Dark matter, neutrino mass and baryogenesis in the radiative seesaw model

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We study the simplest viable dark matter model with an additional neutral real singlet scalar, including a vectorlike singlet and doublet fermions. We find a considerable enhancement in the allowed region of the scalar dark matter parameter spaces in the presence of these fermions. The decay of the lightest component of the fermion doublet enhances the lepton number violating process, which produces sufficient lepton number asymmetry in the strong wash-out regime. It helps to explain baryogenesis via the mechanism of thermal leptogenesis. This model could also accommodate tiny neutrino masses and mixing at one loop-level through the radiative seesaw mechanism. Dilepton+${\not} E_T$ signature arising from the new fermionic sector can observe at Large Hadron Collider (LHC), satisfying relic density, including other theoretical and experimental bounds. We perform such analysis for a benchmark point in the context of 14 TeV LHC experiments with a future integrated luminosity of 3000 fb$^{-1}$.

I. INTRODUCTION

Pieces of evidence from various astrophysical observations like gravitational lensing effects in Bullet cluster, anomalies in the galactic rotation curves, etc., have confirmed the existence of dark matter (DM) in the Universe. Since no particle within the SM has adequate properties to play the role of DM, we must go beyond the SM in the search of new physics. The recent LHC Higgs signal strength data [1, 2] also suggests that one can have rooms for the new physics beyond the SM. To address DM within BSM, various possibilities have been proposed in Refs. [3] and references therein. However, adding a few numbers of fields to the SM, among which the lightest is neutral and stable due to the imposed discrete $Z_n$ and/or $Z_{n^*}$-type ($n \geq 2$, integer) symmetry is the popular one. Heavy scalars or neutrinos, which can behave as weakly interacting massive particles (WIMPs) are the most auspicious candidate as their cross-section results match to be produced as a thermal relic with the observed density. Rich literature on minimal models of DM considering scalar and fermion multiplets are available today [4–8]. In particular, the addition of scalar singlet and fermion singlet, as well as doublet in a minimal model, have rich demand in DM study. As, the mixing of fermion doublet and singlets reduces the coupling to weak gauge bosons and can transform DM from a Dirac into a Majorana particle, yielding the correct relic density with allowed direct detection cross-section [9].

To date, we still can not see any sign of the dark matter from various direct detection experiments. Recent Xenon-1T experiment [10] puts stringent bounds on the dark matter portal interaction strength(s). DM detection experiments indicate that either dark matter may interact with the nucleus very feebly (detection cross-section could reach beyond the line of neutrino floor [11, 12]) or the interaction is completely zero. The dark matter annihilation into the SM particles via $s$-channels may absent. On the other hand, if nature has only one-component dark matter then the $H$- and $Z$-bosons portal dark matter models may not be the right one to give the exact relic density. It is already known from the literature [13–16] that in the presence of another particle one can get the exact relic density via the co-annihilation channels. One may have the interaction terms in such a way that the dark matter can annihilate into the SM particles via the $t$- or $u$-channels, which help to modify the effective annihilation cross-section to give the exact relic density. These types of scenarios can be achieved in the proposed minimal model which gives the correct dark matter density satisfying all the other theoretical and experimental constraints.

At the current Universe, there is an asymmetry in baryon number is observed. Meanwhile, various established suggestions regarding the evolution of our Universe confirm that at the very beginning, there were equal numbers of matter and corresponding anti-matter. This scenario can be explained by the process which is popularly known as baryogenesis. Numerical definition for baryon asymmetry at current date reads as [17],

\[
Y_{\Delta B} = \left( \frac{n_B - n_{\bar{B}}}{s} \right) = (8.75 \pm 0.23) \times 10^{-11},
\]

where $n_B$, $n_{\bar{B}}$, and $s$ are the number densities of, respectively, baryons, antibaryons and entropy, a subscript zero implies ‘at present time’. The numerical value is from the combined microwave background and large scale

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structure data [18]. The SM does not have enough ingredient (three Shakarov conditions [19]) to explain this asymmetry, hence BSM frameworks become ideal for accommodating baryogenesis. An attractive way to explain baryogenesis is via the mechanism of thermal leptogenesis [17, 20]. Thermal Leptogenesis is close to type-I seesaw, and together they possess rich literature [17, 19, 21, 25]. In the process of thermal leptogenesis, the out-of-equilibrium decay of the lightest right-handed neutrino (RHN) produces sufficient lepton asymmetry that converted into baryon asymmetry via the spharelon process [26]. A vital limitation in this process is that it demands a very high scale of RHN mass (above $10^{10}$ GeV) to make the process work[26, 27]. The large RHN mass scale in standard thermal leptogenesis is because of the CP asymmetry in RHN decays is proportional to the product of active and RHN masses. However, these large RHN masses are not well accepted due to several reasons. First of all, these many mass scales are unable to probe at on-going collider experiments. [29] and low-scale leptogenesis might rule out lepton numbers at high scale [30, 31]. Second, for higher RHN mass, the naturalness problem arises due to the fine-tuning of the SM Higgs mass parameter. Thus it would be more alluring to construct such a model where low-scale leptogenesis might be feasible. Various studies for low-scaled leptogenesis has been carried out along with the scotogenic model [31, 33, 34]. Most of the studies were focused on the decay of right-handed Majorana neutrino that produces sufficient lepton asymmetry whereas we have considered the decay of a vectorlike fermion (VLF). The decay of the VLF into a lepton and scalar violates the lepton number by two units hence lepton asymmetry is generated.

In the model-building prospect, models that can address many SM shortfalls are more appealing and well-motivated also. A dark matter model is said to be completed only when it can simultaneously explain light neutrino observable. It would be more attractive if one can establish a relation between dark matter and light neutrino parameters. In this current work, we have not only introduced a viable dark matter candidate but also tried to address the tininess of neutrino mass generation and baryogenesis in a single framework. The framework that is popular in accommodating both dark matter and neutrino mass is known as the *scotogenic* model, first proposed by Ma [8], where the dimension-5 operator is realized in one-loop level. The notable feature of this framework is the way it connects neutrino and DM. Due to the additional $Z_2$ discrete symmetry, new fields that contribute to the loop to produce sizable neutrino mass, acquire opposite parity to the SM fields, hence become stable and can be addressed as a viable dark matter candidate. Due to its convincing features in addressing neutrino and dark matter, the scotogenic model has gained popularity over time [34–36].

Keeping these in view, we consider a minimal model of DM comprise of a vectorlike singlet and doublet fermion along with a singlet scalar. Apart from the SM SU(2) and U(1), an additional $Z_2$ symmetry is introduced. All new fields are assigned odd under $Z_2$-symmetry such that an odd number of BSM particles do not couple with the SM particles. The scalar singlet in this model is behaving as dark matter on the other hand the charged component of the fermion doublet is taking part in lepton number violation processes. The charged VLFs mixes via a mixing angle $\beta$. This mixing angle, couplings, masses, etc. play a significant role in dark matter, neutrino, leptogenesis phenomenology and in collider searches. Moreover, the interaction of vectorlike fermions with SM fields makes them more comfortable to probe in collider searches. We look for collider signature for the lightest charged fermion in the context of 14 TeV LHC experiments with a future luminosity of 3000 fb$^{-1}$ for $pp \rightarrow E^+_T E^+_T$ event processes which yield dilepton plus large transverse missing energy $E_T^\perp$ (arising from the dark matter) in the final state. To the best of our knowledge, the detailed analysis of this model has not yet been done in the literature which motivates us to do the analysis.

The rest of the work is organized as follows. We have given the complete model description in section [II] Constraints from various sources on this model are discussed in section [III]. Numerical analysis from dark matter, baryogenesis and collider searches are discussed under section [IV] and finally we have concluded our work in section [V].

## II. MODEL FRAMEWORK

The model addressed here, contains (i) a real scalar singlet $(S)$, (ii) a vectorlike charged fermion singlet $E^-_S$, and (ii) a vectorlike fermion (VF) doublet, $F_D = (X_1^0, E^-_D)^T$. The charge content of the fields are given in the table [I]. It is to be noted that these additional

| Symmetries | $S$ | $F_D$ | $E_S$ |
|-----------|-----|------|------|
| $SU(2)$   | 1   | 2    | 1    |
| $U(1)_Y$  | 0   | -1   | -2   |
| $Z_2$     | -1  | -1   | -1   |

**TABLE I:** Field content and their charges under three different symmetries. $S$ represents the scalar singlet while $F_D$ and $E_S$ are fermion doublet and singlet respectively.
fermions are vectorlike and hence, they do not introduce any extra anomalies in the theory [39, 40]. The SM satisfies the anomaly free condition because of the presence of a quark family to each lepton family. The additional vector-like fermions used here, have the right chiral components transforming similarly to the left chiral ones under the SM gauge symmetry. Therefore, the model is anomaly free. All the BSM particles are considered odd under the discrete $Z_2$ symmetry, such that, this BSM field does not mix with the SM fields. As a result, the lightest and neutral particle is stable and considered to be a viable dark matter candidate. Let us now elaborated on the model part in detail. The Lagrangian of the model read as,

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_S + \mathcal{L}_F + \mathcal{L}_{int}. \quad (1)$$

where,

$$\mathcal{L}_S = \frac{1}{2} |\bar{\ell}_s| S^2 - \frac{1}{4} m^2_S S^2 - \frac{\lambda_S}{4!} S^4 \quad (2)$$

$$\mathcal{L}_F = \bar{\ell}_D \gamma^\mu D^\mu \ell_D + \bar{E}_s \gamma^\mu D^\mu E_S - M_{ND} \bar{F}_D F_D$$

$$- M_{NS} \bar{F}_S F_S. \quad (3)$$

$$\mathcal{L}_{int} = - Y_N \bar{F}_D \phi^\dagger E_S - Y_f \bar{F}_D S + h.c. \quad (4)$$

$D_\mu$ stands for the corresponding covariant derivative of the doublet and singlet fermions. The SM Higgs potential is given by, $V^{SM}(\phi) = -m^2\phi^2 + \lambda\phi^4$, with, $\phi = (G^+, \frac{H^+, (H+H^\dagger)/\sqrt{2})}{v}$ is the SM Higgs doublet. $G$’s stand for the Goldstone bosons and $v = 246.221$ GeV being the vacuum expectation value of the Higgs $H$ fields. The charged component of the fermion doublet ($E_D^\pm$) and the singlet charged fermion ($E_S^\pm$) mix at tree level. The mass matrix for these charged fermion fields is given by,

$$M = \begin{pmatrix} M_{ND} & M_X \\ M_X^\dagger & M_{NS} \end{pmatrix}, \quad (5)$$

where, $M_X = \frac{\kappa v^2}{2}. \quad$ The mass eigenstates are obtained by diagonalizing the mass matrix with a rotation of the ($E_D^\pm$, $E_S^\pm$) basis,

$$\begin{pmatrix} E_D^\pm \\ E_S^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} E_D^\pm \\ E_S^\pm \end{pmatrix}, \quad (6)$$

The mixing angle ($\beta$) between the fermions can be written as,

$$\tan2\beta = \frac{2M_X}{M_{NS} - M_{ND}}.$$ 

Diagonalization of eqn. [6] gives the following eigenvalues for the charged leptons ($M_{NS} - M_{ND} \gg M_X$) as,

$$M_{E_1^\pm} = M_{ND} - \frac{2(M_X)^2}{M_{NS} - M_{ND}}.$$ 

The masses of the neutral fermion scalar fields can be calculated as,

$$M_{X_1^0} = M_{ND}, \quad M_S^2 = \frac{m_S^2 + kv^2}{2}, \quad M_H^2 = 2\lambda v^2.$$ 

Hence, in this model, neutral fermion can not serve as the DM candidate as $M_{E_1^\pm} < M_{X_1^0} < M_{E_1^\pm}$. Only the scalar fields $S$ for $M_S < M_{E_1^\pm}$ can behave as a viable DM candidate. We keep $M_{E_1^\pm} = 1500$ GeV and $\cos\beta = 0.995$ fixed through out the analysis and will discuss the detailed discussion on the new region of the allowed parameter spaces and the effect of the presence of additional $Z_2$-odd fermion in the dark matter section [IV A].

The parameter space of this model is constrained by various bounds arising from theoretical considerations like absolute vacuum stability and unitarity of the scattering matrix and observation phenomena like dark matter relic density and baryogenesis. Also, the LHC puts severe constraints on this model. In the following section, the constraints on the model will be discussed.

III. CONSTRAINTS ON THIS MODELS

A. Constraints on scalar potential couplings from stability, perturbativity and unitarity

Most severe constraints come from the ‘bounded from below’ of the potential, which ensure the absolute stability of the electroweak vacuum. The potential bounded from below signifies that there is no direction in field space along which the potential tends to minus infinity. In unitary gauge, for $H, S \gg v$, the scalar potential of equation [2] can be further simplified as,

$$V(H , S) = \frac{1}{4} \left\{ \sqrt{\lambda}H^2 + \sqrt{\frac{\lambda_S}{6}} S^2 \right\}^2$$

$$+ \frac{1}{4} \left[ \kappa + \sqrt{\frac{2\lambda S}{3}} \right] H^2 S^2. \quad (7)$$

The necessary conditions for the scalar potential are given by,

$$\lambda(\Lambda) > 0, \quad \lambda_S(\Lambda) > 0 \quad \text{and} \quad \kappa(\Lambda) + \sqrt{\frac{2\lambda(\Lambda)\lambda_S(\Lambda)}{3}} > 0.$$ 

Here, all the coupling constants in this model are evaluated at a scale $\Lambda$ using RG equations [11]. However, these conditions become nonfunctional if the Higgs
quartic coupling $\lambda$ becomes negative at some energy scale to contribute the electroweak vacuum metastable. In this situation, we need to handle metastability constraints on the potential differently, shown in Ref. [42]. In addition, for the radiatively improved Lagrangian of our model to be perturbative, we have [43, 44],

$$\lambda(\Lambda) < \frac{4\pi}{3}; \ |\kappa(\Lambda)| < 8\pi; \ |\lambda S(\Lambda)| < 8\pi. \quad (8)$$

The couplings of the scalar potential ($\lambda, \kappa$ and $\lambda_S$) of this model are constrained by the unitarity of the scattering matrix (S-matrix). At very high field values, one can obtain the S-matrix by using various scalar-scalar, gauge boson-gauge boson, and scalar-gauge boson scatterings. Using the equivalence theorem, we reproduced the S-matrix for this model. The unitarity demands that the eigenvalues of the S-matrix should be less than $8\pi$. The unitary bounds are given by [44],

$$\lambda \leq 8\pi \quad \text{and} \quad |12\lambda + \lambda_S \pm \sqrt{16\kappa^2 + (-12\lambda + \lambda_S)^2}| \leq 32\pi.$$  

B. LHC diphoton signal strength bounds

At one-loop level, the physical charged fermion $E_1^\pm$ and $E_2^\pm$ add extra contribution to the decay width as,

$$\Gamma(H \to \gamma\gamma) = A \left| \sum_i Q_i^2 Y_N F_{1/2}(\tau E_i^\pm) + C \right|, \quad (9)$$

where, $A = \frac{\alpha^2 M_H^3}{2\sqrt{6} M_{\gamma\gamma}^3}$, $C$ is the SM contribution, $C = \sum_i N_i^2 Q_i^2 y_f F_{1/2}(\tau E_i^\pm) + y_W F_1(\tau W)$ and $\tau_x = \frac{M_{\gamma\gamma}^2}{M_{\gamma\gamma}^2}$. $Q$ denote electric charge of corresponding particles and $N_i^2$ is the color factor. Higgs $H$ coupling to $f\bar{f}$ and $WW$ is denoted by $y_f$ and $y_W$. $Y_{N1} = \sqrt{2}\cos\beta \sin\beta Y_N$ and $Y_{N2} = -\sqrt{2}\cos\beta \sin\beta Y_N$ stand for corresponding couplings $H E_i + E_i^\gamma$ ($i = 1, 2$) and the loop function $F_{(0,1/2,1)}(\tau)$ can be found in Ref [45]. In this analysis, we find that $M_{E_{1,2}^\pm} > 200$ GeV for $Y_N = O(1)$ is still allowed from the LHC di-photon signal strength $\mu_{\gamma\gamma} = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to ZZ)_{BSM}}$ data. It is similarly true for $\mu_{Z\gamma}$ as $\cos\beta \sim 1$ in this model.

C. Bounds from electroweak precision experiments

Beyond the EW scale, electroweak precision bounds are affected by the presence of extra virtual particles in loops through vacuum polarization correction. Bounds from electroweak precision experiments are added in new physics contributions via self-energy parameters $S, T, U$ from EW precision experiments does put bounds on new physics contributions [10, 17]. The $S$ and $T$ parameters allows the new physics contributions to the neutral and the difference between neutral and charged weak currents respectively. However, the $U$ parameter is only sensitive to the mass and width of the $W$-boson, thus in some cases, this parameter is neglected. The NNLO global electroweak fit results from the GFitter group [46], $\Delta S_{BSM} < 0.05 \pm 0.11$, $T_{BSM} < 0.09 \pm 0.13$ and $\Delta U_{BSM} < 0.011 \pm 0.11$. In this model, a very small mass difference $\Delta M \sim 20$ GeV between the charged and neutral fermions of the doublet $F_D$ [17, 49] with $M_N > 200$ GeV and heavy singlet charged fermion mass $O(1)$ TeV are considered to evade these bounds.

D. Dark matter

The lightest stable $Z_2$ odd particle in our model $S$, behaves as proper DM candidate in our model. As per our choice of parameter space, DM relic density constraints should satisfy current results from Planck and WMAP [10],

$$\Omega_{DM}h^2 = 0.1198 \pm 0.0012 \quad (10)$$

Recent direct-detection experiments like the Xenon-1T [10] and invisible Higgs decay width data including indirect Fermi-LAT data have restricted the arbitrary Higgs portal coupling and the dark matter mass [42, 50]. It is also possible to explain various observations in the indirect DM detection experiments from this model. However, we do not discuss it here, as these estimations involve proper knowledge of the astrophysical backgrounds and an assumption of the DM halo profile which contains some arbitrariness.

In our study we use FeynRules [51] along with micrOMEGAs [52] to compute the relic density of the scalar DM. A comprehensive discussion on DM has been carried out in the numerical analysis section.

E. Lepton flavor violation and Baryogenesis

It is well-known lepton flavor violation (LFV) processes put severe constraints on the LFV couplings and in general on the model parameter space. The size of the LFV is controlled by the lepton number violating couplings $Y_{f_i}$ ($i = 1, 2, 3$). Since the observed dark matter abundance is typically obtained for $\kappa = O(0-1)$ and $Y_{f_i} = O(0-1)$ through s-channel, t-channel annihilation and the combination of these two processes (co-annihilation, i.e., mass differences can also play a crucial role), the lepton flavor observable are expected to
generate additional stringent constraints. Among the various LFV processes, the radiative muon decay $\Gamma(\mu \rightarrow e\gamma)$ is most popular and restrictive one, which in the present model is mediated by charged particles $E_{1\pm}^{\pm}, E_{2\pm}^{\pm}$ present in the internal lines of the one-loop diagram. The corresponding expression for the branching ratio is given by, 

$$\text{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha\epsilon_{\text{em}}}{64\pi G_F} \left| \cos^2 \beta Y_{f1}^1 Y_{f2}^2 \frac{F(M_{E_1}^2/M_S^2)}{M_S^2} + \sin^2 \beta Y_{f1}^1 Y_{f2}^2 \frac{F(M_{E_2}^2/M_S^2)}{M_S^2} \right|^2$$

where, $F(x) = \frac{x^3-6x^2+3x+2+xtn(x)}{6(x-1)^4}$.

The most recent experimental bounds for LFV could be found in Ref. [53]. Throughout this analysis we keep fixed $Y_{f2} = O(10^{-3})$ and put constraints to the other parameters from the flavor violating decay [53] $\text{BR}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ at 90% CL.

Our motivation is also to check the validity of baryogenesis produced via the mechanism of thermal leptogenesis. The lightest vectorlike fermion $E_{1}^{1-}$ is decaying to a lepton and the scalar singlet $S$, which eventually produces the desired lepton asymmetry in our model. The interactions of $E_{1}^{1-}$ violate lepton number (L) because $L$ cannot be consistently assigned to $F_D, E_S$. We focus on the decay and inverse decay of the charged particle ($E_{1}^{1-}$) of the fermion sector into a lepton and dark matter, corresponding to lepton number violation by $\Delta L = 2$ via the wash-out processes. The asymmetries generated by $E_{1}^{1-}$ decay dominated the whole process by the strong wash-out processes over the asymmetries generated by the other particles like $X_1^0, E_{2}^{1-}$. In standard thermal leptogenesis scenario, the decay parameter plays a significant role to distinguish between weak and strong washout regime. Decay parameter is the ratio between decay width of the decaying VLF to the Hubble constant at $T = M_{E_1}^{1-}$, which is expressed as, 

$$K = \frac{\Gamma_1}{H(T = M_{E_1}^{1-})} = \frac{(A_{f1}^1 A_{f1}) M_{E_1}^{1-}}{8\pi} \frac{M_{\text{Planck}}}{1.66\sqrt{g_*(M_{E_1}^{1-})^3}}$$

where, $\Gamma_1 = \frac{(A_{f1}^1 A_{f1}) M_{E_1}^{1-}}{8\pi}$ and the Hubble constant at $T = M_{E_1}^{1-}$ is defined as $H(T = M_{E_1}^{1-}) = \frac{M_{\text{Planck}}}{1.66\sqrt{g_*(M_{E_1}^{1-})^3}}$.

$M_{\text{Planck}}$ is the the Planck mass $(\approx 1.22 \times 10^{19} \text{ GeV})$ and $g^*$ is the effective number of degree of freedom which is approximately $g^* \sim 110$ for two VLF case. We used the parameterization of the Yukawa matrix w.r.t. the mixing angle $\beta$, as $A_{f1} = Y_{f1} \cos \beta$ and $B_{f1} = Y_{f1} \sin \beta$. The regime is considered to be in weak washout if $K \lesssim 1$ while for $K \gtrsim 10^6$ is considered to be a strong washout regime. The region in between them is considered to be a strong washout regime. This washout factor $K$ evoke the parameterization of dilution factor $k$, which can be found in [17].

Next, we check the CP asymmetry produced by the LVF process in our model. To produce non-vanishing lepton asymmetry, the decay of $E_{1}^{1-}$ must have lepton number violating process with different decay rates to a final state with particle and anti-particle. Asymmetry in lepton flavor $\alpha$ produced in the decay of $E_{1}^{1-}$, defined by, 

$$\alpha = \frac{N_{\text{lepton}} - N_{\text{anti-lepton}}}{N_{\text{lepton}} + N_{\text{anti-lepton}}}$$

where, $N_{\text{lepton}}$ and $N_{\text{anti-lepton}}$ are the number of produced particles in each lepton flavor. The asymmetry is produced when $K \gtrsim 10^6$.
as,
\[ \epsilon_{xx} = \frac{\Gamma(E_1^- \rightarrow l^-_x S) - \Gamma(E_1^+ \rightarrow l^+_x S)}{\Gamma(E_1^- \rightarrow l^- S) + \Gamma(E_1^+ \rightarrow l^+ S)}. \]  
(13)

where, \( l^+_x \) is the antiparticle of \( l^-_x \) and \( S \) is the dark matter candidate in our model.

Following the calculation for non-degenerate RH mass from the work of [17], we obtain the asymmetry term as,
\[ \epsilon_{xx} = \frac{1}{8\pi} \frac{1}{(A_{f_1}^* A_{f_1})} \sum_j \text{Im}\{(A_{f_1}^* (A_{f_2}^* B_{f_2})_j B_{f_1})\} g(p_j) + \frac{1}{8\pi} \frac{1}{(A_{f_1}^* A_{f_1})} \sum_j \text{Im}\{(A_{f_1}^* (A_{f_2}^* B_{f_2})_j B_{f_1})\} \frac{1}{1-p_j}. \]  
(14)

Here, \( p_j \equiv M_{f_2}^2 \) and within the SM \( g(p_j) \) is defined as,
\[ g(p_j) = \sqrt{p_j} \left( 2 - p_j - \frac{1 - p_j^2}{1 - p_j} \right). \]  
(15)

If we take sum over the final state flavor \( x \), neglecting the flavor effect, the second line from equation (14) violates the single lepton flavor, however, it conserves the total CP-asymmetry. Thus the total CP-asymmetry produced by the tree-level and one-loop level is given by,
\[ \epsilon_{11} = \sum_x \epsilon_{xx} = \frac{1}{8\pi} \frac{1}{(A_{f_1}^* A_{f_1})} \text{Im}\{[(A_{f_2}^* B_{f_2})_j] \}^2 g(p_2). \]  
(16)

The total baryon asymmetry generated is read as,
\[ Y_B = c k \epsilon_{11} g_s. \]  
(17)

Where \( c \) and \( k \) are the conversion factor and dilution factor respectively. We consider the effective relativistic degrees of freedom to be \( g = 110.75 \), slightly higher than that of the SM contribution. Various corrections corresponding to the asymmetry generations are not discussed in this work and they are left for future study. This situation under study is equivalent to the heavy Majorana mediated thermal leptogenesis processes, where the lightest Majorana particle is decaying to a lepton and Higgs doublet. The scale of the vector-like fermion, which undergoes the decay processes is around 500 GeV, hence low-scaled leptogenesis is applicable in our study.

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1 For degenerate mass with mass spiting equal to decay width, one have to consider resonant leptogenesis.
the vanishing neutrino masses are quite obvious as $\kappa$ in the scalar potential breaks lepton number by two units, when considered together with the SM-singlet fermions Lagrangian. Hence, the smallness of $\kappa$ is technically natural in the t Hooft sense [56], as adjusting $\kappa \to 0$ allows us to define global $U(1)$ lepton number symmetry. At the same time, by adjusting both the real and imaginary parts of the Yukawa couplings the mixing angles could be produced. This smallness of the Higgs portal coupling enhances the allowed region of the parameter space and the relic density could produce via the other channels which we will discuss in detail in the dark matter numerical analysis section. The analysis of neutrino mass carried out in this work is more of a perfunctory rather than being comprehensive. The relation between dark matter mass and neutrino mass matrix is established in Eqn. (18). One can scan over the parameter space by adjusting the couplings and analysis neutrino phenomenology in details as per current experimental demands.

IV. NUMERICAL ANALYSIS

A. Dark matter

As pointed out in the previous section, the viable DM candidate in this model is the lightest $Z_2$-odd singlet scalar $S$. The production mechanism of this DM candidate depends upon the Higgs portal couplings $\kappa$ through $s$-channel and $p$-channels (see Figs. 8(a), (b) and (c)). It is to be noted that in the presence of the Yukawa couplings $Y_{fi}$ and $Y_{N}$, a huge improvement to the region of the dark matter parameter space is noticed here in this model. It was not been discussed in the literature previously which motivates us to study this model. Depending upon the size of the Yukawa couplings $Y_{fi}$, one can get a dominant DM annihilation through $t$- and $u$-channels (see Fig. 8(d)) in our model. The interference between the $s$- and $p$-channel and $t$, $u$-channels also played a crucial role to achieve the correct DM density. The co-annihilation channels (e.g., see Fig. 5) also played an important role to get a viable region of allowed dark matter parameter space.

It is already evident that if we neglect the effect of other $Z_2$-odd fermions, i.e., annihilation through $t$-channels and other co-annihilation processes, a very small low-DM mass region around $55 < M_{DM} < 70$ for Higgs portal coupling $\kappa \sim 0.005$ is giving the exact relic density, allowed by the direct detection [10] and LHC data. The main dominant channels for low-DM mass region is $SS \to b\bar{b}$. For $M_{DM} > 100$ GeV, $SS \to VV$, where $V = W^\pm, Z$ gauge bosons [57] dominates over other DM annihilation channels. Under the approximation $M_{DM} \gg M_V, M_H$, in the non-relativistic limit one can get the DM annihilation cross-section as $\sigma(SS \to W^+W^-) \propto \frac{\kappa^2}{M_{DM}^2}$. The allowed relic density (dominated by $s$- and $p$-channels only) for the high-DM mass region in $\kappa - M_{DM}$ plane is displayed in Fig. 6. We also present corresponding benchmark points BP-1a and the percentage of differ-
ent annihilation channel’s contributions in the Tab. III
As usual, the main dominant channels are $SS \to YY$ with $Y = W, Z$ and $H$ for the high-DM mass region. Between the color lines, we marked the allowed region

FIG. 6: The dark matter relic density through s- and p- channels only, with direct detection and other theoretical and experimental constraints. The Yukawa couplings $Y_{fi}$ and $Y_N$ are taken to be zero.

ensuing from relic density constraints. The green lines stand for $\Omega h^2 = 0.1234$ (upper limit at $3\sigma$) whereas red lines corresponds $\Omega h^2 = 0.1162$ (lower limit at $3\sigma$). One can get the exact relic density for the DM-mass region $70 < M_{MD} < 450$, however it is ruled out by the present direct detection cross-section [10]. So far we

FIG. 7: The dark matter relic density through t-channels only, with direct detection and other theoretical and experimental constraints. The Higgs portal couplings $\kappa$ is taken to be zero.

do not have any direct signature of the DM in the direct detection experiments, which suggest that we may have the dark matter with a tiny or zero Higgs portal coupling and the remaining effective cross-section $< \sigma_{eff} v >$ can be adjusted by the other annihilation and co-annihilation processes to achieve the exact dark matter density. In this model, we considered such scenarios to achieve the goals.

For example, for various dark matter masses, one can get the exact density with vanishing Higgs portal coupling ($\kappa$) by adjusting the charged fermion mass and Yukawa couplings $Y_{fi}$. We portrait such variation in $Y_f - M_{DM}$ plane in Fig. 7 for two different values of charged fermion mass $M_{E^\pm} = 500$ GeV and $M_{E^\pm} = 1000$ GeV. We also consider $Y_{f1} = Y_{f3} = Y_f$ and $Y_{f2} = O(10^{-3})$ to avoid the flavor violating decay processes (see eqn. [11]). The dynamical reasons for such choice of coupling parameters lie somewhere else which is out of the scope of this paper. It can be noticed from Fig. 7 that one could get exact relic density for the dark matter mass as low as $M_{DM} = 10$ GeV. As $\kappa = 0$, the parameter space $M_{DM} < \frac{M_H}{2}$ is not restricted by the Higgs decay width and direct detection cross-section constraints. These data points also passed through other experimental constraints such as Higgs signal strength, electroweak precision test (EWPT) and theoretical bounds, viz., stability, unitarity, etc. The main dominant $t, u$-channel annihilation processes are $SS \to \nu\nu$ (see BP-b1,b2 and b3 in Tab. [11]) and $SS \to ll$, where $l = e, \tau$ and $\nu = \nu_e, \nu_\tau$ only as $Y_{f2} = O(10^{-3})$.

FIG. 8: The coupling $y_f = 0.05$ and second charged fermion mass $M_{E^\pm} = 1500$ GeV are fixed. $M_{DM}$, $\kappa$ and $M_{E^\pm}$ parameters are varied in this plot. These red points satisfy the relic density at $3\sigma$ C.L. with $\Omega h^2 = 0.1198 \pm 0.0012$, satisfying all the theoretical and experimental bounds.

We now perform scans over the three dimensional parameter space. The mass parameter $M_{E^\pm}$ is varied from
200 GeV (to avoid the experimental constraints) to 1000 GeV with a step size 0.25 GeV and \( \kappa \) from \(-0.35\) to 0.35 with a step size 0.002. The dark matter mass \( M_{DM} \) from \( \sim 200 \) GeV to 1000 GeV with a step size 2 GeV. For \( \Delta M^{\pm,0} < 0.1 M_{DM} \) \( (\Delta M^{\pm} = M_{E_1^{\pm}} - M_{DM} \) and \( \Delta M^0 = M_N - M_{DM} \) ), the co-annihilation channels play an important role for the dark matter density calculation. We fixed the coupling \( Y_f \) at 0.05 to reduce the \( t, u \)-channel annihilation contributions in the relic density. The effect is almost negligible for the second charged fermion mass \( M_{E_2^{\pm}} = 1500 \) GeV and \( \cos \beta = 0.995 \). These parameters play an important role to get the baryon asymmetry of the Universe. In Fig. 9 we display the allowed parameters in the \( \kappa - M_{DM} \) plane. These red points satisfy the relic density at 3\( \sigma \) C.L. with \( \Omega h^2 = 0.1198 \pm 0.0012 \). The two middle bands close to \( |\kappa| \sim 0.03 - 0.10 \) are mainly dominated by the co-annihilation channels. For example, we present two such benchmark points (BP-c1 and BP-c2) and the corresponding contributions in Tab. II. The other two bands dominated by the annihilation of the dark matter through \( s + p \)- as well as \( t + u \)-channels. Large Higgs portal coupling, such as \( \kappa = 0.148 \) (BP-c4) are mainly dominated by the \( s + p \)-channel annihilation processes. However, the relic density for the point BP-c3 is coming due to the combined contributions of \( s + p \)- and \( t + u \)-channels.

We also scans in the other three dimensional parameter space. The dark matter mass \( M_{DM} \) is varied from 5 GeV to 540 GeV and \( \kappa \) from \(-0.35\) to 0.35 with a step size 0.002 and \( Y_f \) from \(-0.35\) to 0.35 GeV with a step size 0.005 GeV with fixed \( M_{E_1^{\pm}} = 500 \) GeV. It is noted that the co-annihilation effect are completely absent here as \( \Delta M^{\pm,0} > 0.1 M_{DM} \). We display the allowed parameters \( \kappa - M_{DM} \) plane in Fig. 9. One can see, in the presence of DM annihilation via \( t, u \)-channel as most of the region is giving the correct DM density which is also allowed by other experimental constraints. For \( \kappa \neq 0 \), the \( s \)-channel annihilation dominates near Higgs resonance region \( \sim \frac{M_H}{2} \). This region gives over-abundance of dark matter density in our study. For a small \( \kappa \sim 0 \), the \( t + u \)-channels helps to get the correct relic density at 3\( \sigma \) C.L. We show the \( \kappa - Y_f \) plane in Fig. 10 for the same data points as in Fig. 9. We get two circular ring-type structures here. The empty region violates one of the constraints such as relic density of the dark matter, direct detection and Higgs decay width for the DM mass \( < \frac{M_H}{2} \). However, in the pres-

| Channel | \( M_{DM} \) (GeV) | \( \kappa \) | \( M_{E_1^{\pm}} \) (GeV) | \( Y_f \) | \( \Omega_{DM} h^2 \) | Percentage |
|---------|------------------|--------|-----------------|--------|-----------------|-----------|
| BP-a1   | 570              | 0.1703 | 2000            | 0.0    | 0.1198          | \( \sigma(SS \rightarrow W^{\pm}W^{\pm}) \) 47% |
|         |                   |        |                 |        |                 | \( \sigma(SS \rightarrow HH) \) 24% |
|         |                   |        |                 |        |                 | \( \sigma(SS \rightarrow ZZ) \) 23% |
|         |                   |        |                 |        |                 | \( \sigma(SS \rightarrow t\bar{t}) \) 6% |
| BP-b1   | 10               | 0.0    | 500             | 0.1665 | 0.1198          | \( \sigma(SS \rightarrow \nu\nu) \) 98% |
|         |                   |        |                 |        |                 | \( \sigma(SS \rightarrow t\bar{t}) \) 2% |
| BP-b2   | 60               | 0.0    | 500             | 0.1640 | 0.1198          | \( \sigma(SS \rightarrow \nu\nu) \) 98% |
|         |                   |        |                 |        |                 | \( \sigma(SS \rightarrow t\bar{t}) \) 2% |
| BP-b3   | 100              | 0.0    | 500             | 0.1677 | 0.1198          | \( \sigma(SS \rightarrow \nu\nu) \) 98% |

FIG. 9: The first and second charged fermion masses \( M_{E_1^{\pm}} = 500 \) GeV and \( M_{E_2^{\pm}} = 1500 \) GeV are fixed. \( M_{DM} \), \( \kappa \) and \( Y_f \) parameters are varied in this plot. These red points satisfy the relic density at 3\( \sigma \) of \( \Omega h^2 = 0.1198 \pm 0.0012 \) and pass all the theoretical and experimental bounds.

TABLE II: The benchmark points allowed by all the theoretical and experimental constraints. The density of the dark matter \( S \) is dominated by either \( s \)- or \( t, u \)-channel annihilation processes.
ence of the co-annihilation processes with/or a different choice of the $M_{E_i^±}$ the gaps between these two circular rings could be filled. We also display a similar plots in $\kappa \sim M_{DM}$ and $\kappa \sim Y_f$ planes in Figs. [11] and [12] for the $M_{E_i^±} = 1000$ GeV, where we change the variation for DM mass $M_{DM}$ from 5 GeV to 1000 GeV. We get a similar type of plot with a large region of the parameter spaces allowed by all the experimental and theoretical constraints. Few BMPs and their corresponding contributions are presented in Tab. [IV] $\sigma(SS \rightarrow \nu \nu)$ is mainly dominated by the $t + u$-channel annihilation processes whereas $\sigma(SS \rightarrow YY)$, $Y = W, Z, H, t$ dominated by the $s + p$-channel annihilation processes.

### B. Baryon asymmetry and Neutrino

In this minimal model, with the choice of parameter space, we try to give some numerical insights to neutrino phenomenology and baryogenesis. Using equation [18], with the masses for subsequent fields $M_{DM} = 700$ GeV $M_N = 1000$ GeV and choice of Yukawa parameters $|Y_{f1}| = 0.4, |Y_{f2}| = 10^{-4}, |Y_{f3}| = 0.157$, we get the sum of the neutrino masses of the order of sub-eV range ($\sim 0.12$ eV) for Higgs portal coupling $\kappa < 10^{-5}$. This tiny $\kappa$ is directly associated with dark matter relic density via the $t$-channel process. We are able to generate mixing angles $\theta_{12} = 32.7^\circ$, $\theta_{13} = 8.4^\circ$, $\theta_{23} = 44.71^\circ$ and mass differences $\Delta m^2_{21} = 7.31 \times 10^{-5}$ and $\Delta m^2_{31} = 2.63 \times 10^{-3}$ with phases $\alpha = \delta = 45^\circ$. Although $\Delta m^2_{31}$ is within the present $3\sigma$ bound however, $\Delta m^2_{31}$ is slightly deviate from the actual range. This inconsistency can be resolved by introducing one extra field into the model. We can play with other parameters to get the correct experimental values for the light neutrinos.

We also checked the ability of this model to explain the baryogenesis via thermal leptogenesis. We worked out the low-scale leptogenesis within a strong wash-out regime. One can understand that the source of CP-violation from Fig. [2] and corresponding Eqns. [13]...
TABLE IV: The benchmark points allowed by all the theoretical and experimental constraints. $\sigma(SS \rightarrow \nu \nu)$ is mainly dominated by the $t + u$-channel annihilation processes whereas $\sigma(SS \rightarrow YY)$, $Y = W, Z, H, t$ dominated by the $s + p$-channel annihilation processes.

| Channel | $M_{DM}$ (GeV) | $\kappa$ | $M_{E_1}^\pm$ (GeV) | $Y_f = Y_{f1, f3}$ | $\Omega_{DM} h^2$ | Percentage |
|---------|----------------|----------|----------------------|-------------------|------------------|------------|
| BP-d1   | 325            | 0.05     | 1000                 | 0.225             | 0.1173           | $\sigma(SS \rightarrow \nu \nu)$ 72% |
|         |                |          |                      |                   |                  | $\sigma(SS \rightarrow W^\pm W^\mp)$ 12% |
|         |                |          |                      |                   |                  | $\sigma(SS \rightarrow HH)$ 7% |
|         |                |          |                      |                   |                  | $\sigma(SS \rightarrow ZZ)$ 6% |
|         |                |          |                      |                   |                  | $\sigma(SS \rightarrow t\bar{t})$ 4% |
| BP-d2   | 500            | 0.05     | 1000                 | 0.250             | 0.1219           | $\sigma(SS \rightarrow \nu \nu)$ 88% |
|         |                |          |                      |                   |                  | $\sigma(SS \rightarrow W^\pm W^\mp)$ 5% |
|         |                |          |                      |                   |                  | $\sigma(SS \rightarrow ZZ)$ 3% |
|         |                |          |                      |                   |                  | $\sigma(SS \rightarrow HH)$ 3% |
| BP-d3   | 675            | 0.05     | 1000                 | 0.280             | 0.1169           | $\sigma(SS \rightarrow \nu \nu)$ 96% |
|         |                |          |                      |                   |                  | $\sigma(SS \rightarrow W^\pm W^\mp)$ 3% |
|         |                |          |                      |                   |                  | $\sigma(SS \rightarrow ZZ)$ 1% |
|         |                |          |                      |                   |                  | $\sigma(SS \rightarrow HH)$ 1% |

FIG. 10: The first and second charged fermion masses $M_{E_1}^\pm = 500$ GeV and $M_{E_2}^\pm = 1500$ GeV are fixed. $M_{DM}$, $\kappa$ and $y_f$ parameters are varied in this plot. These red points satisfy the relic density at 3$\sigma$ of $\Omega h^2 = 0.1198 \pm 0.0012$ and pass all the theoretical and experimental bounds.

FIG. 11: The first and second charged fermion masses $M_{E_1}^\pm = 1000$ GeV and $M_{E_2}^\pm = 1500$ GeV are fixed. $M_{DM}$, $\kappa$ and $y_f$ parameters are varied in this plot. These red points satisfy the relic density at 3$\sigma$ of $\Omega h^2 = 0.1198 \pm 0.0012$ and pass all the theoretical and experimental bounds.

We adopted the numerical formalism from [17, 28] to carry-out our numerical analysis. The allowed region with correct baryon asymmetry value is shown in Fig. [3] in the $\text{Im}[Y_{f2}] - M_{E_1}^\pm$ plane. The purple band satisfies baryon asymmetry value at 3$\sigma$ C.L. with $Y_{AB} = (8.75 \pm 0.23) \times 10^{-11}$. $\text{Im}[Y_{f2}]$ is the imaginary part of the second Yukawa coupling $Y_f$. The real part of this coupling is also taken to be very small to avoid the LFV bounds [53] (see Eqn. [11]). The other parameters are fixed as $M_{E_2}^\pm = 1500$ GeV, $\cos \beta = 0.995$, $Y_f = 0.4 + 8 \times 10^{-5} i$. The dynamical reasons for the smallness of these imaginary parts of these coupling may lie somewhere else. Influence of the small Yukawa coupling $Y_{f2}$, that satisfies the observed baryon asymmetry value can also be found in generating neutrino mass and mixing angles. With the choice of new parameter scale
FIG. 12: The first and second charged fermion masses $M_{E_1^\pm} = 1000$ GeV and $M_{E_2^\pm} = 1500$ GeV are fixed. $M_{DM}$, $\kappa$ and $y_f$ parameters are varied in this plot. These red points satisfy the relic density at $3\sigma$ of $\Omega h^2 = 0.1198 \pm 0.0012$ and pass all the theoretical and experimental bounds.

and new fields, the study on various wash-out processes and complete analysis of neutrino phenomenology are left for future work.

FIG. 13: The purple bands are giving the correct numbers which can explain the baryon asymmetry of the Universe.

C. Collider Searches

We perform a search for the lightest charged fermion $E_1^\pm$ in the context of 14 TeV LHC experiments with integrated luminosity of 3000 fb$^{-1}$ for event’s process $pp \rightarrow E_1^\pm E_1^\mp$, where a SM leptons $l$ is produced through decays of the charged fermion as $E_1^\pm \rightarrow l^\pm S$. Hence in the final state events have two same flavors opposite sign (SFOS) leptons including significant missing transverse energy coming from the LSP $S$. The events are selected with two same flavors opposite sign (SFOS) isolated electron$^2$ with transverse momentum $p_T$ larger than 30 GeV. The charged lepton isolation requires that there is no other charged particle with $p_T > 0.5$ GeV/c within a cone of $\Delta R = \sqrt{\Delta \Phi^2 + \Delta \eta^2} < 0.5$ centered on the cell-associated to the charged lepton. Besides, the ratio of the scalar sum of the transverse momenta of all tracks to $p_T$ of the lepton (chosen for isolation) is less than 0.12 (0.25) for the electron (muon). Here $p_T$, $\Phi$ and $\eta$ are the transverse momentum, polar angle and pseudo-rapidity of charged leptons respectively.

The charged lepton candidates are required to be within a pseudorapidity range of $|\eta| < 2.5$. Number of light and $b$-jets in the final state are taken to be zero. The invariant mass $M_{ll}$ and transverse missing energy distributions $E_T$ can be a useful probe to search for the charged fermion $E_1^\pm$ of this model. We show these distributions in Figs. 14 and 15 respectively for the benchmark points $\cos \beta = 0.995$, $Y_f = 0.165$, $M_{E_1^\pm} = 500$ GeV and $M_{E_2^\pm} = 1500$ GeV. Here, processes like $pp \rightarrow WW$ ($W \rightarrow l\nu$), $pp \rightarrow ZZ$ ($Z \rightarrow ll, Z \rightarrow \nu\nu$) and $pp \rightarrow ZZ$ ($Z \rightarrow ll, Z \rightarrow \nu\nu$) can add to the SM background if additional charged leptons get misidentified or remain unreconstructed. Also other reducible

$^2$ Total number of muon remains zero in the final state events as $Y_{f2} \sim 0$.
significance pp backgrounds like the dark matter. These type of scenarios are observed in hiliation cross-section and give the right relic density of among these channels helps to modify the effective anni-

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comes around S=300 TeV run of the LHC with luminosity L=300 fb^{-1} for process pp \rightarrow E_1^{\pm}E_1^{\pm} where a SM leptons l is produced through decays of the charged fermion as E_1^{\pm} \rightarrow l^{\pm}S. We have only analyzed the familiar 2l+E_T final states to get the signature at the future collider. The leptonic final states produce relatively clean signals which are easy to identify in a hadron-rich environment like the LHC experiment. We choose benchmark points that ensure the relic density, baryon asymmetry, and neutrino parameters. We further optimized the selection cuts in order to enhance the 2l+E_T signal significance over the SM backgrounds. Our collider study showed that the dilepton final state gives promising results for the discovery of the heavy charged particle at 14 TeV LHC experiments with an integrated luminosity of 3000 fb^{-1} which may be an indication of the dark matter at the collider.

One can also put bound on the Yukawa coupling as larger Yukawa coupling may violate the stability of the scalar potential any of the direction the scalar fields at any scale (at least up to the Planck scalar 1.22 \times 10^{19} GeV). In this model, we work with such a choice of the Yukawa couplings and \kappa (especially \lambda_S) so that there is no new minima arise along any of the scalar field directions. In the future, we will elaborate on the details stability and/or metastability analysis for a various regions of the parameter space which could also explain all the neutrino masses and mixing angles, exact relic density and baryon-asymmetry of the Universe altogether.

In the concluding remark: if nature selects a single component WIMP dark matter candidate, which inter-
acts with the nucleus feebly through s-channel, helps to get the neutrino mass of order $O(0.1)\ eV$. On the assumption that the relic density can achieve via t-channel annihilation processes. We have to think of a new way to detect dark matter in the direct-detection experiments. In that case, collider searches with high luminosity are better options to detect dark matter.

VI. ACKNOWLEDGEMENT

The research work of P.D. and M.K.D. is supported by the Department of Science and Technology, Government of India under the project grant EMR/2017/001436. NK would like to thank Dilip Kumar Ghosh for his support at IACS.

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