# Sneutrino Dark Matter in the BLSSM

**Luigi Delle Rose,**[a,b] **Shaaban Khalil,**[c] **Simon J.D. King,**[a] **Suchita Kulkarni,**[d] **Carlo Marzo,**[e] **Stefano Moretti**[a,b] **and Cem S. Un**[f]

[a]*School of Physics and Astronomy, University of Southampton,*
*Highfield, Southampton SO17 1BJ, U.K.*

[b]*Particle Physics Department, Rutherford Appleton Laboratory,*
*Chilton, Didcot, Oxon OX11 0QX, U.K.*

[c]*Center for Fundamental Physics,*
*Zewail City of Science and Technology, Sheikh Zayed,12588 Giza, Egypt*

[d]*Institut für Hochenergiephysik, Österreichische Akademie der Wissenschaften,*
*Nikolsdorfer Gasse 18, 1050 Wien, Austria*

[e]*National Institute of Chemical Physics and Biophysics,*
*Rävala 10, 10143 Tallinn, Estonia*

[f]*Department of Physics, Uluda g University,*
*TR16059 Bursa, Turkey*

*E-mail:* L.Delle-Rose@soton.ac.uk, Skhalil@zewailcity.edu.eg,
SJD.King@soton.ac.uk, suchita.kulkarni@oeaw.ac.at,
Carlo.Marzo@kbfi.ee, S.Moretti@soton.ac.uk, cemsalihun@uludag.edu.tr

Abstract: In the framework of the $(B - L)$ Supersymmetric Standard Model (BLSSM), we assess the ability of ground and space based experiments to establish the nature of its prevalent Dark Matter (DM) candidate, the sneutrino, which could either be CP-even or -odd. Firstly, by benchmarking this theory construct against the results obtained by the Planck spacecraft, we extract the portions of the BLSSM parameter space compliant with relic density data. Secondly, we show that, based on current sensitivities of the Fermi Large Area Telescope (FermiLAT) and their future projections, the study of high-energy $\gamma$-ray spectra will eventually enable us to extract evidence of this DM candidate through its annihilations into $W^+W^-$ pairs (in turn emitting photons), in the form of both an integrated flux and a differential energy spectrum which cannot be reconciled with the assumption of DM being fermionic (like, e.g., a neutralino), although it should not be possible to distinguish between the scalar and pseudoscalar hypotheses. Thirdly, we show that, while underground direct detection experiments will have little scope in testing sneutrino DM, the Large Hadron Collider (LHC) may be able to do so in a variety of multi-lepton signatures, with and without accompanying jets (plus missing transverse energy), following data collection during Run 2 and 3.

# Contents

## 1 Introduction

In addition to solving major flaws of the Standard Model (SM), such as the hierarchy problem, the absence of gauge coupling unification, etc., Supersymmetry (SUSY) provides a candidate for Dark Matter (DM), when $R-$parity conservation is imposed at the low scale, which in turn requires the Lightest Supersymmetric Particle (LSP) to be stable. In fact, at present, the possibility of either scalar [1–4] or fermionic [5–11] DM is still allowed by observations. Among the possible candidates, Weakly Interactive Massive Particles (WIMP) are of special importance [12], since they can potentially be observable in direct detection [13–17], indirect detection [18, 19] and collider experiments [20–22], in addition to the measurements of the WMAP [23] and Planck [24] satellites. Excluding the regions where a charged SUSY particle becomes LSP, the Minimal Supersymmetric SM (MSSM) has, in principle, three candidates for DM in the form of the lightest sneutrino, gravitino or neutralino. The former is an example for a scalar DM, while the last two are fermionic candidates. Due to its large interactions with the $Z$ boson, the Left-Handed (LH) sneutrino LSP case as a potential DM candidate is excluded by direct LEP searches and cosmological observations [25, 26]. In the MSSM context then, the only viable DM candidates are fermionic. A sneutrino LSP can manifest itself also through missing energy in collider experiments [27], however, the experimental analyses herein can provide only weak constraints on the gravitino mass $m_{3/2}$ (i.e., $m_{3/2} \gtrsim 10^{-13}$ GeV) [28]. In contrast, DM observations provide significant constraints on the gravitino LSP. For instance, the current limit on the relic abundance of the LSP yields $m_{3/2} \simeq 200$ eV or below. At this mass scale, the gravitino can be a good candidate for hot DM, however, in standard scenarios, the gravitino as a hot DM candidate cannot contribute to DM formation more than 15%, which further constrains the gravitino mass to $m_{3/2} \lesssim 30$ eV [29, 30]. In this context, standard cosmological scenarios require other candidates for cold DM. (Note that the DM implications of the gravitino LSP would be different in non-standard cosmological

scenarios [29, 30]. In the end, the neutralino is the most plausible candidate for cold DM in MSSM. The neutralino LSP can be formed by a bino, wino, higgsinos or a mixture of these particles. Each yields different implications in DM experiments [31–33]. However, if one consider the Constrained MSSM (CMSSM), the higgsino mass parameter $\mu$ is constrained by Electro-Weak Symmetry Breaking (EWSB) to be much larger than the gaugino masses. Numerical analyses have also shown that $M_2 \sim 2M_1$ [34–37], where $M_1$ and $M_2$ are the bino and wino masses at the EW scale, respectively.[1]

Hence, quite apart from other motivations emerging from self-consistency of the SUSY theory (like the so-called $\mu$ problem) and other experimental data, the DM sector alone calls for some form of extended SUSY scenario. Furthermore, neutrino mass generation remains a problem for minimal SUSY. In contrast, recent studies [38, 40] have shown that a simple extension of the MSSM with a $(B - L)$ symmetry (termed as BLSSM), i.e., $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$ with a gauged $\mathrm{U}(1)_{B-L}$, enriches the variety of possible DM candidates and can easily account for all experimental results mentioned above. Moreover, such an extension requires three Right-Handed (RH) neutrinos and their SUSY partners to cancel the ensuing $\mathrm{U}(1)_{B-L}$ anomalies. RH sneutrinos have also been suggested as a DM candidate in CMSSM models with added RH neutrinos [41]. Therefore, the BLSSM is also a natural framework for implementing a seesaw mechanism which then provides a dynamics for the generation of neutrino masses and mixings [42]. Herein, in addition to the neutralino LSP, the fundamental parameter space also allows DM solutions with a sneutrino LSP able to saturate the DM relic density and to remain compliant with scattering processes against nuclei. However, to validate such a solution, one needs first to make sure that the sneutrino mass eigenstates should be formed mostly by the RH sneutrino, since the LH sneutrino is excluded as a DM candidate (as mentioned above). One of the challenges in finding such a sneutrino LSP as DM solution is the constraint that the 125 GeV Higgs boson data yield a rather heavy mass spectrum for the SUSY particles, which in turn leads to heavy sneutrinos when a universal mass parameter is imposed for all scalars at the Grand Unification Theory (GUT) scale. In addition, $Z'$ and RH sneutrino masses receive contributions from the (BLSSM-specific) singlet Vacuum Expectation Values (VEVs), see later on, which are responsible for breaking the $\mathrm{U}(1)_{B-L}$ symmetry, and the heavy mass bound on the $Z'$, $M_{Z'} \geq 4\,\mathrm{TeV}$ [43],[2] requires such singlet fields to develop large VEVs, which, again, points to so heavy a RH sneutrino that can hardly be the LSP in the mass spectrum.

Despite this preamble, in this work, we do investigate the feasibility of the RH sneutrino LSP as a suitable DM candidate within the BLSSM framework, the latter embedding a Type-I seesaw mechanism for the neutrino masses. In this case though, realising that consistency with relic density of such a DM candidate is difficult due to the tiny Yukawa couplings ($Y_\nu \lesssim 10^{-6}$) involved [45], one may be tempted to conclude that our task is

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[1]Since we will employ CMSSM-like boundary conditions also in the BLSSM framework, we will emphasise the cases which yield mostly a bino-like LSP, which is in fact viable only in a narrow region of the CMSSM parameter space [38].

[2]However, a recent study has showed that this bound can be reduced to about 3.6 TeV if BR($Z' \to l^+l^-) \lesssim 10\%$ [44].

extremely difficult. This perception may be further reinforced by the fact, even though the RH sneutrino can annihilate through the $Z$ boson in virtue of the gauge kinetic mixing between U(1)$_Y$ and U(1)$_{B-L}$, the ensuing interaction is strongly suppressed by the heavy mass bound on the gauge boson associated with the $(B-L)$ symmetry (the aforementioned $Z'$). These difficulties can however be overcome by identifying some new DM annihilation channels, which we will discuss below, in which the specific $(B-L)$ sector plays a crucial role. In this case then, one may even attempt to extract evidence of such a new DM dynamics, which can be tested, if not at present, in near future experiments, both collider and astrophysical ones.

The rest of the paper is organised as follows. We first start with discussing RH sneutrinos in the BLSSM in section 2 by studying their mass matrix and the fundamental parameters entering the calculation of observable quantities related to this potential DM state. We also include a discussion of the numerical scan we have performed to obtain our spectra. Then section 3 presents the possible (co)annihilation channels and resulting relic abundance of the RH sneutrinos. Once consistent solutions are identified, we investigate possible signatures of RH sneutrino DM in Fermi Large Area Telescope (FermiLAT) and Large Hadron Collider (LHC) data for some benchmark points in sections 4 and 5, respectively. Finally, we conclude in section 6.

## 2  RH sneutrinos in the BLSSM

We now consider the RH sneutrino sector in the BLSSM. Within a TeV scale BLSSM with Type-I seesaw and very small neutrino Yukawa coupling, $Y_\nu \lesssim \mathcal{O}(10^{-6})$, the sneutrino mass matrix, in the basis $(\tilde{\nu}_L, \tilde{\nu}_L^*, \tilde{\nu}_R, \tilde{\nu}_R^*)$, is approximately given by a $2 \times 2$ block diagonal matrix. This small Dirac Yukawa coupling leads to a small soft-breaking term in the Lagrangian, $T_\nu = Y_\nu A_\nu$ and hence the LH and RH sneutrino sectors are approximately decoupled. The element 11 of this matrix is given by the diagonal LH sneutrino mass matrix and the element 22 represents the RH sneutrino mass matrix, $M_{RR}$, defined as [62]

$$M_{RR}^2 = \begin{pmatrix} M_N^2 + m_{\tilde{N}}^2 + m_D^2 + \frac{1}{2}M_{Z'}^2 \cos 2\beta' & M_N(A_N - \mu' \cot \beta') \\ M_N(A_N - \mu' \cot \beta') & M_N^2 + m_{\tilde{N}}^2 + m_D^2 + \frac{1}{2}M_{Z'}^2 \cos 2\beta' \end{pmatrix}. \quad (2.1)$$

It is notable that a large mixing between the RH sneutrinos and RH anti-sneutrinos is quite plausible, indeed potentially observable [63], since it is given in terms of large Yukawa couplings, $Y_N \sim \mathcal{O}(1)$. Therefore, $\tilde{\nu}_R, \tilde{\nu}_R^*$ are not the mass eigenstates. The mass splitting and mixing between the RH sneutrino $\tilde{\nu}_R$ and RH anti-sneutrino $\tilde{\nu}_R^*$ are a result of the induced $\Delta L = 2$ lepton number violating term $M_N N^c N^c$. One can show that the mass eigenvalues of RH sneutrinos are given by [64, 65]

$$m_{\tilde{\nu}_\mp}^2 = M_N^2 + m_{\tilde{N}}^2 + m_D^2 + \frac{1}{2}M_{Z'}^2 \cos 2\beta' \mp \Delta m_{\tilde{\nu}_R}^2, \quad (2.2)$$

where $\Delta m_{\tilde{\nu}_R}^2 = \left| M_N(A_N - \mu' \cot \beta') \right|$ and the mass eigenstates $\tilde{\nu}_{\mp}$ are defined in terms of $\tilde{\nu}_R, \tilde{\nu}_R^*$ as follows:

$$\tilde{\nu}_- = \frac{-i}{2} \left( e^{i\phi/2} \tilde{\nu}_R - e^{-i\phi/2} \tilde{\nu}_R^* \right), \tag{2.3}$$

$$\tilde{\nu}_+ = \frac{1}{2} \left( e^{i\phi/2} \tilde{\nu}_R + e^{-i\phi/2} \tilde{\nu}_R^* \right), \tag{2.4}$$

where $\phi$ is the phase of the off-diagonal element of $M_{RR}$, i.e., $\phi = \arg(M_N(A_N - \mu' \cot \beta'))$. In case of real soft SUSY breaking terms, one finds $\phi = 0$ or $\phi = \pi$, depending on the relative sign of $A_N$ and $\mu'$. In the former case, we see that $\tilde{\nu}_-(\phi = 0) = \mathrm{I}(\tilde{\nu}_R) \equiv \tilde{\nu}_1^{\mathrm{I}}$, so the lightest state is an imaginary sneutrino with $m_{\tilde{\nu}_1^{\mathrm{I}}} = m_{\tilde{\nu}_-}$ and the real type, $\mathrm{R}(\tilde{\nu}_R) \equiv \tilde{\nu}_1^{\mathrm{R}}$, has a larger mass $m_{\tilde{\nu}_1^{\mathrm{R}}} = m_{\tilde{\nu}_+}$. The other possibility is $\phi = \pi$, where now $\tilde{\nu}_-(\phi = \pi) = \tilde{\nu}_1^{\mathrm{R}}$ is the lightest state with $m_{\tilde{\nu}_1^{\mathrm{R}}} = m_{\tilde{\nu}_-}$ and $\tilde{\nu}_R^{\mathrm{I}}$ is heavier with $m_{\tilde{\nu}_R^{\mathrm{I}}} = m_{\tilde{\nu}_+}$.

Before we consider the effect this will have on spectrum points in parameter space, we must first discuss how we obtain our numerical results. In this work, we have used the spectra for RH sneutrino LSP candidates in the BLSSM, previously obtained in [38], where the exact details of the numerical results are discussed in great detail, though we summarise them here. We have used the SARAH [46] and SPheno [47] programs, considering a complete universal scenario where the gauge couplings all unify at the GUT scale. We have scanned over the range $[0,5]$ TeV in both $m_0$ and $m_{1/2}$, $\tan \beta$ in $[0,60]$, $A_0$ in $[-15, 15]$ TeV, $\tan \beta'$ in the interval $[0,2]$ with neutrino Yukawa couplings $Y^{(1,1)}$, $Y^{(2,2)}$, $Y^{(3,3)}$ in $[0,1]$. Once determined, the boundary conditions are imposed at the GUT scale and the gauge couplings and gaugino masses are evolved back to the low scale through two-loop Renormalisation Group Equations (RGEs).

In addition, the masses of the SUSY scalars are determined at low scale where one- and two-loop corrections are employed for the SM-like Higgs boson mass. In addition, the masses of the SUSY scalars are determined at low scale where one and two-loop corrections are employed for the SM-like Higgs boson mass. In this work, we employ an approximate error in the estimated Higgs boson mass of $\pm 3$ GeV [49]. This ban includes only the experimental error from the uncertainty of the top mass and strong coupling measurements. There are potentially further errors arising from theoretical uncertainties associated with the minimisation of the potential at a given loop order. Here we use SPheno, which minimises the Higgs potential using the two-loop corrected effective potential. Consequently, higher loop orders can provide additional contributions to the Higgs mass and can increase this error in the Higgs mass beyond $\pm 3$ GeV. Furthermore, there may be corrections to the Higgs mass at higher loop orders due to the large Yukawa couplings of the RH neutrinos, though they do not directly couple to the Higgs. These issues will likely increase the uncertainty in the determination of the Higgs mass, but we do not quantify this here. Nevertheless, since our study concerns mainly the LSP, which will not largely be affected by the determination of the Higgs mass, the exact level of uncertainty here will not affect the conclusions of this work.

The $M_{Z'}$ value has been fixed to $4$ TeV to comply with dedicated $\mathrm{U}(1)_{B-L}$ searches, in particular, the 95% Confidence Level (CL) bound extracted from the di-lepton channel
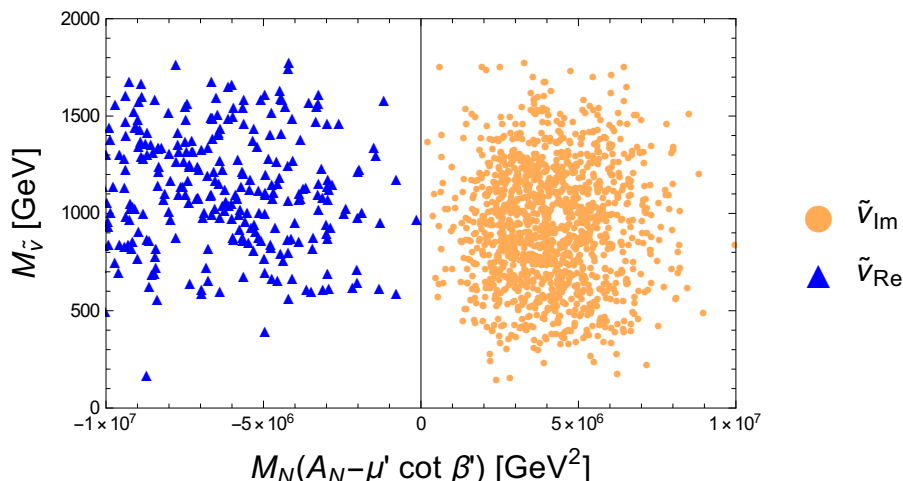
**Figure 1**. Masses of real and imaginary RH sneutrino LSP candidates are plotted against the mass difference of the two eigenstates, $M_N(\mu' \cot \beta' - A_N)$.

at the LHC with $\sqrt{s} = 13\,\mathrm{TeV}$ and $\mathcal{L} = 40\,\mathrm{fb}^{-1}$ luminosity in ref. [50]. In doing so, both the $Z'$ signal and its interference with the SM background have been properly taken into account, as described in [51–55], as well as the efficiency and acceptance factors as reported in [50]. The $Z'$ values of the gauge couplings, $g_{BL} \simeq 0.55$ and $\tilde{g} \simeq -0.144$, have been obtained from a Renormalisation Group Equation (RGE) analysis assuming unification at the GUT scale [38]. We note that the LHC limit on the Z' is reduced due to the presence of gauge-kinetic mixing [39]. The spectra are then processed into HiggsBounds [56–59] which, considering all the available collider searches, expresses whether a parameter point has been excluded at 95% CL or not. Finally, the compatibility fit of the generated Higgs signal strengths with the ones measured at LHC is taken into account by HiggsSignals [60], which provides the corresponding $\chi^2$. By asking for a $2\sigma$ interval around the minimum $\chi^2$ generated, we obtain a further constraint over the parameter space investigated. After these conditions are satisfied, we then enforce that all spectra satisfy the SUSY mass bounds for gluinos, staus, neutralinos, charginos and stops [61]. It is worth noting at this point that fixing $M_{Z'} = 4\,\mathrm{TeV}$ enforces a heavy SUSY spectrum, so that requiring compliance with SUSY searches is in general not more constraining than doing so with Higgs data alone. We would also like to stress here that the additional content of the BLSSM, compared to the MSSM, will not act so as to enhance greatly the SUSY production rates with respect to simpler models, so it is reasonable to use the aforementioned limits, though they do not remove many spectrum points after all other constraints are imposed. Finally, for the work in this paper, we specifically isolate the points generated by our scan in which the RH sneutrino LSP is the DM candidate.

One can now see the behaviour of the mass difference, $\Delta m^2_{\tilde{\nu}_R}$, on the sneutrino mass, applied to our scan, in figure 1. When the mass difference is positive, $\phi = 0$ and so the $\tilde{\nu}_1^{\mathrm{I}}$ acquires the lightest mass $m_{\tilde{\nu}_-}$. In the case of a negative mass difference ($\phi = \pi$), one has a $\tilde{\nu}_1^{\mathrm{R}}$ LSP, with mass $m_{\tilde{\nu}_-}$. In general, one finds that $M_N(A_N - \mu' \cot \beta')$ tends to
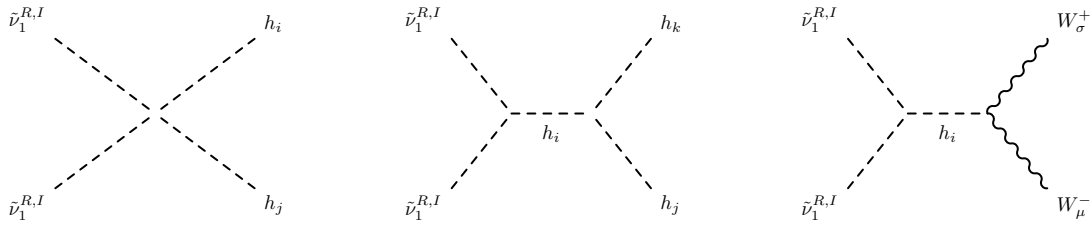
**Figure 2**. Feynman diagrams of the dominant interaction terms of two real or two imaginary RH sneutrinos.

be positive and so there are many more CP-odd sneutrino LSPs than CP-even ones (by a factor of $\sim 10$).

Now, we briefly describe the relevant interactions of sneutrino DM, for $\tilde{\nu}_R^I$ and $\tilde{\nu}_R^R$ LSPs. The relic abundance of the sneutrino DM is a direct consequence of the strength of these interactions, in addition to revealing what signatures this DM candidate may provide. The main interactions which contribute to the annihilations of the sneutrino DM are given by the four-point interaction $\left( \tilde{\nu}_1^{(R,I)} \tilde{\nu}_1^{(R,I)} \to h_i h_j \right)$ and processes mediated by the CP-even Higgs sector $\left( \tilde{\nu}_1^{(R,I)} \tilde{\nu}_1^{(R,I)} \to h_i \to h_i h_j \text{ or } W^+ W^- \right)$, as shown in figure 2. With $Y_\nu \ll 1$, the Lagrangian of these interactions can be written as follows:

$$
\begin{aligned}
\mathcal{L} \supset i \Bigg\{ & \left( \tilde{\nu}_1^{R,I} \right)^2 h_i \sum_{a=1}^{3} (Z_{13+a}^{(R,I)})^2 \Big[ \frac{g_B^2}{2} \left( v_\eta Z_{i3}^H - v_{\bar{\eta}} Z_{i4}^H \right) \pm \sqrt{2} \Big( Z_{i4}^H \mu_\eta Y_{x,aa} - Z_{i3}^H T_{x,aa} \Big) - 4 v_\eta Z_{i3}^H Y_{x,aa}^2 \Big] \\
& + \left( \tilde{\nu}_1^{R,I} \right)^2 h_i h_j \sum_{a=1}^{3} (Z_{13+a}^{(R,I)})^2 \Big[ \frac{g_B^2}{2} \left( Z_{i3}^H Z_{j3}^H - Z_{i4}^H Z_{j4}^H \right) + \frac{g_B g_{YB}}{4} \left( Z_{i1}^H Z_{j1}^H - Z_{i2}^H Z_{j2}^H \right) - 4 Z_{i3}^H Z_{j3}^H Y_{x,aa}^2 \Big] \\
& + (h_i h_j h_k) \, g_B^2 \Big[ v_\eta \Big( -3 Z_{i3}^H Z_{j3}^H Z_{k3}^H + Z_{i3}^H Z_{j4}^H Z_{k4}^H + Z_{i4}^H Z_{j3}^H Z_{k4}^H + Z_{i4}^H Z_{j4}^H Z_{k3}^H \Big) \\
& + v_{\bar{\eta}} \Big( Z_{i3}^H Z_{j3}^H Z_{k4}^H + Z_{i3}^H Z_{j4}^H Z_{k3}^H + Z_{i4}^H Z_{j3}^H Z_{k3}^H - 3 Z_{i4}^H Z_{j4}^H Z_{k4}^H \Big) \Big] \\
& + h_i W_\mu^- W_\sigma^+ \frac{g_2^2}{2} \Big( v_d Z_{i1}^H + v_u Z_{i2}^H \Big) \Big( g^{\sigma\mu} \Big) \Bigg\},
\end{aligned}
\tag{2.5}
$$

where $h_i$ is one of the four mixed CP-even Higgs mass eigenstates [66] ($h_1$ is the lightest SM-like Higgs, $h_2$ is the light $(B-L)$-like Higgs, $h_3$ is the heavy MSSM-like Higgs and $h_4$ is the heavy $(B-L)$-like state). These states are all mixed and the matrix which diagonalises the Higgs mass matrix is written as $Z^H$. There are four Higgs VEVs, corresponding to the MSSM $H_u$ and $H_d$ doublets and the BLSSM $\eta$ and $\bar{\eta}$ singlets, written as $(v_u, \ v_d, \ v_\eta, \ v_{\bar{\eta}})$, respectively. The diagonalising mass matrices for the CP-even and CP-odd sneutrinos are denoted by $Z^{(R,I)}$ while the $Y_{x,aa}$'s are the Yukawa couplings for the RH neutrinos, which are assumed to be diagonal along with the trilinear couplings, the $T_{x,aa}$'s. The gauge couplings $g_B$ and $g_{YB}$ will be rotated, along with the (unseen) $g_{YY}$ and $g_{BY}$ couplings, to become the physical $g_1$, $g_{BL}$ and $\tilde{g}$ couplings.

## 3 Annihilation cross section and DM relic abundance

The two CP-eigenstate RH sneutrinos, $\tilde{\nu}_1^{\mathrm{I}}$ and $\tilde{\nu}_1^{\mathrm{R}}$, produce different phenomena in respect of the cross sections of their annihilation channels, which may yield detectable consequences in cosmological measurements. The DM is annihilating at low (thermal) energies, so the final product masses must be $\lesssim 2m_{\tilde{\nu}}$. As indicated by the interaction terms in (2.5), the highest cross section channel (for both CP-even and -odd) is $\tilde{\nu}\tilde{\nu} \to h'h'$,[3] as long as $M_{h'} < m_{\tilde{\nu}}$. If this is not the case then the next highest cross section channel is $\tilde{\nu}\tilde{\nu} \to W^+W^-$. We find that other channels have small contributions to the total annihilation cross section in comparison to these two. So, what separates the phenomena of the real and imaginary sneutrinos is then simply the mass relation between $h'$ and $\tilde{\nu}$. If $m_{\tilde{\nu}} > M_{h'}$, the annihilation cross section will be dominated by $h'h'$ production and, if not, then $W^+W^-$. In order to determine which mass is larger, and hence the phenomenology of a given state, we must consider the dependence of the mass splitting relation (2.2) on the trilinear coupling $A_0$. This initial input parameter will determine the properties of our sneutrino LSP at the low scale. For $A_0 \lesssim 0$, this mass splitting will favour a lower mass CP-even sneutrino and hence LSP, while for $A_0 \gtrsim 0$ we find CP-odd LSPs. The exact details were discussed previously, in section 2, but one does finds this general trend, as seen in figure 3.

Now, we turn to how the lightest $(B-L)$ Higgs is affected by the trilinear coupling,

$$M_{h'} = \frac{1}{2}\Big[(M_{A'}^2 + M_{Z'}^2) - \sqrt{(M_{A'}^2 + M_{Z'}^2)^2 - 4M_{A'}^2 M_{Z'}^2 \cos^2 2\beta'}\,\Big], \qquad (3.1)$$

where $M_{A'}^2$ is the mass of the $(B-L)$ CP-odd Higgs,

$$M_{A'} = \frac{2B_{\mu'}}{\sin 2\beta'}, \qquad (3.2)$$

and $B_{\mu'}$ is determined by the $B-L$ minimisation condition,

$$B_{\mu'} = \frac{1}{4}\Big[-2g_{BL}^2 v'^2 \cos 2\beta' + 2m_{\chi_1}^2 - 2m_{\chi_2}^2 + \tilde{g}g_{BL}v^2 \cos 2\beta\Big]\tan 2\beta'. \qquad (3.3)$$

At low scale, $m_{\chi_{1,2}}^2$ depends on $A_0$ (due to the RGE running from the GUT to EW scale). This directly affects $B_{\mu'}$ and also $\tan\beta'$ and hence induces an $A_0$ dependence on $M_{A'}$ and also $M_{h'}$. Though we have written these expressions at tree-level, to schematically demonstrate the dependence of $A_0$, numerically, we have calculated the masses at loop level, using SPheno (as discussed in section 2), which includes all relevant loop effects. Figure 3 displays this relation and we see that, for large and positive $A_0$ values, a wide range of $M_{h'}$ masses are allowed ($\sim 100-2000\,\mathrm{GeV}$) whereas, for $A_0 \lesssim 0$, lower $M_{h'}$ values are favoured, with the largest density of points over the interval $\sim 100-500\,\mathrm{GeV}$.

Combining this trend with larger mass scales for CP-even sneutrinos, as seen in figure 1, provides us with two general cases based on the GUT parameters. Firstly, $A_0$ is negative, the sneutrino LSP is CP-even, with $m_{\tilde{\nu}} \gtrsim 500\,\mathrm{GeV}$ and $M_{h'} \lesssim 500\,\mathrm{GeV}$, hence, in general, $m_{\tilde{\nu}} > M_{h'}$. The other possibility is that $A_0$ is positive, here, the sneutrino LSP is CP-odd

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[3]For ease of notation, hereafter, we identify $h' \equiv h_2$.
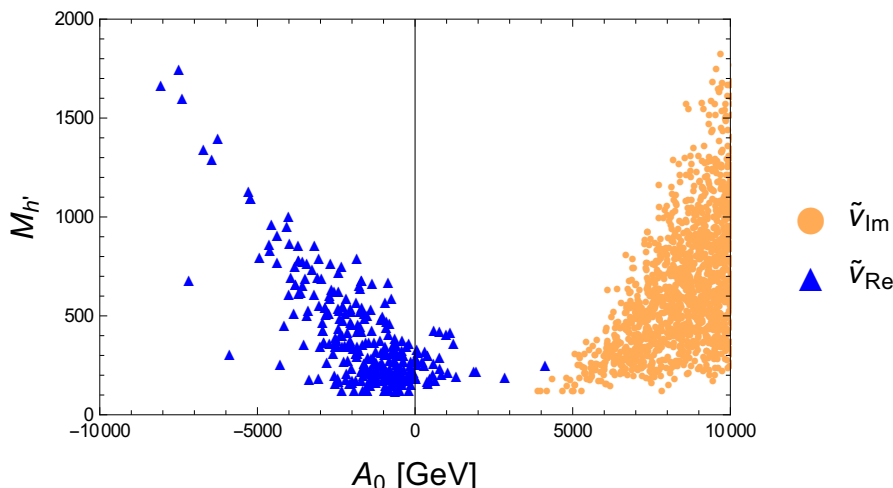
**Figure 3**. Mass of lightest $(B-L)$-like Higgs versus the GUT parameter $A_0$, for CP-even sneutrino LSPs (red) and CP-odd sneutrino LSPs (blue).

and both masses are similar, $100 \lesssim m_{\tilde{\nu}}, M_{h'} \lesssim 2000\,\text{GeV}$. Further, there are cases where $m_{\tilde{\nu}}$ is larger and also $M_{h'}$ is larger.

This behaviour is reflected in figure 4, where the histogram counts the number of spectrum points where the annihilation channels $h'h'$, $W^-W^+$ or something else have the largest cross section. The different spectrum points are coloured according to the value of their normalised annihilation cross section for a particular channel (e.g., $\sigma(\tilde{\nu}\tilde{\nu} \to h'h')/\sigma(\tilde{\nu}\tilde{\nu} \to X)$, for any combination of particles $X$). As mentioned, the CP-even case has many more parameter points with $m_{\tilde{\nu}} > M_{h'}$, hence a larger number of our spectra have the largest annihilation into $h'h'$. The CP-odd case has a larger number of points in our parameter space with the largest cross section of annihilation into $W^+W^-$. A particular point in parameter space will have a specified cross section into $W^+W^-$, which will strongly affect the ability to detect that scenario via indirect detection, as we detail in the next section. If Nature realises a given point in parameter space, it may be the case that this is detectable via indirect detection methods in the near future as we also detail in the next section.

However, further to this we should like to comment regarding the parameter space as a whole. Firstly, we see general differences between the CP-even and CP-odd scenarios, which are a direct consequence of the initial GUT conditions, especially the value of the trilinear coupling $A_0$, for which we choose a wide range of positive and negative values $(-15\,\text{TeV} < A_0 < 15\,\text{TeV})$. Choosing this positive and scanning over our parameter space (detailed in section 2), one will find that the majority of the sneutrino-LSP points will be CP-odd and for many of these, where $m_{\tilde{\nu}} < M_{h'}$, they will annihilate most strongly into $W^+W^-$, which can lead to a detectable signal. So one may make the point that positive $A_0$ values will generally lead to larger indirect detection signals. We emphasise here, though, that we are not suggesting a particular scenario is more likely realised in Nature, but rather that one may observe interesting features of our choice of parameter space.
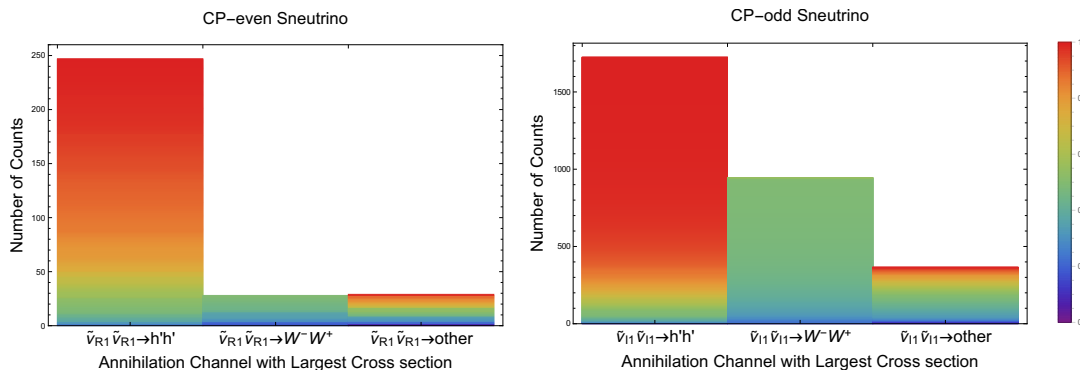
**Figure 4**. Histogram counting the number of spectrum points with the largest annihilation cross section being in either the $h'h'$, $W^+W^-$ or other channel. This has been done for spectrum points which have a CP-odd (left) or CP-even (right) sneutrino LSP. Each count is also coloured by the normalised cross section (so that the sum of annihilation cross section channels for a given point is unity), where a red coloured point means the given annihilation channel has a larger cross section.

These annihilation cross sections will be what determine the relic abundance of the sneutrinos. In this work we consider a standard cosmological scenario, where the DM particles were in thermal equilibrium with the SM ones in the early Universe and decoupled when the temperature fell below their relativistic energy. The relic density of our sneutrino species is written as [67]:

$$\Omega h^2_{\tilde{\nu}_1^{\mathrm{R,I}}} = \frac{2.1 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma^{\mathrm{ann}}_{\tilde{\nu}_1^{\mathrm{R,I}}} v \rangle} \left( \frac{x_F}{20} \right) \left( \frac{100}{g_*(T_F)} \right)^{\frac{1}{2}}, \tag{3.4}$$

where $\langle \sigma^{\mathrm{ann}}_{\tilde{\nu}_1^{\mathrm{R,I}}} v \rangle$ is a thermal average for the total cross section of annihilation to SM objects multiplied by the relative sneutrino velocity, $T_F$ is the freeze out temperature, $x_F \equiv m_{\tilde{\nu}_1^{\mathrm{R,I}}}/T_F \simeq \mathcal{O}(20)$ and $g_*(T_F) \simeq \mathcal{O}(100)$ is the number of degrees of freedom at freeze-out.

Figure 5 shows the thermal relic abundance for sneutrinos. This has been computed by MicrOMEGAs [68, 69] and one can see that both CP-even and CP-odd candidates are allowed by current limits of $0.09 < \Omega h^2 < 0.14$, which is the $2\sigma$ allowed region by the Planck collaboration [24]. It should be noted that one-loop corrections to the annihilation cross sections can change the theoretical predictions, thus altering the allowed parameter space. The exercise of estimating the theoretical uncertainty for the annihilation cross sections by taking into account the one-loop corrections has been done in the MSSM. For the BLSSM there are no concrete examples available. Within the MSSM setup, the corrections to the cross sections are shown to be of order 10–15% [70–75]. Taking this to be a benchmark scenario, it is true to say that the theoretical uncertainty on the relic density prediction is larger than the experimental counterpart. However, in the absence of any concrete corrections within the BLSSM, we do not make any assumptions of potential corrections to the annihilation cross section. In addition, the above figure is included in order to demonstrate the impact of exact relic density limits. In actual analyses elsewhere
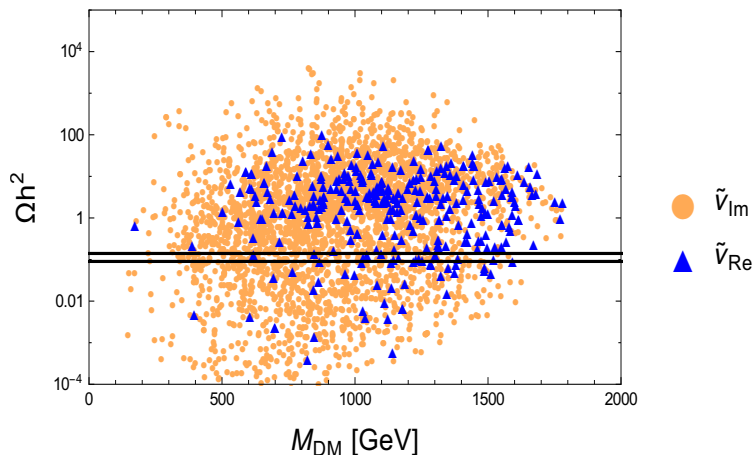
**Figure 5**. Relic density of CP-even and CP-odd sneutrinos versus their mass in GeV, where horizontal lines correspond to the Planck limits for the relic abundance.

in the paper, we only impose the upper limit for the relic density, thus making the impact of the aforementioned corrections less severe as compared to imposing the exact limit. These points also satisfy the HiggsSignals/HiggsBounds [58, 60] constraints (that the lightest CP-even Higgs must be SM-like and subject to negative Higgs searches), in addition to SUSY mass bounds for gluinos, staus, neutralinos, charginos and stops [61].

## 4 Indirect detection

When the sneutrino contribute to the observed or a part of DM abundance, its annihilation to SM particles produces an energetic spectrum of SM particles which has chances of being measured in DM indirect detection experiments. In this section, we will focus on the photon spectrum, produced as secondaries when sneutrino DM annihilates to SM final states. We will analyse the impact of FermiLAT searches from dwarf spheroidal galaxies (dSphs) and the galactic center in order to constrain and understand the future potential to explore sneutrino DM. The annihilation of sneutrinos in astrophysical objects with DM density $\rho_{\text{DM}}$ yields a $\gamma-$ray flux which is given by

$$\frac{d\Phi}{dE_\gamma} = \left( \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_{\text{DM}}^2} \frac{dN_\gamma}{dE_\gamma} \right) \times \left( \int_{\Delta\Omega} \int_{l.o.s.} \rho_{\text{DM}}^2 \, dl \, d\Omega' \right) , \tag{4.1}$$

where it is possible to separate a particle-dependent part, as the cross section $\langle \sigma v \rangle$ and the differential distribution $dN_\gamma/dE_\gamma$, from the astrophysical term involving the integration of $\rho_{\text{DM}}$ over the line-of-sight (l.o.s) and the solid angle $\Delta\Omega$. The last term, dubbed J-factor, depends on the particular $\gamma-$ray source where the DM annihilation takes place. The Fermi-LAT experiment has searched for $\gamma-$ray production with a sensitivity in the energy range from $20\,\text{MeV}$ to $\sim 300\,\text{GeV}$. Now, dSphs of the Milky Way, which are expected to have a sizable DM content, have a J-factor of $10^{19}\,\text{GeV}^2\,\text{cm}^{-5}$ and a small non-thermal $\gamma-$ray background. These features make their observation particularly suitable in constraining $\langle \sigma v \rangle$ and we challenge the BLSSM sneutrino prediction against the bounds coming from
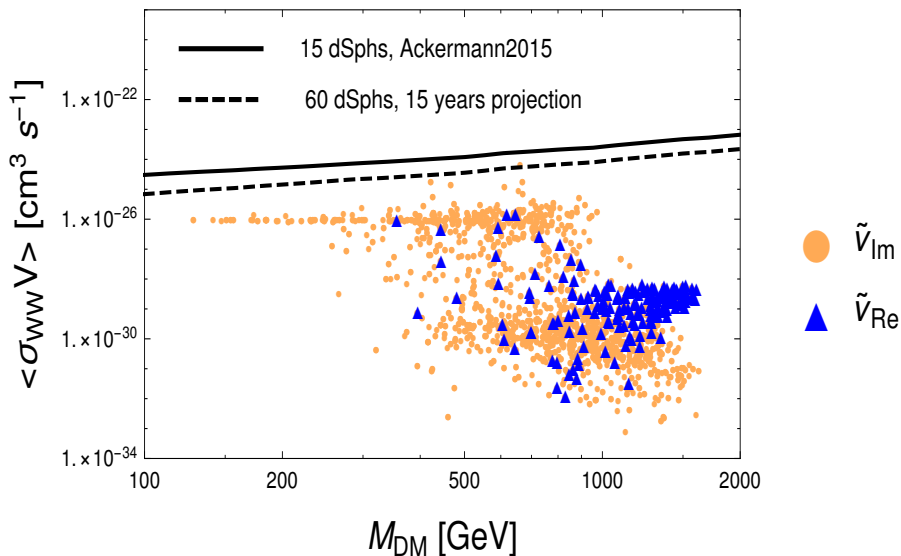
**Figure 6**. Thermal cross section for DM DM $\to W^+W^-$ annihilation as predicted by theory as a function of the DM mass, for CP-even (blue) and CP-odd (orange) sneutrinos. Also shown are the FermiLAT limit from dSphs at present (solid black) and as projection for 15 years from now (dashed black). All points obey the relic density upper limit, for which rescaling, where necessary, has been applied.

6 years of observation over 15 dSphs [76]. It should be noted that the assumed J-factor suffers from astrophysical uncertainties [77], but we do not consider any impact of these uncertainties within this study. Consistently with the result of the previous section that, by far, the main *charged* annihilation channel is represented by $W^+W^-$, we have checked that also the biggest constraint is provided in the same channel.[4] In figure 6, we plot the sneutrino annihilation cross section in the $W^+W^-$ channel. We denote the two populations of sneutrino DM candidates, namely, CP-odd and CP-even, with two different colours and compare the thermal cross section prediction with the existing bounds form dSphs (solid line). We also show the projection from 15 years of observation of 60 dSphs sample (dashed line). While some CP-odd sneutrino candidates can be tested with future FermiLAT searches, the constraining power for CP-even candidates is far weaker. Most of the parameter space of this model though remains safely allowed from existing and also future searches. It is imperative to note that the constraining power of FermiLAT for sneutrino DM is weaker in our scenarios because of an underabundant DM component. Moreover, our scan reveals the existence of a section of the GUT-constrained parameter space ameanable to investigation in future searches, here represented by the single point above the dashed line.

In a second attempt to confront our model with the FermiLAT observations, we turn to the galactic center and compute the differential $\gamma$-ray flux due to snuetrino annihilation at the center of the Milky Way. The differential distributions for the gamma spectrum as

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[4]We notice that, when the DM candidate is not fully responsible for the measured relic density, the cross section has been rescaled by an appropriate factor as shown in [78].
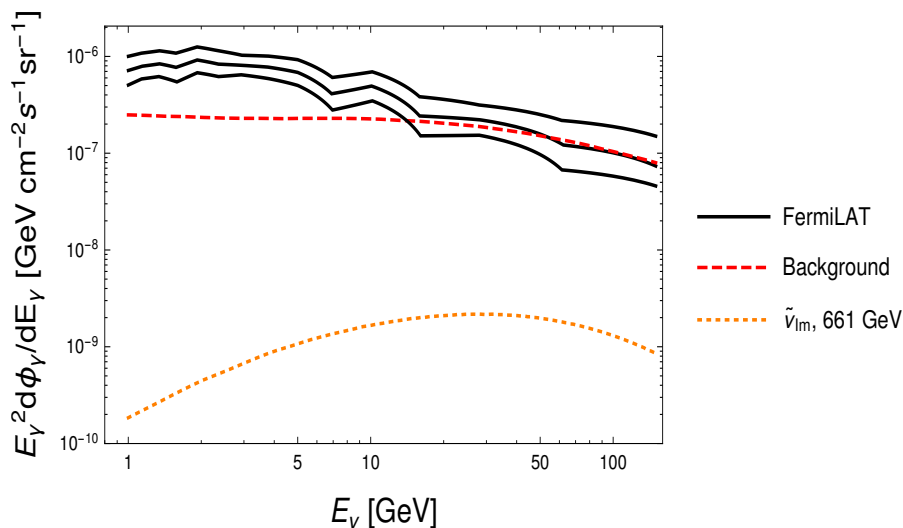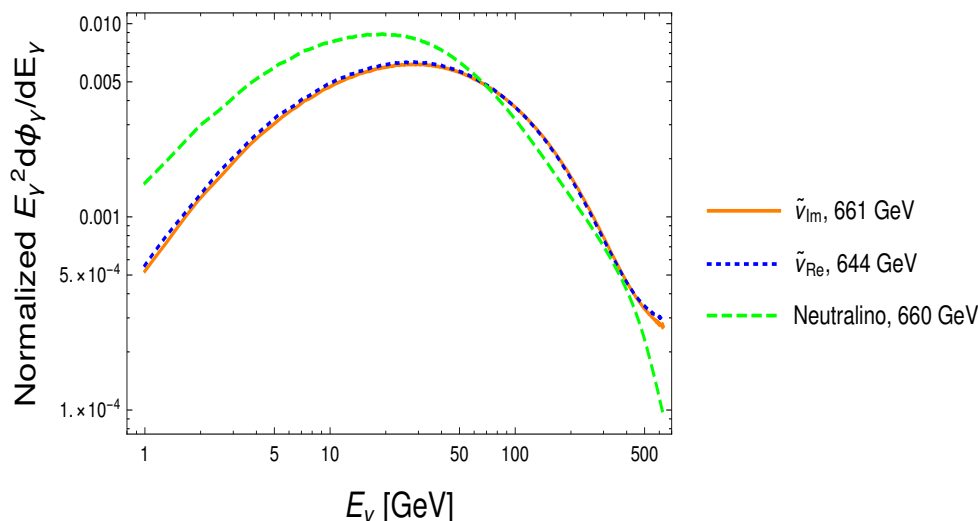
**Figure 7**. Differential flux of $\gamma$-ray secondary radiation induced by DM DM $\to W^+W^-$ annihilation as a function of the photon energy, with fixed DM mass, for our benchmark CP-odd sneutrino (orange). The corresponding distribution for the background is also given (red). The FermiLAT present data (with error) are in black. The sneutrino point considered is compliant with the relic density constraint taken as an upper limit.

computed in (4.1) is itself also a subject of dedicated analyses and experimental searches based on FermiLAT data. The flux detected has therefore two components, of signal (SIG) and background (BG),

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{d\Phi_\gamma^{\mathrm{BG}}}{dE_\gamma} + \frac{d\Phi_\gamma^{\mathrm{SIG}}}{dE_\gamma} \tag{4.2}$$

and we computed the signal flux $(d\Phi_\gamma^{\mathrm{SIG}}/dE_\gamma)$ for the case of the sneutrino corresponding to the largest annihilation cross section in our scan. We notice, as shown in figure 7, how for our benchmark point of mass $661\,\mathrm{GeV}$ and $\langle\sigma_{WW}\rangle \simeq 7 \times 10^{-25}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ the signal is far below the large background (given by $\frac{d\Phi_\gamma^{\mathrm{BG}}}{dE_\gamma}$). Hence, our prediction for FermiLAT is that to a possible detection of a signal in the integrated flux measurement it would not correspond a $\gamma$-ray spectrum significantly distorted from the background shape, at least not in the current experimental run. However, as the FermiLAT data sample will increase, more and more of the spectrum will be accessible at larger energies, where a characteristic signal shape may eventually emerge.

When this will happen, it will be interesting to understand whether such a shape may enable one to distinguish between a (spin-1/2) fermionic DM hypothesis and a (spin-0) CP-even or -odd one (and possibly between the latter two). With this in mind, we compare the shape of the differential $\gamma$-ray flux from CP-even, CP-odd sneutrino and neutralino DM candidates in figure 8. Here, we plot the normalised flux distribution allowing us to make comparison between the three candidates independently of the size of their annihilation cross sections and relic density. The three chosen points have very similar mass, hence also determining similar end points in the spectrum. While the CP-even and CP-odd sneutrinos

**Figure 8**. Differential flux of $\gamma$-ray secondary radiation induced by DM DM $\to W^+ W^-$ scatterings as a function of the photon energy, with fixed DM mass, for our benchmark CP-even (blue) and CP-odd (orange) sneutrinos. The corresponding distribution for a neutralino is also given for comparison (green). Normalisation is the same for all curves.

have a very similar shape, the neutralino one is very different, this result allowing us to speculate on the possibility of extracting the DM spin via indirect detection experiments. It should however be noted that a more complete analysis, taking into account various theoretical and experimental uncertainties, must be carried out in order to make a more concrete statement in this direction. Nonetheless, we find this result to be important, as it may actually be testable via data expected to be collected in the years to come.

## 5 LHC signatures

In this section we discuss the possibility of characterising the sneutrino DM at the LHC by qualitatively describing some of the most interesting signatures provided by the BLSSM.

Since the sneutrino LSP is mostly RH, it carries no $SU(2)_L$ quantum numbers and hence may only interact with the MSSM-like states via mixing with the LH sneutrinos. This is highly suppressed, being proportional to the very small Dirac Yukawa coupling for the LH neutrinos. As such, searches in the neutral or charged Drell-Yan processes, mediated respectively by the SM $Z$ and $W^\pm$ gauge bosons, are hopeless. In contrast, the largest couplings of the RH sneutrinos are with the typical $(B-L)$ degrees of freedom, among the others, the $Z'$ and heavy bi-leptonic scalars. In particular, as required by CP conservation, the $Z'$ couples to $\tilde{\nu}^R$ (CP-even) and $\tilde{\nu}^I$ (CP-odd), where one of the two is the LSP and the other can be the Next-to-LSP (NLSP), while the heavy CP-even Higgses can couple to two LSPs. Hence, for the case of *direct* DM production at the LHC, one can attempt relying upon $pp \to Z' \to \tilde{\nu}_{\mathrm{LSP}} \tilde{\nu}_{\mathrm{NLSP}}$, with the decay of the NLSP to the LSP via $\tilde{\nu}_{\mathrm{NSLP}} \to \tilde{\nu}_{LSP} Z^{(*)}$ providing a di-lepton (plus missing transverse energy) signature through a SM $Z$ boson decay, unlike the heavy Higgs mediated process, which, since the final state is

made up by LSP pairs, is invisible and can only be accessed through mono-jet, -photon, etc. searches. In searching for these direct DM signals, we have scanned over several benchmark CP-even and CP-odd sneutrino LSPs and used MadGraph [79] for the computation of the LHC cross sections. In detail, we have computed the inclusive cross section for $pp \to \tilde{\nu}_1^{\mathrm{I}} \tilde{\nu}_i^{\mathrm{R}}$, where $\tilde{\nu}_1^{\mathrm{I}}$ is the LSP, and allowed for the production of any other CP-even sneutrinos ($i = 1, \ldots 6$) alongside it. We also have explored the $pp \to \tilde{\nu}_1^{\mathrm{R}} \tilde{\nu}_i^{\mathrm{I}}$ channel in which the LSP is represented by the CP-even component of the lightest sneutrino. These cross sections are totally dominated by the $s$-channel exchange of a $Z'$, i.e., $pp \to Z' \to \tilde{\nu}_1^{\mathrm{I}} \tilde{\nu}_i^{\mathrm{R}}, \tilde{\nu}_1^{\mathrm{R}} \tilde{\nu}_i^{\mathrm{I}}$, and found to be $\sigma \simeq 0.025\,\mathrm{fb}$ at most for both the CP charges of the LSP. It is unsurprising that this cross section is so small, as we are forced to have a heavy $Z'$ to comply with current LHC search limits ($M_{Z'} \gtrsim 4\,\mathrm{TeV}$). As this cross section is so small, it would be difficult to observe any signal here without a much higher luminosity than at present.

Another intriguing possibility to search for sneutrino LSP states though is to do so *indirectly*, e.g., via slepton $\tilde{l}$ pair production. The corresponding cross section may lay in the $\sim 0.1\,\mathrm{fb}$ range. When the slepton mass is light enough, the $\tilde{l} \to W^{\pm} \tilde{\nu}_{\mathrm{LSP}}$ channel is the only available decay mode despite its width being suppressed by the smallness of the Dirac Yukawa coupling, yiedling a di-lepton signature. Alternatively, if kinematically allowed, one can have $\tilde{l} \to \tilde{\chi}^0 l$ with $\tilde{\chi}^0 \to \nu_h \tilde{\nu}_{\mathrm{LSP}}$, where $\nu_h$ is the heavy neutrino. The latter will mainly undergo $\nu_h \to W^{\pm} l^{\mp}$ or $\nu_h \to Z \nu_l$ decay, thus providing fully or semi-leptonic signatures (again, accompanied by missing transverse energy). Other interesting DM signatures may arise from squark pair production for which the cross sections can reach several fb's. In this case, e.g., one can exploit the decay chain $\tilde{t} \to \tilde{\chi}^0 t$, which can occur with a BR $\sim 80\%$ if the $\tilde{t}$ is the lightest squark, where $\tilde{\chi}^0 \to \nu_h \tilde{\nu}_{\mathrm{LSP}}$, as discussed above. Here, one would have a variety of jet plus multi-lepton final states recoiling against missing transverse energy.

## 6 Conclusions

The BLSSM provides a preferential DM candidate which is notably different from the one in the MSSM. The former is a spin-0 boson (specifically, a CP-even or CP-odd sneutrino) and the latter a spin-1/2 fermion (specifically, a neutralino). While in a previous paper we had assessed that sneutrino DM affords the BLSSM with an amount of parameter space comparatively much larger than the one of the MSSM offering neutralino DM, both compliant with WMAP/Planck and LUX constraints, here, we have shown that signals of sneutrino DM are, on the one hand, just below the current sensitivity of FermiLAT and, on the other hand, within reach of it in the next 15 years of foreseen data taking, unlike the neutralino case, although this is possible only over a restricted region of parameter space. Furthermore, we have illustrated that, once a DM signal is established by such an experiment as an excess in the integrated photon flux for some DM mass, there exists scope in establishing the (pseudo)scalar nature of sneutrino DM by studying the differential photon flux in energy, as its shape is notably different from the one pertaining to (fermionic) neutralino DM. However, there exists no possibility in this experiment to separate with differential data the CP-even from the CP-odd sneutrino hypothesis, although their integrated rates

are sizeably different, with a predominance of relic CP-odd states over CP-even ones. This phenomenology is enabled by the fact that one of the dominant DM annihilation channels in the case of the BLSSM has charged particles in the final state, notably $W^\pm$ boson pairs, as already noted in such a previous publication of ours. In fact, it is the copious $\gamma$-ray emission from the charged gauge boson pair that puts FermiLAT in the position of exploring signals of sneutrino DM, unlike the MSSM, wherein the annihilation channel of neutralino DM into $W^\pm$ pairs is negligible. Intriguingly, the favourite BLSSM candidate for DM is also potentially accessible at the LHC over the same time scale, 15 years or so. In fact, Run 2 and 3 data from the CERN machine may be able access a series of signatures, involving multi-lepton final states, with and without jets, alongside the expected missing transverse energy. In fact, also customary mono-jet, -photon, etc. searches may eventually develop sensitivity to the BLSSM candidate for DM.

Altogether, we should like to conclude by mentioning that the DM sector of the BLSSM has very distinctive features with respect to those specific to the prevalent SUSY description, i.e., the MSSM, that can be eventually established in both DM indirect detection experiments and at the LHC. In constrast, we do not expect (nor we have investigated here) the possibility of differences in case of DM direct searches, as potential BLSSM mediators, a $Z'$ or additional heavy Higgs states, are either too heavy or too weakly coupled to nuclear constituents, respectively, to play any significant role. We therefore advocate more thorough investigations of DM phenomenology in this non-minimal SUSY scenario, which was beyond the scope of our paper.

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