Electroweak Phase Transition in the Supersymmetric Models

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1. **Introduction**

2. **Minimal Supersymmetric Standard Model**
   (MSSM)

3. **Next-to-Minimal Supersymmetric Standard Model**
   (NMSSM)

4. **Discussions**

for details of EW baryogenesis, please attend the informal seminar

1. Introduction

Baryon Asymmetry of the Universe : $\frac{n_B}{s} \equiv \frac{n_b - n_{\bar{b}}}{s} \simeq (0.37 - 0.88) \times 10^{-10}$

generation of BAU starting from B-symmetric universe

$\Uparrow$

Sakharov's conditions

(1) baryon number violation

(2) C and CP violation

(3) departure from equilibrium

Scenarios of Baryogenesis

1. GUTs

   anomalous $(B+L)$ nonconservation (**"sphaleron process"**)

   in equilibrium at $T \in [T_{EW}, 10^{12}\text{GeV}]$

   $\Downarrow$

   washout of $(B+L)$

2. Leptogenesis, Affleck-Dine : $B = -L$

3. **Electroweak Baryogenesis**

   - the electroweak phase transition (EWPT) must be strongly first order

     [cf. $\Gamma_{EW} \sim 10^{-1}\text{GeV} \gg H(100\text{GeV}) \sim 10^{-14}\text{GeV}$]

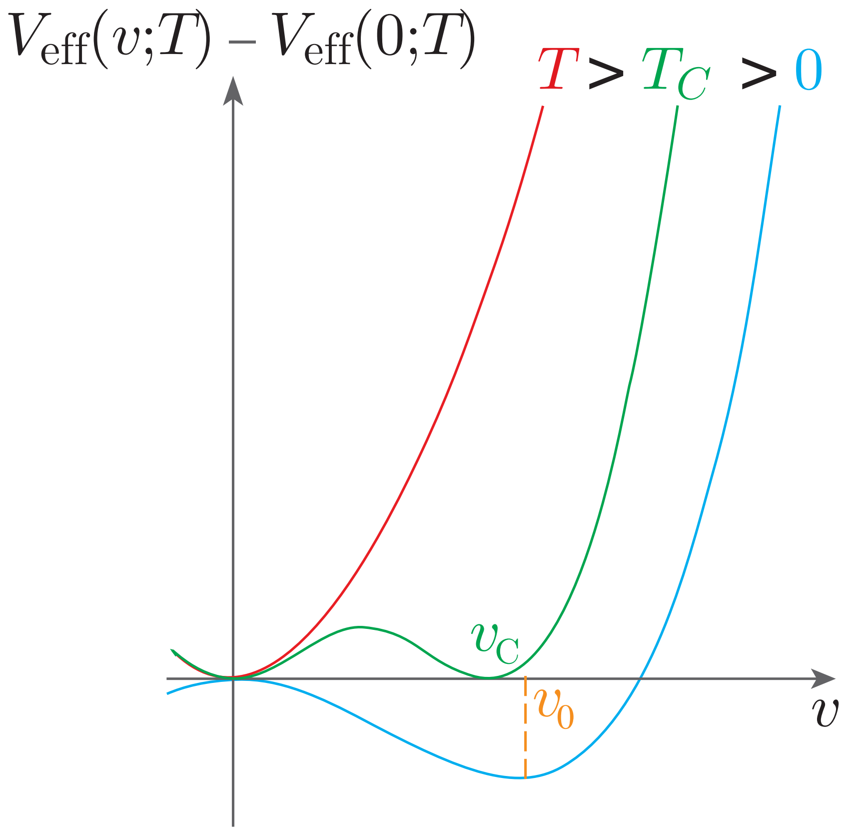
   - needs CP violation other than the KM phase
   - free from proton-decay problem

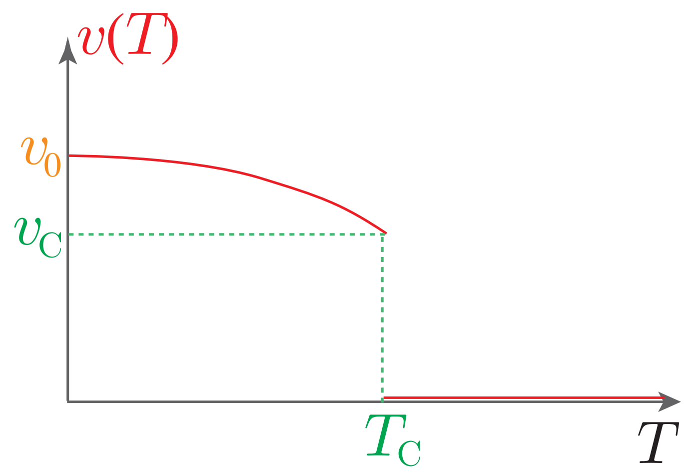
   — related to physics within our reach —

EWPT and Higgs boson

decoupling of the sphaleron process just after the EWPT:

$$\Gamma_{\rm sph}^{\rm (sym)} \simeq \alpha_W^4 T \xrightarrow{T_C} \Gamma_{\rm sph}^{\rm (br)} \simeq \alpha_W^4 T_C e^{-E_{\rm sph}(v_C)/T_C} < H(T_C) \Longrightarrow \boxed{\frac{v_C}{T_C} \gtrsim 1}$$





Minimal SM — perturbation at the 1-loop level

$$V_{\text{eff}}(\varphi;T) = -\frac{1}{2}\mu^2\varphi^2 + \frac{\lambda}{4}\varphi^4 + 2Bv_0^2\varphi^2 + B\varphi^4\left[\log\left(\frac{\varphi^2}{v_0^2}\right) - \frac{3}{2}\right] + \bar{V}(\varphi;T)$$

where $B = \dfrac{3}{64\pi^2 v_0^4}(2m_W^4 + m_Z^4 - 4m_t^4)$,

$$\bar{V}(\varphi;T) = \frac{T^4}{2\pi^2}\left[6I_B(a_W) + 3I_B(a_Z) - 6I_F(a_t)\right], \qquad (a_A = m_A(\varphi)/T)$$

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

high-temperature expansion [$m/T \ll 1$]

$$I_B(a^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}a^2 - \frac{\pi}{6}(a^2)^{3/2} - \frac{a^4}{16}\log\frac{\sqrt{a^2}}{4\pi} - \frac{a^4}{16}\left(\gamma_E - \frac{3}{4}\right)\frac{a^4}{2} + O(a^6)$$

$$I_F(a^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}a^2 - \frac{a^4}{16}\log\frac{\sqrt{a^2}}{\pi} - \frac{a^4}{16}\left(\gamma_E - \frac{3}{4}\right) + O(a^6)$$

For $T > m_W, m_Z, m_t$,

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

where

$$D = \frac{1}{8v_0^2}(2m_W^2 + m_Z^2 + 2m_t^2), \qquad E = \frac{1}{4\pi v_0^3}(2m_W^3 + m_Z^3) \sim 10^{-2}$$

$$\lambda_T = \lambda - \frac{3}{16\pi^2 v_0^4}\left(2m_W^4 \log\frac{m_W^2}{\alpha_B T^2} + m_Z^4 \log\frac{m_Z^2}{\alpha_B T^2} - 4m_t^4 \log\frac{m_t^2}{\alpha_F T^2}\right)$$

$$T_0^2 = \frac{1}{2D}(\mu^2 - 4Bv_0^2), \qquad \log\alpha_{F(B)} = 2\log(4)\pi - 2\gamma_E$$

At T_C, $^{\exists}$degenerate minima: $\varphi_C = \dfrac{2E\,T_C}{\lambda_{T_C}}$

$$\Gamma^{(b)}_{\rm sph}/T_C^3 < H(T_C) \iff \frac{\varphi_C}{T_C} \gtrsim 1$$

$\Longrightarrow$ upper bound on λ $\qquad [m_H = \sqrt{2}\lambda v_0]$

$$m_H \lesssim 46\text{GeV}$$

$\Longrightarrow$ MSM is excluded

⋆ Monte Carlo simulations

[MSM]

effective fermion mass : $m_f(T) \sim O(T) \leftarrow$ nonzero modes

$\therefore$ simulation only with the bosons

QFT on the lattice $\begin{cases} \text{scalar fields:} & \phi(x) \text{ on the sites} \\ \text{gauge fields:} & U_\mu(x) \text{ on the links} \end{cases}$

$$Z = \int [d\phi\, dU_\mu] \exp\{-S_E[\phi, U_\mu]\}$$

- 3-dim. $SU(2)$ system with a Higgs doublet and a triplet — time-component of U_μ
  [Laine & Rummukainen, hep-lat/9809045]

- 4-dim. $SU(2)$ system with a Higgs doublet — [Csikor, hep-lat/9910354]
  EWPT is first order for $m_h < 66.5 \pm 1.4$GeV

Both the simulations found end-point of EWPT at

$$m_h = \begin{cases} 72.3 \pm 0.7 \text{ GeV} \\ 72.1 \pm 1.4 \text{ GeV} \end{cases} \Rightarrow \boxed{\text{no PT (cross-over) in the MSM !}}$$

2. EWPT in the MSSM

- EW Phase Transition

  3 order parameters: $\langle \Phi_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \qquad \langle \Phi_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 + i v_3 \end{pmatrix}$

- CP Violation

  complex parameters: μ, $M_{3,2,1}$, A, $\mu B = m_3^2$

  $v_3 \neq 0$ is induced — $v_3 = 0$ at the tree level

- sphaleron solution

2HDM	[Peccei, et al, PLB '91]
squarks vs sphaleron	[Moreno, et al, PLB '97]
NMSSM	[KF, et al, in progress]

1st-order PT by a light stop

[de Carlos & Espinosa, NPB '97]

stop mass matrix:

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} m^2_{\tilde{t}_L} + \left(\frac{g_1^2}{24} - \frac{g_2^2}{8}\right)(v_u^2 - v_d^2) + \frac{y_t^2}{2} v_u^2 & \frac{y_t}{\sqrt{2}} (\mu v_d + A_t (v_2 - i v_3)) \\ * & m^2_{\tilde{t}_R} - \frac{g_1^2}{6}(v_u^2 - v_d^2) + \frac{y_t^2}{2} v_u^2 \end{pmatrix}$$

$m^2_{\tilde{t}_L} = 0$ or $m^2_{\tilde{t}_R} = 0 \Longrightarrow$ smaller eigenvalue: $m^2_{\tilde{t}_1} \sim O(v^2)$

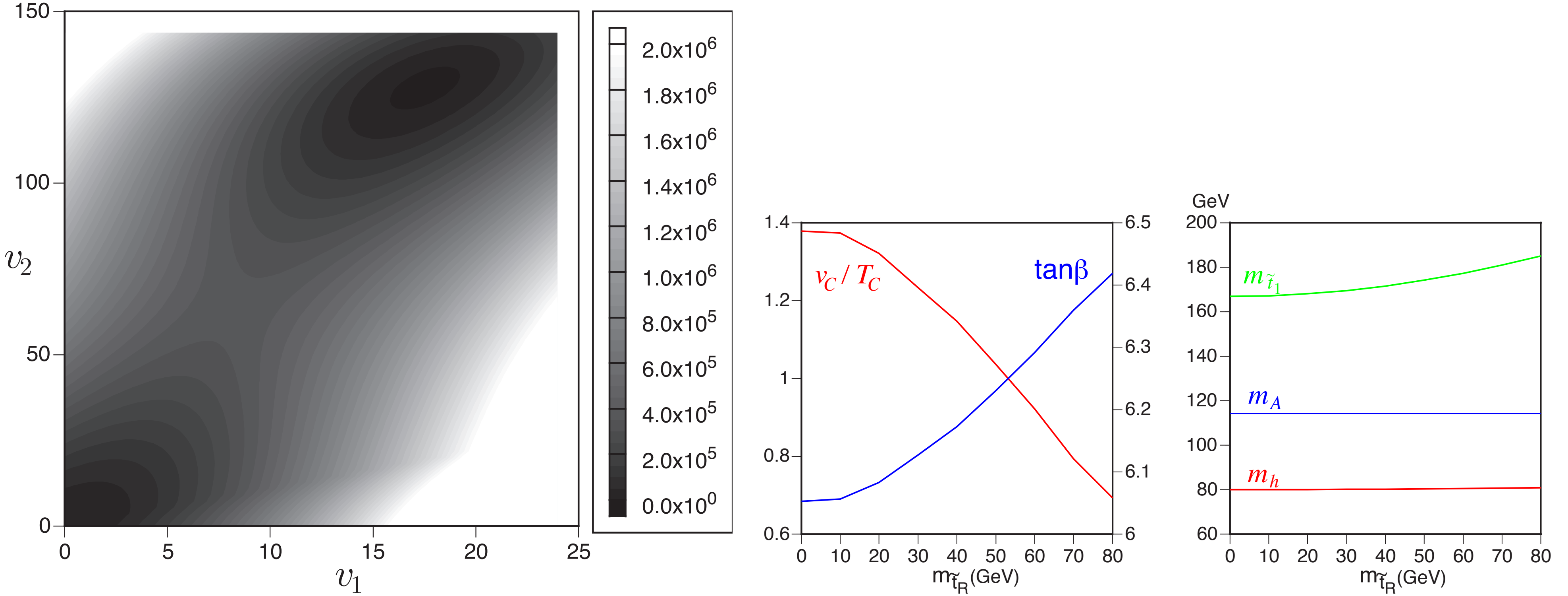
$\therefore$ high-T expansion

$$\bar{V}_{\tilde{t}}(\boldsymbol{v}; T) \Rightarrow -N_c \frac{T}{6\pi} (m^2_{\tilde{t}_1})^{3/2} \sim T v^3 \quad \longrightarrow \text{stronger 1st order PT}$$

effective for larger y_t — smaller $\tan\beta$

An example: $\tan\beta = 6$, $m_h = 82.3\text{GeV}$, $m_A = 118\text{GeV}$, $m_{\tilde{t}_1} = 168\text{GeV}$

$T_C = 93.4\text{GeV}$, $v_C = 129\text{GeV}$ [KF, PTP101]



$V_{\text{eff}}(v_1, v_2, v_3 = 0; T_C)$

m_{t_R}-dependence $(\tan\beta = 6)$

⋆ Lattice MC studies

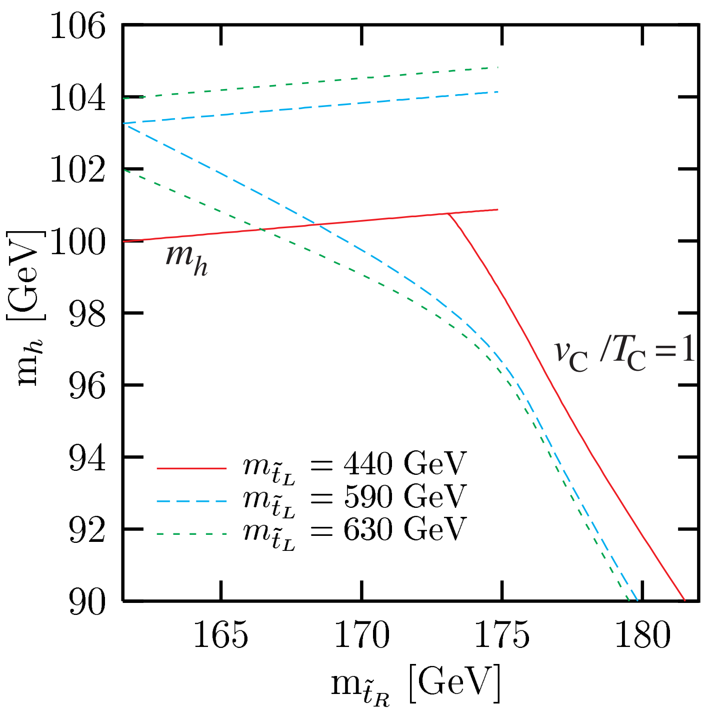
- 3d reduced model [Laine et al. hep-lat/9809045]

  strong 1st order for $m_{\tilde{t}_1} \lesssim m_t$ and $m_h \leq 110\text{GeV}$

- 4d model [Csikor, et al. hep-lat/0001087]

  with $SU(3)$, $SU(2)$ gauge bosons, 2 Higgs doublets, stops, sbottoms

  $A_{t,b} = 0$, $\tan\beta \simeq 6$ $\longrightarrow$ agreement with the perturbation theory within the errors

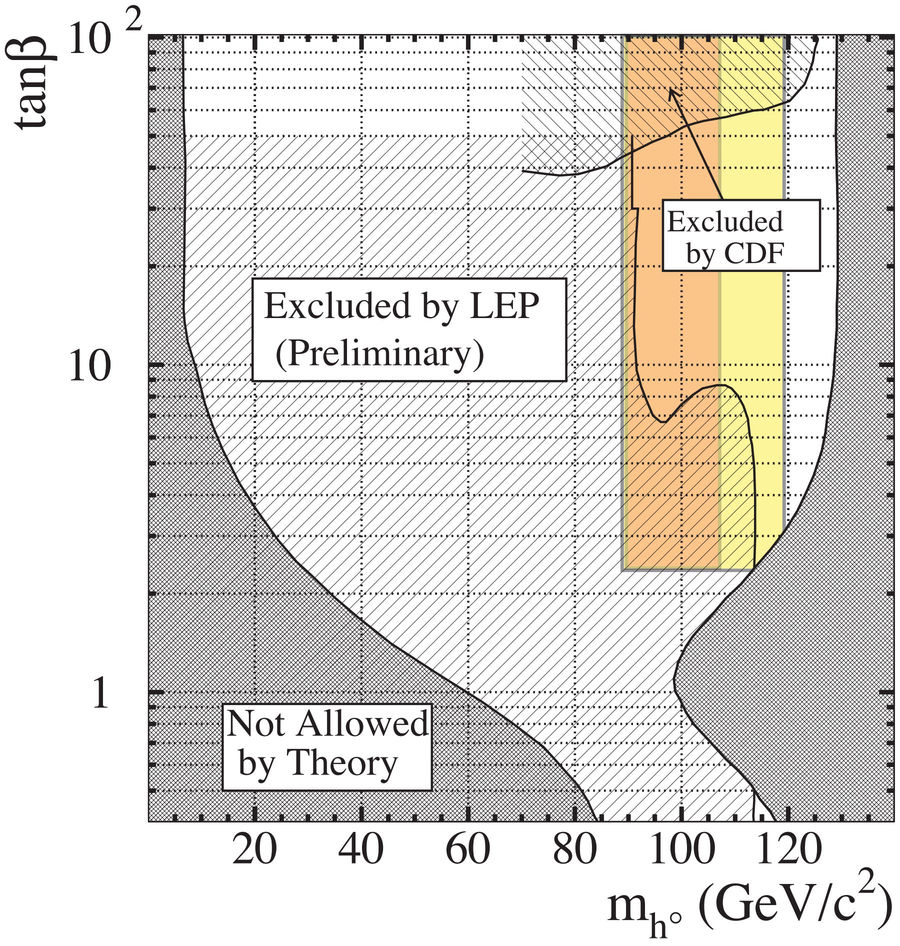


$m_A = 500$ GeV

$v_C/T_C > 1$
below the steeper lines

$\Downarrow$

max. $m_h = 103 \pm 4$ GeV
for $m_{\tilde{t}_L} \simeq 560$ GeV



[PDG, http://ccwww.kek.jp/pdg/]

light stop: $m_{\tilde{t}_R} = 0$

negative soft mass^2: $m^2_{\tilde{t}_R} > -(65\text{GeV})^2$

[Laine & Rummukainen, NPB597]

Effects of CP violation on the EWPT

[KF, Tao & Toyoda, PTP 109]

EWPT in the light-stop scenario [$m_{\tilde{t}_R} = 10\text{GeV}$]

$\mathrm{Im}(\mu A_t e^{i\theta}) \neq 0 \Rightarrow$

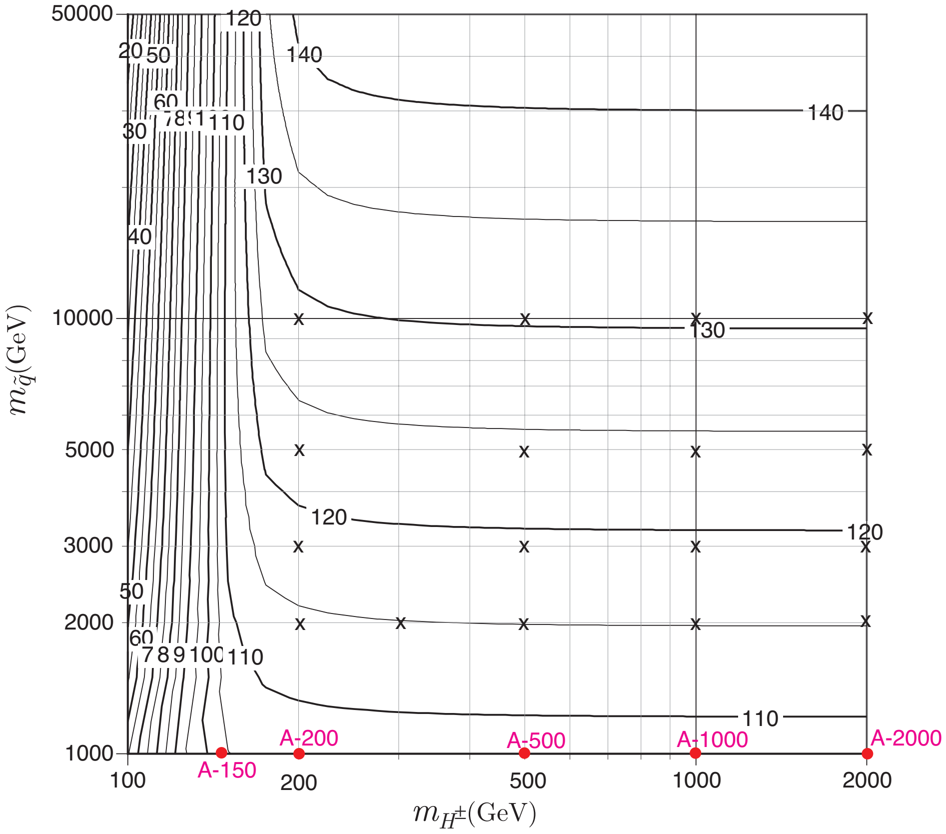
- ▷ scalar-pseudoscalar mixing [Carena, et al., NPB586]
- ▷ induces $\delta = \mathrm{Arg}(m_3^2)$
- • weakens the EWPT

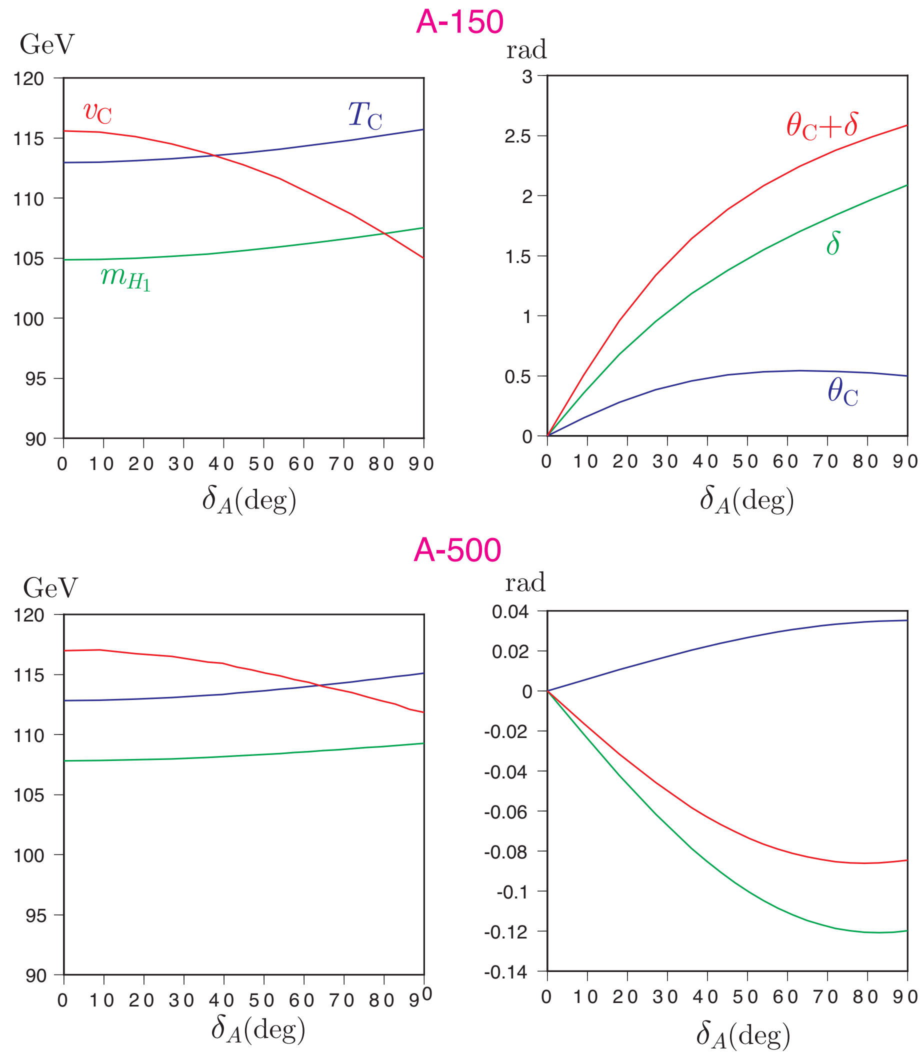
field-dependent mass^2 of the lighter stop:

$$\bar{m}_{\tilde{t}_1}^2 = \frac{1}{2}\Bigg[m_{\tilde{q}}^2 + m_{\tilde{t}_R}^2 + y_t^2 v_u^2 + \frac{g_2^2 + g_1^2}{4}(v_d^2 - v_u^2) - \sqrt{\left(m_{\tilde{q}}^2 - m_{\tilde{t}_R}^2 + \frac{x_t}{2}(v_d^2 - v_u^2)\right)^2 + y_t^2\left|\mu v_d - A_t^* e^{-i\theta} v_u\right|^2}\,\Bigg]$$

$\tan\beta = 10,\ \mu = 1500\text{GeV},\ |A| = 150\text{GeV}$

mass of the lightest Higgs boson (CP conserving)





3. EWPT in the NMSSM

$$W = \epsilon_{ij}\left(y_b H_d^i Q^j B - y_t H_u^i Q^j T + y_l H_d^i L^j E - \lambda N H_d^i H_u^j\right) - \frac{\kappa}{3} N^3$$

$\lambda \langle N \rangle \sim \mu$ in the MSSM

$$\mathcal{L}_{\rm soft} \ni -m_N^2 n^* n + \left[\lambda A_\lambda n H_d H_u + \frac{\kappa}{3} A_\kappa n^3 + \text{h.c.}\right].$$

order parameters: $\langle \Phi_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_{0d} \\ 0 \end{pmatrix}, \quad \langle \Phi_u \rangle = \frac{e^{i\theta_0}}{\sqrt{2}} \begin{pmatrix} 0 \\ v_{0u} \end{pmatrix}, \quad \langle n \rangle = \frac{e^{i\varphi_0}}{\sqrt{2}} v_{0n}$

tree-level Higgs potential:

$$\begin{aligned} V_0 \;=\;& m_1^2 \Phi_d^\dagger \Phi_d + m_2^2 \Phi_u^\dagger \Phi_u + m_N^2 n^* n - \left(\lambda A_\lambda \epsilon_{ij} n \Phi_d^i \Phi_u^j + \frac{\kappa}{3} A_\kappa n^3 + \text{h.c.}\right) \\ & + \frac{g_2^2 + g_1^2}{8} \left(\Phi_d^\dagger \Phi_d - \Phi_u^\dagger \Phi_u\right)^2 + \frac{g_2^2}{2} \left|\Phi_d^\dagger \Phi_u\right|^2 \\ & + |\lambda|^2 n^* n \left(\Phi_d^\dagger \Phi_d + \Phi_u^\dagger \Phi_u\right) + \left|\lambda \epsilon_{ij} \Phi_d^i \Phi_u^j + \kappa n^2\right|^2 \end{aligned}$$

1. 5 neutral and 1 charged scalars (3 scalar and 2 pseudoscalar when CP cons.)

   The lightest Higgs scalar can escape from the lower bound 114GeV, because of small coupling to Z caused by large mixing among 3 scalars. [Miller, et al. NPB 681]

   — "Light Higgs Scenario" —

2. CP violation at the tree level: $\mathrm{Im}\left(\lambda A_\lambda e^{i(\theta+\varphi)}\right)$, $\mathrm{Im}\left(\kappa A_\kappa e^{3i\varphi}\right)$, $\mathrm{Im}\left(\lambda\kappa^* e^{i(\theta-2\varphi)}\right)$

3. $v_n \to \infty$ with λv_n and κv_n fixed $\Longrightarrow$ MSSM [Ellis, et al, PRD 39]

   $\longrightarrow$ new features expected for $v_n = O(100)$GeV

⋆ study of the Higgs spectrum and couplings without/with CP violation ⇐ [KF and Tao, hep-ph/0409294]

⋆ study of the EWPT without/with CP violation ⇐ preliminary

⋆ sphaleron solution [KF, et al. in progress] many parameters in the model — in the Higgs sector, soft masses, λ, κ, A_λ, A_κ

complex parameters

$$R_\lambda = \frac{1}{\sqrt{2}}\mathrm{Re}\left(\lambda A_\lambda e^{i(\theta_0+\varphi_0)}\right), \qquad I_\lambda = \frac{1}{\sqrt{2}}\mathrm{Im}\left(\lambda A_\lambda e^{i(\theta_0+\varphi_0)}\right),$$

$$R_\kappa = \frac{1}{\sqrt{2}}\mathrm{Re}\left(\kappa A_\kappa e^{3i\varphi_0}\right), \qquad I_\kappa = \frac{1}{\sqrt{2}}\mathrm{Im}\left(\kappa A_\kappa e^{3i\varphi_0}\right),$$

$$\mathcal{R} = \mathrm{Re}\left(\lambda\kappa^* e^{i(\theta_0-2\varphi_0)}\right), \qquad \mathcal{I} = \mathrm{Re}\left(\lambda\kappa^* e^{i(\theta_0-2\varphi_0)}\right)$$

"tadpole condition": $\left\langle \frac{\partial V_{\mathrm{eff}}}{\partial h_i} \right\rangle = \left\langle \frac{\partial V_{\mathrm{eff}}}{\partial a_i} \right\rangle = 0$

$$m_1^2 = \left(R_\lambda - \frac{1}{2}\mathcal{R} v_{0n}\right) v_{0n}\tan\beta_0 - \frac{1}{2}m_Z^2\cos(2\beta_0) - \frac{|\lambda|^2}{2}(v_{0n}^2 + v_{0u}^2) + \cdots$$

$$\cdots$$

$$m_N^2 = (R_\lambda - \mathcal{R} v_{0n})\frac{v_{0d}v_{0u}}{v_{0n}} + R_\kappa v_{0n} - \frac{|\lambda|^2}{2}(v_{0d}^2 + v_{0u}^2) - |\kappa|^2 v_{0n}^2 + \cdots$$

$$I_\lambda = \frac{1}{2}\mathcal{I} v_{0n} + \cdots, \qquad I_\kappa = -\frac{3}{2}\mathcal{I}\frac{v_{0d}v_{0u}}{v_{0n}}$$

mass matrix of the neutral Higgs bosons

$$\mathcal{M}^2 \equiv \begin{pmatrix} \left\langle \frac{\partial^2 V_{\rm eff}}{\partial h_i \partial h_j} \right\rangle & \left\langle \frac{\partial^2 V_{\rm eff}}{\partial h_i \partial a_j} \right\rangle \\ \left\langle \frac{\partial^2 V_{\rm eff}}{\partial a_i \partial h_j} \right\rangle & \left\langle \frac{\partial^2 V_{\rm eff}}{\partial a_i \partial a_j} \right\rangle \end{pmatrix} \xrightarrow{\text{extract NG modes}} \begin{pmatrix} \mathcal{M}_S^2 & \mathcal{M}_{SP}^2 \\ \mathcal{M}_{SP}^{2T} & \mathcal{M}_P^2 \end{pmatrix}$$

$$\mathcal{M}_{SP}^2 \propto \mathcal{I}$$

We use $m_{H^\pm}$ as an input, instead of R_λ:

$$m_{H^\pm}^2 = \frac{1}{\sin\beta\cos\beta}\left\langle \frac{\partial^2 V_{\rm eff}}{\partial \phi_d^+ \partial \phi_u^-} \right\rangle = m_W^2 - \frac{1}{2}|\lambda|^2 v^2 + (2R_\lambda - \mathcal{R} v_{0n})\frac{v_{0n}}{\sin 2\beta_0} + \cdots$$

Definition of the couplings

gauge vs mass eigenstates: $\begin{pmatrix} h_d \\ h_u \\ h_n \\ a \\ a_n \end{pmatrix} = \mathcal{O} \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \end{pmatrix}$, $\quad \mathcal{O}^T \mathcal{M}^2 \mathcal{O} = \mathrm{diag}(m_{H_1}^2, \cdots, m_{H_5}^2)$

$$\mathcal{L}_{\mathrm{gauge}} \ni g_2 m_W g_{VVH_i} \left(W_\mu^+ W^{-\mu} + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu \right) H_i + \frac{g_2}{2\cos\theta_W} g_{ZH_iH_j} Z^\mu (H_i \overleftrightarrow{\partial}_\mu H_j)$$

$$\mathcal{L}_{\mathrm{Y}} \ni -\frac{g_2 m_b}{2 m_W} \bar{b}(g_{bbH_i}^S + i\gamma^5 g_{bbH_i}^P) b H_i$$

$$\begin{cases} g_{VVH_i} = \mathcal{O}_{1i}\cos\beta + \mathcal{O}_{2i}\sin\beta \\ g_{ZH_iH_j} = \frac{1}{2}\{(\mathcal{O}_{4i}\mathcal{O}_{2j} - \mathcal{O}_{4j}\mathcal{O}_{2i})\cos\beta - (\mathcal{O}_{4i}\mathcal{O}_{1j} - \mathcal{O}_{4j}\mathcal{O}_{1i})\sin\beta\} \\ g_{bbH_i}^S = \mathcal{O}_{1i}\frac{1}{\cos\beta}, \qquad g_{bbH_i}^P = -\mathcal{O}_{4i}\tan\beta \end{cases}$$

$$g_{bbH_i}^2 \equiv \left(g_{bbH_i}^S\right)^2 + \left(g_{bbH_i}^P\right)^2$$

inputs:

$v_0 = 246\text{GeV},\ \tan\beta_0,\ v_{0n},\ m_{H^\pm},\ |\lambda|,\ |\kappa|,\ |A_\lambda|,\ |A_\kappa|,\ \mathrm{Arg}\kappa\ \ [m_{\tilde{q}},\ m_{\tilde{t}_R} = m_{\tilde{b}_R},\ A_t]$

some combination of the phases is constrained

We require

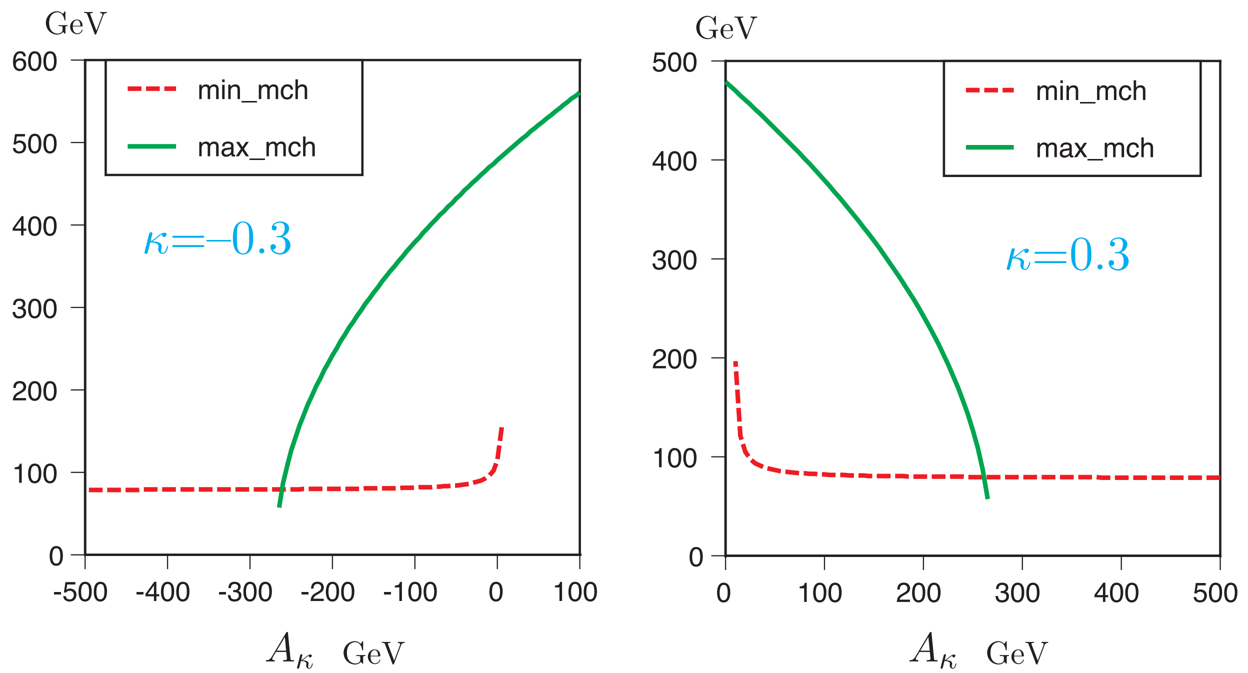
1. all the mass^2 of the scalars > 0
2. $m_{H_i} > 114\text{GeV}$ or $g^2_{H_iZZ} < 0.01$ — spectrum condition
3. $V_{\rm eff}(\mathbf{0}) > V_{\rm eff}(\boldsymbol{v}_0)$ — vacuum condition-0
4. no global mim. of $V_{\rm eff}$ other than $\boldsymbol{v}_0$ — vacuum condition

condition-1 $\ni \det \mathcal{M}_P^2 > 0 \Rightarrow$ lower bound on $m_{H^\pm}$ [cf, $m_{H^\pm}$ vs m_A in the MSSM]

condition-3 at the tree level

$$m_{H^\pm}^2 < m_W^2 + m_Z^2 \cot^2 2\beta_0 + \frac{2|\lambda|^2 v_{0n}^2}{\sin^2 2\beta_0} + \frac{2|\kappa|^2 v_{0n}^4}{v_0^2 \sin^2 2\beta_0} + \frac{\mathcal{R} v_{0n}^2}{\sin 2\beta_0} - \frac{4 R_\kappa v_{0n}^3}{3 v_0^2 \sin^2 2\beta_0}$$

$\tan\beta = 5, \;\; v_n$=300GeV

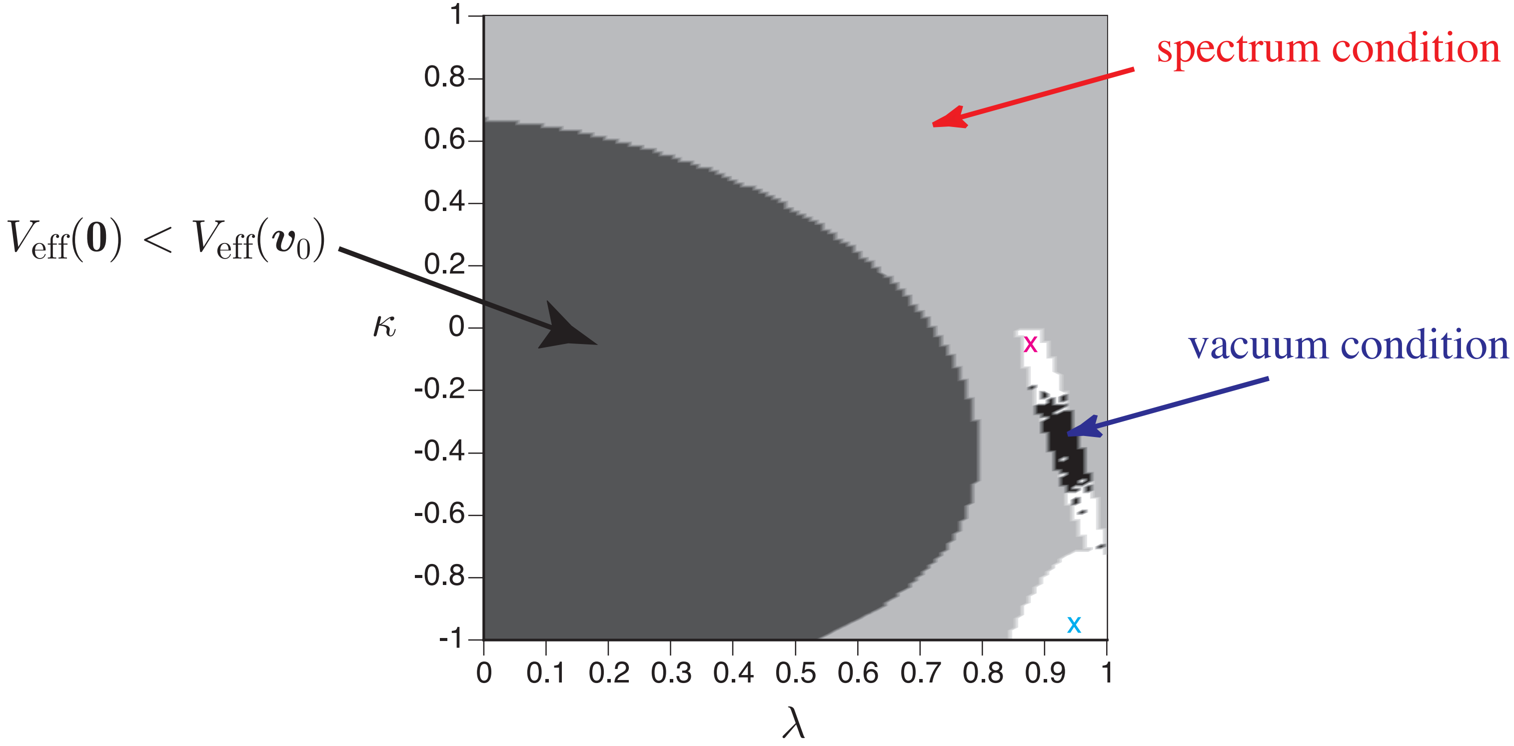


$\Rightarrow \kappa A_k > 0$ is favored

numerical search for allowed parameter region

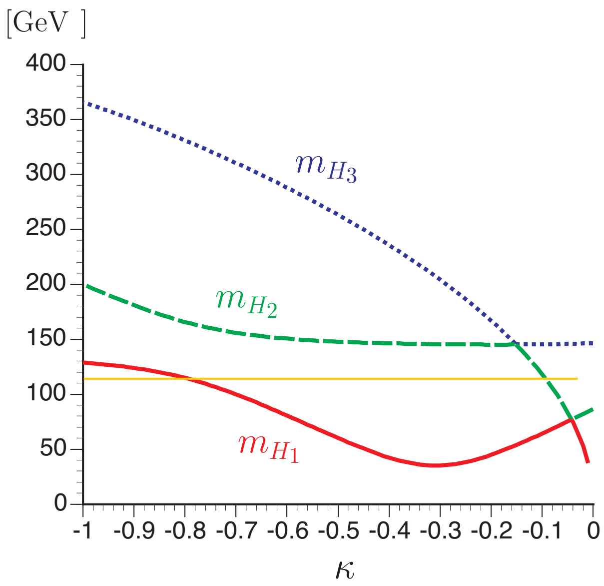
$\tan\beta_0 = 3 - 20$, $v_{0n} = 100 - 1000\text{GeV}$, $m_{H^\pm} = 100 - 5000\text{GeV}$, $-A_\kappa = 0 - 1000\text{GeV}$

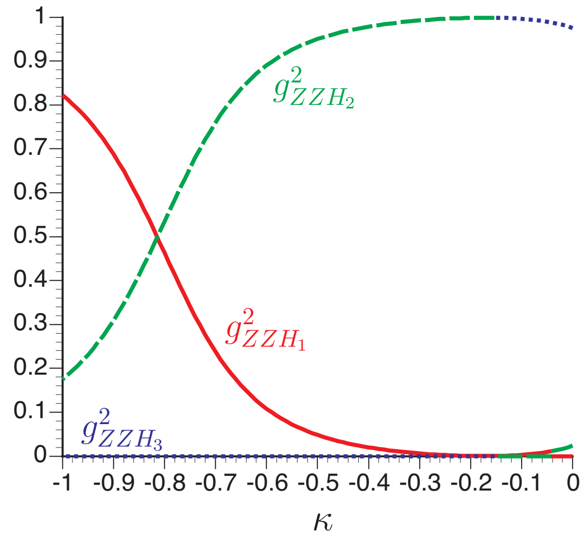
e.g., $\tan\beta_0 = 3$, $v_{0n} = 200\text{GeV}$, $m_{H^\pm} = 400\text{GeV}$, $A_\kappa = -200\text{GeV}$, heavy squark

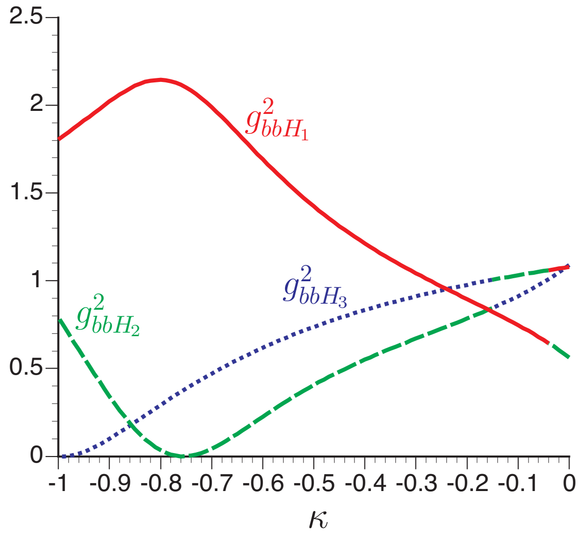


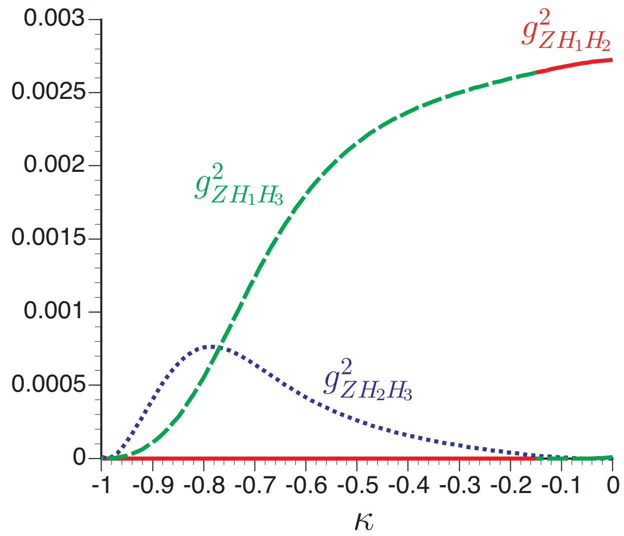
λ	κ	m_{H_1}	m_{H_2}	m_{H_3}	m_{H_4}	m_{H_5}	$g^2_{H_1ZZ}$	$g^2_{H_2ZZ}$	$g^2_{H_3ZZ}$	$g^2_{H_4ZZ}$	$g^2_{H_5ZZ}$
0.9	-0.05	75.0	83.5	145.7	436.0	448.2	0.0094	0	0.9897	0.0009	0
0.95	-0.95	139.6	180.9	360.3	425.4	456.4	0.828	0.170	0	0	0.0028

along the line of $\lambda = 0.9$,









Effects of CP violation

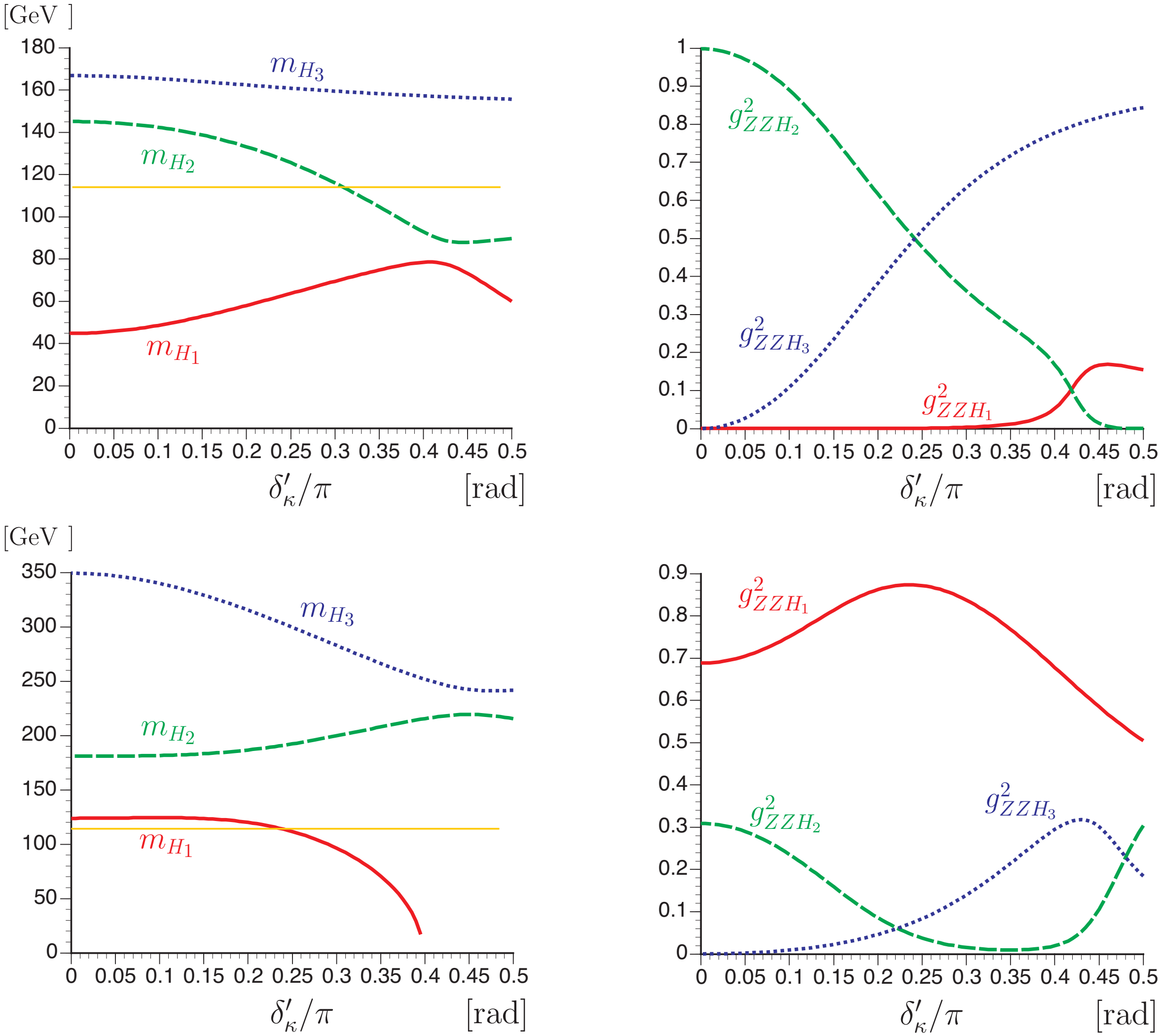
$\delta'_\kappa \equiv \mathrm{Arg}\kappa + 3\varphi_0$ $\quad$ $\mathrm{Arg}\lambda + \theta_0 + \varphi_0 = 0 \Leftrightarrow$ small EDM

λ=0.9

κ=-0.2

λ=0.9

κ=-0.9



[MSSM with nonzero $\mathrm{Im}(\mu A_q e^{i\theta_0})$: Carena, et al. NPB586]

EWPT [preliminary]

naive (?) argument [Pietroni, NPB402]

order parameters :
$$\begin{cases} v_d = v\cos\beta(T) = y\cos\alpha(T)\cos\beta(T), \\ v_u = v\sin\beta(T) = y\cos\alpha(T)\sin\beta(T), \\ v_n = y\sin\alpha(T) \end{cases}$$

$$\begin{aligned} V_0 &= \frac{1}{2}\left((m_1^2\cos^2\beta + m_2^2\sin^2\beta)\cos^2\alpha + m_N^2\sin^2\alpha\right) y^2 \\ &\quad - \left(R_\lambda\cos^2\alpha\sin\alpha\cos\beta\sin\beta + \frac{1}{3}R_\kappa\sin^3\alpha\right) y^3 + \cdots. \end{aligned}$$

strongly 1st order PT by the tree-level cubic term

Is such a parametrization valid ?

— no symmetry between the doublets and the singlet

2-stage Phase Transition

$T_C \equiv$ PT temperature of the EWPT *i.e.*, at which $v = \sqrt{v_d^2 + v_u^2} \to 0$

$T_N \equiv$ PT temparature at which $v_n \to 0$

(1) $T_C > T_N$ — first-order EWPT requires a light stop

for $T_N < T < T_C$, ${}^{\exists}U(1)$ symmetry of the singlet

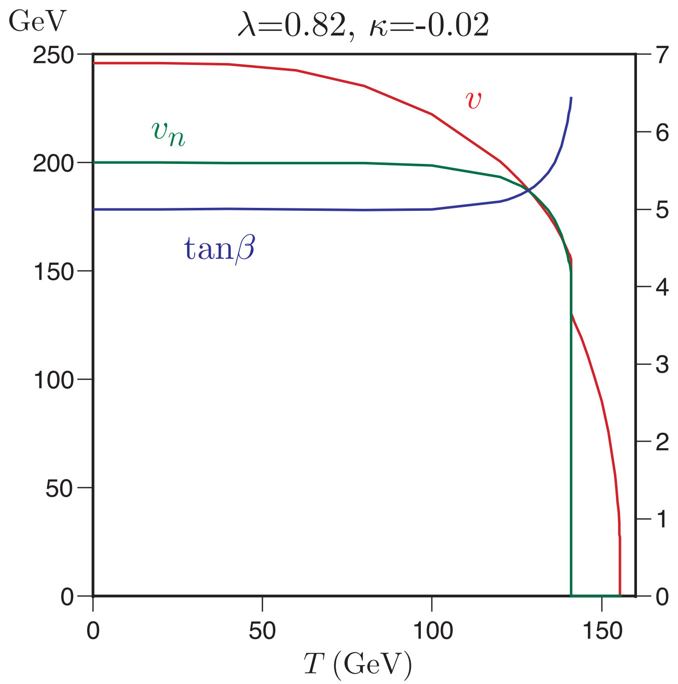
(2) $T_C = T_N$ — strongly first order

(3) $T_C < T_N$ — MSSM-like EWPT

roughly speaking, $\begin{cases} \text{light Higgs} & \Longrightarrow \quad (1),\ (2) \\ \text{heavy Higgs} & \Longrightarrow \quad (3) \end{cases}$

Ex-1 (light Higgs)

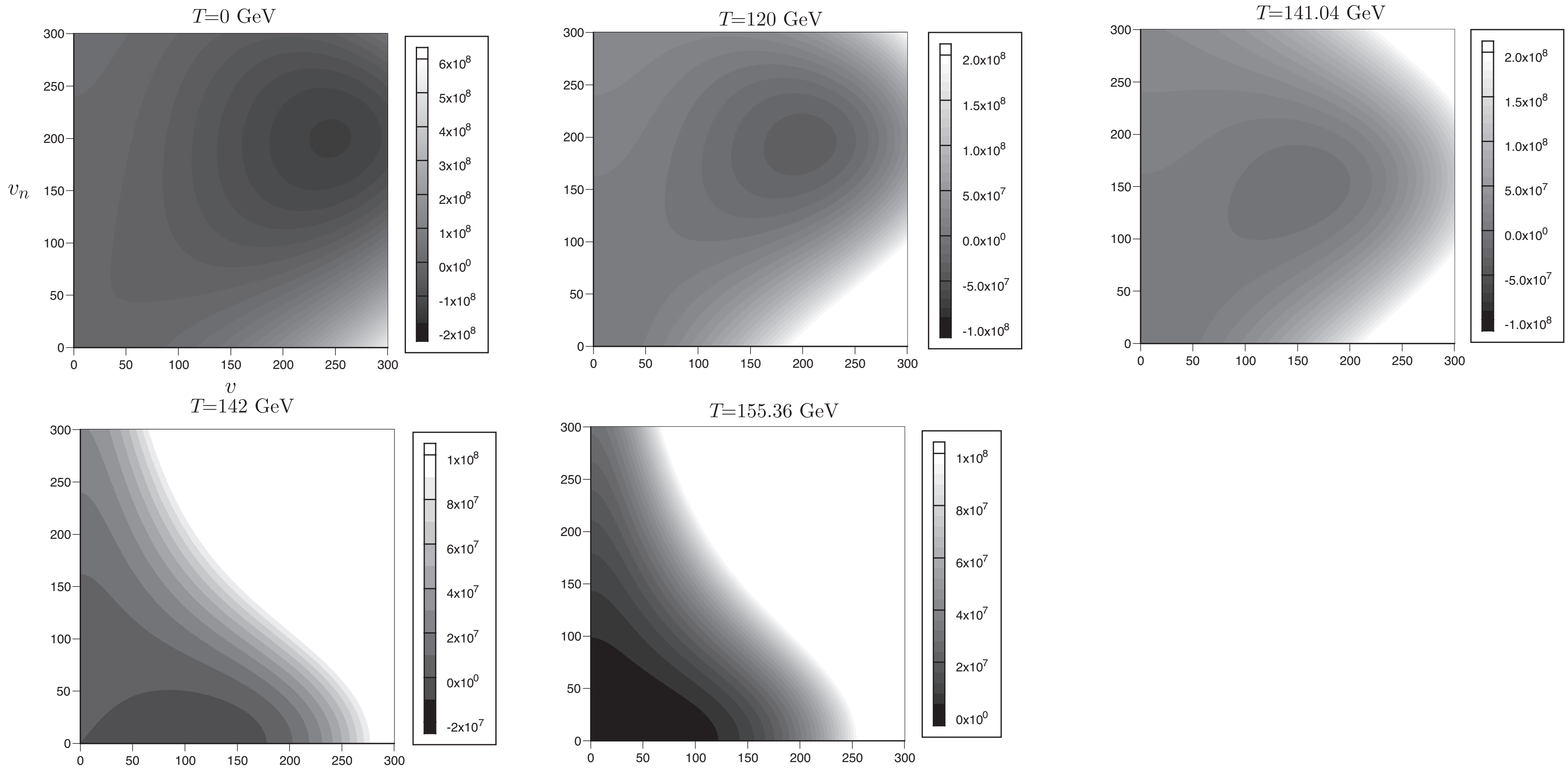
$\tan\beta = 5$, $m_{H^\pm} = 600\text{GeV}$, $A_\kappa = -100\text{GeV}$, $\lambda = 0.82$, $\kappa = -0.02$, heavy squark



$$(v_d, v_u, v_n) = (48.2, 241.2, 200) \to (23.8, 153.3, 149.0) \xrightarrow{T_N=126.8\text{GeV}} (0, 130.2, 0)$$

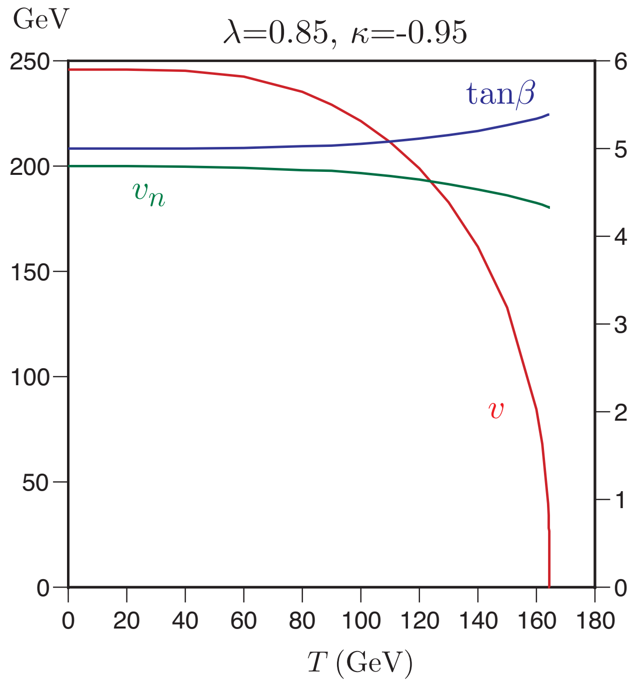
$$\to (0, 26.0, 0) \xrightarrow{T_C=155.4\text{GeV}} (0, 0, 0)$$

reduced effective potential: $\tilde{V}_{\rm eff}(v, v_n; T) \equiv V_{\rm eff}(v\cos\beta(T), v\sin\beta(T), v_n; T)$



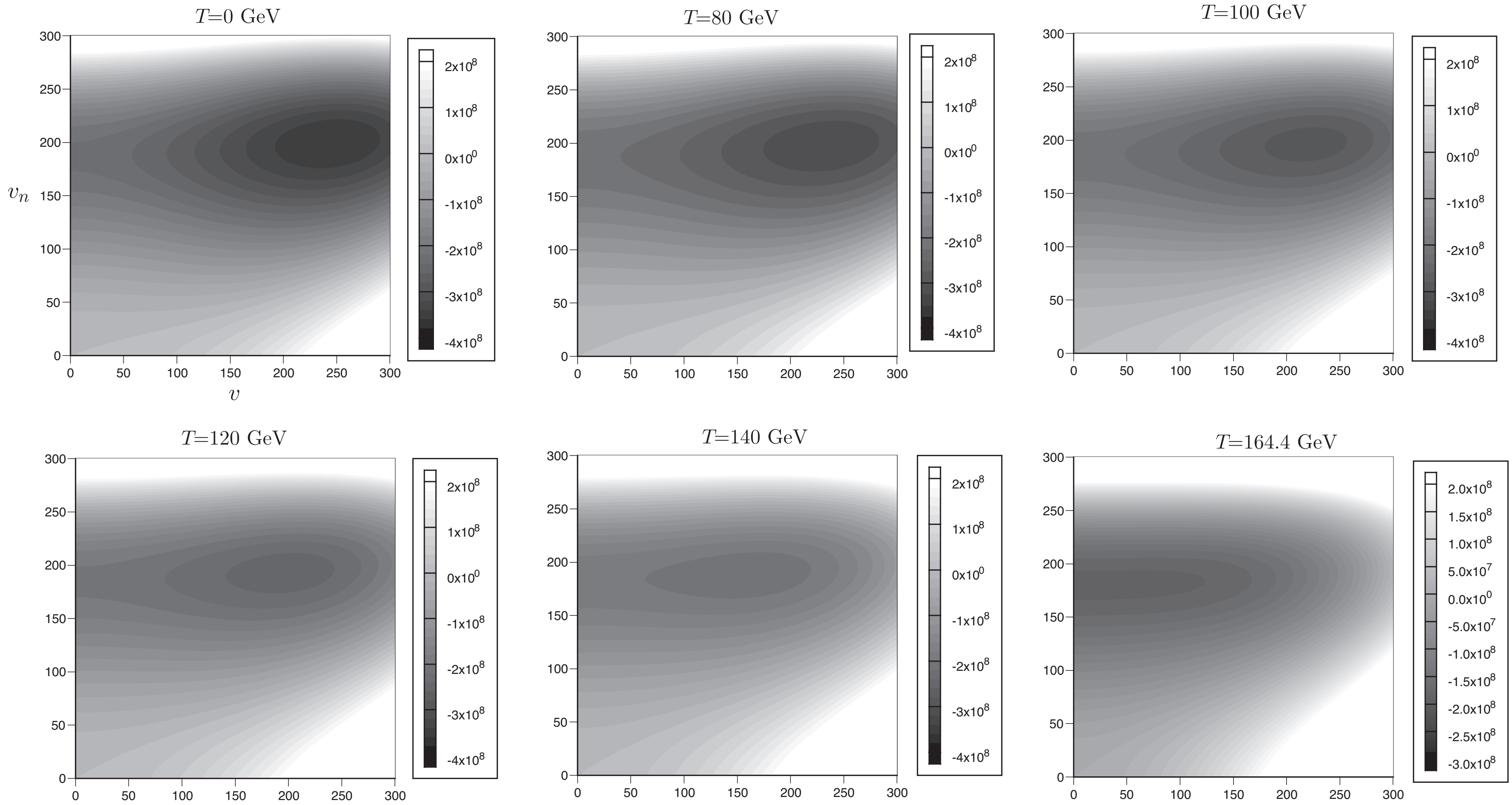
Ex-2 (heavy Higgs)

$\tan\beta = 5$, $m_{H^\pm} = 600\text{GeV}$, $A_\kappa = -100\text{GeV}$, $\lambda = 0.85$, $\kappa = -0.95$, heavy squark



$$(v_d, v_u, v_n) = (48.2, 241.2, 200) \to (4.9, 26.4, 180.5) \xrightarrow{T_C=164.36\text{GeV}} (0, 0, 180.4)$$

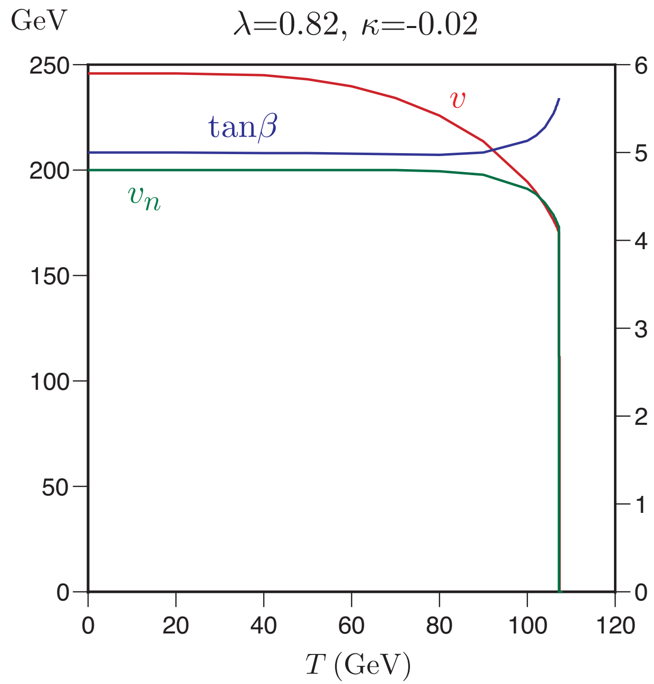
$T_N \gg 200\text{GeV}$



T=0 GeV
T=80 GeV
T=100 GeV
T=120 GeV
T=140 GeV
T=164.4 GeV
v_n
v
0
50
100
150
200
250
300
2x10^8
1x10^8
0x10^0
-1x10^8
-2x10^8
-3x10^8
-4x10^8
2.0x10^8
1.5x10^8
1.0x10^8
5.0x10^7
0.0x10^0
-5.0x10^7
-1.0x10^8
-1.5x10^8
-2.0x10^8
-2.5x10^8
-3.0x10^8

Ex-3 (light Higgs)

the same parameters as Ex-1, except for $m_{\tilde{t}_R} = 800\text{GeV} \rightarrow 10\text{GeV}$ (light squark)



$$(v_d, v_u, v_n) = \quad (48.2, 241.2, 200) \rightarrow (29.8, 167.8, 172.6) \xrightarrow{T_N=107.28\text{GeV}} (0, 111.7, 0)$$

$$\rightarrow \quad (0, 110.2, 0) \xrightarrow{T_C=107.40\text{GeV}} (0, 0, 0)$$

for a lighter squark, $T_C \rightarrow T_N$ and stronger PT

4. Discussions

EW Baryogenesis needs extensions of the SM for

⋆ CP violation

new sources of CP violation precise measurements of CP-viol. BR

⋆ strongly 1st-order EWPT extra scalars: 2HDM, MSSM, NMSSM, ⋯

$\Longrightarrow$ Higgs spectrum and couplings LHC

- $m_H > 120\text{GeV} \Longrightarrow$ 1st-order EWPT in the MSSM **X**
- $m_H > 135\text{GeV} \Longrightarrow$ MSSM **X**

  NMSSM (light Higgs for 1st-order EWPT?)

  2HDM, etc.

◦ No Higgs found $\Longrightarrow$ origin of the matter cannot be explained solely by EW physics

Leptogenesis, Affleck-Dine, GUTs, ⋯

works in progress — NMSSM

- Phase transition in the presence of CP violation

  CP violation not constrained by the EDM

- Sphaleron solution for various boundary conditions

  $v_n = 0$ and $v_n \neq 0$ in the broken phase $(v \neq 0)$

to-do

⋆ CP violation in the phase boundary

⋆ Calculation of the generated baryon number

  * formalism: quantum and semi-classical — CTP ?
  * space-varying $\mathrm{Im}\mu \sim \mathrm{Im}\,\langle N \rangle \neq 0$ in the NMSSM

    $\Rightarrow$ quark/lepton, chargino/neutralino, squark/slepton