

New collider implications on a strongly first order EWPT*

Ricardo R. Florentino^{1,**}, Shinya Kanemura^{1,***}, and Masanori Tanaka^{2,****}

¹Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

²Center for High Energy Physics, Peking University, Beijing 100871, China

Abstract. In order to understand the early history of the universe, and to test baryogenesis models, determining the nature of the electroweak phase transition is imperative. The order and strength of this transition is strongly correlated to relatively large deviations in the hhh coupling. In models where a considerable part of the hhh coupling deviation is caused by charged particle loops, the $h\gamma\gamma$ coupling is also expected to deviate considerably. In this talk, by using a model-independent approach, I explain how to obtain conditions that are sufficient for a strongly first order phase transition. After the $h\gamma\gamma$ coupling is determined with precision at the HL-LHC, these conditions can be tested at Future Linear Colliders by measurements of the hhh coupling, to conclusively determine the nature of the electroweak phase transition and the viability of electroweak baryogenesis on models with new charged scalars.

1 Introduction

The Standard Model (SM) is extremely successful in explaining most currently observed phenomena. Nonetheless, one of its main problems is the absence for an explanation of the observed Baryon Asymmetry of the Universe (BAU)[1]. One of the most promising methods of baryon generation is known as Electroweak Baryogenesis (EWBG)[2]. This kind of baryogenesis is possible when the Electroweak Phase Transition (EWPT), which occurs in the early universe at the electroweak scale, is a Strongly First Order Phase Transition (SFOPT)[3]. In the Higgs sector of the SM, the EWPT is not a SFOPT[4–6]. Therefore, Beyond the SM (BSM) models with extended Higgs sectors are necessary for a successful EWBG.

The occurrence of a SFOPT in the context of EWBG has various experimental consequences. In this work these consequences are studied, both at colliders and in cosmology, using a model independent framework known as the nearly-aligned Higgs Effective Field Theory (naHEFT). Furthermore, it is discussed how the measurement of the $h \rightarrow \gamma\gamma$ decay at future experiments can be used to constrain the allowed parameter space for a SFOPT in given models, which will be available considerably sooner than triple Higgs coupling measurements. Once the triple Higgs coupling is measured with precision in e.g. the latter stages of the ILC, the $h\gamma\gamma$ will be a crucial complement in pinpointing the models capable of generating a SFOPT.

*OU-HET-1245

** Speaker e-mail: rflorentino@hetmail.phys.sci.osaka-u.ac.jp

*** e-mail: kanemu@het.phys.sci.osaka-u.ac.jp

**** e-mail: tanaka@pku.edu.cn

This work is organised as follows. In section 2 the motivation and formalism of the naHEFT is presented. In section 3 the cosmological constraints on a SFOPT, as well as the cosmological observables considered, are discussed. In section 4 the main results are shown as figures constraining the parameter space of various benchmark models. The situation of future collider physics is further explored in section 5, with a focus on the International Linear Collider (ILC) program. Finally, conclusions are given in section 6.

2 The nearly-aligned Higgs EFT

The two main description for BSM physics within an Effective Field Theory (EFT) approach are the Standard Model EFT (SMEFT)[7–9] and the Higgs EFT (HEFT)[10–18]. The former is based on canonical dimension counting, and thus reliable in the decoupling limit. The latter is based on chiral dimension counting, and thus of ideal use in the non-decoupling scenario[19–21]. In the context of EWPT, non-decoupling effects are crucial to produce a SFOPT. HEFT is then the correct framework to study such phenomenology.

In the most general HEFT, infinite operators are generated, even at leading order, so that HEFT by itself has very little prediction power. The naHEFT is based on the HEFT, with the assumption that all deviations to Higgs boson couplings are generated at loop level[22, 23]. This assumption is motivated by the collider measurements being incredibly close to SM predictions. This allows the Lagrangian to take the form of one-loop effects of heavy particles integrated out. The Higgs potential will then assume a Coleman-Weinberg like form, and the resulting Lagrangian will be of the form:

$$\mathcal{L}_{naHEFT} = \mathcal{L}_{SM} + \xi(\mathcal{L}_S + \mathcal{L}_V) \quad \left(\xi = \frac{1}{(4\pi)^2} \right) \quad (1)$$

where \mathcal{L}_S is the scalar sector:

$$\mathcal{L}_S = -\frac{\kappa_0}{4}[\mathcal{M}^2(h)]^2 \log \frac{\mathcal{M}^2(h)}{\mu^2} + \frac{v^2}{2}\mathcal{F}(h)\text{Tr}[D_\mu U^\dagger D^\mu U] + \frac{1}{2}\mathcal{K}(h)(\partial_\mu h)(\partial^\mu h) \quad (2)$$

and \mathcal{L}_V is the scalar-vector potential important to describe the loop generated $h \rightarrow \gamma\gamma$ decay:

$$\mathcal{L}_V = g^2\mathcal{F}_W(h)\text{Tr}[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}] + g^2\mathcal{F}_B(h)\text{Tr}[\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}] - gg'\mathcal{F}_{BW}(h)\text{Tr}[\mathbf{U}\mathbf{B}_{\mu\nu}U^\dagger\mathbf{W}^{\mu\nu}] \quad (3)$$

The non-decouplingness of a particle is given by the fraction of their mass that is generated from the SM Higgs boson, $r = v^2\lambda_p/\Lambda$, where Λ is the particles mass and λ_p it's coupling with the SM Higgs boson. In this work, a further simplification is made, that the mass scale and the non-decouplingness of the BSM particles are approximately degenerate, such that the new physics can be described by three main parameters: the mass scale Λ , the non-decouplingness r , and the degrees of freedom k_0 . The last of which can be further subdivided in the degrees of freedom for scalars of each charge, for the purpose of the $h \rightarrow \gamma\gamma$ calculation. The polynomials of the Higgs boson present in the Lagrangian can in this case be described by:

$$\mathcal{F}(h) = \mathcal{F}_{BW}(h) = 0 \quad (4)$$

$$\mathcal{M}^2(h) = M^2 + \lambda_g(v+h)^2 \quad (5)$$

$$\mathcal{K}(h) = \kappa_0 \frac{\Lambda^2}{3v^2} r \left[1 - (1-r) \frac{\Lambda^2}{\mathcal{M}^2(h)} \right] \quad (6)$$

$$\mathcal{F}_W(h) = \mathcal{F}_B(h) = \frac{b}{2} \ln \left[1 - r + r \left(1 + \frac{h}{v} \right)^2 \right], \quad b = \frac{n_+ + 4n_{++}}{3} \quad (7)$$

Implementing these function in the Lagrangian, it is possible to deduce the following coupling scaling factors:

$$\kappa_V = \kappa_f = 1 - \kappa_0 \frac{\xi}{6} \frac{\Lambda^2}{v^2} r^2, \quad (8)$$

$$\kappa_3 = 1 + \kappa_0 \frac{4\xi}{3} \frac{\Lambda^4}{v^2 m_h^2} \left[r^3 - \frac{m_h^2}{8\Lambda^2} r^2 (3 - 2r) \right], \quad (9)$$

$$\kappa_{\gamma\gamma}^2 \simeq \left| \kappa_V - \frac{br}{F_{SM}} \right|^2, \quad (10)$$

$$\kappa_{Z\gamma}^2 \simeq \left| \kappa_V - \frac{br}{G_{SM}} (J_3^{\text{new}} - s_W^2) \right|^2, \quad (11)$$

where $F_{SM} = 6.492$, $G_{SM} = 11.65$, and s_W is the Weinberg angle. The parameter J_3^{new} parametrizes the ratio between the third isospin component and the electrical charge of new particles. The scaling factors represent deviations from the standard model in the Higgs coupling with gauge/fermion pairs, in the triple Higgs coupling, and in the Higgs decay to $\gamma\gamma$ and $Z\gamma$ respectively. A point to note is that most deviations are proportional to powers in κ_0 , r , and Λ , while the deviations in the $\kappa_{\gamma\gamma}$ is proportional to $b = (n_+ + 4n_{++})/3$, leading to a different, model dependent behaviour.

3 Cosmology of a Strongly First Order EWPT

In order to have a SFOPT and successfully generate the BAU, some cosmological requirements are necessary to employ. The first one says that the sphaleron process must decouple almost instantly after the phase transition. This is often referred to as the sphaleron decoupling condition[2], and can be approximated by:

$$\frac{v_n}{T_n} > 1 \quad (12)$$

where v_n is the Higgs vacuum at the nucleation temperature T_n of the phase transition. This condition is strongly correlated with the strength of the phase transition, and thus, with the deviations in the triple Higgs coupling[24–27].

The second condition says the transition rate of the phase transition must be high enough compared to the expansion of the universe for the transition to complete by today. This is referred to as the completion condition[28], and can be approximated by:

$$\frac{\Gamma}{H^4} > 1 \quad (13)$$

where Γ is the transition rate and H the Hubble parameter.

Being of cosmological nature, a SFOPT also has cosmological observable that can be observed at various experiments. One of them is possible gravitational waves (GW) generated during the phase transition[26, 27, 29, 30]. In general, cosmological phase transitions have three sources of gravitational waves: bubble collision, sound waves, and plasma turbulence:

$$h^2\Omega_{\text{GW}}(f) \simeq h^2\Omega_{\varphi}(f) + h^2\Omega_{\text{sw}}(f) + h^2\Omega_{\text{turb}}(f), \quad (14)$$

The fitting functions used for the GW spectrum $\Omega_{\text{GW}}(f)$ are shown in Ref. [31]. The GW are considered detectable if their signal to noise ratio is larger than ten[32], $SNR > 10$, where

$$SNR = \sqrt{\mathcal{T} \int_{f_{\min}}^{f_{\max}} df \left[\frac{h^2\Omega_{\text{GW}}(f)}{h^2\Omega_{\text{sens}}(f)} \right]^2}, \quad (15)$$

and where $\mathcal{T} = 1.26 \times 10^8$ s is used for detectability at both LISA[33] and DECIGO[34] interferometers.

Finally, the production and detectability of Primordial Black Holes is considered. These are generated in the scenario where a delay of the phase transition happens across a Hubble volume, and a large density contrast is present, leading to the creation of PBH[35, 36]. The same analysis as in [37] is performed. The PBH are considered detectable if the fraction of PBH is larger than 10^{-4} such that it can be detected in experiments like Subaru HSC [38], OGLE [39], PRIME [40] and Roman telescope [41].

4 Parameter Space Examination

Here we summarise some of the main results presented previously in [42].

In figure 1 the parameter region studied is shown. Each graph corresponds to different number of scalar degrees of freedom. These correspond to various know BSM models with extend scalar fields like two Higgs doublet models [43–60], Higgs triplet models [47, 61–66], the SM with singlet scalar fields [26, 47, 60, 67–72], and the Georgi-Machacek model [73–75]. The BSM mass scale Λ and non-decouplingness r are scanned for compliance with the SFOPT conditions and detection at GW interferometers and PBH observations. The white area below the coloured region violates the sphaleron decoupling condition, while the white area above the coloured region violates the phase transition completion condition. The blue, light and dark green, and red regions can thus realise a SFOPT. The blue area can only be probed at colliders, while the light green area and above can generate GW detectable at DECIGO, the dark green area and above can be probed at LISA, and the red area can also produce detectable PBH. The dashed lines represent contours of the triple Higgs coupling scaling factor κ_3 while the other coloured lines represent contours in the $h \rightarrow \gamma\gamma$ decay scaling factor $\kappa_{\gamma\gamma}$. Finally, the transparent blue area represents the area where $\Delta\kappa_{\gamma\gamma} = (-4 \pm 1)\%$.

From figure 1 it can be seen that while LISA and PBH can only probe a small section of the allowed parameter space, DECIGO is able to probe a larger area. On the other hand, the triple Higgs coupling is shown to cover all the area, and as expected, a strong determination of κ_3 is essential for the determination of the nature of the EWPT. Further details on the capacity of future κ_3 measurements to determine the nature of the SFOPT are presented in the next section. The $\kappa_{\gamma\gamma}$ contours, by being unaligned with the other measurements, reveal the $h \rightarrow \gamma\gamma$ measurements can be used as a strong complement to the former to test the nature of the EWPT. As an illustrative example, the possibility of future experiments, like the *HL-LHC*, measuring $\Delta\kappa_{\gamma\gamma} = (-4 \pm 1)\%$ is considered. In that case, only the transparent blue regions in figure 1 are allowed. Thanks to the verticality of these lines, the parameter for a SFOPT

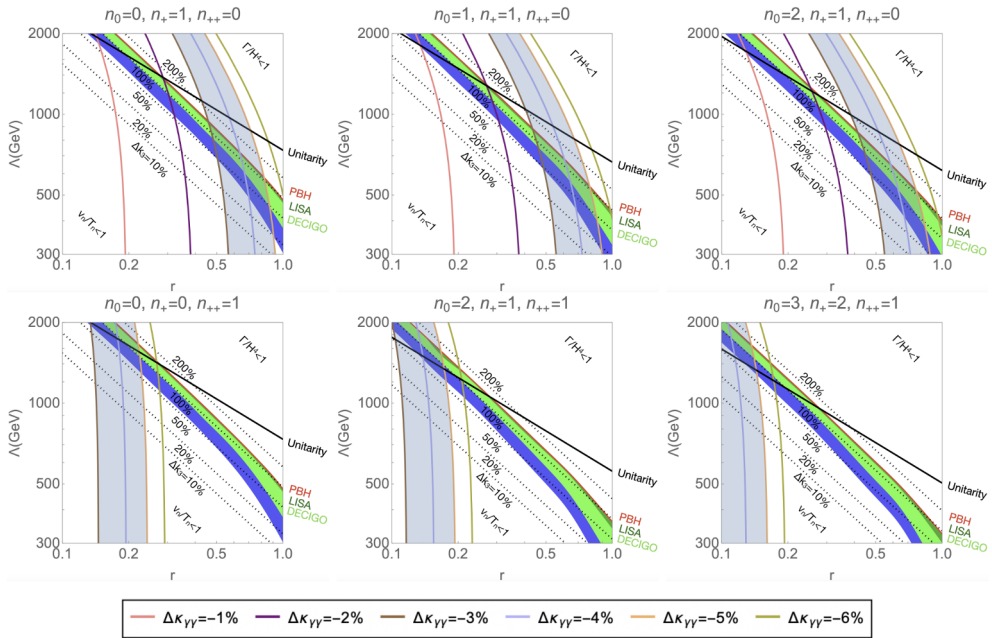


Figure 1. Parameter region in the (Λ, r) space for various possibilities of scalar degrees of freedom corresponding to some benchmark models. The white region cannot satisfy one of the conditions for a SFOPT. The light green region produces gravitational waves that can be tested at DECIGO. The gravitational waves in the dark green region can also be detected at LISA. The red region also generates PBH detectable in the considered experiments. The blue region satisfies the SFOPT, but can only be probed at colliders. The dashed lines represent contours in κ_3 . The remaining coloured lines represent contours in the $\kappa_{\gamma\gamma}$. The transparent blue region represents an illustrative scenario where $\Delta\kappa_{\gamma\gamma} = (-4 \pm 1)\%$ is measured at future colliders.

Table 1. In the illustrative scenario where $\Delta\kappa_{\gamma\gamma} = (-4 \pm 1)\%$ is measured, bounds on the κ_3 are presented for each of the models in figure 1. The bounds in the second column represent intervals for which the EWPT can be strongly first order, meaning measurements outside this range conclusively exclude a SFOPT. The bounds in the third column represent the range for which the EWPT is strongly first order, meaning that measurements within this range conclusively confirm a SFOPT.

(n_0, n_+, n_{++})	Required by SFOPT	Conservative bound	Example of SM extension
(0, 1, 0)	137% > $\Delta\kappa_3$ > 21%	114% > $\Delta\kappa_3$ > 50%	A singly charged scalar
(1, 1, 0)	143% > $\Delta\kappa_3$ > 19%	115% > $\Delta\kappa_3$ > 47%	A real triplet scalar
(2, 1, 0)	135% > $\Delta\kappa_3$ > 18%	114% > $\Delta\kappa_3$ > 44%	A doublet scalar
(0, 0, 1)	153% > $\Delta\kappa_3$ > 62%	148% > $\Delta\kappa_3$ > 65%	A doubly charged scalar
(2, 1, 1)	160% > $\Delta\kappa_3$ > 65%	150% > $\Delta\kappa_3$ > 75%	A complex triplet scalar
(3, 2, 1)	136% > $\Delta\kappa_3$ > 59%	153% > $\Delta\kappa_3$ > 63%	Gerogi-Machacek model

reduces immensely, in a very model dependent way. The $\kappa_{\gamma\gamma}$ can then put strong model-dependent bounds on the parameters. In the $(n_0, n_+, n_{++}) = (0, 1, 0)$ case, corresponding to the real singlet extension of the SM, these bounds can be determined as $\Lambda < 946 \text{ GeV}$ and $r > 0.457$, with the triple Higgs coupling being constrained to $137\% > \Delta\kappa_3 > 21\%$.

Table 2. Expected precision at one sigma of the triple Higgs coupling measurements at the HL-LHC and various stages of the ILC.

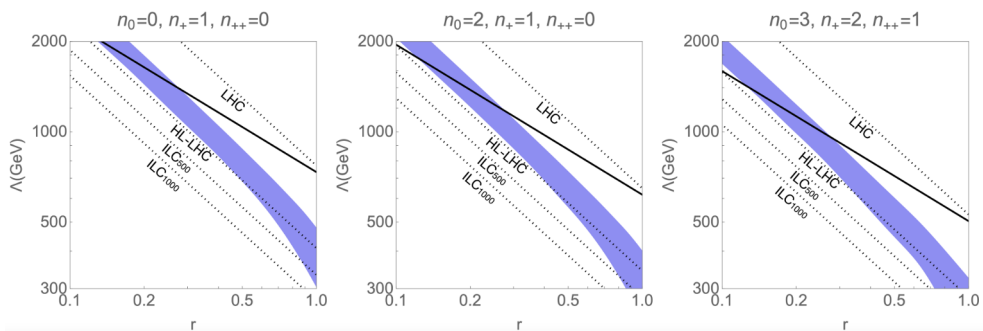
Collider	HL-LHC	ILC ₂₅₀	ILC ₅₀₀	ILC ₁₀₀₀
$\Delta\kappa_3(1\sigma)$	50%	49%	22%	10%

Focusing on the triple Higgs coupling, table 1 explores the type of bounds one can obtain. Still in the illustrative example of $\Delta\kappa_{\gamma\gamma} = (-4 \pm 1)\%$ being measured in future experiments, the same benchmark models in figure 1 are explored. Two different bounds on κ_3 are shown. In the second column, a bound in which both the sphaleron decoupling condition and the completion condition are satisfied is shown. Therefore, inside this interval there can be SFOPT, but it is not guaranteed to happen. A measurement of κ_3 outside this interval can then conclusively deny the capacity of the respective model to explain a SFOPT. The third column, on the other hand, shows the interval for which both the sphaleron decoupling and the completion conditions are guaranteed to be satisfied. This means that a measure inside this interval can conclusively confirm the occurrence of a SFOPT in the respective model. This motivates how $h \rightarrow \gamma\gamma$ measurements will give us precious insight on the nature of the EWPT in various models before the triple Higgs coupling is measured at future colliders.

5 Discussion on Future Colliders

Here further motivation of the importance of $h \rightarrow \gamma\gamma$ measurements in determining the nature of the EWPT is provided, by exploring the expected measurements of the triple Higgs coupling at future colliders and consider their implication on the discussion presented previously.

The current bound from the ATLAS result for the triple Higgs coupling scaling factor is given by $-0.4 < \kappa_3 < 6.3$ [76]. The expected precision for the triple Higgs boson coupling measurements at the HL-LHC and at the three stages, 250GeV, 500GeV, and 1TeV, of the ILC are presented in table 2.

**Figure 2.** Scenario where κ_3 is measured as the standard model value, $\kappa_3 = 1$, with the precisions shown in table 2. The dashed lines represent the respective upper bounds. The data is taken from [77].

In figure 2 the scenario where the triple Higgs coupling is measured to the SM value is considered for the various collider stages. The blue region represents the SFOPT allowed space, while the dashed lines represent the line for which the area below is allowed experimentally in this scenario. Since all the lines are on top or above the blue area, except for the last stage of 1TeV of the ILC, we conclude that, in this scenario, only by the last stage of the ILC the SFOPT could be ruled out.

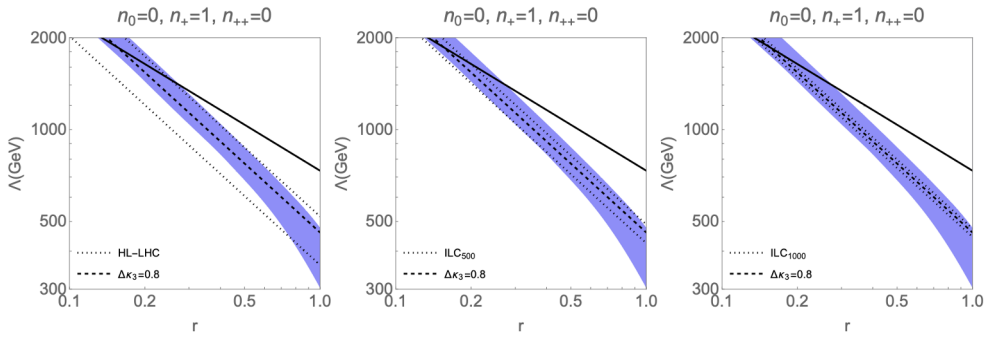


Figure 3. Scenario where κ_3 is measured at the ideal value for a SFOPT, $\kappa_3 = 1.8$, with the precisions shown in table 2. The large dashed line represents the central value, while the smaller dashed lines represent the respective bounds.

In figure 3 the scenario where the triple Higgs coupling is measured at its ideal value for a SFOPT, $\kappa_3 = 1.8$, is considered for the various collider stages. The large dashed line represents the central value, while the smaller dashed lines bound the allowed area. Again, it can be seen that only the last stage of the ILC will be able to confirm the SFOPT by use of the triple Higgs coupling measurements alone. Note that this only happens for this ideal κ_3 value. Slight deviation would make it impossible to confirm the SFOPT even in the last ILC stage.

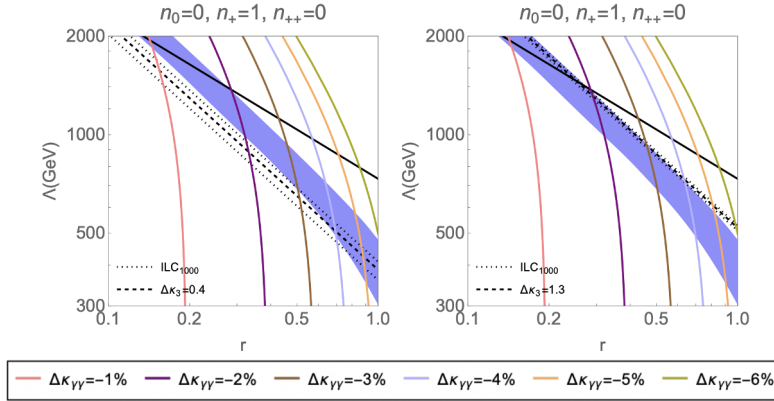


Figure 4. Two example scenarios, $\kappa_3 = 1.4$ (left), $\kappa_3 = 2.3$ (right), where determination of the nature of the SFOPT is impossible by the triple Higgs coupling alone. The $\kappa_{\gamma\gamma}$ contours show how the $h \rightarrow \gamma\gamma$ measurements can remedy this problem.

In figure 4 two scenarios are considered, where the triple Higgs coupling scaling factor is measured as $\kappa_3 = 1.4$ and $\kappa_3 = 2.3$ in the left and right of the figure respectively. These represent different scenarios where not even the most accurate precision of the triple Higgs coupling would be able to determine the nature of the EWPT, for both situations present a central value contour that includes both sections with a SFOPT and without. The $\kappa_{\gamma\gamma}$ contours are shown on top, and reveal that measurements of $h \rightarrow \gamma\gamma$ can restrict the parameter space to a smaller section of the parameter space, such that, in conjunction with the κ_3 measurements,

it can confirm or deny the SFOPT. This exemplifies once again the importance of the $h \rightarrow \gamma\gamma$ measurements in helping to probe the nature of the EWPT, in conjunction with the triple Higgs coupling measurements.

6 Conclusion

In this work the parameter space generating a strongly first order EWPT is studied within the naHEFT framework. The sphaleron decoupling and completion conditions are imposed to said parameter space, and the parameter space generating detectable GW and PBH has been confirmed.

In section 4 this parameter space is studied for six different benchmark models. In figure 1 it can be seen that while PBH and GW at LISA are only able to probe a small section of the allowed parameter space, DECIGO can test a larger area. Contours on the triple Higgs coupling are shown, and it can be seen that it strongly correlates with the existence of a SFOPT. Nonetheless, the $h \rightarrow \gamma\gamma$ is shown as a crucial complement to this study. In table 1 an example scenario of $h \rightarrow \gamma\gamma$ measurement is used in order to put constraints on the triple Higgs coupling values to generate a SFOPT. Both a required bound, outside of which the EWPT cannot be strongly first order, and a conservative bound, within which the EWPT is definitely strongly first order, are shown.

In section 5, the consequences of this study on the determination of the nature of the EWPT at future colliders is discussed. Namely, the HL-LHC and the three stages of the ILC are considered. It is shown that for very specific central values of the triple Higgs coupling, this measurement alone can determine the nature of the EWPT only at the last stage of the ILC. Outside these special cases, not even the most precise measurement of the triple Higgs coupling can conclusively determine the nature of the EWPT. Furthermore, it is discussed how the $h \rightarrow \gamma\gamma$ measurements can alleviate this issue. It is concluded that $h \rightarrow \gamma\gamma$ measurements will play a crucial role, alongside the triple Higgs coupling measurements, in testing the viability of various models to produce a SFOPT at the electroweak symmetry breaking in the early universe and, consequently, in successfully explaining BAU through EWBG.

References

- [1] N. Aghanim et al. (Planck), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020), [Erratum: *Astron. Astrophys.* 652, C4 (2021)], 1807.06209. [10.1051/0004-6361/201833910](https://doi.org/10.1051/0004-6361/201833910)
- [2] V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe, *Phys. Lett. B* **155**, 36 (1985). [10.1016/0370-2693\(85\)91028-7](https://doi.org/10.1016/0370-2693(85)91028-7)
- [3] A.D. Sakharov, Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe, *Pisma Zh. Eksp. Teor. Fiz.* **5**, 32 (1967). [10.1070/PU1991v034n05ABEH002497](https://doi.org/10.1070/PU1991v034n05ABEH002497)
- [4] K. Kajantie, M. Laine, K. Rummukainen, M.E. Shaposhnikov, Is there a hot electroweak phase transition at $m_H \gtrsim m_W$?, *Phys. Rev. Lett.* **77**, 2887 (1996), hep-ph/9605288. [10.1103/PhysRevLett.77.2887](https://doi.org/10.1103/PhysRevLett.77.2887)
- [5] M. D’Onofrio, K. Rummukainen, A. Tranberg, Sphaleron Rate in the Minimal Standard Model, *Phys. Rev. Lett.* **113**, 141602 (2014), 1404.3565. [10.1103/PhysRevLett.113.141602](https://doi.org/10.1103/PhysRevLett.113.141602)
- [6] M. D’Onofrio, K. Rummukainen, Standard model cross-over on the lattice, *Phys. Rev. D* **93**, 025003 (2016), 1508.07161. [10.1103/PhysRevD.93.025003](https://doi.org/10.1103/PhysRevD.93.025003)

- [7] W. Buchmuller, D. Wyler, Effective Lagrangian Analysis of New Interactions and Flavor Conservation, *Nucl. Phys. B* **268**, 621 (1986). [10.1016/0550-3213\(86\)90262-2](https://doi.org/10.1016/0550-3213(86)90262-2)
- [8] K. Hagiwara, S. Ishihara, R. Szalapski, D. Zeppenfeld, Low-energy effects of new interactions in the electroweak boson sector, *Phys. Rev. D* **48**, 2182 (1993). [10.1103/PhysRevD.48.2182](https://doi.org/10.1103/PhysRevD.48.2182)
- [9] B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek, Dimension-Six Terms in the Standard Model Lagrangian, *JHEP* **10**, 085 (2010), [1008.4884](https://arxiv.org/abs/1008.4884). [10.1007/JHEP10\(2010\)085](https://doi.org/10.1007/JHEP10(2010)085)
- [10] F. Feruglio, The Chiral approach to the electroweak interactions, *Int. J. Mod. Phys. A* **8**, 4937 (1993), [hep-ph/9301281](https://arxiv.org/abs/hep-ph/9301281). [10.1142/S0217751X93001946](https://doi.org/10.1142/S0217751X93001946)
- [11] R. Alonso, M.B. Gavela, L. Merlo, S. Rigolin, J. Yepes, The Effective Chiral Lagrangian for a Light Dynamical "Higgs Particle", *Phys. Lett. B* **722**, 330 (2013), [Erratum: *Phys.Lett.B* 726, 926 (2013)], [1212.3305](https://arxiv.org/abs/1212.3305). [10.1016/j.physletb.2013.04.037](https://doi.org/10.1016/j.physletb.2013.04.037)
- [12] I. Brivio, T. Corbett, O.J.P. Éboli, M.B. Gavela, J. Gonzalez-Fraile, M.C. Gonzalez-Garcia, L. Merlo, S. Rigolin, Disentangling a dynamical Higgs, *JHEP* **03**, 024 (2014), [1311.1823](https://arxiv.org/abs/1311.1823). [10.1007/JHEP03\(2014\)024](https://doi.org/10.1007/JHEP03(2014)024)
- [13] G. Buchalla, O. Catà, C. Krause, Complete Electroweak Chiral Lagrangian with a Light Higgs at NLO, *Nucl. Phys. B* **880**, 552 (2014), [Erratum: *Nucl.Phys.B* 913, 475–478 (2016)], [1307.5017](https://arxiv.org/abs/1307.5017). [10.1016/j.nuclphysb.2014.01.018](https://doi.org/10.1016/j.nuclphysb.2014.01.018)
- [14] G. Buchalla, O. Cata, A. Celis, M. Knecht, C. Krause, Complete One-Loop Renormalization of the Higgs-Electroweak Chiral Lagrangian, *Nucl. Phys. B* **928**, 93 (2018), [1710.06412](https://arxiv.org/abs/1710.06412). [10.1016/j.nuclphysb.2018.01.009](https://doi.org/10.1016/j.nuclphysb.2018.01.009)
- [15] A. Falkowski, R. Rattazzi, Which EFT, *JHEP* **10**, 255 (2019), [1902.05936](https://arxiv.org/abs/1902.05936). [10.1007/JHEP10\(2019\)255](https://doi.org/10.1007/JHEP10(2019)255)
- [16] T. Cohen, N. Craig, X. Lu, D. Sutherland, Is SMEFT Enough?, *JHEP* **03**, 237 (2021), [2008.08597](https://arxiv.org/abs/2008.08597). [10.1007/JHEP03\(2021\)237](https://doi.org/10.1007/JHEP03(2021)237)
- [17] H. Sun, M.L. Xiao, J.H. Yu, Complete NLO operators in the Higgs effective field theory, *JHEP* **05**, 043 (2023), [2206.07722](https://arxiv.org/abs/2206.07722). [10.1007/JHEP05\(2023\)043](https://doi.org/10.1007/JHEP05(2023)043)
- [18] H. Sun, M.L. Xiao, J.H. Yu, Complete NNLO operator bases in Higgs effective field theory, *JHEP* **04**, 086 (2023), [2210.14939](https://arxiv.org/abs/2210.14939). [10.1007/JHEP04\(2023\)086](https://doi.org/10.1007/JHEP04(2023)086)
- [19] I. Banta, T. Cohen, N. Craig, X. Lu, D. Sutherland, Non-decoupling new particles, *JHEP* **02**, 029 (2022), [2110.02967](https://arxiv.org/abs/2110.02967). [10.1007/JHEP02\(2022\)029](https://doi.org/10.1007/JHEP02(2022)029)
- [20] I. Banta, A strongly first-order electroweak phase transition from Loryons, *JHEP* **06**, 099 (2022), [2202.04608](https://arxiv.org/abs/2202.04608). [10.1007/JHEP06\(2022\)099](https://doi.org/10.1007/JHEP06(2022)099)
- [21] G. Buchalla, F. König, C. Müller-Salditt, F. Pandler, Two-Higgs Doublet Model Matched to Nonlinear Effective Theory (2023), [2312.13885](https://arxiv.org/abs/2312.13885).
- [22] S. Kanemura, R. Nagai, M. Tanaka, Electroweak phase transition in the nearly aligned Higgs effective field theory, *JHEP* **06**, 027 (2022), [2202.12774](https://arxiv.org/abs/2202.12774). [10.1007/JHEP06\(2022\)027](https://doi.org/10.1007/JHEP06(2022)027)
- [23] S. Kanemura, R. Nagai, A new Higgs effective field theory and the new no-lose theorem, *JHEP* **03**, 194 (2022), [2111.12585](https://arxiv.org/abs/2111.12585). [10.1007/JHEP03\(2022\)194](https://doi.org/10.1007/JHEP03(2022)194)
- [24] C. Grojean, G. Servant, J.D. Wells, First-order electroweak phase transition in the standard model with a low cutoff, *Phys. Rev. D* **71**, 036001 (2005), [hep-ph/0407019](https://arxiv.org/abs/hep-ph/0407019). [10.1103/PhysRevD.71.036001](https://doi.org/10.1103/PhysRevD.71.036001)
- [25] S. Kanemura, Y. Okada, E. Senaha, Electroweak baryogenesis and quantum corrections to the triple Higgs boson coupling, *Phys. Lett. B* **606**, 361 (2005), [hep-ph/0411354](https://arxiv.org/abs/hep-ph/0411354). [10.1016/j.physletb.2004.12.004](https://doi.org/10.1016/j.physletb.2004.12.004)

- [26] M. Kakizaki, S. Kanemura, T. Matsui, Gravitational waves as a probe of extended scalar sectors with the first order electroweak phase transition, *Phys. Rev. D* **92**, 115007 (2015), 1509.08394. [10.1103/PhysRevD.92.115007](https://doi.org/10.1103/PhysRevD.92.115007)
- [27] K. Hashino, M. Kakizaki, S. Kanemura, T. Matsui, Synergy between measurements of gravitational waves and the triple-Higgs coupling in probing the first-order electroweak phase transition, *Phys. Rev. D* **94**, 015005 (2016), 1604.02069. [10.1103/PhysRevD.94.015005](https://doi.org/10.1103/PhysRevD.94.015005)
- [28] M.S. Turner, E.J. Weinberg, L.M. Widrow, Bubble nucleation in first order inflation and other cosmological phase transitions, *Phys. Rev. D* **46**, 2384 (1992). [10.1103/PhysRevD.46.2384](https://doi.org/10.1103/PhysRevD.46.2384)
- [29] C. Grojean, G. Servant, Gravitational Waves from Phase Transitions at the Electroweak Scale and Beyond, *Phys. Rev. D* **75**, 043507 (2007), hep-ph/0607107. [10.1103/PhysRevD.75.043507](https://doi.org/10.1103/PhysRevD.75.043507)
- [30] K. Hashino, R. Jinno, M. Kakizaki, S. Kanemura, T. Takahashi, M. Takimoto, Selecting models of first-order phase transitions using the synergy between collider and gravitational-wave experiments, *Phys. Rev. D* **99**, 075011 (2019), 1809.04994. [10.1103/PhysRevD.99.075011](https://doi.org/10.1103/PhysRevD.99.075011)
- [31] C. Caprini et al., Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions, *JCAP* **04**, 001 (2016), 1512.06239. [10.1088/1475-7516/2016/04/001](https://doi.org/10.1088/1475-7516/2016/04/001)
- [32] J.M. Cline, A. Friedlander, D.M. He, K. Kainulainen, B. Laurent, D. Tucker-Smith, Baryogenesis and gravity waves from a UV-completed electroweak phase transition, *Phys. Rev. D* **103**, 123529 (2021), 2102.12490. [10.1103/PhysRevD.103.123529](https://doi.org/10.1103/PhysRevD.103.123529)
- [33] P. Amaro-Seoane et al. (LISA), Laser Interferometer Space Antenna (2017), 1702.00786.
- [34] S. Kawamura et al., The Japanese space gravitational wave antenna: DECIGO, *Class. Quant. Grav.* **28**, 094011 (2011). [10.1088/0264-9381/28/9/094011](https://doi.org/10.1088/0264-9381/28/9/094011)
- [35] K. Hashino, S. Kanemura, T. Takahashi, Primordial black holes as a probe of strongly first-order electroweak phase transition, *Phys. Lett. B* **833**, 137261 (2022), 2111.13099. [10.1016/j.physletb.2022.137261](https://doi.org/10.1016/j.physletb.2022.137261)
- [36] J. Liu, L. Bian, R.G. Cai, Z.K. Guo, S.J. Wang, Primordial black hole production during first-order phase transitions, *Phys. Rev. D* **105**, L021303 (2022), 2106.05637. [10.1103/PhysRevD.105.L021303](https://doi.org/10.1103/PhysRevD.105.L021303)
- [37] K. Hashino, S. Kanemura, T. Takahashi, M. Tanaka, Probing first-order electroweak phase transition via primordial black holes in the effective field theory, *Phys. Lett. B* **838**, 137688 (2023), 2211.16225. [10.1016/j.physletb.2023.137688](https://doi.org/10.1016/j.physletb.2023.137688)
- [38] H. Niihara et al., Microlensing constraints on primordial black holes with Subaru/HSC Andromeda observations, *Nature Astron.* **3**, 524 (2019), 1701.02151. [10.1038/s41550-019-0723-1](https://doi.org/10.1038/s41550-019-0723-1)
- [39] H. Niihara, M. Takada, S. Yokoyama, T. Sumi, S. Masaki, Constraints on Earth-mass primordial black holes from OGLE 5-year microlensing events, *Phys. Rev. D* **99**, 083503 (2019), 1901.07120. [10.1103/PhysRevD.99.083503](https://doi.org/10.1103/PhysRevD.99.083503)
- [40] I. Kondo, T. Sumi, N. Koshimoto, N.J. Rattenbury, D. Suzuki, D.P. Bennett, Prediction of planet yields by the prime-focus infrared microlensing experiment microlensing survey, *The Astronomical Journal* **165**, 254 (2023). [10.3847/1538-3881/acccf9](https://doi.org/10.3847/1538-3881/acccf9)
- [41] J. Fardeen, P. McGill, S.E. Perkins, W.A. Dawson, N.S. Abrams, J.R. Lu, M.F. Ho, S. Bird, Astrometric microlensing by primordial black holes with the roman space telescope (2023), 2312.13249.

- [42] R.R. Florentino, S. Kanemura, M. Tanaka, Exploring loop-induced first-order electroweak phase transition in the Higgs effective field theory, *Phys. Lett. B* **856**, 138940 (2024), 2406.03957. [10.1016/j.physletb.2024.138940](https://doi.org/10.1016/j.physletb.2024.138940)
- [43] A. Arhrib, M. Capdequi Peyranere, W. Hollik, S. Penaranda, Higgs decays in the two Higgs doublet model: Large quantum effects in the decoupling regime, *Phys. Lett. B* **579**, 361 (2004), hep-ph/0307391. [10.1016/j.physletb.2003.10.006](https://doi.org/10.1016/j.physletb.2003.10.006)
- [44] M. Aoki, S. Kanemura, K. Tsumura, K. Yagyu, Models of Yukawa interaction in the two Higgs doublet model, and their collider phenomenology, *Phys. Rev. D* **80**, 015017 (2009), 0902.4665. [10.1103/PhysRevD.80.015017](https://doi.org/10.1103/PhysRevD.80.015017)
- [45] P. Posch, Enhancement of $h \rightarrow \gamma\gamma$ in the Two Higgs Doublet Model Type I, *Phys. Lett. B* **696**, 447 (2011), 1001.1759. [10.1016/j.physletb.2011.01.003](https://doi.org/10.1016/j.physletb.2011.01.003)
- [46] A. Arhrib, R. Benbrik, N. Gaur, $H \rightarrow \gamma\gamma$ in Inert Higgs Doublet Model, *Phys. Rev. D* **85**, 095021 (2012), 1201.2644. [10.1103/PhysRevD.85.095021](https://doi.org/10.1103/PhysRevD.85.095021)
- [47] C.W. Chiang, K. Yagyu, Higgs boson decays to $\gamma\gamma$ and $Z\gamma$ in models with Higgs extensions, *Phys. Rev. D* **87**, 033003 (2013), 1207.1065. [10.1103/PhysRevD.87.033003](https://doi.org/10.1103/PhysRevD.87.033003)
- [48] D. Fontes, J.C. Romão, J.P. Silva, $h \rightarrow Z\gamma$ in the complex two Higgs doublet model, *JHEP* **12**, 043 (2014), 1408.2534. [10.1007/JHEP12\(2014\)043](https://doi.org/10.1007/JHEP12(2014)043)
- [49] S. Kanemura, M. Kikuchi, K. Yagyu, Radiative corrections to the Yukawa coupling constants in two Higgs doublet models, *Phys. Lett. B* **731**, 27 (2014), 1401.0515. [10.1016/j.physletb.2014.02.022](https://doi.org/10.1016/j.physletb.2014.02.022)
- [50] S. Kanemura, K. Tsumura, K. Yagyu, H. Yokoya, Fingerprinting nonminimal Higgs sectors, *Phys. Rev. D* **90**, 075001 (2014), 1406.3294. [10.1103/PhysRevD.90.075001](https://doi.org/10.1103/PhysRevD.90.075001)
- [51] A. Arhrib, R. Benbrik, J. El Falaki, A. Jueid, Radiative corrections to the Triple Higgs Coupling in the Inert Higgs Doublet Model, *JHEP* **12**, 007 (2015), 1507.03630. [10.1007/JHEP12\(2015\)007](https://doi.org/10.1007/JHEP12(2015)007)
- [52] S. Kanemura, M. Kikuchi, K. Yagyu, Fingerprinting the extended Higgs sector using one-loop corrected Higgs boson couplings and future precision measurements, *Nucl. Phys. B* **896**, 80 (2015), 1502.07716. [10.1016/j.nuclphysb.2015.04.015](https://doi.org/10.1016/j.nuclphysb.2015.04.015)
- [53] K. Hashino, S. Kanemura, Y. Orikasa, Discriminative phenomenological features of scale invariant models for electroweak symmetry breaking, *Phys. Lett. B* **752**, 217 (2016), 1508.03245. [10.1016/j.physletb.2015.11.044](https://doi.org/10.1016/j.physletb.2015.11.044)
- [54] S. Kanemura, M. Kikuchi, K. Sakurai, Testing the dark matter scenario in the inert doublet model by future precision measurements of the Higgs boson couplings, *Phys. Rev. D* **94**, 115011 (2016), 1605.08520. [10.1103/PhysRevD.94.115011](https://doi.org/10.1103/PhysRevD.94.115011)
- [55] E. Senaha, Radiative Corrections to Triple Higgs Coupling and Electroweak Phase Transition: Beyond One-loop Analysis, *Phys. Rev. D* **100**, 055034 (2019), 1811.00336. [10.1103/PhysRevD.100.055034](https://doi.org/10.1103/PhysRevD.100.055034)
- [56] J. Braathen, S. Kanemura, M. Shimoda, Two-loop analysis of classically scale-invariant models with extended Higgs sectors, *JHEP* **03**, 297 (2021), 2011.07580. [10.1007/JHEP03\(2021\)297](https://doi.org/10.1007/JHEP03(2021)297)
- [57] R.R. Florentino, J.C. Romão, J.P. Silva, Off diagonal charged scalar couplings with the Z boson: Zee-type models as an example, *Eur. Phys. J. C* **81**, 1148 (2021), 2106.08332. [10.1140/epjc/s10052-021-09956-2](https://doi.org/10.1140/epjc/s10052-021-09956-2)
- [58] G. Degrassi, P. Slavich, On the two-loop BSM corrections to $h \rightarrow \gamma\gamma$ in the aligned THDM, *Eur. Phys. J. C* **83**, 941 (2023), 2307.02476. [10.1140/epjc/s10052-023-12097-3](https://doi.org/10.1140/epjc/s10052-023-12097-3)
- [59] M. Aiko, J. Braathen, S. Kanemura, Leading two-loop corrections to the Higgs diphoton decay in the Inert Doublet Model (2023), 2307.14976.

- [60] M. Aiko, S. Kanemura, M. Kikuchi, K. Sakurai, K. Yagyu, H-COUP Version 3: A program for one-loop corrected decays of any Higgs bosons in non-minimal Higgs models (2023), 2311.15892.
- [61] A.G. Akeroyd, C.W. Chiang, Phenomenology of Large Mixing for the CP-even Neutral Scalars of the Higgs Triplet Model, *Phys. Rev. D* **81**, 115007 (2010), 1003.3724. [10.1103/PhysRevD.81.115007](https://doi.org/10.1103/PhysRevD.81.115007)
- [62] A. Arhrib, R. Benbrik, M. Chabab, G. Moultaqa, L. Rahili, Higgs boson decay into 2 photons in the type-II Seesaw Model, *JHEP* **04**, 136 (2012), 1112.5453. [10.1007/JHEP04\(2012\)136](https://doi.org/10.1007/JHEP04(2012)136)
- [63] M. Aoki, S. Kanemura, M. Kikuchi, K. Yagyu, Renormalization of the Higgs Sector in the Triplet Model, *Phys. Lett. B* **714**, 279 (2012), 1204.1951. [10.1016/j.physletb.2012.07.016](https://doi.org/10.1016/j.physletb.2012.07.016)
- [64] S. Kanemura, K. Yagyu, Radiative corrections to electroweak parameters in the Higgs triplet model and implication with the recent Higgs boson searches, *Phys. Rev. D* **85**, 115009 (2012), 1201.6287. [10.1103/PhysRevD.85.115009](https://doi.org/10.1103/PhysRevD.85.115009)
- [65] M. Aoki, S. Kanemura, M. Kikuchi, K. Yagyu, Radiative corrections to the Higgs boson couplings in the triplet model, *Phys. Rev. D* **87**, 015012 (2013), 1211.6029. [10.1103/PhysRevD.87.015012](https://doi.org/10.1103/PhysRevD.87.015012)
- [66] F. Arbabifar, S. Bahrami, M. Frank, Neutral Higgs Bosons in the Higgs Triplet Model with nontrivial mixing, *Phys. Rev. D* **87**, 015020 (2013), 1211.6797. [10.1103/PhysRevD.87.015020](https://doi.org/10.1103/PhysRevD.87.015020)
- [67] M.A. Shifman, A.I. Vainshtein, M.B. Voloshin, V.I. Zakharov, Low-Energy Theorems for Higgs Boson Couplings to Photons, *Sov. J. Nucl. Phys.* **30**, 711 (1979).
- [68] A. Katz, M. Perelstein, Higgs Couplings and Electroweak Phase Transition, *JHEP* **07**, 108 (2014), 1401.1827. [10.1007/JHEP07\(2014\)108](https://doi.org/10.1007/JHEP07(2014)108)
- [69] S. Kanemura, M. Kikuchi, K. Yagyu, Radiative corrections to the Higgs boson couplings in the model with an additional real singlet scalar field, *Nucl. Phys. B* **907**, 286 (2016), 1511.06211. [10.1016/j.nuclphysb.2016.04.005](https://doi.org/10.1016/j.nuclphysb.2016.04.005)
- [70] S. Kanemura, M. Kikuchi, K. Yagyu, One-loop corrections to the Higgs self-couplings in the singlet extension, *Nucl. Phys. B* **917**, 154 (2017), 1608.01582. [10.1016/j.nuclphysb.2017.02.004](https://doi.org/10.1016/j.nuclphysb.2017.02.004)
- [71] J. Braathen, S. Kanemura, On two-loop corrections to the Higgs trilinear coupling in models with extended scalar sectors, *Phys. Lett. B* **796**, 38 (2019), 1903.05417. [10.1016/j.physletb.2019.07.021](https://doi.org/10.1016/j.physletb.2019.07.021)
- [72] J. Braathen, S. Kanemura, Leading two-loop corrections to the Higgs boson self-couplings in models with extended scalar sectors, *Eur. Phys. J. C* **80**, 227 (2020), 1911.11507. [10.1140/epjc/s10052-020-7723-2](https://doi.org/10.1140/epjc/s10052-020-7723-2)
- [73] H. Georgi, M. Machacek, DOUBLY CHARGED HIGGS BOSONS, *Nucl. Phys. B* **262**, 463 (1985). [10.1016/0550-3213\(85\)90325-6](https://doi.org/10.1016/0550-3213(85)90325-6)
- [74] C.W. Chiang, A.L. Kuo, K. Yagyu, Radiative corrections to Higgs couplings with weak gauge bosons in custodial multi-Higgs models, *Phys. Lett. B* **774**, 119 (2017), 1707.04176. [10.1016/j.physletb.2017.09.061](https://doi.org/10.1016/j.physletb.2017.09.061)
- [75] C.W. Chiang, A.L. Kuo, K. Yagyu, One-loop renormalized Higgs boson vertices in the Georgi-Machacek model, *Phys. Rev. D* **98**, 013008 (2018), 1804.02633. [10.1103/PhysRevD.98.013008](https://doi.org/10.1103/PhysRevD.98.013008)
- [76] G. Aad et al. (ATLAS), Constraints on the Higgs boson self-coupling from single- and double-Higgs production with the ATLAS detector using pp collisions at $\sqrt{s}=13$ TeV, *Phys. Lett. B* **843**, 137745 (2023), 2211.01216. [10.1016/j.physletb.2023.137745](https://doi.org/10.1016/j.physletb.2023.137745)

- [77] J. Alison et al., Higgs boson potential at colliders: Status and perspectives, *Rev. Phys.* **5**, 100045 (2020), 1910.00012. [10.1016/j.revip.2020.100045](https://doi.org/10.1016/j.revip.2020.100045)