Electroweak Baryogenesis and the triple Higgs boson coupling

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Mar. 18-22, 2005, LCWS 05 @Stanford U.

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Reference: PLB**606** 361 (2005)

Outline

- **Introduction**

  -Higgs physics/Cosmology interface

- **Electroweak baryogenesis**

  -Electroweak phase transition in the 2HDM

- **Quantum corrections to the hhh coupling constant**

  -Collider signals of electroweak baryogenesis?

- **Summary**

Higgs physics/Cosmology interface

- **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.

- **Cosmology**

-Baryon Asymmery of the Universe (BAU) $n_B/s \sim 10^{-10}$

Attempts: GUTs, Affleck-Dine, Leptogenesis, EW baryogenesis, etc...

Connection with collider physics

Electroweak baryogenesis based on the Higgs potential at $T \neq 0$

$\Downarrow$ collider signals??

Higgs self-couplings Higgs potential at $T = 0$

We evaluate the hhh coupling in the possible region of EW baryogenesis.

Conditions for Baryogenesis

- 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**

-B violation sphaleron process

-C violation chiral gauge interation

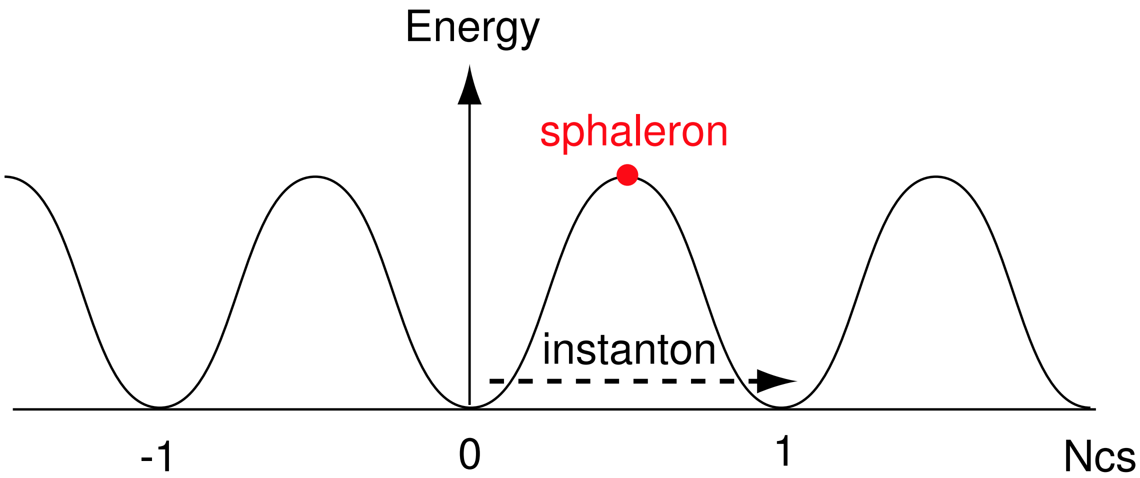
-CP violation KM-phase or other sources in the extension of the SM

-out of equilibrium 1st order phase transition

Sphaleron process

- A saddle point solution of 4d $SU(2)$ gauge-Higgs system

[Manton, PRD28 ('83)]



$$(\Delta B = N_f \Delta N_{CS})$$

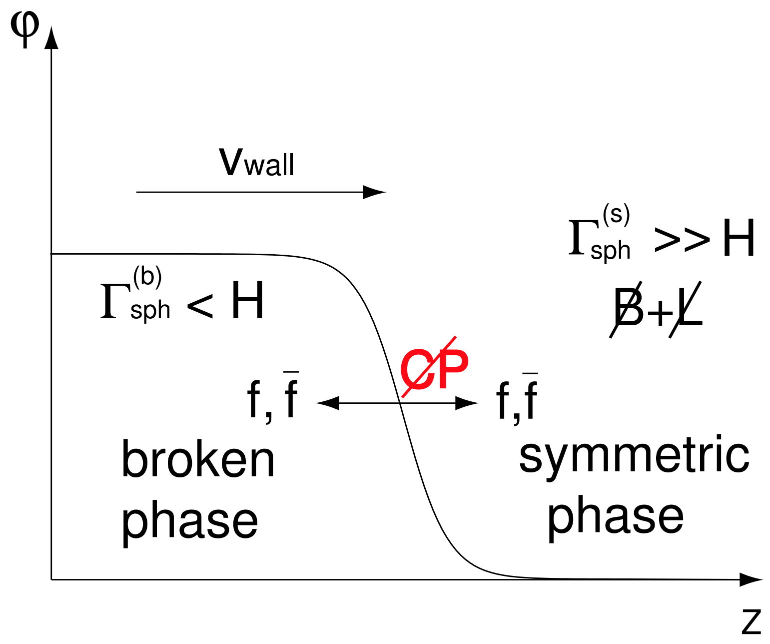
- Transition rate

$$\Gamma_{\rm sph}^{(b)} \sim (\alpha_W T)^4 e^{-E_{\rm sph}/T} \quad \text{(broken phase)}$$

$$\Gamma_{\rm sph}^{(s)} \sim (\alpha_W T)^4 \quad \text{(symmetric phase)}$$

B violation process is effective at finite temperature, but is suppressed at $T = 0$

Baryogenesis mechanism



- Asymmetry of the charge flow of the particle (due to CP violation)

$\Downarrow$

- Accumulation of the charge in the symmetric phase

$\Downarrow$

- B generation via sphaleron process

$\Downarrow$

- Decoupling of sphaleron process in the broken phase

- **Strongly 1st order phase transition**

$\Rightarrow$ Decoupling of the sphaleron process at $T \lesssim T_c$:

$$\Gamma_{\rm sph}^{(b)}/T_c^3 < H(T_c) \quad \Longrightarrow \quad \boxed{\frac{\varphi_c}{T_c} \gtrsim 1}$$

In principle, the SM fulfills all the three Sakharov conditions, BUT

- Phase transition is not 1st order (for $m_h > 114$ GeV)   out of equilibrium $\times$
- KM-phase is too small to generate sufficient BAU

$$\Downarrow$$

Extension of the minimal SM Higgs sector

▷ Two Higgs Doublet Model (2HDM)

▷ Minimal Supersymmetric Standard Model (MSSM)

▷ Next-to-Minimal Supersymmetric Standard Model (NMSSM)

▷ etc...

In this talk we consider

- 2HDM   simple viable model
- MSSM

Two Higgs Doublet Model (2HDM)

- Introduce the additional Higgs doublet Φ
- FCNC suppression $\Rightarrow$ $\Phi_1 \to \Phi_1,\ \Phi_2 \to -\Phi_2$ (Type I, II Yukawa int.)

$$
\begin{aligned}
V_{\mathrm{THDM}} &= m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) \\
&+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\
&+\left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\right], \quad \Phi_{i=1,2}(x) = \begin{pmatrix} \phi_i^+(x) \\ \frac{1}{\sqrt{2}}\Big(v_i + h_i(x) + i a_i(x)\Big) \end{pmatrix}.
\end{aligned}
$$

- $m_3^2,\ \lambda_5 \in \boldsymbol{C}$ (sources of explicit CP violation)

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

7 independent parameters

$m_h,\ m_H,\ m_A,\ m_{H^\pm}$: CP-even, CP-odd and charged Higgs boson masses

α: mixing angle between h and H, $\tan\beta = v_2/v_1$, ($v{=}\sqrt{v_1^2 + v_2^2}$ ~246 GeV)

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

Setup

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

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

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

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

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

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

φ^3-term comes from "boson" loops

Finite temperature Higgs potential

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

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

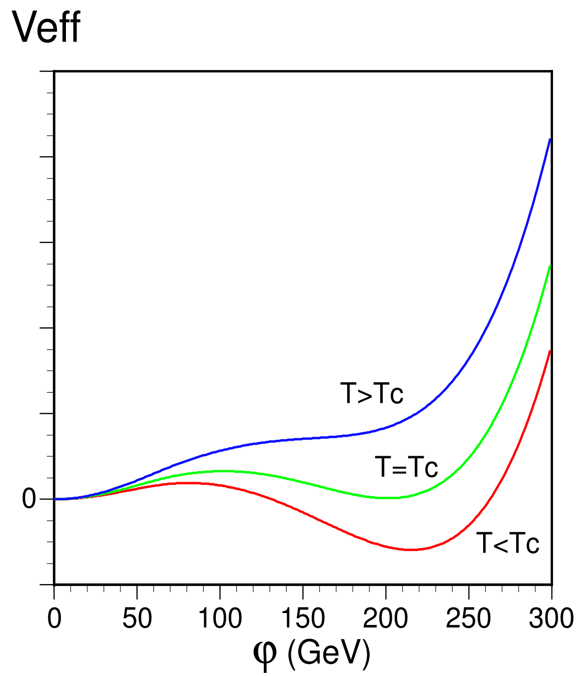
where

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

At T_c, degenerate minima: $\quad \varphi_c = 0, \quad \frac{2ET_c}{\lambda_{T_c}}$

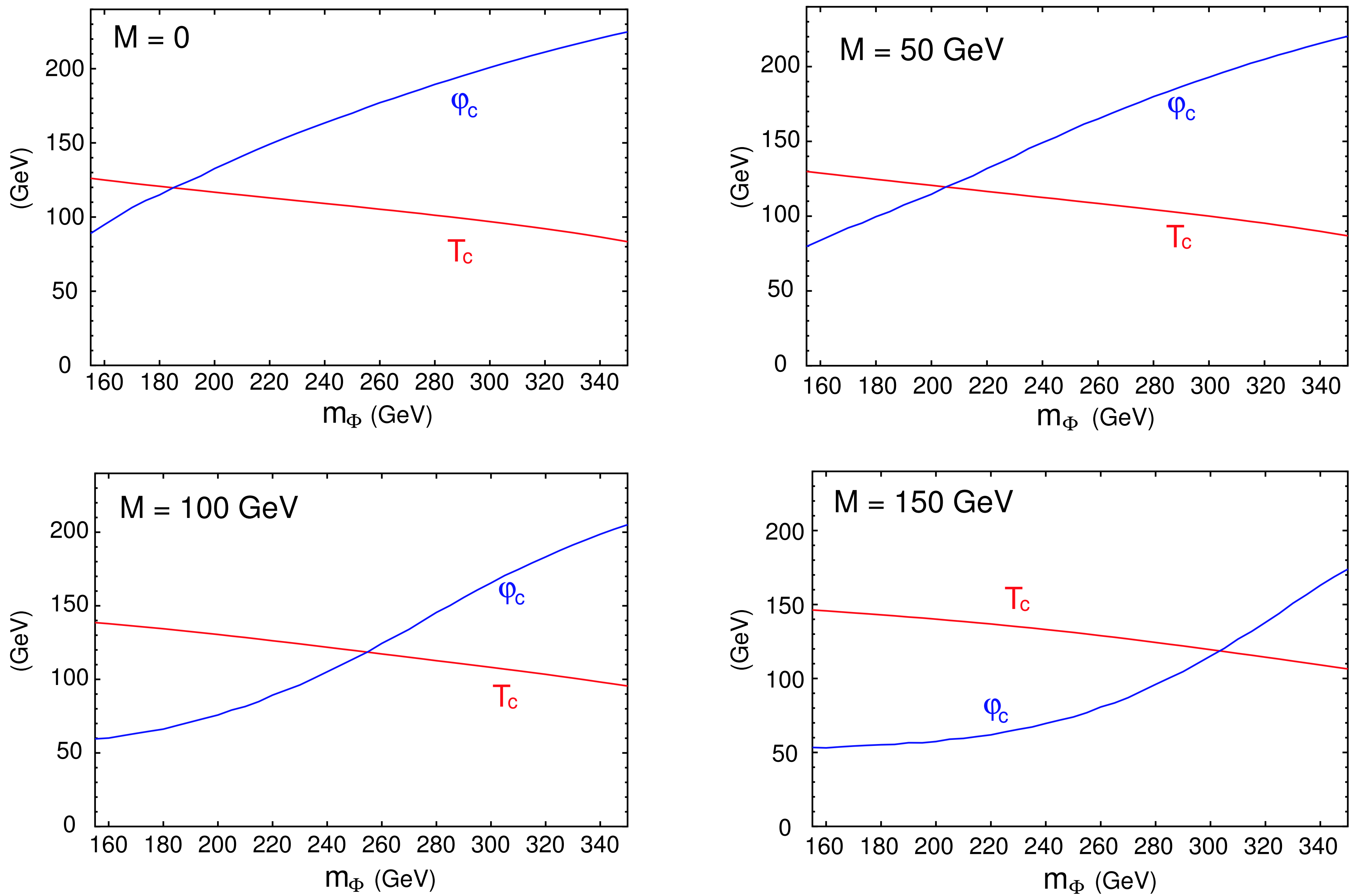
• **The magnitude of E is relevent for the strongly 1st order phase transition**

• We examine the strength of the phase transition without the high temperature expansion.



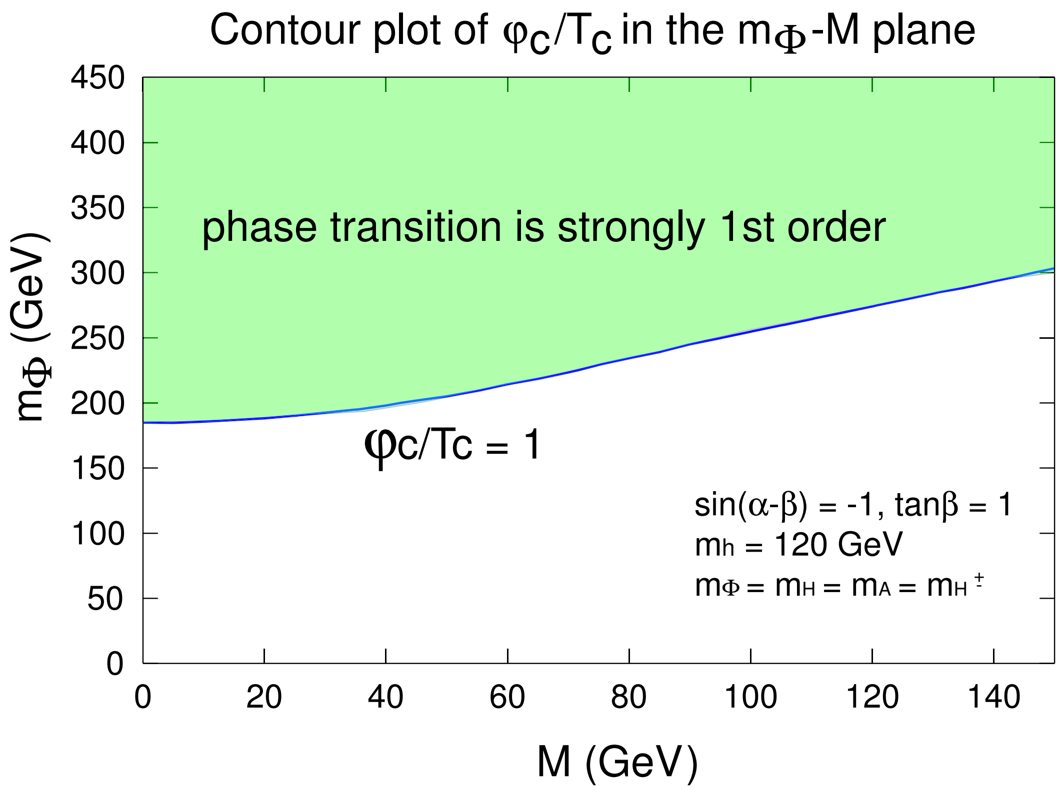
T_c and φ_c vs heavy Higgs boson mass

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



Contours of φ_c/T_c in the m_Φ-M plane

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



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

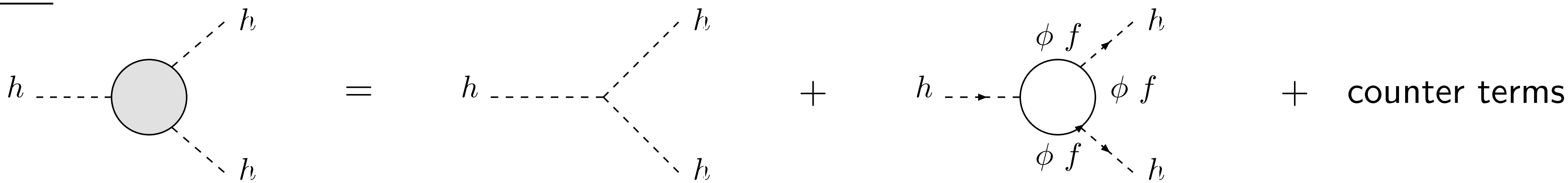
Strongly 1st order phase transition is possible due to the loop effect of the heavy Higgs bosons (φ^3-term is effectively large)

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

Quantum corrections to the hhh coupling

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

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

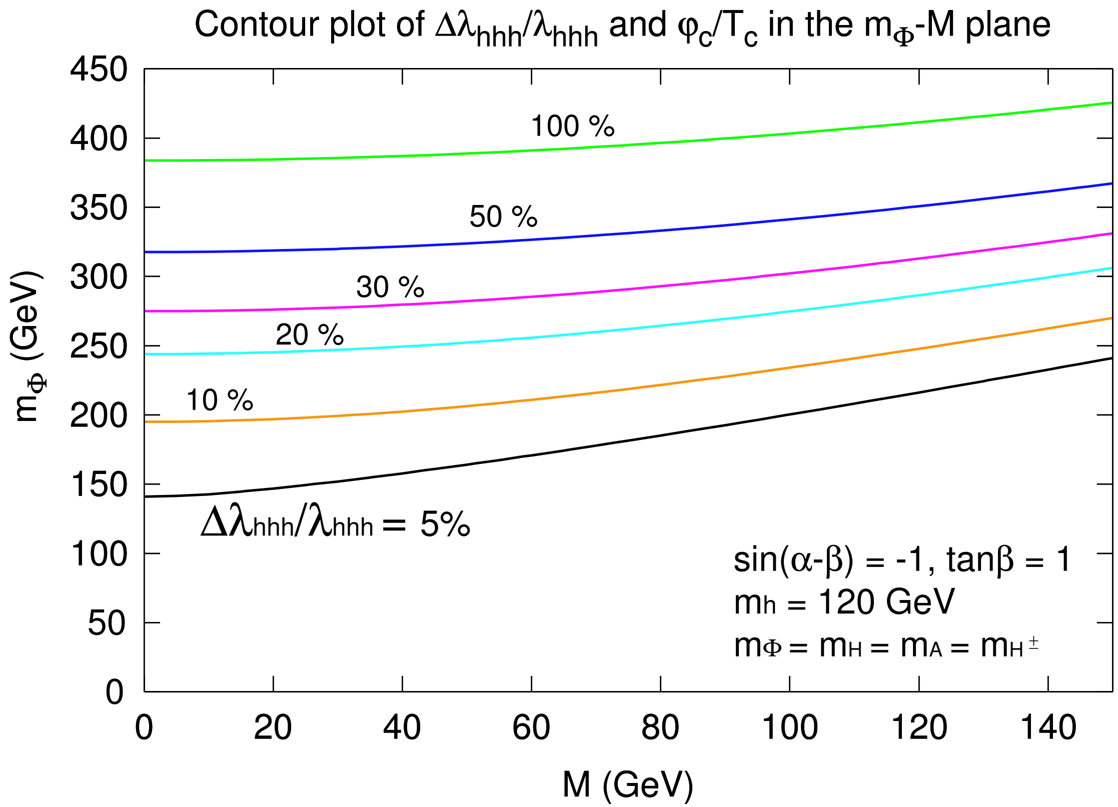
$$\lambda_{hhh} \sim -\frac{3m_h^2}{v}\left[1 + \frac{c}{12\pi^2}\frac{m_\Phi^4}{m_h^2 v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\right] \quad (\Phi = H, A, H^{\pm})$$

$\big(c = 1$ 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. (**nondecoupling effect**)

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

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



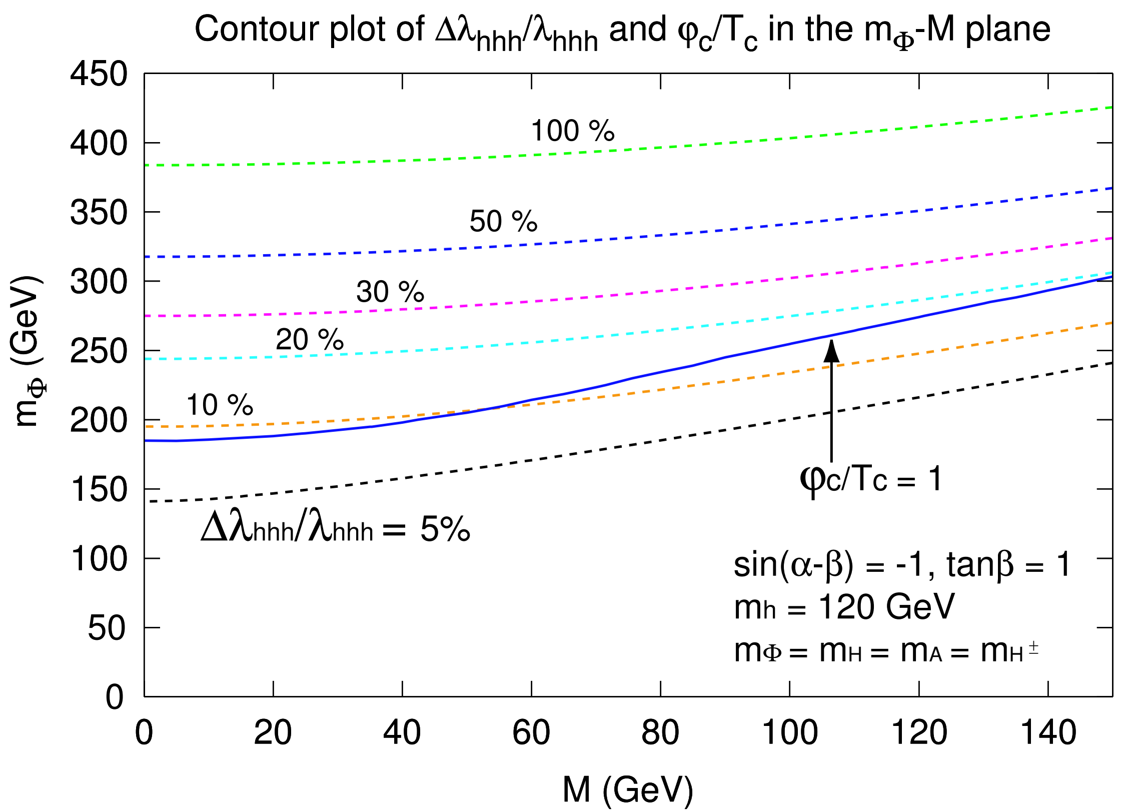
For $m_\Phi^2 \gg M^2, m_h^2$,

- Deviation of the hhh coupling constant from the 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.]

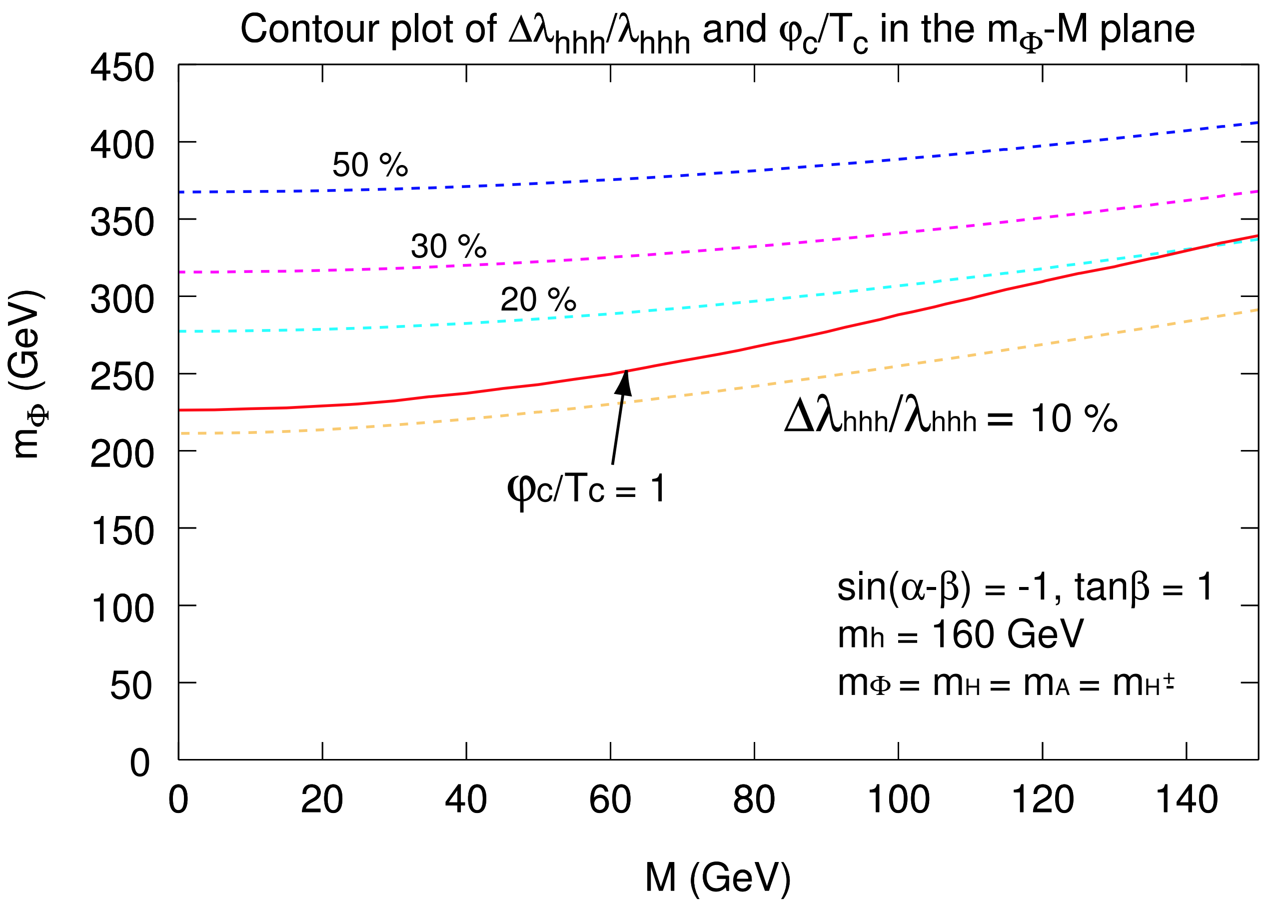


For $m_\Phi^2 \gg M^2, m_h^2$,

- 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

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



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)]

$M_Q^2 \gg M_U^2, m_t^2, \quad m_A^2 \gg m_Z^2 \; (\sin(\beta - \alpha) \simeq 1)$

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

- **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 signals $\Longrightarrow$ $m_{\tilde{t}_1} \lesssim m_t, \quad m_h \lesssim$ 120 GeV

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 the high temperature expansion

work in progress

Summary

We have studied the collider signature of the successful electroweak baryogenesis.

In the 2HDM

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

- Phase transition is strongly 1st order.
- The deviation of the λ_{hhh} coupling from the SM prediction becomes large. ($\Delta\lambda_{hhh}/\lambda_{hhh} \gtrsim 10\%$)

due to the nondecoupling 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 — $V_{\text{eff}}(\varphi, T)$

⇓

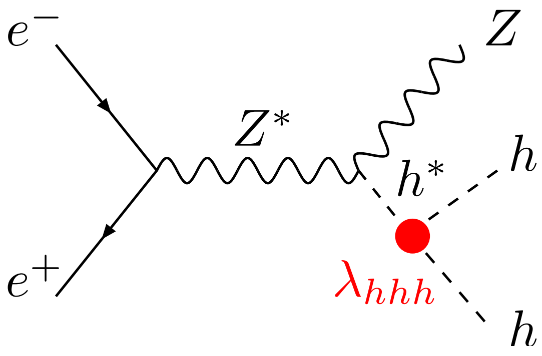
Large loop correction to the λ_{hhh} coupling — $V_{\text{eff}}(\varphi, 0)$

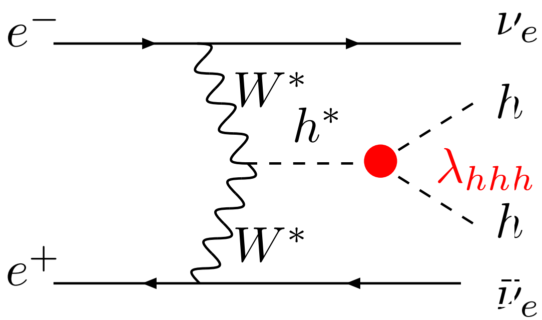
⇓

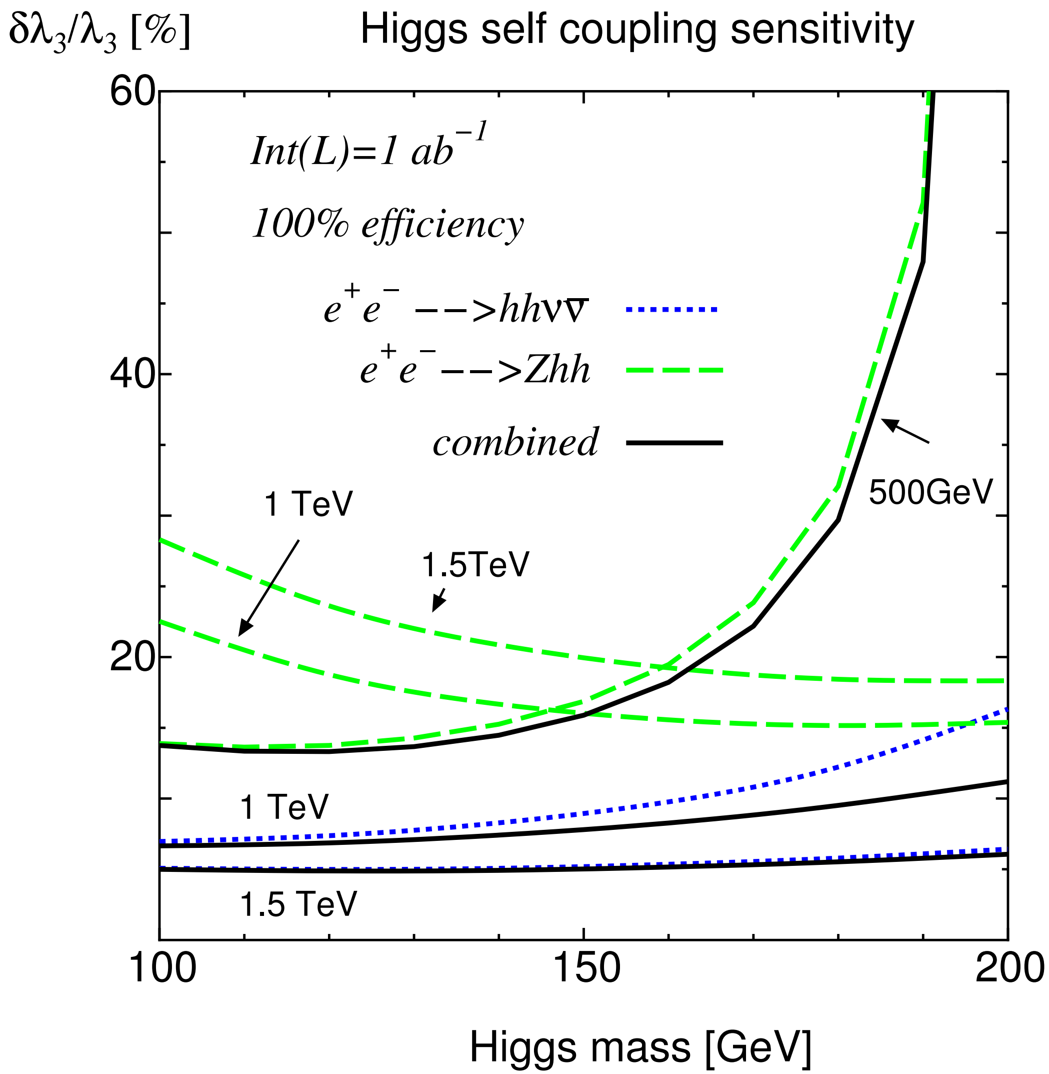
Measurement of λ_{hhh} @ILC

Sensitivity of the hhh coupling at Linear Colliders

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

$$a = \frac{1}{12v_0^2}\left[6m_W^2(v) + 3m_Z^2(v) + 5m_h^2(v) + m_H^2(v) + m_A^2(v) + 2m_{H^\pm}^2(v) - 4M^2\right].$$

Magnitude of the self-couplings λ_i