A relatively light bino-like dark matter in the Z_3-symmetric NMSSM and its implications for the LHC

Subhojit Roy

Harish-Chandra Research Institute,
Prayagraj, India

In collaboration with
Waleed Abdallah and AseshKrishna Datta

JHEP04(2021)122; arXiv:2012.04026

SUSY 2021

Aug 26, 2021

Plan

- Motivations
- Theoretical scenario
- DM aspects
  - Relic abundance
  - Direct Detection
- Collider aspects
- Role of singlino-like NLSP
- Naturalness issues
- Conclusion

Motivations (NMSSM)

- Inclusion of a singlet superfield $\widehat{S}$
  $\Rightarrow$ an elegant solution to the "μ-problem" of MSSM

- Ameliorates the "little hierarchy" problem of MSSM
  $\rightarrow$ Can be more "natural" (fine-tuning is small) than MSSM

- Richer Higgs and Dark Matter (DM) sectors

- Heightened interest in NMSSM post SM-like Higgs boson (125 GeV) discovery

- Strong first order phase transition for EW baryogenesis is still possible

Motivations (present work)

- Augmented neutralino sector (5×5); new "singlino" state of NMSSM
  a popular CDM candidate
  Ellwanger & Hugonie, EPJC 78 (2018) 9
  Baum et al., JHEP 04 (2018) 069
  Cao et al., PRD 99, no. 7, 075020 (2019)
  Abdallah, Chatterjee & Datta, JHEP 09 (2019) 095

- A light, bino ($\widetilde{B}$)-dominated LSP is highly disfavored due to current DM and collider constraints in MSSM.

- NMSSM is a little better placed-
  - New singlet scalars act as funnels
  - Possibility of $\widetilde{B}$-like LSP admixtures with singlino ($\widetilde{S}$) and higgsino ($\widetilde{H}$). $\Rightarrow$ "well-tempered" bino-like LSP

- Recent studies claimed that $m_{LSP} < m_{top}$ is almost ruled out.
  Baum et al., JHEP 04 (2018) 069
  Cao et al., PRD 99, no. 7, 075020 (2019)

- Be not too demanding on low finetuning

  $\rightarrow$ work with heavy stop, gluino (motivated by LHC results)
  $\rightarrow$ rather demand low $\mu_{\rm eff}$ (for mitigation)

The theoretical scenario

- In this work we adopt the Z_3-symmetric NMSSM. The superpotential is given by

$$\mathcal{W} = \mathcal{W}_{\rm MSSM}|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u.\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3.$$

- The μ term in the NMSSM arises from

$$\lambda \widehat{S}\widehat{H}_u.\widehat{H}_d \to \lambda < S > \widehat{H}_u.\widehat{H}_d \to \mu_{eff}\widehat{H}_u.\widehat{H}_d$$

  Solution to the "μ-problem".

- The corresponding soft SUSY-breaking Lagrangian is given by

$$-\mathcal{L}^{\rm soft} = -\mathcal{L}^{\rm soft}_{\rm MSSM}|_{B\mu=0} + m_S^2|S|^2 + (\lambda A_\lambda S H_u \cdot H_d + \frac{\kappa}{3}A_\kappa S^3 + {\rm h.c.}).$$

- Compared with MSSM, NMSSM have extra one CP-even and one CP-odd state in the neutral Higgs sector (Assuming CP conservation) and one additional neutralino state, called singlino.

The scalar (Higgs) sector

- Square mass of the SM-like Higgs boson:

$$m^2_{h_{\rm SM}} = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta_{\rm mix} + \Delta_{\rm rad.corr.}$$

- Tree level square mass of singlet-like Higgs:

$$m^2_{h_S} = \lambda A_\lambda \frac{v_u v_d}{v_S} + \frac{m_{\widetilde{S}}}{2}(A_\kappa + 2m_{\widetilde{S}})$$

$$m^2_{a_S} = \lambda(A_\lambda + 2m_{\widetilde{S}})\frac{v_u v_d}{v_S} - \frac{3}{2}A_\kappa m_{\widetilde{S}}$$

- At small λ and large v_S limit, the first term could be ignored and hence $|m^2_{a_S}| \approx |-\frac{3}{2}A_\kappa m_{\widetilde{S}}|$.
  $\Rightarrow$ Small A_κ corresponds to light a_S

The electroweakino (ewino) sector

- The symmetric neutralino mass matrix has got a dimensionality of 5×5 and, in the basis $\psi^0 = \{\widetilde{B},\ \widetilde{W}^0,\ \widetilde{H}_d^0,\ \widetilde{H}_u^0,\ \widetilde{S}\}$, is given by

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa v_S \end{pmatrix}$$

$M_1,\ M_2 \rightarrow$ soft SUSY breaking masses for the $U(1)_Y$ and the $SU(2)_L$ gauginos, i.e., the bino and the wino, respectively.

$m_{\widetilde{S}} = 2\kappa v_S = 2\frac{\kappa}{\lambda}\mu_{\text{eff}} \rightarrow$ singlino mass term.

The ewino sector

- The neutralino mass-eigenstates (χ_i^0), in terms of the weak eigenstates (ψ_j^0), are given by
$$\chi_i^0 = N_{ij}\psi_j^0$$
'N' is the 5×5 matrix that diagonalizes the neutralino mass-matrix.

- The 2×2 chargino mass matrix in the bases $\psi^+ = \{-i\widetilde{W}^+, \widetilde{H}_u^+\}$ and $\psi^- = \{-i\widetilde{W}^-, \widetilde{H}_d^-\}$ is given by
$$\mathcal{M}_C = \begin{pmatrix} M_2 & g_2 v_u \\ g_2 v_d & \mu_{\rm eff} \end{pmatrix}$$
The asymmetric matrix $\mathcal{M}_C$ can be diagonalized by two 2×2 unitary matrices U and V:
$$U^* \mathcal{M}_C V^\dagger = {\rm diag}(m_{\chi_1^\pm}, m_{\chi_2^\pm}) \; ; \quad \text{with} \;\; m_{\chi_1^\pm} < m_{\chi_2^\pm}$$

Relations among the neutralino admixtures

- When M_2 is decoupled,

$$\frac{N_{j1}}{N_{j5}} = \frac{\lambda^2 v^2(\mu_{\rm eff}\sin 2\beta - m_{\chi_j^0}) + (m_{\tilde{S}} - m_{\chi_j^0})(\mu_{\rm eff}^2 - m_{\chi_j^0}^2)}{\frac{\lambda}{\sqrt{2}} g_1 \mu_{\rm eff}(v_u^2 - v_d^2)} ,$$

$$\frac{N_{j3}}{N_{j5}} = \frac{\frac{\lambda^2}{\sqrt{2}} g_1 v_d v^2 + \frac{g_1}{\sqrt{2}}(m_{\tilde{S}} - m_{\chi_j^0})(v_d m_{\chi_j^0} + v_u \mu_{\rm eff})}{\frac{\lambda}{\sqrt{2}} g_1 \mu_{\rm eff}(v_u^2 - v_d^2)} ,$$

$$\frac{N_{j4}}{N_{j5}} = \frac{-\frac{\lambda^2}{\sqrt{2}} g_1 v_u v^2 - \frac{g_1}{\sqrt{2}}(m_{\tilde{S}} - m_{\chi_j^0})(v_u m_{\chi_j^0} + v_d \mu_{\rm eff})}{\frac{\lambda}{\sqrt{2}} g_1 \mu_{\rm eff}(v_u^2 - v_d^2)} ,$$

Where, N_{i3}, N_{i4}, N_{i5} and N_{i1} $\to$ two higgsinos, the singlino and the bino components, respectively.

Setup

- Light (< 200 GeV) and highly $\widetilde{B}$-dominated ($> 95\%$) LSP
- Targeting relatively small $\mu_{\rm eff}$ (light higgsinos)
- Looking for relatively light $\widetilde{S}$ (implications for the LHC)
- All other sparticles are heavy (multi-TeV)
- Elaborate random scan of the parameter space ($\sim 10^9$)

Variation of parameters

- New parameters of NMSSM: λ, κ, A_λ, A_κ

λ	$\lvert\kappa\rvert$	$\tan\beta$	$\lvert\mu_{\rm eff}\rvert$ (GeV)	$\lvert A_\lambda\rvert$ (TeV)	$\lvert A_\kappa\rvert$ (GeV)	$\lvert M_1\rvert$ (GeV)	A_t (TeV)
0.001 $\downarrow$ 0.7	≤ 0.7	1 $\downarrow$ 65	≤ 1000	≤ 10	≤ 100	$<$ 200	0 $\downarrow$ 10

$m_{\widetilde{g}}$,$m_{\widetilde{f}_{1,2}}$ = 5 TeV; $m_{\widetilde{f}_3}$ = 5.5 TeV; $m_{\widetilde{W}}$ =2.5 TeV

- Toolbox:

  NMSSMTools-v5.4.1 (with micrOMEGAs),

  HiggsBounds-v5.4.0, HiggsSignals-v2.3.0.

Results: Constraints

- Planck-reported 2σ range upper bound on relic density, i.e., $\Omega h^2 \leq 0.131$

- Considered latest spin-independent (SI) and spin-dependent (SD) bounds

  XENON Collaboration, PRL 121(2018) 11, 111302

  XENON Collaboration, PRL 122 (2019) 14, 141301

  PICO Collaboration, PRD 100 (2019) 2, 022001

- Used NMSSMTools LHC bound for $pp \to \chi_1^{\pm}\chi_2^0 \to WZ\not{E}_T \to 3\ell + \not{E}_T$ final state.

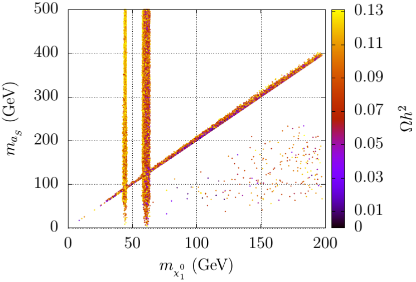
  CMS Collaboration, JHEP 03 (2018)

- In addition, up-to-date constraints pertaining to the observed Higgs sector are checked via dedicated packages like HiggsBounds-v5.4.0 and HiggsSignals-v2.3.0 .

- Have not considered muon $(g-2)$ constraints (have taken heavy smuon).

Relic density

- Resonant s-channel annihilation via Z-boson, h_{SM} and a_S $(2\chi_1^0 \sim m_Z/m_{h_{SM}}/m_{a_S})$.
- Coannihilation with singlino (relative sign between M_1 and $m_{\tilde{S}}$ is needed).
- $g_{Z\chi_1^0\chi_1^0} \propto \mu_{\rm eff}^{-2}$ where as the $g_{h_{SM}\chi_1^0\chi_1^0} \propto \mu_{\rm eff}^{-1}$.
  $\Rightarrow$ $\mu_{\rm eff}$ receives upper bound from observed relic density.
- We see that for Z-funnel region $\mu_{\rm eff} < 450$ GeV. For h_{SM} funnel, it is possible to satisfy relic density for $\mu_{\rm eff}$ up to 1 TeV.



SI cross-section coupling blind spot condition

$$g_{h_i\chi_1^0\chi_1^0} = \sqrt{2}\lambda(S_{i1}N_{14}+S_{i2}N_{13})N_{15}+\sqrt{2}\lambda S_{i3}(N_{13}N_{14}-\frac{\kappa}{\lambda}N_{15}^2)$$
$$+ \quad (g_1N_{11}-g_2N_{12})(S_{i1}N_{13}-S_{i2}N_{14}).$$

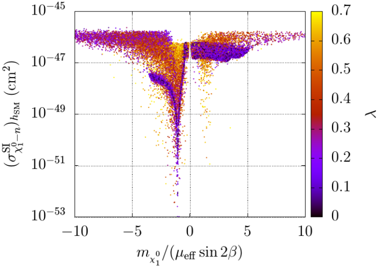
$\widetilde{B}$-like LSP s-channel annihilation via a_S-funnel $\Rightarrow$ Need moderately large λ

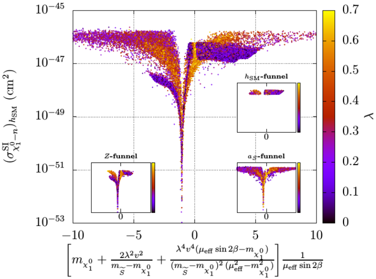
$$g_{h_{\rm SM}\chi_1^0\chi_1^0} \approx \frac{g_1^2 v}{\sqrt{2}I}\left[m_{\chi_1^0}+\mu_{\rm eff}\sin 2\beta+\frac{2\lambda^2v^2}{m_{\widetilde{S}}-m_{\chi_1^0}}+\frac{\lambda^4v^4(\mu_{\rm eff}\sin 2\beta-m_{\chi_1^0})}{(m_{\widetilde{S}}-m_{\chi_1^0})^2\,(\mu_{\rm eff}^2-m_{\chi_1^0}^2)}\right].$$

Coupling SI cross-section blind spot condition:

$$\left(m_{\chi_1^0}+\frac{2\lambda^2v^2}{m_{\widetilde{S}}-m_{\chi_1^0}}\right)\frac{1}{\mu_{\rm eff}\sin 2\beta}\simeq -1\ .$$

SI cross-section coupling blind spot





SI cross-section blind spot condition

$$\sigma^{SI}_{\chi_1^0-(N)} = \frac{4\mu_r^2}{\pi}|f^{(N)}|^2, \qquad f^{(N)} = \sum_{i=1}^{3} \frac{g_{h_i\chi_1^0\chi_1^0}\, g_{h_i NN}}{2m^2_{h_i}}$$

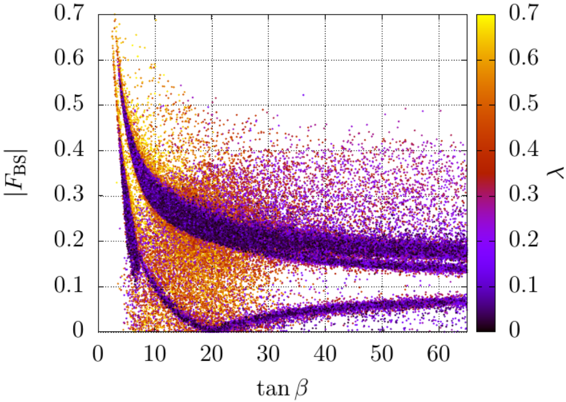
SI cross-section blind spot condition (neglecting the singlet-like CP-even Higgs contribution) is given below.

$$F = \frac{m_{\chi_1^0}}{\mu_{\rm eff}} + \sin 2\beta + \frac{2\lambda^2 v^2}{\mu_{\rm eff}\,(m_{\widetilde{S}} - m_{\chi_1^0})} + \frac{\lambda^4 v^4 \left(\sin 2\beta - m_{\chi_1^0}/\mu_{\rm eff}\right)}{(m_{\widetilde{S}} - m_{\chi_1^0})^2\,(\mu^2_{\rm eff} - m^2_{\chi_1^0})}$$
$$+ \frac{\cos 2\beta}{2}\left(\tan\beta - \frac{1}{\tan\beta}\right)\left[\frac{\lambda^2 v^2\left[\lambda^2 v^2 + 2m_{\chi_1^0}(m_{\widetilde{S}} - m_{\chi_1^0})\right]}{(m_{\widetilde{S}} - m_{\chi_1^0})^2\,(\mu^2_{\rm eff} - m^2_{\chi_1^0})} - 1\right]\frac{m^2_{h_{SM}}}{m^2_H}$$
$$\approx 0$$

The corresponding blind spot condition pertaining to the $\widetilde{B}$-$\widetilde{H}$ system of the MSSM with a $\widetilde{B}$-like LSP is retrieved in the limit $m_{\widetilde{S}} \to \infty$.

$$\frac{m_{\chi_1^0}}{\mu_{\rm eff}} + \sin 2\beta + \frac{m^2_{h_{SM}}}{m^2_H}\,\frac{\tan\beta}{2} \approx 0\,.$$

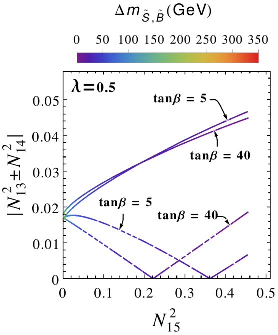
SI cross-section blind spot dependence on $\tan\beta$

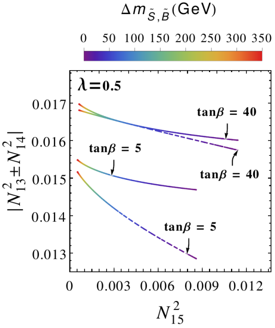


SD cross-section dependence on singlino tempering

$$g_{Z\chi_1^0\chi_1^0} \sim \left(-N_{13}^2 + N_{14}^2 \right)$$

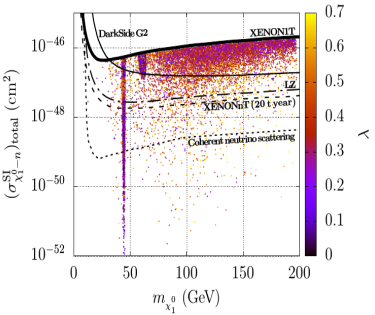
$$N_{13}^2 - N_{14}^2 = \frac{g_1^2 v^2}{2I} \cos 2\beta \left[-1 + \frac{2\lambda^2 v^2}{\left(\frac{m_{\tilde{S}}}{m_{\chi_1^0}} - 1 \right)(\mu_{\text{eff}}^2 - m_{\chi_1^0}^2)} + \frac{\lambda^4 v^4}{(m_{\tilde{S}} - m_{\chi_1^0})^2 (\mu_{\text{eff}}^2 - m_{\chi_1^0}^2)} \right]$$

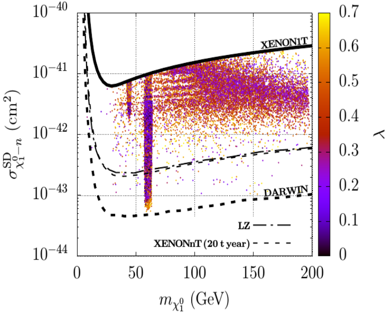




DM Direct Detection

- SD bound pushes $\mu_{\text{eff}} > 280$ GeV.
- Need to satisfy closely the SI blind spot condition to satisfy new SI DMDD bounds.
- Natural NMSSM (low μ_{eff}) is in tension with DM and collider constraints.





Current constraints from LHC direct searches for ewinos

- The most sensitive process $pp \to \chi_1^{\pm}\chi_2^0$.

- $pp \to \chi_1^{\pm}\chi_2^0 \to WZ\not{E}_T \to 3\ell + \not{E}_T$. The most stringent lower bound on $m_{\chi_1^{\pm}}(= m_{\chi_2^0})$ obtained till date in this mode is 650 GeV (assuming wino like $m_{\chi_1^{\pm}}$) for vanishing $m_{\chi_1^0}$.

  CMS Collaboration, JHEP 03 (2018) 160

- Of recent, there have been LHC analyses which consider $pp \to \chi_1^{\pm}\chi_2^0 \to WH\not{E}_T \to 1\ell + 2b\text{-}jet + \not{E}_T$, a corresponding bound as stringent as wino like $m_{\chi_1^{\pm}}\,(= m_{\chi_2^0}) > 800$ GeV.

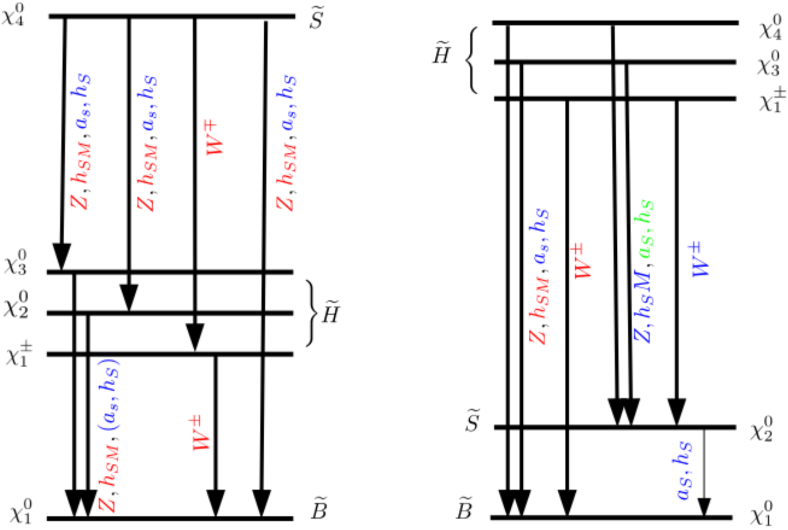
  CMS PAS SUS-20-003

  ATLAS Collaboration, Eur.Phys.J.C 80 (2020) 8, 691

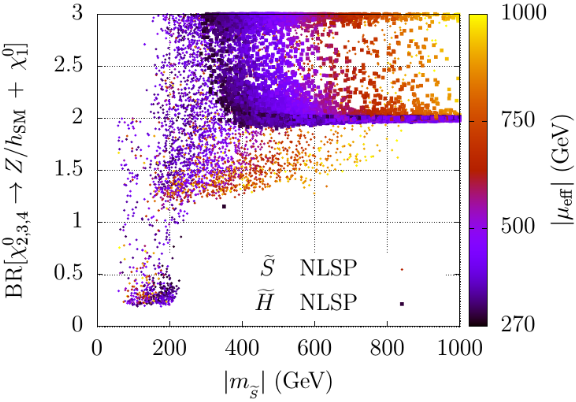
- 'Mixed' mode where χ_2^0 decays 50% of the times to each of the Z-boson and the SM Higgs boson a lower bound of 535 GeV has been reported for wino like $m_{\chi_1^{\pm}}\,(= m_{\chi_2^0})$.

  CMS Collaboration, JHEP 03 (2018) 160

Effect of Singlino NLSP on BRs

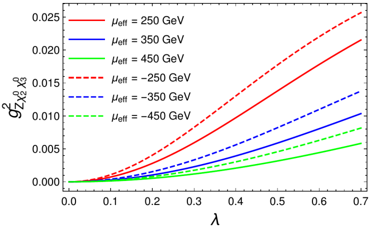


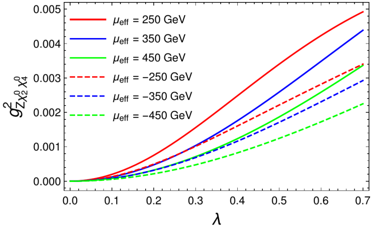
Effect of Singlino NLSP on BRs



Various couplings in (3×3) Higgsino-Singlino neutralino

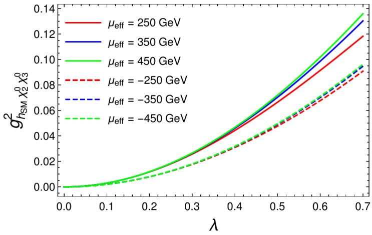
$$g^2_{Z\chi_i^0\chi_j^0} = \frac{g_2^2}{4\cos^2\theta_W} \frac{\left(1 - \frac{m_{\chi_i^0} m_{\chi_j^0}}{\mu_{\rm eff}^2}\right)^2 \cos^2 2\beta}{\prod\limits_{k=i,j} \left[1 + \left(\frac{m_{\chi_k^0}}{\mu_{\rm eff}}\right)^2 - 2\frac{m_{\chi_k^0}}{\mu_{\rm eff}} \sin 2\beta + \left\{1 - \left(\frac{m_{\chi_k^0}}{\mu_{\rm eff}}\right)^2\right\}^2 \left(\frac{\mu_{\rm eff}}{\lambda v}\right)^2\right]} .$$

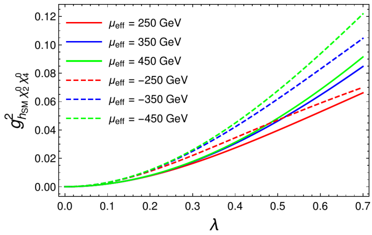




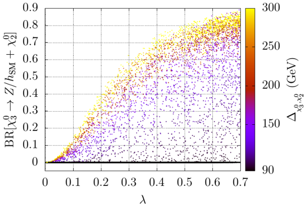
Various couplings in (3×3) Higgsino-Singlino neutralino

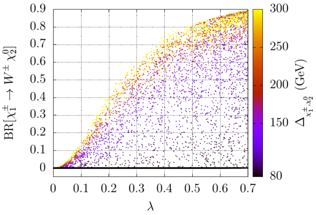
$$g^2_{h_{\rm SM}\chi_i^0\chi_j^0} = \frac{1}{2}\left(\frac{\mu_{\rm eff}}{v}\right)^2 \frac{\left[\left(\frac{m_{\chi_i^0}}{\mu_{\rm eff}} - \sin 2\beta\right)\left\{1 - \left(\frac{m_{\chi_j^0}}{\mu_{\rm eff}}\right)^2\right\} + \left(\frac{m_{\chi_j^0}}{\mu_{\rm eff}} - \sin 2\beta\right)\left\{1 - \left(\frac{m_{\chi_i^0}}{\mu_{\rm eff}}\right)^2\right\}\right]}{\prod_{k=i,j}\left[1 + \left(\frac{m_{\chi_k^0}}{\mu_{\rm eff}}\right)^2 - 2\frac{m_{\chi_k^0}}{\mu_{\rm eff}}\sin 2\beta + \left\{1 - \left(\frac{m_{\chi_k^0}}{\mu_{\rm eff}}\right)^2\right\}^2\left(\frac{\mu_{\rm eff}}{\lambda v}\right)^2\right]}$$





Effect of λ on BRs





- For a fixed $\Delta m_{\widetilde{H},\widetilde{S}}$, the BR of $\widetilde{H}$-like $\chi_1^\pm$ (χ_i^0) decay to $\widetilde{S}$-like χ_j^0 and $W(Z/h_{SM})$ increases with increasing λ.

- $\widetilde{B}$-like LSP, $\widetilde{S}$-like NLSP, large λ $\Rightarrow$ Degraded the BRs of the final states $3\ell + \not{E}_T$ and $1\ell + 2b\text{-}jet + \not{E}_T$.

  Detailed exercise with $\widetilde{S}$-like LSP and $\widetilde{B}$-like NLSP had been done where it was clearly shown that a small λ region is more preferable.

Abdallah, Chatterjee & Datta, JHEP 09 (2019) 095

Benchmark selection

Input parameters	Singlet (pseudo)scalar funnel		Z-boson funnel		SM-like Higgs funnel		Co-annihilation regime
λ	0.608	0.265	0.563	0.267	0.644	0.230	0.641
κ	-0.110	-0.042	0.093	0.030	0.137	-0.031	0.142
$\tan\beta$	19.72	15.34	26.23	17.64	28.43	23.76	9.160
A_t (TeV)	2.739	4.731	9.476	3.916	4.703	8.926	6.407
A_λ (TeV)	8.219	5.653	-9.666	7.083	9.961	9.705	-3.472
A_κ (GeV)	46.83	38.42	42.16	0.423	-64.97	-1.033	2.647
$\mu_{\rm eff}$ (GeV)	381.9	350.8	-374.3	381.2	352.3	396.2	-386.9
M_1 (GeV)	37.21	-31.26	43.14	-43.29	-58.04	-61.86	169.4
$m_{\chi_1^0}$ (GeV)	37.023	30.756	43.268	43.063	57.953	60.688	167.46
$m_{\chi_2^0}$ (GeV)	126.88	112.84	122.97	87.193	143.82	108.81	170.74
$m_{\chi_3^0}$ (GeV)	406.68	366.96	399.43	399.21	382.17	412.95	415.43
$m_{\chi_4^0}$ (GeV)	421.21	372.04	408.03	401.15	392.24	417.23	424.45
$m_{\chi_1^\pm}$ (GeV)	395.58	363.37	388.34	394.76	365.39	410.43	400.98
m_{h_1} (GeV)	123.92	117.14	125.96	101.11	123.18	118.38	126.32
m_{h_2} (GeV)	185.97	123.40	179.36	123.74	204.37	127.85	192.30
m_{a_1} (GeV)	77.641	64.429	31.354	30.024	36.575	25.825	160.72
N_{11}, N_{21}	-0.99, 0.07	0.99, 0.07	-0.99, -0.07	0.99, -0.04	0.99, -0.07	0.99, 0.09	0.99, -0.04
N_{12}, N_{22}	0.00, -0.01	0.00, -0.00	0.00, 0.01	0.00, 0.00	0.00, -0.01	0.00, 0.00	0.00, 0.01
N_{13}, N_{23}	-0.11, -0.09	0.12, -0.04	-0.11, -0.07	0.11, 0.02	0.12, 0.11	0.11, -0.01	-0.12, -0.09
N_{14}, N_{24}	0.00, -0.29	0.01, -0.14	-0.01, 0.26	0.00, -0.12	0.00, -0.33	0.02, -0.10	-0.03, 0.30
N_{15}, N_{25}	0.07, 0.95	-0.07, 0.99	-0.06, 0.96	0.04, 0.99	0.06, 0.93	-0.09, 0.99	0.04, 0.95
Ωh^2	0.115	0.117	0.113	0.126	0.116	0.115	0.124
$\sigma^{\rm SI}_{\chi_1^0-p(n)} \times 10^{47}$ (cm^2)	1.2(1.3)	0.8(0.8)	4.7(4.8)	0.8(0.8)	5.2(5.3)	3.6(3.6)	0.01(0.01)
$\sigma^{\rm SD}_{\chi_1^0-p(n)} \times 10^{42}$ (cm^2)	5.5(4.3)	7.7(5.9)	5.5(4.2)	5.5(4.2)	7.2(5.6)	5.0(3.8)	6.8(5.2)

Benchmark selection

Observables	Singlet (pseudo)scalar funnel		Z-boson funnel		SM-like Higgs funnel		Co-annihilation regime
BR($\chi_1^\pm \to \chi_1^0 W^\pm$)	0.16	0.49	0.18	0.47	0.16	0.56	0.13
BR($\chi_1^\pm \to \chi_2^0 W^\pm$)	0.84	0.51	0.82	0.53	0.84	0.44	0.87
BR($\chi_2^0 \to \chi_1^0 a_1$)	1.00	1.00	1.00	1.00	1.00	1.00	0.00
BR($\chi_2^0 \to \chi_1^0 \gamma$)	0.00	0.00	0.00	0.00	0.00	0.00	0.91
BR($\chi_3^0 \to \chi_1^0 Z$)	0.09	0.31	0.11	0.25	0.09	0.40	0.05
BR($\chi_3^0 \to \chi_2^0 Z$)	0.66	0.41	0.58	0.22	0.64	0.31	0.65
BR($\chi_3^0 \to \chi_1^0 h_1$)	0.06	0.01	0.07	0.00	0.06	0.01	0.08
BR($\chi_3^0 \to \chi_2^0 h_1$)	0.14	0.00	0.18	0.00	0.12	0.00	0.14
BR($\chi_3^0 \to \chi_1^0 h_2$)	0.00	0.18	0.00	0.21	0.00	0.17	0.01
BR($\chi_3^0 \to \chi_2^0 h_2$)	0.01	0.09	0.00	0.31	0.00	0.11	0.00
BR($\chi_3^0 \to \chi_1^0 a_1$)	0.00	0.00	0.00	0.01	0.00	0.00	0.00
BR($\chi_3^0 \to \chi_2^0 a_1$)	0.04	0.01	0.06	0.00	0.09	0.00	0.08
BR($\chi_4^0 \to \chi_1^0 Z$)	0.09	0.23	0.09	0.26	0.08	0.20	0.10
BR($\chi_4^0 \to \chi_2^0 Z$)	0.22	0.15	0.27	0.34	0.21	0.16	0.24
BR($\chi_4^0 \to \chi_1^0 h_1$)	0.06	0.01	0.08	0.00	0.06	0.01	0.02
BR($\chi_4^0 \to \chi_2^0 h_1$)	0.57	0.01	0.54	0.00	0.62	0.01	0.61
BR($\chi_4^0 \to \chi_1^0 h_2$)	0.00	0.25	0.00	0.24	0.00	0.35	0.00
BR($\chi_4^0 \to \chi_2^0 h_2$)	0.04	0.33	0.00	0.16	0.01	0.26	0.02
BR($\chi_4^0 \to \chi_1^0 a_1$)	0.01	0.00	0.01	0.00	0.01	0.00	0.00
BR($\chi_4^0 \to \chi_2^0 a_1$)	0.01	0.00	0.01	0.01	0.01	0.00	0.00
$C_{\rm BR}^{\chi^0_{3(4)}}$	0.15 (0.15)	0.49 (0.48)	0.18 (0.17)	0.46 (0.50)	0.15 (0.14)	0.57 (0.55)	0.13 (0.12)
$C_{\rm BR}^{\chi^0_{3,4}} \times {\rm BR}(\chi_1^\pm \to \chi_1^0 W^\pm)$	0.048	0.475	0.063	0.451	0.046	0.627	0.033
$\sigma \times {\rm BR}(\to 3\ell)$ (fb)	0.88	12.44	1.27	8.40	1.10	10.19	0.55
$\sigma^{\rm CMS\ Upper\ Limit}_{\rm (Figs.\ 7\ \&\ 8a\ of\ 1801.03957)}$ (fb)	33.02	39.81	32.02	32.15	43.40	27.93	46.70

Naturalness

- In NMSSM, the Z-boson mass is given by,

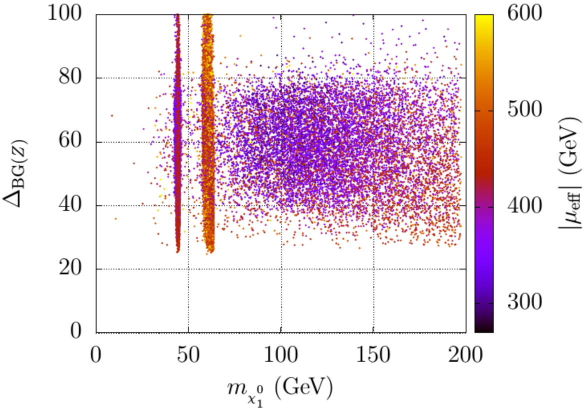
$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{\tan^2\beta - 1} - \mu_{\text{eff}}^2$$

- In order to get m_Z ($\sim$ 91 GeV) without any large cancellation, each term on the right hand side of the above equation cannot be too large compared to m_Z.
- Popular measure of naturalness:

$$\triangle_{BG} = max_i \left| \frac{\partial log m_Z^2}{\partial log p_i} \right|$$

p_i-s denotes the set of Lagrangian parameters of the theory.

- Smaller $\triangle_{BG} \implies$ more natural setup


100
80
60
40
20
0
$\Delta_{BG(Z)}$
0
50
100
150
200
$m_{\chi_1^0}$ (GeV)
600
500
400
300
$|\mu_{eff}|$ (GeV)

Conclusion

- Due to DM and collider constraints the "natural" SUSY (light $\mu_{\rm eff}$) is in tension.

- Found new "well-tempered" bino-higgsino-singlino region in NMSSM.

- Presence of singlino (NLSP) in between higgsino and bino (LSP) has a large impact on evading both collider and DM constraints.

- As we are discussing relatively light LSP mass, the low value of $\frac{m_{\chi_1^0}}{\mu_{\rm eff}}$ requires a relatively large value of $\tan\beta$ to satisfy the SI DMDD bound (blind spot).

Conclusion

- Also, large $\tan\beta$ helps satisfy the relic density bound for pseudoscalar funnel region for LSP mass below top mass via increasing the $g_{a_S b\bar{b}}$ coupling.

- Large λ limit helps achieve small effective BR that leads to suppressed events in $3\ell + \not{E}_T$ and $1\ell + 2b\text{-}jet + \not{E}_T$ final states in the presence of a singlino-like NLSP.

- By compromising a little bit on naturalness, a relatively light (less than m_{top}) bino-like neutralino DM is very much possible in Z_3-symmetric NMSSM.

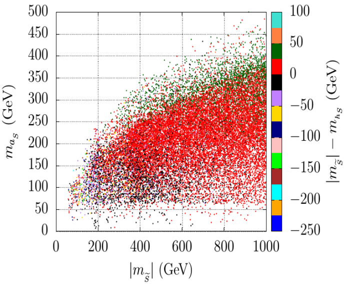
Thank You

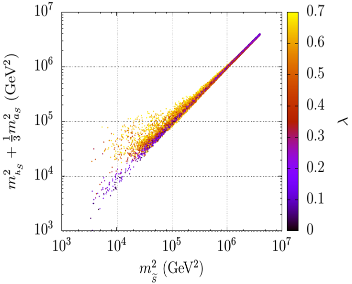
EXTRA SLIDES

Sum rule

- Correlation between m_{h_S}, m_{a_S} and $m_{\widetilde{S}}$ at small 'λ' and large v_S limit (Sum rule):

$$\mathcal{M}^2_{0,55} \simeq \mathcal{M}^2_{S,33} + \frac{1}{3}\mathcal{M}^2_{P,22} \quad \Rightarrow \quad m^2_{\widetilde{S}} \simeq m^2_{h_S} + \frac{1}{3}m^2_{a_S}$$





Interplay among three CP-even Higgs in SI cross section