Dark matter, neutrino masses and high scale validity of an inert Higgs doublet model

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Abstract

We consider a two-Higgs doublet scenario containing three $SU(2)_L$ singlet heavy neutrinos with Majorana masses. The second scalar doublet as well as the neutrinos are odd under a $Z_2$ symmetry. This scenario not only generates Majorana masses for the light neutrinos radiatively but also makes the lighter of the neutral $Z_2$-odd scalars an eligible dark matter candidate, in addition to triggering leptogenesis at the scale of the heavy neutrino masses. Taking two representative values of this mass scale, we identify the allowed regions of the parameter space of the model, which are consistent with all dark matter constraints. At the same time, the running of quartic couplings in the scalar potential to high scales is studied, thus subjecting the regions consistent with dark matter constraints to further requirements of vacuum stability, perturbativity and unitarity. It is found that part of the parameter space is consistent with all of these requirements all the way up to the Planck scale, and also yields the correct signal strength in the diphoton channel for the scalar observed at the Large Hadron Collider.

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I. INTRODUCTION

The discovery of ‘a Higgs-like boson’ [1, 2], apparently completes the Standard electroweak model (SM). However, it also compells us to mull over the necessity of physics beyond the SM. To mention one motivation for this, a SM Higgs of mass around 125 GeV, can break the absolute stability of vacuum at $10^{8-9}$ GeV, if the top quark mass ($M_t$) and the strong coupling constant ($\alpha_s$) are on the upper sides of their respective uncertainty bands. A recent next-to-next-to-leading order (NNLO) study [3] reveals that absolute stability up to the Planck scale requires

$$M_h[GeV] > 129.4 + 1.4\left(\frac{M_t[GeV] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{th}$$ (1)

which, with all theoretical and experimental errors in $M_t$ and $\alpha_s$, implies that the absolute vacuum stability of SM is excluded at 95% CL for $M_h < 126$ GeV. To compensate the negative contribution from the fermion loops (mainly the top quark loop), which rapidly drives the quartic self-coupling of Higgs to below zero, we need extra scalar loops that can ameliorate the problem. This provides one of the important motivations to consider a theory with new scalars which can make the vacuum stable up to high scales while having consistent results at low scales.

At the same time it is worthwhile to remember two rather pressing issues which prompt one to look beyond the Standard Model (BSM). These are the non-zero mass and mixing of neutrinos and the likely existence of Weakly Interacting Massive Particle (WIMP), contributing to Dark Matter (DM). While various Solar, atmospheric, reactor and accelerator-based experiments provide strong evidence for non-zero masses of neutrinos and mixing among their different flavors, several astrophysical and cosmological observations suggest the existence of some exotic particles that constitute the DM content of the universe. Given all this, it is an attractive idea to look for a theory that can simultaneously address all of the aforesaid problems in one framework. Here we consider one such scenario.

We investigate a model, first proposed in reference [4], that extends the SM with an extra Higgs doublet and three right handed neutrinos with a $Z_2$ symmetry, under which all SM particles are even while this additional scalar doublet and the right-handed neutrinos are odd. This symmetry presents the additional doublet from having a vacuum expectation value (vev) thus vetoing the tree-level neutrino mass generation. Moreover, there exists a stable scalar particle in the form of the the lightest neutral mass eigenstate of the additional doublet, which yields an eligible DM candidate. The extra doublet is essentially an Inert Doublet. Although a lot of study has already taken place on minimal Inert Doublet models [5–23], the extra appeal of this model lies in the radiative generation of neutrino mass. Various features
of the specific kind discussed here have been studied earlier [24–32].

Our main motivation in this work lies in resolving the vacuum stability problem in this model with a 125 GeV SM Higgs. The renormalisation group (RG) evolution of the Higgs quartic coupling will be modified due to the contributions of the new scalar particles and right-handed fermions. Using these modified RG equations [given in Appendix A] to evaluate the scalar quartic couplings at different scales, demanding not only vacuum stability but also perturbativity of the couplings as well as unitarity of the $2 \rightarrow 2$ scattering matrix at each scale. Low energy values of the couplings that satisfy all these conditions up to some high scale correspond to ‘allowed’ regions of the low-energy theory valid up to those scales. Benchmark boundary values illustrate these ‘valid regions’. Further, we examine the candidate of the lightest $Z_2$-odd particle as DM candidate, and identify the allowed values of the couplings yield the right relic abundance. Next, we ensure that the DM candidate is consistent with the recent result of direct detection experiments. We identify a substantial region of the parameter space, which simultaneously satisfy the vacuum stability, perturbativity and unitarity requirements and accommodate the DM candidate with the correct relic density. We also examine the 125 GeV scalar and make sure that the signal strengths in the observed channels (such as diphotons) are consistent with data from the Large Hadron Collider (LHC).

We organize the paper as follows. In Section II, we briefly describe the model and its various features. In Section III, we explain all the theoretical constraints and collider constraints that we use in the RG running of different quartic couplings. Next, in Section IV, we discuss the DM aspects of this model. After explaining our analysis strategy in Section V, we present our results related to high-scale validity in Section VI. Finally in Section VII, we summarise our results.

II. THE RADIATIVE NEUTRINO MASS MODEL WITH AN INERT DOUBLET

In addition to the SM fields, the radiative neutrino mass model with an inert doublet [4], contains a Higgs doublet ($\Phi_2$) and three right handed (RH) neutrinos ($N_i$) with an unbroken $Z_2$ symmetry, under which the doublet and the right-handed neutrinos are odd while all other SM particles are even. Being odd under the symmetry, $\Phi_2$ does not acquire any vacuum expectation value (vev) and has no tree-level couplings to fermions.

The relevant Yukawa and mass terms are

$$-\mathcal{L}_Y = y_{ij} \bar{N}_i \Phi_2^\dagger \ell_j + h.c + \frac{M_i}{2} \left( \bar{N}_i^c N_i + h.c \right), (i, j = 1 - 3)$$ (2)

Here $\ell_i$ are the left-handed lepton doublets and $M_i$ are the Majorana mass term for the
heavy right-handed neutrinos $N_i$

The scalar potential is

$$V = \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + h.c. + m_{\Phi_1}^2 \Phi_1 \Phi_1^\dagger + m_{\Phi_2}^2 \Phi_2 \Phi_2^\dagger$$

(3)

where all parameters are real, and $\Phi_1$ is the SM Higgs doublet.

The two scalar doublets can be written as

$$\Phi_1 = \left( \begin{array}{c} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG) \end{array} \right) \quad \text{and} \quad \Phi_2 = \left( \begin{array}{c} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{array} \right)$$

(4)

where, $v = 246$ GeV, is the electroweak vacuum expectation value (vev). One thus has five physical states $(h, H, A, H^\pm)$ and three Goldstone bosons $(G, G^\pm)$. While $h$ corresponds to the physical SM-like Higgs field, the inert doublet components are one CP-even neutral scalar $(H)$, one CP-odd neutral scalar $(A)$ and a pair of charged scalars $(H^\pm)$. The physical masses are given by

$$M_{H^\pm}^2 = m_{\Phi_2}^2 + \frac{1}{2} \lambda_3 v^2$$

$$M_H^2 = m_{\Phi_2}^2 + \lambda_L v^2$$

$$M_A^2 = m_{\Phi_2}^2 + \lambda_A v^2$$

(5)

where $\lambda_{L/A} = \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5)$. The value of $\lambda_1$ is determined using $M_h = 125$ GeV.

Majorana masses for the light neutrinos are generated radiatively through one-loop exchange of the $Z_2$-odd neutral scalars. The general expression for the loop-induced contributions to the light neutrino mass matrix [4] is

$$M_{\nu}^{ij} = \sum_{k=1}^{3} \frac{y_{ik} y_{jk} M_k}{16\pi^2} \left[ \frac{M_H^2}{M_H^2 - M_k^2} \ln \frac{M_H^2}{M_k^2} - \frac{M_A^2}{M_A^2 - M_k^2} \ln \frac{M_A^2}{M_k^2} \right]$$

(6)

Thus, the neutrino masses and mixing are determined by the inert scalar masses and the right-handed neutrino masses $M_i$. These masses represent the scale of lepton number violation and hence that of leptogenesis in this model. With the lightest of the Majorana masses $M_i$ denoted by M; we use M in two different regions, each of them being consistent with leptogenesis [33, 34]. These are, (a) $M = 10^4$ GeV and (b) $M = 10^{12}$ GeV. For simplicity, we consider only one diagonal Yukawa coupling ($y_\nu$). To determine, the value of this Yukawa coupling, we scan over $M_H$ and $M_A$ for a given value of M, keeping $M_\nu \sim O(0.1 \text{ eV})$. As

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1 A more rigorous study with the intricate flavor structure of the neutrino Yukawa matrix can highlight the region of the model space that fits the observed pattern of neutrino mixing. However, the broad conclusions on the high-scale validity of this scenario vis-a-vis the DM constraints remain unchanged.
an example, for \( M = 10^4 \text{ GeV} \) and \( M_H/M_A \sim \mathcal{O}(100 \text{ GeV}) \), the Yukawa coupling \( y_\nu \) is of the order of \( 10^{-4} \). The lightest state between H and A is the DM candidate. We present our illustrative results for cases where H plays this role.

III. CONSTRAINTS FROM PERTURBATIVITY, UNITARITY, VACUUM STABILITY AND COLLIDER DATA

In this section, we briefly describe the constraints that are imposed on the model parameters and how exactly they shape the results so obtained.

A. Vacuum stability

The scalar potential is considered bounded from below, if it does not turn negative for large field values along all possible field directions. In this model, stability of the electroweak vacuum is ensured upto some specified energy scale if the following conditions are satisfied for all scales \( Q \) upto that scale:

\[
\begin{align*}
\text{vsc1 : } & \lambda_1(Q) > 0 \\
\text{vsc2 : } & \lambda_2(Q) > 0 \\
\text{vsc3 : } & \lambda_3(Q) + \sqrt{\lambda_1(Q)\lambda_2(Q)} > 0 \\
\text{vsc4 : } & \lambda_3(Q) + \lambda_4(Q) - |\lambda_5(Q)| + \sqrt{\lambda_1(Q)\lambda_2(Q)} > 0
\end{align*}
\]

Such conditions have been elaborately discussed in literature [35–38]. One should make a note that these conditions ensure absolute stability of the electroweak vacuum. For metastability, the conditions are somewhat less stringent.

B. Perturbativity

For the scalar quartic coupling \( \lambda_i(i = 1 - 5) \), the criterion for perturbativity is,

\[
\lambda_i(Q) < 4\pi
\]

The corresponding constraints for the Yukawa and gauge interactions are,

\[
y_i(Q), \ g_i(Q) < \sqrt{4\pi}
\]

where, \( Q \) represents the energy scale at which they are being computed. We demand that the criteria in Eq. 8 be obeyed at all energy scales upto the cut-off of this model.
C. Unitarity

A further set of conditions come on demanding unitarity of the scattering matrix comprising all $2 \rightarrow 2$ channels involving, by the optical theorem [39–42]. In our context, this translates into the condition that each distinct eigenvalue of the aforementioned amplitude matrix be bounded above at $8\pi$ (after factoring out $\frac{1}{16\pi}$ from the matrix). These eigenvalues are:

\[ a_{\pm} = \frac{3}{2}(\lambda_1 + \lambda_2) \pm \sqrt{\frac{9}{2}(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2} \]
\[ b_{\pm} = \frac{1}{2}(\lambda_1 + \lambda_2) \pm \sqrt{\frac{1}{4}(\lambda_1 - \lambda_2)^2 + \lambda_5^2}, \]
\[ c_{\pm} = d_{\pm} = \frac{1}{2}(\lambda_1 + \lambda_2) \pm \sqrt{\frac{1}{4}(\lambda_1 - \lambda_2)^2 + \lambda_5^2}, \]
\[ e_1 = (\lambda_3 + 2\lambda_4 - 3\lambda_5), \]
\[ e_2 = (\lambda_3 - \lambda_5), \]
\[ f_1 = f_2 = (\lambda_3 + \lambda_4), \]
\[ f_+ = (\lambda_3 + 2\lambda_4 + 3\lambda_5), \]
\[ f_- = (\lambda_3 + \lambda_5). \] (10)

D. Collider data

In addition to the theoretical constraints discussed above, important bounds on scalar mass parameters come from collider data.

- In order to identify $h$ with the SM-like Higgs as observed by the ATLAS and CMS collaborations, one requires $M_h \simeq 125$ GeV.

- To be consistent with the LEP bounds, one must have

\[ M_H + M_A > M_Z \] (11)
\[ M_{H^\pm} + M_{A/H} > M_W \]

Moreover, for neutralino as in the supersymmetric context, LEP-II searches limit pseudo-scalar mass ($M_A$) to 100 GeV when $M_H < M_A$ [8, 43]. Similarly, chargino search data, properly extrapolated, imply $M_{H^\pm} > 70$ GeV [44].
• Though all the tree-level couplings of $h$ are identical to those of the SM Higgs, the charged scalar $H^\pm$ potentially modifies the loop induced couplings $h\gamma\gamma$ and $hZ\gamma$ via loop contributions [45–49]. We theoretically compute the signal strength $\mu_{\gamma\gamma}$ for $h$ decaying to the diphoton channel as the ratio of the decay width in the ‘model’ to that in the SM. Its experimental value reported by the ATLAS and CMS collaborations stand at $1.17\pm0.27$ and $1.13\pm0.24$ respectively [50, 51]. Demanding the signal strength to be within $2\sigma$ limits of the experimentally quoted values puts further constraints on the model. We use the limit on $\mu_{\gamma\gamma}$ weighted as below:

\[
\frac{1}{\sigma^2} = \left(\frac{1}{\sigma^2}\right)_{ATLAS} + \left(\frac{1}{\sigma^2}\right)_{CMS} \tag{12}
\]

\[
\frac{\mu_{\gamma\gamma}}{\sigma^2} = \left(\frac{\mu_{\gamma\gamma}}{\sigma^2}\right)_{ATLAS} + \left(\frac{\mu_{\gamma\gamma}}{\sigma^2}\right)_{CMS} \tag{13}
\]

where, the numerators on the right hand side denotes the central values of the respective experimental results and $\sigma$ are the corresponding uncertainties.

IV. DARK MATTER ISSUES

As stated earlier, we identify $H$ as the DM candidate. For complimentary choice, namely, $A$ with the same mass as the DM candidate, we have checked that the contribution to the relic density is of similar magnitude. The relevant DM constraints to be considered are as follows:

• According to recent PLANCK experiment[52] the observed cold DM relic density is

\[
\Omega_{DM}h^2 = 0.1199 \pm 0.0027 \tag{14}
\]

We restrict our result upto $3\sigma$ deviation from the central value.

• Strong constraints come from direct DM searches. Recently, XENON100[53] and LUX[54] experiments have put upper-bound on the DM-nucleon scattering cross-section for a wide range of the DM mass. In our case, the direct detection cross-section strategy is based on t-channel Higgs mediation. We choose to work in the region of the parameter space allowed by the LUX limit.

• For $M_H \leq M_h/2$, the decay mode of Higgs to two DM particle ($h \to HH$) will presumably contribute to the invisible decay width of the Higgs boson. We take into account the current constraint on the Higgs invisible branching ratio ($< 20\%$) from model independent Higgs precision analysis [55, 56].
A. Case-A: Low mass DM ($50 \text{ GeV} < M_H < 90 \text{ GeV}$)

In this mass region, the dominant annihilation channel for $H$ goes to the DM self-annihilation processes through $h$ mediation. This keeps the relic density at the right level. For both positive and negative values of DM-DM-Higgs couplings, the relic density remains within the allowed range as long as the $M_H < 90 \text{ GeV}$. The sub-dominant contribution to the relic density comes from the $t$-channel processes to vector boson final states mediated by $A$ and $H^\pm$. A detailed discussion in this regard on a similar model can be found, for example in [11, 13, 22]. However, the coupling $\lambda_2$ has no effect in the relic density calculation. In the next section, we will discuss this results elaborately. One more notable point is that, annihilation processes that mediated by the heavy right-handed neutrinos give negligible contribution (less than 1%) to the relic density calculation. These processes are suppressed by the heavy mediator mass.

B. Case-B: High mass DM ($M_H > 500 \text{ GeV}$)

The interesting feature of this region is that, the correct relic abundance can be achieved if and only if $H, A$ and $H^\pm$ are almost degenerate, at most have a mass difference of the order of 10 GeV. This is mainly because at this high mass, the annihilation channels with vector boson final states can have direct quartic couplings ($HHVV, V = W^\pm, Z$) or can be mediated by any of the three scalars through $t/u$ channels. These diagrams yield too large an annihilation cross-section to match with the proper relic density. However, cancellation between direct quartic coupling diagrams and $t/u$ channels diagram occurs for mass-degenerate $H, A$ and $H^\pm$, which in turn brings down the annihilation cross-section to the desired range.

V. ANALYSIS STRATEGY

The aim of this study is to probe the parameter space of an inert doublet model (IDM) augmented with heavy RH neutrinos compatible with various theoretical and experimental constraints elaborated in the previous sections. We carry out our investigation in the two separate mass regions. In each region, we scan over the relevant parameters, namely, the masses $M_H, M_A$ and $M_{H^\pm}$, and the coupling $\lambda_L$. With $M_h$ fixed at 125 GeV, $\lambda_2, \lambda_L, M_H, M_A$ and $M_{H^\pm}$ fix all the remaining quartic interactions. These quartic couplings are then used as the electroweak boundary conditions at $Q = M_t$ and their RG evolution to high scales is studied. Here $M_t$ denotes the top quark pole mass. The reader is reminded that the effect of the RH neutrinos is turned on at a scale $Q = M$. Thus, for $M_t \leq Q \leq M$,
we do not include the RH neutrino contributions to the one-loop RG equations. We include such conditions for $Q \geq M$ and use the RG equations listed in the appendix. The scale upto which the scenario remains consistent is denoted by $\Lambda_{UV}$. For a generic parameter point $\lambda_i(Q = M_t)$, we check the aforementioned theoretical constraints at all intermediate scales upto $\Lambda_{UV}$. If the constraints are all satisfied, we tag $\lambda_i(Q = M_t)$ as an *allowed* point. This marks out an allowed region in the parameter space defined at the electroweak scale. Moreover, the effects of constraints stemming from the DM observables and collider searches are examined independently in this region. The finally allowed parameter regions are thus identified and presented for benchmark values of $\lambda_2$ and $M$. We use the publicly available package micrOMEGAs-v3.6.9.2 [57] for DM analysis.

Amongst the SM fermions, only the top quark plays the dominant role in the evolution of the couplings. The boundary condition for its Yukawa interaction at the electroweak scale is fixed by $y_t(M_t) = \frac{\sqrt{2}}{v}(1 - \frac{8}{3\pi}\alpha_s(M_t))$. We have used $M_t = 173.39$ GeV throughout our analysis.

VI. NUMERICAL RESULTS

A. Low mass DM region

We perform a detailed parameter space scan where $M_H < 100$ GeV. In this scan, we impose the LEP bounds as discussed in Sec 3.4.

$$\lambda_L : [-1.0, 1.0]$$  \hspace{1cm} (15)

$$M_H : [50.0 \text{ GeV}, 90. \text{ GeV}]$$  \hspace{1cm} (16)

$$M_A : [100. \text{ GeV}, 500. \text{ GeV}]$$  \hspace{1cm} (17)

$$M_{H^+} : [100. \text{ GeV}, 500. \text{ GeV}]$$  \hspace{1cm} (18)

We solve the RG equations for two values of $M$, $10^4$ GeV and $10^{12}$ GeV respectively. We then show the allowed parameter space in the $\lambda_L - M_H$ plane for different choices of $\Lambda_{UV}$ in Fig 1 and 2. The value of 2 has been taken to be 0.1 at the electroweak scale throughout our analysis.

The top quark Yukawa coupling in the SM is responsible for the downward evolution of the scalar self-coupling, which poses a threat to the vacuum stability. The presence of the additional scalar quartic couplings ($\lambda'$s) in a model like this offsets such an effect; however, the boost thus provided to these couplings tend to violate the perturbativity and unitarity condition. This necessitates a tightrope walking, and the scale upto which it is possible is
FIG. 1: Regions compatible with the theoretical constraints for $M = 10^4$ GeV (left panel) and $10^{12}$ GeV (right panel) with three different choices of $\Lambda_{UV}$. The regions denoted by A (red), B (cyan) and C (green) obey these constraints up to $\Lambda_{UV} = 10^6$, $10^{16}$ and $10^{19}$ GeV respectively. The grey region denoted by D keeps the Higgs to diphoton signal strength within 2$\sigma$ limits of the current data.

$\Lambda_{UV}$. It is natural that for higher $\Lambda_{UV}$, fewer combinations of parameters will achieve this fine balance, and consequently the allowed region will shrink. Since $\lambda_3 = \frac{2}{v^2}(M_H^2 - M_H^2 + \lambda_L v^2)$, the upper bound on $\lambda_L$ is imposed by the requirement of perturbative unitarity. This is because a higher positive value of $\lambda_L$ makes $\lambda_3$ large at the electroweak scale which violates perturbative unitarity in course of its evolution under RG. On the other hand, a large negative value of $\lambda_L$ induces a large negative value to $\lambda_3$. As a consequence, the vacuum stability condition vsc4 of Eq.7d is violated even near the electroweak(EW) scale. This puts a lower limit on $\lambda_L (> -0.1)$ independent of $M$ and $\Lambda_{UV}$, as evident from Fig.1.

To check the compatibility of the DM constraints with the theoretical ones, we look for the region allowed by the 3$\sigma$ limits on $\Omega_{DM}h^2$ from PLANCK data and 90% CL limit on the spin-independent DM-nucleon scattering cross-section from LUX data. In Fig. 2, we show the parameter space allowed by the entire set of DM constraints. An inspection of Fig. 1 and Fig. 2 shows that a large part of the parameter space allowed by the DM constraints lies in the region which is also favoured by the vacuum stability condition all the way up to the Planck scale. However, the region corresponding to $\lambda_L \leq -0.1$ does not lead to the stable
FIG. 2: Region allowed by imposing the constraints on relic density (RC) and spin-independent cross-section (SI) for DM-nucleon scattering. The red (gray) region is allowed only by the requirement of $\Omega_{DM}h^2$ being in the correct range. The black region is allowed by both the $\Omega_{DM}h^2$ and direct detection constraints. The shaded horizontal band below is disallowed by vacuum stability conditions. Here, $M_{H^\pm} = M_A = 200$ GeV.

vacuum. It should be noted that the region in Fig. 2 was generated with $M_{H^\pm}$ and $M_A$ fixed at 200 GeV. For higher values of $M_{H^\pm}$ and $M_A$, there is hardly any change in the annihilation cross-section. However, for values of $M_{H^\pm}$ and $M_A$ less than 200 GeV, the allowed region of Fig. 2 gets slightly modified. For example, for $M_H \simeq 70$ GeV and $M_{H^\pm} = M_A = 200$ GeV, the DM-DM-Higgs coupling $\lambda_L \simeq 0.007$, but for $M_{H^\pm} = M_A = 100$ GeV, one needs $\lambda_L \simeq 0.009$ to satisfy the relic density constraint. It should be noted however that both of the above points in the parameter space are within the stability region as shown in Fig. 1.

Therefore, it is not possible to constrain $M_{H^\pm}$ and $M_A$ using DM constraints alone, theoretical constraints however predict strong upper bounds on these masses, as is evident from Fig. 3.

The upper bounds on the masses $M_{H^\pm}$ and $M_A$ are imposed by the requirement of per-
FIG. 3: Regions allowed by the theoretical constraints projected in the $\lambda_L - M_A$ and $\lambda_3 - M_H^\pm$ planes. The colour coding is same as in Fig. 1.

perturbativity and unitarity upto the desired cut-off. With $M_H$ in the aforementioned range, large masses of the other $Z_2$-odd scalars imply high values of the quartic couplings at the electroweak scale which potentially violate perturbativity or unitarity at some high scale. We observe that a tight upper bound of $160-170$ GeV is realised on these masses for the
cut-off at the Planck scale. Moreover, the vacuum stability condition $\lambda_3 + \sqrt{\lambda_1 \lambda_2} \geq 0$ forbids large negative values of $\lambda_3$. This results in a decrement in the signal strength for diphoton channel. However, a sizeable portion of the parameter space for $\Lambda_{UV} = 10^{19}$ GeV is still allowed by the current limits on $\mu_{\gamma\gamma}$ defined in Eq. 13.

B. High mass DM region

This section demonstrates the high scale validity of our scenario in the limit of a high DM mass. As discussed earlier, one needs to tune the mass splitting amongst $H$, $H^\pm$, and $A$ and the coupling $\lambda_L$ to an appropriate degree in order to achieve a relic density within the desired bounds. It is seen that the maximal allowed splitting ($\Delta M$) amongst the masses of the $Z_2$ odd scalars is 10 GeV. One is thus motivated to scan the high DM mass region in the following ranges:

$$\lambda_L : [-1.0, 1.0]$$

$$M_H : [550.0 \text{ GeV}, 1000.0 \text{ GeV}]$$

$$M_A : [M_H, M_H + 10.0 \text{ GeV}]$$

$$M_{H^+} : [M_H, M_H + 10.0 \text{ GeV}]$$

The interplay of the theoretical and experimental constraints is studied in the form of correlation plots in the $M_H - \lambda_L$ (Fig. 4) as well as $M_{H^\pm} - \lambda_3$ (Fig. 5) plane. The DM-nucleon scattering cross section draws its dominant contribution from strange quarks. Owing to the uncertainty in the strange quark distribution, the limits on these cross sections from the direct detection experiments are less stringent. Further, a part of the parameter space already within the PLANCK and LUX bounds is ruled out by high-scale stability constraints corresponding to regions marked by $A(\Lambda_{UV} = 10^6 \text{ GeV})$, $B(\Lambda_{UV} = 10^{16} \text{ GeV})$ and $C(\Lambda_{UV} = 10^{19} \text{ GeV})$ as read in Fig. 4.

Similar to the previous section, the upper and lower bounds on $\lambda_L$ are placed from the requirements of perturbative unitarity and vacuum stability conditions respectively. The narrow splitting amongst $M_H$, $M_{H^\pm}$ and $M_A$ in this region implies small negative values for $\lambda_4$ and $\lambda_5$ at the EW scale.

A heavy $H^\pm$ which naturally arises in this region, does not cause any significant deviation in di-photon signal strength for the SM-like scalar. This occurs even with a large $\lambda_3$ (within the bounds shown in Fig. 5). In principle, a large negative $\lambda_3$ could modify $\mu_{\gamma\gamma}$ unacceptably. However, as Fig. 5 shows, such values are inconsistent with the aforementioned theoretical constraints. Therefore, the allowed region of our parameter space are automatically consistent with LHC data.
FIG. 4: Region(s) allowed in the $M_H$-$\lambda_L$ plane obeying the various constraints for $M = 10^4$ GeV (left panel) and $M = 10^{12}$ GeV (right panel). The region marked by ‘RC + SI’ (magenta) is allowed by the DM constraints alone. The region labelled by A (red), B (cyan) and C (green) are consistent with the theoretical constraints upto $\Lambda_{UV} = 10^6, 10^{16}$ and $10^{19}$ GeV respectively.

FIG. 5: Region(s) allowed in the $M_{H^\pm}$-$\lambda_3$ plane obeying the various constraints. The colour coding and other figure legends are same as in Fig. 4
It is worth noting here that the allowed parameter space corresponding to $M = 10^4$ GeV shrinks significantly for $M = 10^{12}$ GeV, as can be seen in Fig. 4 and Fig. 5. The origin of this feature is discussed below.

We have selected two benchmark points (BP1 and BP2) as samples out of the allowed regions consistent with the relic density constraints. These points demonstrate how the different theoretical constraints can truncate the scale of validity of this scenario for two different values of right-handed neutrino masses $M = 10^4$ GeV and $M = 10^{12}$ GeV respectively. The parameter values are listed in Table. I.

| BP  | $M_H$  | $M_{H^+}$ | $M_A$  | $\lambda_L$ |
|-----|--------|-----------|--------|-------------|
| BP1 | 850.0 GeV | 854.0 GeV | 858.0 GeV | 0.02        |
| BP2 | 710.0 GeV | 712.0 GeV | 711.0 GeV | 0.11        |

TABLE I: Benchmark values (BP) of parameters affecting the RG evolution of the quartic couplings. For each BP, two values of $M$, namely, $10^4$ GeV and $10^{12}$ GeV, have been used.

BP1 and BP2 yield $\Omega_{\text{DM}} h^2 = 0.1151$ and 0.1207 respectively, which is within the allowed range of relic density. For $M = 10^4$ GeV, BP1 ensures a stable vacuum till the Planck scale (Fig. 6a). It is also consistent with throughout with perturbativity and unitarity. However, one has $y_\nu = 0.168$ at $M = 10^{12}$ GeV. For this value, the term $\mathcal{O}(\lambda_2 y_\nu^2)$ has a dominant role in the RG evolution and $\lambda_2$ starts increasing rapidly from $10^{12}$ GeV onwards (Fig. 6b).

For $M = 10^4$ GeV, BP2 exhibits similar features in the evolution trajectory as in BP1 (Fig. 7a). For $M = 10^{12}$ GeV, the Yukawa coupling $y_\nu$ starts with an initial value around 0.51. This is accounted for by the very small mass splitting, of the order of a GeV, between $H$ and $A$. Thus, the dominant contribution from the RH neutrinos comes from the $\mathcal{O}(y_\nu^4)$ term that causes $\lambda_2$ to drop sharply (Fig. 7b). Hence, in BP2, vacuum stability is destroyed shortly after $10^{12}$ GeV as the condition $\lambda_2 > 0$ gets violated. This particular feature can only be witnessed in the case of closely spaced $M_H$ and $M_A$, which is the primary requirement to satisfy the relic density constraints discussed before. This completes the explanation of how the allowed area can shrink due to different theoretical constraints for $M = 10^{12}$ GeV.

VII. SUMMARY AND CONCLUSIONS

We have examined the high-scale validity of a scenario that (a) offers a scalar dark matter, (b) radiatively generates Majorana masses for neutrinos, and (c) is responsible for leptogenesis. For this, we extend the SM fields with one additional inert Higgs doublet field ($\Phi_2$)
FIG. 6: RG running of different scalar quartic couplings corresponding to BP1. The solid, dashed, dashed dotted and dotted lines denote the evolution curves of the stability conditions vsc1, vsc2, vsc3 and vsc4 respectively.

FIG. 7: Same as Fig. 6 but for the benchmark point BP2.

and three right handed neutrinos ($N_i$). These new particles are odd under a discrete $Z_2$
symmetry, while all the SM particles are even. Because of this discrete symmetry, $\Phi_2$ does not acquire any vacuum expectation value (vev) and has no tree-level couplings to fermions. In this scenario, one has five physical scalars ($h, H, A, H^\pm$), where, $h$ is denoted as the SM like Higgs boson with a mass of 125 GeV. The lightest state between $H$ and $A$ is the dark matter candidate due to built in $Z_2$ symmetry. In our analysis we have assumed $H$ to be the dark matter candidate. Neutrino masses are generated at the one-loop level. The neutrino masses and mixing angles are determined in terms of Yukawa couplings ($y_{\nu}$), new Higgs particle masses ($M_H, M_A$) and three heavy Majorana masses ($M_{1,2,3}$). In our numerical analysis we have assumed $M_1$ is mass of the lightest state and considered two values, namely, $M_1 \equiv M = 10^4$ GeV and $10^{12}$ GeV. These two mass scales are consistent with Leptogenesis.

For simplicity, in our analysis, we have considered only one diagonal Yukawa coupling and to determine the value of this coupling we have scanned over $M_H$ and $M_A$ for a given value of $M$, by keeping $M_\nu \sim O(0.1 \text{ eV})$.

The parameter space of this model is determined in terms of additional Higgs boson masses, $M_H, M_A, M_{H^\pm}$, one quartic coupling $\lambda_2$ and a set of quartic coupling combinations, $\lambda_L$. While scanning the parameter space of this model, we have imposed the LEP bound on scalar masses, $M_H, M_A$ and $M_{H^\pm}$.

As far as the dark matter constraints are concerned, we have used the relic density limits obtained at 3\sigma uncertainty from the PLANCK experiment and the direct detection cross-section limit from the LUX experiment. Finally, for $M_H < M_h/2$, which would lead to large invisible decay width of the SM like Higgs boson, we demanded that the corresponding branching ratio is less than 20% as obtained from the model independent Higgs precision analysis.

With these set of constraints in hand, we have then scanned the IDM parameter space for two different ranges of dark matter masses, 50 GeV < $M_H < 90$ GeV and $M_H > 500$ GeV. It should be noted that with $M_h$ fixed at 125 GeV, $\lambda_2, \lambda_L, M_H, M_A$ and $M_{H^\pm}$ determined all the remaining quartic couplings. We have used these quartic couplings as the electroweak boundary condition by setting the starting RG running scale $Q = M_t$ and evolved these couplings up to the scale $\Lambda_{\text{UV}}$, where this scenario remained consistent. In the RG evolution of these quartic couplings, the neutrino Yukawa couplings started playing its role from the right handed neutrino mass scale $Q = M$ onwards.

In our study we have explicitly demonstrated that at the low DM mass region, the vacuum stability, perturbativity and unitarity constraints put stringent limits on the low-energy value of the coupling $\lambda_L$ and the $Z_2$-odd scalar masses $M_{H^\pm}, M_A$. These bounds strongly depend upon the scale up to which the theory is valid and the right-handed neutrino mass scale. It is interesting to note that all the parameter space allowed by the DM relic density and
direct detection constraints lies well within the region allowed by the theoretical constraints valid up to the Planck scale. However, once we have imposed the condition that the Higgs to diphoton signal strength ($\mu_{\gamma\gamma}$) should lie within $2\sigma$ of the weighted average value of the ATLAS and CMS data, the allowed parameter space further squeezed.

The scenario with high DM mass region ($M_H > 500$ GeV) is significantly different from that of the low DM mass region. In this case, the DM being very heavy, the constraints from direct detection is rather insignificant. On the other hand, the relic density constraint is ensured by a degenerate $Z_2$-odd scalars ($\Delta M \approx 10$ GeV). As a result of these, a large part of the parameter space in $\lambda_L - M_H$ and $\lambda_3 - M_{H\pm}$ planes remain unconstrained.

However, the study of the high scale validity of this region has interesting consequences. The DM-allowed region reduces substantially after imposing the theoretical constraints and this reduction is strongly dependent on the cut-off scale ($\Lambda_{UV}$). The effect of neutrino Yukawa couplings in the RG evolution of the different quartic couplings are also prominent in this case. We have found that with the increase in the right handed neutrino mass scale $M$, the neutrino Yukawa coupling ($y_\nu$) also increases, which in turn further reduces the allowed parameter space by either destabilizing the vacuum or violating the perturbativity bound. There is nonetheless a clearly identifiable region of the parameter space, which keeps the model valid all the way up to the Planck scale. This scenario is consistent with the measured Higgs-to-diphoton rates as measured during the 8 TeV run of the LHC.

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Appendix

Appendix A: One-loop Renormalization group (RG) equations

The RG equations for the gauge couplings, for this model, are given by [38],

$$16\pi^2 \frac{dg_s}{dt} = -7g_s^3,$$

(A1a)
For the Yukawa couplings the corresponding set of RG equations are,

\begin{align}
16\pi^2 \frac{dg}{dt} &= -3g^3, \\
16\pi^2 \frac{dg'}{dt} &= 7g^3.
\end{align}

Here $g'$, $g$ and $g_s$ denote the U(1), SU(2)$_L$ and SU(3)$_c$ gauge couplings respectively.

The quartic couplings $\lambda_i$ ($i = 1, \ldots, 5$) evolve according to,

\begin{align}
16\pi^2 \frac{d\lambda_1}{dt} &= 12\lambda_1^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2 + \frac{3}{4}(3g^4 + g'^4 + 2g^2g'^2) \\
&- \lambda_1(9g^2 + 3g'^2 - 12y_t^2 - 12y_b^2 - 4y_r^2) - 12y_t^4, \\
16\pi^2 \frac{d\lambda_2}{dt} &= 12\lambda_2^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2 \\
&+ \frac{3}{4}(3g^4 + g'^4 + 2g^2g'^2) - 3\lambda_2(3g^2 + g'^2 - \frac{4}{3}y_v^2) - 4y_v^4, \\
16\pi^2 \frac{d\lambda_3}{dt} &= (\lambda_1 + \lambda_2)(6\lambda_3 + 2\lambda_4) + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 + \frac{3}{4}(3g^4 + g'^4 - 2g^2g'^2) \\
&- \lambda_3(9g^2 + 3g'^2 - 6y_t^2 - 6y_b^2 - 2y_r^2 - 2y_r^2), \\
16\pi^2 \frac{d\lambda_4}{dt} &= 2(\lambda_1 + \lambda_2)\lambda_4 + 8\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_5^2 + 3g^2g'^2 \\
&- \lambda_4(9g^2 + 3g'^2 - 6y_t^2 - 6y_b^2 - 2y_r^2 - 2y_r^2), \\
16\pi^2 \frac{d\lambda_5}{dt} &= (2\lambda_1 + 2\lambda_2 + 8\lambda_3 + 12\lambda_4)\lambda_5 - \lambda_5(9g^2 + 3g'^2 - 6y_b^2 - 2y_r^2 - 2y_r^2). \\
\end{align}

For the Yukawa couplings the corresponding set of RG equations are,

\begin{align}
16\pi^2 \frac{dy_b}{dt} &= y_b\left(-8g_s^2 - \frac{9}{4}g'^2 - \frac{5}{12}g'^2 + \frac{9}{2}y_b^2 + y_r^2 + \frac{3}{2}y_t^2\right), \\
16\pi^2 \frac{dy_t}{dt} &= y_t\left(-8g_s^2 - \frac{9}{4}g'^2 - \frac{17}{12}g'^2 + \frac{9}{2}y_t^2 + y_r^2 + \frac{3}{2}y_b^2\right), \\
16\pi^2 \frac{dy_r}{dt} &= y_r\left(-\frac{9}{4}g'^2 - \frac{15}{4}g'^2 + 3y_b^2 + 3y_t^2 + \frac{1}{2}y_v^2 + \frac{5}{2}y_r^2\right), \\
16\pi^2 \frac{dy_v}{dt} &= y_v\left(-\frac{9}{4}g'^2 - \frac{3}{4}g'^2 - \frac{3}{4}y_r^2 + \frac{5}{2}y_v^2\right).
\end{align}

[1] ATLAS Collaboration, G. Aad et. al., Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys.Lett. B716 (2012) 1–29, [arXiv:1207.7214].

[2] CMS Collaboration, S. Chatrchyan et. al., Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys.Lett. B716 (2012) 30–61, [arXiv:1207.7235].
[3] G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, et al., *Higgs mass and vacuum stability in the Standard Model at NNLO*, JHEP **1208** (2012) 098, [arXiv:1205.6497].

[4] E. Ma, *Verifiable radiative seesaw mechanism of neutrino mass and dark matter*, Phys.Rev. **D73** (2006) 077301, [hep-ph/0601225].

[5] N. G. Deshpande and E. Ma, *Pattern of Symmetry Breaking with Two Higgs Doublets*, Phys.Rev. **D18** (1978) 2574.

[6] R. Barbieri, L. J. Hall, and V. S. Rychkov, *Improved naturalness with a heavy Higgs: An Alternative road to LHC physics*, Phys.Rev. **D74** (2006) 015007, [hep-ph/0603188].

[7] L. Lopez Honorez, E. Nezri, J. F. Oliver, and M. H. Tytgat, *The Inert Doublet Model: An Archetype for Dark Matter*, JCAP **0702** (2007) 028, [hep-ph/0612275].

[8] Q.-H. Cao, E. Ma, and G. Rajasekaran, *Observing the Dark Scalar Doublet and its Impact on the Standard-Model Higgs Boson at Colliders*, Phys.Rev. **D76** (2007) 095011, [arXiv:0708.2939].

[9] S. Andreas, M. H. Tytgat, and Q. Swillens, *Neutrinos from Inert Doublet Dark Matter*, JCAP **0904** (2009) 004, [arXiv:0901.1750].

[10] E. Nezri, M. H. Tytgat, and G. Vertongen, *$e^+\text{ and }\bar{e}^-\text{ from inert doublet model dark matter, JCAP 0904}(2009)014, \text{ arXiv:0901.2556}$.*

[11] T. Hambye, F.-S. Ling, L. Lopez Honorez, and J. Rocher, *Scalar Multiplet Dark Matter*, JHEP **0907** (2009) 090, [arXiv:0903.4010].

[12] L. Lopez Honorez and C. E. Yaguna, *The inert doublet model of dark matter revisited*, JHEP **1009** (2010) 046, [arXiv:1003.3125].

[13] L. Lopez Honorez and C. E. Yaguna, *A new viable region of the inert doublet model*, JCAP **1101** (2011) 002, [arXiv:1011.1411].

[14] E. Dolle, X. Miao, S. Su, and B. Thomas, *Dilepton Signals in the Inert Doublet Model*, Phys.Rev. **D81** (2010) 035003, [arXiv:0909.3094].

[15] X. Miao, S. Su, and B. Thomas, *Trilepton Signals in the Inert Doublet Model*, Phys.Rev. **D82** (2010) 035009, [arXiv:1005.0090].

[16] A. Arhrib, R. Benbrik, and N. Gaur, *$H \to \gamma\gamma$ in Inert Higgs Doublet Model*, Phys.Rev. **D85** (2012) 095021, [arXiv:1201.2644].

[17] M. Gustafsson, S. Rydbeck, L. Lopez-Honorez, and E. Lundstrom, *Status of the Inert Doublet Model and the Role of multileptons at the LHC*, Phys.Rev. **D86** (2012) 075019, [arXiv:1206.6316].

[18] B. Swiezewska and M. Krawczyk, *Diphoton rate in the inert doublet model with a 125 GeV
Higgs boson, Phys.Rev. D88 (2013), no. 3 035019, [arXiv:1212.4100].

[19] A. Goudelis, B. Herrmann, and O. Stl, Dark matter in the Inert Doublet Model after the discovery of a Higgs-like boson at the LHC, JHEP 1309 (2013) 106, [arXiv:1303.3010].

[20] M. Krawczyk, D. Sokolowska, and B. Swiezewska, Inert Doublet Model with a 125 GeV Higgs, arXiv:1304.7757.

[21] M. Krawczyk, D. Sokolowska, P. Swaczyna, and B. wieewska, Higgs → γγ, Zγ in the Inert Doublet Model, Acta Phys.Polon. B44 (2013), no. 11 2163–2170, [arXiv:1309.7880].

[22] A. Arhrib, Y.-L. S. Tsai, Q. Yuan, and T.-C. Yuan, An Updated Analysis of Inert Higgs Doublet Model in light of the Recent Results from LUX, PLANCK, AMS-02 and LHC, arXiv:1310.0358.

[23] A. Arhrib, R. Benbrik, and T.-C. Yuan, Associated Production of Higgs at Linear Collider in the Inert Higgs Doublet Model, Eur.Phys.J. C74 (2014) 2892, [arXiv:1401.6698].

[24] E. Ma, Common origin of neutrino mass, dark matter, and baryogenesis, Mod.Phys.Lett. A21 (2006) 1777–1782, [hep-ph/0605180].

[25] L. M. Krauss, S. Nasri, and M. Trodden, A Model for neutrino masses and dark matter, Phys.Rev. D67 (2003) 085002, [hep-ph/0210389].

[26] J. Kubo, E. Ma, and D. Suematsu, Cold Dark Matter, Radiative Neutrino Mass, μ → eγ, and Neutrinoless Double Beta Decay, Phys.Lett. B642 (2006) 18–23, [hep-ph/0604114].

[27] D. Aristizabal Sierra, J. Kubo, D. Restrepo, D. Suematsu, and O. Zapata, Radiative seesaw: Warm dark matter, collider and lepton flavour violating signals, Phys.Rev. D79 (2009) 013011, [arXiv:0808.3340].

[28] D. Suematsu, T. Toma, and T. Yoshida, Reconciliation of CDM abundance and μ → eγ in a radiative seesaw model, Phys.Rev. D79 (2009) 093004, [arXiv:0903.0287].

[29] D. Suematsu, T. Toma, and T. Yoshida, Enhancement of the annihilation of dark matter in a radiative seesaw model, Phys.Rev. D82 (2010) 013012, [arXiv:1002.3225].

[30] D. Suematsu, Thermal Leptogenesis in a TeV Scale Model for Neutrino Masses, Eur.Phys.J. C72 (2012) 1951, [arXiv:1103.0857].

[31] S. Kashiwase and D. Suematsu, Baryon number asymmetry and dark matter in the neutrino mass model with an inert doublet, Phys.Rev. D86 (2012) 053001, [arXiv:1207.2594].

[32] S. Kashiwase and D. Suematsu, Leptogenesis and dark matter detection in a TeV scale neutrino mass model with inverted mass hierarchy, Eur.Phys.J. C73 (2013) 2484, [arXiv:1301.2087].

[33] M. Fukugita and T. Yanagida, Baryogenesis Without Grand Unification, Phys.Lett. B174 (1986) 45.
[34] A. Pilaftsis, *CP violation and baryogenesis due to heavy Majorana neutrinos*, Phys.Rev. D56 (1997) 5431–5451, [hep-ph/9707235].

[35] M. Sher, *Electroweak Higgs Potentials and Vacuum Stability*, Phys.Rept. 179 (1989) 273–418.

[36] S. Nie and M. Sher, *Vacuum stability bounds in the two Higgs doublet model*, Phys.Lett. B449 (1999) 89–92, [hep-ph/9811234].

[37] P. Ferreira, R. Santos, and A. Barroso, *Stability of the tree-level vacuum in two Higgs doublet models against charge or CP spontaneous violation*, Phys.Lett. B603 (2004) 219–229, [hep-ph/0406231].

[38] G. Branco, P. Ferreira, L. Lavoura, M. Rebelo, M. Sher, et. al., *Theory and phenomenology of two-Higgs-doublet models*, Phys.Rept. 516 (2012) 1–102, [arXiv:1106.0034].

[39] I. Ginzburg and I. Ivanov, *Tree-level unitarity constraints in the most general 2HDM*, Phys.Rev. D72 (2005) 115010, [hep-ph/0508020].

[40] B. Gorczyca and M. Krawczyk, *Tree-Level Unitarity Constraints for the SM-like 2HDM*, [arXiv:1112.5086].

[41] G. Bhattacharyya, D. Das, P. B. Pal, and M. Rebelo, *Scalar sector properties of two-Higgs-doublet models with a global U(1) symmetry*, JHEP 1310 (2013) 081, [arXiv:1308.4297].

[42] N. Chakrabarty, U. K. Dey, and B. Mukhopadhyaya, *High-scale validity of a two-Higgs doublet scenario: a study including LHC data*, JHEP 1412 (2014) 166, [arXiv:1407.2145].

[43] E. Lundstrom, M. Gustafsson, and J. Edsjo, *The Inert Doublet Model and LEP II Limits*, Phys.Rev. D79 (2009) 035013, [arXiv:0810.3924].

[44] A. Pierce and J. Thaler, *Natural Dark Matter from an Unnatural Higgs Boson and New Colored Particles at the TeV Scale*, JHEP 0708 (2007) 026, [hep-ph/0703056].

[45] M. A. Shifman, A. Vainshtein, M. Voloshin, and V. I. Zakharov, *Low-Energy Theorems for Higgs Boson Couplings to Photons*, Sov.J.Nucl.Phys. 30 (1979) 711–716.

[46] J. R. Ellis, M. K. Gaillard, and D. V. Nanopoulos, *A Phenomenological Profile of the Higgs Boson*, Nucl.Phys. B106 (1976) 292.

[47] R. Cahn, M. S. Chanowitz, and N. Fleishon, *Higgs Particle Production by Z → Hγ*, Phys.Lett. B82 (1979) 113.

[48] L. Bergstrom and G. Hulth, *Induced Higgs Couplings to Neutral Bosons in e+e− Collisions*, Nucl.Phys. B259 (1985) 137.

[49] A. Djouadi, *The Anatomy of electro-weak symmetry breaking. II. The Higgs bosons in the minimal supersymmetric model*, Phys.Rept. 459 (2008) 1–241, [hep-ph/0503173].

[50] ATLAS Collaboration, G. Aad et. al., *Measurement of Higgs boson production in the
diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector, Phys.Rev. D90 (2014) 112015, [arXiv:1408.7084].

[51] CMS Collaboration, V. Khachatryan et. al., Observation of the diphoton decay of the Higgs boson and measurement of its properties, Eur.Phys.J. C74 (2014), no. 10 3076, [arXiv:1407.0558].

[52] Planck Collaboration, P. Ade et. al., Planck 2013 results. XVI. Cosmological parameters, Astron.Astrophys. 571 (2014) A16, [arXiv:1303.5076].

[53] XENON100 Collaboration, E. Aprile et. al., Dark Matter Results from 225 Live Days of XENON100 Data, Phys.Rev.Lett. 109 (2012) 181301, [arXiv:1207.5988].

[54] LUX Collaboration, D. Akerib et. al., First results from the LUX dark matter experiment at the Sanford Underground Research Facility, Phys.Rev.Lett. 112 (2014), no. 9 091303, [arXiv:1310.8214].

[55] S. Banerjee, S. Mukhopadhyay, and B. Mukhopadhyaya, New Higgs interactions and recent data from the LHC and the Tevatron, JHEP 1210 (2012) 062, [arXiv:1207.3588].

[56] K. Cheung, J. S. Lee, and P.-Y. Tseng, Higgs precision analysis updates 2014, Phys.Rev. D90 (2014), no. 9 095009, [arXiv:1407.8236].

[57] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, micrOMEGAs 3: A program for calculating dark matter observables, Comput.Phys.Commun. 185 (2014) 960–985, [arXiv:1305.0237].