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Electroweak baryogenesis

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Abstract
In this paper, we review the actual situation of electroweak breaking theories concerning their capabilities to generate the baryon asymmetry of the universe at the electroweak phase transition. First of all we consider the case of the standard model which, in spite of possessing all necessary ingredients, is unable to produce the observed amount of baryon asymmetry. This fact is enough to motivate the existence of physics beyond the standard model. We then present the situation in the minimal supersymmetric extension of the standard model (MSSM) where, only if the Higgs is on the verge of experimental detection and the right-handed stop is lighter than the top quark, the baryon asymmetry of the universe could be likely generated in agreement with observations. Otherwise one should go beyond the MSSM, either by splitting supersymmetry or by assuming the existence of new fields strongly coupled to the Higgs sector. One such model is provided as an example.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The origin of the baryon asymmetry of the universe (BAU) remains one of the most important open questions in particle physics. It was first assumed that this question could be answered by physics at the Grand Unification scale although this assumption was challenged by the discovery that anomalous processes [1] could totally or partially erase the BAU that was generated at very high scales. The conditions for baryogenesis were stated by Sakharov in 1967 [2]. They can be formulated as the three requirements of

- B-violation,
- C- and CP-violation,
- Departure from thermal equilibrium.

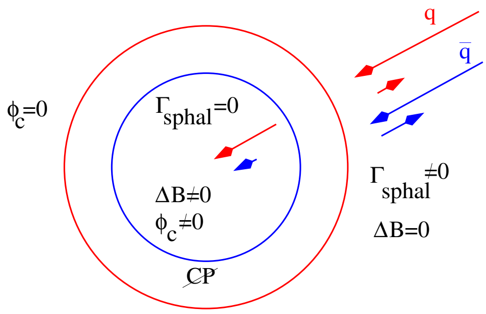

Figure 1. First-order phase transition with CP-violation on the bubble wall.

Kuzmin, Rubakov and Shaposhnikov [3] considered in 1985 the possibility of baryogenesis at the electroweak phase transition: the so-called electroweak baryogenesis (EWBG). The question on whether baryons could be produced within the Standard Model (SM) of electroweak interactions created a lot of excitement in the physics community. In fact, the SM succeeded to satisfy all the three Sakharov conditions:

- Baryon number is non-perturbatively violated in the SM: sphalerons at finite temperature.
- C- and CP-violating (CKM) phases are present in the SM.
- The out-of-equilibrium conditions are present in the bubble wall in a first-order phase transition.

Namely, a mechanism for the generation of the baryon asymmetry of the universe was suggested by Cohen, Kaplan and Nelson [4] in 1993 using CP-violating interactions of fermions with the domain wall of a bubble. Then the reflection and transmission coefficients of fermions and anti-fermions scattering off the CP-violating wall are different as it is shown in figure 1. If the phase transition is not strongly enough first order any previously generated BAU is erased by sphalerons in the symmetric phase, which leads to the condition [5] $\phi_c(T_c)/T_c \geqslant 1$, where $\phi_c(T_c)$ is the value of the Higgs field at the critical temperature T_c of the phase transition.

However although the SM contains all the ingredients for EWBG it fails quantitatively because

- the CP-violation provided by the CKM phase is too small to generate the required BAU [6],
- the phase transition is not strong enough. Would a BAU be generated it would be erased by weak sphalerons in the broken phase [7].

In fact, the strength of the phase transition strongly depends on the Higgs mass and for present experimental limits it is extremely weak. A simple one-loop (improved by hard thermal loops) result is plotted in figure 2. We can see that for the actual experimental bounds on the Higgs mass $m_H \geqslant 114.5$ GeV [8] the phase transition shown in figure 2 is extremely weak. In fact, this negative result is confirmed once higher loop corrections are introduced and even by non-perturbative calculations [7].

In view of this negative result for the SM concerning the possibility of EWBG we are thus led to open up the possibility that new physics on top of the SM interactions can solve the problem of baryons. The best motivated extension of the SM is its minimal supersymmetric extension. A lot of effort has been devoted towards explaining the BAU within the MSSM and we will summarize the main results in section 2. As we will see the constraints imposed on the

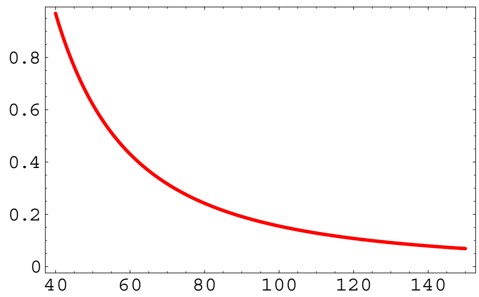

Figure 2. $\phi_c(T_c)/T_c$ as a function of m_H (in GeV) (one loop).

MSSM by the BAU requirements are on the verge of experimental limits and we must be ready to go beyond. We will consider two possible candidates beyond the MSSM. In section 3, we will consider enlarging the MSSM gauge group in such a way that the effective low energy theory looks like one with charginos and neutralinos strongly coupled to the Higgs sector. In section 4, we will consider the possibility of increasing the mass of all squarks and sleptons (except that of the right-handed stops) and remain with a minimal theory where naturalness is no longer a requirement (with the philosophy of split supersymmetry) but with a minimal light particle content dictated by EWBG (light right-handed stop and charginos) and dark matter (light neutralinos).

2. EWBG in the minimal supersymmetric Standard Model

The lesson we learned from the previous section is that new particles (new physics) have to be added to those of the SM. The obvious candidates are *bosons strongly coupled to the Higgs sector*. The technical reason is that bosons have $n = 0$ Matsubara modes and thus they contribute to the cubic terms in the finite temperature effective potential: this cubic term is responsible for the first-order phase transition. All this is very welcome because bosons appear in supersymmetric extensions of the SM (as bosonic partners of SM fermions). In particular, the supersymmetric partner of the top quark (the stop) is strongly coupled to the Higgs sector with a coupling equal (by supersymmetry) to the Yukawa coupling of the top quark.

In fact, in the minimal supersymmetric extension of the Standard Model (MSSM) there is the so-called light stop window [9] where

- BAU is generated by fermions: charginos and neutralinos,
- strong first-order phase transition is triggered by bosons: stops and Higgses.

BAU is barely consistent with WMAP results for $\mathcal{O}(1)$ phases and light charginos and neutralinos. In fact, in the MSSM there are new sources for CP-violation with respect to the SM ones. In particular, the trilinear couplings and the μ parameter that appear in the Lagrangian as

$$\mathcal{L} = -A_t Q_L H_2 U_R - \mu \tilde{H}_1 \tilde{H}_2 \tag{1}$$

can have large CP-violating phases. In that case the lowest diagrams that contribute to the CP-violating currents are shown in figure 3 [9]. For the mechanism to work it is required that CP-violation be (almost) maximal, e.g. $\varphi = \arg(\mu) \sim \mathcal{O}(1)$. In the presence of such large CP-violating phases an electric dipole moment (EDM) for electrons (d_e) and neutrons (d_n) can be generated subject to the experimental bounds: $|d_e| < 1.4 \times 10^{-27}$ e cm and $|d_n| < 3.0 \times 10^{-26}$ e cm. In order to come over this problem two solutions have been proposed:

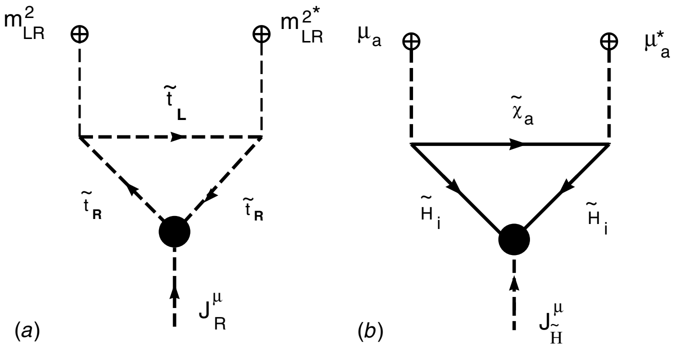

Figure 3. Diagrams contributing to the CP-violating currents from $\varphi(A_t)$ and $\varphi(\mu)$.

- Very heavy first and second generation of sfermions [10] tend to suppress the one-loop contributions to EDMs.
- Different contributions to the EDM cancel each other [11].

As for the first solution, even if one-loop contributions to EDM are very suppressed, there are two-loop contributions where charginos and Higgs bosons are exchanged that are very dangerous. A general analysis of consistency between EWBG and EDM in the MSSM has been done in [12]. It was proved that two-loop contributions to EDM can be suppressed by taking large values of m_A and small values of $\tan\beta$. Although both quantities are constrained by the Higgs boson mass, a region was found in [12] where consistency is achieved. Namely for intermediate values of $\tan\beta$ and not very large values of m_A. As for the second solution, it is calling for a symmetry of the underlying theory that could provide the actual required cancellations.

Concerning the issue of the first-order phase transition the present bounds on the Higgs mass put very severe constraints on it. In fact, the baryogenesis window for the MSSM is on the verge of present experimental limits as it is shown in [9]. This fact will take us as one of the possibilities beyond the MSSM to split supersymmetry as we will comment in the last section.

Finally, we can summarize the results in the MSSM by the two-fold requirement:

- Light right-handed stops $m_{\tilde{t}} < m_t$.
- Light Higgs boson, around its present experimental bounds $m_H > 115$ GeV.

Therefore, two minimal possibilities arise depending on whether the right-handed stop turns out to be heavy or light:

- If $\tilde{t}_R$ is heavy ($\sim m_Q$) we should absolutely go to extensions of the MSSM: either we introduce extra fields, e.g. a singlet as in the NMSSM, or charginos and neutralinos should be strongly coupled and responsible for both the strong phase transition and EWBG. This possibility will be considered in section 3.
- If $\tilde{t}_R$ is light ($\sim m_t$) charginos and neutralinos can be weakly coupled and only responsible for the EWBG. This leads to a split version of the MSSM with light right-handed stops. This possibility will be considered in section 4.

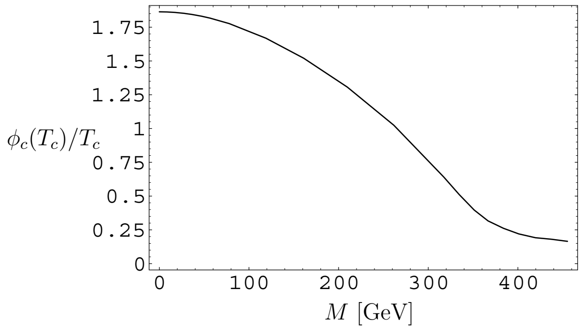

Figure 4. $\phi_c(T_c)/T_c$ as a function of M for $m_H = 120$ GeV, $h = 2$ and $M = -\mu$.

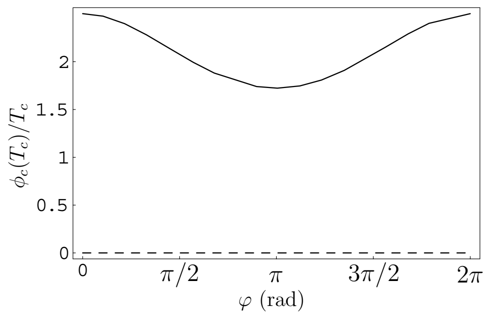

Figure 5. $\phi_c(T_c)/T_c$ for $h = 2$ and $|\mu| = M = 100$ GeV as a function of $\varphi = \arg(\mu)$.

3. Strongly coupled fermions

We will now consider a SM extension with Higgsinos ($\tilde{H}_{1,2}$), Winos and Binos ($\tilde{W}^a$, $\tilde{B}$) coupled to the SM Higgs doublet H with the Lagrangian [13]

$$\mathcal{L} = H^\dagger(h_2\sigma_a\tilde{W}^a + h_2'\tilde{B})\tilde{H}_2 + H^T\epsilon(-h_1\sigma_a\tilde{W}^a + h_1'\tilde{B})\tilde{H}_1 + \frac{M_2}{2}\tilde{W}^a\tilde{W}^a + \frac{M_1}{2}\tilde{B}\tilde{B} + \mu\tilde{H}_2^T\epsilon\tilde{H}_1 + \text{h.c.} \tag{2}$$

The matching with the MSSM couplings and Higgs field would be: $h_2 = g\sin\beta/\sqrt{2}$, $h_1 = g\cos\beta/\sqrt{2}$, $h_2' = g'\sin\beta/\sqrt{2}$, $h_1' = g'\cos\beta/\sqrt{2}$, $H = \sin\beta H_2 - \cos\beta\epsilon H_1^*$. However we will not match them with the MSSM but instead will consider h_i, h_i' as independent parameters. As a consequence, the phase transition can be much stronger than in the SM depending on the values of the Yukawa coupling $h_1 \simeq h_2 = h$ and the various masses. By considering for simplicity the case of independent masses $M_1 = M_2 = M$ and μ we can see in figure 4 the strength of the phase transition.

Up to now we have fixed in the numerical analysis $m_H = 120$ GeV and $\varphi = 0$. Since the phase transition is strong enough we can departure from these conditions. First of all we will study the strength of the phase transition as a function of φ in figure 5. Second we can vary the value of the Higgs mass. Our mechanism of strengthening the phase transition, although certainly sensitive to the Higgs mass, permits us to go to higher values as it is shown in figure 6.

The chargino sector in this model has a similar structure to the chargino sector in the minimal supersymmetric Standard Model. The only difference is that the couplings $g\sin\beta/\sqrt{2}$

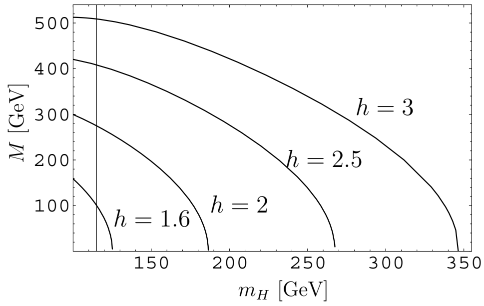

Figure 6. Contours of $\phi_c(T_c)/T_c = 1$ in the (M, m_H)-plane for $h = 1.6, 2, 2.5, 3$ and $M = -\mu$. The vertical line corresponds to the experimental lower bound, for a SM-like Higgs, of $m_H = 115$ GeV.

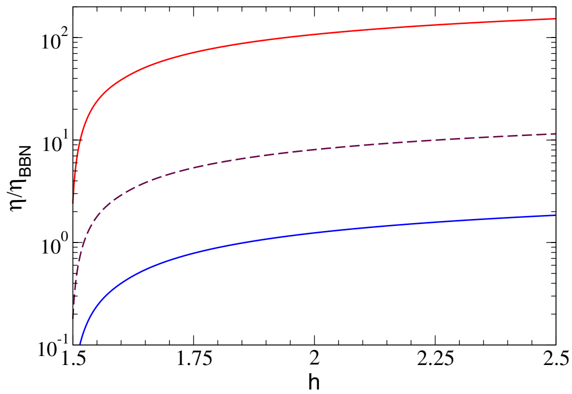

Figure 7. The ratio $\eta/\eta_{\rm BBN}$ as a function of the Yukawa coupling h for $\mu = -M_2 \exp(i\varphi)$, $M_2 = 50$ GeV, $\sin\varphi = 1$ and bubble parameters $L_\omega = 10/T_c$, $v_\omega = 0.1$. Left-handed squarks and right-handed sbottoms are heavy (in the few TeV range). The lower (upper) solid line corresponds to heavy (light) right-handed stops, $m_T > 1$ TeV ($m_T \simeq 100$ GeV). Dashed line corresponds to right-handed stops with $m_T \simeq 500$ GeV. $\eta_{\rm BBN} = (8.7 \pm 0.3) \times 10^{-11}$ from WMAP.

and $g \cos\beta/\sqrt{2}$ are replaced by arbitrary couplings h_2 and h_1, respectively. As in the MSSM, the CP-violating phase can have its origin, after field redefinitions, in the phase φ of the (complex) μ-parameter. A general method for computing the effects of CP-violating mass terms on particle distributions was introduced in [9] leading to an efficient transport of CP-violating quantum numbers into the symmetric phase where weak sphalerons are active and can trigger electroweak baryogenesis for all bubble wall widths. The method was adapted to the MSSM by a number of papers where a set of coupled differential equations, that include the effect of diffusion, particle number changing reactions and CP-violating terms, were solved to find various particle number densities diffused from the bubble wall, where CP-violation takes place, to the symmetric phase where sphalerons are active. These methods can be adapted to the present model. We will further make the simplifying assumption that all CP-violation resides in the fermionic sector. The result of the numerical calculation is shown in figure 7.

This model can also provide the required dark matter candidate. In fact, the charginos and two of the neutralinos acquire masses of about hv. The mass of the lightest neutralino is close to $|\mu|$ and the lightest neutralino (dark matter candidate) is therefore an almost pure

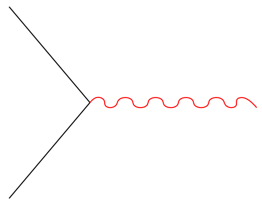

Figure 8. Annihilation $\chi\bar{\chi} \to Z$.

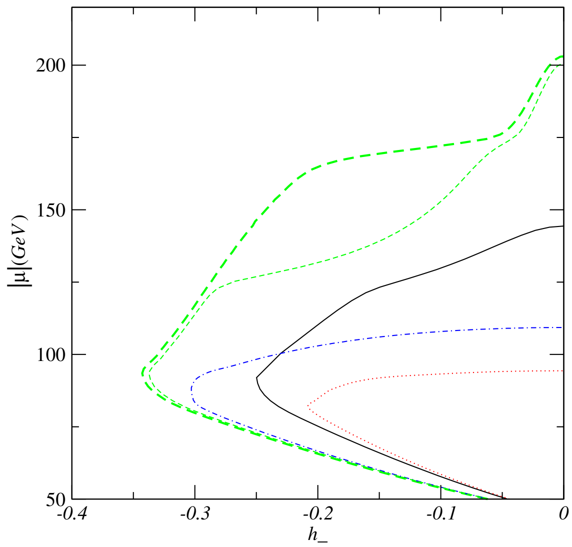

Figure 9. Curves of $\Omega_{LN}h^2 = 0.113$ for h, φ and m_H/ GeV = (2, 0, 300) (thick dashed curve), (2, 0, 150) (thin dashed curve), (1.5, 0, 150) (solid curve), (2, $\pi/2$, 150) (dash-dotted curve), (1.5, $\pi/2$, 150) (dotted curve).

Higgsino state. The annihilation cross-section is governed by the coupling of the lightest neutralino to the Z-gauge boson as shown in figure 8. The coupling of a neutralino state to the Z-gauge boson is proportional to the difference of the square of the components $N_{\tilde{\chi}\tilde{H}_i}$ of the neutralino into the two weak Higgsino states $\tilde{H}_i$ as $g_{\tilde{\chi}Z} \propto \left(h_2^2 - h_1^2\right)/\left(h_2^2 + h_1^2\right)$. The numerical analysis yields for the WMAP dark matter density the results shown in figure 9 [14], while the possibilities for detection are given in figure 10.

4. Splitting the light stop window

Remember that one of the conclusions of EWBG in the MSSM, see section 2, pointed towards the direction of a special version of split supersymmetry. In fact, in the light stop scenario the effective theory below the scale of supersymmetry breaking contains one Higgs doublet, the Higgsinos and gauginos of the MSSM and the right-handed stop. To make up this theory requires two fine-tunings: that of a light Higgs (as in split supersymmetry) and an extra one for a light right-handed squark. However there should be a physical motivation behind each of those: the Higgs fine-tuning is required by the electroweak breaking while the right-handed stop fine-tuning is required by BAU. This theory could in principle be consistent with

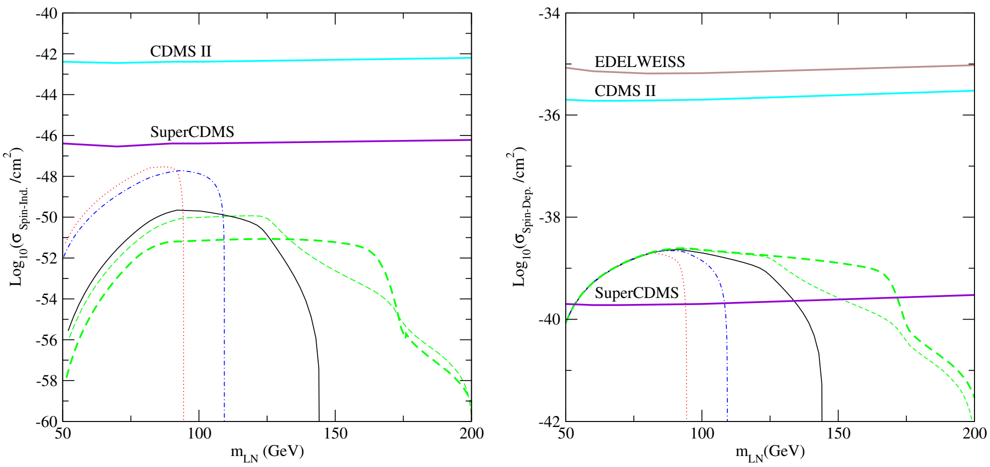

Figure 10. The spin-independent cross-section on a proton (left panel) and the spin-dependent cross-section on a neutron (right panel) versus the lightest neutralino mass, as compared to current exclusion curves (CDMS II) and the projected sensitivity of future detectors (SuperCDMS).

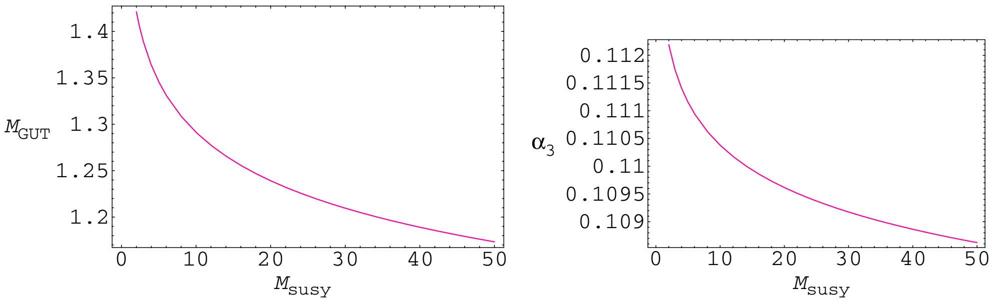

Figure 11. Left panel: M_{GUT} as a function of the scale of supersymmetry breaking m_Q. Right panel: $\alpha_3(M_Z)$ as a function of the scale of supersymmetry breaking. Including two-loop corrections amounts to $\Delta_{2\text{-loop}}\alpha_3(M_Z) \sim 0.01$.

- dark matter,
- gauge-coupling unification,
- EWBG.

Concerning dark matter in this model it should be described by the lightest neutralino in a way similar to split supersymmetry [15]. Second, gauge-coupling unification is consistent with a scale of supersymmetry breaking around 10–100 TeV. Finally, the requirement of EWBG should mainly be constrained by the Higgs mass and its experimental bounds. In particular for getting Higgs masses of ∼120 GeV while keeping a small mixing A_t, as it is required by the condition of a strong first-order phase transition, one should go to values of $m_Q \sim$ 10–100 TeV in agreement with the constraints from gauge-coupling unification in figure 11. A systematic study of this possibility is being performed at present [16].

5. Conclusions

EWBG is a very interesting and appealing mechanism to generate the BAU which can be tested at present and future accelerators that can thus probe the different models. Our conclusions can be summarized in the following way:

- Present LEP data already exclude the SM and thus require new physics.
- If the Higgs mass was on the verge of experimental detection at LEP and the right-handed stop turns out to be light ($\sim m_t$) then the MSSM could still be responsible for the baryon asymmetry.
- If the Higgs mass turns out to be heavier but below ~200 GeV then probably some sort of split light stop scenario can do the job.
- If the Higgs mass is much heavier ($\gg$300 GeV) we should (most probably) abandon the idea of supersymmetry. Then some nonsupersymmetric model as that described in section 3 could be at the origin of EWBG.

Acknowledgments

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