Electroweak Baryogenesis in the nMSSM

T. Konstandin

Department of Theoretical Physics, Royal Institute of Technology (KTH), AlbaNova University Center, Roslagstullsbacken 21, 106 91 Stockholm, Sweden

Abstract. In this talk, electroweak baryogenesis in the nMSSM is discussed following Ref [1]. We focus on differences compared to the MSSM. We conclude that electroweak baryogenesis in the nMSSM is rather generic. Still, sfermions of the first two generations are required to be heavy to evade constraints from electric dipole moments.

INTRODUCTION TO ELECTROWEAK BARYOGENESIS AND THE NMSSM

A viable baryogenesis mechanism aims to explain the observed baryon asymmetry of the Universe (BAU), \( \eta = \frac{n_B - n_{\bar{B}}}{s} \approx 8.7(3) \times 10^{-11} \), and the celebrated Sakharov conditions state the necessary ingredients for baryogenesis: (i) C and CP violation, (ii) non-equilibrium, (iii) B number violation.

B number violation is present in the hot Universe due to sphaleron processes while C is violated in the electroweak sector of the Standard Model (SM). Electroweak baryogenesis (EWBG) requires a strong first-order electroweak phase transition (PT) to drive the plasma out of equilibrium. The CP violation is induced by the moving phase boundary and has to be communicated into the symmetric phase, where the sphaleron process is active [2]. Thus, the two important aspects of EWBG are transport and CP violation. This makes it essential to derive transport equations that contain CP-violating quantum effects in a genuine manner.

Compared to other baryogenesis mechanisms, EWBG has the attractive property that the relevant energy scale will be accessible by the next generation of collider experiments.

The nMSSM of Ref. [3] consists of the MSSM extended by a gauge singlet and the superpotential

\[
W_{\text{NMSSM}} = \lambda S H_1 H_2 + \frac{m_{12}^2}{\lambda} S + W_{\text{MSSM}}.
\]

In this model, a \( Z_5 \) or \( Z_7 \) symmetry is imposed to solve the domain wall problem without destabilizing the electroweak hierarchy. The \( \mu \) term is forbidden and only induced after electroweak symmetry breaking. Thus the \( \mu \) problem is solved. The discrete symmetries

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2 e-mail: konstand@kth.se
FIGURE 1. The left plot shows the produced BAU in the MSSM, $m_A = 200$ GeV. The right plot shows the produced BAU by random nMSSM models, $M_2 = 200$ GeV.

also eliminate the singlet self coupling. A rather large value of $\lambda$ is needed in the nMSSM to fulfill current mass bounds on the Higgsinos and charginos, which might lead to a Landau pole below the GUT scale.

**EWBG IN THE MSSM AND ITS EXTENSIONS**

In the MSSM and its extensions the dominant contribution to baryogenesis comes from the charginos (Higgsino - Wino - mixing) with the mass matrix

$$
\psi_R = \left( \tilde{W}_L^+, \tilde{h}_{1,R} \right), \quad \psi_L = \left( \tilde{W}_R^+, \tilde{h}_{2,L} \right), \quad m(z) = \begin{pmatrix}
M_2 & g H_1^+(z) \\
g H_1^+(z) & \mu(z)
\end{pmatrix},
$$

(2)

where the Wino mass parameter $M_2$ and the $\mu$ parameter contain complex phases. In the nMSSM the $\mu$ parameter is proportional to the vev of the singlet field and hence changes during the phase transition, while it is constant in the MSSM.

As mentioned above, to obtain unambiguous results for the predicted BAU, a formalism is required that treats transport and CP violation in a genuine manner. This formalism is given by the Kadanoff-Baym equations that constitute the statistical analog to the Schwinger-Dyson equations.

The simplest example of CP violation in transport equations is given by the one-flavour case with a $z-$dependent complex phase in the mass term [4], $m(z) = |m(z)| \times e^{i \theta(z)}$. The transport equation for the particle distribution function $f$ is in this case of the Vlasov type ($\omega^2 = k^2 + m^2$)

$$
\frac{k_z}{\omega} \partial_z f_s + F_s \partial_{k_z} f_s = \text{collision terms}, \quad F_s = -\frac{|m|^2}{2\omega} + s \frac{(|m|^2 \theta')'}{2\omega \sqrt{\omega^2 - k^2}}.
$$

(3)

Notice that the second part of the force $F_s$ violates CP and hence sources EWBG.

The multi flavour case can be treated in linear approximation [5]. In this case new sources of baryogenesis are present that are based on flavour mixing. However, these sources are suppressed by flavour oscillations and are only relevant for almost mass
degenerate charginos. Former approaches neglected the flavour oscillation what lead to larger results, especially away from mass degeneracy. The left plot of Fig. 1 shows the produced baryon asymmetry for a maximal CP-violating phase in the chargino mass matrix using the system of diffusion equations suggested in Ref. for the MSSM. The black area denotes the region of the parameter space where EWBG is viable. We note that EWBG in the MSSM is only possible if: (i) The charginos are nearly mass degenerate such that mixing effects are not suppressed. (ii) The CP phases in the chargino sector are $O(1)$. Similar to chargino mediated EWBG, neutralinos can give rise to a contribution to the BAU of similar size.

**Electroweak phase transition**

In contrast to the MSSM, no light stop is needed in the nMSSM, since the additional singlet terms in the Higgs potential strengthen the phase transition. In the nMSSM case these terms read:

$$\mathcal{L} = \mathcal{L}_{MSSM} + m_s^2 |S|^2 + \lambda^2 |S|^2 (H_1 \dagger H_1 + H_2 \dagger H_2) + t_s (S + h.c.) + (a_\lambda S H_1 \cdot H_2 + h.c.).$$

(4)

The parameters $a_\lambda$ and $t_s$ are SUSY breaking and all sources of CP violation in this potential can be contributed to $t_s$. In a simplified scheme without CP violation, a first-order phase transition due to tree-level dynamics occurs if

$$m_i^2 < \frac{1}{\lambda^2} \left| \frac{\lambda^2 t_s}{m_s} - m_s \bar{a} \right|, \quad \bar{a} = \frac{a_\lambda}{2} \sin 2\beta, \quad \lambda^2 = \frac{\lambda^2}{4} \sin^2 2\beta + \frac{g^2}{8} \cos^2 2\beta.$$

(5)

Fig. 2 displays Eq. (5) for random nMSSM models with/without a strong first-order PT and shows that this criterion is also decisive if CP violation and the one-loop effective potential are taken into account.
EDM constraints and baryon asymmetry

Since the trilinear term in the superpotential contributes to the Higgs mass, \( \tan(\beta) \) is generically of \( \mathcal{O}(1) \). Hence two-loop contributions from the charginos to the electron EDM are naturally small. The one-loop contributions to the electron EDM can, as in the MSSM, be reduced by increasing the sfermion masses.

The effective \( \mu \) parameter is dynamical in the nMSSM and its complex phase changes during the phase transition. This leads to new CP-violating sources in the chargino sector that are of second order in the gradient expansion as the contributions in the one flavour case of Eq. (3). These contributions do not rely on flavour mixing and are not suppressed by the flavour oscillations. Thus mass degenerate charginos are not required for viable EWBG in the nMSSM. Additionally, the bubble wall tends to be thinner than in the MSSM what further enhances second order sources compared to first order sources. This leads to the fact that it is rather generic to generate the observed baryon asymmetry in the nMSSM \[1\]. The right plot of Fig. [1] shows the binned BAU for a random set of nMSSM models with a strong first order PT.

CONCLUSIONS

The nMSSM provides a framework in which electroweak baryogenesis seems to be possible without tuning.

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