The NMSSM with CP Violation

$\sim$ An Application to Electroweak Baryogensis

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Outline

- Introduction to Baryogensis.
- EWBG in the MSM and MSSM.
- First order phase transition in NMSSM.
- EDMs of NMSSM as applicatoin on EWBG.
- Summary

Introduction to Baryogensis

The baryon asymmetry of the universe is characterized by the Y_B

$$Y_B \equiv \frac{\rho_B}{s} = \begin{cases} (6.7 \quad - 9.2 \ \ )x10^{-11}, & \text{BBN,} \quad \text{PDG} \\ (8.36 - 9.32)x10^{-11}, & \text{WMAP, 0803.0586} \end{cases}$$

This can not be a consequence of the special separation

- No star made up of anti-baryon in local galaxy.
- No gamma ray produced from annihilation to be observed.
- No mechanism to separate matter from anti-matter in SM of cosmology.

Introduction to Baryogensis

At 1967, Sakharov proposed three conditions:

- Baryon number violation.
- C and CP violation.
  If C conserve, then $i \to f$ will exact equal to $\bar{i} \to \bar{f}$.
  CP conservation, with CPT theorem, expect

  $$i(r_i, p_i, s_i) \to f(r_j, p_j, s_j)$$

  equal to time reverse process

  $$f(f_j, p_j, s_j) \to i(r_i, p_i, s_i)$$

  where r is coordinate, p is momentum, s is spin.
- Departure from thermal equilibrium.
  The CPT theorem expect exact the same mass, decay rate and opposite charge between particle and anti-particle. This symmetries lead us to conclude $n_b = n_{\bar{b}}$. Only when out-of-thermal equilibrium, we can avoid the control of CPT theorem and produce baryon number asymmetry.

Introduction to Baryogensis

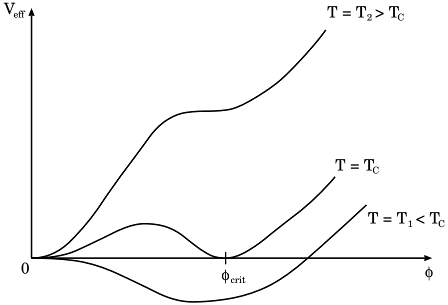
There are two ways to produce the departure from thermal equilibrium.

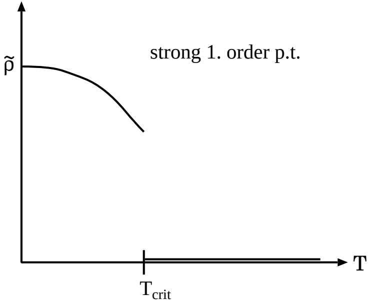
- The out-of-equilibrium condition is attained through the expansion of the universe.

$$\Gamma_A = \sigma(A + target \to X) n_{target} |\mathbf{v}|$$

$$\Gamma_A < H$$

- The thermal non-equilibrium is achieved by the first order phase transition.





hep-ph/0205279

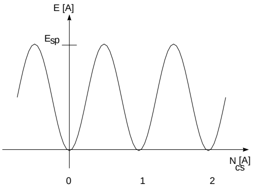
Electroweak Baryognesis in the SM

In 1985, Kuzmin, Rubakov and Shaposhnikov suggest that anomalous baryon number violation in the SM to be the baryon number violation process.

The SM satisfy the three conditions

- The baryon number violation is attained by sphaleron process.
- CP non-conservation happen in the CKM matrix. C is violated in weak interaction.
- The thermal non-equilibrium may be able to attained through the first order phase transition during the electroweak symmetry breaking.

Sphalerton Process



$$\partial_\mu J^\mu_B = i\frac{N_F}{32\pi^2}\left(-g_2^2 F^{a\mu\nu}\widetilde{F}^a_{\mu\nu} + g_1^2 f^{\mu\nu}\widetilde{f}_{\mu\nu}\right),$$

$$\Delta B = N_F(\Delta N_{\rm CS} - \Delta n_{\rm CS}),$$

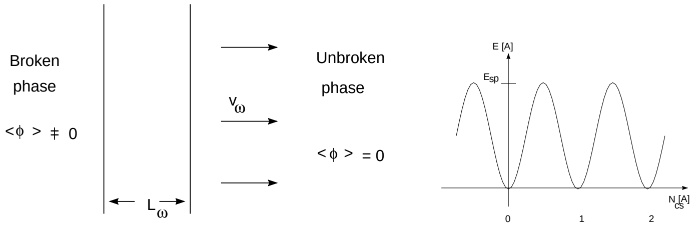
$$N_{\rm CS} = -\frac{g_2^2}{16\pi^2}\int d^3x\, 2\epsilon^{ijk}\,{\rm Tr}\left[\partial_i A_j A_k + i\frac{2}{3}g_2 A_i A_j A_k\right],$$

$$n_{\rm CS} = -\frac{g_1^2}{16\pi^2}\int d^3x\, \epsilon^{ijk}\,\partial_i B_j B_k,$$

$$A_i \to U A_i U^{-1} + \frac{i}{g_2}(\partial_i U)U^{-1},$$

$$\delta N_{\rm CS} = \frac{1}{24\pi^2}\int d^3x\,{\rm Tr}\left[(\partial_i U)U^{-1}(\partial_j U)U^{-1}(\partial_k U)U^{-1}\right]\epsilon^{ijk}.$$

Electroweak Baryognesis



- At zero temperature, the reaction rate of sphaleron process is $e^{-\frac{2\pi}{\alpha_w}}$ suppressed.
- In the broken phase at finite temperature, $\Gamma_{sph} \propto (\frac{m_w(T)}{T})^3 e^{-\frac{E_{sph}}{T}}$, where $E_{sph} = \frac{2m_w(T)}{\alpha_w} B\left(\frac{\lambda}{g_w}\right)$ and $m_w(T) = g_w\langle\phi(T)\rangle/2$.
- In the symmetry phase, $\Gamma_{sph} \propto \alpha_w^5 T^4 > H = 1.66\sqrt{g_*}\frac{T^2}{M_P}$.
- In order to make sure the baryon number transform into the broken phase to be survived, it require strong first order phase transition with criteria $\frac{\langle\phi(T_C)\rangle}{T_C} \gtrsim 1$.

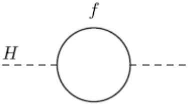
Electroweak Baryognesis in the SM

The SM fail to explain the baryon asymmetry.

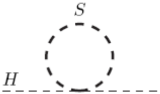
- The condition of strong first order phase transition require $m_H \lesssim 42$ GeV (with $m_H \lesssim 73$ GeV start to be first order). The baryon number generate in the symmetry phase would be washed-out during bubble expansion.
- $Y_B = \frac{n_B}{s} \sim \frac{\alpha_W^4 T^3}{s}\delta_{CP} \sim 10^{-8}\delta_{CP}$ which require the CP violating parameter $\delta_{CP} \gtrsim 10^{-3}$. However, $\delta_{CP} \sim \frac{A_{CP}}{T_C^{12}} \sim 10^{-20}$ is far too small to explain the observed baryon asymmetry.

Introduction of MSSM

The introduction of supersymmetry extend of the SM is motivated by the hierarchy problem.



$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}[-2\Lambda_{\rm UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots]$$



$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\rm UV}^2 - 2m_S^2 \ln(\Lambda_{\rm UV}/m_S) + \ldots\right]$$

- Gauge unification
- dark matter candidate
- More CP source

Introduction of MSSM

$$W_{MSSM} = \hat{U}^c\,\mathbf{h_u}\hat{Q}\hat{H}_u - \hat{D}^c\,\mathbf{h_d}\hat{Q}\hat{H}_d - \hat{E}^c\,\mathbf{h_e}\hat{L}\hat{H}_d + \mu\hat{H}_u\hat{H}_d$$

In order to cause the SUSY breaking, there are lots of soft terms to be introduced into the MSSM, where the

$$\begin{aligned}\mathcal{L}^{\rm MSSM}_{\rm soft} = & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + {\rm c.c.}\right) \\ & -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + {\rm c.c.}\right) \\ & -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\ & - m^2_{H_u}H^*_u H_u - m^2_{H_d}H^*_d H_d - \left(bH_uH_d + {\rm c.c.}\right).\end{aligned}$$

Higgs Sector of MSSM

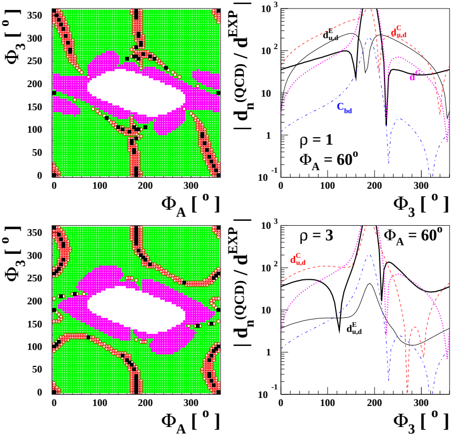
$$
\begin{aligned}
V_{eff} &= V_0 + \Delta V \\
V_0 &= \left(|\mu|^2 + M_{H_u}^2\right)|H_u|^2 + \left(|\mu|^2 + M_{H_d}^2\right)|H_d|^2 - \left(bH_uH_d + c.c.\right) \\
&\quad + \frac{1}{8}(g^2 + g'^2)\left(|H_u|^2 + |H_d|^2\right)^2 \\
\Delta_q V &= N_C \sum_q \left\{ 2 \sum_{j=1,2} \left[F_0(\bar{m}_{\tilde{q}_j}) + \frac{T^4}{2\pi^2}\mathcal{I}_B(\frac{\bar{m}_{\tilde{q}_j}}{T}) \right] \right. \\
&\quad \left. -4\left[F_0(\bar{m}_{q_j}) + \frac{T^4}{2\pi^2}\mathcal{I}_F(\frac{\bar{m}_{q_j}}{T}) \right] \right\}
\end{aligned}
$$

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

The function $I(a^2)$ yields a^3-term with negative coefficient when expended for $a^2 << 1$. The MSSM can have strong first order phase transition as long as the stop mass to be light.

EDMs in the MSSM

According to Funakuba (Prog.Theor.Phys.109:415-432,2003), the storng first order phase transition in MSSM happens when $M_{\tilde{t}} < M_t$, $M_{H_1} \lesssim 110$GeV, and $8 \lesssim \tan\beta \lesssim 30$.



Neutron EDM using QCD sum rule approch.

$|d_n/d^{EXP}| < 1$ (black)

$1 \leq |d_n/d^{EXP}| < 10$ (red)

$10 \leq |d_n/d^{EXP}| < 100$ (green)

$100 \leq |d_n/d^{EXP}|$ (magenta)

John Ellisa, Jae Sik Lee and Apostolos Pilaftsis JHEP 0810:049,2008

Introduction of the NMSSM

The Minimal Supersymmetric Standard Model(MSSM) has additional fine tuning, the μ problem.

$$W_{MSSM} = \hat{U}^c \, \mathbf{h_u} \hat{Q} \hat{H}_u - \hat{D}^c \, \mathbf{h_d} \hat{Q} \hat{H}_d - \hat{E}^c \, \mathbf{h_e} \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d$$

$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} \simeq -\mu^2 - m_{H_u}^2$$

One of the way out is to consider the replacement of the massive coupling by a singlet.

$$W_{NMSSM} = \hat{U}^c \, \mathbf{h_u} \hat{Q} \hat{H}_u - \hat{D}^c \, \mathbf{h_d} \hat{Q} \hat{H}_d - \hat{E}^c \, \mathbf{h_e} \hat{L} \hat{H}_d + \lambda \hat{S} (\hat{H}_u \hat{H}_d) + \frac{1}{3} \kappa \hat{S}^3$$

Higgs Sector of the NMSSM

By introducing the Higgs singlet, the effective μ is replaced by the VEV of the it.

$$W_{NMSSM} = \hat{U}^c\,\mathbf{h_u}\hat{Q}\hat{H}_u - \hat{D}^c\,\mathbf{h_d}\hat{Q}\hat{H}_d - \hat{E}^c\,\mathbf{h_e}\hat{L}\hat{H}_d + \lambda\hat{S}(\hat{H}_u\hat{H}_d) + \frac{1}{3}\kappa\hat{S}^3$$

$$\begin{aligned}
V_F &= |\lambda|^2|S|^2(|H_u|^2+|H_d|^2) + |\lambda|^2|H_uH_d|^2 + |\kappa|^2|S|^4 \\
&\quad + (|\lambda||\kappa|H_uH_dS^{2*}e^{i(\phi_\lambda-\phi_\kappa)} + \mathrm{h.c.}) \\
V_D &= \frac{1}{8}\bar{g}^2(|H_d|^2-|H_u|^2)^2 + \frac{1}{2}g^2|H_u^\dagger H_d|^2 \\
V_{\mathrm{soft}} &= m_1^2|H_d|^2 + m_2^2|H_u|^2 + m_S^2|S|^2 \\
&\quad + (|\lambda||A_\lambda|SH_uH_de^{i(\phi_\lambda+\phi_{A_\lambda})} - \frac{1}{3}|\kappa||A_\kappa|S^3e^{i(\phi_\kappa+\phi_{A_\kappa})} + \mathrm{h.c.}),
\end{aligned}$$

where

$$\lambda = |\lambda|e^{i\phi_\lambda},\, \kappa = |\kappa|e^{i\phi_\kappa},\, A_\lambda = |A_\lambda|e^{i\phi_{A_\lambda}},\, A_\kappa = |A_\kappa|e^{i\phi_{A_\kappa}},$$

Higgs Sector of the NMSSM

As EWSB, the Higgs sector of NMSSM has spontaneous CP phases and explicit CP phases:

$$H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + h_d + ia_d) \\ \phi_d^- \end{pmatrix}, H_u = e^{i\theta} \begin{pmatrix} \phi_u^+ \\ \frac{1}{\sqrt{2}}(v_u + h_u + ia_u) \end{pmatrix},$$

$$S = e^{i\varphi} \frac{1}{\sqrt{2}}(v_s + h_s^0 + ia_s)$$

The effect of spontaneous CP phase is

$$\begin{aligned} \phi_\lambda - \phi_\kappa &\Rightarrow \phi'_\lambda - \phi'_\kappa \\ \phi_\lambda + \phi_{A_\lambda} &\Rightarrow \phi'_\lambda + \phi_{A_\lambda} \\ \phi_\kappa + \phi_{A_\kappa} &\Rightarrow \phi'_\kappa + \phi_{A_\kappa} \end{aligned}$$

where

$$\begin{aligned} \phi'_\lambda &= \phi_\lambda + \theta + \varphi \\ \phi'_\kappa &= \phi_\kappa + 3\varphi \end{aligned}$$

Higgs Sector of the NMSSM at Tree Level

The tadpole conditions keep the presumed vacuum to be local minimum.

$$
\begin{aligned}
0 &= \frac{1}{v_d}\left\langle \frac{\partial V^{(0)}}{\partial h_d} \right\rangle = m_1^2 + \frac{1}{2}|\lambda|^2(v_u^2 + v_s^2) + \frac{1}{8}\bar{g}^2(v_d^2 - v_u^2) - \left(\mathcal{R}_\lambda + \frac{1}{2}\mathcal{R} v_s\right)\frac{v_u v_s}{v_d}, \\
0 &= \frac{1}{v_u}\left\langle \frac{\partial V^{(0)}}{\partial h_u} \right\rangle = m_2^2 + \frac{1}{2}|\lambda|^2(v_d^2 + v_s^2) - \frac{1}{8}\bar{g}^2(v_d^2 - v_u^2) - \left(\mathcal{R}_\lambda + \frac{1}{2}\mathcal{R} v_s\right)\frac{v_d v_s}{v_u}, \\
0 &= \frac{1}{v_s}\left\langle \frac{\partial V^{(0)}}{\partial h_s} \right\rangle = m_S^2 + \frac{1}{2}|\lambda|^2(v_d^2 + v_u^2) + |\kappa|^2 v_s^2 - \mathcal{R}_\kappa v_s - \left(\mathcal{R}_\lambda + \mathcal{R} v_s\right)\frac{v_d v_u}{v_s}, \\
0 &= \frac{1}{v_d}\left\langle \frac{\partial V^{(0)}}{\partial a_d} \right\rangle = \left(\mathcal{I}_\lambda + \frac{1}{2}\mathcal{I} v_s\right)\frac{v_s v_u}{v_d}, \\
0 &= \frac{1}{v_u}\left\langle \frac{\partial V^{(0)}}{\partial a_u} \right\rangle = \left(\mathcal{I}_\lambda + \frac{1}{2}\mathcal{I} v_s\right)\frac{v_s v_d}{v_u}, \\
0 &= \frac{1}{v_s}\left\langle \frac{\partial V^{(0)}}{\partial a_s} \right\rangle = \left(\mathcal{I}_\lambda + \frac{1}{2}\mathcal{I} v_s\right)\frac{v_d v_u}{v_s} + \left(\mathcal{I}_\kappa - \frac{3}{2}\mathcal{I}\frac{v_d v_u}{v_s}\right) v_s,
\end{aligned}
$$

where

$$
\begin{aligned}
\mathcal{R} &= |\lambda||\kappa|\cos(\phi'_\lambda - \phi'_\kappa), & \mathcal{I} &= |\lambda||\kappa|\sin(\phi'_\lambda - \phi'_\kappa), \\
\mathcal{R}_\lambda &= \frac{1}{\sqrt{2}}|\lambda||A_\lambda|\cos(\phi'_\lambda + \phi_{A_\lambda}), & \mathcal{I}_\lambda &= \frac{1}{\sqrt{2}}|\lambda||A_\lambda|\sin(\phi'_\lambda + \phi_{A_\lambda}), \\
\mathcal{R}_\kappa &= \frac{1}{\sqrt{2}}|\kappa||A_\kappa|\cos(\phi'_\kappa + \phi_{A_\kappa}), & \mathcal{I}_\kappa &= \frac{1}{\sqrt{2}}|\kappa||A_\kappa|\sin(\phi'_\kappa + \phi_{A_\kappa}).
\end{aligned}
$$

Higgs Sector of the NMSSM at Tree Level

Two of the tadpole conditions can eliminate two of the physical CP phases, but left an ambiguity on determining the sign of two physical CP phases.

$$I_\lambda = \frac{1}{\sqrt{2}}|\lambda||A_\lambda|\sin(\phi'_\lambda + \phi_{A_\lambda}) = -\frac{1}{2}\mathcal{I}v_s, \quad R_\lambda = \frac{1}{\sqrt{2}}|\lambda||A_\lambda|\cos(\phi'_\lambda + \phi_{A_\lambda}),$$
$$I_\kappa = \frac{1}{\sqrt{2}}|\kappa||A_\kappa|\sin(\phi'_\lambda + \phi_{A_\kappa}) = \frac{3}{2}\mathcal{I}\frac{v_d v_u}{v_s}, \ R_\kappa = \frac{1}{\sqrt{2}}|\kappa||A_\kappa|\cos(\phi'_\kappa + \phi_{A_\kappa})$$

Associated with $v^2 = v_d^2 + v_u^2$ and $\tan\beta = v_u/v_d$, we have 6+1 free parameters and 2 signs at tree level:

$$|\lambda|, |\kappa|, |A_\lambda|, |A_\kappa|, \tan\beta, v_s, (\phi'_\lambda - \phi'_\kappa), \mathrm{sign}[\cos(\phi'_\lambda + \phi_{\mathrm{A}_\lambda})], \mathrm{sign}[\cos(\phi'_\kappa + \phi_{\mathrm{A}_\kappa})].$$

These two tadpole conditions also provide loose bounds on parameters for CP-violating case.

$$1 \geq \sin^2(\phi'_\lambda + \phi_{A_\lambda}) = \frac{\mathcal{I}^2 v_s^2}{2|\lambda|^2|A_\lambda|^2} \geq 0,$$
$$1 \geq \sin^2(\phi'_\lambda + \phi_{A_\kappa}) = \frac{9}{8}\frac{\mathcal{I}^2 s_{2\beta}^2 v^4}{|\kappa|^2|A_\kappa|^2 v_s^2} \geq 0.$$

Electroweak Phase Transition of the NMSSM

It is possible to acquire strong first order phase transition without light top squark in the NMSSM. (Funakubo, Prog.Theor.Phys.114:369,2005)

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

Where $v = \sqrt{v_d^2 + (v_u \cos\theta)^2 + (v_u \sin\theta)^2}$. The effective potential is invariant under glabal $U(1)$, $(v_u \cos\theta + i v_u \sin\theta) \to e^{i\alpha}(v_u \cos\theta + i v_u \sin\theta)$, as $v_s = 0$. As a result, there are four types of phase transition.

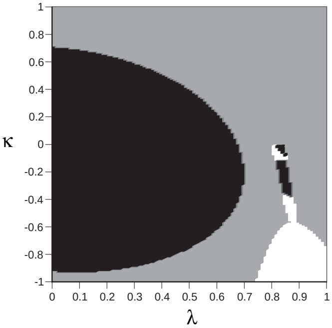
A: SYM $\rightarrow$ I $\Rightarrow$ EW   B: SYM $\rightarrow$ I′ $\Rightarrow$ EW

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

The type of the phase transition is determined by the parameter set.

Electroweak Phase transition of the NMSSM

It shows that, the NMSSM can acquire strong first order phase transition under the limit of global minimal and LEP constraint without light top squark.



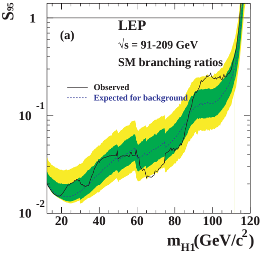
Funakubo et al., Prog.Theor.Phys.114:369,2005

More precisely, only the type B can acquire strong first order phase transition without light top squark, and $\frac{v_C}{T_C} \sim 1.89$, while the other three type phase transition still need a light top squark.

Conditions on the Higgs Sector

In our work, we study the allowed parameter space for the type B strong first order phase transition scenario with three conditions,

- Positivity of the Higgs mass square, $M^2_{H_i} \geq 0$;
- The prescribed vacuum to be global minimum, by numerical downhill simplex method.
- The LEP limit, from Eur. Phys. J. C**47**, 547 (2006).



Besides the one loop contribution, we also take into account the two-loop log enhenced contribution into the effective potential through renormalization group improvement.

The free parameters in Higgs boson sector of the NMSSM at one loop level are,

$$
\begin{aligned}
\text{tree level} \quad &: \quad |\lambda|,\ |\kappa|,\ \tan\beta,\ v_s, |A_\lambda|,\ |A_\kappa|, (\phi'_\lambda - \phi'_\kappa), \\
&\quad \mathrm{sign}[\cos(\phi'_\lambda + \phi_{\mathrm{A}_\lambda})], \mathrm{sign}[\cos(\phi'_\kappa + \phi_{\mathrm{A}_\kappa})] \\
\text{one loop level} \quad &: \quad |A_t|,\ |A_b|,\ M_{Q_3},\ M_{U_3},\ M_{D_3},\ (\phi'_\lambda + \phi_{A_t}),\ (\phi'_\lambda + \phi_{A_b})
\end{aligned}
$$

Kingman Cheung, Tie-Jiun Hou, Jae Sik Lee, and Eibun Senaha Phys.Rev.D82:075007,2010.

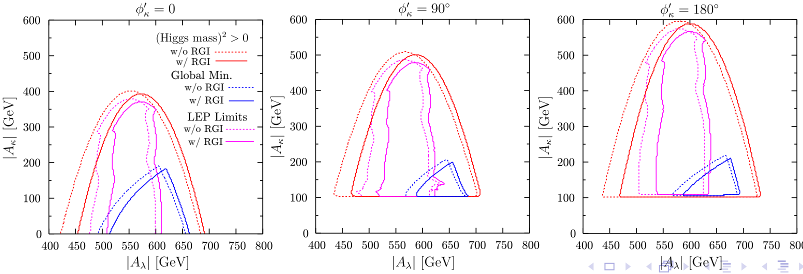
Numerical Result

In this work, we fix part of the parameters to be

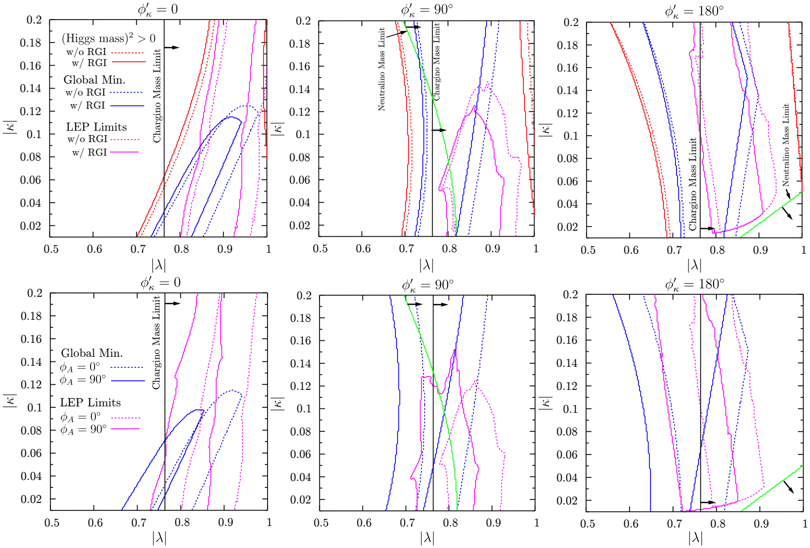
$$|A_t| = |A_b| = M_{Q_3} = M_{U_3} = M_{D_3} = 1000\,\mathrm{GeV},$$
$$\phi'_\lambda = \phi_{A_t} = \phi_{A_b} = 0,\ \mathrm{sign}[\cos(\phi'_\lambda + \phi_{\mathrm{A}_\lambda})] = \mathrm{sign}[\cos(\phi'_\kappa + \phi_{\mathrm{A}_\kappa})] = +1.$$

With the type B scenario suggested by Funakubo,

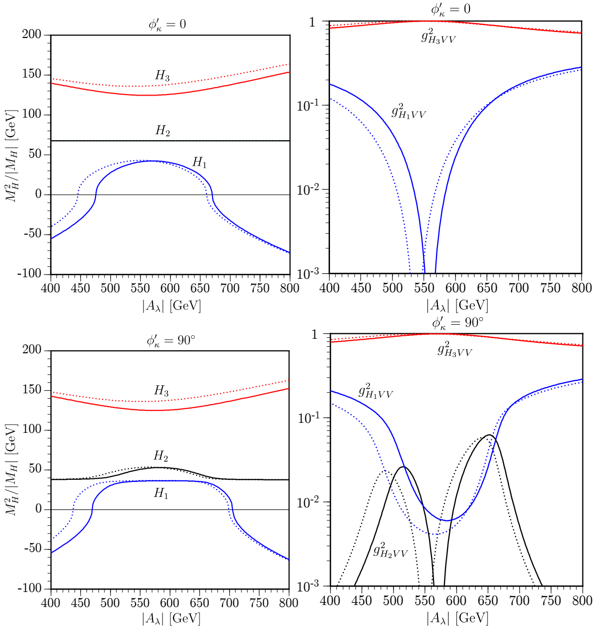
$$\tan\beta = 5\,, \quad v_S = 200\ \mathrm{GeV}\,,$$
$$M_{\tilde{Q}} = M_{\tilde{U}} = M_{\tilde{D}} = |A_t| = |A_b| = 1000\ \mathrm{GeV}\,, \phi'_\lambda = 0\,,$$
$$\mathrm{sign}\,[\cos(\phi'_\kappa + \phi_{A_\kappa})] = \mathrm{sign}\,[\cos(\phi'_\lambda + \phi_{A_\lambda})] = +1\,,$$



Numerical Result



Numerical Result



$|\lambda| = 0.83$, $|\kappa| = 0.05$
$|A_\kappa| = 125$ GeV

H_3 is the SM-like Higgs. H_2 is a_s-like and H_1 is h_s-like.

EDMs in the NMSSM

According to the experience of MSSM, we further consider the EDMs constraint on the CP phase ϕ'_κ.

$$\mathcal{L} = -\frac{i}{2} d_f^E F^{\mu\nu} \bar{f} \sigma_{\mu\nu}\gamma_5 f - \frac{i}{2} d_q^C G^{a\,\mu\nu} \bar{q} \sigma_{\mu\nu}\gamma_5 T^a q + \frac{1}{3} d^{\,G} f_{abc} G^a_{\rho\mu} \widetilde{G}^{b\,\mu\nu} G^c{}_\nu{}^\rho + \sum_{f,f'} C_{ff'} (\bar{f} f)(\bar{f}' i\gamma_5 f') ,$$

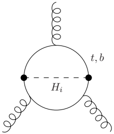
$$d_f^E = (d_f^E)^{\widetilde{\chi}^0} + (d_f^E)^{\mathrm{BZ}} ; \quad d_q^C = (d_q^C)^{\widetilde{\chi}^0} + (d_q^C)^{\mathrm{BZ}} .$$

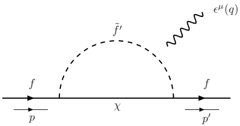
$$\left(d_f^E\right)^{\mathrm{BZ}} = \left(d_f^E\right)^{\gamma H^0} + \left(d_f^E\right)^{W^\mp H^\pm} + \left(d_f^E\right)^{W^\mp W^\pm} + \left(d_f^E\right)^{Z H^0}$$

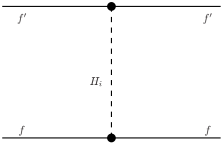
Kingman Cheung, Tie-Jiun Hou, Jae Sik Lee, and Eibun Senaha PhysRevD84.015002,2011.

EDMs in the NMSSM

We focus on the EDMs contributed by the CP phase ϕ'_κ.







$$(d^{\,G})^H \;=\; \frac{4\sqrt{2}\,G_F\,g_s^3}{(4\pi)^4}\sum_{q=t,b}\left[\sum_i g^S_{H_i\bar{q}q}\,g^P_{H_i\bar{q}q}\,h(z_{iq})\right] ,$$

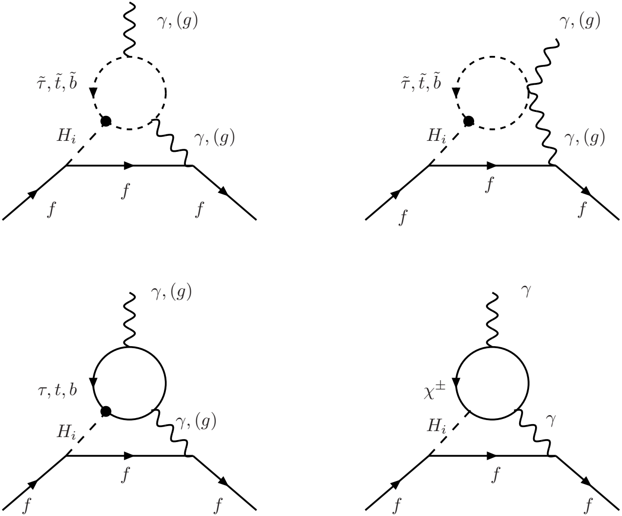
$$\left(\frac{d_f^E}{e}\right)^{\widetilde{\chi}^0} \;=\; \frac{1}{16\pi^2}\sum_{i=1}^{5}\sum_{j=1}^{2}\frac{m_{\widetilde{\chi}^0_i}}{m^2_{\widetilde{f}_j}}\;\Im\mathrm{m}[(g^{\widetilde{\chi}^0 f\widetilde{f}}_{R\,ij})^*\,g^{\widetilde{\chi}^0 f\widetilde{f}}_{L\,ij}]\,Q_{\widetilde{f}}\,B(m^2_{\widetilde{\chi}^0_i}/m^2_{\widetilde{f}_j}) ,$$

$$(C_{ff'})^H \;=\; g_f\,g_{f'}\sum_i\frac{g^S_{H_i\bar{f}f}\,g^P_{H_i\bar{f}'f'}}{M^2_{H_i}} .$$

EDMs in the NMSSM

The Barr-Zee diagram contribution include

$$\left(d_f^E\right)^{\mathrm{BZ}} = \left(d_f^E\right)^{\gamma H^0} + \left(d_f^E\right)^{W^\mp H^\pm} + \left(d_f^E\right)^{W^\mp W^\pm} + \left(d_f^E\right)^{ZH^0}$$



EDMs in the NMSSM

In this work, we consider three observable EDMs, Thallium(Tl), Neutron(n) and Mercury(Hg).

$$d_{\mathrm{Tl}}\,[e\,\mathrm{cm}] \;=\; -585\cdot d_e^E\,[e\,\mathrm{cm}] \;-\; 8.5\times 10^{-19}\,[e\,\mathrm{cm}]\cdot(C_S\,\mathrm{TeV}^2) \;+\; \cdots\,,$$

$$\mathcal{L}_{C_S} = C_S\,\bar{e}i\gamma_5\,e\bar{N}N$$

$$C_S = C_{de}\frac{29\,\mathrm{MeV}}{m_d} + C_{se}\frac{\kappa\times 220\,\mathrm{MeV}}{m_s} + (0.1\,\mathrm{GeV})\,\frac{m_e}{v^2}\sum_{i=1}^{3}\frac{g^S_{H_igg}g^P_{H_i\bar{e}e}}{M^2_{H_i}}$$

EDMs in the NMSSM

For the neutron EDM, there are three hardronic approaches, the Chiral Quark Model (CQM), the Parton Quark Model (PQM) and QCD sum-rule technieque.

$$
\begin{aligned}
d_n^{(CQM)} &= \frac{4}{3}\, d_d^{\rm NDA} - \frac{1}{3}\, d_u^{\rm NDA}\,, \\
d_{q=u,d}^{\rm NDA} &= \eta^E\, d_q^E + \eta^C\, \frac{e}{4\pi}\, d_q^C + \eta^G\, \frac{e\Lambda}{4\pi}\, d^{\,G}\,,
\end{aligned}
$$

$$
d_n^{(PQM)} = \eta^E\, (\Delta_d^{\rm PQM}\, d_d^E + \Delta_u^{\rm PQM}\, d_u^E + \Delta_s^{\rm PQM}\, d_s^E)\,,
$$

$$
\Delta_d^{\rm PQM} = 0.746, \Delta_u^{\rm PQM} = -0.508, \Delta_s^{\rm PQM} = -0.226.
$$

$$
\begin{aligned}
d_n^{(QCD)} &= d_n(d_q^E\,, d_q^C) + d_n(d^{\,G}) + d_n(C_{bd}) + \cdots\,, \\
d_n(d_q^E\,, d_q^C) &= (1.4 \pm 0.6)\,(d_d^E - 0.25\, d_u^E) + (1.1 \pm 0.5)\, e\,(d_d^C + 0.5\, d_u^C)/g_s\,, \\
d_n(d^{\,G}) &\sim \pm\, e\,(20 \pm 10)\ {\rm MeV}\ d^{\,G}\,, \\
d_n(C_{bd}) &\sim \pm\, e\, 2.6 \times 10^{-3}\ {\rm GeV}^2 \left[\frac{C_{bd}}{m_b} + 0.75\frac{C_{db}}{m_b}\right]\,,
\end{aligned}
$$

EDMs in the NMSSM

Using QCD sum-rule, the Mercury EDM is estimate with the uncertainty of Schiff-moment

$$
\begin{aligned}
d_{\rm Hg}^{\rm I\,,II\,,III\,,IV} &= d_{\rm Hg}^{\rm I\,,II\,,III\,,IV}[S] + 10^{-2} d_e^E + (3.5\times 10^{-3}{\rm GeV})\, e\, C_S \\
&+ (4\times 10^{-4}\ {\rm GeV})\, e \left[C_P + \left(\frac{Z-N}{A}\right)_{\rm Hg} C_P' \right] ,
\end{aligned}
$$

where $\mathcal{L}_{C_P} = C_P\, \bar{e} e\, \bar{N} i\gamma_5 N + C_P'\, \bar{e} e\, \bar{N} i\gamma_5 \tau_3 N$

$$
\begin{aligned}
C_P &\simeq -375\ {\rm MeV} \sum_{q=c,s,t,b} \frac{C_{eq}}{m_q} , \\
C_P' &\simeq -806\ {\rm MeV}\, \frac{C_{ed}}{m_d} - 181\ {\rm MeV} \sum_{q=c,s,t,b} \frac{C_{eq}}{m_q} .
\end{aligned}
$$

$$
\begin{aligned}
d_{\rm Hg}^{\rm I}[S] &\simeq 1.8\times 10^{-3}\, e\, \bar{g}_{\pi NN}^{(1)}\, /{\rm GeV} , \\
d_{\rm Hg}^{\rm II}[S] &\simeq 7.6\times 10^{-6}\, e\, \bar{g}_{\pi NN}^{(0)}\, /{\rm GeV} + 1.0\times 10^{-3}\, e\, \bar{g}_{\pi NN}^{(1)}\, /{\rm GeV} , \\
d_{\rm Hg}^{\rm III}[S] &\simeq 1.3\times 10^{-4}\, e\, \bar{g}_{\pi NN}^{(0)}\, /{\rm GeV} + 1.4\times 10^{-3}\, e\, \bar{g}_{\pi NN}^{(1)}\, /{\rm GeV} , \\
d_{\rm Hg}^{\rm IV}[S] &\simeq 3.1\times 10^{-4}\, e\, \bar{g}_{\pi NN}^{(0)}\, /{\rm GeV} + 9.5\times 10^{-5}\, e\, \bar{g}_{\pi NN}^{(1)}\, /{\rm GeV} .
\end{aligned}
$$

EDMs in the NMSSM

We also consider the deuteron EDM and EDM of ^{225}Ra for proposed future experiments.

$$\begin{aligned} d_D \;\simeq\; & -\left[5^{+11}_{-3} + (0.6 \pm 0.3)\right]\, e\,(d_u^C - d_d^C)/g_s \\ & -(0.2 \pm 0.1)\, e\,(d_u^C + d_d^C)/g_s \;+\; (0.5 \pm 0.3)(d_u^E + d_d^E) \\ & +(1 \pm 0.2) \times 10^{-2}\, e\,\mathrm{GeV}^2 \left[\frac{0.5\,C_{dd}}{m_d} + 3.3\kappa\frac{C_{sd}}{m_s} + (1 - 0.25\kappa)\frac{C_{bd}}{m_b}\right] \\ & \pm\; e\,(20 \pm 10)\ \mathrm{MeV}\, d^{\,G}\ . \end{aligned}$$

$$d_{\mathrm{Ra}} \simeq d_{\mathrm{Ra}}[S] \simeq -8.7 \times 10^{-2}\, e\,\bar{g}^{(0)}_{\pi NN}\,/\mathrm{GeV} + 3.5 \times 10^{-1}\, e\,\bar{g}^{(1)}_{\pi NN}\,/\mathrm{GeV}\,.$$

EDMs in the NMSSM

We consider the current experimental bounds

$$
\begin{aligned}
d_{\mathrm{Tl}}^{\mathrm{EXP}} &= 9 \quad \times 10^{-25}\, e\,\mathrm{cm}\,, && \text{PRL,88,071805} \\
d_{\mathrm{n}}^{\mathrm{EXP}} &= 2.9 \times 10^{-26}\, e\,\mathrm{cm}\,, && \text{PRL,97,131801} \\
d_{\mathrm{Hg}}^{\mathrm{EXP}} &= 3.1 \times 10^{-29}\, e\,\mathrm{cm}\,, && \text{PRL,86,2505.}
\end{aligned}
$$

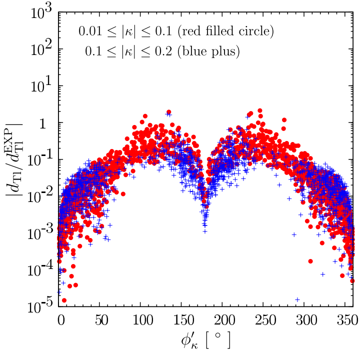
and the projected experimental sensitivity

$$
\begin{aligned}
d_{\mathrm{D}}^{\mathrm{EXP}} &= 3 \times 10^{-27}\, e\,\mathrm{cm} && \text{AIP Conf. Proc. 698 (2004) 200} \\
d_{\mathrm{Ra}}^{\mathrm{EXP}} &= 1 \times 10^{-27}\, e\,\mathrm{cm} && \text{CERN-INTC-2010-049 / INTC-I-115}
\end{aligned}
$$

Numerical Results

The parameter set is taken from the suggestion of Funakubo for type B parameter set.

$$\tan\beta = 5\,, \quad v_S = 200\ \mathrm{GeV}\,,$$
$$M_{\tilde{Q}_{1,2,3}} = M_{\tilde{U}_{1,2,3}} = M_{\tilde{D}_{1,2,3}} = M_{\tilde{L}_{1,2,3}} = M_{\tilde{E}_{1,2,3}} = 1\ \mathrm{TeV}\,,$$
$$|A_e| = |A_u| = |A_d| = |A_s| = |A_\tau| = |A_t| = |A_b| = 1\ \mathrm{TeV}\,,$$
$$\phi_{A_e} = \phi_{A_u} = \phi_{A_d} = \phi_{A_s} = \phi_{A_\tau} = \phi_{A_t} = \phi_{A_b} = 0\,,\ \phi_{1,2,3} = 0\,,$$
$$\phi'_\lambda = 0\,; \quad \mathrm{sign}\,[\cos(\phi'_\kappa + \phi_{A_\kappa})] = \mathrm{sign}\,[\cos(\phi'_\lambda + \phi_{A_\lambda})] = +1\,,$$

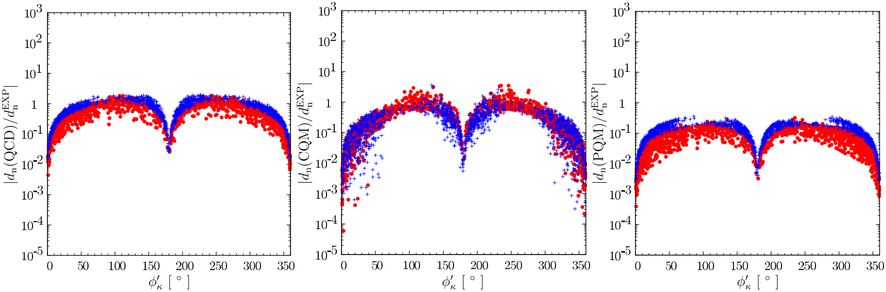


while varying

$$0.75 \le |\lambda| \le 0.95\,,$$
$$0.01 \le |\kappa| \le 0.2\,,$$
$$|A_\lambda|_{\mathrm{MIN}} \le |A_\lambda| \le 800\ \mathrm{GeV}\,,$$
$$|A_\kappa|_{\mathrm{MIN}} \le |A_\kappa| \le 200\ \mathrm{GeV}\,,$$

Numerical Results

neutron

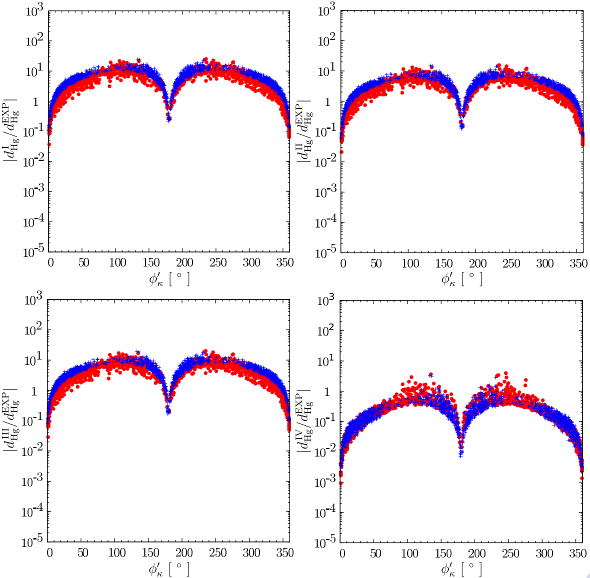


$0.01 \lesssim |\kappa| \lesssim 0.1$ red

$0.1 \lesssim |\kappa| \lesssim 0.2$ blue

Numerical Results

Mercury

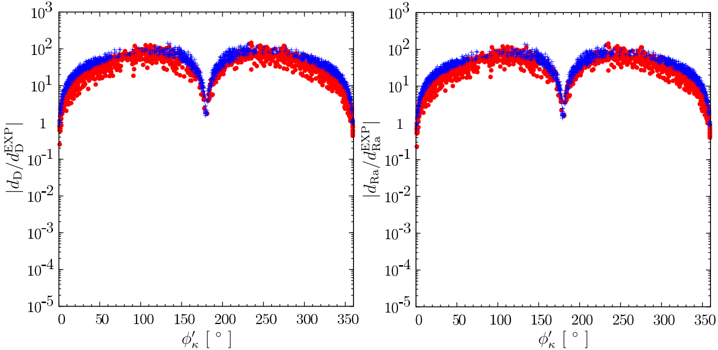


$0.01 \lesssim |\kappa| \lesssim 0.1$ red

$0.1 \lesssim |\kappa| \lesssim 0.2$ blue

Numerical Results

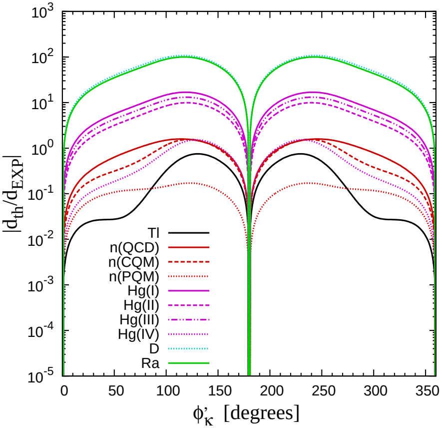
Deutron and Radium



$0.01 \lesssim \quad |\kappa| \quad \lesssim 0.1$ red

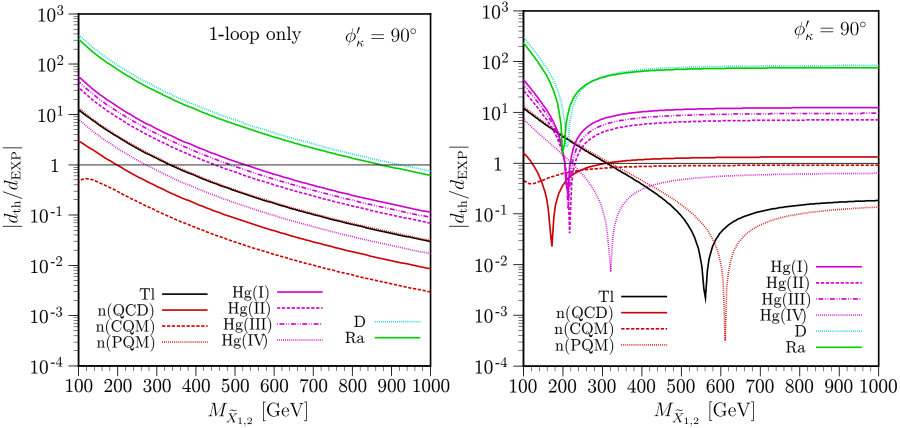
$0.1 \lesssim \quad |\kappa| \quad \lesssim 0.2$ blue

Numerical Results



$$|\lambda| = 0.81\,, |\kappa| = 0.08\,, |A_\lambda| = 575 \ \ \mathrm{GeV}\,, |A_\kappa| = 110 \ \ \mathrm{GeV}.$$

Numerical Results



$$M_{\tilde{X}_{1,2}} \equiv M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}} = M_{\tilde{L}_{1,2}} = M_{\tilde{E}_{1,2}}.$$

Summary

- Baryon asymmetry is possible to be explained by electroweak baryogenesis.
- The SM is fail to explain the baryon asymmetry because the parameter region producing strong first order phase transition has been excluded.
- It require $m_{\tilde{t}} < m_t$ in MSSM to produce strong first order phase transtion. The CP phases in MSSM are restricted by EDMs constraint.
- The corresponding soft term also provide cubic term at tree level. With the phase transition SYM $\to$ I$'$ $\to$ EW, stronge first order phase transtion can be made without light top squark.
- With the virture of the addtional Higgs singlet in the NMSSM, there is one tree level physical CP phase which is compatable with the up-to-date EDMs constraint.
- Ongoing work is to work out the $Y_B = \frac{\rho_B}{s}$ for NMSSM with $\phi'_\lambda - \phi'_\kappa$ to be the CP source during Electroweak phase transition.