Higgs Self-Coupling and Electroweak Baryogenesis

Eibun Senaha(GUAS, KEK)

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in collaboration with
Shinya Kanemura(Osaka U)
Yasuhiro Okada(GUAS, KEK)

Outline

§1. Introduction

-Connection between collider physics and cosmology

§2. Conditions of baryogenesis

-Electroweak phase transition in the THDM

§3. Radiative corrections to hhh coupling constant

-Collider signal of electroweak baryogenesis?

§4. Summary

Introduction

- **Higgs physics at colliders**

  -Discovery of the Higgs boson(s) (@Tevatron, LHC)

  -Measurements of the Higgs couplings with $\left\{ \begin{array}{l} \text{gauge bosons} \\ \text{fermions} \end{array} \right.$ (mass generation)

  $\mathcal{O}(1)\%$ accuracy (@ILC) ACFA Rep. TESLA TDR

  -Measurements of the Higgs self-couplings (reconstruction of the Higgs potential)

  $\mathcal{O}(10-20)\%$accuracy (@ILC) ACFA Higgs WG, Battaglia et al

- **Connection between collider physics and cosmology**

-Baryon Asymmery of the Universe
(1). B-L-gen. above EW phase transition (Leptogenesis, etc)
(2). B-gen. during EW phase transition (EW baryogenesis)

-dark matter

▷ Since the EW baryogenesis depends on the dynamics of the phase transition, we can naively expect that a collider signal of it can appear in the Higgs self-coupling.

▷ We investigate the region where the EW baryogenesis is possible in the THDM, and calculate the deviation of the self-coupling constant from SM prediction in such a region.

Conditions of Baryogenesis

Evidence of the BAU

$$\frac{n_B}{s} \equiv \frac{n_b - n_{\bar{b}}}{s} \simeq (8.7^{+0.4}_{-0.3}) \times 10^{-11}$$

- 3 requirements for generation of the BAU (Sakharov conditions)

1. baryon number violation
2. C and CP violation
3. out of equilibrium

2 scenarios

(1) B-L-generation above EW phase transition. (Leptogenesis, etc)

(2) B-generation at the electroweak phase transition. (Electroweak baryogenesis)

-based on a testable model

Baryogenesis in the electroweak theory

- baryon number violation — sphaleron process
- C violation — chiral interation
- CP violation — KM-phase or other sources in the extension of the SM
- out of equilibrium — 1st order phase transition with expanding bubble walls

In principle, SM fulfills the Sakharov conditions, BUT

• Phase transition is not 1st order for the current Higgs mass bound ($m_h > 114$ GeV)
• KM-phase is too small to generate the sufficient baryon asymmetry

$\Longrightarrow$ Extension of the minimal Higgs sector

THDM, MSSM, Next-to-MSSM, etc.

$\triangleright$ THDM is a simple viable model   not so constrained

Two Higgs Doublet Model (THDM)

Higgs potential

$$V_{\text{THDM}} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right],$$

$$\Phi_i(x) = \begin{pmatrix} \phi_i^+(x) \\ \frac{1}{\sqrt{2}}\left(v_i + h_i(x) + i a_i(x)\right) \end{pmatrix}. \qquad (i = 1, 2)$$

discrete sym.($\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2$)$\to$ FCNC suppression

Yukawa interaction

Type I : $\mathcal{L}^I_{\text{Yukawa}} = \bar{q}_L f_1^{(d)} \Phi_1 d_R + \bar{q}_L f_1^{(u)} \tilde{\Phi}_1 u_R + \bar{l}_L f_1^{(e)} \Phi_1 e_R + \text{h.c.},$

Type II : $\mathcal{L}^{II}_{\text{Yukawa}} = \bar{q}_L f_1^{(d)} \Phi_1 d_R + \bar{q}_L f_2^{(u)} \tilde{\Phi}_2 u_R + \bar{l}_L f_1^{(e)} \Phi_1 e_R + \text{h.c.}$

To avoid complication, we consider [Cline et al PRD54 '96]

$$m_1 = m_2 \equiv m, \quad \lambda_1 = \lambda_2 = \lambda, \qquad \Big(\sin(\beta-\alpha) = \tan\beta = 1\Big)$$

- Higgs VEVs: $\langle \Phi_1 \rangle = \langle \Phi_2 \rangle = \frac{1}{2}\begin{pmatrix} 0 \\ \varphi \end{pmatrix}$

- Tree-level potential

$$V_{\text{tree}}(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda_{\text{eff}}}{4}\varphi^4, \qquad \mu^2 = m_3^2 - m^2, \quad \lambda_{\text{eff}} = \frac{1}{4}(\lambda + \underbrace{\lambda_3 + \lambda_4 + \lambda_5}_{\equiv \lambda_{345}})$$

▷ Mass formulae of the Higgs bosons

$$m_h^2 = \frac{1}{2}(\lambda + \lambda_{345})v^2,$$

$$\left.\begin{aligned} m_H^2 &= \tfrac{1}{2}(\lambda - \lambda_{345})v^2 + M^2, \\ m_A^2 &= -\lambda_5 v^2 + M^2, \\ m_{H^\pm}^2 &= -\tfrac{1}{2}(\lambda_4 + \lambda_5)v^2 + M^2 \end{aligned}\right\}$$

Two origins of the masses : $\sum_i c_i \lambda_i v^2$ and M^2.

where $M^2 = \dfrac{m_3^2}{\sin\beta\cos\beta}$ (soft breaking scale of the discrete symmetry)

1-loop effective potential

- **Zero temperature**

$$V_1(\varphi) = n_i \frac{m_i^4(\varphi)}{64\pi^2}\left(\log\frac{m_i^2(\varphi)}{Q^2} - \frac{3}{2}\right)$$

$$(n_W = 6,\ n_Z = 3,\ n_t = -12,\ n_h = n_H = n_A = 1,\ n_{H^\pm} = 2)$$

- **Finite temperature**

$$V_1(\varphi, T) = \frac{T^4}{2\pi^2}\Big[\sum_{i=\text{bosons}} n_i I_B(a^2) + n_t I_F(a)\Big]$$

where $$I_{B,F}(a^2) = \int_0^\infty dx\, x^2 \log(1 \mp e^{-\sqrt{x^2+a^2}}), \qquad \left(a(\varphi) = \frac{m(\varphi)}{T}\right)$$

▷ **High temperature expansion** $(a^2 \ll 1)$

$$I_B(a^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}a^2 - \frac{\pi}{6}(a^2)^{3/2} - \frac{a^4}{32}\left(\log\frac{a^2}{\alpha_B} - \frac{3}{2}\right) + \mathcal{O}(a^6),$$

$$I_F(a^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}a^2 - \frac{a^4}{32}\left(\log\frac{a^2}{\alpha_F} - \frac{3}{2}\right) + \mathcal{O}(a^6), \quad \left(\log\alpha_{F(B)} = 2\log(4)\pi - 2\gamma_E\right)$$

φ^3-term comes from the "bosonic" loop

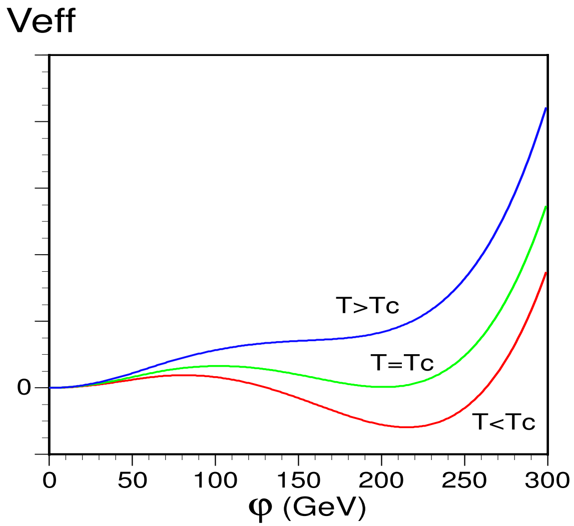
Finite temperature Higgs potential

For $m_\Phi^2(v) \gg M^2, m_h^2(v)$ $\quad m_\Phi^2(\varphi) \simeq m_\Phi^2(v)\frac{\varphi^2}{v^2}, \quad (\Phi = H,\ A,\ H^\pm)$

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

where

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3 + \underbrace{m_H^3 + m_A^3 + 2m_{H^\pm}^3}_{\text{additional contributions}})$$



At T_c, degenerate minima: $\quad \varphi_c = \frac{2ET_c}{\lambda_{T_c}}$

• The magnitude of E is relevent for the strongly 1st order phase transition

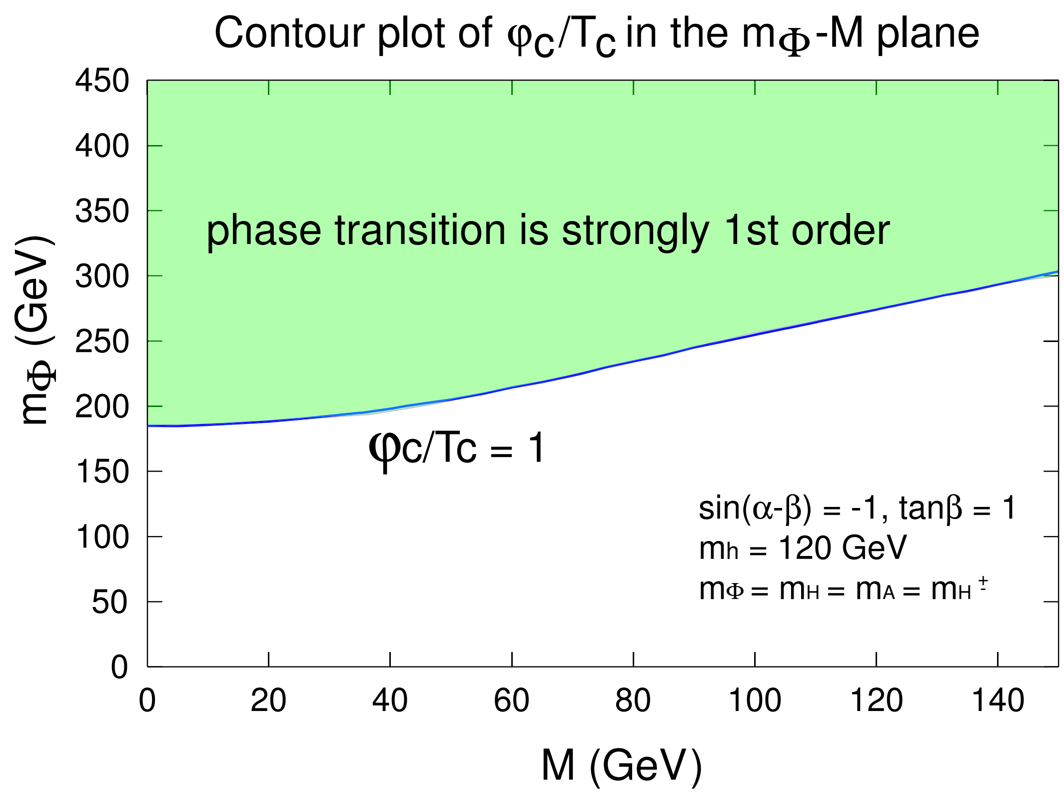
• **Strongly 1st order phase transition:** $\frac{\varphi_c}{T_c} \gtrsim 1$

$\Rightarrow$ Not wash out the baryon density after EW phase transition

▷ CP violation at the bubble wall $\Rightarrow$ Asymmetry of the charge flow

Contour plot of φ_c/T_c in the m_Φ-M plane

$$\sin^2(\alpha-\beta)=\tan\beta=1,\ m_h=120\ \text{GeV},\ m_\Phi\equiv m_A=m_H=m_{H^\pm}$$



- For $\mathbf{m_\Phi^2 \gg M^2, m_h^2}$,

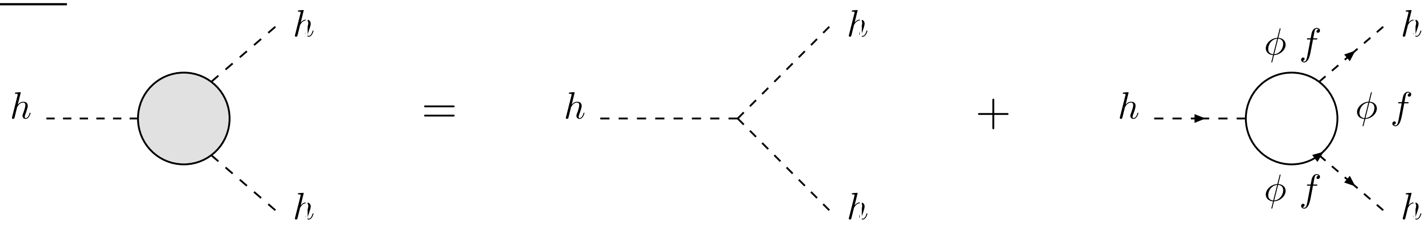
Strongly 1st order phase transition is possible due to the loop effect of the heavy Higgs bosons (**non-decoupling effect**). (φ^3-term is effectively large)

- What the magnitude of the λ_{hhh} coupling at T=0 in such a region?

Radiative corrections to λ_{hhh}

[S. Kanemura, S. Kiyoura, Y. Okada, E.S., C.-P. Yuan PL '03]

- <u>hhh</u>



$+$ counter terms

$(\phi = h, H, A, H^{\pm}, \quad f = t, b)$

- For $\sin(\beta - \alpha) = 1$,

$$\lambda_{hhh}^{\text{tree}} = -\frac{3m_h^2}{v}, \quad \text{(same form as in the SM)}$$

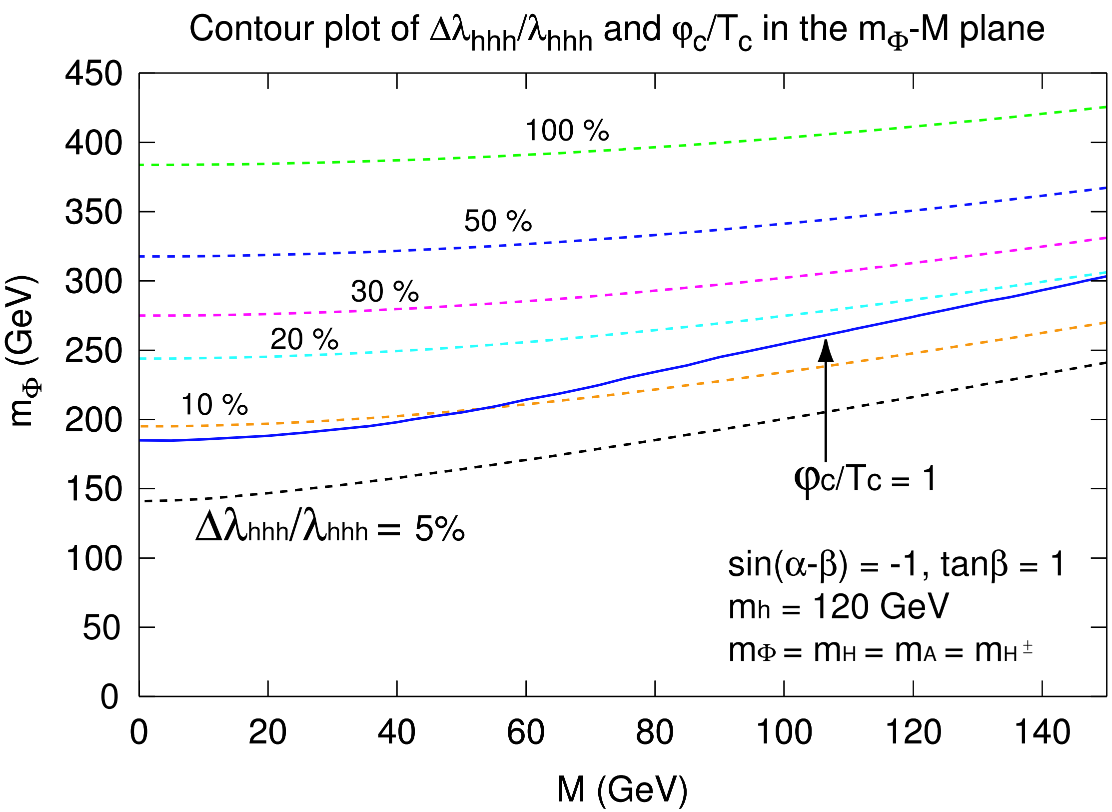
$$\lambda_{hhh} \sim -\frac{3m_h^2}{v}\left[1 + \frac{c}{12\pi^2}\frac{m_\Phi^4}{m_h^2 v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\right] \quad (\Phi = H, A, H^{\pm})$$

$(c = 1$ for neutral Higgs, $c = 2$ for charged Higgs$)$

For $\mathbf{m_\Phi^2 \gg M^2, m_h^2}$, the loop effect of the heavy Higgs bosons is enhanced by m_Φ^4, which does not decouple in the large mass limit. (**non-decoupling effect**)

Contour plots of $\Delta\lambda_{hhh}/\lambda_{hhh}$ and φ_c/T_c in the m_Φ-M plane

$$\sin^2(\alpha - \beta) = \tan\beta = 1,\ m_h = 120\ \text{GeV},\ m_\Phi \equiv m_A = m_H = m_{H^\pm}$$



For $m_\Phi^2 \gg M^2, m_h^2$,

- Phase transition is strongly 1st order, AND
- Deviation of hhh coupling from SM value becomes large. $(\Delta\lambda_{hhh}/\lambda_{hhh} \gtrsim 10\%)$

Summary

We have investigated the region where the electroweak phase transition is strongly 1st order, and calculate the radiative correction to the triple Higgs self-coupling constant in the THDM.

For $\mathbf{m_\Phi^2 \gg M^2, m_h^2}$

- Phase transition is strongly 1st order.

- Deviation of hhh coupling from SM value becomes large. $(\Delta\lambda_{hhh}/\lambda_{hhh} \gtrsim 10\%)$

due to the non-decoupling effect of the heavy Higgs bosons

Such deviation can be testable at a Linear Collider.

EW baryogenesis

$\Downarrow$

Strongly 1st order phase transition — $V_{\text{eff}}(\varphi, T)$

$\Downarrow$

Large loop correction to λ_{hhh} — $V_{\text{eff}}(\varphi, 0)$

$\Downarrow$

Measurement of λ_{hhh} @ILC

Definitions of the mass eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}, \quad \left(-\frac{\pi}{2} \leq \alpha \leq 0 \right),$$

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}, \quad \left(0 < \beta < \frac{\pi}{2} \right)$$

$$\begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

Renormalized h and H

$$
\begin{aligned}
\begin{pmatrix} H_B \\ h_B \end{pmatrix} &= \underbrace{\begin{pmatrix} \cos\alpha_B & \sin\alpha_B \\ -\sin\alpha_B & \cos\alpha_B \end{pmatrix}}_{\equiv R(-\alpha_B)} \begin{pmatrix} h_{1B} \\ h_{2B} \end{pmatrix} = R(-\delta\alpha)R(-\alpha_R) \begin{pmatrix} h_{1B} \\ h_{2B} \end{pmatrix} \\
&= R(-\delta\alpha)R(-\alpha_R)\tilde{Z} \begin{pmatrix} h_{1R} \\ h_{2R} \end{pmatrix} \\
&= R(-\delta\alpha)ZR(-\alpha_R) \begin{pmatrix} h_{1R} \\ h_{2R} \end{pmatrix} \qquad \left(Z \equiv R(-\alpha_R)\tilde{Z}R(\alpha_R)\right) \\
&= R(-\delta\alpha)Z \begin{pmatrix} H_R \\ h_R \end{pmatrix} \\
&\equiv \begin{pmatrix} 1 & \delta\alpha \\ -\delta\alpha & 1 \end{pmatrix} \begin{pmatrix} Z_H^{1/2} & \delta A \\ \delta A & Z_h^{1/2} \end{pmatrix} \begin{pmatrix} H_R \\ h_R \end{pmatrix} \\
&= \begin{pmatrix} 1 + \frac{1}{2}\delta Z_H & \delta A + \delta\alpha \\ \delta A - \delta\alpha & 1 + \frac{1}{2}\delta Z_h \end{pmatrix} \begin{pmatrix} H_R \\ h_R \end{pmatrix},
\end{aligned}
$$

On-shell renormalization in the Electroweak Theory

- Gauge sector

$g_2,\ g_1,\ v$ $\Longleftarrow$ $\alpha_{\text{em}},\ m_Z,\ G_F$ $\quad$ $\alpha_{\text{em}},\ m_Z,\ m_W$

$m_Z,\ m_W,\ G_F$ $\quad$ $\alpha_{\text{em}},\ m_Z,\ \sin\theta_W$ etc...

- Higgs sector

Renormalization conditions for α, β and M_{soft} (our scheme)

$$\text{Re}\Gamma_{hH}(m_h^2) = \text{Re}\Gamma_{hH}(m_H^2) = 0 \quad \Rightarrow \quad Z_{Hh}^{1/2},\ Z_{hH}^{1/2},$$

$$\text{where} \quad Z_{Hh}^{1/2} = \delta A + \delta\alpha,\ Z_{hH}^{1/2} = \delta A - \delta\alpha$$

$$\text{Re}\Gamma_{AG^0}(m_A^2) = \text{Re}\Gamma_{AZ}(m_A^2) = 0 \quad \Rightarrow \quad Z_{G^0A}^{1/2},\ Z_{AG^0}^{1/2},$$

$$\text{where} \quad Z_{G^0A}^{1/2} = \delta B + \delta\beta,\ Z_{AG^0}^{1/2} = \delta B - \delta\beta$$

$\delta M_{\text{soft}} \quad \Leftarrow \quad \overline{MS}$ scheme

Ring-improved Higgs boson masses

$$\begin{aligned}
m_h^2(\varphi,T) &= \frac{3}{2}m_h^2(v_0)\frac{\varphi^2}{v_0^2}-\frac{1}{2}m_h^2(v_0)+aT^2,\\
m_H^2(\varphi,T) &= \left[m_H^2(v_0)+\frac{1}{2}m_h^2(v_0)-2m_3^2\right]\frac{\varphi^2}{v_0^2}-\frac{1}{2}m_h^2(v_0)+2m_3^2+aT^2,\\
m_A^2(\varphi,T) &= \left[m_A^2(v_0)+\frac{1}{2}m_h^2(v_0)-2m_3^2\right]\frac{\varphi^2}{v_0^2}-\frac{1}{2}m_h^2(v_0)+2m_3^2+aT^2,\\
m_{H^\pm}^2(\varphi,T) &= \left[m_{H^\pm}^2(v_0)+\frac{1}{2}m_h^2(v_0)-2m_3^2\right]\frac{\varphi^2}{v_0^2}-\frac{1}{2}m_h^2(v_0)+2m_3^2+aT^2,\\
m_{G^0}^2(\varphi,T) &= m_{G^\pm}^2(\varphi,T)=\frac{1}{2}m_h^2(v_0)\frac{\varphi^2}{v_0^2}-\frac{1}{2}m_h^2(v_0)+aT^2.
\end{aligned}$$

where

$$a=\frac{1}{12v_0^2}\Big[6m_W^2(v_0)+3m_Z^2(v_0)+5m_h^2(v_0)+m_H^2(v_0)+m_A^2(v_0)+2m_{H^\pm}^2(v_0)-8m_3^2\Big].$$