

LHC search for right-handed neutrinos in Z' models

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ABSTRACT: We consider right-handed neutrino pair production in generic Z' models. We propose a new, model-independent analysis using final states containing a pair of same-sign muons. A key aspect of this analysis is the reconstruction of the RH neutrino mass, which leads to a significantly improved sensitivity. Within the $U(1)_{(B-L)_3}$ model, we find that at the HL-LHC it will be possible to probe RH neutrino masses in the range $0.2 \lesssim M_{N_R} \lesssim 1.1$ TeV.

KEYWORDS: Beyond Standard Model, Gauge Symmetry, Neutrino Physics

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Contents

1	Introduction	1
2	Same-sign muon search	2
2.1	Benchmark model	2
2.2	SM backgrounds	3
2.3	Initial selection	4
2.4	N_R reconstruction	5
2.5	Final selection	6
3	Results	7
4	Conclusion	8

1 Introduction

The observation that neutrinos have non-zero masses requires the existence of physics beyond the Standard Model (SM). One of the simplest and most well-motivated SM extensions is the inclusion of right-handed (RH) neutrinos; the observed neutrino masses and mixings can then be explained via the Type-I see-saw mechanism [1–4]. While the small observed neutrino masses may hint at very large Majorana masses for the RH neutrinos, this need not necessarily be the case; indeed, small Yukawa couplings appear to be prevalent amongst the charged leptons. It is therefore interesting to consider the possibility that (at least some of) the RH neutrinos may be relatively light and hence be directly accessible at LHC energies.

There have already been several searches for TeV scale RH neutrinos at the LHC [5–8]. Within the minimal model, the RH neutrinos are produced via mixing with the light neutrinos (see e.g. [9, 10]), which generally leads to small production cross-sections. Although large mixing is also possible [11, 12], current LHC searches are generally not competitive with other constraints [13]. However, in many well-motivated SM extensions there can be new production mechanisms, often via the decay of a new heavy resonance. This is the case for example in left-right symmetric models [14], or a gauged $B - L$ model where the RH neutrinos can be produced through the decay of the new Z' gauge boson [15]. In this paper, we investigate the potential of (HL-)LHC searches for RH neutrino pair production via the decay of a general Z' gauge boson.

The Lagrangian in the neutrino sector is given by

$$\mathcal{L}_Y = -\bar{l}_L Y \tilde{H} N_R - \frac{1}{2} \bar{N}_R M_N N_R^c + h.c., \quad (1.1)$$

leading to three main decay modes for the RH neutrinos:

$$\begin{aligned}
 \Gamma(N_i \rightarrow l_j^\pm W^\mp) &= \frac{g^2 m_N^3}{64\pi m_W^2} |(U_{\ell N})_{ji}|^2 \left(1 - \frac{3m_W^4}{m_N^4} + \frac{2m_W^6}{m_N^6}\right), \\
 \Gamma(N_i \rightarrow \nu Z) &= \frac{g^2 m_N^3}{64\pi m_W^2} \sum_j |(U_{\ell N})_{ji}|^2 \left(1 - \frac{3m_Z^4}{m_N^4} + \frac{2m_Z^6}{m_N^6}\right), \\
 \Gamma(N_i \rightarrow \nu h) &= \frac{g^2 m_N^3}{64\pi m_W^2} \sum_j |(U_{\ell N})_{ji}|^2 \left(1 - \frac{m_h^2}{m_N^2}\right)^2,
 \end{aligned} \tag{1.2}$$

where $U_{\ell N} = U_{PMNS} m_\nu^{1/2} \Omega M_N^{-1/2}$, with Ω an arbitrary complex orthogonal matrix.¹ The lifetimes of the heavy neutrinos are then largely determined by their mass, and the mass scale of the light active neutrinos. For $m_N \lesssim 200$ GeV, they can have macroscopic decay lengths [16, 17] and are best searched for using displaced vertices [17–20]. Here, we focus on the alternative case, $m_N \gtrsim 200$ GeV.

The most promising search channel involves RH neutrino decays to charged leptons, since these give rise to clean same-sign di-lepton final states, with relatively small SM backgrounds. Preliminary studies of the di-lepton [17], tri-lepton [16] and four lepton [21] channels were performed in the context of the $B - L$ model, prior to the start of LHC running. More recently, the prospects for tri-lepton and boosted Higgs final states were investigated in [22], while searches based on neutrino jets have been proposed for when the N_R is highly boosted [23, 24]. Furthermore, current same-sign di-lepton (and tri-lepton) searches [5–8, 25] now have limited sensitivity to RH neutrino production, although limits are rarely presented in the context of Z' models.

In this work, we aim to highlight the benefits of a dedicated analysis. In particular, we demonstrate that with increased integrated luminosity it will become possible to reliably reconstruct the RH neutrino mass. Beyond providing valuable information about the mass in the event of a discovery, we show that this approach also leads to significantly improved sensitivity.

2 Same-sign muon search

In this section we propose in detail a model-independent search for RH neutrinos pair produced via the decay of a new heavy Z' resonance. We restrict our focus to the same-sign di-muon channel, due to increased backgrounds for electron final states that require a data-driven approach to reliably estimate. However, a similar search strategy could in principle be applied to $e^\pm e^\pm$ and $e^\pm \mu^\pm$ final states. The relevant process is shown in figure 1.

2.1 Benchmark model

Although our search is model-independent, we adopt a benchmark model in order to clearly demonstrate the future sensitivity. Perhaps one of the most commonly considered Z' models is gauged $B - L$, where the presence of three RH neutrinos can be further motivated by

¹For a detailed discussion of the neutrino mixing see e.g. [9].

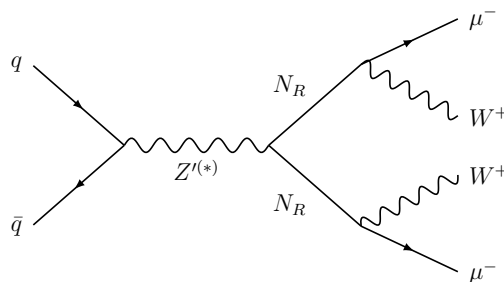


Figure 1. RH neutrino pair production via an s-channel Z' .

anomaly cancellation. However, this model is already highly constrained by $Z' \rightarrow \mu^+ \mu^-$ resonance searches. Regions of parameter space where one has sensitivity to N_R production, even at the HL-LHC, are therefore either already excluded or likely to be excluded in the near future.

We shall instead consider a related model, $U(1)_{(B-L)_3}$. This is a flavoured $B - L$ gauge symmetry under which only the third generation fermions are charged. In this case anomaly cancellation requires a single RH neutrino,² whose Majorana mass is naturally of order the $U(1)_{(B-L)_3}$ breaking scale. Further details of the model can be found in ref. [26]. Interestingly, this model admits the possibility that two additional RH neutrinos could have super-heavy Majorana masses and generate the observed baryon asymmetry via leptogenesis [27, 28]. It was also recently considered as an explanation for certain anomalies observed in rare B decays [26, 29, 30].

The coupling of the Z' to the SM fermions in this model is, in the gauge basis,

$$\mathcal{L}_{Z'} = g_{Z'_\mu} \left(\frac{1}{3} \bar{t} \gamma^\mu t + \frac{1}{3} \bar{b} \gamma^\mu b - \bar{\tau} \gamma^\mu \tau - \bar{\nu}_L \gamma^\mu \nu_L - \bar{N}_R \gamma^\mu N_R \right). \quad (2.1)$$

We assume a gauge coupling $g = 0.6$ for all our benchmark points. After $U(1)_{(B-L)_3}$ breaking and rotation to the mass basis, there may also be couplings to the first and second generation fermions. These will not play a significant role in what follows and we assume them to be small. The dominant Z' production mechanism at the LHC is then $b\bar{b} \rightarrow Z'$. Direct searches for the Z' in the $\tau\tau$ final state [31, 32] currently impose $M_{Z'} \gtrsim 900$ GeV for $g = 0.6$. Searches using the $t\bar{t}$ and $b\bar{b}$ final states do not currently provide competitive bounds.

2.2 SM backgrounds

The production of same-sign leptons is a relatively rare process within the SM and the background can be divided into two main classes. Firstly, there is the prompt background originating from decays of W , Z and t , with the dominant processes being WZ and $t\bar{t}W/\bar{t}tZ$ production. Secondly, there are non-prompt leptons produced via the decays of long-lived particles, predominantly the semi-leptonic decays of heavy flavour hadrons. In existing searches this background is determined using a data-driven approach. For large di-lepton

²For simplicity, we assume N_R decays dominantly to second generation leptons; the required coupling can be generated by $U(1)_{(B-L)_3}$ breaking (see ref. [26]).

invariant masses, which will be relevant to our analysis, the non-prompt contribution to the total background is found to be less than 15% in existing analyses [25] and will therefore be neglected in the following. Lastly, there can be additional sources of background due to lepton charge misidentification and jets misidentified as leptons. These are important for searches involving electrons, but are negligible in the di-muon channel.

In order to estimate the prompt background, we generate monte carlo event samples containing same-sign muon pairs from WZ and $\bar{t}tW/\bar{t}tZ$ production with MadGraph-2.5.4 [33] and PYTHIA-6.4 [34], followed by detector simulation with Delphes 3 [35]. These include muons arising both directly from $W/Z/t$ decays and also from subsequent decays of tau leptons. A weighted approach is used, with events generated in bins of H_T in order to ensure sufficient statistics for studies at high integrated luminosity. In the case of WZ production, events are generated with up to two additional hard jets using MLM matching [36]. The samples are generated at leading order and then normalised to the latest calculations of the total production cross-section for WZ at NNLO [37] and $\bar{t}tW/\bar{t}tZ$ at NLO [38].

2.3 Initial selection

The initial event selection closely resembles that used in the ATLAS 8 TeV same-sign lepton search [25]. We require at least one pair of isolated, same-sign muons satisfying $p_T > 25, 20 \text{ GeV}$ and $|\eta| < 2.4$. The di-muon invariant mass is also required to satisfy $M_{\mu\mu} > 15 \text{ GeV}$. We allow for the presence of additional leptons in the event, since this significantly increases the number of signal events by providing sensitivity to both the two and three muon final states, where up to one of the W bosons decays leptonically. Events containing a pair of opposite-sign, same-flavour leptons consistent with the Z mass, $|M_{ll} - m_Z| < 10 \text{ GeV}$, are vetoed in order to reduce the SM background.

The novel aspect of this analysis is the ability to reconstruct the right-handed neutrino mass. In addition to the above selections, we therefore require at least one hadronically decaying W boson candidate. Depending on the Z' mass, the W bosons from N_R decays may be sufficiently boosted to exploit jet substructure methods for W boson tagging. On the other hand, for lighter Z' masses the two jets from the W decay will be resolved separately. We allow for both possibilities in our analysis and reconstruct up to two hadronically decaying W bosons as described below.

Firstly, we identify hadronically decaying boosted W bosons following the procedure adopted by CMS for their 13 TeV analyses (e.g. [39]). We begin with jets clustered using the anti- k_T algorithm [40], as implemented in FastJet [41], with a distance parameter $R = 0.8$. These jets are further required to satisfy $p_T > 200 \text{ GeV}$ and $|\eta| < 2.5$. Jet grooming is then performed using the soft-drop algorithm [42] with $\beta = 0$ and $z_{\text{cut}} = 0.1$. For the jet to be considered as a W boson, the soft-drop jet mass is required to satisfy $65 < M_{jet} < 95 \text{ GeV}$. Finally, the N-subjettiness [43] ratio $\tau_{21} = \tau_2/\tau_1$ should satisfy $\tau_{21} < 0.75$, which provides further discrimination against gluon and single-quark initiated jets while maintaining $\sim 100\%$ signal efficiency for large Z' masses.

For events containing fewer than two reconstructed boosted W bosons, we also reconstruct W bosons decaying into two resolved jets. Jets are clustered using the anti- k_T

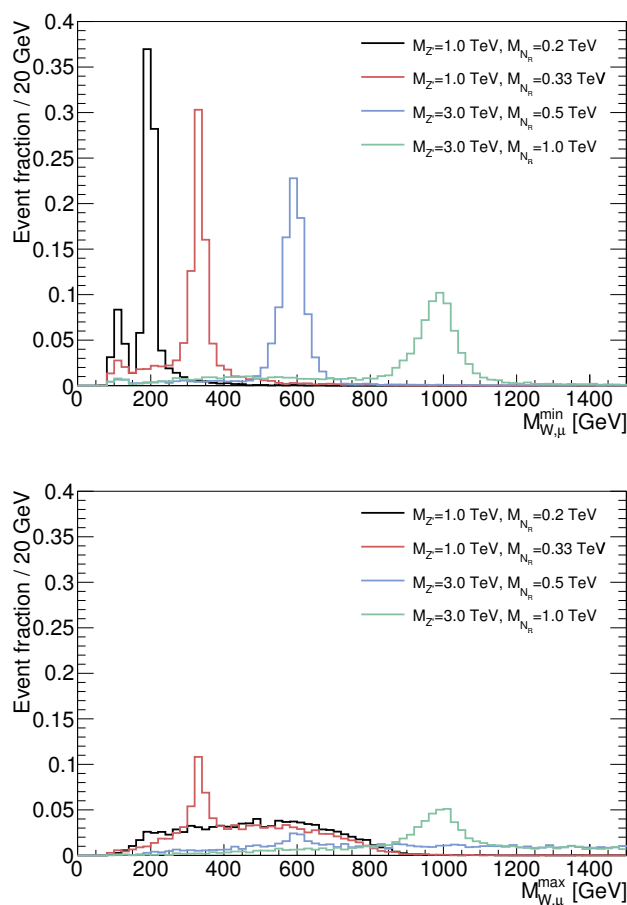


Figure 2. The (W, μ) invariant mass obtained in $1W$ events using the muon with the smallest (top) and largest (bottom) δR separation.

algorithm with distance parameter $R = 0.5$ and are required to satisfy $p_T > 25 \text{ GeV}$ and $|\eta| < 2.4$. If the event contains a boosted W boson, the jets are additionally required to satisfy $\Delta R(W, \text{jet}) > 0.8$. W boson candidates are then reconstructed iteratively by choosing the pair of jets which minimises $|M_{jj} - m_W|$. Finally, the di-jet mass is required to satisfy $50 < M_{jj} < 110 \text{ GeV}$ in order to be identified as a W boson.

2.4 N_R reconstruction

In reconstructing the N_R mass we are faced with two choices when selecting the W boson and muon to associate with each N_R decay. For events containing two reconstructed W bosons, the solution is straightforward: requiring consistency of the two N_R masses, one chooses the combination which minimises the difference in the reconstructed masses $|M_{N_1} - M_{N_2}|$, where $M_{N_{1,2}}$ are the invariant masses of the two (W, μ) systems. The final reconstructed N_R is taken as the mean of M_{N_1} and M_{N_2} in the case of two boosted or two resolved W bosons. In events containing one boosted and one resolved W , only the boosted W is used to determine the final N_R mass as this leads to slightly improved mass resolution.

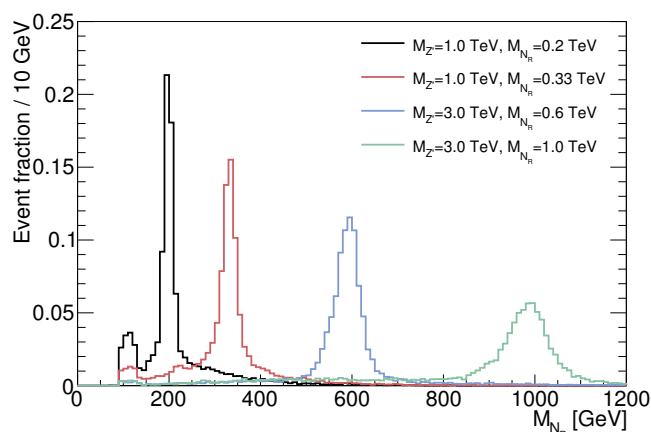


Figure 3. Reconstructed N_R mass for several benchmark signals.

The situation is somewhat more complicated in events with only a single reconstructed W boson. In this case it is, a priori, not clear which muon to identify as originating from the same N_R decay as the W . However, in practice, simply selecting the muon with the smallest δR separation from the W allows one to reliably reconstruct the true N_R mass. This can be clearly seen in figure 2, where we show the reconstructed N_R masses obtained using the two possible combinations. As is to be expected, this approach performs better when $M_{N_R} \ll M_{Z'}$ due to the higher boost of the N_R decay products.

The final reconstructed N_R mass (including both $1W$ and $2W$ events) is shown in figure 3. We find that it's possible to obtain good mass resolution, of the order of $\sim 10\%$, depending on the N_R and Z' masses. This mass resolution will ultimately determine the M_{N_R} bin width in any future search. Here, we simply require instead that

$$|M_{N_R}^{\text{reco}} - M_{N_R}| < 0.1M_{N_R}, \quad (2.2)$$

where M_{N_R} is the “true” right-handed neutrino mass for each benchmark signal point.

2.5 Final selection

After the initial selection detailed in section 2.3, the SM background still dominates over any potential signal, as can be clearly seen in figure 4. However, we have not yet exploited the fact that the same-sign muons produced by our signal are expected to have large p_T and be well-separated. The di-muon invariant mass can therefore be used to provide a good discriminator between the background and expected signal, as is the case in existing analyses (e.g. [25]). The same-sign di-muon invariant mass distribution is shown in figure 4.

We have investigated the expected sensitivity of this search as a function of the selection cut on $M_{\mu\mu}$. We considered 15 benchmark signal points with Z' masses in the range 1–3 TeV and N_R masses equal to 1/3, 1/4 and 1/5 of the Z' mass. In order to obtain good sensitivity across a range of Z' and N_R masses, we find that it is sufficient to define two (overlapping) signal regions: (i) $M_{\mu\mu} > 500$ GeV and (ii) $M_{\mu\mu} > 800$ GeV. These two regions provide optimal sensitivity for low and high Z' masses respectively, with the

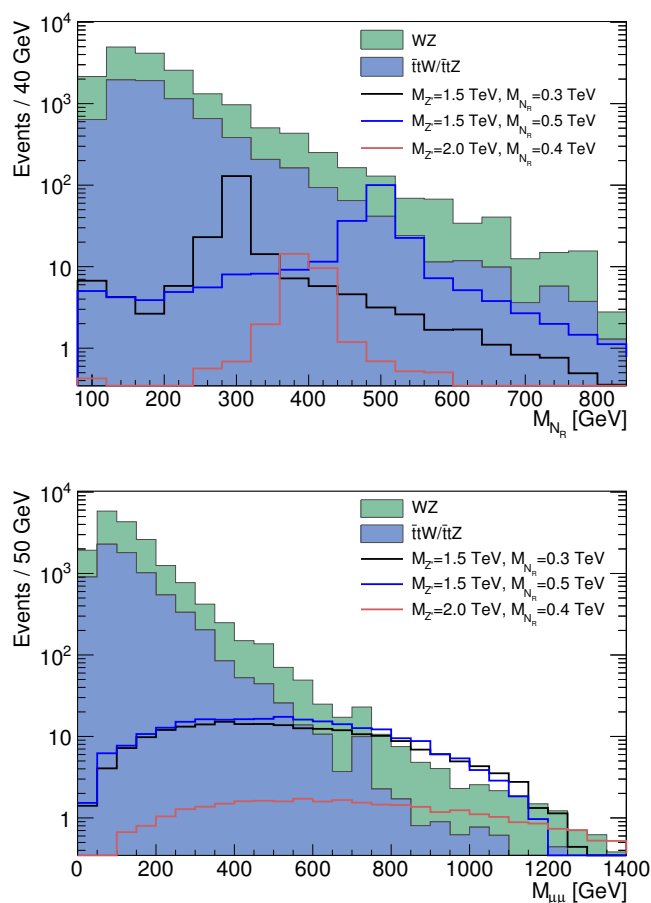


Figure 4. Reconstructed N_R mass (top) and same-sign di-muon invariant mass (bottom) after initial event selection, showing several benchmark signal points.

transition occurring between 1.5 – 2 TeV. Lastly, we add a cut on the reconstructed RH neutrino mass following eq. (2.2). It is remarkable that this greatly increases the signal significance, as shown in table 1.

3 Results

The expected number of signal and background events with 3000 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$ are given in table 1, for a benchmark signal point. As expected, the same-sign di-muon invariant mass cut is highly effective at reducing the SM background. Furthermore, one can clearly see the improvement in sensitivity that can be obtained by reconstructing the RH neutrino mass.

The main results of our analysis are given in figure 5, which shows the projected sensitivity with 300 fb^{-1} and 3000 fb^{-1} integrated luminosity at $\sqrt{s} = 14 \text{ TeV}$. Results are presented in terms of 5σ discovery reach and 95% CLs exclusion limits on $\sigma(pp \rightarrow Z' \rightarrow N_R N_R \rightarrow WW\mu\mu)$, as a function of the Z' mass. Limits are computed using RooStats [44]

	Background	Signal $M_{Z'} = 2.0 \text{ TeV}$ $M_{N_R} = 0.5 \text{ TeV}$	S/\sqrt{B}
Initial Selection	1.79×10^4	35.8	0.3
$M_{\mu\mu} > 800 \text{ GeV}$	32.5	14.8	2.6
$ M_{N_R}^{\text{reco}} - M_{N_R} < 0.1 M_{N_R}$	5.0	10.5	4.7

Table 1. Expected number of events with 3000 fb^{-1} for a benchmark signal point.

and the asymptotic formulae for the profile likelihood [45]. We assume the following gaussian systematic uncertainties: background normalisation (10%), signal efficiency (5%) and luminosity (2.8%). For comparison, we also show in figure 5 the expected cross-section in the $U(1)_{(B-L)_3}$ model, with $g = 0.6$ and $M_{N_R} = M_{Z'}/4$. The cross-section is calculated at NLO in the 5-flavour scheme using `MadGraph`. Note that there is a large uncertainty arising from the b quark PDF.

We find that at the HL-LHC it will be possible to exclude N_R production in the $U(1)_{(B-L)_3}$ model for Z' masses up to $\sim 2.2 \text{ TeV}$. This allows one to probe RH neutrino masses in the range $0.2 \lesssim M_{N_R} \lesssim 1.1 \text{ TeV}$. Our results are relatively independent of the N_R mass, provided that the $Z' \rightarrow N_R N_R$ decay mode is kinematically allowed; however, for heavier Z' masses N_R production via an off-shell Z' can contribute significantly to the total cross-section. Note that this reach is comparable to direct searches for the Z' in the $\tau\tau$ final state, assuming a naive extrapolation of the current limits. With 300 fb^{-1} one can probe N_R production for Z' masses up to $\sim 1.7 \text{ TeV}$. In this case, the sensitivity at lower Z' masses ($\lesssim 1 \text{ TeV}$) could be improved by introducing an additional signal region with a relaxed $M_{\mu\mu}$ cut.

4 Conclusion

We have investigated RH neutrino pair production in general Z' models at the (HL-)LHC. Focusing on final-states containing a pair of same-sign muons, we proposed a new, model-independent search. A novel aspect of this analysis is the ability to reconstruct the RH neutrino, with good mass resolution. This leads to a significantly improved sensitivity over general same-sign di-lepton searches. Within the $U(1)_{(B-L)_3}$ model, we find that in the future it will be possible to probe RH neutrino masses in the range $0.2 \lesssim M_{N_R} \lesssim 1.1 \text{ TeV}$, or equivalently Z' masses up to $\sim 2.2 \text{ TeV}$. While we focused on the di-muon channel due to reduced backgrounds, a similar analysis could be performed for $e^\pm e^\pm$ and $e^\pm \mu^\pm$ final states. Finally, our analysis could also be straightforwardly adapted to RH neutrino production from a W' boson, utilising the same techniques to reconstruct the N_R mass.

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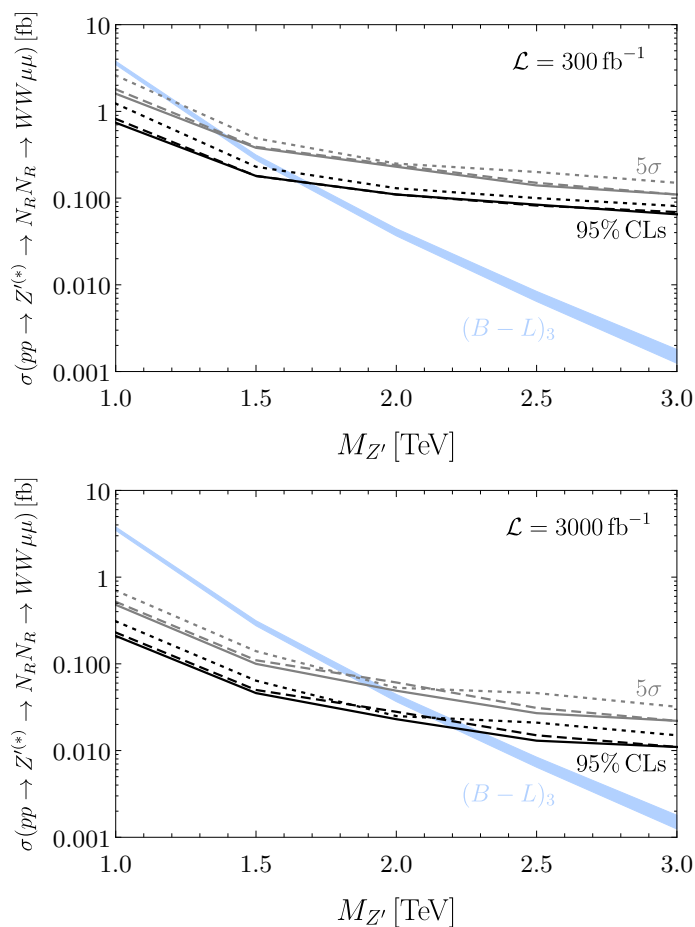


Figure 5. Projected sensitivity with 300 fb^{-1} (top) and 3000 fb^{-1} (bottom) at $\sqrt{s} = 14 \text{ TeV}$. The solid, dashed and dotted lines correspond to $M_{N_R} = (1/3, 1/4, 1/5) \times M_{Z'}$, respectively. The blue band shows the expected cross-section and its associated uncertainty in the $(B - L)_3$ model, assuming $g = 0.6$ and $M_{N_R} = M_{Z'}/4$.

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