R-Parity Violating Decays of Wino Chargino and Bino Neutralino LSPs in the B-L MSSM

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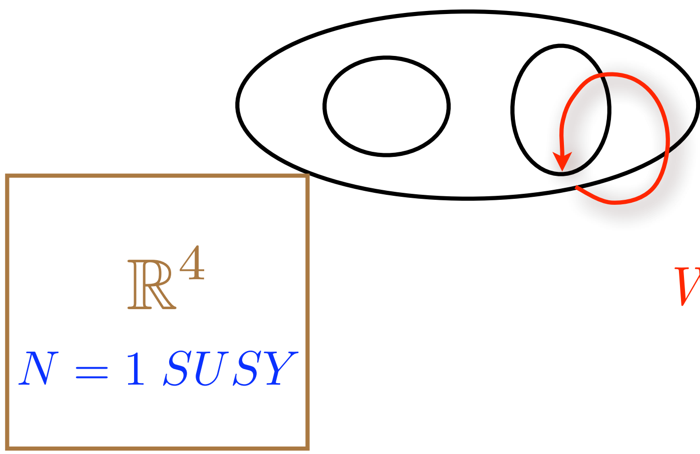
SU(4) Heterotic Compactification:

$X, \; D = 6$ **"Schoen" CY**



$V \; , G = SU(4)$

"slope" stable

$W \; , F = \mathbb{Z}_3 \times \mathbb{Z}_3$

$\mathbb{R}^4$ Theory Gauge Group:

$G = SU(4) \Rightarrow \quad E_8 \rightarrow \; Spin(10)$

Choose the $\mathbb{Z}_3 \times \mathbb{Z}_3$ Wilson lines to be

$$\chi_{T_{3R}} = e^{iY_{T_{3R}} \frac{2\pi}{3}} \quad , \quad \chi_{B-L} = e^{iY_{B-L} \frac{2\pi}{3}}$$

Turning on the Wilson lines $\Rightarrow$

$$Spin(10) \rightarrow \; SU(3)_C \times SU(2)_L \times U(1)_{T_{3R}} \times U(1)_{B-L}$$

$\mathbb{R}^4$ Theory Spectrum:

$n_r = (h^1(X, U_R(V)) \otimes \mathbf{R})^{\mathbb{Z}_3 \times \mathbb{Z}_3} \Longrightarrow$ 3 families of quarks/leptons

$$Q = (U, D)^T = (\mathbf{3}, \mathbf{2}, 0, \frac{1}{3}), \quad u = (\bar{\mathbf{3}}, \mathbf{1}, -\frac{1}{2}, -\frac{1}{3}), \quad d = (\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{2}, -\frac{1}{3})$$
$$L = (N, E)^T = (\mathbf{1}, \mathbf{2}, 0, -1), \quad \nu = (\mathbf{1}, \mathbf{1}, -\frac{1}{2}, 1), \quad e = (\mathbf{1}, \mathbf{1}, \frac{1}{2}, 1)$$

and 1 pair of Higgs-Higgs conjugate fields

$$H = (\mathbf{1}, \mathbf{2}, \frac{1}{2}, 0), \quad \bar{H} = (\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 0)$$

under $SU(3)_C \times SU(2)_L \times U(1)_{T_{3R}} \times U(1)_{B-L}$.

Gauge Coupling Unification:

The Wilson lines associated with 3R and B-L have the mass scales $M_{\chi_{T_{3R}}}$ and $M_{\chi_{B-L}}$ respectively.

In this talk, we will choose the case where

$$M_{\chi_{B-L}} > M_{\chi_{T_{3R}}}$$

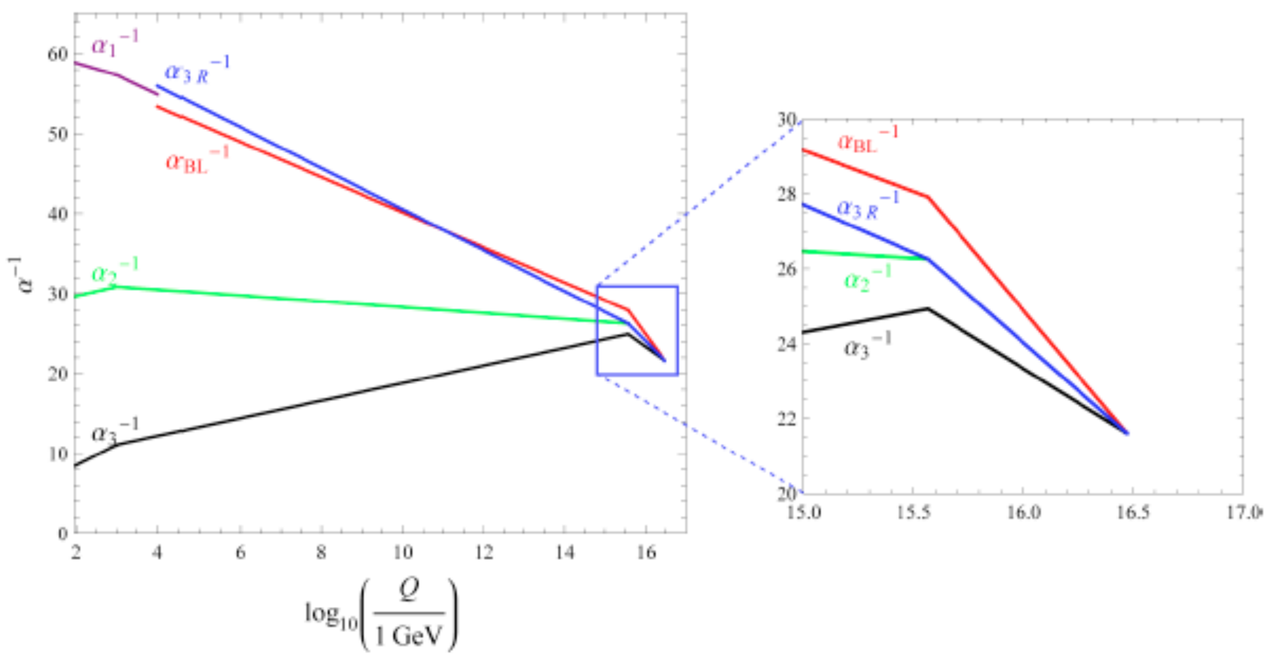
Adjusting the relative sizes of these two masses, one can enforce gauge coupling unification at scale

$$M_{\chi_{B-L}} = M_U \simeq 3.0 \times 10^{16}\text{GeV} \quad , \quad \alpha_U \simeq 0.046$$

where

$$M_{\chi_{T_{3R}}} = M_I \simeq 3.7 \times 10^{15}\text{GeV}$$

That is



The associated particle spectra are

$SO(10)$

$M_U = M_{\chi_{B-L}}$

$\downarrow \chi_{B-L}$

$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

$$\mathbf{16} - \left[\begin{array}{l} L = (\mathbf{1},\mathbf{2},\mathbf{1},-1) \\ L^c = (\mathbf{1},\mathbf{1},\mathbf{2},1) \\ Q = (\mathbf{3},\mathbf{2},\mathbf{1},1/3) \\ Q^c = (\bar{\mathbf{3}},\mathbf{1},\mathbf{2},-1/3) \end{array}\right\} \times 9$$

$$\mathbf{10} - \left[\begin{array}{l} \mathcal{H} = (\mathbf{1},\mathbf{2},\mathbf{2},0) \;\} \times 2 \\ H_C = (\mathbf{3},\mathbf{1},\mathbf{1},2/3) \\ \bar{H}_C = (\bar{\mathbf{3}},\mathbf{1},\mathbf{1},-2/3) \end{array}\right.$$

$M_I = M_{\chi_{3R}}$

$\downarrow \chi_{3R}$

$SU(3)_C \otimes SU(2)_L \otimes U(1)_{3R} \otimes U(1)_{B-L}$

$$\mathbf{16} - \left[\begin{array}{l} L = (\mathbf{1},\mathbf{2},0,-1) \\ e^c = (\mathbf{1},\mathbf{1},1/2,1) \\ \nu^c = (\mathbf{1},\mathbf{1},-1/2,1) \\ Q = (\bar{\mathbf{3}},\mathbf{2},0,1/3) \\ u^c = (\mathbf{3},\mathbf{1},-1/2,-1/3) \\ d^c = (\mathbf{3},\mathbf{1},1/2,-1/3) \end{array}\right\} \times 3$$

$$\mathbf{10} - \left[\begin{array}{l} H_u = (\mathbf{1},\mathbf{2},1/2,0) \\ H_d = (\mathbf{1},\mathbf{2},-1/2,0) \end{array}\right.$$

MSSM + 3 right-handed neutrino supermultiplets

The results on RPV do not substantially change if we choose the other two Wilson line mass relations.

The B-L MSSM begins at scale M_I . Its superpotential is given by

$$W = Y_u Q H_u u^c - Y_d Q H_d d^c - Y_e L H_d e^c + Y_\nu L H_u \nu^c + \mu H_u H_d$$

Supersymmetry is softly broken at that scale with Lagrangian

$$-\mathcal{L}_{\text{soft}} = \Big(\frac{1}{2} M_3 \tilde{g}^2 + \frac{1}{2} M_2 \tilde{W}^2 + \frac{1}{2} M_R \tilde{W}_R^2 + \frac{1}{2} M_{BL} \tilde{B}'^2$$

$$+ a_u \tilde{Q} H_u \tilde{u}^c - a_d \tilde{Q} H_d \tilde{d}^c - a_e \tilde{L} H_d \tilde{e}^c + a_\nu \tilde{L} H_u \tilde{\nu}^c + b H_u H_d + h.c. \Big)$$

$$+ m_{\tilde{Q}}^2 |\tilde{Q}|^2 + m_{\tilde{u}^c}^2 |\tilde{u}^c|^2 + m_{\tilde{d}^c}^2 |\tilde{d}^c|^2 + m_{\tilde{L}}^2 |\tilde{L}|^2 + m_{\tilde{\nu}^c}^2 |\tilde{\nu}^c|^2 + m_{\tilde{e}^c}^2 |\tilde{e}^c|^2$$

$$+ m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2$$

The parameters of the theory are then run down to lower mass scales via complicated renormalization group equations. We find that the third family right-handed sneutrino develops a VEV

$$\langle \tilde{\nu}_3^c \rangle \equiv \frac{1}{\sqrt{2}} v_R$$

thus breaking

$$U(1)_{3R} \times U(1)_{B-L} \to U(1)_Y$$

Scaling to lower energy induces the EW breaking VEVs

$$\langle \tilde{\nu}_i \rangle \equiv \frac{1}{\sqrt{2}} v_{Li}, \;\; \langle H_u^0 \rangle \equiv \frac{1}{\sqrt{2}} v_u, \;\; \langle H_d^0 \rangle \equiv \frac{1}{\sqrt{2}} v_d$$

The gauge boson Z_R arising from breaking to $U(1)_Y$ has mass

$$M_{Z_R}^2 = -2m_{\tilde{\nu}_3^c}^2 \left(1 + \frac{g_R^4}{g_R^2 + g_{BL}^2} \frac{v^2}{v_R^2}\right)$$

Recalling that

$$R = (-1)^{3(B-L)+2s}$$

it follows that $\langle \tilde{\nu}_3^c \rangle$ spontaneously breaks lepton number L and hence R-parity. This induces the lepton number violating terms

$$W \supset \epsilon_i \, e_i \, H_u^+ - \frac{1}{\sqrt{2}} Y_{ei} \, v_{Li} \, H_d^- \, e_i^c \quad \text{where} \quad \epsilon_i \equiv \frac{1}{\sqrt{2}} Y_{\nu i3} v_R \, , \; i = 1, 2, 3$$

in the superpotential and

$$\begin{aligned} \mathcal{L} \supset & -\frac{1}{2} v_{L_i^*} \left[g_2 \left(\sqrt{2} \, e_i \tilde{W}^+ + \nu_{L_i} \tilde{W}^0 \right) - g_{BL} \nu_{L_i} \tilde{B}' \right] \\ & -\frac{1}{2} v_R \left[-g_R \nu_3^c \tilde{W}_R + g_{BL} \nu_3^c \tilde{B}' \right] + \text{h.c.} \end{aligned}$$

from the super-covariant derivatives. The VEV $\langle \tilde{\nu}_3^c \rangle$ also induces Majorana mass terms for the left-handed neutrinos given by

$$m_{\nu \, ij}^D = \left(V_{\text{PMNS}}^T \, m_\nu \, V_{\text{PMNS}} \right)_{ij}$$

where

$$m_{\nu ij} = A v_{L_i^*} v_{L_j^*} + B \left(v_{L_i^*} \epsilon_j + \epsilon_i v_{L_j^*} \right) + C \epsilon_i \epsilon_j$$

A,B and C are complicated functions of the various parameters and VEVs. We choose the RPV parameters ϵ_i, v_{L_i} $i = 1,2,3$ to obtain the most recent values for the neutrino mass given by

- Normal Hierarchy:

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

- Inverted Hierarchy:

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

The dimensional soft supersymmetry breaking parameters will be statistically chosen in the interval

$$[\frac{M}{f}, M f\,] \quad \text{where} \quad M = 1.5\ \mathrm{TeV}\ ,\ f = 6.7$$

That is, approximately $[200\ \mathrm{GeV}\ ,\ 10\ \mathrm{TeV}]$

$\Rightarrow$ potentially allows masses, such as the LSP masses, from just above the EW scale to highest energy scale at the LHC.

Additionally, we randomly scatter the signs of the soft parameter to be $[-,+]$ and the value of $\tan\beta \in [1.2\ ,\ 65]$

Phenomenological constraints:

From all initial random scatterings of the above, we select only those initial values satisfying all of the following phenomenological constraints.

- $$M_{Z_R} \geq 4.1 TeV$$

- The EW bosons masses must have their experimental values

$$M_{Z^0} = 91.1876 \pm 0.0021 \text{ GeV}, \quad M_{W^\pm} = 80.379 \pm 0.012 \text{ GeV}$$

- The mass of all sparticles must exceed their current lower bounds

SUSY Particle	Lower Bound
Left-handed sneutrinos	45.6 GeV
Charginos, sleptons	100 GeV
Squarks, except stop or bottom LSP	1000 GeV
Stop LSP (admixture)	550 GeV
Stop LSP (right-handed)	400 GeV
Sbottom LSP	500 GeV
Gluino	1300 GeV

- The Higgs mass must be within the current ATLAS 3σ bounds

$$M_{h^0} = 124.97 \pm 0.72 \text{ GeV}$$

The RGEs for the 24 soft SUSY parameters are dominated by two parameters

$$S_{BL'} = \mathrm{Tr}\,(2m^2_{\tilde{Q}} - m^2_{\tilde{u}^c} - m^2_{\tilde{d}^c} - 2m^2_{\tilde{L}} + m^2_{\tilde{\nu}^c} + m^2_{\tilde{e}^c})$$
$$S_{3R} = m^2_{H_u} - m^2_{H_d} + \mathrm{Tr}\left(-\tfrac{3}{2}m^2_{\tilde{u}^c} + \tfrac{3}{2}m^2_{\tilde{d}^c} - \tfrac{1}{2}m^2_{\tilde{\nu}^c} + \tfrac{1}{2}m^2_{\tilde{e}^c}\right)$$

The results of 100 million random choices of the initial soft SUSY parameters, expressed in terms of these two dimensional parameters are

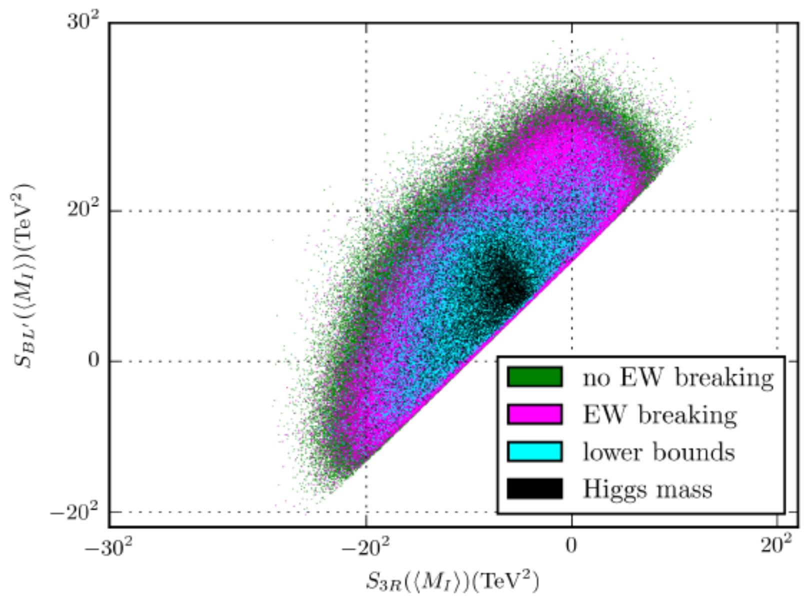


Figure Caption: Plot of the 100 million initial data points for the RG analysis evaluated at M_I .The 4,351,809 green points lead to appropriate breaking of the $B-L$ symmetry. Of these, the 3,142,657 purple points also break the EW symmetry with the correct vector boson masses. The cyan points correspond to 342,236 initial points that, in addition to appropriate $B-L$ and EW breaking, also satisfy all lower bounds on the sparticle masses. Finally, as a subset of these 342,236 initial points, there are 67,576 valid black points which lead to the experimentally measured value of the Higgs boson mass.

Each of the black points corresponds to initial conditions satisfying all low energy experimental constraints. However, they can have different LSPs. We find that

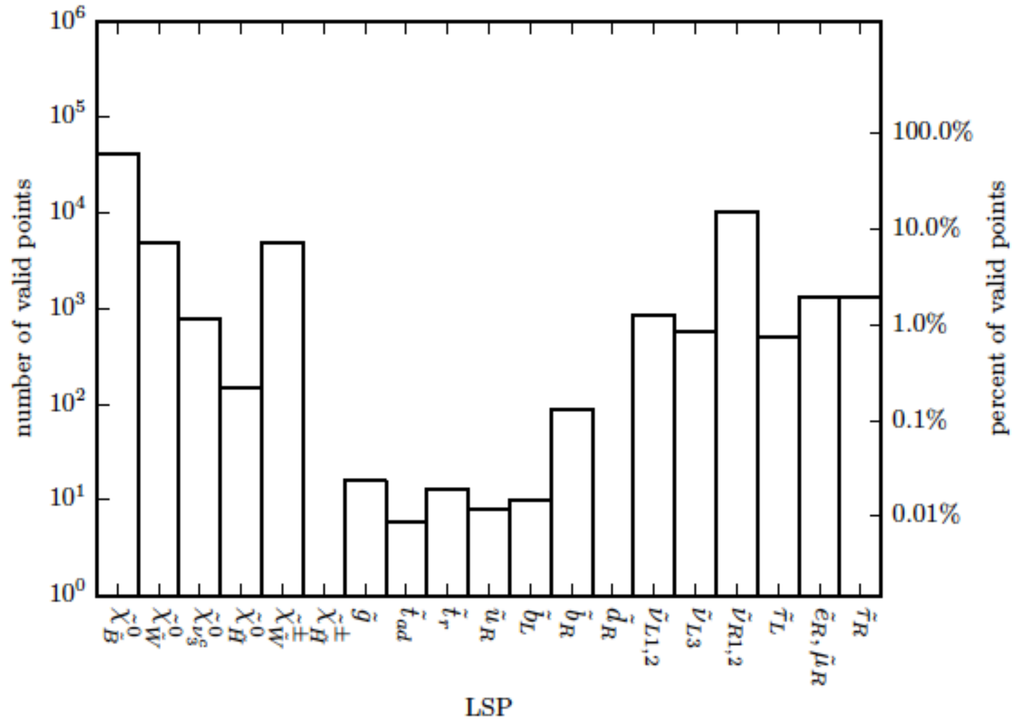


Figure Caption: A histogram of the LSPs associated with a random scan of 100 million initial data points, showing the percentage of valid black points with a given LSP. Sparticles which did not appear as LSP's are omitted. The y-axis has a log scale.

For the present talk, we note that there are

4,858 Wino chargino LSPs, 42,039 Bino neutralino LSPs

and discuss their RPV decays.

The VEVs

$$\langle \tilde{\nu}_3^c \rangle \equiv \frac{1}{\sqrt{2}} v_R, \ \langle \tilde{\nu}_i \rangle \equiv \frac{1}{\sqrt{2}} v_{Li}, \ \langle H_u^0 \rangle \equiv \frac{1}{\sqrt{2}} v_u, \ \langle H_d^0 \rangle \equiv \frac{1}{\sqrt{2}} v_d$$

lead to serious mixing of the gauge eigenstates and, hence, new mass eigenvalues and eigenstates. Rewriting the complete Lagrangian in terms of these new quantities is a difficult job. I will spare you the details.

1) Wino Chargino LSP Decays:

The plot of the mass range of the Wino chargino LSPs is

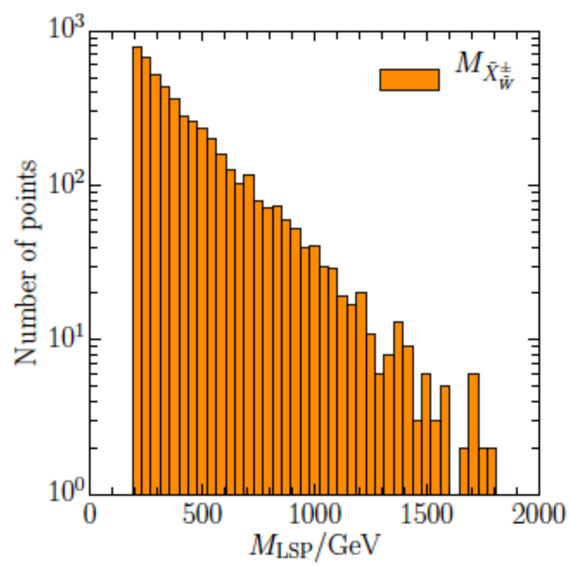
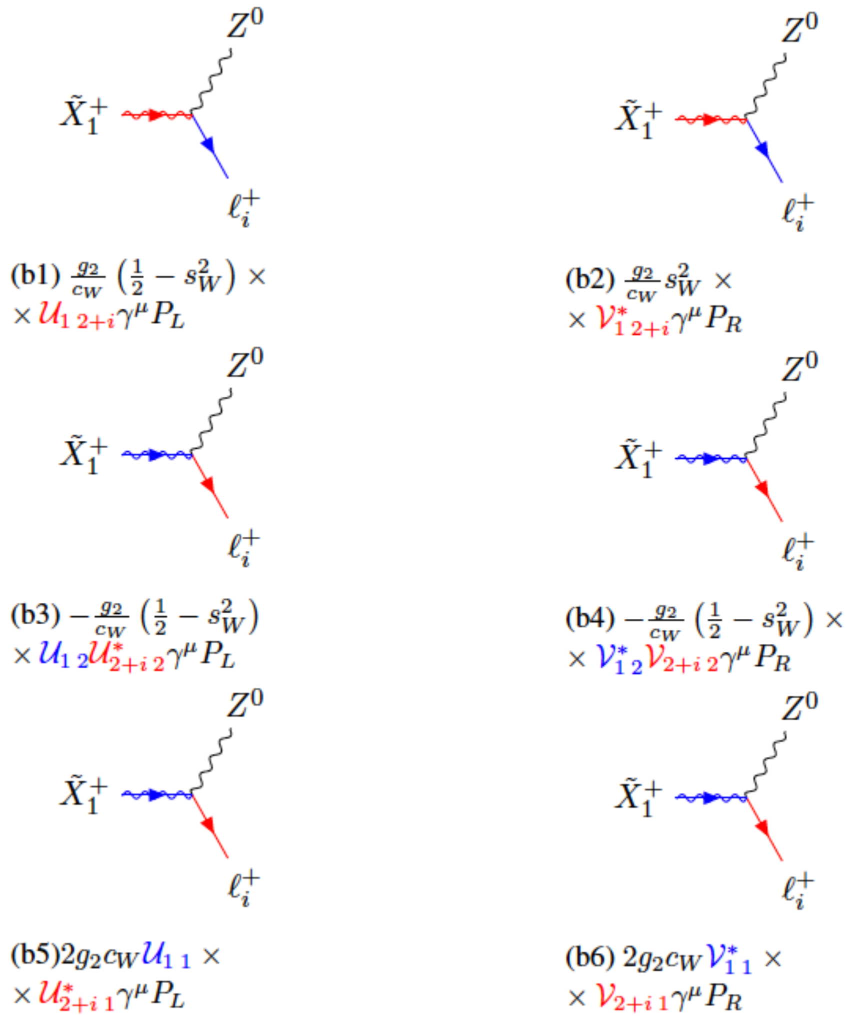


Figure Caption: Mass distribution of the Wino charging LSPs. The mass range is from 194 GeV to 1710 GeV, peaking towards the low mass end.

We find that the pure RPV decays of Wino charginos into standard model matter has 3 possible channels. These are

(a) $\tilde{X}_1^+ \rightarrow W^+\nu_i$, (b) $\tilde{X}_1^+ \rightarrow Z^0\ell_i^+$, (c) $\tilde{X}_1^+ \rightarrow h^0\ell_i^+$

For example,



(b)

where

$$\mathcal{U}_{1\,1} = \cos\phi_- \,, \qquad \mathcal{V}_{1\,1} = \cos\phi_+ \quad \mathcal{U}_{1\,2} = \sin\phi_- \,, \qquad \mathcal{V}_{1\,2} = \sin\phi_+$$

$$\mathcal{U}_{1\,2+i} = -\cos\phi_- \frac{g_2 v_d}{\sqrt{2}M_2\mu}\epsilon_i^* + \sin\phi_- \frac{\epsilon_i^*}{\mu} \,, \qquad \mathcal{V}_{1\,2+i} = -\cos\phi_+ \frac{g_2 \tan\beta m_{e_i}}{\sqrt{2}M_2\mu} v_{L_i} + \sin\phi_+ \frac{m_{e_i}}{\mu v_d} v_{L_i}$$

$$\mathcal{U}_{2+i\,1} = \frac{g_2}{\sqrt{2}M_2\mu}(v_d\epsilon_i^* + \mu v_{L_i}) \,, \ \mathcal{V}_{2+i\,1} = -\frac{1}{\sqrt{2}M_2\mu} g_2 \tan\beta m_{e_i} v_{L_i} \,, \ \mathcal{U}_{2+i\,2} = \frac{\epsilon_i^*}{\mu} \,, \qquad \mathcal{V}_{2+i\,2} = \frac{m_{e_i}}{v_d\mu} v_{L_i}$$

and

$$X_1^+ = cos\phi^+ \tilde{W}^+ + sin\phi^+ \tilde{H}^+$$

The results for X_1^- are given by complex conjugation.

Using these results, one can compute the RPV decay rates and branching ratios for the Wino chargino LSP. The results are the following.

Decay Lengths (= c/Decay Rate):

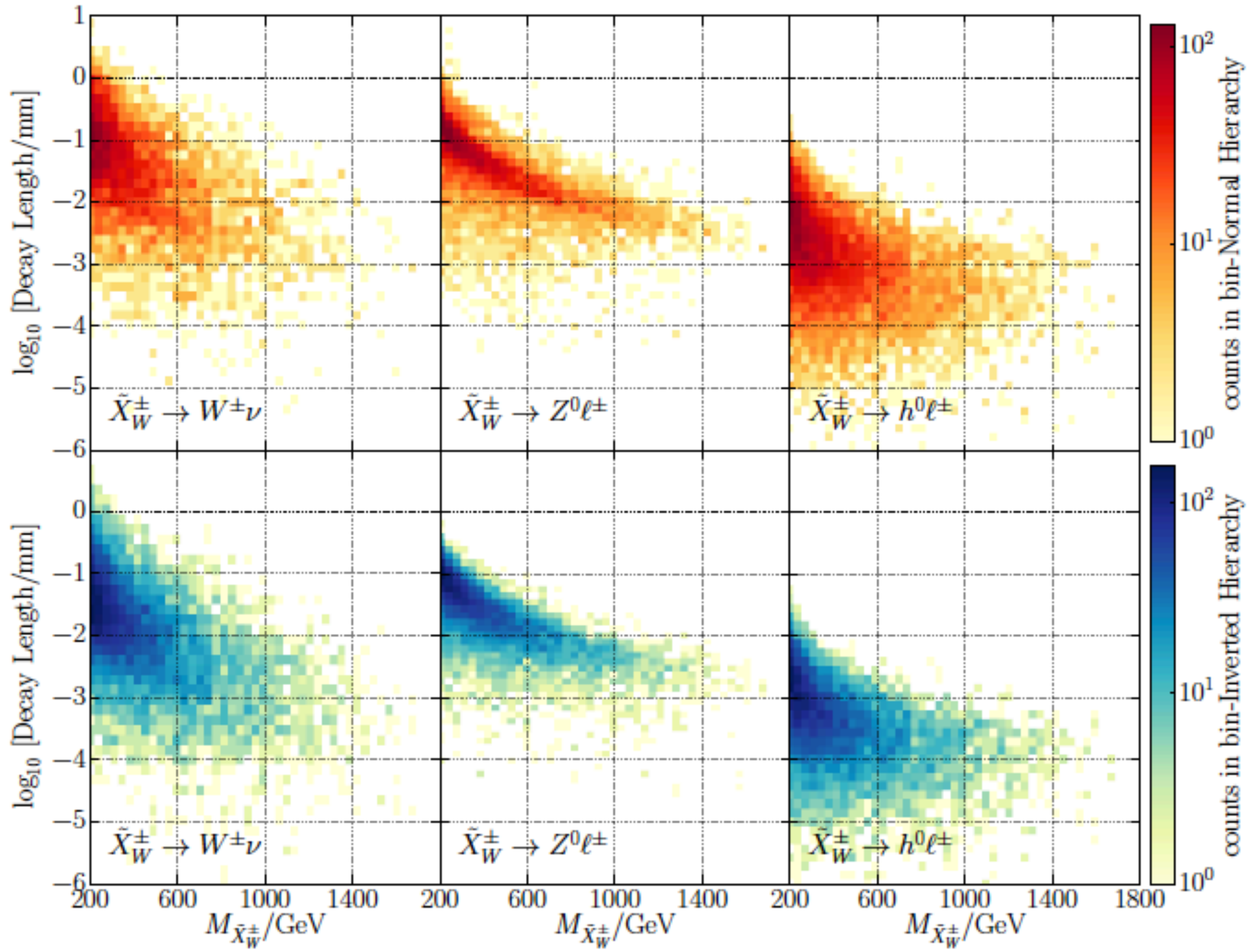


Figure Caption: **Wino Chargino LSP decay length in milimeters, for individual decay channels, for both normal and inverted hierarchies. We have chosen $\theta_{23} = 0.597$ for the normal neutrino hierarchy and $\theta_{23} = 0.529$ for the inverted hierarchy. The choice of θ_{23} has no impact on the decay lengths. All individual channels have decay lengths < 1mm**

Branching Ratios:

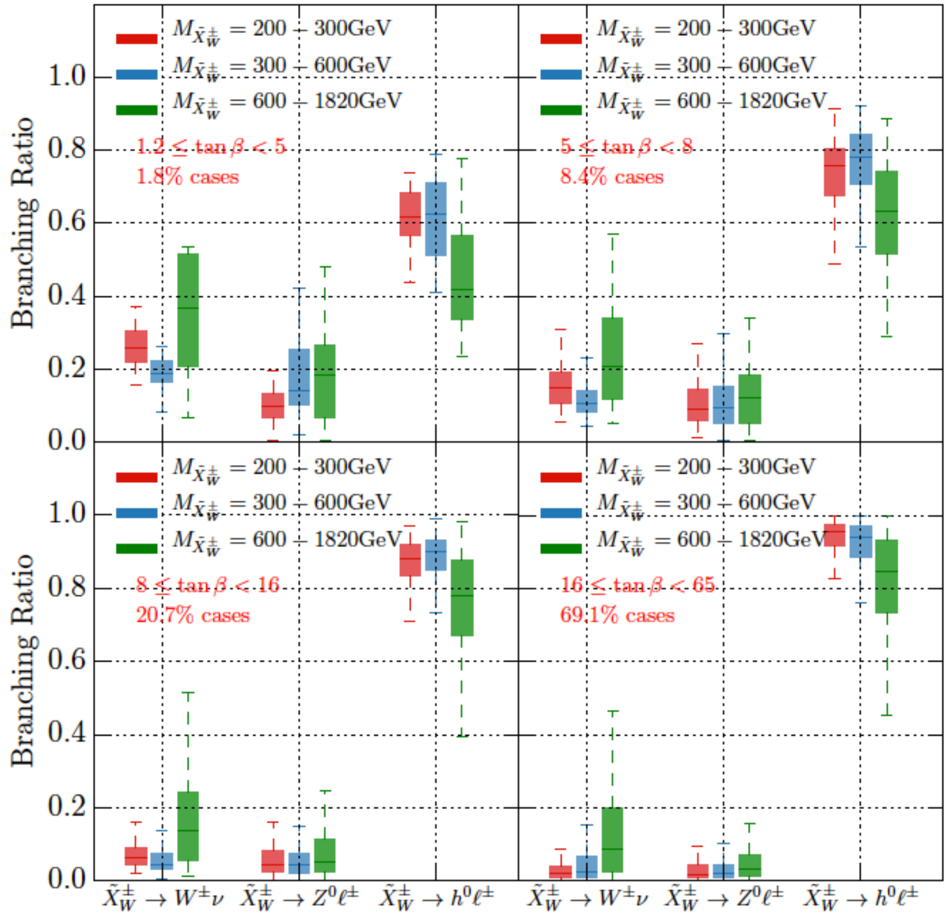


Figure Caption: Branching ratios for the three possible decay channels of the Wino chargino LSP, presented for the three $M_{\tilde{X}_W^\pm}$ mass bins and four $\tan\beta$ regions. The colored horizontal line inside each box indicate the median value of the branching fraction in that bin, the colored 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 $\tilde{X}_W^\pm \to h^0\ell^\pm$ is strongly favored– except perhaps in the $1.2 < \tan\beta < 5$ bin. The calculations were performed assuming a normal neutrino hierarchy, with $\theta_{23} = 0.597$.

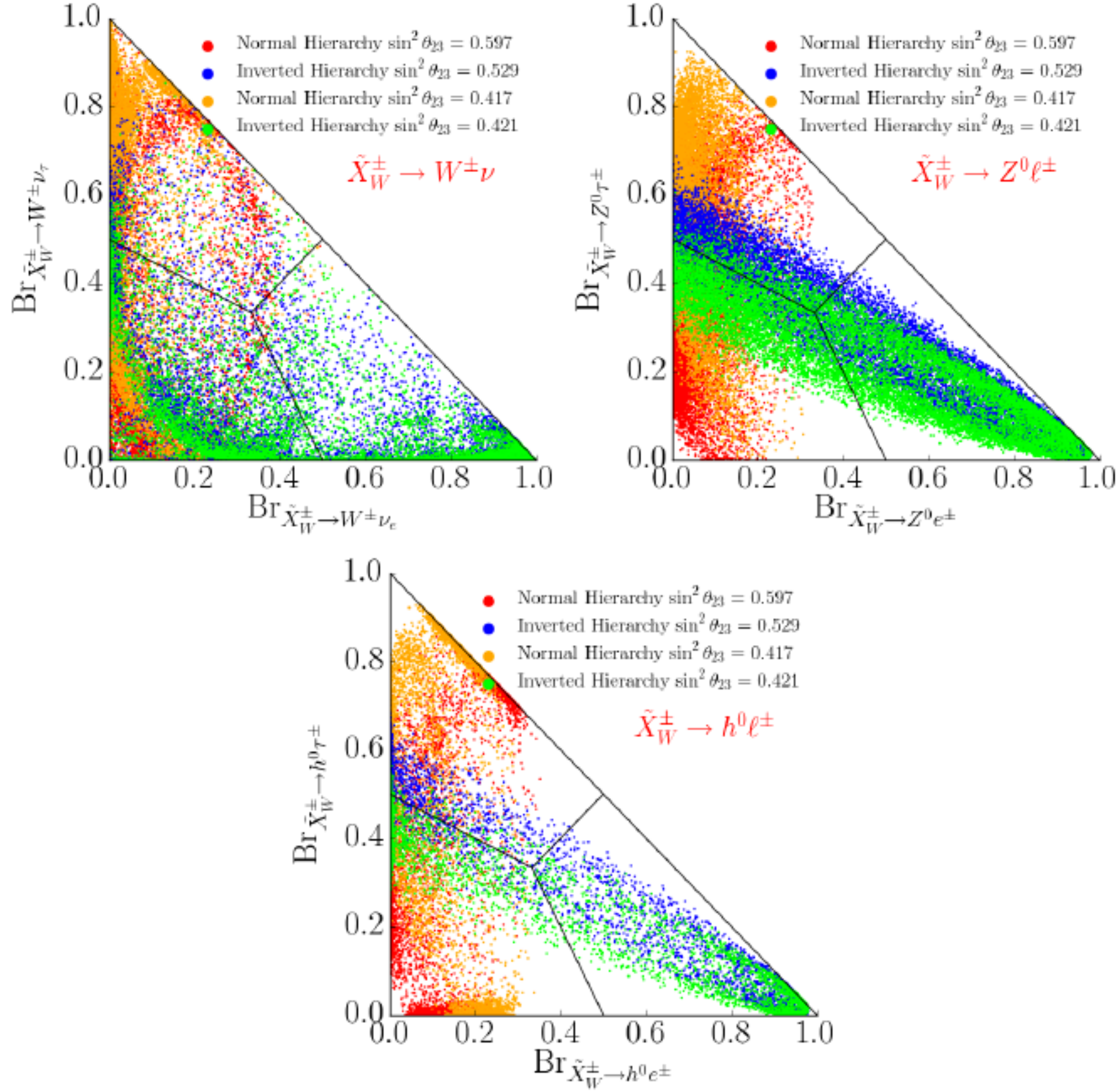


Figure Caption: **Branching ratios into the three lepton families, for each of the three main decay channels of a Wino chargino LSP. The associated neutrino hierarchy and the value of θ_{23} is specified by the color of the associated data point.**

2) Bino Neutralino LSP Decays:

The plot of the mass range of the Bino neutralino LSPs is

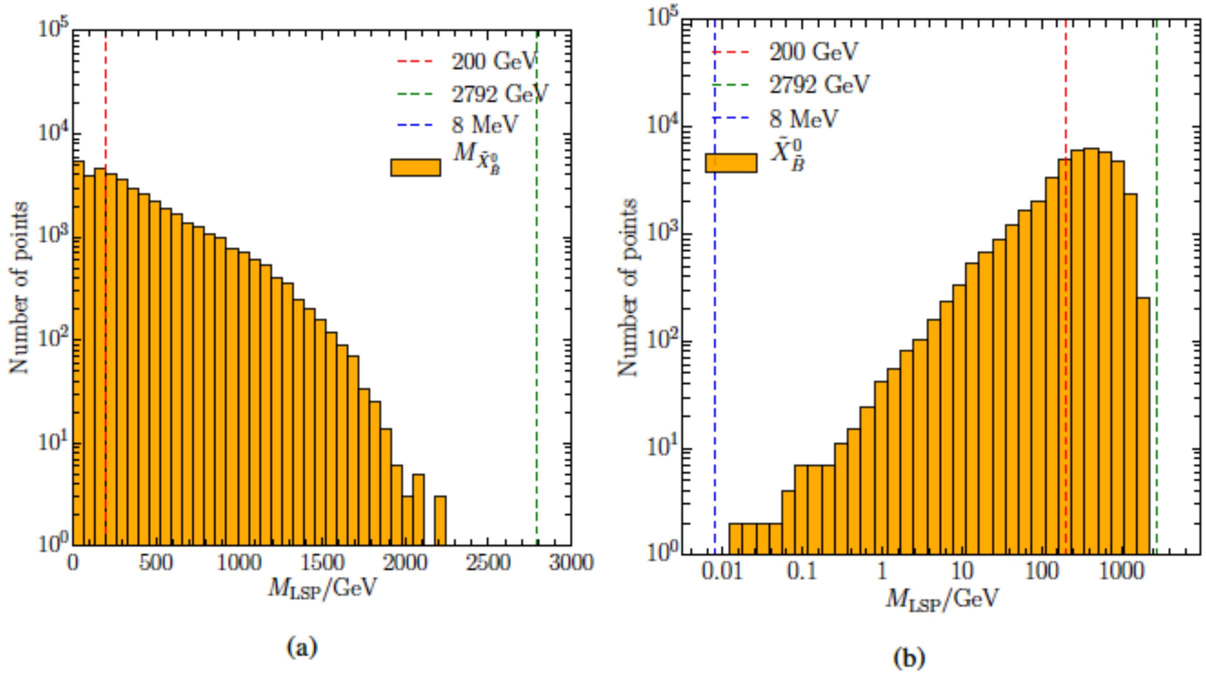


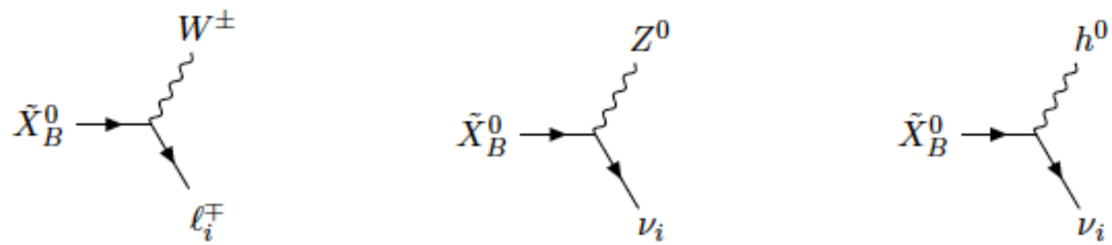
Figure Caption: **The distribution of the Bino neutralino LSP masses for the 42,039 valid black points, shown with linear (a) and logarithmic (b) mass scales. The masses range from 8 MeV to 2792 GeV. Each of the boundary masses occurs only once out of the 42,039 valid points and, hence, they cannot be seen in the histogram.**

Note that, unlike the Wino chargino, the Bino neutrino can be arbitrarily light. $\Rightarrow$

Could the Bino neutralino be Dark Matter??

We find that the RPV decays of “on-shell” (Bino neutralino mass > M_{EW}) Bino neutrinos to standard model matter has 3 possible channels.

These are



$\tilde{X}^0_B \to W^\pm \ell_i^\mp$ $\tilde{X}^0_B \to Z^0 \nu_i$ $\tilde{X}^0_B \to h^0 \nu_i$

As with the Wino chargino, one can compute the RPV decay rates and branching ratios for the Bino neutralino LSP. The results are the following.

<u>Decay Lengths</u> (= c/Decay Rate):

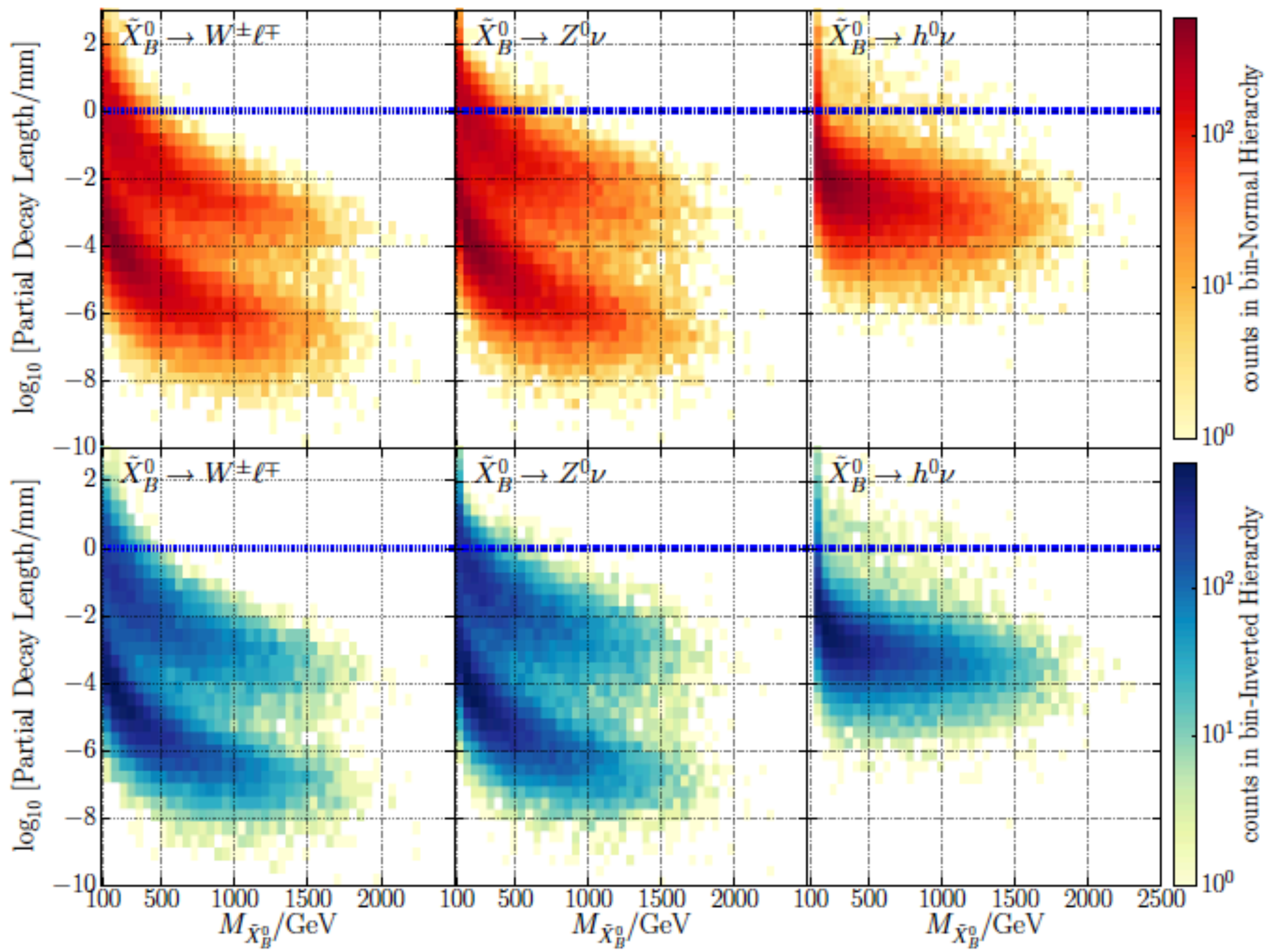


Figure Caption: Bino neutralino LSP partial decay length in millimeters, shown for the individual decay channels, for both normal and inverted hierarchies. We have chosen $\theta_{23} = 0.597$ for the normal neutrino hierarchy and $\theta_{23} = 0.529$ for the inverted hierarchy. The choice of θ_{23} has no impact on the decay length. The blue dashed line denotes a decay length of 1 mm, at and below which decays are "prompt".

Branching Ratios:

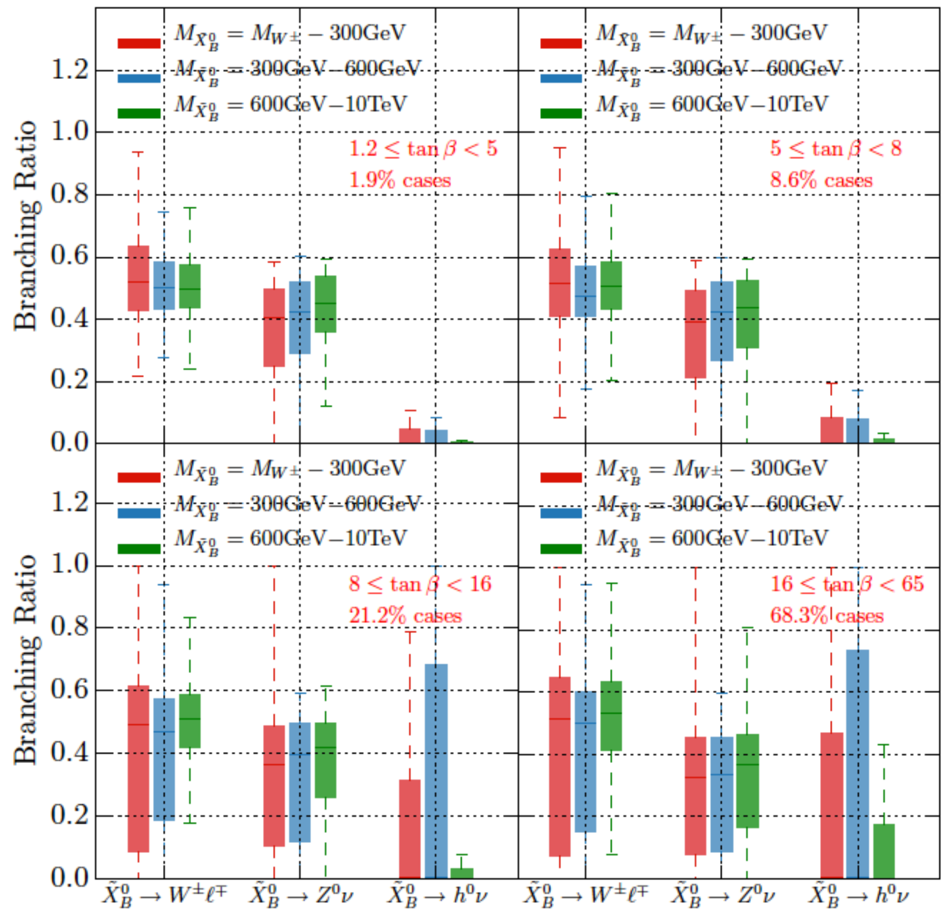


Figure Caption: Branching ratios for the three possible decay channels of a Bino neutralino LSP divided over three mass bins and four $\tan\beta$ regions. The colored horizontal lines inside the boxes indicate the median values of the branching fraction in each bin, the boxes indicate the interquartile range, while the dashed error bars show the range between the maximum and the minimum values of the branching fractions. The case percentage indicate what percentage of the physical mass spectra have $\tan\beta$ values within the range indicated. We assumed a normal neutrino hierarchy, with $\theta_{23} = 0.597$. Note that the median values of the $\tilde{X}_B^0 \to h^0\nu$ decay channel approaches zero for all mass ranges and all values of $\tan\beta$.

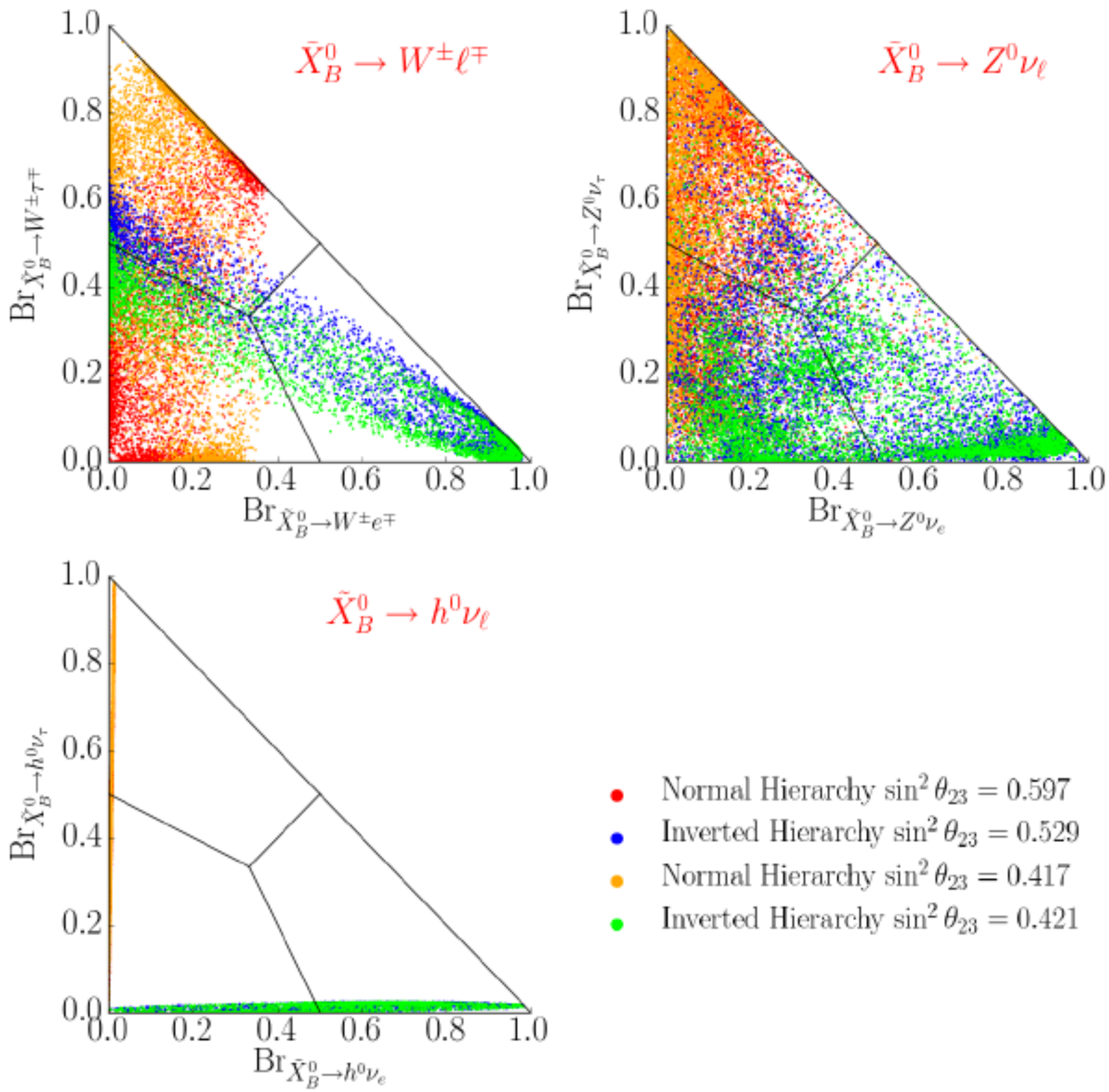


Figure Caption: **Branching ratios into the three lepton families, for each of the three main decay channels of a Bino neutralino LSP. The associated neutrino hierarchy and the value of θ_{23} is specified by the color of the associated data point.**