Illuminating the Dark:

MSSM Dark Matter in the light of Direct Detection

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Based on the works:

1) S. Bisal, A. Chatterjee, D. Das, and S. A. Pasha, *Radiative Corrections to Aid the Direct Detection of the Higgsino-like Neutralino Dark Matter: Spin-Independent Interactions*, arXiv:2311.09937.

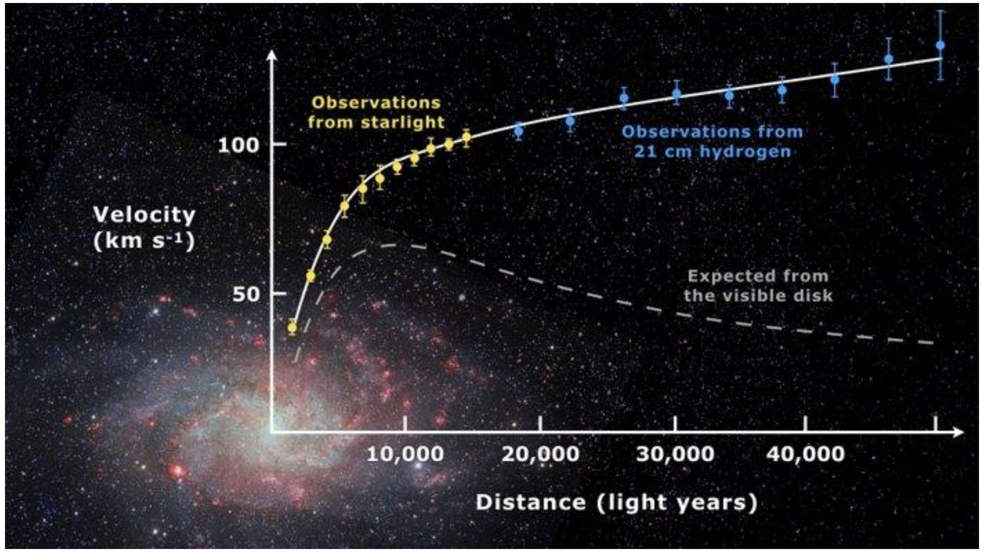
2) S. Bisal, A. Chatterjee, D. Das, and S. A. Pasha, *Confronting electroweak MSSM through one-loop renormalized neutralino-Higgs interactions for dark matter direct detection and muon* $(g-2)$, arXiv:2311.09938.

Motivation

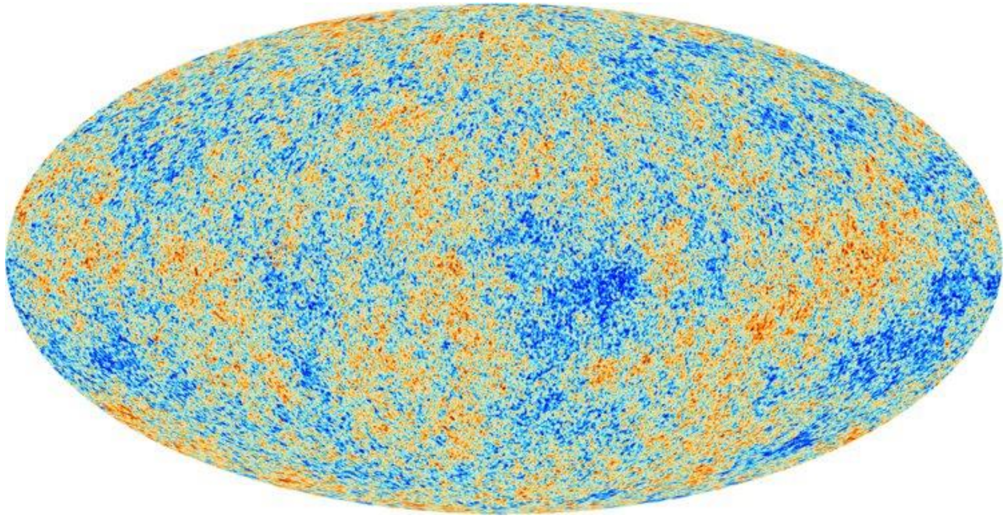
- Galaxies rotation curves can't be explained for visible matter [Rubin (1970s)]
- Galactic velocities in Clusters are anomalous [Zwicky (1936)]
- Gravitational lensing data also suggests extra mass
- Cosmic Microwave Background (CMB) suggests 26.8% of the Energy content of the Universe is invisible Matter [Planck (2018)]
- Presence of non-luminous (Dark) Matter
- 84% of all matter is Dark Matter, in Standard Cosmology

Bullet Cluster [Chandra]

Motivation



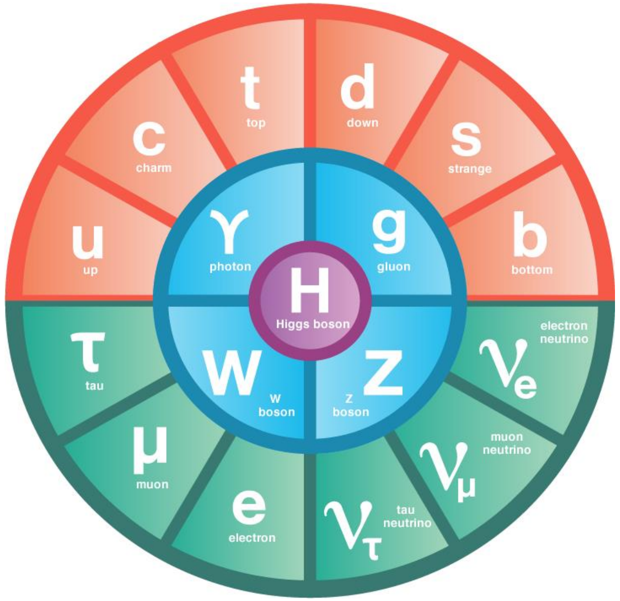
Galaxy Rotation Curve
Source: Corbelli, Salucci (2000)



CMB Map
Source: Planck/ESA

Supersymmetric Dark Matter

- Cosmological observations constrain DM to be "Cold", massive and neutral
- WIMPs: ideal dark matter particle, interact only weakly and gravitationally
- No candidate in Standard Model of Particle Physics, beyond Standard Model (BSM) Physics needed
- **Supersymmetry (SUSY)**: well-motivated BSM framework (Naturalness, Higgs quadratic divergence cancellation)



Source: Kurt Riesselmann

MSSM

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)

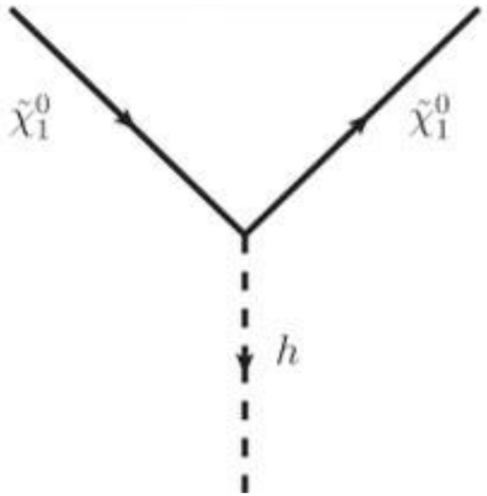
Source : Stephen Martin, A Supersymmetry Primer

Higgsino-like Dark Matter

- The R-parity conserving Lightest Supersymmetric Particle (LSP) is stable
- In MSSM, the lightest neutralino is LSP
- In our work, Higgsino-like neutralino is the LSP and the Dark Matter candidate
- When Higgsino fraction is large (>99.9%), the tree level couplings tend to vanish
- **Radiative corrections** become important
- The tree-level vertex for neutralino-Higgs interaction is shown here

$$\mathscr{L} \supset -\frac{1}{2} h_1 \bar{\tilde{\chi}}_1^0 (\mathscr{C}_1^R P_R + \mathscr{C}_1^L P_L) \tilde{\chi}_1^0 - \frac{1}{2} h_2 \bar{\tilde{\chi}}_1^0 (\mathscr{C}_2^R P_R + \mathscr{C}_2^L P_L) \tilde{\chi}_1^0$$

$$\begin{aligned} \mathscr{C}_1^R &= (S_1 \sin\alpha + S_2 \cos\alpha) \\ \mathscr{C}_2^R &= (S_2 \sin\alpha - S_1 \cos\alpha) \\ S_1 &= g_2 N_{13} (N_{12} - \tan\theta_W N_{11}) \\ S_2 &= g_2 N_{14} (N_{12} - \tan\theta_W N_{11}) \end{aligned}$$

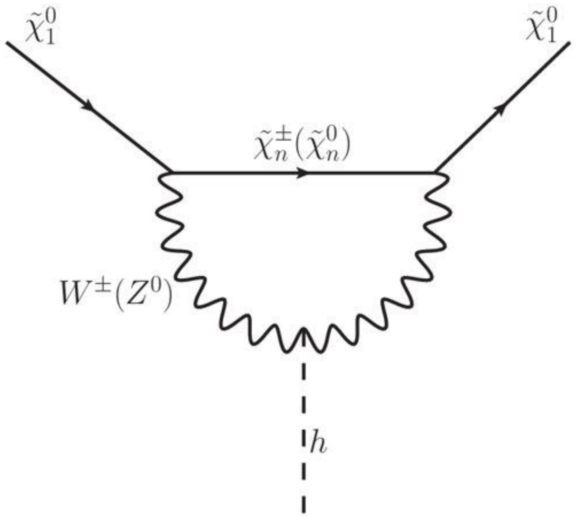


Higgsino-like Dark Matter

- In order to satisfy the thermal relic abundance of $\Omega_{\mathrm{DM}}h^2 \simeq 0.12$ [Planck collaboration (2016)], Higgsino LSP should be ~1 TeV
- May be lowered in presence of coannihilation [Chakraborti et al (2017)]
- Non-thermal production models also exist [Aparicio et al (2016)]
- Other components of Dark Matter may exist [Baer et al (2015)]
- In this case, the DD bounds are relaxed in the same proportion
- In this work we do not concern ourselves with satisfying the thermal relic density in the early Universe
- Loop corrections for a few loops has been studied in literature [Hisano et al (2010), Hisano et al (1997)]
- But a comprehensive study with **renormalization, counter-terms,** and **full set of loops** had not been done before, which we pursue in our work

Radiative corrections to the Direct Detection process

- Various one-loop radiative correction diagrams for Higgsino-like neutralino calculated



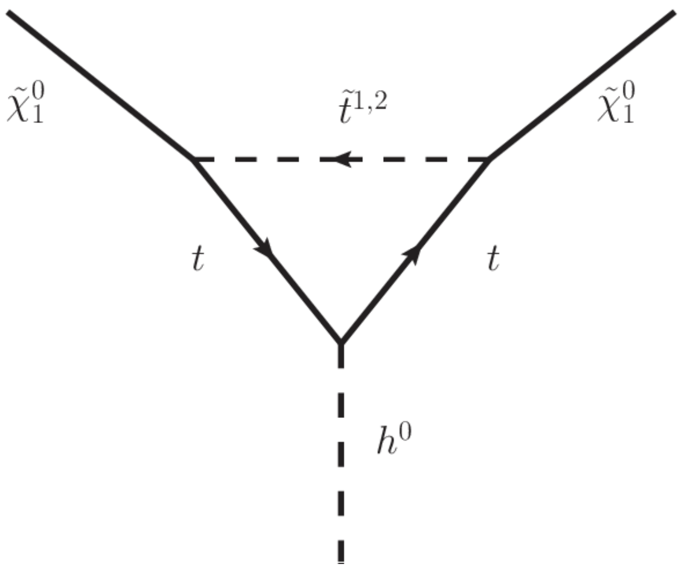
$$i\delta\Gamma_1 = -\frac{i g_2^3 M_W \cos(\beta-\alpha)}{16\pi^2}\left[P_L(2M_1\zeta_1 C_1 + 2M_1\zeta_2 C_2 + 4M_{\pm}\zeta_4 C_0) + P_R(2M_1\zeta_2 C_1 + 2M_1\zeta_1 C_2 + 4M_{\pm}\zeta_3 C_0)\right]$$

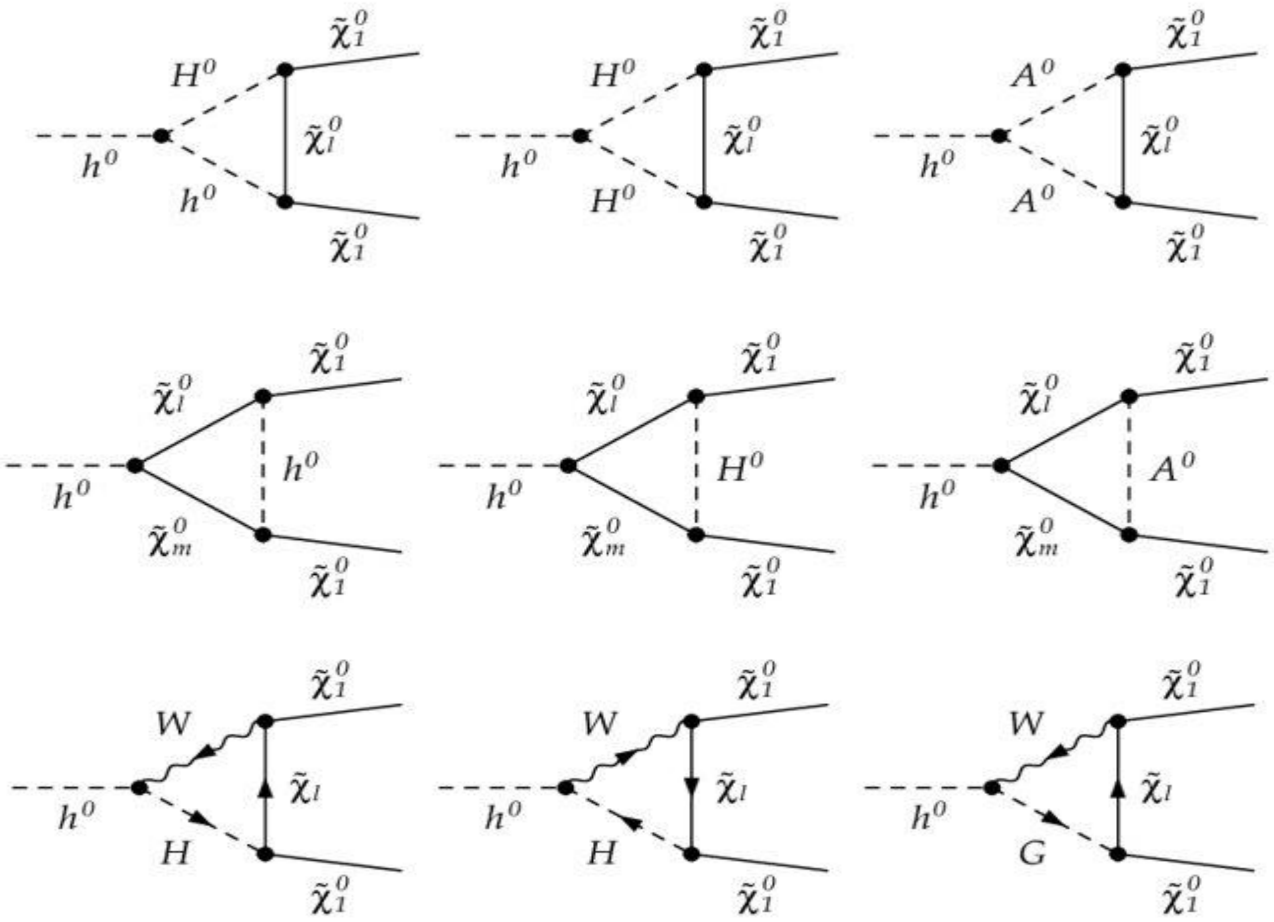
$$C_i = C_i(M_1^2, q^2, M_1^2, M_{\pm}^2, M_W^2, M_W^2) \quad \forall\, \boldsymbol{i = 1, 2, 3, 4}$$

$$\zeta_1 = C_{1n}^{R*} C_{n1}^{L},\ \zeta_2 = C_{1n}^{L*} C_{n1}^{R},\ \zeta_3 = C_{1n}^{R*} C_{n1}^{R},\ \zeta_4 = C_{1n}^{L*} C_{n1}^{L}$$

Ref: Bisal, Chatterjee, Das, Pasha (2023); arXiv:2311.09937

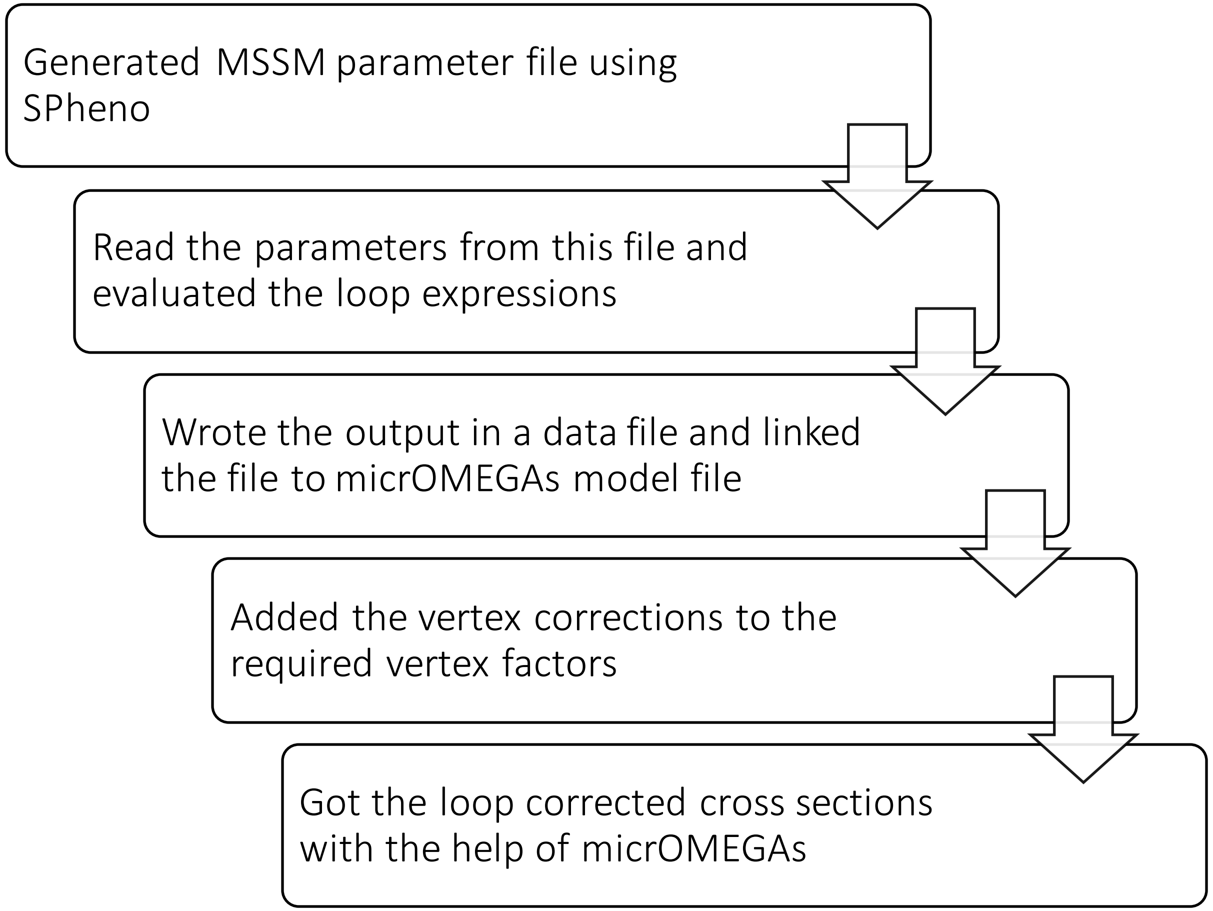
Continued





Ref: Hahn, Perez-Victoria (1999)

Flow Chart



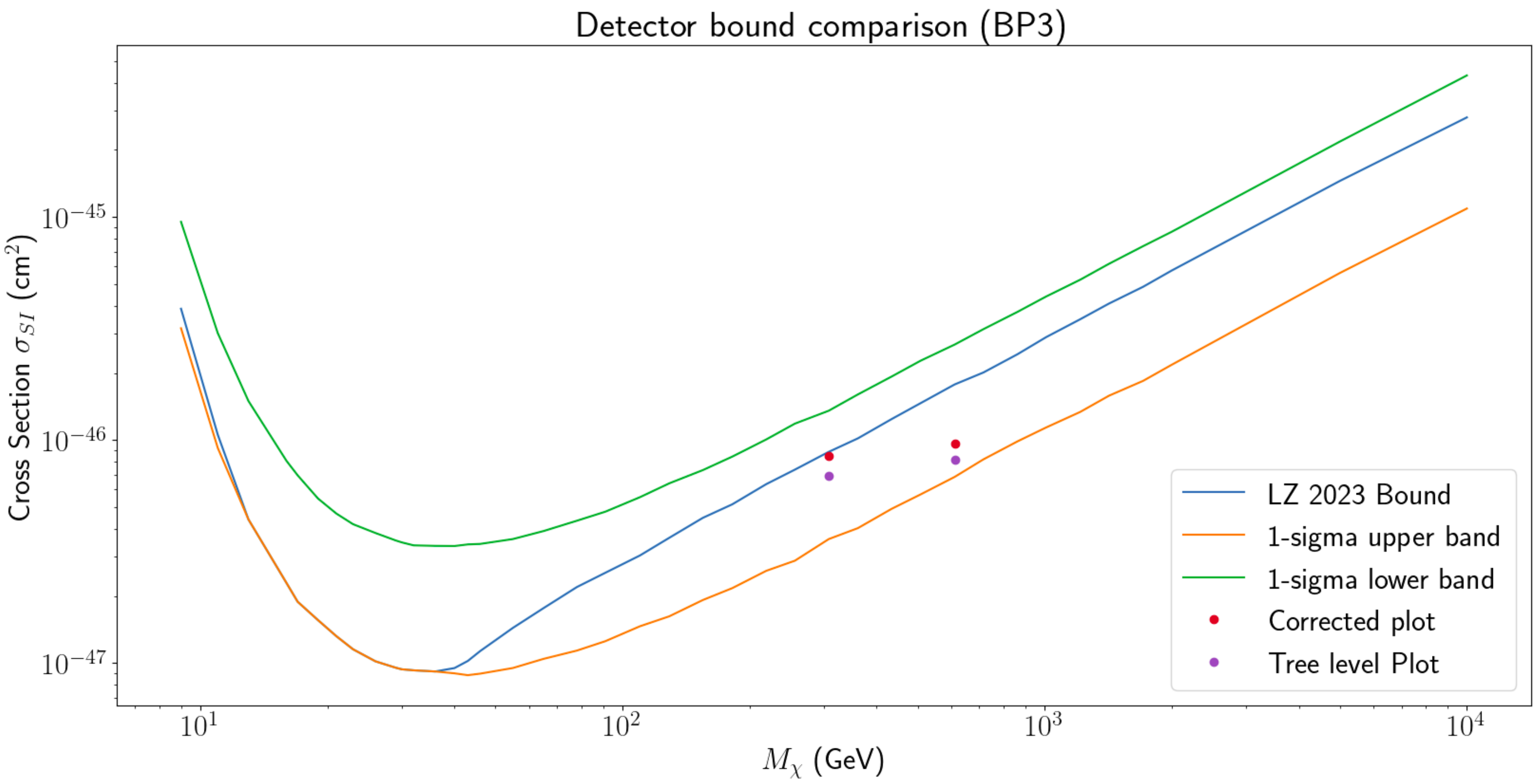
Ref: Belanger, Boudjema, Pukhov, Semenov (2009)

Results Table

BP	$\mathscr{C}_1^{L/R}, \mathscr{C}_2^{L/R}$	$\Delta\mathscr{C}_1^{L/R}$ (%) Total (SQ) (Loop, CT)	$\Delta\mathscr{C}_2^{L/R}$ (%) Total (SQ) (Loop, CT)	σ_{SI} [pb] ($\Delta\sigma_{SI}$ %)
BP1a	7.96×10^{-3} 4.68×10^{-3}	19.74(-22.35) (2.74, 17.0)	-13.96(-2.9) (-17.63, 3.67)	4.13×10^{-11} (41.7)
BP1b	8.64×10^{-3} 5.24×10^{-3}	15.50(-26.62) (-1.52, 17.03)	-14.29(-1.02) (-18.0, 3.74)	4.89×10^{-11} (31.5)
BP2a	6.12×10^{-3} -4.36×10^{-3}	37.88(-29.52) (20.89, 16.99)	-19.87(-9.05) (-23.53, 3.66)	2.29×10^{-11} (96)
BP2b	6.63×10^{-3} -4.82×10^{-3}	32.7(-35.78) (15.73, 16.97)	-21.22(-8.18) (-25, 3.78)	2.71×10^{-11} (81)
BP3a	1.13×10^{-2} 7.77×10^{-3}	11.07(-18.05) (-7.1, 18.2)	-6.98(-1.39) (-11.83, 4.89)	8.46×10^{-11} (22.4)
BP3b	1.21×10^{-2} 8.37×10^{-3}	9.14(-21.22) (-9.13, 18.27)	-7.63(-0.26) (-12.66, 5.03)	9.67×10^{-11} (18.25)
BP4a	8.25×10^{-3} -7.33×10^{-3}	21.11(-24.33) (2.81, 18.3)	-12.36(-6.99) (-17.31, 4.95)	4.13×10^{-11} (49.75)
BP4b	8.82×10^{-3} -7.83×10^{-3}	19.21(-28.89) (0.87, 18.34)	-13.74(-6.57) (-18.83, 5.09)	4.77×10^{-11} (45)
BP5a	6.24×10^{-3} 3.06×10^{-3}	38.95(-25.5) (22.47, 16.48)	-16.6(-2.68) (-20.35, 3.75)	2.53×10^{-11} (89.6)
BP5b	6.74×10^{-3} 3.49×10^{-3}	32.88(-31.58) (16.27, 16.61)	-15.77(-0.26) (-19.72, 3.95)	2.97×10^{-11} (73.8)
BP6a	1.05×10^{-2} 6.94×10^{-3}	17.0(-17.81) (-1.42, 18.42)	-5.32(-0.65) (-10.42, 5.10)	7.26×10^{-11} (35.8)
BP6b	1.11×10^{-2} 7.43×10^{-3}	15.41(-21.43) (-3.20, 18.61)	-5.44(-0.74) (-10.8, 5.36)	8.13×10^{-11} (32.2)

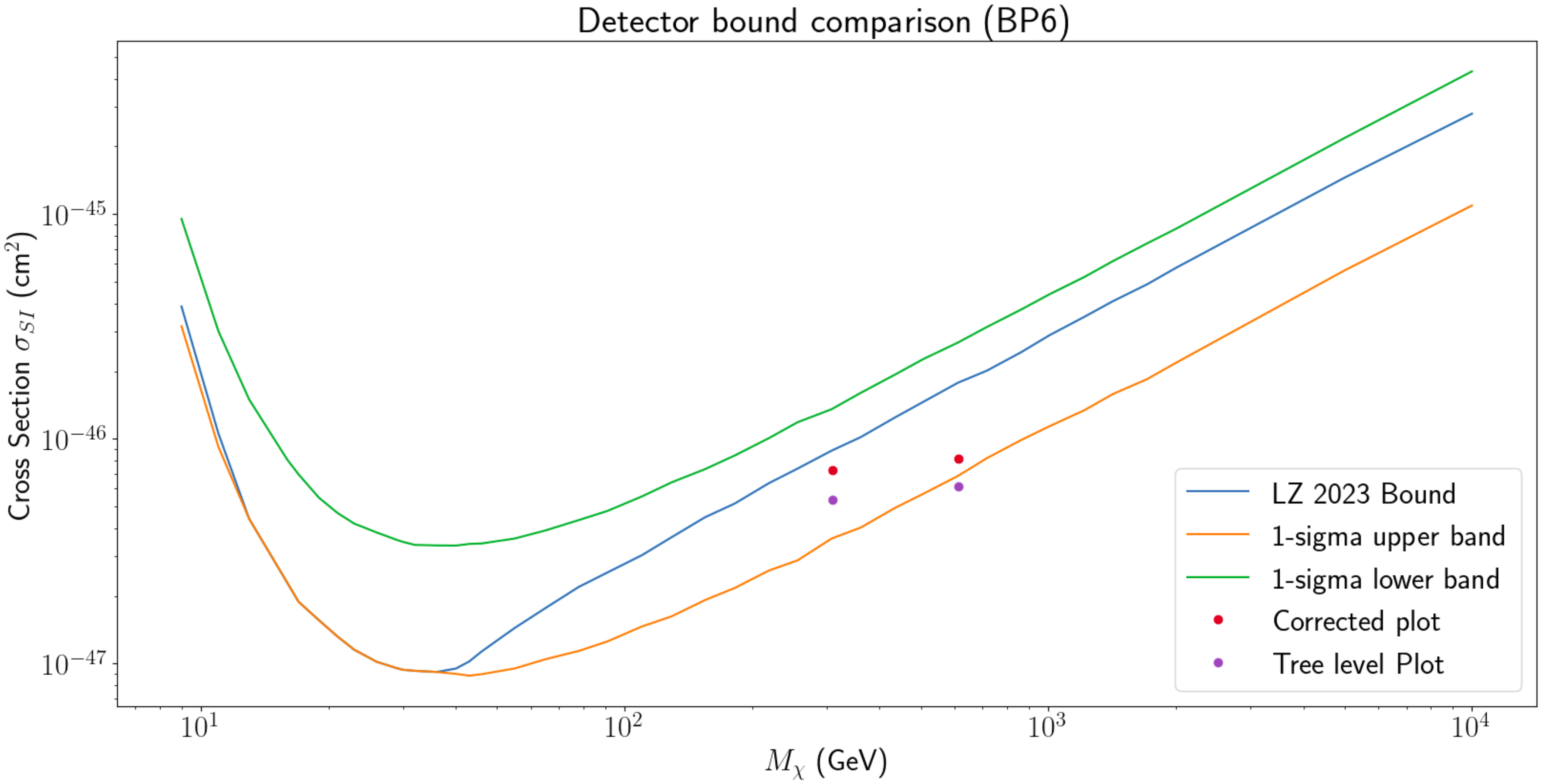
- Benchmark points for spin-independent interaction for Higgsino-like Dark matter

Significance



Ref: LZ Collaboration (2023)

Significance



Ref: LZ Collaboration (2023)

Bino-like DM: Results Table

$\tilde{B}_{\tilde{H}}$ LSP										
BMPs	$\tan\beta$	μ	M_1	M_2	M_A	M_H	$m_{\tilde{\mu}_L}$	$m_{\tilde{\mu}_R}$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
I	30	603	100	1500	2800	2268	178	135	177	131
BMPs	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}$	$(g-2)_\mu$	Ωh^2	$C^{\text{LO}}_{L,R}(h)$	$C^{\text{NLO}}_{L,R}(h)$	$C^{\text{LO}}_{L,R}(H)$	$C^{\text{NLO}}_{L,R}(H)$	$\sigma^{\text{LO}}_{\text{SI}}$	$\sigma^{\text{NLO}}_{\text{SI}}$
I	99	624	2.12×10^{-9}	0.118	0.00583	0.00622	0.02515	0.02625	2.760×10^{-11}	3.130×10^{-11}

$\tilde{B}_{\tilde{W}\tilde{H}}$ LSP										
BMPs	$\tan\beta$	μ	M_1	M_2	M_A	M_H	$m_{\tilde{\mu}_L}$	$m_{\tilde{\mu}_R}$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
II	30	710	190	265	3000	2392	344	248	254	204
BMPs	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}$	$(g-2)_\mu$	Ωh^2	$C^{\text{LO}}_{L,R}(h)$	$C^{\text{NLO}}_{L,R}(h)$	$C^{\text{LO}}_{L,R}(H)$	$C^{\text{NLO}}_{L,R}(H)$	$\sigma^{\text{LO}}_{\text{SI}}$	$\sigma^{\text{NLO}}_{\text{SI}}$
II	189	282	3.54×10^{-9}	0.119	0.00812	0.00858	0.02433	0.02519	4.709×10^{-11}	5.241×10^{-11}

- Benchmark points for spin-independent interaction for the mixed Bino-Higgsino-like and Bino-Wino-Higgsino-like Dark matter

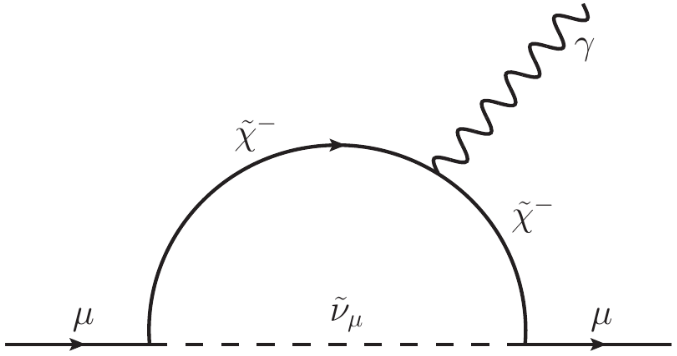
Ref: Bisal, Chatterjee, Das, Pasha (2023); arXiv:2311.09938

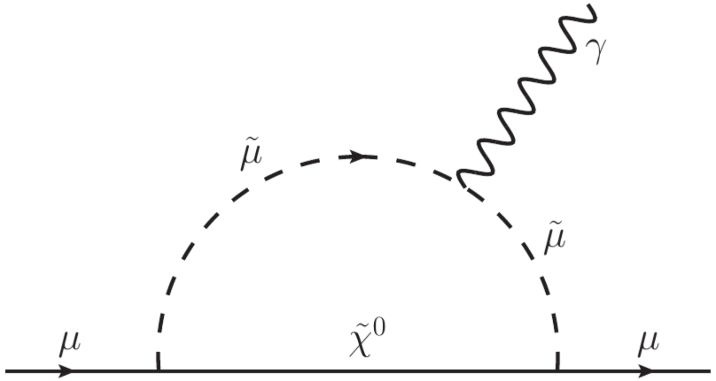
Anomalous magnetic moment of muon

- New Fermilab experiment confirms muon's anomalous magnetic moment from the Standard Model value (Run-1 and Run-2 + Run-3 values shown below)

$$\delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = 251 \pm 59 \times 10^{-11}$$

$$\delta a_\mu^{\mathrm{New}} = (249 \pm 48) \times 10^{-11}$$





Ref: Muon g-2 Collaboration (2023); arXiv:2308.06230

Summary

- We have done a comprehensive study of the Radiative Corrections to the complete Renormalized sector of the Neutralino-Higgs interaction for pure Higgsino-like LSP as well as Bino-Higgsino-like and Bino-Wino-Higgsino-like well-tempered LSP
- The loop corrections are prominent (96%) and push the cross-section inside the 1-sigma band and close to the exclusion region, especially in the pure Higgsino case
- Anomalous muon g-2 and B physics constraints are satisfied in the same parameter space we have considered for Bino-Higgsino and Bino-Wino-Higgsino well-tempered LSP

Thank you

References

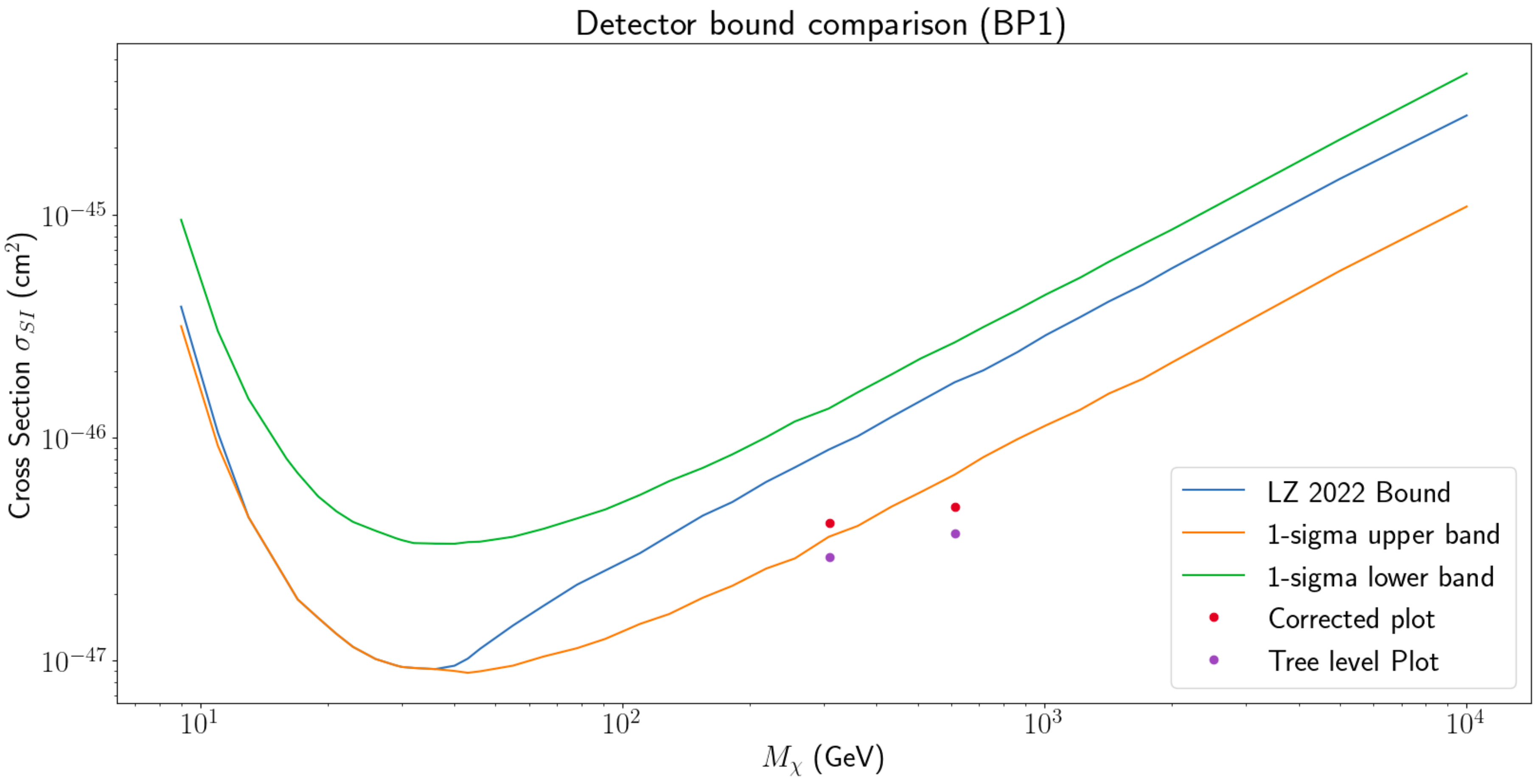
1) J. Küblbeck, M. Böhm and A. Denner, *Feyn arts — computer-algebraic generation of feynman graphs and amplitudes, Computer Physics Communications* 60 (1990) 165–180.
2) T. Hahn and M. Pérez-Victoria, *Automated one-loop calculations in four and d dimensions, Computer Physics Communications* 118 (1999) 153–165.
3) G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, *Dark matter direct detection rate in a generic model with micrOMEGAs 2.2, Comput. Phys. Commun.* 180 (2009) 747–767, [0803.2360].
4) J. Hisano, K. Ishiwata, and N. Nagata, *A complete calculation for direct detection of Wino dark matter*, Phys. Lett. B 690, 311 (2010).

Backup

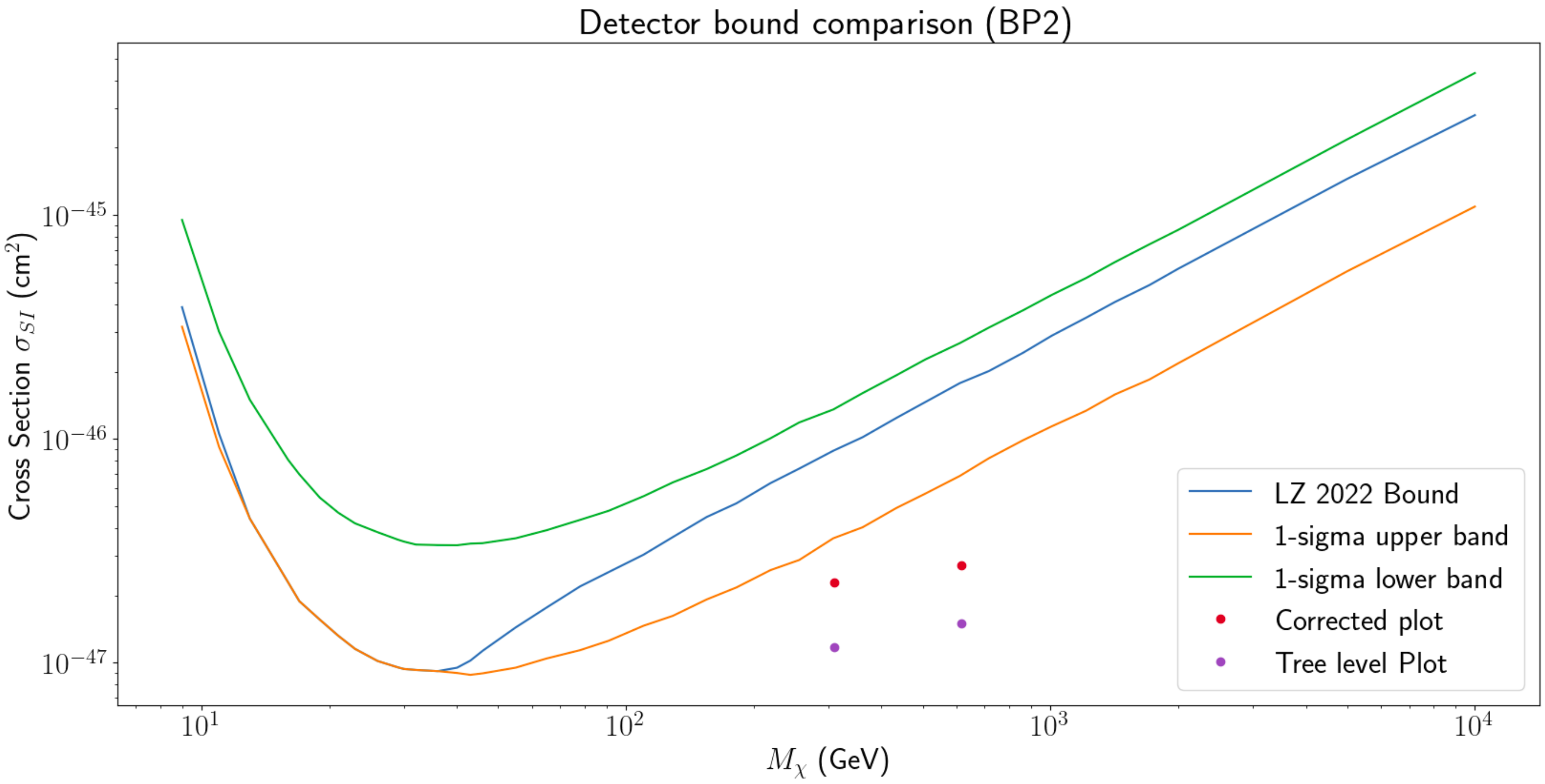
Parameters	BP1a	BP2a	BP3a	BP4a	BP5a	BP6a
μ (GeV)	300	-300	300	-300	300	300
M_1 (GeV)	-5000	-5000	5000	5000	-4000	4000
M_2 (GeV)	4000	4000	4000	4000	5000	5000
$m_{\tilde{\chi}_1^0}$ (GeV)	299.17	299.44	298.72	299.14	299.44	298.88
$m_{\tilde{\chi}_2^0}$ (GeV)	-300.44	-300.66	-300.74	-301.11	-300.29	-300.66
$m_{\tilde{\chi}_3^0}$ (GeV)	4000	4000	4000	4000	-4000	4000
$m_{\tilde{\chi}_4^0}$ (GeV)	-5000	-5000	5000	5000	5000	5000
$m_{\tilde{\chi}_1^\pm}$ (GeV)	299.56	300.2	299.56	300.2	299.67	299.67
$m_{\tilde{\chi}_2^\pm}$ (GeV)	4000	4000	4000	4000	5000	5000
m_{h_1} (GeV)	122.92	122.79	122.73	122.61	122.81	122.65
m_{h_2} (GeV)	1386	1468	1407	1448	1425	1450
HF	0.9997	0.9998	0.9997	0.9998	0.9998	0.9998
$N_{11}(\times 10^{-3})$	-6.291	-5.145	7.087	5.795	-7.756	-9.004
$N_{12}(\times 10^{-2})$	-1.679	-1.373	-1.677	-1.372	-1.322	1.321
N_{13}	0.708	-0.707	0.708	-0.708	0.708	-0.708
N_{14}	-0.706	-0.706	-0.706	-0.706	-0.706	0.706

Parameters	BP1b	BP2b	BP3b	BP4b	BP5b	BP6b
μ (GeV)	600	-600	600	-600	600	600
M_1 (GeV)	-5000	-5000	5000	5000	-4000	4000
M_2 (GeV)	4000	4000	4000	4000	5000	5000
$m_{\tilde{\chi}_1^0}$ (GeV)	599.06	599.37	598.61	599.07	599.36	598.79
$m_{\tilde{\chi}_2^0}$ (GeV)	-600.39	-600.59	-600.7	-601.04	-600.24	-600.62
$m_{\tilde{\chi}_3^0}$ (GeV)	4000	4000	4000	4000	-4000	4000
$m_{\tilde{\chi}_4^0}$ (GeV)	-5000	-5000	-5000	5000	5000	5000
$m_{\tilde{\chi}_1^\pm}$ (GeV)	599.43	600.08	599.43	600.08	599.58	599.58
$m_{\tilde{\chi}_2^\pm}$ (GeV)	4000	4000	4000	4000	5000	5000
m_{h_1} (GeV)	122.94	122.68	122.75	122.51	122.83	122.65
m_{h_2} (GeV)	1347	1506	1390	1465	1423	1450
HF	0.9997	0.9998	0.9996	0.9997	0.9997	0.9997
$N_{11}(\times 10^{-3})$	5.956	-4.872	-7.575	-6.196	-7.252	-9.804
$N_{12}(\times 10^{-2})$	1.827	-1.495	1.827	1.494	-1.412	1.412
N_{13}	-0.707	-0.707	-0.708	0.708	0.707	-0.708
N_{14}	0.707	-0.707	0.706	0.706	-0.707	0.706

Backup


Detector bound comparison (BP1)
Cross Section σ_{SI} (cm^2)
10^{-45}
10^{-46}
10^{-47}
10^1
10^2
10^3
10^4
M_χ (GeV)
LZ 2022 Bound
1-sigma upper band
1-sigma lower band
Corrected plot
Tree level Plot

Backup



Detector bound comparison (BP2)
Cross Section σ_{SI} (cm^2)
10^{-45}
10^{-46}
10^{-47}
10^1
10^2
10^3
10^4
M_χ (GeV)
LZ 2022 Bound
1-sigma upper band
1-sigma lower band
Corrected plot
Tree level Plot

Backup

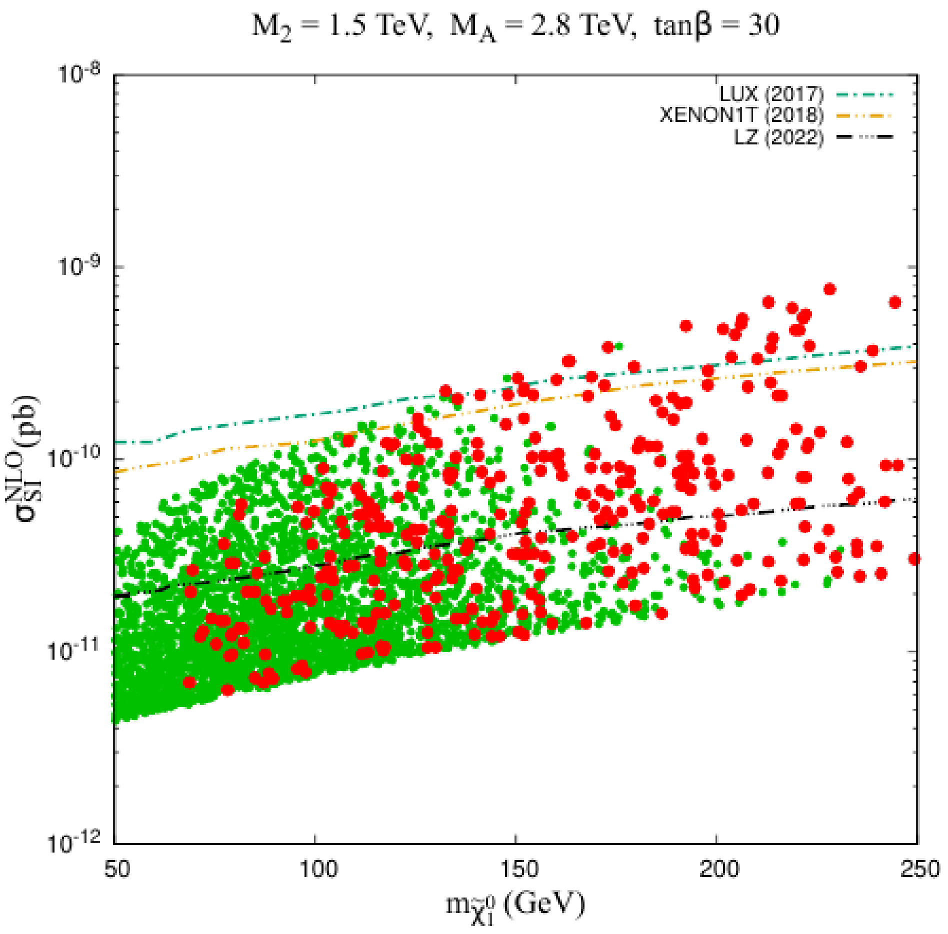
$$\tilde{B}_{\tilde{H}}\ \mathbf{DM}$$

$$\mathbf{50 \le M_1 \le 300,\ \ 400 \le \mu \le 1000,\ \ 100 \le m_{\tilde{\mu}_L,\tilde{\mu}_R} \le 350,\ \ 100 \le m_{\tilde{e}_L,\tilde{e}_R} \le 350}$$

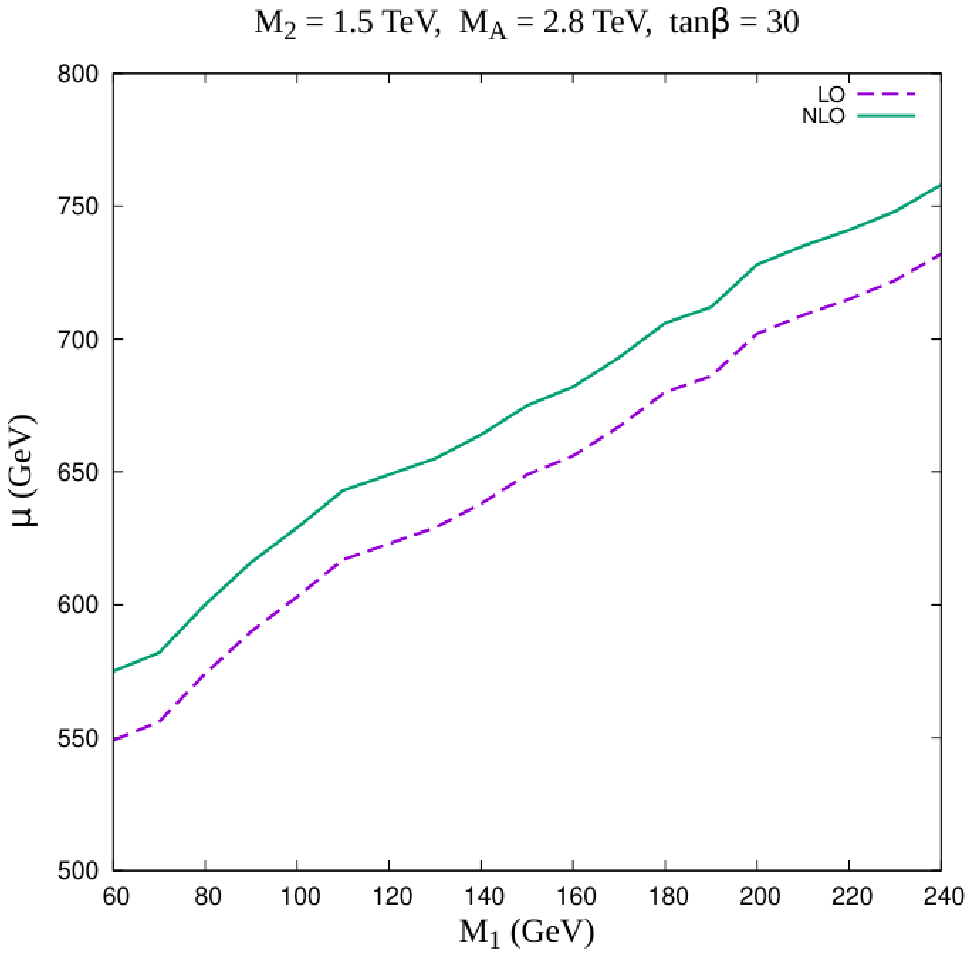
$$\tilde{B}_{\tilde{W}\tilde{H}}\ \mathbf{DM}$$

$$\mathbf{50 \le M_1 \le 300,\ \ 150 \le M_2 \le 600,\ \ 400 \le \mu \le 1000,\ \ 100 \le m_{\tilde{\mu}_L,\tilde{\mu}_R} \le 350,\ \ 100 \le m_{\tilde{e}_L,\tilde{e}_R} \le 350}$$

Backup

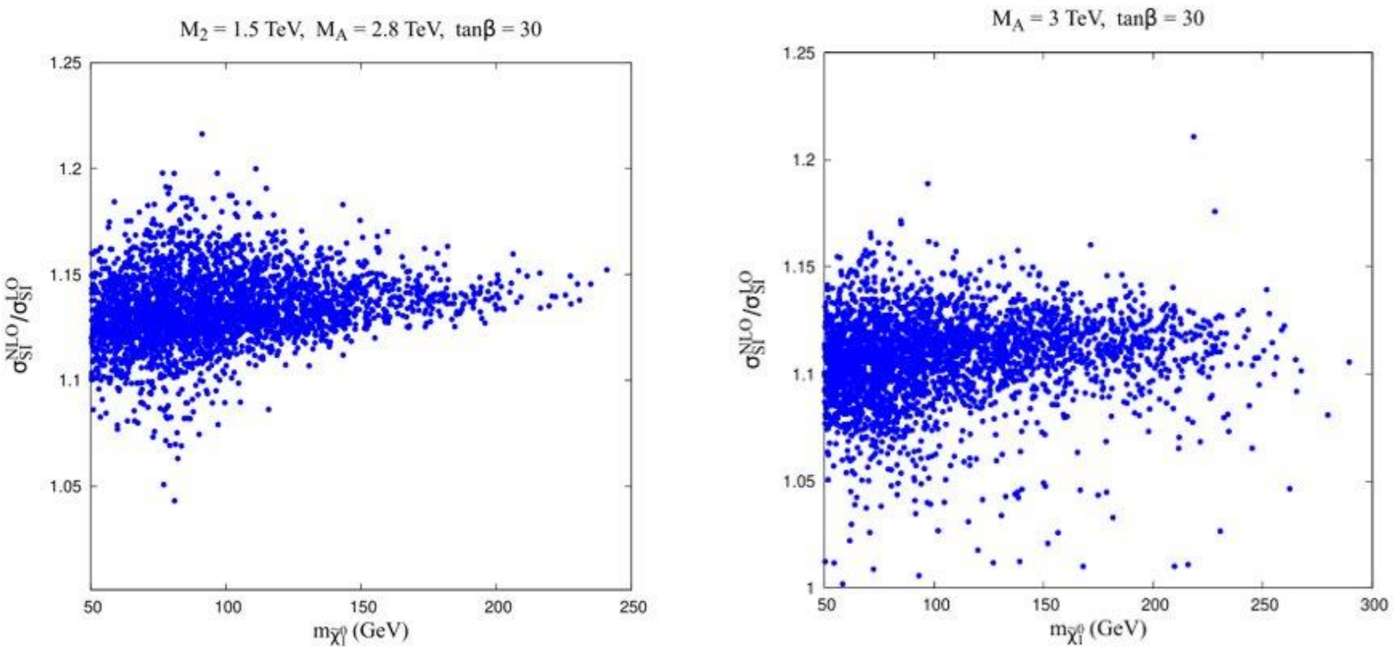


M_2 = 1.5 TeV, M_A = 2.8 TeV, tanβ = 30
LUX (2017)
XENON1T (2018)
LZ (2022)
σ_{SI}^{NLO}(pb)
$m_{\tilde{\chi}_1^0}$ (GeV)



M_2 = 1.5 TeV, M_A = 2.8 TeV, tanβ = 30
LO
NLO
μ (GeV)
M_1 (GeV)

Backup



- Cross-section corrections for Bino-Higgsino (left) and Bino-Wino-Higgsino (right) like Neutralino case