CDF-II W boson mass in the Dirac Scotogenic model

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The Dirac scotogenic model provides an elegant mechanism which explains small Dirac neutrino masses and neutrino mixing, with a single symmetry simultaneously protecting the "Diracness" of the neutrinos and the stability of the dark matter candidate. Here we explore the phenomenological implications of the recent CDF-II measurement of the W boson mass in the Dirac scotogenic framework. We show that, in the scenario where the dark matter is mainly a $SU(2)_L$ scalar doublet, it cannot concurrently satisfy: (a) the dark matter relic density (b) the m_W anomaly and (c) the direct detection constraints. However, unlike the Majorana scotogenic model, the Dirac version also has a "dark sector" $SU(2)_L$ singlet scalar. We show that if the singlet scalar is the lightest dark sector particle i.e. the dark matter, then all neutrino physics and dark matter constraints along with the constraints from oblique S, T and U parameters can be concurrently satisfied for W boson mass in CDF-II mass range.

I. INTRODUCTION

The Standard Model (SM) of particle physics is the most precise theory of scientific history. Its multiple successes culminated with the discovery of a Higgs-like boson in 2012 [1, 2]. However, we know that it must be an incomplete theory. The solid experimental/observational evidences for matter-antimatter asymmetry [3], dark matter (DM) [3] and neutrino masses [4, 5] cannot be accommodated in the SM framework. Moreover, other more theoretical problems like the strong CP problem are present in the SM and if new scales higher than the electroweak (EW) scale are added to the theory in order to solve some or all of the previous issues then the hierarchy problem will arise.

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Among the various shortcomings of SM, one of the most intriguing problem is the small but non-zero mass of neutrinos and the pattern of lepton mixing leading to neutrino oscillations. The so far unknown neutrino mass mechanism is tightly tied with the deeper question of neutrino nature. Neutrinos are singlets under the conserved symmetries of the SM, QCD and QED, and therefore it is a natural expectation that the neutrino mass generation will break lepton number and thus neutrino will be of Majorana nature [6–9]. However, new physics may very well introduce new symmetries that forbid these Majorana mass terms and neutrinos would instead be of Dirac type. This option is becoming popular in recent times, see [10–47] for a few selected examples. Detecting neutrinoless beta decay would settle this issue [48], but so far the experimental searches remain inconclusive in this regard [49].

Any mass mechanism for neutrinos, whether Dirac or Majorana, will require addition of new particles beyond SM. In general these new particles can have an impact on the EW precision observables. It is convenient to parameterize these new effects, in particular on the W and Z gauge boson masses, in a model independent way through the oblique S, T and U parameters [50]. Until very recently, the philosophy for model-building was that the new physics contributions should be small enough so that they do not lead to unacceptably large corrections in the EW sector. However, the theoretical expectation should be to eventually observe deviations from the SM predictions, since we know that the SM has to be extended in some way. Indeed, in 2022 the CDF-II collaboration reported a 7σ excess on the mass of the W boson [51] with respect to the SM prediction [52]. This experimental result is in direct clash with ATLAS measurements of the W boson mass [53]. This issue can be hopefully clarified as the new run of LHC should bring new data very soon. In any case, if CDF-II measurements are correct then new physics beyond Standard Model (BSM) is definitely needed. Keeping the CDF-II results in mind, the new fits to the EW precision oblique parameters S, T and U including the CDF-II W boson mass measurement have been performed [54–61], again indicating need for BSM physics corrections to W boson mass. As emphasized before, these sort of deviations from the SM predictions are actually expected if the SM is extended in order to explain some of its shortcomings. The class of models that can explain the m_W anomaly is, therefore, very wide. See [61–113] for a few examples.

Among these, simple models which can simultaneously explain the existence of DM and small neutrino masses are of particular interest. A simple but well motivated extension of the SM in which neutrinos obtain mass via a one-loop diagram is the so called scotogenic model [114]. In its canonical version a new 'ad-hoc' Z_2 symmetry is added to the model in order to stabilize the lightest particle in the loop, which then becomes a viable DM candidate. If neutrinos are Dirac, however, it is possible to obtain the same stability using just a chiral $U(1)_{B-L}$ symmetry. This $U(1)_{B-L}$ is multipurpose: it stabilizes the DM, protects the Diracness of neutrinos and forbids the tree-level neutrino mass term, thus naturally explaining the smallness of neutrino mass [13]. An additional consequence of the chiral $U(1)_{B-L}$ is that the lightest neutrino will be massless. See [35, 42] for other phenomenological analysis of the Dirac scotogenic variants and [46] for a study on its relation with B anomalies. Here, we will focus on the connection between DM and neutrino masses in the particular framework of the Dirac scotogenic model [13], the implications of the new CDF-II result and the difference with respect to the Majorana scotogenic model.

The work is structured as follows. In Sec. II we present the basic details of the model. In Sec. III we explore the neutrino mass and mixing of the model, with particular focus on the parameter κ, dimensionful analogue of the λ_5 parameter in the original scotogenic model. In Sec. IV we compute the W boson mass corrections of the model and show that the pure $SU(2)_L$ doublet scalar DM case is severely constrained from the need to satisfy CDF-II W boson mass measurement while at the same time keeping the oblique S, T and U parameters within their global fit range. Finally in Sec. V we analyze the DM sector first for the case of doublet scalar DM and then for the singlet scalar DM. We find that the already constrained doublet DM case is incompatible with the relic abundance and direct detection constrains. However, the singlet scalar DM can indeed satisfy all the constraints simultaneously. We conclude with final remarks in Sec. VI

II. THE MODEL SETUP

We will now flesh out the most important characteristics of the model presented in [13]. The field and symmetry inventory is given in Tab. I. The key ingredient of the model is the chiral anomaly free $B - L$ symmetry[1][17–19] with a triple role: protecting the stability of DM, protecting the Dirac nature of the neutrinos and the smallness of neutrino masses by forbidding the tree-level coupling with the Higgs field. It also predicts that the lightest neutrino is massless. The $B - L$ symmetry is then broken to a residual Z_n, $n \in$ positive integer; residual subgroup which remains unbroken. Depending on the Z_n subgroup and charges of the lepton doublets under it, the neutrinos can be Dirac or Majorana in nature [13, 115]. Here, we will focus on the $U(1)_{B-L} \to Z_6$ residual subgroup which arises naturally if $B - L$ symmetry is broken in units of three. The residual Z_6 then ensures the Dirac nature of neutrinos by forbidding all possible Majorana terms to all loop orders of perturbation. It simultaneously also protects the stability of the lightest "dark sector" particle which can be a viable DM candidate [13].

In Tab. I apart from SM particles, we have added three right handed neutrinos ν_{R_i}; $i = 1, 2, 3$ with $B - L$ charges of $(-4, -4, 5)$ and dark sector particles: the singlet fermions N_{L_i}, N_{R_i};

[1] Being anomaly free, the $U(1)_{B-L}$ symmetry can be gauged. However, here for sake of simplicity we will take it to be a global symmetry.

	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L}$	$\mathcal{Z}_6$
Fermions	L_i	$(\mathbf{2}, -1/2)$	-1	ω^4
	ν_{R_i}	$(\mathbf{1}, 0)$	$(-4, -4, 5)$	ω^4
	N_{L_l}	$(\mathbf{1}, 0)$	$-1/2$	ω^5
	N_{R_l}	$(\mathbf{1}, 0)$	$-1/2$	ω^5
Scalars	H	$(\mathbf{2}, 1/2)$	0	1
	η	$(\mathbf{2}, 1/2)$	$1/2$	ω
	ξ	$(\mathbf{1}, 0)$	$7/2$	ω

TABLE I. Charge assignment for all the fields. $\mathcal{Z}_6$ is a residual symmetry coming from $U(1)_{B-L}$ breaking, see [13] for a detailed discussion. ω is the sixth root of unity, i.e. $\omega^6 = 1$.

$i = 1, 2, 3$, the $SU(2)_L$ doublet scalar η and the $SU(2)_L$ singlet scalar ξ, with $B-L$ charges as shown in Tab. I. As mentioned before, the lightest dark sector particle will be stable and will be the DM candidate in our model.

The relevant Yukawa Lagrangian for neutrino masses is given by

$$-\mathcal{L}_Y \supset Y_{il} L_i \tilde{\eta} N_{R_l} + Y'_{li} \bar{N}_{L_l} \nu_{R_i} \xi + M_{lm} \bar{N}_{R_l} N_{L_m} + h.c. \tag{1}$$

Which generates a one-loop neutrino mass in the Dirac version of the scotogenic model. See Fig. 1. Note that owing to different $B-L$ charges for L_i and ν_{R_i}, the tree level direct coupling for neutrinos is forbidden and the neutrino masses can only be generated at one-loop level after $U(1)_{B-L} \to Z_6$ breaking.

In the scalar sector, the Higgs field H will be SM-like. Owing to their Z_6 symmetry charges, the scalar fields η and ξ will be complex fields, thus the real and imaginary parts will be degenerate in mass. However, the neutral component of η can mix with the singlet ξ. Note that mixing between the components of H and η, ξ are forbidden by the Z_6 symmetry. The general form of the scalar potential is given by

$$\begin{aligned} V = &-\mu_H^2 H^\dagger H + \mu_\eta^2 \eta^\dagger \eta + \mu_\xi^2 \xi^* \xi + \frac{1}{2}\lambda_1 (H^\dagger H)^2 + \frac{1}{2}\lambda_2 (\eta^\dagger \eta)^2 + \frac{1}{2}\lambda_3 (\xi^* \xi)^2 + \lambda_4 (H^\dagger H)(\eta^\dagger \eta) \\ &+ \lambda_6 (\eta^\dagger \eta)(\xi^* \xi) + \lambda_7 (H^\dagger \eta)(\eta^\dagger H) + \lambda_8 (H^\dagger H)(\xi^* \xi) + (\kappa\, \eta^\dagger H \xi + h.c.) \end{aligned} \tag{2}$$

Here we have avoided the use of λ_5 in order to prevent confusion with the λ_5 parameter of the Majorana scotogenic case. The $U(1)_{B-L} \to Z_6$ breaking happens because of the presence of the soft term $\kappa\, \eta^\dagger H \xi + h.c.$ Thus, in the Dirac scotogenic model, κ plays the role that λ_5 plays

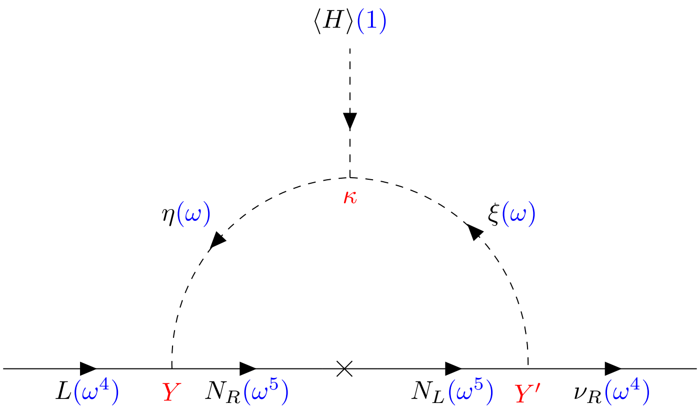

FIG. 1. Leading neutrino mass generation diagram. Note that the tree level mass term between left and right handed neutrinos is forbidden by the chiral $U(1)_{B-L}$ symmetry, only appearing at the one-loop level after the $U(1)_{B-L} \to Z_6$ symmetry breaking. The unbroken residual Z_6 symmetry simultaneously ensures that neutrinos remain Dirac in nature and the lightest dark sector particle is completely stable.

in the Majorana version. The requirement to have a stable minimum for the potential implies the following conditions

$$\lambda_1, \lambda_2, \lambda_3 \geq 0; \qquad \lambda_4 > -\sqrt{\lambda_1\lambda_2}, \quad \lambda_6 > -\sqrt{\lambda_2\lambda_3}, \quad \lambda_8 > -\sqrt{\lambda_1\lambda_3},$$
$$\sqrt{\frac{\lambda_3}{2}}\lambda_4 + \sqrt{\frac{\lambda_1}{2}}\lambda_6 + \sqrt{\frac{\lambda_2}{2}}\lambda_8 + \sqrt{\frac{\lambda_1\lambda_2\lambda_3}{8}} > -\sqrt{(\lambda_4 + \sqrt{\lambda_1\lambda_2})(\lambda_8 + \sqrt{\lambda_1\lambda_3})(\lambda_6 + \sqrt{\lambda_2\lambda_3})} \quad (3)$$

Fleshing out the $SU(2)_L$ components of the scalars, we can write the doublets as

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}, \qquad \eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix} \quad (4)$$
$$H^0 = \frac{1}{\sqrt{2}}(v + h + iA), \quad \eta^0 = \frac{1}{\sqrt{2}}(\eta_R + i\eta_I), \quad \xi = \frac{1}{\sqrt{2}}(\xi_R + i\xi_I) \ . \quad (5)$$

However, as noted before, note that due to the residual symmetry Z_6 the neutral imaginary and real components of each dark sector scalar will be degenerate. We can now compute the masses of the physical scalar states after symmetry breaking

$$m_h^2 = \lambda_1 v^2, \quad (6)$$

$$m_{\eta^\pm}^2 = \mu_\eta^2 + \frac{\lambda_4}{2}v^2, \quad (7)$$

The real part of ξ will mix with the real part of η^0 and similarly the imaginary part of ξ will mix with the imaginary part of η^0 with the same mixing matrix.

$$m^2_{(\xi_R,\eta_R)} = m^2_{(\xi_I,\eta_I)} = \begin{pmatrix} \mu_\xi^2 + \lambda_8 \frac{v^2}{2} & \kappa \frac{v}{\sqrt{2}} \\ \kappa \frac{v}{\sqrt{2}} & \mu_\eta^2 + (\lambda_4 + \lambda_7) \frac{v^2}{2} \end{pmatrix} \tag{8}$$

We can compute the mixing angle

$$\tan 2\theta = \frac{\sqrt{2}\kappa\, v}{(\mu_\xi^2 - \mu_\eta^2) + (\lambda_8 - \lambda_4 - \lambda_7)\frac{v^2}{2}}, \tag{9}$$

and the mass eigenstates for the real/imaginary part of neutral scalars η^0 and ξ are given by

$$m_{1R}^2 = m_{1I}^2 = \left(\mu_\xi^2 + \lambda_8 \frac{v^2}{2}\right)\cos^2\theta + \left(\mu_\eta^2 + (\lambda_4+\lambda_7)\frac{v^2}{2}\right)\sin^2\theta - 2\kappa v \sin\theta\cos\theta = m_\xi^2 \tag{10}$$

$$m_{2R}^2 = m_{2I}^2 = \left(\mu_\xi^2 + \lambda_8 \frac{v^2}{2}\right)\sin^2\theta + \left(\mu_\eta^2 + (\lambda_4+\lambda_7)\frac{v^2}{2}\right)\cos^2\theta + 2\kappa v \sin\theta\cos\theta = m_{\eta^0}^2 \tag{11}$$

Finally, the tree level perturbativity[2] of the dimensionless couplings additionally implies

$$Tr(Y_\eta^\dagger Y_\eta) < 4\pi,\ \ Tr(Y_\xi^\dagger Y_\xi) < 4\pi,\ \ |\lambda_i| \leq \sqrt{4}\pi \tag{12}$$

In summary, apart from a vev carrying $SU(2)_L$ doublet scalar H, we have two additional scalars η and ξ both of which belong to the dark sector. The lighter neutral mass eigenstate can be a good candidate for DM if it is the lightest dark sector particle with its stability ensured by the unbroken residual Z_6 symmetry.

III. NEUTRINO MASSES

The neutrino mass generation mechanism in this model is independent from the modifications to the electroweak precision parameters. Therefore, the results of previous works apply here too. However, we will flesh out the neutrino properties in the model because our setup is more restricted, since the lightest neutrino is massless. The reason for its masslessness comes from the chiral $B-L$ structure shown in [13]. We can calculate neutrino masses from the diagram Fig. 1 as

$$(M_\nu)_{ij} = \frac{1}{16\pi^2}\sum_{k=1}^{3} Y_{ik} Y'_{kj} \frac{\kappa v}{m_\xi^2 - m_\eta^2} M_k \sum_{l=1}^{2} (-1)^l B_0(0, m_l^2, M_k^2). \tag{13}$$

[2] See [116] for a more detailed analysis on loop-corrected perturbativity conditions.

Where m_l, M_k are the masses of the light and heavy neutrinos, respectively, Y, Y' and κ are the couplings described in Eq. 1 and Fig. 1, m_ξ and m_{η^0} are the neutral scalar mass eigenvalues, v is the SM vev and B_0 is the Passarino-Veltman function [117]. Note that these setup leads to only two massive neutrinos since Y' is a rank-2 matrix.

Since the Yukawa matrices are free parameters it is clear that it is possible to fit the mixing parameters of neutrino oscillations given by the global fit [118]. In the analysis that follows we will impose neutrino masses and mixing inside the 3σ range of the global fit. As a benchmark scenario, we have assumed inverted ordering of the light neutrino masses. This is a natural choice since the lightest neutrino mass is zero. However, assuming normal ordering will not change the conclusions.

In the scalar DM case, we can take the fermionic mass $M_k \gg m_\xi, m_{\eta^0}$. In this case, the neutrino mass scale is approximately given by

$$m_\nu \sim \frac{1}{16\pi^2}\frac{\kappa v}{M}YY' \tag{14}$$

For example, for Yukawas of order 1, a fermionic mass of 500 GeV and $m_\nu < 0.1$ eV this leads to a value of $\kappa < 30$ GeV. Note that κ is the dimensionful equivalent of λ_5 in the traditional Majorana scotogenic model. In the limit $\kappa \to 0$, the symmetry of the Lagrangian gets enhanced from a Z_6 to a $U(1)_{B-L}$ symmetry [13] and its smallness can be associated with an inverse seesaw mechanism [33]. Thus, in the same spirit as in [114], κ is a symmetry protected parameter which can therefore be small. For these reasons, we will consider the limit $\kappa \ll \Lambda_{EW}$ throughout this work. One could deviate from this limit by taking heavier neutral fermions or smaller Yukawas. The choice of working in the small κ regime has an additional consequence in the scalar sector. As can be seen from Eq. 9, in this limit there won't be a sizeable mixing between the scalars, with very important consequences in the DM sector and mass of W boson m_W as we will now discuss.

IV. W MASS AND THE S, T, U PARAMETERS

The presence of a new $SU(2)_L$ doublet dark scalar η in our model has important consequences for the W boson mass and the EW precision observables in general. The doublet dark scalar leads to radiative corrections to W boson mass as shown in Fig. IV top left diagram and hence W boson mass can be increased from SM prediction to that obtained by the CDF-II collaboration. However, as discussed in the introduction, an extension of the electroweak sector of the SM will have an impact on many observables which are constrained by multiple experiments. There is a danger that some of the observables can now deviate from the SM prediction by an unacceptably

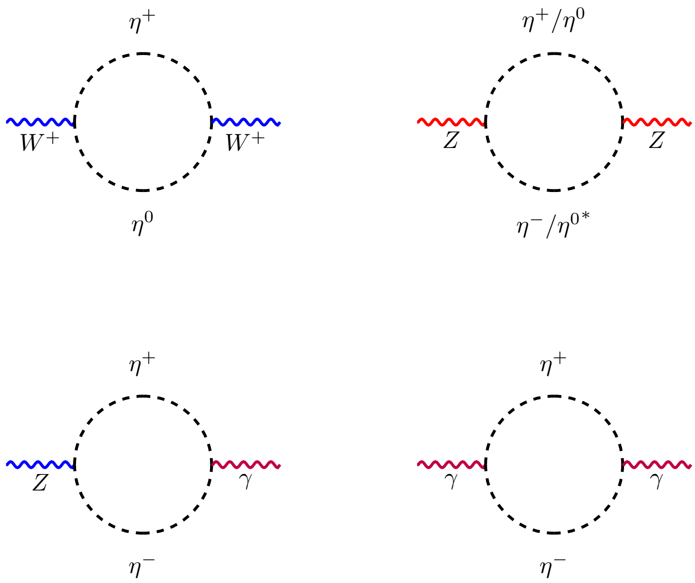

FIG. 2. One loop polarization diagrams that contribute to the oblique S, T and U parameters.

large amount. As shown by [50], it is convenient to parameterize these new physics effects in terms of the oblique S, T and U parameters. A global fit value of the S, T and U parameters can then be obtained by using the EW precision observables as input parameters [52]. Since the CDF-II results, several groups have now updated the S, T and U parameters EW fit [54–61]. In this section we show that our model while simple enough, has enough richness to change W boson mass to the CDF-II measured value while keeping the oblique parameters within their global 3 σ range.

In the context of our model only the new scalar doublet η contributes directly to the electroweak precision observables via the one loop polarization diagrams shown in Fig IV. The neutral scalar singlet ξ will only have a contribution via the mixing with η^0, which we take to be small as argued in Sec. III. Following [119] we can calculate the BSM contributions to S, T and U of the model as

$$
\begin{aligned}
S &= \frac{1}{12\pi} \log \frac{m_{\eta^0}^2}{m_{\eta^+}^2} \\
T &= \frac{G_F}{4\sqrt{2}\pi^2 \alpha_{em}} \left(\frac{m_{\eta^0}^2 + m_{\eta^+}^2}{2} - \frac{m_{\eta^0}^2 m_{\eta^+}^2}{m_{\eta^+}^2 - m_{\eta^0}^2} \log \frac{m_{\eta^+}^2}{m_{\eta^0}^2} \right)
\end{aligned}
\tag{15}
$$

$$U = \frac{1}{12\pi}\left(\frac{(m_{\eta^0}^2+m_{\eta^+}^2)\left(m_{\eta^0}^4-4m_{\eta^0}^2m_{\eta^+}^2+m_{\eta^+}^4\right)\log\left(\frac{m_{\eta^+}^2}{m_{\eta^0}^2}\right)}{(m_{\eta^+}^2-m_{\eta^0}^2)^3} - \frac{5m_{\eta^0}^4-22m_{\eta^0}^2m_{\eta^+}^2+5m_{\eta^+}^4}{3(m_{\eta^+}^2-m_{\eta^0}^2)^2}\right)$$

In terms of the oblique S, T and U parameters, the corrections to the W boson mass are given by [50].

$$m_W^2 = m_W^{2\,(\mathrm{SM})} + \frac{\alpha_{em}\cos^2\theta_w}{\cos^2\theta_w-\sin^2\theta_w}m_Z^2\left[-\frac{1}{2}S+\cos^2\theta_w T+\frac{(\cos^2\theta_w-\sin^2\theta_w)}{4\sin^2\theta_w}U\right] \tag{16}$$

where θ_w is the weak angle, α_{em} is the fine-structure constant and $m_W^{(\mathrm{SM})}$ is the Standard Model prediction for m_W.

For our simple model, one can analytically simplify (16) by noting that S and U only depend on the ratio $x = \frac{m_{\eta^0}^2}{m_{\eta^+}^2}$, while T is an a dimensional function of x which we call T_{adim} times a scaling prefactor $\frac{G_F}{4\sqrt{2}\pi^2\alpha_{em}}m_{\eta^0}^2$.

$$S \equiv S(x), \qquad T \equiv \frac{G_F}{4\sqrt{2}\pi^2\alpha_{em}}m_{\eta^0}^2\,T_{\mathrm{adim}}(x), \qquad U \equiv U(x) \tag{17}$$

We can extract some immediate conclusions. Since S and U only depend on the mass ratio x, they are perfectly correlated with each other, see the first panel of Fig. 3. First thing we note is that in our model the oblique parameters T and U cannot be negative as shown in Fig. 3. Furthermore, if η^0 is the DM candidate this means that $m_{\eta^0}^2 < m_{\eta^+}^2$ implying that $x < 1$ and therefore $S \leq 0$, $T \geq 0$ and $U \geq 0$. Given the electroweak precision fits [54–61], this is already a severe constraint as shown in lower left panel of Fig. 3. The requirement $m_{\eta^0}^2 < m_{\eta^+}^2$ can be accommodated in a $2-3\sigma$ region of the updated global S, T, U fits, depending on what fit is used for the comparison. On the other hand, if the requirement of η^0 as DM is dropped then S can be either positive or negative, but still $T, U \geq 0$. This substantially opens up the parameter space as can be seen from the figure. Various other constraints like the LEP constraints on Z invisible decay $Z \to \eta^0\eta^{0*}$ and and direct search limits from $e^+e^- \to Z \to \eta^+\eta^-$ further rule out more parts of the parameter space, see Fig. 3. Nonetheless for both cases of $SU(2)_L$ doublet scalar η^0 DM (left panel) as well as for the $SU(2)_L$ singlet scalar ξ DM (right panel) parts of parameter space survive as shown by the green bands in Fig. 3. Thus, as far as precision EW constraints are concerned, both η^0 and ξ as DM are allowed.

The correlation between m_{η^0} and $\Delta m_\eta = m_{\eta^+} - m_{\eta^0}$ is shown in Fig. 4 for both cases of η^0 (left) and ξ (right) being DM. The green region in both panels corresponds to the parameter space where W boson mass is within 1 σ of the CDF-II range. As can be seen from Fir. 4 part of

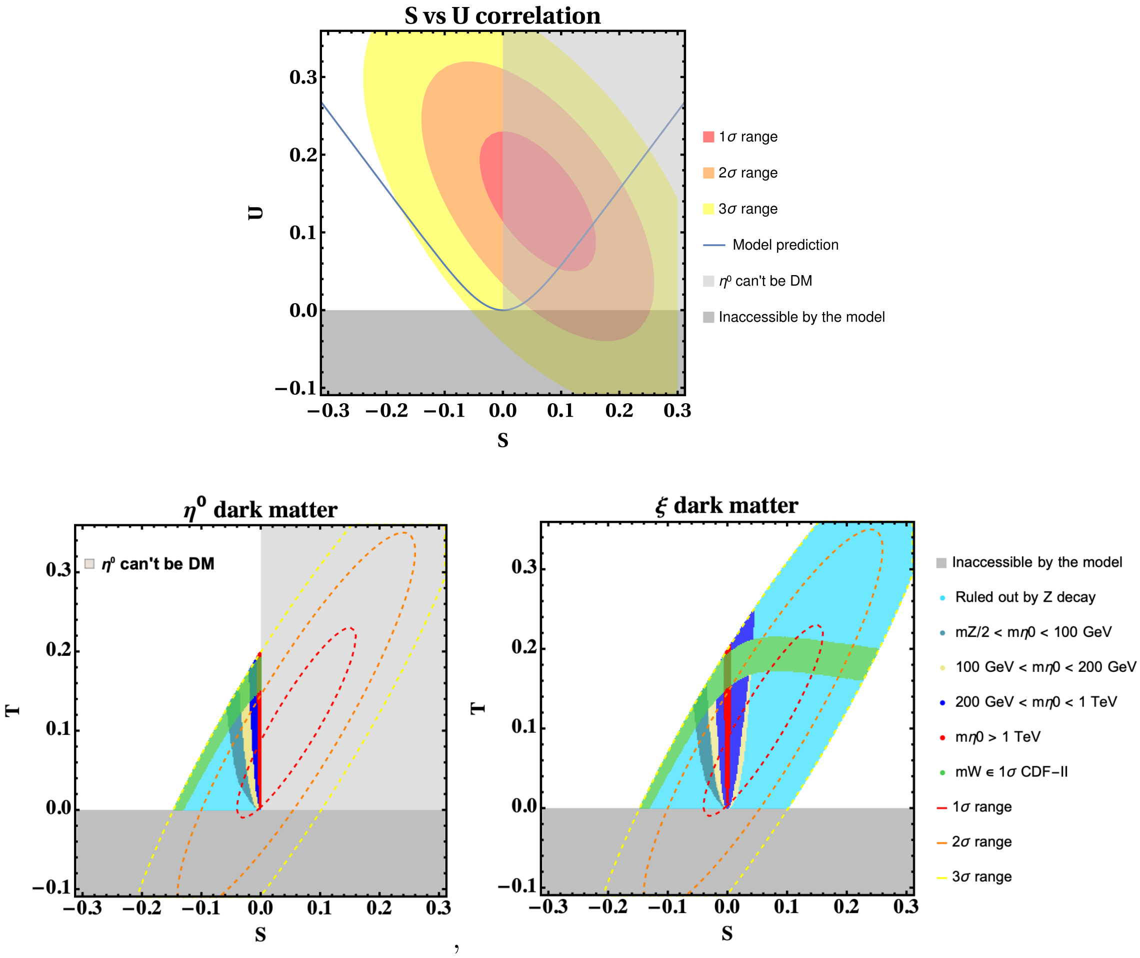

FIG. 3. **Up**: The line represents the correlation between S and U as predicted by the model. **Down Left:** S vs T correlation with allowed parameter space and constraints for the case of $SU(2)_L$ doublet scalar η^0 as DM. In this case the parameter space is tightly constrained. **Down Right:** S vs T correlation when the $SU(2)_L$ singlet scalar is DM. In both cases the green band fits the CDF-II m_W measurement at 1σ, while the color code represents the mass of η^0. Note that our model cannot accommodate $U < 0$ or $T < 0$ while $S > 0$ implies $m_{\eta^0} > m_{\eta^+}$ (see grey regions). Furthermore, the $m_{\eta^0} < m_Z/2$ and $m_{\eta^+} \lesssim 90$ GeV regions are ruled out by LEP [120], shown in cyan color. Here we are using the EW fits of [57].

the green region gets excluded from constraints like perturbativity, spontaneous electric charge breaking vacuum $m_{\eta^+} < 0$, and LEP constraints from $Z \to \eta^0\eta^{0*}$ and $e^+e^- \to Z \to \eta^+\eta^-$. Still for both cases a significant part of the allowed parameter space survives all the constraints.

In our numerical scan of the dark sector in Sec. V we have imposed the S, T and U parameters to be inside their 3σ 2 dimensional allowed regions. In addition, we also impose the W boson

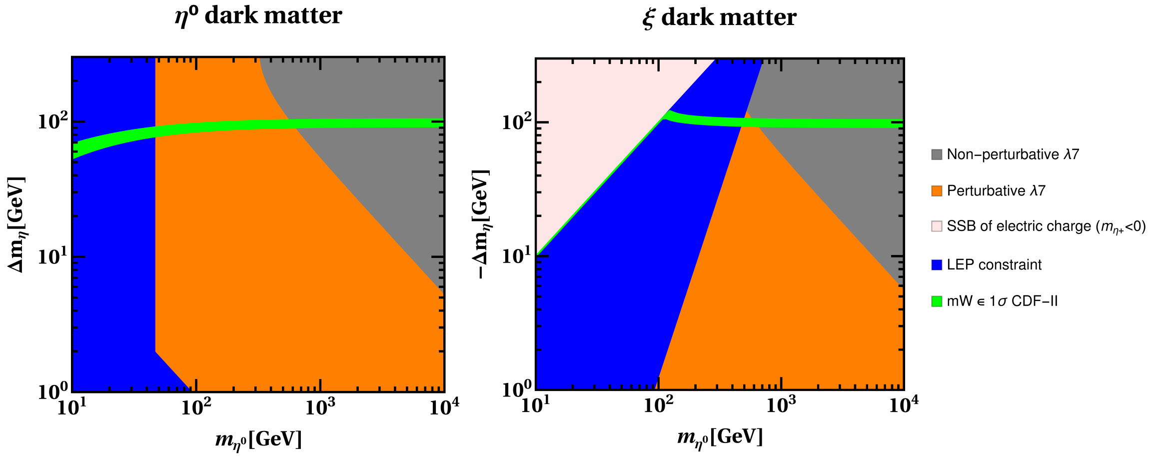

FIG. 4. Parameter space in the m_{η^0} vs $\pm\Delta m_\eta = \pm(m_{\eta^+} - m_{\eta^0})$ plane, in both limiting scalar DM cases. **Left:** doublet DM, which implies $m_{\eta^0} < m_{\eta^+}$. **Right:** Singlet DM case and $\Delta m_\eta < 0$. LEP data on Z decays lead to the constraints $m_{\eta^0} > m_Z/2$ and $m_{\eta^+} \gtrsim 90$ GeV [120] through the processes $Z \to \eta^0\eta^{0*}$ and $e^+e^- \to Z \to \eta^+\eta^-$. This constraint is shown in blue in both panels. Additionally, the orange region features a perturbative (i.e. $|\lambda_7| < \sqrt{4\pi}$) while the grey region features a non-perturbative λ_7. Note that λ_7 is the main parameter responsible for the scalar mass degeneracy Δm_η. Finally, the green regions satisfy the CDF-II W mass measurement in the 1σ range as well as the S, T, U 3σ 2-dimensional regions shown in Fig. 3.

mass to lie inside the recently reported CDF-II 1σ value 80.4241 GeV $\leq m_W \leq$ 80.4429 GeV [51].

V. DARK MATTER

We now focus on the analysis of the dark sector. In the early universe all the particles of the dark sector are in thermal equilibrium with the SM fields due to the production-annihilation diagrams shown in the Appendix A, Figs. 7 and 9. As the universe expands, the temperature drops. For unstable particles there is a maximum temperature below which the thermal bath doesn't have enough energy to produce them, while their annihilation and decays are still allowed and therefore disappear. However, recall that the lightest particle of the dark sector will be completely stable due to the residual Z_6 symmetry. This means that once such stable particle decouples from the thermal bath its relic density will be 'freezed out'. This relic density can then be computed and compared with Planck observations [3]. See [121] for a nice review on different DM production mechanisms. This type of DM could also be detected by nuclear recoil experiments such as XENON1T [122], see the diagrams shown in Fig. 8 and 10.

We already know that the Dirac scotogenic model and its variants can fit all neutrino mixing parameters as well as the observed relic density, as shown in [35, 42] for all three limiting cases: doublet scalar DM, singlet scalar DM or fermionic DM, as well as in the non-negligible mixing limit. We will now analyze how this situation changes when in addition to these constraints we also impose the electroweak precision fits and the m_W measurement as shown in Sec. IV. In particular, the case of a pure doublet DM is ruled out, as we will see in Sec. V A, while the pure singlet case is allowed by all constraints[3]. We perform a detailed numerical scan for the model parameters with various experimental and theoretical constraints. We have implemented the model in SARAH-4.14.5 and SPheno-4.0.5 [123, 124] to calculate all the vertices, mass matrices and tadpole equations, whereas the thermal component to the DM relic abundance as well as the DM nucleon scattering cross sections are determined by micrOMEGAS-5.2.13 [125].

A. Mainly doublet scalar dark matter

As explained before, if the DM particle is mainly formed by the scalar doublet neutral component η^0 then the ratio $x = m_{\eta^0}/m_{\eta^+} < 0$. In turn, this implies that the model prediction for the S, T and U oblique parameters satisfy $S \leq 0$, $T, U \geq 0$. Moreover, the allowed parameter space for the masses is also restricted. In addition to the restrictions above mentioned, we have also imposed the following additional conditions when generating the allowed points:

- Neutrino oscillation parameters as in Sec. III.
- Electroweak precision observables and m_W as in Sec. IV.
- Bounded from below scalar potential, ensured by the vacuum stability constraints of Eq. 3.
- Perturbativity of Yukawas and quartic couplings as in Eq. 12.
- If η^0 is the DM particle its mass must be smaller than the charged counterpart η^+. As can be seen from Eqs. 7 and 8, this implies $\lambda_7 < 0$ in the small mixing limit.
- The parameters are taken in the ranges shown in Tab. II.
- Finally, we impose the LEP constraint on light neutral component of a doublet. As shown by [120, 126], this limit is actually simply $m_{\eta R} + m_{\eta I} > m_Z$ which in our case translates

[3] Not that the two dark sector scalars mix with each other as mentioned in Sec.II. But since small neutrino masses naturally imply $\kappa < 30$ GeV, as argued before, the mixing between doublet and singlet dark scalars always remains negligibly small. In our numerical scan we have still taken this small mixing in account.

Parameter	Range	Parameter	Range
λ_2	$[10^{-8}, \sqrt{4\pi}]$	λ_3	$[10^{-8}, \sqrt{4\pi}]$
λ_4	$[10^{-8}, \sqrt{4\pi}]$	λ_8	$[10^{-8}, \sqrt{4\pi}]$
λ_6	$[10^{-8}, \sqrt{4\pi}]$	$\|\lambda_7\|$	$[10^{-8}, \sqrt{4\pi}]$
κ	$[10^{-8}, 30]$ GeV	μ_η^2	$[10^2, 10^8]$ GeV^2
μ_ξ^2	$[10^2, 10^8]$ GeV^2	M_{N_i}	$[10, 10^5]$ GeV

TABLE II. Value range for the numerical parameter scan for S, T and U parameters, relic density and DM direct detection.

to $m_{\eta^0} > m_Z/2 \approx 45.6$ GeV. In the case of the charged scalar component this limit is $m_{\eta^+} \gtrsim 90$ GeV−

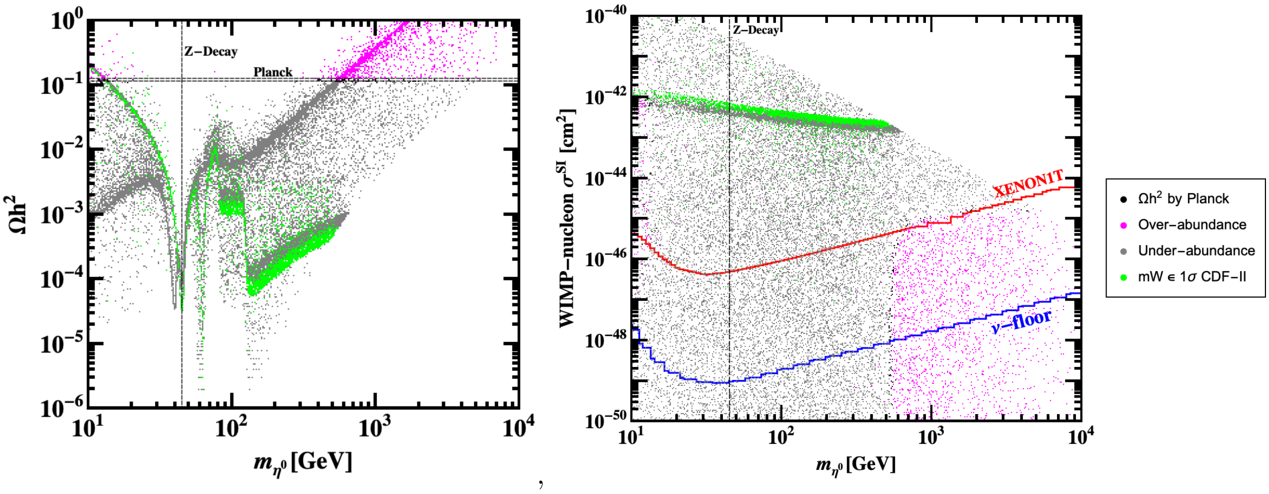

FIG. 5. The pure doublet DM is ruled out after imposing CDF-II m_W measurement. In both panels the green points satisfy CDF-II W mass in the 1σ range. Magenta/grey points represent over/under abundant relic density [3], respectively, while points with correct relic density are instead black. The vertical line labeled as 'Z decay' is the lower limit to m_{η^0} given by LEP. **Left:** Relic density plot for η^0 dominated DM. **Right:** Spin-independent WIMP-nucleon cross section for the η^0 dominated DM candidate case.

The results of the analysis are shown in Fig. 5. It is clear that it is not possible to fit relic density, the m_W CDF-II measurement and the constraints given by Z decays and direct detection at the same time. In particular, it can be seen in the left panel of that figure that a mass of ~ 15 GeV can satisfy the relic density and m_W constraints as well as direct detection, but such a light neutral doublet is ruled out by LEP. On the other hand, a higher mass of ~ 300 GeV can satisfy the correct relic density but not m_W and direct detection at the same time. Note that the results for the doublet DM case are equivalent to those in the Majorana scotogenic case [113]. However, in the scotogenic Dirac case there is an alternative for having scalar DM, namely the singlet DM which we will discuss in Sec. V B.

B. Mainly singlet scalar dark matter

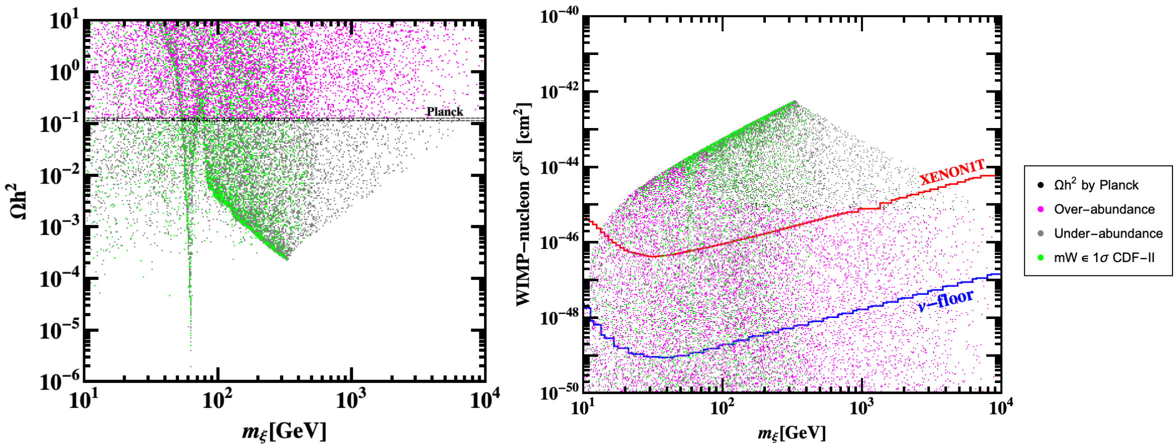

FIG. 6. Predictions for the mainly singlet DM case. In both panels the green points satisfy CDF-II W mass in the 1σ range. Magenta/grey points represent over/under abundance relic density [3], respectively, while points with correct relic density are instead black. **Left:** Relic density vs singlet DM mass. **Right:** Spin-independent WIMP-nucleon cross section for the ξ dominated DM candidate vs DM mass. Since the singlet does not participate directly in the W mass it is possible to fit all the experimental constraints.

We now move on to the case in which the DM is mainly formed by the $SU(2)_L$ singlet scalar. If the mainly singlet scalar is lighter than the neutral and charged doublet components it will be the DM particle of the model. Note that it is now possible to have $S > 0$, i.e. $m_{\eta^0} < m_{\eta^+}$, since the charged scalar will now be kinematically allowed to decay into ξ + leptons. This opens the allowed parameter space that can fit m_W and the oblique parameters as shown in Sec. IV.

Moreover, the expressions for S, T and U do not depend on the mass of the singlet[4]. This decoupling between the dark sector and m_W is the main reason why it is now possible to fit the relic density and the EW observables simultaneously.

[4] The singlet can participate in the loops only via mixing. Therefore, such contributions will be suppressed by $\sin^2\theta$, which we are taking small throughout this work. See Sec. III for a more complete discussion.

The results of the analysis are shown in Fig. 6, showing that the singlet DM is consistent with all the experimental constraints. As a final remark, let us mention that the fermionic DM case in our model is not very different from the Majorana scotogenic model studied in [113]. Moreover, being a SM gauge singlet Majorana fermion, there is no prospect of its direct detection in currently running or even near future experiments. Thus, the fermionic case at this point is not very interesting from phenomenological point of view. Therefore here we have refrained from discussing it in details.

VI. CONCLUSIONS

We have considered the Dirac scotogenic model presented in [13] and analyzed its phenomenology in detail. We have shown that the Dirac scotogenic model can reproduce the neutrino masses and mixing, the DM relic abundance and explain the CDF-II W boson mass anomaly in a single framework. Moreover, we find that the case of a mainly scalar doublet DM is ruled out by the combination of the requirements that W boson mass remains within 1σ of the CDF-II measurement and the constraints coming from DM relic density, direct detection and invisible Z boson decays. Unlike the Majorana scotogenic case, here another scalar DM alternative exists: namely one where the DM candidate is mainly the $SU(2)_L$ singlet scalar. We showed that if the singlet scalar is the DM candidate then all the above constraints are simultaneously satisfied along with W boson mass within 1σ range of the CDF-II measurement.

VII. ACKNOWLEDGEMENTS

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Appendix A: Anihilation, production and detection of DM

In Figs. 7 and 9 we list the possible diagrams for production/anihilation of DM, relevant in the early universe, for the cases in which the DM is mainly a doublet or a singlet, respectively. In Figs. 8 and 10 we show the direct detection prospects of the scalar DM by exchange of a Higgs or Z bosons, in the doublet case, and just a Higgs portal in the singlet case.

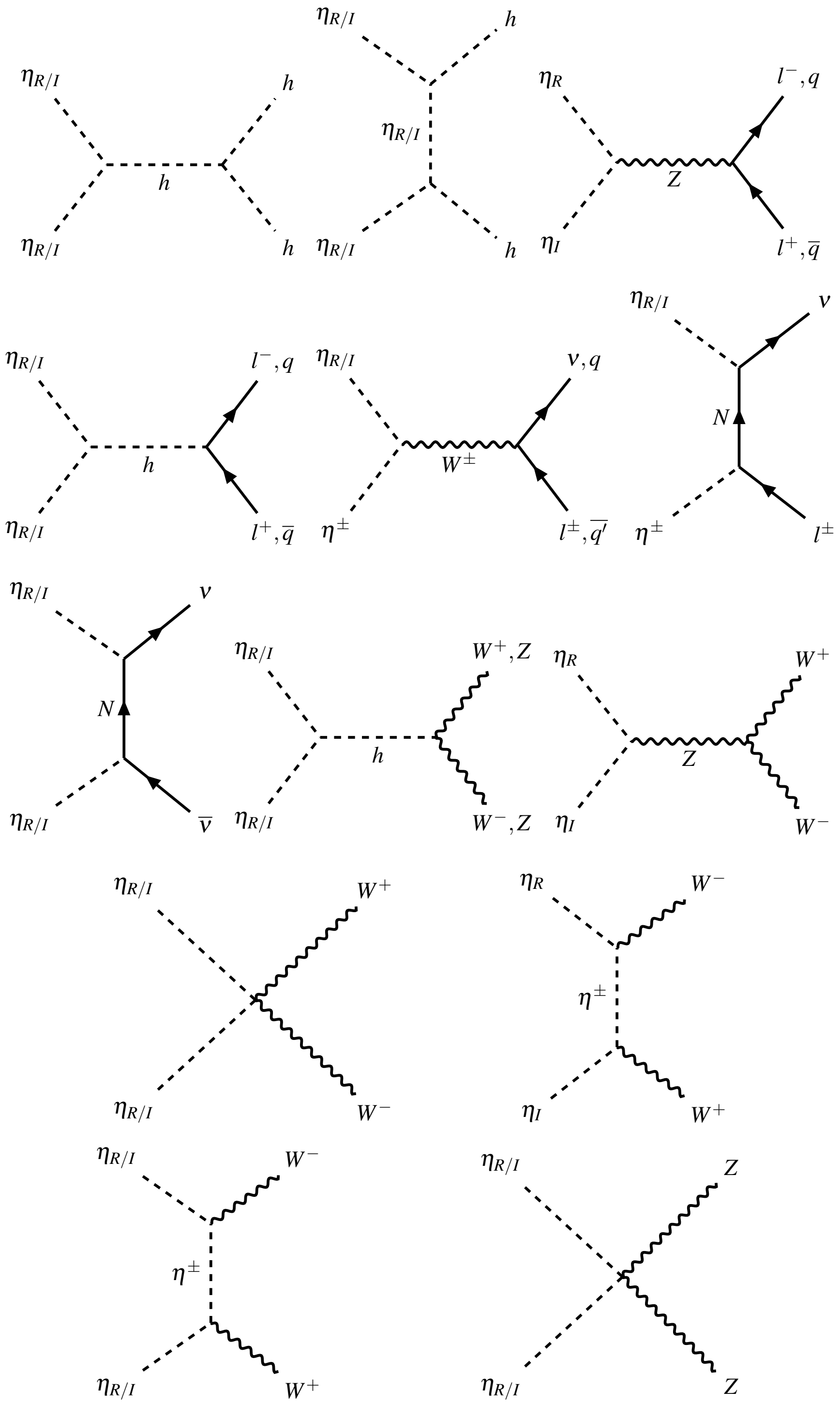

FIG. 7. Relevant diagrams for computing the relic density of η^0 dominated DM.

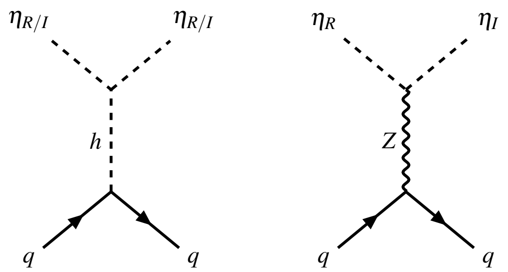

FIG. 8. Relevant diagrams for the direct detection of the η^0 dominated DM.

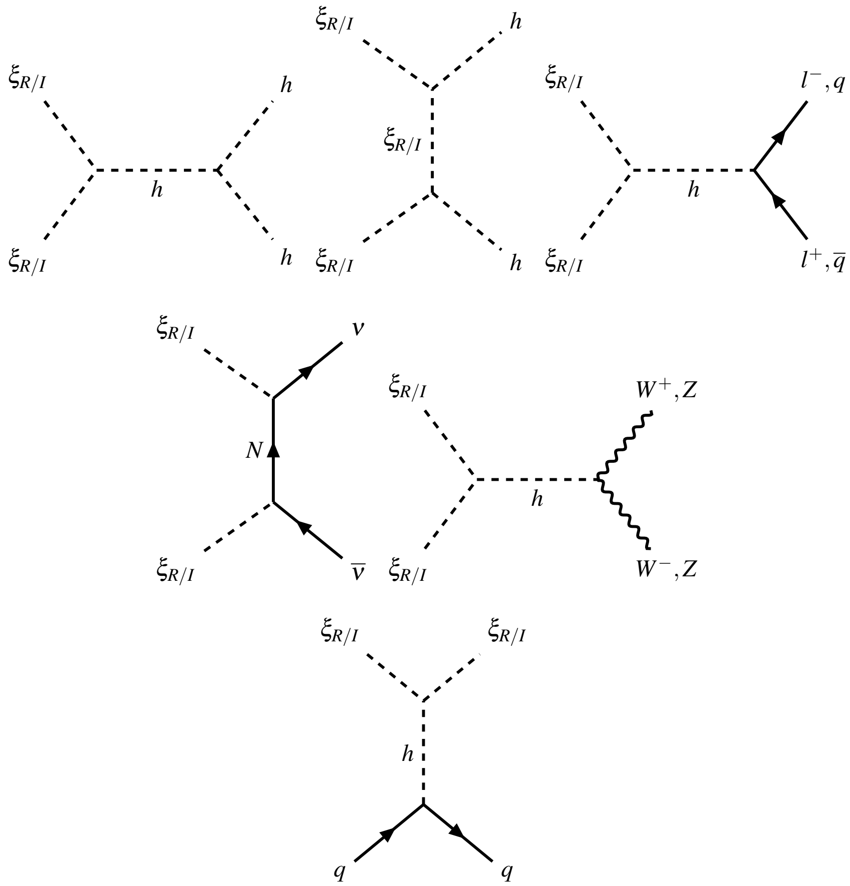

FIG. 9. Relevant diagrams for computing the relic density of ξ dominated DM.

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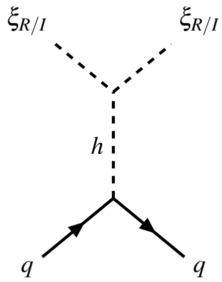

FIG. 10. Relevant diagrams for the direct detection of the ξ dominated DM.

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