Electroweak phase transition triggered by fermion sector

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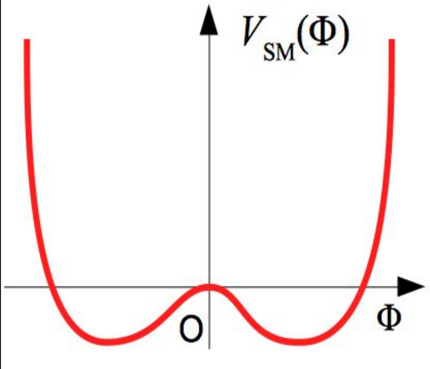
[arXiv:2103.05688]

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.

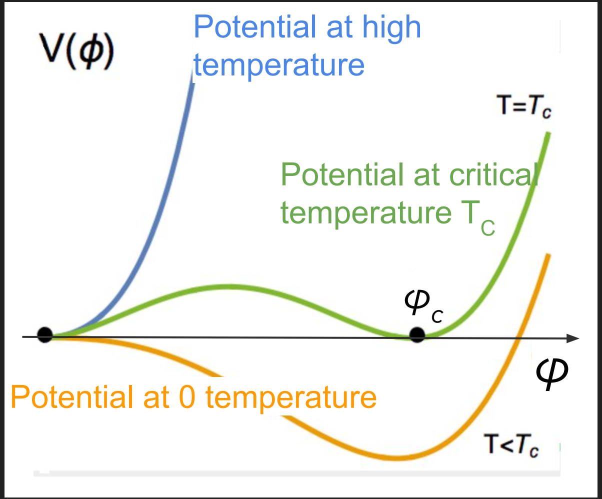
How can we realize the first-order EWPT? What is a source of the EWPT?

First-order EWPT

★ Effective potential with high temperature approximation:

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

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)]

$$V_{\rm eff}^{SM}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 + \frac{\lambda_T}{4}\varphi^4$$ (at T~φ)

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.

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

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

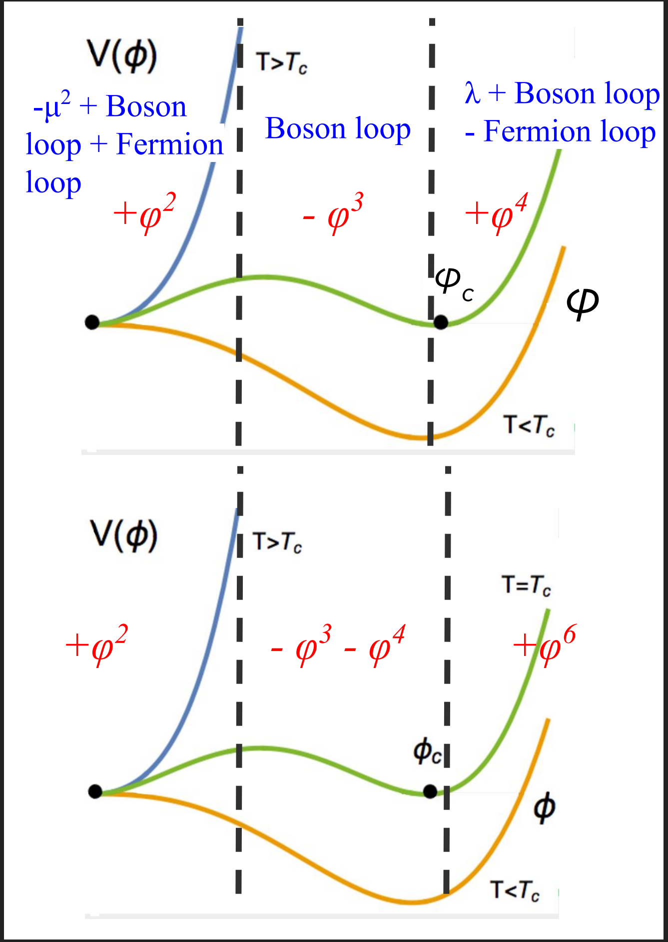
★ The model with heavy fermion (around TeV scale) could generate a barrier through the new fermion effects.

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

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]



EWPT triggered by fermion sector

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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.

★

generate a barrier through the new fermion effects.

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

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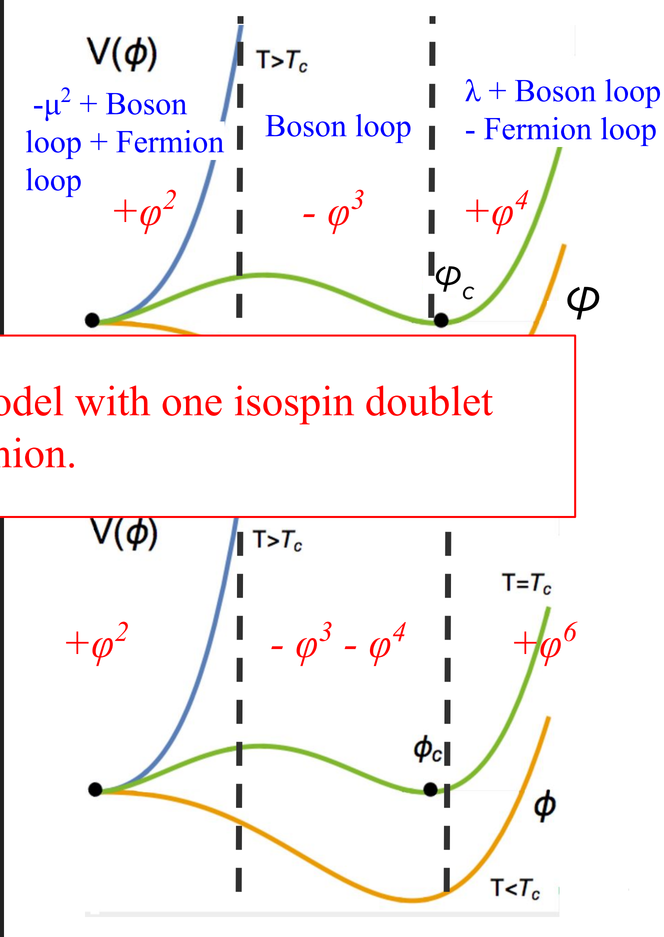

Extended fermion model

★ The Lagrangian for new fermions

$$-\mathcal{L}_{VLL} \supset y_N(\overline{L}HN' + \overline{N}'H^\dagger L) + m_L\overline{L}L + m_N\overline{N}'N'$$

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

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.

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

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Dominant contributions at the critical temperature for EWPT.

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$(- \mu^2$ - Fermion loop$)\ \varphi^2$

$(+ \lambda$ - Fermion loop$)\ \varphi^4$

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

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

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

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

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

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) $(m_L >> m_N >> y_N v,\ m_L \sim m_N >> y_N v)$

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

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

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) $(m_L >> m_N \sim y_N v)$

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

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

$$X = m_N / m_L$$

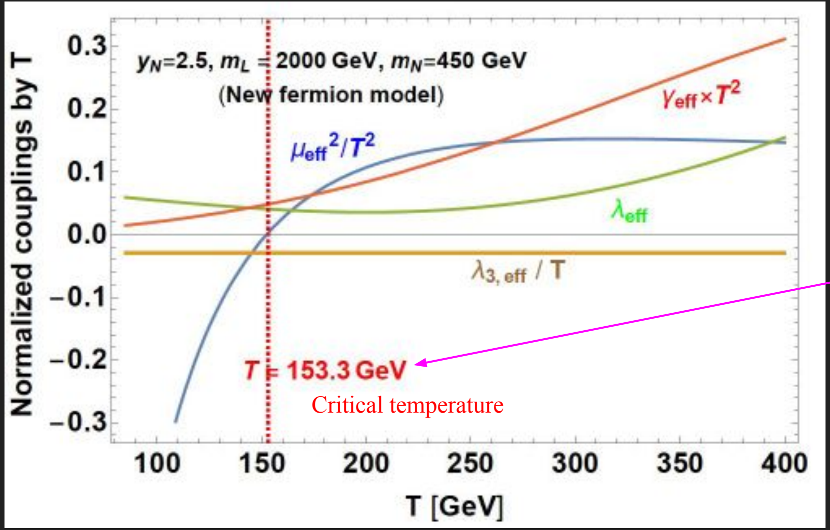
The contributions to φ^2 term are positive, while ones to φ^4 term are negative.

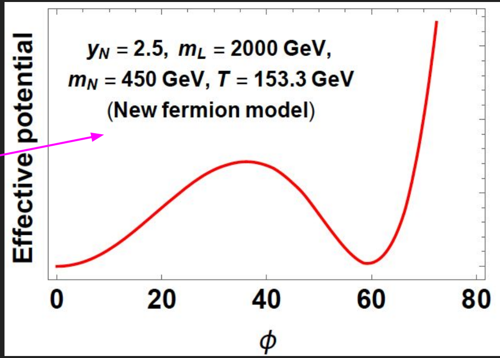
→ The sizable barrier could be developed in the potential in this region.

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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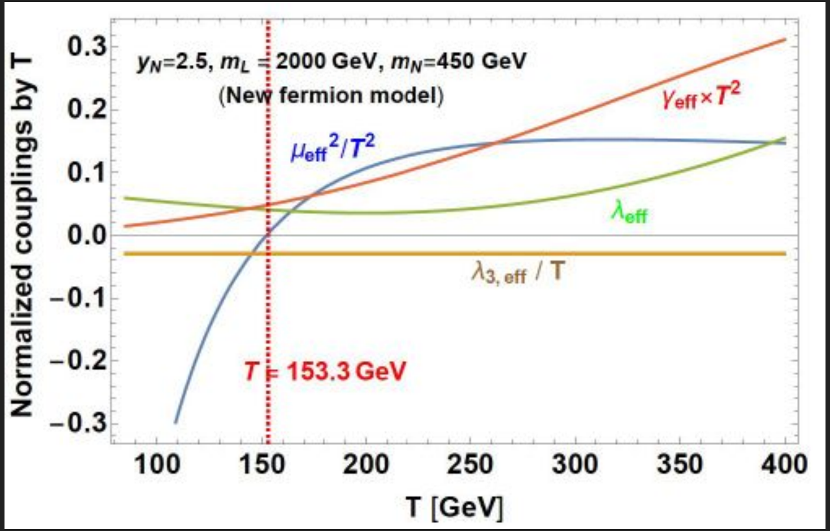
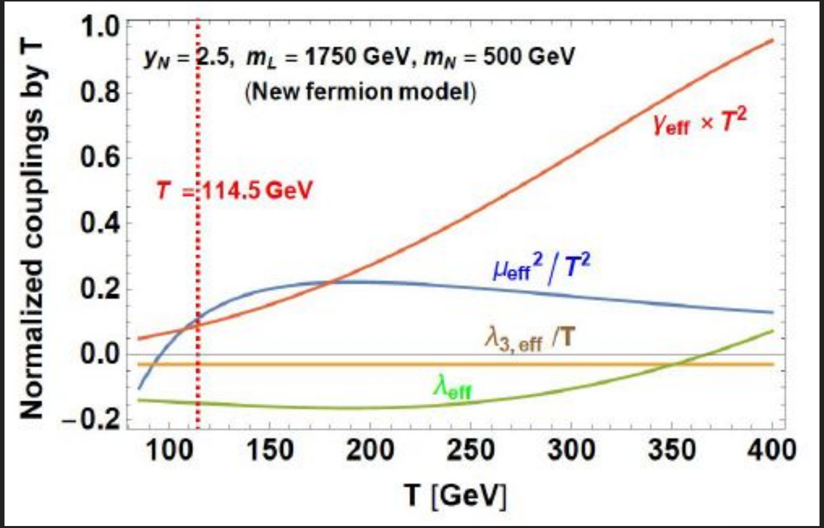


$y_N = 2.5,\ m_L ,= 2000$ GeV, $m_N = 450$ GeV

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



$y_N = 2.5,\ m_L ,= 1750$ GeV, $m_N = 500$ GeV

Mass region (C)

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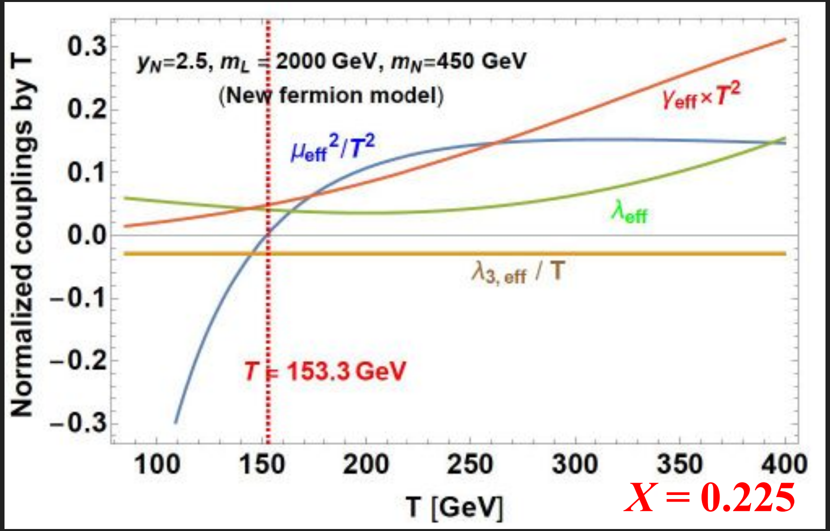

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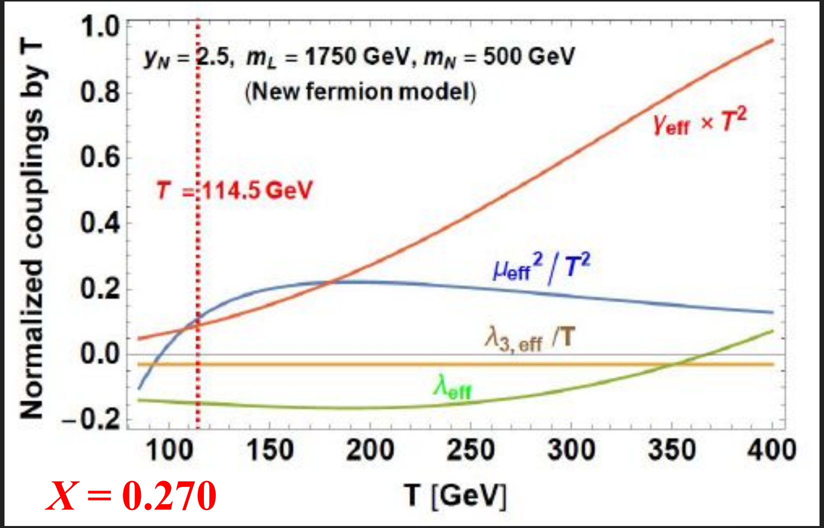


$y_N = 2.5,\ m_L ,= 1750$ GeV, $m_N = 500$ GeV

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

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))

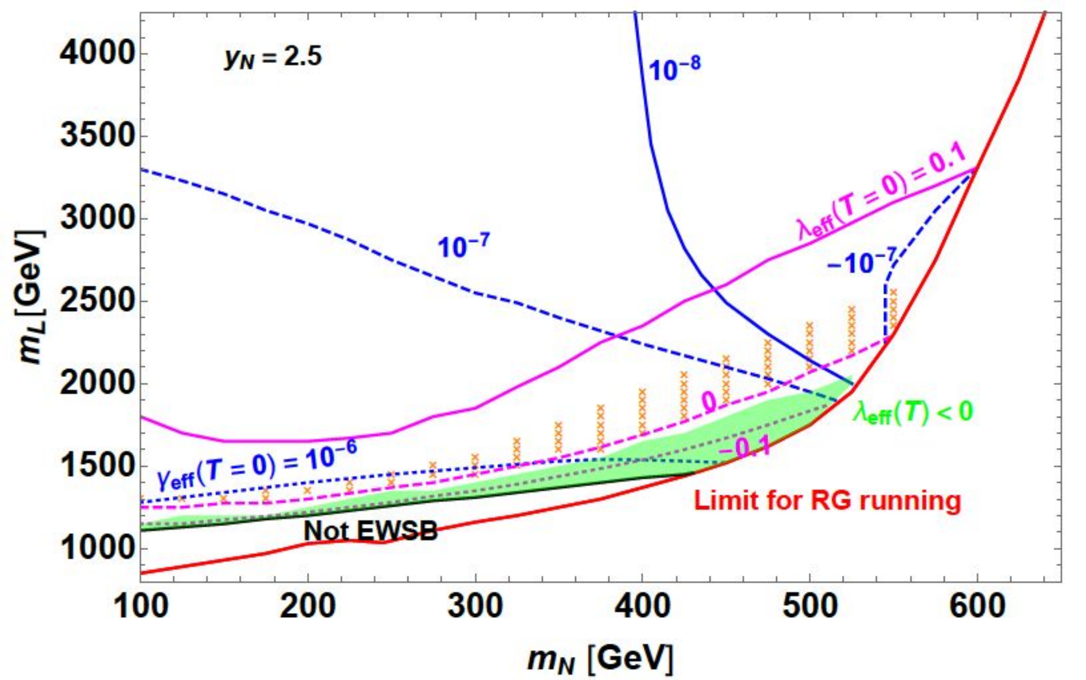
$$V_{\rm eff}(\varphi,T) \simeq \frac{1}{2}\mu^2\varphi^2 - \frac{1}{3}\lambda_3\varphi^3 + \frac{1}{4}\lambda\varphi^4 \left(+\frac{\gamma}{6}\varphi^6\right)$$

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).

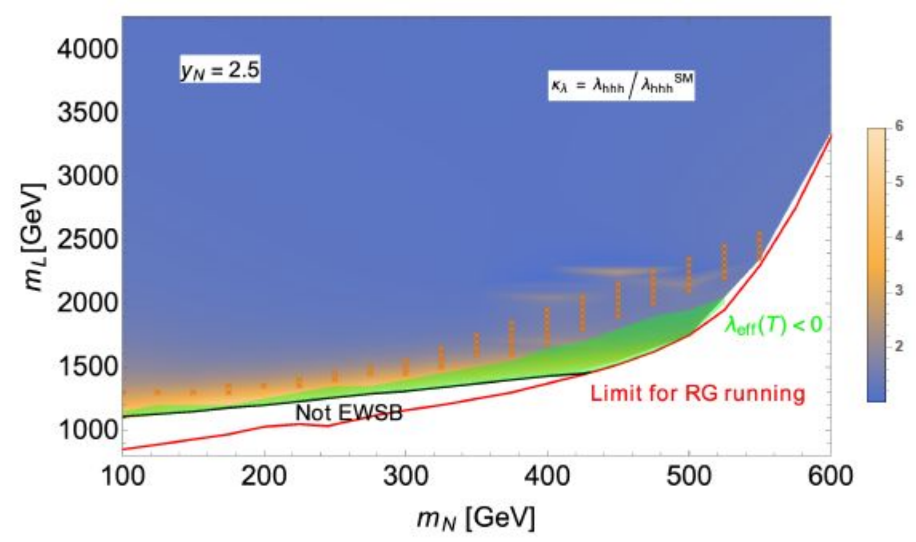
hhh coupling

★ 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

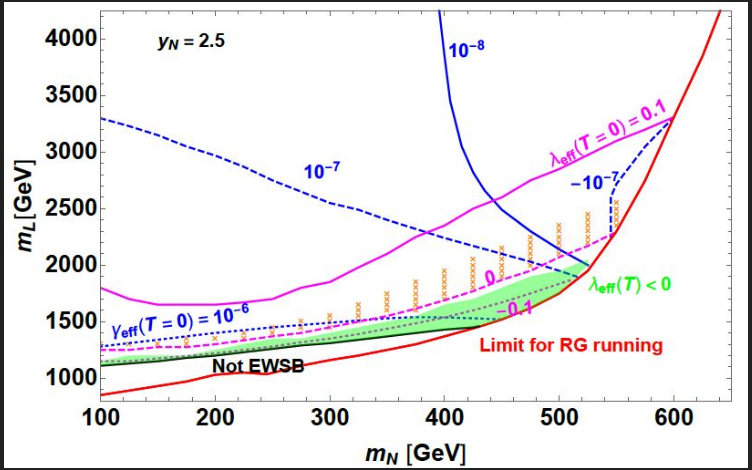
★ In this time, we discuss the phase transition patterns in the simple fermion model, one isospin doublet and one singlet neutral fermions.

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

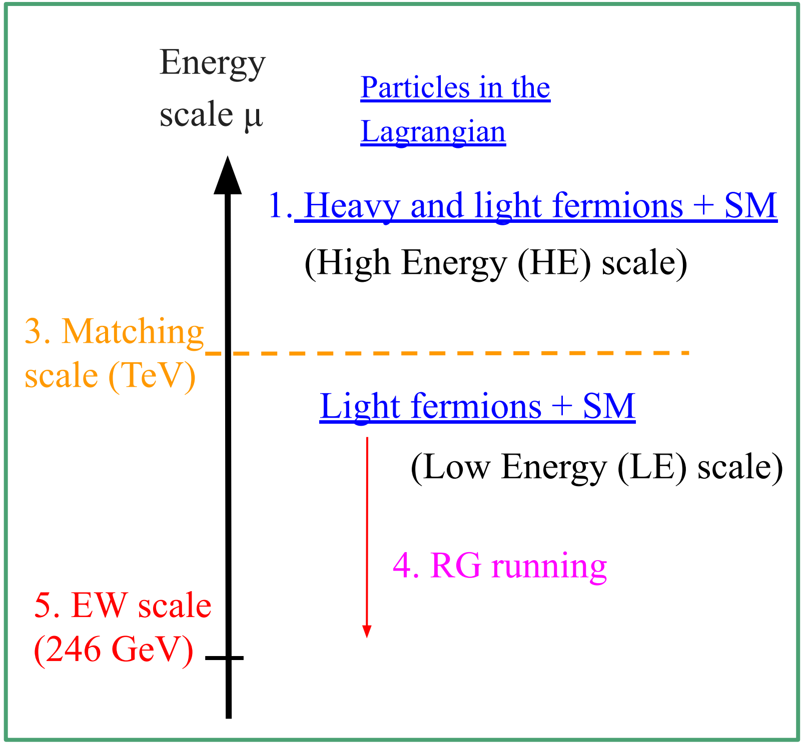


We could check whether a first-order EWPT can be realized in the extended fermion model or not by measurements of the *hhh* coupling.

Backup

Matching condition

❖ In this time, we get the effective potential in EW scale by matching condition.



1. We define the Lagrangian contained all particles.
   Some particles are heavier than EW scale (246 GeV).
2. We calculate the effective potential in HE scale.
   The counter term absorb the divergence in one-loop effects of the potential.
3. We consider the matching condition to get the effective potential in LE scale.
   High dim. operators show up in effective potential.
4. We evaluate RG running from matching scale to EW scale.
   Not only tree-level parameter but also High dim. operators has RG running effects.
5. We can get the effective potential at EW scale.

- The effective potentials in LE and HE scale at matching scale

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

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

- Threshold effects at matching scale

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

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

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

- RG running

$$\sum_a \left(\beta_a \frac{\partial}{\partial\lambda_a} - \gamma_\varphi \varphi \frac{\partial}{\partial\varphi} - \frac{\partial}{\partial Q}\right) V_{eff}^{LE} = 0$$