Electroweak phase transition and Higgs couplings in the singlet-extended SM: revisited

Eibun Senaha (Nagoya U)

MultiHiggs 2014@Lisbon.
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in collaboration with Kaori Fuyuto (Nagoya U)

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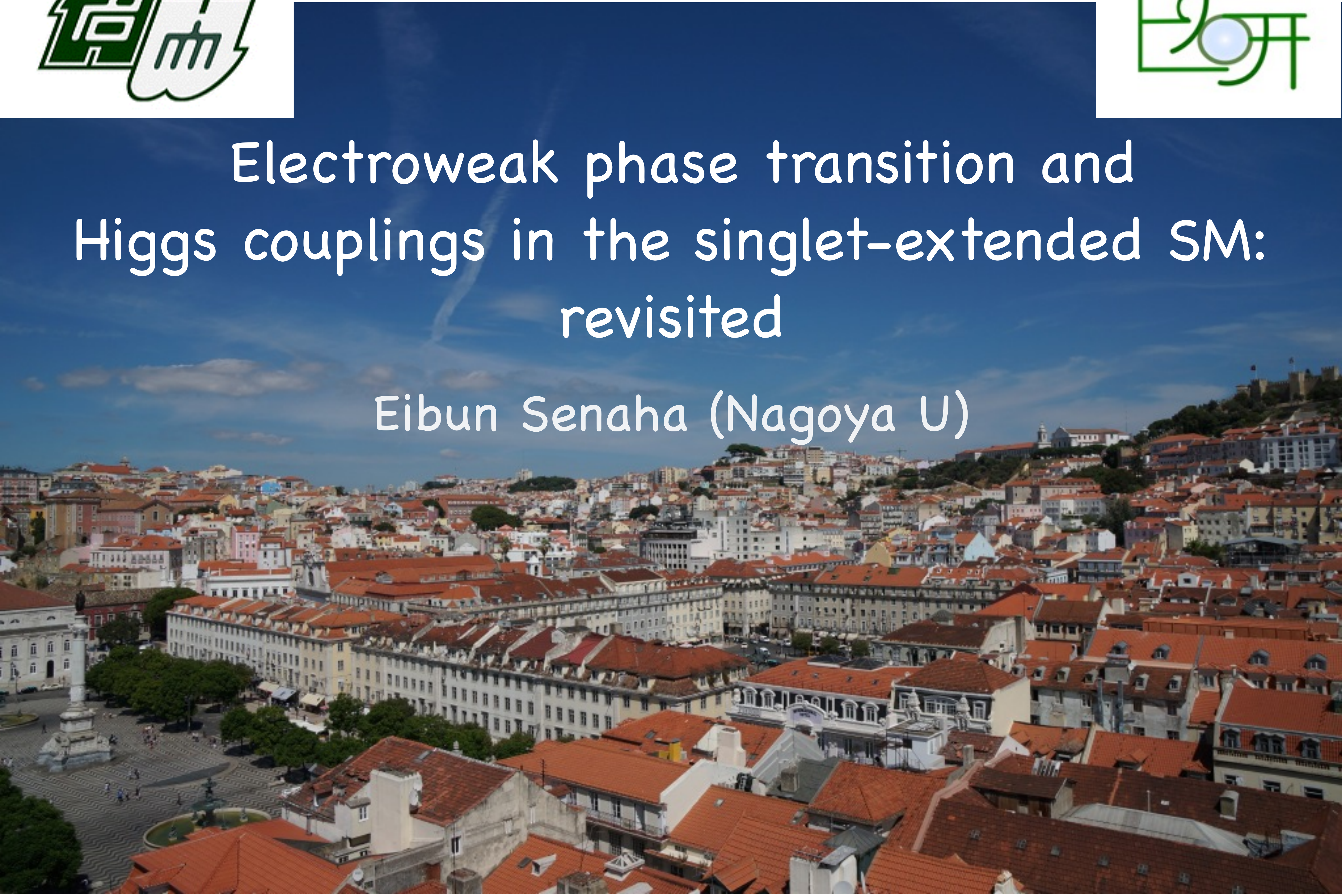

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Outline

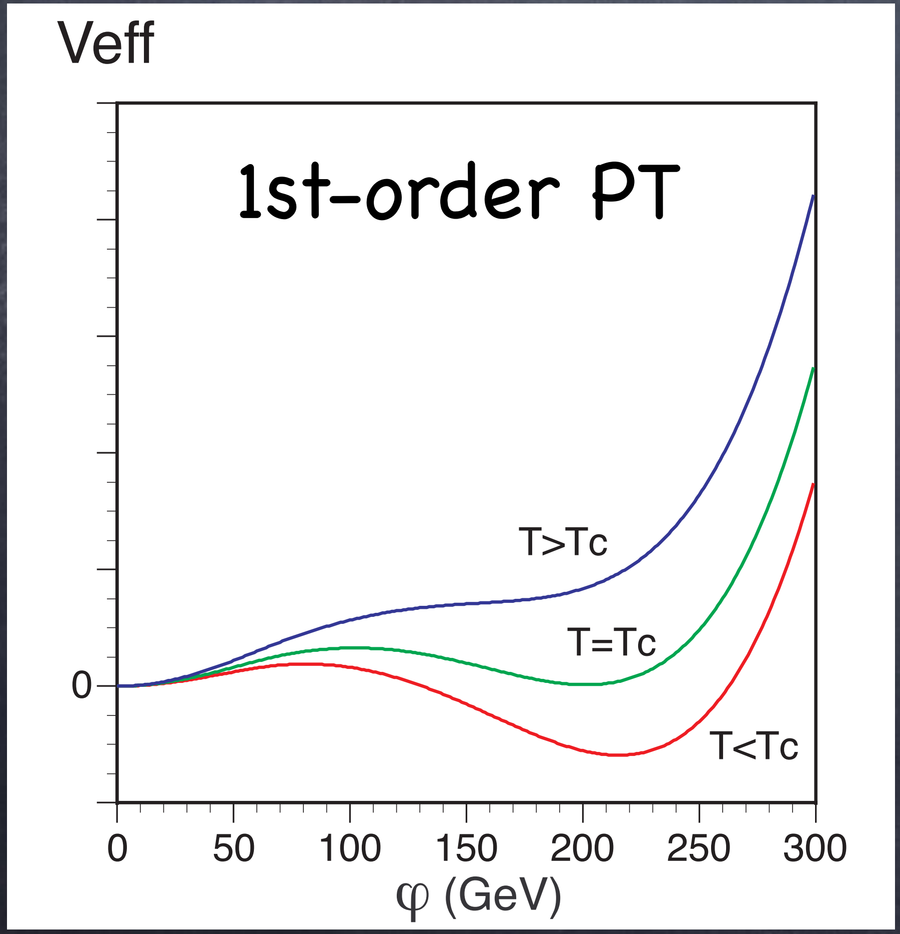
- Introduction
  - Higgs and cosmology
- Real singlet-extended SM (rSM)
  - Electroweak phase transition (EWPT) & sphaleron decoupling condition
  - Impact on the hhh coupling
- Summary

Higgs and cosmology

What is the implications of Higgs physics for cosmology?

- cosmic baryon asymmetry ⇔ EW baryogenesis
- dark matter ⇔ inert Higgs, Higgs portal etc.

EWBG and hhh coupling



Electroweak baryogenesis

based on EW phase transition

⇓ 1st order PT

remnant in Higgs potential at T=0.

⇒ large deviation of hhh coupling

e.g., 2HDM, [PLB606 (2005) 361, S. Kanemura, Y. Okada, E.S.]

Δhhh > some value (depends on "sphaleron decoupling condition")

What are successful models?

SUSY: EWBG in MSSM has been excluded.

Next-to-MSSM (NMSSM), nearly-MSSM (nMSSM),
U(1)'-MSSM (UMSSM), triplet-MSSM (TMSSM) etc.

strong 1^{st}-order EWPT is OK, CPV is OK

SM+extended Higgs sector

	strong 1st order PT	CPV(Higgs sector)
real singlet	OK	X
complex singlet	OK	OK
MHDM ($M \geq 2$)	OK	OK
real triplet	OK	X
complex triplet	OK	X

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real singlet	OK	X
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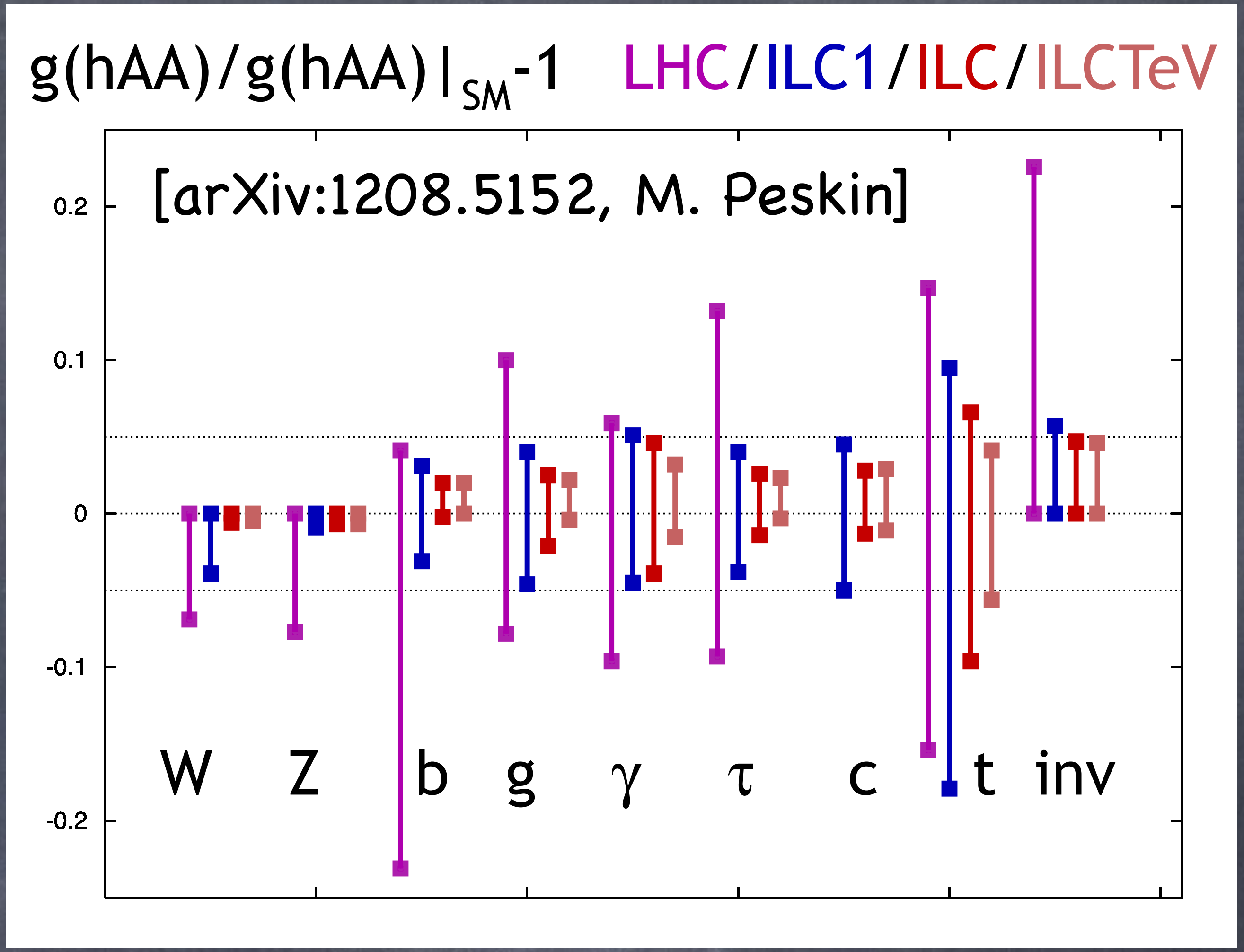
We consider the SM with a real singlet (rSM)

Toward Higgs precision (Higgcision)

- Higgs sector will be clarified with better accuracy at the coming LHC and ILC.



Pressing issue

Theoretical uncertainties in the EWBG calculation also have to be minimized.

In the literature, $\frac{v_C}{T_C} > 1$ is usually used.

In this talk, we evaluate this condition more precisely, and study its impact on $\Delta\lambda_{H_1H_1H_1}$ in the rSM.

Real singlet-extended SM (rSM)

Particle content: SM + S: (1,1,0)

Higgs potential:

$$V_0 = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_{HS} H^\dagger H S + \frac{\lambda_{HS}}{2} H^\dagger H S^2 + \mu_S^3 S + \frac{m_S^2}{2} S^2 + \frac{\mu'_S}{3} S^3 + \frac{\lambda_S}{4} S^4,$$

Scalar fields:

$$H(x) = \begin{pmatrix} G^+(x) \\ \frac{1}{\sqrt{2}}\left(v + h(x) + iG^0(x)\right) \end{pmatrix}, \qquad S(x) = v_S + s(x).$$

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H-S mixings are important to have strong 1st-order PT.

Tadpole conditions:

$$\left\langle \frac{\partial V}{\partial h} \right\rangle = v \left[-\mu_H^2 + \lambda_H v^2 + \mu_{HS} v_S + \frac{\lambda_{HS}}{2} v_S^2 \right] = 0,$$

$$\left\langle \frac{\partial V}{\partial s} \right\rangle = v_S \left[\frac{\mu_S^3}{v_S} + m_S^2 + \mu'_S v_S + \lambda_S v_S^2 + \frac{\mu_{HS}}{2} \frac{v^2}{v_S} + \frac{\lambda_{HS}}{2} v^2 \right] = 0,$$

Mass matrix: $$\frac{1}{2} \begin{pmatrix} h & s \end{pmatrix} \mathcal{M}_H^2 \begin{pmatrix} h \\ s \end{pmatrix}$$

$$\mathcal{M}_H^2 = \begin{pmatrix} 2\lambda_H v^2 & \mu_{HS} v + \lambda_{HS} v v_S \\ \mu_{HS} v + \lambda_{HS} v v_S & -\frac{\mu_S^3}{v_S} + \mu'_S v_S + 2\lambda_S v_S^2 - \frac{\mu_{HS}}{2} \frac{v^2}{v_S} \end{pmatrix},$$

which can be diagonalized by

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \qquad \alpha \in [-\pi/4, \pi/4]$$

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125 GeV Higgs

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \qquad \alpha \in [-\pi/4, \pi/4]$$

Higgs couplings

Higgs-gauge bosons

$$\mathcal{L}_{\rm HVV} = \frac{1}{v}\left(\cos\alpha\ H_1 - \sin\alpha\ H_2\right)\left(2m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z_\mu Z^\mu\right),$$

Higgs-fermions

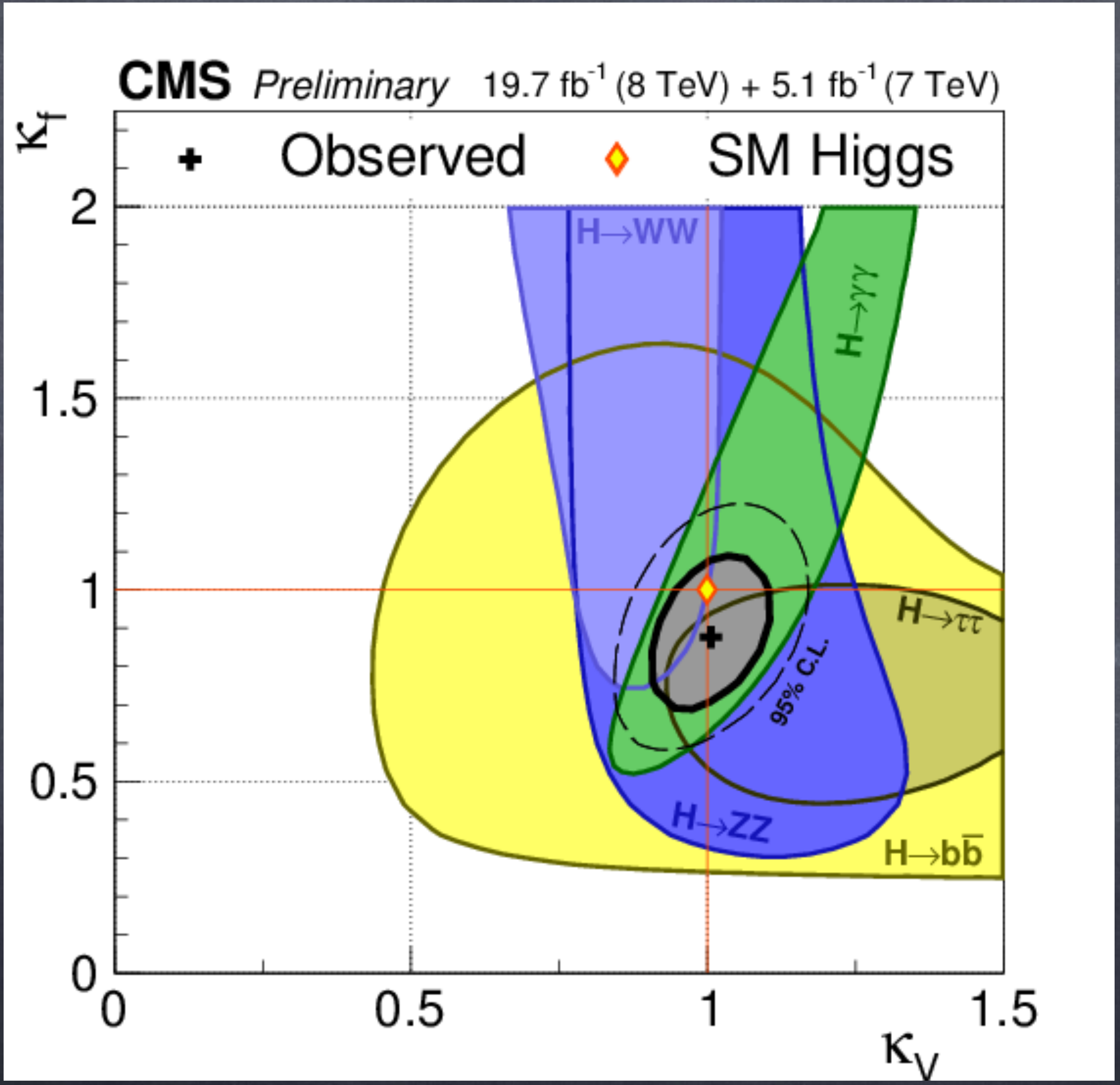
$$\mathcal{L}_{\rm Yukawa} = -\sum_f \frac{m_f}{v}\left(\cos\alpha\ H_1 - \sin\alpha\ H_2\right)\bar{f}f.$$

Normalized couplings:

$$\kappa_V = \frac{g_{H_1VV}}{g_{hVV}^{\rm SM}} = \cos\alpha, \qquad \kappa_F = \frac{g_{H_1ff}}{g_{hff}^{\rm SM}} = \cos\alpha.$$

We collectively denote $\kappa \equiv \kappa_V = \kappa_F$

Current status



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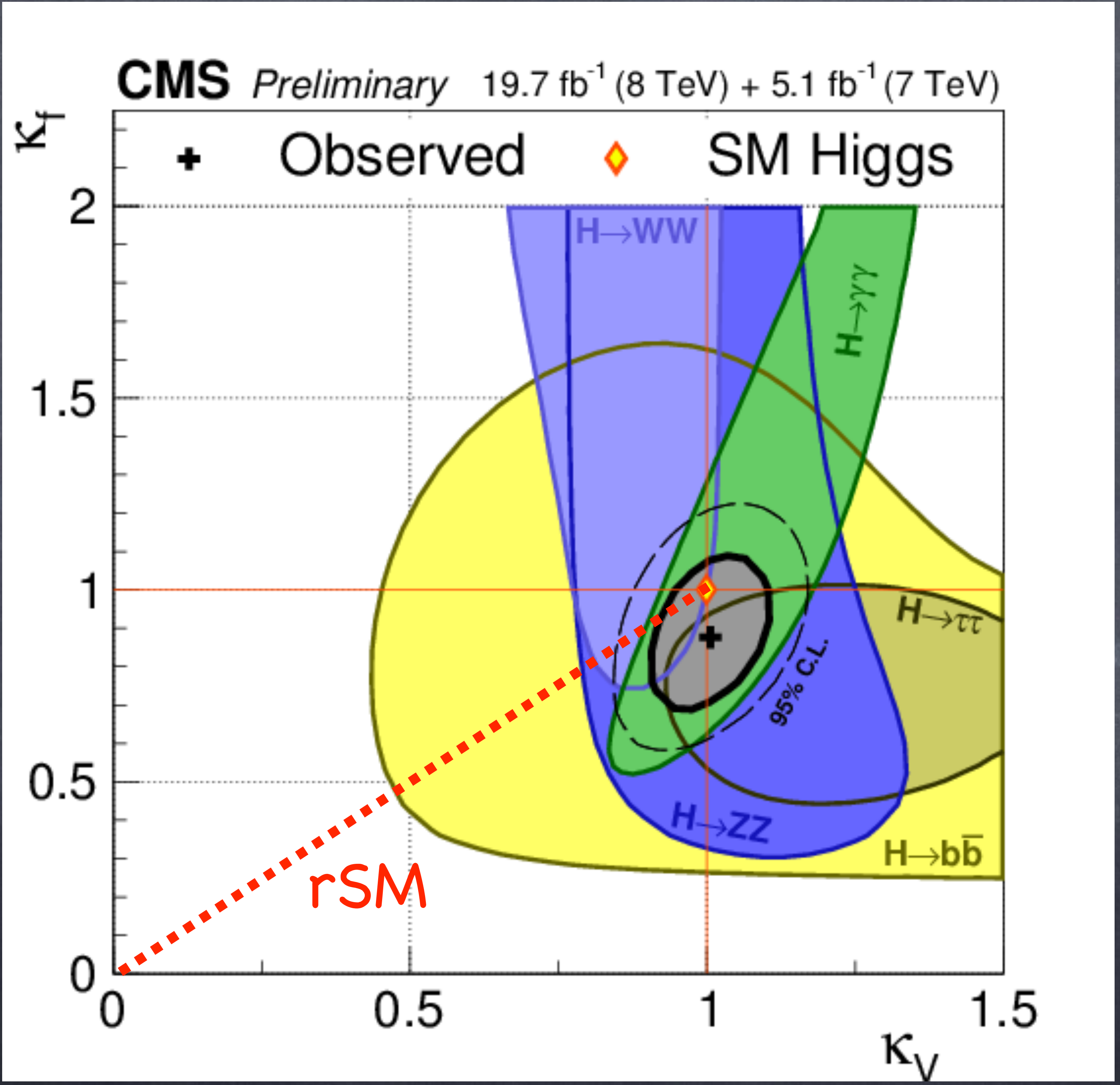

Effective potential

To discuss EWPT, we use the effective potential.

$$V_{\rm eff}(\varphi_H,\varphi_S,T)=V_0(\varphi_H,\varphi_S)+V_1(\varphi_H,\varphi_S)+V_1(\varphi_H,\varphi_S,T)+V_{\rm daisy}(\varphi_H,\varphi_S,T).$$

where

$$V_1(\varphi_H,\varphi_S)=\sum_i n_i\,\frac{\bar{m}_i^4(\varphi_H,\varphi_S)}{64\pi^2}\left(\ln\frac{\bar{m}_i^2(\varphi_H,\varphi_S)}{\mu^2}-c_i\right),$$

$$V_1(\varphi_H,\varphi_S,T)=\sum_i n_i\,\frac{T^4}{2\pi^2}I_{B,F}\left(\frac{\bar{m}_i^2(\varphi_H,\varphi_S)}{T^2}\right),$$

$$V_{\rm daisy}(\varphi_H,\varphi_S,T)=-\sum_j n_j\frac{T}{12\pi}\left[\left\{\bar{M}_j^2(\varphi_H,\varphi_S,T)\right\}^{3/2}-\left\{\bar{m}_j^2(\varphi_H,\varphi_S)\right\}^{3/2}\right],$$

$$I_{B,F}(a^2)=\int_0^\infty dx\;x^2\ln\left(1\mp e^{-\sqrt{x^2+a^2}}\right),$$

$$n_{H_1}=n_{H_2}=n_{G^0}=1,\qquad n_{G^\pm}=2,\qquad n_W=2\cdot 3,\qquad n_Z=3,\qquad n_t=n_b=-4N_c,$$

Sphaleron decoupling condition

After the EWPT, the sphaleron process has to be decoupled.

$$\Gamma_B^{(b)}(T) \simeq (\text{prefactor})e^{-E_{\rm sph}/T} < H(T) \simeq 1.66\sqrt{g_*}T^2/m_{\rm P}$$

g_* massless dof, 106.75 (SM) $m_{\rm P}$ Planck mass ≃ 1.22x10[19] GeV

$E_{\rm sph} = 4\pi v\mathcal{E}/g_2$ (g_2: SU(2) gauge coupling),

$$\frac{v(T)}{T} > \frac{g_2}{4\pi\mathcal{E}(T)}\left[42.97 + \ln\mathcal{N} - 2\ln\left(\frac{T}{100\ \text{GeV}}\right) + \cdots\right] \equiv \zeta_{\rm sph}(T),$$

- Sphaleron energy gives the dominant effect.
- We evaluate vc/Tc, E(Tc), ζ (Tc).

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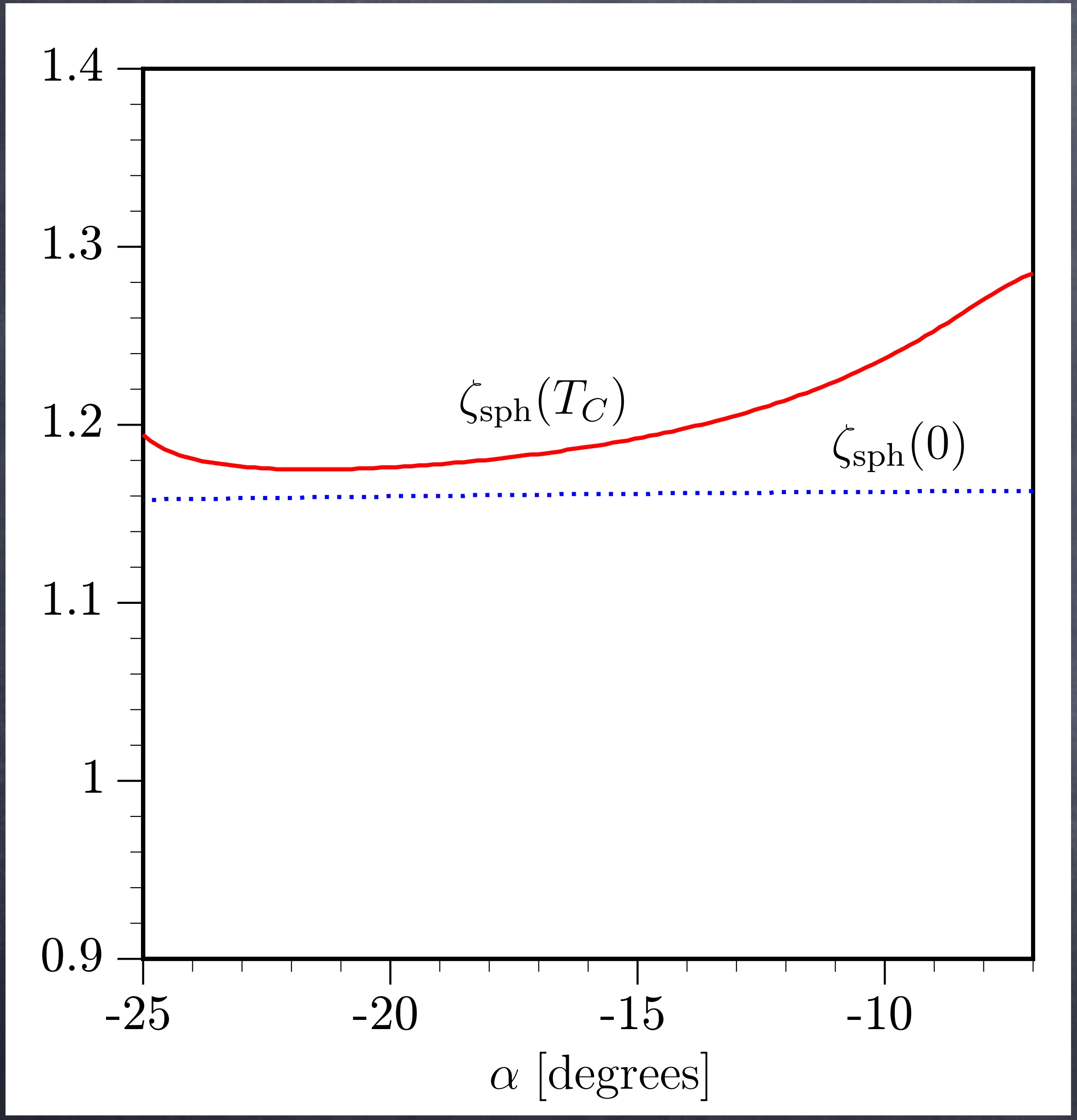
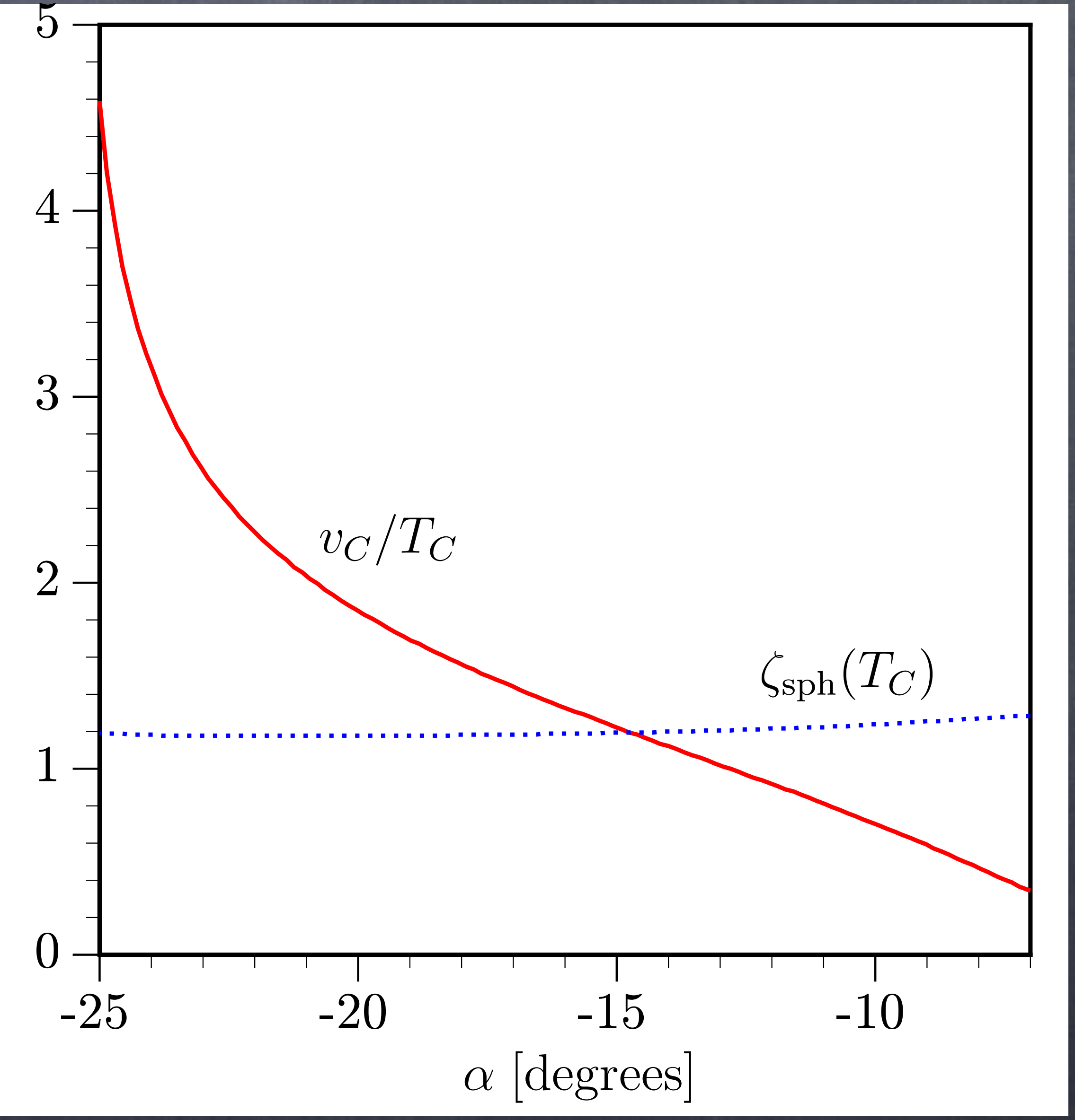
Sphaleron decoupling condition

$$m_{H_2} = 170 \text{ GeV},\ v_S = 90 \text{ GeV},\ \mu'_S = -30 \text{ GeV},\ \mu_{HS} = -80 \text{ GeV}.$$





- $\zeta(T_C)$= (1.2–1.3)
- $v_C/T_C > \zeta(T_C)$ is satisfied for $|\alpha|$ > 15 deg.

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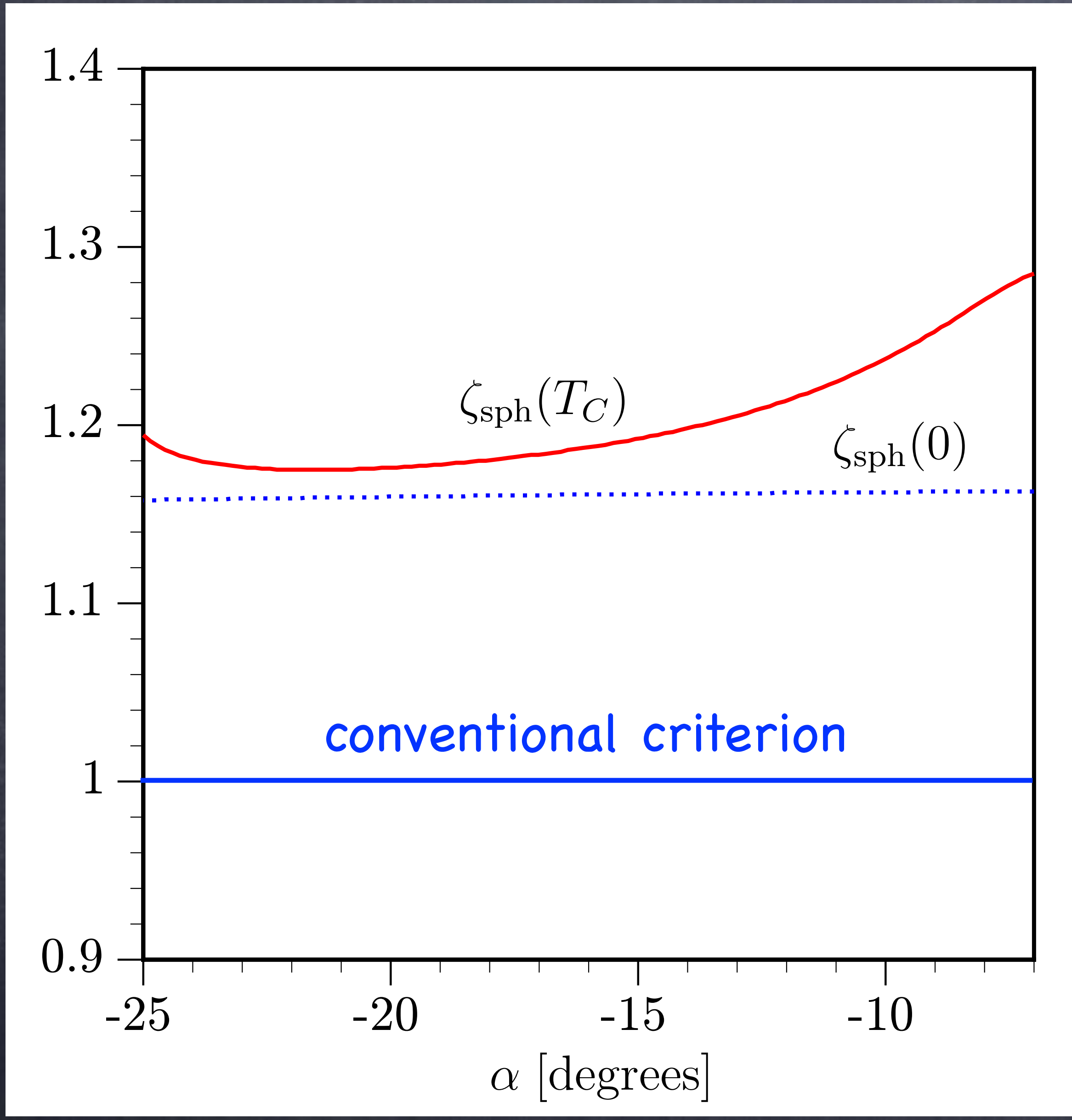

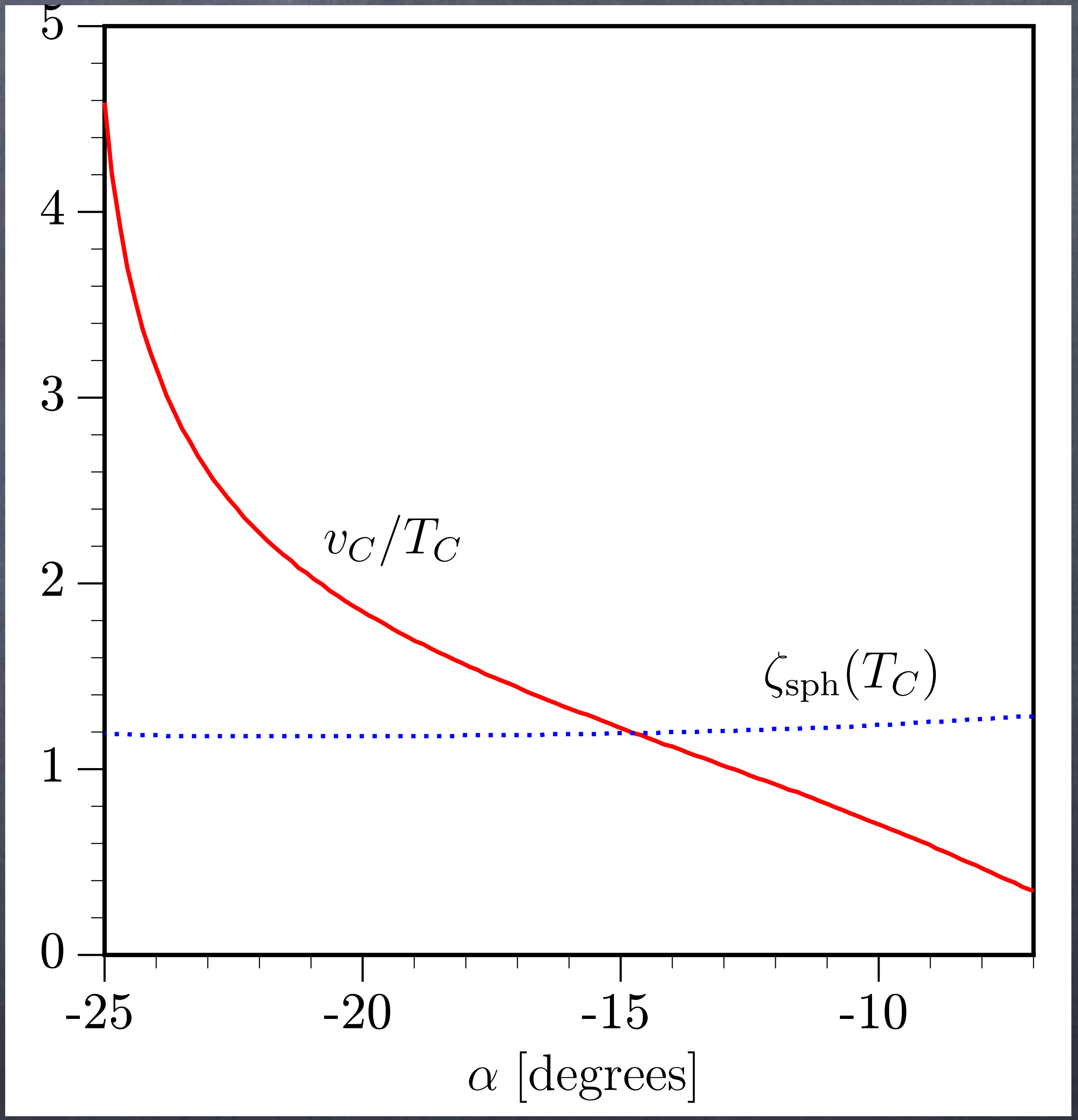

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hhh coupling

❒ hhh coupling in the SM.

$$\lambda^{\rm SM}_{H_1H_1H_1} = \frac{3m^2_{H_1}}{v}\left[1+\frac{9m^2_{H_1}}{32\pi^2v^2}+\sum_{i=W,Z,t,b} n_i\frac{m_i^4}{12\pi^2m^2_{H_1}v^2}\right] \simeq 175.83\ [\rm GeV].$$

The dominant one-loop correction comes from top loop

❒ hhh coupling in the rSM.

$$\lambda^{\rm rSM}_{H_1H_1H_1} = \lambda^{\rm rSM,tree}_{H_1H_1H_1} + \lambda^{\rm rSM,loop}_{H_1H_1H_1},$$

$$\lambda^{\rm rSM,tree}_{H_1H_1H_1} = 6\left[\lambda_H v c_\alpha^3 + \frac{\mu_{HS}}{2}s_\alpha c_\alpha^2 + \frac{\lambda_{HS}}{2}s_\alpha c_\alpha(vs_\alpha + v_S c_\alpha) + \left(\frac{\mu'_S}{3}+\lambda_S v_S\right)s_\alpha^3\right],$$

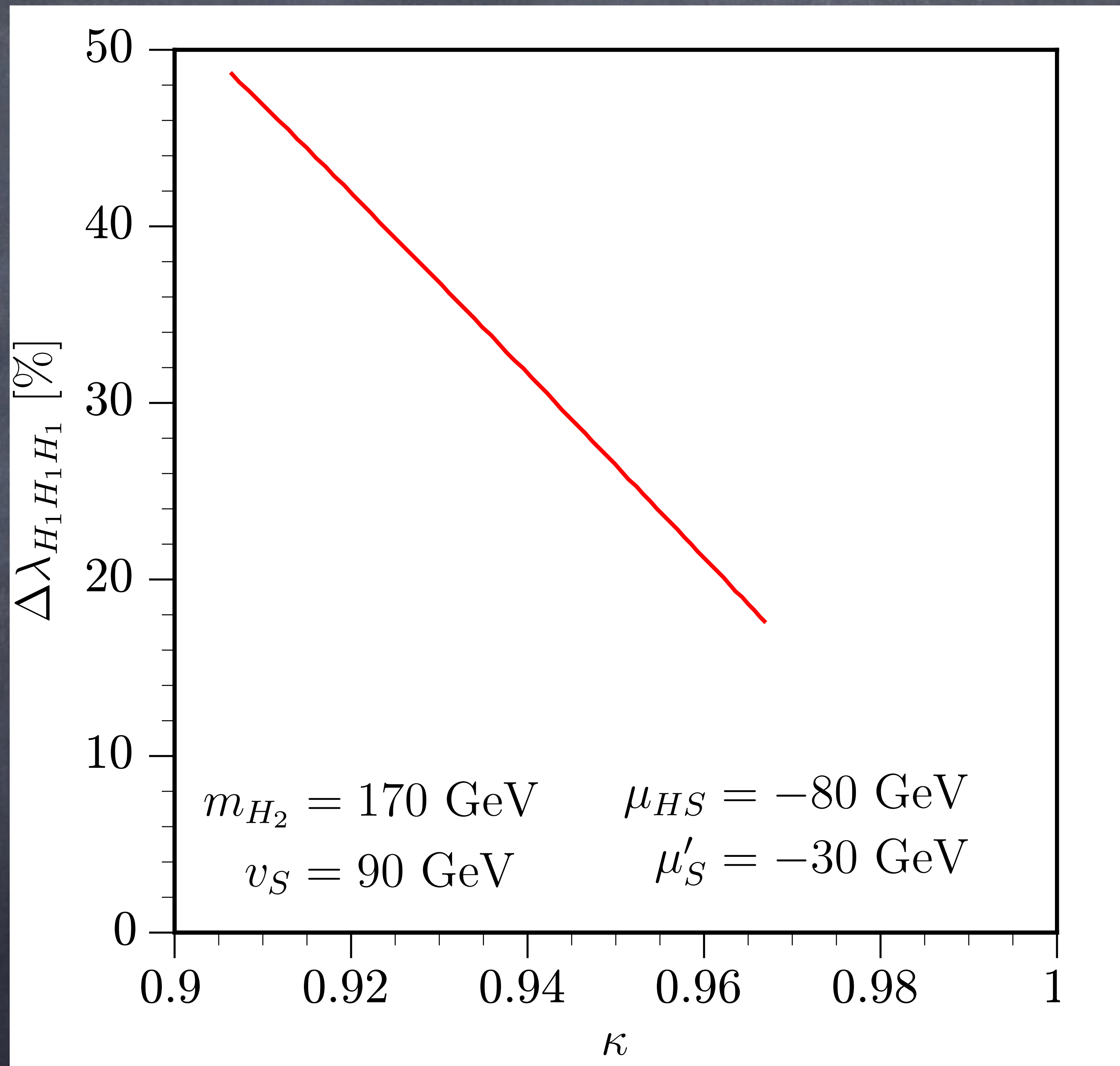
$$\lambda^{\rm rSM,loop}_{H_1H_1H_1} = c_\alpha^3\left\langle\frac{\partial^3 V_1}{\partial\varphi_H^3}\right\rangle + c_\alpha^2 s_\alpha\left\langle\frac{\partial^3 V_1}{\partial\varphi_H^2\partial\varphi_S}\right\rangle + c_\alpha s_\alpha^2\left\langle\frac{\partial^3 V_1}{\partial\varphi_H\partial\varphi_S^2}\right\rangle + s_\alpha^3\left\langle\frac{\partial^3 V_1}{\partial\varphi_S^3}\right\rangle,$$

Larger α gives the larger deviation from the SM value.

(To have strong 1st order PT, (λ_{HS}, μ_{HS}) have to be large.)

κ vs. $\Delta\lambda_{H_1H_1H_1}$

$$\Delta\lambda_{H_1H_1H_1} = \frac{\lambda^{\rm rSM}_{H_1H_1H_1} - \lambda^{\rm SM}_{H_1H_1H_1}}{\lambda^{\rm SM}_{H_1H_1H_1}}$$



- Smaller κ gives larger $\Delta\lambda_{H1H1H1}$.

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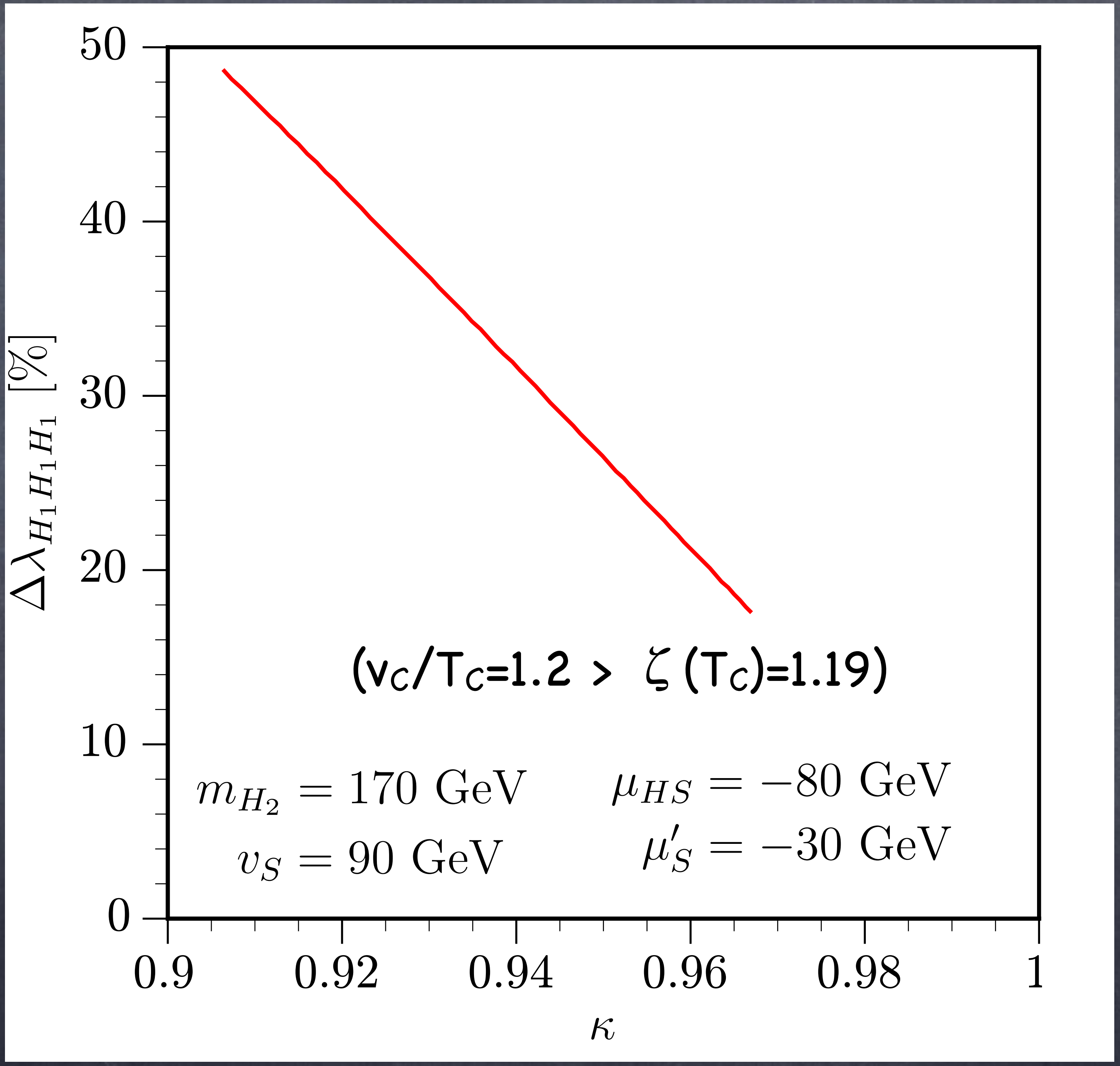

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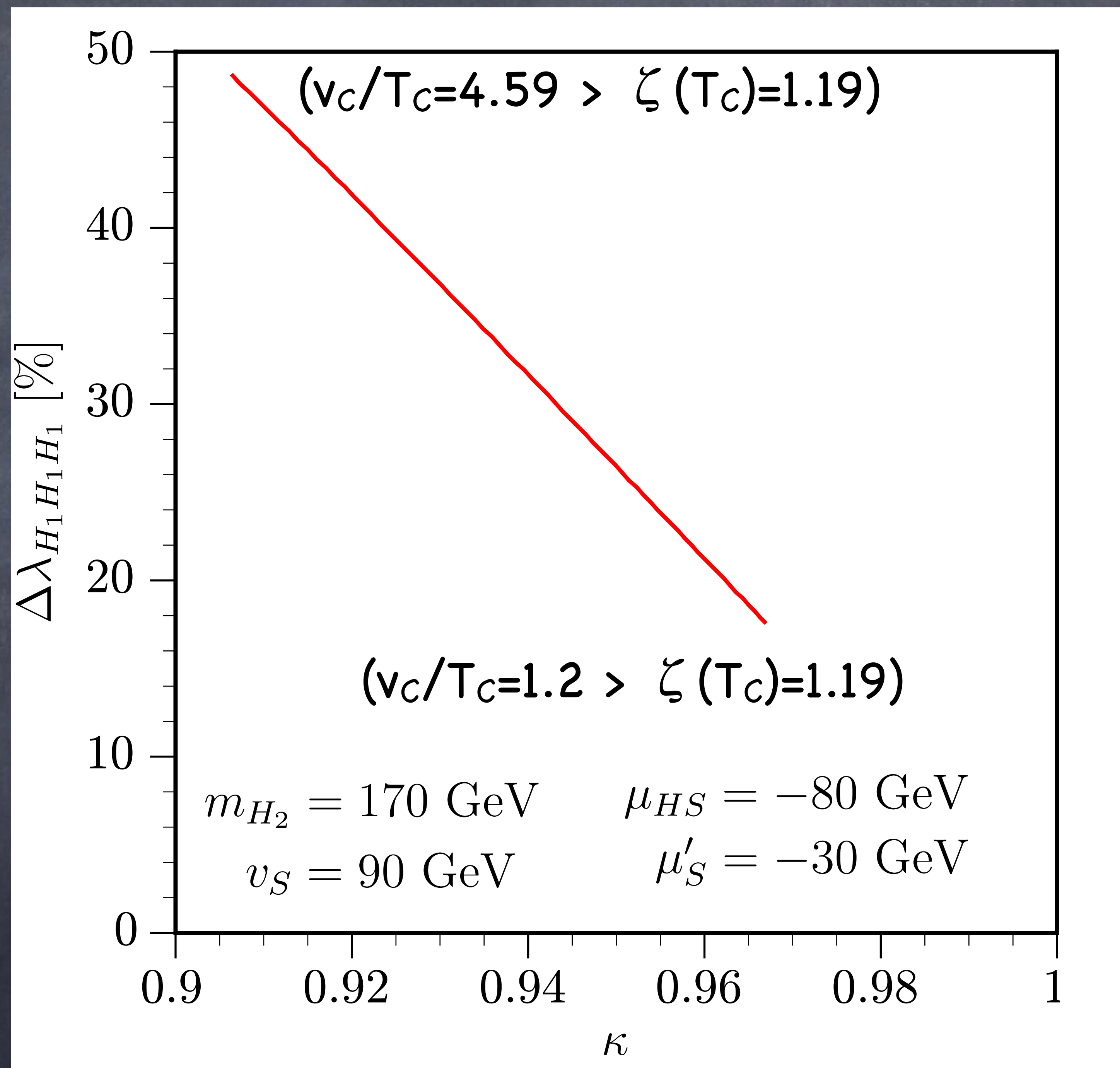
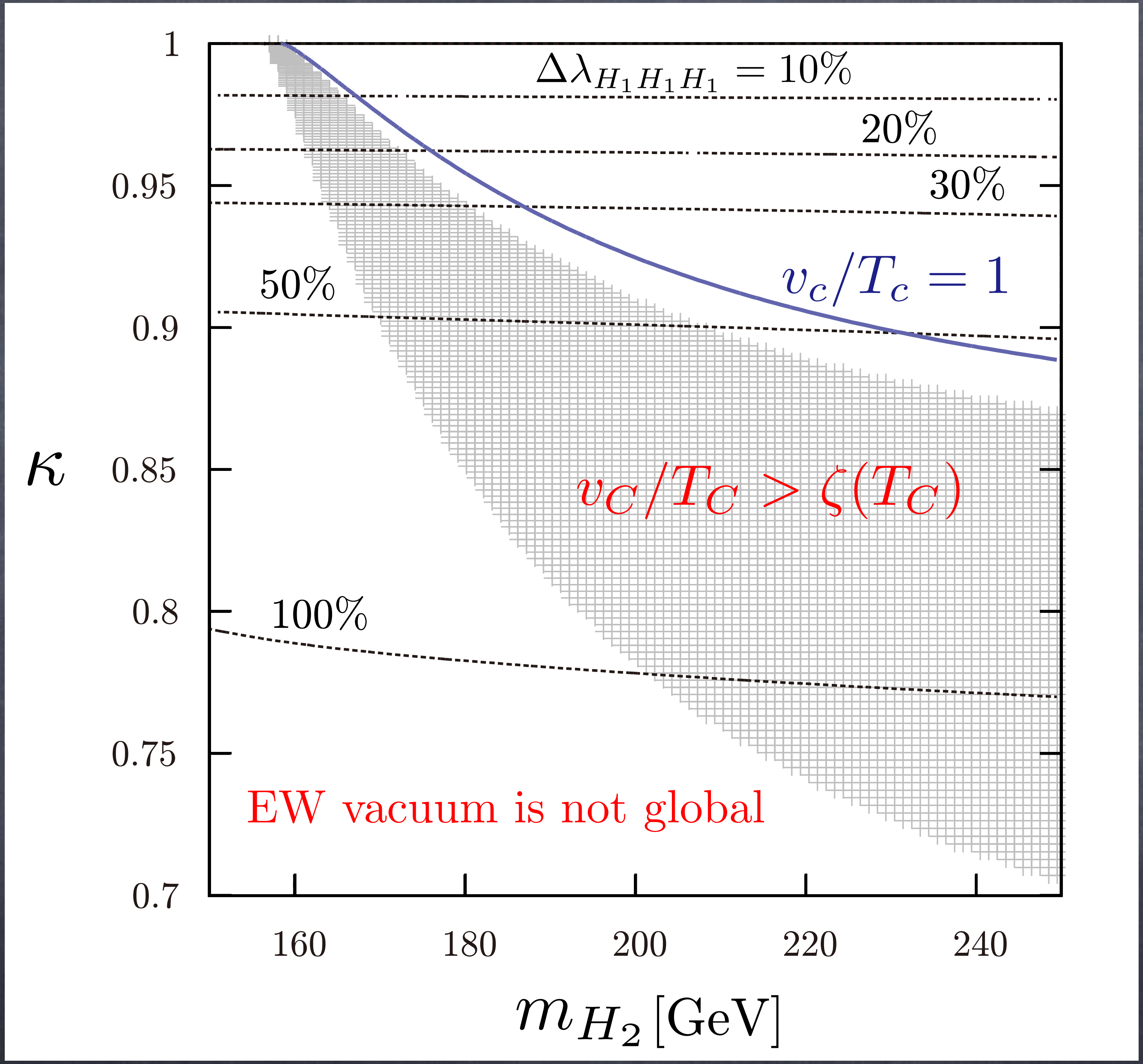


- Smaller κ gives larger $\Delta\lambda_{H1H1H1}$.

$\Delta\lambda_{H_1H_1H_1}$ contours in (m_{H_2}, κ) plane



- $\Delta\lambda_{H_1H_1H_1} \simeq 16\%$ for $\kappa \simeq 0.97$ and 160 GeV $\lesssim m_{H_2} \lesssim$ 169 GeV,
- $\Delta\lambda_{H_1H_1H_1} \simeq 27\%$ for $\kappa \simeq 0.95$, and 163 GeV $\lesssim m_{H_2} \lesssim$ 176 GeV.

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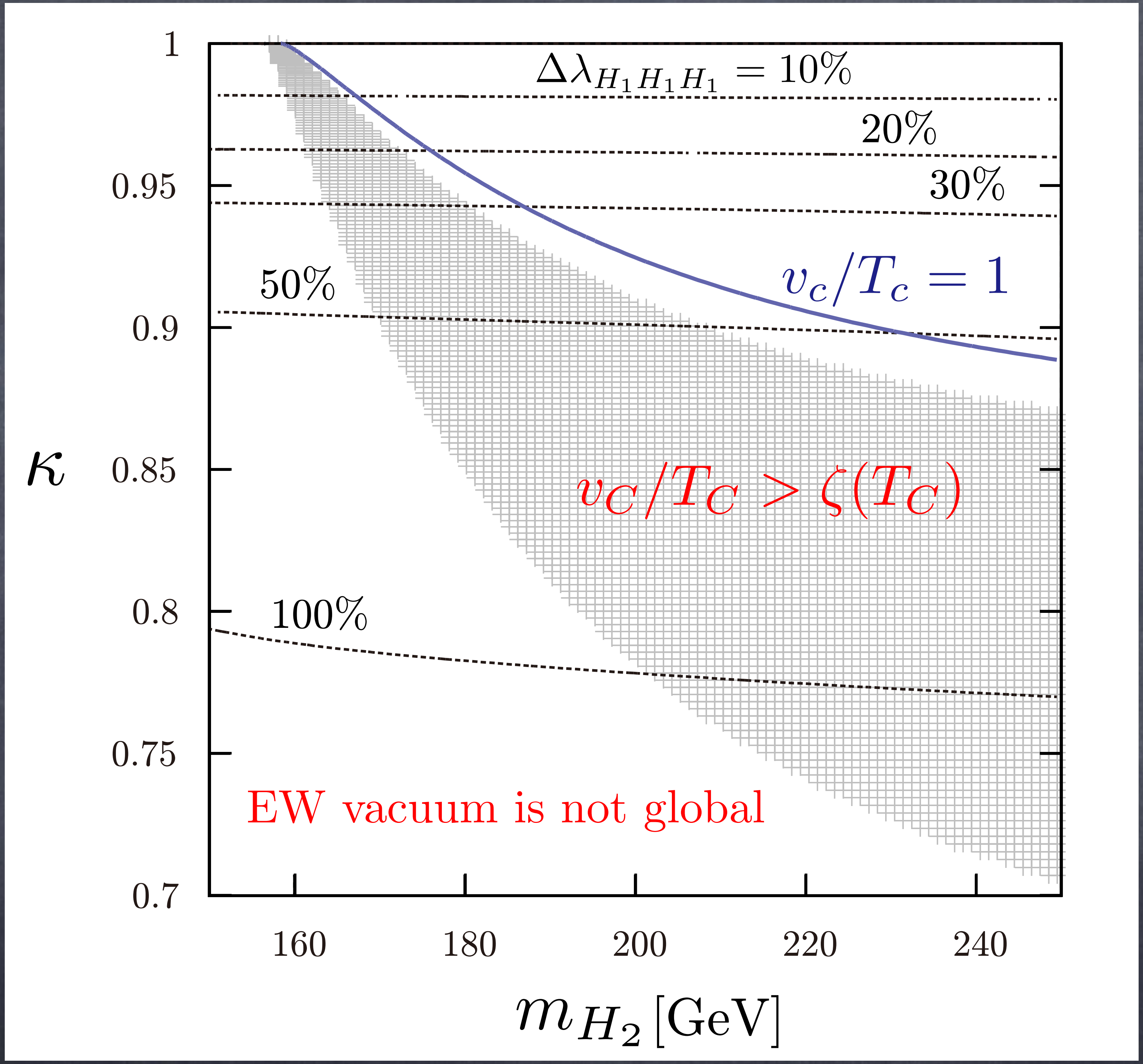

If $\dfrac{v_C}{T_C} > 1$

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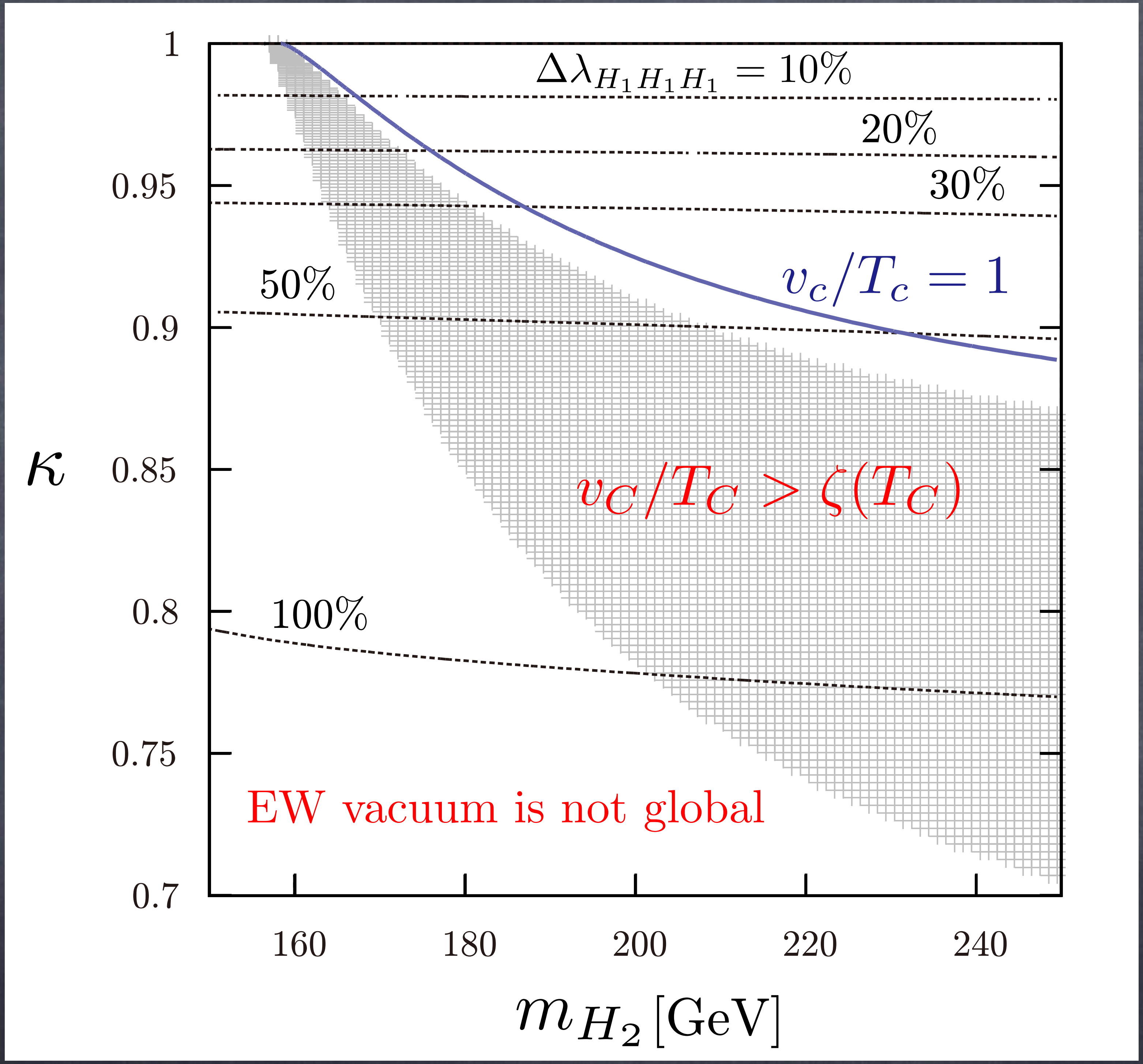

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172

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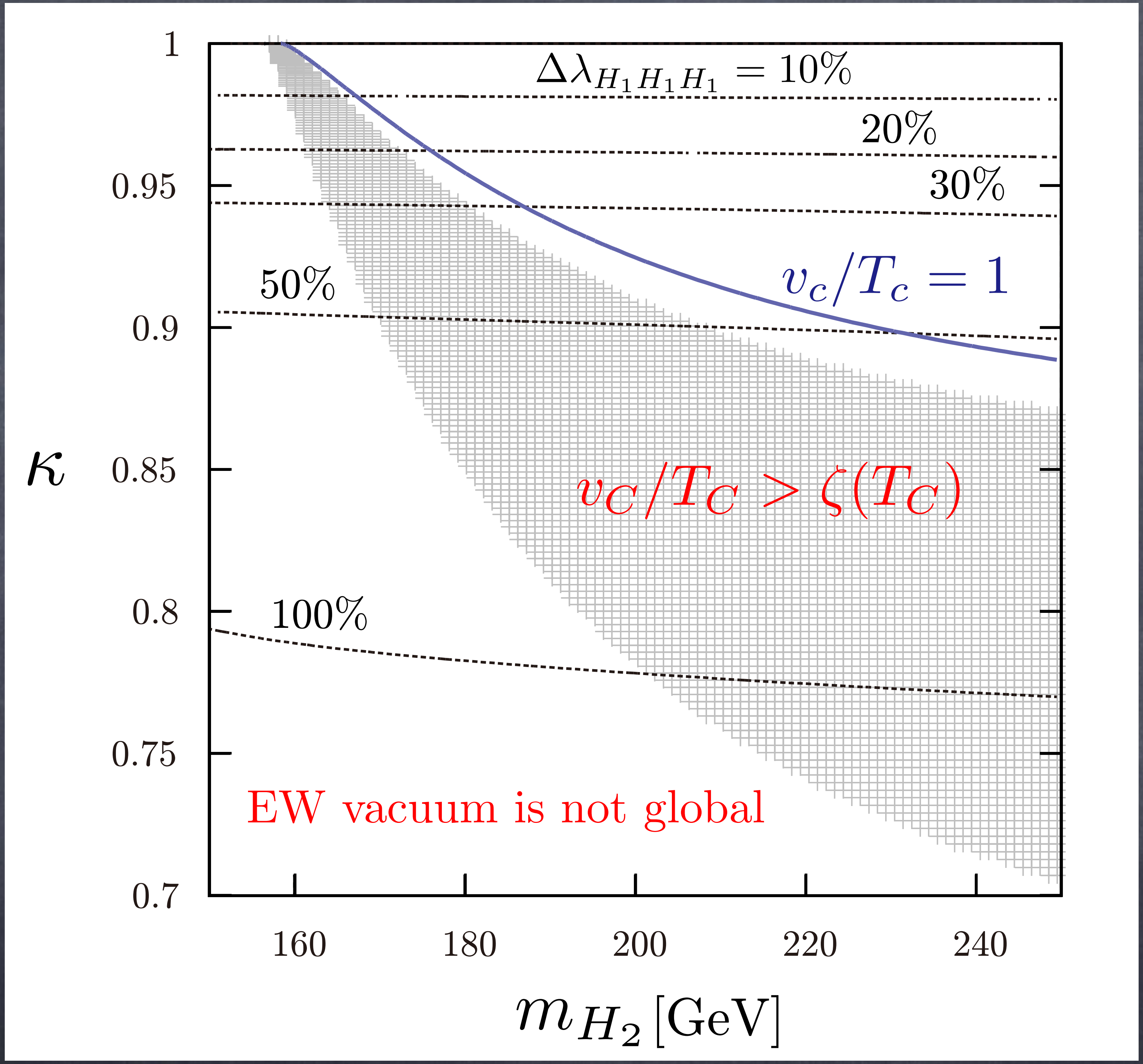

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172

182

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Summary

- ❐ We have discussed the EW phase transition and sphaleron decoupling condition in the rSM.

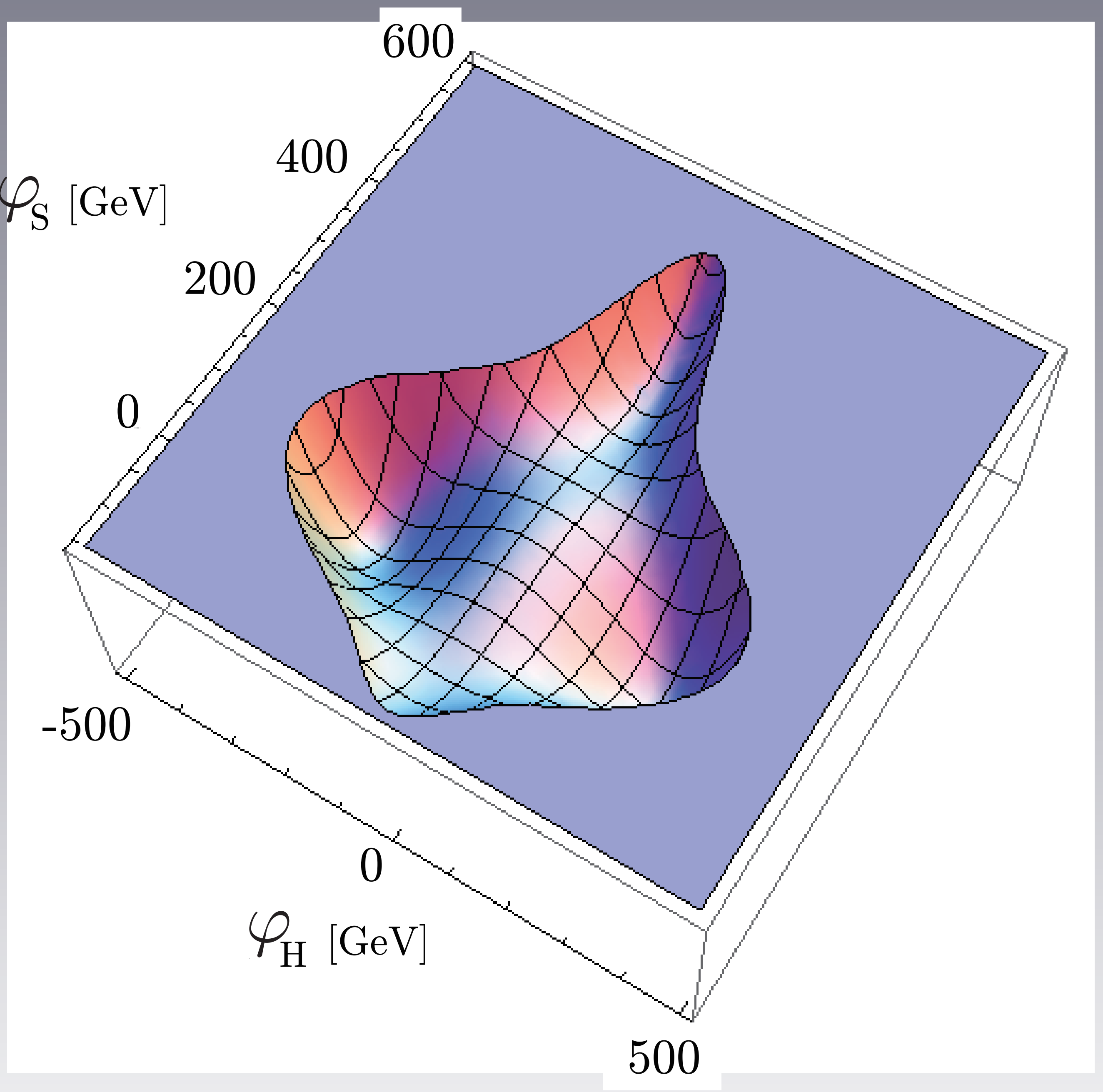
- ❐ v_C/T_C > (1.1-1.2) in the typical cases.

- ❐ We also studied the deviation of the hhh coupling from the SM value based on the improved sphaleron decoupling condition.

- ❐ The deviation is greater than that based on the conventional criterion $v_C/T_C>1$.

Our prediction

- Higgs potential has this form!



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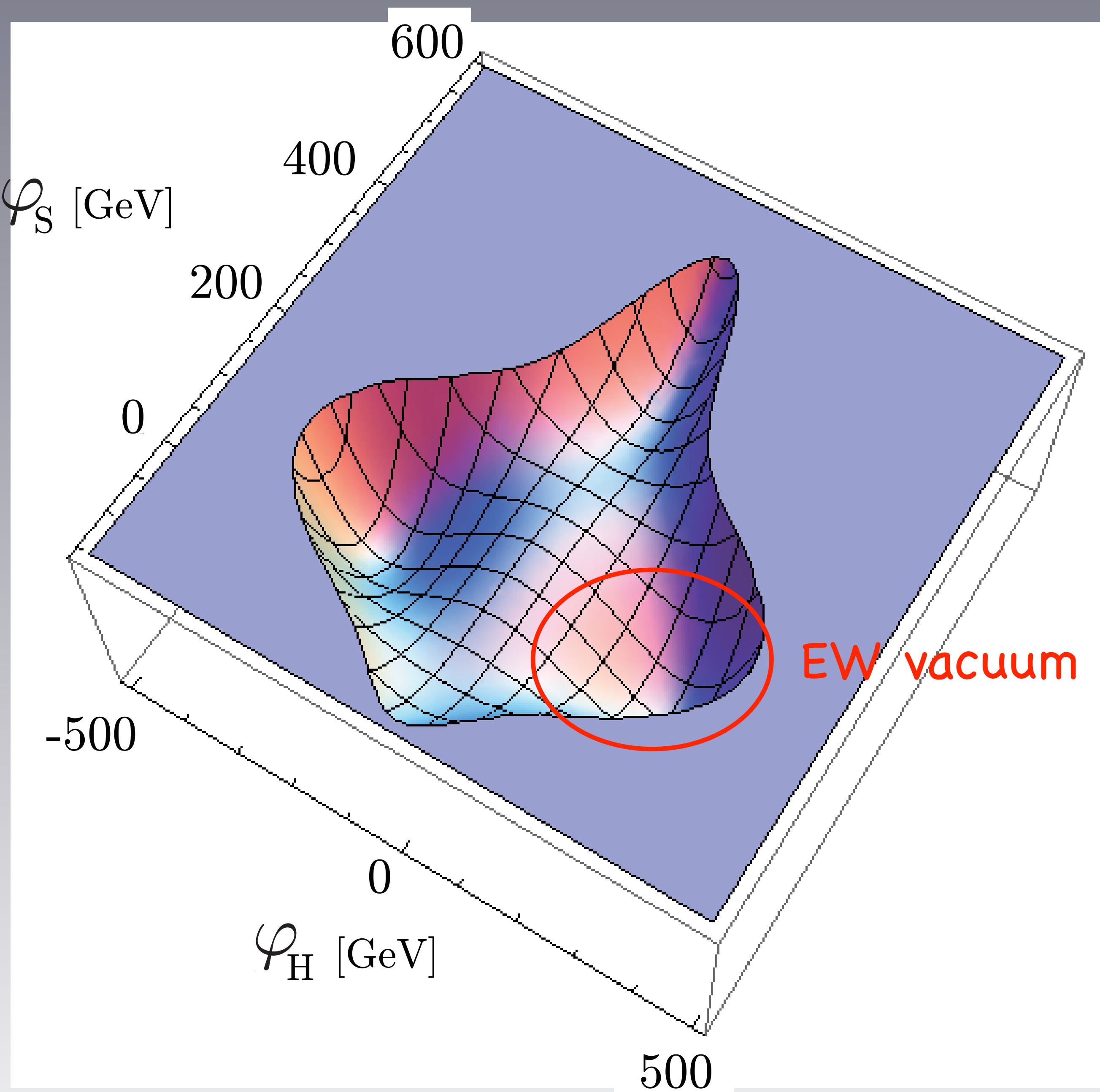

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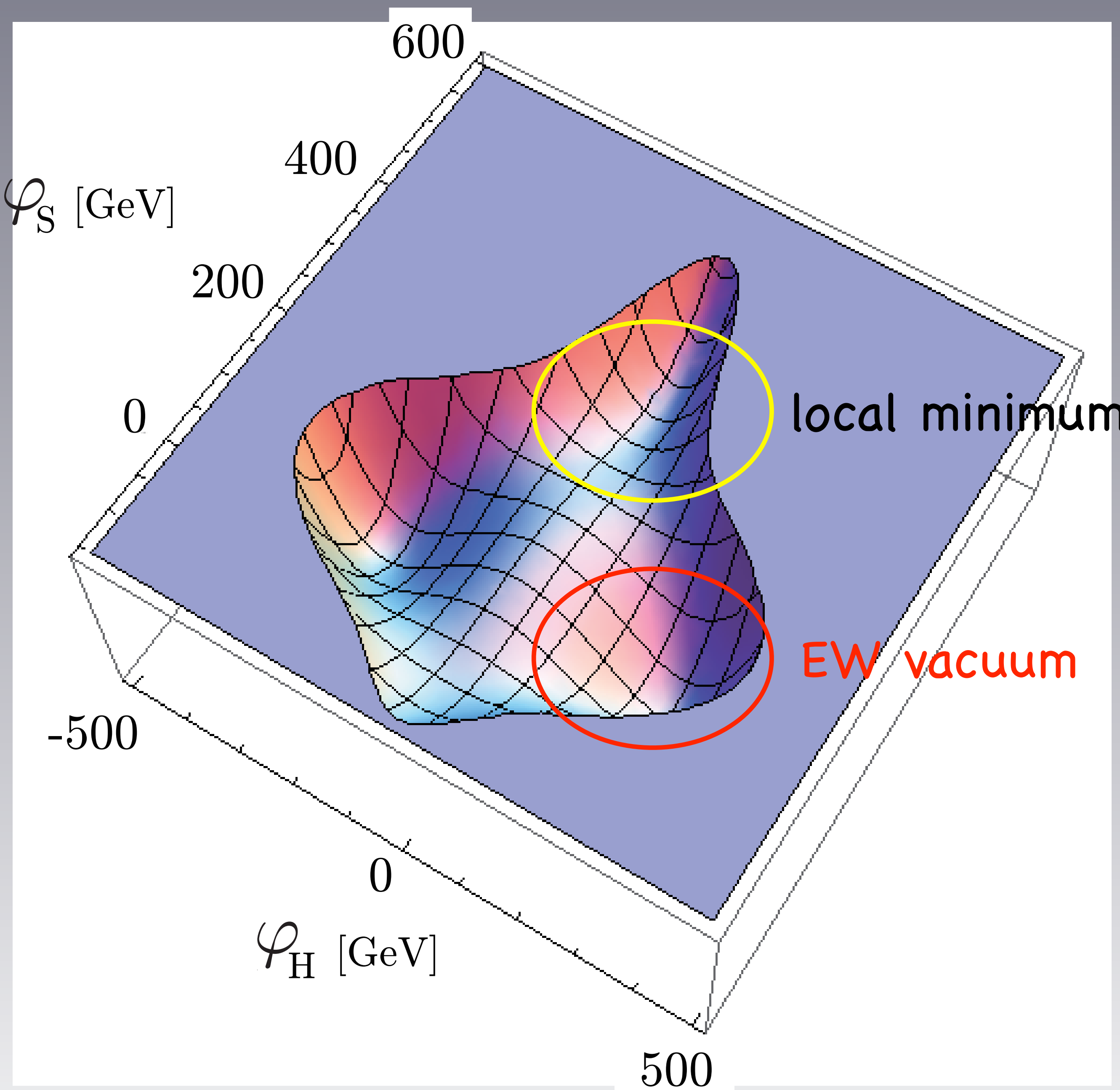


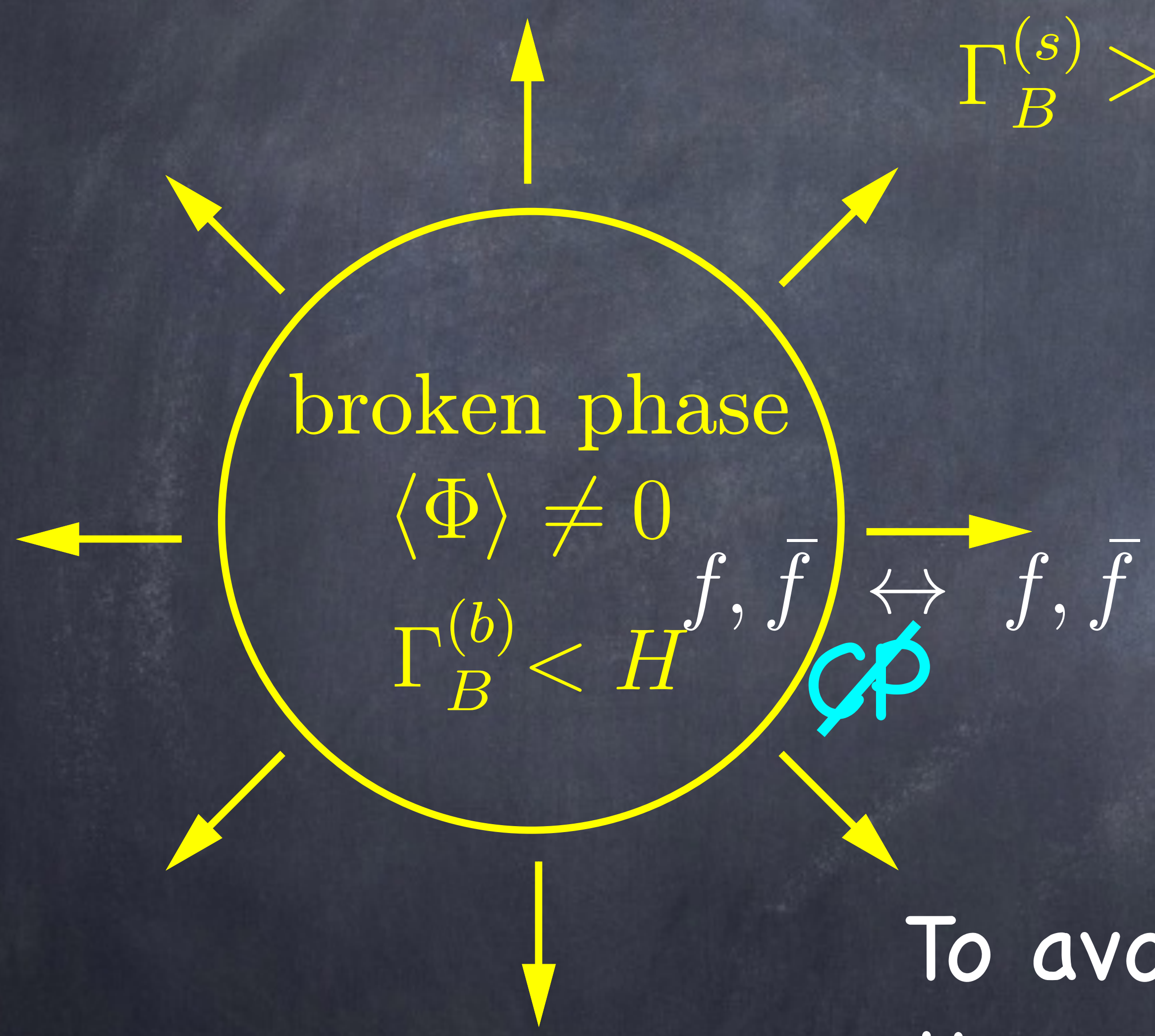
Backup

EW baryogenesis mechanism

[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]

❒ BAU can arise by the growing bubbles.

symmetric phase $\langle\Phi\rangle = 0$



H: hubble constant

$\not{B+L}$: N_g gen., $0 \leftrightarrow \sum_{i=1}^{N_g} (3q_L^i + l_L^i)$

$\not{CP}$: CP-violating interaction between particles and Higgs bubble.

To avoid the washout by the sphaleron,

$$\Gamma_B^{(b)} < H$$

most important condition for collider tests.

Sphaleron energy

For simplicity, we evaluate sphaleron energy at T=0.

[Klinkhammer and Manton, PRD30, ('84) 2212]

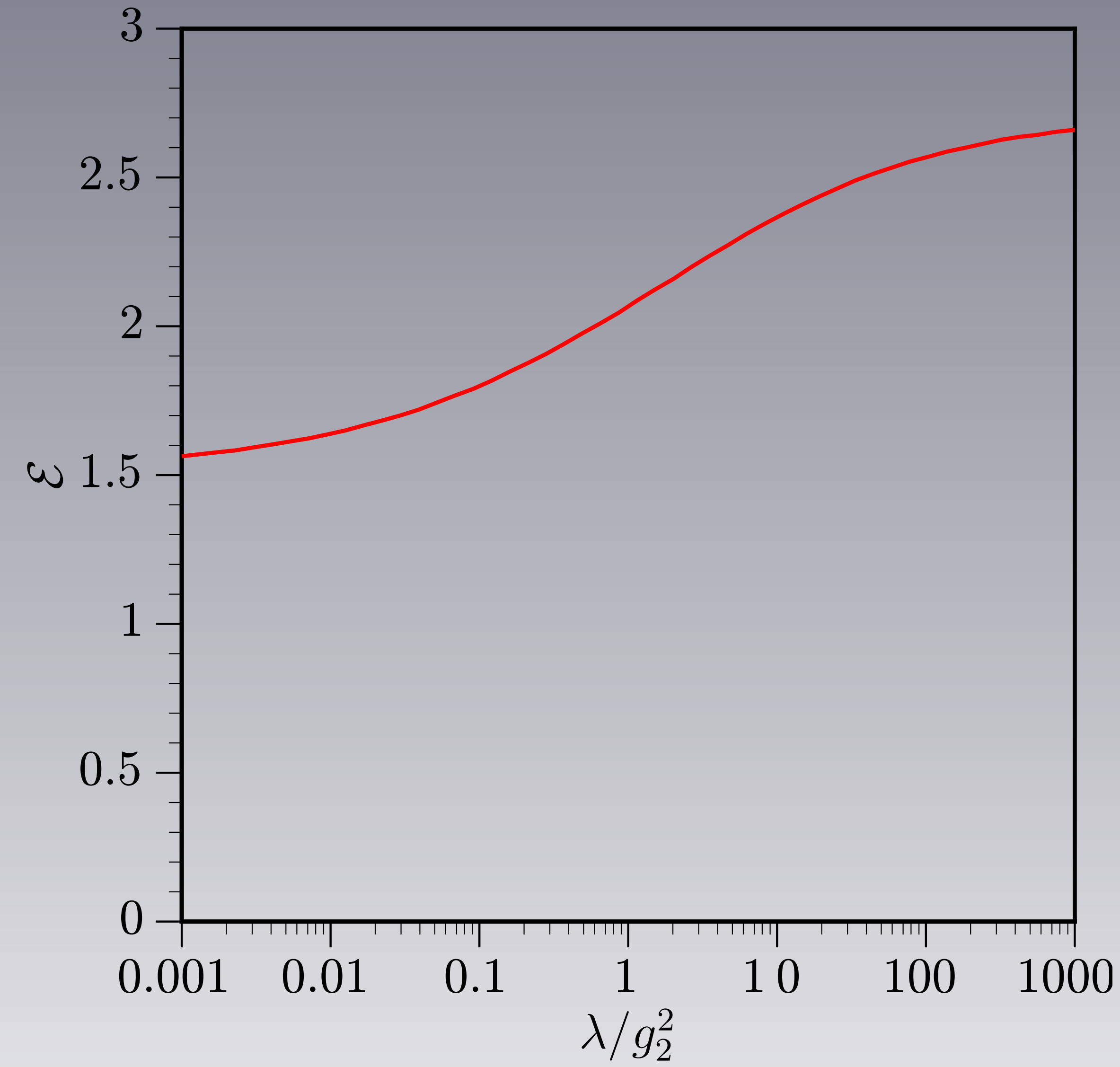
We take SM as an example. ($U(1)_Y$ is neglected)

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + (D_\mu \Phi)^\dagger D^\mu \Phi - V_0(\Phi)$$

$$V_0(\Phi) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$

sphaleron energy:

$$E_{\rm sph} = \frac{4\pi v}{g_2} \mathcal{E}$$



Higgs mass (

$m_h^2 = 2\lambda v^2$

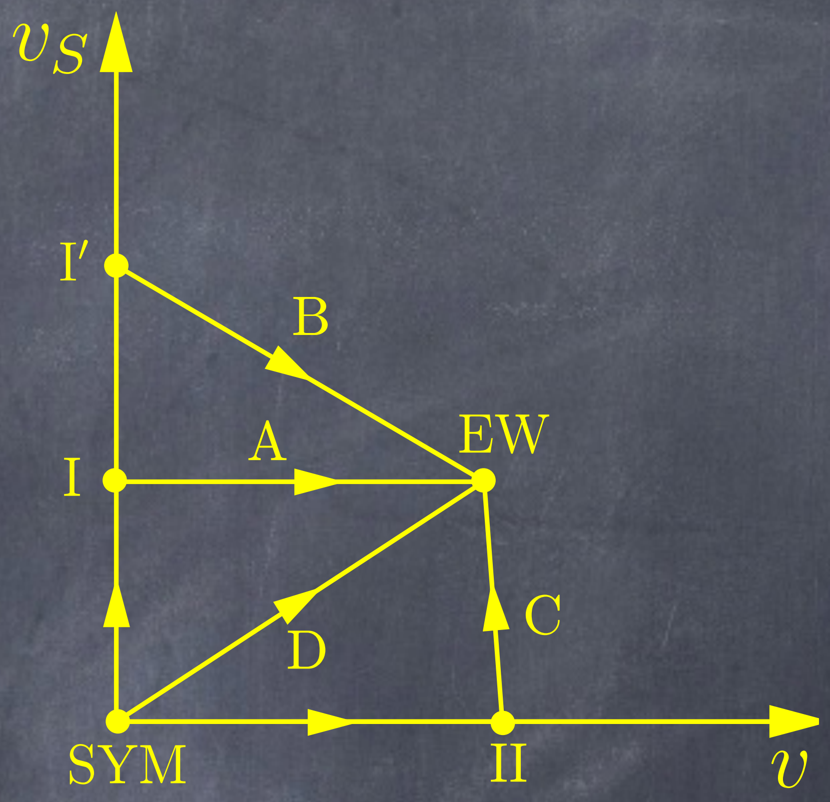
For $m_h = 126$ GeV $(\lambda = 0.13)$, $\mathcal{E} \simeq 1.92$ $\rightarrow$ $\frac{v}{T} \gtrsim 1.16$

Patterns of EWPT

❒ Diverse patterns of the phase transitions.

[K.Funakubo, S. Tao, F. Toyoda., PTP114,369 (2005)]

A: SYM $\rightarrow$ I $\Rightarrow$ EW B: SYM $\rightarrow$ I$'$ $\Rightarrow$ EW
C: SYM $\Rightarrow$ II $\rightarrow$ EW D: SYM $\Rightarrow$ EW



Type B

❒ Before EW symmetry breaking, singlet develops a VEV.

❒ In this case, T_C can be significantly lowered. (v_C/T_C gets enhanced.)

❒ v_S changes a lot during the PT.

Benchmark points

Z2-symmetric

	S1	S2	S3	S4
H-S mixing parameters	λ_{HS}	λ_{HS}, μ_{HS}	λ_{HS}, μ_{HS}	μ_{HS}
PT type	D	B	B	B
m_{H_2} [GeV]	500	170	148	500
α [degrees]	38	-20	0	20
v_S [GeV]	200	90	100	200
μ_{HS} [GeV]	0.00	-80.00	-80.00	-310.72
μ'_S [GeV]	0	-30	-30	0
κ	0.79	0.94	1.0	0.94
$\Delta\lambda_{H_1H_1H_1}$ [%]	-23.7	31.8	0.58	41.1
$\log_{10}(\Lambda/\text{GeV})$	3.90	9.68	13.78	3.90

Benchmark points

Z2-symmetric

	S1	S2	S3	S4
H-S mixing parameters	λ_{HS}	λ_{HS}, μ_{HS}	λ_{HS}, μ_{HS}	μ_{HS}
PT type	D	B	B	B
m_{H_2} [GeV]	500	170	148	500
α [degrees]	38	-20	0	20
v_S [GeV]	200	90	100	200
μ_{HS} [GeV]	0.00	-80.00	-80.00	-310.72
μ'_S [GeV]	0	-30	-30	0
κ	0.79	0.94	1.0	0.94
$\Delta\lambda_{H_1H_1H_1}$ [%]	-23.7	31.8	0.58	41.1
$\log_{10}(\Lambda/\mathrm{GeV})$	3.90	9.68	13.78	3.90

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excluded

Benchmark points

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excluded

no significant deviation

Benchmark points

Z2-symmetric

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excluded

no significant deviation

Benchmark points

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H-S mixing parameters	λ_{HS}	λ_{HS}, μ_{HS}	λ_{HS}, μ_{HS}	μ_{HS}
PT type	D	B	B	B
m_{H_2} [GeV]	500	170	148	500
α [degrees]	38	-20	0	20
v_S [GeV]	200	90	100	200
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μ'_S [GeV]	0	-30	-30	0
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$\Delta\lambda_{H_1H_1H_1}$ [%]	-23.7	31.8	0.58	41.1
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Z2-symmetric (S1)

below GUT scale

excluded

no significant deviation