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Review

A Concise Review on Some Higgs-Related New Physics Models in Light of Current Experiments

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Abstract: The Higgs boson may serve as a portal to new physics beyond the standard model (BSM), which is implied by the theoretical naturalness or experimental anomalies. This review aims to briefly survey some typical Higgs-related BSM models. First, for the theories to solve the hierarchy problem, the two exemplary theories, the low energy supersymmetry (focusing on the minimal supersymmetric model) and the little Higgs theory, are discussed. For the phenomenological models without addressing the hierarchy problem, we choose the two-Higgs-doublet models (2HDMs) to emphatically elucidate their phenomenological power in explaining current measurements of muon $g-2$, the W-boson mass and the dark matter (DM) data. For the singlet extensions, which are motivated by the cosmic phase transition and the DM issue, we illustrate the singlet-extended standard model (xSM) and the singlet-extended 2HDM (2HDM+S), emphasizing the vacuum stability. In the decade since the discovery of the Higgs boson, these theories have remained the typical candidates of new physics, which will be intensively studied in future theoretical and experimental research.

Keywords: Higgs boson; beyond standard model (BSM) physics; minimal supersymmetric standard model (MSSM)

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1. Introduction

With the discovery of the 125 GeV Higgs boson [1,2], high energy physics has entered the post-Higgs era, in which the main goal is to test the Higgs properties and explore new physics BSM. Despite the fact that the current experiments such as the LHC and the DM direct detections have found no clear evidence of new particles, our belief in the existence of BSM physics has never been shaken. This is because the SM is obviously not the ultimate theory due to the problems such as the naturalness, the vacuum stability, the neutrino mass[1], the DM and the matter–antimatter asymmetry in the universe. All these problems seem to be caused or related to the Higgs sector. In other words, the Higgs sector may serve as a portal to the BSM physics implied by theoretical naturalness or experimental anomalies (such as muon $g-2$ and W-mass) or cosmic observations (such as DM and matter–antimatter asymmetry), as illustrated in Figure 1.

From the theoretical side, it is well-known that the observed mass of the Higgs boson leads to a naturalness problem in the SM. Obtaining a Higgs mass of 125 GeV requires an extreme fine-tuning of the model parameters. So from the theoretical point of view, the BSM physics should solve the quadratic divergence of the Higgs boson [7–9]. In this end, the low energy SUSY is the most popular paradigm (for a comprehensive review, see, e.g., [10], while for recent brief reviews, see, e.g., [11–13]). In addition, the quadratic divergence of the Higgs boson mass can be canceled at the one-loop level in the little Higgs theory [14,15], while in the theories with large [16] or warped extra dimensions [17], the naturalness can be obtained by reducing the fundamental scale to a weak scale.

From the experimental side, the W-boson mass recently measured by the CDF II deviates from the SM by 7σ [18], while the muon $g-2$ measured by FNAL and BNL deviates from the SM by 4.2σ [19]. Note that the CDF result disagrees with the recent LHC measurement [20,21], which is in agreement with the SM prediction, albeit with a relatively large uncertainty. For the muon $g-2$ anomaly, the lattice calculations [22–26] seem to shift up the SM value to relax the deviation from 4.2σ to 1.5σ, showing a 2.1σ tension with the e^+e^- data-driven determination of the HVP contribution. The BSM physics should be able to jointly explain both anomalies plus the DM. So far, some models have been found to be feasible, such as the low energy SUSY [27–29] and some specific 2HDMs [30–34] (for recent brief reviews, see, e.g., [35]).

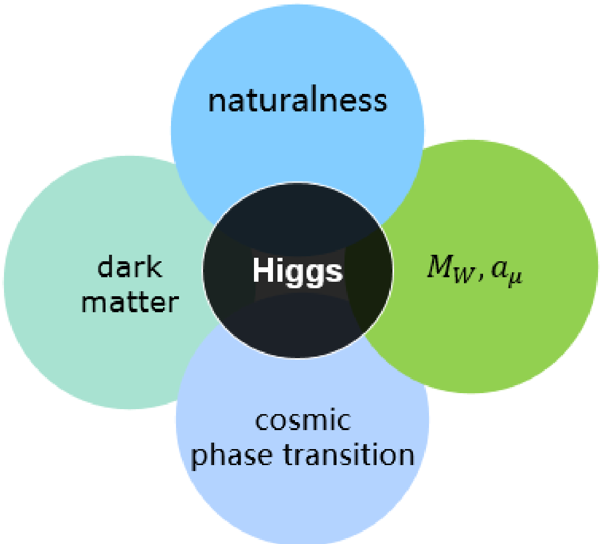

Figure 1. A sketch map showing that the Higgs sector may serve as a portal to BSM physics implied by the naturalness, the experimental anomalies from the muon $g-2$ or W-mass, the cosmic phase transition and DM.

From the cosmic side, a Higgs field may be a portal to the cosmic cold DM (for reviews see, e.g., [36], and for recent studies see, e.g., [37]) and may also trigger the electroweak phase transition in the early universe. The stability of the current electroweak vacuum and the cosmological phase transition can be studied from the Higgs potential. In explaining the baryon asymmetry of the universe, a FOPT is required in the electroweak baryogenesis to provide the departure from the thermal equilibrium (for reviews of baryogenesis, see, e.g., [38–42]). However, it is well known that the EWPT from the SM Higgs is a smooth crossover, i.e., the SM cannot produce a FOPT. In the new physics models such as the singlet extensions, the newly introduced particles and interactions may change the Higgs potential, giving a FOPT and inducing the detectable gravitational waves. On the other hand, the DM, either scalar or fermion, may exist in some hidden sector that couples to the visible sector very weakly via the Higgs portal, and the scalar potential in such a hidden sector may also trigger a FOPT and induce the gravitational waves.

In this note, we briefly survey some typical Higgs-related BSM physics models, including the low energy SUSY (focusing on the minimal SUSY model), the little Higgs models, the 2HDMs and the simple singlet extensions of the Higgs sector. For each illustrated BSM model, we will emphatically discuss its phenomenological power in light of current measurements of the muon $g-2$, the W-boson mass and the DM. For the singlet extensions, we will emphasize the induced cosmic phase transition and the DM relic density as well as the vacuum stability. The demonstrated numerical results are from our previous works, whereas we try to cite relevant works as completely as possible.

2. Low Energy SUSY

2.1. A Light Higgs Boson in SUSY

So far, the LHC experiments are consistent with the elementary Higgs boson predicted by SM. To accommodate such a light elementary scalar particle, low energy SUSY is the most natural framework [43].

In the SM, the masses of fermions or gauge bosons are prohibited by gauge or chiral symmetry. However, the Higgs boson mass is not protected by any symmetry, and it has a quadratic divergence from loop corrections. Therefore, it is sensitive to the UV cut-off energy scale. However, in SUSY, the quadratic divergences from the loop corrections to the Higgs boson mass are "technically" canceled out and only logarithmic divergences remain. So, the Higgs boson mass is stabilized at the weak scale, which is not sensitive to the UV cut-off energy scale.

In SUSY, due to the holomorphicity requirement of the Yukawa couplings, the Higgs sector must be extended to two Higgs doublets H_u and H_d with opposite hypercharges to give masses to both up-type and down-type quarks after electroweak symmetry breaking. As the most economical SUSY model, the MSSM predicts five Higgs bosons, among which the lightest CP-even h is the SM-like Higgs in the decoupling limit, i.e., all other Higgs bosons being sufficiently heavier than the Z-boson mass m_Z, the couplings of h with the SM particles approach the SM predictions. m_h is upper bounded by about 135 GeV in the MSSM,

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right], \tag{1}$$

where $v = \sqrt{v_u^2 + v_d^2} = 246$ GeV with the vevs of two Higgs fields $v_u \equiv \langle H_u \rangle$ and $v_d \equiv \langle H_d \rangle$, β is defined by $\tan\beta = v_u/v_d$, M_S is the geometric average of two stop masses $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ defined to be the SUSY-breaking scale, and X_t is the stop mixing parameter given by $X_t = A_t - \mu/\tan\beta$ with A_t being the stop soft trilinear coupling and μ being the higgsino mass parameter. Therefore, a larger value of $\tan\beta$ is required to maximize the tree-level contribution $m_Z|\cos 2\beta|$, a large M_S value is favored to enhance the logarithmic contribution, and a large stop trilinear coupling $X_t = \sqrt{6}M_S$ can enhance the stop loop contribution [44]. To see this clearly, we perform a scan using the package FEYNHIGGS [45], where the higher-order corrections are from the two-loop level and from the log-resummations at the NNLL level. We vary the sensitive parameters in the ranges

$$0.5 \text{ TeV} \le M_{Q3} = M_{U3} = M_{D3} \le 100 \text{ TeV}, \quad |X_t| \le \sqrt{6 m_{\tilde{t}_1} m_{\tilde{t}_2}}, \quad 1 < \tan\beta < 50. \tag{2}$$

where M_{Q3}, M_{U3}, and M_{D3} are the third-generation squark soft masses. Higgsinos and gauginos are assumed to not be so heavy, i.e., $M_1 = M_2/2 = 1$ TeV and

$$100 \text{ GeV} \le \mu \le 350 \text{ GeV}. \tag{3}$$

Other soft mass parameters, such as the gluino mass M_3, are fixed at 100 TeV. We see from Figure 2 that for a stop in the range of 0.5–100 TeV, the mass of h is approximately in the range of 80–135 GeV. This means that a light Higgs boson is predicted in the MSSM. In comparison, in the SM, the Higgs mass is a free parameter. The requirement of vacuum stability [46,47] and non-triviality [48] restrain the Higgs mass in the range of 40–800 GeV if the UV cut-off scale is around TeV [49].

Therefore, the LHC discovery of a light Higgs boson around 125 GeV can be regarded as a triumph of low energy SUSY. On the other hand, from the detailed analysis in [50] or our Figure 2 above, we see that for a moderate A_t in magnitude, the 125 GeV SM-like Higgs boson mass requires a relatively heavy stop above several hundred GeV, which is consistent with the lower mass bound around 500 GeV from the null search results of stops at the LHC [51] (note that the LHC bounds on the plane of stop mass versus the LSP mass show that for a sizable mass splitting between stop and LSP, the lower bound on the stop mass is about 1.2 TeV while for a stop mass near the LSP mass plus the top quark mass, the lower bound on the stop mass is only about 500 GeV). For a very small size or zero value of A_t, we see from Figure 2 that the 125 GeV SM-like Higgs boson mass requires a stop mass heavier than 3 TeV.

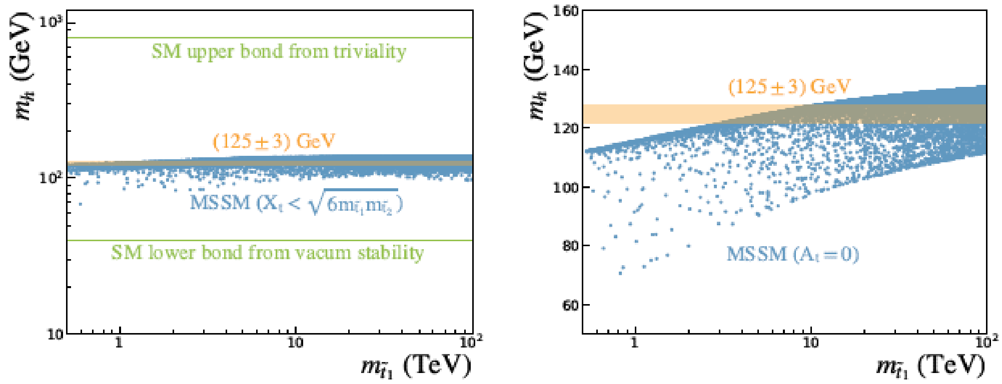

Figure 2. The scatter plots showing the mass of the SM-like Higgs boson versus the stop mass in the MSSM. The SM upper and lower bounds are from the requirement of vacuum stability and non-triviality for the UV cut-off scale around TeV [49].

2.2. DM, Muon $g-2$ and W-Mass in SUSY

In addition to naturally predicting the Higgs boson mass, the beauty of SUSY is also reflected in its ability to jointly explain the muon $g-2$ reported by the FNAL and the W-boson mass measured by the CDF II as well as provide the observed DM relic density under direct detection limits [27,28]. However, such a joint explanation requires a light stop just below 1 TeV in the MSSM [27], as shown in Figure 3, which should be accessible at the next run of the LHC.

Note that without the anomaly of the W-boson mass, the single anomaly of the muon $g-2$ can be readily explained in various low energy effective SUSY models [52–80]. In any case, the sleptons in the loop contributions to the muon $g-2$ cannot be too heavy and may be discovered at the HL-LHC, as shown in Figure 4.

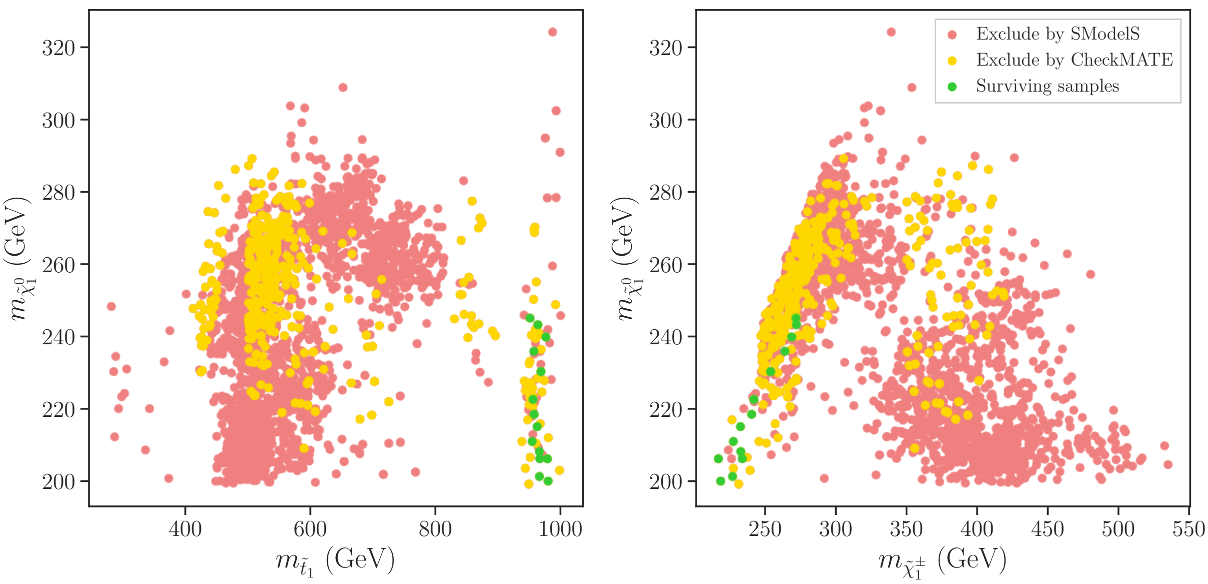

Figure 3. The scatter plots jointly explaining at 2σ level the muon $g-2$ reported by the FNAL and the W-boson mass measured by the CDF II as well as providing the correct DM relic density under direct detection limits. This figure is taken from our previous work [27].

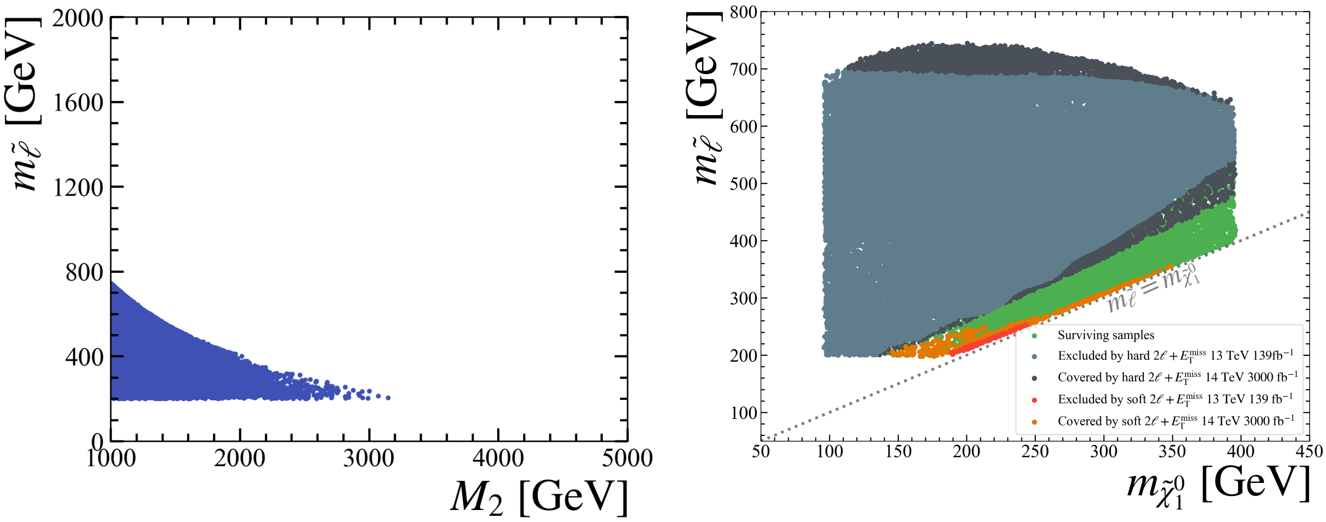

Figure 4. The scatter plots explaining at 2σ level the muon $g-2$ reported by the FNAL, with the higgsino (μ in the range of 100–400 GeV) as the lightest super particle satisfying the 2σ upper bound of the DM relic density and the direct detection limits. This figure is taken from our previous work [79].

One of the most appealing features of low energy SUSY is that the lightest neutralino can act as a typical WIMP, which remains one of the most extensively studied particles despite not having been experimentally probed yet. At the sub-TeV scale, the current direct detection data on DM favor the WIMP being a gauge singlet particle, such as the singlino in the NMSSM[2]. Hence, the muon $g-2$ and the W-boson mass anomaly would have more significance in the phenomenology of LHC/HL-LHC. On the other hand, the higgsino DM that exceeds TeV, for instance, is considerably beyond the limits of LHC probing.

What is unusual[3] is that the MSSM may be the common source of [85,86] the muon $g-2$ anomaly and the negative 2.4σ deviation of the electron $g-2$ between the experimental value [87] and the SM prediction [88] from the measurement of the fine structure constant by the Berkeley experiment [89]. As shown in Figure 5, such a joint explanation at the 2σ level requires a specific parameter space, in which a rather light bino-like LSP and a light higgsino-like NLSP as well as a large $\tan\beta$ are used to predict a positive contribution to the muon $g-2$ and a negative contribution to the electron $g-2$. In this case, the thermal freeze-out of the bino-like LSP gives an over-abundance and cannot be assumed to be the DM candidate (the DM can be some superWIMP as light as GeV and produced from the late-decay of the thermally freeze-out bino-like LSP). Note that the MSSM is found [90–92] to be unable to realize a FOPT due to the current lower mass bound on the stop mass.

However, the MSSM with boundary conditions at the cut-off scale, say the CMSSM or mSUGRA with boundary conditions at the GUT scale, cannot explain the muon $g-2$ or the W-boson mass because sleptons and stops are both too heavy [62]. To explain the muon $g-2$, the boundary conditions at the cut-off scale have to be relaxed [93–96].

The NMSSM [97] extends the MSSM with a gauge singlet superfield, and thus it contains one extra neutralino, named a singlino. With the continuously improving sensitivity of DM direct detections, the singlino-like DM candidate [68,98] has some special phenomenological advantages. For example, the parameter space of the higgsino-like DM in MSSM can not provide a sufficient relic density in explaining the $g-2$ anomaly in front of the LHC data; while in the NMSSM, the corresponding parameter space can be released for the singlino-like DM co-annihilating with the higgsino-like NLSP to relax the experimental tensions. Moreover, the electroweakinos may generate sufficiently large contributions to the W-boson mass [28].

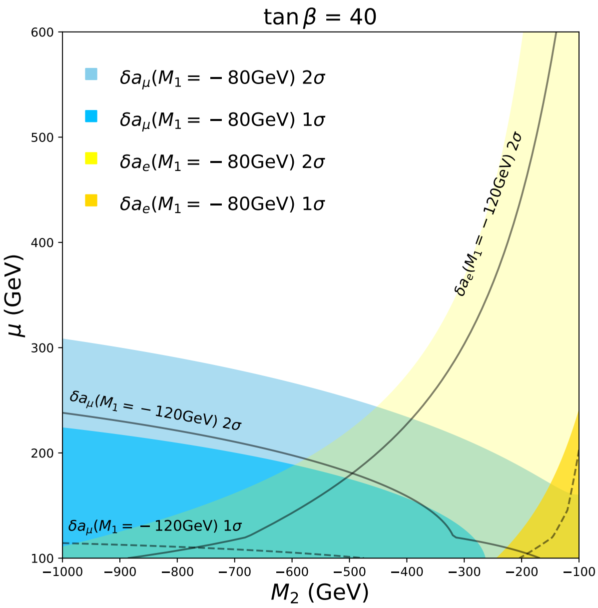

Figure 5. The MSSM parameter space explaining both anomalies of the muon $g-2$ reported by the FNAL and the electron $g-2$ from the Berkeley experiment [89]. This figure is taken from our previous work [85].

The extra singlet Higgs can also achieve the non-zero vev in electroweak symmetry breaking, which can predict a FOPT [99–106] in single- or multi-steps and may also induce the possibly detectable gravitational waves [106,107].

In summary, so far the low energy SUSY can survive all current experiments and explain the plausible experimental anomalies. The light relevant sparticles required by the explanations of anomalies, e.g., light sleptons required by the muon $g-2$ [59,79] or light stops required by the CDF II W-mass [27], should be accessible at the ongoing LHC or the forthcoming HL-LHC. The only problem of low energy SUSY is that it now has a little fine-tuning (percent level for the phenomenological MSSM and per-mille level for the CMSSM [108]) caused by sizably heavier stops than the weak scale[4]. To tackle the little fine-tuning caused by heavy stops, the idea of supersoft stops was proposed to screen the UV-sensitive logs [110].

3. Little Higgs Models

3.1. A Light Higgs in Little Higgs Models

Another popular way to obtain a light Higgs boson naturally is to make the Higgs boson a pseudo-Nambu–Goldstone boson of some broken global symmetry. This idea was proposed in the 1970s, and based on this idea, a model was constructed [111–113] in the 1980s. However, this still needs fine-tuning from the weak scale to the cut-off scale. In the early 21st century, inspired by dimension (de)construction [114], the collective symmetry breaking mechanism was introduced to build some little Higgs models [14,15]. The little Higgs is usually classified into the composite Higgs models, which are not surveyed here (for a review, see, e.g., [115]).

The collective symmetry breaking mechanism is the key point to give the Higgs boson a small mass without incurring a quadratic divergence at the one-loop level. In this mechanism, at least two kinds of interactions (say gauge interactions with coupling constants g_1 and g_2) are introduced and they collectively work to break the global symmetry to give the Higgs boson a mass. Switching off any of them, i.e., $g_1 = 1$ or $g_2 = 0$, the remaining interaction is not sufficient to fulfill this mission. In realization, different groups and breaking modes can be selected. According to how the electroweak gauge group of the SM is obtained from symmetry breaking, the little Higgs models can be product-group models [116–120] or simple-group models [121–123]. A product-group model has multi-

$SU(2) \times U(1)$ gauge groups that break to the electroweak gauge group. The most popular product-group model is the littlest Higgs model, which utilizes the product gauge group $[SU(2) \times U(1)]^2$ [116]. A simple-group model usually has $SU(N) \times U(1)$ gauge groups, which break to the electroweak gauge group. A typical simple-group model is the simplest little Higgs model, which employs the gauge group $SU(3) \times U(1)$ [121,122].

Obviously, these models may give slightly different Higgs couplings and thus different signal rates at the LHC compared with the SM. For example, compared with the SM predictions, at the LHC, the Higgs production and decay rates can be altered [124–127], especially the di-photon signal rate always being suppressed [128] and the signal rates of the Higgs pair production being sizably different [129,130]. Therefore, the LHC Higgs data can constrain the little Higgs models critically [131]. Another important phenomenology is in the top quark physics [132–134], because these models have to treat the top quark sector specially in order to cancel the quadratic divergence of the Higgs mass caused by the top quark loops.

3.2. DM and W-Mass in Little Higgs Models

The most interesting model seems to be the LHT because it can weaken the stringent constraints from the electroweak precision data and provide a DM candidate. The littlest Higgs model, a nonlinear sigma model with a global $SU(5)$ symmetry breaking down to $SO(5)$ by a Higgs vev of order f, predicts new heavy gauge bosons, T-quarks and a scalar particle Φ, which cancel the one-loop quadratic divergences from the SM gauge bosons, top quarks, and Higgs self-interactions, respectively. These new particles couple to the SM particles at the tree level. In particular, the couplings of the new heavy gauge bosons with the SM fermions will incur stringent constraints from the electroweak precision data, pushing the scale f of the model above a few TeV and re-incurring a little fine-tuning to the Higgs mass [135–137]. Similar to the R-parity in SUSY, a similar discrete symmetry called T-parity [138–141] can be imposed to prohibit those interactions that incur strong constraints from the electroweak precision data. If the lightest T-odd particle is neutral (as with the heavy photon A_H) and the T-parity is conserved, it can serve as a DM candidate. For the SM down-type quarks and leptons, the Higgs couplings of LHT have two different cases called, respectively, LHT-A and LHT-B [126,142].

Assuming the heavy photon A_H is the lightest T-odd particle in the LHT, it can serve as a DM candidate. In [131,143], the heavy photon relic density was found to be able to account for the Planck data for the small mass splitting between a mirror lepton and the heavy photon. However, the parameter space for a correct relic density was severely constrained into the range of $m_{A_H} \in [95, 600]$ GeV by the LHC Higgs data. As shown in Figure 6, under the LHC constraints, the allowed parameter space has been almost excluded by the XENON1T(2017) (we checked that the recent LZ experiment result [144] has totally excluded the parameter space).

For the little Higgs explanations of the W-boson mass, it was found [145] (based on previous calculations [137]) that the littlest Higgs model can give a sufficient contribution to explain the CDF II measurement at the 2σ level if the scale f is below 9 TeV. However, such a parameter space violates the T-parity of the LHT and is also not viable for the simplest little Higgs model [145]. For the little Higgs explanations of the muon $g-2$, it is found that the littlest Higgs model [146,147] and LHT [148] give very small contributions to the muon $g-2$ so that the result of the FNAL plus BNL cannot be explained.

The littlest Higgs model is found [149,150] to be unable to realize a FOPT in the allowed temperature range of the model ($0 < T < 4f$), assuming the UV completion factors give the SM electroweak minimum. With the same set of UV completion factors, the LHT is found [150,151] to be able to realize a non-standard FOPT at the TeV scale through which a broken phase is converted into a symmetric phase.

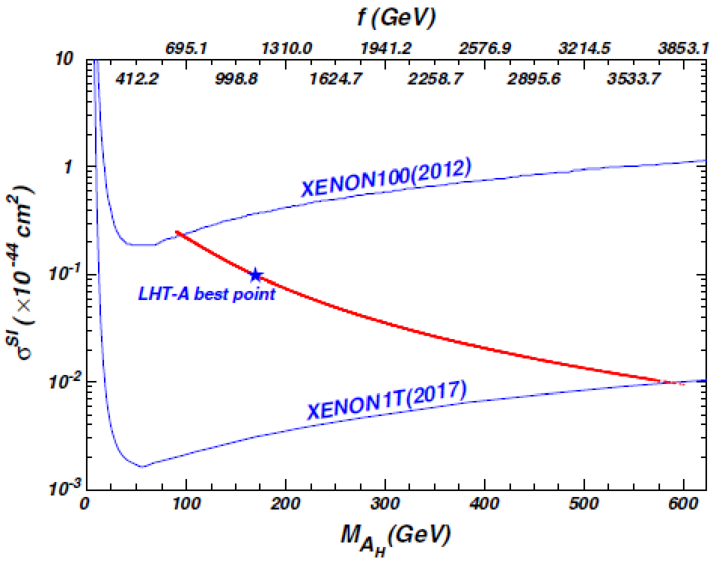

Figure 6. The LHT parameter space allowed by the Planck DM relic density and the CMS Higgs data at the 2σ level, projected on the plane of the spin-independent scattering cross-section off the nucleon versus the heavy photon mass. The best point is with minimal χ^2 value for the CMS Higgs data and with the relic density closest to the measured central value. This figure is taken from our previous work [143].

4. Two-Higgs-Doublet Extensions

4.1. Simplicity of 2HDMs

A 2HDM is an extension of the SM by merely extending the Higgs sector to two weak doublets of scalars, which was first proposed by T. D. Lee [152]. Such an extension predicts five Higgs bosons, and in the CP-conserving version they can be classified into a neutral pseudoscalar, a pair of charged scalars, and two neutral CP-even scalars with one being the SM-like Higgs. Unlike the two Higgs doublets in SUSY, which restrain the Higgs quartic interactions to be gauge couplings and thus predict a light Higgs boson below 135 GeV, a 2HDM has quite a few free couplings for the Higgs doublets and does not have the predictive power for a light Higgs boson. Thus, the 2HDMs cannot address the naturalness problem. The motivation of 2HDM may be that we need to extend the SM Higgs sector because we need more CP-violation phases for baryogenesis and we need the extension to provide the FOPT as discussed in the following. In other words, the SM Higgs sector is too simple to provide CP-violation phases and the FOPT, both of which are needed by electroweak baryogenesis. Compared with the singlet extension of the SM, a 2HDM is not so simple, but it is much simpler than any other fancy frameworks such as SUSY or little Higgs theory. So, 2HDMs have simplicity and bring more light than heat.

To avoid tree-level flavor-changing neutral currents, an additional Z_2 symmetry is usually imposed and hence forbids some couplings in the Higgs potential. According to the Z_2 charge assignments of scalar doublets and the fermions, the 2HDMs can be classified as the type-I [153,154], the type-II [153,155], the lepton-specific (or type-X), the flipped [156–161], the inert [162–165], etc. (i) In the type-I model, the imposed Z_2 symmetry allows one Higgs doublet to couple with fermions and forbids the other Higgs doublet to couple with fermions; (ii) The type-II model is similar to the SUSY case, with one Higgs doublet coupling to up-type quarks while the other Higgs doublet couples to down-type quarks and leptons; (iii) The flipped model is same as the type-II, except that one Higgs doublet couples to up-type quarks and leptons while the other Higgs doublet couples to down-type quarks; (iv) The lepton-specific model is rather specific, in which one Higgs doublet couples with quarks and the other Higgs doublet couples with leptons; (v) In the inert model, the Z_2 charge is even for all the SM fields while it is odd only for the newly introduced Higgs doublet Φ_2, which is hence called an inert doublet and has no vev. This inert doublet cannot couple with fermions and its lightest neutral field is stable. Of course, such Z_2 charge assignments seem to be ad hoc and do not make any deep sense.

Although the 2HDMs cannot address the naturalness problem, their phenomenology is quite rich. Due to the multi-free parameters, the parameter space of the 2HDMs can survive from the current LHC Higgs data and the searches for exotic scalars. Unlike the SM, in the parameter space allowed by the current LHC Higgs data, the extended Higgs sector in 2HDMs can realize all three Sakharov conditions, and possibly achieve the FOPT [166–170]. Some specific models even have the power of providing a DM candidate and explaining the anomalies of the muon $g-2$ and W-boson mass.

4.2. DM, Muon $g-2$ and W-Mass in 2HDMs

DM is pretty hard to explain in 2HDMs because it is not what these models were originally designed to solve. In a sense, this forced explanation is just like gilding the lily for the 2HDMs, which requires ad hoc Z_2 charge assignments or introducing a DM (say a singlet scalar) to the models. In the inert 2HDM, the lightest neutral field of the inert doublet is stable and thus can serve as the DM candidate [171,172]. However, with various theoretical and experimental constraints, especially the DM direct detection limits, the parameter space for a correct relic density is highly restrained (for a recent study, see, e.g, [173]). A more promising scenario is the type-II 2HDM extended by introducing a real singlet scalar S under a Z_2 symmetry [174]. In this scenario, the SM-like Higgs boson may have wrong-sign Yukawa couplings with down-type quarks, which give isospin-violating interactions between the DM and nucleons, relaxing the constraints from the DM direct detection [175]. Other scenarios to satisfy the DM direct detection limits include introducing a DM to a general 2HDM, which has blind spots for the DM scattering off the nucleons [176–181], or introducing a DM to the lepton specific 2HDM where the Higgs portal has suppressed couplings with the quarks [182].

Putting aside the DM, which may be an axion, we check the muon $g-2$ in the 2HDMs. Among these models, the lepton-specific 2HDM can make sufficient contributions to the muon $g-2$ to explain the FNAL measurement. In this model, the Yukawa couplings of exotic Higgs bosons with the leptons can be greatly enhanced, and the analysis in [183] showed that the muon $g-2$ explanation favors wrong-sign Yukawa couplings between the SM-like Higgs and the leptons. Because of the interference contributions between the W-loop and top quark loop, the wrong-sign Yukawa coupling of the top quark is disfavored by the 125 GeV Higgs signal strengths. However, the wrong-sign Yukawa couplings of light quarks and leptons are still consistent with the Higgs boson signal strengths. Besides the muon $g-2$, this model is found to be able to provide the FOPT under the current LHC constraints [184]. However, to explain the muon $g-2$, this model can hardly satisfy the lepton flavor universality in τ decays and hence some further extensions are needed, such as the lepton-specific inert 2HDM [185], the $\mu-\tau$-philic Higgs doublet model [186,187], the muon-specific 2HDM [188], the perturbed lepton-specific 2HDM [189], the aligned 2HDM [190–192], the 2HDM with vectorlike leptons [193], the inert 2HDM [194], etc.

To jointly explain the muon $g-2$ and the W-boson mass, some specific 2HDMs can make it, such as the 2HDM with $\mu-\tau$ LFV interactions [30], the lepton-specific 2HDM with a Higgs-phobic light pseudoscalar [32], the inert 2HDM with an inert charged Higgs singlet plus a vector-like singlet quark and two neutral leptons [34], the 2HDM plus an additional light pseudoscalar and a stable isosinglet massive fermion [33], etc. All these specific models seem to be a little unnatural or weird. In the following, we take the 2HDM with $\mu-\tau$ LFV interactions as an example to show the joint explanation. Of course, without the muon $g-2$, the explanation of the W-boson mass and the FOPT can be relatively easier in the 2HDMs, albeit sensitive to the mass splittings of the exotic Higgs bosons [195,196].

The 2HDM with $\mu-\tau$ LFV interactions is a kind of inert 2HDM except that a Z_4 symmetry is introduced and it allows the inert Higgs doublet to couple with $\mu-\tau$ [186]. Only the exotic Higgs bosons from the inert doublet have $\mu-\tau$ LFV Yukawa couplings, while the SM-like Higgs boson has the SM couplings with the gauge bosons and fermions.

The analysis showed [30] that under current experimental constraints this model has some parameter space to simultaneously satisfy the W-boson mass and the muon $g-2$ as well as the lepton universality in τ-decays. As shown in Figure 7, such a parameter space is rather narrow, which requires tight mass splittings among the exotic Higgs bosons $(H, A, H^{\pm})$. Considering the joint bounds of the 125 GeV Higgs signal, the DM relic density, and the DM detection experiments, there are three allowed DM mass regions in the inert 2HDM: $m_{DM} \sim \frac{m_h}{2}$, 73 GeV $< m_{DM} <$ 75 GeV, and $m_{DM} >$ 500 GeV.

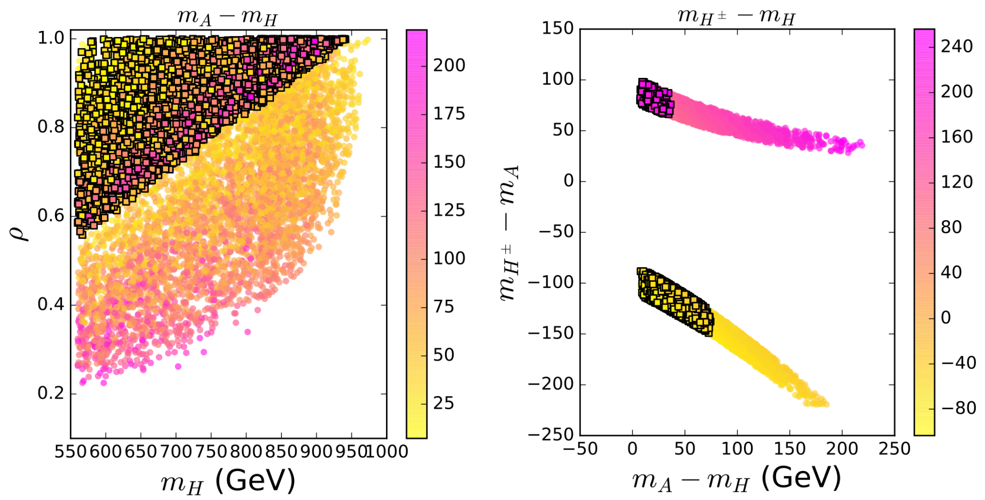

Figure 7. Scatter plots of the parameter space of the 2HDM with $\mu - \tau$ LFV interactions: the dark squares (light bullets) satisfy the data of the muon $g-2$ and the W-boson mass at the 2σ level with (without) the constraints of τ-decays. This figure is taken from our previous work [30].

5. Singlet Scalar Extensions

5.1. Cosmic Phase Transition in Singlet Scalar Extensions

As shown in Figure 8, the early hot universe may have a simple U-shape Higgs potential, while the cold universe may have a Mexican-hat Higgs potential. The transition property between the two shapes is very sensitive to the form of Higgs potential. If the net baryon number is generated by the electroweak baryogenesis [197], the Higgs sector of the SM, which merely gives a rapid smooth cross-over [198,199] instead of a phase transition, must be extended to realize a strong FOPT. Such an EWPT occurs when the temperature of the universe decreases from an extremely high value to near 100 GeV, and then the universe deviates from the thermal equilibrium to realize baryogenesis. When the phase transition is completed, the universe enters into the electroweak broken phase and the Higgs field develops a non-zero value.

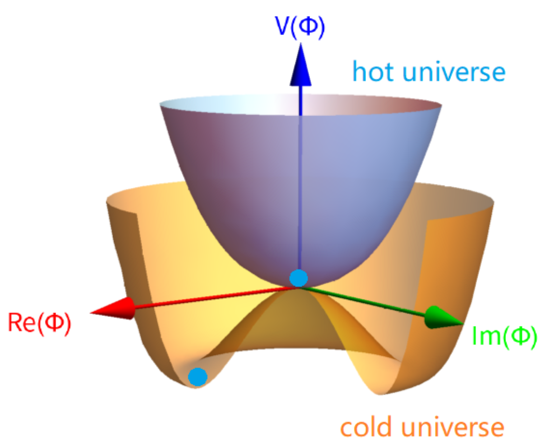

Figure 8. The likely shapes of the Higgs potential at the early hot universe and the cold universe.

To achieve a strong FOPT and also account for the cosmic cold DM, some simple singlet extensions will make it, such as the xSM [200–205]. A slightly more complex model is the 2HDM plus a singlet (2HDM+S) [174] and the NMSSM [97]. Note that, currently, the xSM as an explanation for DM has a very narrow parameter space, with the scalar DM mass being near the Higgs resonance (56–62 GeV) or above 1 TeV [201,206,207], which can be relaxed by introducing some high dimensional operators [208]. Of course, the mysterious DM may just reside in the dark sector or be called the hidden sector, which interacts with the visible sector via the Higgs portal very weakly (for recent studies, see, e.g., [209,210]). In this case, the dark sector scalar potential may also trigger a FOPT in the early universe and the only way to access it is through detecting the induced gravitational wave [209].

In singlet extensions such as the xSM, we have the Higgs field h and a real singlet scalar s, and the phase transition occurs usually in two steps shown in Figure 9: the first step is from the symmetric phase $(h,s) = (0,0)$ to the singlet-broken phase $(h,s) = (0,v_s)$ while the second step is from $(h,s) = (0,v_s)$ to the electroweak vacuum $(h,s) = (v_h,0)$.

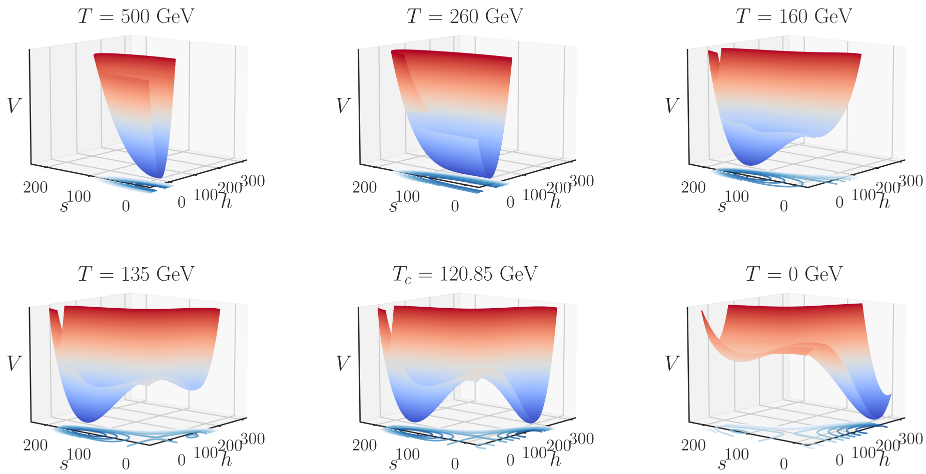

Figure 9. An illustrative diagram of effective potential developing as the temperature is dropping for the xSM, using a benchmark point taken from our previous work [211].

5.2. Vacuum Stability and DM in Singlet Scalar Extensions

As shown in Figure 9, in the xSM the first-step phase transition from the symmetric phase $(h,s) = (0,0)$ to the singlet-breaking phase $(h,s) = (0,v_s)$ occurs quite early at a very high temperature. Then, for the universe to be in a correct electroweak vacuum, the second-step phase transition from $(h,s) = (0,v_s)$ to $(h,s) = (v_h,0)$ must subsequently happen at a low temperature. Obviously, only checking the vacuum situation at zero-temperature cannot guarantee the vacuum's stability because the second-step phase transition shown in Figure 9 may not happen in the thermal evolution of the universe. In other words, if we only examine the vacuum at zero-temperature, we usually say we have the correct vacuum if (i) the electroweak vacuum is the global vacuum, or (ii) the electroweak vacuum is a meta-stable vacuum (its transition time to the global vacuum is longer than the age of the universe). Our recent analysis [211] showed that these two cases should be carefully checked for the whole thermal history. Even if the electroweak vacuum is the global vacuum at zero-temperature, the second-step phase transition shown in Figure 9 may not happen in the thermal evolution of the universe. For the meta-stable electroweak vacuum at zero-temperature, the universe may always reside in the singlet-breaking vacuum, which never transits to this electroweak vacuum.

This unusual effect is often overlooked in studies of the vacuum stability, and the thermal history of the universe may be like this: In the very beginning, we have an extremely hot and dense universe with electroweak symmetry. As the universe expands and the temperature drops, bubbles with broken electroweak symmetry are formed in some regions of the plasma of the universe due to fluctuations. If the driving force of the bubble's expansion is always less than the resistance, then the bubbles with broken electroweak symmetry will contract, leaving the universe trapped in a state with unbroken electroweak symmetry. In addition, the early universe may have a phase transition into other vacuums (say a color-breaking vacuum) whose free-energy is always lower than the free-energy of the physical electroweak vacuum.

As a result, it was found [203,211–213] that for the xSM a large part of the parameter space allowed by only checking the zero-temperature vacuum can be excluded by checking the thermal history of the universe, as shown in Figure 10. A similar story may happen for the phase transitions in SUSY models [105,214] or the 2HDMs [215].

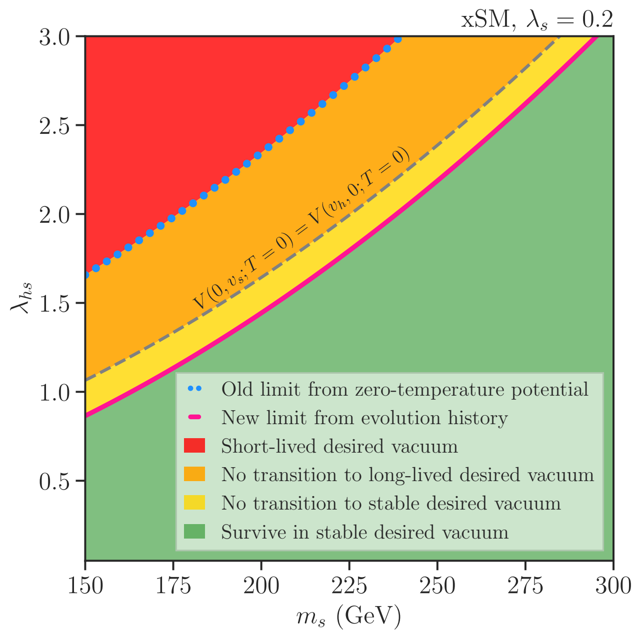

Figure 10. The xSM parameter space excluded by checking the thermal history of the universe, taken from our previous work [211].

These singlet extensions, e.g., xSM, 2HDM+S or NMSSM, can provide a cold DM candidate besides an electroweak FOPT [216]. The temperature at which the electroweak FOPT occurs may be close to the freeze-out temperature of the DM, and so the electroweak FOPT may affect the relic density of the DM in several ways: (i) the deviation from the thermal equilibrium caused by the phase transition may affect the size of the universe and thus change the density of DM; (ii) the particle masses may change after the phase transition, which determine the decay modes of the particles; (iii) the bubble walls formed during the phase transition may filter out most of the DM, leaving only a small amount of it. A recent analysis [217] studied the dilution of the DM relic density caused by the electroweak FOPT in the singlet extension models. It was found that the entropy released by the electroweak FOPT can maximally dilute the relic density to one third. For the xSM and NMSSM with the singlet field being relevant to the phase transition temperature, the phase transition always happens before the DM freeze-out, and hence the dilution effect is negligible for the current relic density. However, for the 2HDM+S with the freeze-out temperature being independent of the FOPT, the dilution effect may be significant. The 2HDM+S can be regarded as the doublet extension of xSM in a sense. The Higgs state h is a superposition of the neutral part of two Higgs doublets, and the electroweak FOPT is also closely related to the mixing of Higgs doublets. Therefore, as shown in Figure 11, the electroweak FOPT can significantly dilute the DM density in the thermal history of the universe, and the dilution factor d is sensitive to the doublet Higgs mass mixing term m_{12}[5].

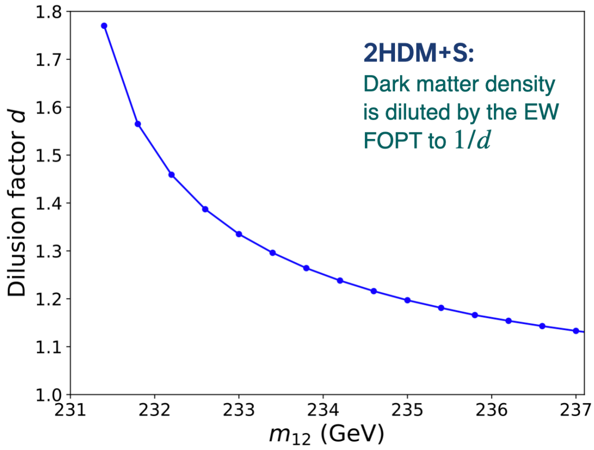

Figure 11. The dilution factor d versus the mass parameter m_{12} for the 2HDM+S, taken from our previous work [217]. The DM density is diluted by the electroweak FOPT to $1/d$.

6. Summary and Outlook

For the Higgs-related BSM physics, we concisely surveyed some popular models, including the low energy SUSY, the little Higgs theory, the 2HDMs and the simplest singlet extensions of the Higgs sector. For each illustrated BSM model, either simple or complex, we see that it has its own specific features and some phenomenological power, as summarized in Table 1. Among these models, the low energy SUSY seems to be the most compelling in phenomenology.

For the new physics models illustrated in Table 1, they will be directly searched for at the LHC. The ongoing Run-III of the LHC will deliver about 150 fb^{-1} of data, while the next phase of LHC, namely the HL-LHC, scheduled to start in 2027, is expected to collect 3000–4000 fb^{-1} of data with a collision energy of 14 TeV. The parameter space of each model will be further covered substantially at the HL-LHC, e.g., the SUSY parameter space accessible at the HL-LHC is shown in Figure 10 in [12]. We also have dozens of ongoing experiments around the world looking for DM and the experiments at Fermilab and J-PARC measuring the muon $g-2$. Some colliders for precision tests, such as CEPC, FCC and ILC, are being planned, which will precisely measure the Higgs property. In addition, various gravitational wave detection experiments, such as the LIGO, LISA, Taiji or Tianqin, will have a certain ability to explore BSM physics related to the phase transition in the early universe. All these experiments can allow for direct or indirect probes of these new physics models. So, leave no stone unturned.

Table 1. The phenomenological merits of some typical Higgs-related new physics models.

	Naturalness	**DM**	**FOPT**	**Muon $g-2$**	**W-Mass**
xSM	✗	✓	✓	✗	✗
2HDMs	✗	✓	✓	✓	✓
low energy SUSY	✓ [1]	✓	✓ [2]	✓	✓
little Higgs theory	✓ [3]	✓	✓	✗	✓

[1] Note here that the naturalness does not mean a perfect naturalness. In SUSY, the tuning extent is at the percent level for the MSSM and at the per mille level for the CMSSM [108]. [2] The MSSM is found to be unable to realize FOPT, and here we mean the extended SUSY model such as NMSSM. [3] The little Higgs theory has no quadratic divergence merely at the one-loop level.

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Abbreviations

BSM	beyond the standard model
LHC	Large Hadron Collider
SM	standard model
SUSY	supersymmetry
2HDM	two-Higgs-doublet model
EWPT	electroweak phase transition
FOPT	first-order phase transition
MSSM	minimal supersymmetric standard model
UV	ultraviolet
NMSSM	next-to-minimal supersymmetric standard model
HL-LHC	High-luminosity Large Hadron Collider
LSP	lightest supersymmetric particle
NLSP	next-to-lightest sparticle
WIMP	weakly interacted massive particle
DM	dark matter
GUT	grand unification theory
CMSSM	constrained minimal supersymmetric standard model
mSUGRA	minimal supergrivity
2HDM+S	2HDM plus a singlet
LHT	littlest Higgs model with T-parity
vev	vacuum expectation value
LFV	lepton flavor violation
xSM	SM plus a singlet

Notes

1. Neutrinos in the SM (the active neutrinos) are massless. However, the explanation of the neutrino mass by introducing right-handed neutrino N_R via the Yukawa interaction like other fermion fields might not be the whole story of nature. Since N_R is sterile, the gauge symmetry allows N_R to acquire the Majorana mass M, and therefore it does not pair up with the active neutrino to make up a Dirac fermion. N_R carries the lepton number, so the neutrino mass is often related to the flavor physics. If M is very large, the only dimension-5 operator allowed by the SM symmetries can generate the active neutrino mass of order v^2/M, where v is the SM Higgs vev. This idea is called the "seesaw" mechanism. The neutrino masses may be also closely related to the origin of flavor mixings, the CP violation and the fermion mass hierarchy, and the neutrino phenomenology is relatively far from the Higgs field. So, in this review, we will not discuss neutrinos further. For the reviews on neutrinos, see, e.g., [3–6].
2. In the representation of $SU(2)_L$, the MSSM can be seen as a realization of the "minimal DM models". In this view, the higgsino (wino) DM in SUSY is a typical triplet (doublet) DM in the minimal DM model [81–83].
3. The combined explanation often requires the introduction of a flavor violation, see Ref. [84].
4. However, an analysis [109] gave a ten percent level fine-tuning for low-energy SUSY.
5. In fact, all terms in the Higgs scalar potential have an effect on the thermal history, such as the Higgs diagonal mass terms m_{11} and m_{22}.

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