Singlino-Higgsino Dark Matter in the NMSSM

Zhao-Huan Yu (余钊焕)

ARC Centre of Excellence for Particle Physics at the Terascale,
School of Physics, The University of Melbourne

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

SUSY 2016 Conference

7 July 2016, Melbourne

THE UNIVERSITY OF MELBOURNE

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Motivation

Shortages of the Standard Model (SM)

- Radiative correction to the Higgs mass term $\Rightarrow$ **hierarchy problem**
- No cold **dark matter (DM)** candidate

Motivation

Shortages of the Standard Model (SM)

- Radiative correction to the Higgs mass term ⇒ **hierarchy problem**
- No cold **dark matter (DM)** candidate

Supersymmetry (SUSY) and R-parity conservation

- Elegant solution to the hierarchy problem
- Lightest supersymmetric particle (LSP) ⇒ DM candidate

Motivation

Shortages of the Standard Model (SM)

- Radiative correction to the Higgs mass term ⇒ **hierarchy problem**
- No cold **dark matter (DM)** candidate

Supersymmetry (SUSY) and R-parity conservation

- Elegant solution to the hierarchy problem
- Lightest supersymmetric particle (LSP) ⇒ DM candidate

No evidence of superpartners in LHC Run 1 data

- Push gluino and squark mass limits up to $\gtrsim \mathcal{O}(1)$ TeV

Motivation

Shortages of the Standard Model (SM)

- Radiative correction to the Higgs mass term ⇒ **hierarchy problem**
- No cold **dark matter (DM)** candidate

Supersymmetry (SUSY) and R-parity conservation

- Elegant solution to the hierarchy problem
- Lightest supersymmetric particle (LSP) ⇒ DM candidate

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 rates 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**

Next-to-Minimal Supersymmetric Standard Model (NMSSM)

No explanation for why μ **is of the same order of the SUSY breaking scale** in the Minimal Supersymmetric Standard Model (MSSM): μ-**problem**

$\Downarrow$

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

Next-to-Minimal Supersymmetric Standard Model (NMSSM)

No explanation for why μ **is of the same order of the SUSY breaking scale** in the Minimal Supersymmetric Standard Model (MSSM): μ**-problem**

$\Downarrow$

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:

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

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 $(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$:

$$M_{\text{N}} = \begin{pmatrix} M_1 & 0 & -g_1 v_d/\sqrt{2} & g_1 v_u/\sqrt{2} & 0 \\ & M_2 & g_2 v_d/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa v_s \end{pmatrix}$$

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 $\tilde{\chi}_1^0 \sim \tilde{S}$ $\Rightarrow$ 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 $\Rightarrow$ $m_{\tilde{\chi}_1^0} \sim \mathcal{O}(10)$ 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

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 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 $\Rightarrow$ $m_{\tilde{\chi}_1^0} \sim \mathcal{O}(10)$ 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
- **Singlino-Wino Scenario** $(2\kappa v_s < M_2 \ll M_1, \mu_{\text{eff}})$: $\tilde{\chi}_1^0 \sim \tilde{S}$; $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \sim \tilde{W}$
  - 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 $\tilde{\chi}_1^0 \sim \tilde{S}$ $\Rightarrow$ 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 $\Rightarrow$ $m_{\tilde{\chi}_1^0} \sim \mathcal{O}(10)$ 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
- **Singlino-Wino Scenario** $(2\kappa v_s < M_2 \ll M_1, \mu_{\text{eff}})$: $\tilde{\chi}_1^0 \sim \tilde{S}$; $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \sim \tilde{W}$
  - 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** $(2\kappa v_s < \mu_{\text{eff}} \ll M_1, M_2)$: $\tilde{\chi}_1^0 \sim \tilde{S}$; $\tilde{\chi}_{2,3}^0, \tilde{\chi}_1^\pm \sim \tilde{H}$
  - Higgsino components of $\tilde{\chi}_1^0$ help satisfy the observed relic density
  - Lower $\tilde{\chi}_{2,3}^0\tilde{\chi}_1^\pm$ 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

$$100 \text{ GeV} \le \mu_{\text{eff}} \le 600 \text{ GeV} \quad -1 \text{ TeV} \le A_\kappa \le 0 \quad 100 \text{ GeV} \le A_\lambda \le 10 \text{ TeV}$$
$$1 \le \tan\beta \le 50 \quad 0.05 \le \lambda \le 0.7 \quad 0.05 \le \kappa/\lambda \le 0.4$$

The condition $\kappa/\lambda \le 0.4$ 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

Parameter Scan

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

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

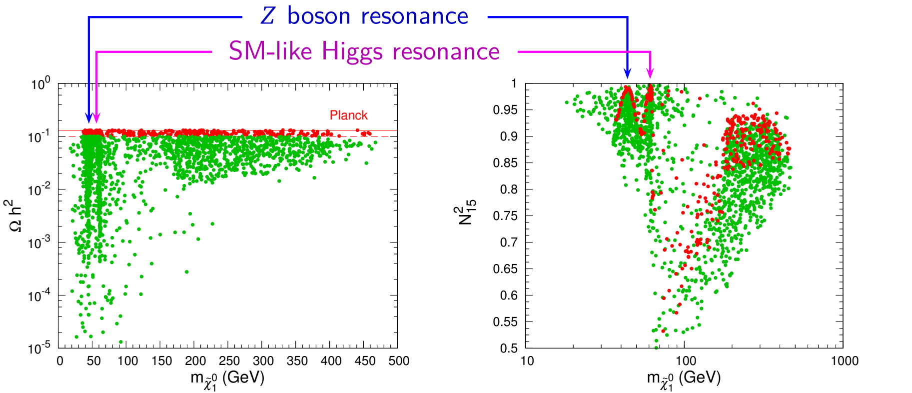
The condition $\kappa/\lambda \leq 0.4$ is imposed for ensuring $\tilde{\chi}_1^0 \sim \tilde{S}$

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 3σ deviation $-5.62 \times 10^{-11} < a_\mu^{\text{NMSSM}} < 5.54 \times 10^{-9}$
- **B physics bounds**: $1.7 \times 10^{-9} < \text{BR}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$; $0.85 \times 10^{-4} < \text{BR}(B^+ \to \tau^+\nu) < 2.89 \times 10^{-4}$; $2.99 \times 10^{-4} < \text{BR}(B_s \to X_s\gamma) < 3.87 \times 10^{-4}$

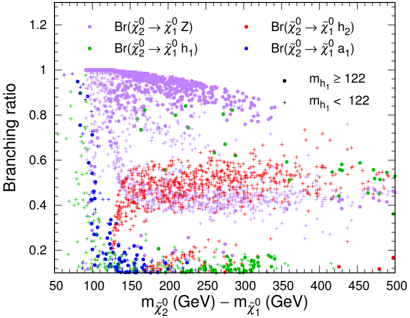
Relic Density $\Omega_{\tilde{\chi}_1^0} h^2$ and singlino component $|N_{15}|^2$



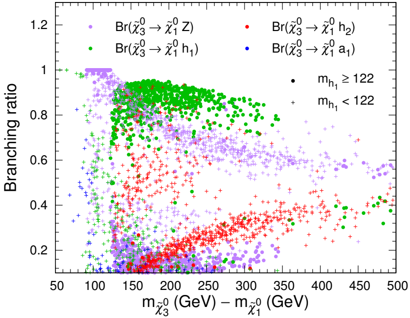
- All points pass the above constraints; red points for $0.107 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.131$
- $m_{\tilde{\chi}_1^0} \sim 45$ GeV and ~ 60 GeV: resonance enhancements of the Z boson and the SM-like Higgs boson for $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ annihilation
- $m_{\tilde{\chi}_1^0} \gtrsim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

Decay patterns of $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$

$\tilde{\chi}_2^0$ decay pattern



$\tilde{\chi}_3^0$ decay pattern

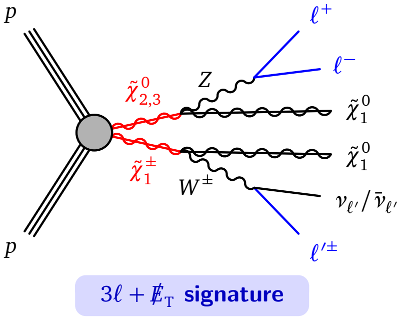


- **$\tilde{\chi}_2^0$ decay:** $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$ is typically dominant
- **$\tilde{\chi}_3^0$ decay:** $\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 Z$, $\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 h_1$, and $\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 h_2$ are significant

Benchmark Points

	BP1	**BP2**	**BP3**
λ, κ	0.091, 0.016	0.270, 0.100	0.368, 0.144
$\tan\beta$, μ_{eff} (GeV)	39.6, 163.3	35.1, 121.3	35.6, 121.0
A_κ (GeV), A_λ (TeV)	−35.9, 8.94	−173.4, 3.79	−8.77, 4.43
$m_{\tilde{\chi}_1^0}$ (GeV)	59.6	77.0	71.7
$m_{\tilde{\chi}_2^0}$, $m_{\tilde{\chi}_3^0}$, $m_{\tilde{\chi}_1^\pm}$ (GeV)	169, 173, 170	134, 146, 126	137, 160, 126
m_{h_1}, m_{h_2}, m_{a_1} (GeV)	46.0, 126, 55.8	23.0, 125, 153	95.3, 125, 38.7
$\|N_{13}\|^2+\|N_{14}\|^2$, $\|N_{15}\|^2$	1.3%, 98.7%	33.2%, 66.8%	43.5%, 56.4%
$\Omega_{\tilde{\chi}_1^0}h^2$	0.120	0.059	0.067
$\text{BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 X)$	Z 98.7%	h_1 84.4%, $q\bar{q}$ 10.6% $\ell^+\ell^-$ 3%, $\nu_\ell\bar{\nu}_\ell$ 3%	a_1 98.6%
$\text{BR}(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 X)$	Z 97.1% a_1 2.7%	h_1 100%	a_1 73.2%, $q\bar{q}$ 14% $\ell^+\ell^-$ 2%, $\nu_\ell\bar{\nu}_\ell$ 4%
$\text{BR}(h_1/a_1 \to b\bar{b}/\tau^+\tau^-)$	/	$h_1 \to b\bar{b}$ 91.8% $h_1 \to \tau^+\tau^-$ 7.3%	$a_1 \to b\bar{b}$ 91.8% $a_1 \to \tau^+\tau^-$ 7.7%

LHC Searches

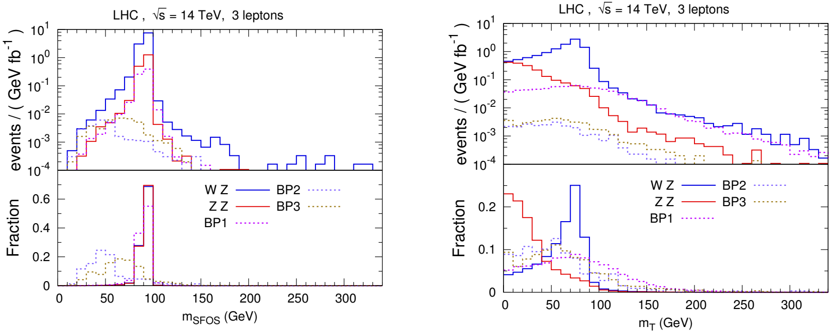


We consider $pp \to \tilde{\chi}^0_{2,3}\tilde{\chi}^\pm_1$ **and** $pp \to \tilde{\chi}^+_1\tilde{\chi}^-_1$ **production** at the LHC for the survived parameter points in the singlino-higgsino scenario

MC simulation: `MadGraph 5` + `PYTHIA 6` + `Delphes 3`

(MadGraph 5 + PYTHIA 6 ↘ ↙) **MLM matching**   (Delphes 3 ↓) **ATLAS setup**

$3\ell + \not{E}_T$ Channel

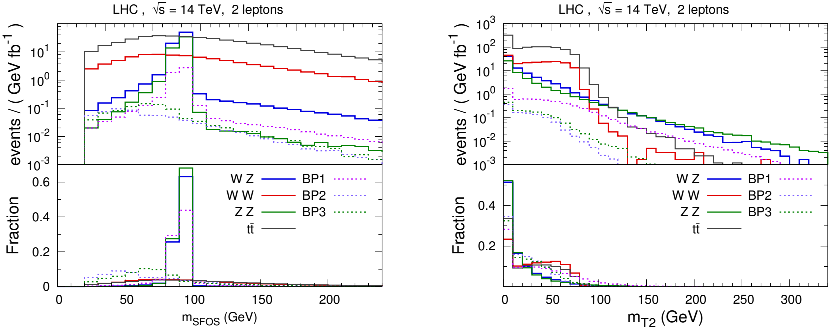


Main backgrounds: WZ + jets and ZZ + jets production

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

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

$2\ell + \not{E}_T$ Channel



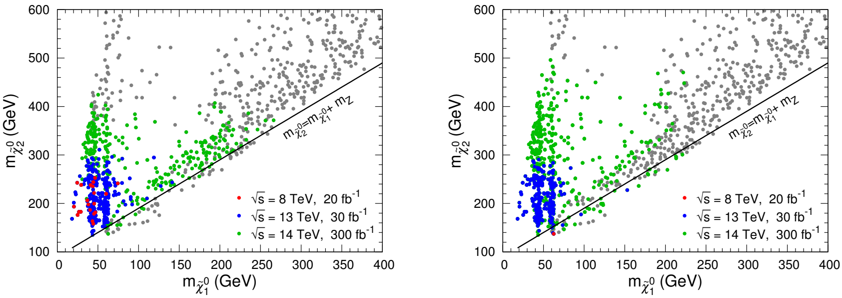
Main backgrounds: $t\bar{t}$ + jets, WW + jets, WZ + jets, and ZZ + jets production

Selection cuts at $\sqrt{s} = 14$ TeV: exact 2 opposite-sign charged leptons with $p_T^{\ell_1} > 30$ GeV, $p_T^{\ell_2} > 20$ GeV, and $|\eta| < 2.5$; $|m_{\mathrm{SFOS}} - m_Z| > 10$ GeV; no jet with $p_T > 30$ GeV and $|\eta| < 2.5$; $m_{T2} > 90$, 120, or 150 GeV

(Stransverse mass $m_{T2} \equiv \min_{\mathbf{p}_T^1 + \mathbf{p}_T^2 = \not{\mathbf{p}}_T} \{\max[m_T(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^1), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{p}_T^2)]\}$.)

(Expected) Exclusion at 95% CL

$3\ell + \not{E}_T$ **channel** | $2\ell + \not{E}_T$ **channel**



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

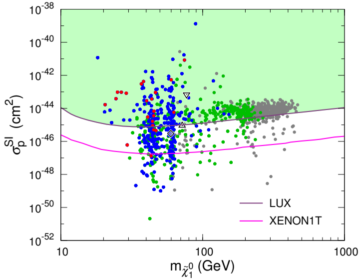
Resonance enhancement for freeze-out

⇓

Small higgsino components in $\tilde{\chi}_1^0$

⇓

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

◇ BP1 ▽ BP2 △ BP3

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

⇓

Small higgsino components in $\tilde{\chi}_1^0$

⇓

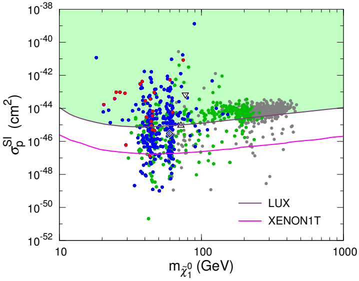
Small scattering cross section

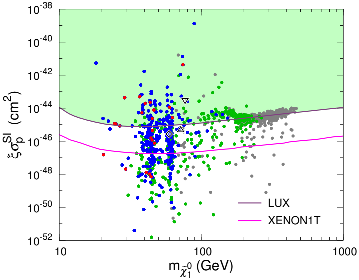
90% CL exclusion limits: **LUX** [1310.8214], **XENON1T** expected for 2 t · yr [1512.07501]

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

◇ 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 ⟶



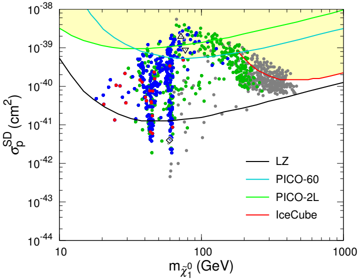


Spin-Dependent (SD) DM-Nuclei Scattering

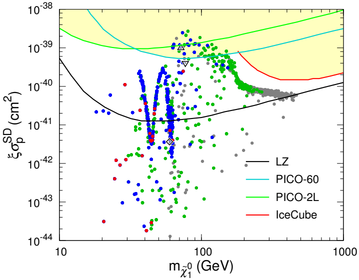
The Z**-mediated SD** DM-nuclei scattering cross section σ^{SD} is typically **larger** than σ^{SI} by $\sim 2-6$ orders of magnitude, but the experimental constraints are quite weak

90% CL exclusion limits:

- **PICO** [1503.00008, 1510.07754]
- **LZ** expected for 5600 $\mathrm{t}\cdot\mathrm{day}$ [1509.02910]
- **IceCube** search for ν_μ from $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to t\bar{t}$ in the center of the Sun [1601.00653]



Introducing ξ will weaken the constraints $\longrightarrow$



Red/blue/green points: 8/13/14 TeV LHC
◇ BP1 ▽ BP2 △ BP3

DM Annihilation

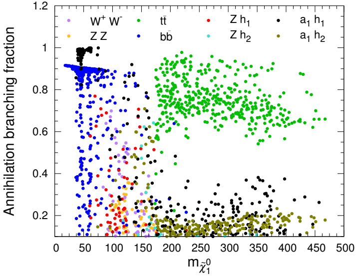
p-**wave annihilation** is important at the freeze-out epoch, but becomes **negligible** for today's nonrelativistic DM relevant to indirect detection

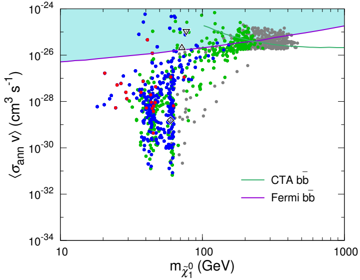
Nonrelativistic $\tilde{\chi}_1^0\tilde{\chi}_1^0$ annihilation

- $m_{\tilde{\chi}_1^0} \lesssim m_t$: $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}$ or a_1h_1 dominant with $\langle\sigma_{\mathrm{ann}}v\rangle \sim \mathcal{O}(10^{-31} - 10^{-27})$ cm^3/s
- $m_{\tilde{\chi}_1^0} \gtrsim m_t$: $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to t\bar{t}$ dominant with canonical $\langle\sigma_{\mathrm{ann}}v\rangle \sim \mathcal{O}(10^{-26})$ cm^3/s

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

Red/**blue**/**green** **points:** 8/13/14 TeV LHC
◇ BP1 ▽ BP2 △ BP3





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** $3\ell + \not{E}_{\mathrm{T}}$ **and** $2\ell + \not{E}_{\mathrm{T}}$ 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**.

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 $3\ell + \not{E}_{\mathrm{T}}$ and $2\ell + \not{E}_{\mathrm{T}}$** 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**.

Thanks for your attention!

Cut Flows

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

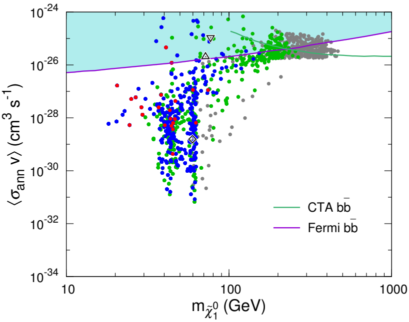
	WZ	ZZ	BP1		BP2		BP3	
	σ	σ	σ	$\mathcal{S}$	σ	$\mathcal{S}$	σ	$\mathcal{S}$
Basic cuts	105	17.3	6.39	9.77	0.021	0.033	0.060	0.095
$\not{E}_T > 50$ GeV	37.2	1.51	4.11	10.9	0.008	0.023	0.034	0.094
$m_T > 100$ GeV	1.22	0.06	1.60	16.3	0.004	0.058	0.014	0.212

$2\ell + \not{E}_T$ channel at $\sqrt{s} = 14$ TeV

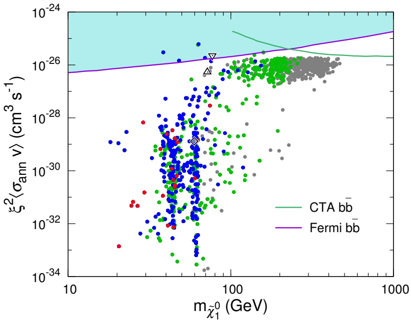
	WZ	ZZ	WW	$t\bar{t}$	BP1		BP2		BP3	
	σ	σ	σ	σ	σ	$\mathcal{S}$	σ	$\mathcal{S}$	σ	$\mathcal{S}$
Basic cuts	88.8	22.3	1798	8930	16.8	2.79	9.75	1.62	12.7	2.12
Jet veto	35.8	7.25	848	253	8.23	4.20	5.42	2.77	6.86	3.50
$m_{T2} > 90$ GeV	0.24	0.32	0.48	0.98	0.58	6.21	0.05	0.61	0.13	1.48

(σ in fb; $\mathcal{S} \equiv S/\sqrt{B+S}$ calculated with an integrated luminosity of 300 fb^{-1})

Indirect Detection: the ξ^2 Factor



Without the ξ^2 factor



With the ξ^2 factor

Red/blue/green points: 8/13/14 TeV LHC
◇ BP1 ▽ BP2 △ BP3