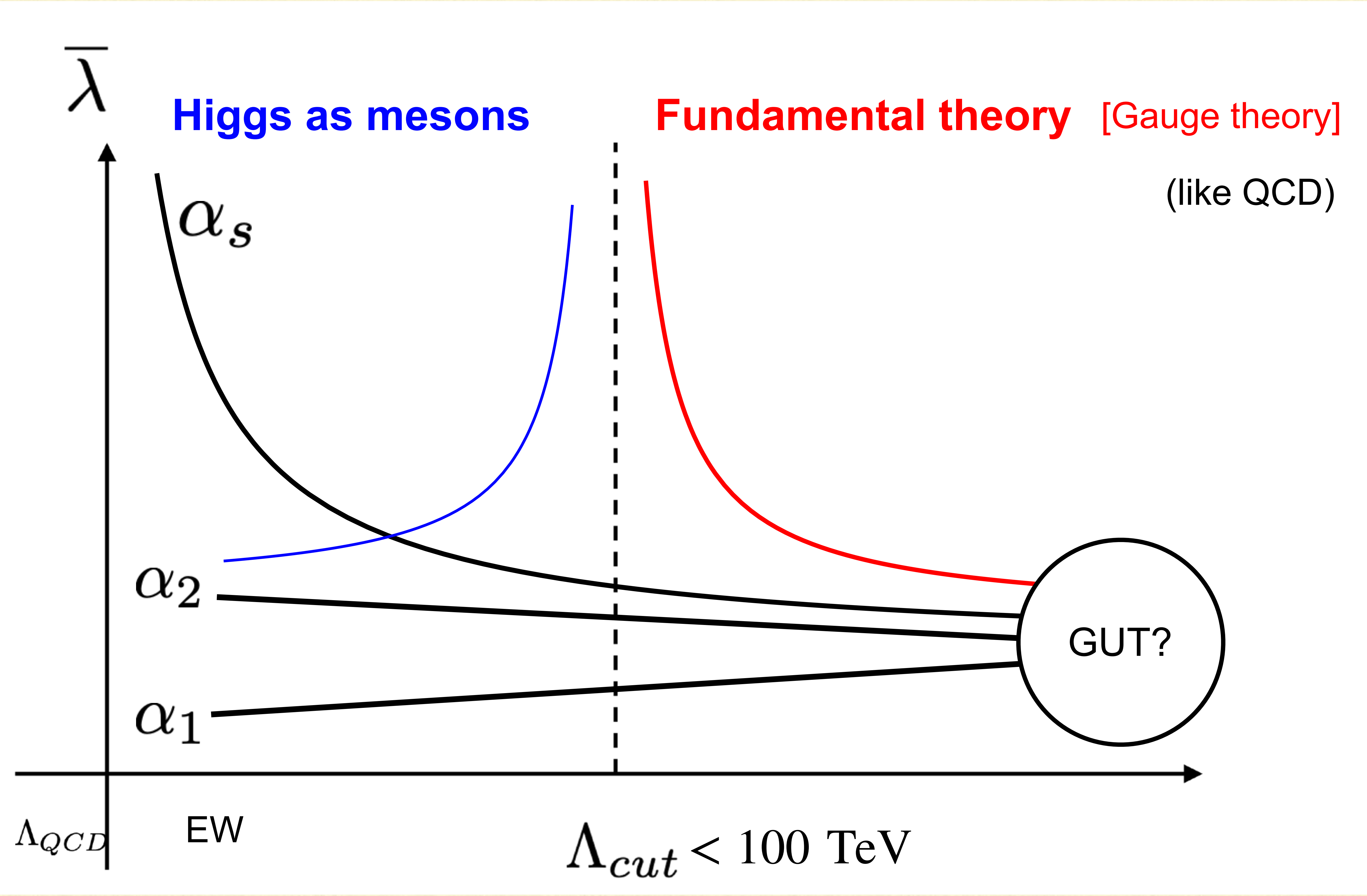
The non-decoupling effect by large scalar coupling predicts the Landau pole.

$$\Lambda_{cut} < 100 \text{ TeV}$$

Kanemura, Senaha, Shindou (2011)

What is physics beyond the Landau pole ?

Landau pole and new physics



Landau pole and new physics

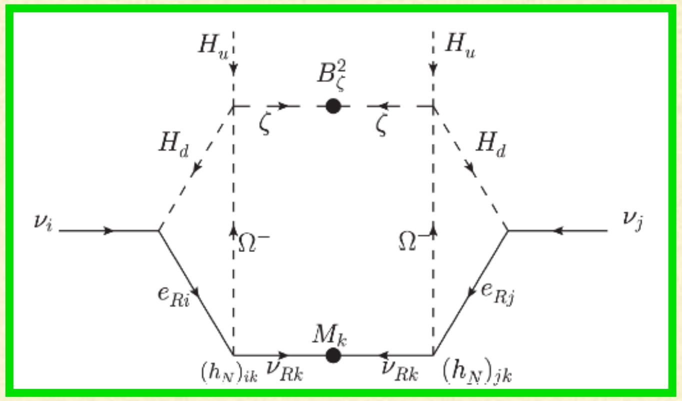
E.g.) SUSY $SU(2)_H$ gauge theory   Kanemura, Shindou, Yamada, PRD (2012)

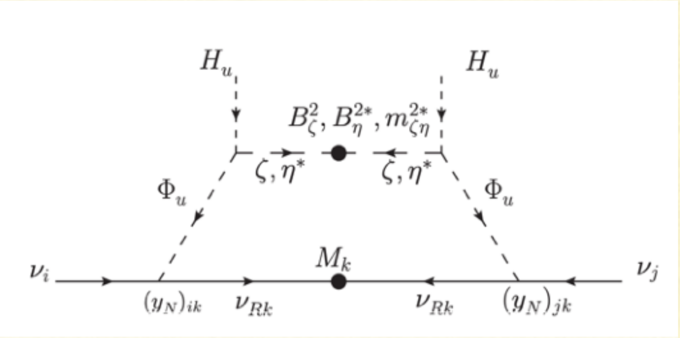
Higgs as mesons

Field	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Z_2
H_u	1	2	$+1/2$	$+1$
H_d	1	2	$-1/2$	$+1$
Φ_u	1	2	$+1/2$	-1
Φ_d	1	2	$-1/2$	-1
Ω^+	1	1	$+1$	-1
Ω^-	1	1	-1	-1
N, N_Φ, N_Ω	1	1	0	$+1$
ζ, η	1	1	0	-1

Gauge theory

Superfield	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	1	2	0	$+1$
T_3	1	1	$+1/2$	$+1$
T_4	1	1	$-1/2$	$+1$
T_5	1	1	$+1/2$	-1
T_6	1	1	$-1/2$	-1





ALL scalar fields in the model can be included!