Electroweak Baryogenesis in the supersymmetric model

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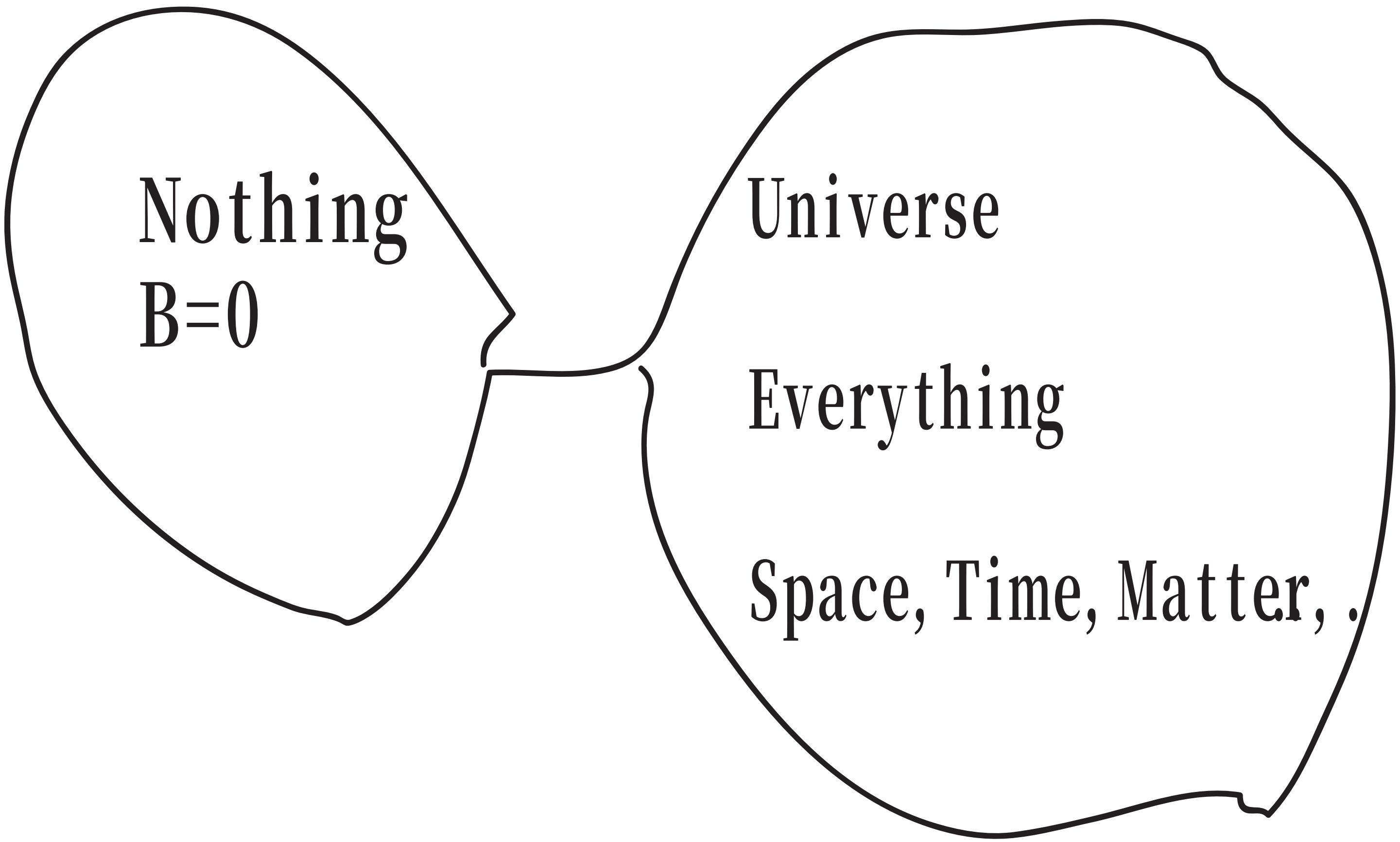
1. Introduction



Matter-Antimatter Asymmetry of the Universe?.

Locally antimatter area (?) $\rightarrow$ Significant Photon Flux ($\times$)

$\rightarrow$ Baryon Asymmetry of the Universe?

-A. D. Sakharov, JETP Lett. 5, 24 (1967)

(1) The presence of baryon number(B) violation: Axial anomaly

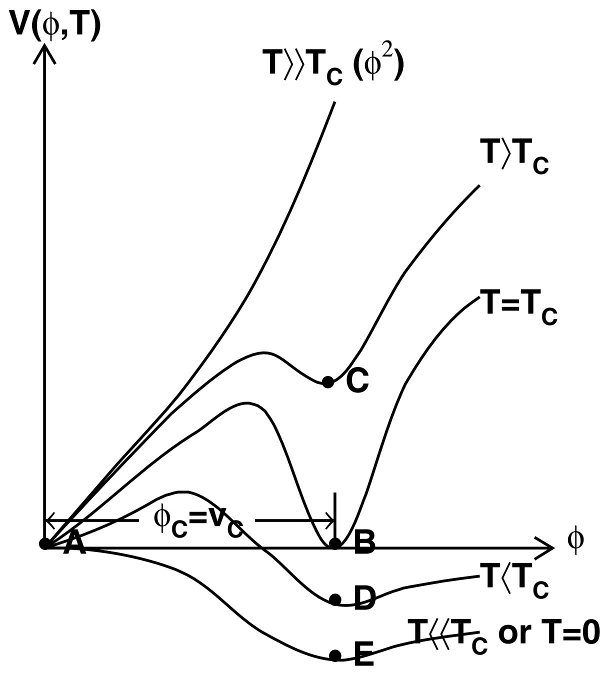
(2) The violation of Both C (Charge Conjugation) and CP:

- C is maximally violated !; $\quad \Gamma(\pi^+ \rightarrow \mu^+ \nu_L) \neq \Gamma(\pi^- \rightarrow \mu^- \bar{\nu}_L) = 0$

- CP Vioaltion: CKM matrix

(3) A departure from thermal equilibrium:

The existence of the thermal non-equilibrium during the evolution of Universe $\longrightarrow$ First order phase transition



First order phase transition (Figure)

Potential at $T \neq 0$

1 GeV $= 1.1605 \times 10^{13}$ **K**

$V = V(\phi, T) = V(\phi, 0) + V_1(\phi, 0) + V_1(\phi, T)$

Symmetry Restoration at High T

A: Symmetric phase state

B: Broken phase state

○ **Strongly first order phase transition(Baryon Preserving condition)**

◇ **Sphaleron(Greek for ready to fall) Constraint;** $\phi_C \geq T_C$

○ **Weakly first order phase transition:** $\phi_C < T_C$

- Sakharov pointed out that the observed baryon asymmetry of the Universe can be produced by processes which violate C, CP and B and occurs out of thermal equilibrium.

- The three conditions can be satisfied in the Standard Model; C-violation exists, CP violating terms can be accomodated, sphaleron at finite temperature can induce sufficient B-violating processes.

- A first order phase transition can provide the nonthermal equilibrium. Furthermore, in order to have sufficient departure from equilibrium, it is necessary that this transition be rather strong.

- The value of the ratio of the Higgs field (v_c) and the critical temperature (T_c) should at least be about 1.0: $v_c/T_c \geq 1$.

(a) Standard Model

- At finite temperature, the SM effective potential constructed so far obtains this ratio to be rather small.

- It has been shown to decrease when the SM Higgs mass is increased.

- ElectroWeak Phase Transition (EWPT) in the Standard Model

$$V(\phi, T) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + V_1(\phi, 0) + V_1(\phi, T) \ .$$

$$V_1(\phi, 0) = \sum_i \frac{n_i}{64\pi^2}\left[m_i^4(\phi)\log\left(\frac{m_i^2(\phi)}{m_i^2(v)}\right) - \frac{3}{2}m_i^4(\phi) + 2m_i^2(v)m_i^2(\phi)\right] \ ,$$

$$V_1(\phi, T) = \sum_i \frac{n_i T^4}{2\pi^2}\int_0^\infty dx \ x^2 \ \log\left[1 \pm \exp\left(-\sqrt{x^2 + m_i^2(\phi)/T^2}\right)\right] \ ,$$

where $i = W, Z, t, \phi, G$**; Boson(−) and Fermion (+).**

- High Temperature Approximation

$$V_1^{(\text{high } T)}(\phi, T) = -\, n_t \left[\frac{T^2 m_t^2(\phi)}{48} + \frac{m_t^4(\phi)}{64\pi^2} \log\left(\frac{m_t^2(\phi)}{c_f T^2}\right)\right] + \sum_i n_i \left[\frac{T^2 m_i^2(\phi)}{24} - \frac{T m_i^3(\phi)}{12\pi} - \frac{m_i^4(\phi)}{64\pi^2}\log\left(\frac{m_i^2(\phi)}{c_b T^2}\right)\right] \; .$$

$\log C_f = 2.64$, $\log C_b = 5.41$

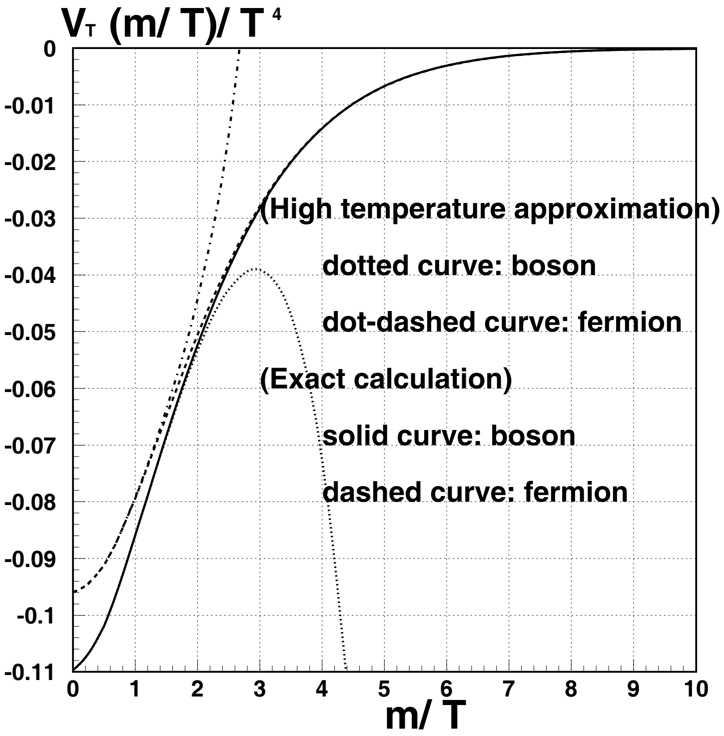
5 % deviation for $m_f/T < 1.6$, $m_b/T < 2.2$

$$V(\phi, T) = (DT^2 - E)\phi^2 - FT\phi^3 + G\phi^4 \; ,$$

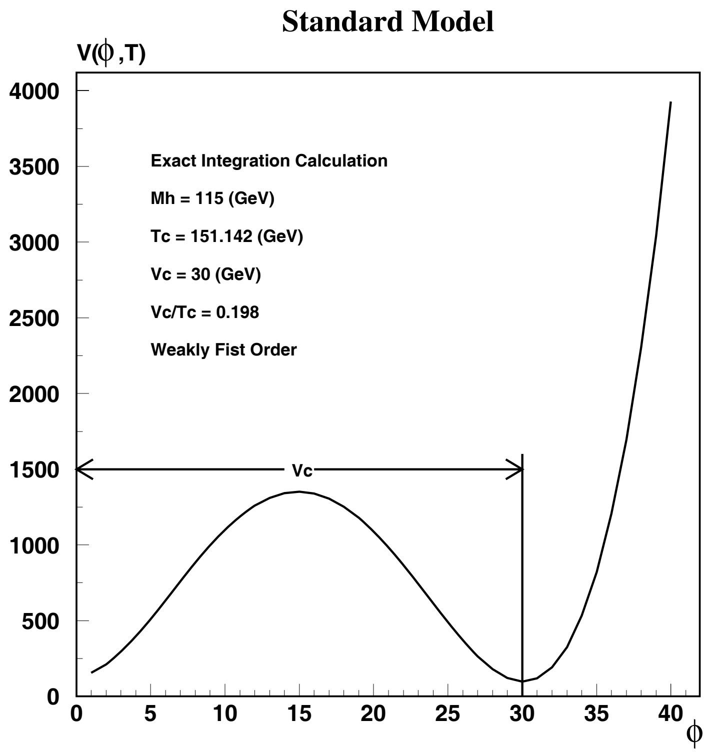
$$D = \frac{1}{24v^2}\left(6m_W^2 + 3m_Z^2 + 6m_t^2\right) \; , \quad E = \frac{m_H^2}{4} - \frac{1}{32\pi^2 v^2}(6m_W^4 + 3m_Z^4 - 12m_t^2\Big) \; ,$$

$$G = \frac{m_H^2}{8v^2} - \frac{1}{64\pi^2 v^4}\left(6m_W^4 \log\left(\frac{m_W^2}{a_b T^2}\right) + 3m_Z^4 \log\left(\frac{m_Z^2}{a_b T^2}\right) - 12 m_t^4 \log\left(\frac{m_t^2}{a_f T^2}\right)\right) \; ,$$

$$F = \frac{1}{14v^3}\left(6m_W^3 + 3m_Z^3\right) \; , \quad a_b = \exp(3.91) \; , \; a_f = \exp(1.14) \; ,$$



V_T (m/ T)/ T^4
(High temperature approximation)
dotted curve: boson
dot-dashed curve: fermion
(Exact calculation)
solid curve: boson
dashed curve: fermion
m/ T



Standard Model
V(φ,T)
Exact Integration Calculation
Mh = 115 (GeV)
Tc = 151.142 (GeV)
Vc = 30 (GeV)
Vc/Tc = 0.198
Weakly Fist Order
Vc
φ

(b) Minimal Supersymmetric Standard Model

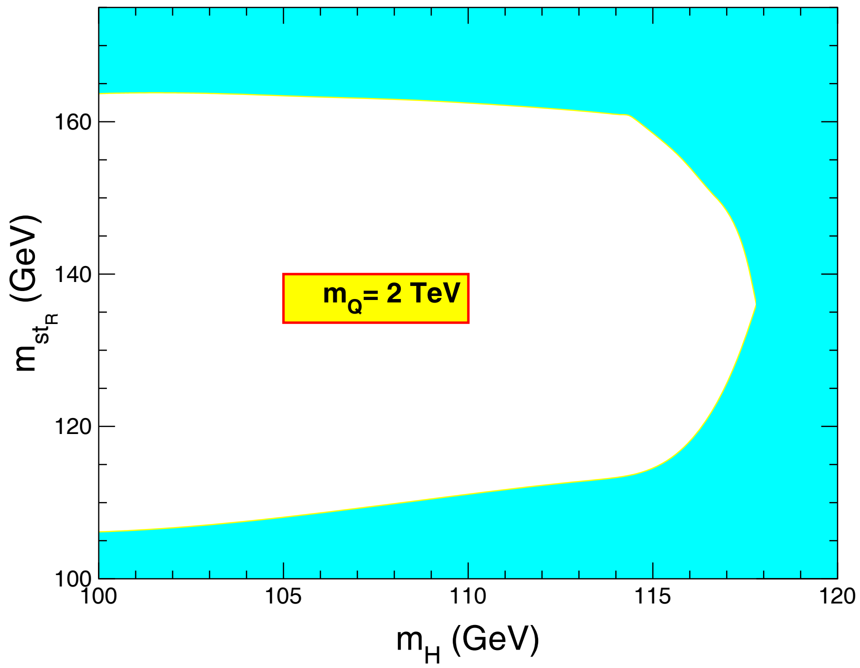
$\odot$ **Light Stop Scenario:** $m_{\tilde{t}_R} < m_t$

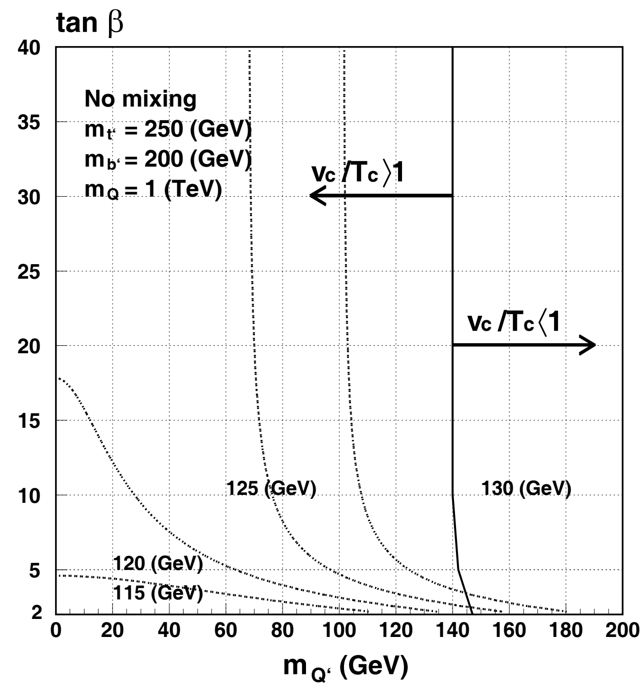
- Opening the window for electroweak baryogenesis, M. Carena, M. Quiros, C.E.M. Wagner, Phys. Lett. B380, 81 (1996).

- A Light stop and electroweak baryogenesis, D. Delepine, J.M. Gerard, R. Gonzalez Felipe, J. Weyers, Phys. Lett. B386, 183 (1996).

In electroweak baryogenesis scenario, we always need a boson particle with a mass of the electroweak scale in order to induce a strong phase transition.

That reason comes from the heavy top quark because a heavy fermion makes weak the phase transition.





EWPT in the MSSM

Left: Electroweak baryogenesis and the Higgs and stop masses, M. Quiros, Nucl. Phys. Proc. Suppl. 101, 401 (2001)

Right: Electroweak phase transition in the MSSM with four generations, S.W. Ham, S.K. Oh, and D. Son, PRD71, 015001 (2005)

(c) Non-Minimal Supersymmetric Standard Model

$\diamond$ **μ-problem** **($\sim \mu H_1 H_2$); J.E. Kim, H.P. Nilles, PLB138, 150 (1984)**

$\odot$ $SU(2) \times U(1)$

Next-to-MSSM (NMSSM), Minimal Non-MSSM (MNMSSM)

Two Higgs doublets + One Higgs singlet

S_1, S_2, S_3, P_1, P_2, $H^\pm$, $\tilde{\chi}_1^0 - \tilde{\chi}_5^0$

$\odot$ $SU(2) \times U(1) \times U(1)'$ **: USSM;** S_1, S_2, S_3, A, $H^\pm$, Z', $\tilde{\chi}_1^0 - \tilde{\chi}_6^0$, D

$\odot$ $SU(2) \times U(1) \times U(1)' \times U(1)''$**:** E_6 **SUSY Model**

S_1, S_2, S_3, S_4, A, $H^\pm$, Z', Z'', $\tilde{\chi}_1^0 - \tilde{\chi}_7^0$, D

- **μ-parameter:** $\mu \sim \lambda\langle N\rangle$, **VEV of Higgs singlet**

- **SU$\!\!\!/$SY : Soft Terms**

- Electroweak phase transition in MSSM with $U(1)'$ in explicit CP violation scenario, S.W. Ham, S.K. Oh, Phys. Rev. D76, 095018 (2007).
- Electroweak phase transitions in the MSSM with an extra $U(1)'$, S.W. Ham, E.J. Yoo, S.K. Oh, Phys. Rev. D76, 075011 (2007).
- Phase transition in a supersymmetric axion model, S.W. Ham, S.K. Oh, Phys. Rev. D76, 017701 (2007).
- Electroweak phase transition in an extension of the standard model with a real Higgs singlet. S.W. Ham, Y.S. Jeong S.K. Oh, J. Phys. G31, 857 (2005).
- Electroweak phase transition in the MSSM with four generations, S.W. Ham, S.K. Oh, D. Son, Phys. Rev. D71, 015001 (2005).
- Electroweak phase transition in the standard model with a dimension-six Higgs operator at the one-loop level, S.W. Ham, S.K. Oh, Phys. Rev. D70, 093007 (2004).
- Electroweak phase transition in a nonminimal supersymmetric model, S.W. Ham, S.K. Oh, C.M. Kim, E.J. Yoo, D. Son, Phys. Rev. D70, 075001 (2004).

EWPT in the Non-MSSMs

$\phi_c > T_c$ **for** $m_{\tilde{t}_1} > m_t$ **(There are Trilinear Terms in the Non-MSSMs)**

NMSSM: $\sim \lambda A_\lambda H_1 H_2 N + k A_k N^3/3$ **(M. Pietroni, NPB402, 27, 1993)**

MNMSSM, USSM: $\sim \lambda A_\lambda H_1 H_2 N$

MNMSSM: Electroweak phase transition in a nonminimal supersymmetric model, S.W. Ham, S.K. OH, C.M. Kim, E.J. Yoo, D. Son, PRD70, 075001 (2004)

USSM: Electroweak phase transitions in the MSSM with an extra $U(1)'$**, S.W. Ham, E.J. Yoo, S.K. Oh, PRD76, 075011 (2007)**

Electroweak phase transition in MSSM with $U(1)'$ **in explicit CP violation scenario, S.W. Ham, S.K. Oh, PRD76, 095018 (2007)**

⊙ Beyond MSSM

- Higgs Physics as a Window Beyond the MSSM (BMSSM), Michael Dine, Nathan Seiberg, Scott Thomas, Phys. Rev. D76:095004 (2007).

⊙ Motivation

- Recently, Dine, Seiberg, and Thomas have investigated the effects of new physics beyond the MSSM within the framework of effective field theory analysis.

- If the new physics beyond the MSSM lies at an energy scale M, the corrections to the MSSM may be described in terms of higher-dimensional operators.

- These higher-dimensional operators emerge from a power series of

$1/M$ in the low-energy effective Lagrangian density.

- Even though the higher dimensional operators are suppressed by the power of the new physics scale $1/M$, the leading order effects of these operators on the physical observables may be phenomenologically comparable to the one-loop effects of some theories beyond the MSSM.

- Thus, it is worthwhile studying the implications of these higher dimensional operators in the Higgs phenomenology.

- Dine, Seiberg, and Thomas show that the effective dimension of the operators are five or more.

- The Higgs sector of the simplest version has just two dimension-five operators with the MSSM particle content, at a energy scale below M.

- We call it as the Dine-Seiberg-Thomas model (DSTM).

- The scale of some gauge-mediated supersymmetric scenarios require $10 - 1000$ **TeV.**

- The effective field analysis may be useful in the phenomenological point of view, since it is valid for a wide range of energy scale from the SUSY breaking scale to the scale of new physics.

- The DSTM has two Higgs doublets like the MSSM, but its Higgs structure is different from the MSSM.

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} = \begin{pmatrix} \phi_1 + \frac{H_{dr}^0 + iH_{di}^0}{\sqrt{2}} \\ H_d^- \end{pmatrix}, \qquad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} = \begin{pmatrix} H_u^+ \\ \phi_2 + \frac{H_{ur}^0 + iH_{ui}^0}{\sqrt{2}} \end{pmatrix} .$$

The Higgs boson masses can be expressed by

$$\begin{aligned} m_h &= m_h^0(m_{A^0}, \tan\beta) + m_h^1(m_t, m_{\tilde{t}_i}) + m_h^{d5}(\epsilon_i) \ , \\ m_{H^\pm} &= m_{A^0} + m_W + m_h^1(m_t, m_{\tilde{t}_i}) + m_h^{d5}(\epsilon_i) \ . \end{aligned}$$

- At the tree-level, the Higgs potential of the DSTM is given as

$$\begin{aligned} V_0 &= m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d - (m_{ud}^2 H_u H_d + \mathrm{H.c.}) + \frac{\lambda_1}{2}(H_u^\dagger H_u)^2 + \frac{\lambda_2}{2}(H_d^\dagger H_d)^2 \\ &\quad + \lambda_3 (H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4 (H_u^\dagger H_u)(H_d^\dagger H_d) \\ &\quad + \left[\frac{\lambda_5}{2}(H_u H_d)^2 + \left\{\lambda_6 (H_u^\dagger H_u) + \lambda_7 (H_d^\dagger H_d)\right\} H_u H_d + \mathrm{H.c.}\right] \ , \end{aligned}$$

where $m_d^2 \equiv m_{H_d}^2 + |\mu|^2$**,** $m_u^2 \equiv m_{H_u}^2 + |\mu|^2$**,** $m_{ud}^2 \equiv -\mu B$**, and** λ_i **(**i **= 1-7) are the quartic couplings.**

- They are defined as

$$\lambda_1 = \lambda_2 = \frac{1}{4}({g'}^2 + g^2), \quad \lambda_3 = \frac{1}{4}(g^2 - {g'}^2) \ ,$$
$$\lambda_4 = -\frac{1}{2}g^2 \ , \quad \lambda_5 = 2\epsilon_2 \ , \quad \lambda_6 = \lambda_7 = 2\epsilon_1 \ ,$$

where g' and g are respectively the gauge coupling coefficients of $U(1)_Y$ and $SU(2)_L$, and ϵ_1 and ϵ_2 are the coupling coefficients representing the interactions of two dimension-five operators.

- Note that m_d and m_u may be eliminated by the two minimum conditions that define the vacuum with respect to ϕ_d and ϕ_u.

Including the DST terms, the one-loop effective potential for the Higgs

scalars at finite temperature is given by

$$\begin{aligned} V &= m_1^2|\phi_1|^2 + m_2^2|\phi_2|^2 - \left(m_{12}^2\phi_1\phi_2 + \text{h.c.}\right) + \frac{g^2+g'^2}{8}\left(|\phi_1|^2 - |\phi_2|^2\right)^2 \\ &- 2\left(|\phi_1|^2 + |\phi_2|^2\right)\left[\epsilon_1\phi_1\phi_2 + \text{h.c.}\right] + \left[\epsilon_2\left(\phi_1\phi_2\right)^2 + \text{h.c.}\right] \\ &+ \sum_{i=\{\text{dof}\}} \frac{n_i m_i^4(\phi)}{64\pi^2}\left[\ln\left(\frac{m_i^2(\phi)}{Q^2}\right) - \frac{3}{2}\right] \\ &+ \sum_{i=\{\text{dof}\}} n_i \frac{T^4}{2\pi^2} J_i\left(\frac{m_i^2(\phi)}{T^2}\right) + \sum_{i=\{\text{sca}\}} \frac{n_i T}{12\pi}\left[m_i^3(\phi) - \bar{m}_i^3(\phi,T)\right] \quad . \end{aligned}$$

The summation goes over

$$\{\text{dof}\} = \{t, b, \tilde{t}_{1,2}, \tilde{b}_{1,2}, H_e, H_o, H_c, W_T, Z_T, \gamma_T, W_L, Z_L, \gamma_L\} \ ,$$

with

$$
\begin{aligned}
n_t &= n_b = -12,\ n_{\tilde{t}_{1,2}} = n_{\tilde{b}_{1,2}} = 6, \\
n_{H_e} &= n_{H_o} = 2,\ n_{H_c} = 4, \\
n_{W_T} &= 4,\ n_{Z_T} = n_{\gamma_T} = 2,\ n_{W_L} = 2,\ n_{Z_L} = n_{\gamma_L} = 1\ .
\end{aligned}
$$

- Here H_e and H_o refer to, respectively, the two CP-even and two CP-odd neutral Higgs bosons; H_c are the charged Higgs bosons; sub-indices T and L stand for, respectively, transverse and longitudinal.

- The fourth line is the finite-temperature contribution. The J_i functions are defined by

$$
J_i(r) = \int_0^\infty dx\ x^2 \ln[1 - (-1)^{2s_i} e^{-\sqrt{x^2+r}}]\ .
$$

The last term corresponds to daisy improvement.

- The masses $\bar{m}_i^2(\phi, T)$ are the field- and temperature-dependent eigenvalues of the mass matrices with first-order thermal masses included.

- The summation is over

$$\{\text{sca}\} = \{\tilde{t}_{1,2}, \tilde{b}_{1,2}, H_e, H_o, H_c, W_L, Z_L, \gamma_L\} \ .$$

The region in MSSM parameter space which is compatible with a strong enough first-order phase transition has two distinctive characteristics

1. A light, (mostly) right-handed stop:

$$m_{\tilde{t}_R} \lesssim m_t;$$

2. A light Higgs, close to the LEP lower bound:

$$m_h \approx 115 \text{ GeV} \ .$$

- The condition for the sphaleron processes in the broken phase not to erase the baryon asymmetry that is produced along the expanding bubble wall reads

$$\frac{\sqrt{2} v_c}{T_c} \gtrsim 1 \ .$$

Here $v_c = v(T_c)$ **and** T_c **are the Higgs VEV and the temperature at the instance in which the symmetric and the asymmetric vacua become degenerate. The normalization is such that** $v_0 = v(T = 0) = 174$ GeV**.**

The light stop constraint comes from the need to reduce thermal screening for at least one scalar which has a large coupling to the Higgs field. EW precision measurements can be accommodated more easily if this light stop is dominantly 'right-handed'. Let us focus on the case of large but finite $m_A^2 \gg m_Z^2$. The minimization of the potential reduces in this case to a one dimensional problem, yielding

$$\frac{v_c}{T_c} \approx \frac{E}{\lambda} \ .$$

Here E is the coefficient of the cubic (barrier) term. If the soft mass-squared of $\widetilde{t}_R$ is chosen negative such that it cancels exactly the thermal

mass at the critical temperature, one has

$$E \approx \frac{h_t^3 \sin^3 \beta \left(1 - X_t^2/m_Q^2\right)^{3/2}}{2\pi}.$$

For small stop mixing, $X_t^2/m_Q^2 \ll 1$**,** E **can be of order** 0.1 **and thus an order of magnitude larger than the SM contribution due to transverse gauge bosons,** $E_{\rm SM} \sim 0.01$**.**

Most importantly, the requirement of negative m_U^2 **forces** $m_{\widetilde{t}_R} < m_t$**. Within one-loop analysis, one must in fact impose a rather strong constraint,** $m_U^2 \sim -\left(80\ GeV\right)^2$ **or equivalently** $m_{\widetilde{t}_R} \sim 150$ **GeV, to obtain**

a strong enough PT. Two-loop calculations extend as

$$\frac{v_c}{T_c} \approx \frac{E}{2\lambda} + \sqrt{\frac{E^2}{4\lambda^2} + \frac{c_2}{\lambda}},$$

where c_2 is the coefficient of the generic two-loop correction,

$$\Delta V^{(2-\text{loop})} \approx -c_2 T^2 \phi^2 \ln \frac{\phi}{T}.$$

The above Eq. explains how two-loop corrections make room for some stop mixing and relax the upper bound on m_U^2. However, sizeable positive values of m_U^2 or large mixing are still forbidden, as they directly decrease E.

3. CP violation in the Higgs sector

(a) CP mixing in the MSSM

- The Magnitude of the Cosmological Baryon Asymmetry, S.M. Barr, G. Segre, H.A. Weldon, PRD20, 2494 (1979)
- **CKM :** $\frac{n_B}{n_\gamma} \sim 10^{-20}$, **Our Universe :** $\frac{n_B}{n_\gamma} \sim 10^{-8}$ (10^{-10})
- Gauge theory of CP violation, S. Weinberg, PRL37, 657 (1976)
- In principle, CP violation is induced by the mixing between the scalar and pseudoscalar Higgs bosons for any model that has at least two Higgs doublets.
- Supersymmetric standard models, including the MSSM and the DSTM, share this property.

- It has been observed that the MSSM has some difficulties in realizing CP violations, although the complex phases in μ and the soft SUSY breaking parameters are the possible sources of CP violation.

- Explicit CP violation, arising directly from the complex phases in these parameters, is viable in the MSSM at the one-loop level due to the radiative CP mixing among the scalar and pseudoscalar Higgs bosons.

- Neutral Higgs boson masses of the MSSM at the one-loop level in an explicit CP violation scenario, S.W. Ham, S.K. Oh, E.J. Yoo, C.M. Kim, D. Son, Phys. Rev. D68, 055003 (2003).

- The mass of the charged Higgs boson in the minimal supersymmetric

standard model with explicit CP violation at 1-loop level, S.W. Ham, S.K. Oh, E.J. Yoo, H.K. Lee, J. Phys. G27, 1 (2001).

- MSSM Radiative CP violation; No CP phase at the tree level

CPsuperH, J.S. Lee, A. Pilaftsis, M.S. Carena, S.Y. Choi, M. Drees, J.R. Ellis, C.E.M. Wagner, Comput. Phys. Commun. 156, 283 (2004)

- FeynHiggs, M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, JHEP 0702, 047 (2007)

- Thermodynamic generation of the baryon asymmetry, Andrew G. Cohen and David B. Kaplan, Phys. Lett. B199, 251 (1987).

- Spontaneous baryogenesis, Andrew G. Cohen and David B. Kaplan, Nucl. Phys. B308, 913 (1988)

- Spontaneous baryogenesis at the weak phase transition, A.G. Cohen, D.B. Kaplan, A.E. Nelson, Phys. Lett. B263, 86 (1991).

- Spontaneous CP violation at the tree-level is impossible in the MSSM, since the complex phases in the vacuum expectation values of the two Higgs doublets may always be eliminated by a global phase rotation.

- At the one-loop level, the complex phases in the vacuum expectation values of two the Higgs doublets do not cancel and thus may trigger the spontaneous CP violation in the MSSM.

- However, one of the scalar Higgs bosons in the MSSM turns out to be very light, which is excluded by the LEP data.

(b) CP Mixing in the Non-Minimal Supersymmetric Standard Model
- NMSSM
- The absolute upper bound on the 1-loop corrected mass of the lightest scalar Higgs boson in the next-to-minimal supersymmetric standard model, S.W. Ham, S.K. Oh, B.R. Kim, J. Phys. G22, 1575 (1996).
- Experimental constraints on the parameter space of the next-to-minimal supersymmetric standard model at LEP 2, S.W. Ham, S.K. Oh, B.R. Kim, Phys. Lett. B414, 315 (1997).
CP Mixing in the NMSSM
- Spontaneous violation of the CP symmetry in the Higgs sector of the next-to-mninimal supersymmetric standard model, S.W. Ham, S.K. Oh, H.S. Song, Phys. Rev. D61, 55010 (2000).
- Charged Higgs Boson in the Next-to-Minimal Supersymmetric Standard Model with Explicit CP Violation, S.W. Ham, J. Kim, S.K. Oh, D. Son, Phys. Rev. D64, 35007 (2001).
- Neutral Higgs sector of the next-to-minimal supersymmetric standard model with explicit CP violation, S.W. Ham, S.K. Oh, D. Son, Phys. Rev. D65, 075004 (2002).

- Possibility of spontaneous CP violation in the nonminimal supersymmetric strandard model with two neutral Higgs singlets, S.W. Ham, S.K. Oh, D. Son, Phys. Rev. D66, 015008 (2002).
- Higgs bosons of the NMSSM with explicit CP violation at the ILC, S.W. Ham, S.H. Kim, S.K. Oh, D. Son, Phys. Rev. D76, 115013 (2007).
- Neutral Higgs bosons in the MNMSSM with explicit CP violation, S.W. Ham, J.O. Im, S.K. Oh, Eur. Phys. J. C58, 579 (2008).
- USSM
- Neutral scalar Higgs bosons in the USSM at the LHC, S.W. Ham, T. Hur, P. Ko, S.K. Oh, J. Phys. G35, 095007 (2008).
- Higgs bosons of a supersymmetric $U(1)'$ model at the ILC, S.W. Ham, E.J. Yoo, S.K. Oh, D. Son, Phys. Rev. D77, 114011 (2008).
- Explicit CP violation in a MSSM with an extra $U(1)'$, S.W. Ham, E.J. Yoo, S.K. Oh, Phys. Rev. D76, 015004 (2007).
- CP Mixing in the SUSY E_6 Model
- Higgs bosons of a supersymmetric E_6 model at the Large Hadron Collider, S.W. Ham, J.O. Im, E.J. Yoo, S.K. Oh, JHEP 0812:017 (2008).

(c) CP Mixing in the DSTM

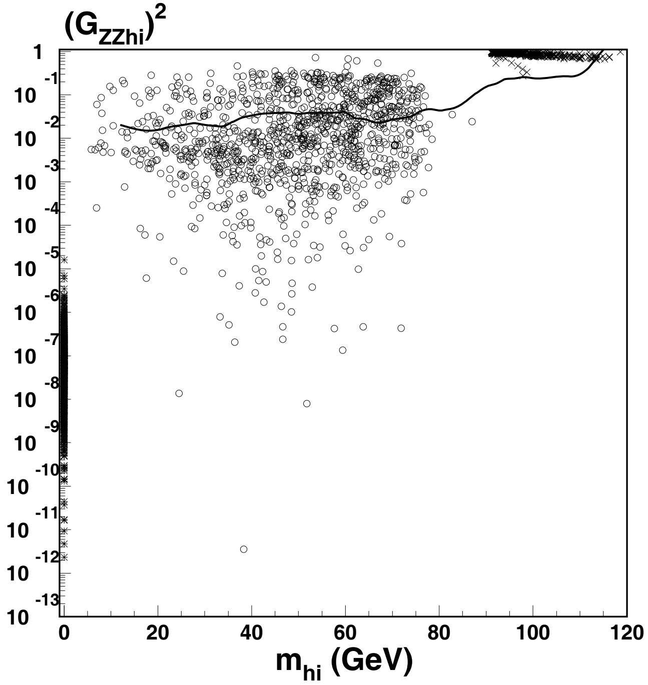
- Possibility of spontaneous CP violation in Higgs physics beyond the minimal supersymmetric standard model, S.W. Ham, Seung-A Shim, S.K. Oh, Phys. Rev. D80, 055009 (2009).

- Since the DSTM has two Higgs doublets, it also has the possibilities of CP violation.

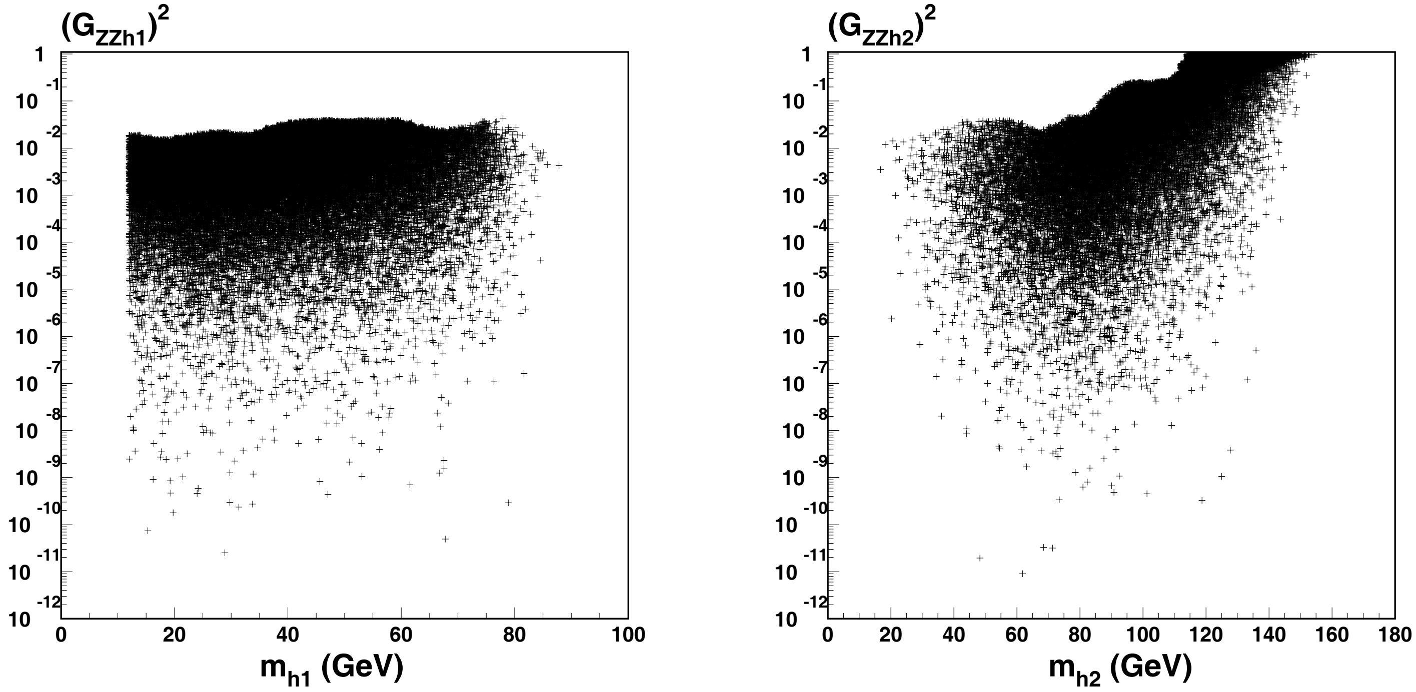
- In this article, we study whether the DSTM may accommodate CP violation in its Higgs sector.

- We find that the CP violation may occur spontaneously in the Higgs sector of the DSTM at the one-loop level, without contradicting the negative results of the light Higgs search at LEP2.

- The radiative corrections to the tree-level Higgs sector of the DSTM are calculated by taking into account the top and scalar top quark loop contributions.



The distribution of $(m_{h_1}, g^2_{ZZh_1})$ (stars), $(m_{h_2}, g^2_{ZZh_2})$ (circles), and $(m_{h_3}, g^2_{ZZh_3})$ (crosses), for each of 1145 points in the parameter region, defined as $|\varphi| < \pi/2$, $0 < \epsilon_1 < 0.05$, $0 < \epsilon_2 < 0.05$, and $2 < \tan\beta < 30$. The solid curve is the model-independent upper bound on g^2_{ZZH}, the square of the coupling coefficient of a Higgs boson to a pair of Z bosons, obtained from the LEP experiments.



The distribution of (a) $(m_{h_1}, g^2_{ZZh_1})$ **and (b)** $(m_{h_2}, g^2_{ZZh_2})$**, for each of 48914 points in the parameter region, defined as** $|\varphi| < \pi/2$**,** $0 < \epsilon_1 < 0.05$**,** $0 < \epsilon_2 < 0.05$**,** $2 < \tan\beta < 30$**,** $|\mu| < 1000$ **GeV,** $0 < A_t$ (GeV) < 2000**,** $100 < m_Q$ (GeV) < 1000**, and** $100 < m_T$ (GeV) < 1000**. The marks are all consistent with the LEP data.**

4. Conclusions

- The BMSSM window for baryogenesis allows for parameters that are significantly more natural than those of the MSSM.
- Spontaneous CP violation may take place in the DSTM at the one-loop level, but not at the tree-level, for a reasonable parameter region.
- We would like note that the spontaneous CP violation in the DSTM is not radiative CP mixings because there is a non-trivial CP phase at the tree level.

⊙ $H-A$ Micing the the Higgs Sector

PYTHIA