The $B-L$ Supersymmetric Standard Model (BLSSM) represents an appealing non-minimal realisation of Supersymmetry (SUSY), as it is more compatible with current Large Hadron Collider (LHC) data than the Minimal Supersymmetric Standard Model (MSSM) and further uniquely accounts for the well established existence of non-zero neutrino masses. In this scenario, which is based on the gauge group $SU(3)C \times SU(2)L \times U(1)Y \times U(1)_{B-L}$, (heavy) right-handed neutrino Superfields are introduced in order to implement a Type I seesaw [1]. Also, it has been shown that the scale of the $B-L$ symmetry breaking is related to the soft SUSY scale [2]. Furthermore, the BLSSM also alleviates the little hierarchy problem of the MSSM, as both the additional singlet Higgs state and right-handed (s)neutrinos release additional parameter space from the LEP, Tevatron and LHC constraints. The $Z'$ and (s)neutrino sectors are ideal hallmark manifestations of the BLSSM as candidate underlying SUSY model. An intriguing signal would be the one involving totally invisible decays of a $Z'$ into (s)neutrinos, thereby being potentially accessible in mono-jet, single-photon or $Z$-radiation probes through sophisticated signal-to-background simulations carried out in presence of parton shower, hadronisation as well as detector effects. We find substantial sensitivity to all such signals for standard luminosities at Run 2.

The invisible signals of right-handed sneutrino decays originating from a $Z'$ are analysed at the Large Hadron Collider. The possibility of accessing these events helps dissentangling the $B-L$ extension of Minimal Supersymmetric Standard Model from more popular scenarios of Supersymmetry. We assess the scope of the CERN machine in establishing the aforementioned signatures when accompanied by mono-jet, single-photon or $Z$-radiation probes through sophisticated signal-to-background simulations carried out in presence of parton shower, hadronisation as well as detector effects. We find substantial sensitivity to all such signals for standard luminosities at Run 2.
In our calculations we have used SARAH [5] and SPheno [6, 7] to build the BLSSM and calculate masses, couplings and BRs. We also considered the following benchmark (given at the SUSY scale): $M_{Z'} = 2.5$ TeV, $M_{\tilde{\ell}_L} \approx M_{\tilde{\ell}_R} \approx M_{\tilde{\nu}_3} \approx 580$ GeV, $M_{\tilde{\ell}_1} \approx M_{\tilde{\nu}_1} \approx 740$ GeV, $m_{\chi_+} \approx 4.0$ TeV, $m_{\chi_0} \approx 440$ GeV and slepton masses of order 700 GeV. Furthermore, the matrix-elements for the parton level signals and backgrounds were derived from MadGraph5 [8]. Then, for showering and hadronisation we have used PYTHIA [9] whereas we have performed the fast detector simulations with MadAnalysis5 [11]. Finally, we have adopted usual selection strategies, wherein cuts are enforced against the kinematics of the highest $p_T$ jet/photons or the $Z$.

We start with the mono-jet case, which is generally dominated by sneutrino decays [22] (hereafter, $j =$jet),

$$Z'\rightarrow \tilde{\nu}_R\tilde{\nu}_R^* \rightarrow \chi_0^0 \chi_1^0 \nu \bar{\nu} + j.\tag{2}$$

The SM backgrounds are the following: $Z \rightarrow \nu \bar{\nu} + j$ (irreducible) plus $W \rightarrow l \nu + j$, $W \rightarrow \tau \nu + j$, $t \bar{t}$ and $ZZ \rightarrow 2\nu 2\bar{\nu} + j$ (all reducible). We closely follow here the selection of [12, 13]. Further, in order to increase the Monte Carlo efficiency and thus obtain reasonable statistics, we have applied a parton level cut of $p_T(j_1) > 120$ GeV for both signals and backgrounds (here $p_T(j_1)$ is the highest jet transverse momentum). According to the estimation of the QCD background based on the full detector simulation of [14, 15], such a noise can be reduced to a negligible level by requiring a large $E_T$ cut. Thanks to the heavy $Z'$ mediation, we can afford to set here $E_T > 500$ GeV [16]. In view of this we can then also implement a $E_T > 100$ GeV cut for both signals and backgrounds at generation level. The beneficial effect of the $E_T$ selection is evident from the left plot in Fig. 1. In contrast, a similar cut on $p_T(j_1)$ is not as selective (and is anyway correlated), see the right plot in Fig. 1, yet it pays off to also enforce it.

In Tab. I, we present the actual cut flow for signal and background events, given at 14 TeV with an integrated luminosity of 300 fb$^{-1}$. After the BLSSM specific cuts, i.e., $E_T$ and $p_T(j_1) > 500$ GeV, all the backgrounds are reduced under the dominant sneutrino signal. Other key steps of the analysis are the lepton, $\tau$- and $b$-jet vetoes, which suppress the $W + j$ and $t \bar{t}$ backgrounds by more than two orders of magnitude [17].

Now we turn to the single-photon signature, which occurs in our BLSSM point mainly via the following process:

$$Z'\rightarrow \tilde{\nu}_R\tilde{\nu}_R^* \rightarrow \chi_0^0 \chi_1^0 \nu \bar{\nu} + \gamma.\tag{3}$$

We have generated single-photon events while requiring the following parton level (generation) cuts: $E_T > 50$ GeV, $p_T(\gamma_1) > 40$ GeV, $p_T(j_1) > 25$ GeV ($p_T(\gamma_1)$ being the leading photon transverse momentum). We also generate the background processes $Z \rightarrow \nu \bar{\nu} + \gamma$ and $W \rightarrow l \nu + \gamma$, where $l = e, \mu$ or $\tau$. The latter are reduced significantly by applying the cut flow shown in Tab. II, see [12, 18] for guidance. Again, the sneutrino signal emerges dramatically over the backgrounds. Further, in Fig. 2, the spectra in $E_T$ and $p_T(\gamma_1)$ are shown. These plots well motivate our high transverse energy/momentum cuts, however, we note that the smaller signal rates here force us to a softer, yet still very effective, requirement, of a 150 GeV threshold.

For the $Z$-ISR signature in the BLSSM,

$$Z'\rightarrow \tilde{\nu}_R\tilde{\nu}_R^* \rightarrow \chi_0^0 \chi_1^0 \nu \bar{\nu} + Z,\tag{4}$$

we generate events with the following parton level cuts: $E_T > 80$ GeV, $p_T(l) > 10$ GeV and $p_T(j) > 20$ GeV.
TABLE I: The cut flow on background versus signal events for \( M_{Z'} = 2.5 \) TeV in the mono-jet channel at \( \sqrt{s} = 14 \) TeV with \( \mathcal{L} dt = 300 \) fb\(^{-1}\). Here, \( M_{Z'} = 2.5 \) TeV.

![Graph](image1.png)

The dominant irreducible background is \( ZZ \rightarrow l^+l^-\bar{\nu}\bar{\nu} \) \((l = e, \mu)\) and the other noise in this category is \( WW \rightarrow l^+l^-\bar{\nu}\bar{\nu} \). As we reconstruct the \( Z \) probe, we enforce a cut on an invariant mass window centered on the \( Z \) mass for two oppositely charged leptons, \( m_{ll} \in [76, 106] \) GeV [19], the latter is strongly reduced. The reducible backgrounds may have jets produced: \( Z + \) jets, \( ZZ \rightarrow q\bar{q}l^+l^- \) and \( ZW \rightarrow l^+l^-q\bar{q} \). After the customary large \( E_T \) cut that the heavy \( Z' \) allows us to enforce (here, \( E_T > 250 \) GeV), this cumulative noise yields no event for the luminosity adopted. In addition, there are other reducible backgrounds with jets that we have dealt with: \( t\bar{t} \rightarrow l^+\nu b\bar{l}^-\bar{v} \) which is reduced by rejecting events containing at least one jet with \( p_T > 25 \) GeV; \( W+jets \) which is reduced by the large \( E_T \) cut. The last leptonic background is \( ZW \rightarrow l\nu l\bar{l}^- \nu \), which is also eliminated by the cut \( E_T > 250 \) GeV. The cut flow (modelled on [20]) and individual responses of signals and backgrounds are shown in Tab. III. In Fig. 3, we show the various distributions in \( E_T \), again, for the purpose of justifying our BLSSM specific \( E_T \) selection. Again, the invisible signal dominated by the sneutrinos and accompanied by the reconstructed \( Z \) stands well above the backgrounds.

In summary, we have proven the sensitivity that the LHC has in Run 2 with standard luminosity settings in probing invisible signals which emerge in the BLSSM from \( Z' \) decays in presence of an associated jet, photon or \( Z \)-boson. For all such signatures, we were able, upon enforcing well established selection procedures for
TABLE III: The cut flow on background versus signal events for $M_{Z'} = 2.5$ TeV in the Z-ISR channel at $\sqrt{s} = 14$ TeV with $\mathcal{L} dt = 300$ fb$^{-1}$. [54x195]luminosity is 300 fb$^{-1}$.

FIG. 3: Number of events versus the missing transverse energy. Distributions are for the Z-ISR case given after the jet selection only. The energy is 14 TeV whereas the integrated energy. Distributions are for the $L$ = 300 fb$^{-1}$. Here, $M_{Z'} = 2.5$ TeV.

these topologies supplemented by BLSSM specific cuts, to establish signals with significances well above the customary 5$\sigma$ discovery limit. Indeed, this has been possible thanks to the fact that the BLSSM mediator of such invisible signals is a very heavy $Z'$, with mass in the TeV region, thereby transferring to its decay products large transverse momenta that can be generically exploited in all cases for background reduction. Furthermore, for all topologies considered, the dominant component of the signal is via sneutrinos (above neutrinos and neutralinos), so that assessing these invisible signatures in the heavy $E_T$ regime would not only signal the presence of a dark matter induced channel within SUSY but also be a circumstantial evidence of a theoretically well motivated non-minimal version of it, the BLSSM. In a forthcoming publication [21], we shall show that the case made here for illustrative purposes using a benchmark with a 2.5 TeV and rather narrow $Z'$ can be extended to a large BLSSM parameter space volume (also covering lighter and/or wider $Z$'s).

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