Non-Standard Higgs and Cosmology

(Electroweak baryogenesis and Higgs self-coupling)

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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)

  -Coupling measurements (g_{hVV}, $g_{hf\bar{f}}$, etc...)

Higgs potential $\Leftarrow$ Higgs self-couplings

λ_{hhh} $\mathcal{O}(10-20)\%$ accuracy (@ILC)

[ACFA Higgs WG, Battaglia et al.]

- **Cosmology**

-Baryon Asymmetry 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

(Sakharov conditions)

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

A saddle point solution of 4d $SU(2)$ gauge-Higgs system [Manton, PRD28 ('83)]

- 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 active at finite temperature, but is suppressed at $T = 0$

- **Strongly 1st order phase transition**

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

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

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

2HDM, MSSM, Next-to-MSSM, SM with a low cutoff

In this talk we consider

- 2HDM simple viable model
- MSSM

Two Higgs Doublet Model (2HDM)

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

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

- $m_3^2,\ \lambda_5 \in \boldsymbol{C}$ (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

We consider the simplified case as [Cline et al PRD54 '96]

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

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

- **Tree-level potential**

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

- **1-loop effective potential** **(zero + finite temperature)**

$$V_1(\varphi) = n_i \frac{m_i^4(\varphi)}{64\pi^2}\left(\log\frac{m_i^2(\varphi)}{Q^2} - \frac{3}{2}\right) + \frac{T^4}{2\pi^2}\Big[\sum_{i=\text{bosons}} n_i I_B(a^2) + n_t I_F(a)\Big]$$

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

where

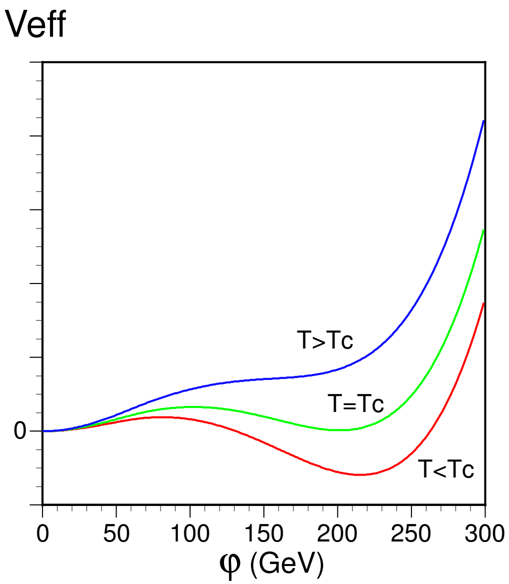
$$I_{B,F}(a^2) = \int_0^\infty dx\, x^2 \log\left(1 \mp e^{-\sqrt{x^2+a^2}}\right), \qquad a(\varphi) \equiv \frac{m(\varphi)}{T}$$

Finite temperature Higgs potential

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

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

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



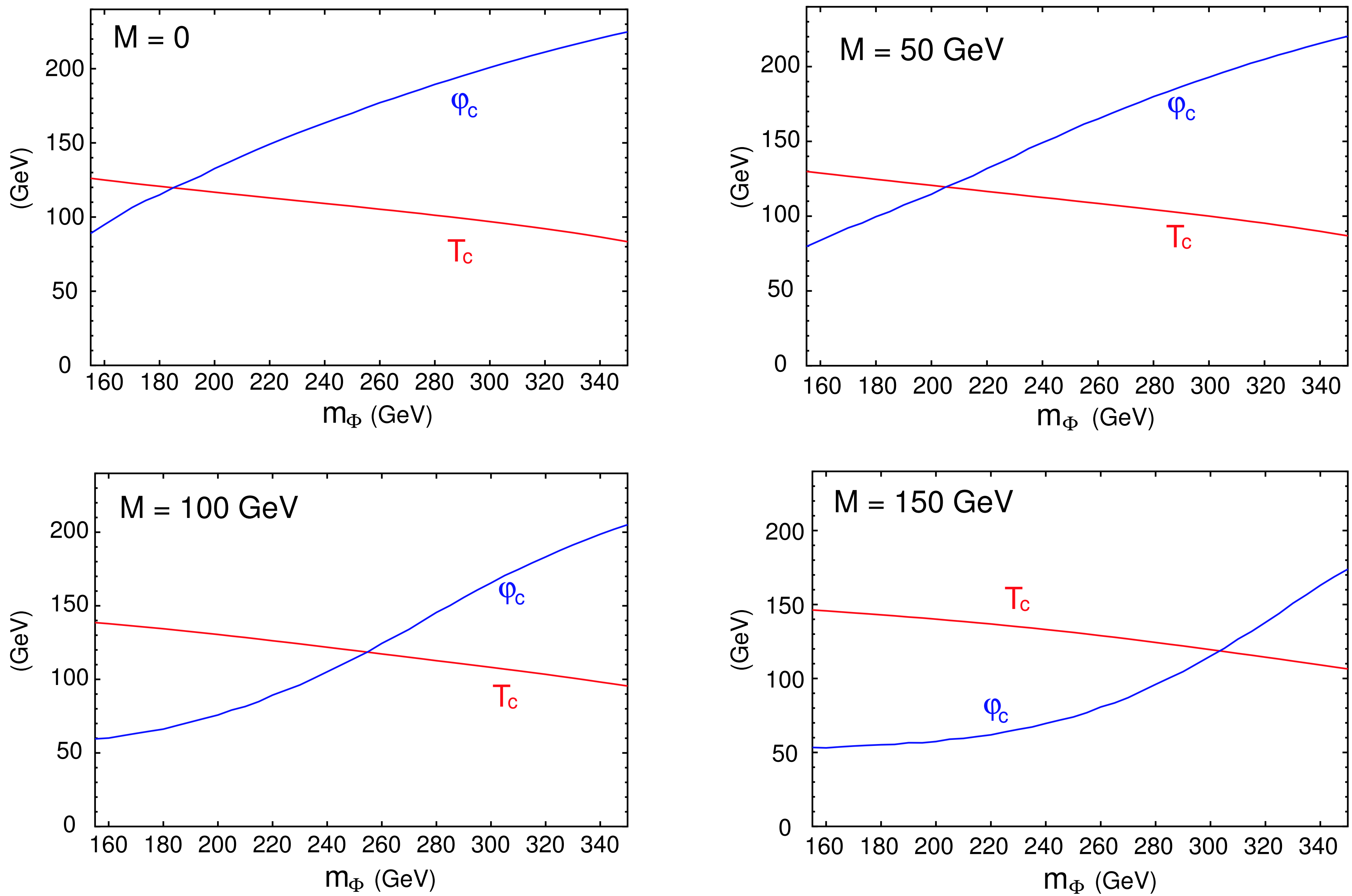
$$\frac{\varphi_c}{T_c} = \frac{2E}{\lambda_{T_c}}$$

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

- **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.

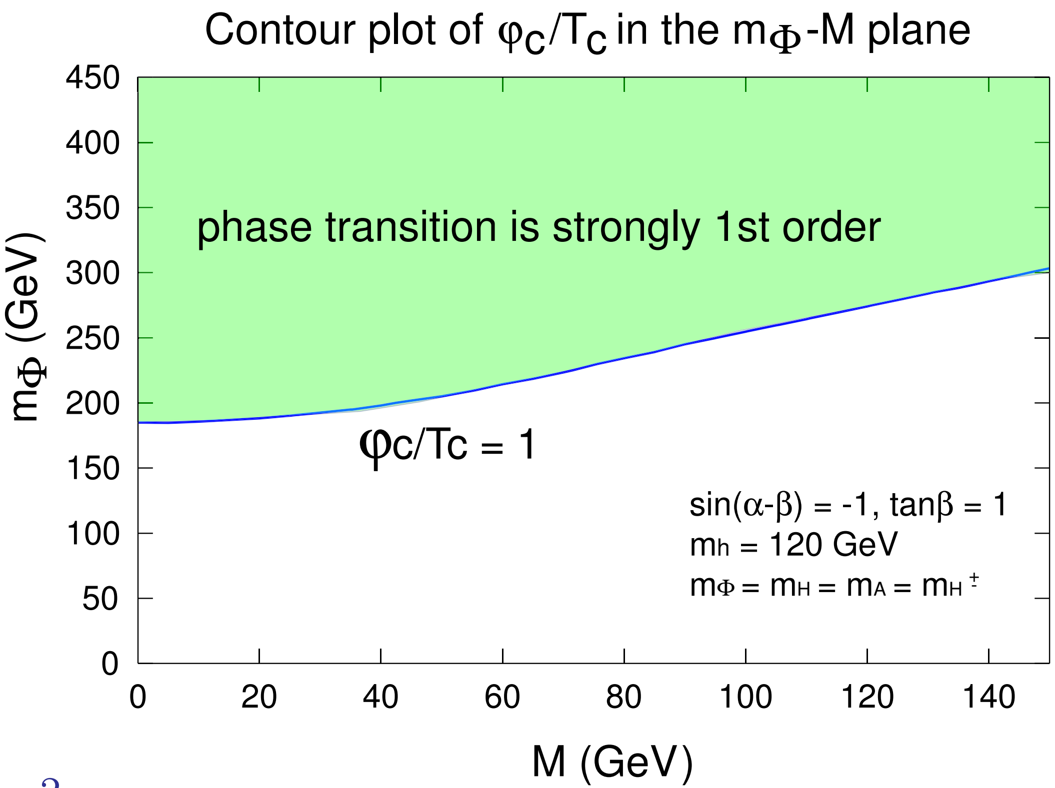
T_c and φ_c vs heavy Higgs boson mass

$m_h = 120$ 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

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



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

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

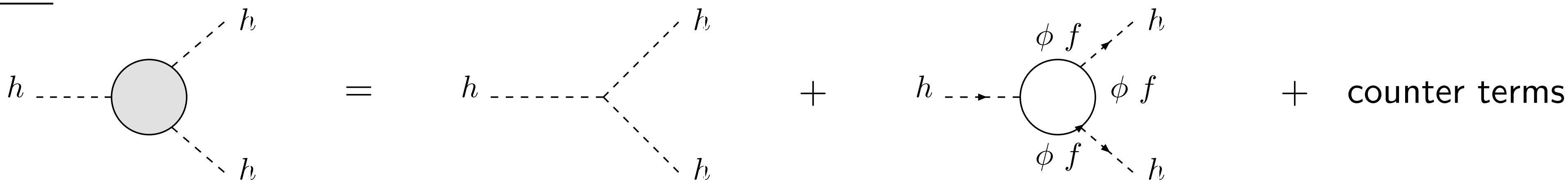
Question

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

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

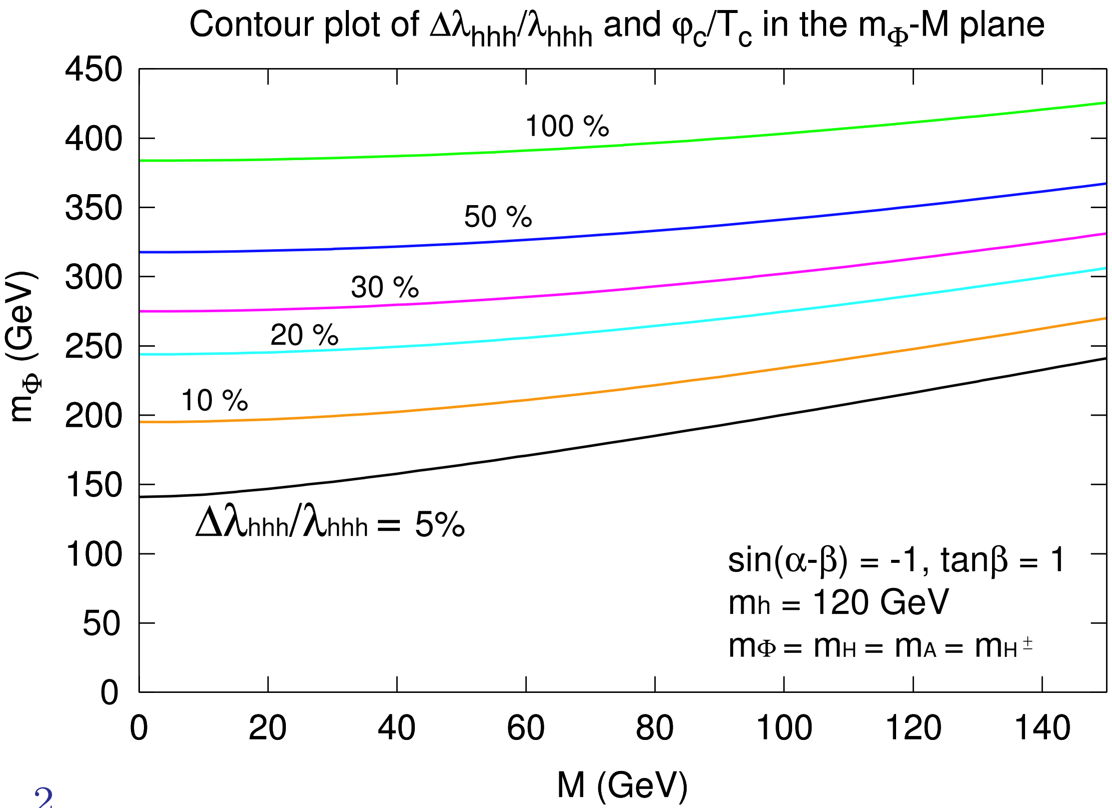
$$\lambda_{hhh} \sim -\frac{3m_h^2}{v}\left[1 + \frac{c}{12\pi^2}\frac{m_\Phi^4}{m_h^2 v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\right] \quad (\Phi = H, A, H^{\pm})$$

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

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

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



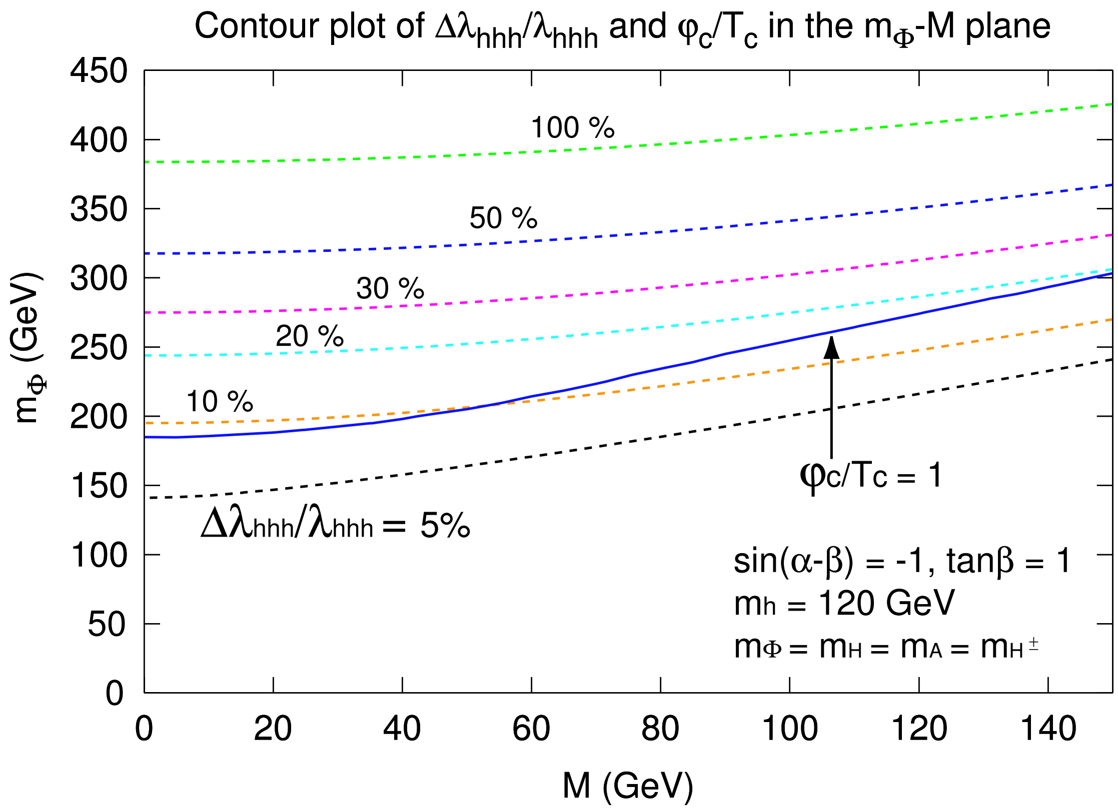
For $m_\Phi^2 \gg M^2, m_h^2$,

- Deviation of λ_{hhh} coupling from the SM value becomes large.
- O(100)% deviation is allowed under the theoretical and present experimental constraints. (vacuum stability, perturbative unitarity, ρ parameter)

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.]



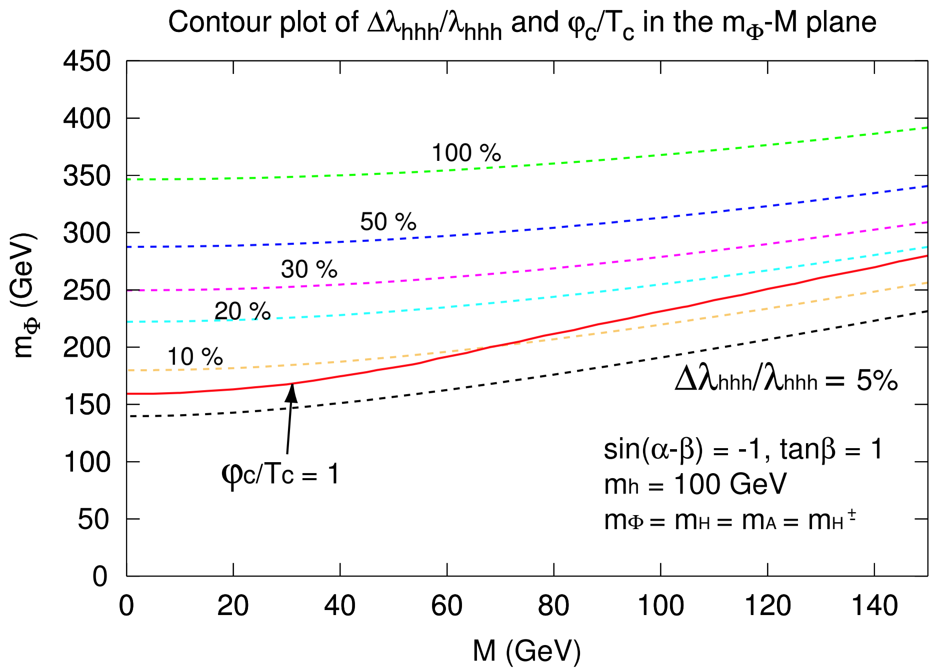
For $m_\Phi^2 \gg M^2, m_h^2$,

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

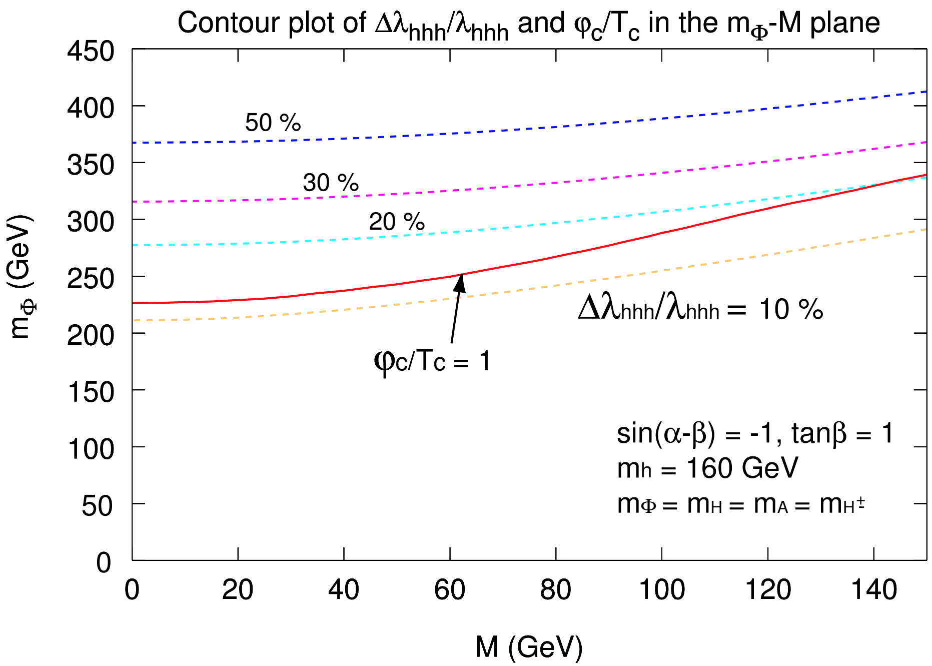
Contour plots of $\Delta\lambda_{hhh}/\lambda_{hhh}$ and φ_c/T_c in the m_Φ-M plane

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

$m_h = 100$ GeV



$m_h = 160$ GeV



The correlation between φ_c/T_c and $\Delta\lambda_{hhh}/\lambda_{hhh}$ is almost same as $m_h = 120$ GeV case. $\Delta\lambda_{hhh}/\lambda_{hhh} \gtrsim 10\%$

cf. In the SM with a low cutoff: $\Delta\lambda_{hhh}/\lambda_{hhh} \sim \mathcal{O}(100)\%$

[C. Grojean, G. Servant, J. Wells, PRD71('05)]

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 makes 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 [Hollik et al, PRD66('02)]

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

$\dfrac{\varphi_c}{T_c} = \dfrac{2E}{\lambda_{T_c}} \gtrsim 1$ gives

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

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

Summary

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

In the 2HDM

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

- 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

$\Delta\lambda_{hhh}/\lambda_{hhh} \gtrsim$ several %

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

EW baryogenesis

⇓

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

⇓

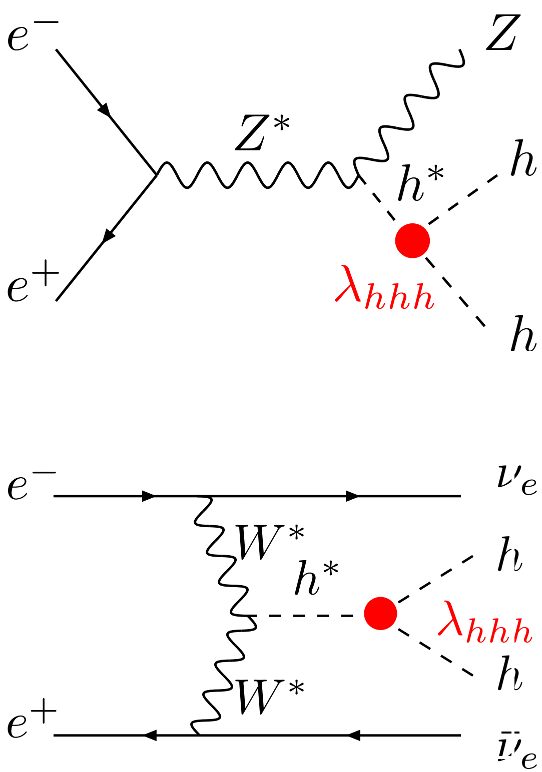
Large loop correction to the λ_{hhh} coupling — $V_{\text{eff}}(\varphi, 0)$

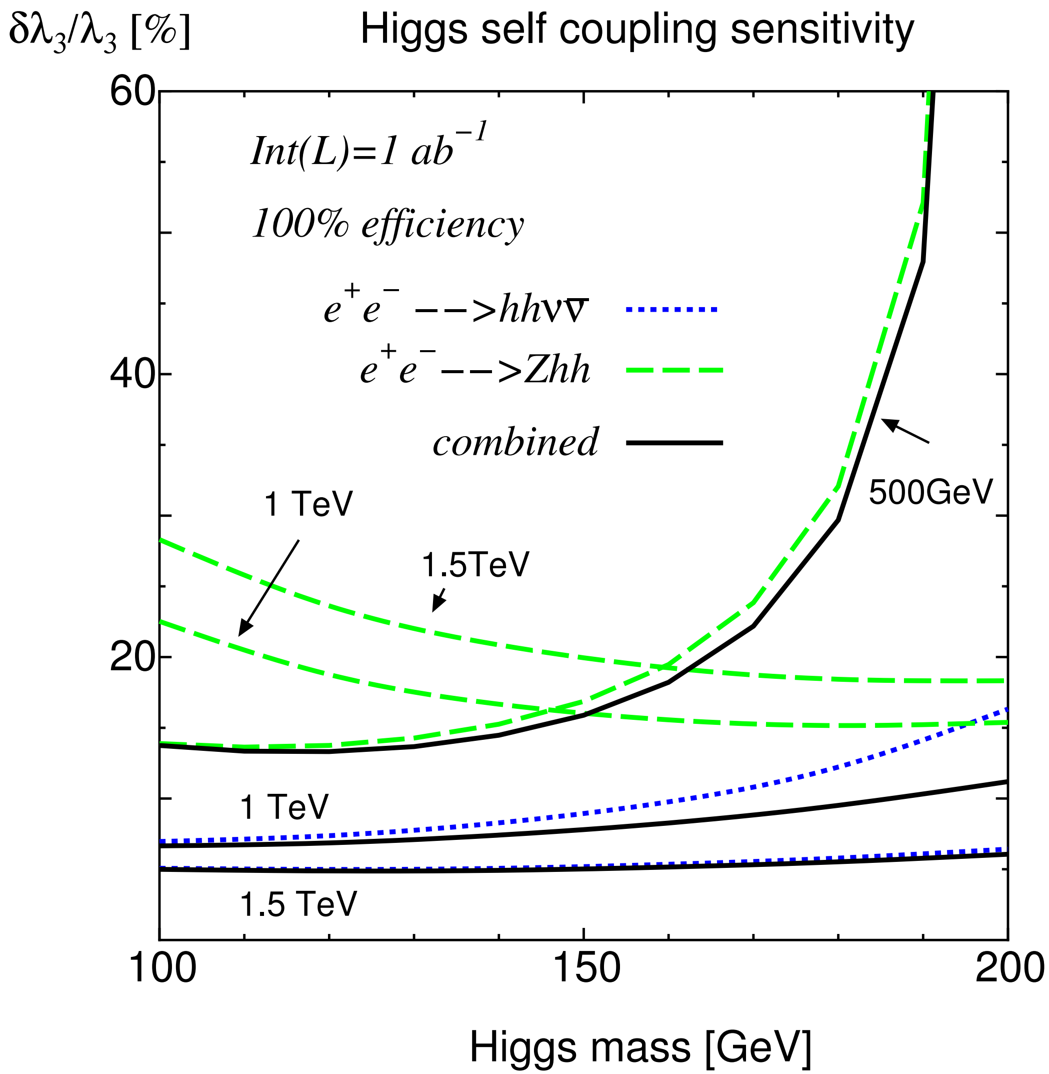
⇓

Measurement of λ_{hhh} @ILC

Sensitivity of the hhh coupling at Linear Colliders

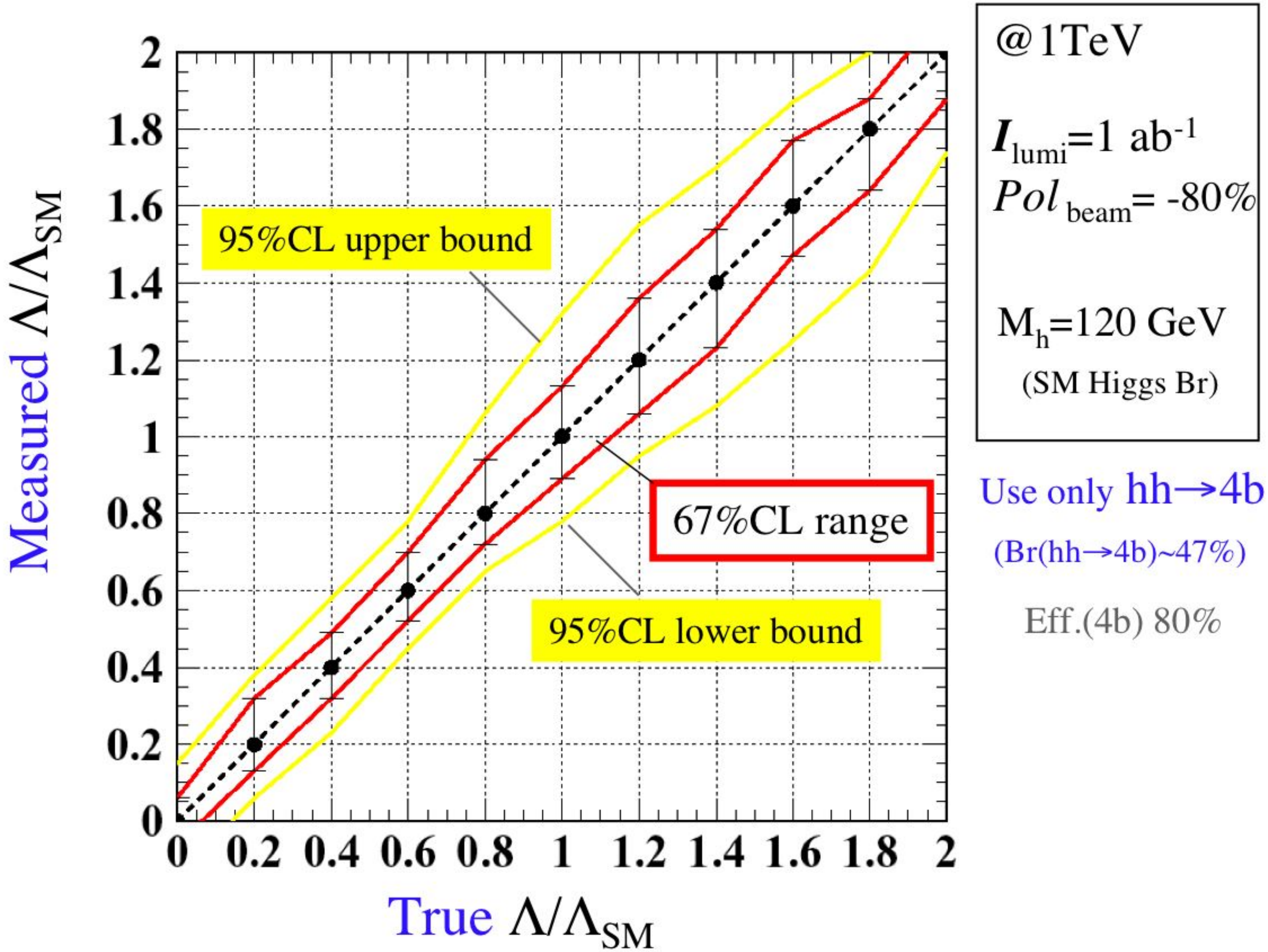
hhh





[Y.Yasui et al ACFA WG]

Sensitivity of the hhh coupling at Linear Colliders



Use only hh→4b

(Br(hh→4b)~47%)

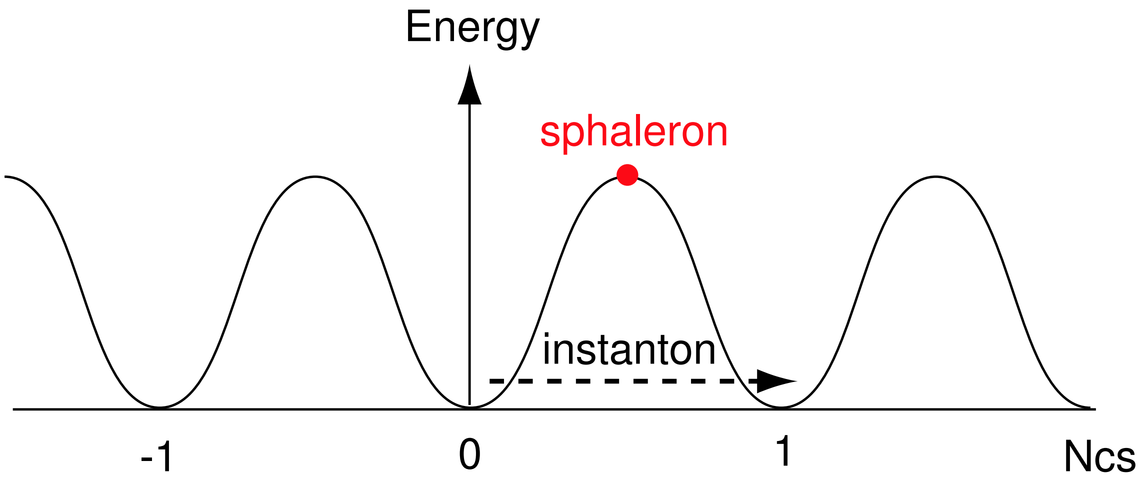
Eff.(4b) 80%

[S.Yamashita et al ACFA WG]

Sphaleron process

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

[Manton, PRD28 ('83)]



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

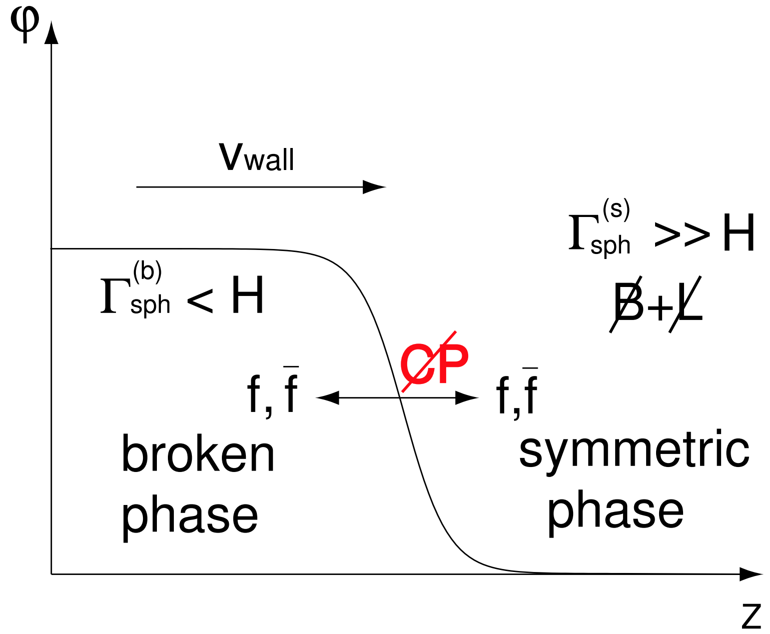
- Transition rate

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

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

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 $T \lesssim T_c$:

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

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

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

Magnitude of the self-couplings λ_i