ELECTROWEAK PHASE TRANSITION AND
BARYOGENESIS IN THE MSSM *

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ABSTRACT
We have analyzed baryogenesis in the MSSM for the light stop scenario, where
the phase transition is strong enough first order. We have found that enough
baryon asymmetry can be generated provided that the phase of \( \mu \) be \( \sim 0.01 \).
Constraints from the electric dipole moment of the neutron enforce the first and
second generation squarks to have masses \( \mathcal{O}(\text{few}) \) TeV.

1. Introduction

The option of generating the cosmological baryon asymmetry at the electroweak
phase transition is not necessarily the one chosen by Nature, but it is certainly fasci-
nating, and has recently deserved a lot of attention. At the quantitative level, the
Standard Model (SM) meets the basic requirements for a successful implementation of
this scenario due to the presence of anomalous processes. However, the electroweak
phase transition is too weakly first order to assure the preservation of the generated
baryon asymmetry at the electroweak phase transition, as perturbative and non-
perturbative analyses have shown. On the other hand, CP-violating processes are
suppressed by powers of \( m_f/M_W \), where \( m_f \) are the light-quark masses. These sup-
pression factors are sufficiently strong to severely restrict the possible baryon number
generation. Therefore, if the baryon asymmetry is generated at the electroweak
phase transition, it will require the presence of new physics at the electroweak scale.

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Low energy supersymmetry is a well motivated possibility, and it is hence highly interesting to test under which conditions there is room for electroweak baryogenesis in this scenario \[4,11,12\]. It was recently shown \[3\] that the phase transition can be sufficiently strongly first order in a restricted region of parameter space: The lightest stop must be lighter than the top quark, the ratio of vacuum expectation values \( \tan \beta \lesssim 3 \), while the lightest Higgs must be at the reach of LEP2. Similar results were independently obtained by the authors of Ref. \[13\]. These results have been confirmed by explicit sphaleron calculations in the Minimal Supersymmetric Standard Model (MSSM) \[14\] while two-loop calculations have the general tendency to strengthen the phase transition \[15,16\] thus making the previous bounds very conservative ones. On the other hand, the MSSM contains, on top of the Cabbibo-Kobayashi-Maskawa matrix phase, additional sources of CP-violation and can account for the observed baryon asymmetry. New CP-violating phases can arise from the soft supersymmetry breaking parameters associated with the stop mixing angle.

In this talk I will review the computation of the baryon asymmetry and the strength of the first order phase transition in the MSSM. I will identify the region in the supersymmetric parameter space where baryon asymmetry is consistent with the observed value and, furthermore, it is not washed out inside the bubbles after the phase transition.

2. The phase transition in the MSSM

A strongly first order electroweak phase transition can be achieved in the presence of a top squark lighter than the top quark \[13\]. In order to naturally suppress its contribution to the parameter \( \Delta \rho \), and hence preserve a good agreement with the precision measurements at LEP, it should be mainly right handed. This can be achieved if the left handed stop soft supersymmetry breaking mass \( m_Q \) is much larger than \( M_Z \). For moderate mixing, the lightest stop mass is then approximately given by

\[
m^2_\tilde{t} = m^2_{\tilde{U}} + D^2_R + m^2_t(\phi) \left(1 - \frac{\tilde{A}_t^2}{m^2_Q}\right)
\]

where \( \tilde{A}_t = A_t - \mu / \tan \beta \) is the particular combination appearing in the off-diagonal terms of the left-right stop squared mass matrix and \( m^2_{\tilde{U}} \) is the soft supersymmetry breaking squared mass parameter of the right handed stop.

In order to overcome the Standard Model constraints, the stop contribution must be large. The stop contribution strongly depends on the value of \( m^2_{\tilde{U}} \), which must be small in magnitude, and negative, in order to induce a sufficiently strong first order phase transition. Indeed, large stop contributions are always associated with small values of the right handed stop plasma mass

\[
m^\text{eff}_{\tilde{t}} = -m^2_{\tilde{U}} + \Pi_R(T)
\]
where \( \tilde{m}_U^2 = -m_{Q}^2 \), \( \Pi_R(T) \simeq 4g_3^2T^2/9 + h_t^2/6[2 - \tilde{A}_t^2/m_Q^2]T^2 \) is the finite temperature self-energy contribution to the right-handed squarks, and \( h_t \) and \( g_3 \) are the top quark Yukawa and strong gauge couplings, respectively. We are considering heavy (decoupled from the thermal bath) gluinos. For light gluinos, their contribution to the squark self-energies, \( 2g_3^2T^2/9 \), should be added to \( \Pi_R(T) \). Moreover, the trilinear mass term, \( \tilde{A}_t \), must be \( \tilde{A}_t^2 \ll m_Q^2 \) in order to avoid the suppression of the stop contribution to \( v(T_c)/T_c \). The dependence of the order parameter \( v(T_c)/T_c \) on \( \tilde{m}_U \) is illustrated in Fig. 1a where we plot it as a function of the light stop mass. We see from it a dramatic increase in \( v(T_c)/T_c \) as \( \tilde{m}_U \) increases.

![Figure 1](image)

Figure 1: a) Plot of \( v(T_c)/T_c \) as a function of \( m_{t} \) for \( m_Q = m_A = 500 \) GeV, \( \tilde{A}_t = 0 \) and \( \tan \beta = 2 \). The diamond denotes \( \tilde{m}_U = \tilde{m}_U^{\text{crit}} \), Eq. (3). b) Plots of \( v(T_c)/T_c \) as functions of \( m_A \) (solid lines) for \( \tan \beta = 1.9 \) (upper line) - 2.3 (lower line), step=0.1, \( m_Q = 500 \) GeV and \( \tilde{m}_U = \tilde{m}_U^{\text{crit}} \). The dashed line corresponds to the experimental bound \( m_h = m_h^{\text{exp}} \).

Although large values of \( \tilde{m}_U \), of order of the critical temperature, are useful to achieve a strongly first order phase transition, they may also induce charge and color breaking minima. Indeed, if the effective plasma mass at the critical temperature vanished, the universe would be driven to a charge and color breaking minimum at \( T \geq T_c \). A conservative bound on \( \tilde{m}_U \) may be obtained by demanding that the electroweak symmetry breaking minimum be lower than any color-breaking minima induced by the presence of \( \tilde{m}_U \) at zero temperature, which yields the condition

\[
\tilde{m}_U < \tilde{m}_U^{\text{crit}} \equiv \left( \frac{m_h^2v^2g_3^2}{12} \right)^{1/4}.
\]  

It can be shown that this condition is sufficient to prevent dangerous color breaking...
minima at zero and finite temperature for any value of the mixing parameter $\tilde{\Lambda}$. In this work, we shall use this conservative bound.

Fig. 1a corresponds to a large value of the mass of the pseudoscalar Higgs, for which the strength of the phase transition is maximized. However, for the purpose of generating the baryon asymmetry, as we will see in the next section, smaller values of $m_A$ should be used. In Fig. 1b we present plots of $v(T_c)/T_c$ as a function of $m_A$ for different values of $\tan \beta$. Every line stops at a lower value of $m_A$, where the experimental LEP bound on the Higgs mass is met. The region to the left of the dashed line in Fig. 1b is excluded by LEP searches of the Higgs boson.

![Figure 2: For $m_Q = m_A = 500$ GeV, $\tilde{\Lambda} = 0$ and $\tilde{m}_U = \tilde{m}_U^{\text{crit}}$: a) $E_{\text{sph}}^\text{MSSM}(0)$ (solid line) as a function of $\tan \beta$. The dashed line is $E_{\text{sph}}^\text{SM}(0)$ for a Higgs mass equal to $m_{\text{eff}}$, Eq. (6). b) $E_{\text{sph}}^\text{MSSM}(T)$ for $\tan \beta = 2$ (solid line). The dashed line denotes a plot of $E_{\text{sph}}^\text{MSSM}(0)v(T)/v$.]

The requirement of not washing out, after the phase transition the previously generated baryon asymmetry provides the condition

$$\frac{v(T_c)}{T_c} > \sim 45,$$

which translates, in the Standard Model, into the condition

$$\frac{v(T_c)}{T_c} > \sim 1.$$  

In the MSSM the condition should hold provided $E_{\text{sph}}^\text{MSSM}(T_c) \sim E_{\text{sph}}^\text{SM}(T_c)$. In particular this will hold if the scaling law

$$4E_{\text{sph}}^\text{MSSM}(T_c) = E_{\text{sph}}^\text{MSSM}(0)\frac{v(T_c)}{v}$$
is approximately satisfied, and at zero temperature $E_{\text{MSSM}}^{\text{sph}} \sim E_{\text{SM}}^{\text{sph}}(m_{\text{eff}})$, where

$$m_{\text{eff}}^2 = \sin^2(\alpha - \beta)m_h^2 + \cos^2(\alpha - \beta)m_H^2$$

$m_{h,H}$ being the light/heavy CP-even mass eigenstates, and $\alpha$ the mixing angle in the Higgs sector, where all radiative corrections effects corresponding to the chosen supersymmetric parameters have been incorporated.

In Fig. 2a we compare $E_{\text{MSSM}}^{\text{sph}}$ (solid line) with $E_{\text{SM}}^{\text{sph}}$ (dashed line) for a Higgs mass equal to $m_{\text{eff}}$. In Fig. 2b we compare the value of $E_{\text{MSSM}}^{\text{sph}}(T)$ (solid line) with the corresponding scaling value given by Eq. (5). We can see that the differences are $< 5 \%$ which makes the use of condition (4) reasonable.

3. Baryogenesis in the MSSM

Baryogenesis is fueled by CP-violating sources which are locally induced by the passage of the bubble wall. These sources should be inserted into a set of classical Boltzmann equations describing particle distribution densities and permitting to take into account Debye screening of induced gauge charges, particle number changing reactions and to trace the crucial role played by diffusion. Indeed, transport effects allow CP-violating charges to efficiently diffuse in front of the advancing bubble wall where anomalous electroweak baryon violating processes are unsuppressed.

Following, we are interested in the generation of charges which are approximately conserved in the symmetric phase, so that they can efficiently diffuse in front of the bubble where baryon number violation is fast, and non-orthogonal to baryon number, so that the generation of a non-zero baryon charge is energetically favoured. Charges with these characteristics are the axial stop ($\tilde{t}$) charge and the Higgsino ($\tilde{H}$) charge, which may be produced from the interactions of squarks and charginos and/or neutralinos with the bubble wall, provided a source of CP-violation is present in these sectors. CP-violating sources $\gamma_{Q}(z)$ (per unit volume and unit time) of a generic charge density $J^0(z)$ associated with the current $J^\mu(z)$ and accumulated by the moving wall at a point $z^\mu$ of the plasma can then be constructed from $J^\mu(z)$ as

$$\gamma_Q(z) = \partial_0 J^0(z).$$

The detailed calculation of $\gamma_{\tilde{q}}$ and $\gamma_{\tilde{H}}$ has been recently performed. It was proven that $\gamma_{\tilde{q}} \ll \gamma_{\tilde{H}}$, due essentially to the chosen region in the supersymmetric parameter space. Moreover, we have found that the Higgsino current is given by

$$\langle J^0_{\tilde{H}}(z) \rangle = |\mu| \sin \phi_\mu \left[ H^2(z)\Delta \beta / L_\omega \right] \left[ 3M_2 g_2^2 \mathcal{G}_{\tilde{H}}^{\tilde{W}} + M_1 g_1^2 \mathcal{G}_{\tilde{H}}^{\tilde{B}} \right],$$

where $\mathcal{G}_{\tilde{H}}^{\tilde{W},(\tilde{B})}$ are integrals over the momentum space of the corresponding Feynman diagrams, $\Delta \beta$ is the variation of the angle $\beta$ through the bubble wall and $L_\omega$ is the bubble wall thickness. The integrand of $\mathcal{G}_{\tilde{H}}^{\tilde{W},(\tilde{B})}$ depends on the masses $\mu$, $M_2$ and $M_1$. 

as well as on the temperature and on the widths (damping rates) that are taken to be \( \Gamma \sim \Gamma_W \sim \Gamma_B \sim \alpha_W T \).

We can now solve the set of coupled differential equations describing the effects of diffusion, particle number changing reactions and CP-violating source terms. We will closely follow the approach taken in Ref. \(^{29}\) where the reader is referred to for more details. The final baryon-to-entropy ratio is found to be given by,

\[
\frac{n_B}{s} = -g(k_i) \frac{\mathcal{A}D\Gamma_{ws}}{v_\omega^2 s},
\]

where \( v_\omega \) is the wall velocity,

\[
\mathcal{A} = \frac{1}{D} \lambda_+ \int_0^\infty du \tilde{\gamma}(u)e^{-\lambda_+ u},
\]

\( D \) is the effective diffusion constant,

\[
\lambda_+ = \frac{v_\omega + \sqrt{v_\omega^2 + 4\tilde{\Gamma}D^2}}{2D},
\]

\( \tilde{\Gamma} \) is the effective decay constant, \( \tilde{\gamma}(z) = v_\omega \partial_z J^0(z) f(k_i) \), and \( f(k_i), g(k_i) \) are numerical coefficients depending upon the light degrees of freedom.

Figure 3: For \( v_\omega = 0.1, L_\omega = 25/T, M_2 = M_1 = 100 \) GeV, \( m_Q = 500 \) GeV, \( \tan \beta = 2 \) and \( m_U = m_{U_{\text{crit}}} \):

(a) Plot of \( \Delta \beta \) as a function of \( m_A \).

(b) Plot of \( \sin \phi_\mu \) by fixing \( n_B/s = 4 \times 10^{-11} \) (its lower bound).

From Eq. (8) one can see that the whole effect is proportional to \( \Gamma_{ws} \sim 6\kappa \alpha_w^4 T \), the weak sphaleron rate in the symmetric phase. We have taken \( \kappa \sim 1 \) \(^{29}\) although
its precise value is at present under debate\[2\]. We can also see from Eq. (7) that the final baryon-to-entropy ratio depends on the parameter $\Delta \beta$. This parameter should go to zero as $m_A \rightarrow \infty$ and triggers the necessity of considering not too large values of $m_A$. We present in Fig. 3a a plot of $\Delta \beta$ as a function of $m_A$ which confirms our expectatives. In Fig. 3b we plot $\sin \phi_\mu$ versus $m_A$ by fixing the value of $n_B/s$ to its lower bound $4 \times 10^{-11}$ for the case $M_2 = M_1 = 100 \text{ GeV}$. The values of the effective diffusion and decay constants are $\overline{D} \sim 0.8 \text{ GeV}^{-1}$, $\overline{\Gamma} \sim 1.7 \text{ GeV}$. We see, as anticipated, that for large values of $m_A$, $\Delta \beta$ becomes very small and, correspondingly, $\sin \phi_\mu$ approaches 1.

We conclude, from Fig. 3b, that the phase $\phi_\mu$ is never much smaller than 0.05. These relatively large values of the phases are only consistent with the constraints from the electric dipole moment of the neutron if the squarks of the first and second generation have masses of the order of a few TeV\[3\]. Moreover, the baryon asymmetry is not washed out inside the bubbles provided that the light stop is lighter than the top quark, the pseudoscalar Higgs boson heavier than $\sim 130 \text{ GeV}$ and the lightest Higgs boson lighter than $\sim 80 \text{ GeV}$.

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