Singlino-Higgsino Dark Matter in the NMSSM

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Based on Xiang, Bi, Yin, ZHY, arXiv:1606.02149

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Motivation

Shortages of the Standard Model (SM)

- Radiative correction to the Higgs mass term ⇒ hierarchy problem
- No cold dark matter (DM) candidate
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Supersymmetry (SUSY) and $R$-parity conservation
- Elegant solution to the hierarchy problem
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- Push gluino and squark mass limits up to $\gtrsim \mathcal{O}(1)$ TeV
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No evidence of superpartners in LHC Run 1 data
- Push gluino and squark mass limits up to $\gtrsim \mathcal{O}(1)$ TeV
- Electroweak (EW) production rate are much lower; $m \sim \mathcal{O}(100)$ GeV EW superpartners could hide in Run 1 searches

LHC Run 2 and further searches are promising to directly probe an $\mathcal{O}(100)$ GeV-scale neutralino-chargino sector
No explanation for why $\mu$ is of the same order of the SUSY breaking scale in the Minimal Supersymmetric Standard Model (MSSM): $\mu$-problem

$\Downarrow$

Introducing a singlet chiral superfield $\hat{S}$ in the NMSSM: $\mu_{\text{eff}} = \lambda v_s$
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Introducing a singlet chiral superfield $\hat{S}$ in the NMSSM: $\mu_{\text{eff}} = \lambda v_s$

$Z_3$-invariant (scale-invariant) superpotential: $W_{\text{MSSM}} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \kappa \hat{S}^3 / 3$

Soft breaking terms in the Higgs sector:

$$V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + (\lambda A_\lambda S H_u H_d + \kappa A_\kappa S^3 / 3 + \text{h.c.})$$

Higgs and higgsino sectors are determined by $\{\lambda, \kappa, A_\lambda, A_\kappa, \mu_{\text{eff}}, \tan \beta \equiv v_u / v_d\}$

Neutralino mass matrix for the gauge basis $(\tilde{B}, \tilde{W}_0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$:

$$M_N = \begin{pmatrix}
M_1 & 0 & -g_1 v_d / \sqrt{2} & g_1 v_u / \sqrt{2} & 0 \\
M_2 & g_2 v_d / \sqrt{2} & -g_2 v_u / \sqrt{2} & 0 & 0 \\
0 & -\mu_{\text{eff}} & -\lambda v_u & -\lambda v_d & 2\kappa v_s 
\end{pmatrix}$$
Simplified Scenarios for the Neutralino-Chargino Sector

Singlino-dominated LSP $\tilde{\chi}_1^0 \sim \tilde{S} \Rightarrow$ different phenomenology from MSSM’s
Simplified Scenarios for the Neutralino-Chargino Sector

Singlino-dominated LSP $\tilde{\chi}_1^0 \sim \tilde{S}$ ⇒ different phenomenology from MSSM's

Simplified scenarios with split spectra

- **Singlino-Bino Scenario** ($2\kappa v_s < M_1 \ll M_2, \mu_{\text{eff}}$): $\tilde{\chi}_1^0 \sim \tilde{S}$, $\tilde{\chi}_2^0 \sim \tilde{B}$
  - Observed DM relic density ⇒ $m_{\tilde{\chi}_1^0} \sim \mathcal{O}(10)$ GeV
  - Very low production rates for $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ at the LHC
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- **Singlino-Wino Scenario** ($2\kappa \nu_s < M_2 \ll M_1, \mu_{\text{eff}}$): $\tilde{\chi}_1^0 \sim \tilde{S}$; $\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm} \sim \tilde{W}$
  - Moderate $\tilde{\chi}_2^0 \tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{+} \tilde{\chi}_1^{-}$ production rates
  - LHC sensitivity is similar to the bino-wino scenario in the MSSM
Simplified Scenarios for the Neutralino-Chargino Sector

Singlino-dominated LSP $\tilde{\chi}_1^0 \sim \tilde{S}$ ⇒ different phenomenology from MSSM’s

Simplified scenarios with split spectra

- **Singlino-Bino Scenario** ($2\kappa \eta_s < M_1 \ll M_2, \mu_{\text{eff}}$): $\tilde{\chi}_1^0 \sim \tilde{S}$, $\tilde{\chi}_2^0 \sim \tilde{B}$
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- **Singlino-Wino Scenario** ($2\kappa \eta_s < M_2 \ll M_1, \mu_{\text{eff}}$): $\tilde{\chi}_1^0 \sim \tilde{S}$; $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \sim \tilde{W}$
  - Moderate $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production rates
  - LHC sensitivity is similar to the bino-wino scenario in the MSSM

- **Singlino-Higgsino Scenario** ($2\kappa \eta_s < \mu_{\text{eff}} \ll M_1, M_2$): $\tilde{\chi}_1^0 \sim \tilde{S}$; $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \sim \tilde{H}$
  - Higgsino components of $\tilde{\chi}_1^0$ help satisfy the observed relic density
  - Lower $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ rates compared with the singlino-wino scenario
  - Previous studies on this scenario focused on LHC [Ellwanger, 1309.1665; Kim & Ray, 1405.3700] and IceCube [Enberg et al., 1506.05714] searches
Parameter Scan

For the singlino-higgsino scenario, we perform a random parameter scan upon

\begin{align*}
100 \text{ GeV} & \leq \mu_{\text{eff}} \leq 600 \text{ GeV} & -1 \text{ TeV} & \leq A_\kappa \leq 0 & 100 \text{ GeV} & \leq A_\lambda \leq 10 \text{ TeV} \\
1 & \leq \tan \beta \leq 50 & 0.05 & \leq \lambda \leq 0.7 & 0.05 & \leq \kappa/\lambda \leq 0.4
\end{align*}

The condition \( \kappa/\lambda \leq 0.4 \) is imposed for ensuring \( \tilde{\chi}^0_1 \sim \tilde{S} \)

Set \( M_1 = M_2 = 2 \text{ TeV} \) and other dimensional parameters to be 5 TeV
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\[
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\]

The condition $\kappa/\lambda \leq 0.4$ is imposed for ensuring $\tilde{\chi}_1^0 \sim \tilde{S}$

Set $M_1 = M_2 = 2$ TeV and other dimensional parameters to be 5 TeV

NMSSMTools 4.6 and micrOMEGAs 3 are employed for calculating mass spectra, relic density, and other observable. The following constraints are imposed.

- **DM relic density:** $\Omega_{\tilde{\chi}_1^0} h^2 < 0.131$
- **Higgs:** an SM-like Higgs with $m_h = 122 - 128$ GeV; current Higgs bounds
- **LEP bounds:** $m_{\tilde{\chi}_1^\pm} > 103.5$ GeV; $\Gamma_{Z}^{\text{inv}} < 2$ MeV
- **Muon $g-2$:** within the 3$\sigma$ deviation $-5.62 \times 10^{-11} < a_{\mu}^{\text{NMSSM}} < 5.54 \times 10^{-9}$
- **B physics bounds:** $1.7 \times 10^{-9} < \text{BR}(B_s \rightarrow \mu^+ \mu^-) < 4.5 \times 10^{-9}$;
  \[0.85 \times 10^{-4} < \text{BR}(B^+ \rightarrow \tau^+ \nu) < 2.89 \times 10^{-4}; \quad 2.99 \times 10^{-4} < \text{BR}(B_s \rightarrow X_s \gamma) < 3.87 \times 10^{-4}\]
Relic Density $\Omega \tilde{\chi}_1^0 h^2$ and singlino component $|N_{15}|^2$

- All points pass the above constraints; red points for $0.107 < \Omega \tilde{\chi}_1^0 h^2 < 0.131$
- $m_{\tilde{\chi}_1^0} \sim 45$ GeV and $\sim 60$ GeV: resonance enhancements of the $Z$ boson and the SM-like Higgs boson for $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ annihilation
- $m_{\tilde{\chi}_1^0} \gtrsim 70$ GeV: smaller $|N_{15}|^2$ and sizable Higgsino components
Decay patterns of $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_3$

- **$\tilde{\chi}^0_2$ decay pattern**
  - $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 Z$ is typically dominant

- **$\tilde{\chi}^0_3$ decay pattern**
  - $\tilde{\chi}^0_3 \to \tilde{\chi}^0_1 Z$, $\tilde{\chi}^0_3 \to \tilde{\chi}^0_1 h_1$, and $\tilde{\chi}^0_3 \to \tilde{\chi}^0_1 h_2$ are significant
<table>
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<th>Benchmark Points</th>
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<td><strong>Parameter Scan</strong></td>
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<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>BP1</strong></th>
<th><strong>BP2</strong></th>
<th><strong>BP3</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda, \kappa$</td>
<td>0.091, 0.016</td>
<td>0.270, 0.100</td>
<td>0.368, 0.144</td>
</tr>
<tr>
<td>$\tan\beta, \mu_{\text{eff}}$ (GeV)</td>
<td>39.6, 163.3</td>
<td>35.1, 121.3</td>
<td>35.6, 121.0</td>
</tr>
<tr>
<td>$A_\kappa$ (GeV), $A_\lambda$ (TeV)</td>
<td>39.6, 163.3</td>
<td>35.1, 121.3</td>
<td>35.6, 121.0</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}_1^0}$ (GeV)</td>
<td>59.6</td>
<td>77.0</td>
<td>71.7</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}<em>2^0}$, $m</em>{\tilde{\chi}<em>3^0}$, $m</em>{\tilde{\chi}_1^\pm}$ (GeV)</td>
<td>169, 173, 170</td>
<td>134, 146, 126</td>
<td>137, 160, 126</td>
</tr>
<tr>
<td>$m_{h_1}$, $m_{h_2}$, $m_{a_1}$ (GeV)</td>
<td>46.0, 126, 55.8</td>
<td>23.0, 125, 153</td>
<td>95.3, 125, 38.7</td>
</tr>
<tr>
<td>$</td>
<td>N_{13}</td>
<td>^2 +</td>
<td>N_{14}</td>
</tr>
<tr>
<td>$\Omega_{\tilde{\chi}_1^0} h^2$</td>
<td>0.120</td>
<td>0.059</td>
<td>0.067</td>
</tr>
<tr>
<td>BR($\tilde{\chi}_2^0$ $\rightarrow$ $\tilde{\chi}_1^0 X$)</td>
<td>$Z$ 98.7%</td>
<td>$h_1$ 84.4%, $q\bar{q}$ 10.6%, $\ell^+\ell^-$ 3%, $\nu_\ell\bar{\nu}_\ell$ 3%</td>
<td>$a_1$ 98.6%</td>
</tr>
<tr>
<td>BR($\tilde{\chi}_3^0$ $\rightarrow$ $\tilde{\chi}_1^0 X$)</td>
<td>$Z$ 97.1%</td>
<td>$h_1$ 100%</td>
<td>$a_1$ 73.2%, $q\bar{q}$ 14%, $\ell^+\ell^-$ 2%, $\nu_\ell\bar{\nu}_\ell$ 4%</td>
</tr>
<tr>
<td>BR($h_1/a_1$ $\rightarrow$ $b\bar{b}$/$\tau^+\tau^-$)</td>
<td>/</td>
<td>$h_1$ $\rightarrow$ $b\bar{b}$ 91.8%, $h_1$ $\rightarrow$ $\tau^+\tau^-$ 7.3%</td>
<td>$a_1$ $\rightarrow$ $b\bar{b}$ 91.8%, $a_1$ $\rightarrow$ $\tau^+\tau^-$ 7.7%</td>
</tr>
</tbody>
</table>
LHC Searches

We consider $pp \rightarrow \tilde{\chi}^0_{2,3} \tilde{\chi}_1^\pm$ and $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ production at the LHC for the survived parameter points in the singlino-higgsino scenario.

MC simulation: MadGraph 5 + PYTHIA 6 + Delphes 3

MLM matching \hspace{1cm} ATLAS setup
**Motivation**

**Parameter Scan**

**LHC Searches**

**Direct and Indirect DM Detection**

**Conclusion**

**Backup**

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### 3\(\ell\) + \(\not{E}_T\) Channel

![Graph showing event distributions for different masses](image)

**Main backgrounds:** \(WZ + \text{jets}\) and \(ZZ + \text{jets}\) production

**Selection cuts at \(\sqrt{s} = 14\text{ TeV}\):** exact 3 charged leptons \(\ell\) (\(\ell = e, \mu\)) with \(p_T > 20\text{ GeV}\) and \(|\eta| < 2.5\); no \(b\)-jet with \(p_T > 30\text{ GeV}\) and \(|\eta| < 2.5\); \(|m_{\text{SFOS}} - m_Z| < 10\text{ GeV}\); \(\not{E}_T > 50\) or \(100\text{ GeV}\); \(m_T > 100\text{ GeV}\)

\(m_{\text{SFOS}}\) is the invariant mass of a same-flavor opposite-sign (SFOS) lepton pair. Transverse mass \(m_T \equiv \sqrt{2(p_T \not{E}_T - p_T \cdot p_T)}\) with \(\ell\) the one not forming the SFOS lepton pair.

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**Zhao-Huan Yu (Melbourne)**

**Singlino-Higgsino Dark Matter in the NMSSM**

**July 2016**
Main backgrounds: \( t \bar{t} \) + jets, \( WW \) + jets, \( WZ \) + jets, and \( ZZ \) + jets production

Selection cuts at \( \sqrt{s} = 14 \text{ TeV} \): exact 2 opposite-sign charged leptons with \( p_{T1} > 30 \text{ GeV}, p_{T2} > 20 \text{ GeV}, \text{ and } |\eta| < 2.5; \ |m_{\text{SFOS}} - m_Z| > 10 \text{ GeV}; \nojet \) with \( p_T > 30 \text{ GeV} \text{ and } |\eta| < 2.5; \ m_{T2} > 90, 120, \text{ or } 150 \text{ GeV} \)

(Stransverse mass \( m_{T2} \equiv \min \{ \max[m_T(p_{T1}, p_{T1}^1), m_T(p_{T2}, p_{T2}^2)] \} \).)
(Expected) Exclusion at 95% CL

Red/blue/green points: $\sqrt{s} = 8/13/14$ TeV with $20/30/300$ fb$^{-1}$ data

8 TeV results are recasted from Run 1 analyses [ATLAS, 1402.7029, 1403.5294]

- $3\ell + \not{E}_T$ channel at 14 TeV: up to $m_{\tilde{\chi}_2^0, \tilde{\chi}_1^\pm} \sim 420$ GeV
- $2\ell + \not{E}_T$ channel at 14 TeV: up to $m_{\tilde{\chi}_2^0, \tilde{\chi}_1^\pm} \sim 500$ GeV
- Some points with $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \lesssim m_Z$ are hard to probe due to soft final states
Spin-Independent (SI) DM-Nuclei Scattering

In the singlino-higgsino scenario, the SI DM-nuclei scattering is mediated by $h_1$ and $h_2$

Resonance enhancement for freeze-out
\[\downarrow\]
Small higgsino components in $\tilde{\chi}_1^0$
\[\downarrow\]
Small scattering cross section

90% CL exclusion limits: LUX [1310.8214], XENON1T expected for 2 t · yr [1512.07501]

Red/blue/green points: 8/13/14 TeV LHC
\[\Diamond\] BP1  \[\triangledown\] BP2  \[\triangle\] BP3
In the singlino-higgsino scenario, the **SI** DM-nuclei scattering is mediated by $h_1$ **and** $h_2$

Resonance enhancement for freeze-out

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◊ BP1  ▽ BP2  △ BP3

Define $\xi = \min(1, \Omega_{\tilde{\chi}_1^0} h^2 / 0.107)$ to take into account the possibility that $\tilde{\chi}_1^0$ just contributes a fraction of dark matter →
Spin-Dependent (SD) DM-Nuclei Scattering

The **Z-mediated SD** DM-nuclei scattering cross section $\sigma^{SD}$ is typically **larger** than $\sigma^{SI}$ by $\sim 2 - 6$ orders of magnitude, but the experimental constraints are quite weak.

90% CL exclusion limits:
- **PICO** [1503.00008, 1510.07754]
- **LZ** expected for 5600 t · day [1509.02910]
- **IceCube** search for $\nu_\mu$ from $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow t \bar{t}$ in the center of the Sun [1601.00653]

Introducing $\xi$ will weaken the constraints →

**Red/blue/green points**: 8/13/14 TeV LHC
- ♦ BP1
- ▽ BP2
- △ BP3
**DM Annihilation**

*p-wave annihilation* is important at the freeze-out epoch, but becomes *negligible* for today's nonrelativistic DM relevant to indirect detection.

Nonrelativistic $\tilde{\chi}^0_1 \tilde{\chi}^0_1$ annihilation

- $m_{\tilde{\chi}^0_1} \lesssim m_t$: $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow b\bar{b}$ or $a_1 h_1$ dominant with $\langle \sigma_{\text{ann}} v \rangle \sim \mathcal{O}(10^{-31} - 10^{-27})$ cm$^3$/s
- $m_{\tilde{\chi}^0_1} \gtrsim m_t$: $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow t\bar{t}$ dominant with canonical $\langle \sigma_{\text{ann}} v \rangle \sim \mathcal{O}(10^{-26})$ cm$^3$/s

95% CL exclusion limits for $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow b\bar{b}$:
- **Fermi-LAT** $\gamma$-ray observation of dwarf galaxies for 6 years [1503.02641], expected **CTA** $\gamma$-ray observation of GC vicinities for 100 h [1208.5356]

**Red/blue/green points:** 8/13/14 TeV LHC

diamond BP1   triangle BP2   triangle BP3

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Conclusion

1. We have investigated the **singlino-higgsino scenario** in the NMSSM, where the LSP should have either resonant annihilation effects or sizable higgsino components to satisfy the observed DM relic density.

2. **LHC $3\ell + \cancel{E_T}$ and $2\ell + \cancel{E_T}$** searches at 13 and 14 TeV can well explore the **low mass resonant region**, but lose sensitivity for compressed mass spectra or heavy LSP.

3. **Direct and indirect DM detection** experiments may not easily probe the resonant region, but are promising to cover the **high mass region**.
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LHC $3\ell + \not{E}_T$ and $2\ell + \not{E}_T$ searches at 13 and 14 TeV can well explore the low mass resonant region, but lose sensitivity for compressed mass spectra or heavy LSP.

Direct and indirect DM detection experiments may not easily probe the resonant region, but are promising to cover the high mass region.

Thanks for your attention!
## Cut Flows

### $3\ell + \not{E}_T$ channel at $\sqrt{s} = 14$ TeV

<table>
<thead>
<tr>
<th></th>
<th>WZ</th>
<th>ZZ</th>
<th>BP1</th>
<th>BP2</th>
<th>BP3</th>
</tr>
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<tbody>
<tr>
<td>$\sigma$</td>
<td>105</td>
<td>17.3</td>
<td>6.39</td>
<td>9.77</td>
<td>0.021</td>
</tr>
<tr>
<td>$S$</td>
<td>0.033</td>
<td>0.060</td>
<td>0.095</td>
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</table>

- Basic cuts
- $\not{E}_T > 50$ GeV
- $m_T > 100$ GeV

<table>
<thead>
<tr>
<th></th>
<th>WZ</th>
<th>ZZ</th>
<th>WW</th>
<th>$t\bar{t}$</th>
<th>BP1</th>
<th>BP2</th>
<th>BP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>88.8</td>
<td>22.3</td>
<td>1798</td>
<td>8930</td>
<td>16.8</td>
<td>2.79</td>
<td>9.75</td>
</tr>
<tr>
<td>$S$</td>
<td>1.62</td>
<td>2.12</td>
<td>12.7</td>
<td>2.12</td>
<td></td>
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</tbody>
</table>

- Jet veto
- $m_{T2} > 90$ GeV

$(\sigma$ in fb; $S \equiv S/\sqrt{B+S}$ calculated with an integrated luminosity of 300 fb$^{-1}$)
Indirect Detection: the $\xi^2$ Factor

Without the $\xi^2$ factor

With the $\xi^2$ factor

Red/blue/green points: 8/13/14 TeV LHC

◊ BP1  ▽ BP2  △ BP3