Gravitational Waves from Phase Transitions in Models with Charged Singlets

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In this work, we investigate the effect of extra singlet(s) on the electroweak phase transition (EWPT) strength and the spectrum of the corresponding gravitational waves (GWs). We consider here the standard model (SM) extended with a singlet scalar with multiplicity N coupled to the SM Higgs doublet. After imposing all the theoretical and experimental constraints and defining the region where the EWPT is strongly first order, we obtain the region in which the GWs spectrum can be reached by different future experiments such as eLISA, DECIGO and BBO.

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I. INTRODUCTION

One of the unsolved puzzles in both particle physics and cosmology is the existence and the origin of matter antimatter asymmetry in the Universe; namely why \( \eta = (n_b - n_{\bar{b}})/n_\gamma = 5.8 - 6.6 \times 10^{-10} \) [1]. As it was shown by Sakharov, there are three necessary criteria for generating an asymmetry between matter and antimatter at high temperature [2]: (1) baryon number violation, (2) C and CP violation, and (3) a departure from thermal equilibrium. These criteria seemed to be qualitatively fulfilled within the standard model (SM) of particle physics where the first criterion occurs through the (B+L) anomaly in the form of nonperturbative sphaleron processes, the second one due to the CP phase in the CKM quark mixing matrix, and the third criterion is fulfilled via a strong first order electroweak phase transition (EWPT) that occurs near the weak scale. This scenario is called the electroweak baryogenesis scenario [3]. It has been shown that in the SM the CP violating source is small, and the EWPT is not strongly first order [4], but it could be strong in some of the SM extensions.

The EWPT can get stronger if new bosonic degrees of freedom are invoked around the electroweak scale [5], or higher dimensional effective operators are considered [6]. The EWPT could be strongly first order for 2HDMs [7], (U)NMSSM [8], and in other models [9]. Whatever the additional fields are, a successful electroweak baryogenesis implies that the new physics can be testable at current and future particle physics experiments. Among the physical observables that can be used to probe a strong EWPT at colliders, the triple Higgs coupling where it is shown that the deviation with respect to its SM value is correlated with the EWPT strength [10].

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Recently, the Advanced Laser Interferometer Gravitational Wave Observatory (aLIGO) [11] detected gravitational waves (GWs). Besides confirming the prediction of Einstein’s general theory of relativity, the GWs opened a new exciting window to probe and test new physics beyond the standard model of particle physics and cosmology. For instance, stochastic GWs backgrounds can be generated during first order cosmological phase transitions (PTs) [12] which can be within the reach of the near future space-based interferometers, such as eLISA [13], DECIGO [14], BBO [15], in addition to the Chinese projects TAIJI [16] and and Tian-Qin [17]. The GWs from first order EWPT that are detectable by current/future experiments can be used to probe extended models beyond the SM [18]. Expected uncertainties in future space-based interferometers on parameters of the models with the strongly first order phase transition can be partially estimated by the Fisher matrix analysis, which is essentially based on a Gaussian approximation of the likelihood function [19].

In this letter, we consider the SM extended by extra massive scalar(s) whose ad hoc multiplicity $N$, that is (are) coupled to the Higgs doublet. Then, after imposing different theoretical and experimental constraints, we will estimate the effect on the EWPT strength as well as on the GWs properties, and whether they are in the reach of current/future experiments.

In section II, we present the SM extended by a new scalar with multiplicity $N$, and discuss different experimental constraints on the model parameters. We show different aspect of the a strong first order EWPT in section III. A brief description of the gravitational waves that could be produced during a strong first order EWPT is discussed in section IV. In section V, we show and discuss our numerical results. Finally, we conclude in section VI.

II. THE MODEL: SM EXTENDED BY SINGLET(S)

In our model, the SM is extended by extra scalar fields $S_{i=1,2,...n}$, which transform as $(1,Q_S)$ under $SU(2)_L \times U(1)_Y$, and for simplicity we assume they have the same mass$^1$. Defining $S \sim (S_1,S_2,...S_n)$, these scalars amount for $N = 2 \times n$ degrees of freedom since $S_i$ are complex scalar fields. The Lagrangian reads,

$$\mathcal{L} = \mathcal{L}_{SM} + |D_\mu S|^2 - V(H,S),$$

(1)

with $D_\mu S = \partial_\mu S - iQ_S g'B_\mu S$ and $B_\mu$ is the $U(1)_Y$ gauge filed. The tree-level scalar potential is given by

$$V(H,S) = -\mu^2 |H|^2 + \frac{\lambda}{6} |H|^4 + \mu_S^2 |S|^2 + \frac{\lambda_S}{6} |S|^4 + \omega |H|^2 |S|^2,$$

(2)

with $H^T = (\chi^\pm,(\phi+i\chi^0)/\sqrt{2})$ is the Higgs doublet and $\lambda$, $\lambda_S$ and $\omega$ are dimensionless scalar couplings. The renormalized one-loop effective potential at zero temperature is given a la $\overline{\text{MS}}$ scheme by [20]

$$V_{1-loop}^{T=0} (\phi) = -\frac{\mu^2}{2} \phi^2 + \frac{\lambda}{24} \phi^4 + \frac{1}{64\pi^2} \sum_{i=\text{all}} n_i m_i^2 (\phi) \left( \log \frac{m_i^2 (\phi)}{\Lambda^2} - c_i \right),$$

(3)

where $n_i$ and $m_i$ are the field multiplicities and the field-dependent masses, respectively. The numerical constants $c_i$ for scalars and fermions (gauge bosons) is $3/2$ ($5/6$) and the renormalization scale is taken to be the measured Higgs mass $\Lambda = m_0 = 125.09$ GeV. The field dependent masses can be written in the form

$^1$ Note that in this limit there is an $O(n)$ symmetry, assumed to be broken by mass squared differences $(m_i^2 - m_j^2)$. 
where the functions $m_0^2(\phi) = -\mu^2 + \frac{\lambda}{2} \phi^2$, $m_0^2(\phi) = -\mu^2 + \frac{\lambda}{6} \phi^2$, and $m_W^2(\phi) = \frac{1}{4} g' \phi^2$,
\begin{align}
m_0^2(\phi) &= \frac{1}{4} (g^2 + g'^2) \phi^2, \\
m_0^2(\phi) &= \frac{1}{2} \omega \phi^2, \\
m_W^2(\phi) &= \frac{1}{2} \nu_{t,b} \phi^2,$
\end{align}
where $\nu = 246.22$ GeV is the Higgs vacuum expectation value, $g$, $g'$ and $\nu_{t,b}$ are the gauge and Yukawa couplings. The parameters $\mu^2$ and $\lambda$ can be expressed in terms of the Higgs mass and the EW vacuum as
\begin{align}
\lambda &= \frac{3m_0^2}{v^2} - \frac{3}{32\pi^2} \sum_i n_i \alpha_i^2 \left( \log \frac{m_i^2}{m_0^2} + c_i \right), \\
\mu^2 &= \frac{1}{6} \lambda v^2 + \frac{1}{32\pi^2} \sum_i n_i \alpha_i m_i^2 \left( \log \frac{m_i^2}{m_0^2} - c_i \right),
\end{align}
where $c_i$ and $c_i'$ for scalars and fermions (gauge bosons) are 0 (1/3) and 1 (1/3), respectively. According to (5), the contribution of a heavy scalar makes the Higgs quartic coupling at tree-level smaller until it gets vanished. This implies a new constraint on the space parameter as
\begin{align}
N \omega^2 \log \frac{m_S^2}{m_0^2} < \frac{32\pi^2 m_0^2}{v^2} - \sum_{i=S,M} n_i \alpha_i^2 \left( \log \frac{m_i^2}{m_0^2} + c_i \right) \sim 88.813.
\end{align}
In case of the scalar $S$ is electrically charged, i.e. $Q_S \neq 0$, the Higgs decay width $\phi \rightarrow \gamma\gamma$ could be modified as
\begin{align}
R_{\gamma\gamma}^\phi = \frac{\Gamma(\phi \rightarrow \gamma\gamma)}{\Gamma_{\text{SM}}(\phi \rightarrow \gamma\gamma)} = \left[ 1 + \frac{N Q_S^2 \omega v^2}{2m_S^2} \frac{\omega v}{A_1/2} \right]^2,
\end{align}
where the functions $A_i$ are given in [21]. This ratio should be in agreement with the recent combined results 1.02$^{+0.09}_{-0.12}$ of ATLAS and CMS [22]. The existence of charged scalar(s) could modify the oblique parameters, namely the $\Delta S$ parameter, however, this contribution is not significant since the singlet does not couple to the $W^\pm$ gauge bosons. We will consider this as constraint on the model free parameters $\{m_S, \omega, N\}$. The existence of an extra scalar that couples to the Higgs can modify its triple coupling with respect to the SM, as [23]
\begin{align}
\Delta_{\phi\phi\phi} = \frac{\lambda_{\phi\phi\phi} - \lambda_{\phi\phi\phi}^{\text{SM}}}{\lambda_{\phi\phi\phi}} = \frac{N \omega^2 v^2}{32\pi^2 m_S^2} \frac{\omega}{\lambda_{\phi\phi\phi}^{\text{SM}}} = 3 \times 10^{-6} N \left( \frac{\omega}{0.1} \right)^3 \left( \frac{m_S}{300 \text{GeV}} \right)^2,
\end{align}
with the one-loop triple Higgs coupling in the SM is given by [24]
\begin{align}
\lambda_{\phi\phi\phi}^{\text{SM}} \simeq \frac{3m_0^2}{v} \left[ 1 - \frac{m_i^4}{\pi^2 v^2 m_0^2} \right].
\end{align}
It is expected that a significant deviation in the triple Higgs coupling (8) can be tested at the LHC [25] as well as at future lepton colliders such as the International Linear Collider (ILC) [26], the Compact Linear Collider (CLIC) [27], or the Future Circular Collider of electrons and positrons (FCC-ee) [28]. At the high-luminosity LHC, the triple Higgs coupling can be constrained in less than 100% [29], while at the ILC it can be measured with a precision of 10% [30].

Another interesting issue that should be considered, is that if the singlet scalar is not electrically neutral ($Q_S \neq 0$), it must be unstable. Depending on the electric charge $Q_S$, the singlet scalar field S could be coupled to SM charged leptons and neutrinos (and/or to quarks) as in many neutrino mass models that involve charged scalars. For instance, if $|Q_S| = 1$, the term $SL^T CL$ is allowed in the Lagrangian of the model², with $C$ the charge conjugation operator, and therefore $S^\pm$ will decay very quickly. In the case where

² If the model contains right handed neutrinos, as it is expected to be the case in many SM extensions that are motivated by neutrino mass and dark matter, then a coupling of the form $Se_L^T C N_R$ is allowed.
$|Q_S| = m > 1$, one can add higher dimensional operators of the form $\frac{S(L^TC_L)_{m}}{\Lambda^{m-1}}$, with $\Lambda > TeV$ is the scale above which the theory needs UV completion\(^3\). For $Q_S > 3$, one expects the life time of the charged scalar $S$ to be very large unless the UV scale is around TeV.

### III. ELECTROWEAK PHASE TRANSITION STRENGTH

The one-loop effective potential at finite temperature is given by [31]

$$V_{eff}^T (\phi, T) = V_{1-\text{loop}}^{T=0} (\phi) + T^4 \sum_{i=\text{all}} n_i J_{B,F} \left( \frac{m_i^2}{T^2} \right), \quad (10)$$

$$J_{B,F} (\alpha) = \frac{1}{2\pi^2} \int_{0}^{\infty} r^2 \log \left[ 1 \mp \exp(-\sqrt{r^2 + \alpha}) \right]. \quad (11)$$

A higher order thermal contribution described by the so-called daisy (or ring) diagrams [32], can be considered by replacing the scalar and longitudinal gauge field-dependent masses in (10) by their thermally corrected values [33]. The thermal self-energies are given by

$$\Pi_1 = \Pi_\chi = \left( \frac{1}{2} \lambda + \frac{3}{16} g^2 + \frac{1}{16} g'^2 + \frac{1}{4} g^2 + \frac{N}{12} \omega \right) T^2, \quad \Pi_W = \frac{11}{6} g^2 T^2,$$

$$\Pi_B = \left( \frac{11}{6} + \frac{N}{3} Q^2_S \right) g'^2 T^2, \quad \Pi_{W,B} \simeq 0, \quad \Pi_S = \left( \frac{Q^2_S}{4} g'^2 + \frac{1}{6} \omega + \frac{N + 1}{36} \lambda S \right) T^2. \quad (12)$$

In case of heavy scalar $S$, its contribution to the thermal mass will be Boltzmann suppressed, then, one can put $N \to 0$. The transition from the wrong vacuum ($\langle \phi \rangle = 0$) to the true one ($\langle \phi \rangle \neq 0$) occurs just below the critical temperature, $T_c$, a temperature value at which the two minima are degenerate. In the case of a strong first order EWPT, a barrier exists between the two vacua and the transition occurs through bubbles nucleation in random points in the space. When the bubble wall passes through a region at which a net baryon asymmetry is generated, the $(B + L)$ violating processes should be suppressed inside the bubble (true vacuum $\langle \phi \rangle \neq 0$) in order to maintain the net generated baryon asymmetry. The criterion to maintain this generated net asymmetry is given in the literature by [4]

$$\phi_c/T_c > 1, \quad (13)$$

where $\phi_c$ is the Higgs vev at the critical temperature.

Due to the fact that the effective potential at the wrong vacuum $V_{eff}(\phi = 0, T)$ does not vanish and is $T$-defendant, then we will take the normalized effective potential as $V_{eff}(\phi, T) - V_{eff}(\phi = 0, T)$ during our analysis. Indeed, it had been shown that when the value of the thermal effective potential at the symmetric phase becomes $T$-defendant, the EWPT dynamics is strongly affected [34].

One has to mention that in the case of second order PT or a crossover, the true minimum $\langle \phi_1 \rangle \neq 0$ may become a local minimum below such temperature value. Another new minimum $\langle \phi_2 \rangle > \langle \phi_1 \rangle$ becomes deeper and match the EW vacuum at zero temperature, i.e., $\langle \phi_2 \rangle = 246.22 GeV$ at $T = 0$. In such situation, the transition from $\langle \phi_1 \rangle$ to $\langle \phi_2 \rangle$ could only occur via bubbles nucleation due to the existing barrier between the two minima. Even if the EW symmetry is already broken (when $\langle \phi_1 \rangle \neq 0$), the transition from $\langle \phi_1 \rangle$ to $\langle \phi_2 \rangle$ may result detectable GWs. So we label this transition by type-II PT, while the usual strong first order EWPT by type-I PT. To illustrate these two pictures, we show in Fig. 1 the effective potential at different temperature values for both type-I PT (left) and type-II PT (right), respectively.

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\(^3\) If the scalar charge $Q_S$ is even, i.e. $Q_S = 2k$, then the operator $\frac{S(L^TC_L)_{m}}{\Lambda^{m-1}}$ is allowed.
FIG. 1: The effective potential at different temperature values for type-I PT (left) and type-II PT (right). Here, we considered the values \( Q_S = 0 \) and \( \lambda_S = 0 \).

IV. GRAVITATIONAL WAVES FROM PHASE TRANSITIONS

We analyze the gravitational waves (GWs) spectrum from first order EWPT in the model. In order to analyze the spectra, we introduce parameters, \( \alpha \) and \( \beta \), which characterize the GWs from the dynamics of vacuum bubble [35]. The parameter \( \beta \) which describes approximately the inverse of time duration of the PT is defined as

\[
\beta = - \frac{dS_E}{dt} \bigg|_{t=t_t} \approx \frac{1}{\Gamma} \frac{dT}{dT} \bigg|_{t=t_t},
\]

(14)

where \( S_E \) and \( \Gamma \) are the Euclidean action of a critical bubble and vacuum bubble nucleation rate per unit volume and unit time at the time of the PT \( t_t \), respectively. We use normalized parameter \( \beta \) by Hubble parameter \( H_T \) in the following analysis:

\[
\tilde{\beta} = \frac{\beta}{H_T} = T_t \frac{d}{dT} \left( \frac{S_3(T)}{T} \right) \bigg|_{T=T_t},
\]

(15)

where \( T_t \) is the transition temperature that is introduced by \( \Gamma / H_T^2 \big|_{T=T_t} = 1 \). The parameter \( \alpha \) is the ratio of the released energy density

\[
\epsilon(T) = -V_{eff}(\phi_t(T), T) + T \frac{\partial V_{eff}(\phi_t(T), T)}{\partial T},
\]

(16)

where \( \phi_t(T) \) is the true minimum at the temperature \( T \), to the radiation energy density \( \rho_{rad} = \left( \frac{\pi^2}{30} \right) g_* T^4 \), where \( g_* \) is relativistic degrees of freedom in the thermal plasma, at the transition temperature \( T_t \):

\[
\alpha = \frac{\epsilon(T_t)}{\rho_{rad}(T_t)}.
\]

(17)

The GWs production during a strong first order PT occurs via three co-existing mechanisms: (1) collisions of bubble walls and shocks in the plasma, where the so-called "envelope approximation" [36] can be used to describe this phenomenon and estimate the contribution of the scalar field to the GWs spectrum. (2) After the bubbles have collided and before expansion has dissipated the kinetic energy in the plasma, the sound waves could result significant contribution to the GWs spectrum [37]. (3) Magnetohydrodynamic (MHD) turbulence in the plasma that is formed after the bubbles collision may also have give rise to the GWs spectrum [38]. Therefore, the stochastic GWs background could be approximated as

\[
\Omega_{GW} h^2 = \Omega_{\phi} h^2 + \Omega_{\text{sw}} h^2 + \Omega_{\text{tw}} h^2.
\]

(18)
The predicted values of $\alpha$ and $\tilde{\beta}$ for different values of $\{N, m_S, \omega\}$ with $Q_S = 1$, $\lambda_S = 0$ and $\mu_S^2 \geq 0$.

The importance of each contribution depends on the PT dynamics, and especially on the bubble wall velocity. Here, we focus on the contribution to GWs from the compression waves in the plasma (sound waves) which is the strongest GWs spectrum among the source of the total GW. A fitting function to the numerical simulations is obtained as [39]

$$\Omega_{sw}(f) h^2 = \tilde{\Omega}_{sw} h^2 \times (f/\tilde{f}_{sw})^3 \left( \frac{7}{4 + 3(f/\tilde{f}_{sw})^2} \right)^{7/2},$$

(19)

where the peak energy density is

$$\tilde{\Omega}_{sw} h^2 \simeq 2.65 \times 10^{-6} v_b \tilde{\beta}^{-1} \left( \frac{\kappa \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_*} \right)^{1/3},$$

(20)

at the peak frequency

$$\tilde{f}_{sw} \simeq 1.9 \times 10^{-5} \text{Hz} \frac{1}{v_b} \tilde{\beta} \left( \frac{T_t}{100 \text{GeV}} \right) \left( \frac{g_*}{100} \right)^{1/6},$$

(21)

where $v_b$ is the velocity of the bubble wall and $\kappa$ is the fraction of vacuum energy that is converted into bulk motion of the fluid. In the following analysis, we take $v_b$ which is uncertain as 0.95 so that strong GW signals are expected.

V. NUMERICAL RESULTS

In our numerical results, we have three free parameters $\{N, m_S, \omega\}$ where we consider the multiplicity values $N = 2, 6, 12, 24$, the scalar-Higgs doublet coupling range $|\omega| \leq 5$, and the scalar mass to lie in the range $m_S \in [100 \text{GeV}, 550 \text{GeV}]$. In Fig. 2, we present the predicted values of $\alpha$ and $\tilde{\beta}$ for different values of $\{N, m_S, \omega = 2(m_S^2 - \mu_S^2)/\nu^2\}$ with $Q_S = 1$ and $\lambda_S = 0$.

In Fig. 2, the gray, red, blue and green regions represent $\{N = 2, 6, 12, 24\}$, respectively. We also show the expected sensitivities of eLISA and DECIGO detector configurations are set by using the sound wave
FIG. 3: The predicted values of $\alpha$ and $\tilde{\beta}$ for different values of $\{N, m_S, \omega\}$ with $Q_S = 1$, $\lambda_S = 0$ and $\mu_S^2 = 0$. contribution for $T_t = 100$ GeV and the bubble wall velocity $v_b = 0.95$. The colored regions are experimental sensitivities reached at future space-based interferometers, eLISA [39–41] and DECIGO [14].

In Fig. 3, we present the special case $\mu_S^2 = 0$. Both left and right panels represent the same results, where in the left panel we present information about parameter values and constraints, and in the right one we show the value of the EWPT strength parameter $\phi_c/T_c$.

In Fig. 3, the black curves correspond to the special case $\mu_S^2 = 0$, for $\{N = 2, 6, 12, 24\}$, and the upper bound (in red) on $\tilde{\beta}$ is set by the condition $\phi_c/T_c = 1$. However, the lower bound (in brown) on $\tilde{\beta}$ is dictated by the vacuum stability condition (6). The labels "C1", "C2", "C3" and "C4", in Fig. 3-left, correspond to the four different configurations of LISA provided in Table. 1 in [39], whereas the labels "Pre-DECIGO", "FP-DECIGO" and "Correlation" are DECIGO designs [14]. From this figure, one notices that for stronger PT with $\phi_c/T_c \geq 1.38$ the generated GWs can be seen by DECIGO, and for $\phi_c/T_c \geq 2.95$ the corresponding GWs can be seen by LISA.

In Fig. 4, we show the regions in the plane $\{m_S, \omega\}$ where there exist a type-I and type-II PT for different multiplicity values $N$, together with the constraints mentioned in section II, such as the unitarity bound, the vacuum stability condition of $\lambda \geq 0$, and $R_{\phi \gamma \gamma}$. In addition, we show few contours that express the relative enhancement in the triple Higgs coupling (8).

From Fig. 4, the GWs detectable region is different from one multiplicity value to another. If the new singlet is electrically charged $Q_S \neq 0$, the EWPT can not be strongly first order while fulfilling the constraint from $\phi \to \gamma \gamma$ [22] for large multiplicity values $N > 2$. However, this conflict can be evaded if there exist more scalar singlets with different sign coupling to the Higgs doublet in order to avoid $\phi \to \gamma \gamma$ constraints while the EWPT is still strongly first order. According to the multiplicity $N$, the scalar mass should lie between 120 GeV and 380 GeV in order to have a strong first order EWPT, i.e., type-I PT. However, detectable GWs signal can be observed even for $m_S < 100$ GeV. In addition, one has to mention that detectable GWs signal implies positive enhancement on the triple Higgs coupling (8) with ratio between 10% to more than 150%, depending on the multiplicity $N$. The main interesting idea one can read from the results in Fig. 4 is that if the EWPT is strongly first order, the GWs signal can be detected either by eLISA [39–41] or DECIGO [14],
in addition to a non-negligible enhancement in triple Higgs coupling (8). If the EWPT is crossover or second order, there could exist another transition at a temperature value smaller than the EWPT where the system vacuum moves to a new, deeper and larger minimum via bubbles nucleation where it leaves detectable signal (type-II PT).

VI. CONCLUSION

We have focused on the model with additional N isospin singlet scalar fields S which have hyper charge $Q_S$. In the model, imposing the condition of strongly first order PT for a successful scenario of electroweak baryogenesis, there appear significant deviations in the Higgs couplings $\phi\phi\phi$ and $\phi\gamma\gamma$ from the SM predictions. At the same time, GW from the first order EWPT is large enough to be detected by future space-based interferometers, such as LISA, DECIGO and BBO. We have discussed how the model can be tested by the synergy between collider experiments and GW observation experiments. Consequently, by the detection of the GWs and the measurement of $\phi\gamma\gamma$, we can test the model. Current experimental data for $\phi\gamma\gamma$ and the parameter region where detectable GW occur from the type-I PT can give a constraint on the number of additional singlet scalar $N \leq 6$.

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