

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

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Anomalies 2020, IIT Hyderabad  
Sep 12, 2020

- 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  $\hat{S}$   
⇒ an elegant solution to the “ $\mu$ -problem” of MSSM
- Ameliorates the “little hierarchy” problem of MSSM  
→ 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 ( $5 \times 5$ ); 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 ( $\tilde{B}$ )-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  $\tilde{B}$ -like LSP admixtures with singlino ( $\tilde{S}$ ) and higgsino ( $\tilde{H}$ ).  $\Rightarrow$  “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  $\mu_{\text{eff}}$  (for mitigation)

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

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

- The  $\mu$  term in the NMSSM arises from

$$\lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d \rightarrow \lambda \langle S \rangle \widehat{H}_u \cdot \widehat{H}_d \rightarrow \mu_{\text{eff}} \widehat{H}_u \cdot \widehat{H}_d$$

Solution to the “ $\mu$ -problem”.

- The corresponding soft SUSY-breaking Lagrangian is given by

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

- 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**.

- Square mass of the SM-like Higgs boson:

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

- Tree level square mass of singlet-like Higgs:

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

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

- At small  $\lambda$  and large  $v_S$  limit, the first term could be ignored and hence  $|m_{a_S}^2| \approx |-\frac{3}{2} A_\kappa m_{\tilde{S}}|$ .  
⇒ **Small  $A_\kappa$  corresponds to light  $a_S$**

- The symmetric neutralino mass matrix has got a dimensionality of  $5 \times 5$  and, in the basis  $\psi^0 = \{\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\}$ , 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.

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

- The neutralino mass-eigenstates ( $\chi_i^0$ ), in terms of the weak eigenstates ( $\psi_j^0$ ), are given by

$$\chi_i^0 = N_{ij}\psi_j^0$$

' $N$ ' is the  $5 \times 5$  matrix that diagonalizes the neutralino mass-matrix.

- The  $2 \times 2$  chargino mass matrix in the bases  $\psi^+ = \{-i\widetilde{W}^+, \widetilde{H}_u^+\}$  and  $\psi^- = \{-i\widetilde{W}^-, \widetilde{H}_d^-\}$  is given by

$$\mathcal{M}_C = \begin{pmatrix} M_2 & g_2 v_u \\ g_2 v_d & \mu_{\text{eff}} \end{pmatrix}$$

The asymmetric matrix  $\mathcal{M}_C$  can be diagonalized by two  $2 \times 2$  unitary matrices  $U$  and  $V$ :

$$U^* \mathcal{M}_C V^\dagger = \text{diag}(m_{\chi_1^\pm}, m_{\chi_2^\pm}); \quad \text{with } m_{\chi_1^\pm} < m_{\chi_2^\pm}$$



- When  $M_2$  is decoupled,

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

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

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

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

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

- New parameters of NMSSM:  $\lambda$ ,  $\kappa$ ,  $A_\lambda$ ,  $A_\kappa$

$\lambda$	$ \kappa $	$\tan \beta$	$ \mu_{\text{eff}} $ (GeV)	$ A_\lambda $ (TeV)	$ A_\kappa $ (GeV)	$ M_1 $ (GeV)	$A_t$ (TeV)
0.001		1					0
↓	$\leq 0.7$	↓	$\leq 1000$	$\leq 10$	$\leq 100$	$< 200$	↓
0.7		65					10

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

- Toolbox:

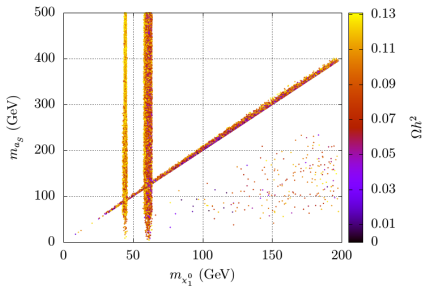
NMSSMTools-v5.4.1 (with micrOMEGAs),

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

- Planck-reported  $2\sigma$  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  $pp \rightarrow \chi_1^\pm \chi_2^0 \rightarrow WZ E_T \rightarrow 3l + E_T$  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).
- $g_{Z\chi_1^0\chi_1^0} \propto \mu_{\text{eff}}^{-2}$  where as the  $g_{h_{SM}\chi_1^0\chi_1^0} \propto \mu_{\text{eff}}^{-1}$ .  
 $\Rightarrow \mu_{\text{eff}}$  receives **upper bound** from observed relic density.
- We see that for  $Z$ -funnel region  $\mu_{\text{eff}} < 450$  GeV. For  $h_{SM}$  funnel, it is possible to satisfy relic density for  $\mu_{\text{eff}}$  up to 1 TeV.



# SI cross-section coupling blind spot condition

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

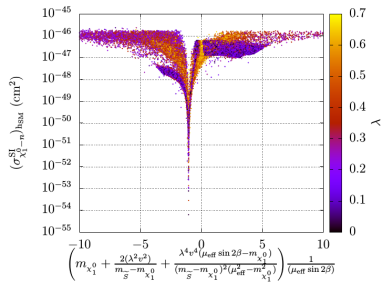
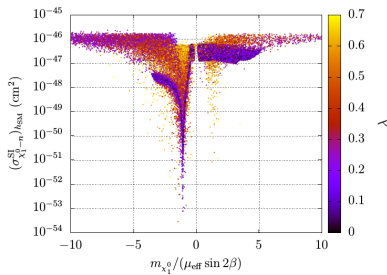
$\tilde{B}$ -like LSP s-channel annihilation via  $a_S$ -funnel  $\Rightarrow$  Need moderately large  $\lambda$

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

Coupling SI cross-section blind spot condition:

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

# SI cross-section coupling blind spot



# SI cross-section blind spot condition

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

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

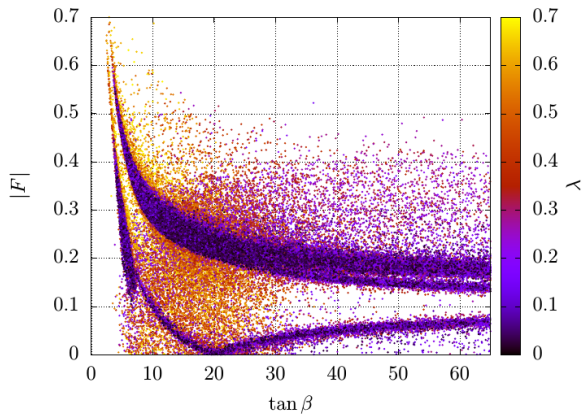
$$\begin{aligned} F &= \frac{m_{\chi_1^0}}{\mu_{\text{eff}}} + \sin 2\beta + \frac{2\lambda^2 v^2}{\mu_{\text{eff}} (m_{\tilde{S}} - m_{\chi_1^0})} + \frac{\lambda^4 v^4 (\sin 2\beta - m_{\chi_1^0} / \mu_{\text{eff}})}{(m_{\tilde{S}} - m_{\chi_1^0})^2 (\mu_{\text{eff}}^2 - m_{\chi_1^0}^2)} \\ &+ \frac{\cos 2\beta}{2} \left( \tan \beta - \frac{1}{\tan \beta} \right) \left[ \frac{\lambda^2 v^2 [\lambda^2 v^2 + 2m_{\chi_1^0} (m_{\tilde{S}} - m_{\chi_1^0})]}{(m_{\tilde{S}} - m_{\chi_1^0})^2 (\mu_{\text{eff}}^2 - m_{\chi_1^0}^2)} - 1 \right] \frac{m_{h_{SM}}^2}{m_H^2} \\ &\approx 0 \end{aligned}$$

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

$$\frac{m_{\chi_1^0}}{\mu_{\text{eff}}} + \sin 2\beta + \frac{m_{h_{SM}}^2}{m_H^2} \frac{\tan \beta}{2} \approx 0.$$



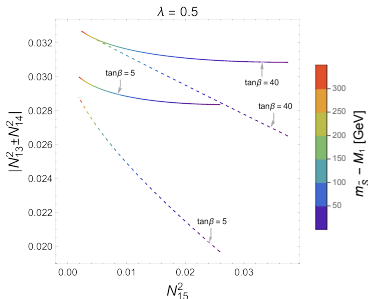
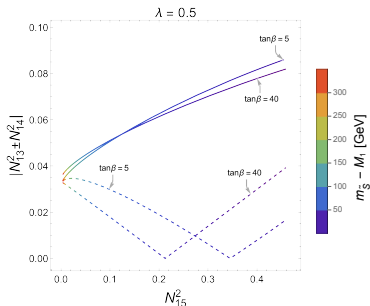
# SI cross-section blind spot dependence on $\tan\beta$



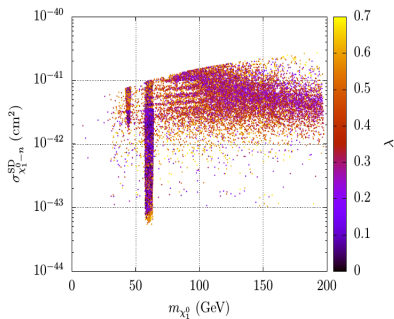
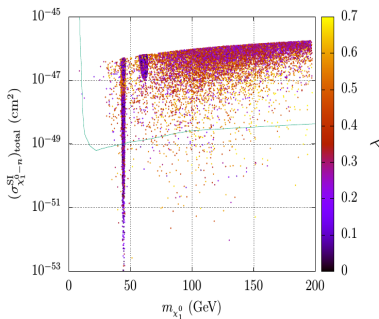
# SD cross-section dependence on singlino tempering

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

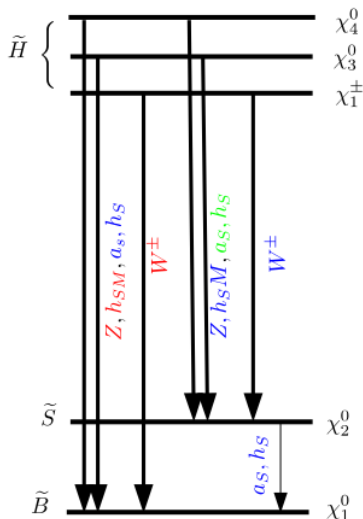
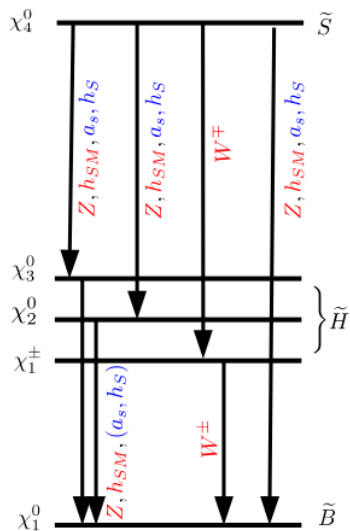
$$N_{13}^2 - N_{14}^2 = \frac{g_1^2 v^2}{2I} \cos 2\beta \left[ -1 + \frac{2\lambda^2 v^2}{\left(\frac{m_{\tilde{S}}}{m_{\chi_1^0}} - 1\right)(\mu_{\text{eff}}^2 - m_{\chi_1^0}^2)} + \frac{\lambda^4 v^4}{(m_{\tilde{S}} - m_{\chi_1^0})^2 (\mu_{\text{eff}}^2 - m_{\chi_1^0}^2)} \right]$$



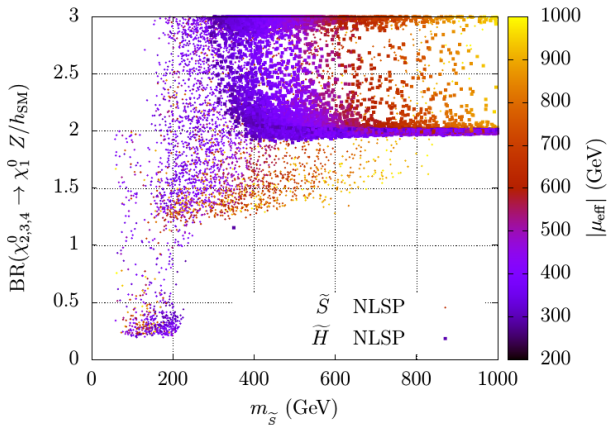
- **SD bound** pushes  $\mu_{\text{eff}} > 280$  GeV.
- Need to satisfy closely the SI **blind spot** condition to satisfy new SI DMDD bounds.
- Natural NMSSM (low  $\mu_{\text{eff}}$ ) is in tension with DM and collider constraints.

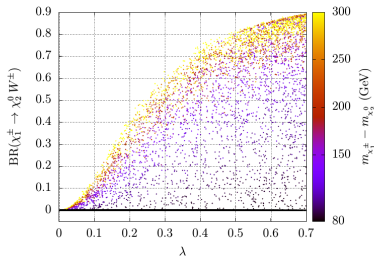
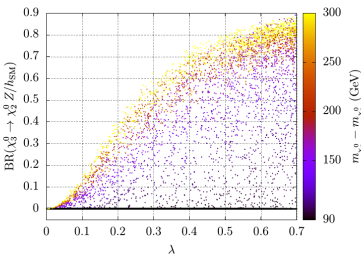


# Effect of Singlino NLSP on BRs



# Effect of Singlino NLSP on BRs





- For a fixed  $\Delta m_{\tilde{H}, \tilde{S}}$ , the BR of  $\tilde{H}$ -like  $\chi_{1^\pm}$  ( $\chi_i^0$ ) decay to  $\tilde{S}$ -like  $\chi_j^0$  and  $W(Z/h_{SM})$  increases with increasing  $\lambda$ .
- $\tilde{B}$ -like LSP,  $\tilde{S}$ -like NLSP, large  $\lambda \Rightarrow$  Degraded the BRs of the final states  $3\ell + \cancel{E}_T$  and  $1\ell + 2b\text{-jet} + \cancel{E}_T$ .

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

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

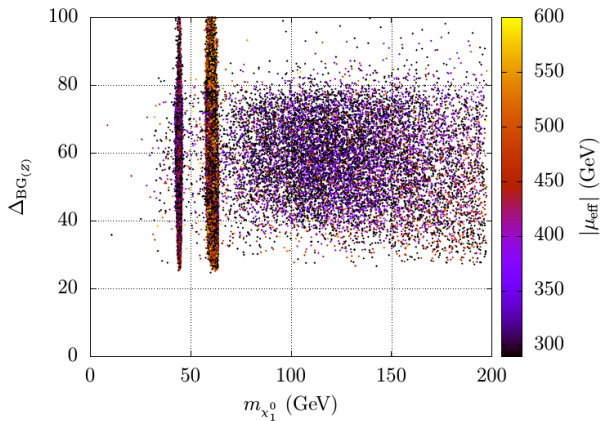
$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d - (m_{H_u}^2 + \Sigma_u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu_{\text{eff}}^2$$

- 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**:

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

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

- **Smaller  $\Delta_{BG} \implies$  more natural setup**





- Due to DM and collider constraints the “**natural**” SUSY (light  $\mu_{\text{eff}}$ ) 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  $\frac{m_{\tilde{\chi}_1^0}}{\mu_{\text{eff}}}$  requires a relatively **large value of  $\tan\beta$**  to satisfy the SI DMDD bound (**blind spot**).

- 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  $\lambda$  limit helps achieve **small effective BR** that leads to suppressed events in  $3\ell + \cancel{E}_T$  and  $1\ell + 2b\text{-jet} + \cancel{E}_T$  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

- The most sensitive process  $pp \rightarrow \chi_1^\pm \chi_2^0$ .
- $pp \rightarrow \chi_1^\pm \chi_2^0 \rightarrow WZ \cancel{E}_T \rightarrow 3\ell + \cancel{E}_T$ . 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  $pp \rightarrow \chi_1^\pm \chi_2^0 \rightarrow WH \cancel{E}_T \rightarrow 1\ell + 2b\text{-jet} + \cancel{E}_T$ , a corresponding bound as stringent as wino like  $m_{\chi_1^\pm} (= m_{\chi_2^0}) > \mathbf{740 GeV}$ .

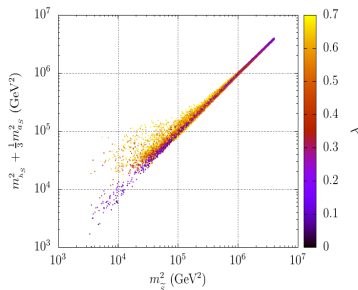
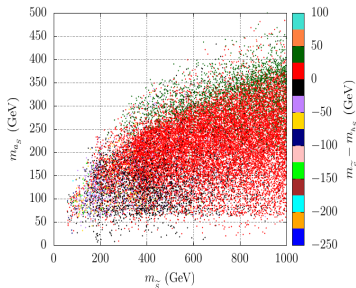
*ATLAS Collaboration, Eur.Phys.J.C 80 (2020) 8, 691*

- 'Mixed' mode where  $\chi_2^0$  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  $m_{\chi_1^\pm} (= m_{\chi_2^0})$ .

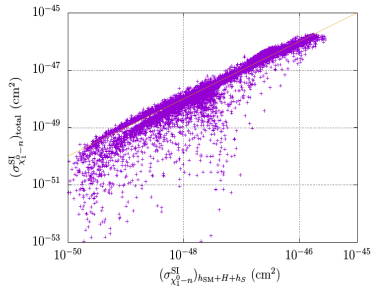
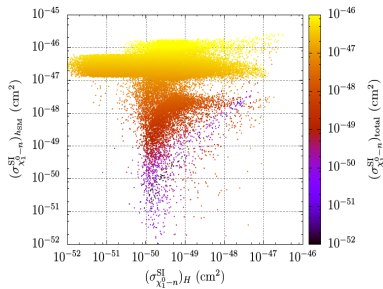
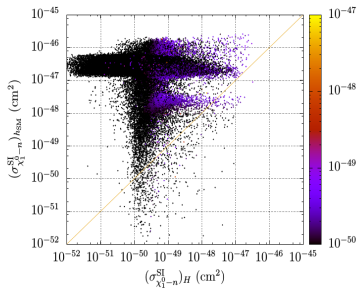
*CMS Collaboration, JHEP 03 (2018) 160*

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

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



# Interplay among three $CP$ -even Higgs in SI cross section



# Benchmark selection

Input parameters	Singlet (pseudo)scalar funnel		Z-boson funnel		SM-like Higgs funnel		Co-annihilation regime
$\lambda$	0.608	0.265	0.563	0.267	0.644	0.230	0.641
$\kappa$	-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
$A_\lambda$ (TeV)	8.219	5.653	-9.666	7.083	9.961	9.705	-3.472
$A_\kappa$ (GeV)	46.83	38.42	42.16	0.423	-64.97	-1.033	2.647
$\mu$ (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
$m_{\chi_0}$ (GeV)	37.023	30.756	43.268	43.063	57.953	60.688	167.46
$m_{\chi_1}$ (GeV)	126.88	112.84	122.97	87.193	143.82	108.81	170.74
$m_{\chi_2}$ (GeV)	406.68	366.96	399.43	399.21	382.17	412.95	415.43
$m_{\chi_3}$ (GeV)	421.21	372.04	408.03	401.15	392.24	417.23	424.45
$m_{\chi_4}$ (GeV)	395.58	363.37	388.34	394.76	365.39	410.43	400.98
$m_{\chi_1^\pm}$ (GeV)	123.92	117.14	125.96	101.11	123.18	118.38	126.32
$m_{h_1}$ (GeV)	185.97	123.40	179.36	123.74	204.37	127.85	192.30
$m_{h_2}$ (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
$\Omega h^2$	0.115	0.117	0.113	0.126	0.116	0.115	0.124
$\sigma_{\chi_1^0-p(n)}^{\text{SI}} \times 10^{47}$ (cm <sup>2</sup> )	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)
$\sigma_{\chi_1^0-p(n)}^{\text{SD}} \times 10^{42}$ (cm <sup>2</sup> )	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
$\text{BR}(\chi_1^\pm \rightarrow \chi_1^0 W^\pm)$	0.16	0.49	0.18	0.47	0.16	0.56	0.13
$\text{BR}(\chi_1^\pm \rightarrow \chi_2^0 W^\pm)$	0.84	0.51	0.82	0.53	0.84	0.44	0.87
$\text{BR}(\chi_2^0 \rightarrow \chi_1^0 a_1)$	1.00	1.00	1.00	1.00	1.00	1.00	0.00
$\text{BR}(\chi_2^0 \rightarrow \chi_1^0 \gamma)$	0.00	0.00	0.00	0.00	0.00	0.00	0.91
$\text{BR}(\chi_3^0 \rightarrow \chi_1^0 Z)$	<u>0.09</u>	<u>0.31</u>	<u>0.11</u>	<u>0.25</u>	<u>0.09</u>	<u>0.40</u>	<u>0.05</u>
$\text{BR}(\chi_3^0 \rightarrow \chi_2^0 Z)$	0.66	0.41	0.58	0.22	0.64	0.31	0.65
$\text{BR}(\chi_3^0 \rightarrow \chi_1^0 h_1)$	<u>0.06</u>	0.01	<u>0.07</u>	0.00	<u>0.06</u>	0.01	<u>0.08</u>
$\text{BR}(\chi_3^0 \rightarrow \chi_2^0 h_1)$	0.14	0.00	0.18	0.00	0.12	0.00	0.14
$\text{BR}(\chi_3^0 \rightarrow \chi_1^0 h_2)$	0.00	<u>0.18</u>	0.00	<u>0.21</u>	0.00	<u>0.17</u>	0.01
$\text{BR}(\chi_3^0 \rightarrow \chi_2^0 h_2)$	0.01	0.09	0.00	0.31	0.00	0.11	0.00
$\text{BR}(\chi_3^0 \rightarrow \chi_1^0 a_1)$	0.00	0.00	0.00	0.01	0.00	0.00	0.00
$\text{BR}(\chi_3^0 \rightarrow \chi_2^0 a_1)$	0.04	0.01	0.06	0.00	0.09	0.00	0.08
$\text{BR}(\chi_4^0 \rightarrow \chi_1^0 Z)$	<u>0.09</u>	<u>0.23</u>	<u>0.09</u>	<u>0.26</u>	<u>0.08</u>	<u>0.20</u>	<u>0.10</u>
$\text{BR}(\chi_4^0 \rightarrow \chi_2^0 Z)$	0.22	0.15	0.27	0.34	0.21	0.16	0.24
$\text{BR}(\chi_4^0 \rightarrow \chi_1^0 h_1)$	<u>0.06</u>	0.01	<u>0.08</u>	0.00	<u>0.06</u>	0.01	<u>0.02</u>
$\text{BR}(\chi_4^0 \rightarrow \chi_2^0 h_1)$	0.57	0.01	0.54	0.00	0.62	0.01	0.61
$\text{BR}(\chi_4^0 \rightarrow \chi_1^0 h_2)$	0.00	<u>0.25</u>	0.00	<u>0.24</u>	0.00	<u>0.35</u>	0.00
$\text{BR}(\chi_4^0 \rightarrow \chi_2^0 h_2)$	0.04	0.33	0.00	0.16	0.01	0.26	0.02
$\text{BR}(\chi_4^0 \rightarrow \chi_1^0 a_1)$	0.01	0.00	0.01	0.00	0.01	0.00	0.00
$\text{BR}(\chi_4^0 \rightarrow \chi_2^0 a_1)$	0.01	0.00	0.01	0.01	0.01	0.00	0.00
$C_{\text{BR}}^{\chi_3^{0(4)}}$	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)
$C_{\text{BR}}^{\chi_3^{0,4}} \times \text{BR}(\chi_1^\pm \rightarrow \chi_1^0 W^\pm)$	0.048	0.475	0.063	0.451	0.046	0.627	0.033
$\sigma \times \text{BR}(\rightarrow 3\ell)$ (fb)	0.88	12.44	1.27	8.40	1.10	10.19	0.55
CMS Upper Limit $\sigma$ (Figs. 7 & 8a of 1801.03957) (fb)	33.02	39.81	32.02	32.15	43.40	27.93	46.70