Measurement of Higgs self-coupling and Electroweak Baryogenesis

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§1. Introduction

Higgs physics at colliders

- LEP SM Higgs $\Rightarrow 114$ GeV $\leq M_h \leq 251$ GeV (95% CL)
- Tevatron(@work), LHC(2007)
  Mass, Width, etc (extra Higgs bosons)

- Linear Collider(future plan) precision measurements
  -Higgs couplings to gauge bosons and fermions (mass generation)
  $\frac{\Delta g_{hVV}^{\rm exp}}{g_{hVV}} = \mathcal{O}(1)\%, \quad \frac{\Delta g_{hf\bar{f}}^{\rm exp}}{g_{hf\bar{f}}} =$ (a few-several) $\%$ ACFA Report, TESLA TDR

  - Higgs self-coupling (Shape of Higgs potential)
  $\frac{\Delta \lambda_{hhh}^{\rm exp}}{\lambda_{hhh}} \sim \mathcal{O}(10-20)\%$ Battaglia et al, ACFA Higgs WG

Connections between collider physics and cosmology

What will be impact of collider physics on cosmolgy?

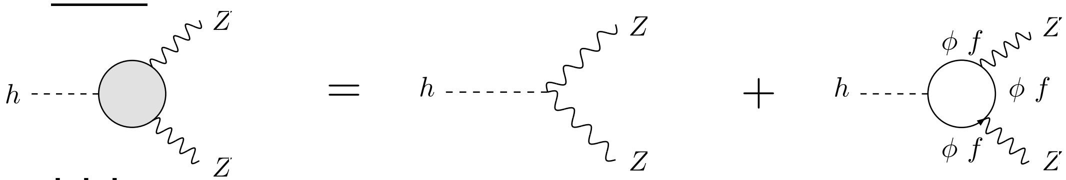
- Baryon Asymmetry of the Universe
- Dark Matter

<u>Plan of this talk</u>

We consider the connection between collider physics and comology

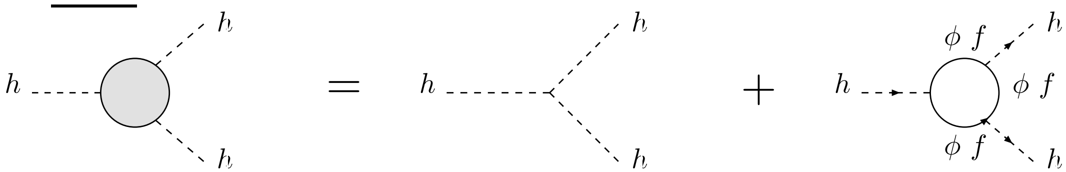
Part 1 Radiative corrections to ZZh and hhh couplings (§2)

- <u>ZZh</u>



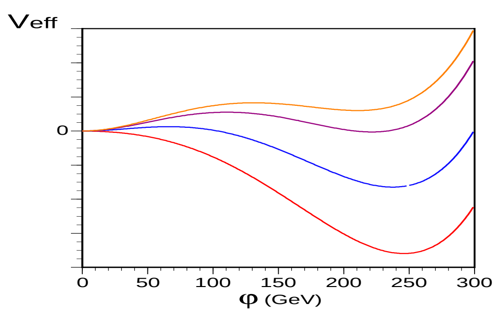
$+$ counter terms

- <u>hhh</u>



$+$ counter terms

Part 2 Electroweak phase transition (EWPT) (§3)



- Study of EWPT is important for electroweak baryogenesis scenario.

Correlation: $\lambda_{hhh} \iff$ EWPT

§2. Radiative corrections to hhh and hVV couplings

• THDM is a simplest extension of the MSM Higgs sector for various theoretical motivations. (extra CP phase, SUSY, Little Higgs etc)

Higgs potential

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

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

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

Yukawa interaction

$$\textbf{Type I}: \quad \mathcal{L}_{\text{Yukawa}}^{I} = \bar{q}_L f_1^{(d)}\Phi_1 d_R + \bar{q}_L f_2^{(u)}\tilde{\Phi}_1 u_R + \bar{l}_L f_1^{(e)}\Phi_1 e_R + \text{h.c.},$$

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

- Independent parameters

h, H, A, $H^{\pm}$, CP-even, CP-odd and charged Higgs
α: mixing angle beween h and H,
$\tan\beta = v_2/v_1$, $(v{=}\sqrt{v_1^2+v_2^2}\sim$246 GeV)
$M_{\text{soft}} = \frac{m_3}{\sqrt{\sin\beta\cos\beta}}$, (soft-breaking scale of the discrete symmetry)

Mass formulae of the Higgs bosons

In the THDM there are two origins of masses.

$$
\begin{aligned}
m_h^2 &= v^2\left[\lambda_1\cos^4\beta + \lambda_2\sin^4\beta + \frac{\lambda_{345}}{2}\sin^2 2\beta\right] + \mathcal{O}(\frac{v^2}{M_{\text{soft}}^2}),\\
m_H^2 &= M_{\text{soft}}^2 + v^2(\lambda_1+\lambda_2-2\lambda_{345})\sin^2\beta\cos^2\beta + \mathcal{O}(\frac{v^2}{M_{\text{soft}}^2}),\\
m_A^2 &= M_{\text{soft}}^2 - \lambda_5 v^2,\\
m_{H^\pm}^2 &= M_{\text{soft}}^2 - \frac{1}{2}(\lambda_4+\lambda_5)v^2, \qquad (\lambda_{345} = \lambda_3+\lambda_4+\lambda_5)
\end{aligned}
$$

$$
m_\phi^2 = M_{\text{soft}}^2 + \lambda_i v^2, \qquad (\phi = H,\ A,\ H^\pm)
$$

tree-level

$$g_{ZZh}^{\text{tree}} = -\frac{2m_Z^2}{v}\sin(\alpha - \beta),$$

$$\lambda_{hhh}^{\text{tree}} = -\frac{3}{2v\sin 2\beta}\Big[\Big\{\cos(3\alpha - \beta) + 3\cos(\alpha + \beta)\Big\}m_h^2 - 4\cos^2(\alpha - \beta)\cos(\alpha + \beta)M_{\text{soft}}^2\Big]$$

- $\sin^2(\alpha - \beta) = 1$ (SM-like limit)

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

$$g_{ZZh}^{\text{tree}} = \frac{2m_Z^2}{v} = g_{ZZh}^{\text{tree}}(\text{SM}), \qquad \lambda_{hhh}^{\text{tree}} = -\frac{3m_h^2}{v} = \lambda_{hhh}^{\text{tree}}(\text{SM})$$

$\Longrightarrow$ Loop correction is essentially important.

- $\sin^2(\alpha - \beta) = 1 - \delta$

Deviation from the SM value

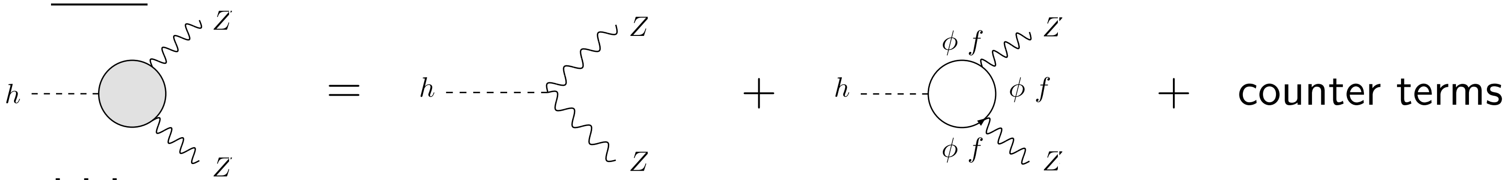
Tree level $+$ 1-loop level

- Especially we are interested in a small δ

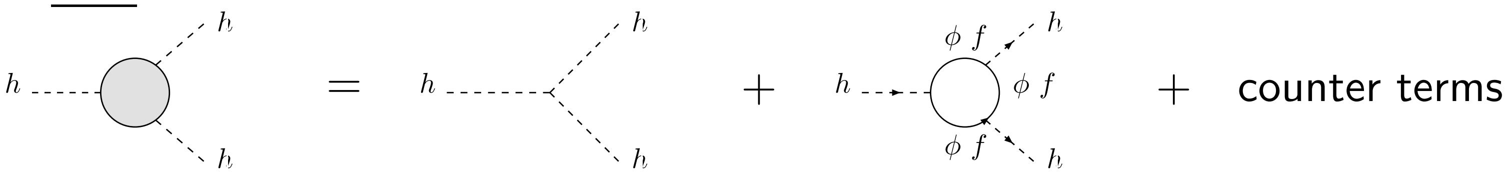
Radiative corrections to ZZh and hhh couplings in the THDM

We calculated one-loop corrections of heavy Higgs bosons in the on-shell scheme.

- <u>ZZh</u>



- <u>hhh</u>



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

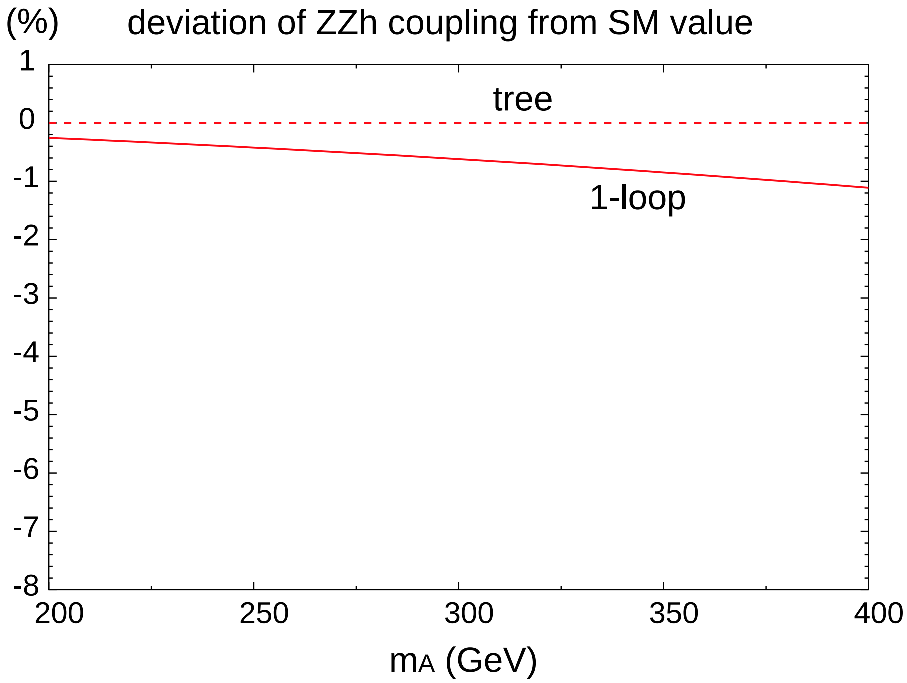
- $\sin^2(\alpha - \beta) = 1$

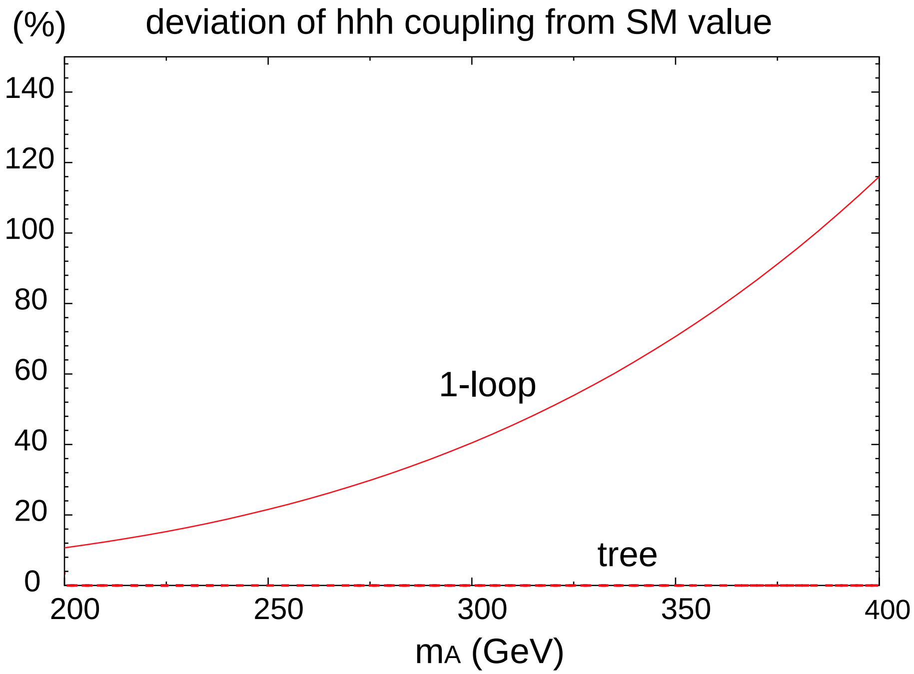
$$g_{ZZh} \sim \frac{2m_Z^2}{v}\left[1 - \frac{c}{16\pi^2}\frac{m_\phi^2}{6v^2}\left(1 - \frac{M_{\text{soft}}^2}{m_\phi^2}\right)^2\right],$$

$$\lambda_{hhh} \sim -\frac{3m_h^2}{v}\left[1 + \frac{c}{16\pi^2}\frac{m_\phi^4}{m_h^2 v^2}\left(1 - \frac{M_{\text{soft}}^2}{m_\phi^2}\right)^3\right]$$

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

Deviation from the SM values $[\sin^2(\alpha-\beta)=1]$





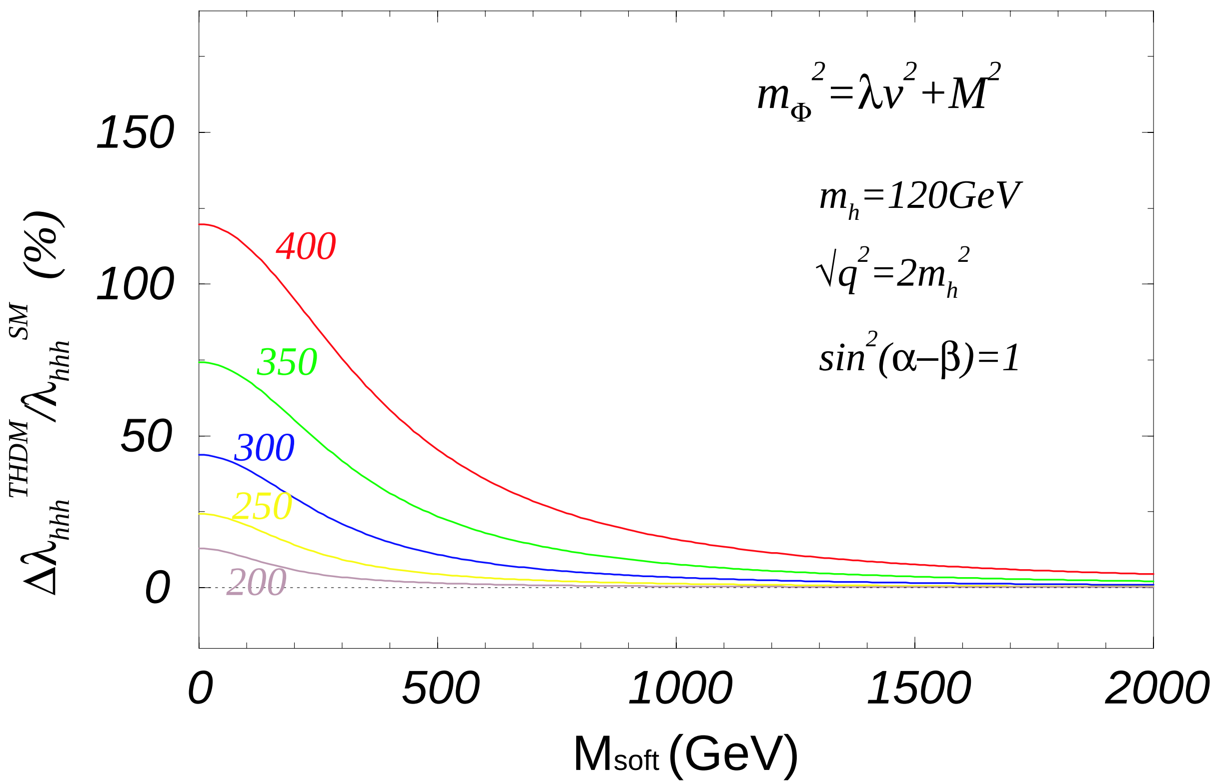
$M_{\text{soft}}=0$ $\quad \sin^2(\alpha-\beta)=1,\ \tan\beta=1,\ m_h=120$ GeV,

$m_A=m_H=m_{H^\pm}, \Rightarrow \rho\approx 1$

- Radiative corrections to g_{ZZh} is $\mathcal{O}(1\%)$ $\Longleftarrow$ m_ϕ^2 corrections
- Radiative corrections to λ_{hhh} is $\mathcal{O}(30\text{-}100\%)$ $\Longleftarrow$ m_ϕ^4 corrections

$$\left|\frac{\Delta\lambda_{hhh}}{\Delta g_{ZZh}}\right| = 6\frac{m_\phi^2-M_{\text{soft}}^2}{m_h^2}. \quad \text{(enhancement factor)}$$

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



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

- $M_{\text{soft}} \lesssim \lambda_i v$ non-decoupling case
  Large loop corrections can be occurred due to Heavy Higgs bosons.

Scan analysis $\sin^2(\alpha - \beta) \neq 1$

Even at the tree-level, there are the deviation from the SM value due to mixing effect.

- Where does the deviation mainly come from? tree-level vs 1-loop.
- Can we distinguish them?

We scan the parameters but $M_{\rm soft}$ and $\delta(= 1 - \sin^2(\alpha - \beta))$ are fixed.
Parameters constrained by

- LEP precision data (S,T)
- Perturbative unitarity Lee, Quigg, Thacker (SM)

  Kanemura, Kubota, Takasugi (THDM)

$|a_0(W_L^+ W_L^- \to W_L^+ W_L^-)| < \frac{1}{4}$

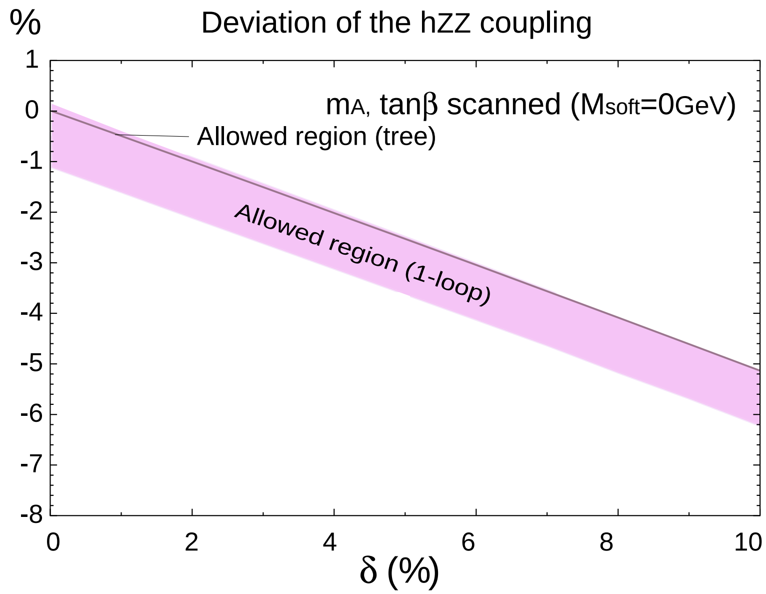
(channel $W_L^+ W_L^-, Z_L Z_L, hh, Zh, \ldots$)

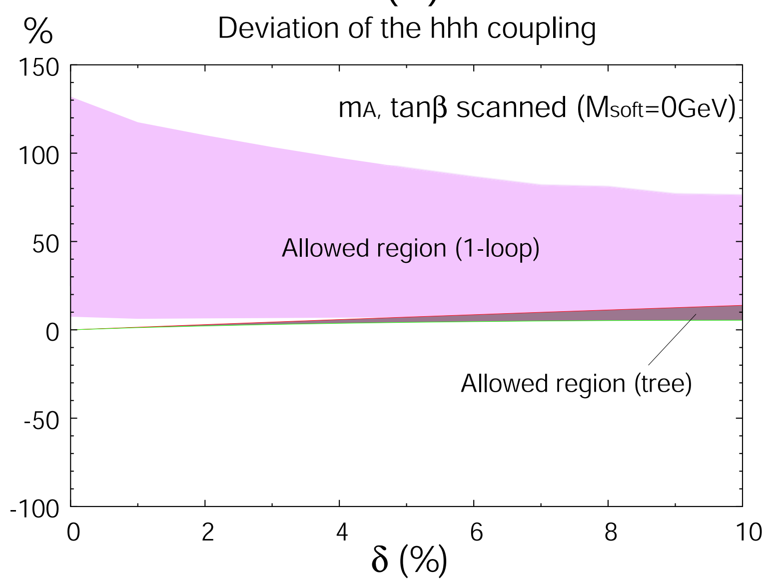
- Vacuum stability Deshpande, Ma; Sher

V($\langle \Phi_i \rangle$)≥ 0 for $\langle \Phi_i \rangle \to \infty$.

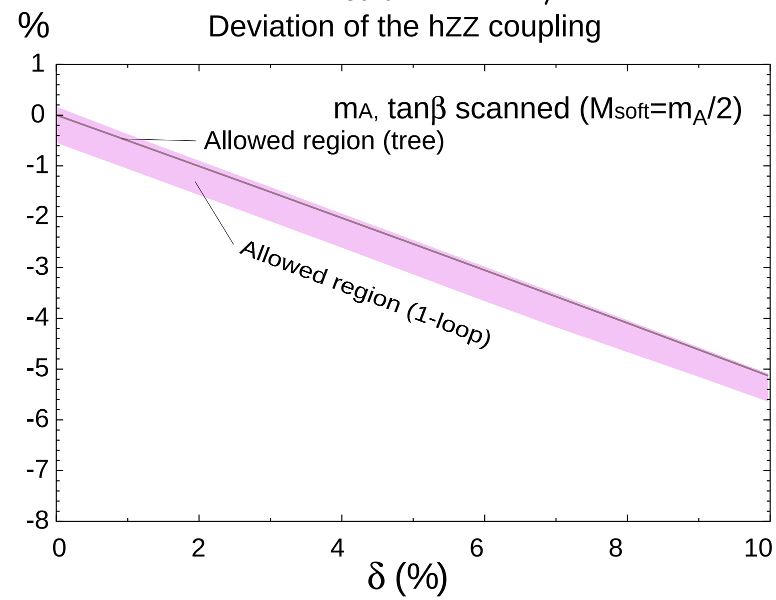
Allowed reigion of the deviation from the SM value ($m_A \tan\beta$ scanned)

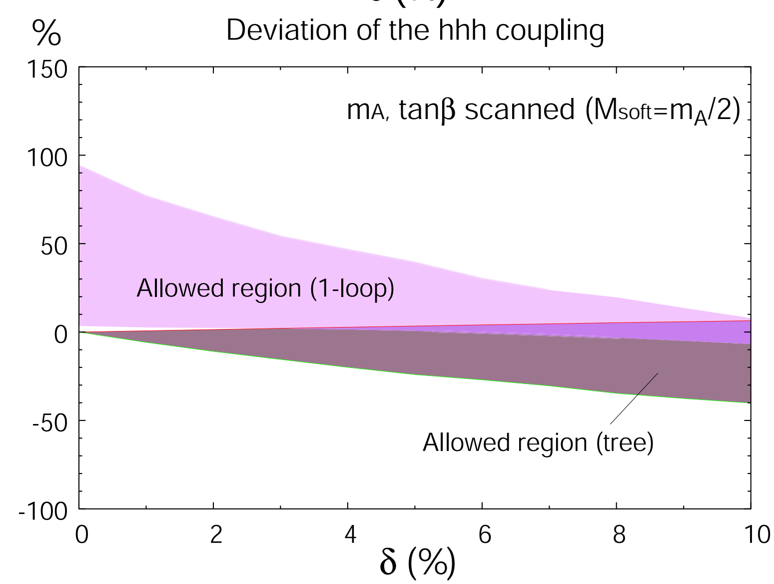
$M_{\text{soft}} = 0$





$M_{\text{soft}} = m_A/2$





Summary of part 1

ZZh coupling

- The deviation of ZZh coupling mainly comes from mixing effects at the tree-level.
- Corrections due to Heavy Higgs loop are $\mathcal{O}(1\%)$.

hhh coupling

- The deviation at the tree-level are negative (30-90%) for the most of M_{soft}.
- Loop effects of Heavy Higgs are positive (30-100%) (non-decoupling effect)

The region in the positive direction which is not allowed at the tree-level can appear at the 1-loop level.

§3. Electroweak phase transition in the THDM

Baryon Asymmetry of the Universe

$$\frac{n_B}{s} \equiv \frac{n_b - n_{\bar{b}}}{s} \simeq (0.37 - 0.88) \times 10^{-10}$$

3 requirements for generation of the BAU staring from B-sym universe.

1. baryon number violation
2. C and CP vlolation
3. departure from equilibrium

Two scenarios

(1) B-L generation above the EWPT (Leptogenesis, etc)

(2) Baryogenesis at the EWPT

-based on a testable model $\Longleftrightarrow$ connection to collider physics

Electroweak Baryogenesis

- B violation   sphaleron process
- C violation   chiral gauge interations
- CP violation   KM phase and beyond the SM
- out of equilibrium   1st order phase transition

MSM was excluded due to

$$\begin{cases} \text{2nd order PT or cross over with acceptable } m_h \\ \text{too small CP violation} \end{cases}$$

$$\Downarrow$$

Extension of the minimal Higgs sector

THDM, MSSM, NMSSM(Tao-san's talk),etc.

- THDM is a simple viable model.   not so constrained

To sidestep complication we assume [Cline et al PRD54 '96]

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

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

- Tree-level potential

$$V_0(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda_{\text{eff}}}{4}\varphi^4, \qquad \mu^2 = m_3^2 - m^2, \quad \lambda_{\text{eff}} = \frac{1}{4}(\lambda + \lambda_{345})$$

- 1-loop effective potential at zero temperature

$$V_1(\varphi) = \frac{n_i}{64\pi^2}\left[2m_i^2(v_0)m_i^2(\varphi) + m_i^4(\varphi)\left(\log\frac{m_i^2(\varphi)}{m_i^2(v_0)} - \frac{3}{2}\right)\right]$$

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

- finite temperature effective potential

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

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

• High temperature expansion [m/T≪1]

In the specific case,

$m_\phi^2(\varphi) = m_\phi^2(v_0)\frac{\varphi^2}{v_0^2}, \quad (\phi = H,\ A,\ H^\pm)$

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

where

$$E = \frac{1}{12\pi v_0^3}(6m_W^2 + 3m_Z^2 + \underbrace{m_H^2 + m_A^2 + 2m_{H^\pm}^2}_{\text{additional contributions}})$$

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

Necessary conditions

• Strong 1st order PT

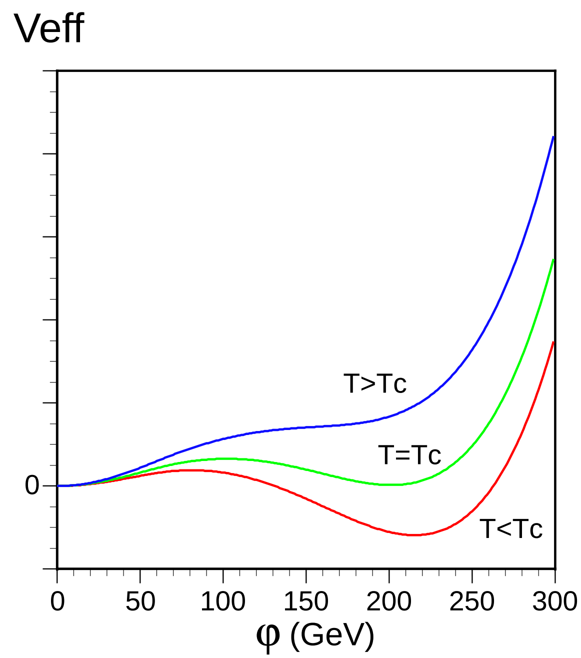
Not to wash out baryon density after EWPT

$$\frac{\varphi_c}{T_c} \gtrsim 1.4, \qquad \text{[Brahm '93]}$$

• CP violation at the bubble wall

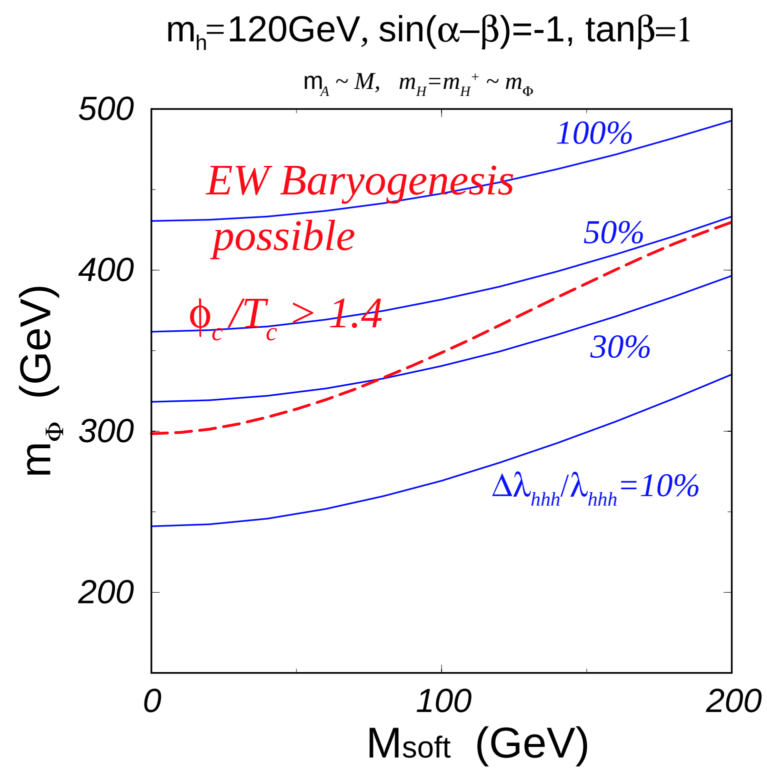
Asymmetry of charge flow.

$\Rightarrow$ B violation in the sym. phase.



Possible range of strongly 1st order PT

- We calculate the finite temperature effective potential without the high temperature expansion.
- Combined hhh coupling constants at zero temperature



- Strongly 1st order electroweak phase transition cause a large deviation ($\gtrsim$ 30%) of hhh coupling from the SM value at zero temperature.

§4. Summary

(1) Radiative corrections to ZZh and hhh couplings in the THDM.

For $\delta = 1 - \sin^2(\alpha - \beta) = 0 - 0.1$

- The deviation of g_{ZZh} from the SM value is $\mathcal{O}(1\%)$
  $\Longleftrightarrow \mathcal{O}(m_\phi^2)$ contributions.

- The deviation of λ_{hhh} from the SM value is $30 - 100\%$
  $\Longleftrightarrow \mathcal{O}(m_\phi^4)$ contributions.

(2) Correlation beween zero temperature and finite temperature Higgs potential.

Strongly 1st order electroweak phase transition cause a large deviation ($\gtrsim$ 30%) of hhh coupling from the SM value at zero temperature.

- Such deviation is testable at a Linear Collider.