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$B - L$ heavy neutrinos and neutral gauge boson Z' at the LHC

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We explore possible signatures for heavy neutrinos and a neutral gauge boson, Z', in the TeV scale $B - L$ extension of the Standard Model with inverse seesaw mechanisms at the Large Hadron Collider. We show that, due to new decay channels of Z' into heavy/inert neutrinos, the LHC stringent bounds imposed on the Z' mass can be significantly relaxed. We analyze the pair production of heavy neutrinos decaying to four leptons plus two neutrinos, four jets plus two leptons, or three leptons plus two jets and one neutrino. We show that the $4l + 2\nu$ is the most promising decay channel for probing both Z' and heavy neutrinos at the LHC.

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The solid evidence for neutrino oscillation, pointing toward nonvanishing neutrino masses, is one of the firm hints for physics beyond the Standard Model (SM). Neutrinos are strictly massless in the SM due to two main reasons: (i) the absence of right-handed neutrinos and (ii) the SM having an exact global baryon minus lepton ($B - L$)-number conservation. The minimal extension of the SM, based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$, can account for the light neutrino masses through either the type-I seesaw or inverse seesaw (IS) mechanism [1,2]. In the type-I seesaw mechanism, right-handed neutrinos acquire Majorana masses at the $B - L$ symmetry breaking scale, which can be related to the supersymmetry breaking scale, i.e., $\mathcal{O}(1)$ TeV [3]. While in IS, these Majorana masses are not allowed by $B - L$ gauge symmetry, and another pair of SM gauge singlet fermions with tiny masses [$\mathcal{O}(1)$ keV] must be introduced. One of these two singlet fermions couples to a right-handed neutrino and is involved in generating the light neutrino masses. The other singlet (usually called an inert neutrino) is completely decoupled and interacts only through the $B - L$ gauge boson; therefore, it may account for warm dark matter [4,5] . In both scenarios, this model predicts several testable signals at the LHC through the new predicted particles: Z' [neutral gauge boson associated with the $U(1)_{B-L}$], extra Higgs [an additional singlet state introduced to break the gauge group $U(1)_{B-L}$ spontaneously], and three (type-I) or six (IS) heavy neutrinos, ν_h, that are required to cancel the associated anomaly and are necessary for the consistency of the model.

In this paper, we aim to provide a comprehensive analysis for the LHC potential discovery of Z' and ν_h's predicted in the $B - L$ extension of the Standard Model (BLSM) with IS neutrino mechanisms. We show that the possibility Z' decays into a pair of heavy/inert neutrinos is the salient feature of this class of model and provides a very important signature for probing both Z' and ν_h of the BLSM at the LHC. Because of the presence of these channels, one finds that the branching ratio of $Z' \to l^+ l^-$ is suppressed with respect to the one in other models of Z', like what is called sequential SM (SSM), which is usually considered a benchmark in experimental searches for the Z' gauge boson [6,7]. Therefore, the recent LHC stringent bounds imposed on Z' mass can be relaxed in the BLSM. We also investigate the LHC discovery potential for the heavy neutrinos in the BLSM through its decay into leptonic, hadronic, and semileptonic decay channels. We provide a phenomenological study for the decay channels with four leptons plus two SM-like neutrinos, four jets plus two leptons, and three leptons plus two jets and one SM-like neutrino. We show that the decay of Z' into two heavy neutrinos that decay to four hard leptons and large missing energy due to the associated neutrinos is very clean with a negligible SM background. It is important to mention that our analysis is a completion of the previous work on type-I BLSM [8,9] and the first of its kind in analyzing the phenomenological implications of the inverse seesaw BLSM.

In the BLSM with the IS mechanism, one assumes that the SM singlet scalar χ, which spontaneously breaks $U(1)_{B-L}$, has $B - L$ charge $= -1$. Also, three pairs of SM singlet fermions, $S_{1,2}$ with $B - L$ charge $= \mp 2$, respectively, are introduced. Therefore, the corresponding Lagrangian of the leptonic sector is given by [2]

$$\begin{aligned}\mathcal{L}_{B-L} = & -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + i\bar{\ell}_L D_\mu \gamma^\mu \ell_L + i\bar{e}_R D_\mu \gamma^\mu e_R \\ & + i\bar{\nu}_R D_\mu \gamma^\mu \nu_R + i\bar{S}_1 D_\mu \gamma^\mu S_1 + i\bar{S}_2 D_\mu \gamma^\mu S_2 \\ & + (D^\mu \phi)^\dagger D_\mu \phi + (D^\mu \chi)^\dagger D_\mu \chi - V(\phi, \chi) \\ & - (\lambda_e \bar{\ell}_L \phi e_R + \lambda_\nu \bar{\ell}_L \tilde{\phi} \nu_R + \lambda_S \bar{\nu}^c_R \chi S_2) + \text{H.c.}. \qquad (1)\end{aligned}$$

After the $B - L$ and the electroweak symmetry breaking, through nonvanishing vacuum expectation values of χ:

$|\langle\eta\rangle| = v'/\sqrt{2}$ and ϕ: $|\langle h\rangle| = v/\sqrt{2}$, one finds that the neutrino Yukawa interaction terms lead to the mass terms [2]

$$\mathcal{L}_m^\nu = m_D \bar{\nu}_L \nu_R + M_N \bar{\nu}_R^c S_2 + \text{H.c.}, \tag{2}$$

where $m_D = \frac{1}{\sqrt{2}}\lambda_\nu v$ and $M_N = \frac{1}{\sqrt{2}}\lambda_S v'$. Here, v' is assumed to be of order TeV and $v = 246$ GeV. Moreover, one may generate very small Majorana masses for $S_{1,2}$ fermions through possible nonrenormalizable terms like $\bar{S}_1^c \eta^{\dagger 4} S_1/M^3$ and $\bar{S}_2^c \eta^4 S_2/M^3$. Hence, the Lagrangian of neutrino masses, in the flavor basis, is given by

$$\mathcal{L}_m^\nu = \mu_s \bar{S}_2^c S_2 + (m_D \bar{\nu}_L \nu_R + M_N \bar{\nu}_R^c S_2 + \text{H.c.}), \tag{3}$$

where $\mu_s = \frac{v'^4}{4M^3} \lesssim 10^{-6}$ GeV. Therefore, the neutrino mass matrix can be written as $\mathcal{M}_\nu \bar{\psi}^c \psi$ with $\psi = (\nu_L^c, \nu_R, S_2)$, and $\mathcal{M}_\nu$ is given by

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_N \\ 0 & M_N^T & \mu_s \end{pmatrix}. \tag{4}$$

Note that, in order to avoid a possible large mass term mS_1S_2 in the Lagrangian Eq. (1) that would spoil the above inverse seesaw structure, one assumes that the SM particles ν_R, χ, and S_2 are even under a Z_2 symmetry, while S_1 is an odd particle. Also other discrete symmetry may be used to avoid other possible nonrenormalizable terms [10].

The diagonalization of the mass matrix Eq. (4) leads to the following light and heavy neutrino masses, respectively:

$$m_{\nu_l} = m_D M_R^{-1} \mu_s (M_R^T)^{-1} m_D^T, \tag{5}$$

$$m_{\nu_H}^2 = m_{\nu_{H'}}^2 = M_R^2 + m_D^2. \tag{6}$$

Thus, one finds that the light neutrino masses can be of order eV, with a TeV scale M_R if $\mu_s \ll M_R$ and order 1 Yukawa coupling λ_ν. Such large coupling is crucial for testing the BLSM with inverse seesaw and probing the heavy neutrinos at the LHC. From Eq. (5), one finds that the 9×9 neutrino mass matrix $\mathcal{M}_\nu$ can be diagonalized by the matrix V, i.e., $V^T \mathcal{M}_\nu V = \mathcal{M}_\nu^{\text{diag}}$ [10], where

$$V = \begin{pmatrix} V_{3\times 3} & V_{3\times 6} \\ V_{6\times 3} & V_{6\times 6} \end{pmatrix}, \tag{7}$$

with $V_{3\times 3}$ given by

$$V_{3\times 3} \simeq \left(1 - \frac{1}{2} F F^T\right) U_{\text{MNS}}. \tag{8}$$

The matrix $V_{3\times 6}$ is defined as

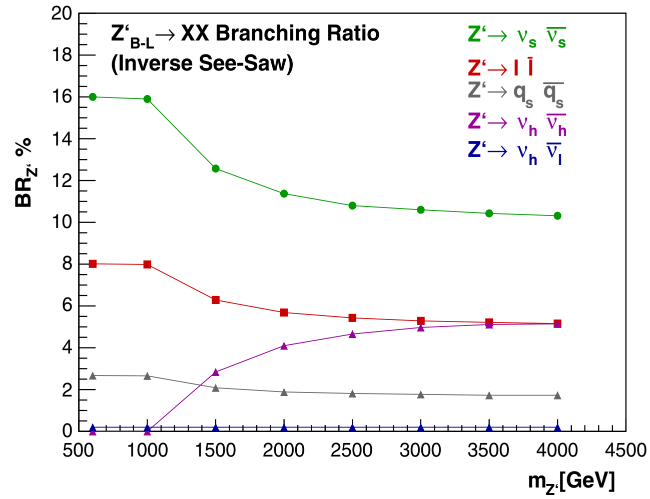

FIG. 1 (color online). Branching ratios of Z' decays in BLSM with IS as function of $M_{Z'}$.

$$V_{3\times 6} = (\mathbf{0}_{3\times 3}, F) V_{6\times 6}, \qquad F = m_D M_R^{-1}. \tag{9}$$

Finally, $V_{6\times 6}$ is the matrix that diagonalizes the $\{\nu_R, S_2\}$ mass matrix. To guarantee that the first three eigenvalues of the light neutrino mass matrix $\mathcal{M}_\nu$ are consistent with the physical light neutrinos, one writes the Dirac neutrino mass matrix m_D as

$$m_D = U_{\text{MNS}} \sqrt{m_{\nu_l}^{\text{diag}}} R \sqrt{\mu_s^{-1}} M_N, \tag{10}$$

where R is an arbitrary orthogonal matrix.

As shown in Ref. [10], the mixings between light and heavy neutrinos are of order $\mathcal{O}(0.01)$. Therefore, the decay widths of these heavy neutrinos into SM fermion are sufficiently large. It is worth mentioning that the second SM-singlet fermion, S_1, remains light, with mass given by

$$m_{S_1} = \mu_s \simeq \mathcal{O}(1)\ \text{keV}, \tag{11}$$

where S_1 is a kind of inert neutrino that has no mixing with active neutrinos. It can be a good candidate for warm dark matter as emphasized in Ref. [5].

TABLE I. $Z' \to ee$ cross sections times branching ratios at different masses.

		σ_{B-L} [fb] with IS		
$M_{Z'}$ [GeV]	σ_{SSM} [fb]	$g_{B-L} = g_Z$	$g_{B-L} = 0.5$	$g_{B-L} = 0.8$
1000	170	6	41	105.7
1500	21.7	0.58	4.5	13.2
2000	3.4	0.087	0.72	2.3
2500	0.8	0.015	0.15	0.58
3000	0.21	0.003	0.04	0.19

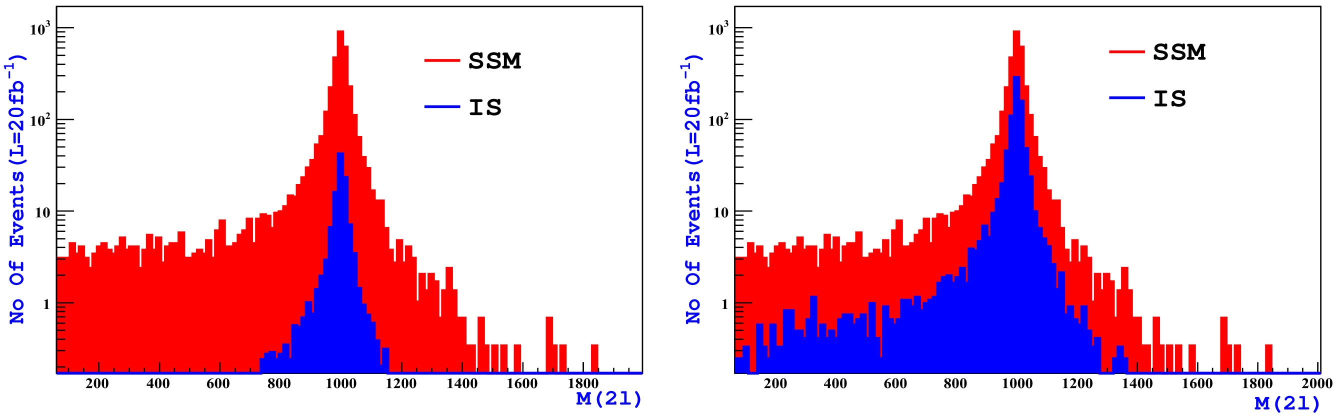

FIG. 2 (color online). Invariant mass of dielectron from Z' decaying to the electron pair in the case of the SSM (red) and in the case of the IS BLSM (blue) at $g_{B-L} = g_Z$ (left) and $g_{B-L} = 0.5$ (right).

Now, we study the signatures of the extra neutral gauge boson Z' in the BLSM with IS mechanisms at the LHC. The possibility of Z' decay into a pair of heavy/inert neutrinos would enlarge the total decay width of Z'. Therefore, the $\mathrm{BR}(Z' \to l^+l^-)$ is suppressed with respect to the prediction of the SSM, which is usually considered a benchmark for the experimental search of Z'. Figure 1 shows the branching ratios of all Z' decays. According to this figure, the branching ratios of Z' decays are given by

$$\sum_l \mathrm{BR}(Z' \to \bar{l}l + v_l\bar{v}_l) \sim 20.4\%$$
$$\sum_q \mathrm{BR}(Z' \to q\bar{q}) \sim 9.2\%$$
$$\sum_{\nu_h} \mathrm{BR}(Z' \to \nu_h\bar{\nu}_h) \sim 24\%$$
$$\sum_{\nu_s} \mathrm{BR}(Z' \to \nu_s\bar{\nu}_s) \sim 41.4\%, \qquad (12)$$

where $l = e$ or μ, $q = u, d, s$, or c, while ν_h refers to the six heavy neutrinos and ν_s refers to the three inert neutrinos.

It is worth noting that in our model the Z' cross sections that were used to derive the ATLAS and CMS current mass limit could be simply rescaled by a factor of $(g_{B-L}/g_Z)^2 \times (1 - \mathrm{BR}(Z'\,\text{decay new channels}))$. If $g_{B-L} = g_Z$ and $\mathrm{BR}(Z'\,\text{decay new channels}) = 0$, this reproduces the SSM cross sections that were used by ATLAS and CMS. Considering the scaling of cross sections, the current Z' mass limits will be lowered by a factor of $\sigma_{B-L}(Z' \to ll)/\sigma_{\mathrm{SSM}}(Z' \to ll)$. This result is consistent with the conclusion of Ref. [11].

If $M'_Z = 1000$ GeV were considered, $\mathrm{BR}(Z' \to l^+l^-) \sim 14\%$ and the $\sigma \times \mathrm{BR} = 16$ fb when $g_{B-L} = g_Z = 0.188$ and the $\sigma \times \mathrm{BR} = 82$ fb when $g_{B-L} = 0.5$, while in the SSM, the $\mathrm{BR}(Z' \to l^+l^-) \sim 7.6\%$ that gives $\sigma \times \mathrm{BR} = 340\ \mathrm{fb}^{-1}$ for both electron and muon channels. In this respect, the experimental limits $M_{Z'} \gtrsim 2.5$ TeV [6] (2.8 TeV) [7] will be lowered to 0.247 of its value when $g_{B-L} = 0.5$. Such a lower Z' mass is the sticking signature of the BLSM with the IS. In another scenario like the type I BLSM, the $\mathrm{BR}(Z' \to l^+l^-) \sim 28.6\%$ and $\sigma \times \mathrm{BR} = 814$ fb that leads to increasing the current mass limit at $g_{B-L} = 0.5$. Table I gives $\sigma \times \mathrm{BR}(Z' \to ee)$ for the SSM and BSLM with the IS at different g_{B-L}. Figure 2 shows the invariant mass of the dilepton from Z' decay to lepton pair in the IS BLSM (blue) and in SSM (red) with 20 fb^{-1} at $\sqrt{s} = 8$ TeV, where lepton here refers to electron only and considering Z' mass of 1000 GeV as a benchmark point.

The dominant production mode for the heavy neutrinos at the LHC would be through the Drell–Yan mechanism, with Z'. The mixing between light and heavy neutrinos generates new couplings between the heavy neutrinos, the weak gauge bosons W and Z, and the associate leptons. These couplings are crucial for the decay of the heavy neutrinos. The main decay channel is through the W gauge boson, which may decay leptonicaly or hadronically, a Feynman diagram is given in Fig. 3. In the case of the multileptons final state, one ends with four leptons plus missing energy $(4l + 2\nu_l)$, while in the case of the multi-hadronic final-state states, one ends with four jets plus two leptons $(4J + 2l)$. In addition, it is also possible to have mixed final states with $(3l + 2j + \nu_l)$. If two flavors of the

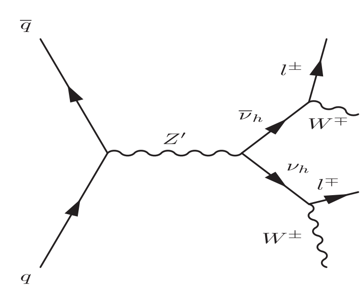

FIG. 3. $q\bar{q} \to Z' \to \nu_h\bar{\nu}_h \to WWll$ Feynman diagram.

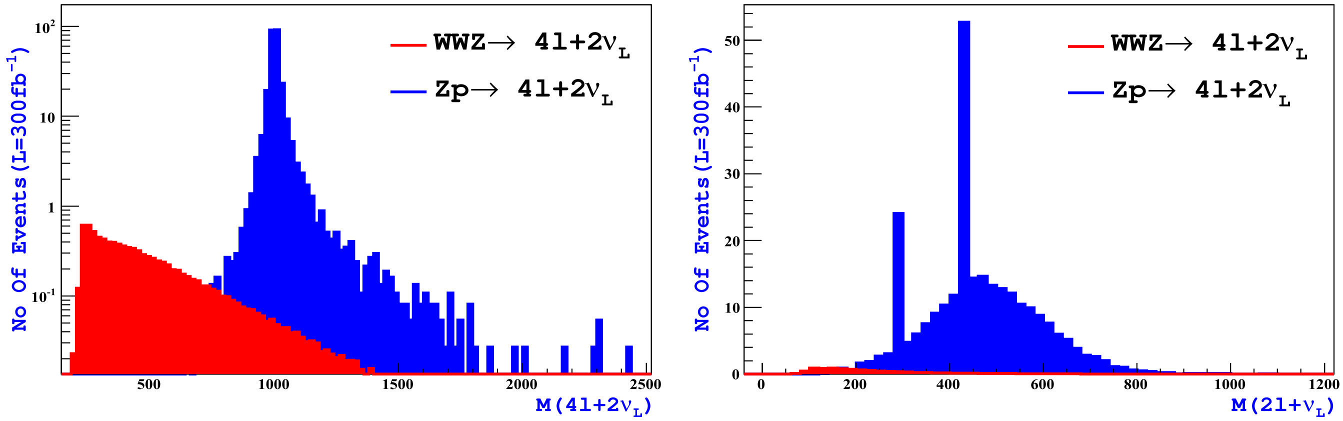

FIG. 4 (color online). (Left) the invariant mass of the four leptons plus two light neutrinos distribution from Z' decay. (Right) the invariant mass of two leptons plus one light neutrino from heavy neutrino decay. The expected SM background is included as well.

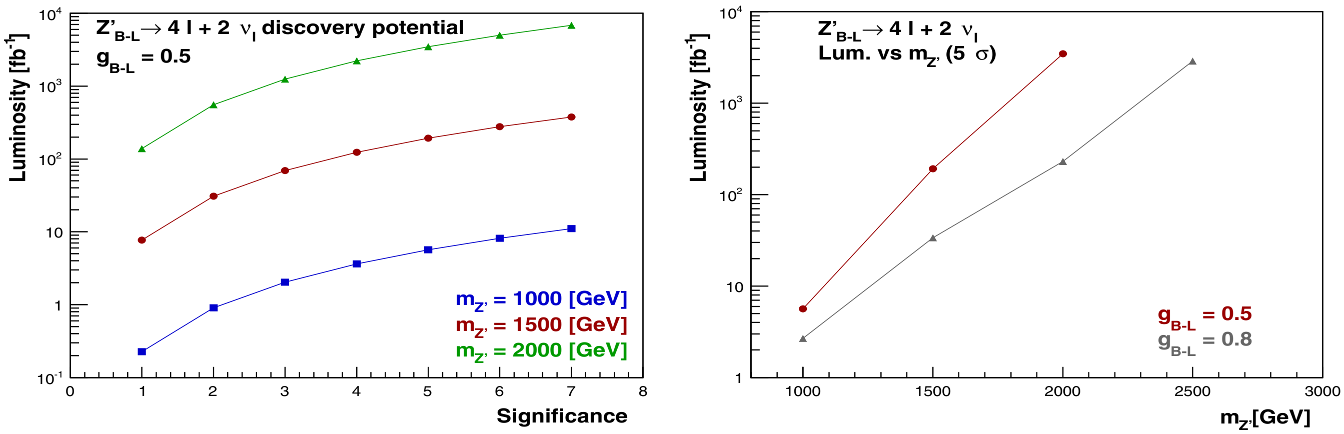

FIG. 5 (color online). For the $4l + 2\nu$ final state, the integrated luminosity of the data needed for (left) the 1–7σ statistical significance discovery at $g_{B-L} = 0.5$ for different $M_{Z'}$ and (right) a 5σ discovery as a function of $\mathrm{Mass}_{Z'}$ at $g_{B-L} = 0.188$, $g_{B-L} = 0.5$, and $g_{B-L} = 0.8$.

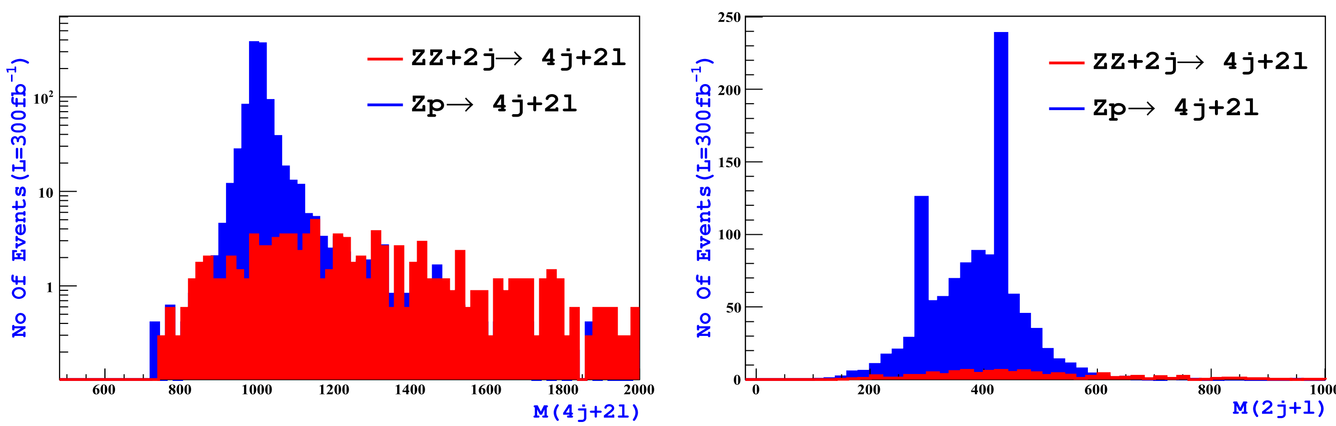

FIG. 6 (color online). (Left) the invariant mass of the four jets plus two leptons distribution from for signal as well as expected SM background. (Right) the invariant mass of two jets plus one lepton from heavy neutrino decay.

TABLE II. Number of events after initial set of cuts, in case $Z' \to 4j + 2l$.

Cut	Signal	ZZjj	$t\bar{t}$	WW
Initial number of events[a]	2042	28913	650000	80000
$p_T > 150$ GeV	1088	102	0	0

[a]Weighted events, the initial generated number of events is 10 k events in the signal and 100 k events for the background sample.

heavy neutrinos are assumed to be degenerate in mass, one gets the same final states for the produced heavy neutrino pair with similar event rates. This will double the number of final-state events, but on the other hand, it makes it difficult to distinguish between final-state leptons. Therefore, throughout the current study, we considered the nondegenerate heavy neutrino masses considering the interference between every two different flavors.

In our analysis, we have used SARAH [12] and SPheno [13] to build the model. The matrix-element calculation and events generation are derived by MadGraph [14]. Finally, we used Pythia [15] to simulate the initial- and final-state radiation, fragmantation, and hadronization effects. We considered the following benchmark: $M_{Z'} = 1000$ GeV, $M_{\nu_4} = M_{\nu_5} = 287$ GeV, $M_{\nu_6} = M_{\nu_7} = 435$ GeV, and $M_{\nu_8} = M_{\nu_9} = 652$ GeV. In addition, the following cuts are assumed: a lower transvers-momentum, p_T, cut of 20 GeV (10 GeV) was set on final-state jets (electrons), and a higher pesudorapidity, η, cut of 4 (2) was set on jets (electrons); finally, the separation between two jets (electrons) $R_{jj}(R_{ll})$ was set to be 0.4 (0.2).

(i) $4l + 2\nu$ *final state*: the main advantage of this channel is that it is almost background free. The main SM background comes from the three gauge boson WWZ production with $\sigma(WWZ) \sim 200$ fb at 14 TeV [16]. In Fig. 4, we show the generator level invariant mass of four leptons plus two light neutrinos from Z' with WWZ background and also the invariant mass of two leptons plus a light neutrino from heavy neutrino decay. In the right plot, it is clear that the heaviest two neutrinos (ν_8 and ν_9) are decayed of shell when the $M_{Z'} = 1000$ GeV. These figures indicate that the decay channel $4l + 2\nu$ is quite a clean channel and quite promising for probing both Z' and ν_h using only a few cuts to extract signals from the background. The number of events left after the set of cuts mentioned above is 270 signal events and 10 background events.

In Fig. 5 (left panel), we display the integrated luminosity of the data needed for 1–7σ statistical significance discovery for $g_{B-L} = 0.5$ and $M_{Z'} =$ 1000, 1500, and 2000 GeV in the right panel, while in the left plot, we plot the integrated luminosity of the data needed for a 5σ discovery as a function of $M_{Z'}$ for $g_{B-L} = 0.5$ and $g_{B-L} = 0.8$. If one considers the case of $g_{B-L} = 0.188$, which corresponds to the case of the SSM, one finds that the luminosity needed for a 5σ discovery is of order 390 fb^{-1} for $M_{Z'} =$ 1000 GeV and about 8.4×10^5 for $M_{Z'} =$ 2500 GeV. This value of luminosity is incredibly high and far beyond the expected data of the LHC experiments during the foreseen run II. Therefore, one may conclude that the scenario of the SSM is rather unfavored not only for the reason of using Z' decays to the dileptons channel but also for using a SM-like value for coupling.

(ii) $4j + 2l$ *final state*: Here, both W's decay hadronically, and because of the higher branching ratio of $W \to jj' \sim 60\%$, we expect a higher number of events than the previous channel ($4l + 2\nu$). The irreducible SM background is due to $ZZ + jj$, where one of the Z's decays to two leptons, while the other Z decays to quark and anti-quark ($Z \to l\bar{l}, Z \to j\bar{j}$).

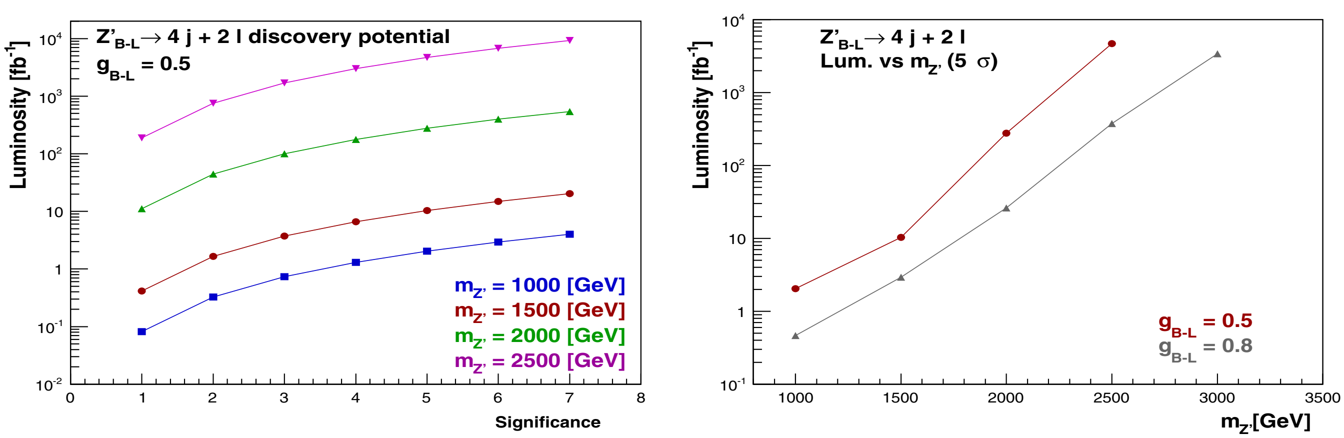

FIG. 7 (color online). For the $4j + 2l$ final state, the integrated luminosity of the data needed (left) for the 1–7σ statistical significance discovery at $g_{B-L} = 0.5$ for different $M_{Z'}$ and (right) for a 5σ discovery as a function of Mass$_{Z'}$ at $g_{B-L} = 0.188$, $g_{B-L} = 0.5$, and $g_{B-L} = 0.8$.

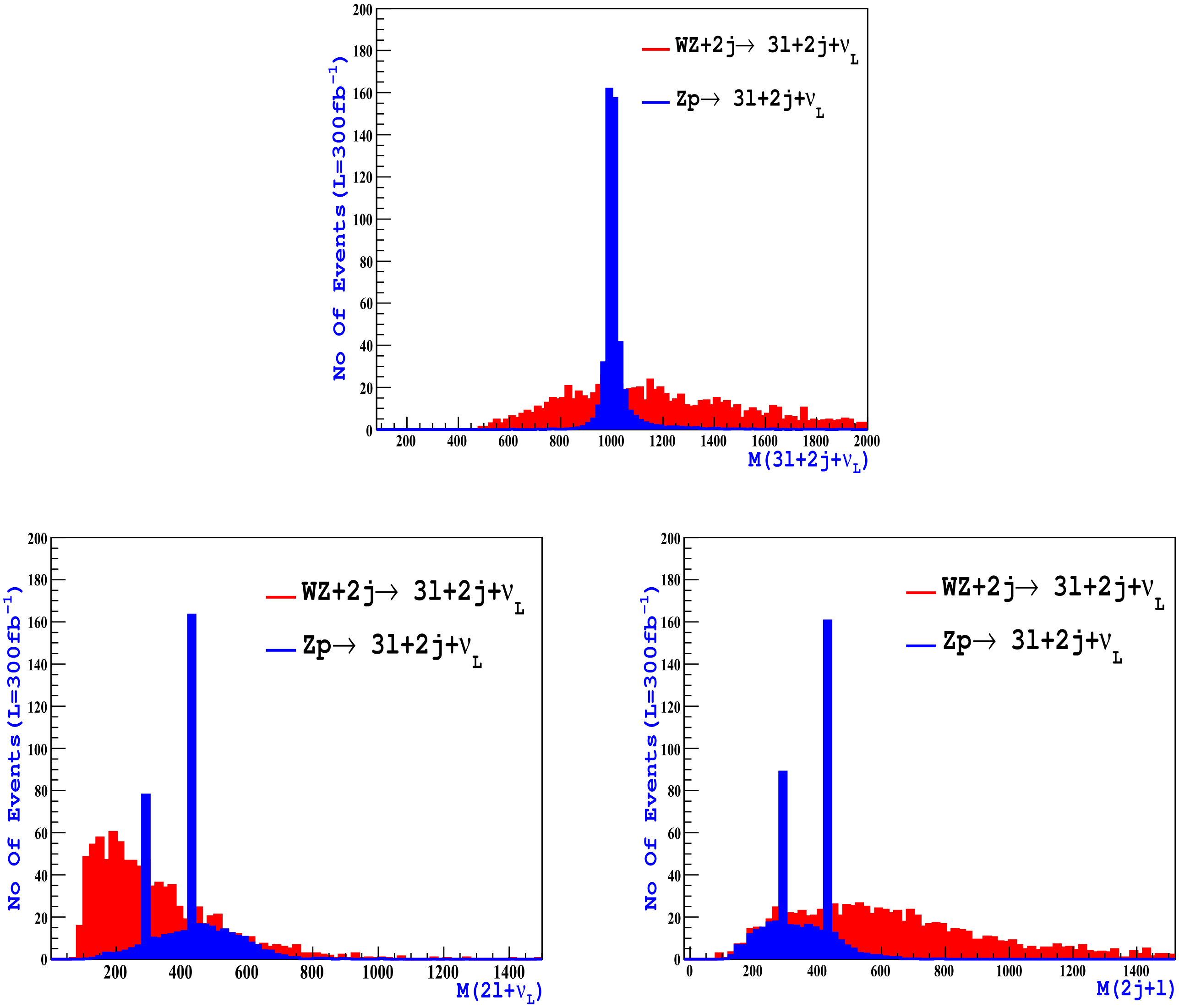

FIG. 8 (color online). (Top) the invariant mass of $3l + 2j + \nu_l$ distribution for both the signal and expected background. (Bottom) the invariant mass of the heavy neutrino that decays to $2l + \nu$ (bottom left) or to $2j + l$ (bottom right) and its background.

The contribution due to $Z +$ jets could be neglected. In addition, there are two reducible backgrounds coming from $t\bar{t}$ and WW. In Fig. 6 we present the invariant mass of $4j + 2l$ (left) and also that of $2j + l$ from the signal and background, after applying an additional p_T cut of 150 GeV on the two p_T-leading leptons. As in the $4l + 2\nu$ channel, the heaviest two neutrinos (ν_8 and ν_9) decay off shell when $M_{Z'} = 1000$ GeV. The number of events left after cuts for the signal and backgrounds is listed in Table II. The integrated luminosity of the data needed for the 1–7σ statistical significance discovery is shown in Fig. 7 (left panel) at $g_{B-L} = 0.5$ and $M_{Z'} = 1000$, 1500, 2000, and 2500 GeV. The presence of four jets in the final state of the signal makes SM backgrounds dominated. However, with a 256 cut $P_T > 150$ GeV, the signal is fully enhanced over the SM backgrounds, which makes the 5σ discovery predictable in the near future at the LHC as shown in Fig. 7 (right panel).

(iii) $3l + 2j + \nu_l$ *final state*: In the semileptonic case in which one of *the* W's decays hadronically and the other decays to $l + \nu_l$, the main background is $WZ + jj$. In the case of $WZ + jj$ associated

TABLE III. Number of events after the initial set of cuts, in case $Z' \to 3l + 2j + \nu_l$.

Cut	Signal	WZjj
Initial number of events[a]	769	37975
$p_T > 150$ GeV	475	910

[a]Weighted events, the initial generated number of events is 10 k events in the signal and 100 k events for the background sample.

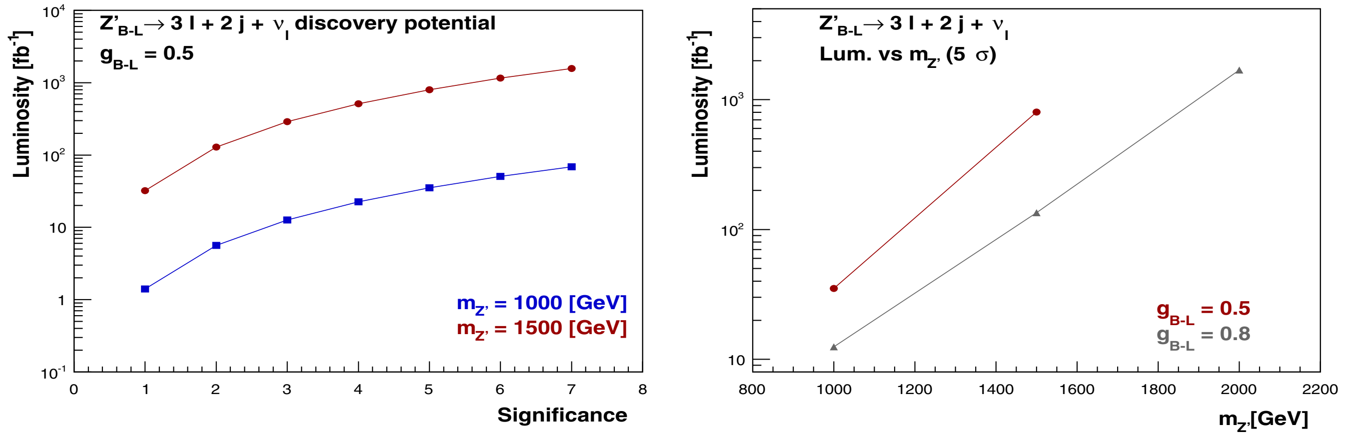

FIG. 9 (color online). For the $3l + 2j + \nu_l$ final state, the integrated luminosity of the data needed (left) for the 1–7σ statistical significance discovery at $g_{B-L} = 0.5$ for different $M_{Z'}$ and (right) for a 5σ discovery as a function of $\mathrm{Mass}_{Z'}$ at $g_{B-L} = 0.188$, $g_{B-L} = 0.5$, and $g_{B-L} = 0.8$.

production, three leptons can be generated from the subsequent leptonic decays of the two gauge bosons. In Fig. 8, we show the invariant mass of $3l + 2j + \nu_l$ (left) for both the signal and background. Also, we show the invariant mass of $2l + \nu_l$ (middle) and that of $2j + \nu_l$ (right). Again, an additional $p_T >$ 150 GeV cut was set on the two p_T-leading leptons. Table III lists the number of events left after cuts for the signal and backgrounds. In Fig. 9 (lift panel), we plot the integrated luminosity of the data needed for the 1–7σ statistical significance discovery at $g_{B-L} =$ 0.5 and $M_{Z'} = 1000$, 1500, and 2000 GeV. In the right panel, we show the integrated luminosity of the data needed for a 5σ discovery as a function of $M_{Z'}$ at $g_{B-L} = 0.5$ and $g_{B-L} = 0.8$.

In summary, we have analyzed the striking signatures of probing the heavy neuterinos, ν_h, and neutral gauge boson, Z', in the TeV-scale $B - L$ extension of the standard model with the inverse seesaw mechanism at the LHC. We have emphasized that in this type of model, where Z' may decay into new channels of heavy and light inert neutrinos, the current experimental limits on the Z' mass from the LHC are relaxed. For instance, the limit on the Z' mass can be lowered to 0.247 of the current experimental value if $g_{B-L} = 0.5$. We have provided detailed analysis for the pair production of heavy jeutrinos and their possible decay to four leptons and missing energy, due to two light neutrinos or to four jets and two leptons or to three leptons and two jets and missing energy due to one light neutrino. In our analysis, we have considered the following benchmark: $M_{Z'} = 1$ TeV, $M_{\nu_4} = M_{\nu_5} = 287$ GeV, $M_{\nu_6} = M_{\nu_7} = 435$ GeV, and $M_{\nu_8} = M_{\nu_9} = 652$ GeV. In addition, the following cuts have been used: transverse-momentum $p_T \gtrsim 20(10)$ GeV on final-state jets (leptons), pesudorapidity $\eta \gtrsim 4(2)$ on jets (leptons), and separation between two jets (leptons) R_{ij} $(R_{ll}) \sim 0.4(0.2)$. In the $4j + 2l$ channel and $3l + 2j + \nu_l$ channel, an additional p_T cut of 150 GeV on the two p_T-leading leptons has also been applied. We showed that the $4l + 2\nu$ channel is almost free from the SM background, and therefore it is the most promising decay channel for probing both Z' and heavy neuterinos at the LHC. We have shown also the Z' discovery potential at 14 TeV center-of-mass energy for the three decay channels under study.

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