Dark Matter and Gauge Coupling Unification in A Supersymmetry Model with Vector-like Matter (Postprint)

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Full Text

Preamble

Dark Matter and Gauge Coupling Unification in A Supersymmetry Model with Vector-like Matter

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Abstract

WIMP dark matter and gauge coupling unification are considered in an R-parity violating MSSM with vector-like matter. Dark matter is contained in an additional vector-like $SU(2)_L$ doublet which possesses a new U(1) gauge symmetry.

The Higgs fields are extended to be in a $\bar{5}$ representation of SU(5). The stability of dark matter is a result of gauge symmetries, and the mass of the dark matter particle is between (1.1-1.5) TeV. Dark matter has a very small cross section with nuclei, thus the model is consistent with current dark matter direct detection experiments such as Xenon100. The model also predicts new charged and colored particles to be observed at LHC.

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Introduction

Dark matter is one of the most important problems in elementary physics [1]. It plays a very important role in understanding some astrophysical observations. If dark matter particles are thermally produced in the early Universe, an attractive scenario appears, namely that the dark matter particle has a mass of hundreds of GeV with typically weak interaction strength [2]. The weakly interacting massive particle (WIMP) scenario of dark matter is interesting for particle physics. In high energy physics experiments searching for the electroweak symmetry breaking (EWSB) mechanism, WIMPs should be found in the near future.

The particle physics beyond the Standard Model (SM) follows the following mainstream logic. SM gauge interactions unify at a high scale ($\sim 10^{16}$ GeV) [3]. Supersymmetry (SUSY) [4] is then required to stabilize the Higgs mass. The minimal SUSY extension of the SM (MSSM), which necessarily involves two Higgs doublets, makes the idea of grand unification theory (GUT) more meaningful due to LEP data [5]. WIMP dark matter is precisely the lightest neutralino [2] when R-parity conservation is further assumed.

We will work in the SUSY paradigm without assuming R-parity conservation. R-parity conservation is usually adopted to avoid rapid proton decays; however, it lacks motivation from first principles. Instead, we only assume baryon number conservation, which is also phenomenologically viable. R-parity violation makes the situation more complicated: the lightest neutralino is no longer stable. To have dark matter, new particles are then needed. To maintain WIMP dark matter, the simplest realization is to introduce a vector-like $SU(2)_L$ doublet, similar to the two Higgs doublets in the MSSM, with a weak-scale mass. We take one fermionic neutral component of the new doublet superfields as the dark matter particle. Its stability requires a new symmetry, which we take to be a gauge symmetry. The necessity of a new gauge symmetry, instead of a discrete symmetry, arises because the elastic scattering of the dark matter particle via Z boson exchange must be suppressed. In our case, the dark matter particle is not truly a Dirac fermion because spontaneous breaking of the new gauge symmetry splits the neutral particle spectrum. As a result, the interaction between dark matter and the Z boson is almost inelastic.

Now we consider how to make the new dark matter particle content compatible with gauge coupling unification. Because one vector-like doublet is introduced in addition to the particles of the MSSM, the gauge coupling constants would no longer unify in this case. The GUT relation of gauge coupling constants could be restored if some colored particles are further added so that all new particles form complete representations of the GUT group [6, 7]. Alternatively, we can keep the dark matter sector as simple as possible—namely, just SUSY two-Higgs-doublet-like—but attach the new colored particles to the two Higgs doublets. In an effort to extend the MSSM, we previously proposed that Higgses are understood as sleptons of an extra vector-like generation [8]. In that model, GUT was lost, and there were no dark matter candidates.

It is interesting to note that when we consider the dark matter scenario discussed above, the GUT relation of the gauge coupling constants can be restored. This makes the whole low-energy SUSY model more meaningful. However, careful consideration of the running gauge coupling constants tells us that things are not so easy and straightforward. The particle content of the extra vector-like generation [8] needs to be reduced. To avoid Landau poles of the coupling constants, the number of new particles at the TeV scale cannot be too large. Instead of a TeV-scale vector-like generation with $\bar{5}$ and 10 representations, we are only allowed to have the $\bar{5}$ in which the two Higgs doublets are contained. Therefore, as far as the Higgs $\bar{5}$ and a 10 content at the TeV scale is concerned, we return to ordinary GUT. Here the new feature is that the $\bar{5}$ representation will mix with ordinary three-generation fermions, and the triplet Higgs mass is around the TeV scale. We impose baryon number conservation by hand for now.

In the next section, we present the model which includes the dark matter sector. In Section III, dark matter properties and collider phenomenology are analyzed. Discussions and summary are given in the last two sections.

II. Model

Let us first look at the SM-relevant sector. Within the framework of SUSY and $\mathrm{SU}(3)_c\times \mathrm{SU}(2)_L\times \mathrm{U}(1)_Y$ gauge symmetry, the particle content is extended such that the two Higgs doublets are contained in an SU(5) $\bar{5}$ representation. These vector-like particles have masses of (100-1000) GeV. Because of R-parity violation, there is no dark matter particle in this sector alone.

To include the dark matter sector, we note that all particles already introduced are in complete representations of SU(5) GUT. For GUT purposes, the WIMP sector should be exactly composed of a pair of $\mathrm{SU}(2)_L$ doublets with opposite $\mathrm{U}(1)_Y$ charges. This motivates us to take them to be SUSY two-Higgs-doublet-like. To avoid extra degrees of freedom that may violate the GUT relation, the new interaction among the WIMPs should be another Abelian gauge interaction $\mathrm{U}(1)_n$. The $\mathrm{U}(1)_n$ charges can be arranged so that after $\mathrm{U}(1)_n$ breaking, an unbroken Z_2 symmetry remains. This Z_2 symmetry makes the dark matter stable.

The model is SUSY $\mathrm{SU}(2)_L\times \mathrm{SU}(3)_c\times \mathrm{U}(1)_Y\times \mathrm{U}(1)_n$ gauge symmetric with baryon number conservation. The particle content is given below with their quantum numbers under the above gauge symmetries and global baryon numbers:

Ordinary three generations ($i = 1, 2, 3$): - $L_i(2, 1, -\frac{1}{2}, 0, 0)$: lepton doublets - $E_i^c(1, 1, 1, 0, 0)$: lepton singlets - $Q_i(2, 3, \frac{1}{6}, 0, \frac{1}{3})$: quark doublets - $U_i^c(1, \bar{3}, -\frac{2}{3}, 0, -\frac{1}{3})$: up-type quark singlets - $D_i^c(1, \bar{3}, \frac{1}{3}, 0, -\frac{1}{3})$: down-type quark singlets

Vector-like $\bar{5}$ representation ($m = 1, \ldots, 4$): - $L_m(2, 1, -\frac{1}{2}, 0, 0)$ - $D_m^c(1, \bar{3}, \frac{1}{3}, 0, -\frac{1}{3})$ - $H_u(2, 1, \frac{1}{2}, 0, 0)$

Dark sector: - $\chi_1(2, 1, -\frac{1}{2}, 1, 0)$ - $\chi_2(2, 1, \frac{1}{2}, -1, 0)$ - $\phi_1(1, 1, 0, 2, 0)$ - $\phi_2(1, 1, 0, -2, 0)$ - $X(1, 1, 0, 0, 0)$

Field notation is conventional: L stands for lepton doublets, E^c for lepton singlets, Q for quark doublets, U^c and D^c for quark singlets, and H_u for the up-type Higgs doublet.

A. SM-relevant part

The superpotential of our sector containing the SM part can be written as

$$W = \mu_m L_m H_u + \mu_D D^c H + \lambda_{mni} L_m L_n E_i^c + \lambda'_{imn} Q_i L_m D_n^c + y_{ij} Q_i H_u U_j^c + \tilde{y}_{ij} E_i^c \ldots \quad (3)$$

where μ_m are mass parameters and $\lambda^{(\prime)}$, y, and $\tilde{y}$ are coefficients. By redefining the down-type Higgs and the fourth down-quark field, the SM-relevant superpotential becomes

$$W = \mu H_d H_u + \mu_D D^c H + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} Q_i L_j D_k^c + y_{ij}^u Q_i H_u U_j^c + y_{ij}^d Q_i H_d D_j^c + y_i^D Q_i H_d D_4^c + \ldots \quad (6)$$

where field decompositions have been generally written as

$$L_m = c_{mi} L_i + c_{m4} H_d, \quad D_m^c = c_{Di} D_i^c + c_{D4} D_4^c$$

and the coefficients are defined accordingly. From the superpotential (6), we see that because of Dirac mass terms for the up-type Higgs and the four doublet leptons, D_H^c and the four singlet down-quarks, one of the four lepton doublets and one of the down-quarks—namely the fourth doublet lepton H_d and the fourth singlet down-quark D_4^c—are always heavy. H_d is identified as the down-type Higgs. The fourth neutrino together with the "neutrino" in H_u consists of neutral Higgsinos. After the mass terms, the next terms in Eq. (6) are ordinary Yukawa interactions and trilinear lepton number (R-parity) violating terms. The remaining terms involve the 4th generation fields, some of which also violate lepton number.

Soft SUSY-breaking mass terms should be included in the Lagrangian. In addition to gaugino masses, they include mass-squared terms for scalars and $B\mu$-type terms corresponding to those μ-terms in the superpotential (3):

$$\mathcal{L}_{\rm soft} \supset M^2_{\tilde{L}}\tilde{L}^\dagger_m\tilde{L}_m+M^2_{\tilde{Q}}\tilde{Q}^\dagger_i\tilde{Q}_i+M^2_{\tilde{U}^c}\tilde{U}^{c\dagger}_i\tilde{U}^c_i+M^2_{H_u}|h_u|^2+M^2_H|H|^2+(B\mu_m\tilde{L}_m h_u+B_D\mu_D\tilde{D}^c H+\text{h.c.}) \quad (9)$$

where tildes denote scalars. We have assumed universality of the mass-squared terms and alignment of the B terms, namely that both mass parameters B and B_D do not depend on the subscript m. In terms of the three light generations from Eq. (6), universality of these soft mass terms is easily seen.

Soft trilinear terms corresponding to Eq. (3) are

$$\mathcal{L}_{\rm tri} = \bar{\lambda}_{mni}\tilde{L}_m\tilde{L}_n\tilde{E}^c_i + \bar{\lambda}'_{imn}\tilde{Q}_i\tilde{L}_m\tilde{D}^c_n + \bar{y}_{ij}\tilde{Q}_i h_u\tilde{U}^c_j + \bar{\bar{y}}_{ij}\tilde{E}^c_i + \text{h.c.} \quad (11)$$

where the following coupling alignment is assumed:

$$\bar{\lambda}_{mni} = \lambda_{mni}m_0, \quad \bar{\lambda}'_{imn} = \lambda'_{imn}m_0, \quad \bar{y}_{ij} = y_{ij}m_0$$

with m_0 being of order the soft masses (~ 100 GeV).

Let us examine gauge symmetry breaking. From the Lagrangian, the scalar potential can be written straightforwardly. To achieve EWSB, one needs a negative determinant of the Higgs mass-squared matrix:

$$\det\begin{pmatrix} M^2_{H_d}+\mu^2 & B\mu \\ B\mu & M^2_{H_u}+\mu^2\end{pmatrix} < 0 \quad (13)$$

with the ordinary condition $M^2_{H_d} + M^2_{H_u} + 2\mu^2 + 2B\mu > 0$. This requirement can be realized when the renormalization group is considered, as $M^2_{H_u}$ becomes negative at the weak scale due to the large top quark Yukawa coupling. Therefore, everything about EWSB here is the same as in the MSSM. The MSSM analysis of EWSB applies here. EWSB in this model occurs at the weak scale. Besides Eq. (13), correct EWSB also requires:

$$M^2_{D^c} + \mu^2_D > 0, \quad M^2_H + \mu^2_D > 0 \quad (14)$$

Then the remaining analysis of EWSB is identical to that of the MSSM with the same Higgs and Higgsino spectra. Eq. (14) can be satisfied easily. Careful consideration of the EWSB conditions (13) and (14) shows that if $\mu < \mu_D$, EWSB occurs naturally.

B. Dark sector

The dark sector Lagrangian is written according to gauge invariance:

$$\mathcal{L}_{\text{dark}} = \int d^4\theta \left[\chi_1^\dagger e^{g_2 V_2 + g_1 V_1 + g' V'}\chi_1 + \chi_2^\dagger e^{-g_2 V_2 - g_1 V_1 - g' V'}\chi_2 + \phi_1^\dagger e^{2g' V'}\phi_1 + \phi_2^\dagger e^{-2g' V'}\phi_2 + X^\dagger X\right] + \int d^2\theta \, (\mu' \chi_1$$

where μ' and μ'' are mass parameters, and g' and c are coupling constants. It is important to note that an accidental Z_2 discrete symmetry appears, under which χ_1 and χ_2 fields are odd and all other fields are even. As we will see, this symmetry remains unbroken even after $U(1)_n$ breaking and EWSB. The Z_2 symmetry keeps the lightest component of χ_i $(i = 1, 2)$ stable—this is the dark matter particle in our model.

When SUSY breaking is considered, soft masses should be included:

$$\mathcal{L}_{\text{dark,soft}} = m^2_{\tilde{\chi}_1}\tilde{\chi}_1^\dagger\tilde{\chi}_1 + m^2_{\tilde{\chi}_2}\tilde{\chi}_2^\dagger\tilde{\chi}_2 + m^2_{\phi_1}|\phi_1|^2 + m^2_{\phi_2}|\phi_2|^2 + m^2_x|x|^2 + (B'\mu'\tilde{\chi}_1\tilde{\chi}_2 + \text{h.c.}) \quad (16)$$

The $U(1)_n$ gauge symmetry breaks spontaneously when $\phi_{1,2}$ acquire non-vanishing vacuum expectation values (VEVs). From Eqs. (15) and (16), the relevant scalar potential is

$$V_{\text{dark}} = 2g'^2\left(|\phi_1|^2 - |\phi_2|^2\right)^2 + m^2_{\phi_1}|\phi_1|^2 + m^2_{\phi_2}|\phi_2|^2 + c^2\left|\phi_1\phi_2 - \mu''^2\right|^2 \quad (17)$$

where we have taken $m^2_{\phi_1} = m^2_{\phi_2}$. The VEVs are then

$$\langle\phi_1\rangle = \langle\phi_2\rangle = \mu'' \quad (18)$$

Vector-like particle masses are all taken to be similar [8], hence $\mu', \mu'' \sim 1$ TeV. It is natural to expect that the bosonic fields of the $SU(2)_L$ doublets $\chi_{1,2}$ do not get VEVs and are heavy enough (~ 100 GeV). The $U(1)_n$ gauge boson γ_n gets a mass

$$m_{\gamma_n} = 4g'\mu'' \sim \mathcal{O}(100\text{ GeV}) \quad (19)$$

The Z_2 symmetry still remains after $U(1)_n$ breaking.

In addition to Eqs. (15) and (16), the Lagrangian should include a gauge field mixing between $U(1)_n$ and $U(1)_Y$:

$$\mathcal{L}_{\text{mixing}} = \epsilon F_n^{\mu\nu}F_{Y\mu\nu} \quad (20)$$

This mixing is accompanied by gaugino mixing because of SUSY:

$$\mathcal{L}_{\text{gaugino mixing}} = 2\epsilon\left(\lambda_1\sigma^\mu\partial_\mu\bar{\lambda}'_1 + \lambda'_1\sigma^\mu\partial_\mu\bar{\lambda}_1\right) \quad (21)$$

It is conventional to choose the mixing to be of size $\epsilon \sim 10^{-3}$. This mixing allows lighter particles in the dark sector, such as $\phi_{1,2}$, to decay into MSSM particles.

We are interested in the spectrum of χ_1 and χ_2 particles because they carry SM quantum numbers. For the fermions, at leading order they form a Dirac particle with mass μ':

$$\mathcal{L}_\chi = \bar{\Psi}_\chi i\gamma^\mu D_\mu \Psi_\chi - \mu' \bar{\Psi}_\chi \Psi_\chi \quad (22)$$

where $D_\mu = \partial_\mu - ig_2 A^a_\mu T^a - ig_1 B_\mu - ig' C_\mu$. Actually, Ψ_χ is a pseudo-Dirac particle because of gauge symmetry breaking. Generally, EWSB splits the neutral and charged components of Ψ_χ, and $\mathrm{U}(1)_n$ breaking further splits the two neutral components. In this model, such mass splittings are described by the following gauge-symmetric dimension-5 and dimension-6 operators:

$$\mathcal{L} \supset \mathcal{L}_{\text{dim-5}} + \mathcal{L}_{\text{dim-6}} \quad (23)$$

where

$$\mathcal{L}_{\text{dim-5}} = \frac{a_1}{\Lambda}(\chi_1 H_u)(\chi_2 H_d)\big|_{\theta\theta} + \frac{a_2}{\Lambda}(\chi_1 H_d)(\chi_2 H_u)\big|_{\theta\theta} + \text{h.c.} \quad (24)$$

$$\mathcal{L}_{\text{dim-6}} = \frac{a_3}{\Lambda^2}\phi_2(\chi_1 H_u)(\chi_1 H_u)\big|_{\theta\theta} + \frac{a_4}{\Lambda^2}\phi_1(\chi_2 H_d)(\chi_2 H_d)\big|_{\theta\theta} + \text{h.c.} \quad (25)$$

with Λ being a cutoff scale, and $a_i \sim \mathcal{O}(1)$ coefficients. These operators arise after integrating out SUSY breaking messengers that form complete SU(5) representations and do not break the unification of SM gauge couplings. As we will see, the dimension-5 operators split the charged and neutral components, while the dimension-6 operators split the two neutral components.

Note that without dimension-5 operators, EWSB itself at the renormalizable level induces mass splitting between charged and neutral components. One-loop diagrams with a Z boson propagator give a splitting roughly

$$\Delta M \sim \frac{\alpha_2}{4\pi} M_Z \sim 0.1 \text{ GeV} \quad (26)$$

To split the two neutral components, we need the new higher-dimensional operators. In our analysis, we take the dimension-5 operators as effective parameters that encode all EWSB effects. The a_1 and a_2 terms give rise to mass splitting between the charged and neutral components:

$$\Delta M = \frac{(a_1 + a_2)v^2 \sin 2\beta}{\Lambda} \quad (27)$$

where $v = 246$ GeV. With $\tan\beta$ between 3 and 10 and Λ between 10 and 100 TeV, this splitting ranges from 0.1 to 1 GeV. Here we choose the positive $(a_1 + a_2)$ case so that the neutral components of χ_i, χ_1^0 and χ_2^0, are lighter. The charged components χ_1^- and χ_2^+ form an exact Dirac particle. The mass splitting generated by dimension-5 operators is at least as large as that generated by loop diagrams.

The two neutral components χ_1^0 and χ_2^0 are split further through the a_3 and a_4 terms. The mass matrix of χ_1^0, χ_2^0 turns out to be

$$\begin{pmatrix} \mu' + \frac{a_3 \sin^2\beta v^2}{\Lambda^2} & \frac{(a_1+a_2)v^2 \sin 2\beta}{2\Lambda} \\ \frac{(a_1+a_2)v^2 \sin 2\beta}{2\Lambda} & \mu' + \frac{a_4 \cos^2\beta v^2}{\Lambda^2} \end{pmatrix} \quad (28)$$

As the off-diagonal elements are much larger than the diagonal ones, the mass eigenvalues are approximately

$$M_{\chi_d, \chi_d'} \approx \mu' \pm \frac{(a_3 \sin^2\beta + a_4 \cos^2\beta)v^2}{2\Lambda^2} \quad (29)$$

and the corresponding mass eigenstates are approximately

$$\chi_d = \frac{\chi_1^0 + \chi_2^0}{\sqrt{2}}, \quad \chi_d' = \frac{i(\chi_1^0 - \chi_2^0)}{\sqrt{2}} \quad (30)$$

with χ_d being the lighter state. Therefore, the mass splitting between the two neutral Majorana fermions is

$$\Delta m = \frac{(a_3 \sin^2\beta + a_4 \cos^2\beta)v^2}{\Lambda^2} \quad (31)$$

This splitting is almost independent of $\tan\beta$. Taking $\Lambda \sim 10 - 100$ TeV, this splitting ranges from 1 to 100 MeV.

The other particles of the dark sector have the following spectrum. As ϕ_1, ϕ_2 get VEVs, their fermionic partners $\tilde{\phi}_{1,2}$, $\tilde{X}$ (the fermion of X), and gaugino λ_1' acquire masses. It is convenient to change the basis to

$$\Phi' = \frac{\tilde{\phi}_1 + \tilde{\phi}_2}{\sqrt{2}}, \quad \Phi = \frac{\tilde{\phi}_1 - \tilde{\phi}_2}{\sqrt{2}} \quad (32)$$

Φ' and $\tilde{X}$ form a Dirac particle with mass $\sqrt{2}c\mu''$, and λ'_1 gets a mass from its soft term. The mass matrix of Φ and λ'_1 is

$$\begin{pmatrix} \sqrt{2}c\mu'' & m_{\lambda'} \\ m_{\lambda'} & 0 \end{pmatrix} \quad (33)$$

The matrix elements are all ~ 100 GeV, so the mass eigenstates N and N' are of the same mass scale, with N being the lighter one.

The scalars $\tilde{\chi}_{1,2}$ and $\phi_{1,2}$ are heavy (~ 1 TeV) due to soft SUSY breaking. Note that the singlet x has no gauge couplings and can have a vanishing soft mass in the case of gauge-mediated SUSY breaking. In this case, the boson x will have mass $\sqrt{2}c\mu''$, degenerate with the corresponding fermion.

It is convenient to express the fermions in four-component form:

$$\Psi_d = \begin{pmatrix} \chi_d \\ \bar{\chi}_d \end{pmatrix}, \quad \Psi'_d = \begin{pmatrix} \chi'_d \\ \bar{\chi}'_d \end{pmatrix}, \quad \Psi^- = \begin{pmatrix} \chi^- \\ \bar{\chi}^+ \end{pmatrix} \quad (34)$$

In terms of all the above mass eigenstates, the dark sector Lagrangian relevant for dark matter annihilation can be expressed as

$$\mathcal{L}_{\text{dark}} \supset -\frac{g_2}{\cos\theta_W} Z_\mu \left(\bar{\Psi}'_d\gamma^\mu\Psi'_d - \bar{\Psi}_d\gamma^\mu\Psi_d\right) - eA_\mu\bar{\Psi}^-\gamma^\mu\Psi^- + \epsilon'\left(\bar{\Psi}_d\gamma^\mu\Psi_d - \bar{\Psi}'_d\gamma^\mu\Psi'_d\right)Z'_\mu + \ldots \quad (35)$$

It is seen that the dark matter particle χ_d mainly scatters inelastically via gauge interactions. Note that there are still small diagonal χ_d-χ_d-gauge boson couplings of order $\epsilon' \sim \Delta m/\mu'$, as can be seen from Eq. (26).

C. UV-completion

Up to now, our model is a TeV-scale effective theory that does not include particles much heavier than a TeV. The cutoff Λ may be, as we have mentioned, understood as a result of integrating out SUSY-breaking messengers in a gauge-mediated SUSY-breaking scenario. Here we present a UV-completion model that reproduces our effective theory.

The SUSY-breaking messengers have the following quantum numbers under $SU(2)_L \times U(1)_Y \times SU(3)_c \times U(1)_n$:

- $\eta(2, 1, 1, 1)$
- $\eta'(1, -\frac{2}{3}, \bar{3}, 1)$
- $\kappa(1, 0, 1, -1)$

with conjugate representations $\bar{\eta}$, $\bar{\eta}'$, and $\bar{\kappa}$. The SUSY-breaking spurion field S couples to the messengers:

$$W_{\text{spurion}} = S(\eta\bar{\eta} + \eta'\bar{\eta}' + \kappa\bar{\kappa}) \quad (36)$$

where S gets a VEV $\langle S \rangle = \Lambda + \theta^2 F$. The soft masses are the same as in normal gauge mediation. For the dark sector, $\tilde{\chi}_{1,2} \sim \phi_{1,2} \sim \mathcal{O}(100\text{ GeV})$.

The $\mathrm{U}(1)_n$ messengers κ and $\bar{\kappa}$ have Yukawa couplings with the Higgs and dark sector:

$$W_{\text{messenger}} = b_1\chi_1 H_u\bar{\kappa} + b_2\chi_2 H_d\kappa + b_3\phi_2\kappa\kappa + b_4\phi_1\bar{\kappa}\bar{\kappa} \quad (37)$$

These couplings generate the a_i coefficients at tree level by integrating out κ and $\bar{\kappa}$:

$$a_1 = b_1 b_2, \quad a_3 = b_3 b_2, \quad a_4 = b_4 b_1 \quad (38)$$

The lack of a_2 does not change the mass splitting results of the dark sector significantly because a_1 is non-zero. There could be models in which a_2 does not vanish.

The Yukawa couplings b_i cause small mixing between messengers and the dark sector, which allows messengers to decay into dark sector particles. After EW and $\mathrm{U}(1)_n$ breaking, a Z_2 symmetry remains in both the messenger and dark sectors, which is the same Z_2 that appears only in the dark sector when messengers are integrated out.

III. Analysis

A. Dark matter relic density

From the discussions of the last section and Eq. (31), we see that the only stable particle in this model is χ_d, which is the dark matter. In relic density calculations, coannihilation of all four components of χ_1 and χ_2 should be considered. We use the program micrOMEGAs to calculate the relic density [20][21][22]. As long as χ_d has the correct relic density, the dark matter mass μ' can be determined by the coupling g'.

From [Figure 1: see original paper] we can see that the dark matter mass is between $\mu' = (1.1 - 1.5)$ TeV when g'^2 ranges between 0 and g_2^2. This means that taking g' not too far from 1 satisfies the normal WIMP expectation.

B. Detection of dark matter

Direct detection experiments for dark matter have given strict upper limits on the cross sections for its scattering with nuclei. As χ_d mainly interacts with the Z boson inelastically, it is possible to suppress the scattering cross section with nuclei. It is known that if the mass splitting Δm between χ_d and χ_d' were zero, the χ_d-nucleon spin-independent cross section would be about 10^{-38} cm^2 [11], while Xenon100 gives an upper limit of 10^{-44} cm^2 for ~ 1 TeV dark matter [12]. In our model, Δm ranges from (1-100) MeV depending on the cutoff Λ, which is larger than the possible kinetic energy of dark matter with maximum speed 600 km/s. Therefore, dark matter will not scatter through vector interactions with Xe nuclei at tree level.

The axial-vector coupling of χ_d with the Z boson still requires consideration. This coupling is elastic and of size $\epsilon' \sim \Delta m/\mu'$, which is between 10^{-4} and 10^{-6}. It leads to spin-dependent scattering with Xe. The spin-dependent tree-level cross section for WIMPs elastically scattering at zero momentum transfer is [13]:

$$\sigma_{\rm SD} = \frac{32 G_F^2 \mu_r^2}{\pi} \frac{J+1}{J} \left(\langle S_p \rangle a_p + \langle S_n \rangle a_n \right)^2 \quad (39)$$

where J is the nuclear spin, μ_r is the reduced mass of the dark matter-nucleus system, and $\langle S_{p,n} \rangle$ are spin expectation values of protons and neutrons in the nucleus. The couplings $a_{p,n}$ for χ_d are of magnitude $\epsilon' \sim \Delta m/\mu'$. The χ_d-Xe spin-dependent cross section is $(10^{-45} - 10^{-41})$ cm^2 for Xe^{129} and $(10^{-46} - 10^{-42})$ cm^2 for Xe^{131}. These cross sections are far beyond the detection capability of Xenon100 or Xenon-1t.

At one-loop level, the dark matter-nucleus cross section is essentially the same as that discussed in Ref. [14]: the one-loop χ_d-nucleon spin-independent cross section is about 10^{-48} cm^2, which is also too small to be detected.

Dark matter in our model cannot produce the positron excess observed by cosmic-ray experiments such as PAMELA and Fermi-LAT [27, 28]. The reason is that there is no light particle to provide sufficient Sommerfeld enhancement for dark matter annihilation. As a result, we must consider the observed positron excess as an astrophysical phenomenon.

C. Collider phenomenology

Experimental constraints should be considered. In this model, particles beyond those of the MSSM that carry color or electric charges are D_4^c, D_H^c, and χ_1^-, χ_2^+. Each pair forms an exact Dirac particle. The former is down-type quark-like, and the latter is charged lepton-like.

The direct experimental search at LEP requires that they be heavier than 100 GeV. The Tevatron limit for down-type heavy quarks requires them to be heavier than 372 GeV [15], and the current LHC limit is 675 GeV for down-type heavy quarks [16]. These results can be satisfied if $\mu_D > 675$ GeV and $\mu' > 100$ GeV. Electroweak precision measurements generally give weak constraints on this model because these extra particles are vector-like, with contributions scaling as $1/\mu_D^2$ and $1/\mu'^2$ as expected from the decoupling theorem. The effects of the extra particles can be small enough ($\sim m_t^2/\mu_D^2 < 10\%$) if we take $\mu_D, \mu' \sim 1$ TeV.

Noting that these direct search limits assume a single dominant decay channel, we will take $\mu_D = 500$ GeV and $\mu' = 1.1$ TeV for numerical illustration.

There are constraints from the unitarity of the 3×3 CKM quark mixing matrix of three chiral generations [15]. This unitarity is consistent with current data within experimental errors. In our model, extra down-type quarks mix with ordinary three-generation down-type quarks, which necessarily breaks CKM unitarity. The violation is of order $(m_{i4}/\mu_D)^2$, where the mixing mass parameter m_{i4} appears in Eq. (6). This μ_D dependence is generally expected with extra vector-like quarks. Hierarchical or small mixing masses m_{i4} can easily make the CKM matrix approximately unitary within errors. For example, if only the third generation mixes with extra quarks, the constraint is still loose: $(m_{34}/\mu_D)^2 < 0.01$. The quantity m_{34} is at most about m_t, giving $\mu_D > 280$ GeV. It is easy to see that there are new phases in the fermion mixing matrices; however, these new matrix elements are at most of order m_t/μ_D, so new CP violation effects are generally suppressed.

Decay signals of these new particles can be easily identified. From the trilinear Yukawa interactions in Eq. (6), we see that D_4^c and D_H^c decay into SM particles. Denoting the new Dirac quark (D_4^c, D_H^c) as Ψ_D, the decays of Ψ_D give

$$\Gamma(\Psi_D \to d_i h^0) \sim \frac{|y_i^D|^2}{16\pi}\mu_D \quad (39)$$

Taking relevant Yukawa coefficients $y_i^D \sim 10^{-2}$, the decay width is ~ 500 MeV. When EWSB is considered, Ψ_D mixes with SM fermions, allowing the decay $\Psi_D \to \bar{t}W^+$ via $\mathrm{SU}(2)_L$ gauge interaction at level (m/μ_D):

$$\Gamma(\Psi_D \to \bar{t}W^+) \sim \frac{G_F m_t^2}{8\sqrt{2}\pi}|V_{t4}|^2\mu_D \quad (40)$$

where V_{t4} is the mixing element. Taking $|V_{t4}| \sim 1/3$, the width is about 1 GeV. In this process, the top quark further decays into three quarks (one being a bottom), and the W can decay into a charged lepton plus neutrino. Taking this as the main decay channel, for Ψ_D pair production the signal would be events with 2 charged leptons (electron or muon), 6 jets (two being b-jets), and large missing energy.

Denoting the heavy charged Dirac lepton (χ_1^-, χ_2^+) as Ψ^-, its mass is only $\Delta M \sim (0.1-1)$ GeV above the dark matter. It can decay into Ψ_d or Ψ_d' together with a pion or with a charged lepton (electron or muon) and a neutrino. In the limit $\Delta M \ll \mu'$, the typical decay width is

$$\Gamma(\Psi^- \to \Psi_d e^- \bar{\nu}_e) \sim \frac{G_F^2 \Delta M^5}{15\pi^3} \quad (41)$$

This lifetime is about $10^{-12} - 10^{-7}$ s. For larger ΔM, Ψ^- decays rapidly into a charged lepton and missing energy, making detection difficult. For $\Delta M < 0.3$ GeV, Ψ^- is long-lived and can leave tracks in detectors. Since Ψ^- is always produced in pairs, the signal should be easy to identify.

The new quark can be produced at the LHC via gluon fusion: $gg \to \Psi_D \bar{\Psi}_D$. The production mechanism is essentially the same as for the top quark [18], with an estimated cross section of hundreds of fb for $\mu_D = 500$ GeV and $\sqrt{s} = 14$ TeV. For the new charged lepton, the Drell-Yan process is the main production mechanism. The cross section is estimated to be a few fb, meaning only a few events per year at most [19].

IV. Discussion

Finally, we discuss some physical aspects related to this model. First, it is important to address GUT. We have maintained gauge coupling unification at high scales, but a real GUT model with a simple gauge group has not been constructed—it remains beyond our reach. From the particle content and assumptions of this model, it is doubtful whether such a GUT model exists. We wonder if a simple gauge group is truly necessary for so-called unification. In fact, in certain string models, unification is achieved without requiring a GUT gauge group, but the gauge coupling constants unify at a scale of $\sim 10^{16}$ GeV [23]. It would be interesting if this model could be reconstructed as a string model.

The assumption of baryon number conservation may have a better foundation. It has been shown that it can be replaced by a Z_3 discrete symmetry called baryon parity [24]. As we know, any global symmetry is not favored from the quantum gravity perspective because black holes can violate such symmetries. However, baryon parity can be considered as a result of gauge symmetry breaking [25].

The two U(1) gauge interactions have mixing. With such mixing, which is symmetry-allowed, it is guaranteed that dark matter is composed only of χ_d. The other particles of the dark sector can decay via this mixing even if they are lighter than χ_d. This is a simple scenario for dark matter in our model, although a more complicated one with vanishingly small ϵ is possible. Without the mixing, the lightest particle of the dark sector other than $\chi_{1,2}$ would be stable and contribute to the relic density. In that case, dark matter would have multiple components.

Our dark matter model has nothing to do with the so-called indirect indications of dark matter from astrophysical observations by ATIC [26], PAMELA [27], and Fermi-LAT [28]. It appears that our model has the potential to accommodate these observations, which have detected an excess of cosmic electrons and positrons. Although the Fermi-LAT experiment [28] does not support ATIC, it agrees with PAMELA. These observations have inspired much theoretical reconsideration of WIMP dark matter [6, 29, 30]. Arkani-Hamed et al. [6] proposed a scenario to understand all dark matter experiments naturally: WIMPs should have a new interaction mediated by a light, GeV-scale particle that enhances their annihilation cross section via the Sommerfeld mechanism. This GeV particle is supposed to be the main annihilation product, and because of its lightness, it eventually decays only into leptons. Many theoretical models realize this scenario [29].

There is a point similar to our case: in our model, the WIMP also has a new interaction, but with a typical energy scale of hundreds of GeV. If we tuned the mass parameter μ'' to reduce the new interaction scale to the GeV range, this model would realize most of the Arkani-Hamed et al. scenario. However, because of the dark matter structure of our model, the Sommerfeld enhancement factor would be about 10^4, which has been ruled out [31].

V. Summary

Within the framework of R-parity violation, we have studied the dark matter problem with the constraint of gauge coupling constant unification. The WIMP dark matter is contained in a new vector-like $SU(2)_L$ doublet that possesses a new U(1) gauge symmetry. The Higgs particles are included in a $\bar{5}$ representation of SU(5). Instead of R-parity, baryon number conservation is assumed. In this model, the dark matter particle is stable as a result of gauge invariance. An accidental discrete Z_2 symmetry remains after spontaneous gauge symmetry breaking, which makes the dark matter particle stable.

The main results of this model are as follows. The mass of the dark matter particle is $(1.1 - 1.5)$ TeV. The dark matter-nucleus interaction has small cross sections that are consistent with current dark matter direct detection experiments like Xenon100. In addition to the particle content of the MSSM, we have a new down-type Dirac quark and a new Dirac charged lepton with masses around $(500 - 1000)$ GeV. These charged particles, especially the new quark, can be produced at the LHC and hopefully observed.

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Note: Figure translations are in progress. See original paper for figures.