Prospect of heavy right-handed neutrino search at energies reached at the Superconducting Super Collider and CERN Large Hadron Collider

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Right-handed neutrinos with a large Majorana mass occur naturally in the left-right-symmetric model. We explore the prospect of such a heavy right-handed neutrino search via W_R decay in the like-sign dilepton channel at the Superconducting Super Collider (SSC) and CERN Large Hadron Collider (LHC). The standard model background can be effectively eliminated by suitable lepton p_T and isolation cuts without affecting the signal cross section seriously. In this way it seems possible to explore the bulk of the parameter space $0<M_{N_R}<M_{W_R}$, with M_{W_R} going up to 3000 (2000) GeV at energies reached at the SSC (LHC).

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I. INTRODUCTION

The precision measurements at the CERN e^+e^- collider LEP have revealed that the Glashow-Salam-Weinberg standard model (SM) of unified electroweak interactions is indeed in very good agreement with the experimental data [1]. Yet there are several aspects of the SM which are regarded as unnatural and thus indicative of the physics beyond the SM. For example, in the SM parity violation is introduced by hand. Moreover, the present experimental bounds on the neutrino masses [2] indicate that these masses, even if they exist, must be very small compared to the masses of the other fermions present in the theory. There is no natural explanation of such small neutrino masses within the framework of the SM. In the left-right-symmetric (LRS) model [3] both these problems can be taken care of naturally. In this model parity is broken spontaneously at a high-energy scale characteristic of the masses of the $SU(2)_R$ gauge bosons (W_R and Z_R). Moreover, the vacuum expectation value (VEV) of the $SU(2)_R$-triplet Higgs bosons, which make the right-handed gauge bosons heavy, suppresses the light neutrino masses [4] via the celebrated seesaw mechanism [5]. With three generations of quarks and leptons, the model contains three heavy Majorana neutrinos of right chirality in addition to the three light neutrinos of left chirality, which are routinely observed in low-energy leptonic and semileptonic interactions. While the former dominantly couples to the W_R, the latter couples to the standard W_L boson.

An interesting experimental signature of these heavy Majorana neutrinos ($N_l, l=e,\mu,\tau$) is their lepton-number-violating interactions. For example, each of these neutrinos can decay into the corresponding charged leptons of both signs with equal branching ratios (neglecting *CP* violation). A characteristic of these decays is the production of like-sign dileptons (LSD) at hadron colliders via reactions such as

$$PP \rightarrow W_R \rightarrow l^+ N_l \rightarrow l^+ l^+ q\overline{q'} \;, \tag{1}$$

$$PP \rightarrow Z_R \rightarrow N_l N_l \rightarrow l^+ l^+ q\overline{q'} q'' \overline{q'''} \;. \tag{2}$$

The possibility of testing one of the most stringent conservation laws of particle physics, therefore, opens up with the advent of high-energy hadron colliders. This was pointed out a long time back [6]. Subsequently this has been studied by several authors [7,8]. The major SM background to the LSD signature arises via the reactions

$$PP \rightarrow Q\overline{Q} \rightarrow (q' l^+ \nu)(\overline{q'} q_i \overline{q_j}) \;, \quad \overline{q'} \rightarrow l^+ \nu \overline{q''} \;, \tag{3}$$

where Q stands for a heavy quark (t,b, or c), while the q' refers to the corresponding decay quark (b,c, or s) which arise due to the decays of the heavy quarks via charged-current interactions. If the produced b quark fragments into a neutral B meson (B_d^0 or B_s^0) then LSD's may also arise due to B^0-$\overline{B}^0$ mixing. Obviously the viability of detecting lepton number violation via the LSD depends on the relative size of the signal and the background.

The cross section for the signal strongly depends on the mass of the W_R (M_{W_R}) and the mass of the heavy neutrino (denoted generically as M_{N_R}). There are several lower limits on W_R derived on the basis of different assumptions. (i) A strong low-energy constraint on W_R comes from the K_L-K_S mass difference. From the box diagram with both W_L and W_R exchanges a lower bound of 1.6 TeV is obtained [9]. For this one has to assume the so-called manifest LR symmetry, i.e., the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrices of the left- and right-handed sectors (V_L and V_R) are the same, which is rather artificial. If manifest LR symmetry is not assumed [10], the bound on W_R is relaxed; even with restrictions on fine-tunings, it can be as low as 300 GeV [11]. (ii) A bound on M_{W_R} comes from the direct search by the Collider Detector at Fermilab (CDF) Collaboration [12]. Assuming that the new charged gauge bosons decay into leptons and stable neutrinos of negligible masses, events with high-p_T electrons or muons and large missing energy are looked for. Their lower bound $M_{W_R} > 520$ GeV, will, however, not apply in models which we are analyzing where the W_R couples only to heavy neutrinos which can decay within the detector. (iii) A bound independent of the above assumptions comes from the upper bound on $\Delta\rho$ (the deviation of the ρ parameter from unity) obtained from LEP data [13]. Using the popular choices of the Higgs fields in the literature it can be shown that a conservative lower limit on W_R is approximately 500 GeV. Models with exotic Higgs multiplets can, however, evade this bound. In view of the above discussions we find it reasonable to restrict our analysis to $W_R \geq 500$ GeV. The bound on M_{N_R} is even more uncertain. The limits from neutrinoless double β decay can only restrict M_{W_R}, M_{N_R}, and $(V_R)_{ud}$ (the u-d element of the right-handed quark mixing matrix) simultaneously [11,14]. Thus the mass limit always depends on the choice of $(V_R)_{ud}$. However, purely from the theoretical argument of vacuum stability one can show that $M_{W_R} \geq M_{N_R}$ [14]. We shall restrict our analysis to this case.

As we shall discuss below, the main background after imposing suitable kinematical cuts comes from $t\bar{t}$ production. The main uncertainty in estimating the background, therefore, arises due to the yet unknown top-quark mass. The present limits can be summarized as follows: (i) $m_t \geq 91$ GeV from direct mass limits from the Fermilab Tevatron [15]; (ii) $m_t = 140 \pm 30$ GeV from the analysis of precision electroweak data from LEP [1,16]. The observation of B^0-$\bar{B}^0$ mixing [17] favors a large m_t, although the precise value of the lower bound is somewhat model dependent.

The prospect of massive neutrino search via the LSD signal was considered in Ref. [8] along with the SM background. However, their background analysis was done for a top-quark mass of 50 GeV, which now appears to be unrealistic in view of the above limits. More importantly, they could explore only a limited range of W_R and N_R masses since they did not exploit the most effective kinematical cut for the suppression of this background, namely, the one coming from lepton isolation [18]. It is well known that the angle between a lepton and its accompanying jet is necessarily small for leptons arising from the decays of b and c quarks. Since the SM background inevitably involves one such decay, it is natural to expect that it will be severely suppressed by the lepton isolation cut, while the signal remains essentially unaffected. In fact, as we shall discuss below, it is a combination of the isolation cut and the p_T cut on the lepton which is most effective in enhancing the signal-to-background ratio [19]. As a result one can probe a much larger region of W_R and N_R masses than shown in [8]. This work is devoted to a systematic exploration of these mass limits which can be probed at SSC and LHC.

The paper is organized as follows. In Sec. II we briefly discuss our computation of the signal and background processes for the LSD cross section. The results are presented in Sec. III. Our conclusions are summarized in Sec. IV.

II. THE SIGNAL AND BACKGROUND PROCESSES FOR LSD

It has already been shown in Ref. [8] that the largest cross section for the production of right-handed neutrinos and the resulting LSD's arises from the process given in Eq. (1) of the last section. Reactions given in Eq. (2) also yield LSD's accompanied by four jets. However, the contribution of this process is significantly smaller over most of the parameter space of interest, as it involves two heavy neutrinos in the final state. We shall therefore focus our attention on reaction (1) in obtaining the region in the (M_{W_R}, M_{N_R}) plane that can yield an observable LSD signature at the SSC or CERN Large Hadron Collider (LHC). In any case, a simultaneous analysis of both of the above reactions can only improve the conservative search limits estimated by us. We have done a parton-level Monte Carlo calculation for the production and decay sequence

$$u\bar{d} \to W_R^+ \to l^+ + N_l \ , \quad N_l \to l^+ q\bar{q}' \cdots \ , \tag{4}$$

where the decay is via a virtual W_R with $B(N_l \to l^+ q\bar{q}') = 0.5$. The relevant formulas may be found, e.g., in Ref. [20]. Since the production cross section of W_R^+ (W_R^-) involves the up (down) quark and down (up) antiquark densities in the proton, the former dominates over the latter by approximately a factor of 2. We have therefore computed only the former cross section. In computing the cross section we have used the quark density functions given in Ref. [21], which were parametrized using the input densities of Diemoz, Ferroni, Longo, and Martinelli (DFLM) [22].

In order to make the search scenario not too complicated we have assumed that each heavy neutrino couples dominantly with one lepton species and have focused on like-sign lepton pairs of a single species (e^+e^+ or $\mu^+\mu^+$). If one assumes that N_μ is approximately degenerate in mass with N_e and considers leptons of both types, then the signal size will simply be enhanced by a factor of 2. Of course, this would not affect the signal-to-background ratio.

The most significant background comes from the $t\bar{t}$ production and decay processes

$$gg \to t\bar{t} \ , \quad t \to bl^+\nu_l \ , \quad \bar{t} \to \bar{b} \to \bar{c}l^+\nu_l \ . \tag{5}$$

We have calculated this production and decay sequence using the gluon density function of Gluck, Hofmann, and Reya (GHR) [23] as input. The resulting LSD cross section (after applying the kinetic cuts) shows a modest increase with the top-quark mass. The results presented in the following section correspond to a top-quark mass $m_t = 150$ GeV.

There is a LSD background from the $b\bar{b}$ production, arising from the corresponding sequential decay

$b \to c \to s l^+ \nu_e$. However, it is practically impossible for this sequential-decay lepton to survive the large p_T and isolation cuts. A more serious background in this case arises from B^0-$\bar{B}^0$ mixing, followed by direct semileptonic decay of both of the $\bar{B}^0$ particles. We have calculated this background assuming a B^0-$\bar{B}^0$ mixing parameter $\chi \simeq 0.15$, as measured at LEP and Tevatron energies [24]. The $b\bar{b}$ production cross section is calculated for the next-to-leading-order QCD process [25]

$$gg \to g b\bar{b} \ , \tag{6}$$

which dominates over the lowest-order $b\bar{b}$ cross section in the large p_T region of interest. In addition, the lowest-order $b\bar{b}$ background can be easily distinguished from the signal by the back-to-back configuration of the decay leptons.

We have also checked the dependence of the above signal and background cross sections on the choice of quark and gluon density functions. Taking these density functions from the Eichten-Hinchliffe-Lane-Quigg (EHLQ) (set 2) parameterization [26] gives a somewhat larger signal cross section, while the background remains practically the same.

III. RESULTS

Figs. 1–3 show the LSD signal of Eq. (4) for various W_R and N_R masses along with the dominant background from $t\bar{t}$ [Eq. (5)]. An isolation cut of

$$E^{\mathrm{T}}_{\mathrm{AC}} < 10 \text{ GeV} \tag{7}$$

has been applied to both the leptons, where $E^{\mathrm{T}}_{\mathrm{AC}}$ represents the total transverse energy accompanying the lepton track within an angle of 0.4 rad [27]. Figure 1 shows the signal and the background LSD cross sections against the p^T of the softer lepton p_2^T for $p_{1,2}^T > 20$ GeV. The background decreases rapidly with increasing p_2^T for two reasons. (1) The lepton coming from the sequential decay $\bar{t} \to \bar{b} \to c l^+ \nu_l$ has a relatively soft p^T distribution. (2) More importantly, the isolation cut becomes more effective with increasing p^T of the lepton coming from b decay, as pointed out in [19]. Indeed, to a first approximation, there is a kinematic bound [19]

$$E^{\mathrm{T}}_{\mathrm{AC}} > \frac{p_l^T m_c^2}{m_b^2 - m_c^2} - \frac{m_b^2 - m_c^2}{4 p_l^T} \ , \tag{8}$$

which implies an upper bound of $p_l^T < 100$ GeV for $m_b = 5$ GeV, $m_c = 1.5$ GeV, and $E^{\mathrm{T}}_{\mathrm{AC}} < 10$ GeV. This is reflected in Fig. 1, where the background cross section goes down by one order of magnitude by increasing the lepton p^T cut from 20 to 40 GeV, and by two orders by increasing it to 60 GeV. It may not be possible in practice to decrease the background by two orders of magnitude due to effects like jet fragmentation, which have not been taken into account above. A detailed investigation of these effects is in progress. However, it is reasonable to expect on the basis of existing simulations [27] that the background can be decreased by at least one order of magnitude by increasing the lepton p^T cut to 40 GeV, say. As we shall see below, this will be adequate for our purpose, since a background of this level can be

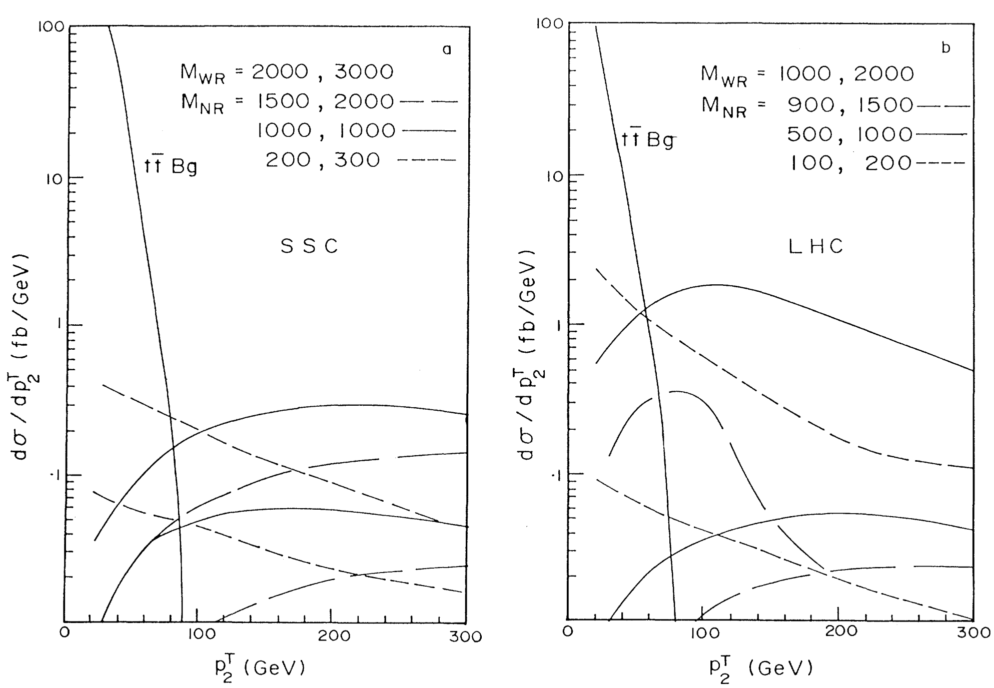

FIG. 1. Isolated dilepton (e^+e^+ or $\mu^+\mu^+$) cross section is shown against the p^T of the softer lepton at (a) SSC and (b) LHC energies. The signal cross sections are shown for different choices of the W_R and N_R masses, along with the dominant background from $t\bar{t}$ cascade decay. The upper (lower) set of signal curves correspond to the lower (higher) W_R mass.

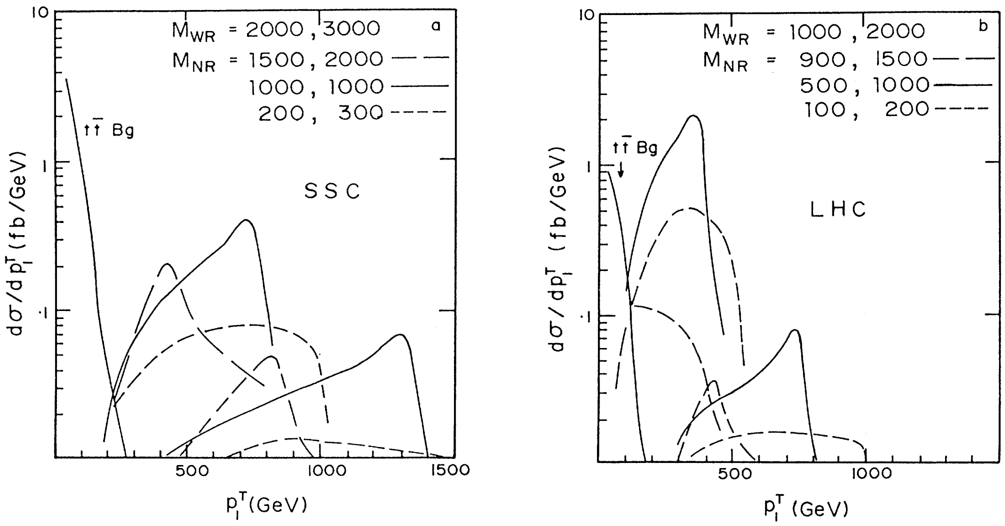

FIG. 2. Isolated dilepton cross section, with a $p^T > 40$ GeV cut for both the leptons, is shown against the p^T of the harder lepton at (a) SSC and (b) LHC energies. The cross-section curves are as in Fig. 2.

effectively eliminated by other kinematic cuts. It should be mentioned here that the $p_2^T > 40$ GeV cut has little effect on the signal cross section except when $M_{N_R} \simeq M_{W_R}$ or when M_{N_R} is very small. In the former case the lepton produced in association with N_R is too soft to survive the $p_2^T > 40$ GeV cut, while in the latter case the lepton coming from the N_R decay does not survive the isolation cut.

Figure 2 shows the signal and background LSD cross sections against the p^T of the harder lepton p_1^T, with the $p_{1,2}^T > 40$ GeV cut. Although the magnitude of the background is still large compared to the signal for most of the parameter space, the two can be easily separated from their p_1^T distributions. While the background decreases rapidly with p_1^T, the signal shows a Jacobian peak at [28]

$$p_1^T = (M_{W_R}^2 - M_{N_R}^2)/2M_{W_R} . \quad (9)$$

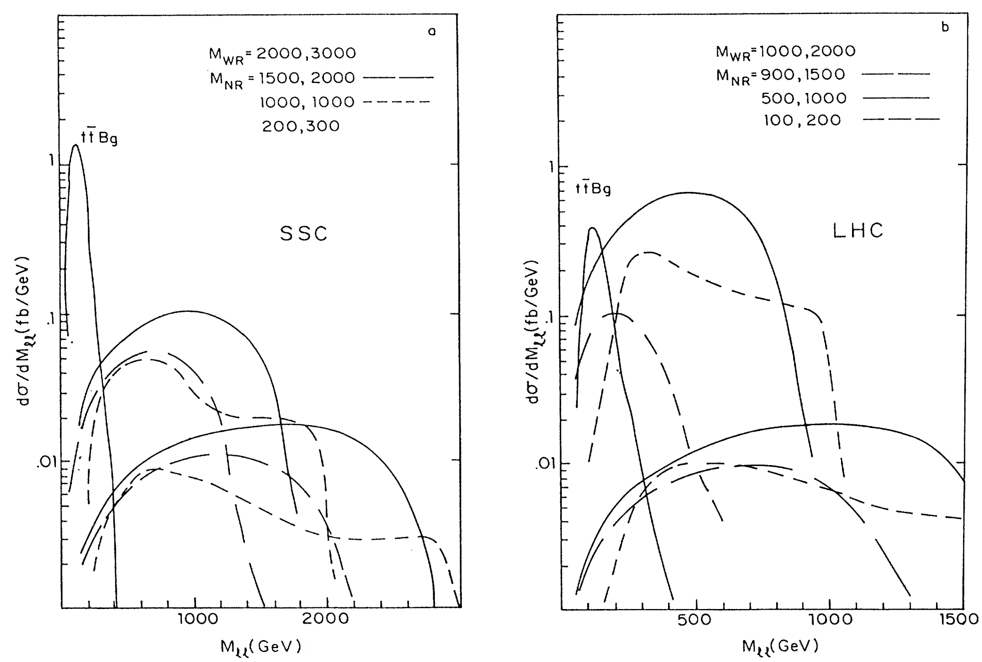

FIG. 3. Isolated dilepton cross section, with a $p^T > 40$ GeV cut on both the leptons, is shown as a function of the dilepton invariant mass at (a) SSC and (b) LHC energies. The cross-section curves are as in Fig. 2.

TABLE I. Expected size of like-sign dilepton (e^+e^+ or $\mu^+\mu^+$) cross sections, with $p_l^T > 40$ GeV and the isolation cut described in the text, for various W_R and N_R masses.

Energy	SSC ($\sqrt{s}=40$ TeV)						LHC ($\sqrt{s}=16$ TeV)					
M_{W_R} (GeV)		2000			3000			1000			2000	
M_{N_R} (GeV)	200	1000	1500	300	1000	2000	100	500	900	200	1000	1500
$\sigma_{l^+l^+}$ (fb)	46	117	48	12	33	16	110	350	30	10	21	8

Thus a $p_1^T > 200$ GeV (150 GeV) cut in Fig. 2(a) [2(b)] will effectively eliminate the background without affecting the signal. Alternatively one can also separate the signal and the background from the dilepton invariant-mass distribution shown in Fig. 3. Of course, we do not see any particular reason to prefer the dilepton invariant-mass distribution over the p^T distribution of the harder lepton.

We have checked that the LSD background from $b\bar{b}$ production and mixing is comparable to that from $t\bar{t}$ for the $p_{1,2}^T > 20$ GeV cut. Increasing the cut to $p_{1,2}^T > 40$ GeV, however, suppresses the $b\bar{b}$ background more strongly than the $t\bar{t}$ for the following reason. While for the $t\bar{t}$ case one of the decay leptons is hard and isolated and hence not affected by the increasing p^T cut, the cut affects both the decay leptons for the $b\bar{b}$ case. As a result, the LSD background from $b\bar{b}$ is an order of magnitude smaller than that from $t\bar{t}$ for the $p_{1,2}^T > 40$ GeV cut. Moreover, the p_1^T distribution in this case is even softer than that of the $t\bar{t}$ background shown in Fig. 2. Therefore we have not displayed the $b\bar{b}$ background.

It is clear from the above discussions that the right-handed neutrino signal can be effectively separated from the standard model background in the isolated LSD channel with $p_{1,2}^T > 40$ GeV. Thus, the prospect of heavy right-handed neutrino search is essentially controlled by the signal size in this channel. This is shown in Table I for $M_{W_R} = 2000$, 3000 GeV (1000, 2000 GeV) at SSC (LHC) energy. For each W_R mass the signal cross section is shown for three representative N_R masses in the range $0 < M_{N_R} < M_{W_R}$. It is clear from this table that one can explore the bulk of the mass range $M_{N_R} < M_{W_R}$ with M_{W_R} going up to 3000 GeV (2000 GeV) at SSC (LHC), with the expected luminosity of 10 events/fb. With the high-luminosity option of 100 events/fb, the LHC search can also go up to $M_{W_R} = 3000$ GeV. Finally, the search can be extended to somewhat larger values of M_{W_R}, but only for a limited range of M_{N_R} around $M_{W_R}/2$.

The distinctive features of the signal are (1) clustering of the total invariant mass of the two jets and the two leptons at M_{W_R} and (2) clustering of the invariant mass of the two jets with one of the leptons at M_{N_R}. The right-handed W and neutrino masses can be easily obtained from these mass peaks. For most of the parameter space of M_{N_R} the mass peak is expected to show up in the invariant mass of the two jets with the softer lepton. For $M_{N_R} \simeq M_{W_R}$, however, the lepton produced in association with N_R becomes softer than the lepton from N_R decay [Eq. (4)], so that the N_R mass peak shows up in the invariant mass of the two jets with the harder lepton. This is illustrated in Fig. 4.

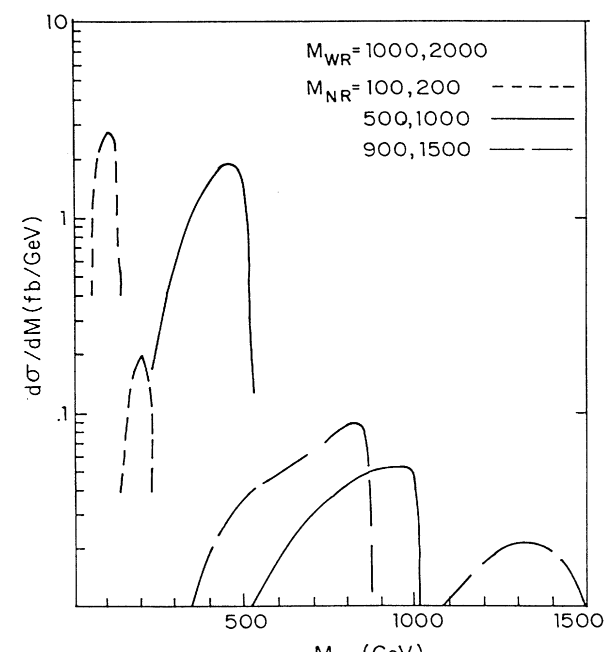

FIG. 4. Distribution of the signal cross section in the invariant mass of the two jets and the softer lepton (the harder lepton for $M_{N_R} \simeq M_{W_R}$, shown by the long-dashed curves) at LHC energy.

IV. SUMMARY

In the left-right-symmetric models one expects heavy right-handed neutrinos with mass $M_{N_R} \le M_{W_R}$. We explore the prospect of searching for such neutrinos at the SSC and/or LHC. The most prominent source of N_R production is via W_R decay, resulting in a characteristic signature of like-sign dileptons. The standard model background to this channel can be eliminated by a combination of lepton p^T and isolation cuts without any serious reduction in the signal. Thus the search limit is essentially controlled by the size of the signal. One expects a viable signal for most of the mass range $M_{N_R} < M_{W_R}$, with M_{W_R} going up to 3000 GeV at SSC and 2000 GeV at LHC.

ACKNOWLEDGMENTS

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[28] The Jacobian peak is suppressed for $M_{N_R} \ll M_{W_R}$ (short dashed lines of Fig. 2) due to the isolation cut on the softer lepton coming from the N_R decay. A large value of p_l^T corresponds to a large value of p_T for the associated N_R and hence to a significant isolation cut on its decay lepton.