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Electroweak Baryogenesis and Higgs Signatures

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Abstract

We explore the connection between the strength of the electroweak phase transition and the properties of the Higgs boson. Our interest is in regions of parameter space that can realize electroweak baryogenesis. We do so in a simplified framework in which a single Higgs field couples to new scalar fields charged under $SU(3)_c$ by way of the Higgs portal. Such new scalars can make the electroweak phase transition more strongly first-order, while contributing to the effective Higgs boson couplings to gluons and photons through loop effects. For Higgs boson masses in the range $115 \lesssim m_h \lesssim 130$ GeV, whenever the phase transition becomes strong enough for successful electroweak baryogenesis, we find that Higgs boson properties are modified by an amount observable by the LHC. We also discuss the baryogenesis window of the minimal supersymmetric standard model (MSSM), which appears to be under tension. Furthermore, we argue that the discovery of a Higgs boson with standard model-like couplings to gluons and photons will rule out electroweak baryogenesis in the MSSM.

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1 Introduction

The origin and structure of electroweak symmetry breaking is the leading question driving current research in elementary particle physics. In the Standard Model (SM) and many of its extensions, electroweak symmetry breaking is induced by a complex scalar Higgs field. Consequently, the main priority of modern high energy particle colliders like the Tevatron and the Large Hadron Collider (LHC) is to find the corresponding Higgs boson particle [1–3].

Electroweak symmetry breaking may also be closely related to the origin of the observed baryon asymmetry. If the early Universe was very hot, the full $SU(2)_L \times U(1)_Y$ electroweak symmetry is likely to have been restored [4]. As the Universe expanded and cooled, the Higgs field obtained a vacuum expectation value (VEV) thereby breaking the electroweak symmetry down to its $U(1)_{em}$ subgroup. The dynamics of this phase transition could be responsible for generating the observed excess of baryons via electroweak baryogenesis (EWBG) [5–10].

The paradigm of EWBG requires a strongly first-order electroweak phase transition. This manifests physically as bubbles of electroweak-broken phase which nucleate within a plasma of the symmetric phase. Outside the bubbles, baryon-number violating electroweak sphalerons are active, while within the bubbles this rate is exponentially suppressed. Chiral asymmetries result from CP-violating scattering of particles with the bubble walls. These asymmetries bias the rapid sphaleron transitions in the unbroken phase to create more baryons than anti-baryons, which are subsequently swept up by the expanding bubbles into the broken phase. From this point on, the baryon asymmetry is expected to be unchanged.

For EWBG to create the entire baryon asymmetry, the electroweak phase transition must be very strongly first order. Quantitatively, this requirement is [11–13]

$$\frac{\varphi_C}{T_C} \gtrsim 0.9\,, \tag{1}$$

where $\varphi_C = \langle H\rangle/\sqrt{2}$ is the VEV of the Higgs field at the critical temperature T_C when the symmetric- and broken-phase minima of the free energy are degenerate. If this condition is not met, the baryon excess created by EWBG will be washed out by residual sphaleron transitions in the broken phase.

Fulfilling the requirement of Eq. (1) while obtaining a phenomenologically acceptable Higgs boson can be a challenge. This is certainly the case in the SM, where detailed calculations show that the requirement of Eq. (1) is met only if the mass of the SM Higgs boson is small $m_h < 42$ GeV [14, 15], well below the current direct collider limit of $m_h < 115.5$ GeV (95% *c.l.*) [16, 17]. (Preliminary data from ATLAS extends this exclusion nearly all the way up to 122 GeV [18]). Furthermore, recent LHC searches for the Higgs boson provide tantalizing hints of a signal near $m_h \simeq 125$ GeV [16, 17], made even more exciting by a (less significant) hint in the same region at the Tevatron [19].

Going beyond the SM, extensions containing new matter that couples to the Higgs field can lead to a more strongly first-order electroweak phase transition, and possibly also viable EWBG. This is possible for supersymmetric extensions of the SM which contain scalar superpartners of the top quark, and more generally in theories containing exotic scalar fields. New fields that couple to the Higgs can lead to modifications of the rates for Higgs boson production and decay. In particular, the effective couplings of the Higgs boson to pairs of gluons or photons, both of which are generated exclusively by loop effects, can be significantly affected [20–26]. It is the connection between the strength of the electroweak phase transition and the properties of the Higgs boson that we investigate in the present work.

We study the correlation between the strength of the EWPT and the collider signatures of the Higgs boson in a simplified model. We assume that electroweak symmetry breaking is induced by a single complex electroweak doublet scalar Higgs field $H = (v + h)/\sqrt{2}$ as in SM, but we also include a new scalar field X that couples to H according to

$$\begin{aligned} -\mathcal{L} &\supset M_X^2|X|^2 + \frac{K}{6}|X|^4 + Q|X|^2|H|^2, \\ &\supset M_X^2|X|^2 + \frac{K}{6}|X|^4 + \frac{1}{2}Q\left(v^2 + 2vh + h^2\right)|X|^2. \end{aligned} \tag{2}$$

The physical mass of X is

$$m_X = \sqrt{M_X^2 + \frac{Q}{2}v^2}\,. \tag{3}$$

Although we will allow for values of $M_X^2 < 0$, we will demand that the new scalar X does not develop a VEV in the course of its cosmological evolution.

The basic interactions of Eq. (2) describe a broad range of theories. In particular, they provide a reasonable approximation to the minimal supersymmetric standard (MSSM) in the limit of the MSSM where EWBG is viable. There, X corresponds to a light mostly right-handed scalar top quark (stop) [12, 27]. Motivated in part by the MSSM and its extensions, we will concentrate mainly on the case where X is a $SU(3)_c$ triplet.[1] Colored scalars also lead to a significant two-loop enhancement of φ_C/T_C [29]. On the other hand, the assumption that only the Higgs field develops a non-zero VEV means that our analysis does not apply to the large class of models where the electroweak phase transition is strengthened by the evolution of other fields, such as singlet and gauge extensions of the SM [30–34].

The primary conclusion of our study is that if new colored (triplet) states induce a strongly first-order electroweak phase transition with $\varphi_C/T_C \gtrsim 0.9$, the collider signals of the Higgs boson are modified in a measurable way. For example, the modification of the production rate of the Higgs via gluon fusion will be large enough to be observed at the LHC. When applied to the MSSM, our results imply that the discovery of a Higgs boson with SM-like couplings to gluons and photons would rule out the EWBG window in this class of theories.

The outline of this paper is as follows. In Section 2 we will describe our calculation of the strength of the electroweak phase transition. Section 3 contains the formalism for estimating the effects of the new scalars on Higgs boson production and decay modes. Our combined quantitative results will be presented in Section 4. Section 5 applies our results to

[1] See Ref. [28] for a supersymmetric model which can allow for Q to be a free parameter.

the MSSM. Other phenomenological implications of the exotic X scalars will be discussed in Section 6. Finally, Section 7 is reserved for our conclusions.

2 The Electroweak Phase Transition

To realize EWBG, we are interested in models which manifest a strongly first-order electroweak phase transition. Given the bounds on the Higgs boson mass, it is well known that the SM alone realizes a second-order phase transition. New particle content which couples to the Higgs boson is required.

One way to enhance the strength of the electroweak phase transition is to introduce a new boson X with a quartic coupling as in Eq. (2) [35]. The resummed one-loop effective potential in the high temperature limit, $m_X \ll T$, will now contain a term of the form

$$V_{\rm eff}(\varphi, T) \supset n_X \frac{T}{12\pi} \left(\overline{m}_X^2 (\varphi, T) \right)^{3/2} , \qquad (4)$$

where n_X is the number of degrees of freedom of the X scalar, $\overline{m}^2_X(\varphi, T) \equiv m^2_X(\varphi) + \Pi_X(T)$, $m_X(\varphi)^2$ is the field dependent mass of the X scalar in the presence of the background field φ, and $\Pi_X(T)$ is the temperature-dependent contribution to the mass of X. The appearance of $\Pi_X(T)$ in this expression comes from the daisy-resummation of the leading thermal corrections to the effective potential. If X receives all of its mass from the Higgs (neglecting Π_X), this term is cubic in φ. It then acts to introduce a second local minimum in the effective potential. As described in the introduction, the measure of the strength of the phase transition is then given by φ_C/T_C.

If both the "soft mas" M_X^2 and $\Pi_X(T)$ were to vanish, the term in Eq. (4) would be cubic in φ and would help to induce a more strongly first-order phase transition. With either non-zero, the naive increase can be spoiled.[2] However, it was recognized in Ref. [36] (in the context of the MSSM) that if one introduces a negative squared-mass parameter for X, it can cancel against $\Pi_X(T_C)$ yielding the desired cubic term. Depending on the quantum numbers of X, one must be careful that negative squared-masses do not cause evolution to a vacuum with $\langle X \rangle \neq 0$ before reaching the vacuum with $\langle \varphi \rangle \neq 0$. We include this constraint in our results below.[3]

As discussed above, following Ref. [29], we will usually assume that the X state is a fundamental of $SU(3)_c$. This choice is important when one includes higher-order contributions to the finite-temperature potential [14] since the coupling between X and the gluon contributes to the effective potential for the Higgs at two-loops. The result is that these additional terms act to fix the Higgs field at the origin, postponing the phase transition. This increases φ_C/T_C above the value one would calculate at one-loop order by as much as a

[2] For example, if $\Pi_X(T) \gg Q\varphi^2$ and $M_X^2 = 0$, we obtain $T\overline{m}^3 \to T^2\varphi^2$, which is clearly not cubic.

[3] There is a small difference between T_C and the actual temperature for nucleating bubbles as computed from the bounce action. We account for this when computing the charge-color breaking region by taking the

criterion for exclusion to be $T_C > (T_C)_X + 1.6$ GeV where $(T_C)_X$ is the 2-loop critical temperature in the X direction [12].

factor of 3.5 [29]. This effect was first observed for the MSSM in Refs. [36,37]. So, while it is not impossible that a first-order phase transition might occur in the absence of new colored states, it seems much easier to obtain in their presence.

3 Higgs Production and Decay

New colored scalars modify the production and decay properties of the Higgs boson. The most important effects arise in the gluon fusion production channel $gg \to h + n_j$ and the di-photon decay mode $h \to \gamma\gamma + n_j$, where $n_j = 0, 1, 2\ldots$ refers to any number of additional of jets. Both channels are generated by loops, with gluon fusion being dominated by a top quark loop in the SM, and the di-photon decay coming primarily from a $W^\pm$ loop [38]. New colored scalars coupling to the Higgs as in Eq. (2) will contribute to the amplitudes for these processes as well, leading to potentially observable effects.

Gluon fusion is the dominant Higgs production mechanism at the LHC and it therefore plays a central role in Higgs boson searches. To an excellent approximation, the production rate in this mode is proportional to the decay width of the Higgs to a pair of gluons, given at leading order (LO) by

$$\Gamma_{gg} = \frac{\alpha_s^2}{128\,\pi^3}\frac{m_h^3}{m_W^2}\left|\sum_i g_i T_2^i F_{s_i}(\tau_i)\right|^2 , \tag{5}$$

where the sum i runs over all particles that couple to the Higgs. In the summand, T_2^i is the trace invariant of the i-th particle's $SU(3)_c$ representation,[4] and the $F_{s_i}(\tau_i)$ are loop functions of $\tau_i = 4m_i^2/m_h^2$ that depend on the particle spin s_i and are given in Ref. [38]. The factors g_i are equal to $g_i = g$ (the $SU(2)$ gauge coupling) for all SM states, while for an exotic scalar X coupling to the Higgs as in Eq. (2) it is given by

$$g_X = \frac{2}{g}\left(\frac{m_W}{m_X}\right)^2 Q\,. \tag{6}$$

For $Q > 0$ the new contribution from a complex scalar has the same sign as the top quark contribution that dominates in the SM.

One of the most important LHC search channels for a lighter Higgs ($m_h \lesssim 135$ GeV) is through its decays to pairs of photons, $h \to \gamma\gamma + n_j$. The width to di-photons at LO is [38]

$$\Gamma_{\gamma\gamma} = \frac{\alpha^2\, m_h^3}{1024\,\pi^3\, m_W^2}\left|\sum_i g_i q_i^2 d_i F_{s_i}(\tau_i)\right|^2 , \tag{7}$$

where the sum i runs over all charged particles coupling to the Higgs, d_i is the dimension of the corresponding $SU(3)_c$ representation ($d_i = 1$ for color singlets), q_i is the electromagnetic charge of the state, and the $F_{s_i}(\tau_i)$ loop functions and the couplings g_i are the same as for

[4] Specifically, $\mathrm{tr}(t_r^a t_r^b) = T_2^r\delta^{ab}$, normalized to $1/2$ for the N of $SU(N)$.

gluon fusion. The SM contribution to the di-photon amplitude is dominated by the $W^\pm$ loop and has a subleading but significant destructive contribution from the top quark. The contribution from an exotic scalar will also interfere destructively with the $W^\pm$ loop if $Q > 0$.

In contrast to the production rate by gluon fusion and the decay rate to di-photons, other phenomenologically important production and decay channels of the Higgs boson are essentially unchanged. Most importantly, the production rates for vector boson fusion and the branching fractions to $W^\pm W^{\mp(*)}$ and $Z^0 Z^{0(*)}$ will be the same as in the SM (provided the shift in Γ_{gg} is not exceedingly large). Thus, the effects of a new scalar will be isolated in specific production and decay channels leading to a distinctive pattern of modifications away from the SM values.

The alterations in gluon fusion and di-photon decay presented here have only been computed to leading order in the perturbative expansion. It is well known that higher-order corrections to these channels are extremely important, particularly for the production rate by gluon fusion. Even so, these corrections are found to be nearly the same for the SM as they are for new matter multiplets with $m_i > m_h/2$ [39–44].[5] As such, we incorporate the effects of higher-order corrections by normalizing our LO results to the corresponding predictions in the SM.

4 Combined Results

Having discussed the effects of exotic scalars on the strength of the electroweak phase transition and the production and decay properties of the Higgs boson, we turn next to the correlation between these two quantities. Motivated by recent results from Higgs searches at the LHC [16, 17], we focus primarily on a Higgs boson mass of $m_h = 125$ GeV. However, our results for the mass range $115\,\text{GeV} \lesssim m_h \lesssim 130\,\text{GeV}$ are very similar.

We begin by investigating the effects of a single $SU(3)_c$ triplet scalar. In the left panel of Fig. 1 we show the strength of the phase transition along with the Higgs production cross section via gluon fusion relative to the SM for such a color triplet as a function of the Higgs portal coupling Q and the mass parameter M_X^2. We also set the X scalar quartic coupling to $K = 1.6 \simeq (g_s^2 + 4/3 g'^2)$, which corresponds to the appropriate quartic D-term for an MSSM stop, and we tune the Higgs quartic coupling to obtain $m_h = 125$ GeV. The region to the right of the dark solid contour delineates where the phase transition is strong enough to realize EWBG ($\varphi_C/T_C > 0.9$), and the adjacent lighter solid lines show increments of $\Delta(\varphi_C/T_C) = 0.2$. The upper yellow region is excluded because the Universe would have evolved to a charge-color breaking vacuum. We also occlude the region with $Q \gtrsim 1.8$ because the high-temperature expansion used to estimate the strength of the phase transition breaks down there. From this plot, we see that throughout the entire region consistent with EWBG the rate of Higgs production by gluon fusion is increased by at least a factor of 1.6.

[5] This can be understood from the fact that these corrections are approximated very well by the higher-order corrections to the point-like vertices $h\,G^a_{\mu\nu}G^{a,\,\mu\nu}$ and $h\,F_{\mu\nu}F^{\mu\nu}$ obtained by integrating out heavy particles ($m_i > m_h/2$) in the loops.

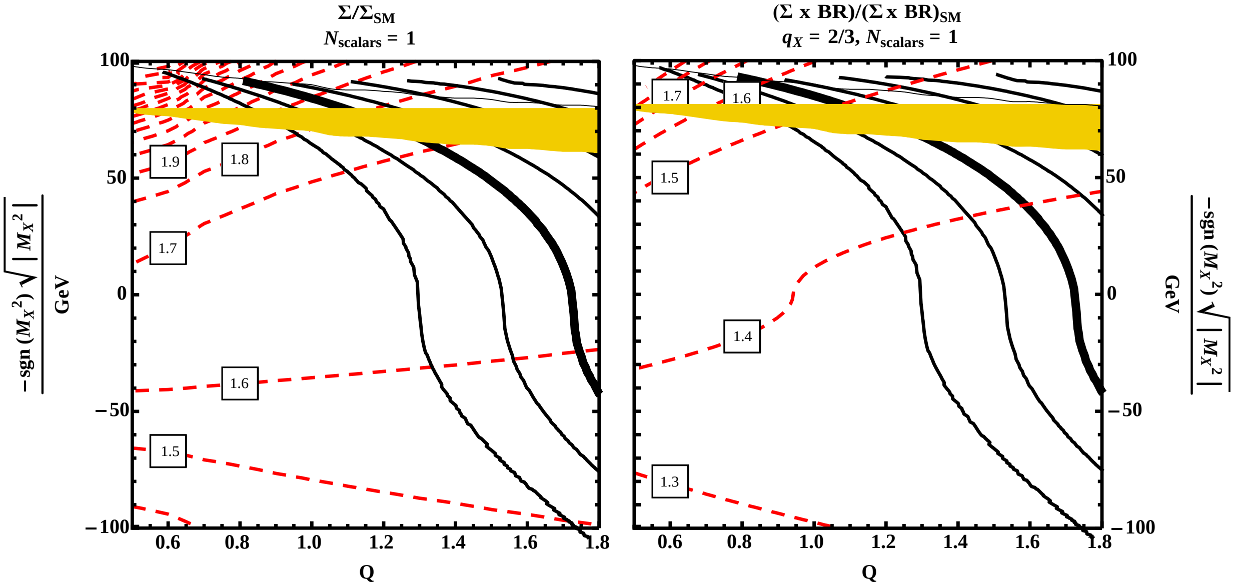

Figure 1: Contours of φ_C/T_C [black, solid lines] in the $-\mathrm{sgn}\left(M_X^2\right)\sqrt{|M_X^2|}$ vs. Q plane for one new color-triplet scalar. The bolded line corresponds to $\varphi_C/T_C = 0.9$ and the adjacent solid lines delineate steps of $\Delta(\varphi_C/T_C) = 0.2$. The yellow shaded region is excluded because for these parameters the Universe would have evolved to a charge-color breaking minimum. In the *left* plot we also show contours of the ratio of the gluon fusion cross section to the SM value [red, dotted lines]. In the *right* plot we show contours of the ratio of the gluon fusion cross section times the branching ratio to di-photons to the SM value [red, dotted lines] when the charge of the colored scalar is taken to be $q_X = 2/3$.

In the right panel of Fig. 1, we plot contours of Higgs production via gluon fusion times the branching ratio to di-photon pairs ($\sigma \times$ BR) relative to the SM for an additional color triplet scalar with an electric charge of $q_X = 2/3$. This canonical value of the charge is what one would expect if the scalar were related to a new up-type quarks via supersymmetry [28]. We see that $\sigma \times$ BR is increased with respect to the SM everywhere in the region that is viable for EWBG. However, the increase is smaller than the enhancement of the rate of gluon fusion production since the X scalar interferes destructively with the (dominant) W loop in the $h \to \gamma\gamma$ amplitude.

Both plots in Fig. 1 extend to values of Q which are larger than unity. One might therefore worry that Q could encounter a Landau pole at relatively low energies. We have checked this running for the simple model of Eq. (2) and we find that $Q = 2$ ($Q = 4$) at the weak scale hits a Landau pole at 100 TeV (1 TeV). This implies that there are no inconsistent points in the plots presented here from the effective theory point of view. Additional matter in the theory, as would be expected in a supersymmetric completion of this model, could also help to tame these potential Landau poles [28].

For all the results we present, we cut off the plots when the high temperature expansion approximately breaks down (*i.e.*, $m_X(\varphi_C)/T_C \gtrsim 1$). We expect that the region with a strong electroweak phase transition would persist for larger values of Q. Physically, in this region

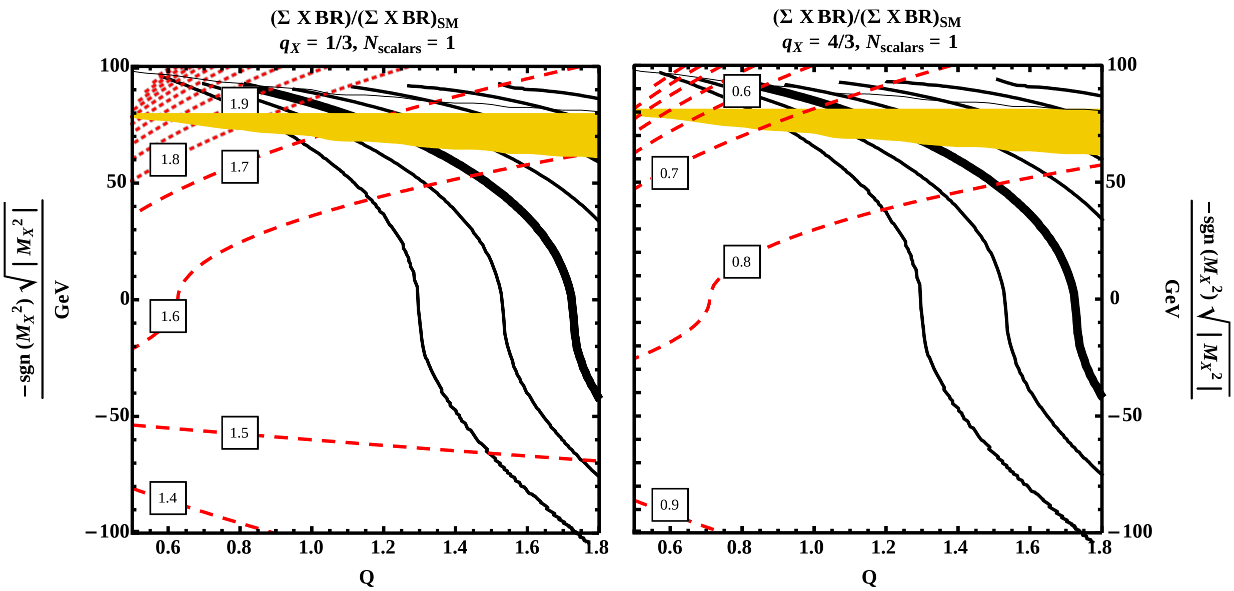

Figure 2: Contours of φ_C/T_C [black, solid lines] and $\sigma \times$ BR [red, dotted lines] in the $-\text{sgn}\left(M_X^2\right)\sqrt{|M_X^2|}$ vs. Q plane for one new color-triplet scalar. In the *left* plot we have taken $q_X = 1/3$ and on the *right* we have $q_X = 4/3$. The yellow region shows the range of parameters for which the Universe would have evolved to a charge-color breaking vacuum as in Fig. 1.

the X would begin to be Boltzmann-suppressed as one approaches field values close to φ_C. This effect would lead to a weakening of the phase transition when Q becomes so large that X is Boltzmann-suppressed near the origin. This does not change our conclusion that there is a lower bound on the modification to the Higgs properties which will be observable at the LHC.

Next we examine the effect of varying the electric charge of the color-triplet X scalar away from $q_X = 2/3$. The gluon fusion cross section is the same as in Fig. 1. In the left panel of Fig. 2 we show the ratio of $\sigma \times$ BR for a color triplet X with $q_X = 1/3$, while in the right panel we show the same quantity for $q_X = 4/3$. The enhancement in $\sigma \times$ BR is larger (smaller) with $q_X = 1/3$ ($q_X = 4/3$) than for $q_X = 2/3$ because there is less (more) destructive interference between X and the W in the di-photon loop. We concentrate on these specific values of q_X since they allow X to decay in a straightforward manner [45]. For even larger charges, the contribution of X to the di-photon amplitude could even overwhelm the W loop leading to an enhancement in the width $\Gamma_{\gamma\gamma}$ and an even larger enhancement in $\sigma \times$ BR.

As a further variation, we consider multiple scalar triplets. For simplicity, we choose the parameters for all scalars to be identical and of the form of Eq. (2) with $K = 1.6$. In doing so, we neglect possible mass and quartic mixing effects between the different X scalars. This greatly simplifies the estimation of the charge-color breaking region, which we obtain by taking the multiple X directions in the potential to be independent of each other.

In Fig. 3 we show contours of φ_C/T_C and σ_{gg} (left) and $\sigma_{gg} \times \text{BR}_{\gamma\gamma}$ (right) for $N = 2$

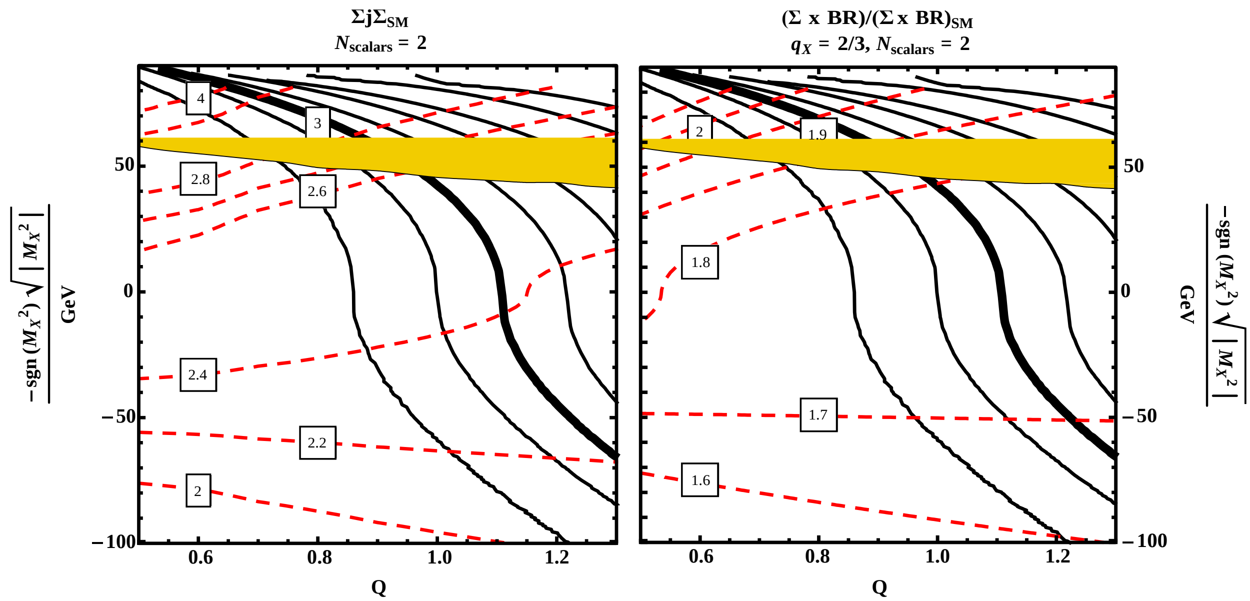

Figure 3: Contours of φ_C/T_C [black, solid lines] and σ_{gg} (*left*) or $\sigma \times$ BR (*right*) [red, dotted lines] in the $-\text{sgn}\left(M_X^2\right)\sqrt{|M_X^2|}$ vs. Q plane for two new color-triplet scalars with $q_X = 2/3$. The yellow region shows the range of parameters for which the Universe would have evolved to a charge-color breaking vacuum, as in Fig. 1.

complex triplets. This figure should be compared to Fig. 1, which shows the same quantities for a single ($N = 1$) triplet. For a given value of Q, we see that both the strength of the electroweak phase transition and the modifications of the Higgs boson rates are significantly increased. Adding more scalars would clearly increase the effects further.

In addition to multiple independent scalar triplets, one could also consider mixing between triplets, or higher-dimensional $SU(3)_c$ representations. A full investigation of such effects lies beyond the scope of the present work, but we will make some brief comments. Based on studies of the MSSM, we generally expect mixing among triplets to coincide with smaller or negative effective values of Q, thus weakening the strength of the electroweak phase transition [12] and reducing (increasing) the coupling of the Higgs boson to gluons (photons) [23]. On the other hand, we expect higher color representations (without mixing) to coincide qualitatively with $N > 1$ triplets [26, 46]. Therefore, we expect the correlation between Higgs boson properties and the strength of the electroweak phase transition to hold for other $SU(3)_c$ representations as well.

Our simplified model can also be expanded by additional states that couple to the triplet X. While such states need not change the properties of the Higgs boson, they will modify the finite temperature potential for X. Their net effect on the phase transition temperature is very similar to varying the value of the X quartic coupling, which we have fixed at $K = 1.6$. We find that changing K chiefly moves the bound from ending up in a charge-color breaking vacuum. While this limits the maximal shift in Higgs properties in this scenario, it does not change our main conclusion about the lower bound in the alteration of the Higgs boson properties.

We conclude this section by commenting on the possibility of X being a color singlet. This would remove the correlation between the strength of the electroweak phase transition and the gluon fusion production rate, although a measurable change in the di-photon branching fraction may result if X carries an electric charge. With such an X, there are no contributions to the finite-temperature potential from diagrams involving gluons. This implies a milder two-loop enhancement with respect to the one-loop computation [29]. For example, with a real singlet scalar coupling to the Higgs, an extremely large coupling $Q \simeq 4$ only gives $\varphi_C/T_C \simeq 0.4$ which would not lead to viable EWBG. If one includes six real singlet scalars (to match the degrees of freedom of a color triplet scalar), demanding $\varphi_C/T_C \gtrsim 0.9$ implies that $Q \gtrsim 2$. While this is a logical possibility with very few phenomenological consequences, we feel that such models are not as well motivated as non-trivial $SU(3)_c$ representations.

5 Application to the MSSM

As a specific application of our simplified model, we estimate the implications of MSSM EWBG on the properties of the Higgs boson. For EWBG to be viable in the MSSM, the superpartner spectrum must conform to the MSSM-EWBG window described in Ref. [12], with the only physical light scalars in the theory consisting of a SM-like Higgs boson h and a mostly right-handed stop X. Light charginos and neutralinos are also needed to supply CP-violating scattering processes near the expanding bubble walls during the phase transition. The CP violation in this case comes from the irreducible phases $\arg(\mu M_1^*, \mu M_2^*)$ [47–49], so light Higgsinos and a light gaugino are both needed. All other superpartners are assumed to be considerably heavier, and not directly relevant to the properties of the Higgs or to EWBG.

Thus, to compare with the MSSM-EWBG window we should match the Q and K couplings of X to those expected for a stop and include additional fields and couplings beyond those of Eq. (2). Following Ref. [27], we take

$$\Delta L = Y_t \widetilde{H}_u Q_{L_3} X^* + \text{h.c.}, \tag{8}$$

where Y_t is the new Yukawa coupling, $\tilde{H}_u$ is a fermion doublet with the quantum numbers of a Higgsino, and Q_{L_3} is the left-handed 3rd generation quark doublet, and X corresponds to the light stop with $q_X = 2/3$.

The interaction of Eq. (8) has an impact on the strength of the electroweak phase transition. With this coupling, the thermal mass of the X scalar becomes

$$\Pi_X = \left(\frac{5}{27}g_Y^2 + \frac{1}{3}g_3^2 + \frac{1}{9}K + \frac{1}{6}Q + \frac{1}{6}Y_t^2\right) T^2. \tag{9}$$

The Y_t coupling therefore increases the thermal mass, which has the effect of reducing the size of the effective cubic term in the Higgs effective potential for a given value of M_X^2. At the

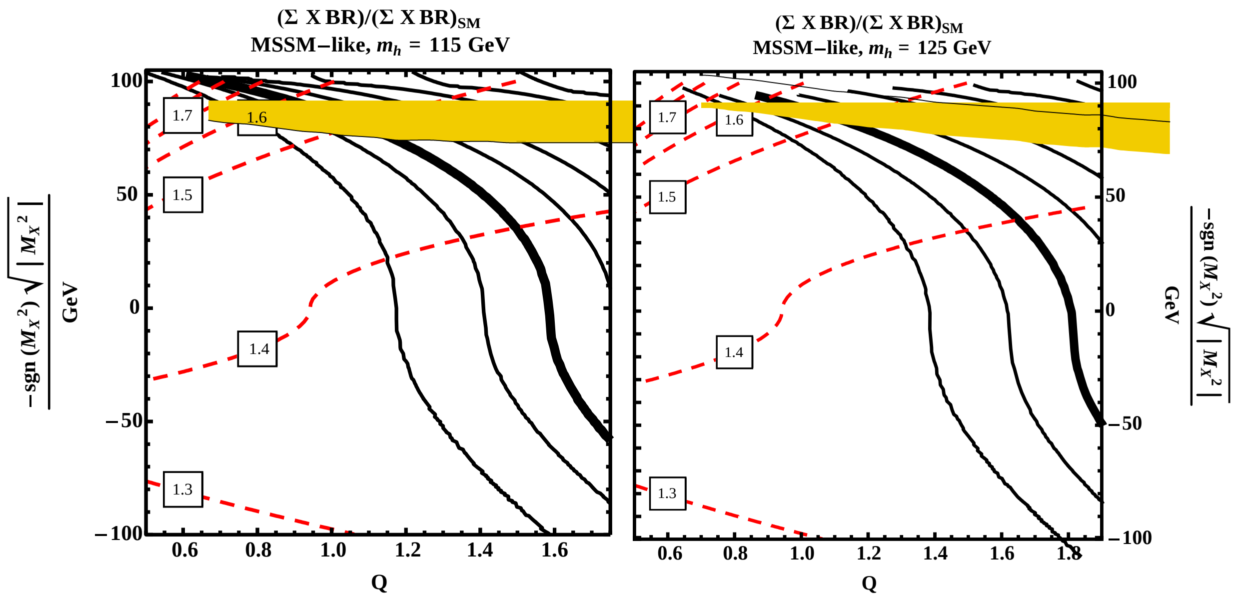

Figure 4: Contours of φ_C/T_C [black, solid lines] and $\sigma \times$ BR [red, dotted lines] in the $-\mathrm{sgn}\left(M_X^2\right)\sqrt{|M_X^2|}$ vs. Q plane for the MSSM-like model. On the *left* (*right*) we have taken the Higgs boson mass to be 115 GeV (125 GeV). The yellow region shows the range of parameters for which the Universe would have evolved to a charge-color breaking vacuum.

same time, Y_t further stabilizes the X direction against developing a charge-color breaking VEV, allowing for more negative values of M_X^2.

The charginos that result from light Higgsinos (and possibly a light Wino) also enter in loops that contribute to the amplitude for $h \to \gamma\gamma$. We find this to be at most an $O(5\%)$ effect when the LEP bound on the chargino mass is taken into account [50]. Therefore, we neglect the chargino contributions to these processes in our analysis since they will not significantly change our conclusions.

In Fig. 4 we show the strength of the electroweak phase transition and the modification of the Higgs $\sigma \times$ BR for gluon fusion production and decay to di-photons. In the left panel we show $m_h = 115$ GeV and in the right we have taken $m_h = 125$ GeV. We have also set $Y_t = 0.8$, $K = 1.6$, which are both typical values for the MSSM [27]. Comparing with Fig. 1 we see that the strength of the phase transition is slightly weaker for fixed (M_X^2, Q), but more negative values of M_X^2 are possible. An electroweak phase transition that is strong enough for EWBG ($\varphi_C/T_C > 0.9$) requires $Q \gtrsim 1.0$ for $m_h = 115$ GeV and $Q \gtrsim 1.2$ for $m_h = 125$ GeV, and for both case there are large modifications to the properties of the Higgs boson.

How does this map onto the MSSM? Beyond introducing new couplings to the light colored scalar, the coupling constants and masses must run to their full MSSM values at the scale associated with the mass of the heavy superpartners. This implies that only a restricted range of Q can be achieved, closely related to the top quark Yukawa coupling [27]. From Fig. 4 we see that $Q \gtrsim 1.2$ (1.0) is required for EWBG with $m_h = 125$ GeV (115 GeV). By comparison, Ref. [25] finds a conflicting range: $Q \lesssim 0.9$ for MSSM inputs $M_X^2 = -(80\,\mathrm{GeV})^2$, $\tan\beta = 10$, and $m_{Q_3} = 1000$ TeV. While this is only a single example, it suggests a significant tension in achieving EWBG in the MSSM with a Higgs mass of $m_h = 125$ GeV.

We do not attempt to make a definitive pronouncement on the viability of EWBG in the MSSM in the present work. Non-perturbative effects can strengthen the phase transition beyond our estimates here [51–53], and mixing between the two CP-even Higgs bosons can modify the result as well (although a lower pseudoscalar Higgs mass m_A has been found to decrease the strength of the phase transition [54]). Even so, our results do show that if EWBG is to be the origin of the baryon asymmetry in the MSSM, the properties of the Higgs boson must differ significantly from the SM. Therefore we can confidently state that if a 125 GeV (or 115 GeV) Higgs boson is measured to have SM-like production cross sections and decays to photons, *this will rule out electroweak baryogenesis for the MSSM*.

6 Collider Signals

We have demonstrated that a strongly first-order electroweak phase transition can be induced by a new colored scalar. To do so effectively, the new state must be relatively light with a mass below about $m_X \lesssim 200$ GeV. Such a particle would be produced abundantly at both the Tevatron and the LHC, and one might wonder if its existence can be consistent with direct collider searches. We have also found that this new scalar necessarily induces significant changes in the production and decay properties of the Higgs. In this section we consider both of these collider signals.

6.1 X Signals

The collider signals of a new colored scalar depend very strongly on how it decays. While the gauge couplings of the scalar are fixed by its representation, the couplings to matter fields are not, and the specific decay modes depend on other new particles present in the theory, *i.e.* the signals of X are highly model-dependent. We consider several possibilities.

A challenging possibility is that the new scalar decays to light jets, $X \to jj$. This could arise from a $X q_i q_j$ coupling, analogous to a $U^c D^c D^c$ superpotential coupling in supersymmetry. A search for decays of this type was performed by ATLAS with limited luminosity (34 pb^{-1}) [55]. Limits were not sensitive to colored scalars in the fundamental representation. Therefore a light X decaying in this way is consistent with current data. Indeed, with current jet thresholds, it will be difficult to probe the low X mass region to any extent at the LHC. However, the Tevatron might be able to test a light X decaying to di-jets if a dedicated analysis were to be performed [56], and the reach might be extended if one of the decay products is a heavy-flavor jet [57].

A second possibility that can be consistent with existing limits is for X to decay to a SM quark and a long-lived neutral fermion N (which might be the dark matter). This is the model-independent analog of stop decays to a charm quark and the lightest neutralino that occurs in the MSSM. It is not unreasonable to expect the existence of such novel states, even in the stripped-down model we discuss here (which makes no claims to solve the gauge hierarchy problem). After all, even with a first order EWPT, a new source of CP violation is required, and this N could easily be a remnant of that sector.

The collider bounds on this possibility depend sensitively on the $X{-}N$ mass splitting [58, 59]. For arbitrarily small splitting, LEP places a bound, $m_X > 96$ GeV. For mass splittings greater than about 35 GeV, the limits from the Tevatron extend to $m_X > 180$ GeV, and LHC searches for jets and missing E_T can extend this reach even further. However, for mass splittings below about 35 GeV, the LHC searches for jets and missing E_T rapidly become much less effective and the Tevatron limits disappear completely. A light X decaying to a jet and a quasi-stable N can therefore also be consistent with existing collider searches.

If decays of this type dominate the X phenomenology, the most promising search strategy appears to be the search for one (or more) hard jet and missing E_T [60] (mono-jet). The analyses of Refs. [61, 62] have applied LHC mono-jet results to constrain the parameter space of this model. They find that such searches exclude a range of X masses up to about $m_X \lesssim 160$ GeV when the X and N are very degenerate. Nevertheless, a small window in the mass differences exists between the Tevatron and the LHC bounds. Searches for multiple jets and missing E_T are also found to rule out X masses below about $m_X \lesssim 130$ GeV independent of the $X - N$ mass splitting. For now, this scenario is viable but the window is closing rapidly as more LHC data pours in [63].

Another strategy which is applicable in a different region of parameter space is a search for X-onium, a bound state of X and X^*. In the context of stoponium, this was discussed in Ref. [64]. To form X-onium efficiently, the lifetime of the X state be sufficiently long so that it does not decay before it binds, $\Gamma_X \ll E_{\text{onium}}$, where E_{onium} is the binding energy. Whether this condition obtains is a model-dependent statement – it can easily be satisfied if the dominant decays of X are loop induced, for example. A recent analysis of LHC data [65] finds that at present the data does not constrain much of the parameter space. Moreover if X-onium decays to Higgs bosons dominate [66], it can become even more challenging to find them.

If X is unable to decay efficiently to SM final states, it will give rise to long-lived charged states (even if it is neutral) via hadronization. Strong bounds on this distinctive final state have already been obtained by the LHC experiments. If it were produced with a cross section corresponding to a colored fundamental, CMS derives a limit $m_X > 735$ GeV [67], with some uncertainty arising from hadronization probabilities. In any case, this bound indicates that if the X were long-lived, it would have to be too heavy to effect the first order phase transition as needed for EWBG.

6.2 Higgs Signals

The existence of a light colored scalar X responsible for inducing a first-order electroweak phase transition can also be tested by measuring the properties of the Higgs boson. In Sec. 2 we showed that such a particle will significantly enhance (relative to the SM) the Higgs production rate via gluon fusion, and can also modify the branching fraction to di-photons in an important way. Can such changes be measured with LHC and Tevatron data?

Recent analyses by the ATLAS and CMS collaborations using nearly $5\,\mathrm{fb}^{-1}$ of data at $\sqrt{s} = 7$ TeV rule out a relatively light SM-like Higgs boson except in the mass windows $117.5\,\mathrm{GeV} < m_h < 119.5\,\mathrm{GeV}$ and $122.5\,\mathrm{GeV} < m_h < 129.5\,\mathrm{GeV}$ [68, 69]. Moreover, both groups find tantalizing excesses in the inclusive $h \to \gamma\gamma$ and $h \to ZZ^*$ channels near $m_h = 125$ GeV, and results consistent with a SM Higgs of this mass in the $h \to WW^*$, $b\bar{b}$, and $\tau\bar{\tau}$ channels. This excess is also supported by Tevatron Higgs searches, which are dominated by searches for $W/Z + h$ with $h \to b\bar{b}$ [70].

While these results do not represent a statistically significant discovery of the Higgs boson, they can still be used to derive strict upper limits on Higgs production rates. The dominant LHC production mode for the inclusive $\gamma\gamma$, ZZ^*, and WW^* channels (that dominate the Higgs limits) is gluon fusion. Combining them, a very conservative upper bound can be placed on the gluon fusion rate of about twice the value in the SM [45, 71–74]. If one looks at the most constraining channel, $h \to WW^*$ where there is no hint of a signal, a more aggressive bound of $\sigma_{gg}/(\sigma_{gg})_{\mathrm{SM}} < 1.7$ from ATLAS and $\sigma_{gg}/(\sigma_{gg})_{\mathrm{SM}} < 1.7$ from CMS can be inferred. Note that gluon fusion is only 83% of the total production cross section for a SM-like Higgs boson which acts to weaken the bound [75, 76]. This is already enough to exclude some of the interesting parameter space discussed in Sections 2. While it is difficult to predict the specific reach of LHC Higgs searches with upcoming data, it plausible that it will be capable of ruling out the possibility of a strongly first-order EWPT induced by a colored scalar X.

A much more exciting possibility would be the discovery of a SM-like Higgs with an enhanced gluon fusion rate. In this case, a precise measurement of the rates in multiple Higgs detection channels would provide an indirect probe of an underlying X scalar. The enhancement of the inclusive $h \to ZZ^*$ and $h \to WW^*$ channels relative to the SM expectation would provide the increase in the gluon fusion rate. Similarly, the enhancement of these channels relative to inclusive $h \to \gamma\gamma$ would yield the modification of $\mathrm{BR}(h \to \gamma\gamma)$. Note that a Higgs mass of $m_h \simeq 125$ GeV is serendipitous since all three channels will have measurable rates. Comparing the di-photon rates in the exclusive $\gamma\gamma + 0j,\ 1j,\ 2j$ channels would also provide an independent test of the gluon rate since the production with more jets is increasingly dominated by vector boson fusion [75].

With enough data, these measurements will eventually be limited by the uncertainties in predicting the SM rates, which are currently dominated the 20% combined (theoretical and PDF) uncertainty on the gluon fusion rate [77]. The shift in Higgs production due to an X scalar inducing a strong EWPT should therefore be measurable.

For observing the change in the di-photon branching ratio, one would like to measure $\sigma \times \mathrm{BR}_{\gamma\gamma}/(\sigma \times \mathrm{BR}_{WW})$. In this case the main sources of error are not theory driven. Even so, the expected change in the diphoton branching is realtively small and it seems likely that this measurement will be more challenging to detect unless the electric charge of X is reasonably large ($q_X = 2/3,\ 4/3$ both seem doable, $q_X = 1/3$ likely not).

Ultimately, we would like to use the data to perform a simultaneous fit of the effective couplings of the Higgs to all SM states, as discussed in Refs. [78–82]. These studies indicate that such a program would require a very large data set, and suggest that even with the full LHC luminosity significant coupling uncertainties will remain. However, given how well the machine and the collaborations are performing, we are cautiously optimistic that a high-precision determination of the properties of the Higgs boson will be feasible at the LHC.

7 Conclusions

In this paper, we have investigated the correlation between the strength of the electroweak phase transition as required for successful electroweak baryogenesis and the properties of the Higgs boson. We performed our analysis in the context of a simple model with new colored scalars (X) which couple via the Higgs portal. The sizable coupling between the Higgs and the X states dominates the physics of the electroweak phase transition for the parameter space of interest. The choice of quantum numbers for the scalars is well motivated since the strength of the electroweak phase transition is significantly enhanced at two-loops due to diagrams involving gluons. These new scalars also contribute to the loop induced couplings between the Higgs boson and gluons/photons. The main conclusion of our work is to demonstrate that in the region of parameter space which is viable for electroweak baryogenesis, the cross section for production of Higgs bosons from gluon fusion and the branching ratio for their subsequent decays to di-photons are altered by an amount which should be observable at the LHC with this years upcoming data set.

We also related our model to the MSSM in the baryogenesis window. We are able to make the same robust conclusion in this case. If electroweak baryogenesis is realized in the MSSM, the Higgs boson properties will not be SM-like.

Depending on additional model-dependent couplings of the X, there can result a variety of collider signatures from direct X production. If it decays to a light quark and missing energy (as it would in the MSSM or other supersymmetric extensions of the standard model), there are a variety of relevant searches in the mass range of interest. While a viable region of parameter space is currently not excluded, the LHC is narrowing this region by searching for mono-jets, multi-jets, and jets plus missing $\not{E}_T$. It is also possible that the X can decay to a pair of jets. In this case, the search in the region of interest is much more difficult due to high trigger thresholds. It will be possible to hide the X from direct searches using this decay mode for the foreseeable future.

There are currently hints of a Higgs boson with a mass of around 125 GeV. If this signal persists, we immediately begin to narrow in on the actual value of the Higgs boson production cross sections and branching ratios. As demonstrated in this work, much can be learned about various theories beyond the standard model from these measurements.

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