Extended Left-Right SUSY

(With Radiative Neutrino Mass
and **Multipartite Dark Matter**)

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COMPETE

PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

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The model

- $SU_L(2)$ X $SU_R(2)$ & Supersymmetry

Neutrino masses
Strong CP
Parity violation

Gauge coupling unification
Hierarchy
DM Candidate

- Unification→ particle content (No Higgs triplet)
- Radiative neutrino masses →extra symmetry

3 DM candidates

$SU(3)_c \times SU(2)_R \times SU(2)_L \times U(1)_X \times S \times H \times M$

$$\Delta_1 = \begin{pmatrix} \delta^0_{11} & \delta^+_{12} \\ \delta^-_{11} & \delta^0_{12} \end{pmatrix} \sim (1,2,2,0;1/2,+,+),\ \Delta_2 = \begin{pmatrix} \delta^0_{21} & \delta^+_{22} \\ \delta^-_{21} & \delta^0_{22} \end{pmatrix} \sim (1,2,2,0;-1/2,+,+)$$

$$\Phi_{L1} = \begin{pmatrix} \phi^0_{L1} \\ \phi^-_{L1} \end{pmatrix} \sim (1,2,1,-1/2;0,+,+), \quad \Phi_{L2} = \begin{pmatrix} \phi^+_{L2} \\ \phi^0_{L2} \end{pmatrix} \sim (1,2,1,1/2;0,+,+)$$

$$\Phi_{R1} = \begin{pmatrix} \phi^0_{R1} \\ \phi^-_{R1} \end{pmatrix} \sim (1,1,2,-1/2;-1/2,+,+),\ \Phi_{R2} = \begin{pmatrix} \phi^+_{R2} \\ \phi^0_{R2} \end{pmatrix} \sim (1,1,2,1/2;1/2,+,+)$$

$$\eta_{L1} = \begin{pmatrix} \eta^0_{L1} \\ \eta^-_{L1} \end{pmatrix} \sim (1,2,1,-1/2;0,+,-), \quad \eta_{L2} = \begin{pmatrix} \eta^+_{L2} \\ \eta^0_{L2} \end{pmatrix} \sim (1,2,1,1/2;0,+,-)$$

$$\eta_{R1} = \begin{pmatrix} \eta^0_{R1} \\ \eta^-_{R1} \end{pmatrix} \sim (1,1,2,-1/2;1/2,+,-),\ \eta_{R2} = \begin{pmatrix} \eta^+_{R2} \\ \eta^0_{R2} \end{pmatrix} \sim (1,1,2,1/2;-1/2,+,-)$$

$$s_1 = s_1^- \sim (1,1,1,-1;0,+,-), \quad s_2 = s_2^+ \sim (1,1,1,1;0,+,-), \quad s_3 = s_3^0 \sim (1,1,1,0;0,+,-)$$

$$\psi = (\nu, e) \sim (1,2,1,-1/2;0,-,+), \qquad \psi^c = (e^c, n^c) \sim (1,1,2,1/2;-1/2,-,+)$$

$$N \sim (1,1,1,0;0,-,-), \qquad n \sim (1,1,1,0;1,-,+)$$

$$Q = (u,d) \sim (3,2,1,1/6;0,-,+), \qquad Q^c = (h^c, u^c) \sim (3^*,1,2,-1/6;1/2,-,+)$$

$$d^c \sim (3^*,1,1,1/3;0,-,+), \qquad h \sim (3,1,1,-1/3;-1,-,+)$$

Superpotential

$$
\begin{aligned}
W &= -\mu_L \Phi_{L1}\Phi_{L2} - \mu_R \Phi_{R1}\Phi_{R2} - \mu_\Delta Tr(\Delta_1\Delta_2) \\
&- \mu_{L2}\eta_{L1}\eta_{L2} - \mu_{R2}\eta_{R1}\eta_{R2} - \mu_{s12}\zeta_1\zeta_2 - \mu_{s3}\zeta_3\zeta_3 \\
&+ f_1\Phi_{L1}\Delta_2\Phi_{R2} + f_2\Phi_{L2}\Delta_1\Phi_{R1} \\
&+ f_3\eta_{L1}\Delta_1\eta_{R2} + f_4\eta_{L2}\Delta_2\eta_{R1} + f_5\Phi_{L1}\eta_{L1}\zeta_2 \\
&+ f_6\Phi_{R1}\eta_{R1}\zeta_2 + f_7\Phi_{L2}\eta_{L2}\zeta_1 + f_8\Phi_{R2}\eta_{R2}\zeta_1 \\
&+ f_9\Phi_{L1}\eta_{L2}\chi_3 + f_{10}\Phi_{L2}\eta_{L1}\zeta_3 \\
&+ f_{11}\psi\Delta_1\psi^c + f_{12}Q\Delta_2Q^c + f_{13}Q\Phi_{L1}d^c \\
&+ f_{14}n\psi^c\Phi_{R1} + f_{15}hQ^c\Phi_{R2} \\
&+ f_{16}\psi N\eta_{L2} + f_{17}\psi^c N\eta_{R1}
\end{aligned}
$$

Superpotential

$$W = -\mu_L \Phi_{L1}\Phi_{L2} - \mu_R \Phi_{R1}\Phi_{R2} - \mu_\Delta Tr(\Delta_1\Delta_2)$$

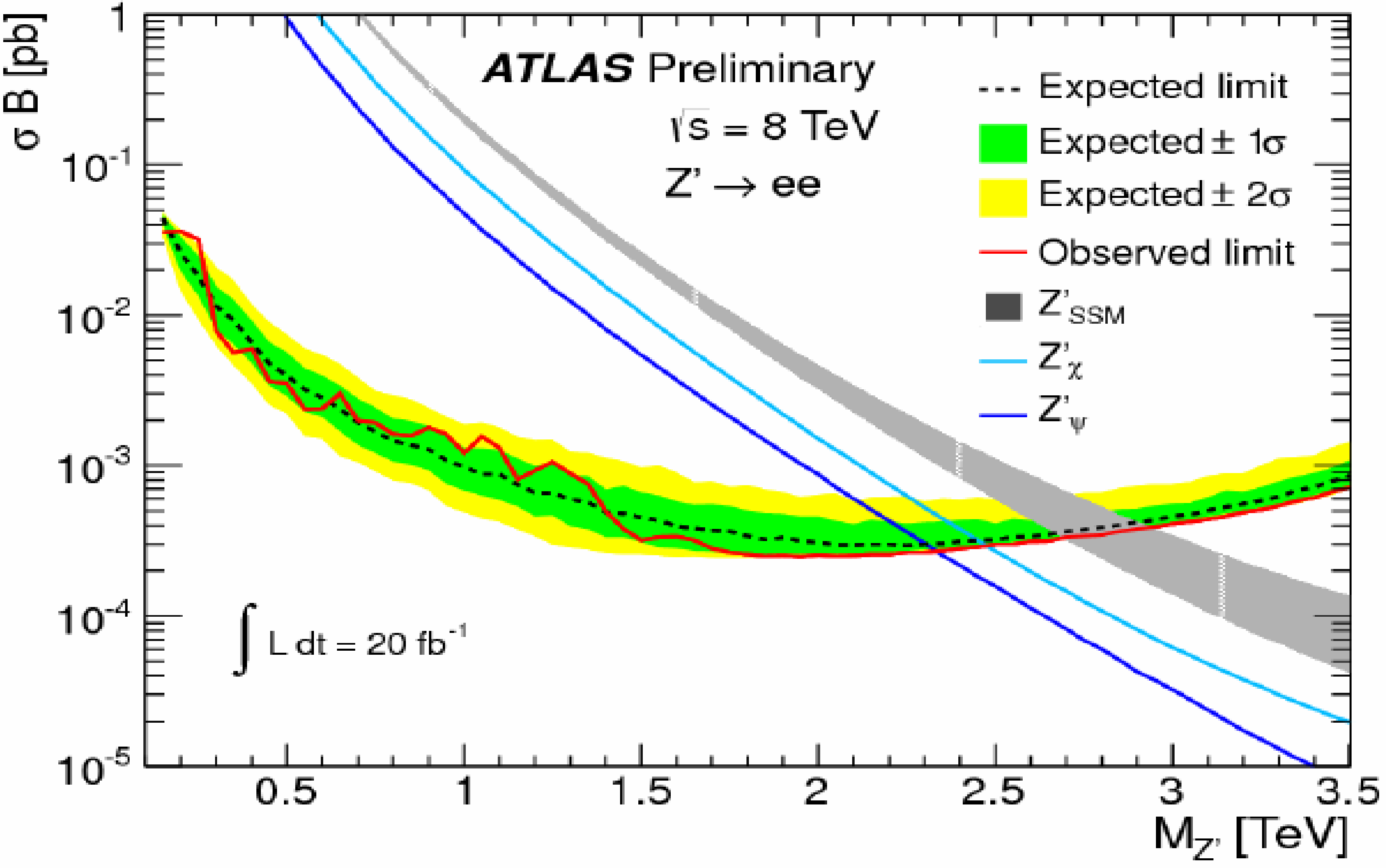
$$\begin{aligned}
W_2 &= Y_e(e\delta^0_{11}e^c - \nu\delta^-_{11}e^c - e\delta^+_{12}n^c + \nu\delta^0_{12}n^c) + Y_u(d\delta^0_{21}h^c - u\delta^-_{21}h^c - d\delta^+_{22}u^c + u\delta^0_{22}u^c) \\
&+ Y_d(u\phi^-_{L1}d^c - d\phi^0_{L1}d^c) + Y_n(ne^c\phi^-_{R1} - nn^c\phi^0_{R1}) + Y_h(hh^c\phi^0_{R2} - hu^c\phi^+_{R2}) \\
&+ Y_{N1}(N\nu\eta^0_{L2} - N\eta^+_{L2}e) + Y_{N2}(N\eta^-_{R1}e^c - N\eta^0_{R1}n^c)
\end{aligned}$$

$$\langle\phi^0_{L1}\rangle = v_{L1} \quad \langle\phi^0_{R1}\rangle = v_{R1} \quad \langle\delta^0_{11}\rangle = u_1$$

$$\langle\phi^0_{L2}\rangle = v_{L2} \quad \langle\phi^0_{R2}\rangle = v_{R2} \quad \langle\delta^0_{22}\rangle = u_4$$

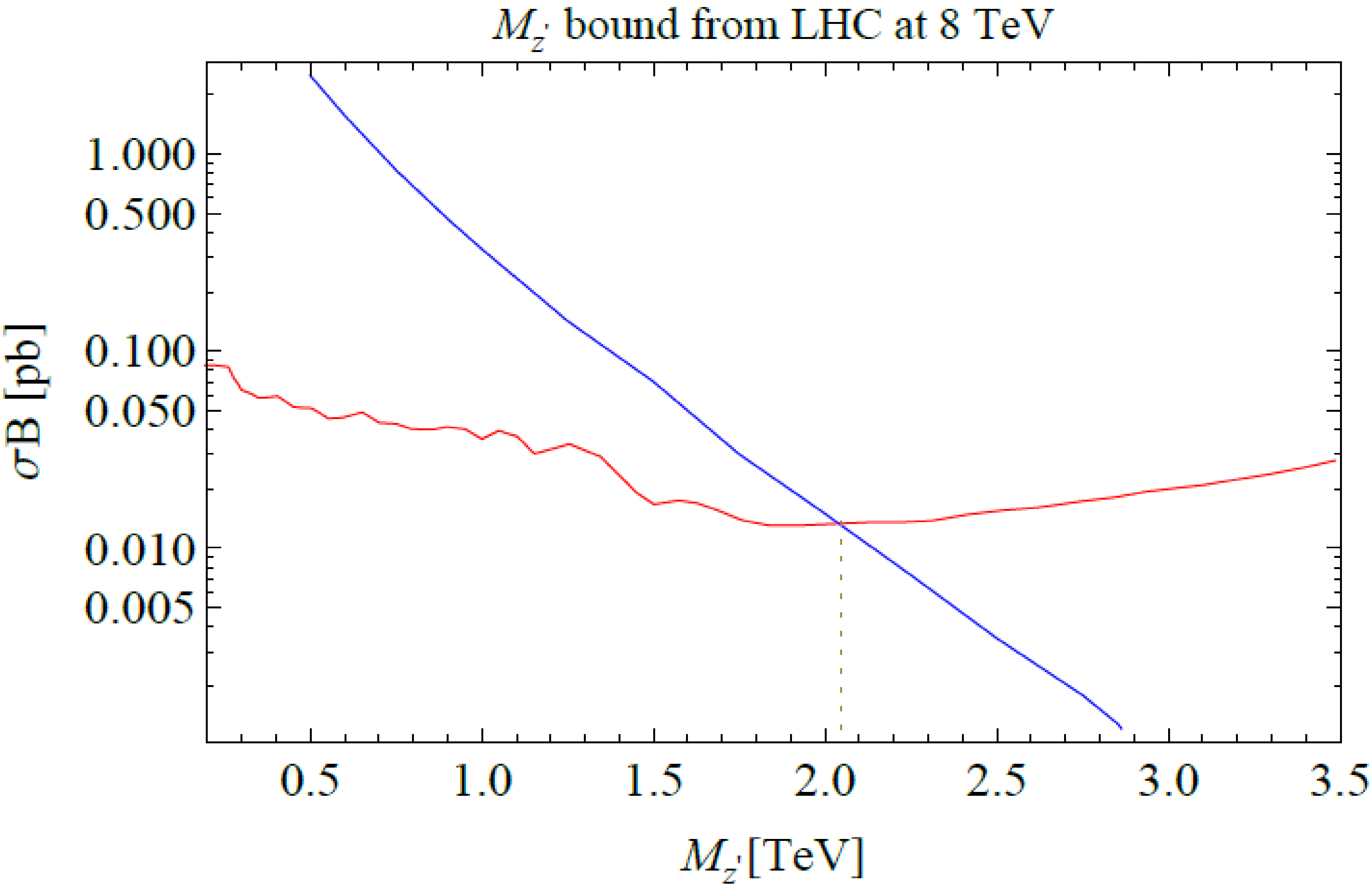
$$+ f_{16}\psi N\eta_{L2} + f_{17}\psi^c N\eta_{R1}$$

Bound on Z'



ATLAS Preliminary
$\sqrt{s}$ = 8 TeV
Z' → ee
∫ L dt = 20 fb⁻¹
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
Z'SSM
Z'χ
Z'ψ
σ B [pb]
M_Z' [TeV]
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0.5
1
1.5
2
2.5
3
3.5

Bound on Z'



$M_{Z'}$ bound from LHC at 8 TeV
1.000
0.500
0.100
0.050
0.010
0.005
σB [pb]
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$M_{Z'}$[TeV]

Numerical Value of vevs

~~M_Z~~ → M_Z

$$v_L = \frac{\sqrt{(1-2\sin^2\theta_W)}}{\sqrt{1-\sin^2\theta_W}} v_{SM} \simeq 0.837 * v_{SM} \simeq 145 \text{ GeV}$$

~~$M_{ZZ'}$~~

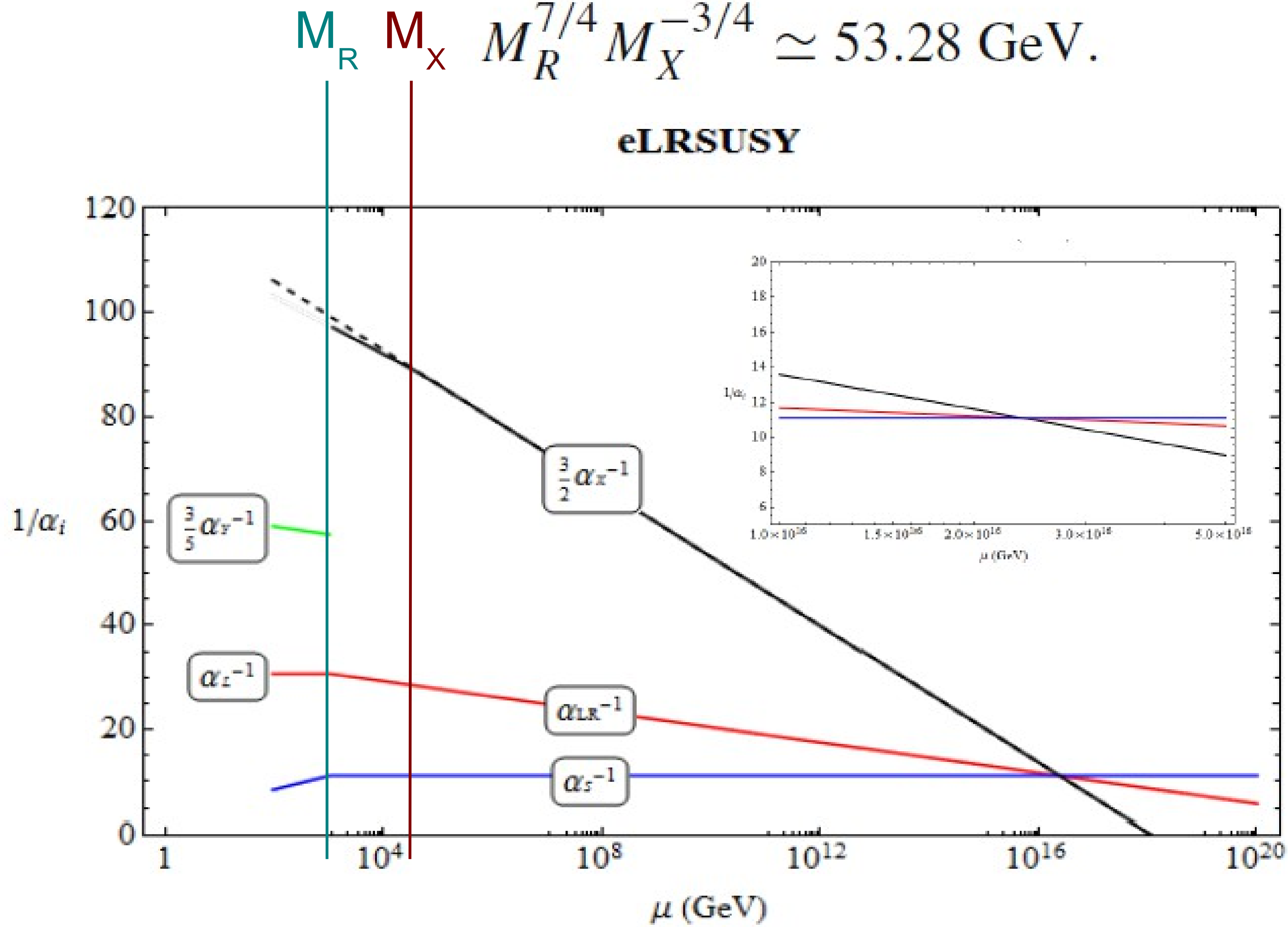
$$u = \sqrt{\left(\frac{\sin^2\theta_W}{1-2\sin^2\theta_W}\right)} v_L \simeq 0.653 * v_L \simeq 95 \text{ GeV}$$

$M_{Z'} >$

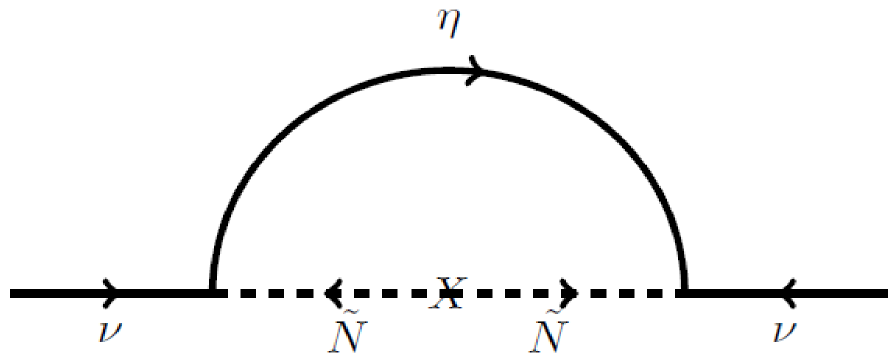
$$v_R \geq r * v_L = 25 * v_L \simeq 3625 \text{ GeV}$$

Gauge Coupling Unification

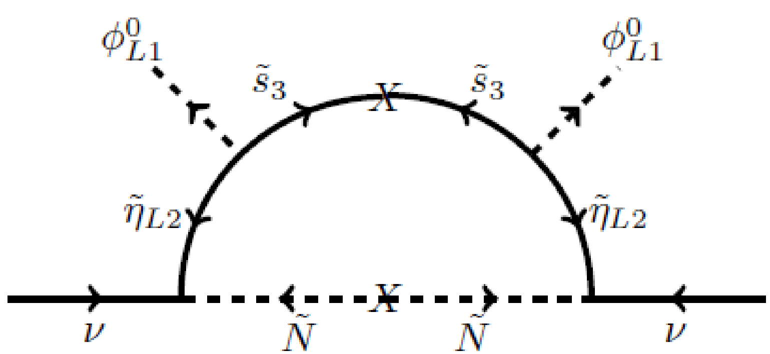
$$M_R^{7/4} M_X^{-3/4} \simeq 53.28\ \text{GeV}.$$

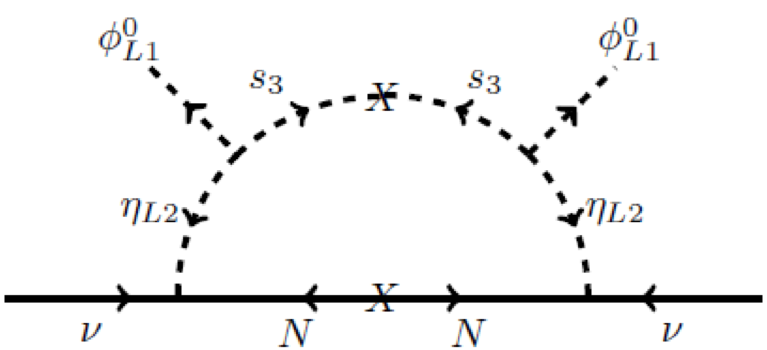


Radiative Neutrino Mass



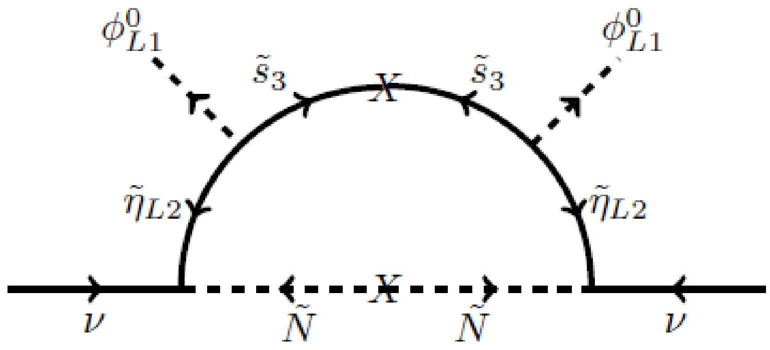
$$(M_\nu)_{\alpha\beta} = \sum_K \frac{h_{\alpha K} h_{\beta K} M_K}{16\pi^2} \left[\frac{m_R^2}{m_R^2 - M_K^2} \ln\left(\frac{m_R^2}{M_K^2}\right) - \frac{m_I^2}{m_I^2 - M_K^2} \ln\left(\frac{m_I^2}{M_K^2}\right) \right]$$

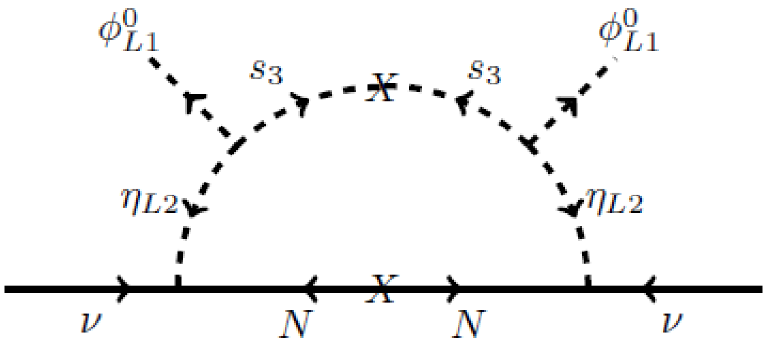




$$(M_\nu)_{\alpha\beta} = \sum_i \left\{ \frac{h_{\alpha i} h_{\beta i} M_{Ni}}{16\pi^2} \sum_j \left[(U_R)_{1j} \frac{m_{Rj}^2}{m_{Rj}^2 - M_{Ni}^2} \ln\left(\frac{m_{Rj}^2}{M_{Ni}^2}\right) - (U_I)_{1j} \frac{m_{Ij}^2}{m_{Ij}^2 - M_{Ni}^2} \ln\left(\frac{m_{Ij}^2}{M_{Ni}^2}\right) \right] \right\}$$

Radiative Neutrino Mass





$$(M_\nu)_{\alpha\beta} = \sum_i \left\{ \frac{h_{\alpha i} h_{\beta i} M_{Ni}}{16\pi^2} \sum_j \left[(U_R)_{1j} \frac{m^2_{Rj}}{m^2_{Rj} - M^2_{Ni}} \ln\left(\frac{m^2_{Rj}}{M^2_{Ni}}\right) - (U_I)_{1j} \frac{m^2_{Ij}}{m^2_{Ij} - M^2_{Ni}} \ln\left(\frac{m^2_{Ij}}{M^2_{Ni}}\right) \right] \right\}$$

$$m_\nu \simeq \frac{h^2 v^2_{L1} f^2}{16\pi^2 M^3_N}$$

DM Candidates

S'	M	H	Superfields
0	$-$	$+$	u, d, ν, e
0	$+$	$+$	$g, \gamma, W_L^{\pm}, Z, Z'$
0	$+$	$+$	$\phi_{L1}^0, \phi_{L1}^-, \phi_{L2}^+, \phi_{L2}^0, \phi_{R1}^0, \phi_{R2}^0$
0	$+$	$+$	$\delta_{11}^0, \delta_{11}^-, \delta_{22}^+, \delta_{22}^0$
1	$-$	$+$	n, h^c
-1	$-$	$+$	n^c, h
1	$+$	$+$	$W_R^+, \phi_{R2}^+, \delta_{12}^+, \delta_{12}^0$
-1	$+$	$+$	$W_R^-, \phi_{R1}^-, \delta_{21}^0, \delta_{21}^-$
0	$-$	$-$	N
0	$+$	$-$	$\eta_{L1}^0, \eta_{L1}^-, \eta_{L2}^+, \eta_{L2}^0, \eta_{R1}^-, \eta_{R2}^+$
0	$+$	$-$	$\zeta_1^-, \zeta_2^+, \zeta_3$
1	$+$	$-$	η_{R1}^0
-1	$+$	$-$	η_{R2}^0

1. (- -) $N, \tilde{N}$
2. (- +) $n\ \tilde{n}\ \tilde{\nu}$
3. (+ -) $\eta, \tilde{\eta}, \zeta, \tilde{\zeta}$
4. (+ +) χ

DM Candidates

S'	M	H	Superfields
0	$-$	$+$	u, d, ν, e
0	$+$	$+$	$g, \gamma, W_L^{\pm}, Z, Z'$
0	$+$	$+$	$\phi_{L1}^0, \phi_{L1}^-, \phi_{L2}^+, \phi_{L2}^0, \phi_{R1}^0, \phi_{R2}^0$
0	$+$	$+$	$\delta_{11}^0, \delta_{11}^-, \delta_{22}^+, \delta_{22}^0$
1	$-$	$+$	n, h^c
-1	$-$	$+$	n^c, h
1	$+$	$+$	$W_R^+, \phi_{R2}^+, \delta_{12}^+, \delta_{12}^0$
-1	$+$	$+$	$W_R^-, \phi_{R1}^-, \delta_{21}^0, \delta_{21}^-$
0	$-$	$-$	N
0	$+$	$-$	$\eta_{L1}^0, \eta_{L1}^-, \eta_{L2}^+, \eta_{L2}^0, \eta_{R1}^-, \eta_{R2}^+$
0	$+$	$-$	$\zeta_1^-, \zeta_2^+, \zeta_3$
1	$+$	$-$	η_{R1}^0
-1	$+$	$-$	η_{R2}^0

1. (- -) ~~$N, \tilde{N}$~~
   - Neutrino masses N~100 TeV
2. (- +) n ~~$\tilde{n}$ $\tilde{\nu}$~~
   - $\tilde{n}$ and $\tilde{\nu}$ large Z coupling
3. (+ -) ~~η~~, $\tilde{\eta}$, ~~ζ, $\tilde{\zeta}$~~
   - $\langle\sigma v\rangle_\eta \sim v$
   - Gauge coupling ζ~50 TeV
4. (+ +) χ

Currents

$$J_A = eQ(\overline{X}\gamma^\mu X) = g_L s_L Q(\overline{X}\gamma^\mu X)$$

$$J_Z = \frac{g_L}{c_L}(I_{3L} - s_L^2 Q)(\overline{X}\gamma^\mu X)$$

$$J_{Z'} = g_{Z'}(c_L^2 I_{3R} + s_R^2 I_{3L} - s_R^2 Q)(\overline{X}\gamma^\mu X)$$

$$J_{W^+_{(L/R)}} = \frac{g_{(L/R)}}{\sqrt{2}}(\overline{X_1}\gamma^\mu X_2)$$

Currents

$$J_A = eQ(\overline{X}\gamma^\mu X) = g_L s_L Q(\overline{X}\gamma^\mu X)$$

$$J_Z = \frac{g_L}{c_L}(I_{3L} - s_L^2 Q)(\overline{X}\gamma^\mu X)$$

$$J_{Z'} = g_{Z'}(c_L^2 I_{3R} + s_R^2 I_{3L} - s_R^2 Q)(\overline{X}\gamma^\mu X)$$

$$J_{W^+_{(L/R)}} = \frac{g_{(L/R)}}{\sqrt{2}}(\overline{X_1}\gamma^\mu X_2)$$

Neutralino Mass Matrices

$$\left(\Psi_{\tilde{N2}}{}^{0}\right)^{T} = \{\eta^{\tilde{0}}_{L1}, \eta^{\tilde{0}}_{L2}, s^{\tilde{0}}_{3}\} \qquad M_{N2} = \begin{pmatrix} 0 & -\mu_{L2} & f_{10}v_{L2} \\ -\mu_{L2} & 0 & f_9 v_{L1} \\ f_{10}v_{L2} & f_9 v_{L1} & -\mu_{s3} \end{pmatrix}$$

$$\left(\Psi_{\tilde{N3}}{}^{0}\right)^{T} = \{\eta^{\tilde{0}}_{R1}, \eta^{\tilde{0}}_{R2}\} \qquad M_{N3} = \begin{pmatrix} 0 & -\mu_{R2} \\ -\mu_{R2} & 0 \end{pmatrix}$$

$$\left(\Psi_{\tilde{N4}}{}^{0}\right)^{T} = \{\delta^{\tilde{0}}_{12}, \delta^{\tilde{0}}_{21}\} \qquad M_{N4} = \begin{pmatrix} 0 & -\mu_{\Delta} \\ -\mu_{\Delta} & 0 \end{pmatrix}$$

Neutralino masses

$$\left(\Psi_{\tilde{N1}}^{0}\right)^T = \{\tilde{B}, \tilde{W}_L, \tilde{\phi_{L1}}, \tilde{\phi_{L2}}, \tilde{W}_R, \tilde{\delta_{11}}, \tilde{\delta_{22}}, \tilde{\phi_{R1}}, \tilde{\phi_{R2}}\}$$

$$\left(\begin{array}{cccc|ccccc}
M_B & 0 & -\frac{g_1 v_{L1}}{\sqrt{2}} & \frac{g_1 v_{L2}}{\sqrt{2}} & 0 & 0 & 0 & -\frac{g_1 v_{R1}}{\sqrt{2}} & \frac{g_1 v_{R2}}{\sqrt{2}} \\
0 & M_L & \frac{g_L v_{L1}}{\sqrt{2}} & -\frac{g_L v_{L2}}{\sqrt{2}} & 0 & -\frac{g_L u_1}{\sqrt{2}} & \frac{g_L u_4}{\sqrt{2}} & 0 & 0 \\
-\frac{g_1 v_{L1}}{\sqrt{2}} & \frac{g_L v_{L1}}{\sqrt{2}} & 0 & -\mu_L & 0 & 0 & \frac{f_1 v_{R2}}{2} & 0 & \frac{f_1 u_4}{2} \\
\frac{g_1 v_{L2}}{\sqrt{2}} & -\frac{g_L v_{L2}}{\sqrt{2}} & -\mu_L & 0 & 0 & \frac{f_2 v_{R1}}{2} & 0 & \frac{f_2 u_1}{2} & 0 \\
\hline
0 & 0 & 0 & 0 & M_R & -\frac{g_R u_1}{\sqrt{2}} & \frac{g_R u_4}{\sqrt{2}} & \frac{g_R v_{R1}}{\sqrt{2}} & -\frac{g_R v_{R2}}{\sqrt{2}} \\
0 & -\frac{g_L u_1}{\sqrt{2}} & 0 & \frac{f_2 v_{R1}}{2} & -\frac{g_R u_1}{\sqrt{2}} & 0 & -\mu_\Delta & \frac{f_2 v_{L2}}{2} & 0 \\
0 & \frac{g_R u_4}{\sqrt{2}} & \frac{f_1 v_{R2}}{2} & 0 & \frac{g_R u_4}{\sqrt{2}} & -\mu_\Delta & 0 & 0 & \frac{f_1 v_{L1}}{2} \\
-\frac{g_1 v_{R1}}{\sqrt{2}} & 0 & 0 & \frac{f_2 u_1}{2} & \frac{g_R v_{R1}}{\sqrt{2}} & \frac{f_2 v_{L2}}{2} & 0 & 0 & -\mu_R \\
\frac{g_1 v_{R2}}{\sqrt{2}} & 0 & \frac{f_1 u_4}{2} & 0 & -\frac{g_R v_{R2}}{\sqrt{2}} & 0 & \frac{f_1 v_{L1}}{2} & -\mu_R & 0
\end{array}\right)$$

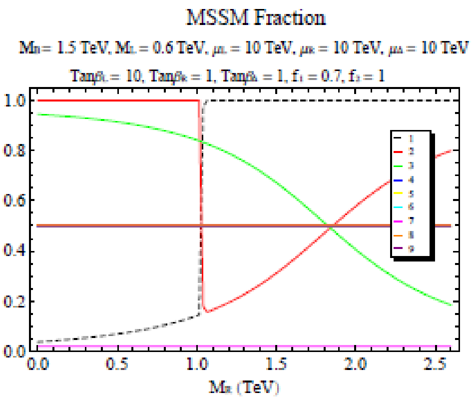
Neutralino masses

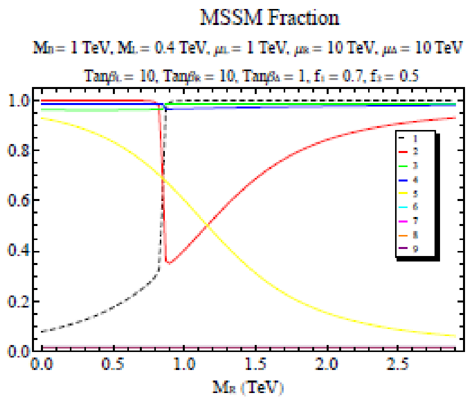
Is MSSM inside eLRSUSY?

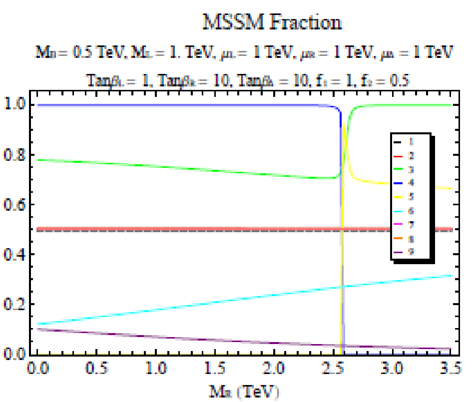
$$
\left(\begin{array}{cccc|ccccc}
M_B & 0 & -\frac{g_1 v_{L1}}{\sqrt{2}} & \frac{g_1 v_{L2}}{\sqrt{2}} & 0 & 0 & 0 & -\frac{g_1 v_{R1}}{\sqrt{2}} & \frac{g_1 v_{R2}}{\sqrt{2}} \\
0 & \cdots & \cdots & \cdots & 0 & \cdots & \cdots & \cdots & 0 \\
\cdots & \cdots & \cdots & \cdots & 0 & \cdots & \cdots & \cdots & \frac{f_1 u_4}{2} \\
\cdots & \cdots & \cdots & \cdots & 0 & \cdots & \cdots & \cdots & 0 \\
\hline
0 & 0 & 0 & 0 & M_R & -\frac{g_R u_1}{\sqrt{2}} & \frac{g_R u_4}{\sqrt{2}} & \frac{g_R v_{R1}}{\sqrt{2}} & -\frac{g_R v_{R2}}{\sqrt{2}} \\
0 & \cdots & \cdots & \cdots & -\frac{g_R u_1}{\sqrt{2}} & \cdots & \cdots & \cdots & 0 \\
0 & \cdots & \cdots & \cdots & \frac{g_R u_4}{\sqrt{2}} & \cdots & \cdots & \cdots & \frac{f_1 v_{L1}}{2} \\
\cdots & \cdots & \cdots & \cdots & \frac{g_R v_{R1}}{\sqrt{2}} & \cdots & \cdots & \cdots & -\mu_R \\
\frac{g_1 v_{R2}}{\sqrt{2}} & 0 & \frac{f_1 u_4}{2} & 0 & -\frac{g_R v_{R2}}{\sqrt{2}} & 0 & \frac{f_1 v_{L1}}{2} & -\mu_R & 0
\end{array}\right)
$$

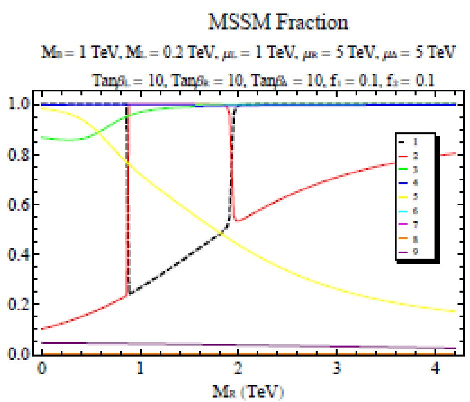
$$
\begin{pmatrix} M_{MSSM} \; (4 \times 4) & G \; (4 \times 5) \\ G \; (5 \times 4) & M_{heavy} \; (5 \times 5) \end{pmatrix}
$$

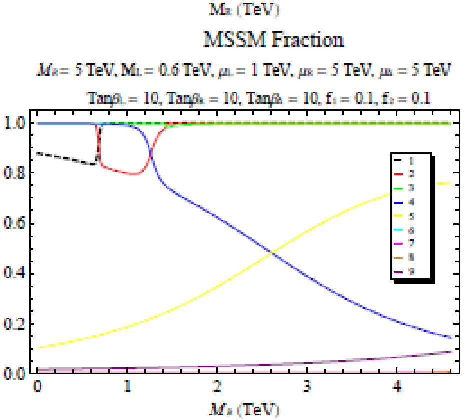
No, But...

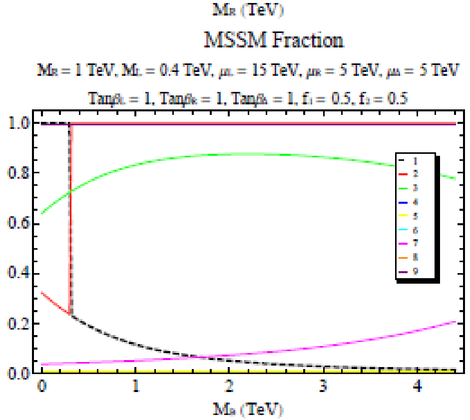

MSSM Fraction
M_D = 1.5 TeV, M_L = 0.6 TeV, μ_L = 10 TeV, μ_R = 10 TeV, μ_A = 10 TeV
Tanβ_L = 10, Tanβ_R = 1, Tanβ_A = 1, f_1 = 0.7, f_2 = 1
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
M_R (TeV)
1
2
3
4
5
6
7
8
9


MSSM Fraction
M_D = 1 TeV, M_L = 0.4 TeV, μ_L = 1 TeV, μ_R = 10 TeV, μ_A = 10 TeV
Tanβ_L = 10, Tanβ_R = 10, Tanβ_A = 1, f_1 = 0.7, f_2 = 0.5
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
M_R (TeV)
1
2
3
4
5
6
7
8
9

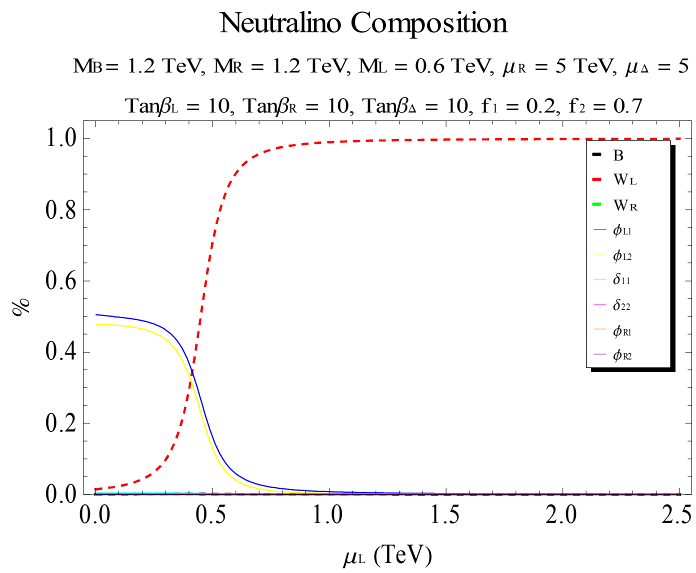

MSSM Fraction
M_D = 0.5 TeV, M_L = 1. TeV, μ_L = 1 TeV, μ_R = 1 TeV, μ_A = 1 TeV
Tanβ_L = 1, Tanβ_R = 10, Tanβ_A = 10, f_1 = 1, f_2 = 0.5
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
M_R (TeV)
1
2
3
4
5
6
7
8
9

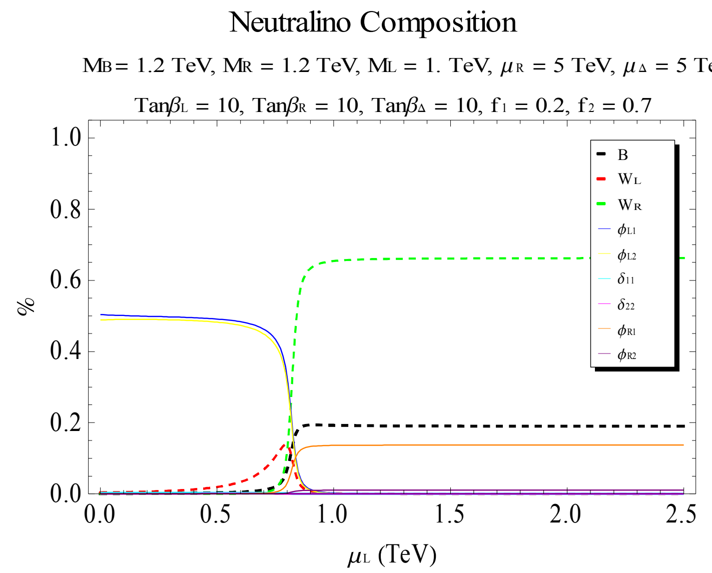

MSSM Fraction
M_D = 1 TeV, M_L = 0.2 TeV, μ_L = 1 TeV, μ_R = 5 TeV, μ_A = 5 TeV
Tanβ_L = 10, Tanβ_R = 10, Tanβ_A = 10, f_1 = 0.1, f_2 = 0.1
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
M_R (TeV)
1
2
3
4
5
6
7
8
9

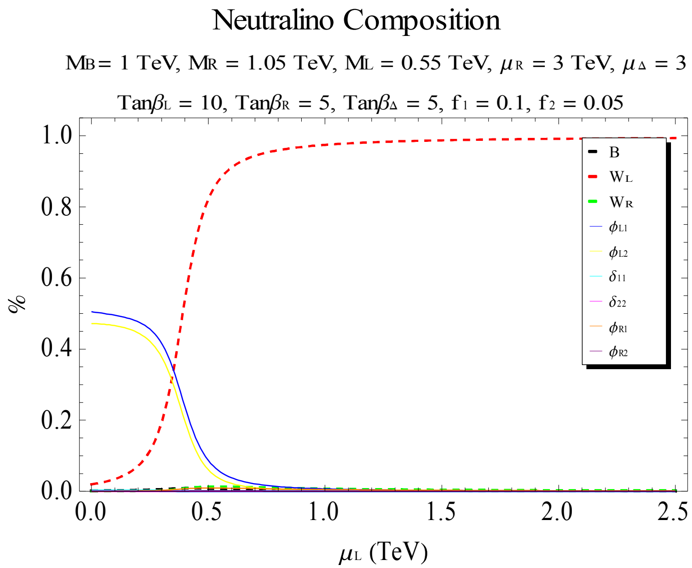

MSSM Fraction
M_R = 5 TeV, M_L = 0.6 TeV, μ_L = 1 TeV, μ_R = 5 TeV, μ_A = 5 TeV
Tanβ_L = 10, Tanβ_R = 10, Tanβ_A = 10, f_1 = 0.1, f_2 = 0.1
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
M_a (TeV)
1
2
3
4
5
6
7
8
9

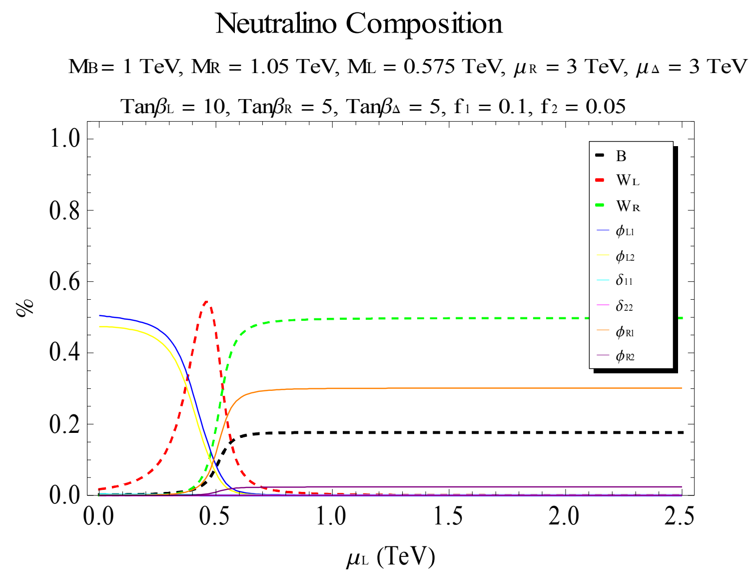

MSSM Fraction
M_R = 1 TeV, M_L = 0.4 TeV, μ_L = 15 TeV, μ_R = 5 TeV, μ_A = 5 TeV
Tanβ_L = 1, Tanβ_R = 1, Tanβ_A = 1, f_1 = 0.5, f_2 = 0.5
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
M_a (TeV)
1
2
3
4
5
6
7
8
9

Lightest Neutralino Plots

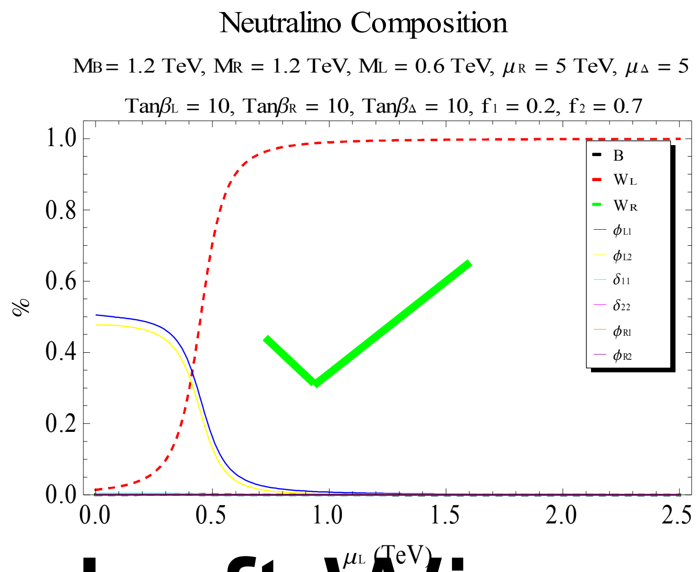


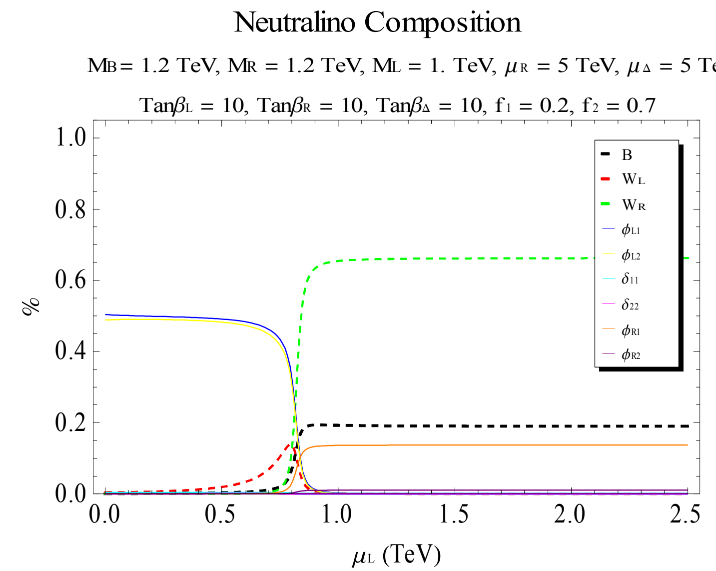




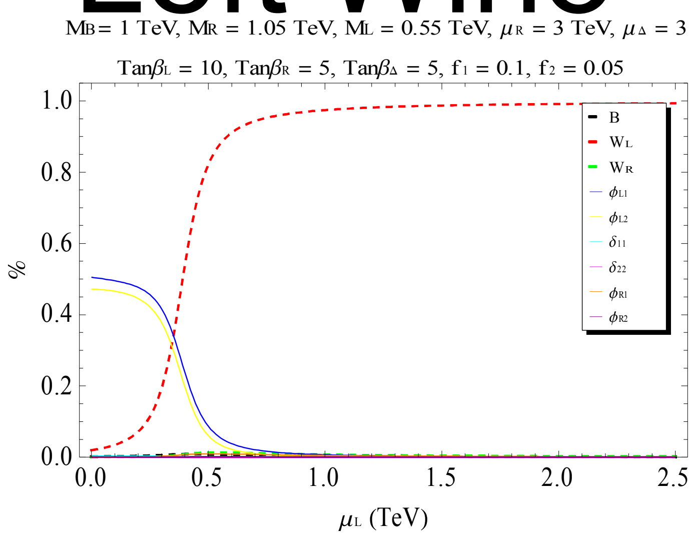


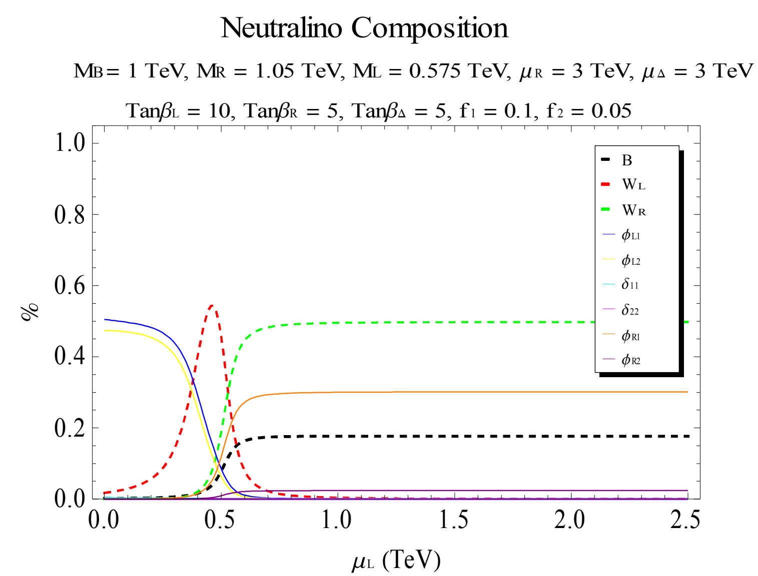
Lightest Neutralino Plots





Left Wino





Relic abundance

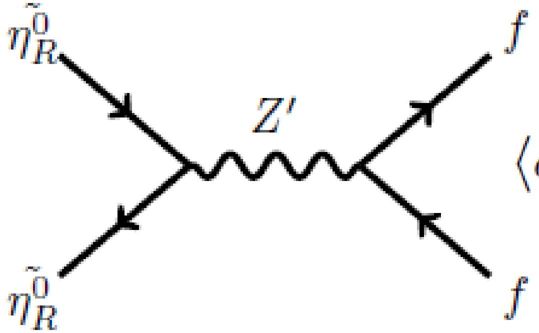
- 2 conserve symmetries $\longrightarrow 4(-1)=3$ candidates: χ, n, η
- Assumption: $m_\chi<m_n<m_\eta \longrightarrow T_\chi>T_n>T_\eta$

  (Decoupling from hot soup is independent of interactions with each other)

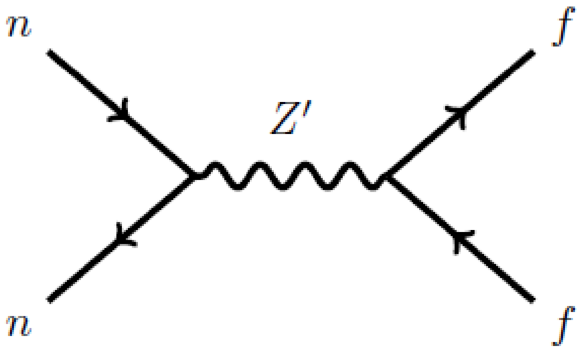
$$\Omega_i h^2 \simeq \frac{0.1pb}{\langle\sigma v\rangle_i}$$

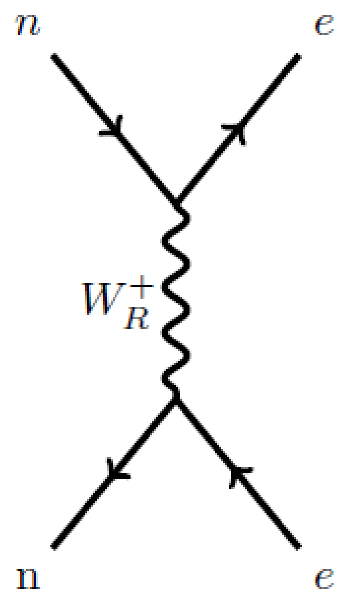
- 1st Assign parameters for MSSM neutralino, find Ω_χ
- 2nd Choose % relic abundance for n and η, $\Omega_n > \Omega_\eta$
- 3rd Find masses and direct detection scattering.

Pair Annihilation of n and η_R



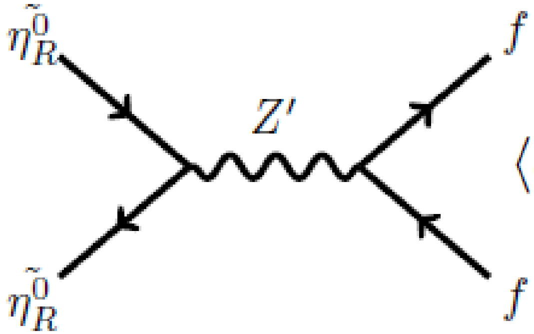
$$\langle \sigma v \rangle_\eta \simeq \frac{g_L^4 m_{\eta_{R^0}}^2}{64\pi}\left[\frac{10 s_W^4 - 9 s_W^2 c_W^2 + 3 c_W^4}{(4m_{\eta_{R^0}}^2 - M_{Z'}^2)^2 (c_W^2 - s_W^2)^2}\right]$$



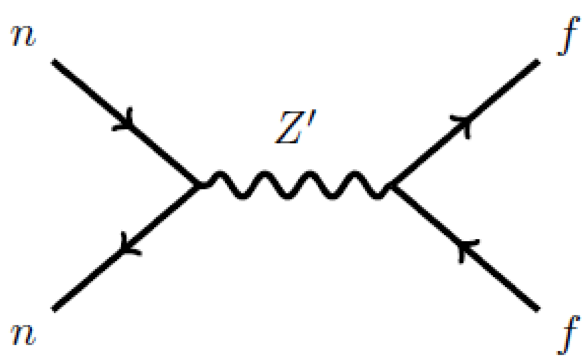


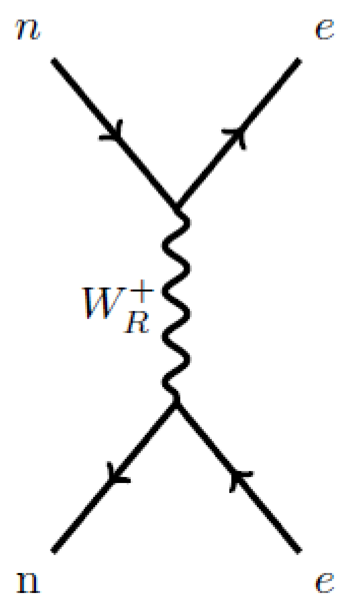
$$\langle \sigma v \rangle_n \simeq \frac{g_L^4 m_n^2}{64\pi}\left[\frac{10 s_W^4 - 9 s_W^2 c_W^2 + 3 c_W^4}{(4m_n^2 - M_{Z'}^2)^2 (c_W^2 - s_W^2)^2} + \frac{3}{(m_n^2 + M_{W_R}^2)^2} + \frac{3(c_W^2 - 2 s_W^2)}{(4m_n^2 - M_{Z'}^2)(m_n^2 + M_{W_R}^2)(c_W^2 - s_W^2)}\right]$$

Pair Annihilation of n and η_R



$$\langle \sigma v \rangle_\eta \simeq \frac{g_L^4 m_{\eta_{R^0}}^2}{64\pi}\left[\frac{10 s_W^4 - 9 s_W^2 c_W^2 + 3 c_W^4}{(4m_{\eta_{R^0}}^2 - M_{Z'}^2)^2 (c_W^2 - s_W^2)^2}\right]$$





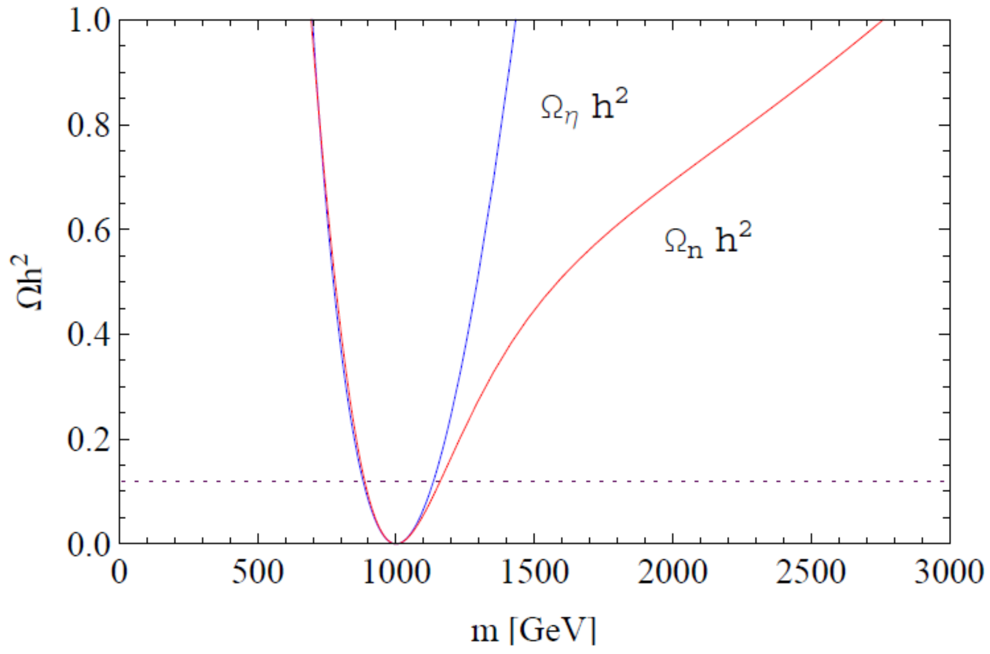
$$m \to \frac{M_{Z'}}{2}$$
$$\langle \sigma v \rangle \to \infty$$
$$\Omega h^2 \to 0$$

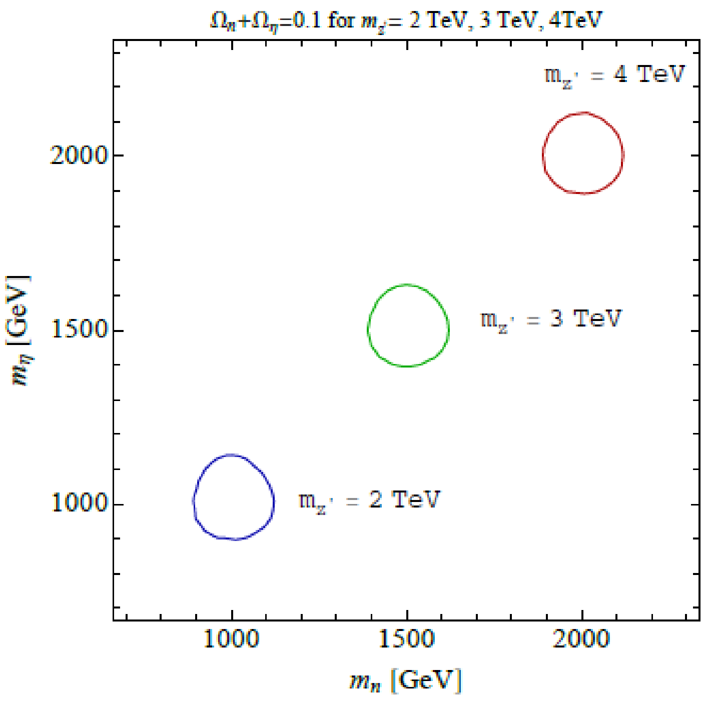
$$\langle \sigma v \rangle_n \simeq \frac{g_L^4 m_n^2}{64\pi}\left[\frac{10 s_W^4 - 9 s_W^2 c_W^2 + 3 c_W^4}{(4m_n^2 - M_{Z'}^2)^2 (c_W^2 - s_W^2)^2} + \frac{3}{(m_n^2 + M_{W_R}^2)^2} + \frac{3(c_W^2 - 2s_W^2)}{(4m_n^2 - M_{Z'}^2)(m_n^2 + M_{W_R}^2)(c_W^2 - s_W^2)}\right]$$

Relic Abundance- Plots

$$\Omega_{DM_{tot}} h^2 = \Omega_\eta h^2 + \Omega_n h^2 + \Omega_{\chi_1^0} h^2$$

$$0.094 < \Omega_{DM_{tot}} h^2 < 0.130$$





Relic Abundance- Plots

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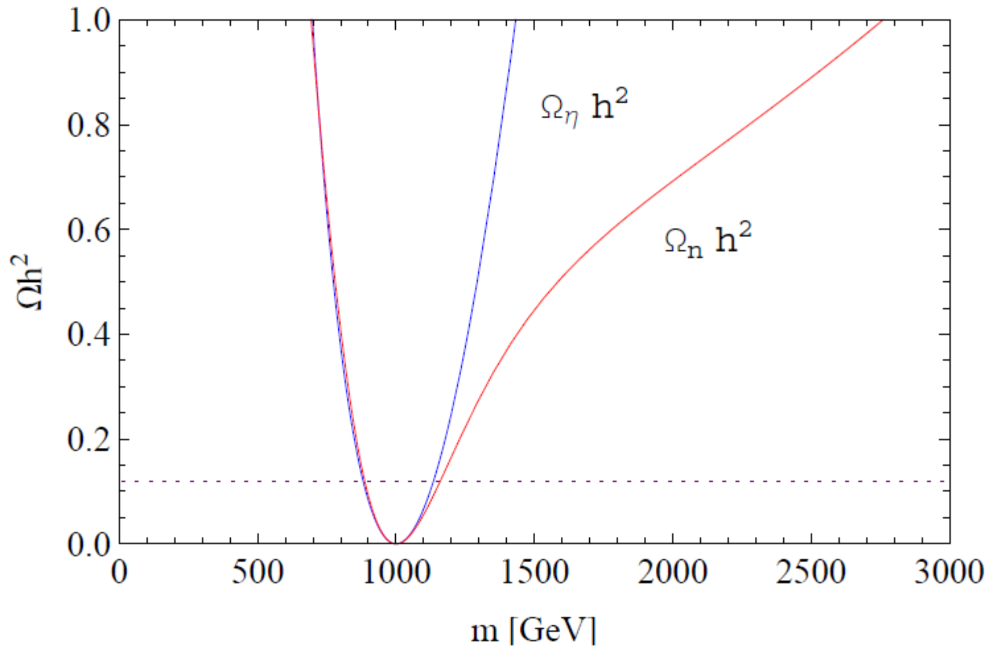
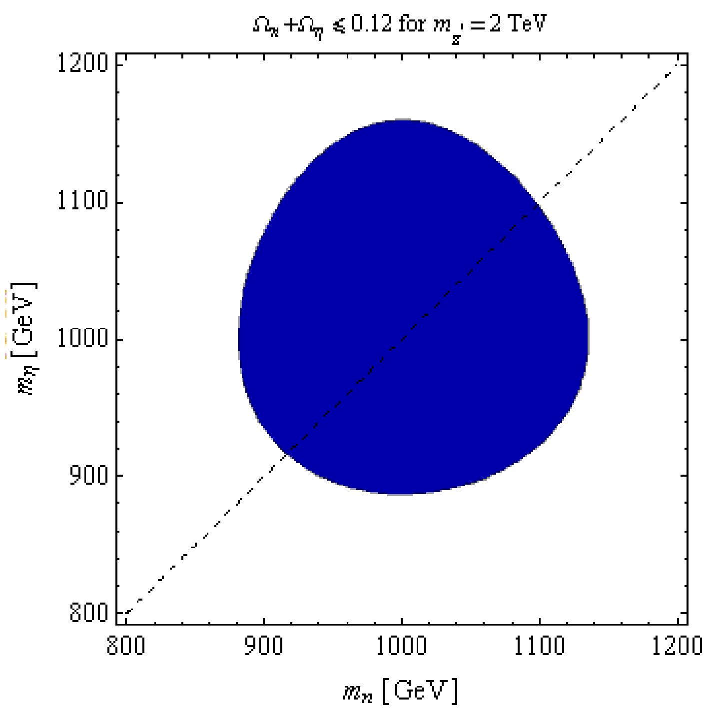
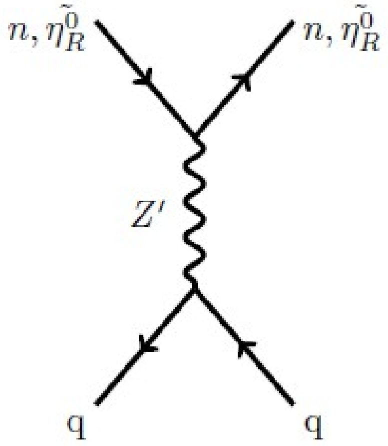


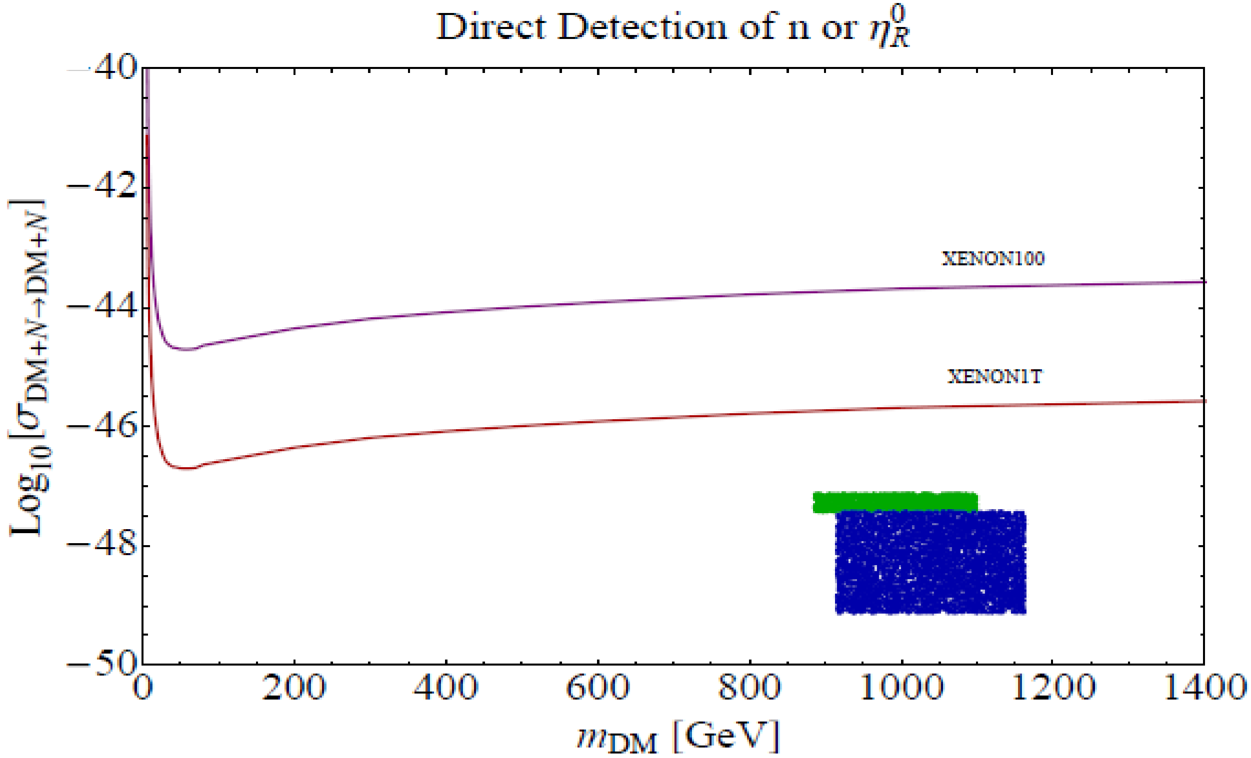


Direct detection



$$\sigma^{SI} = \frac{4}{\pi}\left(\frac{m_\chi m_n}{m_\chi + m_n}\right)^2 f_N^2$$

$$f_N = m_N \left(\sum_{q=u,d,s} f_q^N \frac{A_q}{m_q} + \frac{2}{27}\left(1 - \sum_{q=c,b,t} f_q^N\right) \sum_{q=u,d,s} \frac{A_q}{m_q} \right)$$



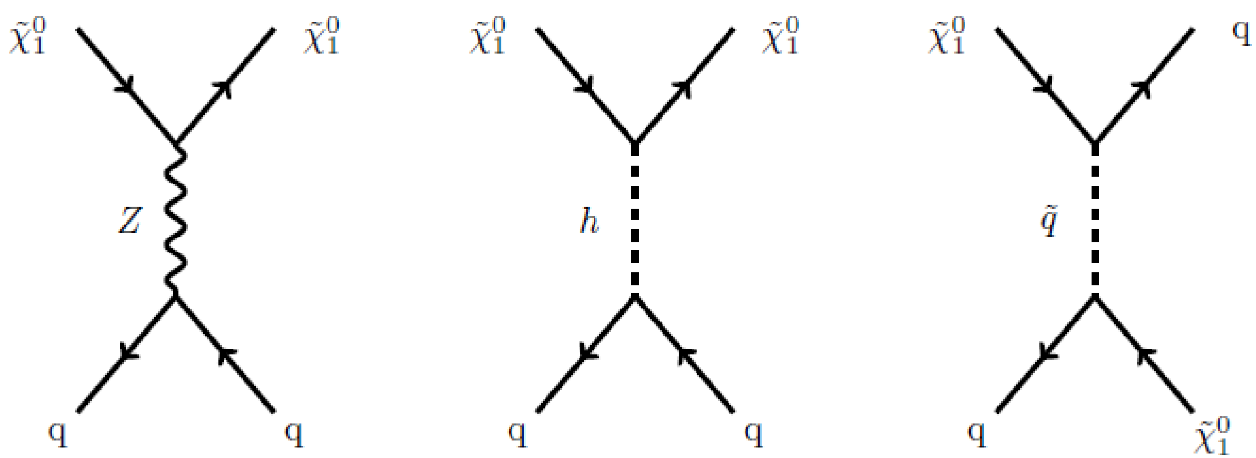
Neutralino Abundance and Detection

Relic abundance

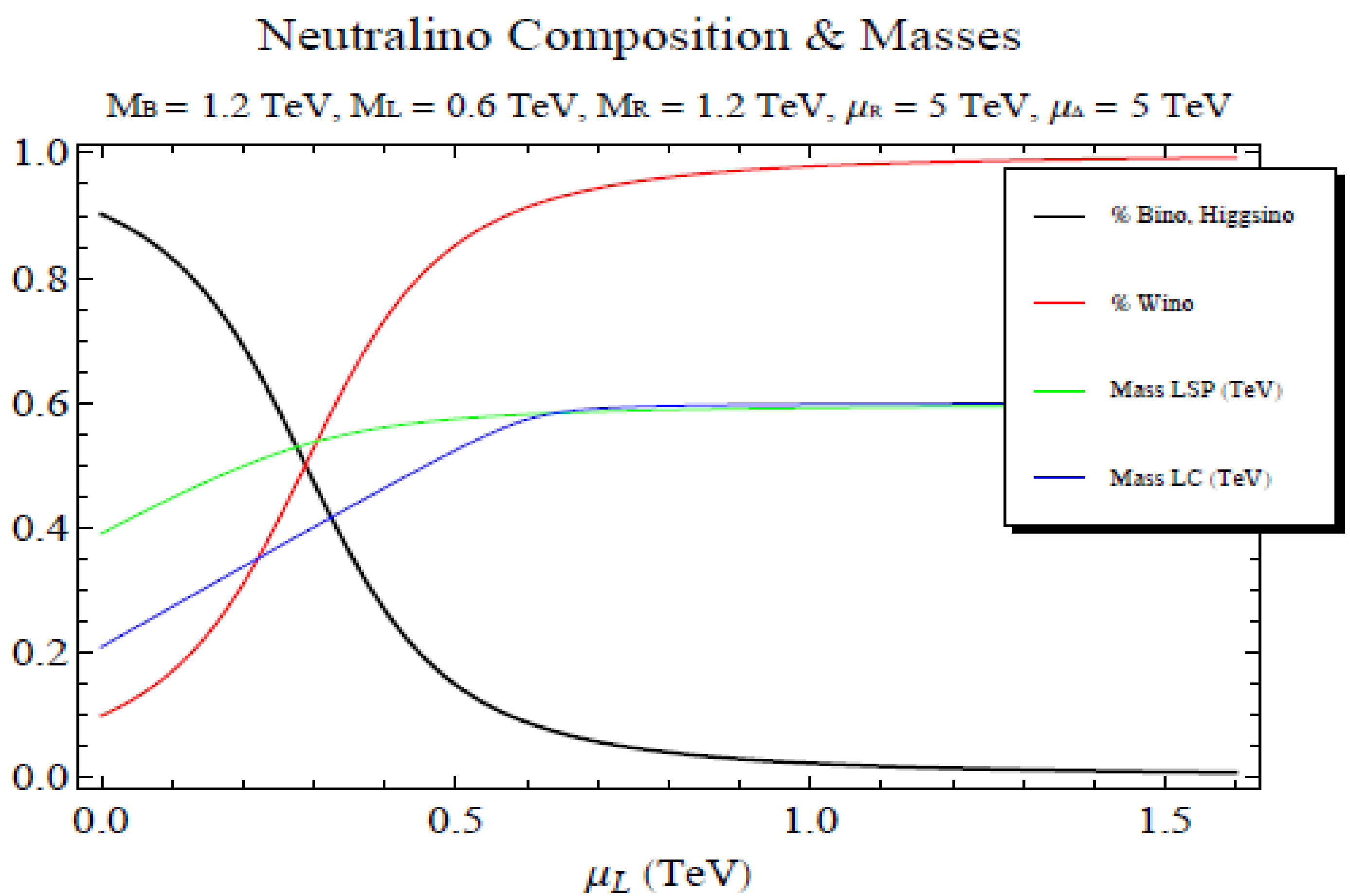
Initial state	Final state	channel (intermediate)
$\chi_i^0 \chi_j^0$	$H_1H_1,\ H_1H_2,\ H_2H_2,\ H_3H_3$	$t(\chi_k^0),\ u(\chi_k^0),\ s(H_{1,2})$
	$H_1H_3,\ H_2H_3$	$t(\chi_k^0),\ u(\chi_k^0),\ s(H_3),\ s(Z^0)$
	H^-H^+	$t(\chi_e^+),\ u(\chi_e^+),\ s(H_{1,2}),\ s(Z^0)$
	$Z^0H_1,\ Z^0H_2$	$t(\chi_k^0),\ u(\chi_k^0),\ s(H_3),\ s(Z^0)$
	Z^0H_3	$t(\chi_k^0),\ u(\chi_k^0),\ s(H_{1,2})$
	$W^-H^+,\ W^+H^-$	$t(\chi_e^+),\ u(\chi_e^+),\ s(H_{1,2,3})$
	Z^0Z^0	$t(\chi_k^0),\ u(\chi_k^0),\ s(H_{1,2})$
	W^-W^+	$t(\chi_e^+),\ u(\chi_e^+),\ s(H_{1,2}),\ s(Z^0)$
	$f\bar{f}$	$t(\tilde{f}_{L,R}),\ u(\tilde{f}_{L,R}),\ s(H_{1,2,3}),\ s(Z^0)$

J. Edsjo and P. Gondolo, Phys. Rev. D **56**, 1879 (1997) [hep-ph/9704361]

Direct detection



MSSM Co-annihilation

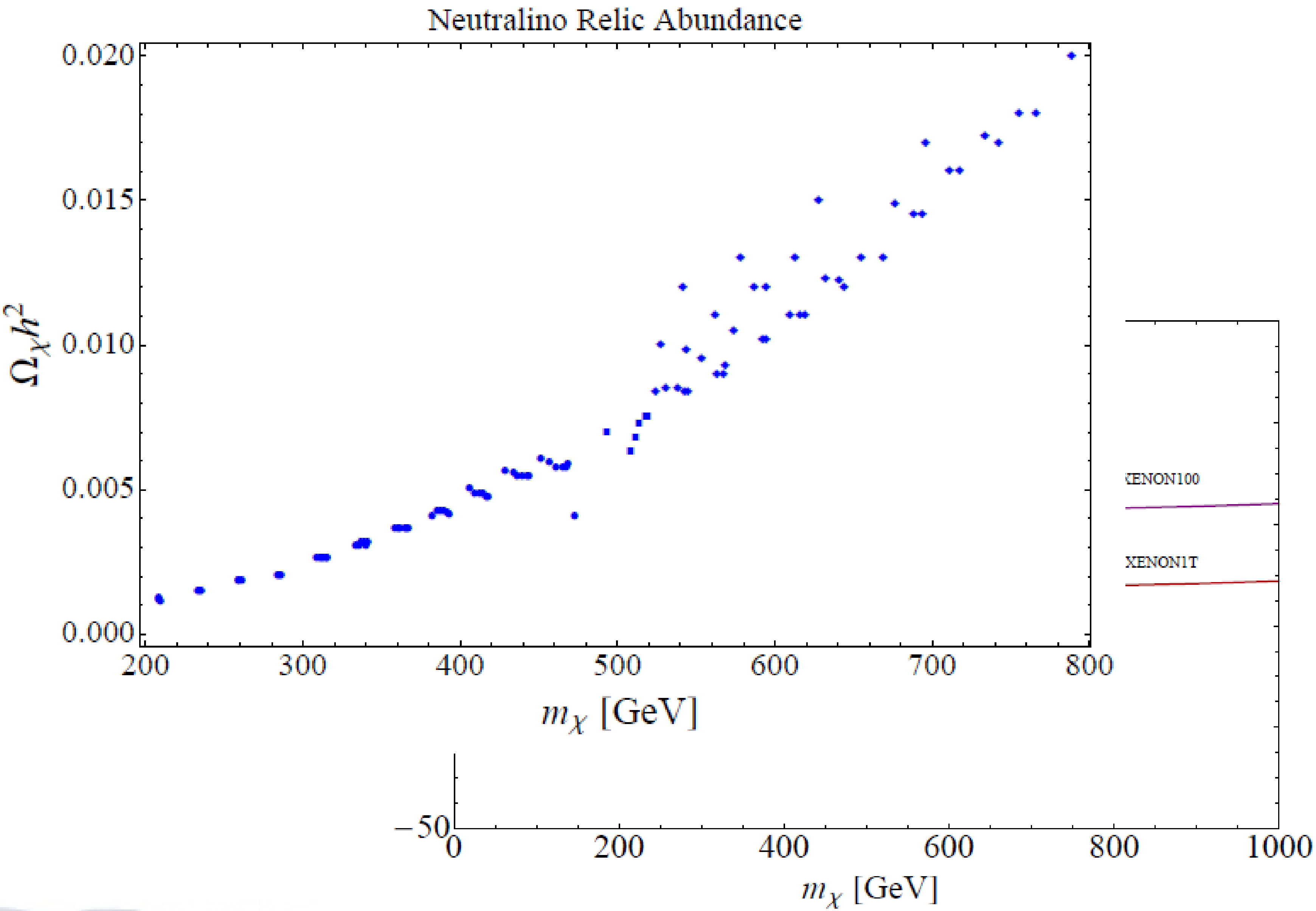


MSSM Co-annihilation

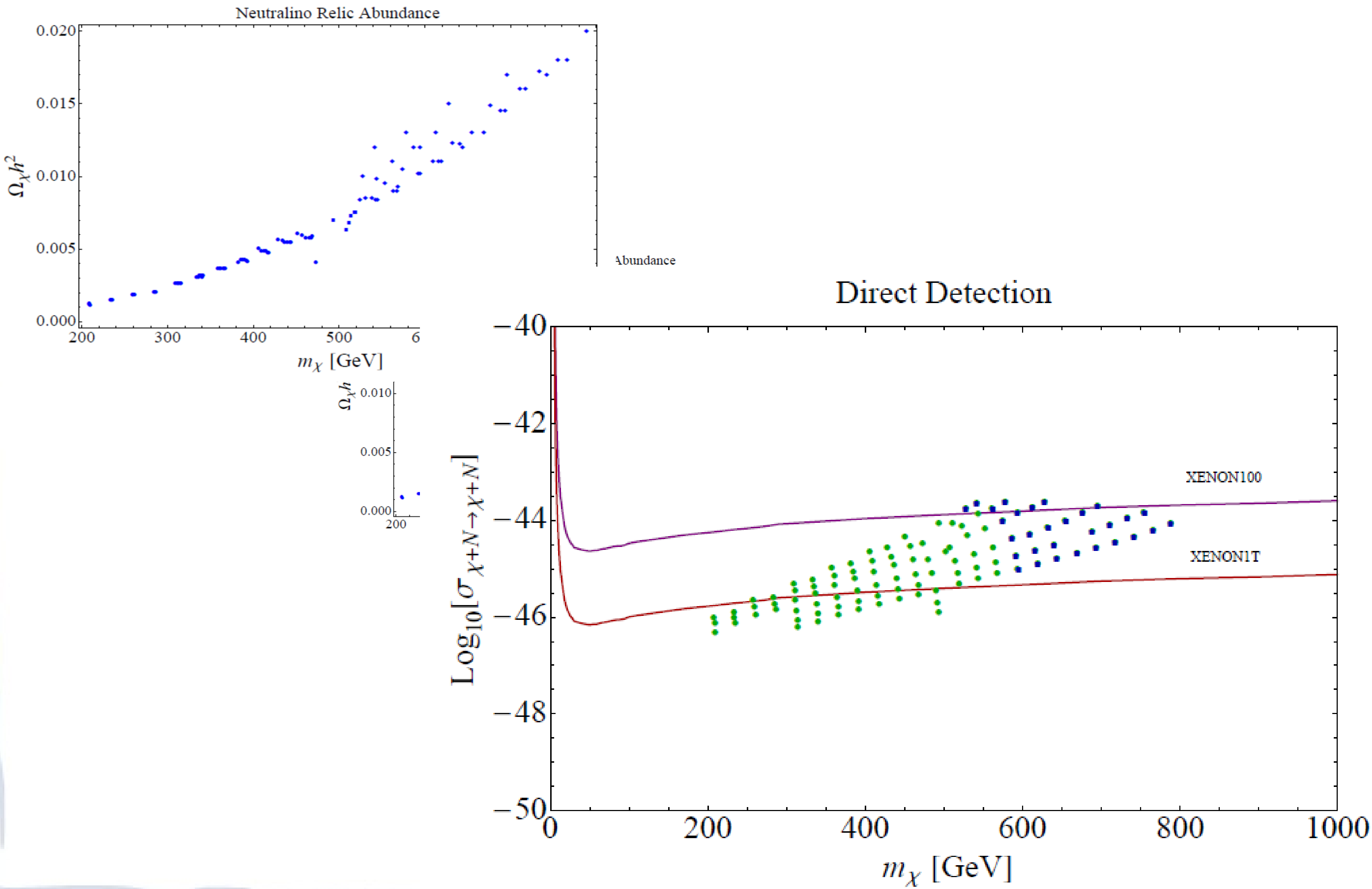
1.0 0.8 0.6 0.4 0.2 0.0

$\chi_c^+\chi_i^0$	H^+H_1, H^+H_2	$t(\chi_k^0)$, $u(\chi_e^+)$, $s(H^+)$, $s(W^+)$
	H^+H_3	$t(\chi_k^0)$, $u(\chi_e^+)$, $s(W^+)$
	W^+H_1, W^+H_2	$t(\chi_k^0)$, $u(\chi_e^+)$, $s(H^+)$, $s(W^+)$
	W^+H_3	$t(\chi_k^0)$, $u(\chi_e^+)$, $s(H^+)$
	H^+Z^0	$t(\chi_k^0)$, $u(\chi_e^+)$, $s(H^+)$
	γH^+	$t(\chi_c^+)$, $s(H^+)$
	W^+Z^0	$t(\chi_k^0)$, $u(\chi_e^+)$, $s(W^+)$
	γW^+	$t(\chi_c^+)$, $s(W^+)$
	$u\bar{d}$	$t(\tilde{d}_{L,R})$, $u(\tilde{u}_{L,R})$, $s(H^+)$, $s(W^+)$
	$\nu\bar{\ell}$	$t(\tilde{\ell}_{L,R})$, $u(\tilde{\nu}_L)$, $s(H^+)$, $s(W^+)$
$\chi_c^+\chi_d^-$	H_1H_1, H_1H_2, H_2H_2, H_3H_3	$t(\chi_e^+)$, $u(\chi_e^+)$, $s(H_{1,2})$
	H_1H_3, H_2H_3	$t(\chi_e^+)$, $u(\chi_e^+)$, $s(H_3)$, $s(Z^0)$
	H^+H^-	$t(\chi_k^0)$, $s(H_{1,2})$, $s(Z^0,\gamma)$
	Z^0H_1, Z^0H_2	$t(\chi_e^+)$, $u(\chi_e^+)$, $s(H_3)$, $s(Z^0)$
	Z^0H_3	$t(\chi_e^+)$, $u(\chi_e^+)$, $s(H_{1,2})$
	H^+W^-, W^+H^-	$t(\chi_e^+)$, $s(H_{1,2,3})$
	Z^0Z^0	$t(\chi_e^+)$, $u(\chi_e^+)$, $s(H_{1,2})$
	W^+W^-	$t(\chi_k^0)$, $s(H_{1,2})$, $s(Z^0,\gamma)$
	$\gamma\gamma$ (only for $c=d$)	$t(\chi_c^+)$, $u(\chi_c^+)$
	$Z^0\gamma$	$t(\chi_d^+)$, $u(\chi_c^+)$
	$u\bar{u}$	$t(\tilde{d}_{L,R})$, $s(H_{1,2,3})$, $s(Z^0,\gamma)$
	$\nu\bar{\nu}$	$t(\tilde{\ell}_{L,R})$, $s(Z^0)$
	dd	$t(\tilde{u}_{L,R})$, $s(H_{1,2,3})$, $s(Z^0,\gamma)$
	$\ell\ell$	$t(\tilde{\nu}_L)$, $s(H_{1,2,3})$, $s(Z^0,\gamma)$
$\chi_c^+\chi_d^+$	H^+H^+	$t(\chi_k^0)$, $u(\chi_k^0)$
	H^+W^+	$t(\chi_k^0)$, $u(\chi_k^0)$
	W^+W^+	$t(\chi_k^0)$, $u(\chi_k^0)$

Wino Neutralino Abundance and Detection



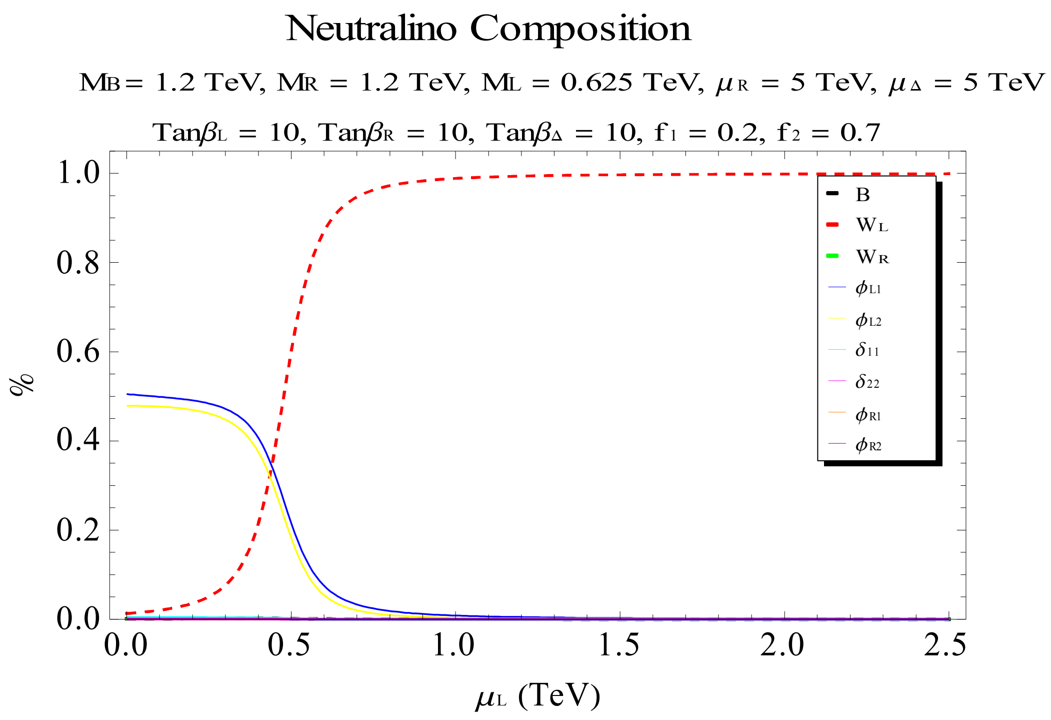
Wino Neutralino Abundance and Detection



Example

$$M_1 = 1200 \text{ GeV} \quad \mu = 1000 \text{ GeV}$$
$$M_2 = 625 \text{ GeV} \quad \tan\beta = 10$$

$$\chi_1^0 = 0.009\tilde{B} - 0.986\tilde{W} + 0.138\tilde{H}_1 - 0.096\tilde{H}_2$$



$$\chi_1^0 = 0.0067\tilde{B} - 0.9902\tilde{W}_L + 0.1152\tilde{\phi}_{L1} - 0.0784\tilde{\phi}_{L2}$$
$$-0.0020\tilde{W}_R - 0.0002\tilde{\delta}_{11} - 0.0011\tilde{\delta}_{22} + 0.0022\tilde{\phi}_{R1} - 0.0005\tilde{\phi}_{R2}$$

Example II

Contribution	Initial	final
9%	$\chi_1^0\chi_1^0$	W^+W^-
9%	$\chi_1^0\chi_1^+$	$\overline{s}c$
9%	$\chi_1^0\chi_1^+$	$u\overline{d}$
9%	$\chi_1^+\chi_1^+$	W^+W^+
8%	$\chi_1^0\chi_1^+$	$t\overline{b}$
7%	$\chi_1^0\chi_1^+$	ZW^+
5%	$\chi_1^+\chi_1^-$	ZZ
5%	$\chi_1^+\chi_1^-$	W^+W^-
3%	$\chi_1^0\chi_1^+$	$\mu\nu_\mu$
3%	$\chi_1^0\chi_1^+$	$\overline{e}\nu_e$
3%	$\chi_1^0\chi_1^+$	nlL
3%	$\chi_1^+\chi_1^-$	AZ
2%	$\chi_1^+\chi_1^-$	$c\overline{c}$
2%	$\chi_1^+\chi_1^-$	$u\overline{u}$
2%	$\chi_1^+\chi_1^-$	$s\overline{s}$
2%	$\chi_1^+\chi_1^-$	$d\overline{d}$
2%	$\chi_1^0\chi_1^+$	AW^+
2%	$\chi_1^+\chi_1^-$	$t\overline{t}$
2%	$\chi_1^+\chi_1^-$	$b\overline{b}$

$$\Omega_\chi h^2 = 0.012$$

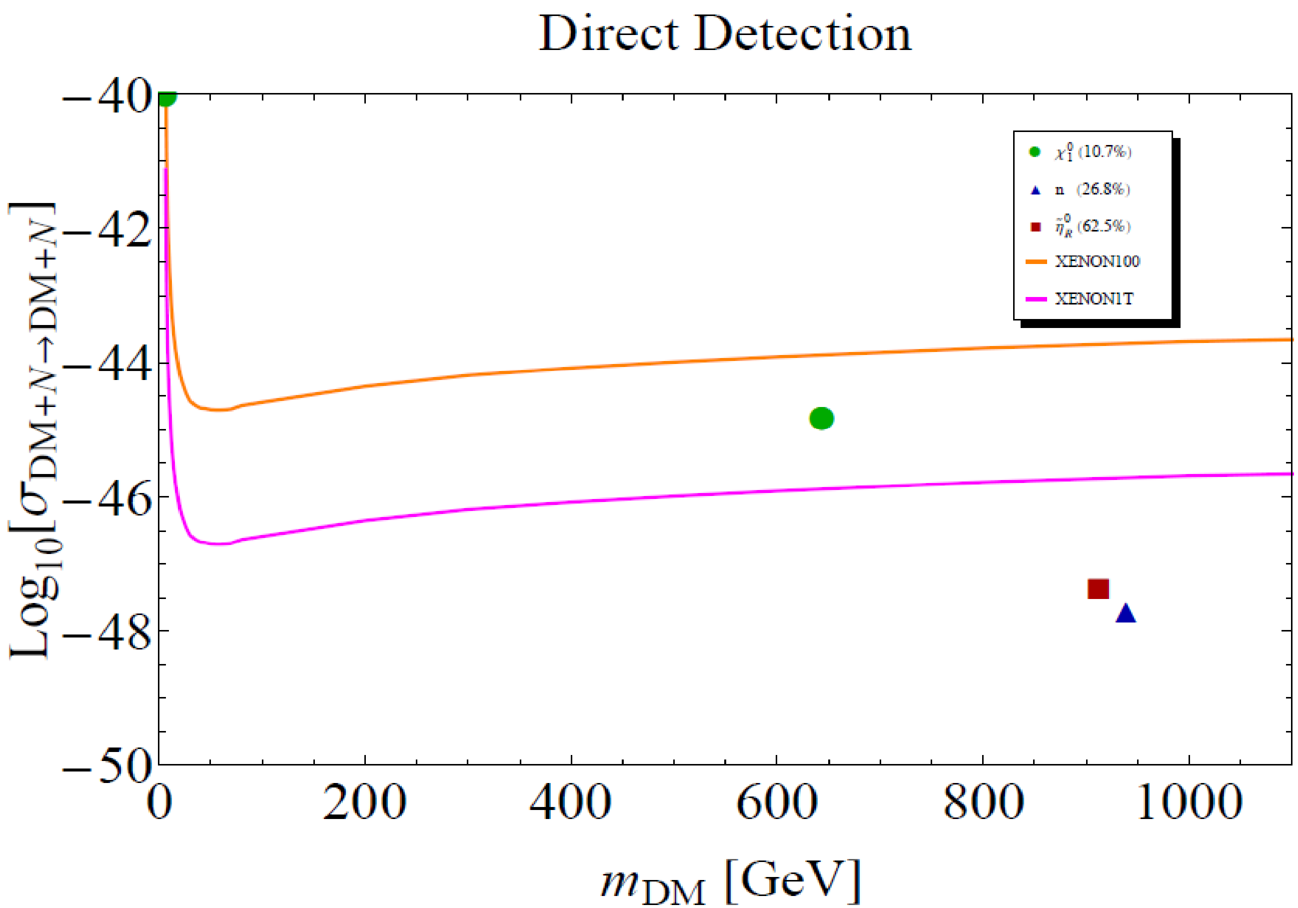
Example III

$$\Omega_{tot} h^2 = 0.112$$

$$\Omega_\chi h^2 = 0.012$$

$$\Omega_\eta h^2 = 0.03$$

$$\Omega_n h^2 = 0.07$$



Conclusions/more work

- LHC signatures
- Coupled Boltzmann equation
- Messenger sector (Anomaly mediated)
- Scan over parameter space (Pheno)
- Alternate DM: mix neutralino, Left Higgsino...

Conclusions/more work

- LHC signatures
- Coupled Boltzmann equation
- Messenger sector (Anomaly mediated)
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- Alternate DM: mix neutralino, Left Higgsino...

- SUSY $\neq$ MSSM
- Why 1 DM component?
- Why Seesaw?

Thank You!

Lagrangian

$$\mathcal{L} = \mathcal{L}_{gauge-scalar} + \mathcal{L}_{gauge-fermion} + \mathcal{L}_{scalar-fermion} + \mathcal{L}_{gaugino-fermion-scalar}$$
$$+\mathcal{L}_{gaugino-gauge} + \mathcal{L}_{gauge} + +V(\phi,\phi^*) + \mathcal{L}_{soft}$$

$$\mathcal{L}_{gauge-scalar} = |D_\mu \phi|^2$$

$$\mathcal{L}_{gauge-fermion} = \imath\overline{\psi}\sigma^\mu D_\mu \psi$$

$$\mathcal{L}_{gaugino-fermion-scalar} = \imath\sqrt{2} g \phi_i^* \lambda_a \psi_i$$

$$\mathcal{L}_{scalar-fermion} = \frac{\partial^2 W}{\partial\phi_i \partial\phi_j}\Psi_i \Psi_j + h.c$$

$$\mathcal{L}_{gaugino-gauge} = \imath\overline{\lambda}^a \sigma^\mu D_\mu \lambda_a$$

$$\mathcal{L}_{gauge} = F^a_{\mu\nu} F^{\mu\nu a}$$

$$V(\phi,\phi^*) = W_i^* W^i + \frac{1}{2}\sum_a D^a D^a = \sum_i |\frac{\partial W}{\partial \Phi_i}|^2 + \frac{1}{2}\sum_a g_a^2 (\phi^* T^a \phi)^2$$

Soft Breaking Terms

$$
\begin{aligned}
V_{1soft} = \quad & -m_{L1}^2(\overline{\phi_{L1}^0}\phi_{L1}^0 + \phi_{L1}^-\phi_{L1}^+) - m_{L2}^2(\overline{\phi_{L2}^0}\phi_{L2}^0 + \phi_{L2}^-\phi_{L2}^+) - m_{R1}^2(\overline{\phi_{R1}^0}\phi_{R1}^0 + \phi_{R1}^-\phi_{R1}^+) \\
& -m_{R2}^2(\overline{\phi_{R2}^0}\phi_{R2}^0 + \phi_{R2}^-\phi_{R2}^+) - m_{\eta_{L1}}^2(\overline{\eta_{L1}^0}\eta_{L1}^0 + \eta_{L1}^-\eta_{L1}^+) - m_{\eta_{L2}}^2(\overline{\eta_{L2}^0}\eta_{L2}^0 + \eta_{L2}^-\eta_{L2}^+) \\
& -m_{\eta_{R1}}^2(\overline{\eta_{R1}^0}\eta_{R1}^0 + \eta_{R1}^-\eta_{R1}^+) - m_{\eta_{R2}}^2(\overline{\eta_{R2}^0}\eta_{R2}^0 + \eta_{R2}^-\eta_{R2}^+) - m_{s1}^2 s_1^- s_1^+ - m_{s2}^2 s_2^- s_2^+ - m_{s3}^2\overline{s_3^0}s_3^0 \\
& -m_{\Delta 1}^2(\overline{\delta_{11}^0}\delta_{11}^0 + \delta_{11}^+\delta_{11}^- + \overline{\delta_{12}^0}\delta_{12}^0 + \delta_{12}^+\delta_{12}^-) - m_{\Delta 2}^2(\overline{\delta_{21}^0}\delta_{21}^0 + \delta_{21}^+\delta_{21}^- + \overline{\delta_{22}^0}\delta_{22}^0 + \delta_{22}^+\delta_{22}^-) \\
& -B_L(\phi_{L1}^0\phi_{L2}^0 - \phi_{L1}^-\phi_{L2}^+) - B_R(\phi_{R1}^0\phi_{R2}^0 - \phi_{R1}^-\phi_{R2}^+) - B_\Delta(\delta_{11}^0\delta_{22}^0 - \delta_{11}^-\delta_{22}^+ - \delta_{12}^+\delta_{21}^- + \delta_{12}^0\delta_{21}^0) \\
& -B_{\eta_L}(\eta_{L1}^0\eta_{L2}^0 - \eta_{L1}^-\eta_{L2}^+) - B_{\eta_R}(\eta_{R1}^0\eta_{R2}^0 - \eta_{R1}^-\eta_{R2}^+) - B_{s12}s_1^- s_2^+ - B_{s3}s_3^0 s_3^0 \\
& +A_1(\phi_{L1}^-\delta_{21}^0\phi_{R2}^+ - \phi_{L1}^0\delta_{21}^-\phi_{R2}^+ - \phi_{L1}^-\delta_{22}^+\phi_{R2}^0 + \phi_{L1}^0\delta_{22}^0\phi_{R2}^0) \\
& +A_2(\phi_{L2}^0\delta_{11}^0\phi_{R1}^0 - \phi_{L2}^+\delta_{11}^-\phi_{R1}^0 - \phi_{L2}^0\delta_{12}^+\phi_{R1}^- + \phi_{L2}^+\delta_{12}^0\phi_{R1}^-) \\
& +A_3(\eta_{L1}^-\delta_{11}^0\eta_{R2}^+ - \eta_{L1}^0\delta_{11}^-\eta_{R2}^+ - \eta_{L1}^-\delta_{12}^+\eta_{R2}^0 + \eta_{L1}^0\delta_{12}^0\eta_{R2}^0) \\
& +A_4(\eta_{L2}^0\delta_{21}^0\eta_{R1}^0 - \eta_{L2}^+\delta_{21}^-\eta_{R1}^0 - \eta_{L2}^0\delta_{22}^+\eta_{R1}^- + \eta_{L2}^+\delta_{22}^0\eta_{R1}^-) \\
& +A_5(\phi_{L1}^0\eta_{L1}^-s_2^+ - \phi_{L1}^-\eta_{L1}^0 s_2^+) + A_6(\phi_{R1}^0\eta_{R1}^- s_2^+ - \phi_{R1}^-\eta_{R1}^0 s_2^+) \\
& +A_7(\phi_{L2}^+\eta_{L2}^0 s_1^- - \phi_{L2}^0\eta_{L2}^+ s_1^-) + A_8(\phi_{R2}^+\eta_{R2}^0 s_1^- - \phi_{R2}^0\eta_{R2}^+ s_1^-) \\
& +A_9(\phi_{L1}^0\eta_{L2}^0 s_3^0 - \phi_{L1}^-\eta_{L2}^+ s_3^0) + A_{10}(\phi_{L2}^+\eta_{L1}^- s_3^0 - \phi_{L2}^+\eta_{L1}^- s_3^0) \\
& +m_\psi^2(\tilde{e}\tilde{e} + \tilde{\nu}\tilde{\nu}) + m_{\psi^c}^2(\tilde{e^c}\tilde{e^c} + \tilde{n^c}\tilde{n^c}) + m_N^2\tilde{N}\tilde{N} + m_n^2\tilde{n}\tilde{n} \\
& +m_Q^2(\tilde{u}\tilde{u} + \tilde{d}\tilde{d}) + m_{\psi^c}^2(\tilde{h^c}\tilde{h^c} + \tilde{u^c}\tilde{u^c}) + m_{d^c}^2\tilde{d^c}\tilde{d^c} + m_h^2\tilde{h}\tilde{h} \\
& +A_e(\tilde{e}\delta_{11}^0\tilde{e^c} - \tilde{\nu}\delta_{11}^-\tilde{e^c} - \tilde{e}\delta_{12}^+\tilde{n^c} + \tilde{\nu}\delta_{12}^0\tilde{n^c}) + A_u(\tilde{d}\delta_{21}^0\tilde{h^c} - \tilde{u}\delta_{21}^-\tilde{h^c} - \tilde{d}\delta_{22}^+\tilde{u^c} + \tilde{u}\delta_{22}^0\tilde{u^c}) \\
& +A_d(\tilde{u}\phi_{L1}^-\tilde{d^c} - \tilde{d}\phi_{L1}^0\tilde{d^c}) + A_n(\tilde{n}\phi_{R1}^-\tilde{e^c} - \tilde{n}\phi_{R1}^0\tilde{n^c}) + A_h(\tilde{h}\phi_{R2}^0\tilde{h^c} - \tilde{h}\phi_{R2}^+\tilde{u^c}) \\
& +A_{N1}(\tilde{N}\eta_{L2}^0\tilde{\nu} - \tilde{N}\eta_{L2}^+\tilde{e}) + A_{N2}(\tilde{N}\eta_{R1}^-\tilde{e^c} - \tilde{N}\eta_{R1}^0\tilde{n^c})
\end{aligned}
$$

MSSM Bino

$M_B \approx M_R \equiv M_Y$

$$M'_{heavy} = \begin{pmatrix} \frac{g_1^2 M_B + g_R^2 M_R}{g_1^2+g_R^2} & \frac{g_1 g_R (M_B - M_R)}{g_1^2+g_R^2} & 0 & 0 \\ \frac{g_1 g_R (M_B - M_R)}{g_1^2+g_R^2} & \frac{g_R^2 M_B + g_1^2 M_R}{g_1^2+g_R^2} & -\frac{\sqrt{g_1^2+g_R^2}}{\sqrt{2}} v_{R1} & \frac{\sqrt{g_1^2+g_R^2}}{\sqrt{2}} v_{R2} \\ 0 & -\frac{\sqrt{g_1^2+g_R^2}}{\sqrt{2}} v_{R1} & 0 & -\mu_R \\ 0 & \frac{\sqrt{g_1^2+g_R^2}}{\sqrt{2}} v_{R2} & -\mu_R & 0 \end{pmatrix}$$

$$\{\tilde{B}, \tilde{W}_R^0, \tilde{\phi}_{R1}^0, \tilde{\phi}_{R2}^0\} \to \{\tilde{B}_Y, \tilde{W}_2^0, \tilde{\phi}_{R1}^0, \tilde{\phi}_{R2}^0\}$$

$$\begin{pmatrix} \tilde{B}_Y \\ \tilde{W}_2 \end{pmatrix} = \frac{1}{\sqrt{g_1^2 + g_R^2}} \begin{pmatrix} g_R & g_1 \\ g_1 & -g_R \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}_R \end{pmatrix}$$

MSSM Lightest Neutralino

$$\begin{pmatrix} M_B & 0 & -\frac{g_1 v_{L1}}{\sqrt{2}} & \frac{g_1 v_{L2}}{\sqrt{2}} \\ 0 & M_L & \frac{g_L v_{L1}}{\sqrt{2}} & -\frac{g_L v_{L2}}{\sqrt{2}} \\ -\frac{g_1 v_{L1}}{\sqrt{2}} & \frac{g_L v_{L1}}{\sqrt{2}} & 0 & -\mu_L \\ \frac{g_1 v_{L2}}{\sqrt{2}} & -\frac{g_L v_{L2}}{\sqrt{2}} & -\mu_L & 0 \end{pmatrix}$$

$$v_{L1} = R * c_{\beta L} * v_{SM} = \left(\frac{\sqrt{2}}{g_L}\right) R * M_Z * c_{\beta L} * c_W$$

$$v_{L2} = R * s_{\beta L} * v_{SM} = \left(\frac{\sqrt{2}}{g_L}\right) R * M_Z * s_{\beta L} * c_W$$

$$R = v_L / v_{SM} = 0.837$$

$$M_{MSSM} = \begin{pmatrix} M_Y & 0 & -M_Z * s_W * c_{\beta L} & M_Z * s_W * s_{\beta L} \\ 0 & \frac{M_L}{R^2} & M_Z * c_W * c_{\beta L} & -M_Z * c_W * s_{\beta L} \\ -M_Z * s_W * c_{\beta L} & M_Z * c_W * c_{\beta L} & 0 & -\mu_L \\ M_Z * s_W * s_{\beta L} & -M_Z * c_W * s_{\beta L} & -\mu_L & 0 \end{pmatrix}$$

$$M_{MSSM} = \begin{pmatrix} M_1 & 0 & -M_Z * s_W * c_\beta & M_Z * s_W * s_\beta \\ 0 & M_2 & M_Z * c_W * c_\beta & -M_Z * c_W * s_\beta \\ -M_Z * s_W * c_\beta & M_Z * c_W * c_\beta & 0 & -\mu \\ M_Z * s_W * s_\beta & -M_Z * c_W * s_\beta & -\mu & 0 \end{pmatrix}$$