Electroweak Baryogenesis and Quantum Corrections to the Triple Higgs Boson Coupling

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Outline

- BAU: Baryon Asymmetry of Universe
- Electroweak Baryogenesis
- EWBG cannot be consistent in the SM
- Viable models
  - those with extended Higgs sectors, new CPV sources, specific particle mass spectrum, ………
  - MSSM, NMSSM, 2HDM, models with dim 6 operators, …..
- What is the collider signature for each EWBG scenario at LHC/LC?
  - Higgs physics
  - New physics particle property, CP …

Outline (cont.)

- Here,
  - I will discuss the connection of the successful EWBG scenario to the collider physics in simple models (2HDM, MSSM).
- The condition for strong 1st order EWPT.
  - a constraint on the effective potential at finite temperature
  - Correlation to the effective potential at T=0

$$\boxed{V_{eff}(\phi) \leftrightarrow V_T(\phi, T)}$$

  - Deviation on the Higgs coupling from its SM value, which is detectable at a LC
- Summary

BAU

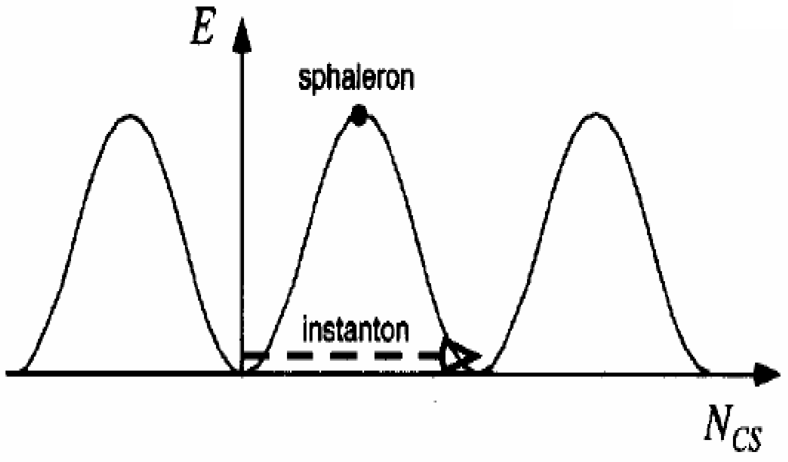
- Baryogenesis $n_B/s = 10^{-11} - 10^{-10}$
- Sakharov's 3 conditions:
  - Baryon number violation
  - C, and CP violation
  - Departure from thermal equilibrium
- Scenarios for baryogenesis
  - B-L generation above the EW phase transition (Leptogenesis, etc).
  - B+L gen. at the EW phase transition. (EWBG)
- EWBG can in principle be tested at collider experiments
  - EW phase transition
  - CP violation

$$\boxed{V_{eff}(\phi) \leftrightarrow V_T(\phi, T)}$$

Electroweak Baryogenesis

- In the electroweak theories, B+L violation is enhanced at high temperatures. (Weak sphaleron interaction)

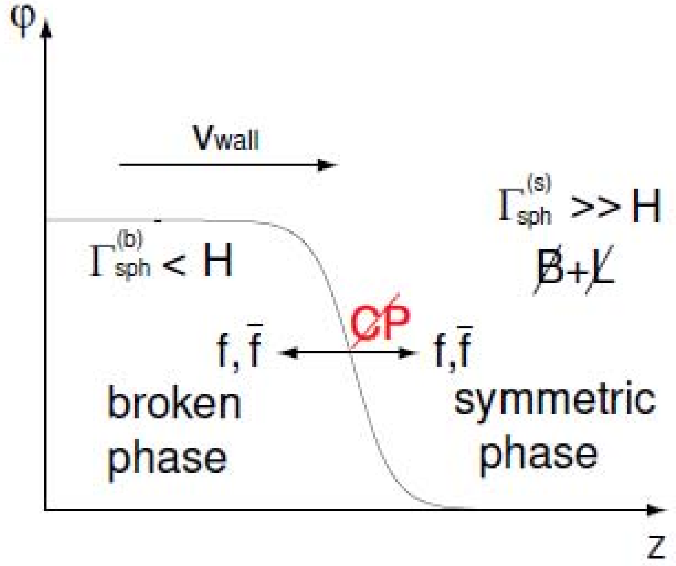
$$B(t_f) - B(t_i) = \frac{N_f}{32\pi^2}\int_{t_i}^{t_f} d^4x \left[g^2 \mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right]$$
$$= N_f\left[N_{CS}(t_f) - N_{CS}(t_i)\right],$$



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

$$E_{sph} = \frac{2M_W}{\alpha_W} B\left(\frac{\lambda}{g^2}\right)$$

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

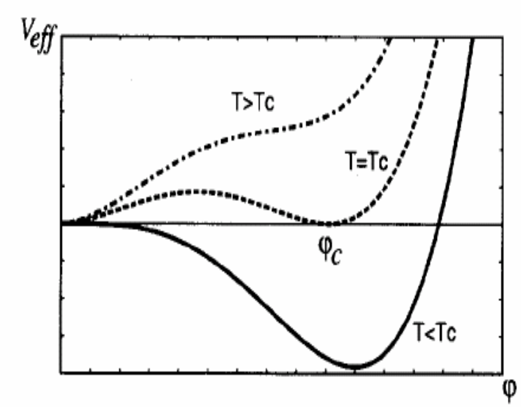
$\Downarrow$

- Decoupling of sphaleron process in the broken phase

- **Strongly 1st order phase transition**

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

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



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** $(a^2 \ll 1)$

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

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

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

Finite temperature effective potential

Description using high temperature expansion (T>>m)

$$V_T(\phi,T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + ...$$

$$\phi_c \simeq 2ET_c/\lambda_{T_c} \qquad \phi_c/T_c > 1 \Rightarrow 2E/\lambda_{T_c} > 1$$

In the SM, the coefficient of the cubic term

$$E(SM) \simeq \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) \qquad \lambda_T \simeq m_h^2/2v^2$$

$$m_h < 45 \text{ GeV}$$

inconsistent with current data $m_h > 114$ GeV

By new physics contributions, larger m_h is possible

$$E = E(SM) + (\text{new phys. contribution})$$

EWBG in the extension of the SM

$$E = E_{SM} + (\text{new phys. contribution})$$

For strong first order EWPT,

- Additional bosonic loop contribution with non-decoupling property (fermion contribution is less important)
  - MSSM — C.Balazs,M.Carena,A.Menon,D.E.Morrissey, C.E.M.Wagner 2005
  - 2HDM — A.Nelson, D.B.Kaplan, A.G.Cohen, 1991, M.Joyce, T.Prokopec,and N.Turok 1991; J.M.Cline,K.Kainulainen,A.P.Vischer, 1996

Modification of tree level potential

- SM+U(1)’ — J.Kang, P.Langacker,T.Li, T.Liu,2005
- SM with dim6 operators — D.Bodeker,L.Fromme,S.J.Huber,M.Seniuch,2005
- NMSSM

Non-decoupling effect

- Mass of a boson (stop, extra Higgs, ..): $m_\phi^2 = \lambda v^2 + M^2$.
- When $\lambda v^2 << M^2$, loop contribution of ϕ to the effective potential decouples in the large large M limit. (decoupling limit)
- When $\lambda v^2 > M^2$, so that large mass of ϕ comes from λv^2, the loop contribution becomes proportional to a positive power of m_ϕ.
  - Large contribution to the cubic term of $V(\phi,T)$. (successful baryogenesis)
  - Such a non-decoupling effect on $V(\phi,T)$ also give large correction to the effective potential at T=0, $V(\phi)$.

Phenomenological consequence of the strong first order EWPT

- EWBG requires a large correction to the finite temperature effective potential
- Such a non-decoupling effect of new particles also affects the effective potential at T=0.
- Prediction on the triple Higgs boson coupling.
- We demonstrate this connection in 2HDM and MSSM. S.K., Y. Okada, E.Senaha, 2004

Cf. An extension to quartic coupling, S.W. Ham and S.K.Oh, 2005

A similar connection in the model with a dim-6 Higgs potential term, C.Grojean,G.Servant, J.D.Wells, 2004

2HDM

Higgs potential

$$V_{2\mathrm{HDM}} = m_1^2 |\varphi_1|^2 + m_2^2 |\varphi_2|^2 - m_3^2 \left(\varphi_1^\dagger\varphi_2 + \varphi_2^\dagger\varphi_1\right) + \frac{\lambda_1}{2}|\varphi_1|^4 + \frac{\lambda_2}{2}|\varphi_2|^4$$
$$+\lambda_3 |\varphi_1|^2 |\varphi_2|^2 + \lambda_4 \left|\varphi_1^\dagger\varphi_2\right|^2 + \frac{\lambda_5}{2}\left\{\left(\varphi_1^\dagger\varphi_2\right)^2 + \left(\varphi_2^\dagger\varphi_1\right)^2\right\},$$

Physical Higgs bosons: $h, H, A, H^{\pm}$

Two cases

Heavy Higgs boson masses

$$m_\Phi^2 \simeq M^2 + \lambda_i v^2$$

$$M = m_3 / \sqrt{\cos\beta \sin\beta}$$

$$\tan\beta = <\phi_2> / <\phi_1>$$

(1) Decoupling case: $M^2 \gg 0(\lambda_i v^2)$

(2) Non-decoupling case $M^2 \leq O(\lambda_i v^2)$

Finite temperature Higgs potential

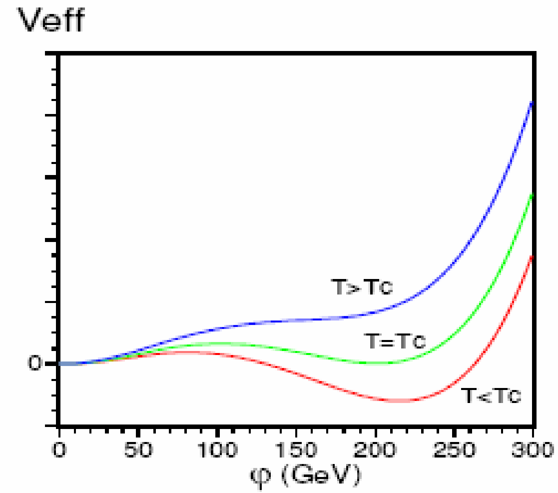
For $m_\Phi^2(v) \gg M^2, m_h^2(v)$ $\qquad m_\Phi^2(\varphi) \simeq m_\Phi^2(v)\frac{\varphi^2}{v^2}, \quad (\Phi = H,\ A,\ H^\pm)$

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

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



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

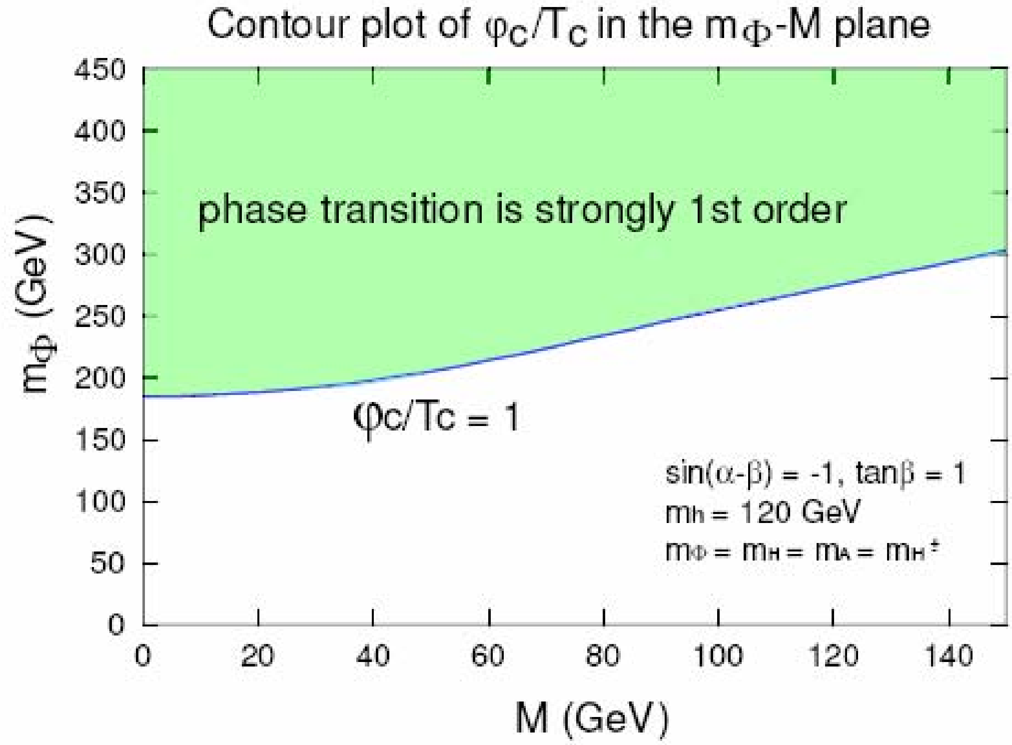
- **Strongly 1st order phase transition:** $\dfrac{\varphi_c}{T_c} \gtrsim 1$

$\Rightarrow$ 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

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

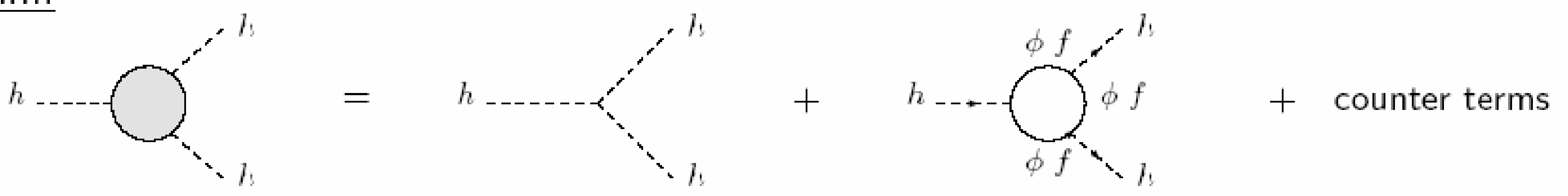
Strongly 1st order phase transition is possible due to the loop effect of the heavy Higgs bosons (φ^3-term is effectively large)

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

Radiative corrections to hhh coupling constant

[S.K., S. Kiyoura, Y. Okada, E. Senaha, C.-P. Yuan PLB'03]

- hhh



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

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

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

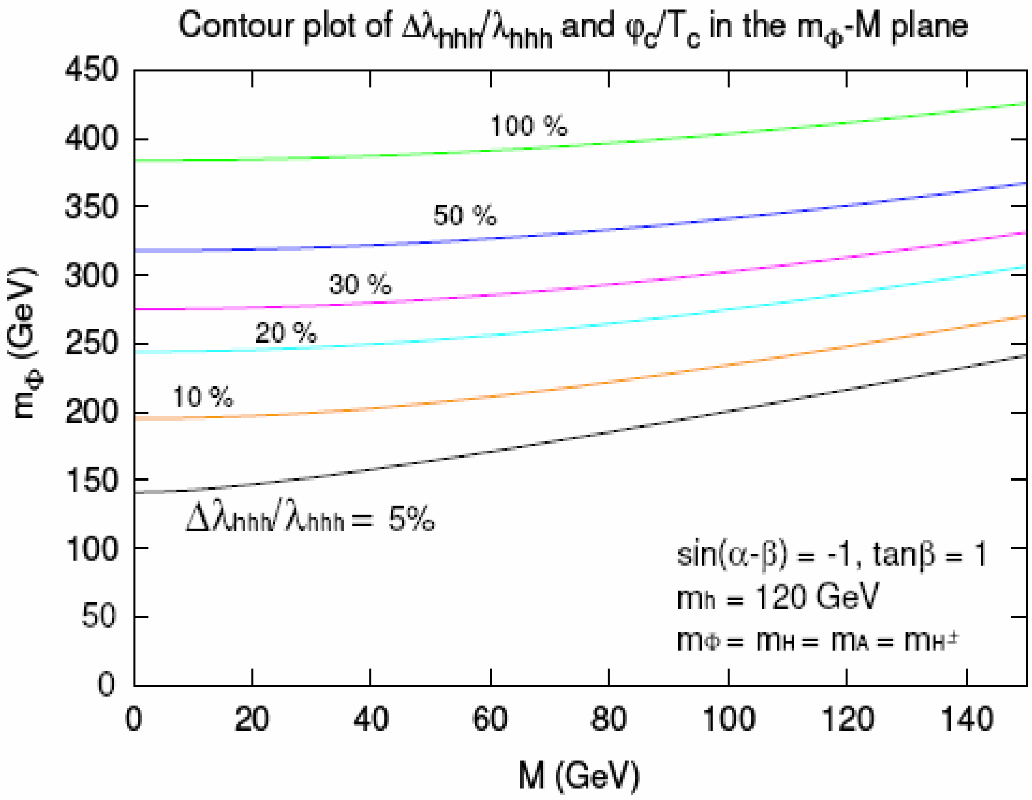
$$\lambda_{hhh} \sim -\frac{3m_h^2}{v}\left[1 + \frac{c}{12\pi^2}\frac{m_\Phi^4}{m_h^2 v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\right] \quad (\Phi = H, A, H^\pm)$$

($c = 1$ 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 $\Delta\lambda_{hhh}/\lambda_{hhh}$ in the m_Φ-M plane

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

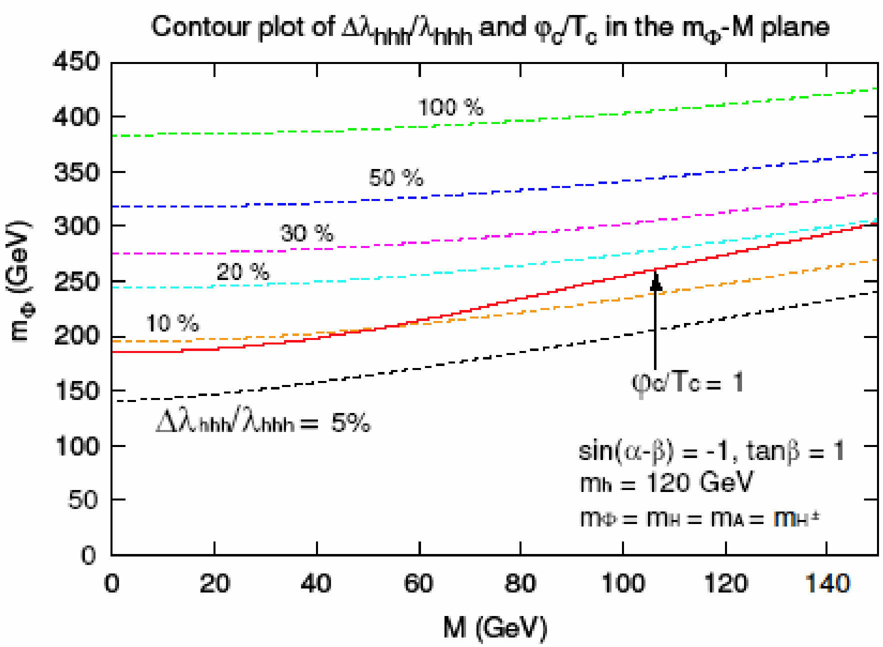


For $m_\Phi^2 \gg M^2, m_h^2$,

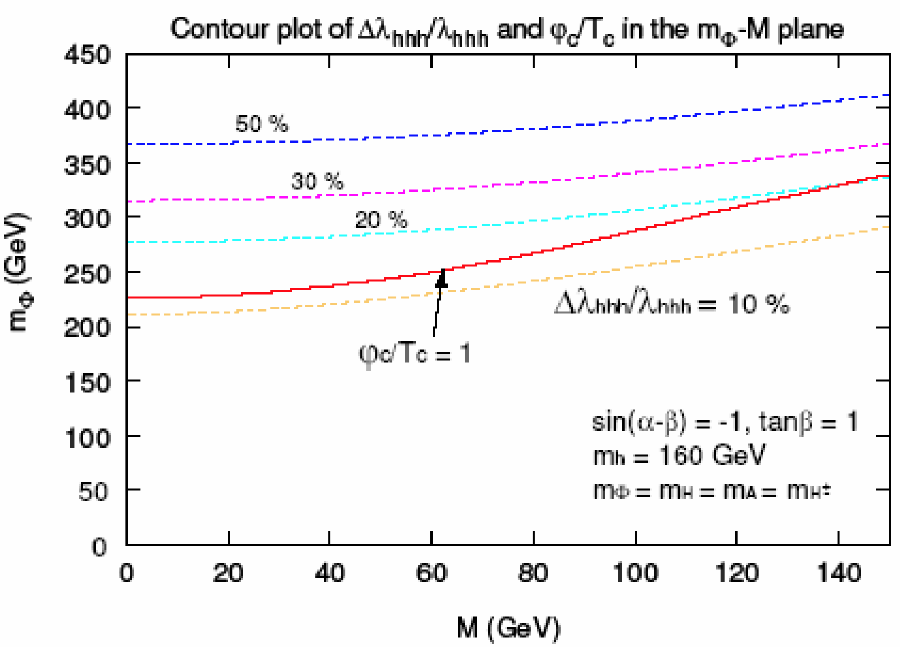
- Deviation of the hhh coupling constant from SM value becomes large.

Numerical results on radiative correction to the hhh coupling (not using high temp expansion)

mh= 120 GeV



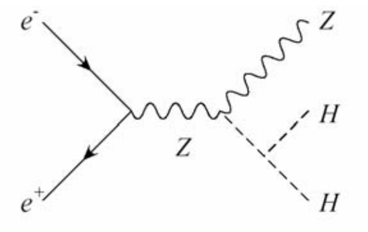
mh= 160 GeV

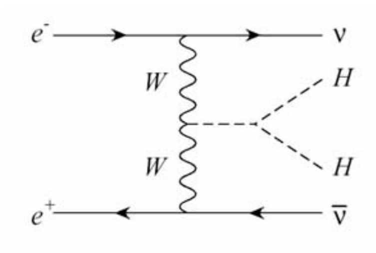


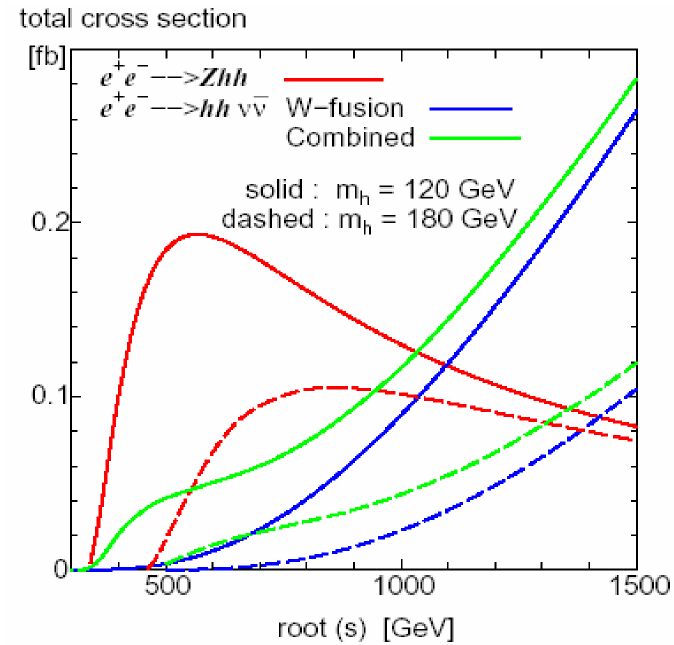
If we require the strong first order phase transition for EWBG,

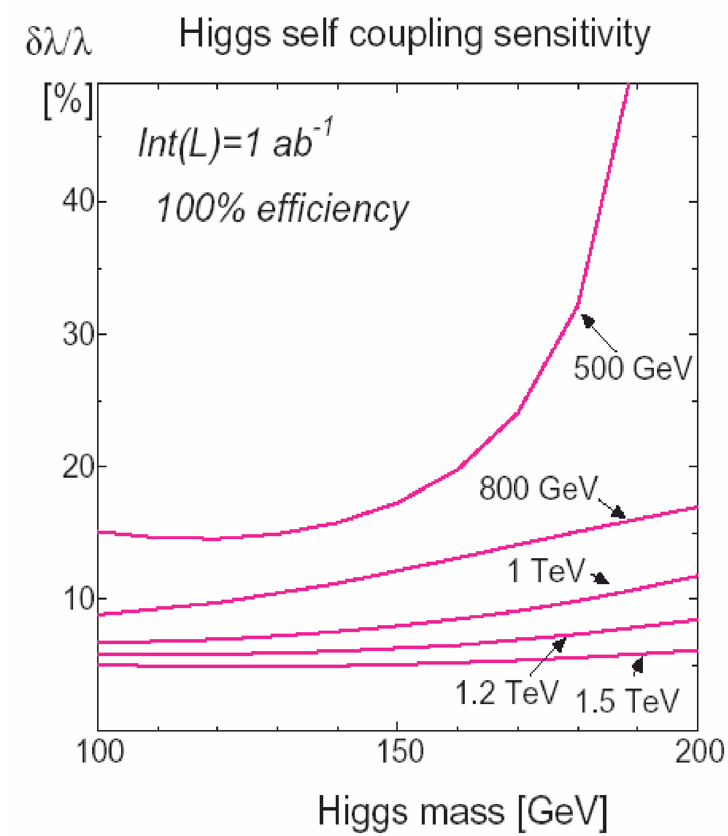
$$\Delta\lambda_{hhh}/\lambda_{hhh} \gtrsim 10\%$$

Measurement of the hhh coupling at ILC









For mh=120GeV, hhh is expected to be measured with about 10 %

At LHC, for 150<mh<180GeV: several 100% Baur et al.

ACFA Higgs WG

Expected efficiency is 40 %,
S.Yamashita et.al, LCWS 04.

We need ILC to test the EWBG scenario.

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?

- 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

$$\frac{\Delta\lambda_{hhh}(\mathrm{MSSM})}{\lambda_{hhh}(\mathrm{SM})} \sim \mathcal{O}(10\%)$$

In the MSSM, the condition of strong first order phase transition also predicts to large quatum correction to the hhh coupling

Summary

- Electroweak baryogenesis provides an important connection between cosmology and collider physics.
- Baryon number generation at the EWPT requires new physics related to the Higgs sector.

  Ex. Correction to the Higgs potential, new particles with a sizable interaction to the Higgs field
- The successful scenarios for EWBG can be tested by measuring the triple Higgs boson coupling.
- Separation of each EWBG scenario can also be done by exploring new particles/interactions including possible new sources of CP violation. (depend on details of scenario)
- ILC will play an important role to do it.

  (Ex. LHC cannot measure the hhh coupling accurately.)

Electroweak Baryogenesis in MSSM

- Light right-handed stop (m(stop) < m(top)) is required for the strong 1st order phase transition

$$\phi_c/T_c = 2E/\lambda_{T_c}$$

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) + \Delta E_{\tilde{t}_1}$$

$$\Delta E_{\tilde{t}_1} \sim \frac{m_t^3}{2\pi v^3}(1 - \frac{|A_t + \mu \cot\beta|^2}{M_Q^2})^{3/2}$$

- Sources of new CP violation
  Stop A term (At)
  chargino/neutralino mass matrixes (μ parameter)

Chargino effect turns out to be dominant source of the baryon number generation

Required mass spectrum

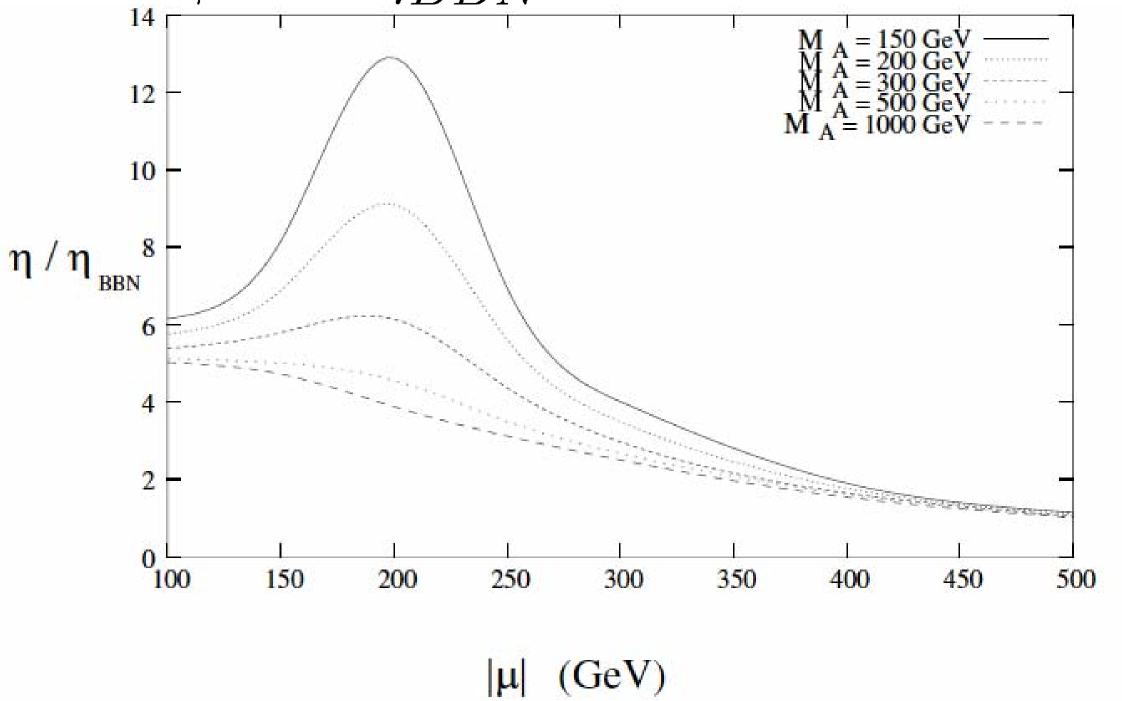
Right-handed stop (<top mass)   LSP neutralino Chargino (< ~ 200 GeV)

Left-handed stop should be multi TeV (precision EW and Higgs mass constraints)

Numerical results on baryon number

$$\frac{n_B}{n_\gamma} = \left(\frac{\eta}{\eta_{BBN}} \sin\phi_\mu\right) \times \eta_{BBN}$$

$$M_2 = 200 \text{ GeV}$$
$$\tan\beta = 5$$



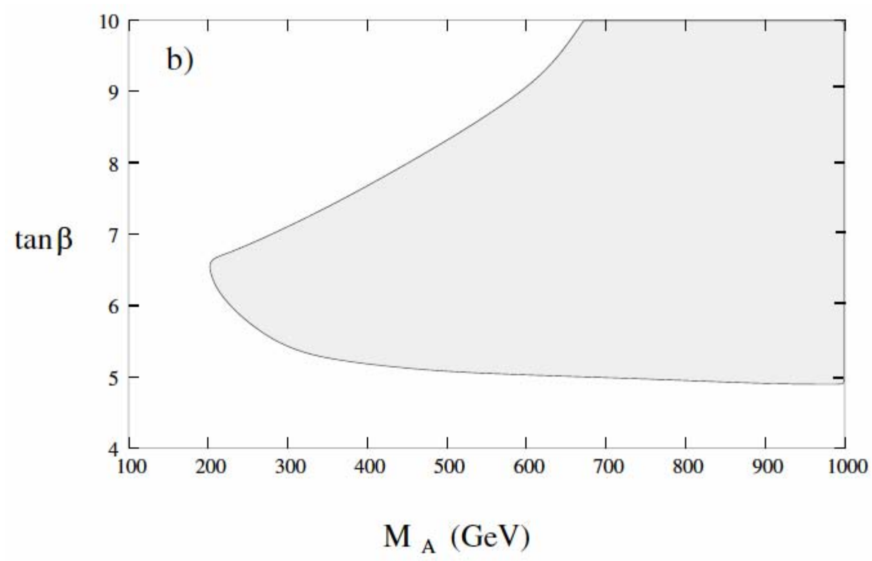
C.Balazs,M.Carena,A.Menon,D.E.Morrissey, C.E.M.Wagner 2005

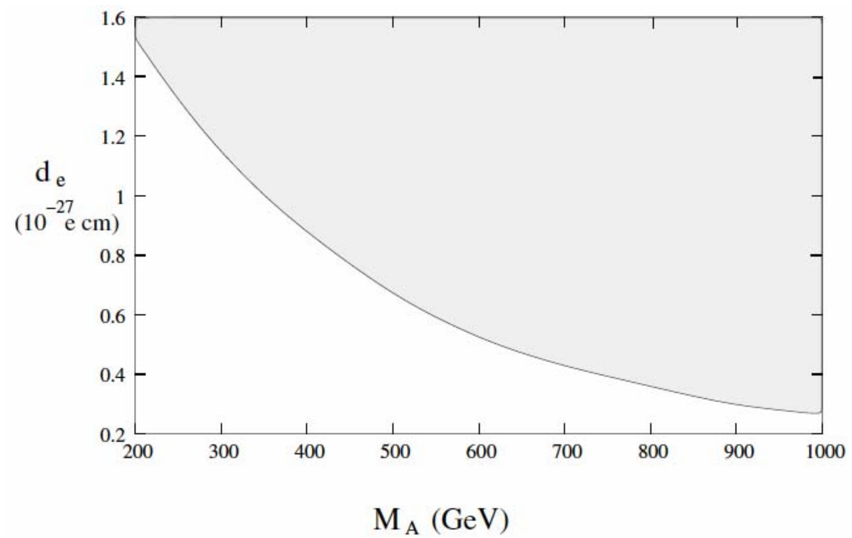
Parameter space allowed by EWBG and EDM

- Phenomenological impacts

Light right-handed stop whose mass is close to LSP neutralino.
Light chargino/neutralino with a complex phase of sin ϕ_μ >0.1
=> ILC physics

EDM closed to the present bounds





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