RECEIVED: May 9, 2020

REVISED: July 9, 2020

ACCEPTED: July 23, 2020

PUBLISHED: August 20, 2020

Leptogenesis from a $U(1)_D$ resonance

Eung Jin Chun,^a Arnab Dasgupta^b and Sin Kyu Kang^b

^a*School of School of Physics, Korea Institute for Advanced Study,
Seoul 02455, Korea*

^b*School of Liberal Arts, Seoul-Tech,
Seoul 139-743, Korea*

E-mail: ejchun@kias.re.kr, arnabdasgupta@protonmail.ch,
skkang@seoultech.ac.kr

ABSTRACT: We propose a novel mechanism to realize leptogenesis through the Breit-Wigner resonance of a dark $U(1)_D$ gauge boson Z_D , which mediates lepton number violating annihilations of dark matter (DM) in the context of the scotogenic model with a $U(1)_D$. The processes occur out of equilibrium and DM freezes out later giving rise to the observed abundance. The CP violation required for leptogenesis can be achieved by the interference between tree-level t-channel scattering of DM and the subsequent 1-loop mediated by Z_D , which arises due to the unremovable imaginary part of either the Z_D propagator coming from its self-energy correction or the 1-loop giving rise to the effective coupling of $Z_D \bar{\nu} \nu$.

KEYWORDS: Beyond Standard Model, Cosmology of Theories beyond the SM, Neutrino Physics

ARXIV EPRINT: [2004.14189](https://arxiv.org/abs/2004.14189)

Contents

1	Introduction	1
2	Model	3
3	Leptogenesis through resonance of $U(1)_D$ gauge boson	5
4	Results and discussion	8
5	Conclusion	10
A	Details of the effective Z_D coupling	10
B	Details of the loop function $\mathcal{F}_\pm$	12

1 Introduction

One of the great mysteries of our universe is the origin of the baryon asymmetry due to which net resultant baryons comprising almost 4% of the entire energy budget of the Universe are generated. Long time ago, Sakharov found three ingredients to achieve the excess of baryon over anti-baryon through some processes, which are 1) B/L violation 2) C and CP violation and 3) a departure from thermal equilibrium. In addition to these conditions, the processes resulting in CP asymmetry should abide by Nanopoulos-Weinberg theorem [1] and furthermore Adhikari-Rangarajan theorem [2].

There have been early attempts to generate the baryon asymmetry from $1 \rightarrow 2$ decay proposed in [3, 4] and also it can be dynamically generated via leptogenesis where lepton number, C and CP violating 2-body out-of-equilibrium decays of heavy Majorana neutrinos produce a primordial lepton asymmetry, which is partially converted into the baryon asymmetry via $B + L$ violating sphaleron processes [5]. However, leptogenesis through type I seesaw is successful for the mass scale of the heavy Majorana neutrino larger than 10^9 GeV [6], which is undesirable due to the hopeless possibility to probe it at collider experiments and a tension with naturalness of Higgs potential [7, 8].

Motivated by those problems in vanilla leptogenesis, in this work, we propose a new promising possibility for leptogenesis realized naturally at low scale. The major difficulty to achieve leptogenesis at low scale such as 1-10 TeV is that the condition for out of equilibrium decay in general requires very small coupling, which in turn generates lepton asymmetry insufficiently at low scale. To remedy this, mass degeneracy of decaying particles and hierarchy of couplings that affect the lepton number violating decay processes have been suggested leading to the realization of resonant leptogenesis [9]. But, they are rather unnatural to fit the right amount of the lepton asymmetry. More natural solution for low

scale leptogenesis would be generation of the lepton asymmetry through $2 \rightarrow 2$ scatterings or three-body decays [10]. This is due to the fact that the scattering cross section or decay rate constrained by out of equilibrium condition is presented in terms of a quartic expression of two couplings, while the lepton asymmetry is in general only quadratic in nature. Then, the lepton asymmetry can be naturally large enough with sufficiently suppressed rates of the processes even at low scale. In this work, we take into account the possibility of the lepton asymmetry generated through $2 \rightarrow 2$ scatterings.

On the other hand, roughly 25% of the Universe is made of mysterious dark matter (DM). While the nature of DM and the mechanism behind baryogenesis might be uncorrelated to each other, it is tempting to construct models unifying both origins. A plethora of attempts has been proposed in recent years to explain the coincidence between the baryon asymmetry and the DM abundance, $\Omega_{\text{DM}} \approx 5\Omega_B$, discarding simple numerical coincidence as an explanation for the closeness of both. To incorporate low scale leptogenesis with DM, a plausible option is to generate the lepton asymmetry and the DM abundance simultaneously through DM annihilations into a pair of leptons [11–16]. To achieve the goal with it, the processes occur out of equilibrium and DM freezes out later giving rise to the observed abundance.

In this scenario, we propose a new novel way of generating the lepton asymmetry through resonance of *Dark* $U(1)_D$ gauge boson, Z_D , which mediates lepton number violating ($\Delta L = 2$) DM annihilations. In fact, those processes do not occur at tree level because of no lepton number violating neutral current mediated by Z_D . However, as will be shown later, they are possible through chiral breaking effective vertex at 1-loop level. To get CP violation required for leptogenesis, we take into account another DM annihilation through t -channel exchange of vector-like fermions. Then, the interference of those two distinct amplitudes results in CP violation when there exists the unremovable imaginary part stemming from either the Z_D propagator coming from its self-energy correction or the effective vertex at 1-loop. This mechanism of generating the asymmetry from the imaginary part of the propagator has been pointed out by Dasgupta et al.[17].

To show how the new way of leptogenesis works, we adopt the framework of the scotogenic model where tiny Majorana neutrino masses naturally generated at 1-loop and there exist DM candidates. We extend the standard model(SM) gauge symmetry by introducing a *Dark* $U(1)$ gauge symmetry. The $\mathbb{Z}_2$ symmetry, an essential ingredient in scotogenic scenarios, naturally appears from spontaneous breaking of the *Dark* $U(1)$, and tiny neutrino masses are generated at 1-loop. The neutral components of new scalar doublet will be responsible for DM and their co-annihilations lead to the lepton asymmetry as explained above. It is shown that such discovery and/or constraint can be connected with the matter anti-matter asymmetry through leptogenesis.

This article is arranged as follows: first in section 2 we discuss about the model and its details regarding the mass spectrum of the scalars and the additional fermions, in section 3 we explain how the asymmetry can be generated through the resonance of the *Dark* gauge Z_D boson, and in section 4 we present the result and conclusion. Some useful formulae are presented in appendix A.

	$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_D$	F(fermion)/S(Scalar)	Lepton Number
$Q = \begin{pmatrix} u \\ d \end{pmatrix}$	$(3, 2, 1/6, 0)$	F	0
$L = \begin{pmatrix} \nu \\ e \end{pmatrix}$	$(1, 2, -1/2, 0)$	F	1
$\bar{u}$	$(\bar{3}, 1, -2/3, 0)$	F	0
$\bar{d}$	$(\bar{3}, 1, 1/3, 0)$	F	0
$\bar{e}$	$(2, 1, 1, 0)$	F	-1
$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$	$(1, 2, 1/2, 0)$	S	0
$\eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$	$(1, 2, 1/2, 1)$	S	0
$\bar{\xi}$	$(1, 1, 0, 1)$	F	1
ξ	$(1, 1, 0, -1)$	F	-1
ϕ	$(1, 1, 0, 2)$	S	-2
Δ	$(1, 3, -1, -2)$	S	2

Table 1. Summary of the matter fields. The upper half of the table corresponds to the SM and the lower half of the table to new particles.

2 Model

For our purpose, we extend the SM gauge symmetry by introducing a $U(1)_D$. To radiatively generate tiny neutrino masses and to have natural DM candidates, we take the framework of the scotogenic model where vector-like neutral fermions¹ and a new scalar doublet η are introduced. We also introduce a singlet scalar field ϕ and a $SU(2)_L$ triplet scalar field Δ to break the $U(1)_D$ symmetry and to naturally generate tiny mass splitting between neutral components of η , respectively. The complete content of the matter fields in the model is given in table 1. We note that the model is anomaly free.

The Lagrangian for the entire scalar sector is given as

$$\begin{aligned}
 \mathcal{L}_s = & \mu_H^2 |H|^2 + \mu_\eta^2 |\eta|^2 + \mu_\Delta^2 |\Delta|^2 + \mu_\phi^2 \phi^\dagger \phi + \lambda_H (H^\dagger H)^2 + \lambda_{H\eta} (H^\dagger H)(\eta^\dagger \eta) + \lambda'_{H\eta} (H^\dagger H)(\eta^\dagger \eta) \\
 & + \lambda_{H\phi} (H^\dagger H)\phi^* \phi + \lambda_\eta (\eta^\dagger \eta)^2 + \lambda_{\eta\phi} (\eta^\dagger \eta)\phi^* \phi + \lambda_\phi (\phi^* \phi)^2 + \lambda_\Delta \text{Tr}[\Delta^\dagger \Delta]^2 + \lambda'_\Delta \text{Tr}[\Delta^\dagger \Delta \Delta \Delta^\dagger] \\
 & + \mu_{\eta\Delta} \tilde{\eta}^\dagger \Delta \eta + \lambda_{\eta\Delta} \eta^\dagger \eta \text{Tr}[\Delta^\dagger \Delta] + \lambda'_{\eta\Delta} \eta^\dagger \Delta^\dagger \Delta \eta + \lambda_{H\Delta} H^\dagger H \text{Tr}[\Delta^\dagger \Delta] \\
 & + \lambda'_{H\Delta} \text{Tr}[H^\dagger \Delta^\dagger \Delta H] + \lambda_6 \tilde{H}^\dagger \Delta H \phi.
 \end{aligned}$$

In this setup the $U(1)_D$ symmetry is broken to $\mathbb{Z}_2$ symmetry by the vacuum of ϕ , which makes the lightest neutral component of the doublet η a DM candidate. The scalar Δ

¹Note that we take into account vector-like neutral fermions instead of right-handed neutrinos, which is different from the minimal scotogenic model.

also gets vacuum expectation value (VEV) along with ϕ breaking both $U(1)_D$ and $SU(2)_L$, however the VEV is taken to be very small as it is responsible for the mass splitting between two neutral components of the scale η .

Solving the tadpole equation, one can get the following mass spectrum for the scalar sector in $\{H, \Delta^0, \phi\}$ basis given as

$$m_s^2 = \begin{pmatrix} \lambda_H v^2 & 2(\lambda_{H\Delta} + \lambda'_{H\Delta})vv_\Delta - \lambda_6 vv_\phi & (2\lambda_{H\phi}v_\phi - \lambda_6 v_\Delta)v \\ 2(\lambda_{H\Delta} + \lambda'_{H\Delta})vv_\Delta - \lambda_6 vv_\phi & \frac{\lambda_6}{2v_\Delta}v^2v_\phi - 2\lambda_\Delta v_\Delta^2 & \frac{\lambda_6}{2}v^2 \\ (2\lambda_{H\phi}v_\phi - \lambda_6 v_\Delta)v & \frac{\lambda_6}{2}v^2 & \frac{\lambda_6}{2v_\phi}v^2v_\Delta + \lambda_\phi v_\phi^2 \end{pmatrix},$$

where v is the VEV of the SM Higgs, $v_\phi = \langle \phi^0 \rangle$ and $v_\Delta = \langle \Delta^0 \rangle$, and the mass of the pseudo-scalar is given as

$$m_A^2 = \frac{\lambda_6}{2v_\Delta v_\phi} [4v_\Delta^2 v_\phi^2 + v^2(v_\Delta^2 + v_\phi^2)]. \quad (2.1)$$

The masses of the charged scalars are given as

$$m_{\Delta^\pm}^2 = \frac{1}{2} \left(\lambda'_{H\Delta} + \frac{\lambda_6}{v_\Delta} v_\phi \right) (v^2 + 2v_\Delta^2), \quad m_{\Delta^{\pm\pm}}^2 = 4\lambda'_\Delta v_\Delta^2 + v^2 \left[\lambda'_{H\Delta} + \frac{1}{2} \frac{\lambda_6}{v_\Delta} v_\phi \right], \quad (2.2)$$

$$m_{\eta^\pm}^2 = \mu_\eta^2 + \frac{1}{2} \lambda'_{H\eta} v^2 + \lambda_{\eta\phi} v_\phi^2. \quad (2.3)$$

Now, for the limit $v_\phi/v_\Delta = \epsilon \gg 1$ the masses for the triplet scalar field become $m_{\Delta^{\pm\pm}} = m_{\Delta^\pm} = m_{\Delta_{R,I}^0} \equiv m_\Delta \simeq \lambda_6/2v^2\epsilon$. And finally the masses for the neutral components of η are given as

$$m_{\eta_R}^2 = \mu_\eta^2 + \frac{1}{2}(\lambda_{H\eta} + \lambda'_{H\eta})v^2 + \sqrt{2}\mu_{\eta\Delta}v_\Delta + \lambda_{\eta\phi}v_\phi^2, \quad (2.4)$$

$$m_{\eta_I}^2 = \mu_\eta^2 + \frac{1}{2}(\lambda_{H\eta} + \lambda'_{H\eta})v^2 - \sqrt{2}\mu_{\eta\Delta}v_\Delta + \lambda_{\eta\phi}v_\phi^2. \quad (2.5)$$

The mass splitting between the real and imaginary parts is controlled by $\mu_{\eta\Delta}$. Now, the Lagrangian for the fermionic sector is given as

$$\begin{aligned} \mathcal{L} = & m_\xi \xi \bar{\xi} + Y_u \tilde{H}^\dagger Q \bar{u} + Y_d H^\dagger Q \bar{d} + Y_l H^\dagger L \bar{e} + Y_\nu \tilde{\eta}^\dagger L \xi \\ & + Y_L \phi^* \xi \bar{\xi} + Y_R \phi \bar{\xi} \xi + H.c. \end{aligned} \quad (2.6)$$

All the quarks and leptons acquire the masses through the standard Higgs mechanism. From the above equation the mass matrix of the vector-like fermions $\xi, \bar{\xi}$ comes out to be

$$M = \begin{pmatrix} Y_L v_\phi & m_\xi \\ m_\xi & Y_R v_\phi \end{pmatrix}, \quad (2.7)$$

in the interaction basis of $\{\xi, \bar{\xi}\}$. Without loss of generality, we take m_ξ, Y_L and Y_R to be diagonal.² The mixing angle θ for each generation of ξ 's that diagonalizes this mass matrix

²The parameters required in our numerical analysis are the mass eigenvalues $M_{i\pm}$ and mixing angles θ_i of the vector-like fermions. Although their expressions depend on the structures of m_ξ, Y_L , and Y_R , what we need is just numerical values of $M_{i\pm}$ and θ_i in the numerical analysis. Thus, our results and conclusion would not change for different choice of m_ξ, Y_L and Y_R .

is given as

$$\tan 2\theta_i = \frac{2m_{\xi_i}}{(Y_{L_i} - Y_{R_i})v_\phi}. \quad (2.8)$$

Hence the masses of the vector-like fermions are given as

$$M_{i\pm} = (Y_{L_i} + Y_{R_i})\frac{v_\phi}{\sqrt{2}} \pm \frac{1}{2}\sqrt{(Y_{L_i} - Y_{R_i})^2 v_\phi^2 + 2m_{\xi_i}^2}, \quad (2.9)$$

and finally the neutrinos will acquire the masses at 1-loop shown in fig 1 and the expressions are given as

$$\begin{aligned} (m_\nu)_{\alpha\beta} &= \sum_i Y_{\nu_{i\alpha}} Y_{\nu_{i\beta}} \left(\cos^2 \theta_i \frac{M_{i+}}{32\pi^2} \left[\frac{m_{\eta_R}^2}{m_{\eta_R}^2 - M_{i+}^2} \ln \left(\frac{m_{\eta_R}^2}{M_{i+}^2} \right) - \frac{m_{\eta_I}^2}{m_{\eta_I}^2 - M_{i+}^2} \ln \left(\frac{m_{\eta_I}^2}{M_{i+}^2} \right) \right] \right. \\ &\quad \left. + \sin^2 \theta_i \frac{M_{i-}}{32\pi^2} \left[\frac{m_{\eta_R}^2}{m_{\eta_R}^2 - M_{i-}^2} \ln \left(\frac{m_{\eta_R}^2}{M_{i-}^2} \right) - \frac{m_{\eta_I}^2}{m_{\eta_I}^2 - M_{i-}^2} \ln \left(\frac{m_{\eta_I}^2}{M_{i-}^2} \right) \right] \right), \\ (m_\nu)_{\alpha\beta} &= (Y_\nu^T \Lambda Y_\nu)_{\alpha\beta}, \\ \Lambda_i &= \left(\cos^2 \theta_i \frac{M_{i+}}{32\pi^2} \left[\frac{m_{\eta_R}^2}{m_{\eta_R}^2 - M_{i+}^2} \ln \left(\frac{m_{\eta_R}^2}{M_{i+}^2} \right) - \frac{m_{\eta_I}^2}{m_{\eta_I}^2 - M_{i+}^2} \ln \left(\frac{m_{\eta_I}^2}{M_{i+}^2} \right) \right] \right. \\ &\quad \left. + \sin^2 \theta_i \frac{M_{i-}}{32\pi^2} \left[\frac{m_{\eta_R}^2}{m_{\eta_R}^2 - M_{i-}^2} \ln \left(\frac{m_{\eta_R}^2}{M_{i-}^2} \right) - \frac{m_{\eta_I}^2}{m_{\eta_I}^2 - M_{i-}^2} \ln \left(\frac{m_{\eta_I}^2}{M_{i-}^2} \right) \right] \right). \end{aligned} \quad (2.10)$$

One may recall that $\Lambda_i = 0$ if $m_{\eta_R} = m_{\eta_I}$ ($v_\Delta = 0$) or $M_{i+} = -M_{i-}$ ($v_\phi = 0$) for which a conserved $U(1)_L$ can be defined. For the sake of numerical analysis satisfying the observed neutrino oscillation data, we take the Casas-Ibarra parameterization of the Yukawa matrix Y_ν as follows;

$$Y_{\nu_{i\alpha}} = \left(\sqrt{\Lambda}^{-1} R \sqrt{m_\nu^{\text{diag}}} U_{\text{PMNS}}^\dagger \right)_{i\alpha}. \quad (2.11)$$

Here, U_{PMNS} is the so-called PMNS neutrino mixing matrix, R is a general complex orthogonal matrix and $m_\nu^{\text{diag}} = \text{Diag}(m_1, m_2, m_3)$. In our case the general complex matrix R can be parameterized by three complex parameters of $\theta_{\alpha\beta} = \theta_{\alpha\beta}^R + i\theta_{\alpha\beta}^I \in [0, 2\pi]$. In general, the orthogonal matrix R for n flavors can be nC_2 number of rotation matrices of type:

$$R_{\alpha\beta} = \begin{pmatrix} \cos(\theta_{\alpha\beta}^R + i\theta_{\alpha\beta}^I) & \cdots & \sin(\theta_{\alpha\beta}^R + i\theta_{\alpha\beta}^I) \\ \vdots & \ddots & \vdots \\ -\sin(\theta_{\alpha\beta}^R + i\theta_{\alpha\beta}^I) & \cdots & \cos(\theta_{\alpha\beta}^R + i\theta_{\alpha\beta}^I) \end{pmatrix}. \quad (2.12)$$

In this scenario, since we take the scalar doublet η as DM, all the ξ 's can decay and do not take part in the Boltzmann evolution.

3 Leptogenesis through resonance of $U(1)_D$ gauge boson

In this section we discuss the mechanism for generating the lepton asymmetry through the Breit-Wigner resonance of the $U(1)_D$ gauge boson which mediates lepton number violating

Figure 1. One-loop diagram for neutrino mass.

Figure 2. Two distinct amplitudes whose interference gives rise to the lepton asymmetry.

($\Delta L = 2$) neutral current. In appendix A, we present how lepton number violating neutral currents are generated at 1-loop, which give rise to the effective vertex as explicitly presented in eq. (A.4). Thanks to the effective coupling given in eq. (A.4), lepton number violating $2 \rightarrow 2$ processes mediated by Z'_D can arise as shown in figure 2 in which the blob represents the effective coupling. In addition, lepton number is violated through the exchange of ξ_i as shown in figure 2. Then, the CP violating lepton asymmetry can be obtained from the interference between both amplitudes for the lepton number violating processes. The general expression for the lepton asymmetry arising from the difference between the amplitude squared for the particles and that for the anti-particles is given as

$$\delta \equiv |\mathcal{M}(\eta\eta \rightarrow \nu\nu)|^2 - |\mathcal{M}(\eta\eta \rightarrow \bar{\nu}\bar{\nu})|^2 = 4\Im[C_0^*C_1]\Im[\mathcal{A}_0^*\mathcal{A}_1], \quad (3.1)$$

where the first part of the asymmetry (i.e C 's) arises only from the multiplication of the couplings in two amplitudes and the second one (i.e $\mathcal{A}$'s) comes from the pure amplitudes except for the couplings. The effective amplitudes are given as

$$\begin{aligned} i\mathcal{M}_0 = C_0\mathcal{A}_0 &= i \sum_i Y_{\nu i\alpha} Y_{\nu i\beta} (x_\alpha^\dagger x_\beta^\dagger) \left(\cos^2 \theta_i M_{i+} \left[\frac{1}{t - M_{i+}^2} + \frac{1}{u - M_{i+}^2} \right] \right. \\ &\quad \left. + \sin^2 \theta_i M_{i-} \left[\frac{1}{t - M_{i-}^2} + \frac{1}{u - M_{i-}^2} \right] \right), \\ i\mathcal{M}_1 = C_1\mathcal{A}_1 &= ig^2 \sum_i Y_{\nu i\alpha} Y_{\nu i\beta} f_i \frac{x_\alpha^\dagger \bar{\sigma}_{\mu\nu} x_\beta^\dagger (p_\alpha - p_\beta)^\mu (p_R - p_I)^\nu}{(s - m_{Z_D}^2 + iM_{Z_D}\Gamma_{Z_D})}. \end{aligned} \quad (3.2)$$

The above amplitudes are written in terms of two-spinor notation where $x^\dagger$'s are the *commuting* two-component spinor wave function as explained in [18].

The loop function f_i is given in eq. (A.4). In order to understand the dependence of the above asymmetry with respect to temperature it is convenient to separate δ in eq. (3.1)

into two contributions as follows:

$$\begin{aligned}
 \delta_R &= \sum_{\alpha,\beta} \frac{\Im[Y_{\nu j\alpha}^* Y_{\nu j\beta}^* Y_{\nu i\alpha} Y_{\nu i\beta}] g^2 \Re[f_i] m_{Z_D} \Gamma_{Z_D}}{((s - m_{Z_D}^2)^2 + m_{Z_D}^2 \Gamma_{Z_D}^2)} (m_{\eta_R}^2 - m_{\eta_I}^2) \frac{(s + m_{Z_D}^2)}{m_{Z_D}^2} \\
 &\quad \times \left(\cos^2 \theta_i M_{j+} \left[\frac{1}{t - M_{j+}^2} + \frac{1}{u - M_{j+}^2} \right] + \sin^2 \theta_i M_{j-} \left[\frac{1}{t - M_{j-}^2} + \frac{1}{u - M_{j-}^2} \right] \right), \\
 \delta_I &= \sum_{\alpha,\beta} \frac{\Re[Y_{\nu j\alpha}^* Y_{\nu j\beta}^* Y_{\nu i\alpha} Y_{\nu i\beta}] g^2 \Im[f_i] (s - m_{Z_D}^2)}{((s - m_{Z_D}^2)^2 + m_{Z_D}^2 \Gamma_{Z_D}^2)} (m_{\eta_R}^2 - m_{\eta_I}^2) \frac{(s + m_{Z_D}^2)}{m_{Z_D}^2} \\
 &\quad \times \left(\cos^2 \theta_i M_{j+} \left[\frac{1}{t - M_{j+}^2} + \frac{1}{u - M_{j+}^2} \right] + \sin^2 \theta_i M_{j-} \left[\frac{1}{t - M_{j-}^2} + \frac{1}{u - M_{j-}^2} \right] \right). \quad (3.3)
 \end{aligned}$$

We observe that δ_R (δ_I) is proportional to the real (imaginary) part of the chirality violating vertex of the Z_D . Here, we note that $\delta_{R,I} = 0$ for $m_{\eta_R} = m_{\eta_I}$ (or $M_{i+} = M_{i-}$) restoring to $U(1)_D$ conservation. Thus, the asymmetry is suppressed for $m_{\eta_R} \approx m_{\eta_I}$, which eliminates the effect of the Z_D resonance. Note also that the asymmetry $\delta_R \propto \Gamma_D$ is due to the imaginary part of the re-summed Z_D propagator. Then, the corresponding thermally averaged cross-sections are given as

$$\gamma_R^\delta = \frac{T}{8\pi^4} \int_{s_{\text{in}}}^\infty \int_{-1}^1 \delta_R \frac{p_{\text{in}} p_{\text{out}}}{\sqrt{s}} K_1(\sqrt{s}/T) d(\cos \theta) ds, \quad (3.4)$$

$$\gamma_I^\delta = \frac{T}{8\pi^4} \int_{s_{\text{in}}}^\infty \int_{-1}^1 \delta_I \frac{p_{\text{in}} p_{\text{out}}}{\sqrt{s}} K_1(\sqrt{s}/T) d(\cos \theta) ds, \quad (3.5)$$

where K_1 is the modified Bessel function of the second kind.

Now, in order to get the lepton asymmetry along with the relic abundance we solve the coupled Boltzmann equations given as

$$\begin{aligned}
 \frac{dX_{DM}}{dz} &= \frac{-z}{sH(M_{\eta_R})} \left(\frac{X^2}{(X_{DM}^{\text{eq}})^2} - 1 \right) \gamma_{\text{scatt}}^{\text{eq}}(DM DM \rightarrow SM SM), \\
 \frac{dX_L}{dz} &= \frac{z}{sH(M_{\eta_R})} \left[\left(\frac{X_{\eta_R} X_{\eta_I}}{X_{\eta_R}^{\text{eq}} X_{\eta_I}^{\text{eq}}} - 1 \right) (\gamma_R^\delta - \gamma_I^\delta) \right. \\
 &\quad - \frac{X_L}{X_l^{\text{eq}}} \left(2\gamma_{\text{scatt}}^{\text{eq}}(\eta\eta \rightarrow LL) + \gamma_{\text{scatt}}^{\text{eq}}(\eta\xi \rightarrow LSM) + \gamma_{\text{scatt}}^{\text{eq}}(\eta L \rightarrow \eta\bar{L}) \right. \\
 &\quad \left. \left. + \gamma_{\text{scatt}}^{\text{eq}}(\eta L \rightarrow \xi SM) + \gamma_D(\xi \rightarrow \eta L) + \gamma_{\text{scatt}}^{\text{eq}}(\xi L \rightarrow \eta SM) \right) \right], \quad (3.6)
 \end{aligned}$$

where $DM \in \{\eta_R, \eta_I, \eta_\pm\}$ and $X_i = n_i/s$ is the comoving number density in which n_i is the number density and $s = g_* 2\pi^2/45T^3$ is the entropy density with g_* being the number of relativistic degrees of freedom. The first equation in eq. (3.6) is for the evolution of the number density of the dark sector and the second one is for that of the lepton asymmetry. In the second equation, the first line of the right-handed side corresponds to the generation of the lepton asymmetry, whereas the other two lines to the washout.

4 Results and discussion

In this section we present numerical results for the evolution of the lepton asymmetry along with the relic abundance of DM. The important point to be noticed before presenting our results is that the contribution coming from the resonance of the Z_D to the asymmetry in eq. (3.1) is always dominant over the one coming from the imaginary part of the loop function. This is due to the reason that near the resonance point $s \sim m_{Z_D}^2$ the δ_I in eq. (3.3) goes to zero and thus the required baryon asymmetry can be achieved via δ_R . This is a novel way to generate the asymmetry for successful baryogenesis. But, to realize this mechanism through the resonance of the unstable neutral gauge boson, there should exist another distinct amplitudes which are interfered with the amplitude mediated by the neutral gauge boson. In our case they are through the t -channel processes mediated by the vector-like fermions as shown in figure 2.

For the numerical analysis, we take the central values of neutrino oscillation data as input [19]. The values of the model parameters we take as two benchmark points are presented in table 2. One may notice that we have taken $\lambda_{H\eta} = -\lambda'_{H\eta}$ for all the benchmark points, which makes Δm_{η^0} trivially small with respect to $m_{\eta^\pm}$. The plots in figure 3 show how the relic density of DM (red line) and the baryon asymmetry (green lines) evolve along with temperature. Their experimental results are given by

$$\Omega_{\text{DM}} h^2 = 0.120 \pm 0.001, \quad (4.1)$$

$$Y_{\Delta B} = 8.237 \times 10^{-11} \quad (4.2)$$

at 68% CL [20]. The equilibrium number density of DM tracks the red dashed line. The left(right) panel corresponds to $M_{\text{DM}} = 600(800)$ GeV. The solid green lines represent the prediction of the baryon asymmetry for $m_{Z_D} = 1.25$ TeV (left panel) and 1.65 TeV (right panel), respectively, which are nearly $m_{Z_D} \sim 2M_{\text{DM}}$. Note that our mechanism also works for $m_{Z_D} > 2M_{\text{DM}}$. The plots show that the DM freezes out at $T_{f_D} \sim 30$ GeV, whereas the baryon asymmetry freezes out at $T_{f_B} \sim 200 - 300$ GeV. One may notice that although the integrand in eq. (3.4) has a peak near the resonance (i.e. $\sqrt{s} = m_{Z_D}$), γ_R^δ can be suppressed due to a Boltzmann suppression coming from the modified Bessel function ($K_1(m_{Z_D}/T_{f_B})$). When $T_{f_B} \simeq 200$ GeV the suppression is the least for the case of $m_{Z_D} \simeq 2m_{\text{DM}}$, for which the correct asymmetry is achieved for rather small values of $\theta_{ij}^{R,I}$. On the other hand, for $m_{Z_D} > 2m_{\text{DM}}$, the right amount of the asymmetry can be obtained only when $\theta_{ij}^{R,I}$ is large. The green-dashed lines depicted in figure 3 correspond to this case, for which we take $m_{Z_D} = 10$ TeV. As presented in table 2, the required values of $\theta_{ij}^{R(I)}$ to achieve the right amount of the baryon asymmetry in that case are 40 times larger than those for the case with $m_{Z_D} = 1.25$ TeV corresponding to the solid green lines. This is due to the fact that for larger m_{Z_D} the resonance occurs at higher $\sqrt{s}$ which makes the asymmetry suppressed by the Boltzmann factor mentioned above, so taking larger values of $\theta_{ij}^{R,I}$ for fixed other inputs can help to compensate this Boltzmann suppression. As can be seen from figure 3, the right amount of the baryon asymmetry and the relic density of DM can be simultaneously achieved in our scenario.

	BP1		BP2	
v_Δ	1 GeV			
μ_η	600 GeV		800 GeV	
$M_{i(=1,2,3)}$	6 TeV		8 TeV	
$m_{\eta_I^0}$	601 GeV	678 GeV	802 GeV	860 GeV
Δm_{η^0}	7.06 MeV	6.25 MeV	5.3 MeV	4.93 MeV
$m_{\eta^\pm}$	606 GeV	685 GeV	808 GeV	868 GeV
m_ϕ	3.95 TeV	31.62 TeV	5.22 TeV	31.62 TeV
m_Δ	603 GeV	1.74 TeV	707 GeV	1.74 TeV
λ_H	0.253			
$\lambda_{H\eta}$	0.15	0.29	0.34	0.43
$\lambda'_{H\eta}$	-0.15	-0.29	-0.34	-0.43
$\theta_{13}^R = \theta_{13}^I$	$\pi/800$	$\pi/20$	$\pi/800$	$\pi/20$
g_D	0.05			
Γ_{Z_D}	2.04×10^{-3} GeV	1.96 TeV	0.0454 GeV	1.96 TeV
M_{Z_D}	1.25 TeV	10 TeV	1.65 TeV	10 TeV
$\mu_{\eta\Delta}$	3 GeV			

Table 2. Input values of the parameters for two benchmark points. Here $m_\Delta = m_{\Delta^{\pm\pm}} = m_{\Delta^\pm} = m_{\Delta_{R,I}^0}$. The scalar triplet (Δ^*, Δ) and the scalar doublet (η^*, η) denote $(\Delta_R^0, \Delta_I^0), (\Delta^{++}, \Delta^{--}), (\Delta^+, \Delta^-)$ and $(\eta_R^0, \eta_I^0), (\eta^+, \eta^-)$, respectively.

Figure 3. Number densities as a function of T . Red solid, green (solid and dashed) lines correspond to the relic density and the baryon asymmetry, respectively. For the plots of the baryon asymmetry, we take M_{Z_D} to be 1.25 (green solid), 10 (green dashed) TeV for $M_{DM} = 600$ GeV in the left panel, and 1.65 (green solid), 10 (green dashed) TeV as input for $M_{DM} = 800$ GeV in the right panel.

Figure 4. Diagram for the effective vertex of $Z_D \nu \nu$.

5 Conclusion

We have proposed a novel mechanism to generate the baryon asymmetry through the Breit-Wigner resonance of a dark $U(1)_D$ gauge boson Z_D , which mediates lepton number violating annihilations of DM in the context of the scotogenic model with a $U(1)_D$. The origin of CP asymmetry required for leptogenesis is the interference between tree-level t-channel scattering of DM and the subsequent 1-loop mediated by Z_D , which arises due to the unremovable imaginary part of either the Z_D propagator coming from its self-energy correction or the 1-loop vertex giving rise to the effective coupling of $Z_D \bar{\nu} \nu$. The former is always dominant over the latter thanks to the occurrence of the resonance of the gauge boson Z_D . The processes occur out of equilibrium and the DM freezes out later giving rise to the observed abundance. We could show that the right amount of the baryon asymmetry and the relic density of DM can be simultaneously achieved in our scenario.

Acknowledgments

This work was supported by the Research Program funded by the Seoul Tech (Seoul National University of Science and Technology).

A Details of the effective Z_D coupling

In this section we present the details of the effective Z_D coupling depicted as the bolb shown in figure 4 by adopting two-spinor notations (see [18] for details). The Feynman diagrams for the 1-loop contributions to the effective coupling are shown in figures 5 and 6. The 1-loop contributions in figure 5 are mediated by scalars, whereas those in figure 6 are mediated by fermions.

The contributions from the top two rows in figure 5 lead to the effective Lagrangian given as:

$$\begin{aligned} \mathcal{L}_{\text{eff}}^a = & 2i\nu_\alpha^\dagger \bar{\sigma}^{\mu\nu} \nu_\beta^\dagger (p_\alpha - p_\beta)_\nu Z_{\mu D} \sin 2\theta \\ & \times \left[(M_{i-} - M_{i+})(\mathcal{F}_+(m_{\eta_R}, M_{i+}, M_{i-}) - \mathcal{F}_+(m_{\eta_I}, M_{i+}, M_{i-})) \right. \\ & \left. + (M_{i-} + M_{i+})(\mathcal{F}_-(m_{\eta_R}, M_{i+}, M_{i-}) - \mathcal{F}_-(m_{\eta_I}, M_{i+}, M_{i-})) \right], \end{aligned} \quad (\text{A.1})$$

Figure 5. One-loop contributions mediated by scalars to the effective vertex presented in figure 4. We adopt two-spinor notation presented in [18] for drawing the diagrams and calculations.

Figure 6. One-loop contributions mediated by fermions to the effective vertex.

where the mixing angle θ is given in eq. (2.8) and $\mathcal{F}_{\pm}$ is given in eq. (B.10). The contributions coming from the bottom two rows in figure 5 give rise to the effective Lagrangian as follows:

$$\mathcal{L}_{\text{eff}}^b = 2i\nu_{\alpha}^{\dagger}\bar{\sigma}^{\mu\nu}\nu_{\beta}^{\dagger}(p_{\alpha}-p_{\beta})_{\nu}Z_{\mu D}\cos 2\theta\left[M_{i-}(\mathcal{F}_{-}(m_{\eta_R},M_{i-},M_{i-})-\mathcal{F}_{-}(m_{\eta_I},M_{i-},M_{i-}))\right. \\ \left.-M_{i+}(\mathcal{F}_{-}(m_{\eta_R},M_{i+},M_{i+})-\mathcal{F}_{-}(m_{\eta_I},M_{i+},M_{i+}))\right]. \quad (\text{A.2})$$

Similarly, the effective Lagrangian from the contributions shown in figure 6 is given as:

$$\mathcal{L}_{\text{eff}}^c = -2i\nu_{\alpha}^{\dagger}\bar{\sigma}^{\mu\nu}\nu_{\beta}^{\dagger}(p_{\alpha}-p_{\beta})_{\nu}Z_{\mu D}(2\cos^2\theta\mathcal{F}_{+}(M_{i+},m_{\eta_R},m_{\eta_I})+2\sin^2\theta\mathcal{F}_{+}(M_{i-},m_{\eta_R},m_{\eta_I})) \quad (\text{A.3})$$

So, combining all the contributions the final form of the effective Lagrangian is given as:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{eff}}^a + \mathcal{L}_{\text{eff}}^b + \mathcal{L}_{\text{eff}}^c \\ = 2i\nu_{\alpha}^{\dagger}\bar{\sigma}^{\mu\nu}\nu_{\beta}^{\dagger}(p_{\alpha}-p_{\beta})_{\nu}Z_{\mu D}\left[(M_{i-}-M_{i+})(\mathcal{F}_{+}(m_{\eta_R},M_{i+},M_{i-})-\mathcal{F}_{+}(m_{\eta_I},M_{i+},M_{i-}))\right. \\ \left.+(M_{i-}+M_{i+})(\mathcal{F}_{-}(m_{\eta_R},M_{i+},M_{i-})-\mathcal{F}_{-}(m_{\eta_I},M_{i+},M_{i-}))\right. \\ \left.+M_{i-}(\mathcal{F}_{-}(m_{\eta_R},M_{i-},M_{i-})-\mathcal{F}_{-}(m_{\eta_I},m_{\xi_-},m_{\xi_-}))\right]$$

$$\begin{aligned}
 & -M_{i+}(\mathcal{F}_-(m_{\eta_R}, M_{i+}, M_{i+}) - \mathcal{F}_-(m_{\eta_I}, M_{i+}, M_{i+})) \\
 & -2\cos^2\theta\mathcal{F}_+(M_{i+}, m_{\eta_R}, m_{\eta_I}) - 2\sin^2\theta\mathcal{F}_+(M_{i-}, m_{\eta_R}, m_{\eta_I}) \Big] \\
 & = 2i\nu_\alpha^\dagger \bar{\sigma}^{\mu\nu} \nu_\beta^\dagger (p_\alpha - p_\beta)_\nu Z_{\mu D} f_i.
 \end{aligned} \tag{A.4}$$

where f_i represents the entire loop function.

B Details of the loop function $\mathcal{F}_\pm$

In order to derive the $\mathcal{F}_\pm$ functions we first start with the well known scalar integral functions

$$\mathcal{C}_0(p_1^2, p_2^2, p_1.p_2, m_1^2, m_2^2, m_3^2) = \int \frac{dl^4}{2\pi^4} \frac{1}{(l^2 - m_1^2)((l - p_1)^2 - m_2^2)((l + p_2)^2 - m_3^2)}, \tag{B.1}$$

$$\mathcal{B}_0(p^2, m_1^2, m_2^2) = \int \frac{dl^4}{2\pi^4} \frac{1}{(l^2 - m_1^2)((l + p)^2 - m_2^2)}, \tag{B.2}$$

where $p_1^2 = p_2^2 = 0$ for outgoing neutrinos in our case and $p_1.p_2 = s/2$. Let us calculate the following integral

$$\int \frac{dl^4}{2\pi^4} \frac{l^\mu}{(l^2 - m_1^2)((l - p_1)^2 - m_2^2)((l + p_2)^2 - m_3^2)} = p_1^\mu \mathcal{C}_1 + p_2^\mu \mathcal{C}_2, \tag{B.3}$$

where the scalars $\mathcal{C}_1$ and $\mathcal{C}_2$ are functions of the above scalar integrals. One can derive $\mathcal{C}_1$ and $\mathcal{C}_2$ by considering the following integral,

$$\begin{aligned}
 & \int \frac{dl^4}{2\pi^4} \frac{1}{(l^2 - m_1^2)} \left[\frac{1}{(l - p_1)^2 - m_2^2} - \frac{1}{(l + p_2)^2 - m_3^2} \right] = \mathcal{B}_0(0, m_1^2, m_2^2) - \mathcal{B}_0(0, m_1^2, m_3^2), \\
 & \int \frac{dl^4}{2\pi^4} \frac{2l.p_1 + 2l.p_2 + m_2^2 - m_3^2}{(l^2 - m_1^2)((l - p_1)^2 - m_2^2)((l + p_2)^2 - m_3^2)} = \mathcal{B}_0(0, m_1^2, m_2^2) - \mathcal{B}_0(0, m_1^2, m_3^2),
 \end{aligned} \tag{B.4}$$

which is simplified to

$$2p_1.p_2(\mathcal{C}_1 + \mathcal{C}_2) = \mathcal{B}_0(0, m_1^2, m_2^2) - \mathcal{B}_0(0, m_1^2, m_3^2) + (m_3^2 - m_2^2)\mathcal{C}_0(0, 0, s/2, m_1^2, m_2^2, m_3^2).$$

Then, we get

$$\mathcal{C}_1 + \mathcal{C}_2 = \frac{1}{s} [\mathcal{B}_0(0, m_1^2, m_2^2) - \mathcal{B}_0(0, m_1^2, m_3^2) + (m_3^2 - m_2^2)\mathcal{C}_0(0, 0, s/2, m_1^2, m_2^2, m_3^2)]. \tag{B.5}$$

Now, let us extract $\mathcal{C}_2$ by considering the following integral,

$$\begin{aligned}
 & \int \frac{dl^4}{2\pi^4} \frac{1}{(l + p_2)^2 - m_3^2} \left[\frac{1}{l^2 - m_1^2} - \frac{1}{(l - p_1)^2 - m_2^2} \right] = \mathcal{B}_0(0, m_1^2, m_3^2) \\
 & - \int \frac{dl^4}{2\pi^4} \frac{1}{((l + p_2)^2 - m_3^2)((l - p_1)^2 - m_2^2)}.
 \end{aligned} \tag{B.6}$$

Performing the transformation $l \rightarrow k + p_1$ on the right-hand side in eq. (B.6) we get

$$\begin{aligned} \int \frac{dl^4}{2\pi^4} \frac{1}{(l+p_2)^2 - m_3^2} \left[\frac{1}{l^2 - m_1^2} - \frac{1}{(l-p_1)^2 - m_2^2} \right] &= \mathcal{B}_0(0, m_1^2, m_3^2) \\ &\quad - \int \frac{dk^4}{2\pi^4} \frac{1}{((k+p_1+p_2)^2 - m_3^2)(k^2 - m_2^2)}, \\ \int \frac{dl^4}{2\pi^4} \frac{m_1^2 - m_2^2 - 2l \cdot p_1}{(l^2 - m_1^2)((l-p_1)^2 - m_2^2)((l+p_2)^2 - m_3^2)} &= \mathcal{B}_0(0, m_1^2, m_3^2) - \mathcal{B}_0(s, m_2^2, m_3^2), \end{aligned} \quad (\text{B.7})$$

which is simplified to

$$-2p_1 \cdot p_2 \mathcal{C}_2 = \mathcal{B}_0(0, m_1^2, m_3^2) - \mathcal{B}_0(s, m_2^2, m_3^2) + (m_1^2 - m_2^2) \mathcal{C}_0(0, 0, s/2, m_1^2, m_2^2, m_3^2).$$

Then, $\mathcal{C}_2$ is obtained as follows,

$$\mathcal{C}_2 = \frac{1}{s} [\mathcal{B}_0(s, m_2^2, m_3^2) - \mathcal{B}_0(0, m_1^2, m_3^2) + (m_2^2 - m_1^2) \mathcal{C}_0(0, 0, s/2, m_1^2, m_2^2, m_3^2)]. \quad (\text{B.8})$$

From eqs. (B.5), (B.8), we get $\mathcal{C}_1$ given as,

$$\mathcal{C}_1 = \frac{1}{s} [\mathcal{B}_0(s, m_1^2, m_2^2) - \mathcal{B}_0(s, m_2^2, m_3^2) + (m_3^2 - m_1^2) \mathcal{C}_0(0, 0, s/2, m_1^2, m_2^2, m_3^2)], \quad (\text{B.9})$$

and from the scalar functions $\mathcal{C}_1$ and $\mathcal{C}_2$ we construct $\mathcal{F}_\pm$ as follows,

$$\begin{aligned} \mathcal{F}_+(m_1, m_2, m_3) &= \mathcal{C}_1 + \mathcal{C}_2, \\ &= \frac{1}{s} [\mathcal{B}_0(0, m_1^2, m_2^2) - \mathcal{B}_0(0, m_1^2, m_3^2) + (m_3^2 - m_2^2) \mathcal{C}_0(0, 0, s/2, m_1^2, m_2^2, m_3^2)], \\ \mathcal{F}_-(m_1, m_2, m_3) &= \mathcal{C}_1 - \mathcal{C}_2, \\ &= \frac{1}{s} [\mathcal{B}_0(0, m_1^2, m_2^2) + \mathcal{B}_0(0, m_1^2, m_3^2) - 2\mathcal{B}_0(s, m_2^2, m_3^2) \\ &\quad + (m_2^2 + m_3^2 - 2m_1^2) \mathcal{C}_0(0, 0, s/2, m_1^2, m_2^2, m_3^2)]. \end{aligned} \quad (\text{B.10})$$

In our work, the scalar integrals $\mathcal{C}_0$ and $\mathcal{B}_0$ given in eqs. (B.1), (B.2) have been calculated by using the **Package-X** [21, 22].

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] D.V. Nanopoulos and S. Weinberg, *Mechanisms for cosmological baryon production*, *Phys. Rev. D* **20** (1979) 2484 [[INSPIRE](#)].
- [2] R. Adhikari and R. Rangarajan, *Baryon number violation in particle decays*, *Phys. Rev. D* **65** (2002) 083504 [[hep-ph/0110387](#)] [[INSPIRE](#)].
- [3] S. Dimopoulos and L. Susskind, *Baryon asymmetry in the very early universe*, *Phys. Lett. B* **81** (1979) 416 [[INSPIRE](#)].

- [4] S. Weinberg, *Cosmological production of baryons*, *Phys. Rev. Lett.* **42** (1979) 850 [INSPIRE].
- [5] M. Fukugita and T. Yanagida, *Baryogenesis without grand unification*, *Phys. Lett. B* **174** (1986) 45 [INSPIRE].
- [6] S. Davidson and A. Ibarra, *A lower bound on the right-handed neutrino mass from leptogenesis*, *Phys. Lett. B* **535** (2002) 25 [hep-ph/0202239] [INSPIRE].
- [7] F. Vissani, *Do experiments suggest a hierarchy problem?*, *Phys. Rev. D* **57** (1998) 7027 [hep-ph/9709409] [INSPIRE].
- [8] J.D. Clarke, R. Foot and R.R. Volkas, *Electroweak naturalness in the three-flavor type-I seesaw model and implications for leptogenesis*, *Phys. Rev. D* **91** (2015) 073009 [arXiv:1502.01352] [INSPIRE].
- [9] A. Pilaftsis, *CP violation and baryogenesis due to heavy Majorana neutrinos*, *Phys. Rev. D* **56** (1997) 5431 [hep-ph/9707235] [INSPIRE].
- [10] T. Hambye, *Leptogenesis at the TeV scale*, *Nucl. Phys. B* **633** (2002) 171 [hep-ph/0111089] [INSPIRE].
- [11] Y. Cui, L. Randall and B. Shuve, *A WIMPy baryogenesis miracle*, *JHEP* **04** (2012) 075 [arXiv:1112.2704] [INSPIRE].
- [12] J. Kumar and P. Stengel, *WIMPy leptogenesis with absorptive final state interactions*, *Phys. Rev. D* **89** (2014) 055016 [arXiv:1309.1145] [INSPIRE].
- [13] J. Racker and N. Rius, *Helicitogenesis: WIMPy baryogenesis with sterile neutrinos and other realizations*, *JHEP* **11** (2014) 163 [arXiv:1406.6105] [INSPIRE].
- [14] A. Dasgupta, C. Hati, S. Patra and U. Sarkar, *A minimal model of TeV scale WIMPy leptogenesis*, arXiv:1605.01292 [INSPIRE].
- [15] D. Borah, A. Dasgupta and S.K. Kang, *TeV scale leptogenesis via dark sector scatterings*, *Eur. Phys. J. C* **80** (2020) 498 [arXiv:1806.04689] [INSPIRE].
- [16] T. Hugle, M. Platscher and K. Schmitz, *Low-scale leptogenesis in the scotogenic neutrino mass model*, *Phys. Rev. D* **98** (2018) 023020 [arXiv:1804.09660] [INSPIRE].
- [17] A. Dasgupta, P.S. Bhupal Dev, S.K. Kang and Y. Zhang, *Matter-antimatter asymmetry without loops*, arXiv:1911.03013 [INSPIRE].
- [18] H.K. Dreiner, H.E. Haber and S.P. Martin, *Two-component spinor techniques and Feynman rules for quantum field theory and supersymmetry*, *Phys. Rept.* **494** (2010) 1 [arXiv:0812.1594] [INSPIRE].
- [19] I. Esteban, M.C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni and T. Schwetz, *Global analysis of three-flavour neutrino oscillations: synergies and tensions in the determination of θ_{23} , δ_{CP} , and the mass ordering*, *JHEP* **01** (2019) 106 [arXiv:1811.05487] [INSPIRE].
- [20] PLANCK collaboration, *Planck 2018 results. VI. Cosmological parameters*, arXiv:1807.06209 [INSPIRE].
- [21] H.H. Patel, *Package-X: a Mathematica package for the analytic calculation of one-loop integrals*, *Comput. Phys. Commun.* **197** (2015) 276 [arXiv:1503.01469] [INSPIRE].
- [22] H.H. Patel, *Package-X 2.0: a Mathematica package for the analytic calculation of one-loop integrals*, *Comput. Phys. Commun.* **218** (2017) 66 [arXiv:1612.00009] [INSPIRE].