

# Is electroweak baryogenesis dead?

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Electroweak baryogenesis is severely challenged in its traditional settings: the Minimal Supersymmetric Standard Model, and in more general two Higgs doublet models. Fine tuning of parameters is required, or large couplings leading to a Landau pole at scales just above the new physics introduced. The situation is somewhat better in models with a singlet scalar coupling to the Higgs so as to give a strongly first order phase transition due to a tree-level barrier, but even in this case no UV complete models had been demonstrated to give successful baryogenesis. Here we point out some directions that overcome this limitation, by introducing a new source of CP violation in the couplings of the singlet field. A model of electroweak baryogenesis requiring no fine tuning and consistent to scales far above 1 TeV is demonstrated, in which dark matter plays the leading role in creating a CP asymmetry that is the source of the baryon asymmetry.

## 1 Introduction

Readers old enough to remember Hinchliffe’s rule<sup>1</sup> will guess that the answer to the question of the title given here is “no.” But before elaborating the challenges faced by electroweak baryogenesis, it is well to remind the reader why they should care. The preferred paradigm of many physicists for creating the baryon asymmetry of the universe (BAU) is leptogenesis, since it is a feasible mechanism that comes almost for free just by invoking the seesaw mechanism for neutrino masses. However with the notable exception of resonant leptogenesis using low-scale right-handed neutrinos<sup>2</sup>, this appealing idea may never be experimentally verifiable, since it relies upon new physics at the scale of the heavy neutrinos,  $\sim 10^{10}$  GeV.

Electroweak baryogenesis (EWBG) is by design highly testable at colliders since it relies upon new physics at the scale of the electroweak phase transition. In principle, we expect that it should be verified during the LHC era. One might question whether that test has essentially been already carried out now, with a negative conclusion, hence the title of this contribution. Here we will present one class of examples to the contrary, but in fact there are also others that have been discussed at this meeting<sup>3</sup>.

For completeness we briefly recapitulate the essential ingredients of electroweak baryogenesis<sup>4,5,6</sup>, summarized in fig. 1(a). If the electroweak phase transition (EWPT) is first order, bubbles of the broken phase with nonvanishing Higgs VEV  $v$  will nucleate and grow. Standard model fermions should interact with the bubble walls in a CP-violating manner so as to produce a chiral asymmetry—an excess of left-handed versus right-handed fermions in front of the wall. In this region, baryon-violating sphaleron interactions are in thermal equilibrium, and try to erase the chiral asymmetry, converting it into a baryon asymmetry. These baryons eventually fall inside the expanding bubble, and are safe from washout by sphalerons inside the bubble as long as

$$v > 1.1 T, \tag{1}$$

the condition for the sphaleron interactions to go out of equilibrium<sup>7</sup>. To achieve a first order phase transition, the Higgs potential must develop a barrier between the symmetric and symmetry-breaking minima, as illustrated in the rightmost of fig. 1(b).

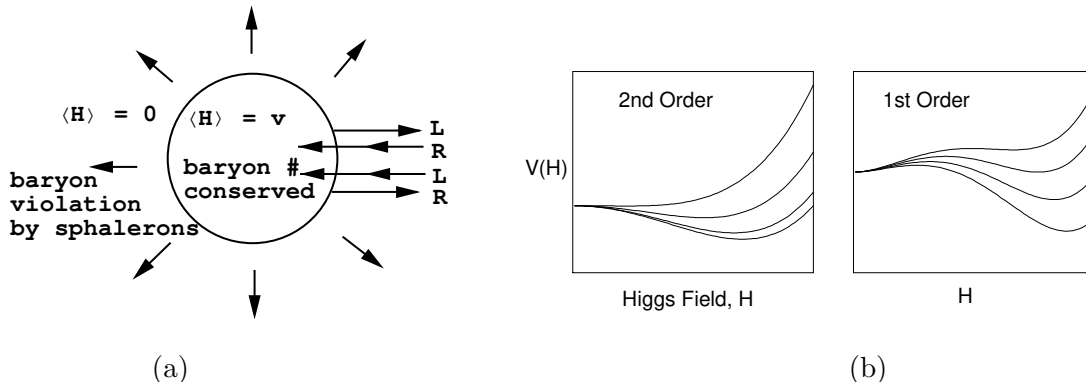


Figure 1 – (a) The essential ingredients of electroweak baryogenesis, surrounding a bubble nucleated during a first order electroweak phase transition. (b) Evolution of the Higgs potential with temperature for a second or first order phase transition.

There are two main difficulties for getting successful EWBG. The first is that condition (1) is hard to achieve from a barrier generated by thermal corrections to the effective potential. The most important such correction, in an expansion of field-dependent masses over temperature, is the cubic term

$$\Delta V(h) \ni -\frac{T}{12\pi} \sum_i (m_i^2(h))^{3/2} = -\frac{T}{12\pi} \sum_i (m_{i,0}^2 + g_i^2 h^2 + c_i T^2)^{3/2} \quad (2)$$

In the absence of the bare mass and thermal correction, this would have a pure cubic form,  $(g_i h)^3 T / 12\pi$ , leading to the desired barrier in the potential. But if  $m_{i,0}^2 + c_i T^2$  is not small or the coupling  $g_i$  is weak, then the barrier is low and leads to a smaller VEV than required by (1). To overcome this one typically needs to choose large couplings and tune the bare mass.

The second difficulty is in getting strong enough CP-violation in the interactions of fermions with the bubble wall. The new CP-violating interactions are often highly constrained by experimental limits on electric dipole moments of the neutron, electron, and certain atomic nuclei.

The Minimal Supersymmetric Standard Model (MSSM) was an initially promising model for EWBG, since having a relatively light right-handed top squark with mass  $m_{\tilde{t}_R} \lesssim m_t$  was sufficient for satisfying condition (1)<sup>8,9</sup>, and the CP-violating phase in the chargino mass matrix could lead to a chiral chargino asymmetry, which through interactions would equilibrate into a chiral quark asymmetry and induce the baryon asymmetry via sphalerons<sup>10,11</sup>. But the difficulties mentioned in section 1, in light of increasingly stringent LHC constraints on the stop mass, as well as EDM constraints, have essentially ruled out this scenario. The light stop leads to enhanced Higgs production via fig. 2(a), in conflict with the observed cross section. Ref.<sup>12</sup> showed that one could hide the increased cross section if the lightest stable particle had mass  $m_\chi < m_h/2$ , by introducing a large invisible branching ratio for  $h \rightarrow \chi\chi$  of order 30–60%, which however is now ruled out<sup>13,14</sup>. Other finely-tuned loopholes have been pointed out in ref.<sup>15</sup>, but have not generated great enthusiasm in the community, perhaps because of the continuing lack of experimental evidence for low-energy supersymmetry.

## 2 MSSM and two Higgs doublet models

Beyond the difficulty of getting a strong enough phase transition in the MSSM, there is controversy about how to reliably compute the baryon asymmetry. Everyone agrees that fluid equations describing the diffusion of relevant particle species must be solved, to find the spatially

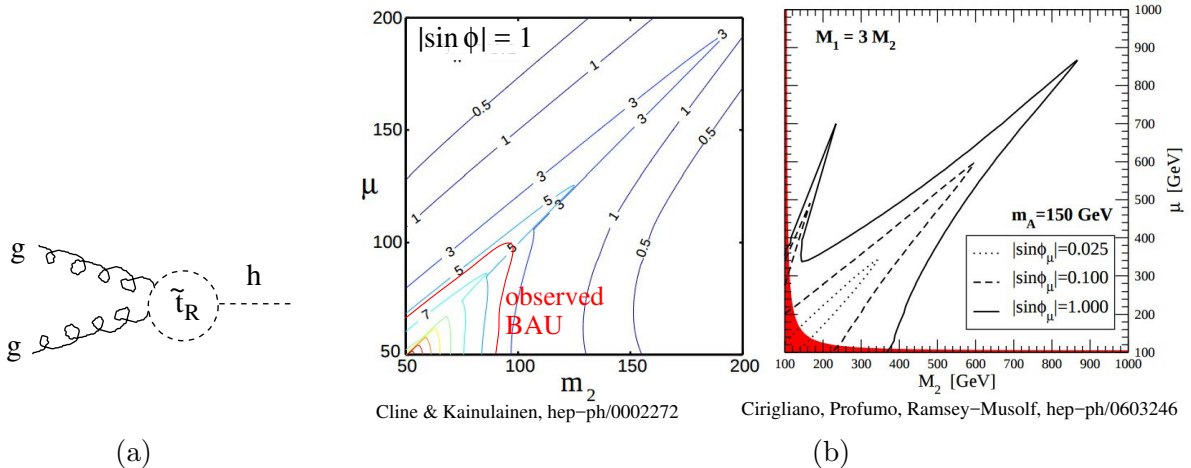


Figure 2 – (a) MSSM contribution to Higgs production via gluon fusion with light  $\tilde{t}_R$  in the loop. (b) Comparison of predictions for the baryon asymmetry versus chargino mass parameters  $\mu$  and  $m_2$ . Left plot, using classical chiral force formalism (WKB)<sup>23</sup>, assumes maximal CP violating phase  $\phi$  and right plot using mass insertion in closed time path formalism, considers varying phase<sup>24</sup>.

dependent chemical potentials of left-handed fermions with respect to the bubble wall; these determine the rate of biased sphaleron-induced baryon violation. The controversy is about how to compute the inhomogeneous source term  $S$  that feeds these asymmetries. It arises from the CP-violating interactions near the bubble wall.

Two competing formalisms have emerged for computing  $S$ . The WKB method<sup>16,17</sup> starts with a classical CP-violating force exerted by the wall on particles of different chirality,

$$F = \pm \frac{(|m|^2 \theta)'}{2E^2} \quad (3)$$

(see eq. (5) below for the definition of  $\theta$ ) and encodes the chiral charge separation created by this force as the origin of  $S$ . The other popular method is to make an expansion in powers of the  $z$ -dependent Higgs VEV in thermal Green's functions, starting from the closed time path (CTP) formulation of thermal field theory<sup>18</sup>, in order to obtain calculable expressions. The WKB formalism, although originally derived from classical dispersion relations, was also shown to arise starting from CTP<sup>19,20</sup>, and gives the leading terms in a systematic expansion in derivatives of the background fields in the bubble wall. This approximation is controlled as long as the average de Broglie wavelength  $\sim 1/T$  of particles in the plasma is small compared to the width  $L_w$  of the wall. In contrast, the expansion in powers of the VEV is not known to be convergent (though certain subclasses of higher powers can be resummed<sup>21,22</sup>), which may be related to the fact that this formalism can predict sizable sources even for masses significantly greater than  $T$ , despite the expected Boltzmann suppression.

As a result, the WKB method gives much less optimistic estimates of the baryon asymmetry compared to the VEV expansion, as fig. 2(b) illustrates for the MSSM. In order to get the observed BAU, ref.<sup>23</sup> needed to assume maximal CP violation ( $\phi = \arg[\mu m_2] = \pi/2$ ) in the chargino mass matrix, as well as light charginos  $\mu \sim m_2 \sim 100$  GeV, now ruled out by LHC, whereas ref.<sup>24</sup> could do so with a phase of order  $10^{-2}$  for light charginos, or for chargino mass  $> 800$  GeV if the phase was maximal.

EWBG in the next-to-minimal supersymmetric standard model (NMSSM) was shown to have more breathing room in refs.<sup>25,26</sup>, since the extra singlet field could help to strengthen the phase transition as well as provide new sources of CP violation that are relatively unconstrained by EDMs. The analysis has been updated in the context of split SUSY models where the scalar superpartners are much heavier than the neutralinos and charginos, finding positive results<sup>27</sup>, in models predicting an electron EDM that should be discovered in upcoming searches. One

drawback with the NMSSM is that the extra scalar self-couplings are less protected from running to Landau poles than those in the MSSM, which are determined by the gauge couplings.

Electroweak baryogenesis in general two Higgs doublet models (2HDMs) is also in a state of mild controversy. Ref. <sup>28</sup> undertook an extensive study of the allowed parameter space, finding only a small handful of viable examples in a Monte Carlo Markov chain (MCMC) search yielding 10,000 models. The result is shown in fig. 3. In that study, a correlation was sought between the predicted baryon asymmetry (horizontal axis) and possible new sources of CP violation in the  $b$ -quark Yukawa couplings (vertical axis), motivated by the  $D\emptyset$  like-sign dimuon asymmetry, which has since gone away. As fig. 3 shows, no such correlation was found, but for the present argument all that matters is that very few models exist that predict a large enough BAU. These few are not very satisfactory, because they require such large Higgs self-couplings (to get a strong enough phase transition) that a Landau pole is imminent, near 1 TeV. Recently ref. <sup>29</sup> presented a more optimistic outlook for EWBG in 2HDMs. To understand these results in light of ref. <sup>28</sup>, it seems likely that the successful models presented there suffer from requiring very large scalar self-couplings, leading to low-scale Landau poles, as well as very narrow bubble walls,  $L_w \sim 1/T$ , in which the derivative expansion assumed for the classical force treatment of the source is not under quantitative control.

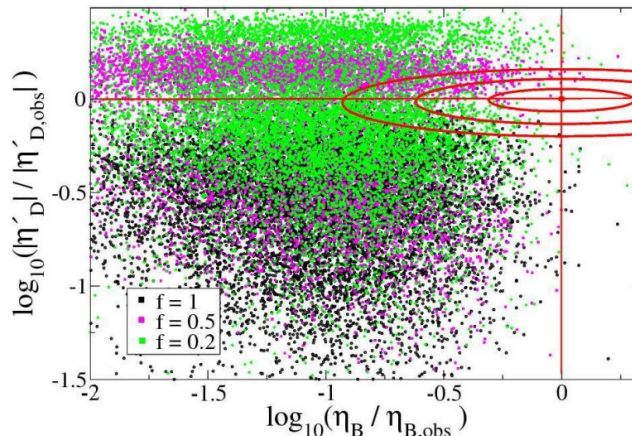


Figure 3 – Distribution of two Higgs doublet models passing experimental and consistency constraints, from ref. <sup>28</sup>. Horizontal axis is the predicted BAU in units of the observed value.

### 3 Adding a scalar singlet

It was realized long ago <sup>30</sup> that coupling the Higgs field to a scalar singlet  $S$  can provide a strongly first order EWPT, if there is already a barrier at tree level (coming from the  $(\lambda_m/4)h^2s^2$  interaction) between the false vacuum at  $(h, s) = (0, w)$  and the true one at  $(h, s) = (v, 0)$ . There is a two-step transition in the early universe in which the EWPT is preceded by that where the fully symmetric vacuum  $(h, s) = (0, 0)$  evolves to a VEV along the  $s$  axis. The second transition, to the  $h$  axis, breaks electroweak symmetry. The potential for the scalar fields

$$V = \frac{1}{4}\lambda_h(h^2 - v^2)^2 + \frac{1}{4}\lambda_s(s^2 - w^2)^2 + \frac{1}{4}\lambda_m h^2 s^2 \quad (4)$$

is illustrated in fig. 4. (For simplicity we impose  $s \rightarrow -s$  symmetry on the potential.) The transition can easily be very strong since the barrier height is not suppressed by loops or thermal factors. If the two minima are not too different in height, the small effects of temperature are sufficient to interchange their relative heights to induce the phase transition.

This idea did not gain popularity immediately since at first it seemed that the cubic terms in the finite-temperature correction would be sufficient for getting a strong enough transition.

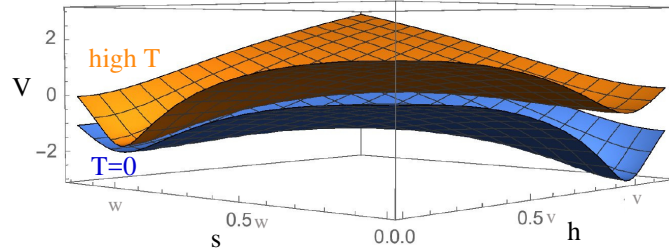


Figure 4 – Evolution of sample scalar potential  $V(h, s)$  with temperature, illustrating tree-level barrier.

But as the experimental limits that constrain such contributions have continued to become more stringent, the singlet has become a favored means of boosting the transition strength, starting with refs. <sup>31,32</sup>.

In ref. <sup>32</sup>, it was realized that the singlet field could also be used to provide a source for the baryon asymmetry, by introducing a dimension-5 operator coupling  $s$  to the usual top quark Yukawa interaction,  $(s/\Lambda)\bar{Q}_3H(\eta' + i\eta\gamma_5)t_R$ . The field-dependent top quark mass then becomes

$$m_t(h, s) = \frac{h}{\sqrt{2}} \left( y_t + (\eta' + i\eta) \frac{s}{\Lambda} \right) \equiv |m_t| e^{i\theta} \quad (5)$$

where  $h = h(z)$  and  $s = s(z)$  in the bubble wall. If  $\eta$  is nonzero, then there is a CP-violating phase  $\theta(z)$ . This is useful for baryogenesis since in the classical force formalism, the source term in the top quark diffusion equation is proportional to  $(|m_t|^2\theta)'$ , where  $'$  denotes  $d/dz$ , and  $z$  is distance transverse to the bubble wall.

Ref. <sup>33</sup> showed that this also works using the analogous dimension-6 operator that is quadratic in  $s/\Lambda$ , with the advantage that  $s \rightarrow -s$  symmetry can be preserved, allowing  $s$  to be a dark matter candidate. It was found to be easy to generate many models, by a random scan, giving a large enough baryon asymmetry. To get a strong enough phase transition, fairly large values of the Higgs-scalar cross coupling  $\lambda_m \sim 0.5$  are needed, which suppress the relic density of  $s$  because of the large Higgs-mediated cross section for  $ss$  annihilation. However even though  $s$  might only constitute  $\sim 1\%$  of the dark matter, it could still be detected in direct searches due to the correspondingly strong Higgs-mediated cross section for scattering on nucleons.

A shortcoming of this model, however, is that the scale  $\Lambda$  must be rather low,  $\lesssim 3$  TeV, to get a large enough BAU. This leads one to question whether the new particles needed to generate the dimension-6 operator would entail additional constraints from collider searches, and if large couplings leading to low-scale Landau poles might appear in a complete model. One is thus motivated to look for renormalizable models that take advantage of the singlet for enhancing the phase transition, as well as providing the new source of CP violation needed for EWBG.

#### 4 A more complete model

We have proposed a model that overcomes the above-mentioned concerns, by introducing a neutral Majorana fermion  $\chi$  that couples to  $s$  as <sup>34</sup>

$$\frac{1}{2}\bar{\chi}(m_\chi + [\eta' + i\eta\gamma_5]s)\chi \quad (6)$$

where  $m_\chi, \eta, \eta'$  are real-valued. This gives a complex mass for  $\chi$  in the bubble wall, where the phase  $\theta$  varies with  $z$  as in eq. (5). The classical force exerted by the wall thus leads to the CP asymmetry, in the form of a separation between the two helicity states of  $\chi$ . That is not sufficient for biasing sphalerons since  $\chi$  is neutral under  $SU(2)_L$ . Thus we require a further interaction for communicating the CP asymmetry to the standard model doublets. We introduce an inert Higgs doublet  $\phi$  with the *CP-portal* interaction

$$y_i\bar{\chi}\phi L_i \quad (7)$$

where  $L_i$  is the left-handed doublet of the  $i$ th generation. For simplicity we assume that  $y_\tau$  is the dominant coupling,  $\eta' = 0$ , and we neglect possible couplings between  $\phi$  and  $h$  (especially  $(H^\dagger\phi)^2$ , which would induce too-large radiative neutrino masses in conjunction with (7)). Decays and inverse decays  $\phi \leftrightarrow \chi L_\tau$  cause the helicity-asymmetry in  $\chi$  to be partially converted to a chemical potential for  $L_\tau$ , which then drives the baryon production via sphalerons.

A bonus in this model is that  $\chi$  is a good dark matter candidate, which can get the right thermal relic density through  $\chi\bar{\chi} \rightarrow L_\tau\bar{L}_\tau$  annihilations. (If  $m_\phi < m_\chi$  then  $\phi$  would be the dark matter, but since we assume there is no mass splitting between the neutral components of  $\phi$ , this would be ruled out by direct detection constraints on scattering of  $\phi$  on nucleons by  $Z$  exchange). The relic density is largely determined by  $y_\tau$ , which also has a strong impact on the BAU, making the model more constrained. Nevertheless, we find many models with reasonable values of the parameters ( $\lambda_m \sim \eta \sim 0.5$ ,  $y_\tau \sim 0.6$ ,  $m_\chi \sim 50$  GeV,  $m_\phi \sim 120$  GeV,  $m_s \sim 110$  GeV) that are consistent with the observed BAU and dark matter density. The results of a random scan are shown in fig. 5. In contrast to the analogous result fig. 3 for 2HDMs, where MCMC was needed to find the few viable models, here no great effort is required to generate successful examples.

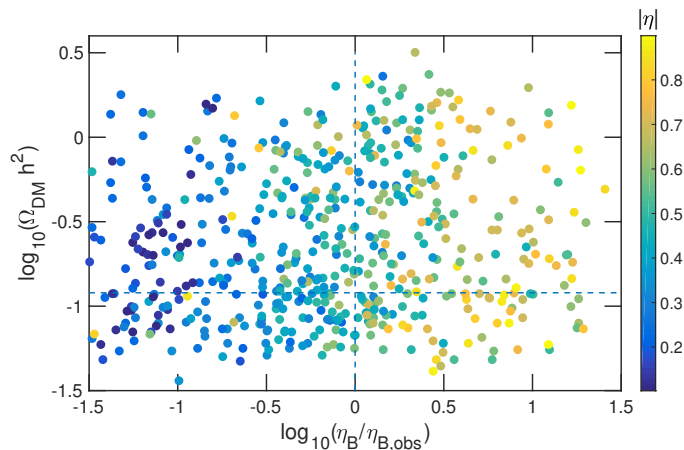


Figure 5 – Scatter plot of dark matter density versus baryon asymmetry for the model with dark-matter induced electroweak baryogenesis.  $\eta$  is the pseudoscalar coupling of the DM to the scalar singlet, eq. (6).

This model has strong potential for discovery at LHC. The Drell-Yan production of  $\phi^\pm$  pairs, followed by  $\phi \rightarrow \tau\chi$  decays, is similar to  $\tilde{\tau}$  pair production followed by  $\tilde{\tau} \rightarrow \tau\chi_0$  in the MSSM. Fig. 6 shows the ATLAS limit from Run 1 on the production cross section, versus the predicted cross section, as a function of  $m_{\tilde{\tau}_R}$  and neutralino mass of 60 GeV. To within factors of 2 (since ATLAS considers combined production of  $\tilde{\tau}_R$  and  $\tilde{\tau}_L$  pairs, whereas  $\phi$  has no right-handed counterpart), these limits also apply to our model. They indicate that for  $m_\phi \sim 120$  GeV and  $m_\chi \sim 60$  GeV (as predicted by our model), the limiting cross section is only a few times greater than the predicted one, giving hope that detection could be possible with the Run 2 data.

There is also potential for indirect detection through the emission of gamma ray lines from  $\chi\bar{\chi} \rightarrow \gamma\gamma$ , from the diagram of fig. 6(b). Unlike the tree-level annihilation  $\chi\bar{\chi} \rightarrow \tau\bar{\tau}$  which is  $p$ -waved suppressed, this process is  $s$ -wave, with  $\langle\sigma v\rangle \cong 4 \times 10^{-30} \text{cm}^3/\text{s}$ . This is not far below the most optimistic constraint  $\sim 10^{-30} \text{cm}^3/\text{s}$  (depending upon assumptions about the DM density profile in the galactic center) from Fermi/LAT<sup>36</sup>.

For direct detection, the cross section is unobservably small unless we allow for a small VEV  $\langle s \rangle$  at zero temperature. Then singlet-Higgs mixing gives rise to the diagram of fig. 6(c). Current bounds from direct searches limit the mixing angle at the level  $\theta_{hs} < 0.04$ . In fact, some small amount of mixing is required for successful baryogenesis in this model, since if  $s \rightarrow -s$  is an exact symmetry of the scalar potential, then the early universe will be equally populated by



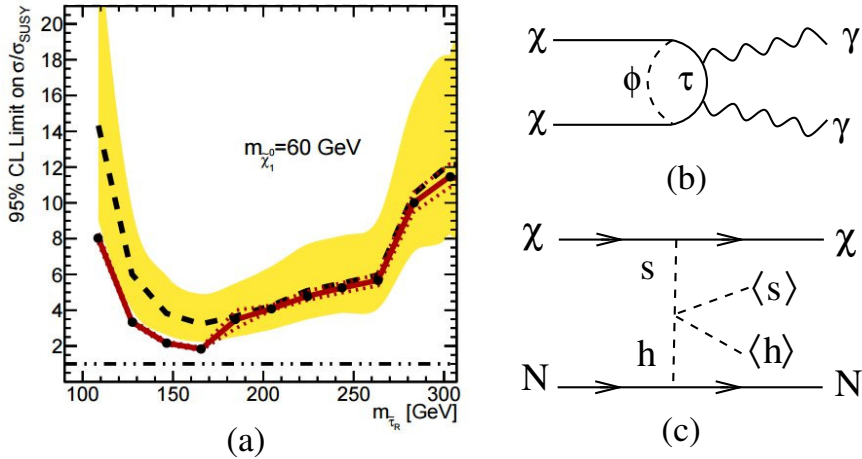


Figure 6 – (a) ATLAS upper limit on  $\tilde{\tau}$  pair production cross section in the MSSM for lightest superpartner (dark matter) mass of 60 GeV from ref. <sup>35</sup>. Dash-dotted line is the predicted cross section. We can reinterpret  $\tilde{\tau}$  as  $\phi$  and the neutralino as  $\chi$  to apply the constraints to our model. (b) Diagram for producing gamma ray lines from dark matter annihilation. (c) Diagram generating DM scattering on nuclei, in the presence of nonvanishing  $\langle s \rangle$  VEV.

domains with  $s > 0$  and  $s < 0$  during the EWPT, containing equal and opposite values of the BAU that will eventually average to zero. Only very small (Planck-suppressed) mixing is needed to avoid this problem: lifting the degeneracy between the  $s < 0$  and  $s > 0$  false vacua before the EWPT will eliminate the higher energy phase as long as the domain walls separating the two phases annihilate faster than the Hubble rate. Hence we do not expect that relaxing this simplifying approximation will change our quantitative estimates of the BAU.

## 5 Outlook

The model described in section 4 is one example showing that electroweak baryogenesis, far from being dead, can be achieved in renormalizable models that are within the reach of discovery at LHC, without requiring fine tuning or unreasonably large dimensionless couplings. It is likely that many such models exist, that take advantage of a scalar singlet to get a strong EWPT and relatively unconstrained CP violation.

For example, one can easily generate eq. (5) by integrating out a heavy vectorlike isosinglet top partner  $T$ , with interactions

$$\eta \bar{t}_R S T_L + M \bar{T}_L T_R + y' \bar{T}_R H t_L \quad (8)$$

This gives a nonstandard contribution to the top quark mass in the bubble wall,  $(\eta y'/M) \bar{t}_R S H t_L$  that operates just like eq. (5) to produce a CP asymmetry, if  $\eta y'$  has a phase relative to the SM top Yukawa coupling. The current mass limit on vector-like top partners is around 1 TeV <sup>37</sup>, making this an excellent candidate for testable new physics that can give the baryon asymmetry. Work on this is in progress.

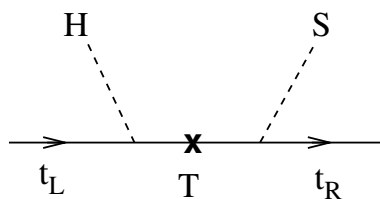


Figure 7 – Generation of dimension-5 contribution to top quark mass,  $\bar{Q}_3 H S t_R / \Lambda$ , through a heavy vectorlike top partner.

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