

Impact of conversion-driven processes on singlet-doublet Majorana dark matter relic

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The singlet-doublet dark matter model offers a rich framework for exploring the nature of dark matter (DM) through its unique fermion structure. In this model, the important parameters are the singlet-doublet mass splitting ΔM , the singlet-doublet mixing angle $\sin \theta$, and the DM mass M_{DM} . If the DM is assumed to be of Dirac nature, then the annihilation, coannihilation, and conversion driven processes combined allow a range of parameter space: $100 \text{ GeV} \lesssim M_{\text{DM}} \lesssim 750 \text{ GeV}$ and $10^{-6} \lesssim \sin \theta \lesssim 0.04$ for $\Delta M > 1 \text{ GeV}$. While the nature of DM, either Dirac or Majorana, is not known, in this work, we assume the singlet-doublet DM to be of Majorana type and find that the relic density and direct detection can be satisfied over a larger parameter space. In particular, the allowed ranges of DM mass and $\sin \theta$ are $100 \text{ GeV} \lesssim M_{\text{DM}} \lesssim 1750 \text{ GeV}$ and $2 \times 10^{-7} \lesssim \sin \theta \lesssim 0.45$ for $\Delta M > 1 \text{ GeV}$.

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I. INTRODUCTION

Dark matter (DM) constitutes approximately 26.8% of the Universe's total energy budget ($\Omega_{\text{DM}} h^2 \simeq 0.12$) [1], evidencing its presence through galaxy rotation curves, gravitational lensing, the formation of large-scale structures, etc. [2,3]. Given the absence of a DM candidate within the standard model (SM), the weakly interacting massive particle (WIMP) emerges as a compelling contender, capable of accounting for the DM relic density through freeze-out processes in the early Universe. A simple extension of the SM for the explanation of DM could be a singlet fermion, which is odd under $\mathcal{Z}_2$ symmetry. However, the parameter space faces stringent constraints from both relic density requirements and direct detection experiments [4,5]. Another alternative would be to consider a $\mathcal{Z}_2$ odd doublet fermion, which also fails due to excessive annihilation and detection constraints. These issues can be resolved if one considers the combination of singlet and doublet fermions. The neutral component of the doublet mixes with the singlet fermion to give the so-called fermionic singlet-doublet DM (SDDM) [4–34]. The attractive part of this model is that it is a very minimal model in

the beyond the SM scenario, having only three parameters: DM mass M_{DM} , singlet-doublet (SD) mixing $\sin \theta$, and SD mass splitting ΔM . This model not only predicts the DM relic but also facilitates probes at different terrestrial experiments. The DM relic is decided not only by annihilation and coannihilation processes but also by conversion-driven [35–37] processes (which include cospin, decay, and inverse-decay). It was found that, if the SD mixing is large (typically $\sin \theta \gtrsim 0.05$), annihilation and coannihilation processes determine the relic abundance [4]. On the other hand, in the small-mixing-angle limit, conversion-driven processes play an important role in determining the relic of DM. It was shown that for $\sin \theta \gtrsim 10^{-6}$ the singlet can be brought to equilibrium [34]. However, for small $\sin \theta$, the singlet component decouples early with a larger abundance. Nevertheless, through conversion-driven processes, the DM particles scatter into a higher-mass state within the dark sector, such as the doublet, which then annihilates into SM particles, thereby reducing the singlet abundance. As a result, the final relic of the DM can be brought to the correct ballpark even if $\sin \theta$ is small. For $\sin \theta < 10^{-7}$, the singlet never attains equilibrium. In this case, the relic can be produced by nonthermal mechanisms, such as SuperWIMP and freeze-in. Assuming the SDDM to be Dirac type, the full parameter space of the DM relic, including annihilation, coannihilation, cospin, decay, and inverse decay, was estimated in [34]. In fact, the allowed parameter space for a Dirac SDDM was found to be $100 \text{ GeV} \lesssim M_{\text{DM}} \lesssim 750 \text{ GeV}$ and $10^{-6} \lesssim \sin \theta \lesssim 0.04$ for $\Delta M > 1 \text{ GeV}$. On the other hand, in the Majorana fermionic DM scenario, where the DM particle is its own antiparticle, its dynamics or the relic-determining processes

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differ from those of its Dirac counterpart. Consequently, this distinction leads to a modified parameter space for Majorana DM candidates.

In this paper, we assume the SDDM to be of Majorana type and study the allowed parameter space for the correct relic density, including annihilation, coannihilation, and conversion-driven processes. We show that, in the case of Majorana SDDM, the correct relic density allows the ranges of DM mass and $\sin \theta$ are $100 \text{ GeV} \lesssim M_{\text{DM}} \lesssim 1750 \text{ GeV}$ and $2 \times 10^{-7} \lesssim \sin \theta \lesssim 0.45$ for $\Delta M > 1 \text{ GeV}$. We also note that inclusion of the conversion-driven processes shifts the relic parameter space to the sensitivity ranges of LHC [38,39] and MATHUSLA [40].

The paper is organized as follows. In Sec. II, we describe the singlet-doublet Majorana DM model in detail. The DM phenomenology and detection prospects are discussed in Sec. III. We finally conclude in Sec. IV.

II. THE MODEL

The SM is extended with a singlet fermion, χ , and a doublet fermion, $\Psi = (\psi^0 \psi^-)^T = (\psi_L^0 + \psi_R^0 \psi^-)^T$, which are odd under a discrete symmetry $\mathcal{Z}_2$. The DM Lagrangian can be written as

$$\mathcal{L}_{\text{DM}} = \bar{\Psi} i \gamma^\mu \mathcal{D}_\mu \Psi - M_\Psi \bar{\Psi} \Psi + \bar{\chi} i \gamma^\mu \partial_\mu \chi - \frac{1}{2} M_\chi \bar{\chi} \chi - \frac{y_\chi}{\sqrt{2}} \bar{\Psi} \tilde{H} (\chi + \chi^c) + \text{H.c.} \quad (1)$$

The neutral fermion mass matrix can be written in the basis $((\psi_R^0)^c, \psi_L^0, (\chi)^c)^T$ as

$$\begin{pmatrix} 0 & M_\Psi & \frac{m_D}{\sqrt{2}} \\ M_\Psi & 0 & \frac{m_D}{\sqrt{2}} \\ \frac{m_D}{\sqrt{2}} & \frac{m_D}{\sqrt{2}} & M_\chi \end{pmatrix}, \quad (2)$$

where $m_D = y_\chi v_h / \sqrt{2}$ and v_h is the vacuum expectation value (vev) of the SM Higgs boson, H . The mass matrix can be diagonalized with a unitary matrix of the form $U(\theta) = P \cdot U_{13}(\theta_{13} = \theta) \cdot U_{23}(\theta_{23} = 0) \cdot U_{12}(\theta_{12} = \frac{\pi}{4})$. The details can be found in Appendix A. The three neutral states mix and give three Majorana states as $\chi_i = \frac{\chi_{iL} + \chi_{iL}^c}{\sqrt{2}}$, where

$$\begin{aligned} \chi_{1L} &= \frac{\cos \theta}{\sqrt{2}} (\psi_L^0 + (\psi_R^0)^c) + \sin \theta N_1^c, \\ \chi_{2L} &= \frac{i}{\sqrt{2}} (\psi_L^0 - (\psi_R^0)^c), \\ \chi_{3L} &= -\frac{\sin \theta}{\sqrt{2}} (\psi_L^0 + (\psi_R^0)^c) + \cos \theta N_1^c. \end{aligned} \quad (3)$$

The corresponding mass eigenvalues are

$$\begin{aligned} M_{\chi_1} &= M_\Psi \cos^2 \theta + M_\chi \sin^2 \theta + m_D \sin 2\theta, \\ M_{\chi_2} &= M_\Psi, \\ M_{\chi_3} &= M_\Psi \sin^2 \theta + M_\chi \cos^2 \theta - m_D \sin 2\theta, \end{aligned} \quad (4)$$

where the mixing angle is given as

$$\tan 2\theta = \frac{2m_D}{M_\Psi - M_\chi}. \quad (5)$$

In Appendix B, we have provided the interaction Lagrangian in the mass basis. In this setup, we consider M_{χ_3} to be the lightest among the dark sector particles and identify χ_3 as the DM candidate with $M_{\chi_3} = M_{\text{DM}}$. The Yukawa coupling, using Eq. (A6), can be expressed as

$$y_\chi = \frac{\Delta M \sin 2\theta}{\sqrt{2} v_h}, \quad (6)$$

where the SD mass splitting $\Delta M = M_{\chi_1} - M_{\chi_3}$.

III. DARK MATTER PHENOMENOLOGY AND DETECTION PROSPECTS

We investigate the DM phenomenology of the SDDM model, considering a singlet Majorana fermion as the DM candidate within a thermal freeze-out framework. A comprehensive numerical scan is performed over the model parameter space, incorporating conversion-driven processes alongside conventional annihilation and coannihilation mechanisms (respective Feynman diagrams are provided in Appendix C). The Feynman diagrams relevant for the relic density calculation are given in Appendix C. The analysis explores the viable mass range for the DM candidate between 10 and 2000 GeV. In earlier studies of the SDDM framework [5], it was commonly assumed that all dark sector particles decouple simultaneously. However, this assumption does not necessarily hold for small mixing angles. In particular, for values of $\sin \theta \lesssim 0.05$, the DM particles fail to maintain chemical equilibrium with the thermal bath. Consequently, the singlet typically decouples earlier, while the doublet remains in equilibrium for a longer period owing to its gauge interactions.

In accordance with this, we consider three distinct sectors to trace the evolution of DM independently of other particles in the thermal bath. The DM component (χ_3) is assigned to sector 1, while the remaining dark sector particles ($\chi_1, \chi_2, \psi^\pm$) belong to sector 2, and the SM particles constitute sector 0. Note that the fermion doublet components ($\chi_1, \chi_2, \psi^\pm$) maintain chemical equilibrium among themselves with the help of gauge-mediated interactions, e.g., processes like $\psi^\pm \chi_{1,2} \leftrightarrow \text{SM SM}$ with $W^\pm$ exchange and that decouple at the same epoch. This

justifies treating them as a single sector, i.e., sector 2. In this setup, particles in sectors 1 and 2 can interact with each other and with sector 0 (i.e., SM particles). Consequently, the cosmological evolution of sectors 1 and 2 must be tracked simultaneously for all ranges of $\sin \theta$. We define the comoving number densities of sector 1 and sector 2 as

$$\begin{aligned} \frac{dY_1}{dT} = \frac{1}{3\mathcal{H}} \frac{ds}{dT} & \left[\langle \sigma_{1100} v \rangle (Y_1^2 - Y_1^{\text{eq}2}) + \langle \sigma_{1122} v \rangle \left(Y_1^2 - Y_2^2 \frac{Y_1^{\text{eq}2}}{Y_2^{\text{eq}2}} \right) + \langle \sigma_{1200} v \rangle (Y_1 Y_2 - Y_1^{\text{eq}} Y_2^{\text{eq}}) \right. \\ & \left. + \langle \sigma_{1222} v \rangle \left(Y_1 Y_2 - Y_2^2 \frac{Y_1^{\text{eq}}}{Y_2^{\text{eq}}} \right) - \langle \sigma_{1211} v \rangle \left(Y_1 Y_2 - Y_1^2 \frac{Y_2^{\text{eq}}}{Y_1^{\text{eq}}} \right) - \frac{\Gamma_{2 \rightarrow 1}}{s} \left(Y_2 - Y_1 \frac{Y_2^{\text{eq}}}{Y_1^{\text{eq}}} \right) \right], \end{aligned} \quad (7)$$

$$\begin{aligned} \frac{dY_2}{dT} = \frac{1}{3\mathcal{H}} \frac{ds}{dT} & \left[\langle \sigma_{2200} v \rangle (Y_2^2 - Y_2^{\text{eq}2}) - \langle \sigma_{1122} v \rangle \left(Y_1^2 - Y_2^2 \frac{Y_1^{\text{eq}2}}{Y_2^{\text{eq}2}} \right) + \langle \sigma_{1200} v \rangle (Y_1 Y_2 - Y_1^{\text{eq}} Y_2^{\text{eq}}) \right. \\ & \left. - \langle \sigma_{1222} v \rangle \left(Y_1 Y_2 - Y_2^2 \frac{Y_1^{\text{eq}}}{Y_2^{\text{eq}}} \right) + \langle \sigma_{1211} v \rangle \left(Y_1 Y_2 - Y_1^2 \frac{Y_2^{\text{eq}}}{Y_1^{\text{eq}}} \right) + \frac{\Gamma_{2 \rightarrow 1}}{s} \left(Y_2 - Y_1 \frac{Y_2^{\text{eq}}}{Y_1^{\text{eq}}} \right) \right], \end{aligned} \quad (8)$$

where $Y_i^{\text{eq}} (= n_i^{\text{eq}}/s)$ are the equilibrium abundances, $\mathcal{H} = 1.66 \sqrt{g_*} \frac{T^2}{M_{\text{Pl}}}$ is the Hubble parameter with $M_{\text{Pl}} = 1.22 \times 10^{19}$ GeV being the Planck mass, and $\langle \sigma_{\alpha\beta\gamma\delta} v \rangle$ are the thermally averaged cross-sections for the processes $\alpha\beta \leftrightarrow \gamma\delta$. The term $\Gamma_{2 \rightarrow 1}$ in Eq. (8) includes both decay, Γ_{D} , and cospattering rates as given by

$$\Gamma_{2 \rightarrow 1} = \Gamma_{\text{D}} \frac{K_1(M_{\Psi}/T)}{K_2(M_{\Psi}/T)} + n_{\text{SM}}^{\text{eq}} \langle \sigma_{2010} v \rangle. \quad (9)$$

In the left panel of Fig. 1, we present the parameter space yielding the observed relic abundance in the ΔM - M_{DM} plane, obtained by numerically solving Eqs. (7) and (8) without incorporating the cospattering contributions in the $\Gamma_{2 \rightarrow 1}$ term.¹ The different colors correspond to distinct ranges of the SD mixing angle $\sin \theta$, as indicated in the figure inset. At larger mass splittings ($\Delta M \gtrsim 100$ GeV), DM interacts with the SM bath via annihilation processes, providing a correct freeze-out relic, while for smaller ΔM ($\Delta M \lesssim 100$ GeV), the co-annihilation processes become dominant in comparison to the annihilation processes. Nevertheless, the decay and inverse-decay processes also play a significant role in maintaining equilibrium among the sector 1 and sector 2 particles [34]. As the DM mass increases, the cross-section decreases. To enhance the cross-section in the annihilation-dominant region, ΔM has to be increased to get the relic abundance of DM in the correct ballpark. For the same reason, in the co-

annihilation dominating region, ΔM has to be reduced with increasing M_{DM} to obtain the correct relic density. This is why, for $\sin \theta \gtrsim 10^{-1}$, we see an upward trend in ΔM in the region $\Delta M \gtrsim 100$ GeV, while a downward trend in ΔM for $\Delta M \lesssim 100$ GeV with an increase in DM mass. This leads to a minimum value of M_{DM} for each $\sin \theta$ as shown by different colored bands. For each color band, the region to its right corresponds to an overabundant relic density, whereas the region to its left leads to an underabundant relic density. In the small $\sin \theta$ ($\lesssim 0.05$) region, the dominating processes that decide the relic density are coannihilation, decay, and inverse-decay. In this region, due to the interplay between co-annihilation and decay and inverse-decay processes,² there exists a maximum allowed M_{DM} for each $\sin \theta$ beyond which the relic remains overabundant. To understand this behavior, we have provided four benchmark points, namely, A, B, C, and D in Table I. For example, for BP-A ($\sin \theta = 9.5 \times 10^{-3}$), $\Delta M = 3.3$ GeV gives the correct relic abundance, as shown in the left panel of Fig. 1. If we switch off the term $\Gamma_{2 \rightarrow 1}$ while solving Eqs. (7) and (8) (i.e. without including the effect of cospattering, decay and inverse-decay processes), the same set of parameters result in a slightly increased relic density as shown in the Table I. This is because the rate of coannihilation processes decreases for small $\sin \theta$, leading to an overabundant relic that can be brought into the correct ballpark in the presence of decay and inverse-decay processes. Now in BP-B, we keep the M_{DM} and $\sin \theta$ same as BP-A, but with a smaller

¹We use `micrOMEGAS` [42] to calculate the relic density. Here we explicitly verify the thermalization of the DM by considering $\Gamma/\mathcal{H} > 1$ using the function `checkTE`, where Γ is the total interaction rate and $\mathcal{H}$ is the Hubble parameter.

²Note that the interaction rate of the coannihilation process enhances with a decrease in ΔM , while the decay width decreases with decrease in ΔM .

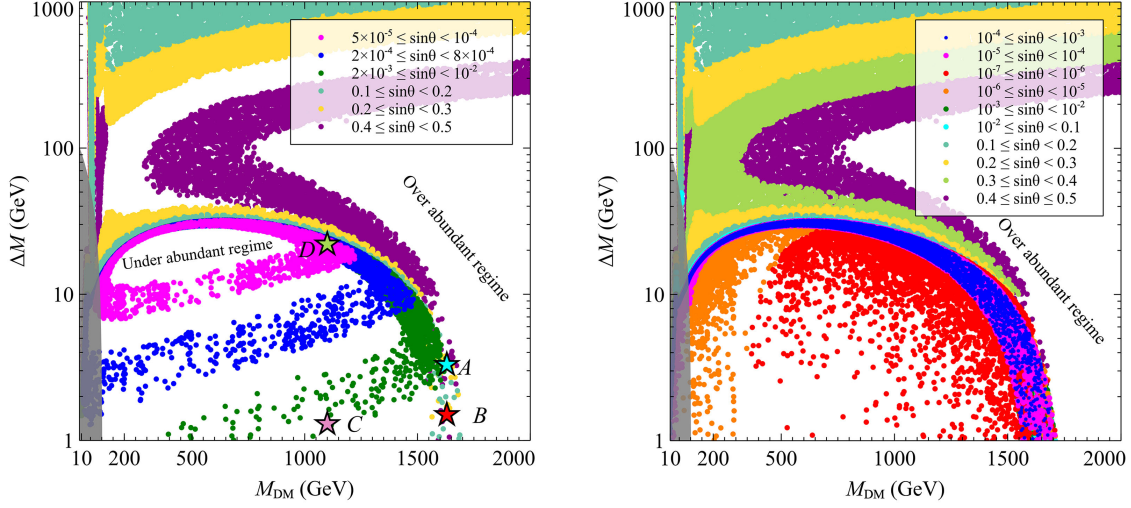


FIG. 1. Left: correct dark matter relic points are shown in the plane of ΔM vs M_{DM} for different ranges of $\sin \theta$ as mentioned in the inset of the figure, without considering coscattering contributions while solving Eqs. (7) and (8). Right: correct dark matter relic points are shown in the plane of ΔM vs M_{DM} for different ranges of $\sin \theta$ as mentioned in the inset of the figure, considering all the relevant contributions including annihilation, coannihilation, coscattering and decay, inverse-decay while solving Eqs. (7) and (8). The gray region is excluded from the LEP bound [43].

$\Delta M = 1.5$ GeV. This small ΔM reduces the effect of decay and inverse-decay, and with this small $\sin \theta$, the coannihilation effects are not sufficient, leading to an overabundant BP-B. However, we note that by increasing the $\sin \theta$, the relic density of BP-B can be brought to the correct ballpark. In BP-C ($\Delta M = 1.3$ GeV and $\sin \theta$ same as point A), we consider a smaller $M_{\text{DM}} = 1100$ GeV, which yields a correct relic density. Similarly, we have considered another BP-D, with same M_{DM} and $\sin \theta$ as that of C, but with a larger $\Delta M (= 22$ GeV). We note that D also gives the correct relic density. To understand why the BP-C and -D give correct relic density, we provide two evolution plots along with the interaction rates, which are compared with the Hubble expansion rate in Fig. 2. In the bottom panel, we show the evolution of the abundances of dark sector particles along with the interaction rates for BP-D. In this case, the rate of decay/inverse decay width is larger than the Hubble expansion rate because of the large ΔM . Although the coannihilation rates (“1200” process) decouple early, the efficient decay/inverse decay rates

keep changing the DM relic density until the “2200” processes go out of thermal equilibrium ($T \approx 20$ GeV), resulting in the correct relic density. In the top plot, we show the evolution of the abundances of dark sector particles along with the interaction rates for BP-C. At high temperature, the DM was in thermal equilibrium due to the efficient coannihilation processes. In this case, the rates of decay and inverse-decay processes are weaker than those of coannihilation processes. As a result, the DM decouples chemically from the thermal bath when the coannihilation rates drop below the Hubble expansion rate. However, at smaller temperatures, the inverse decay processes, which are not yet negligible, populate the abundance of sector 2 particles, leading to an enhanced rate of “2200” processes. Until the “2200” processes maintain thermal equilibrium ($T \approx 10$ GeV) with the SM thermal bath, the decay and inverse-decay processes help to bring the DM relic density into the correct ballpark.

From the above discussion, we conclude that, for $\sin \theta \gtrsim 0.05$, where annihilation and coannihilation

TABLE I. Relic density for benchmark points are given: (a) without considering co-scattering, and (b) without considering co-scattering and decay.^a

Point	M_{DM} (GeV)	ΔM (GeV)	$\sin \theta$	$\Omega_{2s} h^2$ (No coscattering) with Decay	$\Omega_{2s} h^2$ (No coscattering) without Decay
A	1630	3.3	9.5×10^{-3}	0.12	0.896
B	1630	1.5	9.5×10^{-3}	0.21	0.796
C	1100	1.3	9.5×10^{-3}	0.12	1.21
D	1100	22	9.5×10^{-3}	0.12	5.1

^aWe get the relic “ $\Omega_{2s} h^2$ (no coscattering) without decay” by using a flag ExcludedForNDM=“2010 DMdecay” inside micrOMEGAS. On the other hand, “ $\Omega_{2s} h^2$ (no coscattering) with decay” is obtained by using ExcludedForNDM=“2010”.

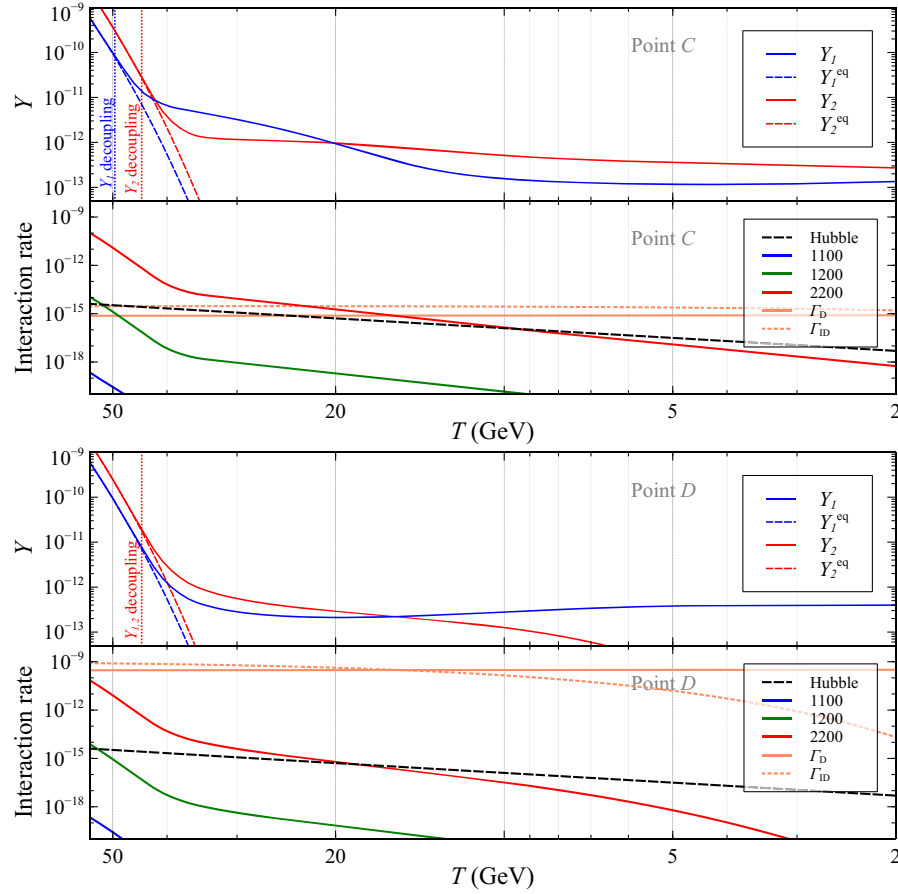


FIG. 2. Top: cosmological evolution of abundances of sector 1 and sector 2 particles and comparison of interaction rates with Hubble as a function of temperature for the point *C* as mentioned in Table I. Bottom: cosmological evolution of abundances of sector 1 and sector 2 particles and comparison of interaction rates with Hubble as a function of temperature for the point *D* as mentioned in Table I.

processes are significant, the singlet and doublet decouple at the same epoch and give the correct relic density. On the other hand, for $\sin \theta \lesssim 0.05$, the singlet decouples early with a larger abundance. However, it can be brought to the correct ballpark with the help of decay/inverse decay, followed by the annihilation of the doublet to SM particles. As a result, in this case, the gross features of the relic density parameter space differ significantly from the larger $\sin \theta$ ($\gtrsim 0.05$) case.

So far, we have switched off the cospattering (“2010” processes) effects while solving Eqs. (7) and (8). Now we solve Eqs. (7) and (8) without switching off the cospattering processes and showcase the correct relic points in the plane of M_{DM} and ΔM in the right panel of Fig. 1. The various colored points represent the range of $\sin \theta$ as given in the inset of the figure. For $\sin \theta \gtrsim 0.05$, the annihilation, coannihilation, decay, and inverse-decay processes are sufficient enough to keep the DM in equilibrium with the SM bath until the sector 2 particles decouple from the SM through “2200” processes. Once the sector 2 particles decouple, the

cospattering processes can not alter the relic density. At most, it can interchange Y_1 and Y_2 , but $Y_1 + Y_2$ remains constant. This is the reason why cospattering processes do not play any role in the large $\sin \theta$ region. For $\sin \theta \lesssim 0.05$, the cospattering processes play a significant role as the chemical decoupling of the singlet and doublet happens at different epochs.

To illustrate the effects of cospattering and decay, we choose two sets of benchmark points as mentioned Table II. We show the cosmological evolution of the abundances of

TABLE II. Benchmark points for the evolution of dark sector abundances. These two points are also shown with a yellow star and a yellow diamond in Fig. 4.

Benchmark Points	M_{DM} (GeV)	ΔM (GeV)	$\sin \theta$
<i>BP1</i>	285.721	24.5826	0.039039
<i>BP2</i>	972.047	21.6068	6.97978×10^{-7}

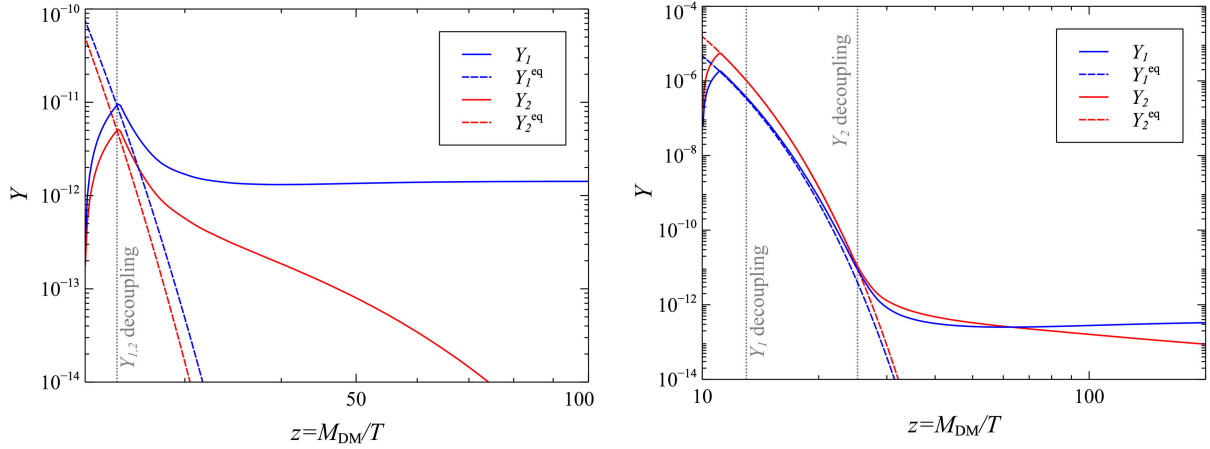


FIG. 3. Cosmological evolution of abundances of sector 1 and sector 2 particles for two sets of parameters illustrating coannihilation (left) and cospattering and decay effects (right). The parameters are mentioned in Table II.

BP1 in the left panel of Fig. 3. The blue (red) solid and dashed lines represent the abundance of the singlet (doublet) and its equilibrium values, respectively. We see that the large mixing angle leads to a simultaneous decoupling of the singlet and doublet components around $z \sim 24.5$. In this case, the relic is determined by the coannihilation processes. The annihilation processes are subdominant because of the small mass splitting. We now move to *BP2*. Here, we see that the singlet decouples very early, around $z \sim 19$, whereas the doublet stays in equilibrium due to its gauge interactions up to $z \sim 25.2$. Although the singlet decouples with a larger abundance due to cospattering and decay processes, its relic abundance is reduced to the observed value with the help of “2200” processes. From the right panel of Fig. 1, we see that cospattering plays a significant role for $\sin \theta \lesssim 0.05$. It should be mentioned that the rate of the cospattering processes increases with a decrease in ΔM . Upon adding the cospattering processes, the cospattering rate dominates over the decay and inverse-decay rates. As a result, the singlet will be efficiently converted to the doublet, followed by annihilation of the doublet to the SM particles (“2200” processes). As a result, the parameter space that previously yielded the correct relic density when cospattering was excluded becomes underabundant in the presence of the cospattering processes. On the other hand, the overabundant points with $\sin \theta \lesssim 10^{-5}$, which did not provide the correct relic density in the absence of cospattering processes, now yield the correct relic density once these processes are included.

To demonstrate the effect of cospattering quantitatively, we define a new parameter,

$$\rho_2 = \frac{\Omega_{2s} h^2}{\Omega_{2s} h^2(\text{no cospattering})}, \quad (10)$$

where $\Omega_{2s} h^2$ is obtained by solving Eqs. (7) and (8) which takes into account the effects of cospattering in addition to all other number-changing processes, such as decay, inverse decay, annihilation, and coannihilation. In contrast, $\Omega_{2s} h^2$ (no cospattering) refers to the relic density computed by solving Eqs. (7) and (8) while switching off the cospattering processes in $\Gamma_{2 \rightarrow 1}$. According to the definition of ρ_2 provided in Eq. (10), a value of $\rho_2 = 1$ signifies that the relic density is independent of cospattering effects. Consequently, any deviation from unity indicates the influence of cospattering on the final relic density. The magnitude of this deviation serves as a measure of the impact of cospattering; specifically, a larger deviation indicates a more significant effect. Moreover, as mentioned, $\Omega_{2s} h^2$ encompasses all relevant processes, including annihilation, coannihilation, cospattering, and decay, whereas $\Omega_{2s} h^2$ (no cospattering) is limited to the processes of annihilation, coannihilation, and decay. This distinction implies that the effective cross-section associated with $\Omega_{2s} h^2$ is always greater than or equal to that of $\Omega_{2s} h^2$ (no cospattering). Therefore, we can conclude that: $\Omega_{2s} h^2 \leq \Omega_{2s} h^2$ (no cospattering), which leads to $\rho_2 \leq 1$.

In Fig. 4, we present the correct relic satisfying points in the plane of $\sin \theta - M_{\text{DM}}$. The color map depicts the ρ_2 values. The blue colored points correspond to $\rho_2 \simeq 1$. This represents the parameter space where cospattering effects are negligible, and the relic is decided solely by annihilation and/or coannihilation processes. As $\sin \theta$ decreases, ρ_2 deviates from unity, indicating the increasing significance of cospattering processes across a wider parameter space, as shown by the light bluish and brown-colored regions. For the purpose of illustration, we show *BP1* and *BP2* in Fig. 4. It is straightforward to note that even $\sin \theta$ is quite different for *BP1* and *BP2*, yet they can yield the correct relic density due to the significance of the different

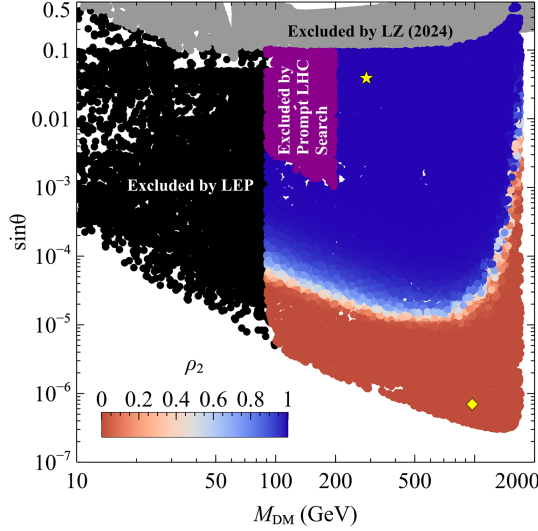


FIG. 4. Correct dark matter relic points are shown in the plane of $\sin \theta$ vs M_{DM} . The color code represents the parameter ρ_2 . The gray shaded region is excluded by the direct detection experiment LZ [44]. LEP [43] constraint on the doublet fermion excludes the black shaded region. The magenta shaded region is excluded by the LHC prompt search [45,46].

processes involved in relic computation. Below the colored region, even though DM can be produced thermally, conversion-driven processes, including decay, inverse decay, and cospattering, are not efficient at producing the correct relic abundance, leading to an overabundant relic. If $\sin \theta$ is reduced further, the DM can never be thermalized. The relic, in this case, is determined by nonthermal processes such as freeze-in and SuperWIMP mechanisms [34]. The black shaded region is excluded from the large electron positron (LEP) [43] constraint. The current direct detection limit from LUX-ZEPLIN (LZ) [44] excludes the gray region. Unlike the Dirac case, in the Majorana singlet–doublet dark matter scenario, the Z-mediated spin-independent direct detection channel is absent. As a result, the dominant contribution to spin-independent direct detection arises only from Higgs-mediated interactions. Since Z-exchange typically yields much stronger constraints, its absence significantly relaxes the bounds. Consequently, larger values of $\sin \theta$ are allowed by direct detection experiments in the Majorana case ($\sin \theta \lesssim 0.45$) compared to the Dirac case ($\sin \theta \lesssim 0.04$).

It is interesting to note that, in the Majorana SDDM scenario, significantly heavier dark matter masses are allowed. In the Majorana case, the effective cross section is enhanced due to additional contributing channels. This allows the observed relic density to be satisfied at higher dark matter masses than in the Dirac scenario. In particular, masses up to about 1750 GeV remain viable, whereas in the Dirac case the allowed mass range is restricted to approximately 750 GeV.

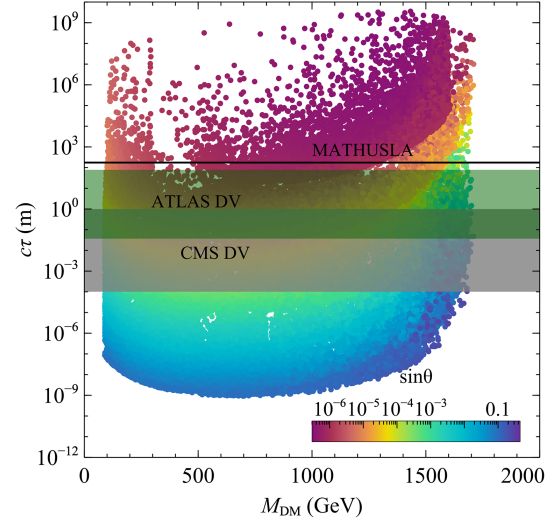


FIG. 5. Decay length of the doublet fermion as a function of DM mass with $\sin \theta$ in the color code. The gray and green shaded regions represent the sensitivities of CMS [39] and ATLAS [38], respectively, and the MATHUSLA [40] sensitivity is shown with a black solid line.

A. Collider searches

1. Displaced vertex signatures

We note that the doublet fermion ($\psi^\pm$) can be produced because of its gauge interaction, which further can decay to DM and charged leptons via the singlet-doublet mixing through off-shell gauge boson exchange. This can give rise to displaced vertex signatures in the LHC [38,39] and, in the future, MATHUSLA [40]. As already discussed, conversion-driven processes allow smaller $\sin \theta$ ($\lesssim \mathcal{O}(10^{-3})$) which results in smaller decay widths of $\psi^\pm$, thereby increasing the decay length, which can fall in the reach of LHC and MATHUSLA [34]. We calculate the decay length ($c\tau$) for the points satisfying DM relic density, direct detection, and LEP constraints and show them in the plane of $c\tau$ vs M_{DM} in Fig. 5 considering the decay mode $\psi^\pm \rightarrow \chi_3 e^\pm \nu_e$. The color code depicts the values of $\sin \theta$. The region of sensitivity of the CMS (10^{-4} m – 1 m) and ATLAS (0.04 m – 72.4 m) displaced vertex searches is shown with gray and green shaded regions, respectively. The figure shows that the inclusion of cospattering processes increases the lifetime of the dark partners, bringing them within the sensitivity reach of the LHC and MATHUSLA.

2. Prompt LHC search

If the decay length of the charged doublet is smaller than 10^{-4} m, it decays before reaching the detector volume, leading to prompt decay signatures at the LHC. From Fig. 5, we select all points with $c\tau < 10^{-4}$ m, which

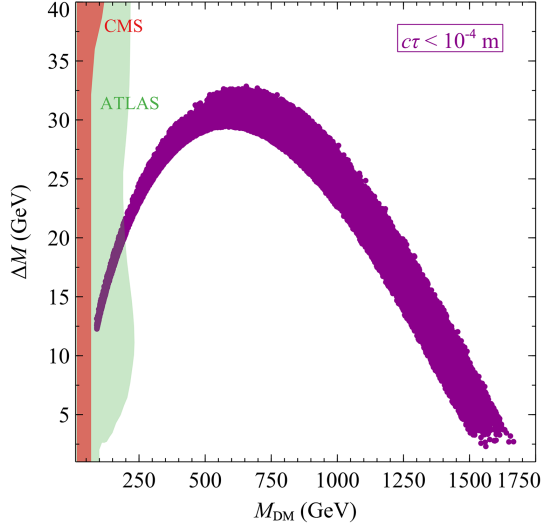


FIG. 6. Prompt decay parameter space ($c\tau < 10^{-4}$ m) is shown in the plane of ΔM vs M_{DM} . The 95% exclusion limits from CMS [46] and ATLAS [45] using $pp \rightarrow 3l + E_T^{\text{miss}}$ are shown with red and green shaded regions, respectively.

correspond to $3.4 \times 10^{-4} < \sin \theta < 0.4$, that are displayed in the ΔM - M_{DM} plane in Fig. 6. The exclusion limits from CMS [46] and ATLAS [45] using $pp \rightarrow 3l + E_T^{\text{miss}}$ (E_T^{miss} denotes the missing transverse energy) are overlaid as red and green shaded regions, respectively. We find that dark matter masses $M_{\text{DM}} \lesssim 197$ GeV with $c\tau < 10^{-4}$ m and $\sin \theta \gtrsim 10^{-3}$ are excluded by prompt searches at ATLAS. In Fig. 4, the excluded regions from prompt LHC searches are shown as a magenta shaded region in the $\sin \theta$ - M_{DM} plane.

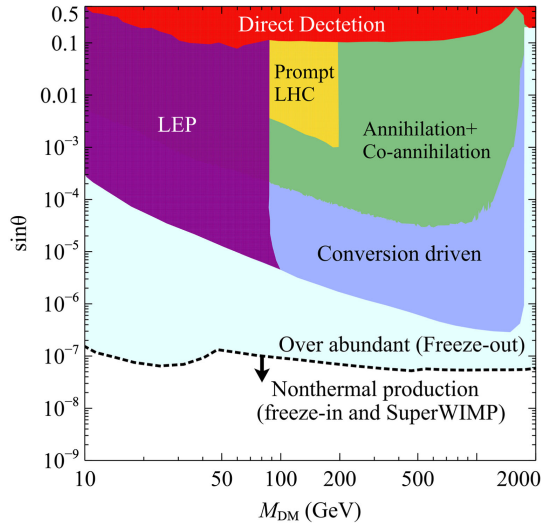


FIG. 7. Phase diagram illustrating the SDDM parameter space. The black dashed line separates the thermal regime (above) from the nonthermal regime (below).

IV. CONCLUSION AND FUTURE OUTLOOK

In this work, we analyzed the parameter space of the singlet-doublet Majorana DM considering the thermal freeze-out scenario. We found that the combined upper limit on the mixing angle from LZ and LEP leads to $\sin \theta \lesssim 0.45$. We summarize our analysis in Fig. 7, in the plane of M_{DM} and $\sin \theta$. In the green-shaded region, annihilation and coannihilation processes determine the relic abundance of DM depending on the value of ΔM . In the blue-shaded region, conversion-driven processes determine the relic. The LEP exclusion is shown with the magenta shaded region. The exclusion from the LHC prompt search is shown in the yellow-shaded region. In the cyan shaded region, even though the DM can be in thermal equilibrium, due to such a small $\sin \theta$, it decouples early with a larger abundance. Conversion-driven processes are inefficient in this region. The black dashed line serves as the boundary, above which DM can be brought to thermal equilibrium with the SM thermal bath. In the region below the black dashed line, the DM never reaches thermal equilibrium because of the small SD mixing angle. We find the allowed ranges of DM mass and $\sin \theta$ for the thermal relic of DM to be $100 \text{ GeV} \lesssim M_{\text{DM}} \lesssim 1750 \text{ GeV}$ and $2 \times 10^{-7} \lesssim \sin \theta \lesssim 0.45$ for $\Delta M > 1 \text{ GeV}$. We also note that incorporating conversion-driven processes substantially enlarges the region of parameter space accessible to both the LHC and MATHUSLA experiments.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: FERMION MASS DIAGONALIZATION

The neutral fermion mass matrix can be written in the basis: $((\psi_R^0)^c, \psi_L^0, (\chi)^c)^T$ as

$$\mathcal{M} = \begin{pmatrix} 0 & M_\Psi & \frac{m_D}{\sqrt{2}} \\ M_\Psi & 0 & \frac{m_D}{\sqrt{2}} \\ \frac{m_D}{\sqrt{2}} & \frac{m_D}{\sqrt{2}} & M_\chi \end{pmatrix}, \quad (\text{A1})$$

where $m_D = y_\chi v_h / \sqrt{2}$, and v_h is the vev of the SM Higgs boson, H . The mass matrix can be diagonalized with a unitary matrix of the form

$$\begin{aligned}
U(\theta) &= P.U_{13}(\theta_{13} = \theta).U_{23}(\theta_{23} = 0).U_{12}\left(\theta_{12} = \frac{\pi}{4}\right) \\
&= \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\pi/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos \theta/\sqrt{2} & \cos \theta/\sqrt{2} & \sin \theta \\ -1/\sqrt{2} & 1/\sqrt{2} & 0 \\ -\sin \theta/\sqrt{2} & -\sin \theta/\sqrt{2} & \cos \theta/\sqrt{2} \end{pmatrix} \\
&= \begin{pmatrix} \cos \theta/\sqrt{2} & \cos \theta/\sqrt{2} & \sin \theta \\ -i/\sqrt{2} & i/\sqrt{2} & 0 \\ -\sin \theta/\sqrt{2} & -\sin \theta/\sqrt{2} & \cos \theta/\sqrt{2} \end{pmatrix}. \tag{A2}
\end{aligned}$$

The diagonal mass matrix is given by

$$\mathcal{M}_{\text{diag}} = U.\mathcal{M}.U^T, \tag{A3}$$

with eigenvalues M_{χ_1}, M_{χ_2} , and M_{χ_3} . Then the flavor masses can be expressed in terms of the physical masses as

$$\begin{aligned}
M_\Psi &= \frac{1}{2}(M_{\chi_1} + M_{\chi_3} + (M_{\chi_1} - M_{\chi_3}) \sec 2\theta - 2m_D \tan 2\theta), \\
M_\chi &= \frac{1}{2}(M_{\chi_1} + M_{\chi_3} - (M_{\chi_1} - M_{\chi_3}) \sec 2\theta + 2m_D \tan 2\theta), \tag{A4}
\end{aligned}$$

where the mixing angle is given as

$$\tan 2\theta = \frac{2m_D}{M_\Psi - M_\chi}. \tag{A5}$$

Now using Eq. (A4), Eq. (A5) simplifies to

$$\sin 2\theta = \frac{2m_D}{M_{\chi_1} - M_{\chi_3}}. \tag{A6}$$

APPENDIX B: LAGRANGIAN IN MASS BASIS

The interaction Lagrangian between χ_1, χ_2, χ_3 and ψ^- with the SM gauge boson is given by

$$\begin{aligned}
\mathcal{L}_{\text{Gauge}} &= \left(\frac{e}{2s_w c_w}\right) (-c_\theta \bar{\chi}_1 i\gamma^\mu Z_\mu P_L \chi_2 - s_\theta \bar{\chi}_2 i\gamma^\mu Z_\mu P_L \chi_3 \\
&\quad + \text{H.c.}) + \frac{e}{\sqrt{2}s_w} (c_\theta \bar{\chi}_1 \gamma^\mu W_\mu^+ \psi^- + c_\theta \bar{\chi}_2 \gamma^\mu W_\mu^+ \psi^- \\
&\quad - s_\theta \bar{\chi}_3 \gamma^\mu W_\mu^+ \psi^-) + \frac{e}{\sqrt{2}s_w} (c_\theta \psi^+ \gamma^\mu W_\mu^- \chi_1 \\
&\quad + c_\theta \psi^+ \gamma^\mu W_\mu^- \chi_2 - s_\theta \psi^+ \gamma^\mu W_\mu^- \chi_3) - e\psi^+ \gamma^\mu A_\mu \psi^- \\
&\quad - \left(\frac{ec_{2w}}{2s_w c_w}\right) \psi^+ \gamma^\mu Z_\mu \psi^-, \tag{B1}
\end{aligned}$$

where $s_w = \sin \theta_w$, $c_w = \cos \theta_w$, $c_{2w} = \cos 2\theta_w$, $s_\theta = \sin \theta$, $c_\theta = \cos \theta$. The Yukawa Lagrangian can be written as

$$\begin{aligned}
\mathcal{L}_{\text{Yukawa}} &= \frac{y_\chi}{\sqrt{2}} (\sin 2\theta (\bar{\chi}_1 h \chi_1 - \bar{\chi}_3 h \chi_3) \\
&\quad + \cos 2\theta (\bar{\chi}_1 h \chi_3 - \bar{\chi}_3 h \chi_1)). \tag{B2}
\end{aligned}$$

APPENDIX C: FEYNMAN DIAGRAMS

1. Annihilation processes of DM

Here, we have provided the Feynman diagram of annihilation (corresponding to 1100 processes) of sector 1 particles (i.e., DM or χ_3) to sector 0 particles (i.e., SM particles) in Fig. 8.

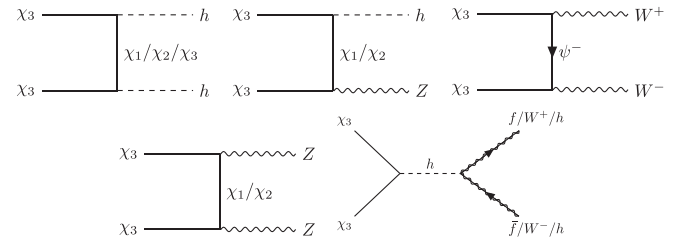


FIG. 8. DM annihilating to the SM particles through 1100 processes.

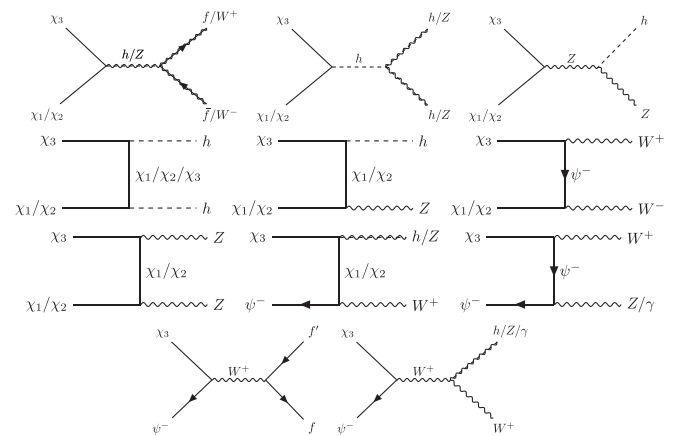


FIG. 9. DM coannihilating with the doublet components to the SM particles through 1200 processes.

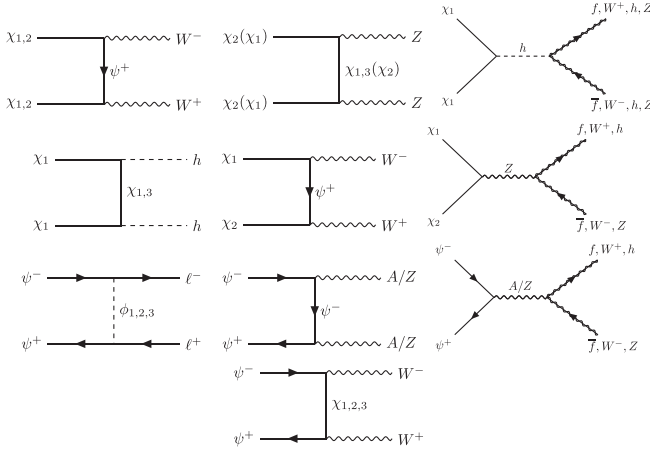


FIG. 10. Annihilation and coannihilation among sector 2 particles to SM particles corresponding to the 2200 processes.

2. Coannihilation between sector 1 and sector 2 particles

The coannihilation (corresponds to 1200 processes) between the sector 1 (χ_3) and sector 2 particles (i.e. χ_1, χ_2, ψ^-) to SM particles is shown in Fig. 9.

3. Annihilation and coannihilation among sector 2 particles

Annihilation and coannihilation (corresponding to 2200 processes) among sector 2 particles to SM particles are given in Fig. 10.

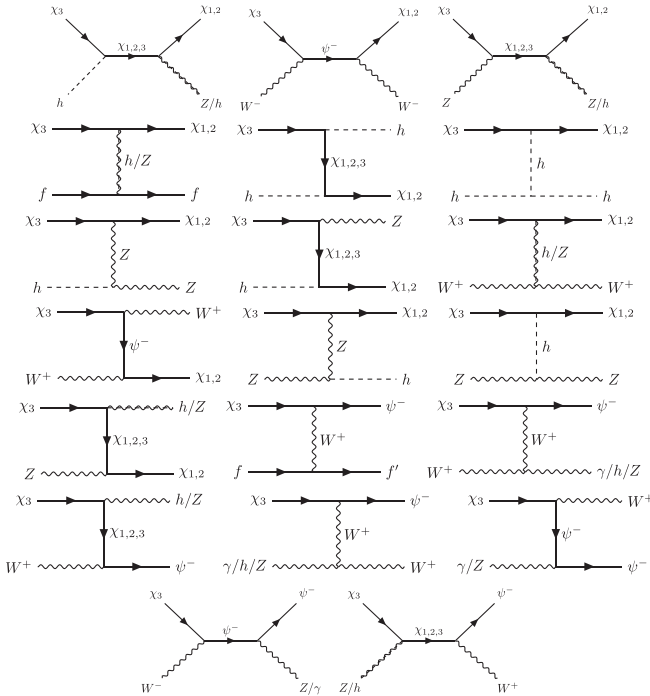


FIG. 11. DM cospattering with the SM bath particles to the doublet states through 2010 processes.

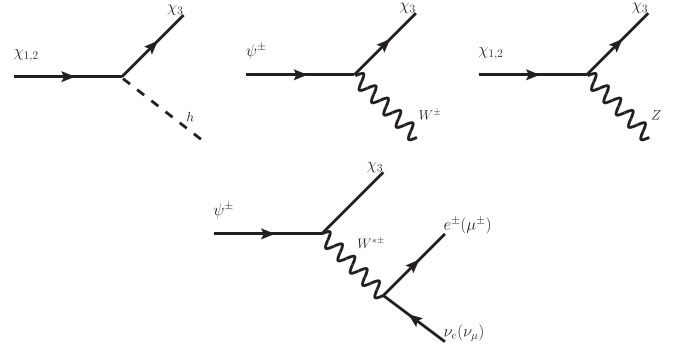


FIG. 12. DM production from doublet fermion decay.

4. Cospattering between DM and doublet fermion

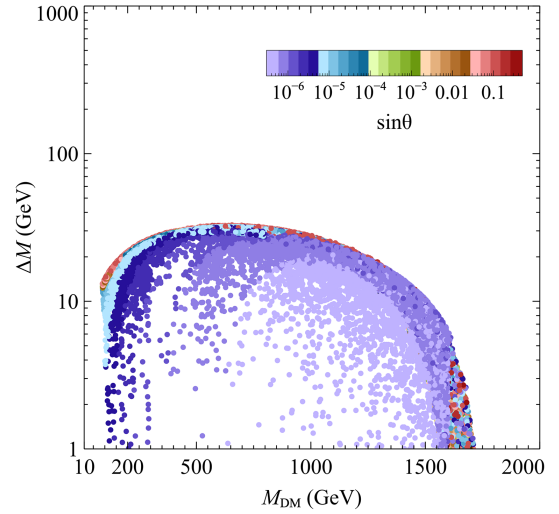
Cospattering (corresponding to 2010 processes) among sector 1 and sector 2 particles is given in Fig. 11.

5. DM production from decay

We list the two and three-body decays of the doublet fermion for the production of DM in Fig. 12.

APPENDIX D: CORRECT DM RELIC PARAMETER SPACE APPLYING DIRECT DETECTION AND LEP CONSTRAINTS

We show the correct relic points allowed from LEP and direct detection constraints in the plane of M_{DM} and ΔM in Fig. 13. The color band represents the $\sin\theta$ values.

FIG. 13. The correct relic points allowed by LEP, prompt LHC searches, and direct detection bound. The color band represents the $\sin\theta$ values.

- [1] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020); *Astron. Astrophys.* **652**, C4(E) (2021).
- [2] F. Zwicky, Die Rotverschiebung von extragalaktischen Nebeln, *Helv. Phys. Acta* **6**, 110 (1933).
- [3] V. C. Rubin and W. K. Ford, Jr., Rotation of the Andromeda Nebula from a spectroscopic survey of emission regions, *Astrophys. J.* **159**, 379 (1970).
- [4] S. Bhattacharya, P. Ghosh, N. Sahoo, and N. Sahu, Mini review on vector-like leptonic dark matter, neutrino mass, and collider signatures, *Front. Phys.* **7**, 80 (2019).
- [5] M. Dutta, S. Bhattacharya, P. Ghosh, and N. Sahu, Singlet-doublet Majorana dark matter and neutrino mass in a minimal Type-I seesaw scenario, *J. Cosmol. Astropart. Phys.* **03** (2020) 008.
- [6] G. Cynolter, J. Kovács, and E. Lendvai, Doublet–singlet model and unitarity, *Mod. Phys. Lett. A* **31**, 1650013 (2016).
- [7] S. Bhattacharya, N. Sahoo, and N. Sahu, Minimal vectorlike leptonic dark matter and signatures at the LHC, *Phys. Rev. D* **93**, 115040 (2016).
- [8] S. Bhattacharya, N. Sahoo, and N. Sahu, Singlet-doublet fermionic dark matter, neutrino mass and collider signatures, *Phys. Rev. D* **96**, 035010 (2017).
- [9] S. Bhattacharya, P. Ghosh, and N. Sahu, Multipartite dark matter with scalars, fermions and signatures at LHC, *J. High Energy Phys.* **02** (2018) 059.
- [10] S. Bhattacharya, B. Karmakar, N. Sahu, and A. Sil, Flavor origin of dark matter and its relation with leptonic nonzero θ_{13} and Dirac CP phase δ , *J. High Energy Phys.* **05** (2016) 068.
- [11] D. Borah, M. Dutta, S. Mahapatra, and N. Sahu, Lepton anomalous magnetic moment with singlet-doublet fermion dark matter in a scotogenic $U(1)_{L\mu - L\tau}$ model, *Phys. Rev. D* **105**, 015029 (2022).
- [12] D. Borah, M. Dutta, S. Mahapatra, and N. Sahu, Singlet-doublet self-interacting dark matter and radiative neutrino mass, *Phys. Rev. D* **105**, 075019 (2022).
- [13] D. Borah, S. Mahapatra, and N. Sahu, Singlet-doublet fermion origin of dark matter, neutrino mass and W-mass anomaly, *Phys. Lett. B* **831**, 137196 (2022).
- [14] D. Borah, S. Mahapatra, D. Nanda, S. K. Sahoo, and N. Sahu, Singlet-doublet fermion dark matter with Dirac neutrino mass, $(g-2)_\mu$ and ΔN_{eff} , *J. High Energy Phys.* **05** (2023) 096.
- [15] P. K. Paul, N. Sahu, and P. Shukla, Thermal leptogenesis, dark matter, and gravitational waves from an extended canonical seesaw scenario, *Phys. Rev. D* **112**, 015032 (2025).
- [16] R. Mahbubani and L. Senatore, The minimal model for dark matter and unification, *Phys. Rev. D* **73**, 043510 (2006).
- [17] F. D'Eramo, Dark matter and Higgs boson physics, *Phys. Rev. D* **76**, 083522 (2007).
- [18] T. Cohen, J. Kearney, A. Pierce, and D. Tucker-Smith, Singlet-doublet dark matter, *Phys. Rev. D* **85**, 075003 (2012).
- [19] A. Freitas, S. Westhoff, and J. Zupan, Integrating in the Higgs portal to fermion dark matter, *J. High Energy Phys.* **09** (2015) 015.
- [20] L. Calibbi, A. Mariotti, and P. Tziveloglou, Singlet-doublet model: Dark matter searches and LHC constraints, *J. High Energy Phys.* **10** (2015) 116.
- [21] C. Cheung and D. Sanford, Simplified models of mixed dark matter, *J. Cosmol. Astropart. Phys.* **02** (2013) 011.
- [22] S. Banerjee, S. Matsumoto, K. Mukaida, and Y.-L. S. Tsai, WIMP dark matter in a well-tempered regime: A case study on singlet-doublets fermionic WIMP, *J. High Energy Phys.* **11** (2016) 070.
- [23] A. Dutta Banik, A. K. Saha, and A. Sil, Scalar assisted singlet doublet fermion dark matter model and electroweak vacuum stability, *Phys. Rev. D* **98**, 075013 (2018).
- [24] S. Horiuchi, O. Macias, D. Restrepo, A. Rivera, O. Zapata, and H. Silverwood, The Fermi-LAT gamma-ray excess at the galactic center in the singlet-doublet fermion dark matter model, *J. Cosmol. Astropart. Phys.* **03** (2016) 048.
- [25] D. Restrepo, A. Rivera, M. Sánchez-Peláez, O. Zapata, and W. Tangarife, Radiative neutrino masses in the singlet-doublet fermion dark matter model with scalar singlets, *Phys. Rev. D* **92**, 013005 (2015).
- [26] T. Abe, Effect of CP violation in the singlet-doublet dark matter model, *Phys. Lett. B* **771**, 125 (2017).
- [27] P. Konar, A. Mukherjee, A. K. Saha, and S. Show, Linking pseudo-Dirac dark matter to radiative neutrino masses in a singlet-doublet scenario, *Phys. Rev. D* **102**, 015024 (2020).
- [28] P. Konar, A. Mukherjee, A. K. Saha, and S. Show, A dark clue to seesaw and leptogenesis in a pseudo-Dirac singlet doublet scenario with (non)standard cosmology, *J. High Energy Phys.* **03** (2020) 044.
- [29] L. Calibbi, L. Lopez-Honorez, S. Lowette, and A. Mariotti, Singlet-doublet dark matter freeze-in: LHC displaced signatures versus cosmology, *J. High Energy Phys.* **09** (2018) 037.
- [30] P. Ghosh, P. Konar, A. K. Saha, and S. Show, Self-interacting freeze-in dark matter in a singlet doublet scenario, *J. Cosmol. Astropart. Phys.* **10** (2021) 017.
- [31] P. K. Das, P. Konar, S. Kundu, and S. Show, Jet substructure probe to unfold singlet-doublet dark matter in the presence of non-standard cosmology, *J. High Energy Phys.* **06** (2023) 198.
- [32] S. Bhattacharya, S. Jahedi, and J. Wudka, Probing heavy charged fermions at e^+e^- collider using the optimal observable technique, *J. High Energy Phys.* **05** (2021) 009.
- [33] R. Enberg, P. J. Fox, L. J. Hall, A. Y. Papaioannou, and M. Papucci, LHC and dark matter signals of improved naturalness, *J. High Energy Phys.* **11** (2007) 014.
- [34] P. K. Paul, S. K. Sahoo, and N. Sahu, Anatomy of singlet-doublet dark matter relic: Annihilation, co-annihilation, co-scattering, and freeze-in, *J. Cosmol. Astropart. Phys.* **10** (2024) 053.
- [35] R. T. D'Agnolo, D. Pappadopulo, and J. T. Ruderman, Fourth exception in the calculation of relic abundances, *Phys. Rev. Lett.* **119**, 061102 (2017).
- [36] M. Garny, J. Heisig, B. Lülfi, and S. Vogl, Coannihilation without chemical equilibrium, *Phys. Rev. D* **96**, 103521 (2017).
- [37] T. N. Maity and T. S. Ray, Exchange driven freeze out of dark matter, *Phys. Rev. D* **101**, 103013 (2020).
- [38] G. Aad *et al.* (ATLAS Collaboration), Search for events with a pair of displaced vertices from long-lived neutral particles

- decaying into hadronic jets in the ATLAS muon spectrometer in pp collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* **106**, 032005 (2022).
- [39] A. Hayrapetyan *et al.* (CMS Collaboration), Search for long-lived particles using displaced vertices and missing transverse momentum in proton-proton collisions at $s = 13$ TeV, *Phys. Rev. D* **109**, 112005 (2024).
- [40] C. Alpigiani *et al.* (MATHUSLA Collaboration), Explore the lifetime frontier with MATHUSLA, *J. Instrum.* **15**, C06026 (2020).
- [41] G. Alguero, G. Belanger, S. Kraml, and A. Pukhov, Co-scattering in micrOMEGAs: A case study for the singlet-triplet dark matter model, *SciPost Phys.* **13**, 124 (2022).
- [42] G. Alguero, G. Belanger, F. Boudjema, S. Chakraborti, A. Goudelis, S. Kraml, A. Mjallal, and A. Pukhov, micrOMEGAs 6.0: N-component dark matter, *Comput. Phys. Commun.* **299**, 109133 (2024).
- [43] J. Abdallah *et al.* (DELPHI Collaboration), Searches for supersymmetric particles in e^+e^- collisions up to 208-GeV and interpretation of the results within the MSSM, *Eur. Phys. J. C* **31**, 421 (2003).
- [44] J. Aalbers *et al.* (LZ Collaboration), Dark matter search results from 4.2 tonne-years of exposure of the LUX-ZEPLIN (LZ) experiment, *Phys. Rev. Lett.* **135**, 011802 (2025).
- [45] G. Aad *et al.* (ATLAS Collaboration), Search for chargino-neutralino pair production in final states with three leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, *Eur. Phys. J. C* **81**, 1118 (2021).
- [46] A. Tumasyan, Andrew J. McLeod, and Matthias Wilhelm (CMS Collaboration), Search for electroweak production of charginos and neutralinos in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **04** (2021) 147.