ニュートリノ質量、暗黒物質、バリオン数非対称性を同時に説明する模型とその現象論

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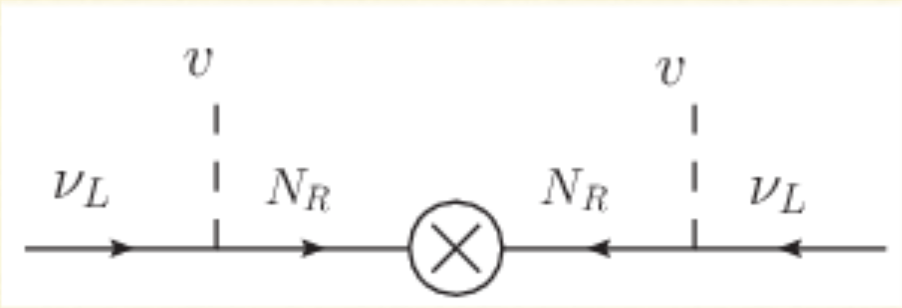
Paper in preparation

Introduction

What is the origin of tiny neutrino mass?

■ **Seesaw mechanism** Minkowski (1977); Yanagida (1979); Gell-Mann, Ramond, Slansky (1979); Mohapatra, Senjanovic (1980); Schechter, Valle (1980)

Right-handed Majorana ν's: N_R



$$(m_\nu)_{\ell\ell'} \propto \frac{v^2}{M_N} \quad \mathcal{O}(M_N) = \text{GUT scale}$$

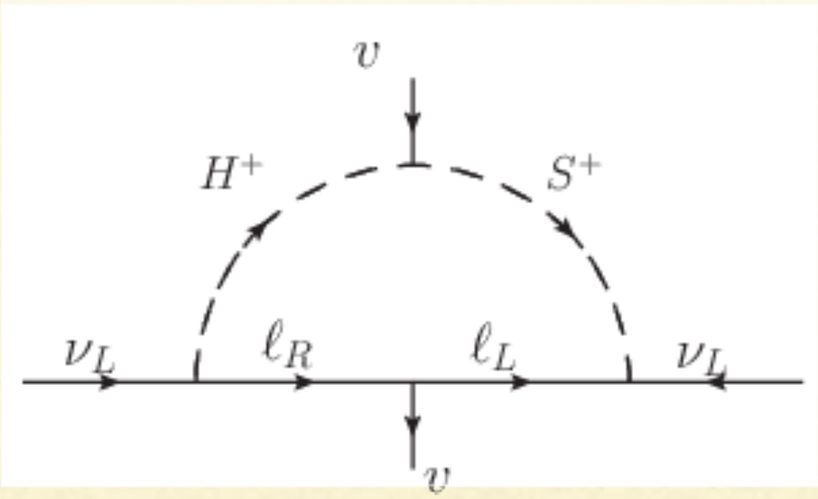
Difficult to test

■ **Radiative seesaw** (quantum effects)

e.g.) Zee model A. Zee (1980)

$\phi_2 : (\mathbf{2}, +1/2)$

$S : (\mathbf{1} + 1)$



The loop suppression

$$\left(\frac{1}{16\pi^2}\right)^n$$

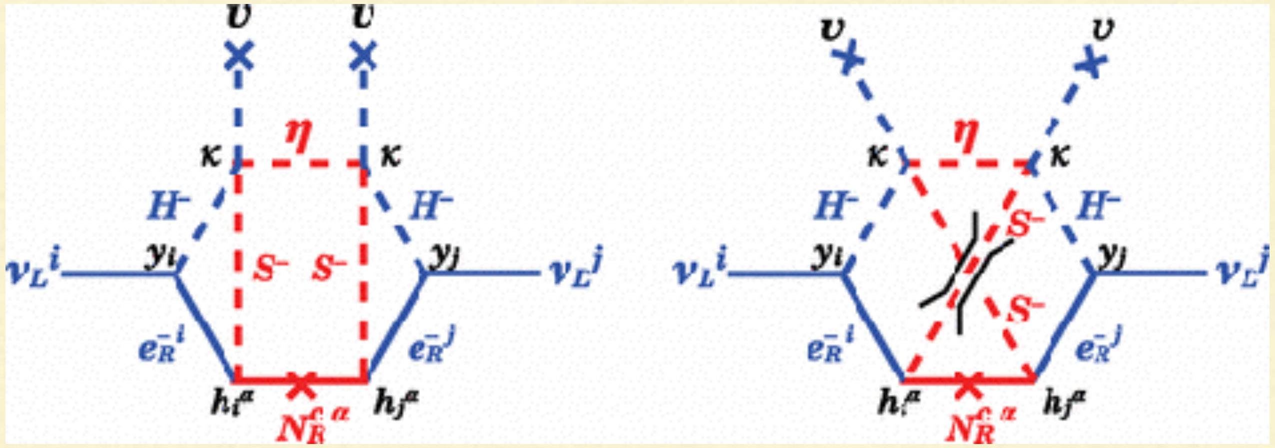
Can be tested

Introduction

A radiative seesaw model
proposed in M. Aoki, S. Kanemura, O. Seto (2009)

	Scalar			Fermion
New Fields	Φ_2	S^+	η	N_{aR}
$SU(2)_L$	**2**	**1**	**1**	**1**
$U(1)_Y$	$+1/2$	$+1$	0	0
Z_2	$+$	$-$	$-$	$-$

$(a = 1,2,3)$



- ν masses：3-loop diagram
- DM： Unbroken Z_2 symmetry
- BAU： Electroweak baryogenesis by extended Higgs sector

(BAU = Baryon Asymmetry of the Universe)

Introduction

In the previous works, Aoki, Kanemura, Seto (2009) Aoki, Kanemura, Yagyu (2011)

CP-violation was neglected

for simplicity

➡ BAU has not been evaluated.

(They have evaluated ν mass and DM.)

Q. Can this model explain ν mass, DM, and BAU simultaneously?

Our work

Aoki, KE, Kanemura (2022) in preparation

Revisit (and extend) the model considering CPV phases.

➡ New benchmark scenario

The model

Aoki, Kanemura, Seto (2009); Aoki, KE, Kanemura in preparation

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

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

CP-violation

Φ_2

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

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

$S^\pm$

6 CP-violating couplings

The model Aoki, Kanemura, Seto (2009); Aoki, KE, Kanemura in preparation

Mass of Neutral Higgs Bosons

Higgs basis

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

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

Φ_2

In the limit

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

(Higgs couplings coincide with SM ones)

$\boxed{\text{The model}}$ Aoki, Kanemura, Seto (2009); Aoki, KE, Kanemura in preparation

Higgs alignment scenario

Simple scenario $\lambda_6 = 0$

Kanemura, Kubota, Yagyu (2020), (2021)
KE, Kanemura, Mura (2021)
Kanemura, Takeuchi, Yagyu (2021)

- 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

$\lambda_6 = 0$

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

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

$S^\pm$

The model

Aoki, Kanemura, Seto (2009); Aoki, KE, Kanemura in preparation

Yukawa interaction

Both Higgs doublets couple with the SM fermions.

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

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

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 in preparation

Yukawa interaction

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

$$\frac{1}{2} M_{N^a} \overline{(N_R^a)^c} N_R^a$$

Lepton # violating

$$\mathscr{L}_Y = -(Y_N)_{ai} \overline{(N_R^a)^c} \ell_R^i S^+ + \mathrm{h.c.}$$

Lepton flavor violating

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

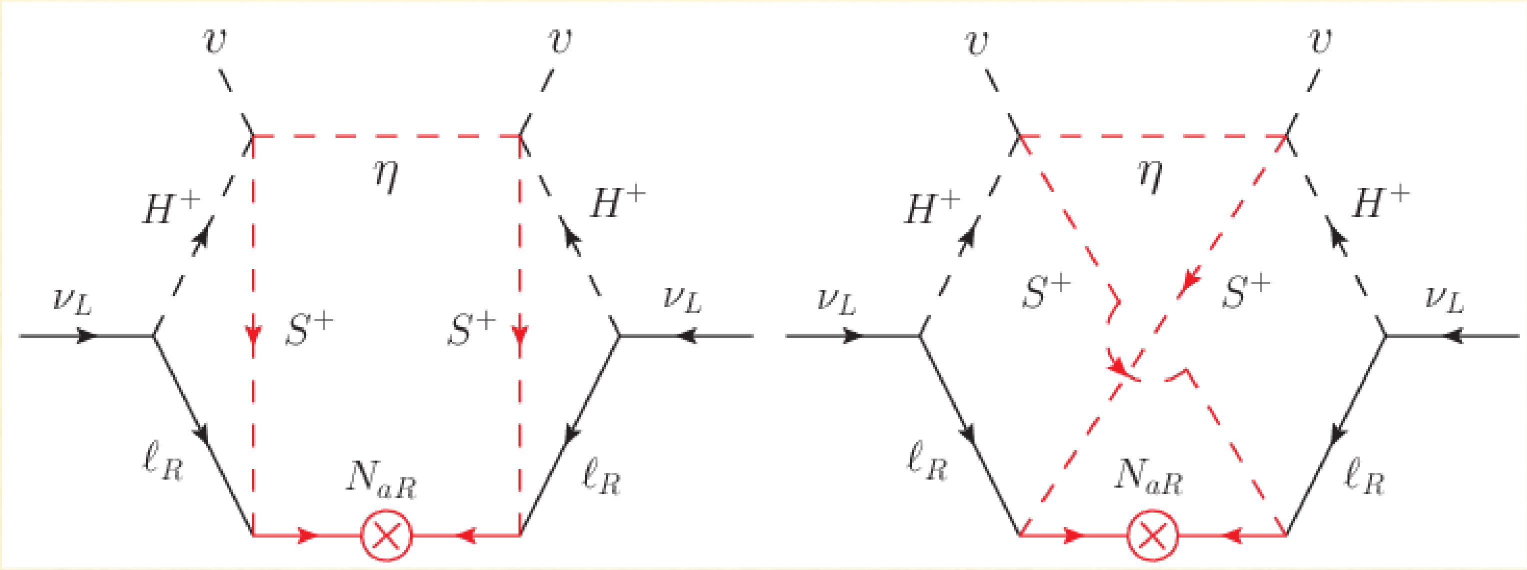
(H_1 is the SM Higgs) (No FCNC)

CP-violation: λ_7, ρ_{12}, σ_{12} & ζ_u, ζ_d, ζ_τ, ζ_μ, ζ_e, $(Y_N)_{ai}$

Neutrino masses

🚫 $\overline{L_{iL}}\tilde{\Phi}_1 N_{aR}$ (N_{aR} is Z_2-odd)

Neutrino masses are generated via 3-loop diagrams



$\kappa\, \tilde{\Phi}_1 \Phi_2 S^- \eta$

$(Y_N)_{ai}\, \overline{N^c_{aR}}\, \ell_{iR} S^+$

$\zeta_e \dfrac{\sqrt{2} m_{\ell_i}}{v} \overline{L_{iL}}\, \Phi_2\, \ell_{iR}$

Input parameters

$$|\zeta_e| = 122,\ |\zeta_\mu| = 0.588,\ |\zeta_\tau| = 0.350,\ \arg[\zeta_e] = \arg[\zeta_\mu] = \arg[\zeta_\tau] = -2.94$$

$$m_{H^\pm} = 250\ \text{GeV}, \quad m_S = 400\ \text{GeV}, \quad \kappa = 2.0$$

$$m_\eta = 63\ \text{GeV}, \quad M_{N^i} = (3000, 3500, 4000)\ \text{TeV}$$

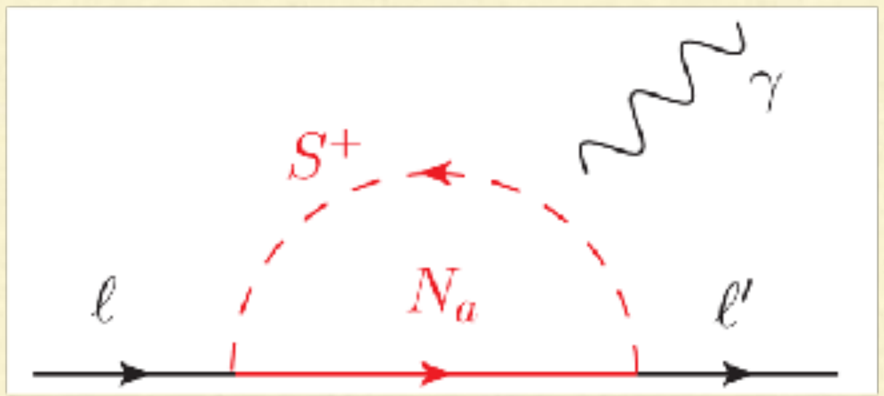
$$Y_N \simeq \begin{pmatrix} 0.951 - 0.309i & 0.187 + 0.0582i & -0.759 - 0.711i \\ -0.330 - 1.03i & -0.0470 - 0.200i & -0.723 + 0.746i \\ -0.414 + 0.174i & 1.31 - 0.0434i & 0.0809 + 0.0588i \end{pmatrix}$$

$\boxed{\text{LFV decays}}$ (LFV = Lepton Flavor Violating)

$$m_S = 400\ \text{GeV},\qquad M_N = \{3000,\ 3500,\ 4000\}\ \text{GeV}$$

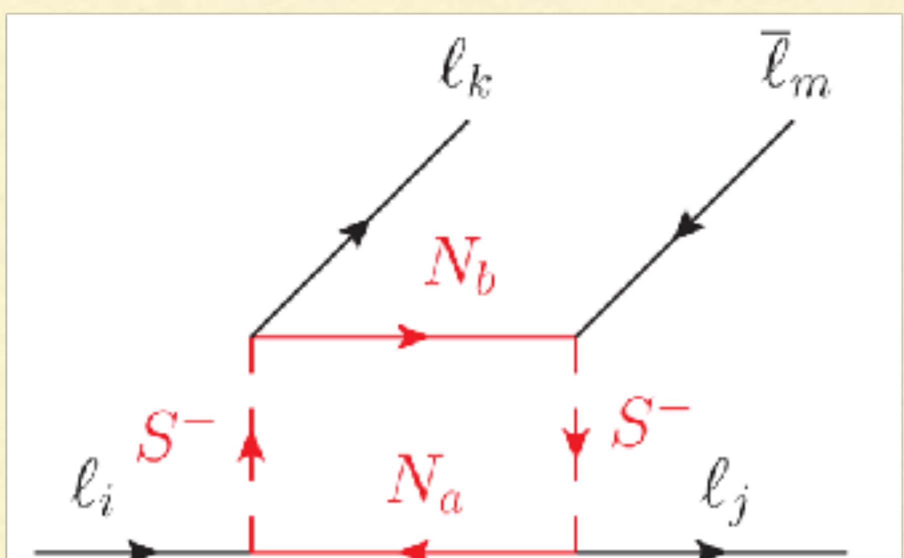
$$Y_N \simeq \begin{pmatrix} 0.951 - 0.309i & 0.187 + 0.0582i & -0.759 - 0.711i \\ -0.330 - 1.03i & -0.0470 - 0.200i & -0.723 + 0.746i \\ -0.414 + 0.174i & 1.31 - 0.0434i & 0.0809 + 0.0588i \end{pmatrix}$$

■ $\ell \to \ell'\gamma$



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}

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

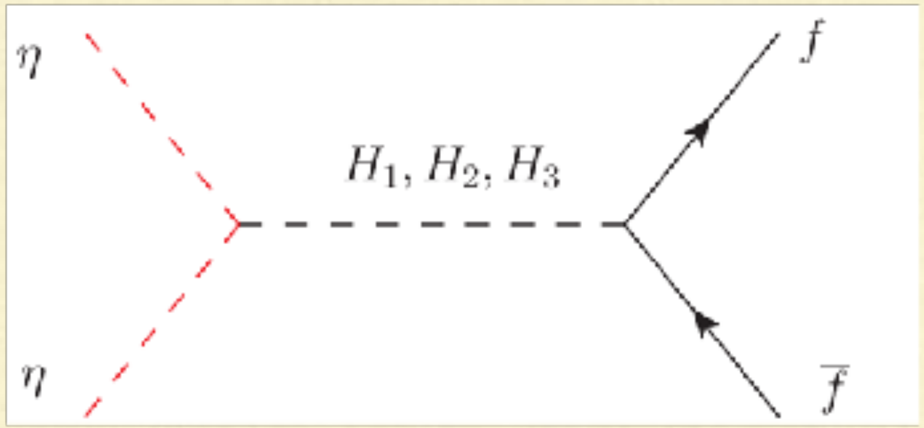


Processes	BR	Upper limits
$\mu \to 3e$	1.0×10^{-13}	1.0×10^{-12}
$\tau \to 3e$	6.2×10^{-10}	2.7×10^{-8}
$\tau \to 3\mu$	2.4×10^{-11}	2.1×10^{-8}
$\tau \to e\mu\bar{e}$	5.1×10^{-12}	1.8×10^{-8}
$\tau \to \mu\mu\bar{e}$	1.1×10^{-12}	1.7×10^{-8}
$\tau \to ee\bar{\mu}$	4.5×10^{-13}	1.5×10^{-8}
$\tau \to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

Dark matter

DM candidates：real scalar η, Majorana fermion N_a

In the benchmark scenario, DM is η.



$$\frac{\sigma_1}{2}|\Phi_1|^2\eta^2 + \left(\frac{\sigma_{12}}{2}(\Phi_1^\dagger\Phi_2)\eta^2 + \mathrm{h.c.}\right)$$

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

$$\sigma_1 = |\sigma_{12}| = 1.1\times 10^{-3},\quad \arg[\rho_{12}] = -2.94$$

Relic abundance

$$\Omega_{\eta 0}h^2 = 0.12$$

Planck (2018) $\Omega_{DM}h^2 = 0.1200 \pm 0.0012$

Direct detection

$$\sigma(\eta N \to \eta N) = 2.3\times 10^{-48}\ \mathrm{cm}^2$$

XENON1T (2018)
PANDAX-4T (2022) $\sigma \lesssim 10^{-47}\ \mathrm{cm}^2$

Electroweak baryogenesis

Kuzmin, Rubakov, Shaposhnikov (1985)

The Sakharov conditions

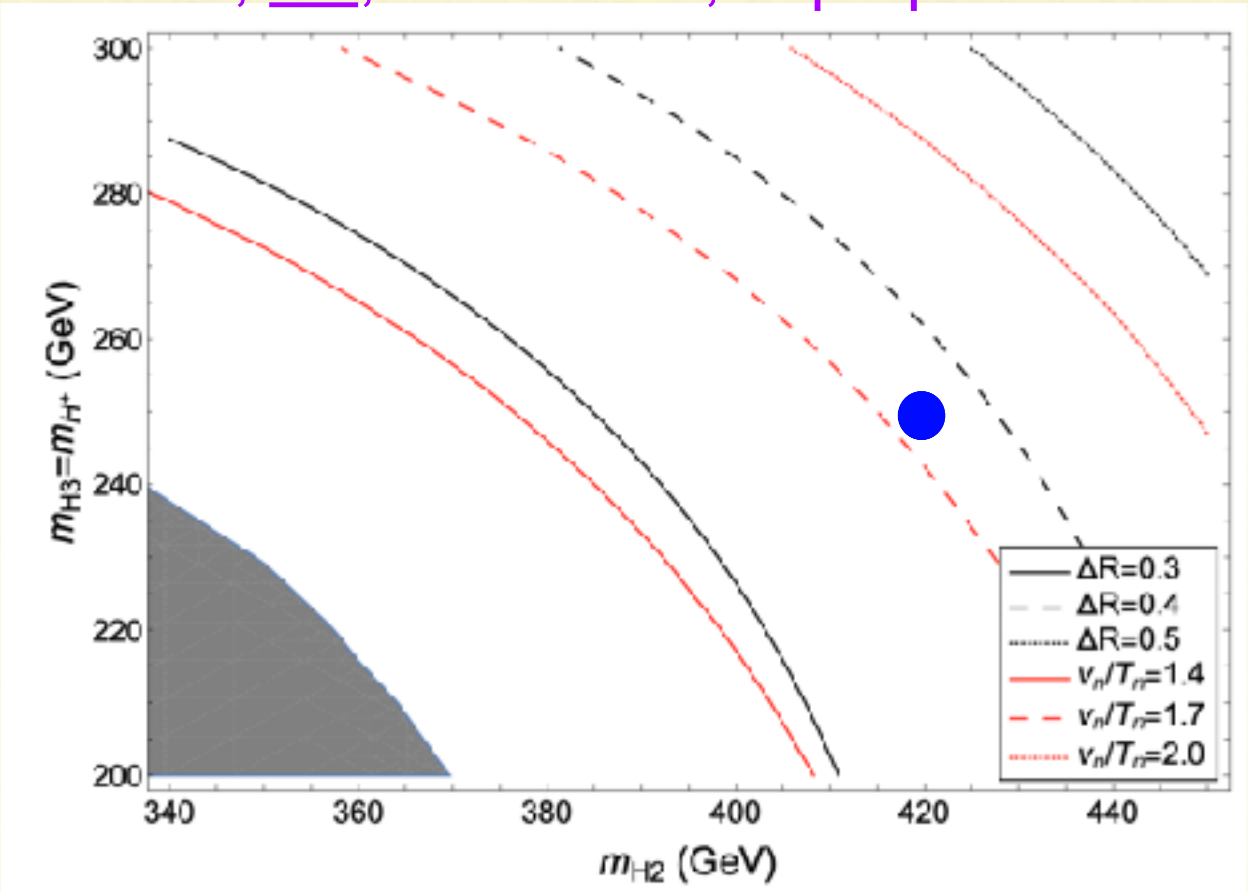
Sakharov (1967)

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)

Aoki, KE, Kanemura, in preparation



Blue point : Benchmark scenario

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

Sphaleron decoupling condition

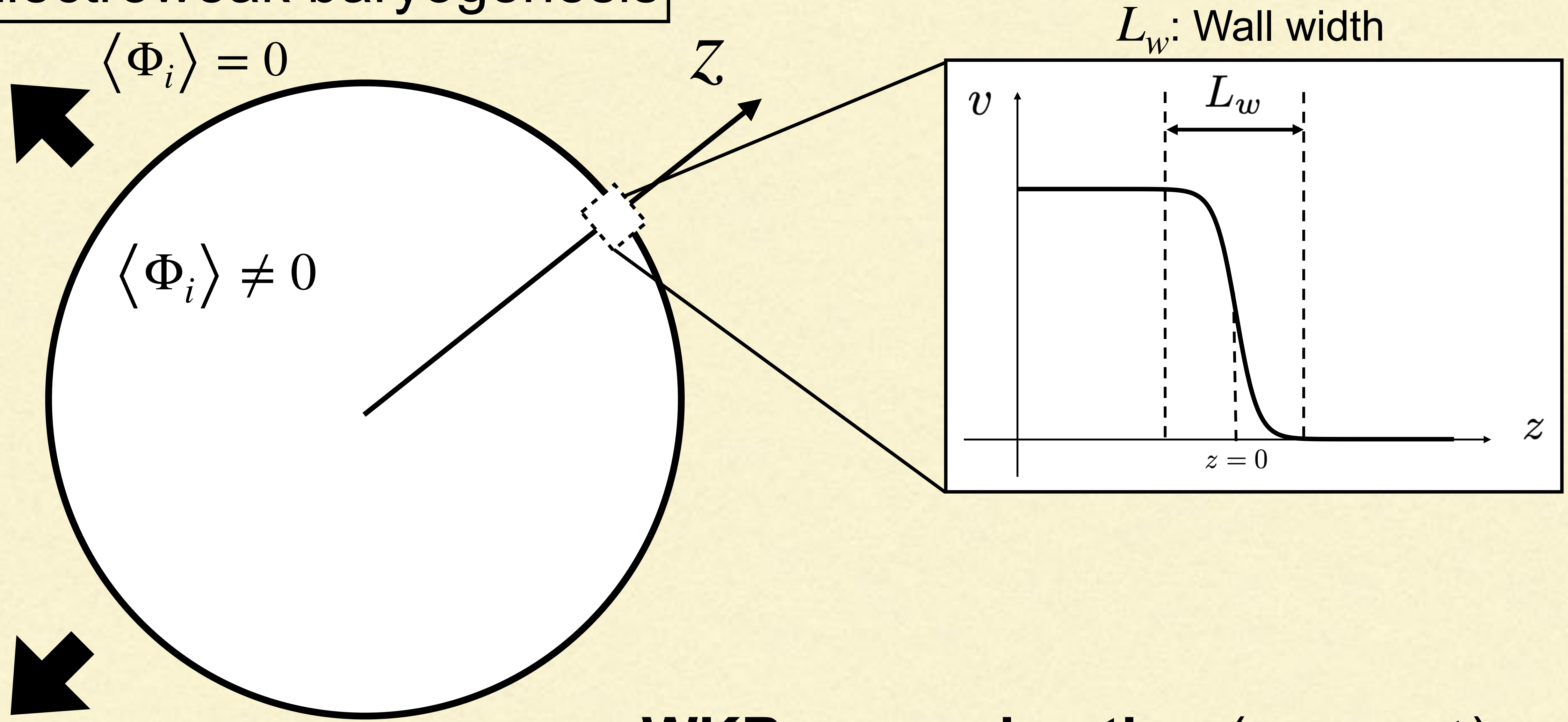
$$v_n/T_n = 1.74$$

Triple Higgs coupling

Kanemura, Okada, Senaha (2005)

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

Electroweak baryogenesis



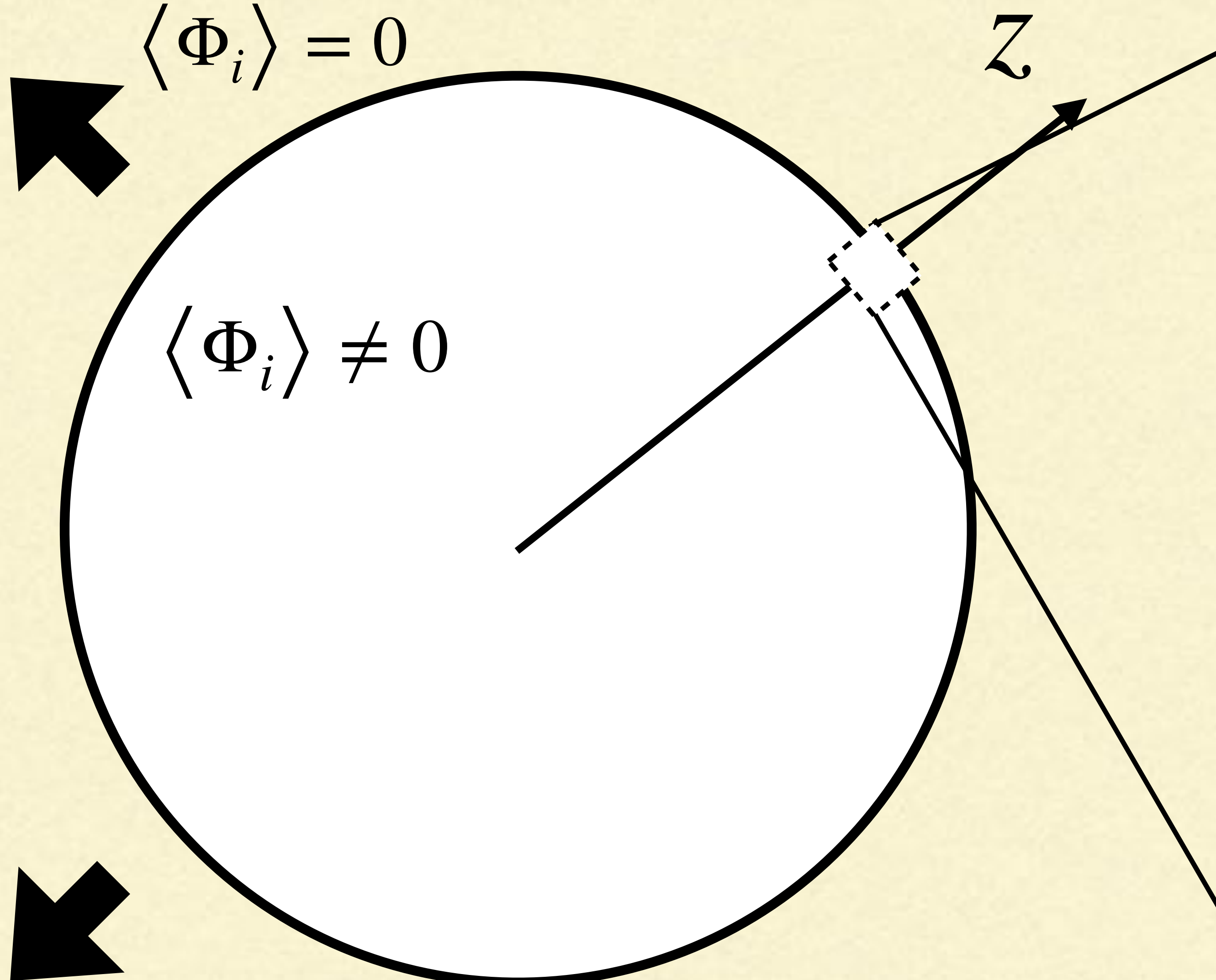
v_w: wall velocity

$v_w = 0.1$ is assumed

WKB approximation $(L_w T_n \gg 1)$

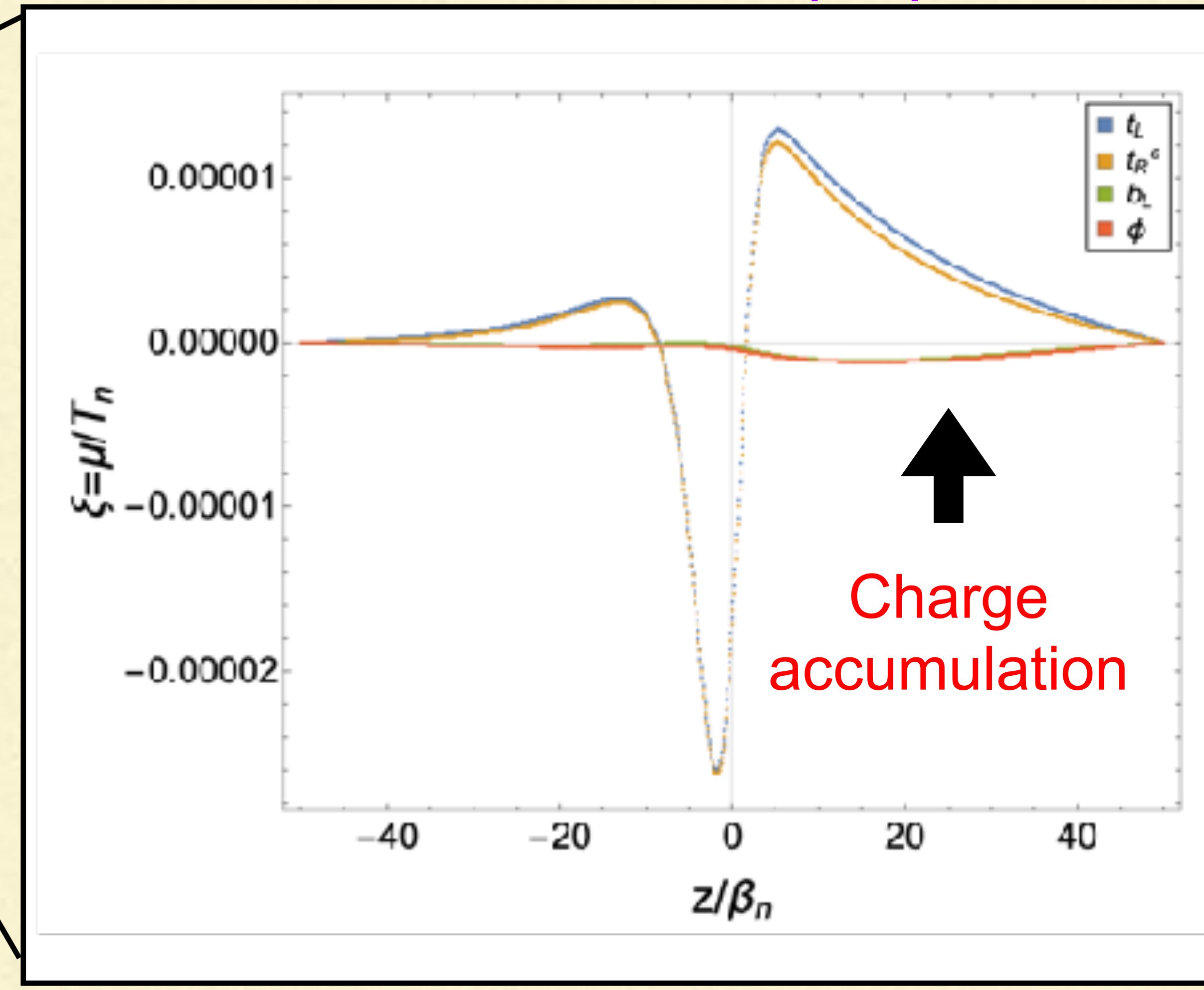
Joyce, Prokopec, Turok (1995);
Cline, Joyce, Kainulainen (2000); Cline, Kainulainen (2020)

Electroweak baryogenesis



Chemical potential

Aoki, KE, Kanemura in preparation



v_w: wall velocity

$v_w = 0.1$ is assumed

$$\boxed{\eta_B \sim \Gamma_{ws} \int_0^\infty \mathrm{d}z \, \mu_{q_L} e^{-kz} = 6.14 \times 10^{-10}}$$

WKB approximation $(L_w T_n \gg 1)$

Joyce, Prokopec, Turok (1995);
Cline, Joyce, Kainulainen (2000); Cline, Kainulainen (2020)

Experimental value

Explained !!!

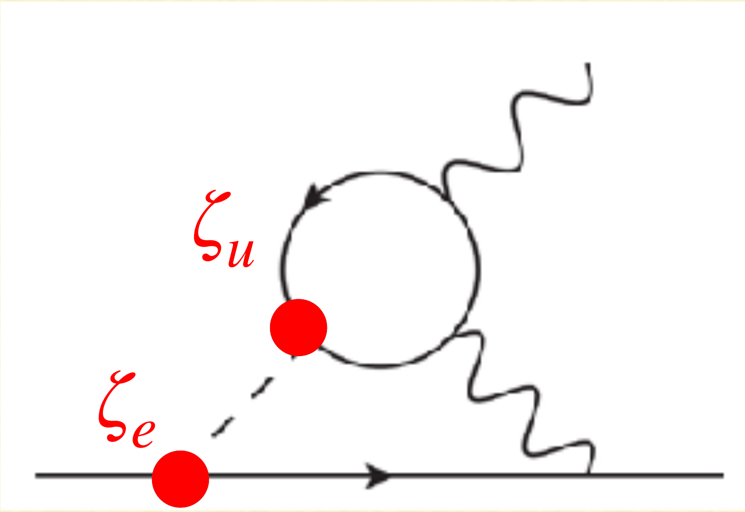
BBN) $5.8 \times 10^{-10} \leq \eta_B \leq 6.5 \times 10^{-10}$

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

electron Electric Dipole Moment (eEDM)

Two kinds of Barr-Zee type diagrams Barr, Zee (1990)

Fermion loop **Scalar loop**



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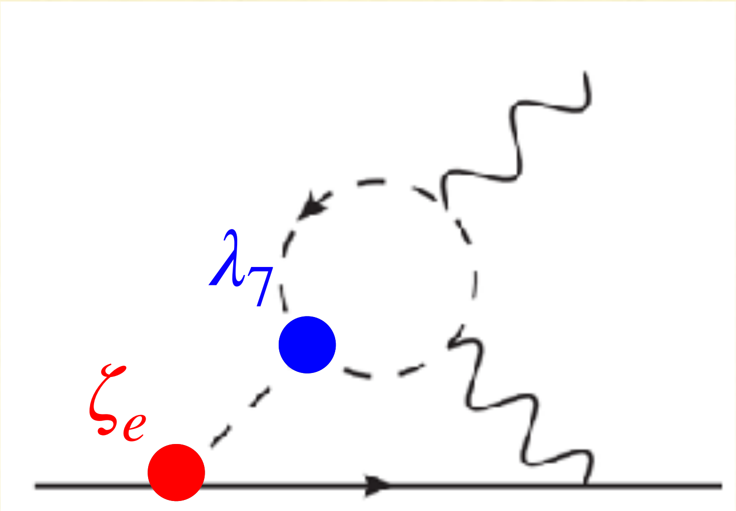


eEDM can be small by **destructive interference**

S. Kanemura, M. Kubota, K. Yagyu, JHEP(2020)

$$m_{H_2} = 420 \text{ GeV}, \quad m_{H_3} = m_{H^\pm} = 250 \text{ GeV}$$
$$|\lambda_7| = 0.835, \quad \arg[\lambda_7] = -2.34$$
$$|\zeta_u| = 0.246, \quad \arg[\zeta_u] = 0.245$$
$$|\zeta_e| = 122, \quad \arg[\zeta_e] = -2.94$$

In our benchmark scenario,

$$|d_e| = 0.41 \times 10^{-29} \text{ ecm}$$

ACME (2018)

$$|d_e| < 1.0 \times 10^{-29} \text{ ecm}$$

How to test the benchmark scenario

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 $\mu \to 3e, \quad \tau \to 3e$ 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

Details of these are currently under investigation.

Summary of this talk

- 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

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

$$\mu_2^2 = (50\ \text{GeV})^2, \quad \mu_s^2 = (330\ \text{GeV})^2, \quad \mu_\eta^2 \simeq (62.7\ \text{GeV})^2, \quad (\mu_{12}^2 = 0)$$

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

$$|\lambda_7| = 0.821, \quad \arg[\zeta_7] = -2.34,$$

$$\rho_1 = 1.90, \quad |\rho_{12}| = 0.1, \quad \arg[\rho_{12}] = -2.94$$

$$\rho_2 = 0.1, \quad \sigma_1 = |\sigma_{12}| = 1.1 \times 10^{-3}, \quad \theta_\sigma = 0, \quad \sigma_2 = 0.1$$

Benchmark Scenario

Yukawa interaction

$$|\zeta_u| = |\zeta_d| = 0.25, \quad |\zeta_\tau| = 0.35, \quad |\zeta_\mu| = 0.588, \quad |\zeta_e| = 122$$

$$\left(\begin{array}{l} y_t|\zeta_u| \simeq 0.25, \quad y_b|\zeta_d| \simeq 6\times 10^{-3}, \quad y_\tau|\zeta_\tau| \simeq 3.6\times 10^{-3}, \\ y_\mu|\zeta_\mu| = 3.6\times 10^{-4}, \quad y_e|\zeta_e| = 3.6\times 10^{-4} \end{array} \right)$$

$$\arg[\zeta_u] = 0.245, \quad \arg[\zeta_d] = 0$$

$$\arg[\zeta_\tau] = \arg[\zeta_\mu] = 0, \quad \arg[\zeta_e] = -2.94$$

$$Y_N \simeq \begin{pmatrix} 0.951 - 0.309i & 0.187 + 0.0582i & -0.759 - 0.711i \\ -0.330 - 1.03i & -0.0470 - 0.200i & -0.723 + 0.746i \\ -0.414 + 0.174i & 1.31 - 0.0434i & 0.0809 + 0.0588i \end{pmatrix}$$

The Higgs potential

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

$$\begin{aligned}
V_\Phi =& \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \left(\mu_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right) \\
&+ \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_3|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\
&+ \left\{\left(\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6|\Phi_1|^2 + \lambda_7|\Phi_2|^2\right)(\Phi_1^\dagger\Phi_2) + \mathrm{h.c.}\right\}
\end{aligned}$$

$$\begin{aligned}
V_{S\eta} =& \mu_S^2|S^+|^2 + \frac{\mu_\eta^2}{2}\eta^2 \\
&+ \rho_1|\Phi_1|^2|S^+|^2 + \rho_2|\Phi_2|^2|S^+|^2 + \left(\rho_{12}(\Phi_1^\dagger\Phi_2)|S^+|^2 + \mathrm{h.c.}\right) \\
&+ \frac{\sigma_1}{2}|\Phi_1|^2\eta^2 + \frac{\sigma_2}{2}|\Phi_2|^2\eta^2 + \left(\frac{\sigma_{12}}{2}(\Phi_1^\dagger\Phi_2)\eta^2 + \mathrm{h.c.}\right) \\
&+ \left(\sum_{a,b=1}^{2}\kappa(\epsilon_{ab}\tilde{\Phi}_a^\dagger\Phi_b)S^-\eta + \mathrm{h.c.}\right) + \frac{\lambda_s}{4}|S^+|^4 + \frac{\lambda_\eta}{4!}\eta^4 + \frac{\xi}{2}|S^+|^2\eta^2
\end{aligned}$$

Masses of scalar bosons

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

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

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

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

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

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

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

CPV phases in $(Y_N)_{a\ell}$

Rephasing of lepton fields

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

$$\phi_e, \phi_\mu, \phi_\tau \in \mathbb{R}$$

Lagrangian except $(Y_N)_{ai}\overline{N^c_{aR}}\ell_{iR}S^+$ is invariant under this rephasing

→ Three of phases in $(Y_N)_{ai}$ are **not physical (not CPV phases)**

We use this degree of freedom to vanish 3 phases from PMNS matrix.

$$\begin{pmatrix} \nu'_{eL} \\ \nu'_{\mu L} \\ \nu'_{\tau L} \end{pmatrix} = P_\phi \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix}$$

$$U_{\text{PMNS}} = P_\phi U'_{\text{PMNS}}$$

Unitary matrix : 6 phases

Using P_ϕ, 3 of phases can be 0. (CPV phases) $\delta_{CP},\ \alpha_1,\ \alpha_2$

In this talk, we consider the basis where PMNS have only 3 phases.

Yukawa sector in THDM with Softly broken Z_2

$$-\mathcal{L}_Y = \frac{\sqrt{2}m_{u_i}}{v}\overline{Q_{iL}}\left(\Phi_1^c + \zeta_u \Phi_2^c\right)u_{iR} + \frac{\sqrt{2}m_{d_i}}{v}\overline{Q_{iL}}\left(\Phi_1 + \zeta_d \Phi_2\right)d_{iR} + \frac{\sqrt{2}m_{\ell_i}}{v}\overline{L_{iL}}\left(\Phi_1 + \zeta_\ell \Phi_2\right)\ell_{iR} + \text{h.c.}$$

	I	II	X	Y
ζ_u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ζ_d	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
ζ_ℓ	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$

Type-I like： $|\zeta_u| = |\zeta_d| = |\zeta_e|$

Type-II like： $|\zeta_u| = 1/|\zeta_d| = 1/|\zeta_e|$

Type-X like： $|\zeta_u| = |\zeta_d| = 1/|\zeta_e|$

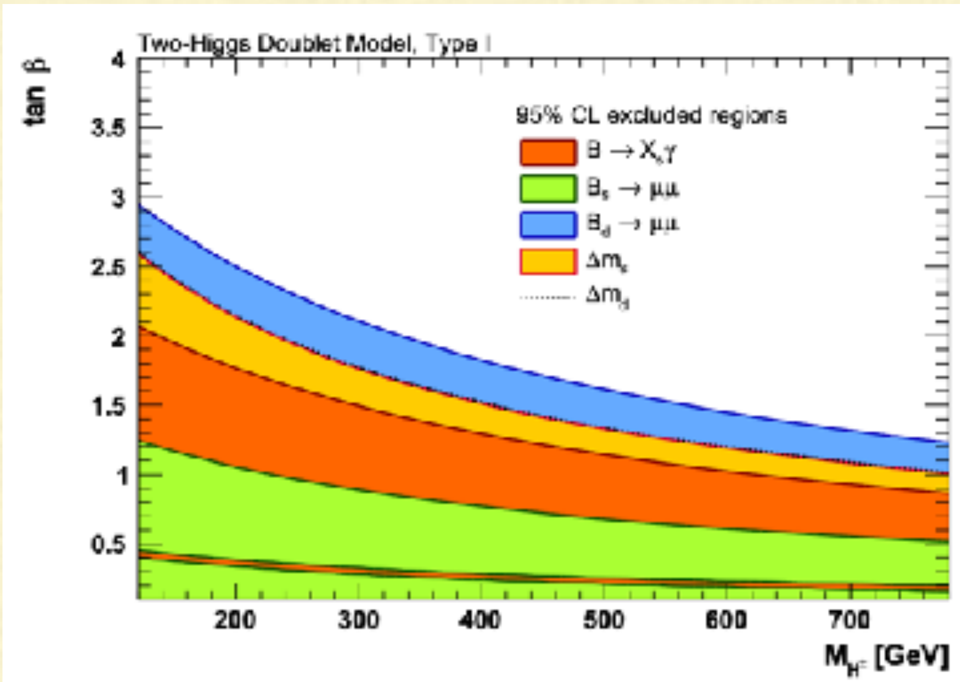
Type-Y like： $|\zeta_u| = 1/|\zeta_d| = |\zeta_e|$

Constraints from flavor exps.

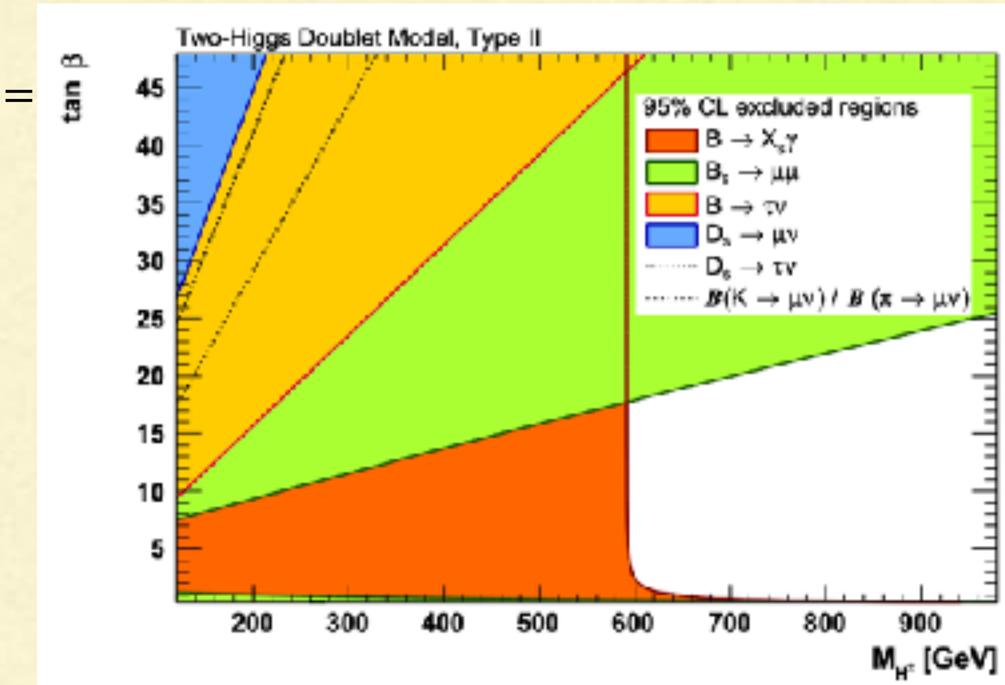
$$|\zeta_u| = |\zeta_d| = |\zeta_e|$$

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

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



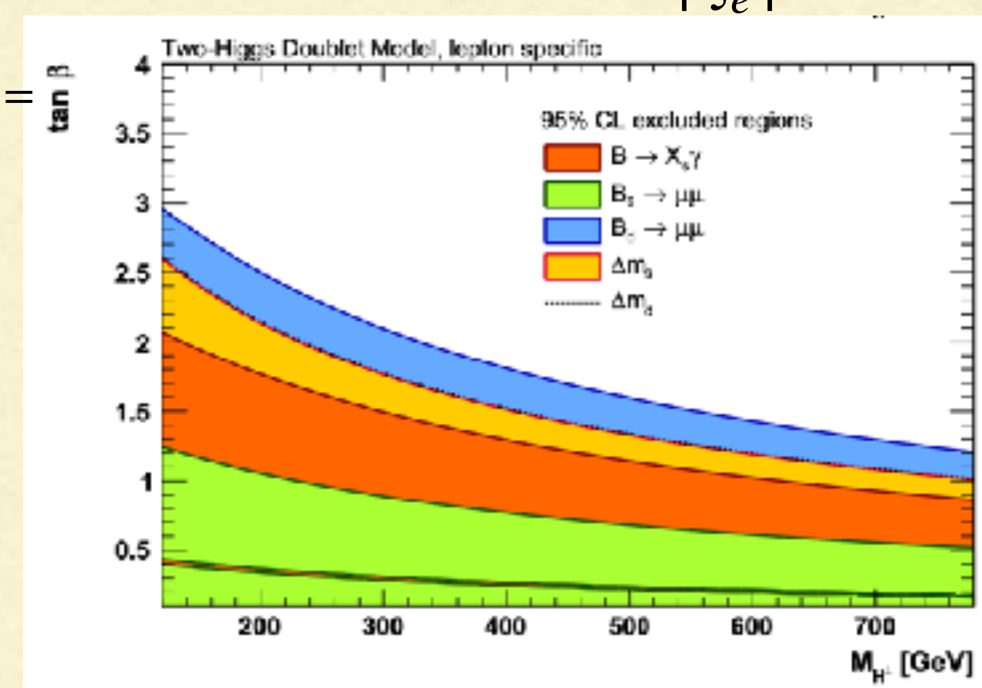
$\frac{1}{|\zeta_u|} =$



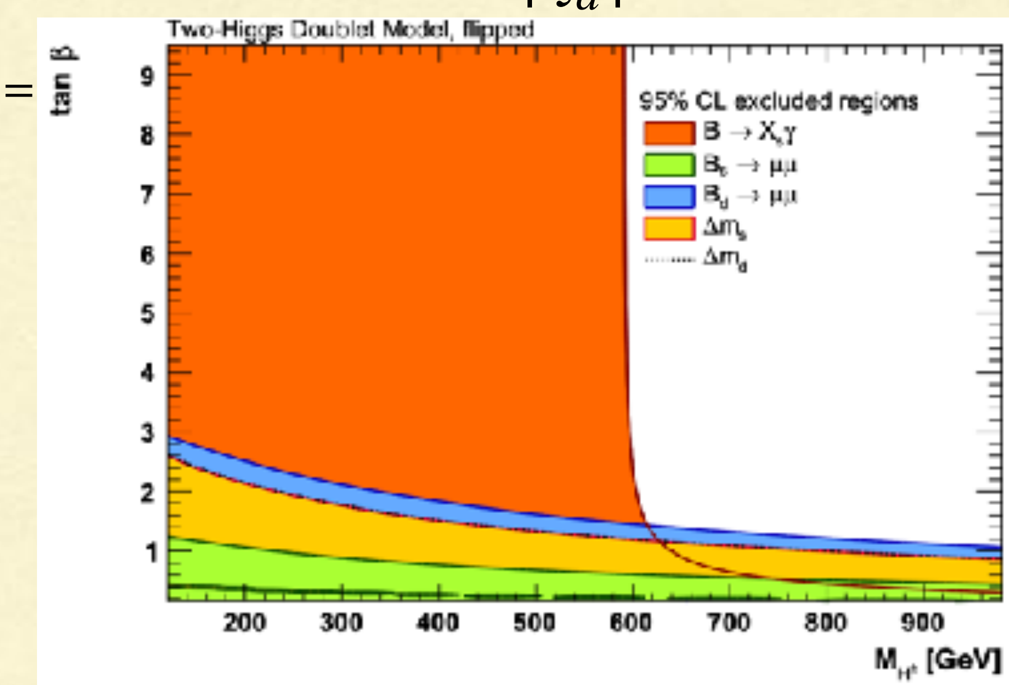
$$|\zeta_u| = |\zeta_d| = \frac{1}{|\zeta_e|}$$

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

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



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

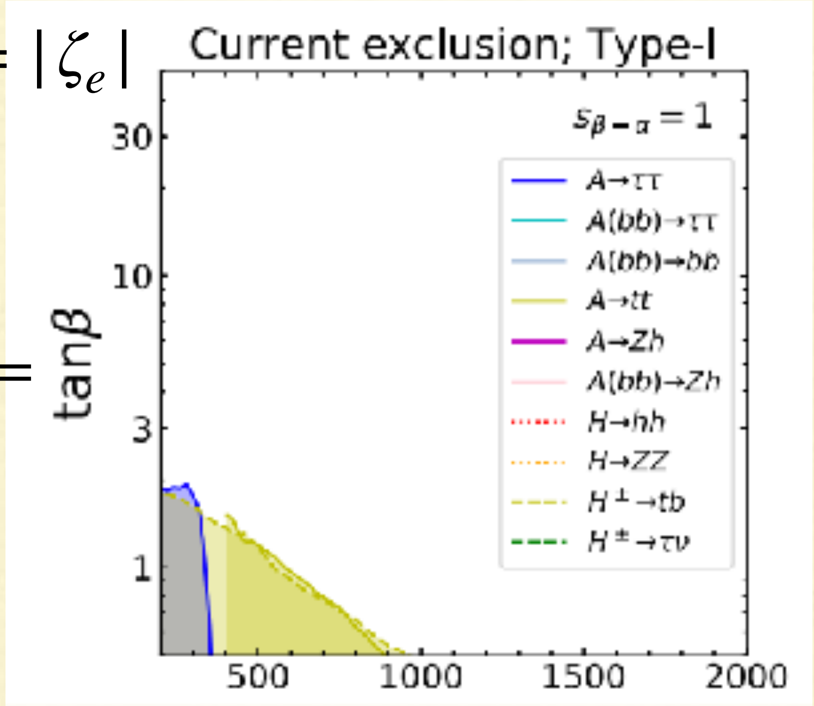


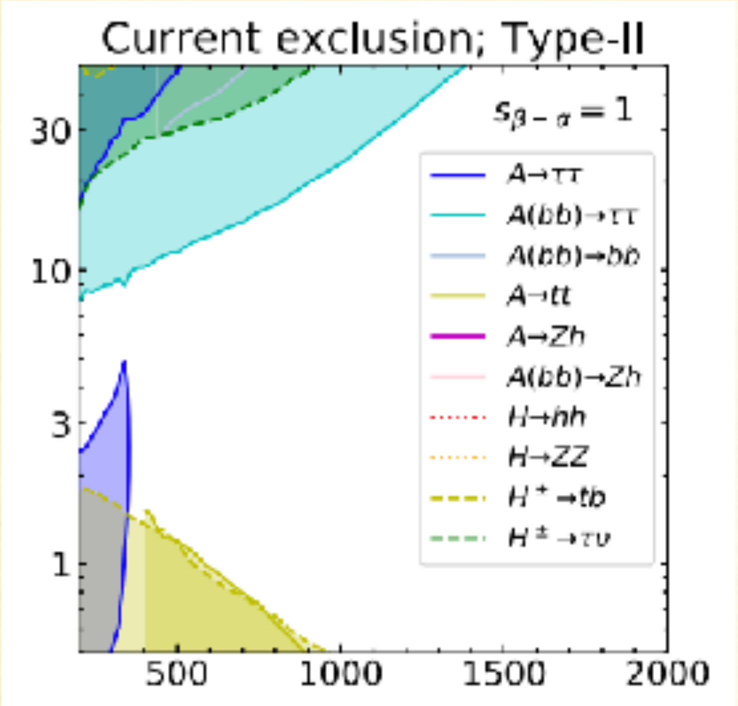
Constraints from Collider exps.

M. Aiko, S. Kanemura, M. Kikuchi, K. Mawatari, K. Sakurai, K. Yagyu, NPB (2021)

$|\zeta_u| = |\zeta_d| = |\zeta_e|$

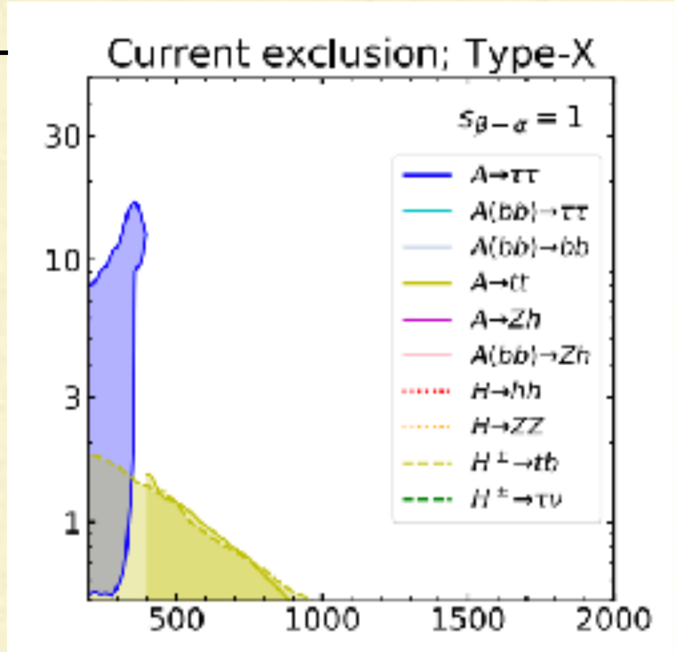
$\frac{1}{|\zeta_u|} =$

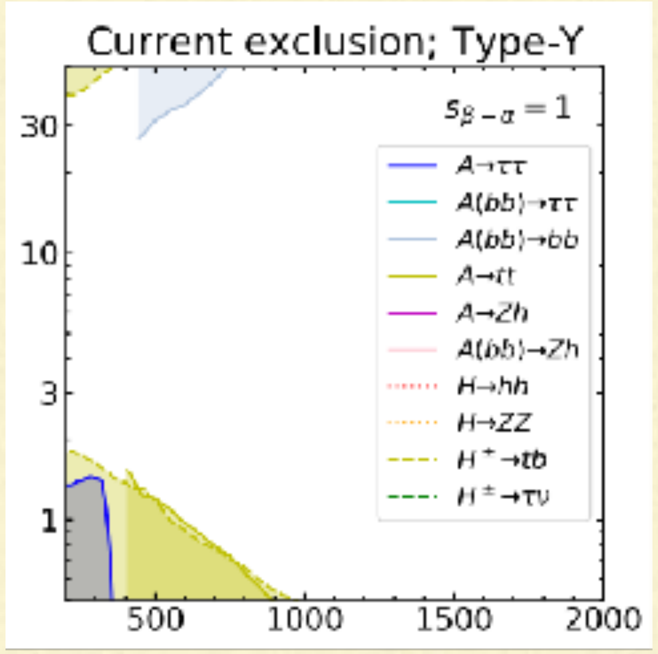




$\frac{1}{|\zeta_u|} = |\zeta_d| = |\zeta_e|$

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





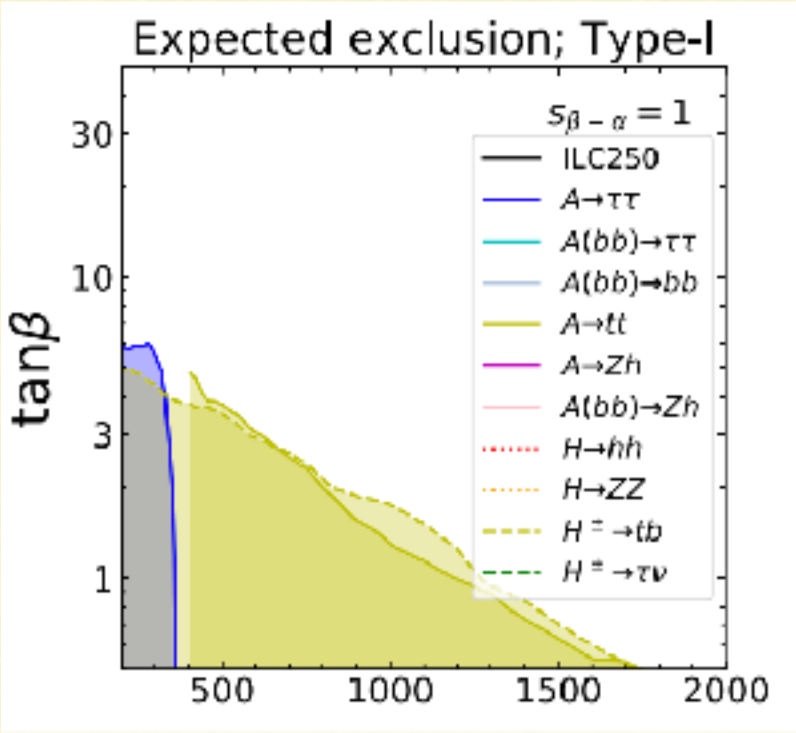
$|\zeta_u| = \frac{1}{|\zeta_d|} = |\zeta_e|$

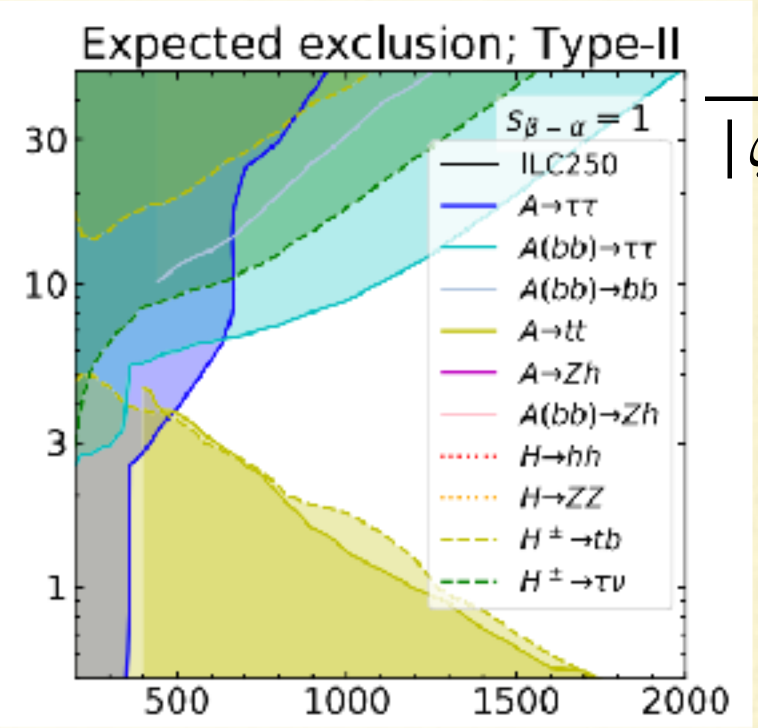
Direct search by future HL-LHC

M. Aiko, S. Kanemura, M. Kikuchi, K. Mawatari, K. Sakurai, K. Yagyu, NPB (2021)

$$|\zeta_u| = |\zeta_d| = |\zeta_e|$$

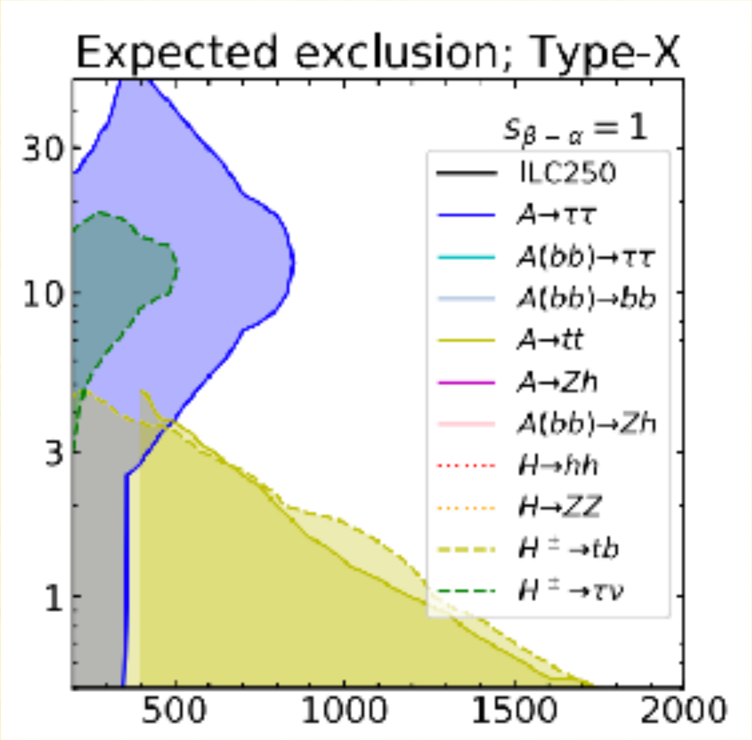
$$\frac{1}{|\zeta_u|} =$$

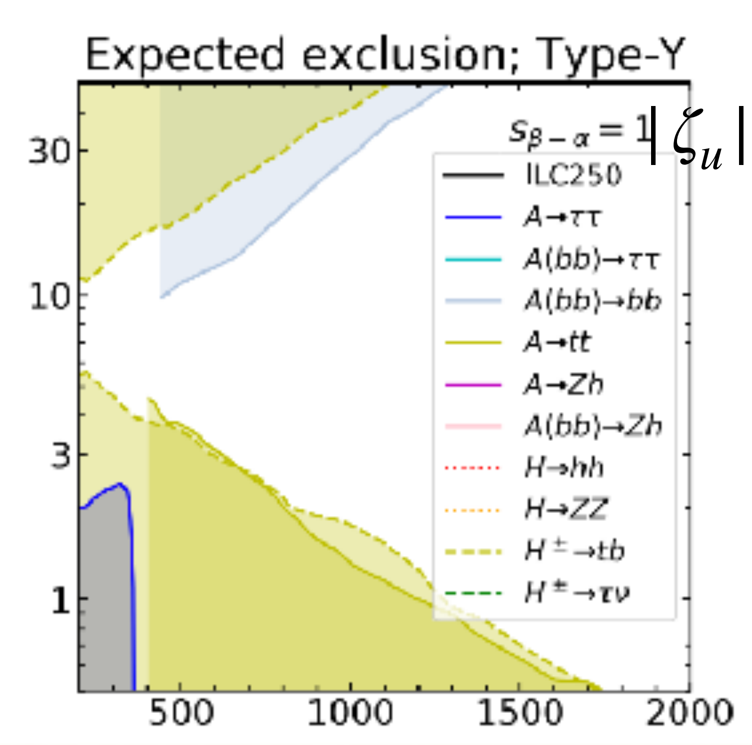




$$\frac{1}{|\zeta_u|} = |\zeta_d| = |\zeta_e|$$

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



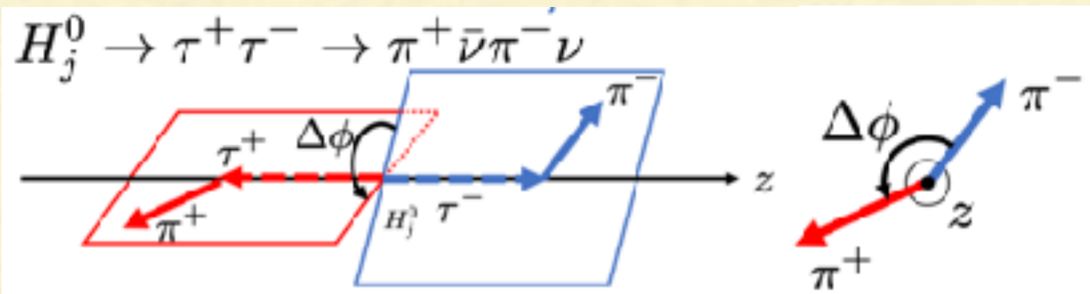


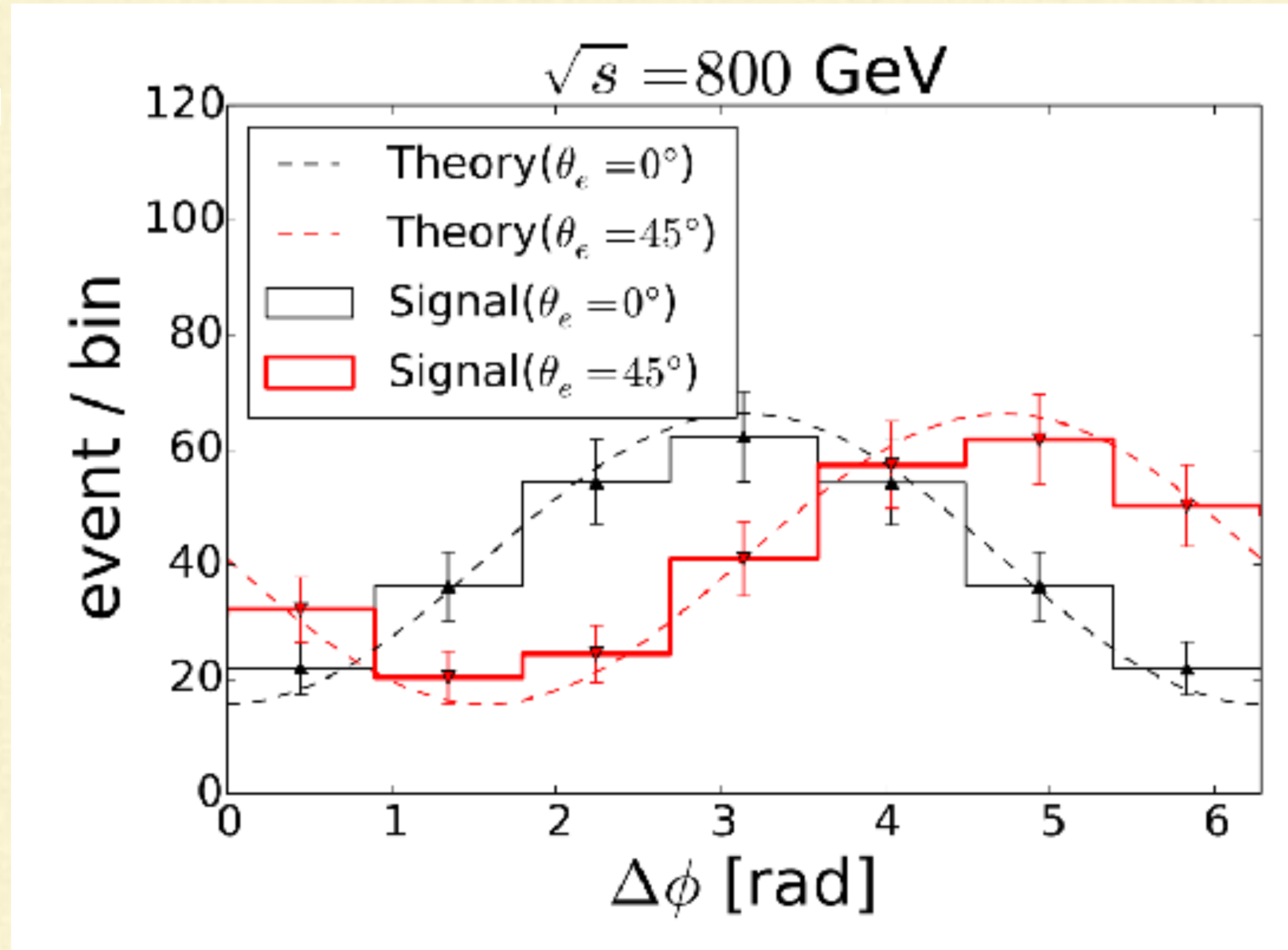
$$|\zeta_u| = \frac{1}{|\zeta_d|} = |\zeta_e|$$

The measurement of $\arg[\zeta_e]$ @ e^+e^- colliders

$$e^+ e^- \to H_2 H_3, \begin{cases} H_2 \to \tau^+ \tau^-, H_3 \to b\bar{b} \\ H_2 \to b\bar{b}, H_3 \to \tau^+ \tau^- \end{cases}$$

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





$M = 240,$	$m_{H_2^0} = 280,$	$m_{H_3^0} = 230,$	$m_{H^\pm} = 230$	(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)

Future LFV experiments

Processes	BR	Expected limits	Experiment
$\mu \to e\gamma$	1.4×10^{-14}	6×10^{-14}	MEG-II
$\tau \to e\gamma$	5.3×10^{-10}	3×10^{-9}	Belle-II
$\tau \to \mu\gamma$	1.1×10^{-11}	1×10^{-9}	Belle-II

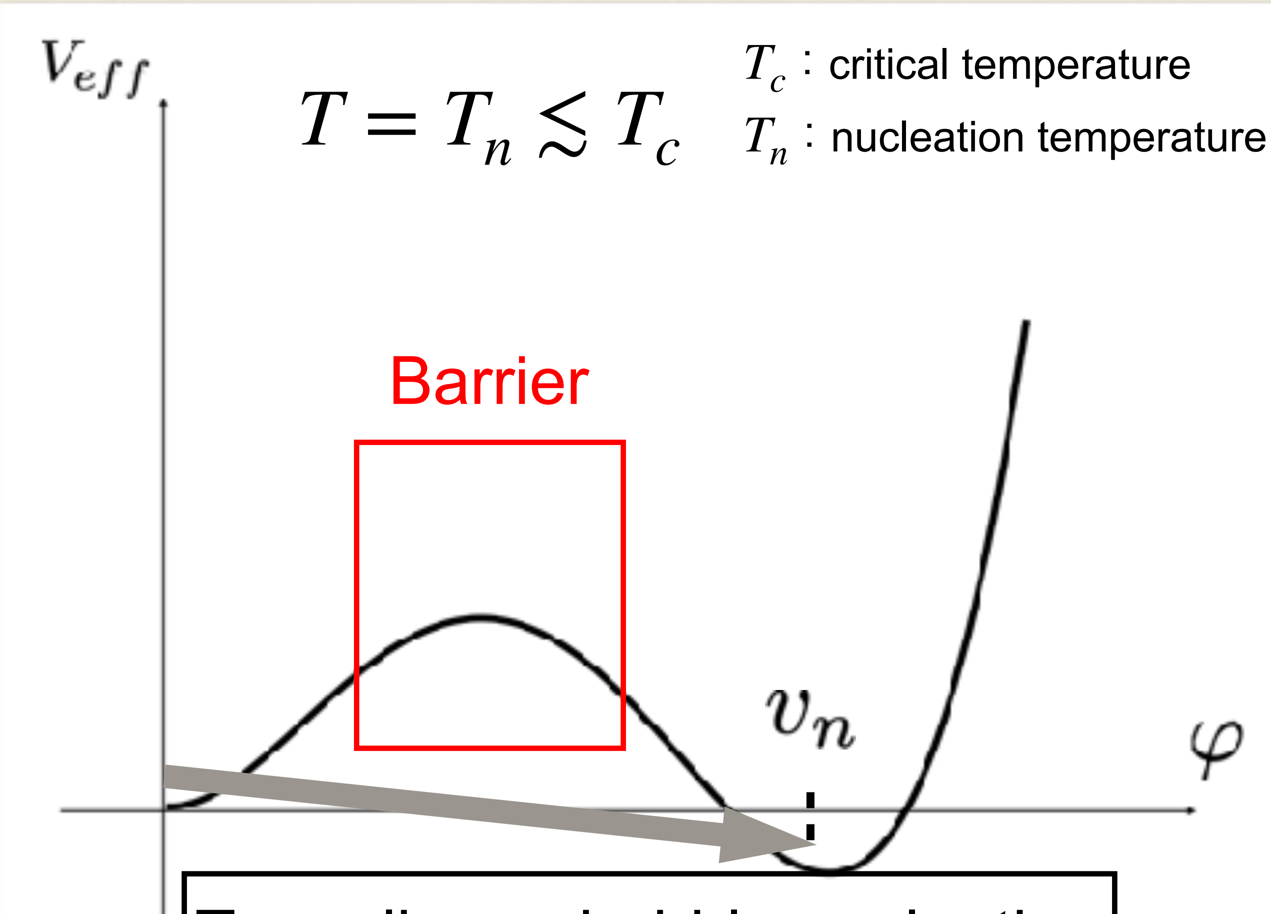
Processes	BR	Expected limits	Experiment
$\mu \to 3e$	1.0×10^{-13}	1.0×10^{-16}	Mu3e
$\tau \to 3e$	6.2×10^{-10}	4×10^{-10}	Belle-II
$\tau \to 3\mu$	2.4×10^{-11}	3×10^{-10}	Belle-II
$\tau \to e\mu\bar{e}$	5.1×10^{-12}	3×10^{-10}	Belle-II
$\tau \to \mu\mu\bar{e}$	1.1×10^{-12}	3×10^{-10}	Belle-II
$\tau \to ee\bar{\mu}$	4.5×10^{-13}	1×10^{-10}	Belle-II
$\tau \to e\mu\bar{\mu}$	9.6×10^{-11}	4×10^{-10}	Belle-II

The electroweak phase transition in the model

$$T = T_n \lesssim T_c$$

T_c : critical temperature

T_n : nucleation temperature



Tunneling →bubble nucleation

(High temperature expansion)

$$V_{eff} = E(T^2 - T_0^2)\varphi^2 \boxed{- ET\varphi^3} + \lambda_T \varphi^4$$

Sphaleron decoupling condition

$$\Gamma_{sph}^{br} < H(T_n) \quad \Rightarrow \quad \frac{v_n}{T_n} > 1$$

$$\frac{v_c}{T_c} = \frac{E}{2\lambda_{T_c}}$$

Large E is necessary for strongly 1st order EWPT

The cubic term E can be large by the non-decoupling effects of $H^{\pm}$, $H_{2,3}$, $S^{\pm}$, and η

$$\boxed{E = \frac{1}{12\pi v^3} \sum_{s=H^{\pm},H_{2,3},S^{\pm},\eta} g_i m_i^3 \left(1 - \frac{M_i^2}{m_i^2}\right)}$$

$(m_i^2 \gg M_i^2)$

$$m_i^2 = M_i^2 + \frac{1}{2}\lambda_i v^2$$

M_i^2 : Invariant mass parameter

The electroweak phase transition in the model

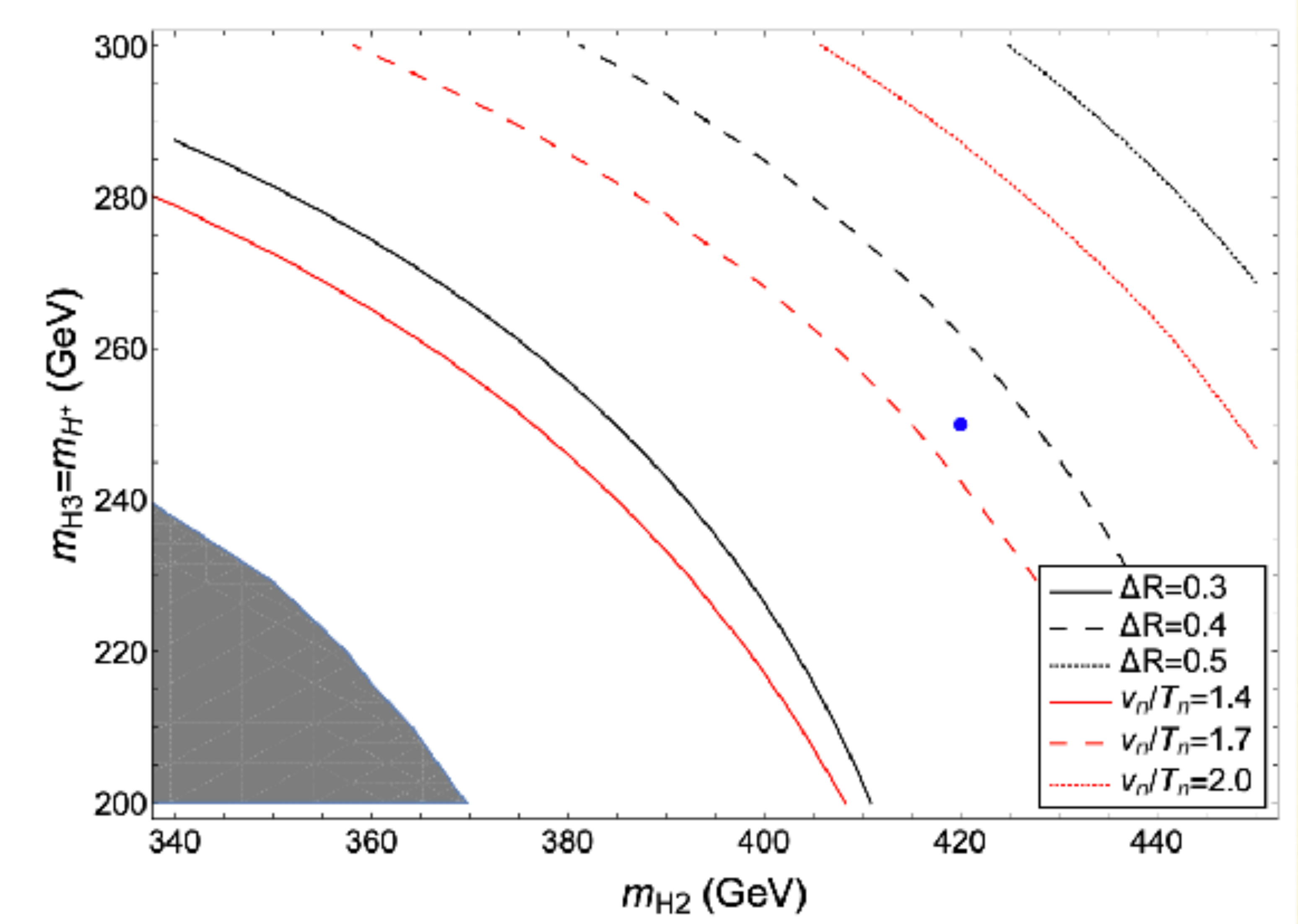
Non-decoupling effects of new scalars predicts large enhancement of the hhh coupling

$$\Delta R = \frac{\lambda_{hhh} - \lambda_{hhh}^{SM}}{\lambda_{hhh}^{SM}} = \boxed{\frac{1}{12\pi^2 v^2 m_h^2} \sum_{i=H^\pm, H_{2,3}, S^\pm, \eta} m_i^4 \left(1 - \frac{M^2}{m_i^2}\right)^3}$$

$$(m_i^2 \gg M^2)$$

Testable at future colliders

Kanemura, Kiyoura, Okada, Senaga, Yuan (2003)
Kanemura, Okada, Senaha, Yuan (2004)
Kanemura, Okada, Senaha (2005)



Local mass of the particles

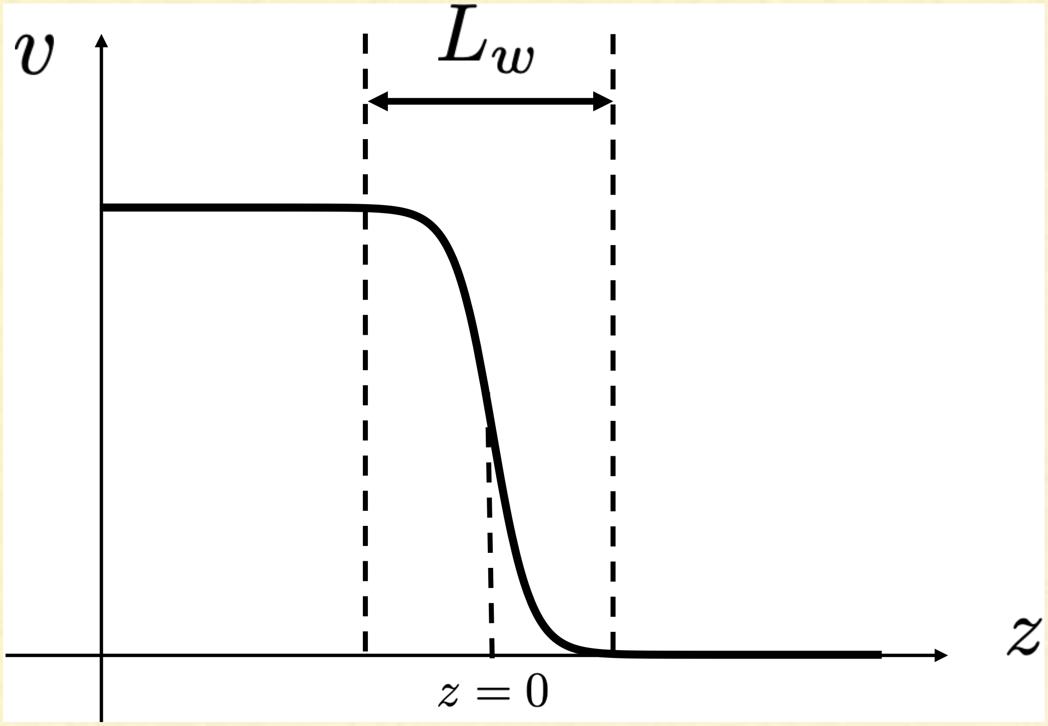
In expanding the vacuum bubbles, the VEV is space-dependent.

The mass of the particles also varies with spatial coordinate（Local mass）

$$\mathscr{L}_{mass} = m(z)\,\overline{\psi}P_R\psi + m(z)^*\,\overline{\psi}P_L\psi$$
$$= \mathrm{Re}[m]\,\overline{\psi}\psi + \boxed{i\mathrm{Im}[m]\,\overline{\psi}\gamma_5\psi}$$

CP-odd

P-odd



CP-violating Force

$$F_{\mathrm{odd}} = \pm\lambda\mathrm{sign}(p_z)\left\{\frac{(|m|^2\theta')'}{2E_0E_{0z}} - \frac{|m|^2\theta'(|m|^2)'}{4E_0^3E_{0z}}\right\}$$

+: Particles、−: Anti-particles

λ：helicity $\simeq$ chirality

$$\theta = \arg[m(z)] \qquad E_0^2 = p_x^2 + p_y^2 + p_z^2 + m^2 \qquad E_{0z}^2 = p_z^2 + m^2$$

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：$\Gamma / V = \omega T^4 e^{-S_E/T} \quad \left(\omega = \mathcal{O}(1)\right)$

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 of the following equation

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

Finite temperature $\alpha = 2$

(Boundary)

$$\varphi(\infty) = \varphi_F$$

$$\left.\frac{\mathrm{d}\varphi}{\mathrm{d}\rho}\right|_{\rho=0} = 0$$

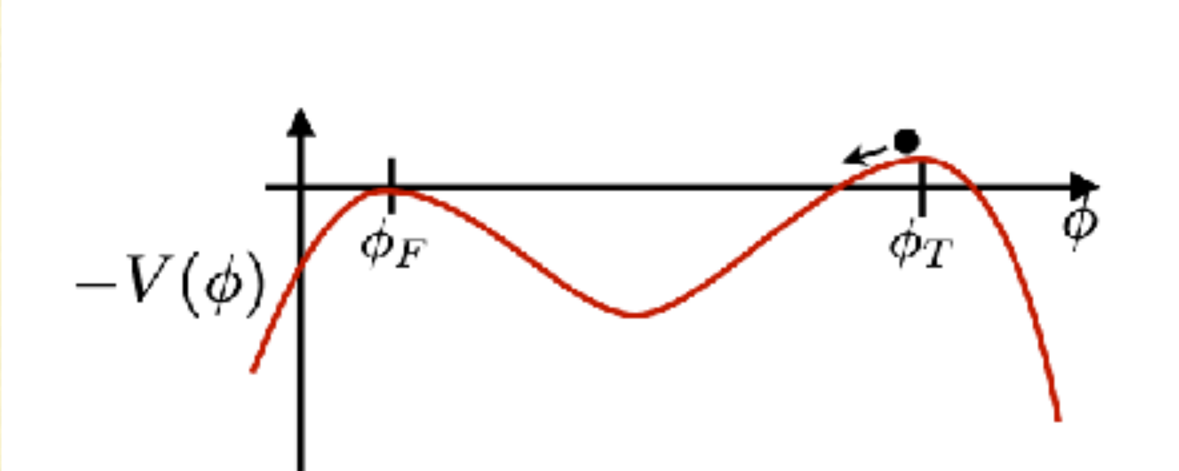


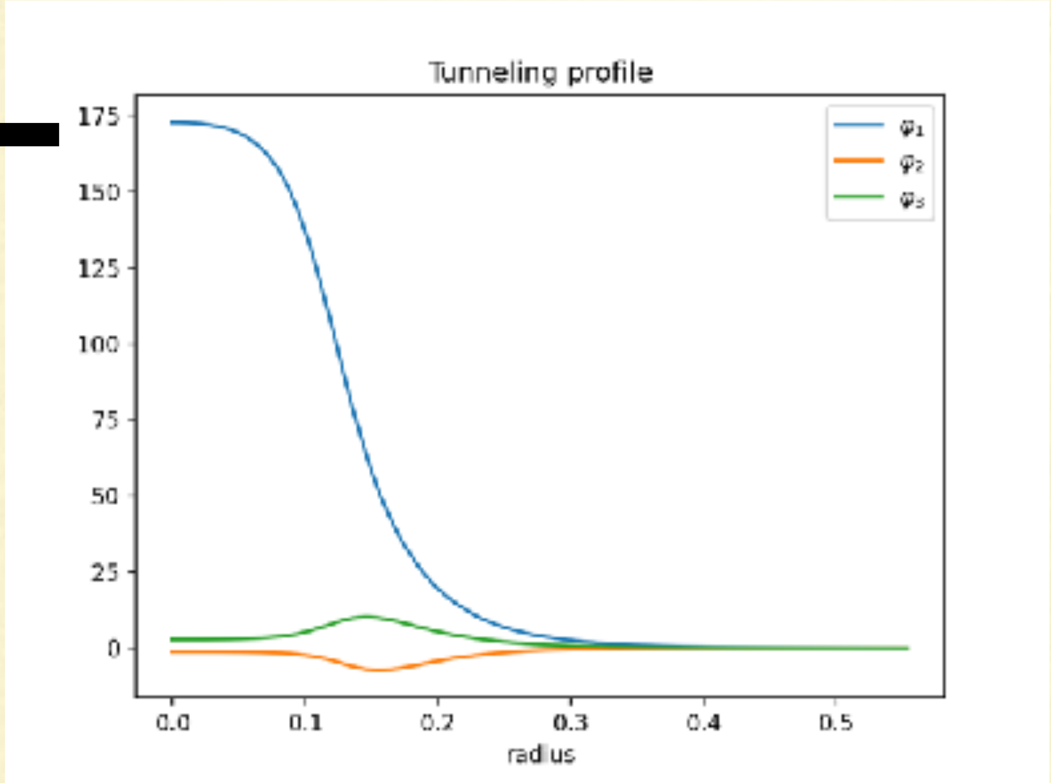
Figure from 1109.4189

The WKB method

Joyce, Cline, Kainulainen (2000); Fromme, Huber, (2007); Cline, Kainulainen (2020)

■ **WKB approximation**

CosmoTransitions



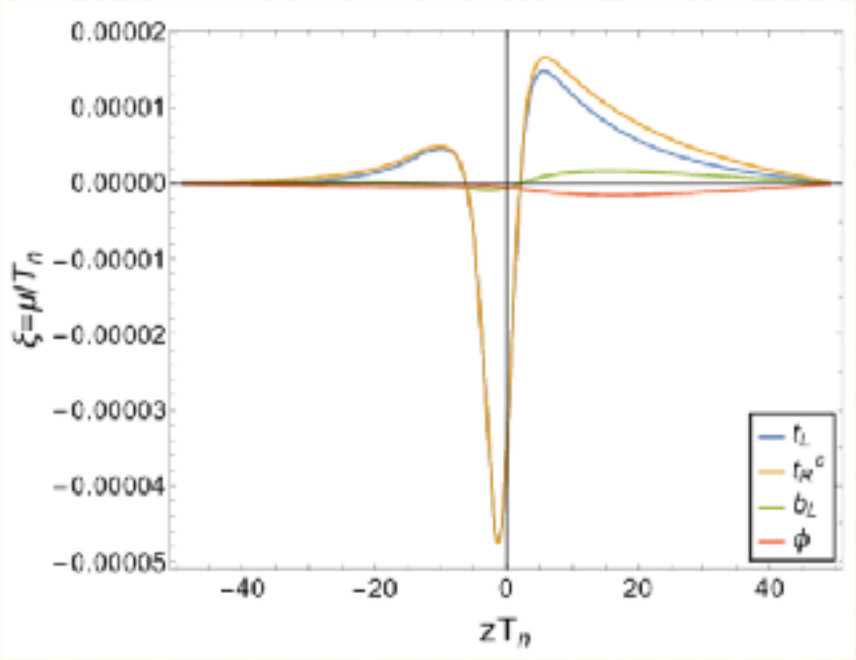
$m(z)$ is obtained

Dirac eq. $(i\partial\!\!\!/ - m(z))\psi = 0$

CPV Force $F \propto (|m|^2\theta')',\ \theta'(|m|^2)'$

Boltzmann eq.

$$(\partial_t + v\partial_z + F\partial_{p_z})f = C[f]$$



Sphaleron process

$$\eta_B \sim \Gamma_{ws} \int_0^\infty \mathrm{d}z\, \mu_{q_L}(z) e^{-kz}$$

η_B: baryon to photon ratio, Γ_{ws}: weak sphaleron rate

L_w dependence of baryon asymmetry

Cline, Laurent (2021)

Generated baryon asymmetry is roughly estimated as

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

A is a function of v_w and L_w

With some value of A,
the first and second terms
are canceled.

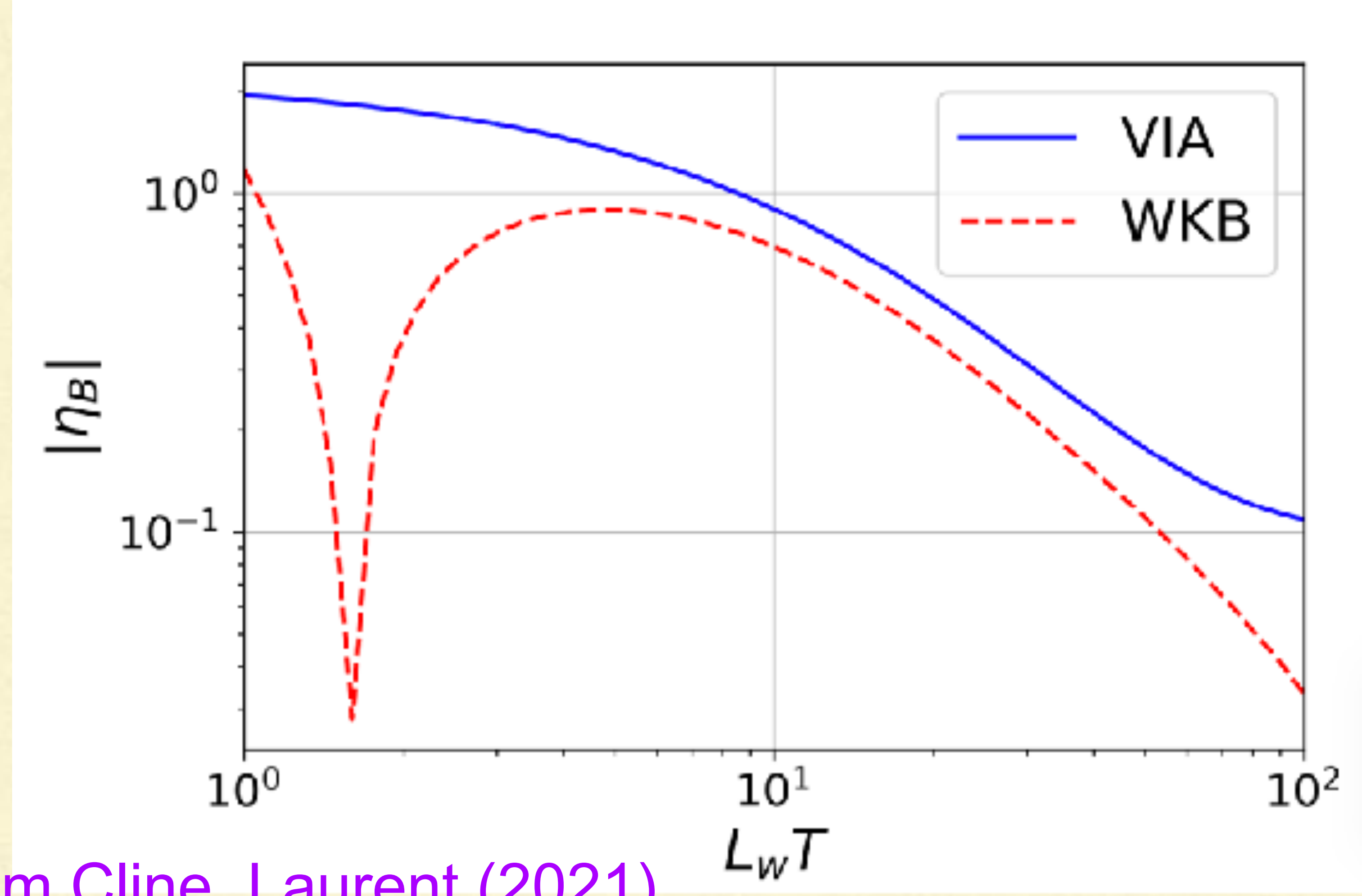
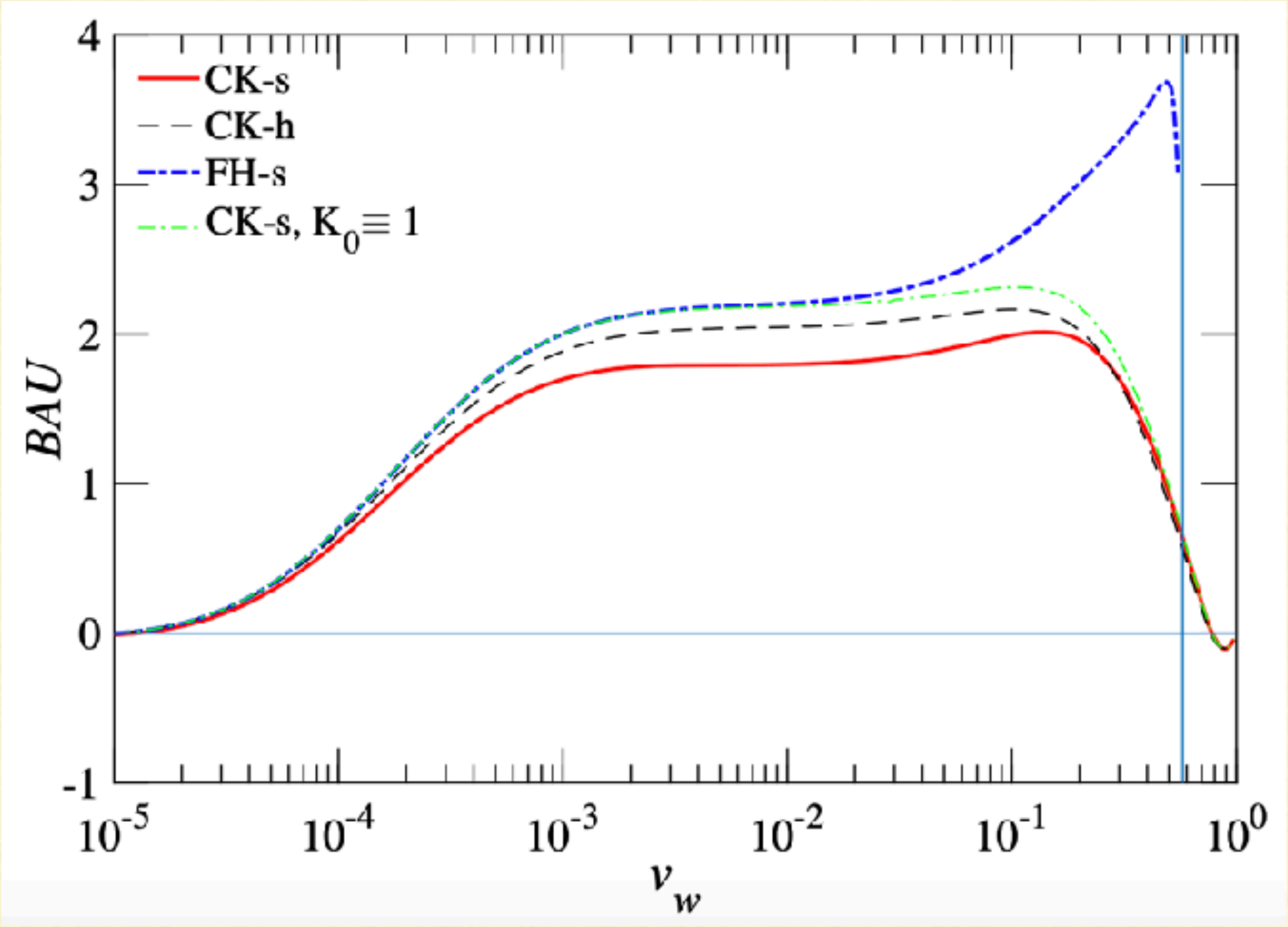


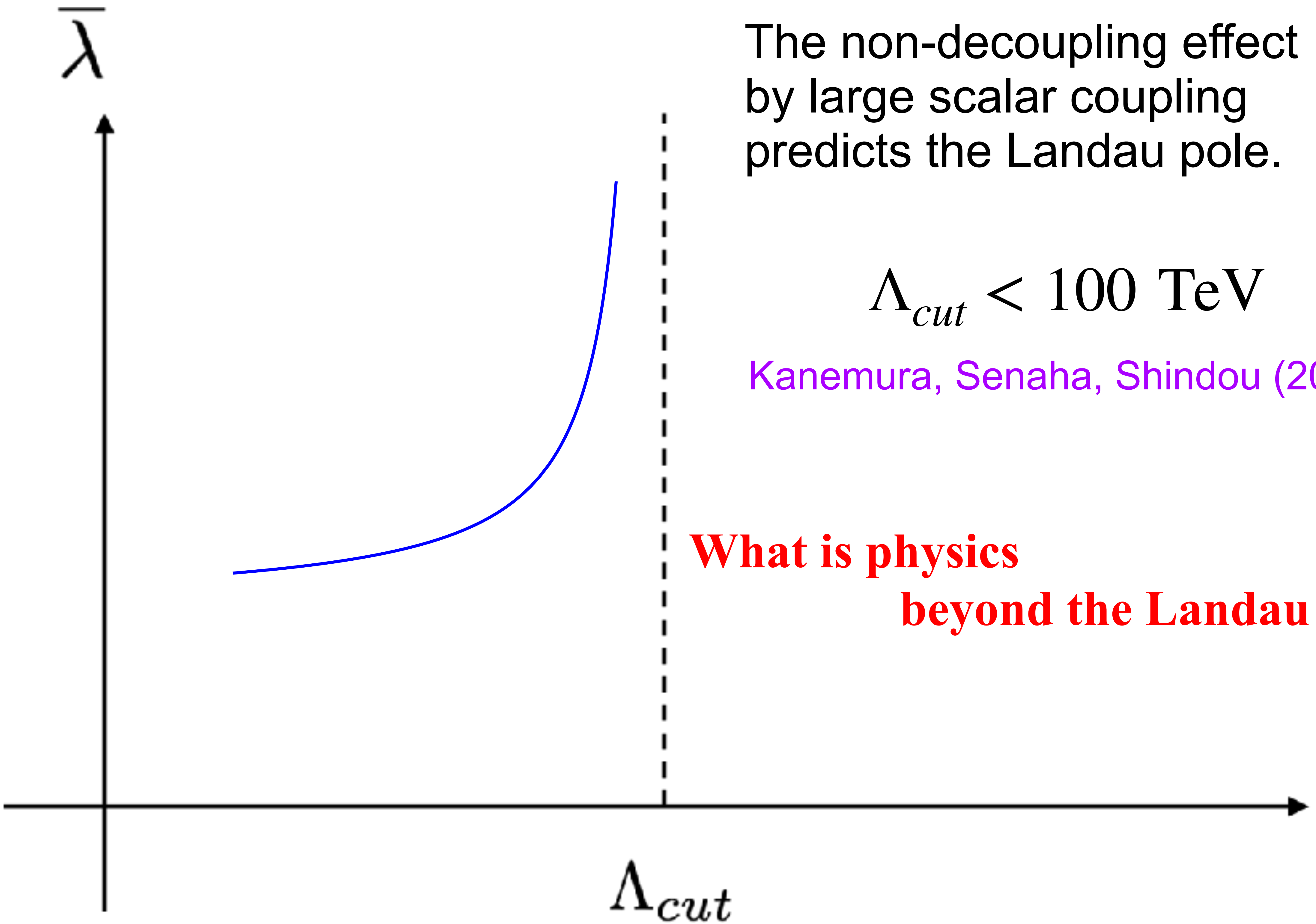
Figure from Cline, Laurent (2021)

Relativistic effect of v_w

We used the linear expansion of v_w.
The higher-order effect has been investigated in Cline, Kainulainen (2020)



Landau poleについて



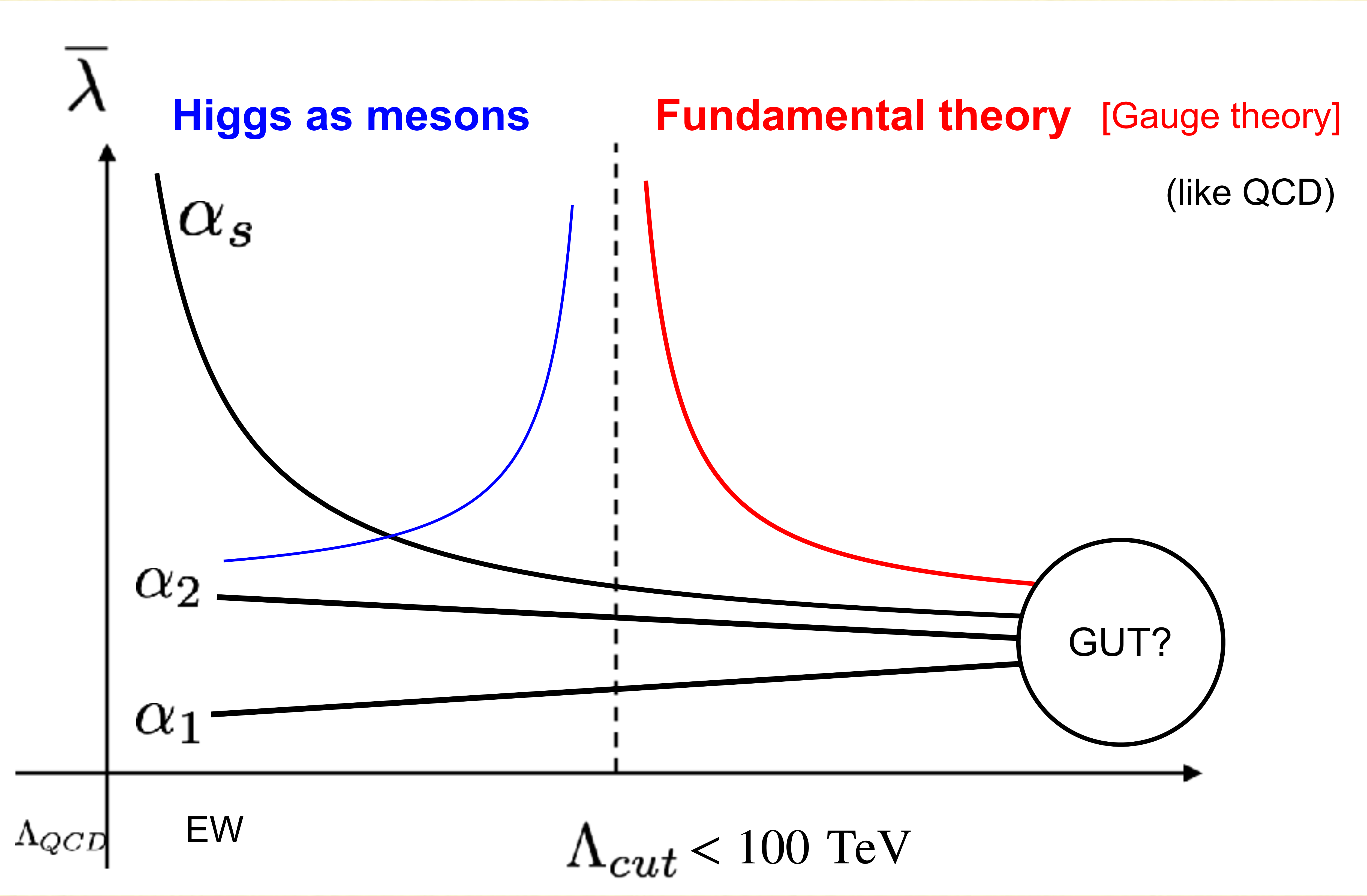
The non-decoupling effect by large scalar coupling predicts the Landau pole.

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

Kanemura, Senaha, Shindou (2011)

What is physics beyond the Landau pole？

Landau poleについて



New physics beyond the Landau pole

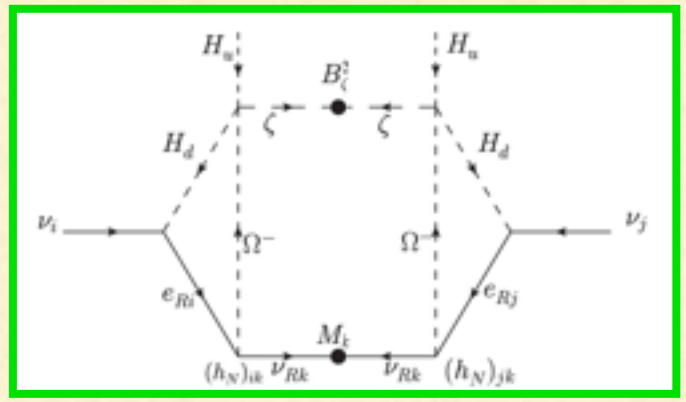
e.g.) SUSY $SU(2)_H$ gauge theory Kanemura, Shindou, Yamada (2012)

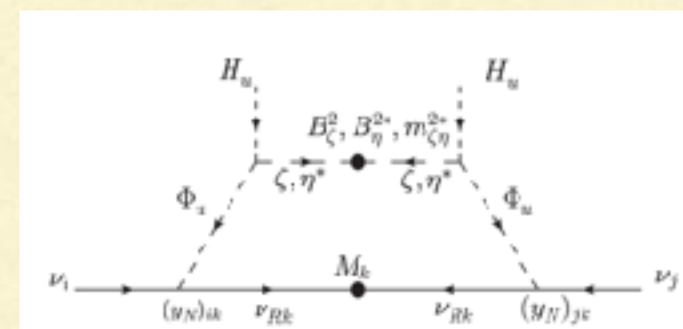
Higgs as mesons

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





Predicts all scalar fields
in the model of Aoki, Kanemura, Seto (2009)