Electroweak Symmetry Non-restoration in Models with New Fermions

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INTRODUCTION

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  - Symmetry Non-Restoration (SNR): Symmetry that is broken at lower temperature is never stored at higher temperature
  - Inverse Symmetry Breaking (ISB): Symmetry that is unbroken at lower temperature becomes broken at higher temperature

- Meade & Ramani (arXiv:1807.07578) showed that Electroweak (EW) symmetry will never be restored or only temporarily restored (TR) at higher temperature with a simple scalar extension of SM.
- Is it possbile to achive SNR or TR for EW symmetry by adding new fermions to SM?

SCALAR MODEL WITH $O(N_s)$ GLOBAL SYMMETRY

- Extend SM by adding SM-singlet scalar fields s_i with $O(N_s)$ global symmetry

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\mu_s^2(s_i s_i) - \frac{1}{4}\lambda_s(s_i s_i)^2 - \frac{1}{2}\lambda_{hs}h^2(s_i s_i)$$

- The leading term in temperature of thermal mass correction of h is

$$\Pi_h = \frac{\partial^2 V_{th}}{\partial h^2} = T^2\left(\frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}\lambda_t^2 + \frac{1}{2}\lambda + \frac{N_s}{12}\lambda_{hs}\right)$$

- SNR can be achieved by choosing $\lambda_{hs} < 0$ and large N_s .

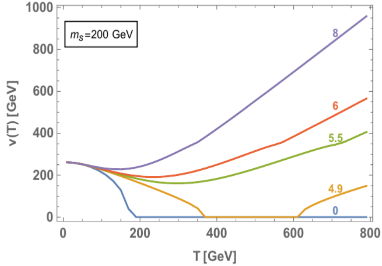

Figure: Temperature dependent vev for different values of $N_s|\lambda_{hs}|$.

- Temporary restoration phase becomes longer as $N_s|\lambda_{hs}|$ decreases.

Meade & Ramani, arXiv:1807.07578

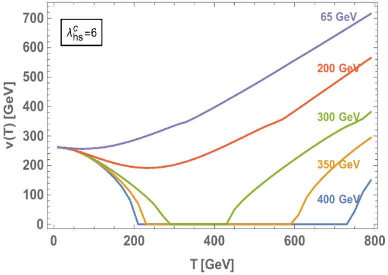

Figure: Temperature dependent vev for different values of m_s.

- Temporary restoration phase becomes longer as m_s increases.

A TOY MODEL WITH NEW FERMIONS

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{N_\nu} \mathcal{L}^i_{D+M} \;, H = \begin{bmatrix} G^+ \\ (h + iG^0)/\sqrt{2} \end{bmatrix}$$

Each $\mathcal{L}^i_{D+M}$ has the same form:

$$\begin{aligned} \mathcal{L}_{D+M} &= -y_\nu \left(\overline{\nu_R} \widetilde{H}^\dagger L_L + \overline{L_L} \widetilde{H} \nu_R \right) + \frac{1}{2} m_R \left(\nu_R^T \mathcal{C}^\dagger \nu_R + \nu_R^\dagger \mathcal{C} \nu_R^* \right) \\ &\supset -m_D(h) \left(\overline{\nu_R} \nu_L + \overline{\nu_L} \nu_R \right) + \frac{1}{2} m_R \left(\nu_R^T \mathcal{C}^\dagger \nu_R + \nu_R^\dagger \mathcal{C} \nu_R^* \right) \\ &\supset \frac{1}{2} N^T \mathcal{C}^\dagger M N + h.c. \end{aligned}$$

with

$$m_D(h) = \frac{y_\nu h}{\sqrt{2}}, \;\; M = \begin{bmatrix} 0 & m_D \\ m_D & m_R \end{bmatrix}, \;\; N = \begin{bmatrix} \nu_L \\ \nu_R^C \end{bmatrix} \tag{1}$$

M can be diagonalized by a unitary transformation U:

$$U^T M U = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}, \ \ N = U \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$

$$\mathcal{L}_{D+M} \supset \frac{1}{2} \sum_{k=1,2} m_k \nu_k^T \mathcal{C}^\dagger \nu_k + h.c.$$

where physical masses are:

$$m_{1,2} = \frac{1}{2} \left[m_R \mp \sqrt{m_R^2 + 4 m_D^2} \right]$$

The one-loop thermal potential for the new Majorana fermions ν_R are

$$V_{th,\nu} = -N_\nu \frac{T^4}{2\pi^2} \sum_{k=1,2} J_F\left(\frac{m_k^2}{T^2}\right)$$

with thermal function

$$J_F(y^2) = \int_0^\infty dx\, x^2 \log\left[1 + \exp\left(-\sqrt{x^2+y^2}\right)\right]$$

The leading term in temperature of thermal mass correction of h is

$$\Pi_h = \frac{\partial^2 V_{th}}{\partial h^2} = T^2\left(\frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}\lambda_t^2 + \frac{1}{4}\lambda + \frac{N_\nu}{24}y_\nu^2\right)$$

- choose y_ν to be purely imaginary in order to have maximum negative mass correction from the new fermions.
- When $N|y_\nu|^2$ is large enough, the negative contribution outweighh the usual positive contributions and SNR can be achieved at high temperature

The full one-loop mass correction of h is obtained by solving the gap equation

$$\delta m_h^2(h,T) = \sum_i \frac{\partial}{\partial h}\left[\frac{\partial V_{CW}^i}{\partial h}\left(m_i^2(h)+\delta m_i^2(h,T)\right)+\frac{\partial V_{th}^i}{\partial h}\left(m_i^2(h)+\delta m_i^2(h,T),T\right)\right]$$

The effective potential is

$$V_{\rm eff}^{\rm pd}(h,T) = V_0 + \sum_i \int_0^h dh' \left[\frac{\partial V_{CW}^i}{\partial h'}\left(m_i^2(h')+\delta m_i^2(h',T)\right) + \frac{\partial V_{th}^i}{\partial h'}\left(m_i^2(h')+\delta m_i^2(h',T),T\right)\right]$$

- The effective potential is calculated using *Partial Dressing* method, which resum the important higher-loop contributions (i.e. daisy and super-daisy diagrams) to thermal mass correctly.

Results

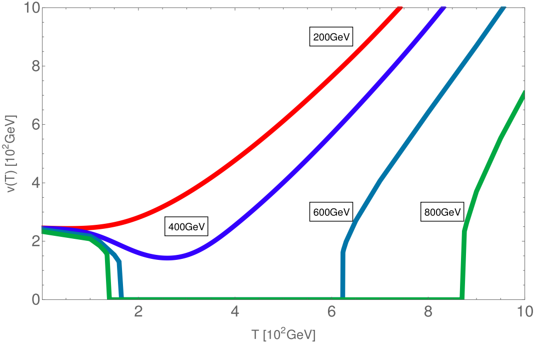

Figure: Temperature dependent vev for different values of m_R.

- Temporary restored period becomes longer as m_R increase. As $T < m_R$ and m_R is much heavier than SM particles, the thermal mass correction from the new fermions becomes less important.

RESULTS

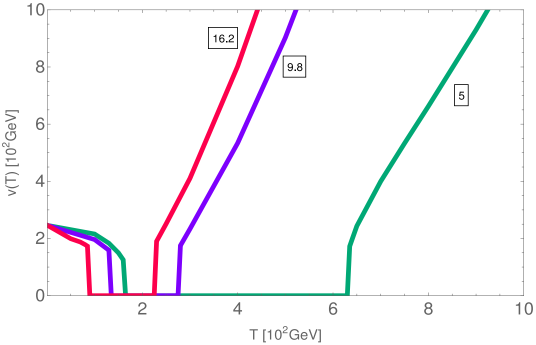

Figure: Temperature dependent vev for different values of $N_\nu |y_\nu|^2$.

- Temporary restored period becomes longer as $N_\nu |y_\nu|^2$ decrease as shown above.

SUMMARY AND OUTLOOK

- SNR and TR can be achieved by adding new fermions to SM. The effect is stronger when $N_\nu |y_\nu|^2$ or m_R is larger.
- Find a realistic model with new fermions
- Investigate the cosmological implications (thermal evolution of universe, gravitational wave signal etc.) and collider signals.

Daisy and Super-Daisy contributions to thermal mass

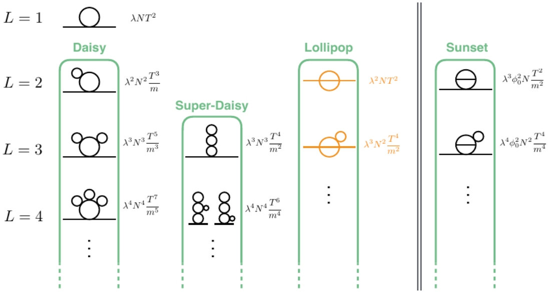

Figure 2. Complete set of 1- and 2- loop contributions to the scalar mass, as well as the most important higher loop contributions, in ϕ^4 theory. The scaling of each diagram in the high-temperature approximation is indicated, omitting symmetry- and loop-factors. Diagrams to the right of the vertical double-lines only contribute away from the origin when $\langle \phi \rangle = \phi_0 > 0$. We do not show contributions which trivially descend from e.g. loop-corrected quartic couplings. Lollipop diagrams (in orange) are not automatically included in the resummed one-loop potential.

Curtin, Meade & Ramani, arXiv:1612.00466

EFFECTIVE POTENTIAL

- Tree-level potential:

$$V_0 = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$$

- Coleman-Weinberg potential (for *i*-th particle)

$$V_{CW}^i = (-1)^F g_i \frac{m_i^4}{64\pi^2}\left[\log\left(\frac{m_i^2}{\mu_R^2}\right) - c_i\right]$$

- One-loop thermal potential (for *i*-th particle)

$$V_{th}^i = (-1)^F g_i \frac{T^4}{2\pi^2} J_{B/F}\left(\frac{m_i^2}{T^2}\right)$$

where

$$J_B/F(y^2) = \int_0^\infty dx\, x^2 \log\left[1 \mp \exp\left(-\sqrt{x^2+y^2}\right)\right]$$

- Effective potential

$$V_{eff} = V_0 + \sum_i \left(V^i_{CW} + V^i_{th} \right)$$