

Probing the Nature of the Electroweak Phase Transition from Particle Colliders to Gravitational Wave Detectors (Postprint)

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Abstract

In this letter, we explore the nature of the electroweak phase transition (EWPT) with both particle colliders and gravitational wave (GW) detection. With the observed Higgs mass, the shape of the Higgs potential is fully determined within the standard model (SM) of particle physics. However, it could be changed if there exists new physics beyond the SM. Working with the effective field theory, we show that a modified Higgs potential with a sextic term included can keep the observed 125 GeV Higgs mass but behave different when compared with the SM case. Furthermore, this potential can produce a strong first order phase transition (SFOPT) for the electroweak baryogenesis and interestingly predict new phenomena in the Higgs sector, which can be tested at colliders such as the Large Hadron Collider (LHC) and the planning Circular Electron Positron Collider (CEPC). We point out this SFOPT can lead to detectable signals for the GW interferometers, such as eLISA, DECIGO and BBO. Our present study on the EWPT bridges the particle physics at colliders with the astrophysics and cosmology in the early universe.

Full Text

Preamble

Probing the Nature of the Electroweak Phase Transition from Particle Colliders to Gravitational Wave Detectors

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In this Letter, we explore the nature of the electroweak phase transition (EWPT) through both particle colliders and gravitational wave (GW) detection. With the observed Higgs mass, the shape of the Higgs potential is fully determined within the Standard Model (SM) of particle physics. However, it could be altered if new physics beyond the SM exists. Working within the effective field theory framework, we demonstrate that a modified Higgs potential including a sextic term can maintain the observed 125 GeV Higgs mass while exhibiting different behavior compared to the SM case. Furthermore, this potential can produce a strong first-order phase transition (SFOPT) for electroweak baryogenesis and, interestingly, predicts new phenomena in the Higgs sector that can be tested at colliders such as the Large Hadron Collider (LHC) and the planned Circular Electron Positron Collider (CEPC). We point out that this SFOPT can lead to detectable signals for GW interferometers such as eLISA, DECIGO, and BBO. Our present study on the EWPT bridges particle physics at colliders with astrophysics and cosmology in the early universe.

Introduction

One scientific target in fundamental physics after the discovery of the Higgs boson [?, ?] is to explore the nature of the electroweak phase transition (EWPT) [?, ?]. This issue is closely related to the details of the Higgs potential beyond the Standard Model (SM) of particle physics. So far, current data from particle colliders can only provide very limited information about the Higgs potential. Except for the quadratic oscillations around the vacuum expectation value (vev) v which have determined the 125 GeV mass, our knowledge about the Higgs potential remains scarce. For example, without the help of new observational approaches, we cannot tell whether the Higgs potential in reality might be $V_{\text{tree}}(h) = \frac{1}{8\Lambda^2}h^6$ rather than the regular case $V_{\text{tree}}(h) = \frac{1}{2}\mu^2h^2 + \frac{\lambda}{4}h^4$ in the SM, as sketched in Fig.~1 [Figure 1: see original paper]. Theoretically, the Higgs scenario including a sextic term has been shown to produce the strong first-order phase transition (SFOPT) for electroweak baryogenesis [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?].

In this Letter, we study new predictions of this model for collider physics and gravitational wave (GW) detection. Our results show that new physics associated with the modified trilinear Higgs coupling can be tested at the LHC and CEPC [?]. Furthermore, associated with the SFOPT, large anisotropic fluctuations can be produced in the stress-energy tensor and hence lead to unique patterns in GW spectra [?, ?, ?, ?, ?], which can be detected by GW detectors such as eLISA [?], DECIGO [?, ?, ?], and BBO [?].

The Effective Potential and Collider Signals of EWPT

To investigate the EWPT, we begin with the following tree-level Higgs potential [?, ?]:

$$V_{\text{tree}}(h) = \mu^2 h^2 + \frac{\lambda}{4} h^4 + \frac{1}{8\Lambda^2} h^6.$$

Accordingly, the finite-temperature effective potential up to one-loop level can be written as $V_{\text{eff}}(h, T) = V_{\text{tree}}(h) + V_{T=0}(h) + \Delta V_{T \neq 0}(h, T)$ [?], where $V_{T=0}(h)$ is the one-loop Coleman-Weinberg potential at $T = 0$, and $\Delta V_{T \neq 0}(h, T)$ is the thermal contribution with the daisy resummation. In our case, the dominant contribution for the EWPT is from the tree-level barrier, and accordingly, the effective potential with finite temperature effects is approximated as

$$V_{\text{eff}}(h, T) \approx (\mu^2 + cT^2) h^2 + \frac{\lambda}{4} h^4 + \frac{1}{8\Lambda^2} h^6,$$

with $c = \frac{1}{48\pi^2 v^2} (3g'^2 + 3g^2 + 4y_t^2)$. The complete one-loop effective potential was given in Ref. [?]. To fix the observed Higgs mass $m_h = 125$ GeV and the vev v , the model parameters λ and μ^2 are shifted to:

$$\lambda = \lambda_{\text{SM}} \left(1 - \frac{\Lambda^2}{\Lambda_{\text{max}}^2} \right) \quad \text{and} \quad \mu^2 = \mu_{\text{SM}}^2 \left(1 - \frac{\Lambda^2}{\Lambda_{\text{max}}^2} \right),$$

with $\Lambda_{\text{max}} \equiv \sqrt{3\kappa v^2/m_h}$. The coefficients g' and g are the $U(1)_Y$ and $SU(2)_L$ gauge couplings, respectively, and y_t is the top quark Yukawa coupling in the SM.

Following EWPT/baryogenesis analysis, the critical temperature T_c and the washout parameter $v(T_c)/T_c$ are approximated as follows:

$$T_c \simeq \sqrt{\frac{\lambda^2 \Lambda^2 - 4\kappa \mu^2}{\kappa v^2/m_h}},$$

$$v(T_c) \simeq \sqrt{\frac{\lambda^2 \Lambda^2 - 4\kappa \mu^2}{\kappa}}.$$

The condition $T_c > 0$ gives a lower bound $\Lambda_{\text{min}} \equiv \Lambda_{\text{max}}/\sqrt{2}$. For $m_h = 125$ GeV, one gets $\Lambda_{\text{min}} \approx 480\sqrt{\kappa}$ GeV. One also expects $\mu^2 + cT^2 > 0$ to stabilize the false vacuum, $\lambda < 0$ to produce a tree-level potential barrier, and then a positive h^6 term to stabilize the true vacuum. Therefore, the negative λ can yield an upper bound on Λ , namely, $\Lambda < \Lambda_{\text{max}} \approx 840\sqrt{\kappa}$ GeV. In addition, from the requirement of perturbativity, $\kappa < 4\pi$. If one chooses a larger κ , however, a larger bound Λ_{max} may be achieved.

For $480 \text{ GeV} < \Lambda/\sqrt{\kappa} < 840 \text{ GeV}$, the washout factor $v(T_c)/T_c$ is larger than one, which means the SFOPT can be achieved. An interesting consequence is that the requirement of the SFOPT can lead to an obvious modification of the trilinear Higgs coupling as

$$\mathcal{L}_{hhh} = -\frac{1}{6}(1 + \delta_h)A_h h^3,$$

with $A_h = 3m_h^2/v$ being the trilinear Higgs coupling in the SM and $\delta_h = 2\Lambda_{\text{min}}^2/\Lambda^2$. In our model δ_h varies from $2/3$ to 2 . Based on this property, we can test this EWPT scenario by measuring the deviation of the trilinear Higgs coupling at colliders. For the LHC, the deviation of the trilinear Higgs coupling leads to different invariant mass distribution of the Higgs boson pair from the SM case. Due to the challenge of suppressing the large backgrounds at hadron colliders, the trilinear Higgs coupling is difficult to be completely pinned down at the 14 TeV LHC. However, at lepton colliders such as the International Linear Collider (ILC) and CEPC, the trilinear Higgs coupling could be measured precisely.

At the CEPC with $\sqrt{s} = 240 \text{ GeV}$, the dominant one-loop contribution to the hZ cross section (σ_{hZ}) beyond the SM is given by the modified trilinear Higgs coupling [?], which leads to the deviation of σ_{hZ} [?]. Such a deviation is defined as $\delta\sigma_{hZ} \equiv \sigma_{hZ}/\sigma_{hZ}^{\text{SM}} - 1$, which is approximately proportional to δ_h as $\delta\sigma_{hZ} \simeq 1.6\% \delta_h$ at $\sqrt{s} = 240 \text{ GeV}$. Thus, for $\kappa = 1$, one gets $\delta\sigma_{hZ} \simeq 7514.17 \text{ GeV}^2/\Lambda^2$. For the future CEPC with an integrated luminosity of 10 ab^{-1} , the precision of σ_{hZ} can reach 0.4% [?], which corresponds to $|\delta_h| \sim 25\%$ [?]. In our scenario, $\delta_h \in (2/3, 2)$, and hence, the associated signals are of observable interest at the CEPC.

GW Signals of EWPT

For a first-order EWPT, there exists a potential barrier between the metastable false vacuum and the true one. When the EWPT is strong enough, true vacuum bubbles are nucleated via quantum tunneling. The temperature goes down with the expansion of the universe, and the nucleation probability of one bubble per horizon volume becomes larger and larger. The EWPT completes when the probability is of $\mathcal{O}(1)$ at the transition temperature, i.e., $\Gamma(T_*) \simeq H^4$ and then, we obtain $S_3(T_*)/T_* = 4 \ln(T_*/100 \text{ GeV}) + 137$, in which $S_3 \equiv \int d^3r [\frac{1}{2}(\nabla h)^2 + V_{\text{eff}}(h, T)]$ is the three-dimensional Euclidean action.

The properties of the EWPT and of the bubbles are determined by two key parameters α and β . Note that α is defined by

$$\alpha \equiv \frac{\epsilon(T_*)}{\rho_{\text{rad}}(T_*)}$$

at the transition temperature T_* , which depicts the ratio of the false vacuum energy density $\epsilon(T)$ (the latent heat where $\epsilon(T_*) = \left[T \frac{dV_{\text{eff}}^{\text{min}}}{dT} \right]_{T=T_*}$) to the plasma thermal energy density $\rho_{\text{rad}}(T)$ (which is equal to $\frac{\pi^2}{30} g_*(T) T^4$) in the symmetric phase. Moreover, one has

$$\beta \equiv - \left. \frac{dS_E}{dt} \right|_{t=t_*}$$

where $S_E(T) \simeq S_3(T)/T$, and $\Gamma = \Gamma_0(T) \exp[-S_E(T)]$ represents the variation of the bubble nucleation rate with $\Gamma_0(T) \propto T^4$. The parameter α gives a measure of the strength of the EWPT, namely, a larger value for α corresponds to a stronger EWPT. Furthermore, β^{-1} corresponds to the typical time scale of the EWPT and its product with the bubble wall velocity $\beta^{-1} v_b(\alpha)$ represents the size of the bubble.

The collisions of the Higgs vacuum bubbles and their turbulence with plasma are the two distinct mechanisms to generate stochastic GWs. The peak frequency produced by bubble collisions is given by

$$f_{\text{co}} \simeq 5.2 \times 10^{-6} \text{ Hz} \left(\frac{\beta}{H_*} \right) \left(\frac{T_*}{100 \text{ GeV}} \right)^{1/6} \left(\frac{g_*}{100} \right)^{1/6}$$

and the corresponding GW intensity is calculated as

$$\Omega_{\text{co}}(f_{\text{co}}) h^2 \simeq c \epsilon^2 \left(\frac{H_*}{\beta} \right)^2 \left(\frac{\alpha}{1 + \alpha} \right)^2 \left(\frac{0.24 + v_b^3}{0.24} \right) \left(\frac{100}{g_*} \right)$$

with $c = 1.1 \times 10^{-6}$ [?]. The coefficient ϵ (which characterizes the fraction of the latent heat that is transformed into fluid kinetic energy), the bubble velocity v_b , and the turbulent fluid velocity u_s are functions of α [?]. Here, g_* ($= g_*(T_*)$) is the total number of degrees of freedom at T_* . It is interesting to notice that, in the low frequency regime the spectrum $\Omega_{\text{co}}(f) h^2$ increases as $f^{2.8}$, but in the high frequency regime it decreases as f^{-1} [?]. In this regard, the EWPT has predicted particular patterns of the intensity spectrum which could serve as observational signals in GW surveys.

On the other side, the GW signals produced by turbulence interaction have a peak frequency at about

$$f_{\text{tu}} \simeq 3.4 \times 10^{-6} \text{ Hz } u_s \left(\frac{\beta}{H_*} \right) \left(\frac{T_*}{100 \text{ GeV}} \right)^{1/6} \left(\frac{g_*}{100} \right)^{1/6}$$

with the intensity

$$\Omega_{\text{tu}}(f_{\text{tu}})h^2 \simeq 1.4 \times 10^{-4} u_s^5 \left(\frac{H_*}{\beta} \right)^2 \left(\frac{100}{g_*} \right)^{1/3}.$$

Again, in the low frequency regime the spectrum $\Omega_{\text{tu}}(f)h^2$ increases as f^2 , but in the high frequency regime it decreases as $f^{-3.5}$ [?].

The two characteristic parameters α and β can be evaluated by solving the Higgs bubble profile from the following equation

$$\frac{d^2h}{dr^2} + \frac{2}{r} \frac{dh}{dr} = \frac{\partial V_{\text{eff}}}{\partial h}$$

with the boundary conditions $h(r \rightarrow \infty) = 0$, $\left. \frac{dh}{dr} \right|_{r=0} = 0$.

Using the overshoot/undershoot method, one can numerically determine the exact profile of the Higgs bubble after fixing the model parameters κ and Λ . As a demonstration, we present one numerical solution in Fig.~2 [Figure 2: see original paper] for the specific case of $\kappa = 1$ and $\Lambda = 600$ GeV. It is worth noting, however, that the bubble wall runs away if Λ becomes smaller than 590 GeV [?, ?]. Once the Higgs profile has been found, all associated parameters can be derived, and accordingly, the predicted GW spectra can be calculated as shown in Fig.~3 [Figure 3: see original paper].

Results and Discussions

In Fig.~3 [Figure 3: see original paper], the GW spectra $h^2\Omega_{\text{GW}}$ and the hZ cross section deviations $\delta\sigma_{hZ}$ are presented by taking different values of the cutoff scale Λ (590 GeV, 600 GeV, 650 GeV, and 700 GeV) with κ being fixed to unity in the Higgs scenario under consideration. For instance, the red curve in the figure depicts the GW signals for $\Lambda = 590$ GeV predicted by our model, which also predicts a collider signature of the cross section deviation $\delta\sigma_{hZ} \simeq 2.2\%$ (the corresponding deviation of the trilinear Higgs coupling δ_h is 1.32) which is expected to be tested at the CEPC. In addition, we numerically present the theoretical curves for the cases of 600 GeV, 650 GeV, and 700 GeV, as shown by the blue, green, and black lines, respectively. These curves correspond respectively to the values of 2.1%, 1.8%, and 1.5% for $\delta\sigma_{hZ}$.

From our result, it is obvious that the amplitude of the GW spectrum is more significant for smaller cutoff scales. This fact can be naturally explained by the observation that in the potential a smaller Λ yields a larger contribution of the sextic operator which then leads to a stronger EWPT. Moreover, it can be found that the GW signals are peaked around 10^{-4} Hz, which lies in the detectable range of satellite-based GW experiments. The colored regions in Fig.~3 show the expected experimental sensitivities of future GW interferometers including eLISA [?], SKA, BBO, DECIGO [?], and Ultimate-DECIGO (U-DECIGO) [?].

The eLISA C1 and C4 in the figure are two representative configurations studied in Ref.~[?]. From Fig.~3, one can explicitly see that eLISA, BBO, and U-DECIGO are all capable of detecting the GW signals generated from the EWPT at low cutoff scales described by our model.

As a result, the collider experiments in particle physics and the GW experiments are naturally related to each other through the exploration of the nature of the EWPT, i.e., there is a strong correlation between the strength of the GWs and the deviation of the trilinear Higgs coupling. As shown in Fig.~3, each line relates the GW signals to the associated collider signals with the same cutoff scale. To obtain a global picture of this correlation, we present the observational abilities of different experiments in Fig.~4 [Figure 4: see original paper]. For the CEPC with $\sqrt{s} = 240$ GeV, the sensitive region is $\Lambda/\sqrt{\kappa} < 1357.65$ GeV; for the LHC, it corresponds to $\Lambda/\sqrt{\kappa} < 280$ GeV; the theoretical condition for the SFOPT roughly requires $480 \text{ GeV} < \Lambda/\sqrt{\kappa} < 840$ GeV; and the detectable region of GW interferometers reads $590 \text{ GeV} < \Lambda/\sqrt{\kappa} < 650$ GeV. Consequently, we can find that, in order to probe the physics of the EWPT, the detectable ability of the LHC is weak, but the future CEPC and the GW detections are very promising in precisely detecting or even measuring the predicted signals. For example, for the cutoff scale $\Lambda = 590$ GeV, the deviation of the trilinear Higgs coupling is 1.32, which cannot be tested at the LHC. However, the GW experiments could indirectly measure this trilinear Higgs coupling, which corresponds to the red line in Fig.~3.

We conclude that the GW interferometers can provide a complementary approach to explore the nature of the EWPT beyond terrestrial colliders, and vice versa.

Conclusion

After the discovery of the 125 GeV Higgs boson, it becomes an urgent problem to unravel the nature of the EWPT. If the EWPT is a strong first-order process, it will naturally relate to the mechanism of spontaneous symmetry breaking, electroweak baryogenesis, and GW physics. We have studied the EWPT in the framework of effective field theory and investigated its predicted signals at colliders, i.e., the deviation of the trilinear Higgs coupling from the SM. Moreover, we put forward a complementary approach to exploring the nature of the EWPT by analyzing its GW signals generated in the early universe. From our calculation, the GW spectrum produced via bubble collisions and turbulence with the plasma during the first-order EWPT can be significant enough to be detected by forthcoming GW experiments. The study performed in this Letter will help us to deeply understand the nature of the EWPT, which may open a new window in particle physics, and it highlights the interactions between particle physics and cosmology.

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References

- [1] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716, 1 (2012) [arXiv:1207.7214 [hep-ex]].
- [2] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 716, 30 (2012) [arXiv:1207.7235 [hep-ex]].
- [3] CEPC-SPPC Study Group, IHEP-CEPC-DR-2015-01, IHEP-TH-2015-01, HEP-EP-2015-01.
- [4] N. Arkani-Hamed, T. Han, M. Mangano and L. T. Wang, arXiv:1511.06495 [hep-ph].
- [5] C. Grojean and G. Servant, Phys. Rev. D 75, 043507 (2007) [hep-ph/0607107].
- [6] C. Delaunay, C. Grojean and J. D. Wells, JHEP 0804, 029 (2008) [arXiv:0711.2511 [hep-ph]].
- [7] S. J. Huber and T. Konstandin, JCAP 0805, 017 (2008) [arXiv:0709.2091 [hep-ph]].
- [8] S. Das, P. J. Fox, A. Kumar and N. Weiner, JHEP 1011, 108 (2010) [arXiv:0910.1262 [hep-ph]].
- [9] J. R. Espinosa, T. Konstandin, J. M. No and M. Quiros, Phys. Rev. D 78, 123528 (2008) [arXiv:0809.3215 [hep-ph]].
- [10] M. Jarvinen, C. Kouvaris and F. Sannino, Phys. Rev. D 81, 064027 (2010) [arXiv:0911.4096 [hep-ph]].
- [11] J. R. Espinosa, T. Konstandin, J. M. No and G. Servant, JCAP 1006, 028 (2010) [arXiv:1004.4187 [hep-ph]].
- [12] M. Kakizaki, S. Kanemura and T. Matsui, Phys. Rev. D 92, 115007 (2015) [arXiv:1509.08394 [hep-ph]].
- [13] X. m. Zhang, Phys. Rev. D 47, 3065 (1993) [hep-ph/9301277].
- [14] X. Zhang and B. L. Young, Phys. Rev. D 49, 563 (1994) [hep-ph/9309269].
- [15] X. Zhang, B. L. Young and S. K. Lee, Phys. Rev. D 51, 5327 (1995) [hep-ph/9406322].
- [16] X. Zhang, S. K. Lee, K. Whisnant and B. L. Young, Phys. Rev. D 50, 7042 (1994) [hep-ph/9407259].
- [17] K. Whisnant, B. L. Young and X. Zhang, Phys. Rev. D 52, 3115 (1995) [hep-ph/9410369].
- [18] B. Grzadkowski, J. Pliszka and J. Wudka, Phys. Rev. D 69, 033001 (2004) [hep-ph/0307338].
- [19] F. P. Huang and C. S. Li, Phys. Rev. D 92, 075014 (2015) [arXiv:1507.08168]

- [hep-ph].
- [20] F. P. Huang, P. H. Gu, P. F. Yin, Z. H. Yu and X. Zhang, arXiv:1511.03969 [hep-ph].
- [21] E. Witten, Phys. Rev. D 30, 272 (1984).
- [22] C. J. Hogan, Phys. Lett. B 133, 172 (1983).
- [23] C. J. Hogan, Mon. Not. Roy. Astron. Soc. 218, 629 (1986).
- [24] M. S. Turner and F. Wilczek, Phys. Rev. Lett. 65, 3080 (1990).
- [25] P. Schwaller, Phys. Rev. Lett. 115, 181101 (2015) [arXiv:1504.07263 [hep-ph]].
- [26] P. A. Seoane et al. [eLISA Collaboration], arXiv:1305.5720 [astro-ph.CO].
- [27] N. Seto, S. Kawamura and T. Nakamura, Phys. Rev. Lett. 87, 221103 (2001) [astro-ph/0108011].
- [28] S. Kawamura et al., Class. Quant. Grav. 23, S125 (2006).
- [29] S. Kawamura et al., Class. Quant. Grav. 28, 094011 (2011).
- [30] V. Corbin and N. J. Cornish, Class. Quant. Grav. 23, 2435 (2006) [gr-qc/0512039].
- [31] M. Quiros, hep-ph/9901312.
- [32] M. Bicer et al. [TLEP Design Study Working Group Collaboration], JHEP 1401, 164 (2014) [arXiv:1308.6176 [hep-ex]].
- [33] A. Nicolis, Class. Quant. Grav. 21, L27 (2004) [gr-qc/0303084].
- [34] M. Kamionkowski, A. Kosowsky and M. S. Turner, Phys. Rev. D 49, 2837 (1994) [astro-ph/9310044].
- [35] S. J. Huber and T. Konstandin, JCAP 0809, 022 (2008) [arXiv:0806.1828 [hep-ph]].
- [36] D. Bodeker and G. D. Moore, JCAP 0905, 009 (2009) [arXiv:0903.4099 [hep-ph]].
- [37] S. J. Huber and M. Sopena, arXiv:1302.1044 [hep-ph].
- [38] C. Caprini et al., arXiv:1512.06239 [astro-ph.CO].
- [39] C. J. Moore, R. H. Cole and C. P. L. Berry, Class. Quant. Grav. 32, 015014 (2015) [arXiv:1408.0740 [gr-qc]].
- [40] H. Kudoh, A. Taruya, T. Hiramatsu and Y. Himemoto, Phys. Rev. D 73, 064006 (2006) [gr-qc/0511145].

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