Lightest Neutralino as a Dark Matter Candidate

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Más Allá del Modelo Estándar y Astropartículas

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Objetives

- Explore 4 cases of the relation between M_1, M_2 and other free parameters such as μ and tanβ, considering consistencies with HiggsBounds & HiggsSignals in MicrOMEGAs.
- Calculate the masses of the first neutralinos (LSP) and charginos exploring the dependence of free parameters.
- Explore the neutralino couplings to Z^0 boson and analyze the σ_{ann} .

Evidence for DM

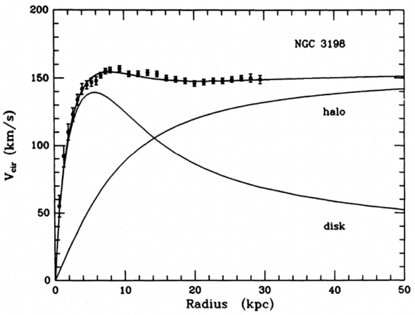


Figure: Rotation curve of NGC 3198 galaxy.
[Rubin, 1983 & Van Albada et al., 1985]

Clusters & Large Structures

Figure: CL0024+1654 cluster [ESA Hubble, 1996]

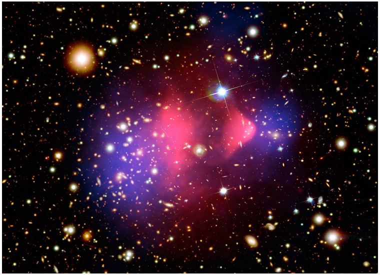


Figure: Bullet cluster Chandra Observatory [ESA Hubble, 2012]

Cosmological Scale

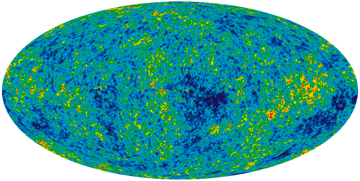


Figure: Cosmic Microwave Background [Penzias and Wilson, 1965 Hinshaw, 2013]

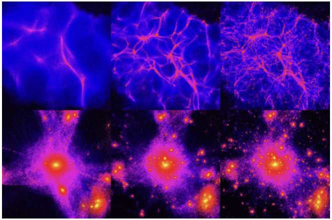


Figure: CDM simulation [University of Zurich]

Standard Model

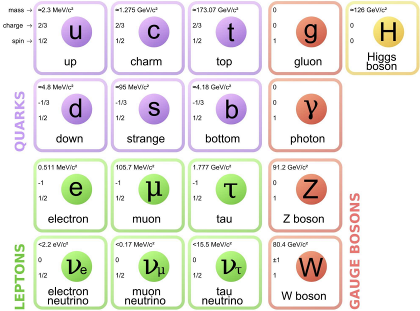


Figure: Standard Model of Particle Physics

Higgs Mechanism

Scalar complex doublet:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \ , \tag{1}$$

such that

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \ . \tag{2}$$

where

$$\langle |\Phi| \rangle_0 = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \Rightarrow \quad v = \sqrt{\frac{-\mu^2}{\lambda}} = 246.66 \text{ GeV} \ . \tag{3}$$

Supersymmetry

- New hidden symmetry between bosons and fermions.
- Single particle states are contained in Supermultiplets with equal DOF:

$$n_B = n_F \ . \tag{4}$$

- Chiral & Vector supermultiplets.
- It Doubles (at least) number of particles.

SUSY Higgs

- Higgs must reside in a Chiral supermultiplet.
- In SM exists "miraculously" gauge anomaly cancellation including:
$$\mathrm{Tr}[T_3^2 Y] = \mathrm{Tr}[Y^3] = 0\ . \tag{5}$$
- Higgs superpartner $Y = +1/2$ or $Y = -1/2$.
- Can be avoided introducing two Higgs Supermultiplets.

SUSY Higgs

$$H_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} , \qquad \text{and} \qquad H_d = \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix} , \tag{6}$$

- where the conjugate of H_u plays the role of the SM Higgs field Langacker, 2017.
- Both fields acquire VEVs

$$v_u = \langle h_u^0 \rangle \qquad \text{and} \qquad v_d = \langle h_d^0 \rangle , \tag{7}$$

- Introducing

$$\tan\beta = \frac{v_u}{v_d} . \tag{8}$$

Higgs Sector

After EWSB, five Higgs states remaining:

- h (CP-even)
- H (CP-even)
- $H^{\pm}$ (Charged)
- A (Pseudoscalar)

where

$$M_A^2 = M_{\mathbf{H_u}}^2 + M_{\mathbf{H_d}}^2 + 2|\mu|^2 = \frac{2b}{\sin(2\beta)} ,$$

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

$$M_{h,H}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 + 4M_Z^2 M_A^2 \sin^2(2\beta)}\right) . \quad (9)$$

Soft SUSY breaking

$$\begin{aligned}\mathcal{L}_{\text{soft}}^{\text{MSSM}} =& -\frac{1}{2}\left(M_1\tilde{B}\tilde{B} + M_2\tilde{W}\tilde{W} + M_3\tilde{g}\tilde{g} + c.c.\right)\\ & -\left(\tilde{\bar{u}}\mathbf{A_u}\tilde{Q}\mathbf{H_u} - \tilde{\bar{d}}\mathbf{A_d}\tilde{Q}\mathbf{H_d} - \tilde{\bar{e}}\mathbf{A_e}\tilde{L}\mathbf{H_d} + c.c.\right)\\ & - \tilde{Q}^\dagger\mathbf{m_Q^2}\tilde{Q} - \tilde{L}^\dagger\mathbf{m_L^2}\tilde{L} - \tilde{\bar{u}}\mathbf{m_{\bar{u}}^2}\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\mathbf{m_{\bar{d}}^2}\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\mathbf{m_{\bar{e}}^2}\tilde{\bar{e}}^\dagger\\ & - M_{\mathbf{H_u}}^2\mathbf{H_u^*}\mathbf{H_u} - M_{\mathbf{H_d}}^2\mathbf{H_d^*}\mathbf{H_d} - (\mu b\mathbf{H_u}\mathbf{H_d} + c.c.)\ .\end{aligned} \tag{10}$$

Neutralinos

- MSSM candidate for DM called neutralino.
- Mixing of $(\tilde{h}_u^0, \tilde{h}_d^0)$ and $(\tilde{B}^0, \tilde{W}^0)$.
- In interaction basis, its mass matrix is given by:

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta \\ * & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta \\ * & * & 0 & -\mu \\ * & * & * & 0 \end{pmatrix}. \tag{11}$$

- Diagonalized by

$$\Theta_N \mathcal{M}_N \Theta_N^T = \mathrm{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}) \tag{12}$$

Charginos

- Mixing of $(\tilde{h}_u^+, \tilde{h}_d^-)$ and $(\tilde{W}^+, \tilde{W}^-)$.
- In interaction basis, its mass matrix is given by:

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2}\, M_W \cos\beta \\ \sqrt{2}\, M_W \sin\beta & \mu \end{pmatrix} \tag{13}$$

- Diagonalized by

$$\Theta_C \mathcal{M}_C \Theta_C^T = \mathrm{diag}(m_{\tilde{C}_1}, m_{\tilde{C}_2}) \tag{14}$$

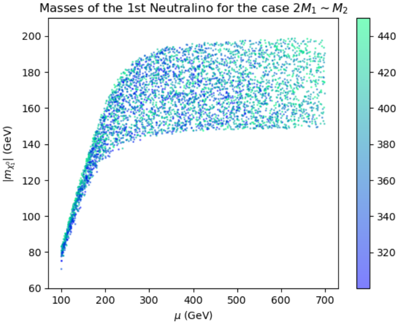
[Kuroda, 2005]

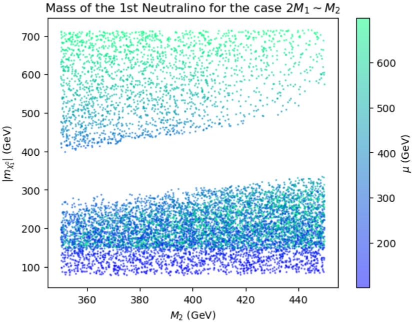
Results

- $2M_1 \sim M_2$: Mostly bino-like neutralino
- $M_1 \sim M_2$: Gaugino/higgsino-like neutralino
- $M_1 \ll M_2$: Purely bino-like neutrlino
- $M_1 \gg M_2$: Purely wino-like neutralino

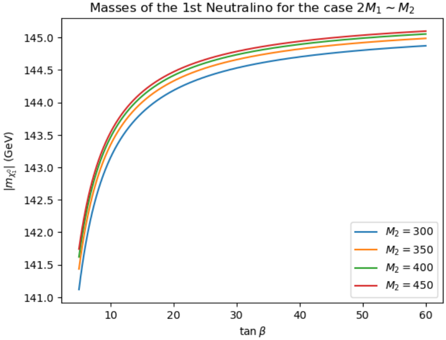
[Djouadi et al., 2022]

$2M_1 \sim M_2$


Masses of the 1st Neutralino for the case $2M_1 \sim M_2$
$|m_{\chi_1^0}|$ (GeV)
μ (GeV)
M_2 (GeV)
200
180
160
140
120
100
80
60
100
200
300
400
500
600
700
440
420
400
380
360
340
320

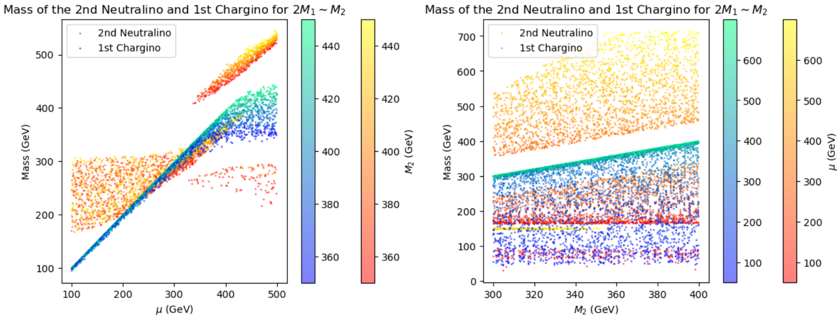

Mass of the 1st Neutralino for the case $2M_1 \sim M_2$
$|m_{\chi_1^0}|$ (GeV)
M_2 (GeV)
μ (GeV)
700
600
500
400
300
200
100
360
380
400
420
440
600
500
400
300
200

$2M_1 \sim M_2$

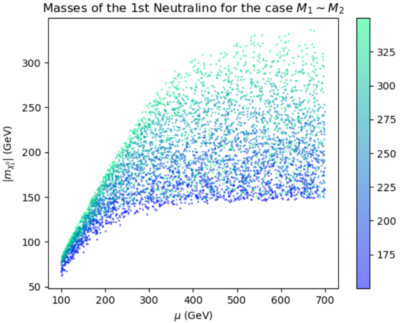


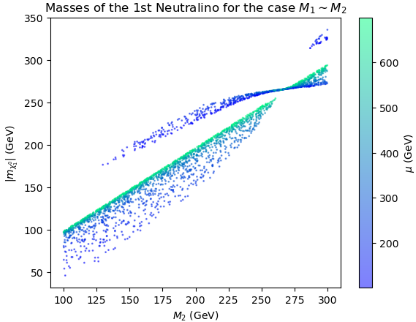
$$\tilde{\chi}_1^0 \approx \; 0.975\ \tilde{B}^0 - 0.037\ \tilde{W}^0 + 0.196\ \tilde{h}_d^0 - 0.098\ \tilde{h}_u^0\ , \qquad (15)$$

$2M_1 \sim M_2$

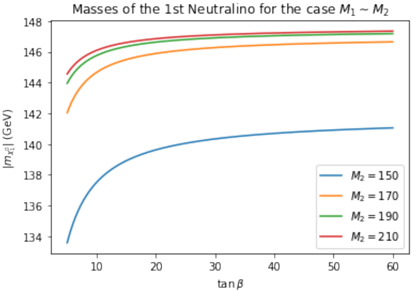

Mass of the 2nd Neutralino and 1st Chargino for $2M_1 \sim M_2$
2nd Neutralino
1st Chargino
Mass (GeV)
μ (GeV)
M_2 (GeV)
Mass of the 2nd Neutralino and 1st Chargino for $2M_1 \sim M_2$
2nd Neutralino
1st Chargino
Mass (GeV)
M_2 (GeV)
μ (GeV)

$M_1 \sim M_2$


Masses of the 1st Neutralino for the case $M_1 \sim M_2$
$|m_{\chi_1^0}|$ (GeV)
μ (GeV)
M_2 (GeV)

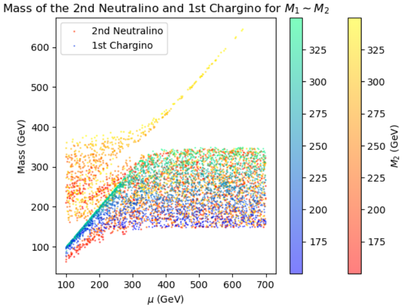

Masses of the 1st Neutralino for the case $M_1 \sim M_2$
$|m_{\chi_1^0}|$ (GeV)
M_2 (GeV)
μ (GeV)

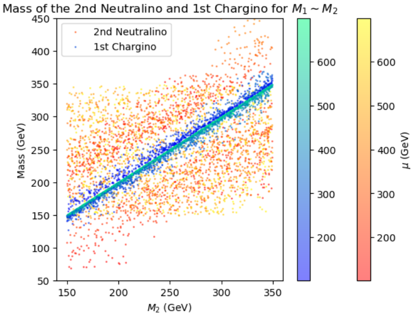
$M_1 \sim M_2$



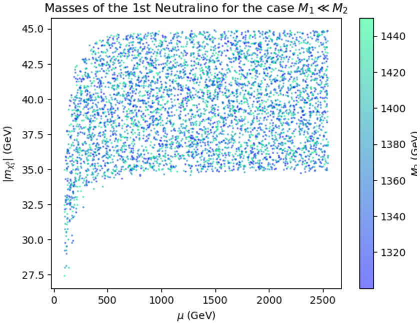
$$\tilde{\chi}_1^0 \approx 0.823\ \tilde{B}^0 - 0.514\ \tilde{W}^0 + 0.221\ \tilde{h}_d^0 - 0.097\ \tilde{h}_u^0\ , \tag{16}$$

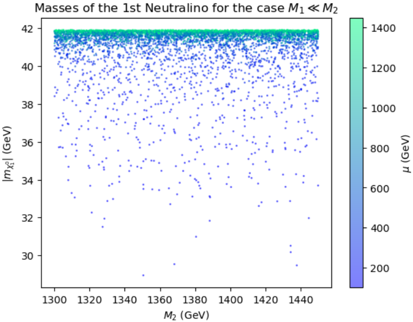
$M_1 \sim M_2$


Mass of the 2nd Neutralino and 1st Chargino for $M_1 \sim M_2$
2nd Neutralino
1st Chargino
Mass (GeV)
100
200
300
400
500
600
700
μ (GeV)
175
200
225
250
275
300
325
M_2 (GeV)

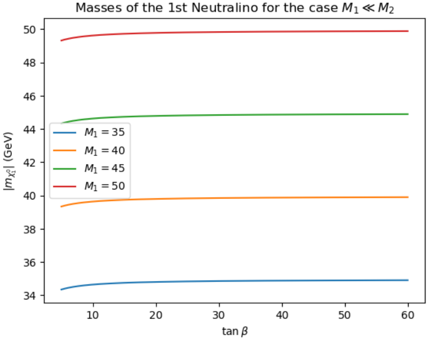

Mass of the 2nd Neutralino and 1st Chargino for $M_1 \sim M_2$
2nd Neutralino
1st Chargino
Mass (GeV)
50
100
150
200
250
300
350
400
450
M_2 (GeV)
500
600
μ (GeV)

$M_1 \ll M_2$


Masses of the 1st Neutralino for the case $M_1 \ll M_2$
$|m_{\chi_1^0}|$ (GeV)
μ (GeV)
0
500
1000
1500
2000
2500
27.5
30.0
32.5
35.0
37.5
40.0
42.5
45.0
1320
1340
1360
1380
1400
1420
1440

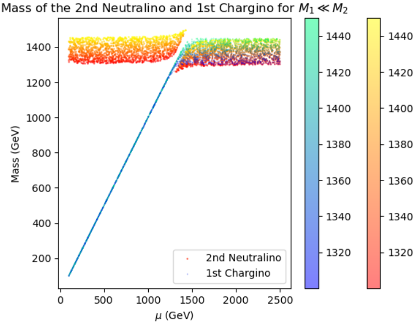

Masses of the 1st Neutralino for the case $M_1 \ll M_2$
$|m_{\chi_1^0}|$ (GeV)
M_2 (GeV)
μ (GeV)
1300
1320
1340
1360
1380
1400
1420
1440
30
32
34
36
38
40
42
200
400
600
800
1000
1200
1400

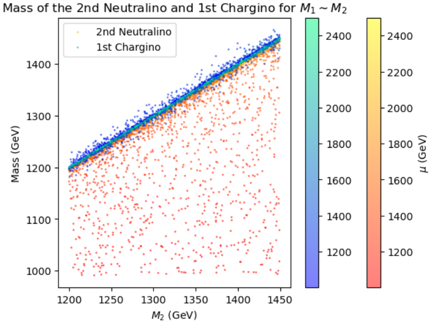
$M_1 \ll M_2$



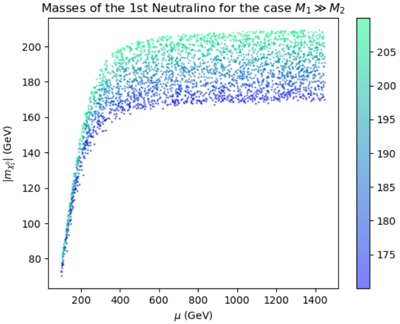
$$\tilde{\chi}_1^0 \approx 0.999\ \tilde{B}^0 - 0.000\ \tilde{W}^0 + 0.034\ \tilde{h}_d^0 - 0.002\ \tilde{h}_u^0\ . \qquad (17)$$

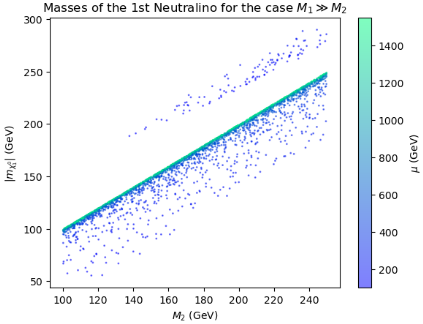
$M_1 \ll M_2$


Mass of the 2nd Neutralino and 1st Chargino for $M_1 \ll M_2$
Mass (GeV)
μ (GeV)
2nd Neutralino
1st Chargino

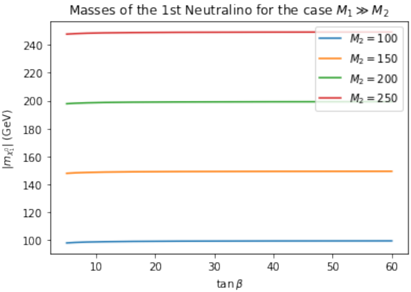

Mass of the 2nd Neutralino and 1st Chargino for $M_1 \sim M_2$
Mass (GeV)
M_2 (GeV)
μ (GeV)
2nd Neutralino
1st Chargino

$M_1 \gg M_2$


Masses of the 1st Neutralino for the case $M_1 \gg M_2$
$|m_{\chi_1^0}|$ (GeV)
μ (GeV)
M_2 (GeV)


Masses of the 1st Neutralino for the case $M_1 \gg M_2$
$|m_{\chi_1^0}|$ (GeV)
M_2 (GeV)
μ (GeV)

$M_1 \gg M_2$



$$\tilde{\chi}_1^0 \approx 0.000\ \tilde{B}^0 - 0.999\ \tilde{W}^0 + 0.053\ \tilde{h}_d^0 - 0.006\ \tilde{h}_u^0\ , \qquad (18)$$

Values

	M_1 (GeV)	M_2 (GeV)	$\tan\beta$	μ (GeV)
$2M_1 \sim M_2$	[150, 210]	[300, 450]	[5, 60]	[100, 500]
$M_1 \sim M_2$	[150, 350]	[150, 350]	[5, 60]	[100, 700]
$M_1 \ll M_2$	[35, 45]	[1200, 1450]	[5, 60]	[1000, 2500]
$M_1 \gg M_2$	[1200, 1300]	[170,210]	[5, 60]	[100, 1450]

Table: Values for the free parameters.

Conclusiones

- 4 possible scenarios with a consistent Higgs sector.
- To consider values of relic density, σ_{ann} and nucleon scatering.
- Calculate contribution Channels to Ωh^2.
- Lastly, see dependence with M_A and stop sector.

To be continued...

THANK YOU.

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