Results on the Electroweak Phase Transition

in the NMSSM with Explicit CPV

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Contents

- We study the PT in the NMSSM
- The weak scale vev. of the singlet scalar is considered
- We find four different types of phase transitions
- Three of which have two-stage nature
- One of the two-stage transitions admits strongly first order EWPT, even with heavy squarks
- We introduce tree-level CP violation

Introduction

Electroweak baryogenesis (EWBG)

- is related to physics at our reach
- require strongly first-order phase transition
  $\rightarrow$ light boson is required

EWBG in the Minimal SM

- light boson, $m_h > 50\,\mathrm{GeV}$ conflict to present bound, $m_{h_{\mathrm{SM}}} > 114\,\mathrm{GeV}$
- CPV in the CKM matrix is too small to generate sufficient baryon number

Introduction

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EWBG in the MSSM

- with a light top squark
  The bound on the lightest Higgs boson restricts the acceptable parameter space severely
- CPV in the soft SUSY X terms
  first-order EWPT is weakened, when the stop-sector CP violation is large [K. Funakubo, S. T. and F. Toyoda, PTP101]

Introduction

Electroweak baryogenesis (EWBG)

- is related to physics at our reach
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EWBG in the NMSSM

- reduces to the MSSM in some limit
  For such peculiar parameters, we expect the same behavior of the EWPT as that in the MSSM, which has been extensively studied
- We focus on the parameter space far from the MSSM

NMSSM

Next-to-Minimal Supersymmetric Standard Model

- Light Higgs
- CP Violation
- Parameter Set

  [K. Funakubo and S. T. hep-ph/0409294]

The Model

$\langle$NMSSM$\rangle$ = $\langle$MSSM$\rangle$ + (one gauge singlet)

$$W = f_d H_d Q D^c - f_u H_u Q U^c - \lambda N H_d H_u - \frac{\kappa}{3} N^3$$

- solves the μ-problem in the MSSM
  μ-parameter is induced as $\mu = \lambda \langle N \rangle$
- no dimensional parameter in W
  The scale by which NMSSM is characterized comes from SUSY-breaking terms

In the NMSSM, $m_{\rm SUSY} \gg \langle H \rangle$ or $\langle N \rangle$ is unnatural

The Model

$\langle \text{NMSSM} \rangle = \langle \text{MSSM} \rangle + (\text{one gauge singlet})$

$$W = f_d H_d Q D^c - f_u H_u Q U^c - \lambda N H_d H_u - \frac{\kappa}{3} N^3$$

SUSY-breaking soft terms:

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

- unremovable CP phases
- global Z_3 symmetry $\longrightarrow$ Domain wall problem
  We assume it's already broken by higher dimensional operator

The Model - Higgs Sector

The tree-level Higgs potential:

$$V = m_1^2 \Phi_d^\dagger \Phi_d + m_2^2 \Phi_u^\dagger \Phi_u + m_N^2 n^* n - \left(\lambda A_\lambda n \Phi_d \Phi_u + \frac{\kappa}{3} A_\kappa n^3 + \text{h.c.}\right)$$
$$+ \frac{g_2^2 + g_1^2}{8} (\Phi_d^\dagger \Phi_d - \Phi_u^\dagger \Phi_u)^2 + \frac{g_2^2}{2} (\Phi_d^\dagger \Phi_u)(\Phi_u^\dagger \Phi_d)$$
$$+ |\lambda|^2 n^* n (\Phi_d^\dagger \Phi_d + \Phi_u^\dagger \Phi_u) + |\lambda \Phi_d \Phi_u + \kappa n^2|^2$$

Vacuum expectation values:

$$\langle \Phi_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \quad \langle \Phi_u \rangle = \frac{e^{i\theta}}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \quad \langle n \rangle = \frac{e^{i\phi}}{\sqrt{2}} v_n$$

Light Higgs

The structure of the mass matrix changes from that in the MSSM (3 scalar and 2 pseudoscalar if CP cons.)

$$\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_S^2\big|_{2\times 2} & \\ & m_A^2 \end{pmatrix} \to \begin{pmatrix} \mathcal{M}_S^2\big|_{3\times 3} & \mathcal{I} \\ \mathcal{I} & \mathcal{M}_P^2\big|_{2\times 2} \end{pmatrix}$$

- "light-Higgs bosons" are allowed $\rightarrow$ Strong 1st order PT

$$m_{h_1} < 114\text{GeV} \quad \text{with} \quad g_{ZZh_1} \sim 0.1$$

because of the small g_{ZZh_1}
Then the lightest Higgs scalar h_1 can escape from the bound

$$m_{h_{\rm SM}} > 114\text{GeV}$$

Therefore, we can consider $h_2 \sim h_{\rm SM}$ [Miller, et. al. NPB681]

Virtues of the NMSSM

- light Higgs $\longrightarrow$ Strong 1st order PT

Virtues of the NMSSM

- light Higgs $\rightarrow$ Strong 1st order PT
- CP violation at the tree level, $\mathcal{I}$ $\rightarrow$ Sufficient B number

$$\mathcal{I} = \mathrm{Im}(\lambda\kappa^* e^{i(\theta-2\phi)})$$

from the vacuum condition, $\mathcal{I}$ related to the other combinations

$$\mathcal{I} \sim \mathrm{Im}(\lambda A_\lambda e^{i(\theta+\phi)}) \sim \mathrm{Im}(\kappa A_\kappa e^{3i\phi})$$

  - Only one combination of the phases is physical
  - Our formalism is independent of prametrisation for the phases
  - One can choose the phase combination not to affect the nEDM

Virtues of the NMSSM

- light Higgs $\longrightarrow$ Strong 1st order PT
- CP violation at the tree level, $\mathcal{I} \longrightarrow$ Sufficient B number
- Pure NMSSM parameter set

  vs. MSSM limit

  $v_n \to \infty$ with λv_n and κv_n fixed $\Rightarrow$ MSSM [Ellis, et. al. PRD39]

  Moderate v_n value $\sim 200\,\mathrm{GeV}$, and soft masses $<$ TeV

  $\longrightarrow$ new features expected

  - light Higgs bosons are realized
  - mass bound on the charged Higgs bosons

    [K. Funakubo and S. T. hep-ph/0409294]

Virtues of the NMSSM

- light Higgs $\longrightarrow$ Strong 1st order PT
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- Pure NMSSM parameter set

These are Good features for Electroweak baryogenesis

EWPT

Electroweak Phase Transition in the NMSSM

- Cubic Term
- Types of the PT
- Effects of the CPV

  [K. Funakubo and S. T. hep-ph/0501052]

Effective Potential

The effective potential at finite temperature

$V_{\rm eff}(\boldsymbol{v};T) = V_{\rm tree}(\boldsymbol{v}) + \Delta V(\boldsymbol{v};T)$

The one-loop correction

$$\Delta V(\boldsymbol{v};T) = 3\left[F_0(\bar{m}_Z^2) + \frac{T^4}{2\pi^2} I_B\left(\frac{\bar{m}_Z}{T}\right) + 2F_0(\bar{m}_W^2) + 2\cdot\frac{T^4}{2\pi^2} I_B\left(\frac{\bar{m}_W}{T}\right)\right]$$
$$- 2\left[F_0(\bar{m}_{\psi_N}^2) + \frac{T^4}{2\pi^2} I_F\left(\frac{\bar{m}_{\psi_N}}{T}\right)\right]$$
$$+ N_C \sum_{q=t,b}\left\{2\sum_{j=1,2}\left[F_0(\bar{m}_{\tilde{q}_j}^2) + \frac{T^4}{2\pi^2} I_B\left(\frac{\bar{m}_{\tilde{q}_j}}{T}\right)\right] - 4\left[F_0(\bar{m}_q^2) + \frac{T^4}{2\pi^2} I_F\left(\frac{\bar{m}_q}{T}\right)\right]\right\}$$

where $\bar{m}$ denotes the field-dependent masses and

$$F_0(m^2) = \frac{1}{64\pi^2}\left(m^2\right)^2\left(\log\frac{m^2}{M^2} - \frac{3}{2}\right), \quad I_{B(F)}(a) = \int_0^\infty dx\, x^2 \log\left(1 \mp e^{-\sqrt{x^2+a^2}}\right)$$

Effective Potential

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The order parameters

$$\begin{aligned}\boldsymbol{v} &= (v_1, v_2, v_3, v_4, v_5) \\ &\equiv (v_d,\ v_u\cos\Delta\theta,\ v_u\sin\Delta\theta,\ v_n\cos\Delta\varphi,\ v_n\sin\Delta\varphi)\end{aligned}$$

where $\Delta\theta = \theta - \theta_0$ and $\Delta\varphi = \varphi - \varphi_0$ (The $_0$ means $T = 0$ value)

EWPT is a first-order PT $\Leftrightarrow$ the $\boldsymbol{v}$ Jump vacuum to vacuum

We numerically minimize the $V_{\rm eff}(\boldsymbol{v};T)$ in 5 dim. space, and observe the phase transition

EWPT – naive argument

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

$\longrightarrow$ y^3-term, even at the tree level [Pietroni, NPB402]

$$V = \frac{1}{2}\left((m_1^2\cos^2\beta + m_2^2\sin^2\beta)\cos^2\alpha + m_N^2\sin^2\alpha\right)y^2 - \left(R_\lambda\cos^2\alpha\sin\alpha\cos\beta\sin\beta + \frac{1}{3}R_\kappa\sin^3\alpha\right)y^3 + \cdots$$

The y^3-term makes the phase transition along y-direction strongly first order

but

validity of the parametrization with a constant α is not obvious

EWPT – naive argument

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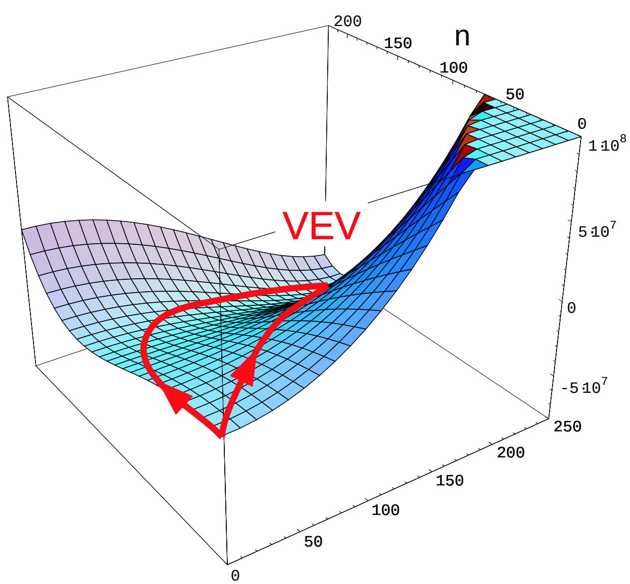

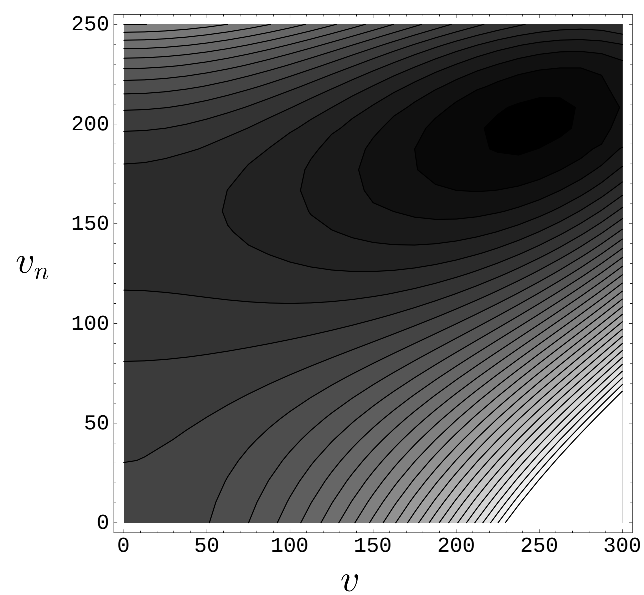

The phase transitions in the NMSSM are classified into several types

Classification of the Phases

We found four phases

phase	order parameters	symmetries
EW	$v \neq 0$, $v_n \neq 0$	fully broken
I, I′	$v = 0$, $v_n \neq 0$	local $SU(2)_L \times U(1)_Y$
II	$v \neq 0$, $v_n = 0$	global $U(1)$
SYM	$v = v_n = 0$	$SU(2)_L \times U(1)_Y$, global $U(1)$

Symmetries

v : order parameter of the gauge symmetry

v_n : order parameter of a global $U(1)$ symmetry

because in the subspace of $v_n = 0$ $(v_4 = v_5 = 0)$, the effective potential is invariant under the global $U(1)$ transformation

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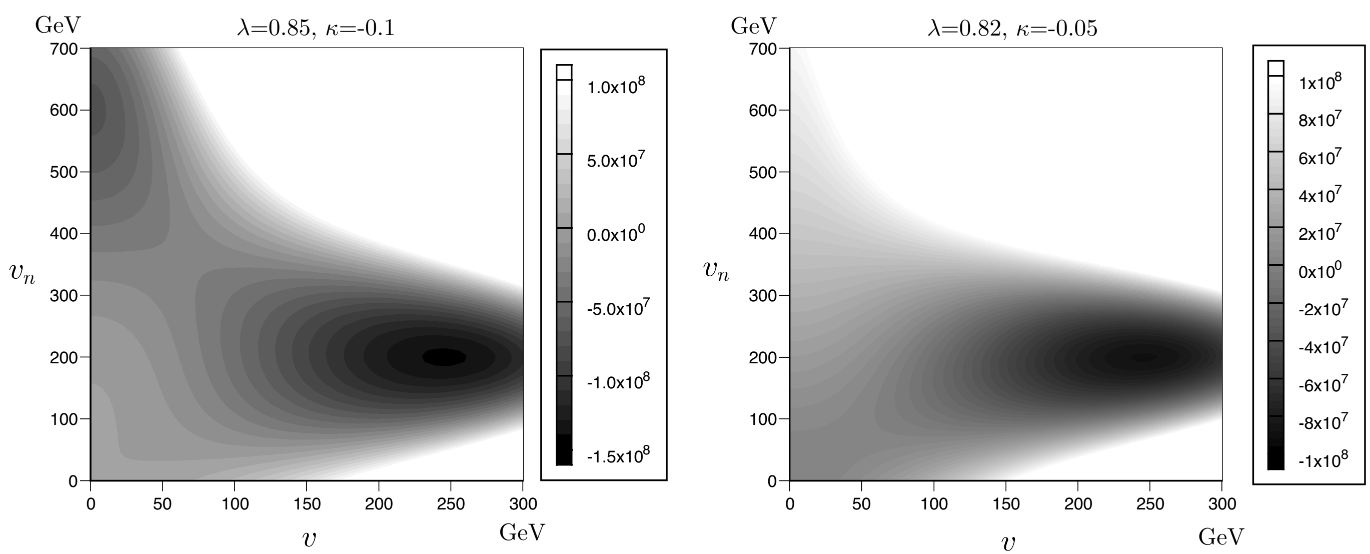
Examples which develop the phase-I′ and II at high T



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The existence of the phases-I, I′ and II is a novel feature of the NMSSM

phase-I and I′ can be understood: in subspace $v = 0$

$$\hat{V}_0(v_n) = V_0(0,0,0,v_n \cos\Delta\varphi, v_n \sin\Delta\varphi) = \frac{1}{2} m_N^2 v_n^2 - \frac{1}{3}\hat{R}_\kappa v_n^3 + \frac{|\kappa|^2}{4} v_n^4,$$

where $\hat{R}_\kappa \propto \kappa$

For a very small $|\kappa|$, the intermediate vacuum can develop far from the origin, phase-I′

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Types of transitions

A: SYM $\rightarrow$ I $\Rightarrow$ EW   B: SYM $\rightarrow$ I′ $\Rightarrow$ EW

C: SYM $\Rightarrow$ II $\rightarrow$ EW   D: SYM $\Rightarrow$ EW

- $\triangle$ Type A: MSSM-like EWPT, which proceeds with almost constant $v_n(T)$
- $\circledcirc$ Type B: Strongly first-order EWPT, without light stop, It's NEW!
- $\times$ Type C: It's NEW, but CP phase is ambiguous $\rightarrow$ cannot produce net baryon number
- $\ominus$ Type D: Strongly first-order (need light Higgs), with light stop

EWPT – Type B

Parameters

- heavy stop
- small κ

$\tan\beta$	$m_{H^\pm}$	A_κ	v_n	λ	κ	$m_{\tilde{q}}$	$m_{\tilde{t}(\tilde{b})_R}$
5	600GeV	-100GeV	200GeV	0.85	-0.1	1000GeV	800GeV

Mass spectrum

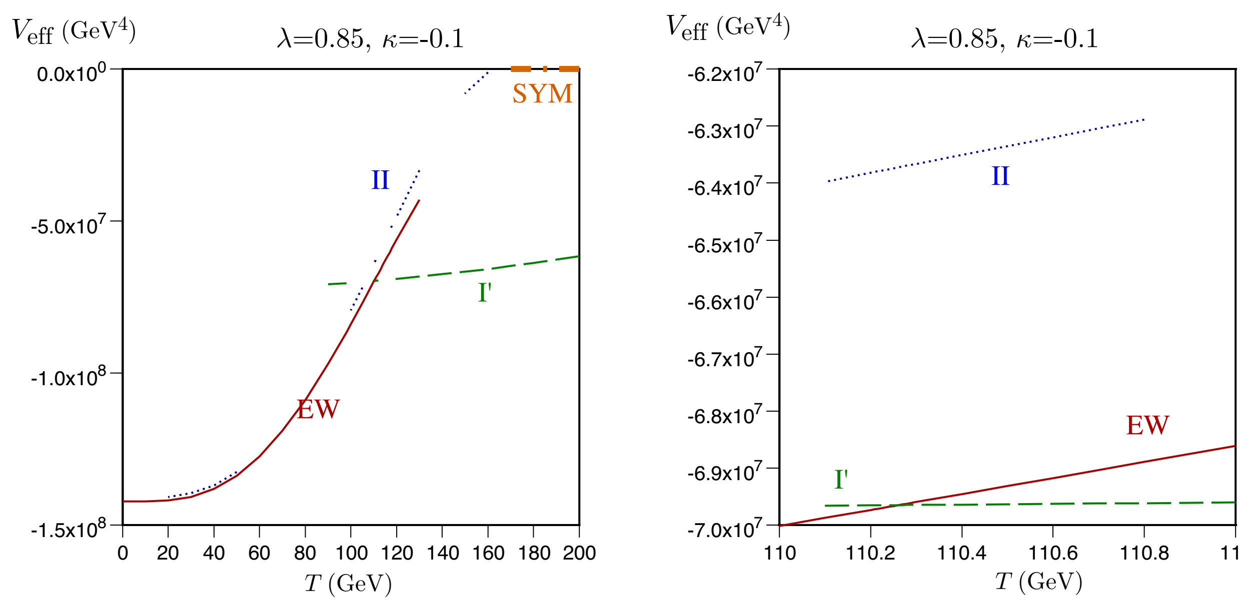
- SM-like Higgs is a third-lightest one
- h_2 and h_5 are pseudoscalar
- heaviest scalar mass and heaviest pseudoscalar mass are the same order
  $\mathrm{Tr}\mathcal{M}_S \simeq \mathrm{Tr}\mathcal{M}_P$ if $m_{H^\pm}$ is large

	h_1	h_2	h_3	h_4	h_5
mass(GeV)	38.89	75.31	131.11	625.61	627.95
$g^2_{H_iZZ}$	6.213×10^{-8}	0	0.999	6.816×10^{-5}	0

EWPT – Type B

The T dependence of the local minima of the $V_{\rm eff}$

- distinct convergent points at the same T are displayed
- The values of the $V_{\rm eff}$ are subtracted by the value at the origin
- right-hand plot is the close view of the left-hand one near the T_C



- The T dependence of phase-I$'$ is weak because at that phase, $v = 0$

$(v, v_n) = (208.13\ {\rm GeV}, 248.85\ {\rm GeV}) \longrightarrow (0, 599.93\ {\rm GeV})$ at $T_C = 110.26\ {\rm GeV}$

$\Rightarrow$ strongly first order PT; $v_C/T_C \sim 2$

CP-Violating Case

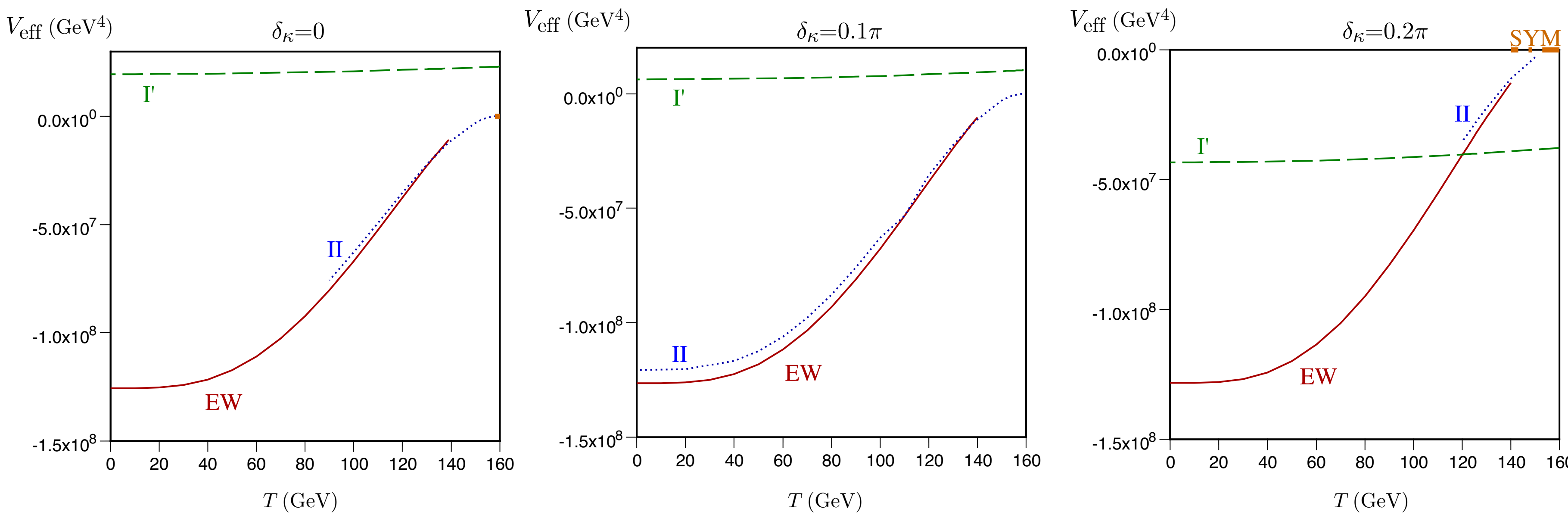
Source of the CPV

- There are infinite sets of CP violating parameters which yield the same value of $\mathcal{I}$
  $\longrightarrow$ We constrain them so that the phase relevant to the nEDM vanish
- We take $\mathrm{Arg}\kappa \equiv \delta_\kappa$ as an independent parameter

CP-Violating Case

Parameters

- almost same as Type-B example, but $(\lambda, \kappa) = (0.85, -0.1) \to (0.83, -0.07)$



- For $\delta_\kappa \gtrsim 0.3\pi$, the zero-temperature vacuum is in the phase-I$'$
- value of the phase-I$'$ is decreases with δ_κ
- PT is type-C for $\delta_\kappa = 0, 0.1\pi \Rightarrow$ type-B for $\delta_\kappa = 0.2\pi$, strongly 1st order
- first-order EWPT is not weakend by tree-level CPV

Summary

In the NMSSM, we worked out to

- search allowed parameters (previous work)
- classify the phases into four types of the phase transitions

Our next interest is in

- For calculating the generated baryon number, sphaleron transition rate is needed $\leftarrow$ sphaleron solution and energy in the NMSSM
- drawing a phase diagram $\leftarrow$ more computer power
- application of the phases