Electroweak phase transition triggered by fermion sector

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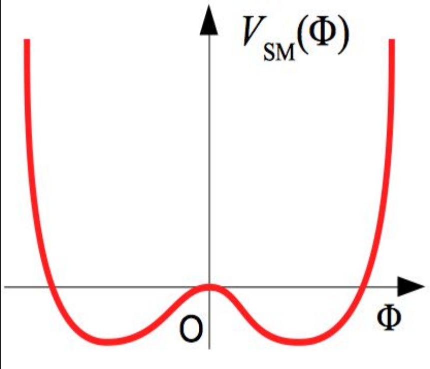
[arXiv:2103.05688]

Introduction

★ The shape of Higgs potential is still undetermined...

$$V_{SM}(\phi)=\mu^2|\phi|^2+\lambda|\phi|^4$$

(The SM case)



★ The dynamics of electroweak phase transition (EWPT) is governed by the shape of the Higgs potential.

If the model realizes the first-order EWPT...

- Baryon asymmetry of the universe could be explained by electroweak baryogenesis scenario.
- The model could be tested by the measurement of gravitational wave from first-order PT.

How can we realize the first-order EWPT? What is a source of the EWPT?

First-order EWPT

★ Effective potential with high temperature approximation:

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

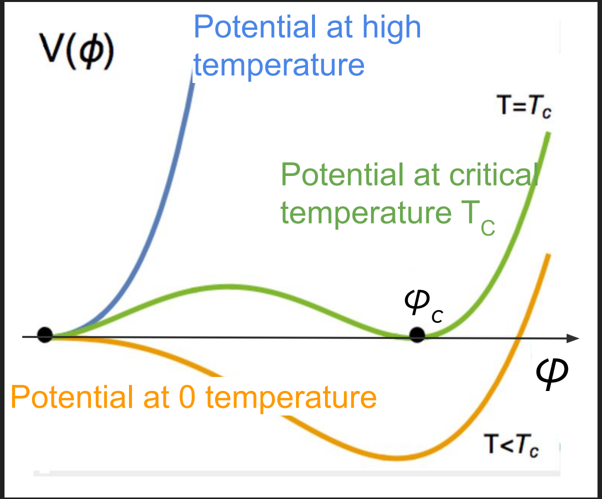
E : Thermal loop effect of bosons

★ To realize first-order EWPT, it is necessary to develop a sizable barrier in the thermal potential.

The SM does not generate such a sizable barrier.

[Y. Aoki, F. Csikor, Z. Fodor and A. Ukawa, Phys. Rev. D 60, 013001 (1999)]

$$V_{\text{eff}}^{SM}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 + \frac{\lambda_T}{4}\varphi^4 \quad \text{(at } T\sim\varphi)$$



Usually, the sizable barrier could be developed by additional contribution to E term.

Although the fermion does not enhance the E term, the extended fermion model can generate a sizable barrier in the potential.

EWPT triggered by fermion sector

★ The fermion model could have additional reductions in φ^2 and φ^4 terms through new fermion effects.

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

The new fermion effects make φ^2 and φ^4 terms comparable to φ^3 term.

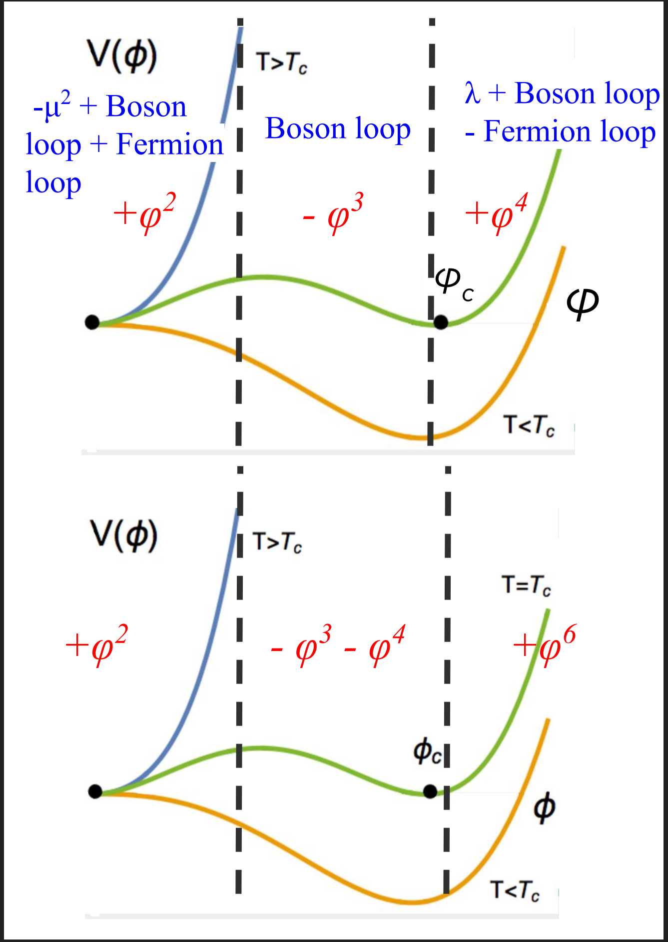
★ The model with heavy fermion (around TeV scale) could generate a barrier through the new fermion effects.

$$V_{\rm eff}(\phi, T) \simeq \frac{1}{2}\mu^2\varphi^2 - \frac{1}{4}\lambda\varphi^4 + \frac{1}{6}\gamma\varphi^6 \quad (\mu^2, \lambda, \gamma > 0)$$

Not only φ^3 term but also φ^4 term are negative.

The simple model with extended fermion sector could develop a sizable barrier by above two scenarios.

[Qing-Hong Cao, K. H., Xuxiang Li, Zhe Ren, Jiang-Hao Yu, arXiv:2103.05688]



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The new fermion effects make φ^2 and φ^4 terms

In this talk, we will discuss the detail in a simple fermion model with one isospin doublet fermion and one singlet neutral fermion.

★

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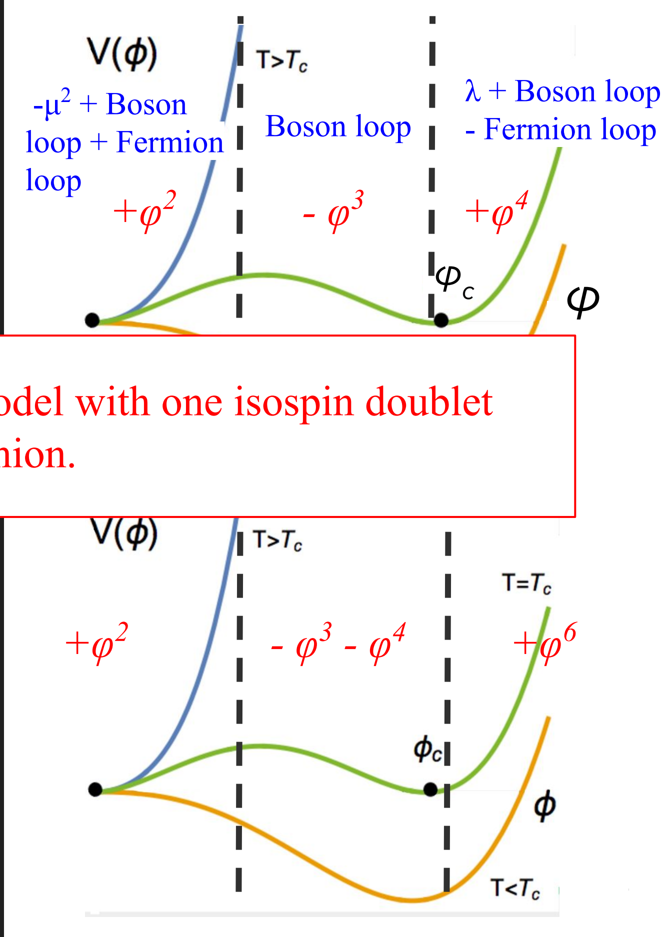

Extended fermion model

★ The simple Lagrangian for new fermions

$L = \begin{pmatrix} N \\ E \end{pmatrix}$

$$-\mathcal{L}_{VLL} = y_N(\bar{L}_L \tilde{H} N'_R + \bar{N}'_L \tilde{H}^\dagger L_R) + m_N \bar{L}_L L_R + m_L \bar{N}'_L N'_R + \text{h.c.}$$

Double lepton: L
Singlet neutral lepton: N'
SM-like Higgs doublet field : H

★ New parameters in the model: y_N , m_L , m_N

Mass parameter region

A. $m_L \sim m_N \sim y_N v$ (Both fermions are at EW scale)

[M. Carena, A. Megevand, M. Quiros and C. E. Wagner, Nucl. Phys. B 716 (2005), 319, M. Fairbairn and P. Grothaus, JHEP 10 (2013), 176, A. Aranda, E. Jim é nez and C. A. Vaquera-Araujo, JHEP01 (2015), 070, D. Egana-Ugrinovic, JHEP 12 (2017), 064, A. Angelescu and P. Huang, Phys. Rev. D 99 (2019) no.5, 055023]

B. $m_L >> m_N >> y_N v$, $m_L \sim m_N >> y_N v$, (Both are at TeV scale)

C. $m_L >> m_N \sim y_N v$ (One is at TeV scale, another is at EW scale)

[H. Davoudiasl, I. Lewis and E. Ponton, Phys. Rev. D 87 (2013) no.9, 093001, O. Matsedonskyi and G. Servant, JHEP 09 (2020), 012]

The light m_L region is already prohibited by collider experiments.
[A. M. Sirunyan et al. [CMS Collaboration], Phys. Rev. D 100, no. 5, 052003 (2019)]

How to generate a barrier?

★ Effective couplings

$$\lambda_{n,eff} \equiv \frac{1}{(n-1)!}\frac{\partial^n}{\partial\varphi^n}(V_{eff}+\Delta V_T)\Big|_{\varphi=0}$$

We extract the temperature dependence of the coefficient of φ^n in potential.

$$V_{eff}^P = \lambda_{1,eff}\varphi + \frac{\mu_{eff}^2}{2}\varphi^2 + \frac{\lambda_{3,eff}}{3}\varphi^3 + \frac{\lambda_{eff}}{4}\varphi^4 + \frac{\lambda_{5,eff}}{5}\varphi^5 + \frac{\gamma_{eff}}{6}\varphi^6 + \frac{\lambda_{7,eff}}{7}\varphi^7 + \frac{\delta_{eff}}{8}\varphi^8 + \frac{\lambda_{9,eff}}{9}\varphi^9 + \frac{\epsilon_{eff}}{10}\varphi^{10} + \mathcal{O}(\varphi^{11}).$$

★ Mass region (A) $(m_L \sim m_N \sim y_N v)$

$$(\mu_{eff}^{2\,\text{fermions}})^2 \simeq \frac{y_N^2}{12}\left(2T^2 - \frac{9m_L^2}{\pi^2}\left(\ln\frac{\alpha_F T^2}{v^2} - \frac{3}{2}\right)\right),$$

$$\lambda_{eff}^{2\,\text{fermions}} \simeq -\frac{y_N^4}{8\pi^2}\left(\ln\frac{\alpha_F T^2}{v^2} - \frac{3}{2}\right),$$

Dominant contributions at the critical temperature for EWPT.

Both terms have the same signs.

(- μ^2 - Fermion loop) φ^2

(+ λ - Fermion loop) φ^4

Typically, there are no reduction effects in φ^2 and φ^4 terms at the same time.

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★ Mass region (A) $(m_L \sim m_N \sim y_N v)$

It is difficult to generate a sizable barrier in this region.

$$(\mu_{eff}^{2\,\text{fermions}})^2 \simeq \frac{y_N^2}{12}\left(2T^2 - \frac{9m_L^2}{\pi^2}\left(\ln\frac{\alpha_F T^2}{v^2} - \frac{3}{2}\right)\right),$$

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Typically, there are no reduction effects in φ^2 and φ^4 terms at the same time.

How to generate a barrier?

★ Mass region (B) and (C) have heavy fermion with TeV scale.

We used “matching method” to treat the multi-scale effective potential.

[Qing-Hong Cao, K. H., Xuxiang Li, Zhe Ren, Jiang-Hao Yu, arXiv:2103.05688]

Energy scale Q

$$V_{eff}^{HE} = \frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \sum_{i=\text{all fields}} \frac{n_i}{64\pi^2} M_i(\varphi)^4 \left(\log\frac{M_i(\varphi)^2}{Q_M^2} - c_i\right)$$

Matching scale Q_M — Matching condition

$$(\mu^2)^{LE} = \left(1+2Z_\varphi^{\text{heavy}}\right)\mu^2 + \frac{\partial^2}{\partial\varphi^2}\sum_{i=\text{heavy fields}} \frac{n_i}{64\pi^2} M_i(\varphi)^4 \left(\log\frac{M_i(\varphi)^2}{Q_M^2} - c_i\right)\Bigg|_{\varphi=0}$$

$$\lambda^{LE} = \left(1+4Z_\varphi^{\text{heavy}}\right)\lambda + \frac{1}{6}\frac{\partial^4}{\partial\varphi^4}\sum_{i=\text{heavy fields}} \frac{n_i}{64\pi^2} M_i(\varphi)^4 \left(\log\frac{M_i(\varphi)^2}{Q_M^2} - c_i\right)\Bigg|_{\varphi=0}$$

$$\lambda_{(n)}^{LE} = \frac{1}{(n-1)!}\frac{\partial^n}{\partial\varphi^n}\sum_{i=\text{heavy fields}} \frac{n_i}{64\pi^2} M_i(\varphi)^4 \left(\log\frac{M_i(\varphi)^2}{Q_M^2} - c_i\right)\Bigg|_{\varphi=0}$$

$$V_{eff}^{LE} = \frac{(\mu^2)^{LE}}{2}\varphi^2 + \frac{\lambda^{LE}}{4}\varphi^4 + \sum_{i=\text{light fields}} \frac{n_i}{64\pi^2} M_i(\varphi)^4 \left(\log\frac{M_i(\varphi)^2}{Q_M^2} - c_i\right) + \sum_n \frac{\lambda_{(n)}^{LE}}{n}\varphi^n$$

RG running

EW scale Q_{EW}

$$V_{eff}^{EW} = \frac{(\mu^2)^{EW}}{2}\varphi^2 + \frac{\lambda^{EW}}{4}\varphi^4 + \sum_i \frac{n_i}{64\pi^2} M_i(\varphi)^4 \left(\log\frac{M_i(\varphi)^2}{Q_{EW}^2} - c_i\right) + \sum_n \frac{\lambda_{(n)}^{EW}}{n}\varphi^n$$

★ This treatment can be extended to other new physics models with heavy fields and light fields not limited to the fermion degree of freedom.

How to generate a barrier?

★ Mass region (B) $(m_L >> m_N >> y_N v,\ m_L \sim m_N >> y_N v)$

$$\lambda_{eff}^{T=0} \sim \lambda_{eff}^{SM} - \frac{y_N^6 v^2}{8\pi^2 M_L^2} \qquad (M_L \gg m_N \gg y_N v)$$

$$\lambda_{eff}^{T=0} \sim \lambda_{eff}^{SM} - \frac{y_N^6 v^2}{160\pi^2 m_L^2} \qquad (m_L \sim m_N \gg y_N v)$$

New fermion effects show up in the potential through the high dimensional operator, like second terms.

The contributions to φ^n terms are small...

It is difficult to generate a sizable barrier in this region.

★ Mass region (C) $(m_L >> m_N \sim y_N v)$

$$(\mu_{eff}^{\text{new fermion}})^2 \simeq \gamma_{eff}^{T=0} v^4 + \frac{y_N^2 X}{2(1-X)}\left(-\frac{T^2}{3} + \frac{X^2 m_L^2}{2\pi^2}\left(\ln\frac{\alpha_F T^2}{v^2} - \frac{3}{2}\right)\right),$$

$$\lambda_{eff}^{\text{new fermion}} \simeq -2\gamma_{eff}^{T=0} v^2 + \frac{4 y_N^4 (1+X)}{16 m_L^2 (1-X)^3}\left(\frac{T^2}{3} - \frac{X^2 m_L^2 (3-X)}{2\pi^2(1+X)}\left(\ln\frac{\alpha_F T^2}{v^2} - \frac{3}{2}\right)\right)$$

$$X = m_N / m_L$$

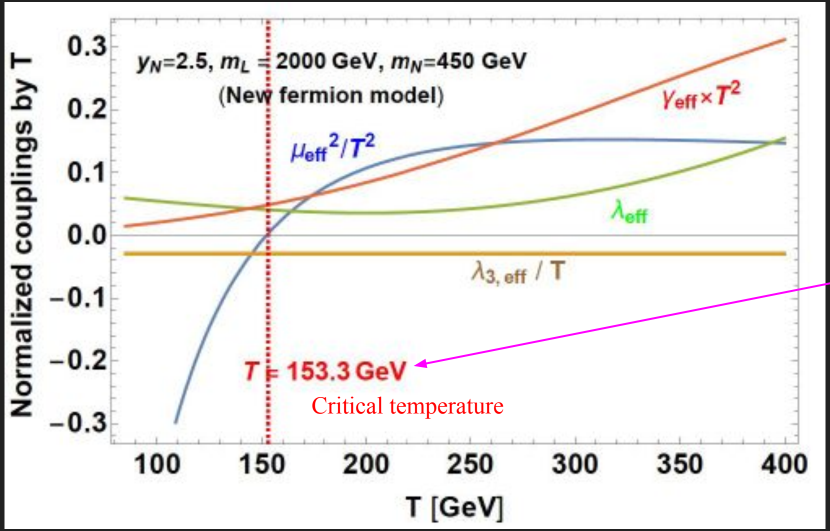
The contributions to φ^2 term are positive, while ones to φ^4 term are negative.

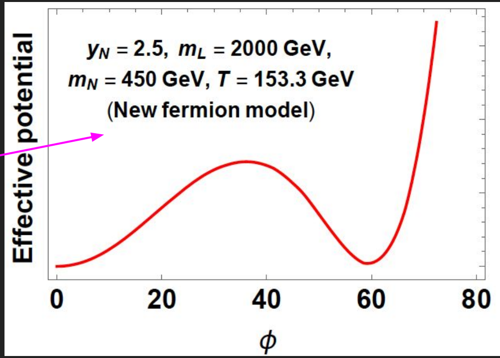
→ The sizable barrier could be developed in the potential in this region.

Mass region (C)

★ Temperature dependence of normalized effective couplings

Scenario (I) : $V_{\rm eff}(\varphi,T) \simeq \frac{1}{2}\mu^2\varphi^2 - \frac{1}{3}\lambda_3\varphi^3 + \frac{1}{4}\lambda\varphi^4$





$y_N = 2.5,\ m_L ,= 2000$ GeV, $m_N = 450$ GeV

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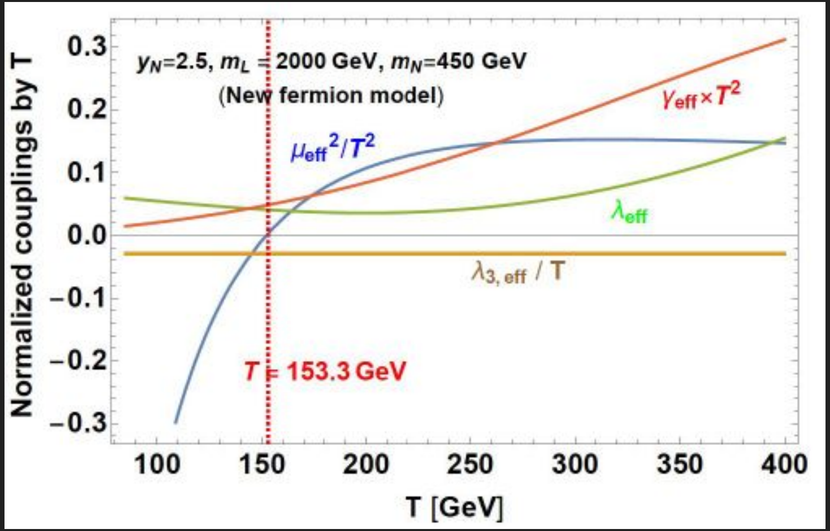

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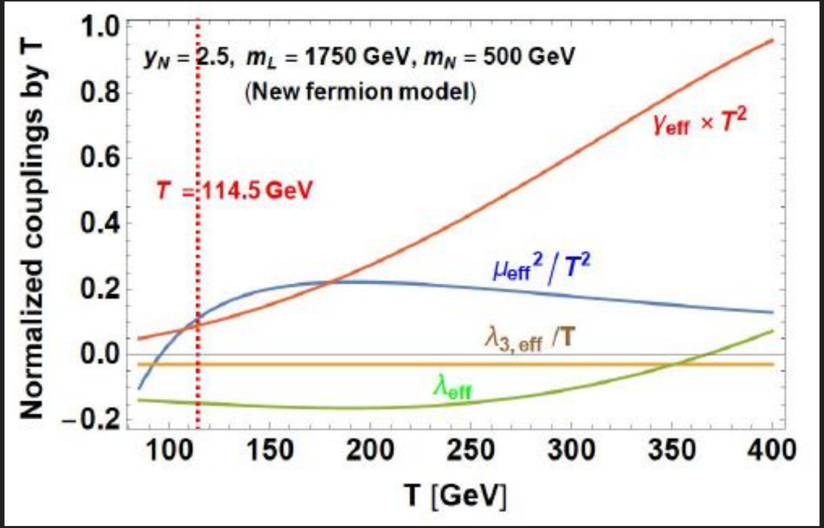
Scenario (II) : $V_{\rm eff}(\phi,T) \simeq \frac{1}{2}\mu^2\varphi^2 - \frac{1}{4}\lambda\varphi^4 + \frac{1}{6}\gamma\varphi^6$



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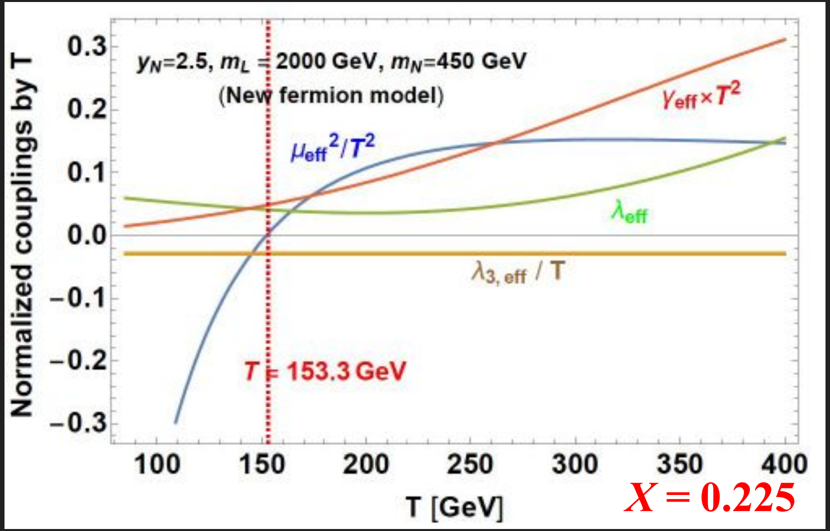

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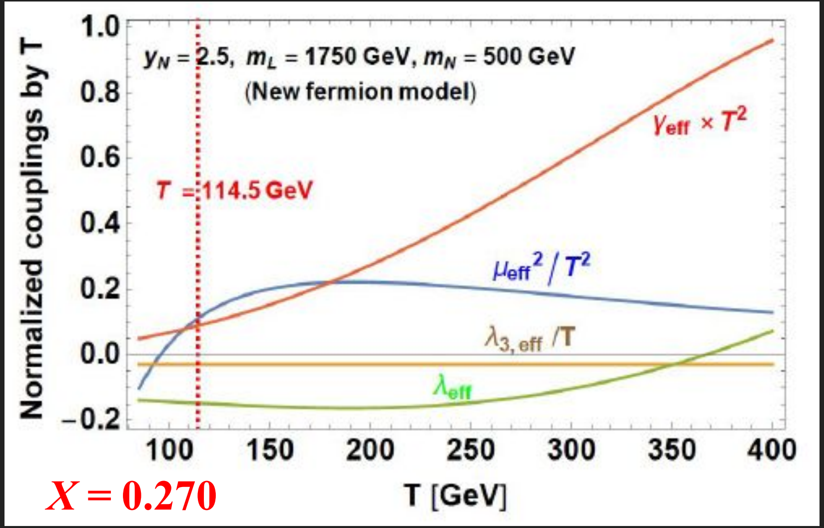

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$$\mu^2_{eff} \supset \frac{y_N^2 m_L^2 X^3}{4\pi^2(1-X)}\left(\ln\frac{\alpha T^2}{v^2} - \frac{3}{2}\right),\quad \lambda_{eff} \supset -\frac{y_N^4 X^2(3-X)}{8\pi^2(1-X)^3}\left(\ln\frac{\alpha T^2}{v^2} - \frac{3}{2}\right) \quad X = m_N/m_L$$

Fermionic reduction contributions depends on the value of m_N /m_L.

Mass region (C)

★ Parameter region where a sizable barrier could be developed in mass region $m_L >> m_N \sim y_N v$.

Orange (Scenario (I))

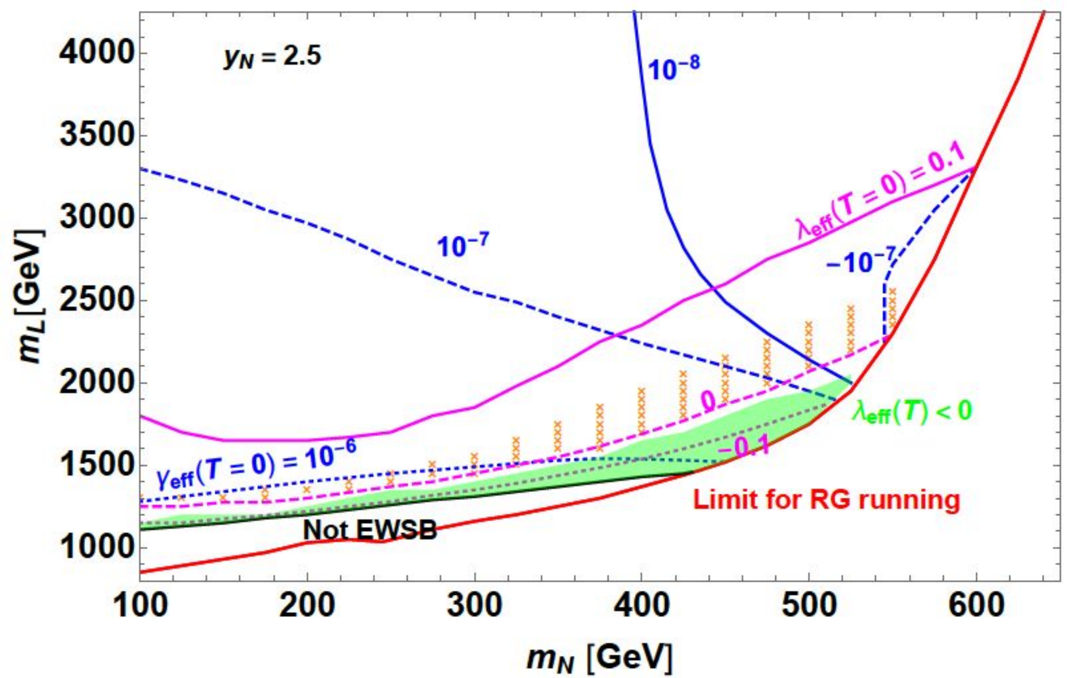
$$V_{\rm eff}(\varphi,T) \simeq \frac{1}{2}\mu^2\varphi^2 - \frac{1}{3}\lambda_3\varphi^3 + \frac{1}{4}\lambda\varphi^4 \left(+\frac{\gamma}{6}\varphi^6\right)$$

Green (Scenario (II))

$$V_{\rm eff}(\phi,T) \simeq \frac{1}{2}\mu^2\varphi^2 - \frac{1}{4}\lambda\varphi^4 + \frac{1}{6}\gamma\varphi^6$$

Magenta and blue contours correspond to λ_{eff} and γ_{eff} at T=0.

A sizable barrier could be generated by large m_N/m_L value.



The first-order EWPT could be realized in the simple extended fermion model, especially, one is heavy (TeV scale) and another is light (EW scale).

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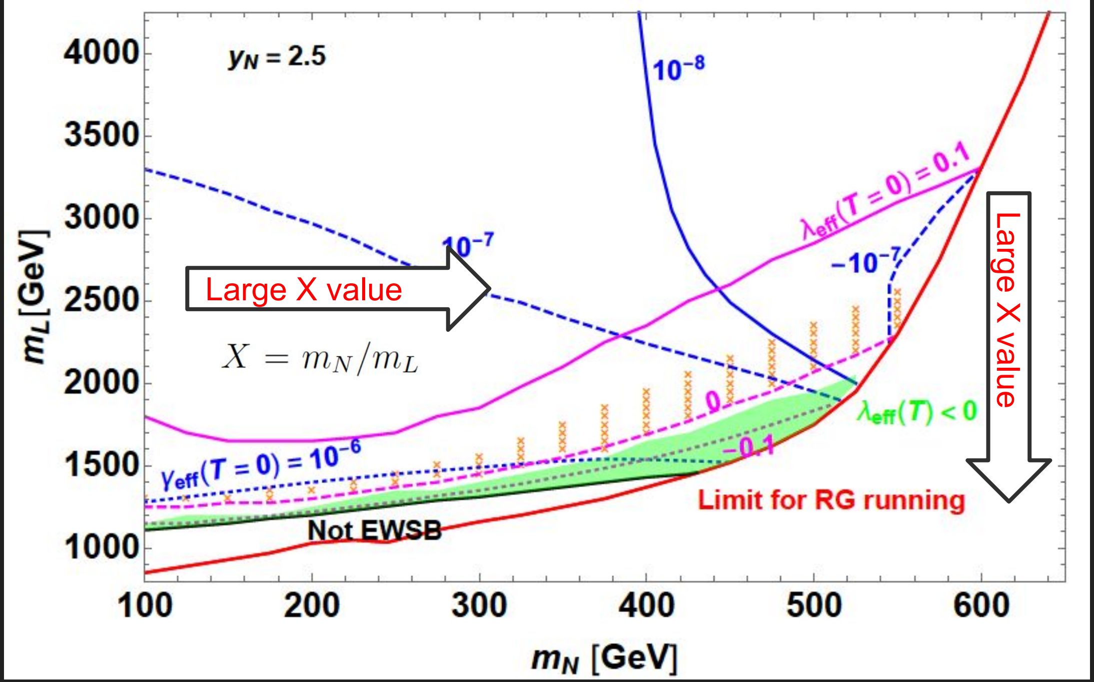

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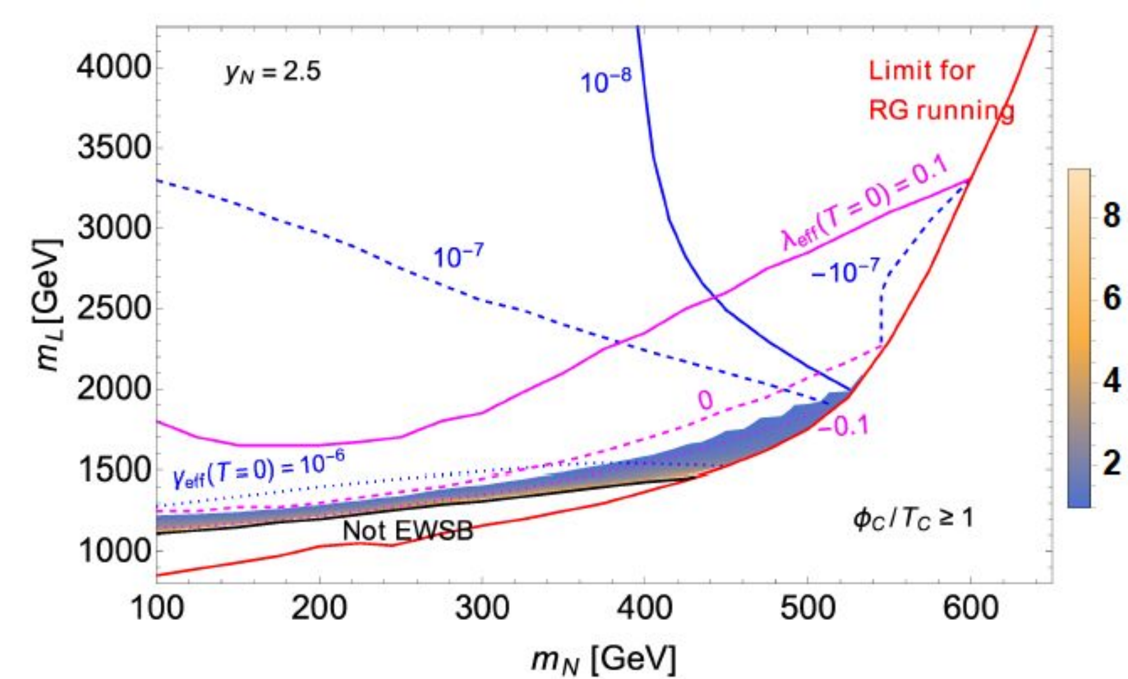

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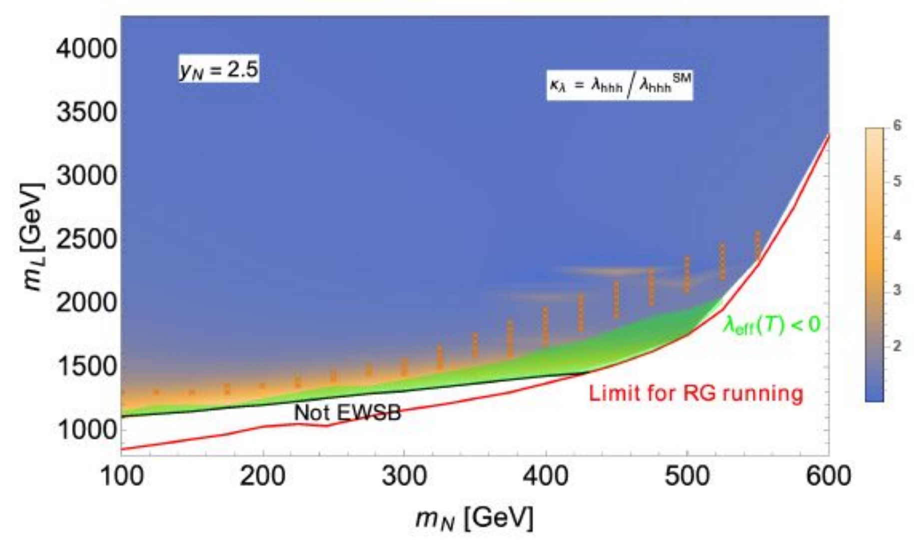
hhh coupling

★ Typically, the triple Higgs boson coupling in the model with strongly first-order EWPT is enhanced from the SM prediction value. [S. Kanemura, Y. Okada and E. Senaha, Phys. Lett. B 606 (2005), 361]

★ Triple Higgs boson coupling $\lambda_{hhh} \equiv \left.\frac{\partial^3 V_{eff}}{\partial \varphi^3}\right|_{\varphi=v}$

$$\lambda_{hhh}^{\text{new fermion}} \sim 8\gamma v^3 + \frac{y_N^6 v^3 X}{\pi^2 m_L^2 (1-X)^2 \left(1 - X - \frac{y_N^2 v^2}{X m_L^2}\right)}$$

The value of *hhh* coupling could be enhanced by large m_N/m_L value.



In these parameter region being able to generate a barrier, the value of *hhh* coupling is <u>10%</u> larger than the SM prediction value.

Future collider experiments can measure the *hhh* coupling at 10% accuracy. [arXiv:1506.05992, PRD 97 (2018) no.11, 113004, PRD 100 (2019) no.9, 096001, EPJ. C 80 (2020) no.11, 1010, CERN Yellow Rep. Monogr. 7 (2019), 221]

We could check whether a first-order EWPT can be realized or not by measurements of the *hhh* coupling.

[Qing-Hong Cao, K. H., Xuxiang Li, Zhe Ren, Jiang-Hao Yu, arXiv:2103.05688]

Summary

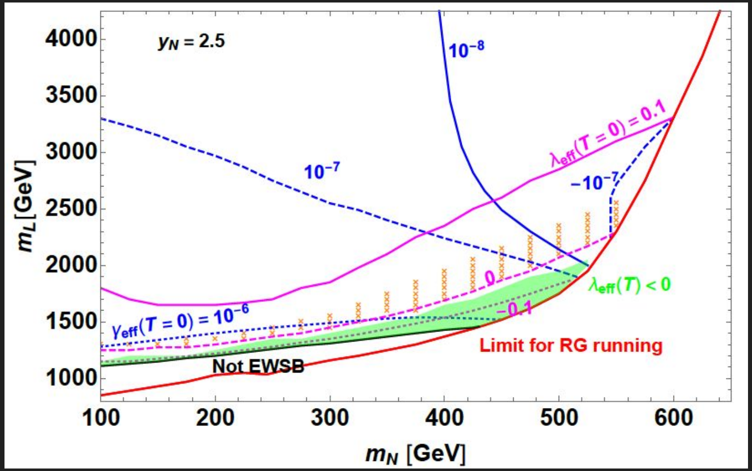
★ In this time, we discuss the phase transition patterns in the simple fermion model, one isospin doublet and one singlet neutral fermions.

★ Although the fermion does not contribute to φ^3 term, a sizable barrier could be developed by the fermionic reduction effects.

★ Especially, the model with one heavy and one light fermions can realize the first-order electroweak phase transition by following two scenarios:

(I) scenario $$V_{\rm eff}(\varphi, T) \simeq \frac{1}{2}\mu^2\varphi^2 - \frac{1}{3}\lambda_3\varphi^3 + \frac{1}{4}\lambda\varphi^4 \quad (\mu^2, \lambda_3, \lambda > 0)$$

(II) scenario $$V_{\rm eff}(\phi, T) \simeq \frac{1}{2}\mu^2\varphi^2 - \frac{1}{4}\lambda\varphi^4 + \frac{1}{6}\gamma\varphi^6 \quad (\mu^2, \lambda, \gamma > 0)$$



We could check whether a first-order EWPT can be realized in the extended fermion model or not by measurements of the *hhh* coupling.