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Pure leptonic gauge symmetry, neutrino masses and dark matter

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ABSTRACT

A possible extension of the Standard Model to include lepton number as local gauge symmetry is investigated. In such a model, anomalies are canceled by two extra fermions doublet. After leptonic gauge symmetry spontaneously broken, three active neutrinos may acquire non-zero Majorana masses through the modified Type-II seesaw mechanism. Constraints on the model from electro-weak precision measurements are studied. Due to the Z_2 discrete flavor symmetry, right-handed Majorana neutrinos can serve as cold dark matter candidate of the Universe. Constraint from dark matter relic abundance is calculated.

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1. Introduction

The Standard Model (SM) is in spectacular agreement with all known experiments. However, it is almost certainly fundamentally incomplete. The solar [1], atmosphere [2], reactor [3] and accelerator [4] neutrino experiments have provided us very convincing evidence that neutrinos are massive and lepton flavors are mixed. Besides, precisely cosmological observations have confirmed the existence of non-baryonic cold dark matter: $\Omega_D h^2 = 0.1123 \pm 0.0035$ [5]. These two important discoveries cannot be accommodated in the SM without introducing extra ingredients.

A possible extension of the SM is to add three right-handed heavy Majorana neutrinos N_R so that light neutrino masses can be generated by the famous canonical seesaw mechanism (i.e., $M_\nu = -M_D M_R^{-1} M_D^T$, where M_D is the Dirac mass matrix linking left-handed light neutrinos to right-handed heavy neutrinos and M_R is the mass matrix of N_R). This is the so-called Type-I seesaw mechanism [6]. Actually, there are three types of tree-level seesaw mechanisms [6–8] and three types of loop-level seesaw mechanisms [9–12]. An advantage of the seesaw mechanism is that they can both explain neutrino masses and the baryon asymmetry of the Universe with the help of leptogenesis [13]. Putting some discrete flavor symmetry on the seesaw mechanism, heavy seesaw particles can also serve as cold dark matter (CDM) candidate [10, 14, 15]. This builds a bridge between the dark matter and neutrino physics.

We do not have enough information on the detailed nature of CDM, except for its relic density. There are major experimental efforts for direct and indirect detection of dark matter particle beside

the gravitational effect that it has on the Universe, because they must have some connection to the SM particles. A direct detection probes the scattering of dark matter off nuclei in the dark matter detectors, while indirect detection investigate the SM final states from the annihilation of the dark matter by cosmic ray detectors.

In this Letter, we consider the possible extension of the SM to include lepton number (L) as local gauge symmetry. Two reasons drive us to investigate this possibility:

- Baryon number (B) and L are accidental global symmetries in the SM. B must be broken to explain the baryon asymmetry of the Universe. L should be broken to accommodate the Majorana masses of active neutrinos. Investigating the possibility of L as spontaneously broken local gauge symmetry would help us to study the origin of small neutrino masses and describe the seesaw scale.
- Recent results from PAMELA [16, 17] and FERMI [18] suggest there should be pure leptonic interactions for dark matter to explain the e^+e^- excesses observed by these experiments. Inspired by Ref. [19], we investigate the case dark matter being charged under L , which is taken as local gauge symmetry.

We extend the SM with three right-handed Majorana neutrinos, two generation fermions doublet as well as pure leptonic gauge symmetry $U(1)_X$ and Z_2 discrete flavor symmetry. In this model, all the quarks have zero $U(1)_X$ charge, while all the leptons (including right-handed neutrinos) have unit $U(1)_X$ charge. After $U(1)_X$ gauge symmetry spontaneously broken, right-handed neutrinos acquire heavy Majorana masses, while three active neutrinos may acquire non-zero Majorana masses through the modified Type-II seesaw mechanism. Due to the Z_2 symmetry, right-handed Majorana neutrinos don't couple to the SM fermions, so that they

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Table 1
Charges of particle contents in the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X \times Z_2$ scenario.

Particles	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_X$	Z_2
$(u, d)_L$	$(3, 2, \frac{1}{6})$	m	1
u_R	$(3, 1, \frac{2}{3})$	m	1
d_R	$(3, 1, -\frac{1}{3})$	m	1
$(\nu, e)_L$	$(1, 2, -\frac{1}{2})$	k	1
e_R	$(1, 1, -1)$	k	1
N_R	$(1, 1, 0)$	k	-1
$(\psi_1, \psi_2)_L^1$	$(1, 2, a)$	b	1
$(\psi_1, \psi_2)_L^2$	$(1, 2, -a)$	b	1
ψ_{1R}^1	$(1, 1, a + \frac{1}{2})$	b	1
ψ_{2R}^1	$(1, 1, a - \frac{1}{2})$	b	1
ψ_{1R}^2	$(1, 1, -a + \frac{1}{2})$	b	1
ψ_{2R}^2	$(1, 1, -a - \frac{1}{2})$	b	1
H	$(1, 2, 1/2)$	0	1
Δ	$(1, 3, -1)$	$2k$	1
ϕ	$(1, 1, 0)$	$-2k$	1

can be cold dark matter candidate. We study constraints on our model from neutrino physics and electroweak precision measurements. We also investigate constraints on the leptonic gauge coupling constant and the mass of the lightest right-handed neutrino from the dark matter relic abundance.

The Letter is organized as following: Section 2 is a brief introduction to the setup of the $U(1)_X$ gauge symmetry. In Section 3 and Section 4, we study constraints on our model from the neutrino physics and electroweak precision measurements. In Section 5, we investigate the possibility of taking the lightest right-handed neutrino as cold dark matter. Some conclusions are drawn in Section 6.

2. The leptonic $U(1)_X$ gauge symmetry

Now we consider the extension of the SM with three right-handed Majorana neutrinos N_R , two generation fermions doublet $(\Psi_1, \Psi_2)_L^{1T}$, $(\Psi_1, \Psi_2)_L^{2T}$ and singlet $\psi_{1R}^1, \psi_{2R}^1, \psi_{1R}^2, \psi_{2R}^2$ as well as new gauge symmetry $U(1)_X$ and Z_2 discrete flavor symmetry. To generate Majorana masses for right-handed neutrinos, one Higgs singlet ϕ with $U(1)_X$ charge $-2k$ is added to the model. Due to the Z_2 discrete symmetry, right-handed neutrinos do not couple to the SM particles, such that they can serve as cold dark matter candidate. We also include one Higgs triplet Δ with $U(1)_X$ charge $2k$ in our model, so that small but non-zero neutrino masses can be generated through the modified Type-II see-saw mechanism. Representations of particles under the symmetry, $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X \times Z_2$, are listed in Table 1.

Now we investigate how to cancel anomalies of the model. The global $SU(2)_L$ anomaly [22] requires fermions doublet to be even. Considering the conditions for the absence of axial-vector anomaly [23–25] in the presence of $U(1)_X$ and the absence of the gravitational-gauge anomaly [26–28], which requires the sum of the $U(1)_X$ charges to vanish, one has

$$SU(3)_C^2 U(1)_X: 2m - m - m = 0, \quad (1)$$

$$SU(2)_L^2 U(1)_X: \frac{9}{2}m + \frac{3}{2}k + b = 0, \quad (2)$$

$$U(1)_Y^2 U(1)_X: \frac{1}{2}m - 4m - m + \frac{3}{2}k - 3k + \sum_i b \left[2a_i^2 - \left(a_i + \frac{1}{2} \right)^2 - \left(a_i - \frac{1}{2} \right)^2 \right] = 0, \quad (3)$$

$$U(1)_X^2 U(1)_Y: 3m^2 - 6m^2 + 3m^2 - 3k^2 + 3k^2 + \sum_i b^2 \left[2a_i - \left(a_i + \frac{1}{2} \right) - \left(a_i - \frac{1}{2} \right) \right] = 0, \quad (4)$$

$$U(1)_X^3: 3(6m^3 - 3m^3 - 3m^3 + 2k^3 - k^3 - k^3) + 2(2b^3 - b^3 - b^3) = 0, \quad (5)$$

$$U(1)_X: 3(6m - 3m - 3m + 2k - k - k) + 2(2b - b - b) = 0, \quad (6)$$

$$SU(2)_L^2 U(1)_Y: \frac{3}{2} - \frac{3}{2} + \frac{1}{2} \sum_i a_i = 0, \quad (7)$$

$$U(1)_Y^3: \sum_i \left[2a_i^3 - \left(a_i + \frac{1}{2} \right)^3 - \left(a_i - \frac{1}{2} \right)^3 \right] = 0, \quad (8)$$

$$U(1)_Y: \sum_i \left[2a_i - \left(a_i + \frac{1}{2} \right) - \left(a_i - \frac{1}{2} \right) \right] = 0, \quad (9)$$

where a_i is the weak hypercharge of ψ^i with $a_{1(2)} = a(-a)$. We find that Eqs. (1), (4)–(6) and (7)–(9) hold automatically, while Eq. (2) and Eq. (3) are equivalent. As a result, the upper equations can be simplified to the following relation:

$$9m + 3k + 2b = 0. \quad (10)$$

Anomalies put no constraint on a . We set $a = 1/2$ in our Letter. Four interesting scenarios can be derived from Eq. (10):

- $m = 0$ and $k = 1$. All the quarks have zero $U(1)_X$ charge. As a result, $U(1)_X$ is a pure lepton number gauge symmetry.
- $k = 0$ and $m = 1/3$. All the leptons have zero $U(1)_X$ charge. Such that $U(1)_X$ is a pure baryon number gauge symmetry.
- $b = 0$ and $k = -3m = -1$. It corresponds to $U(1)_{B-L}$ gauge symmetry, the phenomenology of which has been well-studied.
- $k = 1$, $m = 1/3$ and $b = -3$. It correspond to $U(1)_{B+L}$ gauge symmetry.

In this Letter, we only investigate the phenomenologies of the first scenario. We will study constraints on the model from neutrino physics, electroweak precision measurements and cosmological observations. The phenomenology of the second scenario, which is interesting but beyond the reach of this Letter, will be shown in somewhere else. The following is the leptonic part of the full Lagrangian

$$\begin{aligned} \mathcal{L}_{\text{lep}} = & \bar{\Psi}_L i \not{D} \Psi_L + \bar{N}_R i \not{D} N_R + \bar{\Psi}_R i \not{D} \Psi_R + \bar{\ell}_L i \not{D} \ell_L + \bar{E}_R i \not{D} E_R \\ & - \left[\bar{\ell}_L Y_E H E_R + \bar{\Psi}_L^i Y_{\Psi_1} \tilde{H} \Psi_{1R}^i + \bar{\Psi}_L^i Y_{\Psi_2} H \Psi_{2R}^i \right. \\ & \left. + \frac{1}{2} \bar{N}_R^c Y_N \phi N_R + \bar{\ell}_L Y_\Delta \Delta \ell_L^c + \text{h.c.} \right], \end{aligned} \quad (11)$$

with

$$D_\mu = \partial_\mu + i g_1 Y B_\mu + i g_2 \delta_{\frac{1}{2} I} \sigma^k W_\mu^k + i g_X Y' X_\mu.$$

There are no Yukawa interactions between new fermions (ψ^i) and SM particles because of their special $U(1)_X$ quantum numbers. Then the neutral component of Ψ is stable and can be

dark matter candidate. However, Ψ is strongly coupled to the SM Higgs boson in our model, i.e., $\mathcal{O}(Y_\Psi) > 1$ (of course it should be smaller than 4π to satisfy the perturbativity limit [20]). Assuming $m_\Psi > 400$ GeV and $m_H \sim 200$ GeV, We can estimate the relic density of Ψ : $\Omega_\Psi h^2 < 2 \times 10^{-3}$, which is quite small compared with the dark matter relic density, even smaller than its statistical error. Therefore the contribution of Ψ to the dark matter relic density is almost ignorable. For simplification, we will not discuss the phenomenology of Ψ in this Letter.

3. Neutrino masses

We now investigate the possible origin of Majorana masses for three active neutrinos in our model. Conventional seesaw mechanisms explicitly break the lepton number, which is gauged and spontaneously broken in our model. To overcome this difficulty, we modify the Type-II seesaw mechanism slightly. The most general gauge invariant Higgs potential can be written as¹

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = & m_1^2 H^\dagger H + m_3^2 \phi^\dagger \phi + M_\Delta^2 \text{Tr}(\Delta^\dagger \Delta) + \frac{1}{2} \lambda_1 (H^\dagger H)^2 \\ & + \frac{1}{2} \lambda_3 (\phi^\dagger \phi)^2 + \lambda_5 (\phi^\dagger \phi) (H^\dagger H) \\ & + [\lambda_7 \phi H^T i \sigma_2 \Delta H + \text{h.c.}]. \end{aligned} \quad (12)$$

Here H plays the role of the SM Higgs doublet. On the contrary to the conventional Type-II seesaw mechanism, the last term in Eq. (12) conserves the lepton number. When ϕ gets vacuum expectation value (VEV), $U(1)_X$ gauge symmetry is broken down and right-handed neutrinos acquire Majorana masses. We set $\langle H \rangle = v$ and $\langle \phi \rangle = v'$. After imposing the conditions of global minimum, one obtains

$$\begin{aligned} \langle H \rangle^2 & \approx \frac{\lambda_3 m_1^2 - \lambda_5 m_3^2}{\lambda_5^2 - \lambda_1 \lambda_3}, & \langle \phi \rangle^2 & \approx \frac{\lambda_1 m_3^2 - \lambda_5 m_1^2}{\lambda_5^2 - \lambda_1 \lambda_3}, \\ \langle \Delta \rangle & = -\frac{\lambda_7 v' v^2}{2M_\Delta^2}. \end{aligned} \quad (13)$$

The light neutrino mass matrix is then

$$M_\nu = Y_\Delta \langle \Delta \rangle = -Y_\Delta \frac{\lambda_7 v' v^2}{2M_\Delta^2}. \quad (14)$$

Present constraint on the neutrino mass matrix from neutrino oscillation experiments and cosmological observations is $\mathcal{O}(M_\nu) \sim 0.1$ eV [29]. By setting $\langle \phi \rangle = 1$ TeV and $M_\Delta = 10^8$ GeV, one has $Y_\Delta \lambda_7 \sim 10^{-2}$.

4. Electroweak precision measurement constraints

We now perform an analysis of the electroweak precision observable on our model. The most stringent restrictions come from the S and T parameters [21], which can be expressed by the following equations

$$S \approx \sum_{\alpha=1}^2 \frac{1}{6\pi} \left[1 - Y_\alpha \ln \left(\frac{M_{\Psi_1}^\alpha}{M_{\Psi_2}^\alpha} \right)^2 \right], \quad (15)$$

¹ Actually the full Higgs potential should also contain the following terms: $\lambda_1 (\text{Tr}(\Delta^\dagger \Delta))^2$, $\lambda_2 \text{Tr}(\Delta^\dagger \Delta \Delta^\dagger \Delta)$, $\lambda_3 \phi^\dagger \phi \text{Tr}(\Delta^\dagger \Delta)$, $\lambda_4 H^\dagger H \text{Tr}(\Delta^\dagger \Delta)$ and $\lambda_5 H^\dagger [\Delta^\dagger, \Delta] H$. Here we assume their coupling constant are small and thus these terms are ignorable, just like what we do with the Higgs potential of the conventional Type-II seesaw model. The author would like to thank the anonymous referee for pointing out these terms.

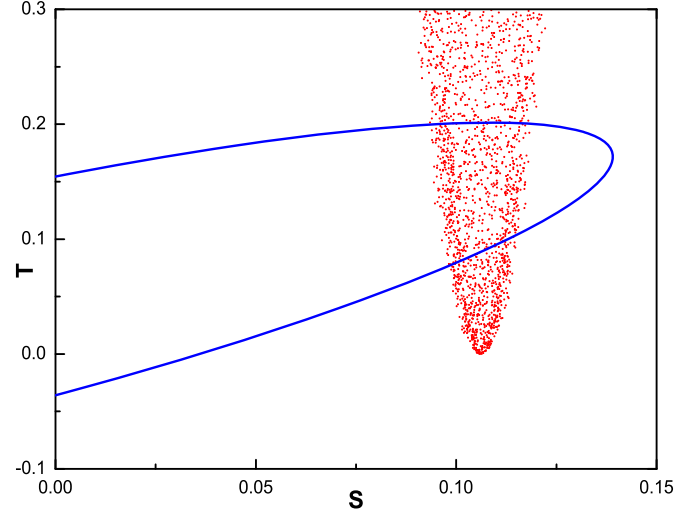


Fig. 1. Numerical illustration of the 90% Confidence Level contour (ellipse) and new heavy fermions' predictions in the (S, T) plane. The dots indicate points where all the heavy fermions lie between 400 GeV and 1000 GeV.

$$\begin{aligned} T \approx & \sum_{\alpha=1}^2 \frac{1}{16\pi s^2 c^2 M_Z^2} \left[(M_{\Psi_1}^\alpha)^2 + (M_{\Psi_2}^\alpha)^2 \right. \\ & \left. - \frac{2(M_{\Psi_1}^\alpha)^2 (M_{\Psi_2}^\alpha)^2}{(M_{\Psi_1}^\alpha)^2 - (M_{\Psi_2}^\alpha)^2} \ln \left(\frac{M_{\Psi_1}^\alpha}{M_{\Psi_2}^\alpha} \right)^2 \right], \end{aligned} \quad (16)$$

where $s = \sin \theta_W$, $c = \cos \theta_W$ with θ_W the Weinberg angle. Y_α is the weak hypercharge of Ψ_α with $Y_{1,2} = -1/2, 1/2$. To obtain a better understanding of the importance of the S and T parameters in constraining our model, we show in Fig. 1 the 90% Confidence Level contour (ellipse) in the (S, T) plane, as obtained from the Electroweak Working Group [29], together with the new heavy fermion's predictions. In plotting the figure, we have assumed the masses of heavy fermions lie in the range [400, 1000] GeV. It is clear from the figure that there is sizeable region in the parameter space lying within 90% Confidence Level contour.

We proceed to consider the constraint on the model from the muon $g-2$. There has been a long history in measuring and calculating the muon abnormal magnetic moment a_μ . In particular the steadily improving precision of both the measurements and the predictions of a_μ and the disagreement observed between the two have made the study of a_μ one of the most active research fields in particle physics in recent years. The final result of the ‘‘Muon $g-2$ Experiment’’ (E821) for a_μ reads $a_\mu^{\text{exp}} = (11659208 \pm 6) \times 10^{-10}$ [30], which deviates from the SM prediction by

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 22(10) \times 10^{-10}. \quad (17)$$

In our model, heavy neutral gauge boson Z' will contribute to Δa_μ , which is

$$\Delta a_\mu = \frac{g_X^2}{8\pi^2} \int_0^1 dx \frac{2m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) M_{Z'}^2}, \quad (18)$$

where $M_{Z'}$ is the mass of Z' . There are a lot of works on the heavy neutral gauge bosons. For a recent review, see Ref. [31], and recent studies Z' at Tevatron and LHC [32]. In our model, the mass of the new gauge boson Z' is given by $M_{Z'} = 2g_X v'$. To satisfy the experimental lower bound, $M_{Z'}/g_X > 5 \sim 10$ TeV [33]. Given $M_{Z'} > 500$ GeV and $g_X < 0.1$, we can find the biggest contribution to Δa_μ is 4×10^{-12} , which is far below the discrepancy listed in Eq. (17). In short there is almost no strong constraint on the g_X and $M_{Z'}$ from the muon $g-2$.

5. Dark matter

In our model, the lightest heavy Majorana neutrino serves as dark matter candidate. Assuming $M_N < M_\psi$, there are two dominant annihilation channels: $\bar{N}N \rightarrow Z' \rightarrow \bar{\ell}\ell$ and $\bar{N}N \rightarrow \varphi \rightarrow \bar{q}q(\bar{\ell}\ell)$, where φ is the SM Higgs. The second channel is heavily suppressed by the mixing between ϕ and H , such that we only consider the first channel. Ignoring charged lepton masses, one can write down the thermal average of the interaction rate σv in non-relativistic limit

$$\begin{aligned} \langle \sigma v_{\text{Mol}} \rangle &= \langle \sigma v_{\text{lab}} \rangle \approx a^{(0)} + \frac{3}{2} a^{(1)} x_f^{-1} \\ &= \frac{m^2 g_X^4}{4\pi [(4m^2 - M_{Z'}^2) + M_{Z'}^2 \Gamma_{Z'}^2]} x_f^{-1}, \end{aligned} \quad (19)$$

where $x_f = M_N/T_f$ with T_f the freeze-out temperature of the relic particle. In assumption $M_{Z'} < 2M_\phi$, the decay width of Z' is

$$F_{Z'} = \frac{g_X^2 M_{Z'}}{8\pi}. \quad (20)$$

The present density of dark matter is simply given by $\rho_N = M_N s_0 Y_\infty$, where $s_0 = 2889.2 \text{ cm}^{-3}$ is the present entropy density and Y_∞ is the asymptotic value of the ratio n_N/s_0 with $Y_\infty^{-1} = 0.264 \sqrt{g_*} M_{Pl} M_N (a^{(0)} + 3a^{(1)}/4x_f)$, where g_* accounts the number of relativistic degrees of freedom at the freeze-out temperature. The relic density can finally be expressed in terms of the critical density

$$\Omega h^2 \simeq \frac{1.07 \times 10^9 \text{ GeV}^{-1}}{M_{Pl}} \frac{x_f}{\sqrt{g_*} a^{(0)} + 3a^{(1)}/4x_f}, \quad (21)$$

where h is the Hubble constant in units of 100 km/s-Mpc and $M_{Pl} = 1.22 \times 10^{19} \text{ GeV}$ is the Planck mass. The freeze-out temperature x_f can be estimated through the iterative solution of the following equation [34]

$$\begin{aligned} x_f &= \ln \left[c(c+2) \sqrt{\frac{45}{8}} \frac{g}{2\pi^3} \frac{M_{Pl} M_N \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle}{\sqrt{g_* x_f}} \right] \\ &\simeq \ln \frac{0.038 M_{Pl} M_N (a^{(0)} + 3a^{(1)}/2x_f)}{\sqrt{g_* x_f}} \end{aligned} \quad (22)$$

where c is the constant of order one determined by matching the late-time and early-time solutions.

We set x_f equals to 20, a typical value at freeze-out for weakly interacting particles. In Fig. 2, we plot g_X versus the mass of the lightest right-handed neutrino, M_N , constrained by the dark matter relic abundance. The solid, dashed and dotted lines correspond to $M_{Z'} = 600 \text{ GeV}$, 800 GeV and 1000 GeV , separately. One finds poles at $M_N = 1/2 M_{Z'}$, where the annihilation cross section is resonantly enhanced. All the experimental constraints can be fulfilled near these region.

Notice that heavy Majorana neutrinos only annihilate into leptons, our model could explain e^+ , e^- excess reported by PAMELA [16,17] and Fermi [18] with resonant enhancement [35–37] as boost factor. For similar analysis on this subject, see Refs. [38–40] for detail.

6. Conclusions

We have investigated the possibility of taking the lepton number as local gauge symmetry. In such a model, at least two fermions doublet are needed to cancel the anomaly. We have introduced a modified Type-II seesaw mechanism to generate Majorana

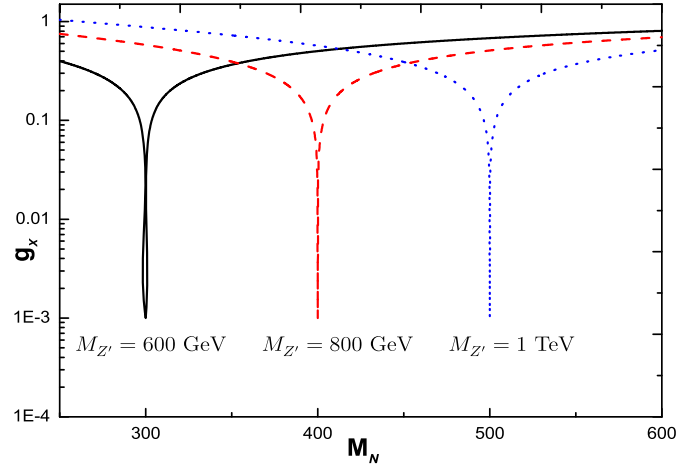


Fig. 2. g_X versus dark matter mass m_N constrained by the dark matter relic abundance.

masses for three active neutrinos. Constraints from electroweak precision measurements were studied. The result shows that there are adequate parameter space for our model. Taking heavy Majorana neutrinos as dark matter candidate, we have studied the constraint on the leptonic gauge coupling constant and the mass of the lightest right-handed neutrino from dark matter relic abundance.

Note added

During the completion of this work, Ref. [41], which investigate the $U(1)_B \times U(1)_L$ gauge symmetry, appeared. We built similar frameworks, but focused on different phenomenologies.

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