PHYSICAL REVIEW D **84,** 095003 (2011)

Identifying sneutrino dark matter: Interplay between the LHC and direct search

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(Received 16 August 2011; published 3 November 2011)

Under R parity, the lightest supersymmetric particle (LSP) is stable and may serve as a good dark matter candidate. The R parity can be naturally introduced with a gauge origin at the TeV scale. We go over why a TeV scale $B - L$ gauge extension of the minimal supersymmetric standard model is one of the most natural, if not demanded, low energy supersymmetric models. In the presence of a TeV scale Abelian gauge symmetry, the (predominantly) right-handed sneutrino LSP can be a good dark matter candidate. Its identification at the LHC is challenging because it does not carry any standard model charge. We show how we can use the correlation between the LHC experiments (dilepton resonance signals) and the direct dark matter search experiments (such as CDMS and XENON) to identify the right-handed sneutrino LSP dark matter in the $B - L$ extended minimal supersymmetric standard model.

DOI: 10.1103/PhysRevD.84.095003 PACS numbers: 95.35.+d, 12.60.Jv, 14.80.Ly

I. INTRODUCTION

There is strong evidence that about 22% of the energy budget of the Universe is in the form of dark matter (DM) [1]. The most precise measurement comes from fitting the WMAP measured anisotropy of the cosmic microwave background to the cosmological parameters [2]. One has to rely on the other methods including direct and indirect DM searches as well as colliders to pinpoint the identity of the DM (see Ref. [3] for a review), which has far-reaching implications for particle physics. With all standard model (SM) particles ruled out as viable DM candidates, DM is one of the strongest pieces of empirical evidence for the beyond SM physics.

The Large Hadron Collider (LHC) at CERN will explore the physics of the electroweak (EW) symmetry breaking and beyond. The low energy supersymmetry (SUSY), which is one of the most popular scenarios to stabilize the EW scale, is expected to be largely explored at the LHC. In fact, the early search at the LHC with total energy $\sqrt{s} = 7$ TeV and integrated luminosity of $L = 35\ \mathrm{pb}^{-1}$ has already started to put new constraints on SUSY scenarios [4].

SUSY is one of the best-motivated new physics scenarios. It can address the gauge hierarchy problem, help unification of three SM gauge coupling constants, and may provide a natural DM candidate. The minimal supersymmetric standard model (MSSM) consists of the SM fields, one more Higgs doublet, and their superpartners. Typically, the MSSM is accompanied by R parity, which can protect a proton from decaying through renormalizable baryon number (B) or lepton number (L) violating terms. Under the R parity, the lightest supersymmetric particle (LSP) is stable and may serve as a DM candidate. The MSSM provides two natural LSP DM candidates: neutralino (superpartner of neutral gauge bosons and Higgs bosons) and sneutrino (superpartner of neutrinos).

The neutralino LSP DM candidate has been extensively studied and proven to be a good DM candidate [5,6]. Many studies have been done also for the detection of the neutralino LSP signal in the collider experiments. For example, the trilepton signals ($\chi_1^\pm + \chi_2^0 \to 3\ell +$ MET) can be used to look for a SUSY signal with the neutralino LSP final states, and the invariant mass distribution of a dilepton ($\chi_2^0 \to \ell^+\ell^- + \chi_1^0$) can be used to measure superparticle masses. (A brief summary of detecting the neutralino LSP DM signals is included in a general SUSY review, Ref. [7].)

On the other hand, the sneutrino (at earlier time, only the left-handed one) LSP DM candidate has not been studied much, despite the fact it is one of only a few candidates in the SUSY scenario. It is basically because it was excluded early as a viable DM candidate by a combination of cosmological (DM relic density constraint) and terrestrial constraints (direct DM search by nuclear recoil) [8–11]. The major channel for the relic density and direct search is mediated by the SM Z boson, whose coupling to the left-handed sneutrino LSP is too large to make it a good DM candidate.

It has been demonstrated, however, in Ref. [12] that the (predominantly) right-handed (RH) sneutrino ($\tilde{\nu}_R$) can be a good cold DM candidate, satisfying all the constraints for a viable thermal DM candidate, when there is a TeV scale neutral gauge boson Z' that couples to the RH sneutrinos. (For an extensive review of the heavy neutral gauge boson, see Ref. [13].) There are few studies on the RH sneutrino LSP search in the collider experiments. Since the RH sneutrino LSP does not carry any SM charge, we cannot use the methods developed for the neutralino LSP. In fact, unlike the situation where the sneutrino is not the LSP and therefore can decay [14], it would be very hard to see the signal related to $Z' \to \tilde{\nu}_R \tilde{\nu}_R^*$ with the sneutrino LSP in the LHC experiments.

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In this paper, we aim to establish a correlation between the LHC experiments and DM direct search experiments (such as CDMS and XENON) for a $U(1)$ gauge symmetry and discuss how we can use it to confirm the RH sneutrino LSP DM. We choose a TeV scale $U(1)_{B-L}$ gauge symmetry. As discussed in Sec. II, this is a remarkably well motivated (if not demanded) addition to the MSSM, and further, the economy of the model is also preserved in the sense that we do not need the R parity independently.

The rest of this paper is organized as follows. In Sec. II, we describe our theoretical framework. In Sec. III, we discuss the correlation of the DM direct search experiment and the LHC dilepton resonance search experiment. In Sec. IV, we show various results of the numerical analysis. In Sec. V, we summarize our results.

II. THEORETICAL FRAMEWORK

Here, we describe the theoretical framework in our study. The model we will work on is a well-known extension of the MSSM: MSSM + three RH neutrinos/sneutrinos + TeV scale $U(1)_{B-L}$ gauge symmetry.

The RH neutrinos are well motivated to explain the observed neutrino masses [15]. They are also necessary to introduce $B - L$ as an anomaly-free gauge symmetry.

The $U(1)_{B-L}$ is one of the most popular gauge extensions as we can see from the plethora of the literature on the subject. (For very limited instances, see Refs. [18–25].) It has a strong motivation especially in the SUSY framework: (i) It is the only possible flavor-independent Abelian gauge extension of the SM/MSSM without introducing exotic fermions (except for the RH neutrinos which are well motivated themselves by neutrino masses). (ii) It can originate from grand unification theory models such as $SO(10)$ and E_6. (iii) The radiative $B - L$ symmetry breaking, similarly to the radiative EW symmetry breaking, in SUSY may be achievable [19]. (iv) It can contain matter parity $(-1)^{3(B-L)}$, which is equivalent to R parity $(-1)^{3(B-L)+2S}$, as a residual discrete symmetry [25].

In particular, the MSSM already carries the R parity in order to stabilize the proton and the LSP DM candidate. When a discrete symmetry does not have a gauge origin, it may be vulnerable from the Planck scale physics [26]. Therefore it is more than natural to assume a $U(1)_{B-L}$ gauge symmetry, which is a gauge origin of the R parity.

Once an Abelian gauge symmetry is introduced in the SUSY models, its natural scale is set to be the TeV scale. This is because the masses of sfermions (such as stop) get an extra D-term contribution from a new $U(1)$ gauge symmetry and we need to make sure the sfermion scale does not exceed the TeV scale in order to keep the SUSY as a solution to the gauge hierarchy problem. Since a much lighter scale $U(1)$ with an ordinary size coupling should have been discovered by the collider experiments, we can see that (roughly) the TeV scale is the right scale for the new $U(1)$ gauge symmetry in SUSY.

Therefore, replacing the R parity with the TeV scale $U(1)_{B-L}$ gauge symmetry is one of the most natural and economic extensions of the MSSM. One of the direct consequences of this model is the existence of a TeV scale Z' gauge boson, which couples to both quarks and leptons with specific charges (B for all quarks/squarks and $-L$ for all leptons/sleptons). We assume one of the RH sneutrinos is the LSP. It does not couple to any SM gauge boson, but it does couple to the Z' gauge boson.

It would be appropriate to comment about more general cases at this point, before we discuss our main findings. The aforementioned attractiveness does not exclusively apply to the $B - L$. Some mixtures with the hypercharge Y [that is, $(B - L) + \alpha Y$ with some constant α] or lepton flavor dependent $U(1)$ gauge symmetry ($B - x_i L$) [27] are also known to be anomaly-free without introducing exotic fermions, and can have the matter parity as a residual discrete symmetry. (For some references about discrete symmetries from a gauge origin, see Refs. [28–32].) It would not be difficult to distinguish them with the LHC experiments though. The forward-backward asymmetry can tell about the Z' couplings [33,34]. The $B - L$ is vectorial which can distinguish itself from the axial coupling provided by the Y in the forward-backward asymmetry measurement. The lepton flavor dependence of couplings can be easily seen by comparing the dilepton Z' resonance signals [27].

III. CORRELATION OF TWO EXPERIMENTS

In this section, we discuss the interplay between two experiments: the dilepton Z' search at the LHC and the direct DM search experiments.

We will not consider the relic density constraints in our study. We are mainly interested in establishing the correlation between the LHC and the direct DM search with minimal assumptions. The relic density constraint in principle depends on the cosmological assumptions (for example, whether the DM was thermally in equilibrium in the early Universe or not). Furthermore, the channels to reproduce the right DM relic density are not unique: it may involve Z' as well as its superpartner $\tilde{Z}'$. The former suggests the RH sneutrino LSP DM mass is quite close to a half of the Z' mass, but the latter does not suggest it. (See Ref. [12] for details.) However, once the RH sneutrino is confirmed by our suggested interplay of the LHC and the direct DM search, one can compare the measured DM mass with those that can satisfy the relic density constraint to test consistency with the standard cosmology.

The direct DM search experiments such as CDMS [35] and XENON [36] can detect the DM by observing the signal from the nuclear recoil. For the RH sneutrino LSP DM, which is a SM singlet, it is mediated by the Z'. [See Fig. 1(a).] Following the approach of Ref. [12], we can see that the effective Lagrangian for the direct DM search in our framework is given by

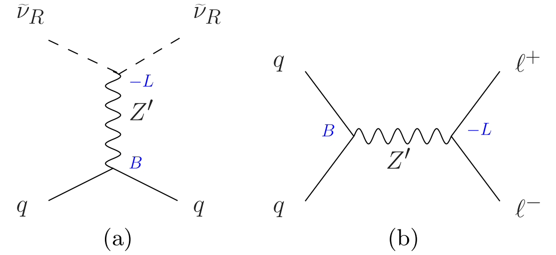

FIG. 1 (color online). (a) Sneutrino LSP dark matter direct search using nuclear recoil. (b) Dilepton Z' resonance at the LHC.

$$\mathcal{L} = i\frac{g_{Z'}^2}{M_{Z'}^2}(-1)(\tilde{\nu}_R^* \partial_\mu \tilde{\nu}_R - \partial_\mu \tilde{\nu}_R^* \tilde{\nu}_R) \sum_{i=u,d} \left(\frac{1}{3}\right) \bar{q}_i \gamma_\mu q_i. \quad (1)$$

The spin-independent cross section per nucleon via a Z' gauge boson exchange, in the nonrelativistic limit, is given by

$$\sigma_{\text{nucleon}}^{\text{SI}} = \frac{(Z\lambda_p + (A-Z)\lambda_n)^2}{\pi A^2} \mu_n^2, \quad (2)$$

where the μ_n ($\simeq m_{\text{proton}}$ for $m_{\tilde{\nu}_R} \gg m_{\text{proton}}$) is the effective mass of the nucleon and the DM. In general, the u and d quarks would have different couplings to the Z', and the cross section would depend on the detector type. Under $B - L$, however, the u and d quarks carry the same charge, and the Z' couplings to proton and neutron are the same $\lambda_p = \lambda_n = -\frac{g_{Z'}^2}{M_{Z'}^2}$. Thus Eq. (2) has a simple form of

$$\sigma_{\text{nucleon}}^{\text{SI}} = \left(\frac{g_{Z'}^2}{M_{Z'}^2}\right)^2 \frac{\mu_n^2}{\pi} \quad (3)$$

which depends only on the $g_{Z'}/M_{Z'}$ regardless of the detector type.

The process at the LHC that is directly correlated with the direct search is the di-sneutrino Z' resonance process ($q\bar{q} \to Z' \to \tilde{\nu}_R \tilde{\nu}_R^*$), whose observation would be practically impossible since it does not leave anything but the missing energy. Nevertheless, a typical dilepton Z' resonance ($q\bar{q} \to Z' \to \ell^+\ell^-$) can reveal the relevant information, because all leptons and sleptons carry the same charge ($-L$), though the spin and mass of the final particles are different. [See Fig. 1(b).] If we neglect the effect of the analysis cuts, the dilepton Z' resonance cross section for the $B - L$ model is determined by 3 parameters: mass of Z' ($M_{Z'}$), width of Z' ($\Gamma_{Z'}$), and gauge coupling constant ($g_{Z'}$).

The details of the dilepton Z' resonance at the hadron collider was elegantly analyzed in Ref. [37], although the focus was given for the $p\bar{p}$ collider. In the narrow width approximation, one can write down the dilepton Z' resonance cross section as

$$\sigma_{\text{Dilepton}} \equiv \sigma(pp \to Z' \to \ell^+\ell^-) = \frac{\pi g_{Z'}^2}{48s}\left[2\cdot\left(\frac{1}{3}\right)^2 w_u + 2\cdot\left(\frac{1}{3}\right)^2 w_d\right]\text{Br}(Z' \to \ell^+\ell^-), \quad (4)$$

where the functions w_u and w_d includes the parton distribution function information for the u and d quarks, respectively. (See Ref. [37] for details.) The branching ratio can be written as

$$\text{Br}\,(Z' \to \ell^+\ell^-) = \frac{g_{Z'}^2 M_{Z'}}{24\pi\Gamma_{Z'}}\left[2\cdot(-1)^2\right]. \quad (5)$$

With $M_{Z'}$ and $\Gamma_{Z'}$ fixed, the σ_{Dilepton} is proportional to $g_{Z'}^4$, the same dependence as the direct detection cross section $\sigma_{\text{nucleon}}^{\text{SI}}$. While $\sigma_{\text{nucleon}}^{\text{SI}}$ is proportional to $M_{Z'}^{-4}$, the σ_{Dilepton} carries different and more complicated dependence on the mass $M_{Z'}$. The contribution to the σ_{Dilepton} from the Z' propagator is $[(M_{l^+l^-}^2 - M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2]^{-1} \approx \pi\delta(M_{l^+l^-}^2 - M_{Z'}^2)/M_{Z'}\Gamma_{Z'}$ in the narrow width approximation. The dependence of σ_{Dilepton} on parton distribution functions further makes the $M_{Z'}$ dependence more complicated. Moreover, the σ_{Dilepton} also depends on the total width $\Gamma_{Z'}$ and is therefore implicitly dependent on how many Z' decay channels are open given the specific spectrum of the model, which is an irrelevant factor for $\sigma_{\text{nucleon}}^{\text{SI}}$.

An appropriate quantity for the examination of the correlation is the ratio of two cross sections $\sigma_{\text{nucleon}}^{\text{SI}}/\sigma_{\text{Dilepton}}$. The gauge coupling cancels and the ratio only depends on the mass and width of Z'. In practice, with signal events observed, the mass and total width can be determined by fitting the resonance peak to the Breit-Wigner form $1/[(M_{l^+l^-}^2 - M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2]$. Thus, we can confirm the RH sneutrino LSP DM by checking if the experimental results and theoretical predictions of the $\sigma_{\text{nucleon}}^{\text{SI}}/\sigma_{\text{Dilepton}}$ are consistent. (We will discuss it further in the following section.) This method to identify the RH sneutrino LSP DM using the interplay of the LHC and the direct DM search experiments is our main finding in this paper.

Before the presentation of numerical analysis in the next section, we briefly comment about the experimental bounds and the LHC discovery potential of the model here. A dedicated study of this has been carried out in Ref. [22], where the bounds on $g_{Z'}$ and $M_{Z'}$ from LEP [38] and the recent Tevatron search [39,40] have been discussed [41], and the reaches at the LHC of 7, 10, and 14 TeV with various luminosity have been explored. According to Ref. [22], the LHC will probe a large portion of the region with $g_{Z'}$ larger than 0.01 and $M_{Z'}$ within a few TeV. The value of $\sigma_{\text{nucleon}}^{\text{SI}}$ in the major portion of such parameter region is larger than 10^{-48} [cm^2]. It would be explored by the upcoming direct detection experiments, at SNOLAB and DUSEL, for instance, if their precision can be improved by another 2 to 3 orders of magnitude beyond the current most stringent bounds from XENON100 [36]. We therefore conclude that there is a large common region in the $g_{Z'}$-$M_{Z'}$ plane that will be probed in both experiments. It is thus possible to test the model by the correlations of these two phenomenological aspects.

IV. NUMERICAL ANALYSIS

In the following, we discuss the dilepton resonance production cross section $\sigma_{\rm Dilepton}$ and the ratio $\sigma^{\rm SI}_{\rm nucleon}/\sigma_{\rm Dilepton}$ as functions of the mass $M_{Z'}$ for different values of width $\Gamma_{Z'}$.

Taking into account the decay modes to SM particles only, we find the width of Z' is roughly $\Gamma^{\rm SM}_{Z'} \approx 0.2 g^2_{Z'} M_{Z'}$. With all the possible decay channels included, the total width $\Gamma_{Z'}$ depends on the full mass spectrum, with the $\Gamma^{\rm SM}_{Z'}$ setting the minimum value. For the purpose of illustration, we will take $\Gamma_{Z'}/M_{Z'} = 3\%$ and 6% in the analysis.

For the simulation of the dilepton resonance production process $pp \to Z' \to l^+ l^-$ at the LHC, we use the CTEQ6.1L parton distribution functions [44]. We adopt the event selection criteria with the basic cuts [45]

$$p_{T_l} > 20 \text{ GeV}, \qquad |\eta_l| < 2.5, \tag{6}$$

and we further impose a cut on the invariant mass of lepton pair

$$|M_{l^+l^-} - M_{Z'}| < 3\Gamma_{Z'}. \tag{7}$$

The cross sections $\sigma_{\rm Dilepton}$ normalized by gauge coupling for the process $pp \to Z' \to l^+ l^-$ at the LHC of 7, 10, and 14 TeV, with cuts in Eq. (6) and (7) imposed, are shown in Fig. 2.

In Fig. 3, we show the ratios $\sigma^{\rm SI}_{\rm nucleon}/\sigma_{\rm Dilepton}$, for various center of mass energies 7, 10, and 14 TeV at the LHC, as functions of $M_{Z'}$ for $\Gamma_{Z'}/M_{Z'} = 3\%$, 6%. As the gauge coupling cancels, the ratio only depends on the mass $M_{Z'}$ and width $\Gamma_{Z'}$ of Z'.

The future direct detection experiments will reach the sensitivity beyond the 10^{-45} cm^2 level. The future running of the LHC at 7, 10, and 14 TeV will have integrated luminosity ranging from a few fb^{-1} to a few 100 fb^{-1}. Assuming the background is negligible compared to the signal as is the case here, the discovery at the LHC at 3σ and 5σ significance requires 5 and 15 events, respectively. The LHC with integrated luminosity of 1 fb^{-1} (100 fb^{-1}) will be able to probe the cross section at the 10 fb (0.1 fb) level. If positive signals are observed in both experiments, and they obey the predicted ratio as shown in Fig. 3, it should be taken as a rather strong hint for the sneutrino LSP DM scenario. Otherwise, the model can be ruled out if positive signals are observed in either or both experiments but are not consistent with the predicted ratio shown in Fig. 3.

The mass and width of Z' need to be determined from the LHC data for the purpose of this examination of the ratio of cross sections. Since the momentum resolution of $e^\pm$ is better than $\mu^\pm$ in the high P_T region, the e^+e^- final state is more favorable than the $\mu^+\mu^-$ final state for this purpose. For e^+e^- at high energy, the energy resolution at both ATLAS and CMS should be good enough for the determination of the Z' width. For example, the energy resolution of $e^-(e^+)$ with energy higher than 200 GeV at CMS is better than 0.5% [46], well below the width $\Gamma_{Z'}$ above $3\% M_{Z'}$. There are also errors in the determination of width arising from fitting to the Breit-Wigner form with a limited number of events. A quantitative study of it is beyond the scope of this paper. However, this needs to be considered when a comparison of cross sections is carried out in the future after positive signals are observed.

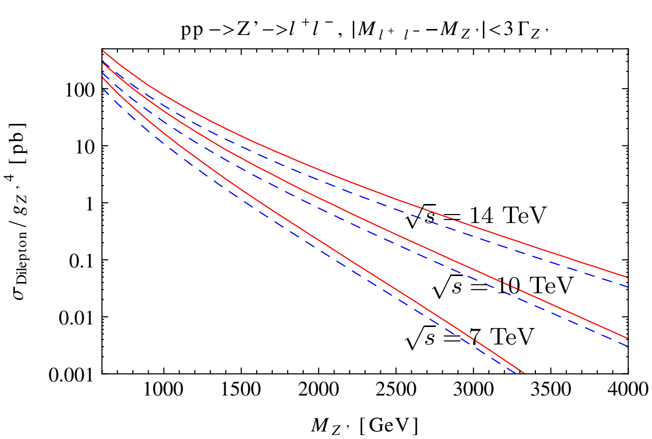

FIG. 2 (color online). The coupling normalized cross section of $pp \to Z' \to l^+l^-$ ($l = e, \mu$) with invariant mass cut $|M_{l^+l^-} - M_{Z'}| < 3\Gamma_{Z'}$ imposed in the $U(1)_{B-L}$ model at the LHC with $\sqrt{s} = 7$, 10, and 14 TeV. The Z' width $\Gamma_{Z'}$ is taken as 3% (red solid line) and 6% (blue dashed line) of the mass $M_{Z'}$.

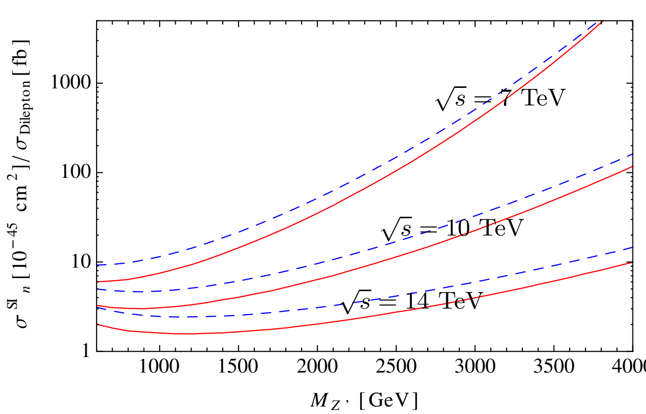

FIG. 3 (color online). The ratio of cross sections of the spin-independent sneutrino-nucleus elastic scattering $\tilde{\nu}_R q \to \tilde{\nu}_R q$ (normalized to a single nucleon) in the DM direct detection experiments and the process $pp \to Z' \to l^+l^-(|M_{l^+l^-} - M_{Z'}| < 3\Gamma_{Z'})$ at the LHC at 7, 10, and 14 TeV. The Z' width $\Gamma_{Z'}$ is taken as 3% (red solid line) and 6% (blue dashed line) of the mass $M_{Z'}$.

V. SUMMARY

We study the sneutrino LSP DM scenario in the SUSY $U(1)_{B-L}$ model in the LHC and direct detection experiments. The sneutrino only couples to the Z', making it extremely hard to test this model at the LHC. However, since charged leptons and sneutrinos carry the same $B-L$ charge, the charged lepton $e^{\pm}$, $\mu^{\pm}$ can serve as a good replacement of the sneutrino for diagnosing purposes.

Following this spirit, we propose to test this scenario at the LHC with the process $pp \to Z' \to l^+l^-(l = e, \mu)$. The cross section of this process is tightly correlated with that of the sneutrino-nucleus spin-independent elastic scattering in the direct detection experiments. Since a large common region of the parameter space will be probed by both experiments, the correlation can be used to confirm or rule out such a model. In particular, with the signal events of dilepton resonance production observed at the LHC and with the Z' mass and width extracted from the data, the ratio $\sigma^{\rm SI}_{\rm nucleon}/\sigma_{\rm Dilepton}$ is fixed in this scenario and can be examined against the experimental data.

ACKNOWLEDGMENTS

We thank T. Han and F. Paige for helpful discussions. We further thank T. Han for providing the Fortran code HANLIB that is used in the Monte Carlo simulations. This work is supported by the U.S. DOE under Grant Contract No. DEAC02-98CH10886.

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