$R$-parity Violating Decays of
Wino Chargino and Wino Neutralino
LSPs and NLSPs at the LHC

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ABSTRACT: The $R$-parity violating decays of both Wino chargino and Wino neutralino LSPs are
analyzed within the context of the $B – L$ MSSM “heterotic standard model”. These LSPs correspond
to statistically determined initial soft supersymmetry breaking parameters which, when evolved using
the renormalization group equations, lead to an effective theory satisfying all phenomenological re-
quirements; including the observed electroweak vector boson and Higgs masses. The explicit decay
channels of these LSPs into standard model particles, the analytic and numerical decay rates and the
associated branching ratios are presented. The decay lengths of these RPV interactions are discussed.
It is shown that the vast majority of these decays are “prompt”, although a small, but calculable, num-
ber correspond to “displaced vertices” of various lengths. It is demonstrated that for a Wino chargino
LSP, the NLSP is the Wino neutralino with a mass only slightly higher than the LSP– and vice-versa.
As a consequence, we show that both the Wino chargino and Wino neutralino LSP/NLSP $R$-parity
violating decays should be simultaneously observable at the CERN LHC.

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1 Introduction

In a previous paper [1] we presented, within the context of the $N = 1$ supersymmetric $B - L$ MSSM, the decay channels and the associated analytic decay rates for Wino/Higgsino chargino and arbitrary neutralino $R$-parity violating (RPV) decays to standard model particles. These results were valid for any such charginos and neutralinos, regardless of their mass; that is, whether or not they are the lightest supersymmetric particles (LSPs). As was discussed in detail in that paper, the dimensionful soft supersymmetry breaking parameters were chosen statistically to lie in an interval that, although centered around a mass of several TeV, was wide enough to allow chargino and neutralino masses to be as low as $\sim 200$ GeV and as heavy as $\sim 10$ TeV. That is, the mass spectrum of these sparticles overlaps with the range potentially observable at the CERN LHC.

The $B - L$ MSSM is a minimal extension of the MSSM that arises as a vacuum state of heterotic M-theory [2–6]. It was shown using a series of papers [7–10] that, when compactified to four-dimensions on a specific Calabi-Yau threefold [11], this vacuum has exactly the particle spectrum of the MSSM— that is, three families of quark and lepton chiral supermultiplets, a pair of Higgs-Higgs conjugate chiral superfields and three right-handed neutrino chiral supermultiplets, one per family. The associated gauge group is $SU(3)_C \times SU(2)_L \times U(1)_Y$ of the standard model augmented, however, by an additional gauged Abelian group factor, $U(1)_{B - L}$. This extra gauge factor contains $R$-parity and sufficiently suppresses both proton decay and lepton number violating decays, even after it is spontaneously broken [1, 12]. As discussed in many of the previously referenced papers, as well as in [1], when supersymmetry is softly broken in an interval of order the TeV scale, and then run to lower mass scales using the renormalization group (RG), we find— for a large number of statistically scattered and uncorrelated initial conditions — that the $B - L$ MSSM is consistent with all present experimental bounds. Specifically, it was shown that 1) the gauged $U(1)_{B - L}$ symmetry is radiatively broken by the third family right-handed sneutrino acquiring a vacuum expectation value (VEV). This VEV is sufficiently large that the associated vector boson mass exceeds the present experimental bound. The process of $B - L$ breaking also yields a natural explanation for Majorana neutrino masses via a seesaw mechanism [13, 14]. 2) Electroweak symmetry is radiatively broken by the neutral Higgs fields acquiring radiative VEVs. The associated $W^\pm$ and $Z^0$ vector bosons have precisely their experimentally measured values. 3) All supersymmetric sparticles exceed their present experimental lower bounds. 4) Finally, and remarkably, the Higgs boson mass satisfies the three sigma bound established at the LHC.

Furthermore, several important “stringy” theoretic aspects of the $B - L$ MSSM are potentially amenable to calculation. First, it has been demonstrated that, in principle, the potential energy functions for the geometric, vector bundle and five-brane moduli can be calculated and the vacuum state of these moduli stabilized [15–18]. Second, it has been shown [19–22] that the Yukawa couplings are, in principle, directly calculable from the harmonic representatives of the sheaf cohomology classes [23]. Similarly, gauge couplings are potentially calculable from string unification threshold corrections [24–33]. Finally, gauging the $N = 1$ supersymmetry couples the $B - L$ MSSM directly to $N = 1$ supergravitation. This allows both theories of inflation [34–37] and “bouncing universe” cosmologies [38, 39] to naturally arise within this context. We note in passing that for the $B - L$ MSSM
inflation theory to be consistent with the present cosmological data, its soft supersymmetry breaking scale must be raised to the order of $10^{13}$ GeV. Be that as it may, it was shown in [34] that the low energy theory can remain completely consistent with all phenomenological bounds listed above.

For all of these reasons, the $B - L$ MSSM appears to be the simplest possible phenomenologically realistic theory of heterotic superstring/M-theory; being exactly the MSSM with right-handed neutrino chiral supermultiplets and spontaneously broken $R$-parity. We would like to point out that, although the $B - L$ MSSM was originally derived from the “top-down” point of view of heterotic M-theory, it was also constructed from a low energy, “bottom-up” approach in [40–45]. For all of these reasons, it would seem to be to be a rich arena to study the phenomenological predictions of the $B - L$ MSSM at energies low enough to be observable by the ATLAS detector at the LHC at CERN. This requires taking the interval of soft supersymmetry breaking parameters to be in the range discussed in detail in our recent paper [1]. We will do this, henceforth. However, the generic supersymmetric interactions of the $B - L$ MSSM are extremely complicated for arbitrary mass sparticles, with the RP conserving processes being much larger than, and, hence, potentially making unobservable, the RPV decays calculated in [1]. However, there is one very clean and obvious window where experimental observation of supersymmetric interactions becomes vastly simplified. That window is for the so-called lightest supersymmetric particle—the LSP. By definition, in an $R$-parity conserving theory, the LSP cannot further decay, either to other sparticles or to standard model particles. However, in a theory in which $R$-parity is spontaneously broken, the LSP, while still unable to decay via RP conserving interactions, can now decay through RPV processes to standard model particles. In the $B - L$ MSSM, these decay channels, their decay rates and the associated branching fractions can be explicitly calculated. We propose, therefore, that the RPV decays of the LSPs of the $B - L$ MSSM be searched for experimentally, and the results compared to the theoretical predictions. Any positive result obtained in this regard could be a first indication of the existence of $N = 1$ supersymmetry, as well as a potential confirmation of the $B - L$ MSSM theory.

This program has already been carried out for the lightest admixture stop, which was shown to be one of the LSPs of the $B - L$ MSSM. The branching ratios for the RPV decay of the lightest stop LSP to a bottom quark and a charged lepton, the dominant decay mode, along with the relationship of these decays to the neutrino mass hierarchy and the $\theta_{23}$ neutrino mixing angle, were presented in [12, 46]. The admixture stop LSP was chosen for two reasons. First, it carries both electric and color charge and, therefore, is “exotic”; in the sense that in RP conserving theories such an LSP would contribute to “dark matter” which must be gauge neutral. Second, it has a high production cross section at the LHC. Based on the results of these two papers, a search for stop LSP decays in the recent ATLAS LHC data was carried out in [47–50]. No direct detection was observed. However, the lower bounds on the stop LSP mass were significantly strengthened. Be that as it may, as was discussed in [1, 51, 52] and will be described in the next section, the number of physically realistic initial conditions leading to a stop LSP are relatively small compared to other sparticles. Therefore, in a series of papers, we will pursue this program focussing, however, on other sparticles that occur more frequently as LSPs of the $B - L$ MSSM. Specifically, in this paper, we will explore the decay channels, the decay rates and calculate the branching ratios to standard model particles for Wino chargino and Wino neutralino LSPs, using the explicit results for generic chargino and neutralino sparticles presented in [1].
Wino charginos/neutralinos occur with much more frequency as LSPs of realistic initial conditions of the $B - L$ MSSM. As in the case of the stop LSP, we will discuss the relationship of their decays to standard model particles to the neutrino mass hierarchy and the $\theta_{23}$ neutrino mixing angle.

## 2 The LSPs of the $B - L$ MSSM

A review of the $B - L$ MSSM, including the structure of its $R$-parity violating interactions, was presented in [1]. In that paper, we also discussed the relationship between the Majorana neutrino masses, for both the normal and inverted neutrino hierarchies, and the RPV parameters $\epsilon_i$ and $\nu_{Li}$, $i = 1, 2, 3$ using the most up-to-date neutrino data. The basic input parameters of our RG computer code were also presented. We refer the reader to [1] for details. Here, we want to emphasize that the interval over which all 24 dimensionful soft supersymmetry breaking parameters are statistically scattered was chosen in [1] to be

$$\left[ \frac{M}{f}, M f \right] \quad \text{where} \quad M = 1.5 \, \text{TeV} \ , \ f = 6.7 \, . \quad (2.1)$$

This guarantees, as mentioned above, that all mass parameters in the theory lie approximately in the range

$$[200 \, \text{GeV}, 10 \, \text{TeV}] \quad (2.2)$$

and, hence, are potentially amenable to observation at the LHC. In addition to a discussion of the input parameters for the computer code, reference [1] also presented all of the phenomenological requirements that must be fulfilled for the low energy $B - L$ MSSM vacuum to be physically realistic. Whether or not these requirements are satisfied depends entirely on the initial soft supersymmetry breaking parameters that are chosen. As discussed in detail in a number of previous papers, we choose these initial conditions statistically, randomly throwing all 24 soft breaking parameters over the interval (2.1). A detailed analysis of this was presented in [1]. Here, we simply present the relevant results. Out of 100 million initial statistical data points, we found that 65,576 satisfied all phenomenological requirements when scaled to low energy using the RGEs. These were called “valid black points”.

Although each such black point satisfies all physical requirements, they can have different LSPs. A statistical study of the LSPs associated with the 65,576 black points was carried out in [1]. The results are reproduced below in the histogram in Figure 1. First, notice that, despite having a large production cross section, the percentage of physically realistic vacua having an admixture stop LSP is, as mentioned above, relatively small—of the order of 0.01%. Much more statistically favored are the “Wino chargino”, $\tilde{\chi}_W^\pm$, and the associated “Wino neutralino”, $\tilde{\chi}_W^0$. A generic chargino is an $R$-parity conserving mixture of a charged Wino, $\tilde{W}^\pm$, and a charged Higgsino, $\tilde{H}^\pm$, along with a small RPV component of charged leptons, $e_i^c, e_i$, $i = 1, 2, 3$. A Wino chargino is a chargino which is predominantly the charged Wino. A generic neutralino is an $R$-parity conserving linear combination of six neutralino sparticles, including the neutral Wino, $\tilde{W}^0$, along with a small RPV component of neutrinos, $\nu_i$, $i = 1, 2, 3$. We refer the reader to [1] for details. A Wino neutralino is a neutralino that is predominantly the neutral Wino. Our statistical analysis shows that the Wino chargino, $\tilde{\chi}_W^\pm$,
and the Wino neutralino, $\tilde{\chi}_0^W$, arise from 4,858 and 4,869 valid black points respectively; that is, each occurring approximately 7.40% of the time. Therefore, even though each has a lower production cross section than the stop LSP, they clearly would play a significant role in any experimental search for RPV decays in the $B - L$ MSSM. It is also of interest, and important, to note that the percentage of “Higgsino chargino” LSPs, $\tilde{\chi}_0^\pm$, that is, a chargino which is predominantly a charged Higgsino, is approximately zero. In fact, out of the 65,576 valid black points, only 1 was found to have a Higgsino chargino LSP. The reason for this paucity of charged Higgsinos was explained in [1]. Hence, in this and future publications we will ignore the Higgsino chargino LSP.

It is clear from the histogram in Figure 1 that, in addition to the Wino chargino and Wino neutralino, there are other possible LSPs of the $B - L$ MSSM that are potentially of interest experimentally. For example, the RPV decays of $\tilde{\chi}_0^B$ and $\tilde{\chi}_0^H$, with 42,039 and 105 valid black points respectively, are possibly observable at the LHC. However, in this paper we will confine our analysis to Wino charginos and Wino neutralinos only, returning to other LSP RPV decays in future publications.

![Figure 1](image-url)

**Figure 1**: A histogram of the LSPs associated with a random scan of 100 million initial data points, showing the percentage of valid black points with a given LSP. Sparticles which did not appear as LSPs are omitted. The y-axis has a log scale. The notation and discussion of the sparticle symbols on the x-axis were presented in [1].

It will be helpful in our analysis to be more explicit about the properties of Wino charginos and Wino neutralinos. We begin by pointing out that the RPV terms in both of these sparticles are always very small compared to the $R$-parity conserving terms. It follows that, although essential in the discussion of RPV decays to standard model particles in the following sections, these RPV terms give negligible contributions to the mass eigenvalues. Hence, in this section, where we are discussing
their LSP properties, we will consider only the $R$-parity conserving components of $\tilde{\chi}_W^\pm$ and $\tilde{\chi}_W^0$. Let us first consider the Wino chargino. As discussed in [1], if the dimensionful parameters $M_2$ and $\mu$ in the $B-L$ MSSM satisfy $|M_2| < |\mu|$, which we find to be the case for all 4,858 black points, then the $R$-parity conserving component of $\tilde{\chi}_W^\pm$ is given by

$$\cos \phi^\pm \tilde{W}^\pm + \sin \phi^\pm \tilde{H}^\pm. \quad (2.3)$$

Here, $W^\pm$ and $\tilde{H}^\pm$ are the pure charged Wino and charged Higgsino respectively and $\phi^\pm$ are such that $\cos \phi^\pm > \sin \phi^\pm$. The angles $|\phi^\pm|$ can be evaluated for each of the 4,858 associated black points. The results are shown as a histogram in Figure 2. It is clear that both angles are extremely small for any such black point. Hence, to a very high degree of approximation,

$$\tilde{\chi}_W^\pm \simeq \tilde{W}^\pm. \quad (2.4)$$

**Figure 2:** The mixing angles $|\phi^+|$ and $|\phi^-|$ plotted against the 4,858 valid black points leading to a Wino chargino LSP’s. It is clear that both angles are extremely small and, hence $\cos \phi^\pm \approx 1$ and $\sin \phi^\pm \approx 0$ for any such LSP.

That is, the Wino chargino LSP mass eigenstate is almost exactly the charged Wino. The mass of a Wino chargino was discussed in [1]. An analytic expression for the $R$-parity preserving part of the mass eigenvalue was presented, as was the method for numerically computing the RPV extension. Using these results, the Wino chargino mass can be evaluated numerically for each of the 4,858 associated black points. The results were presented in [1] and, for clarity, are reproduced here in Figure 3. The reason that the Wino chargino mass distribution peaks toward the low mass values was discussed in detail in [1], and we refer the reader to that paper for details.
Let us now consider the Wino neutralino. As discussed in [1], ignoring the very small RPV corrections, there are 6 neutralino mass eigenstates, each a complicated linear combination of the neutral gauge eigenstates. Here, we will only consider one of them, the Wino neutralino LSP, $\tilde{\chi}_W^0$, and the 4,869 valid black points associated with it. As discussed in [1], a complicated numerical calculation allows us to compute, for each valid black point, the coefficients of the linear combination of neutral gauge eigenstates comprising the Wino neutralino. Here, we will simply state the result that the coefficient of the neutral Wino, $W^0$, component is largely predominant, whereas all other coefficients are very small. Hence, to a high degree of approximation,

$$\tilde{\chi}_W^0 \simeq W^0.$$  \hspace{1cm} (2.5)

![Graph 1](image1.png)  \hspace{1cm} ![Graph 2](image2.png)

**Figure 3**: a) Mass distribution of the Wino chargino LSP’s for the 4,858 valid black points. The masses range from 200 GeV to 1820 GeV, peaking towards the low mass end. b) Mass distribution of the Wino neutralino LSP’s for the 4,869 valid black points. The masses range from 200 GeV to 1734 GeV, peaking towards the low mass end.

That is, the Wino neutralino LSP mass eigenstate is almost the neutral Wino. The methods for numerically evaluating both the $R$-parity conserving and the RPV contributions to the Wino neutralino mass were discussed in [1]. Using these methods, the Wino neutralino mass can be evaluated numerically for each of the 4,869 associated valid black points. The results were presented in [1] and, for clarity, are reproduced here in Figure 3. Again, the reason that the Wino neutralino mass distribution peaks toward the low mass values was discussed in detail in [1], and we refer the reader to that paper for details.
3 Wino Chargino LSP Decays

The minimal B-L extension of the MSSM, that is, the $B-L$ MSSM, introduces RPV vertices that allow LSPs to decay directly into SM particles. In this section, we will investigate the RPV decays of a Wino chargino LSP. As discussed in [1], a generic chargino mass eigenstate is a superposition of a charged Wino, a charged Higgsino and charged lepton gauge eigenstates. The $R$-parity conserving component of the Wino chargino is given by the linear combination of a charged Wino and charged Higgsino presented in (2.3), where the charged Wino component dominates. The smaller RPV contribution to the Wino chargino was presented in subsection 5.1 of [1]. For the case at hand, where $|M_2| < |\mu|$, this was found to be

$$\mathcal{V}_{12+i} e_i^c \quad \text{where} \quad \mathcal{V}_{12+i} = -\cos \phi_+ \frac{g_2 \tan \beta m_{e_i}}{\sqrt{2} M_2 \mu} v_{L_i} + \sin \phi_+ \frac{m_{e_i}}{\mu} v_{L_i}$$

(3.1) for $\tilde{\chi}_W^+$ and

$$\mathcal{U}_{12+i} e_i \quad \text{where} \quad \mathcal{U}_{12+i} = -\cos \phi_- \frac{g_2 v_d}{\sqrt{2} M_2 \mu} e_i^* + \sin \phi_- \frac{e_i^*}{\mu}$$

(3.2) for $\tilde{\chi}_W^-$. We sum (3.1) and (3.2) over $i = 1, 2, 3$.

One of the goals of this paper is to predict the possible signals produced by the RPV decays of Wino chargino LSPs, were such particles to exist and be light enough to be detected at the LHC. In our previous paper [1], we analyzed RPV decay channels using 4-component spinor notation for the mass eigenstates. For example, the Dirac spinor associated with the Weyl fermions $\tilde{\chi}_W^\pm$ is defined to be

$$\tilde{X}_W^\pm = \begin{pmatrix} \tilde{\chi}_W^+ \\ \tilde{\chi}_W^- \end{pmatrix}. \quad \text{(3.3)}$$

We found that $\tilde{X}_W^\pm$ can decay into standard model particles via four RPV channels. These are

(a) $\tilde{X}_W^\pm \to W^\pm \nu_i$

(b) $\tilde{X}_W^\pm \to Z^0 \ell_i^\pm$

(c) $\tilde{X}_W^\pm \to \gamma^0 \ell_i^\pm$

(d) $\tilde{X}_W^\pm \to h^0 \ell_i^\pm$

**Figure 4:** RPV decays of a general massive chargino state $X_W^\pm$. There are four possible channels, each with $i = 1, 2, 3$, that allow for Wino chargino LSP decays. The decay rates into each individual channel were calculated for generic charginos in our previous paper, and are reproduced here in Appendix A
Each of these 4 channels have different properties concerning their potential experimental detection. The $\tilde{X}_W^{\pm} \to Z^0 \ell_i^{\pm}$ and $\tilde{X}_W^{\pm} \to \gamma^0 \ell_i^{\pm}$ processes are the Wino chargino decays most easily observed at the LHC. On the other hand, the left handed neutrinos produced during $\tilde{X}_W^{\pm} \to W^{\pm} \nu_i$ can only be detected as missing energy, while the Higgs boson $h_0$ resulting from the decay $\tilde{X}_W^{\pm} \to h_0 \ell_i^{\pm}$ couples to both quarks and leptons, leading to traces in the detector that are harder to interpret. In the following, we will explicitly compute the decay rates and branching ratios for all 4 channels. Sufficiently large probabilities for the processes $\tilde{X}_W^{\pm} \to Z^0 \ell_i^{\pm}$ and $\tilde{X}_W^{\pm} \to \gamma^0 \ell_i^{\pm}$ may indicate favorable prospects for detecting Wino chargino LSPs at the LHC, whereas finding that these 2 channels are subdominant would then make these experimental efforts more difficult.

3.1 Branching ratios of the decay channels

The decay rates into each individual channel were calculated analytically for generic charginos in our previous paper and are reproduced in Appendix A. For a fixed lepton family $i$, these decay rates depend explicitly on the choice of the neutrino hierarchy and the value of $\theta_{23}$\textsuperscript{1}. We will discuss this in detail at the end of this section. However, for the present, we will confine ourselves to a calculation of the overall branching ratio for a given type of decay process, which explicitly involves a sum $\sum_{i=1}^{3}$ over the lepton families. The relative prevalence of each channel type is determined by its associated branching ratio. A statistical analysis shows that, for any given decay channel, the sum over the three lepton families makes the branching ratio approximately independent of both the choice of the neutrino hierarchy and the value of $\theta_{23}$. We will now evaluate these branching ratios for each of the 4,858 valid black points associated with a Wino chargino LSP, separating the data into statistically relevant bins of both $\tan \beta$ and the Wino chargino mass. To begin with, these calculations will be carried out assuming a normal hierarchy with $\theta_{23} = 0.597$. Later on in this section, we will discuss the small statistical differences that would occur had we chosen one of the other possible neutrino data sets. To make this process transparent, we now present our explicit calculational procedure.

For specificity, let us first discuss $\tilde{X}_W^{\pm} \to Z^0 \ell_i^{\pm}$ for any $i = 1, 2, 3$. For this decay channel, the branching ratio is defined by

$$ Br_{\tilde{X}_W^{\pm} \to Z^0 \ell_i^{\pm}} = \frac{\sum_{i=1}^{3} \Gamma_{\tilde{X}_W^{\pm} \to Z^0 \ell_i^{\pm}}}{\sum_{i=1}^{3} \left( \Gamma_{\tilde{X}_W^{\pm} \to W^{\pm} \nu_i} + \Gamma_{\tilde{X}_W^{\pm} \to Z^0 \ell_i^{\pm}} + \Gamma_{\tilde{X}_W^{\pm} \to \gamma^0 \ell_i^{\pm}} + \Gamma_{\tilde{X}_W^{\pm} \to h_0 \ell_i^{\pm}} \right) } . \quad (3.4) $$

We now proceed to evaluate (3.4) for each of the valid black points associated with a Wino chargino LSP. Since there will be 4,858 different values of $Br_{\tilde{X}_W^{\pm} \to Z^0 \ell_i^{\pm}}$, we find it convenient to divide up this data into separate bins. Specifically, we will do the following. First, recall from Figure 3 that the physical mass of a Wino chargino is much more likely to be small, on the order of 200 GeV, and approximately $10^{-2}$ times less likely to be on the order of 1 TeV. This leads us to divide the Wino

\textsuperscript{1} As shown in [1], each of the measured values of $\theta_{23}$ in both the normal and inverted hierarchies have small uncertainties around a central value. These uncertainties are incorporated into our computer code in all calculations. However, for simplicity of notation, when we refer to the value of $\theta_{23}$ in the text of this paper, we will suppress these error intervals and indicate the central values only.
chargino LSP mass range into three bins given by

\[ M_{\tilde{X}_W^\pm} \in [200, 300], [300, 600], [600, 1820] \text{ GeV} \, . \]  

(3.5)

![Figure 5: A scatter plot of all 4,858 branching ratios, Br_{\tilde{X}_W^\pm \rightarrow Z^0\ell^\pm}, associated with a Wino chargino LSP versus tan \beta. The plot is broken up into the three M_{\tilde{X}_W^\pm} mass bins given in (3.5). In each plot, the values of the branching fractions are highly scattered around the a green curve which represents the “best fit” to the data. The vertical blue lines mark the boundaries of the four regions where the behavior of the best fit lines are approximately identical.](image)

The range of each bin is chosen so that each contains approximately a third of the 4,858 valid
black points. Second, as we will see below, the value of $\tan \beta$ plays a significant role in the relative sizes of the branching ratios of the four decay channels. With this in mind, we plot the values of $\text{Br} \tilde{X}^±_W \to Z^0 \ell^±$ against $\tan \beta$ for each of the three mass bins in (3.5). In each case, we present the “best fit” to the data as a green curve. We further partition each of these plots into bins—represented by the vertical, dashed blue lines—where the best fit curves in each plot behave similarly. The results are presented in Figure 5. We see from these plots that the range of $\tan \beta$ is naturally broken into four regions approximately given by

$$\tan \beta \in [1.2, 5], [5, 8], [8, 16], [16, 65]. \quad (3.6)$$

Having broken up the ranges of $M_{\tilde{X}^±_W}$ and $\tan \beta$ into 3 and 4 bins respectively, we now calculate the median, the interquartile range and the maximum and the minimum values\footnote{To make these terms explicit: a) the “median” is the value of a quantity for which 50% of that quantity have larger values and 50% are smaller and b) the “interquartile” range is the interval of that quantity which contains 25% of all values that lie above the median and 25% that lie below it. 3) The meaning of the “maximum” and “minimum” values is self-evident} of the branching ratio $\text{Br} \tilde{X}^±_W \to Z^0 \ell^±$ for the decay channel $\tilde{X}^±_W \to Z^0 \ell^±$ in each of the 3 × 4 data bins. Using an identical procedure, one can compute the same quantities for the remaining three branching ratios $\text{Br} \tilde{X}^±_W \to W^± \nu$, $\text{Br} \tilde{X}^±_W \to \gamma \ell^±$ and $\text{Br} \tilde{X}^±_W \to h^0 \ell^±$ as well. The results are displayed in Figure 6.

For example, for the valid black points with Wino chargino LSP mass between 200 and 300 GeV and with $\tan \beta$ between 8 and 16, Figure 6 can be interpreted in the following way:

- The branching ratios have median values of 0.058 for the $\tilde{X}^±_W \to W^± \nu$ channel, 0.124 for the $\tilde{X}^±_W \to Z^0 \ell^±$ channel, 0.009 for the $\tilde{X}^±_W \to \gamma \ell^±$ channel and 0.794 for the $\tilde{X}^±_W \to h^0 \ell^±$ channel. We therefore expect $h^0$ Higgs boson production via chargino RPV decays to dominate for these ranges of mass and $\tan \beta$.

- After solving for the RPV couplings and the decay rates, we generally obtain different branching ratio values for different viable initial conditions in our simulation. The data is scattered around the “best fit” values, as shown in Figure 5. However, the branching ratios take values only within certain ranges, allowing for theoretical predictions for the decay patterns of the Wino Chargino LSPs. The dashed error bars in Figure 6 indicate the full range of values that the branching ratios take. For example, in our chosen bin, the branching ratios for the $\tilde{X}^±_W \to Z^0 \ell^±$ channel are not higher than approximately 0.42 while they can be very close to 0. At the same time, the branching ratios for the $\tilde{X}^±_W \to h^0 \ell^±$ channel are approximately between 0.96 and 0.43.

- The boxes show the interquartile ranges, within which 50% of the points lie around the median value. In our chosen bin we learn, for example, that while the branching ratios for the $\tilde{X}^±_W \to Z^0 \ell^±$ channel can take any value between approximately 0.42 and 0, they tend to accumulate in the more restricted interval 0.07 – 0.21.
Figure 6: Branching ratios for the four possible decay channels of the Wino chargino LSP, presented for the three $M_{\tilde{X}^\pm}$ mass bins and four $\tan \beta$ regions. The colored horizontal line inside each box indicate the median value of the branching fraction in that bin, the colored box indicates the interquartile range in that bin, while the dashed error bars show the range between the maximum and the minimum values of the branching ratio for that bin. The case percentage indicate what percentage of the valid initial points have $\tan \beta$ values within the range indicated. For each channel, we sum over all three families of possible leptons. Note that $\tilde{X}^{\pm}_W \rightarrow h^0 \ell^\pm$ is strongly favored, followed by the $\tilde{X}^{\pm}_W \rightarrow Z^0 \ell^\pm$ channel– except in the $1.2 < \tan \beta < 5$ bin, where they are approximately comparable. The calculations were performed assuming a normal neutrino hierarchy, with $\theta_{23} = 0.597$. 
Generically, for all three mass ranges and all four $\tan \beta$ bins in Figure 6, one can conclude the following. It is clear that the $\tilde{X}_{W}^{\pm} \to h^0 \ell^\pm$ channel, except in the $1.2 < \tan \beta < 5$ bin, is the most abundant and becomes increasingly so for higher values of $\tan \beta$. The channel $\tilde{X}_{W}^{\pm} \to \gamma \ell^\pm$, although interesting from an experimental point of view, is highly suppressed in every region of parameter space. The most optimistic scenario for chargino detection is in the regions for which $\tan \beta$ takes smaller values. For $\tan \beta < 5$, the medians of the branching fractions for the most experimentally visible channel, $\tilde{X}_{W}^{\pm} \to Z^0 \ell^\pm$, lie between 0.20-0.50, depending on the mass bin. However, there are very few such cases in our simulation-only 1.8%. Much more likely is a scenario in which $\tan \beta$ is large. We find that 69.1% of the total number of points have $\tan \beta > 16$. For this parameter region, however, the branching fraction of $\tilde{X}_{W}^{\pm} \to Z^0 \ell^\pm$ drops between 0.05-0.10, and the prospects of detecting it become slimmer.

The results in Figure 6 were calculated using numerical inputs into the complicated expressions for the decay rates given in Appendix A. Hence, the origin of the physical trends displayed in that Figure is obscure. However, the formulas for the decay rates can, under certain assumptions, be simplified allowing for a physical interpretation for the observed relationships between the 4 decay channels. To do this, we note the following:

- As shown in Figure 2 above, the values for the angles $|\phi_{\pm}|$ are very small for each of the 4,858 black points associated with the Wino chargino; with $|\phi_{-}|$ being generically smaller than $|\phi_{+}|$. Hence, to a high degree of approximation, one can set $\cos \phi_{-} = 1$ and $\sin \phi_{-} = 0$. However, due to the fact that the values for $|\phi_{+}|$, although very small, tend to be somewhat larger than $|\phi_{-}|$, we can only take $\cos \phi_{+} \approx 1$ and $\sin \phi_{+} \approx 0$.

- The lepton masses, $m_{\ell_{i}}$, are insignificant compared to the other masses in the expressions for the decay rates and, hence, the terms containing them can be neglected. Note that all occurrences of the angle $\phi_{+}$ are contained in these terms. This facilitates our simplification even further, since the slightly larger values of $|\phi_{+}|$ no longer enter the approximation of the decay rates.

Using these two approximations, we obtain simplified expressions for the decay rates of each of the four decay channels. They are

$$
\Gamma_{\tilde{X}_{W}^{\pm} \to W^{\pm} \nu_{i}} \approx \frac{g_{3}^{2}}{64\pi} \left( \frac{v_{d}}{\sqrt{2}M_{2}\mu} \epsilon_{i} + \frac{2M_{BL}v_{d}}{M_{1}v_{R}} \epsilon_{j} [V_{PMNS}]_{ji} \right) 2 \frac{M_{3}^{2}}{M_{2}^{2}} \left( 1 - \frac{M_{W}^{2}}{M_{X_{W}^{\pm}}} \right)^{2} \left( 1 + 2 \frac{M_{W}^{2}}{M_{X_{W}^{\pm}}} \right),
$$

(3.7)

$$
\Gamma_{\tilde{X}_{W}^{\pm} \to Z^{0} \ell^{\pm}} \approx \frac{g_{3}^{2}}{64\pi} \left( \sqrt{2}c_{W}(v_{d}\epsilon_{i} + \mu v_{R}^{*}) + \frac{1}{v_{W}} \left( \frac{1}{2} - s_{W}^{2} \right) v_{d}\epsilon_{i} \right)^{2} \times

\frac{M_{X_{W}^{\pm}}^{3}}{M_{Z_{0}^{0}}^{2}} \left( 1 - \frac{M_{Z_{0}^{0}}^{2}}{M_{X_{W}^{\pm}}^{2}} \right)^{2} \left( 1 + 2 \frac{M_{Z_{0}^{0}}^{2}}{M_{X_{W}^{\pm}}^{2}} \right),
$$

(3.8)
By examining (3.7)-(3.10), we understand why the \( \tilde{X}_W^\pm \rightarrow h^0 \ell^\pm \) channel dominates, being directly proportional to \( \epsilon/\mu \), without the suppression \( v_d/M_2 \) that is present in the other decay channels for similar terms. However, the \( v_d/M_2 \) suppression becomes less pronounced for small \( \tan \beta \) values, since \( v_d = 174 \text{ GeV}/(1 + \tan \beta) \) increases. Therefore, channels of interest such as \( \tilde{X}_W^\pm \rightarrow Z^0 \ell^\pm \) become increasingly more significant towards smaller \( \tan \beta \) values. The Goldstone equivalence theorem tells us that the first two channels are amplified by the longitudinal degrees of freedom of the massive \( Z^0 \mu \) and \( W^\pm \mu \) bosons, so the traces of these two decays become more apparent in scenarios with more massive LSP’s. The \( \tilde{X}_W^\pm \rightarrow \gamma^0 \ell^\pm \) channel is subdominant for all parameter regions, partly because of the smaller coupling constants for this process, but also because the Goldstone amplification theorem tells us that we get no amplification for processes with massless gauge bosons.

### 3.2 Choice of neutrino data

The neutrino mass hierarchy can be normal or inverted. Furthermore, for each of those possible hierarchies, two different values of the neutrino mixing angle \( \theta_{23} \) fit the existing data. See [53, 54].

For the normal hierarchy, the angle \( \theta_{23} \) can be 0.597 or 0.417, while for the inverted one, \( \theta_{23} \) can be 0.529 or 0.421. So far, out of the four possibilities, we have chosen a normal neutrino hierarchy with \( \sin \theta_{23} = 0.597 \) to compute the branching ratios– each summed over all three families of leptons –and their relative properties for each decay channel. The results were shown in Figures 5 and 6. Can choosing the other neutrino hierarchy and/or different values of \( \theta_{23} \) modify those predictions?

To explore this question, we begin by repeating the calculations of Subsection 3.1 leading to Figure 6, but this time for an inverted hierarchy with \( \theta_{23} = 0.529 \). We find that the new median values of the branching ratios change, but are never outside the interquartile ranges displayed in Figure 6. Furthermore, we find that switching between the two possible values of the angle \( \theta_{23} \) while keeping the hierarchy the same has no impact on the results– for either the normal or the inverted hierarchy.

These results are best illustrated by plotting the branching ratios (summed over all mass and \( \tan \beta \) bins) for each decay channel against the other three channels– and doing this for each of the four choices of neutrino input data. Each such plot is simplified by using the fact

\[
\text{Br}_{\tilde{X}_W^\pm \rightarrow W^\pm \nu} + \text{Br}_{\tilde{X}_W^\pm \rightarrow Z^0 \ell^\pm} + \text{Br}_{\tilde{X}_W^\pm \rightarrow \gamma^0 \ell^\pm} + \text{Br}_{\tilde{X}_W^\pm \rightarrow h^0 \ell^\pm} = 1
\]

and, furthermore, that

\[
\text{Br}_{\tilde{X}_W^\pm \rightarrow \gamma^0 \ell^\pm} \approx 0.
\]
We have demonstrated (3.11) explicitly for the normal hierarchy with $\theta_{23} = 0.597$, and have numerically shown that it remains true for the other three neutrino input possibilities. It follows that $\text{Br}_{\tilde{X}_W^\pm \to W^\pm \nu}$ can be determined, using (3.11), from the remaining two decay channels. Hence, one can plot 2D histograms associated with all 4,858 valid black points associated with a Wino chargino LSP for each of the four possible neutrino input scenarios. These are presented in Figure 7.

**Figure 7**: Branching ratio to $h^0\ell^\pm$ versus branching ratio to $Z^0\ell^\pm$ for Wino chargino LSP decays, for both normal and inverted hierarchy. Wino chargino LSP decays via the $\tilde{X}_W^\pm \to Z^0\ell^\pm$ channel tend to be more abundant for a normal hierarchy. The choice of the angle $\theta_{23}$ has no impact on the statistics of these decays, for any of the two possible hierarchies. The percentages indicate what proportion of the points is contained within each third of the four plots.

The most obvious fact that one learns by comparing the top and bottom plots for each individual neutrino hierarchy in Figure 7 is that the $\theta_{23}$ angles play no role in determining the branching ratios—
as stated above. The reason for this is the following. First, note that the simplified expressions (3.7) - (3.10), although originally presented for the normal hierarchy with $\theta_{23} = 0.597$, remain valid for the other three sets of neutrino data as well. When we sum over the three lepton families in these expressions, the decay rates for each individual channel are proportional to the squared amplitudes of the RPV couplings. Changing the value of the $\theta_{23}$ angle results in a different unitary $V_{PMNS}$ matrix, which rotates the $\epsilon_i$ and $v_{Li}$, $i = 1, 2, 3$ components differently, but does not change the squared amplitudes of these couplings to produce a statistically observable effect. For this reason, switching between different $\theta_{23}$ values inside any hierarchy doesn’t result in different data patterns, as clearly shown in Figure 7. This is why using only one value of the angle (for example $\theta_{23} = 0.597$ for the normal hierarchy and $\theta_{23} = 0.529$ for the inverted hierarchy) is sufficient to make experimental predictions. Note, however, that if one does not sum over the three lepton families, this argument is no longer valid, and the value of $\theta_{23}$ can play a substantial role. We will explore this scenario in Subsection 3.4.

The second fact that one learns from comparing the left-hand and right-hand plots of Figure 7 is that there is a difference in the distribution of branching ratios between the normal and the inverted neutrino hierarchies. This is because, in our theory, the three generations of left handed neutrinos have Majorana masses, directly proportional to the squared amplitudes of these RPV couplings. In the normal hierarchy

$$m_1 = 0, \quad m_2 = (8.68 \pm 0.10) \times 10^{-3} \text{ eV}, \quad m_3 = (50.84 \pm 0.50) \times 10^{-3} \text{ eV}$$

while in the inverted one

$$m_1 = (49.84 \pm 0.40) \times 10^{-3} \text{ eV}, \quad m_2 = (50.01 \pm 0.40) \times 10^{-3} \text{ eV}, \quad m_3 = 0.$$

We expect, therefore, that the amplitudes of the couplings will change with the choice of neutrino hierarchy—leading to the differences in the branching ratios that we observe in Figure 7. Note, however, from the distribution of points—plotted as percentages—in the subsections of each plot, that the difference in branching ratios between the normal and inverted hierarchies is relatively small, on the order of a few percent. This is consistent with our statement above that the “new median values of the branching ratios (for the inverted hierarchy) change, but are never outside the interquartile ranges displayed in Figure 6 (the normal neutrino hierarchy).” Moreover, in the next section we show that the chargino decay lengths are generally smaller when we assume the inverted hierarchy, compared to when we assume a normal one.

Finally, from Figure 7 we learn that the Wino chargino decays via the $\tilde{X}_W^\pm \rightarrow h^0 \ell^\pm$ channel tend to be slightly more abundant for a normal hierarchy. However, the incremental difference is relatively small, since the bulk of the points lie in the top left corner, where the decay to $h^0 \ell^\pm$ dominates. Although the effect is too small to be statistically distinguishable, it is of interest to note how the choice of neutrino hierarchy can have small influence over the decay rates.

### 3.3 Decay Length

There is one more issue to be discussed; that is, are the decays of the Wino chargino “prompt”—defined to be decays where the overall decay length $L$, defined in (3.15), satisfies $L < 1\text{ mm}$? The key to this
problem lies in the magnitudes of the RPV parameters, $\epsilon_i$ and $v_{L_i}$. We find that for prompt decays, at least one of the couplings $\epsilon_i$ needs to be larger than $10^{-4} \text{ GeV}$. The overall scale of neutrino masses guarantees that this is well satisfied. Putting the lower limit of this interval any lower would not change our results significantly. The upper limit of this interval eliminates the problem of unphysical finely tuned cancellations in the neutrino mass matrices. See [1] for details.

**Figure 8:** Wino Chargino LSP decay length in millimeters, for the normal and inverted hierarchies. The average decay length $L = c \times \frac{1}{\Gamma}$ decreases for larger values of $M_{\tilde{X}^\pm_W}$, since the decay rates are amplified because of the longitudinal degrees of freedom of the massive bosons produced. We have chosen $\theta_{23} = 0.597$ for the normal neutrino hierarchy and $\theta_{23} = 0.529$ for the inverted hierarchy. However, the choice of $\theta_{23}$ has no impact on the decay length.

In Figure 8, we present two scatter plots– one for the normal and one for the inverted neutrino hierarchy–of the decay length $L = c \times \frac{1}{\Gamma}$ against the Wino chargino LSP mass for all of the 4,858 valid black points with a Wino chargino LSP. The parameter $c$ is the speed of light. Since the overall decay rate involves a sum over the three lepton families, it follows from the results of the previous section that the value of $\theta_{23}$ plays no role for either hierarchy. We find that the viable Wino chargino LSPs in our simulation decay promptly and produce prompt vertices in the detector for both neutrino hierarchies. However, we note that the decay lengths tend to be slightly smaller in the case of the inverted hierarchy. This follows from the fact that the masses of the neutrinos are, overall, slightly larger in the inverted case. Hence, the RPV couplings will be somewhat larger as well– resulting in a tiny increase in the decay rates and, therefore, smaller decay lengths in the inverted hierarchy.
Although Figure 8 shows that Wino chargino LSPs decay promptly for all viable initial points, their decay rates are strongly dominated by the $\tilde{X}_W^\pm \rightarrow h^0 \ell^\pm$ channel in general. Recall that the notion of “prompt” used above involved a sum over all four separate channels. This stimulates us to study the “promptness” of each individual decay channel independently—although we continue to sum over the three lepton families.

For example, the decay length of $\tilde{X}_W^\pm \rightarrow Z^0 \ell^\pm$ is given by

$$L_{\tilde{X}_W^\pm \rightarrow Z^0 \ell^\pm} = c \times \frac{1}{\sum_{i=1}^{3} \Gamma_{\tilde{X}_W^\pm \rightarrow Z^0 \ell_i^\pm}}.$$  \hspace{1cm} (3.16)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{Wino Chargino LSP decay length in milimeters, for individual decay channels, for both normal and inverted hierarchies. We have chosen $\theta_{23} = 0.597$ for the normal neutrino hierarchy and $\theta_{23} = 0.529$ for the inverted hierarchy. The choice of $\theta_{23}$ has no impact on the decay lengths. All individual channels have decay lengths $< 1$mm, except for $\tilde{X}_W^\pm \rightarrow \gamma^0 \ell^\pm$ which has higher probability to produce displaced vertices in the detector.}
\end{figure}
In Figure 9 we show that the Wino chargino LSP has decay lengths smaller than 1mm when decaying via any of the channels $\tilde{X}_W^\pm \to Z^0 \ell^\pm$, $\tilde{X}_W^\pm \to h^0 \ell^\pm$ and $\tilde{X}_W^\pm \to W^\pm \nu$. Note, however, that the vertices have a relatively small possibility of being “displaced” for decays via the process $\tilde{X}_W^\pm \to \gamma^0 \ell^\pm$.

### 3.4 Lepton family production

As discussed above, for any one of the four generic decay channels, the branching ratio for the decay into a single lepton family can, in principal, depend on the choice of the neutrino hierarchy and the value of $\theta_{23}$ used in determining the values of the $\epsilon_i$ and $v_{L_i}$ parameters. Using the available neutrino data with $3\sigma$ errors for the neutrino masses, along with the $V_{PMNS}$ rotation matrix angles and CP violating phases—see [1] for details—one can calculate, for any valid black point associated with a Wino chargino LSP, the decay rate into each individual lepton family for a given decay channel. Clearly, the value of the decay rate will depend explicitly on the choice of neutrino hierarchy—either normal or inverted—and, for a given hierarchy, on the choice of the two allowed values of $\theta_{23}$. For example, to quantify the probability to observe an electron $e^\pm$ in the generic decay process $\tilde{X}_W^\pm \to Z^0 \ell^\pm$, we compute

$$\text{Br}_{\tilde{X}_W^\pm \to Z^0 e^\pm} = \frac{\Gamma_{\tilde{X}_W^\pm \to Z^0 e^\pm}}{\Gamma_{\tilde{X}_W^\pm \to Z^0 \mu^\pm} + \Gamma_{\tilde{X}_W^\pm \to Z^0 \tau^\pm}}, \quad (3.17)$$

and similarly for a muon, $\mu^\pm$, and a tauon, $\tau^\pm$, final state. Using this result, we proceed to quantify the branching ratios for each of the 4 decay processes $\tilde{X}_W^\pm \to W^\pm \nu_i$, $\tilde{X}_W^\pm \to Z^0 \ell^\pm$, $\tilde{X}_W^\pm \to h^0 \ell^\pm_i$ and $\tilde{X}_W^\pm \to h^0 \ell^\pm_i$ into their individual lepton families. The results are shown in Figure 10. Each subgraph in Figure 10 has the following characteristics. For a point near the top left corner of each subgraph, the branching ratio into a third family lepton is the largest, whereas for a point near the bottom right corner, the branching ratio into a first family lepton is the largest. Finally, using the fact that

$$\text{Br}_{\tilde{X}_W^\pm \to Z^0 e^\pm} + \text{Br}_{\tilde{X}_W^\pm \to Z^0 \mu^\pm} + \text{Br}_{\tilde{X}_W^\pm \to Z^0 \tau^\pm} = 1,$$ \quad (3.18)

it follows that for a point near the the bottom left corner, the branching ratio into a second family lepton is the largest. Perhaps the most striking feature of each such graph is the connection between the Wino chargino decays, the neutrino hierarchy and the $\theta_{23}$ angle. Should experimental observation measure these branching ratios with sufficient precision, that could help shed light on the neutrino hierarchy and the value of $\theta_{23}$. For each neutrino hierarchy, there are two sets of points of different color, since the present experimental data allows for two values of $\theta_{23}$.

For example, let us consider the subgraph associated with the $\tilde{X}_W^\pm \to Z^0 \ell^\pm$ decay channels. If experimental observation finds that electrons are predominant after the Wino chargino LSP decays, then the hierarchy is inverted. Depending on whether the experimental result is a green or a blue point, implies that $\theta_{23}$ will be 0.0421 or 0.529 respectively. However, if the branching ratios to either the second or third family leptons are highly dominant, then the hierarchy will be normal, with $\theta_{23}$ given, most likely, by 0.597 and 0.417 respectively. That is, with sufficiently precise measured branching...
ratios one could determine the type of neutrino hierarchy and the value of the $\theta_{23}$ mixing angle from the color of the associated data point.

**Figure 10**: Branching ratios into the three lepton families, for each of the three main decay channels of a Wino neutralino LSP. The associated neutrino hierarchy and the value of $\theta_{23}$ is specified by the color of the associated data point.
4 Wino Neutralino LSP Decays

In this section, we analyze the RPV decay signatures of the Wino neutralino LSPs. Written in 4-component spinor notation, the Wino neutralino Weyl spinor, $\tilde{\chi}_W^0$, becomes

$$\tilde{\chi}_W^0 = \begin{pmatrix} \tau_0^{\chi_W^0} \\ \tilde{\chi}_W^0 \end{pmatrix},$$

(4.1)

which is a Majorana spinor. In our previous paper [1], we analyzed the RPV decay channels using 4-component spinor notation for all neutralino mass eigenstates. These are presented, for specificity, in Appendix B of this paper. The Wino neutralino corresponds to the case where $n=2$. Unlike the Wino chargino, the Wino neutralino has only three possible decay channels, reproduced here in Figure 11.

![Figure 11: RPV decays of a general massive Wino neutralino $\tilde{\chi}_W^0$. There are three possible channels, each with $i = 1, 2, 3$, that allow for Wino neutralino LSP decays. The decay rates into each individual channel were calculated analytically in our previous paper and are reproduced in Appendix B.](image)

4.1 Branching ratios of the decay channels

The $\tilde{\chi}_W^0 \rightarrow W^\pm \ell_i^\mp$ processes is the most favored for detection at the LHC. Similarly to the Wino chargino decay products, the left handed neutrinos produced during $\tilde{\chi}_W^0 \rightarrow Z^0 \nu_i$ decays can only be detected as missing energy, while the Higgs boson $h^0$ arising from $\tilde{\chi}_W^0 \rightarrow h^0 \nu_i$ couples to both quarks and leptons, leading to decay remnants in the detector that are harder to interpret. Hence, the most interesting decay experimentally appears to be the Wino neutralino decay into a $W^\pm$ massive boson and a charged lepton. The decay rates into each individual channel were calculated in our previous paper and are reproduced in Appendix B. The abundance of each channel is proportional to its branching ratio. For example, for the process $\tilde{\chi}_W^0 \rightarrow W^\pm \ell_i^\mp$ the branching ratio is defined to be

$$\text{Br}_{\tilde{\chi}_W^0 \rightarrow W^\pm \ell_i^\mp} = \frac{\sum_{i=1}^{3} \Gamma_{\tilde{\chi}_W^0 \rightarrow W^\pm \ell_i^\mp}}{\sum_{i=1}^{3} \left( \Gamma_{\tilde{\chi}_W^0 \rightarrow Z^0 \nu_i} + \Gamma_{\tilde{\chi}_W^0 \rightarrow W^\pm \ell_i^\mp} + \Gamma_{\tilde{\chi}_W^0 \rightarrow h^0 \nu_i} \right)},$$

(4.2)

We now study the decay patterns and branching ratios for each for the 3 decay channels of the Wino neutralino. There are 4,869 valid black points associated with Wino neutralino LSPs. For
each of these, we compute the decay rates via RPV processes, using the expressions (B.1)-(B.7) with $n = 2$ given in Appendix B. The branching ratios of the main channels take different values for different valid points in our simulation. These values are scattered around the median values of
these quantities. We compute the median values, interquartile ranges and the minimum and maximum values of the branching fractions in the same “bins” of the parameter space as we used in the study of the Wino chargino LSP decay channels. That is, we sample the average branching fractions in the three bins for the LSP mass $M_{\tilde{X}_0^W} \in [200, 300], [300, 600], [600, 1734]$ GeV and in the four intervals for $\tan \beta \in [1.2, 5], [5, 8], [8, 16], [16, 65]$. The results are presented in Figure 12. To carry out the explicit calculations, we have chosen a normal neutrino hierarchy with $\theta_{23} = 0.597$. We again find that assuming an inverted neutrino hierarchy changes these results only slightly, while the exact value of $\theta_{23}$ is statistically irrelevant.

Note that no decay channel is strongly dominant in any region of the parameter space. The $\tilde{X}_0^W \rightarrow W^\pm \ell^\mp$ process has relatively high occurrence, especially for spectra characterized by small $\tan \beta$ values. Just as for charginos, the equations for the decay rates are complicated and do not allow a simple explanation of the relative results. Furthermore, unlike for charginos, the rotation matrices involved are much more complicated since there are six neutralino species, while only two chargino species. Nevertheless, simplifying assumptions can be made. One such assumption is that the soft breaking terms have much larger magnitudes than the electroweak scale. This renders the Wino neutralino to be almost purely neutral Wino. Furthermore, using the fact that the charged lepton masses are much smaller than the soft breaking parameters further simplifies the equations. Using these approximations in the expressions in Appendix B, one obtains the following simplified formulas for the decay rates. They are given by

$$\Gamma_{\tilde{X}_0^W \rightarrow Z^0 \nu_i} \approx \frac{1}{16\pi} \left( \frac{g_2}{2M_2\mu} (v_d\epsilon_i + \mu v_L^i) \right) \left( \frac{M_{\tilde{X}_0^W}^3}{M_{Z^0}^2} \right) \left(1 - \frac{M_{Z^0}^2}{M_{\tilde{X}_0^W}^2} \right)^2 \left(1 + 2 \frac{M_{Z^0}^2}{M_{\tilde{X}_0^W}^2} \right), \quad (4.3)$$

$$\Gamma_{\tilde{X}_0^W \rightarrow W^\pm \ell^\mp i} \approx \frac{1}{16\pi} \left( \frac{g_2}{2M_2\mu} \left[ v_d\epsilon_i + \mu v_L^i \right] + \frac{g_2}{2M_2\mu} \left[ v_d\epsilon_i + \mu v_L^i \right] \right)^2 \times \frac{M_{\tilde{X}_0^W}^3}{M_{W^\pm}^2} \left(1 - \frac{M_{W^\pm}^2}{M_{\tilde{X}_0^W}^2} \right)^2 \left(1 + 2 \frac{M_{W^\pm}^2}{M_{\tilde{X}_0^W}^2} \right), \quad (4.4)$$

$$\Gamma_{\tilde{X}_0^W \rightarrow h^0 \nu_i} \approx \frac{1}{16\pi} \left( \frac{g_2}{2} \left[ V_{PMNS}^\dagger \right]_{ij} \left( \sin \omega \frac{\epsilon_j^*}{\mu} \right) \right) \left( \frac{M_{\tilde{X}_0^W}^3}{M_{h^0}^2} \right) \left(1 - \frac{M_{h^0}^2}{M_{\tilde{X}_0^W}^2} \right)^2. \quad (4.5)$$

Unlike the approximate expressions for the decay rates of Wino charginos in eqs. (3.7)-(3.10), the above expressions are less exact. The neutralino mass matrix contains a significantly larger number of soft mass parameters which can take values of a few GeV, close to the electroweak breaking scale, where the approximation breaks down. Nevertheless, the above expressions still provide valuable insights into which decay channel is expected to dominate in the chosen regions of parameter

\textsuperscript{4}Note that the highest mass for a Wino neutralino is somewhat smaller than that for a Wino chargino.
space. Analyzing (4.3)-(4.5), we expect the decay channels to have comparable contributions. Interestingly, the channels $\tilde{X}_0^0 W \to W^\pm \ell^\mp_i$ and $\tilde{X}_0^0 W \to Z^0 \nu_i$ receive a suppression proportional to $v_d \frac{M_2}{M_2\sqrt{1+\tan^2\beta}}$. Therefore, for large values of $\tan\beta$, the channel involving the Higgs boson, $h^0$, dominates for Wino neutralino decays, just as the Higgs channel dominated the Wino chargino LSP decays for this range of $\tan\beta$.

4.2 Decay length

Figure 13 shows that Wino neutralino LSP decays are prompt— that is, the overall decay length $L$ is less than 1mm—just as it is for Wino chargino LSP decays. Therefore, signals of both Wino chargino and Wino neutralino LSP decays produce point-like vertices. This insight is particularly useful when considering that the NLSPs of these two sparticle species (Wino neutralino NLSP for Wino chargino LSP and Wino chargino NSLP for Wino neutralino LSP) are almost degenerate in mass with the LSPs. We observe that in the case of the inverted hierarchy, the decay lengths are generally a little smaller, since the values of the RPV couplings are somewhat larger, as we explained in the previous section.

![Figure 13](image-url)

**Figure 13:** Wino neutralino LSP decay length in millimeters, for the normal and inverted hierarchies. The average decay length $L = c \times \frac{1}{\Gamma}$ decreases for larger values of $M_{\tilde{X}_0^0 W}$, since the decay rates are amplified because of the longitudinal degrees of freedom of the massive bosons produced. We have chosen $\theta_{23} = 0.597$ for the normal neutrino hierarchy and $\theta_{23} = 0.529$ for the inverted hierarchy. However, the choice of $\theta_{23}$ has no impact on the decay length.

In Figure 14, we study the decay lengths of the three decay channels separately. We find that the $\tilde{X}_W^0 \to W^\pm \ell^\mp_i$ and $\tilde{X}_W^0 \to Z^0 \nu_i$ processes occur promptly in the detector. However, for the vertex $\tilde{X}_W^0 \to h^0 \nu_i$, we find a small number of “displaced” vertices: that is with decay lengths $> 10$cm. They arise mostly from the small $\tan\beta$ parameter regime, where the branching ratio of this channel
is significantly reduced. Only for 1.1% of the points do we obtain decay lengths larger than 10cm for
the $\tilde{X}_W^0 \rightarrow h^0 \nu$ decay channel.

Figure 14: Wino neutralino LSP decay length in millimeters, for individual decay channels, for both
normal and inverted hierarchies. We have chosen $\theta_{23} = 0.597$ for the normal neutrino hierarchy and
$\theta_{23} = 0.529$ for the inverted hierarchy. The choice of $\theta_{23}$ has no impact on the decay length.

4.3 Lepton family production

We again study which of the three lepton families, if any, is favored within each of the three decay
channels. For example, to quantify the probability to observe an electron $e^\pm$ in the $\tilde{X}_W^0 \rightarrow W^\pm e^\mp$
process, over a muon $\mu^\mp$ or a tauon $\tau^\mp$, we compute

$$\text{Br}_{\tilde{X}_W^0 \rightarrow W^\pm e^\mp} = \frac{\Gamma_{\tilde{X}_W^0 \rightarrow W^\pm e^\mp}}{\Gamma_{\tilde{X}_W^0 \rightarrow W^\pm e^\mp} + \Gamma_{\tilde{X}_W^0 \rightarrow W^\pm \mu^\mp} + \Gamma_{\tilde{X}_W^0 \rightarrow W^\pm \tau^\mp}}$$  \hspace{1cm} (4.6)

Using this formalism, we proceed to quantify the branching ratios for each of the three decay processes
$\tilde{X}_W^0 \rightarrow W^\pm e^\mp$, $\tilde{X}_W^0 \rightarrow Z^0 \nu_i$ and $\tilde{X}_W^0 \rightarrow h^0 \nu_i$ into their individual lepton families. The results are
Figure 15: Branching ratios into the three lepton families, for each of the four main decay channels of a Wino neutralino LSP. The associated neutrino hierarchy and the value of $\theta_{23}$ is specified by the color of the associated data point.

shown in Figure 15. In Figure 15 we see that the $X_W^0 \rightarrow W^\pm \ell^\mp$ process has an almost identical statistical distribution for lepton family production as does the chargino decay channel $X_W^\pm \rightarrow Z^0 \ell^\pm$. Additionally, note that in a Wino neutralino decay via $X_W^0 \rightarrow h^0 \nu$, the decay rate has a dominant term proportional to the square of $|V_{PMNS}^i|^2 \epsilon_j$. The combination leads to a branching ratio distribution as that observed in Figure 15—no $\nu_\tau$ neutrino is produced in the case of an inverted hierarchy and no $\nu_e$ is produced in the case of a normal hierarchy.
5 Wino Neutralino NLSPs and Wino Chargino NLSPs

Having analyzed the RPV decays of both Wino chargino LSPs and Wino neutralino LSPs, we now discuss the RPV decays of the NLSPs associated with each case. The reason this is important is the following. Let us begin with the Wino chargino LSPs associated with 4,858 valid black points. Now choose one of these black points. In Figure 16a, we plot the entire sparticle spectrum of the theory for this fixed point.

Figure 16: a) A plot of the sparticle spectrum for a choice of one of the 4,858 valid black points associated with Wino chargino LSPs. The Wino neutralino NLSP is almost degenerate in mass with the LSP Wino chargino mass. b) A plot of the sparticle spectrum for a choice of one of the 4,869 valid black points associated with Wino neutralino LSPs. The Wino chargino NLSP is almost degenerate in mass with the LSP Wino neutralino mass.

Of course, a Wino chargino is the LSP by construction. Interestingly, however, we see that the associated NLSP is, in fact, a Wino neutralino. This is not simply an accident of our specific choice of black point. In Figure 17a, we plot the mass difference in MeV between the Wino neutralino NLSP and the Wino chargino LSP for all 4,858 black points. It is clear that for every Wino chargino LSP, the NLSP is a Wino neutralino whose mass is larger than, but very close to, the mass of the LSP– as in Figure 16a. This is, perhaps, not surprising since the dominant contribution to the mass of both sparticles is given by the soft supersymmetry breaking parameter $M_2$. See [1] for details.

Not surprisingly, we find that a similar, but reversed, situation occurs when the LSP is a Wino neutralino. Choosing one of the 4,869 associated valid black points, we find that the complete sparticle spectrum is given in Figure 16b. Of course, a Wino neutralino is the LSP by construction. Now we find that the situation is reverse and that the associated NLSP is now a Wino chargino. Again, this is not simply an accident of our specific choice of black point. In Figure 17b, we plot the mass difference in
Figure 17: a) The Wino neutralino NLSPs are all almost degenerate in mass with the LSPs, the Wino charginos. The mass difference is smaller than 200 MeV for most of the valid black points, as can be seen in the mass difference histogram. b) The Wino chargino NLSPs are all almost degenerate in mass with the LSPs, the Wino neutralinos. The mass difference is smaller than 200 MeV for most of the viable cases, as can be seen in the mass difference histogram.

MeV between the Wino chargino and the Wino neutralino for all 4,869 Wino neutralino black points. It is clear that for every Wino neutralino LSP, the NLSP is a Wino chargino whose mass is larger than, but very close to, the mass of the LSP– as in Figure 16b. Once again, this is hardly surprising since the dominant contribution to the mass of both sparticles is given by the soft supersymmetry breaking parameter $M_2$.

The near degeneracy in mass between the Wino chargino LSP and the Wino neutralino NLSP shown in Figure 17a, and the similar mass degeneracy between a Wino neutralino LSP and its Wino chargino NLSP displayed in Figure 17b, imply that, in both cases, the only decay mode of the LSP and the dominant decay mode of the NLSP are precisely the RPV violating decays discussed in Sections 3 and 4 above.

The LSP will, indeed, decay exactly as discussed in those two sections. However, are the NLSP RPV decay rates and branching ratios the same as though they were actual LSPs? Does a Wino chargino NLSP, associated with the initial conditions for a Wino neutralino LSP, decay in the same way as an actual Wino chargino LSP? The same question arises for the Wino neutralino NLSP. The answer is not immediately obvious, since the decay rates and branching ratios do not depend only on the masses of these particle species, which are indeed similar. The decay rates for charginos and neutralinos given in Appendix A and B are completely general, and apply for any chargino and neutralino species, regardless of if they are the LSP or just another particle in the spectrum. Those
equations depend on a large number of parameters of the theory, such as $M_{BL}$, $v_R$, $\tan \beta$, $M_R$, as well as on the RPV couplings $\epsilon_i, v_{L_i}, i = 1, 2, 3$. A Wino chargino LSP and a Wino chargino NLSP (associated with a Wino neutralino LSP) have the same decay patterns only if all these parameters are contained within similar statistical intervals.

![Graph showing log10(\epsilon) vs. log10(\epsilon) for Wino chargino LSP and Wino neutralino LSP](image)

(a)

**Figure 18**: Absolute values of the $\epsilon_1, \epsilon_2$ and $\epsilon_3$ parameters associated with the 4,858 black points with Wino chargino LSP (red) and with the 4,869 black points with Wino neutralino LSP (blue). We assume a normal hierarchy with $\theta_{23}=0.597$. We find that these RPV parameters lie in the same statistical regions, regardless of LSP species.

In Figure 18 we plot the absolute values of the $\epsilon_1, \epsilon_2$ and $\epsilon_3$ couplings, associated with the the 4,858 black points with Wino chargino LSP and with the 4,869 black points with Wino neutralino LSP, respectively. We assumed a normal hierarchy, with $\theta_{23}=0.597$. We find that these RPV parameters are statistically similar, whether associated with a Wino chargino LSP, or with a Wino neutralino LSP-as it is clear from the Figure 18, the points lie substantially on top of eachother. Plotting $\epsilon_1$ against $\epsilon_2$ and $\epsilon_3$ for both initial conditions with Wino chargino and Wino neutralino LSP is only one of the many tests we can make, since the parameter space of our theory is rich. However, this scatter plot is a particularly relevant one, since the RPV couplings depend on the neutrino masses and neutrino mixing angles, as well as on numerous mass terms from the B-L MSSM Lagrangian of our theory. We conclude that, when analyzing Wino chargino LSP decays, one should simultaneously look for the RPV decays of the Wino neutralino— as though it were the LSP – and, vice versa. This insight
should improve the prospects for experimental detection of RPV decays at the LHC.

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Appendices

Appendix A  Chargino decay rates

1. $\tilde{X}_1^\pm \to W^\pm \nu$

$$
\Gamma_{\tilde{X}_1^\pm \to W^\pm \nu} = \frac{|G_L|_{\tilde{X}_1^\pm \to W^\pm \nu}^2 + |G_R|_{\tilde{X}_1^\pm \to W^\pm \nu}^2}{64\pi} \frac{M_{\tilde{X}_1^\pm}^3}{M_W^2} \left(1 - \frac{M_W^2}{M_{\tilde{X}_1^\pm}^2}\right)^2 \left(1 + 2 \frac{M_W^2}{M_{\tilde{X}_1^\pm}^2}\right),$$

where

$$
G_L_{\tilde{X}_1^\pm \to W^\pm \nu} = -G_R^{*}_{L_{\tilde{X}_1^\pm \to W^\pm \nu}} = \frac{g_2}{\sqrt{2}} \left[-\cos \phi - \frac{g_2 v_d}{\sqrt{2} M_2 \mu} \epsilon^*_j + \sin \phi \frac{\epsilon^*_j}{\mu}\right] + \sin \phi \frac{1}{16d_{\tilde{X}_1^\pm}} \left(M_\chi^2 v_R^2 v_u (v_d \epsilon_j - \mu v_L^*) - 4M_2 \mu (M_Y v_R^2 + g_R^2 M_{BL} v_u^2) \epsilon_j\right) - 2\sqrt{2} \cos \phi \frac{g_2 \mu}{8d_{\tilde{X}_1^\pm}} \left[2g_R^2 M_{BL} v_d v_u^2 \epsilon_j + M_Y v_R^2 (v_d \epsilon_j + \mu v_L^*)\right] \left[V_{PMNS}^{\dagger}\right]_{ij} \tag{A.2}
$$

and

$$
G_R_{\tilde{X}_1^\pm \to W^\pm \nu} = -G_L^{*}_{R_{\tilde{X}_1^\pm \to W^\pm \nu}} = \frac{g_2}{\sqrt{2}} \left[-\sin \phi + \frac{1}{16d_{\tilde{X}_1^\pm}} \left[M_\chi^2 v_R^2 v_u (v_d \epsilon_j + \mu v_L^*) - 4g_R^2 \mu M_{BL} v_d v_u \epsilon_j\right] \right] + 2\sqrt{2} \cos \phi \frac{g_2 \mu}{8d_{\tilde{X}_1^\pm}} \left[2g_R^2 M_{BL} v_d v_u^2 \epsilon_j + M_Y v_R^2 (v_d \epsilon_j + \mu v_L^*)\right] \left[V_{PMNS}^{\dagger}\right]_{ij}. \tag{A.3}
$$

2. $\tilde{X}_1^\pm \to Z^0 \ell_i^\pm$

$$
\Gamma_{\tilde{X}_1^\pm \to Z^0 \ell_i^\pm} = \frac{|G_L|_{\tilde{X}_1^\pm \to Z^0 \ell_i^\pm}^2 + |G_R|_{\tilde{X}_1^\pm \to Z^0 \ell_i^\pm}^2}{64\pi} \frac{M_{\tilde{X}_1^\pm}^3}{M_{Z^0}^2} \left(1 - \frac{M_{Z^0}^2}{M_{\tilde{X}_1^\pm}^2}\right)^2 \left(1 + 2 \frac{M_{Z^0}^2}{M_{\tilde{X}_1^\pm}^2}\right), \tag{A.4}
$$
where

\[
G_{L \tilde{X}_1^+ \gamma^0 \ell_i^+} = -G_{R \tilde{X}_1^- \gamma^0 \ell_i^-} = 2g_2c_W \left( \frac{g_2}{\sqrt{2M_2 \mu}} (v_d \epsilon_i + \mu v_{L_i}^*) \right) \cos \phi_- + \\
+ \frac{g_2}{c_W} \left( 1 - s_W^2 \right) \left( - \cos \phi_- \frac{g_2 v_d}{\sqrt{2M_2 \mu}} \epsilon_i + \sin \phi_- \frac{\epsilon_i}{\mu} \right) - \frac{g_2}{c_W} \left( \frac{1}{2} - s_W^2 \right) \left( \frac{\epsilon_i}{\mu} \right) \sin \phi_-
\]

(A.5)

and

\[
G_{R \tilde{X}_1^+ \gamma^0 \ell_i^+} = -G_{L \tilde{X}_1^- \gamma^0 \ell_i^-} = 2g_2c_W \cos \phi_+ \left( - \frac{1}{\sqrt{2M_2 \mu}} g_2 \tan \beta m_{e_i} v_{L_i} \right) - \\
+ \frac{g_2}{c_W} s_W^2 \left( - \cos \phi_+ \frac{g_2 \tan \beta m_{e_i} v_{L_i}^*}{\sqrt{2M_2 \mu}} \right) + \sin \phi_+ \frac{m_{e_i}}{\mu v_d v_{L_i}} \left( \frac{1}{2} - s_W^2 \right) \sin \phi_+ \left( \frac{m_{e_i}}{\mu v_d v_{L_i}} \right).
\]

(A.6)

There is no sum over the \( i \) in \( v_{L_i} m_{e_i} \).

3. \( \tilde{X}_1^\pm \rightarrow \gamma^0 \ell_i^\pm \)

\[
\Gamma_{\tilde{X}_1^\pm \rightarrow \gamma^0 \ell_i^\pm} = \frac{|G_L|^2_{\tilde{X}_1^\pm \rightarrow \gamma^0 \ell_i^\pm} + |G_R|^2_{\tilde{X}_1^\pm \rightarrow \gamma^0 \ell_i^\pm}}{64 \pi} M_{\tilde{X}_1^\pm}.
\]

(A.7)

where

\[
G_{L \tilde{X}_1^+ \gamma^0 \ell_i^+} = -G_{R \tilde{X}_1^- \gamma^0 \ell_i^-} = 2g_2s_W \left( \frac{g_2}{\sqrt{2M_2 \mu}} (v_d \epsilon_i + \mu v_{L_i}^*) \right) \cos \phi_- + \\
+ eg_2 \left( - \cos \phi_- \frac{g_2 v_d}{\sqrt{2M_2 \mu}} \epsilon_i + \sin \phi_- \frac{\epsilon_i}{\mu} \right) - eg_2 \left( \frac{\epsilon_i}{\mu} \right) \sin \phi_-
\]

(A.8)

and

\[
G_{R \tilde{X}_1^+ \gamma^0 \ell_i^+} = -G_{L \tilde{X}_1^- \gamma^0 \ell_i^-} = 2g_2s_W \cos \phi_+ \left( - \frac{1}{\sqrt{2M_2 \mu}} g_2 \tan \beta m_{e_i} v_{L_i} \right) \\
- eg_2 \left( - \cos \phi_+ \frac{g_2 \tan \beta m_{e_i} v_{L_i}^*}{\sqrt{2M_2 \mu}} \right) + \sin \phi_+ \frac{m_{e_i}}{\mu v_d v_{L_i}} \left( \frac{1}{2} - s_W^2 \right) \sin \phi_+ \left( \frac{m_{e_i}}{\mu v_d v_{L_i}} \right).
\]

(A.9)

There is no sum over the \( i \) in \( v_{L_i} m_{e_i} \).

4. \( \tilde{X}_1^\pm \rightarrow h^0 \ell_i^\pm \)

\[
\Gamma_{\tilde{X}_1^\pm \rightarrow h^0 \ell_i^\pm} = \frac{|G_L|^2_{\tilde{X}_1^\pm \rightarrow h^0 \ell_i^\pm} + |G_R|^2_{\tilde{X}_1^\pm \rightarrow h^0 \ell_i^\pm}}{64 \pi} M_{\tilde{X}_1^\pm} \left( 1 - \frac{M_h^2}{M_{\tilde{X}_1}^2} \right)^2.
\]

(A.10)

where

\[
G_{L \tilde{X}_1^+ \rightarrow h^0 \ell_i^+} = -G_{R \tilde{X}_1^- \rightarrow h^0 \ell_i^-} = - \frac{1}{2} \sqrt{2} Y_{e_i} \sin \alpha \left( - \cos \phi_+ \frac{g_2 \tan \beta m_{e_i} v_{L_i}^*}{\sqrt{2M_2 \mu}} \right) + \\
- \frac{1}{2} g_2 \sin \alpha \cos \phi_+ \left( \frac{\epsilon_i}{\mu} \right) - \frac{1}{2} g_2 \cos \alpha \sin \phi_+ \left( \frac{g_2}{\sqrt{2M_2 \mu}} (v_d \epsilon_i + \mu v_{L_i}^*) \right)
\]

(A.11)
and

\[
G_{R \tilde{X}_i^0 \rightarrow h_0 \ell_i^-} = -G_{L \tilde{X}_i^0 \rightarrow h_0 \ell_i^-} = -\frac{1}{\sqrt{2}} Y_{\ell_i} \sin \alpha \left( -\cos \phi_- \frac{g_2 v_d}{\sqrt{2} M_2 \mu} + \sin \phi_- \frac{c_2}{\mu} \right) 
+ \frac{1}{2} g_2 \sin \alpha \sin \phi_- \left( -\cos \phi_+ \frac{1}{\sqrt{2} M_2 \mu} g_2 \tan \beta m_{\ell_i} v_{L_i} - \sin \phi_+ \frac{m_{\ell_i}}{\mu v_d} v_{L_i} \right) 
- \frac{1}{2} g_2 \cos \alpha \cos \phi_- \frac{(m_{\ell_i})}{v_{d} \mu} v_{L_i} \right). \quad (A.12)
\]

There is no sum over \( i \) in either of these expressions.

**Appendix B  Neutralino decay rates**

1. \( \tilde{X}_n^0 \rightarrow Z^0 \nu_i \)

\[
\Gamma_{\tilde{X}_n^0 \rightarrow Z^0 \nu_i} = \frac{|G_L|^2_{\tilde{X}_n^0 \rightarrow Z^0 \nu_i} + |G_R|^2_{\tilde{X}_n^0 \rightarrow Z^0 \nu_i}}{64 \pi} \frac{M_{\tilde{X}_n^0}^2}{M_{Z^0}^2} \left( 1 - \frac{M_{Z^0}^2}{M_{\tilde{X}_n^0}^2} \right)^2 \left( 1 + 2 \frac{M_{Z^0}^2}{M_{\tilde{X}_n^0}^2} \right), \quad (B.1)
\]

where

\[
G_L_{\tilde{X}_n^0 \rightarrow Z^0 \nu_i} = g_2 \left( -\frac{1}{2 c_W} N_{n 6+j} N_{n^* 6+i} - \frac{1}{c_W} \left( \frac{1}{2} + s_W^2 \right) N_{n^* 4} N_{6+i 4} \right) 
+ g_2 \left( \frac{1}{c_W} \left( \frac{1}{2} + s_W^2 \right) N_{n^* 3} N_{6+i 3} \right) \quad (B.2)
\]

and

\[
G_R_{\tilde{X}_n^0 \rightarrow Z^0 \nu_i} = g_2 \left( \frac{1}{c_W} \left( \frac{1}{2} + s_W^2 \right) N_{n^* 6+i 3} \right) 
- g_2 \left[ -\frac{1}{2 c_W} N_{n^* 4} N_{n^* 6+i 6+i} - \frac{1}{c_W} \left( \frac{1}{2} + s_W^2 \right) N_{n^* 4} N_{6+i 4} \right] \quad (B.3)
\]

2. \( \tilde{X}_n^0 \rightarrow W^\mp \ell_{\pm} \)

\[
\Gamma_{\tilde{X}_n^0 \rightarrow W^\mp \ell_{\pm}} = \frac{|G_L|^2_{\tilde{X}_n^0 \rightarrow W^\pm \ell_{\mp}} + |G_R|^2_{\tilde{X}_n^0 \rightarrow W^\pm \ell_{\mp}}}{64 \pi} \frac{M_{\tilde{X}_n^0}^2}{M_{W^\pm}^2} \left( 1 - \frac{M_{W^\pm}^2}{M_{\tilde{X}_n^0}^2} \right)^2 \left( 1 + 2 \frac{M_{W^\pm}^2}{M_{\tilde{X}_n^0}^2} \right), \quad (B.4)
\]

where

\[
G_L_{\tilde{X}_n^0 \rightarrow W^- \ell^+_i} = -G_R_{\tilde{X}_n^0 \rightarrow W^+ \ell^-_i} = \frac{g_2}{\sqrt{2}} \left[ N_{n^* 4} N_{2+i 2} - 2 \sqrt{2} N_{2+i 1} N_{n^* 2} \right] \quad (B.5)
\]

and

\[
G_R_{\tilde{X}_n^0 \rightarrow W^- \ell^+_i} = -G_L_{\tilde{X}_n^0 \rightarrow W^+ \ell^-_i} = \frac{g_2}{\sqrt{2}} \left[ -U_{2+i 2} N_{n^* 6+j} - U_{2+i 2} N_{n^* 3} + 2 \sqrt{2} N_{n^* 2} U_{2+i 1} \right] \quad (B.6)
\]
3. $\tilde{X}_n^0 \to h^0\nu$

\[
\Gamma_{\tilde{X}_n^0 \to h^0\nu_i} = \frac{\left| G_L[\tilde{X}_n^0 \to h^0\nu_i] + |G_R[\tilde{X}_n^0 \to h^0\nu_i] \right|^2}{64\pi} \left( 1 - \frac{M_{h^0}^2}{M_{\tilde{X}_n^0}^2} \right)^2 \quad (B.7)
\]

where

\[
G_L[\tilde{X}_n^0 \to h^0\nu_i] = \frac{g_2}{2} \left( \cos \alpha (N_{n 4}^* N_{6+i 2}^* + N_{6+i 4}^* N_{n 2}^*) + \sin \alpha (N_{n 3}^* N_{6+i 3}^* + N_{0+i 3}^* N_{n 2}^*) \right)
- \frac{g'}{2} \left( \cos \alpha (\sin \theta_R (N_{n 4}^* N_{6+i 1}^* + N_{6+i 4}^* N_{n 1}^*) + \cos \theta_R (N_{n 4}^* N_{6+i 5}^* + N_{6+i 4}^* N_{n 5}^*)) \\
+ \sin \alpha (\sin \theta_R (N_{n 3}^* N_{6+i 1}^* + N_{0+i 3}^* N_{n 1}^*) + \cos \theta_R (N_{n 3}^* N_{6+i 5}^* + N_{0+i 3}^* N_{n 5}^*)) \right) + \frac{1}{\sqrt{2}} Y_{\nu 3} \cos \alpha (N_{n 6+j}^* N_{6+i 6}^* + N_{0+i 6+j}^* N_{n 6}^*) \quad (B.8)
\]

and

\[
G_R[\tilde{X}_n^0 \to h^0\nu_i] = \frac{g_2}{2} \left( \cos \alpha (N_{n 4}^* N_{6+i 2}^* + N_{6+i 4}^* N_{n 2}^*) + \sin \alpha (N_{n 3}^* N_{6+i 2}^* + N_{0+i 3}^* N_{n 2}^*) \right)
+ \frac{g'}{2} \left( \cos \alpha (\sin \theta_R (N_{n 4}^* N_{6+i 1}^* + N_{6+i 4}^* N_{n 1}^*) + \cos \theta_R (N_{n 4}^* N_{6+i 5}^* + N_{6+i 4}^* N_{n 5}^*)) \\
+ \sin \alpha (\sin \theta_R (N_{n 3}^* N_{6+i 1}^* + N_{0+i 3}^* N_{n 1}^*) + \cos \theta_R (N_{n 3}^* N_{6+i 5}^* + N_{0+i 3}^* N_{n 5}^*)) \right) + \left( N_{n 6+j}^* N_{6+i 6}^* + \frac{1}{\sqrt{2}} Y_{\nu 3} \cos \alpha (N_{0+i 6+j}^* N_{n 6}^*) \right) \quad (B.9)
\]

The matrices $U$, $V$ and $N$ matrices rotate the gaugino eigenstates into the neutralino and chargino mass eigenstates. They are presented in Appendices B.1 and B.2 of [1].

Note that in all cases in Appendix A and B above, we sum over $j = 1, 2, 3$.

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