Electroweak Baryogenesis and Quantum Corrections to the Triple Higgs Boson Coupling

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Outline

§1. Connections between collider physics and cosmology

-Higgs physics and electroweak baryogenesis

§2. Conditions of baryogenesis

-Electroweak phase transition in the 2HDM

§3. Radiative corrections to hhh coupling constant

-Collider signal of electroweak baryogenesis?

§4. Summary

Higgs physics at colliders

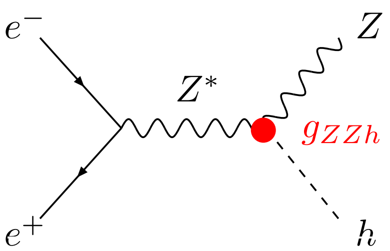
Establish mass generation mechanism and electroweak symmetry breaking

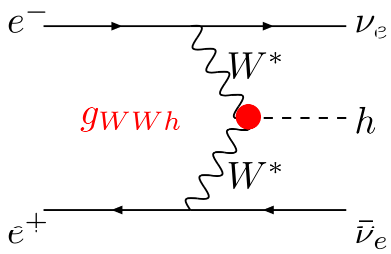
LEP: SM Higgs ⇒ 114 GeV $\lesssim M_h \lesssim$ 251 GeV (95% CL)
Tevatron, LHC: Discovery of the Higgs boson(s), mass, width, etc..
Linear Collider: (**precision measurements**)

-Measurements of the Higgs couplings with { gauge bosons / fermions } (mass generation)

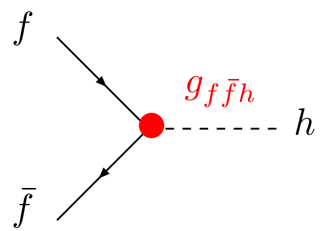
-Measurements of the Higgs self-couplings (reconstruction of the Higgs potential)

ZZh, WWh ($\sqrt{s} = 300$ GeV, $\mathcal{L} = 500\ fb^{-1}$, $m_h = 120$ GeV) $hf\bar{f}$



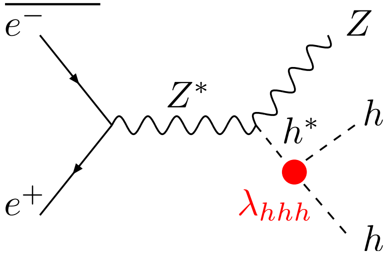


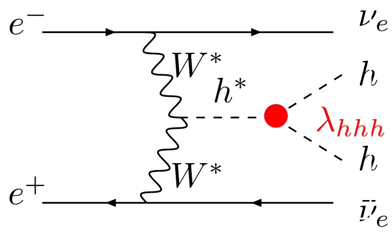
$$\frac{\Delta\lambda_{VVh}}{\lambda_{VVh}} \sim \mathcal{O}(1)\%$$



$$\frac{\Delta\lambda_{hf\bar{f}}}{\lambda_{hf\bar{f}}} \sim \text{(a few-several)}\%$$

hhh





$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}} \sim \mathcal{O}(10-20)\%$$

($\sqrt{s} = 0.5 - 1.5$ TeV, $\mathcal{L} = 1\ ab^{-1}$)
Battaglia et al, ACFA Higgs WG

Connections between collider physics and cosmology

There many open problems in cosmology.

- Baryon Asymmery of the Universe (BAU)
- Dark Matter
- etc...

What will be impact of the collider physics on cosmology?

We consider electorweak baryogenesis in connection with Higgs physics at colliders.

Electroweak baryogenesis $\Longleftrightarrow$ **Higgs physics**

2 scenarios of baryogenesis

(1). B-L-gen. above EW phase transition (Leptogenesis, etc)
(2). B-gen. during EW phase transition (EW baryogenesis)

▷ Since 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-couplings.

▷ We investigate the possible region of EW baryogenesis in 2HDM and MSSM, and calculate the quantum corrections to the trilinear Higgs boson coupling in such a region.

Conditions of Baryogenesis

Evidence of the BAU (WMAP data and other CMB results)

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

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

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

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

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

2HDM, MSSM, Next-to-MSSM, etc.

▷ 2HDM is a simple viable model

Two Higgs Doulet Model (2HDM)

• 2HDM is a simplest extension of the MSM Higgs sector for various theoretical motivations (extra CP phase, EW baryogenesis, SUSY, Little Higgs, etc)

Higgs potential

$$\begin{aligned} V_{\text{2HDM}}(\Phi_1,\Phi_2) &= m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\ &+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\ &+\left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \left\{\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right\}(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right], \end{aligned}$$

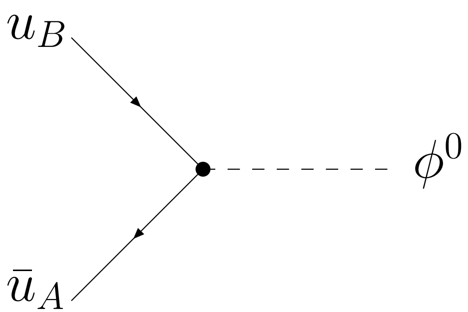
$m_3^2,\ \lambda_{5-7} \in \boldsymbol{C}$ (sources of explicit CP violation)

In the MSSM: $\lambda_1 = \lambda_2 = (g_2^2 + g_1^2)/4, \quad \lambda_3 = (g_2^2 - g_1^2)/4, \quad \lambda_4 = g_2^2/2,$
$\lambda_5 = \lambda_6 = \lambda_7 = 0.$

Yukawa interaction

$$\begin{aligned} \mathcal{L}_{\text{Yukawa}} &= \bar{q}_L(f_1^{(d)}\Phi_1 + f_2^{(d)}\Phi_2)d_R + \bar{q}_L(f_1^{(u)}\tilde{\Phi}_1 + f_2^{(u)}\tilde{\Phi}_2)u_R \\ &+\bar{l}_L(f_1^{(e)}\Phi_1 + f_2^{(e)}\Phi_2)e_R + \text{h.c.}, \quad (\tilde{\Phi}_i = i\tau^2\Phi_i^*) \end{aligned}$$

Discrete symmetry for FCNC suppression



Vertex which can produce FCNC. $(A \neq B)$

To suppress the FCNC, we impose the Z_2 symmetry as

$$\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad u_R \to u_R, \quad d_R \to d_R, \quad e_R \to e_R,$$

or

$$\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad u_R \to -u_R, \quad d_R \to d_R, \quad e_R \to e_R,$$

$$\Downarrow$$

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

- MSSM Higgs sector corresponds to Type II-2HDM.

$$
\begin{aligned}
V_{\text{THDM}} &= m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\
&+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\
&+\frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right],
\end{aligned}
$$

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

Independent parameters

$$
\boxed{\alpha,\ \tan\beta,\ M,\ m_h,\ m_H,\ m_A,\ m_{H^\pm}}
$$

h, H, A, $H^\pm$, CP-even, CP-odd and charged Higgs bosons

G^0, $G^\pm$, Nambu-Goldstone bosons

α: mixing angle beween h and H,

$\tan\beta = v_2/v_1$, $v{=}\sqrt{v_1^2 + v_2^2}$ ~246 GeV: vacuum expectation value (VEV)

$M = \frac{m_3}{\sqrt{\sin\beta\cos\beta}}$ (soft-breaking scale of the Z_2 symmetry)

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

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

- **Field dependent masses of the Higgs bosons**

$$\begin{aligned}
m_h^2(\varphi) &= \frac{3}{2}m_h^2(v)\left(\frac{\varphi^2}{v^2} - \frac{1}{3}\right), \\
m_H^2(\varphi) &= \left[m_H^2(v) + \frac{1}{2}m_h^2(v) - M^2\right]\frac{\varphi^2}{v^2} - \frac{1}{2}m_h^2(v) + M^2, \\
m_A^2(\varphi) &= \left[m_A^2(v) + \frac{1}{2}m_h^2(v) - M^2\right]\frac{\varphi^2}{v^2} - \frac{1}{2}m_h^2(v) + M^2, \\
m_{H^\pm}^2(\varphi) &= \left[m_{H^\pm}^2(v) + \frac{1}{2}m_h^2(v) - M^2\right]\frac{\varphi^2}{v^2} - \frac{1}{2}m_h^2(v) + M^2.
\end{aligned}$$

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

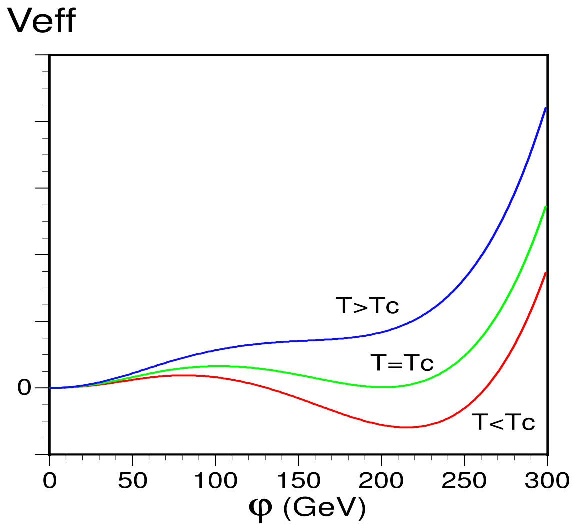
For $m_\Phi^2(v) \gg M^2, m_h^2(v)$ $\qquad m_\Phi^2(\varphi) \simeq m_\Phi^2(v)\frac{\varphi^2}{v^2}, \quad (\Phi = H,\ A,\ H^\pm)$

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

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: $\qquad \varphi_c = \frac{2ET_c}{\lambda_{T_c}}$



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

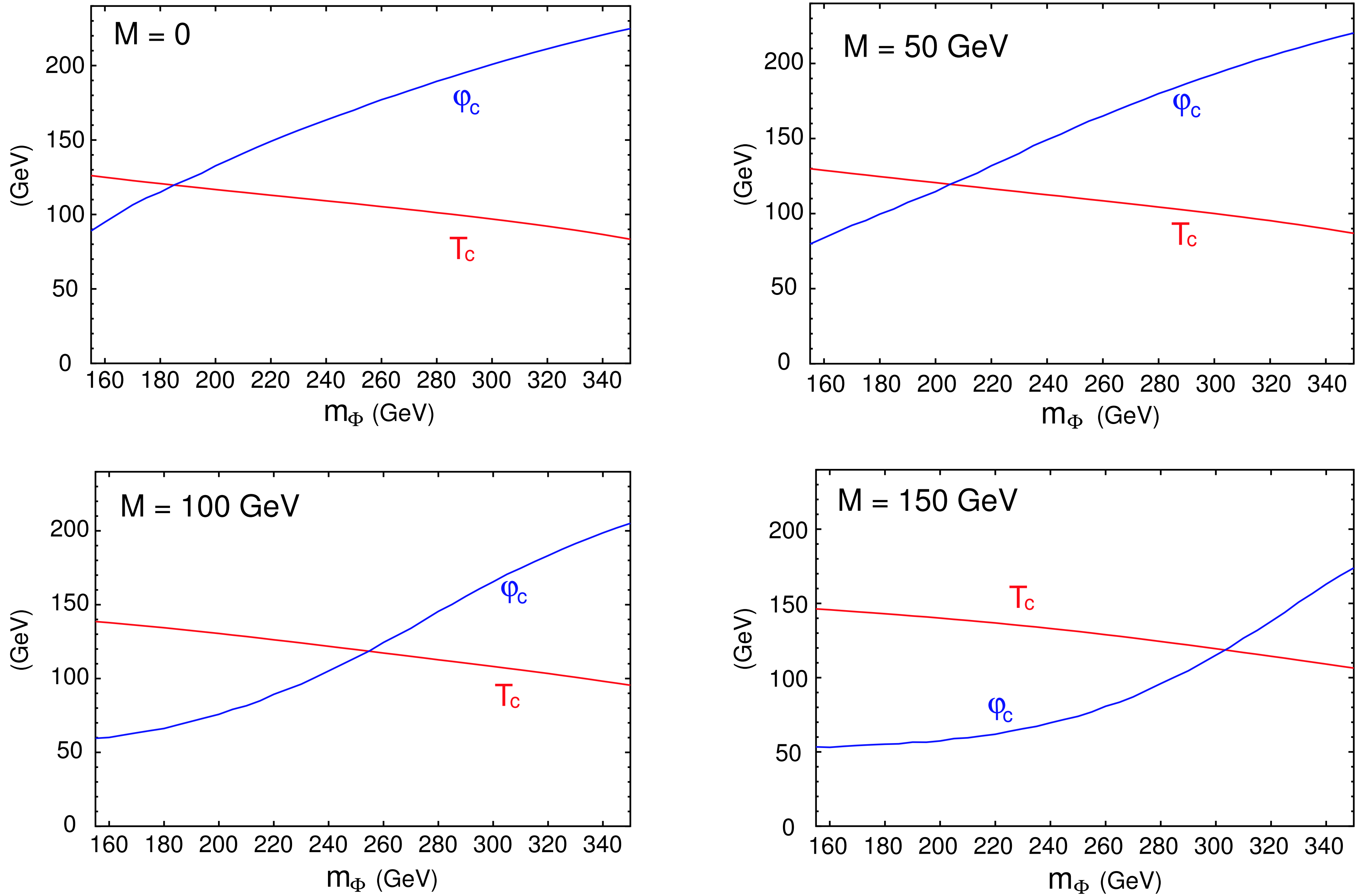
- **Strongly 1st order phase transition:** $\frac{\varphi_c}{T_c} \gtrsim 1$

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

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

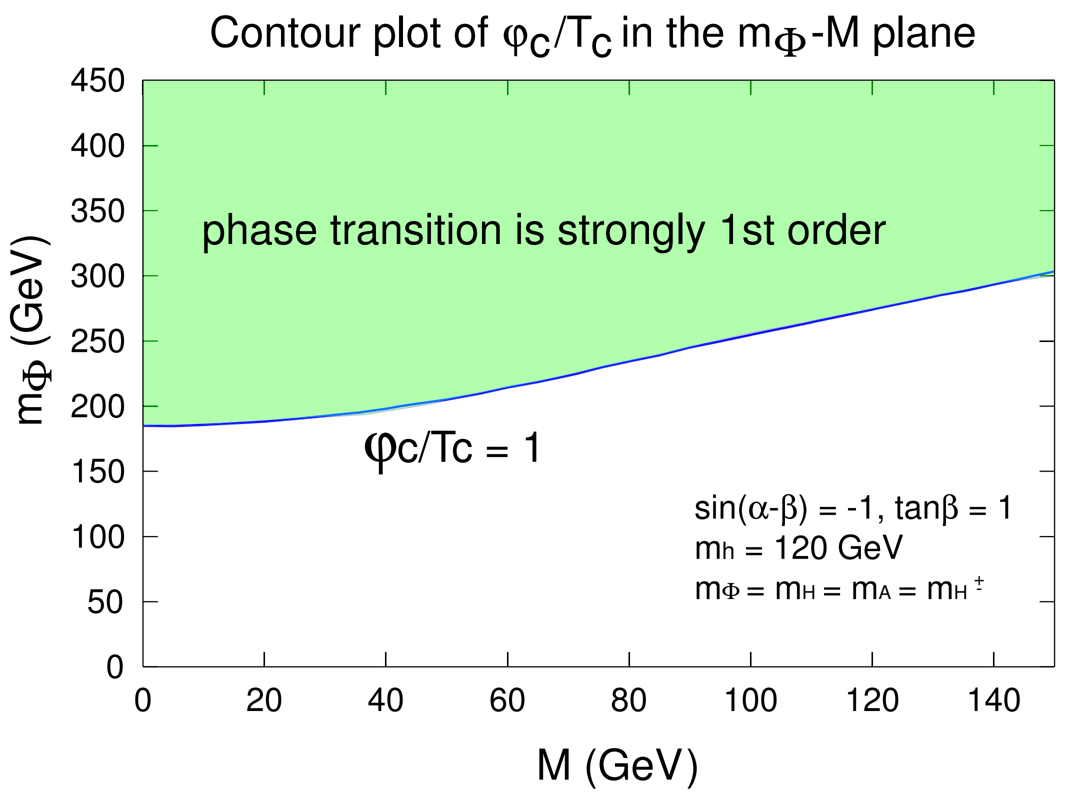
T_c and φ_c vs heavy Higgs boson mass

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



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

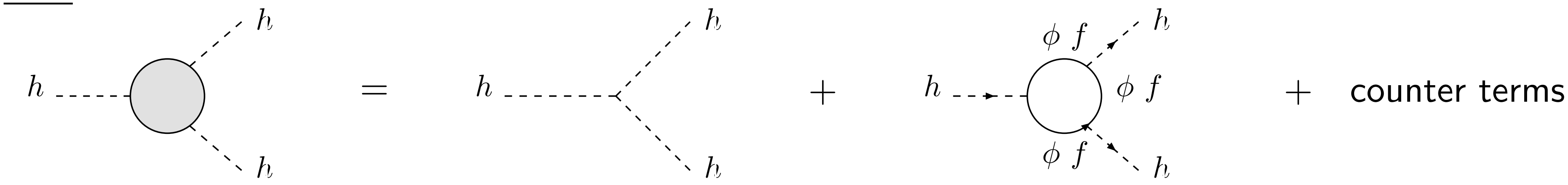
Strongly 1st order phase transition is possible due to the loop effect of the heavy Higgs bosons (φ^3-term is effectively large)

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

Radiative corrections to hhh coupling constant

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

- hhh



$(\phi = h, H, A, H^{\pm}, G^0, G^{\pm}, \quad f = t, b)$

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

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

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

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

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**)

▷ Heavy Higgs boson masses

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

decouple? or non-decouple?

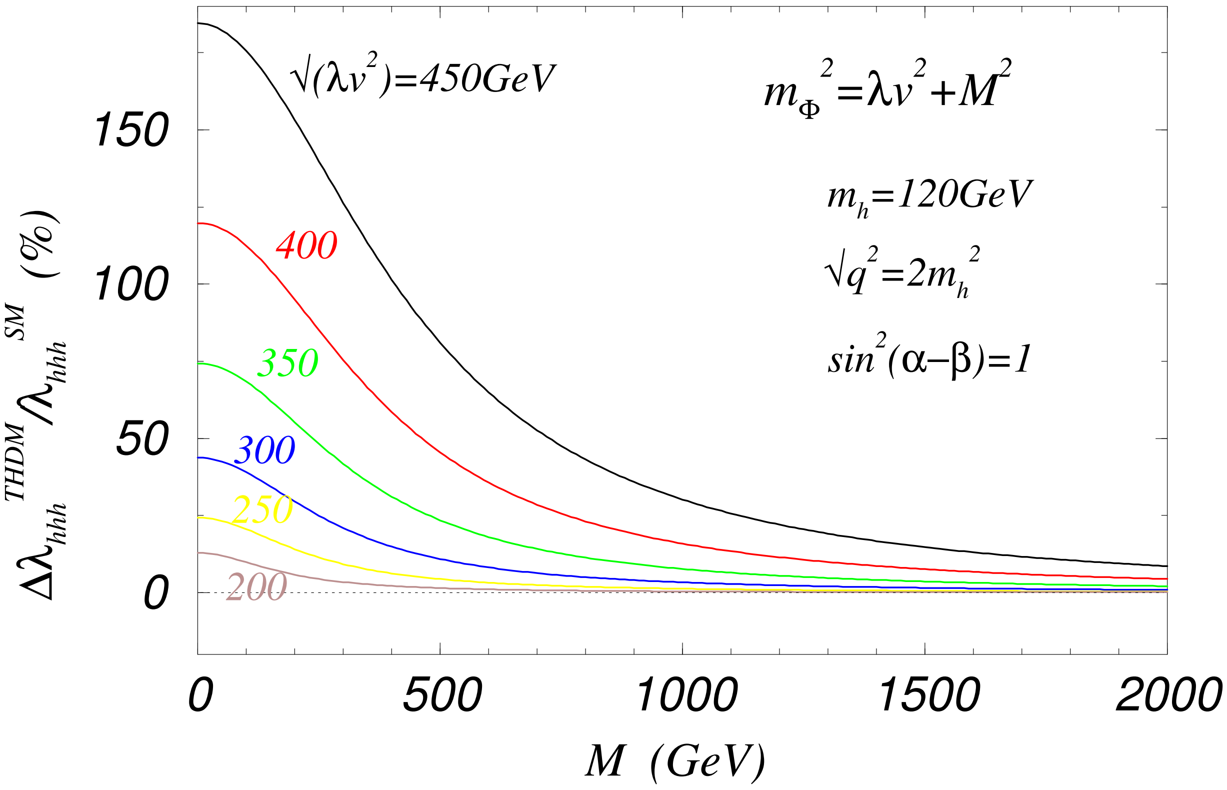
- hhh

$$m_\Phi^4 \left(1 - \frac{M^2}{m_\Phi^2}\right)^3 \Longrightarrow \begin{cases} \dfrac{(\lambda_i v^2)^3}{m_\Phi^2}, \quad (M^2 \gg \lambda_i v^2), \\ \text{(decoupling for } m_\Phi \to \infty) \\ m_\Phi^4, \quad (M^2 \lesssim \lambda_i v^2), \\ \text{(non-decoupling effect)} \end{cases}$$

Loop corrections can be large if a theory has non-decoupling property.

$m_\Phi^2 \simeq \lambda_i v^2 \ (m_\Phi^2 \gg M^2)$

Decoupling behavior of $\Delta\lambda_{hhh}/\lambda_{hhh}$

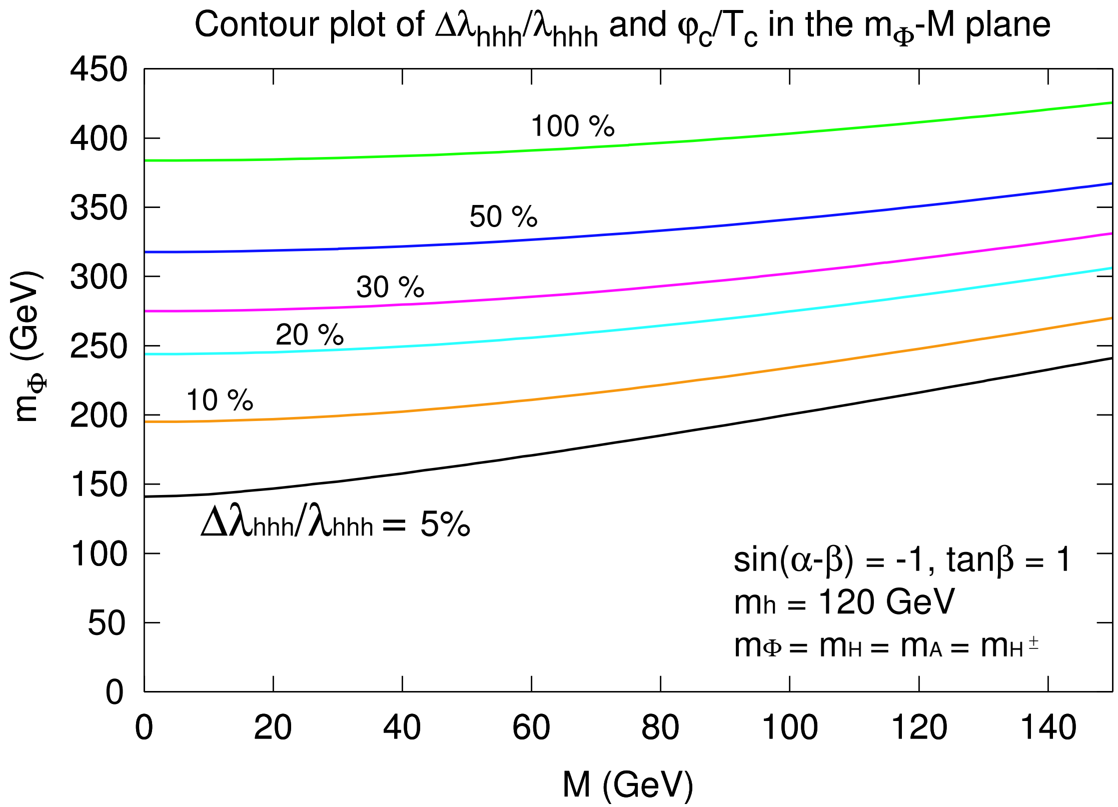


- $M^2 \gg \lambda_i v^2$ decoupling case
  Loop corrections are decoupled in the large mass limit.
  MSSM Higgs sector corresponds to this case. $M = m_A,\ \lambda_i \sim \mathcal{O}(g)$

- $M^2 \lesssim \lambda_i v^2$ non-decoupling case
  Large loop corrections can be induced by the heavy Higgs bosons.

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

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



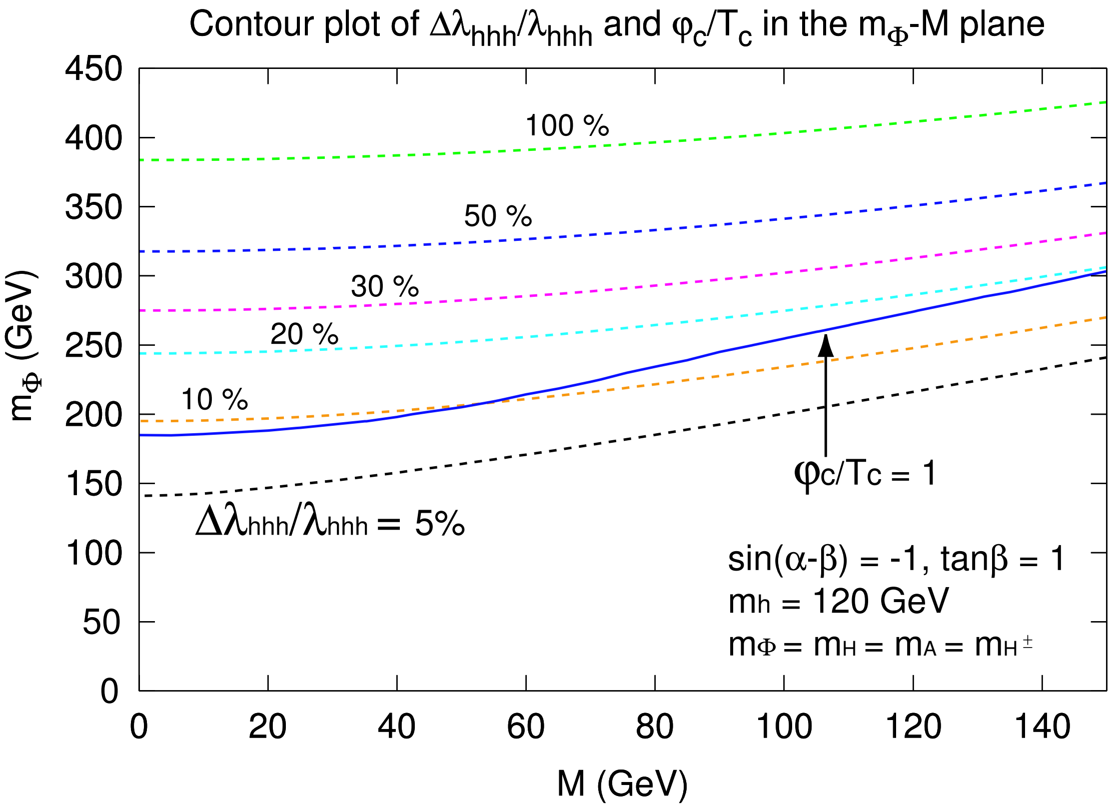
For $m_\Phi^2 \gg M^2, m_h^2$,

- Deviation of the hhh coupling constant from SM value becomes large.

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

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

[S.Kanemura, Y.Okada, E.S.]

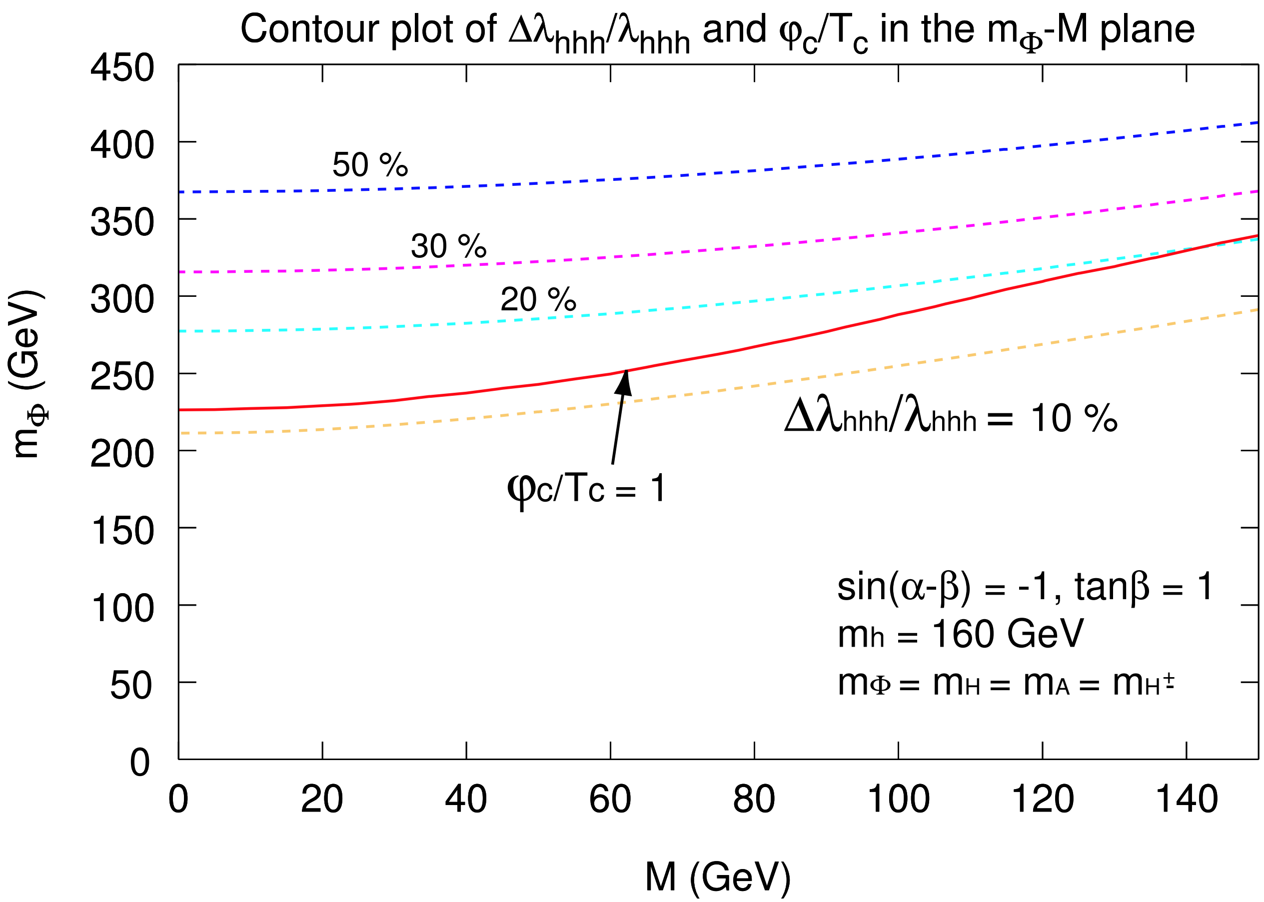


For $m_\Phi^2 \gg M^2, m_h^2$,

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

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

$$\sin^2(\alpha-\beta) = \tan\beta = 1, \; m_h = 160 \text{ GeV}, \; m_\Phi \equiv m_A = m_H = m_{H^\pm}$$



The correlation between φ_c/T_c and $\Delta\lambda_{hhh}/\lambda_{hhh}$ is almost same as the lighter m_h case.

Electroweak phase transition in the MSSM

- **Light stop scenario** [Carena, Quiros, Wagner, PLB380 ('96)]

$M_Q^2 \gg M_U^2, m_t^2, \quad m_A^2 \gg m_Z^2$

$$m_{\tilde{t}_1}^2(\varphi,\beta) \simeq M_U^2 + \mathcal{O}(m_Z^2) + \frac{y_t^2 \sin^2\beta}{2}\left(1 - \frac{|X_t|^2}{M_Q^2}\right)\varphi^2, \quad (X_t = A_t - \mu\cot\beta)$$

- **High termperature expansion**

For $M_U^2 \simeq 0, \quad (m_{\tilde{t}_1} \simeq m_t)$

$$\Delta E_{\tilde{t}_1} \simeq \frac{1}{2\pi}\frac{m_t^3}{v^3}\left(1 - \frac{|X_t|^2}{M_Q^2}\right)^{3/2}$$

Stop contribution make the phase transition stronger enough for successful electroweak baryogenesis.

Collider signal $\Longrightarrow$ light stop ($m_{\tilde{t}_1} \lesssim m_t$)

In this scenario, how large is the magnitude of the λ_{hhh} coupling?

Deviation of the λ_{hhh} from the SM value

- Leading contribution of stop loop

$$\frac{\Delta\lambda_{hhh}(\mathrm{MSSM})}{\lambda_{hhh}(\mathrm{SM})} \simeq \frac{m_t^4}{2\pi^2 v^2 m_h^2}\left(1 - \frac{|X_t|^2}{M_Q^2}\right)^3 = \frac{3v^4}{m_t^2 m_h^2}(\Delta E_{\tilde{t}_1})^2.$$

$\varphi_c/T_c = 2E/\lambda_{T_c} > 1$ gives

$$\frac{\Delta\lambda_{hhh}(\mathrm{MSSM})}{\lambda_{hhh}(\mathrm{SM})} \sim 6\%. \quad (\text{for } m_h = 120 \text{ GeV})$$

In the MSSM, the condition of strongly 1st order phase transition also leads to large quantum corrections to the hhh coupling constant.

- Numerical evaluation without high temperature expansion

work in progress

Summary

We investigate the region where the electroweak phase transition is strongly 1st order, and also calculate the deviation of the trilinear Higgs coupling from SM value in such a region.

In the 2HDM, 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

In the MSSM with light stop scenario, $\Delta\lambda_{hhh}/\lambda_{hhh} \sim$ several %

Such deviations can be testable at a future e^+e^- Linear Collider.

EW baryogenesis

⇓

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

⇓

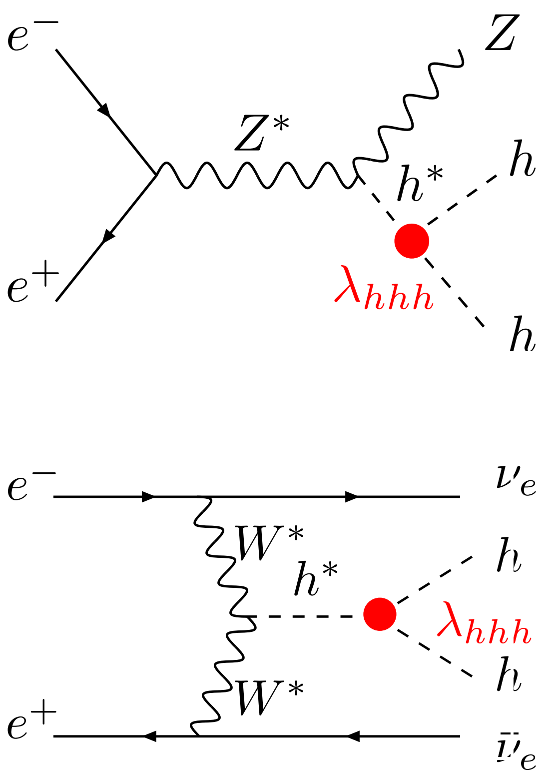
Large loop correction to the λ_{hhh} coupling — $V_{\text{eff}}(\varphi, 0)$

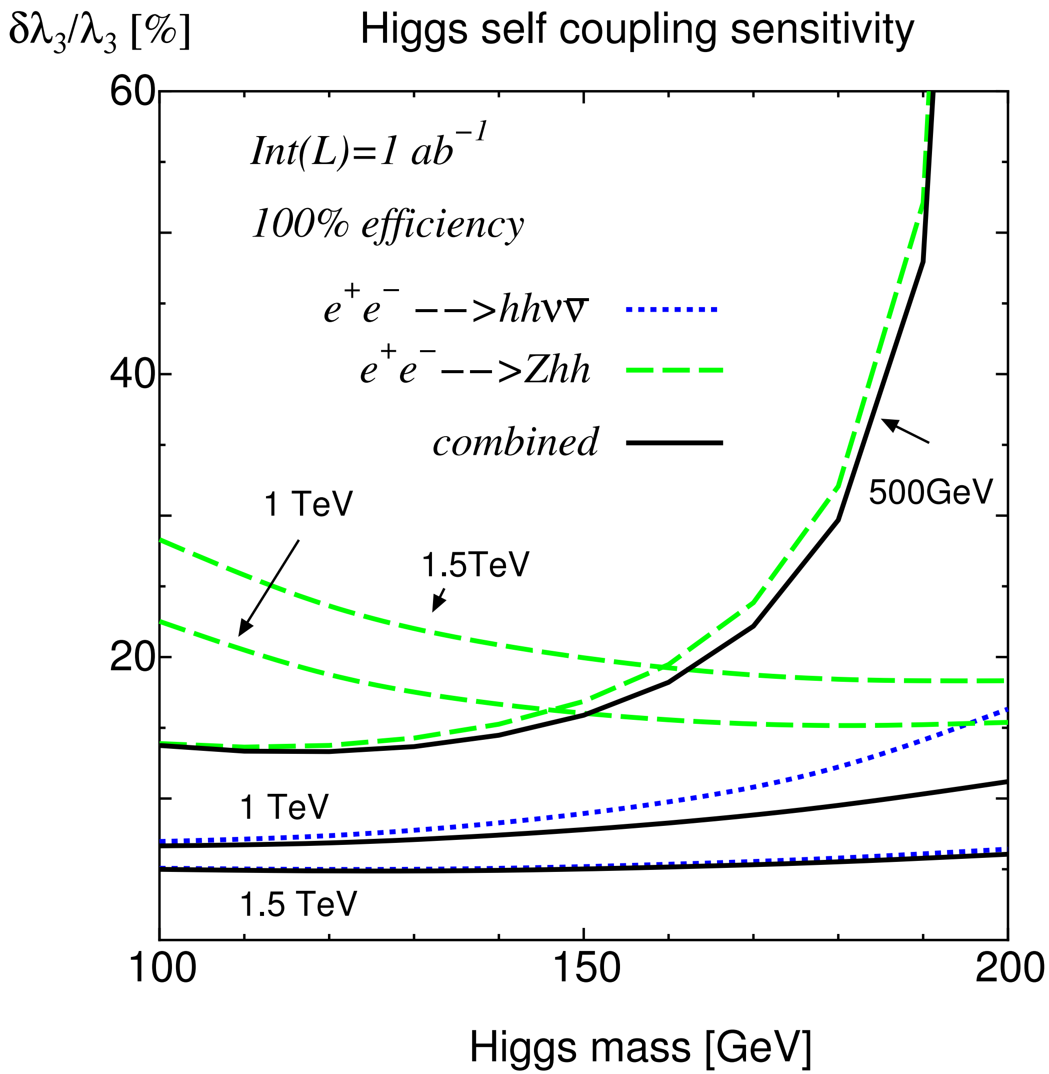
⇓

Measurement of λ_{hhh} @ILC

Sensitivity of the hhh coupling at Linear Colliders

$\underline{hhh}$





[Y.Yasui et al ACFA WG]

Ring-improved Higgs boson masses

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

where

$$
a = \frac{1}{12v^2}\left[6m_W^2(v) + 3m_Z^2(v) + 5m_h^2(v) + m_H^2(v) + m_A^2(v) + 2m_{H^\pm}^2(v) - 4M^2\right].
$$