Electroweak Baryogenesis in the Next-to-MSSM

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Summary

- One-loop formulation with all CP phases
- Parameter search
  $\longrightarrow$ mass bounds for the charged Higgs boson
- EWPT in CP conserving case
- Higgs spectrum in CP violating case

Todo

- EWPT in CP violated case

Features of the NMSSM

- 5 neutral and 1 charged scalars
  (3 scalar and 2 pseudoscalar when CP cons.)
  The lightest Higgs scalar H_1 can escape from the bound

$$m_{H_{\rm SM}} > 114 {\rm GeV}$$

because of small $g_{H_1 ZZ}$, $\quad \Rightarrow H_{\rm SM} = H_2$ [Miller, et. al. NPB681]

$$\mathcal{M}_N^2 = \begin{pmatrix} \mathcal{M}_S^2 & \mathcal{M}_{SP}^2 \\ (\mathcal{M}_{SP}^2)^T & \mathcal{M}_P^2 \end{pmatrix}, \quad \mathcal{M}_{SP}^2 = \begin{pmatrix} 0 & \frac{3}{2}\sin\beta \\ 0 & \frac{3}{2}\cos\beta \\ -\frac{1}{2} & -\sin 2\beta \end{pmatrix} \mathcal{I} v_n v$$

Features of the NMSSM

- 5 neutral and 1 charged scalars
- CP violation at the tree level: $\mathcal{I}$

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

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 escape from the EDM constraint

Features of the NMSSM

- 5 neutral and 1 charged scalars
- CP violation at the tree level: $\mathcal{I}$
- Pure NMSSM regime

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

  $\longrightarrow$ new features expected for $v_n = \mathcal{O}(100)\mathrm{GeV}$

  we focus on this regime

NMSSM

Superpotential:

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

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

- Z_3 symmetry
  $\leftarrow$ We assume it's already broken by higher dimensional operator
  If one include tadpole term $\rightarrow$ nMSSM [Menon, et. al. hep-ph/0404184]
- All couplings are dimensionless

NMSSM

Superpotential:

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

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

SUSY X soft terms:

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

$\lambda A_\lambda \langle n \rangle \sim \mu B$ in the MSSM

NMSSM - Higgs sector

The tree-level Higgs potential:

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

Order parameters:

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

Tadpole conditions

$$m_1^2 = R_\lambda v_n \tan\beta - \frac{1}{2} m_Z^2 \cos(2\beta) - \frac{1}{2}|\lambda|^2 (v_u^2 + v_n^2) - \frac{1}{2}\mathcal{R} v_n^2 \tan\beta$$

$$m_2^2 = R_\lambda v_n \cot\beta + \frac{1}{2} m_Z^2 \cos(2\beta) - \frac{1}{2}|\lambda|^2 (v_d^2 + v_n^2) - \frac{1}{2}\mathcal{R} v_n^2 \cot\beta$$

$$m_N^2 = R_\lambda \frac{v_d v_u}{v_n} + R_\kappa v_n - \frac{1}{2}|\lambda|^2 (v_d^2 + v_u^2) - |\kappa|^2 v_n^2 - \mathcal{R} v_d v_u$$

$$I_\lambda = \frac{1}{2}\mathcal{I} v_n, \quad I_\kappa = -\frac{3}{2}\mathcal{I}\frac{v_d v_u}{v_n}.$$

$$\mathcal{R} = \mathrm{Re}[\lambda\kappa^* e^{i(\theta - 2\varphi)}], \qquad \mathcal{I} = \mathrm{Im}[\lambda\kappa^* e^{i(\theta - 2\varphi)}],$$

$$R_\lambda = \frac{1}{\sqrt{2}}\mathrm{Re}[\lambda A_\lambda e^{i(\theta+\varphi)}], \qquad I_\lambda = \frac{1}{\sqrt{2}}\mathrm{Im}[\lambda A_\lambda e^{i(\theta+\varphi)}],$$

$$R_\kappa = \frac{1}{\sqrt{2}}\mathrm{Re}[\kappa A_\kappa e^{i3\varphi}], \qquad I_\kappa = \frac{1}{\sqrt{2}}\mathrm{Im}[\kappa A_\kappa e^{i3\varphi}].$$

Constraints for the parameters

The parameters are restricted

> The vacuum that break electroweak symmetry
> is the absolute minimum of the potential

- $V(\mathrm{vac.}) = \min\{V\}$
- Positive mass^2 of the all scalars

Constrained parameter - example

Charged Higgs mass bound

- Positive mass^2 of pseudo-scalar

$$\det \mathcal{M}_P^2 > 0 \Longrightarrow \text{lower bound of } m_{H^\pm}$$

$$m_{H^\pm} > \frac{3\mathcal{R}^2 v^2 v_n^2}{4R_\kappa - 3\mathcal{R} v^2 \sin 2\beta} + m_W^2 - \frac{1}{2}|\lambda|^2 v^2$$

where

$$\mathcal{R} = \mathrm{Re}[\lambda\kappa^* e^{i(\theta-2\varphi)}], \quad R_\kappa = \frac{1}{\sqrt{2}}\mathrm{Re}[\kappa A_\kappa e^{i3\varphi}]$$

⋆ In the MSSM : $m_{H^\pm}^2 = m_W^2 + m_A^2 \quad \Longrightarrow \quad m_{H^\pm}^2 > m_W^2$

Constrained parameter - example

Charged Higgs mass bound

- Positive mass^2 of pseudo-scalar
- Higgs potential at the vac. is lower than that at origin

$$V(\mathrm{vac.}) < V(0) \Longrightarrow \text{upper bound of } m_{H^\pm}$$

$$m_{H^\pm}^2 < 2|\lambda|^2 v_n^2 \frac{1}{\sin^2 2\beta} + 2|\kappa|^2 \frac{v_n^4}{v^2} \frac{1}{\sin^2 2\beta} + m_Z^2 \cot^2 2\beta + m_W^2$$
$$+ \mathcal{R} \frac{v_n^2}{v^2} \frac{1}{\sin 2\beta} - \frac{4}{3} R_\kappa \frac{v_n^3}{v^2} \frac{1}{\sin^2 2\beta}.$$

$\star$ In the MSSM limit : this bound $\rightarrow \infty$

Constrained parameter - example

Charged Higgs mass bound

- Positive mass^2 of pseudo-scalar
- Higgs potential at the vac. is lower than that at origin

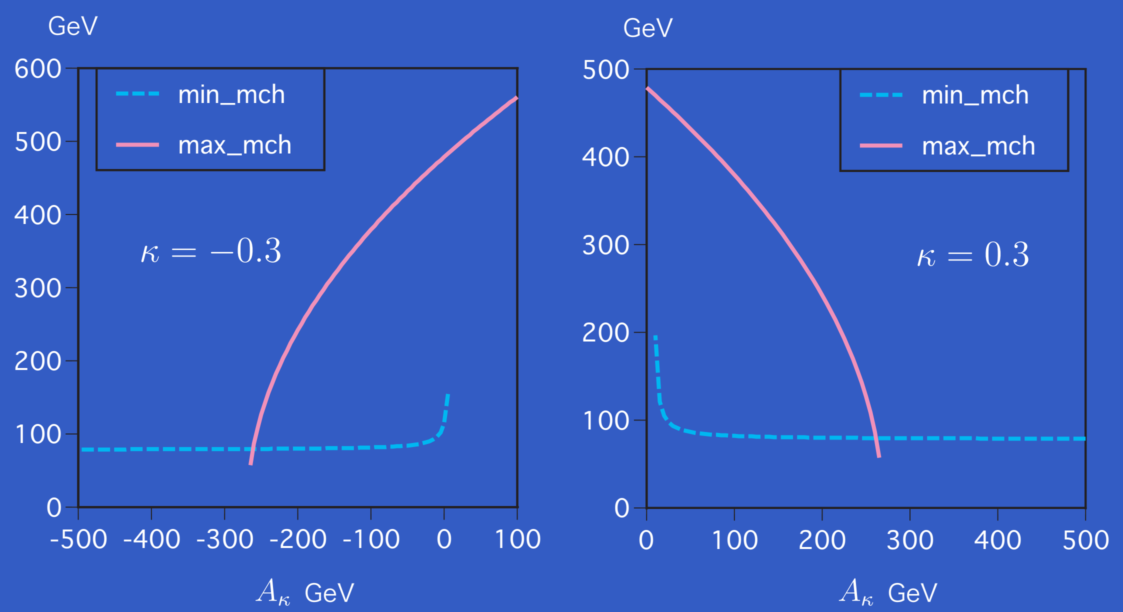
CP cons.

Pure NMSSM regime

Constrained parameter - example

Charged Higgs mass bound

- Positive mass^2 of pseudo-scalar
- Higgs potential at the vac. is lower than that at origin



$\tan\beta = 5$, $v_n = 300\text{GeV}$, $\Rightarrow \kappa A_\kappa > 0$ is favored

Constrained parameter - example

Charged Higgs mass bound

- Positive mass^2 of pseudo-scalar
- Higgs potential at the vac. is lower than that at origin

In fact, we search the allowed parameter numerically and systematically at one-loop level

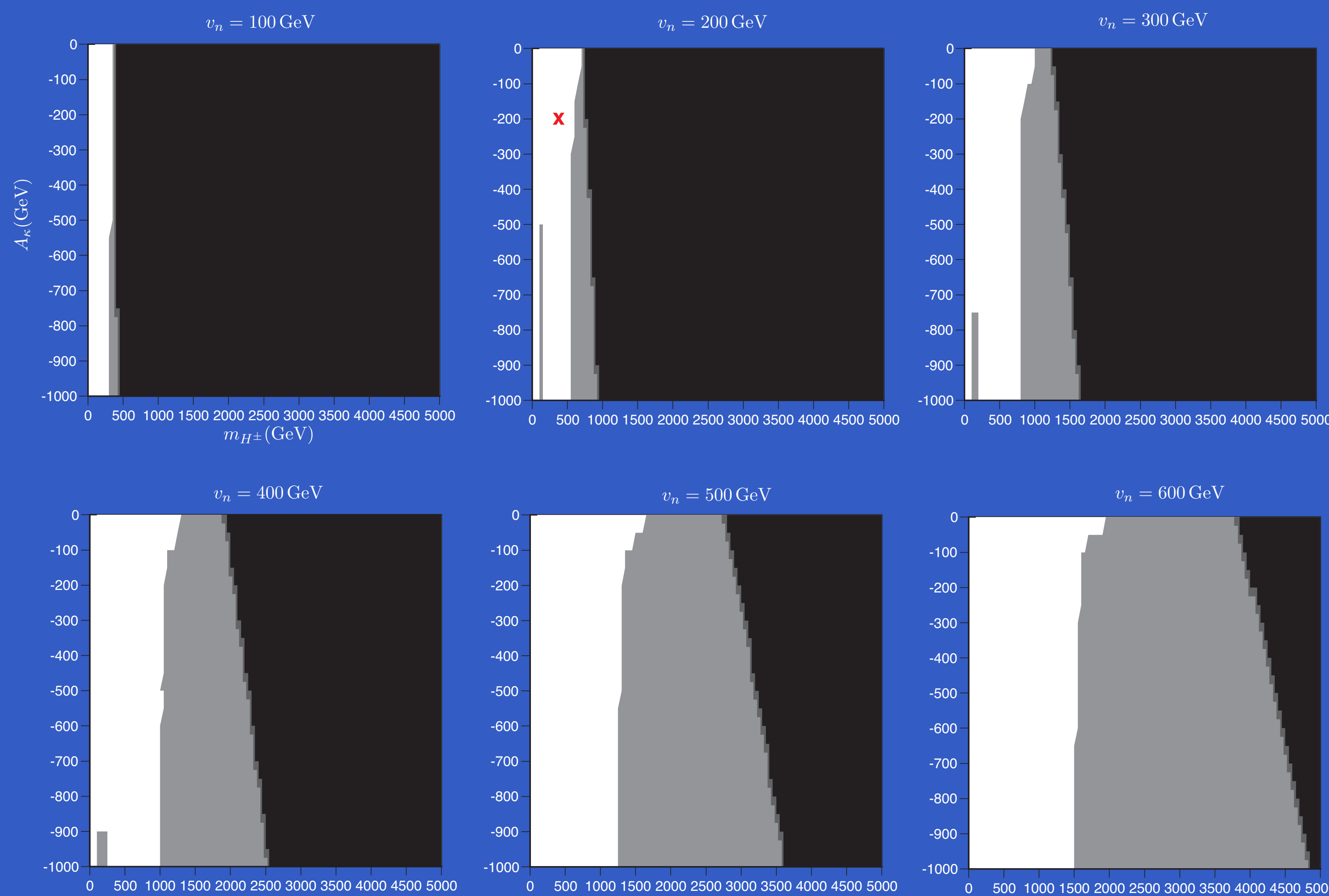
Allowed parameters

1. The masses of the Higgs bosons are heavier than $114\mathrm{GeV}$, or their coupling to Z boson is less than 0.1
2. The electroweak vacuum is the global minimum of the effective potential
3. The mass-squared of the squarks are positive

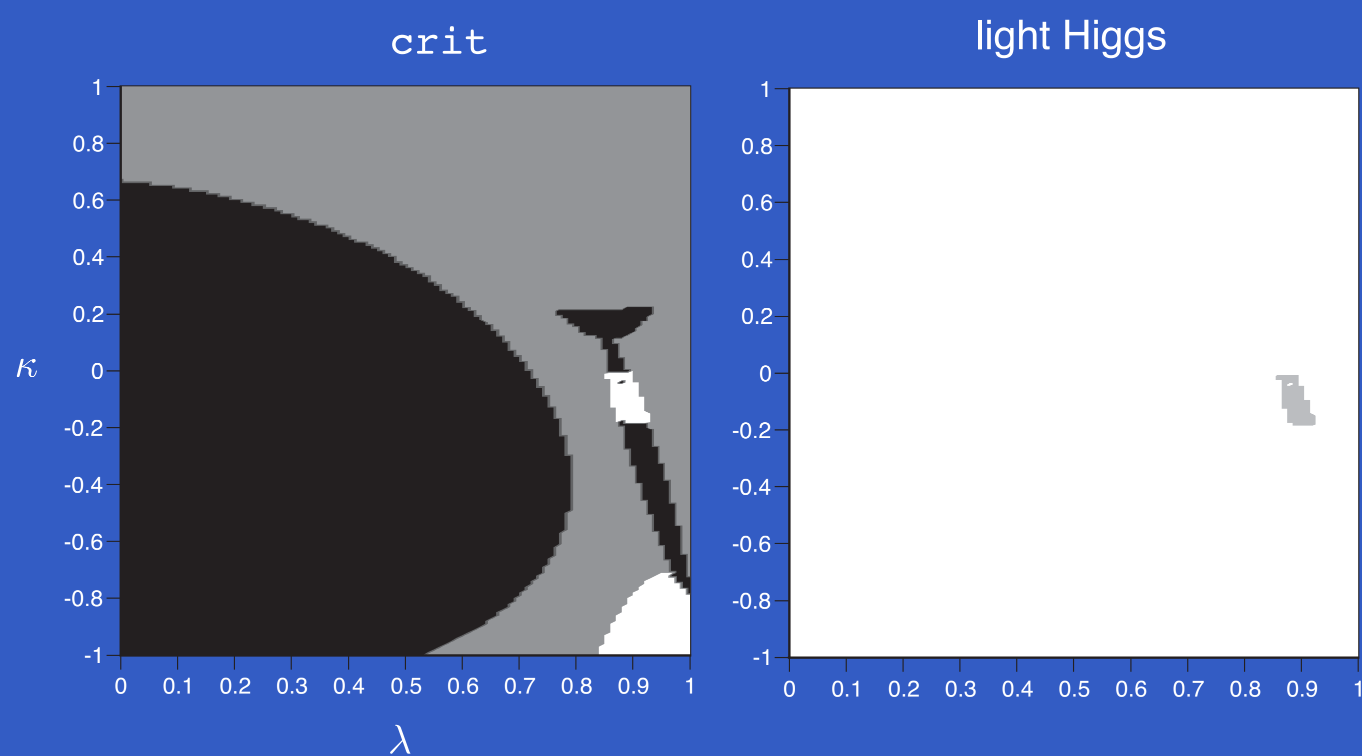
$\tan\beta = 2, 3, 5, 10, 20$ and $v_n = 100, 150, 200, , , 1000$ GeV

- heavy-squark scenario $(m_{\tilde{q}}, m_{\tilde{t}_R}) = (1000, 800)$GeV
- light-squark scenario-1 $(m_{\tilde{q}}, m_{\tilde{t}_R}) = (1000, 10)$GeV
- light-squark scenario-2 $(m_{\tilde{q}}, m_{\tilde{t}_R}) = (500, 10)$GeV

Allowed parameters



Allowed parameters



Electroweak phase transition

- The effective potential at finite temperature

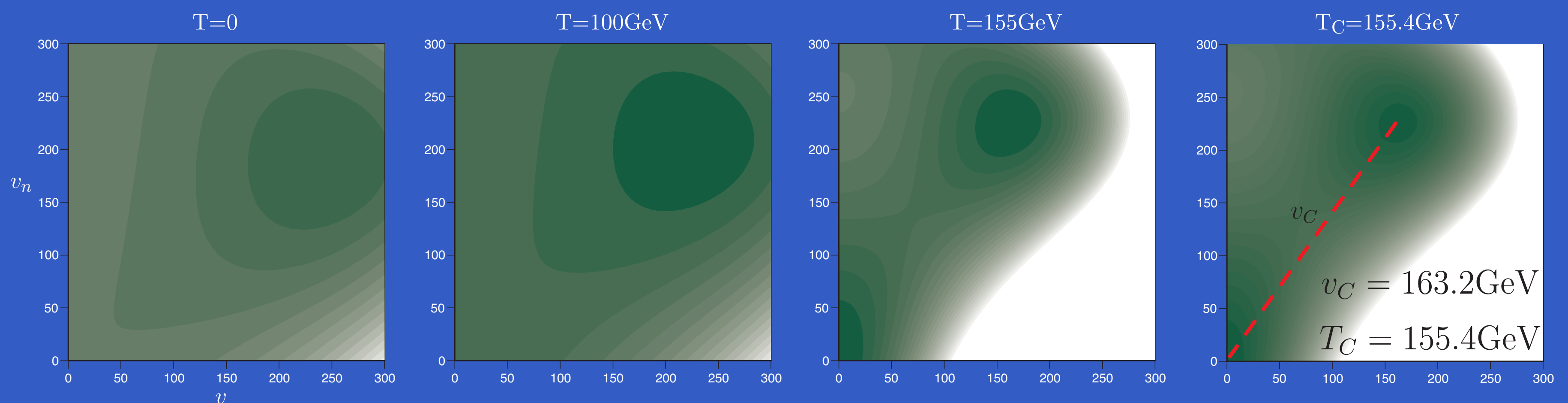
$$V(T) = V_{\rm tree} + \Delta_q V + \Delta_{\tilde{q}} V + \Delta_g V + \Delta_T V$$

- For the Baryogenesis
  - Strong 1st order PT : $v_C > T_C$
  - CPV (but now we investigate the PT in CP cons. case)

Electroweak phase transition

$\tan\beta$	$m_{H^\pm}$	A_κ	v_n	λ	κ	$m_{\tilde{q}}$	$m_{\tilde{t}_R}$
3	400GeV	-200GeV	200GeV	0.9	-0.1	1000GeV	800GeV

	H_1	H_2	H_3	H_4	H_5
mass(GeV)	64.1156	145.332	187.338	436.500	5964.78
$g^2_{H_iZZ}$	2.69889×10^{-3}	0.996300	0	1.00092×10^{-3}	0



example of strong 1st order in light-mass and small-coupling case

CP violation

We used light-mass and small-coupling

- 3 scalar mixing in NMSSM [Miller, et. al. NPB681]
  light Higgs mass $\Rightarrow$ strong 1st order PT
  And more, CPV is nessesary for Baryogenesis
  But now we weren't include CP phase

  Is there other mixing that related to CPV?

CP violation

We used light-mass and small-coupling

- 3 scalar mixing in NMSSM [Miller, et. al. NPB681]
- The squark phase, also in MSSM [Carena, et. al. NPB586]
  Scalar-pseudoscalar mixing at one-loop level
  We investigated the effect of this phase in MSSM

$$\mathrm{Im}(\mu A_t)$$

on the PT in previous paper [Funakubo, et. al. PTP109]
We gain light Higgs, but 1st order PT is weakened by this phase
Is there other phase?

CP violation

We used light-mass and small-coupling

- 3 scalar mixing in NMSSM [Miller, et. al. NPB681]
- The squark phase, also in MSSM [Carena, et. al. NPB586]
- The tree level CP phase in NMSSM
  Scalar-pseudoscalar mixing at tree level
  One can escape EDM constraint
  We expect good result

CP violation

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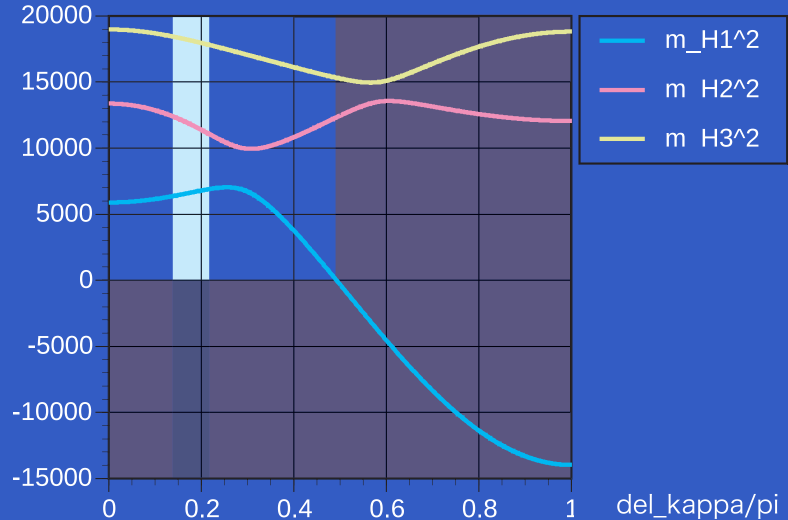
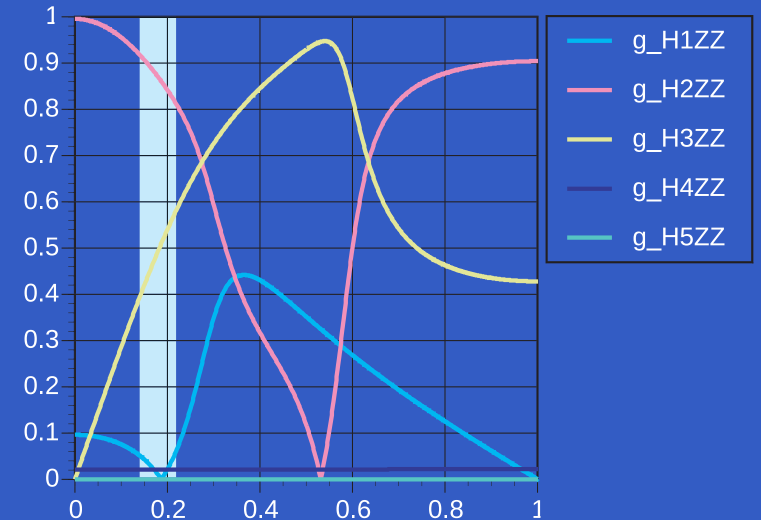
- The tree level CP phase in NMSSM





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- Higgs spectrum in CP violating case

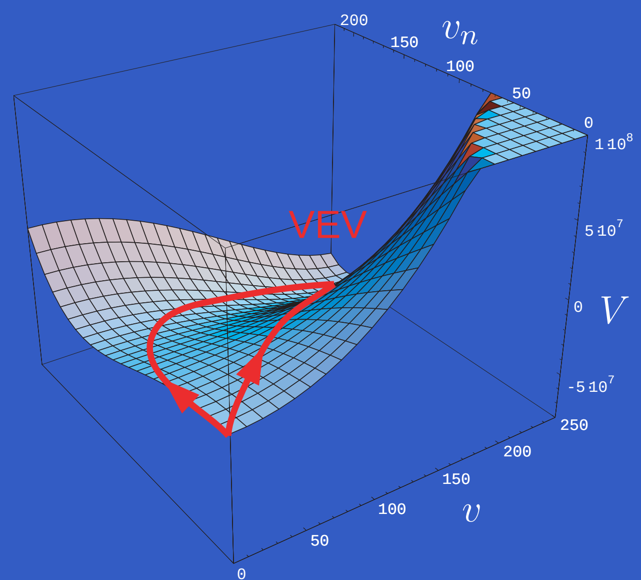
Todo

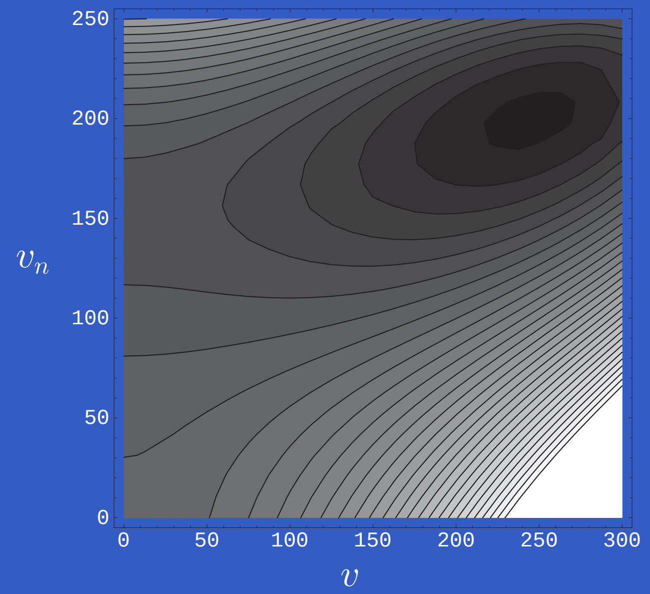
- EWPT in CP violated case

EWPT in the NMSSM

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

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





CP phase and the EDM

The phases apear in following 3 combinations

$$\mathcal{I} = \mathrm{Im}[\lambda\kappa^* e^{i(\theta-2\varphi)}], \quad I_\lambda = \frac{1}{\sqrt{2}}\mathrm{Im}[\lambda A_\lambda e^{i(\theta+\varphi)}], \quad I_\kappa = \frac{1}{\sqrt{2}}\mathrm{Im}[\kappa A_\kappa e^{i3\varphi}]$$

from vacuum condition, these are related

$$I_\lambda = \frac{1}{2}\mathcal{I} v_n, \quad I_\kappa = -\frac{3}{2}\mathcal{I}\frac{v_d v_u}{v_n}.$$

EDM related phases that appear in Higgs sector are

$$\delta_{\mathrm{EDM}} \supset \delta_\lambda + \varphi + \theta$$

CP phase and the EDM

define

$$\delta'_\lambda \equiv \delta_\lambda + \theta + \varphi, \quad \delta'_\kappa \equiv \delta_\kappa + 3\varphi$$

so, describe the phases explicitly

$$\mathrm{Arg}(\lambda\kappa^* e^{i(\theta-2\varphi)}) = \delta_\lambda - \delta_\kappa + \theta - 2\varphi = \delta'_\lambda - \delta'_\kappa,$$

$$\mathrm{Arg}(\lambda A_\lambda e^{i(\theta+\varphi)}) = \delta_\lambda + \delta_{A_\lambda} + \theta + \varphi = \delta'_\lambda + \delta_{A_\lambda},$$

$$\mathrm{Arg}(\kappa A_\kappa e^{i3\varphi}) = \delta_\kappa + \delta_{A_\kappa} + 3\varphi = \delta'_\kappa + \delta_{A_\kappa}$$

and

$$\delta_{\mathrm{EDM}} \supset \delta_\lambda + \varphi + \theta = \delta'_\lambda$$

Although one choose the phase $\delta'_\lambda = 0$, the vacuum condition can be satisfied.

Maximal effect of the CP phase

now we have

$$\mathcal{R} = \mathrm{Re}[\lambda\kappa^*], \qquad \mathcal{I} = \mathrm{Im}[\lambda\kappa^*],$$

$$R_\lambda = \frac{1}{\sqrt{2}}\mathrm{Re}[\lambda A_\lambda], \qquad I_\lambda = \frac{1}{\sqrt{2}}\mathrm{Im}[\lambda A_\lambda],$$

$$R_\kappa = \frac{1}{\sqrt{2}}\mathrm{Re}[\kappa A_\kappa], \qquad I_\kappa = \frac{1}{\sqrt{2}}\mathrm{Im}[\kappa A_\kappa].$$

from the vacuum condition, I_λ and I_κ are described by the function of $\mathcal{I}$. The input parameters are λ, κ, δ_κ, $m_{H^\pm}$, $\delta_{A_\kappa} = 0, \pi$. The input $m_{H^\pm}$ gives R_λ, and the input $\delta_{A_\kappa} = 0, \pi$ gives following simple relation,

$$A_\kappa = \pm\frac{3\lambda v_d v_u}{\sqrt{2} v_n},$$

so the parameter A_κ becomes dependent one. Then R_κ determined.

Note : in this situation, we can see the effect of the CP phase δ_κ maximally.