Status of natural NMSSM in light of LHC 13 TeV and XENON-1T Result



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Why supersymmetry (SUSY)

• Math

A general mathematical symmetry.

Supersymmetry is the only way to extend space-time symmetries!

Coleman-Mandula "No-go theorem".

• Physics

New principle: a symmetry between forces and matters.

Predictive: the 125 GeV Higgs lies in the '115-135' GeV window favored by SUSY.

Possible dark matter candidate. Natural dark matter candidates, many possible baryogenesis mechanism.

Vacuum stability naturally in SUSY at tree-level.

Unification of forces.

Scale invariance: SUSY connect bosons and fermions, so quadratic divergence of boson mass is forbidden, just like fermion case.







Electroweak scale SUSY

In 2012, just after Higgs discovery

"Supersymmetry may not be dead but these latest results have certainly put it into hospital." -Chris Parkes

➤ The SM-like Higgs boson mass

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12M_S^2}\right) \right)$$

- The tree level Higgs mass is smaller than Z boson mass.
- Large top quarks/squarks loop corrections are needed.
- Maximal stop mixing is needed to relax the fine-tuning, and the sum of the two stop mass squares $\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}$ is smaller than 1.2 TeV.
- The gluino mass is needed lighter than 1.5 TeV.

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Patient Label Name: <u>SUSY</u>

Symptom Checklist

ATLAS Preliminary

ATLAS SUSY Searches* - 95% CL Lower Limits

JL	ıly 2019								$\sqrt{s} = 13 \text{ TeV}$		
Model Signature $\int \mathcal{L} dt$ [fb ⁻¹]			<i>L dt</i> [fb ⁻	Mass limit		Reference					
S	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_{1}^{0}$	0 e, µ mono-jet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	36.1 36.1	\$\tilde{q}\$ [2x, 8x Degen.] 0.9 \$\tilde{g}\$ [1x, 8x Degen.] 0.43 0.71	1.55	$m(\tilde{\chi}_{1}^{0}) < 100 \text{ Ge}^{1}$ $m(\tilde{q}) - m(\tilde{\chi}_{1}^{0}) = 5$			
arche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	2-6 jets	$E_T^{\rm miss}$	36.1	β̃ β̃ Forbidden	2.0 0.95-1.6	$m(\tilde{\mathcal{X}}_{1}^{0})$ $m(r^{0}$	The first two-generation squark mass low		
e Sea	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell \ell)\tilde{\chi}_1^0$	3 е, µ ее, µµ	4 jets 2 jets	E_T^{miss}	36.1 36.1	\tilde{g} \tilde{g}	1.85	m(₈ ,	bounds are around 1.6 TeV.		
clusiv	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 e,μ SS e,μ	7-11 jets 6 jets	$E_T^{\rm miss}$	36.1 139	ξ ξ	1.8 1.15	$m(\tilde{\chi}_1)$ $m(\tilde{g}) \cdot m(\tilde{\chi}_1) = $	The gluino mass low bound is around 2.0 TeV.		
5	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0$	0-1 <i>e</i> ,μ SS <i>e</i> ,μ	3 <i>b</i> 6 jets	$E_T^{\rm miss}$	79.8 139	ξ ĝ	2.25	m(ữ̃1)<200 ₪ m(ỹ)-m(ữ̃1)=300 GeV	C C		
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$		Multiple Multiple Multiple		36.1 36.1 139	δ1 Forbidden 0.9 δ1 Forbidden 0.58-0.82 δ1 Forbidden 0.74	$m(\tilde{\chi}_1^0) = 200$ $m(\tilde{\chi}_1^0) = 200$	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($k\tilde{\chi}_1^+$)=0 0 GeV, m($\tilde{\chi}_1^+$)=300 GeV, BR($k\tilde{\chi}_2^+$)			
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 {\rightarrow} b\tilde{\chi}_2^0 {\rightarrow} bh\tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	6 <i>b</i>	$E_T^{ m miss}$	139	B1 Forbidden 0.23-0.48	0.23-1.35 Δm	$(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m$	The stop and shottom mass low bounds		
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ $\tilde{t}_1 \tilde{t}_1 \rightarrow \tilde{t}_2 \phi \tilde{t}_1 \phi \tilde{t}_1 \rightarrow \tau \tilde{C}$	0-2 e, μ 1 e, μ 1 τ + 1 e μ τ	0-2 jets/1-2 3 jets/1 b	$E b E_T^{miss}$ E_T^{miss} F^{miss}	36.1 139 36.1	<i>ī</i> ₁ 1. 1. 1.	0		are around 1 TeV respectively		
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{c} \tilde{\chi}^0_1 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow \tilde{c} \tilde{\chi}^0_1$	0 e, µ	2 c	E_T^{miss} E_T^{miss}	36.1	τ τ̃ τ̃ τ̃ τ΄ τ΄ τ΄ τ΄ τ΄ τ΄ τ΄ τ΄ τ΄ τ΄		$m(\tilde{t}_1, \tilde{c}) - m(\tilde{\tilde{t}}_1)$ $m(\tilde{t}_2) - m(\tilde{\tilde{t}}_2)$	are around 1 rev, respectively.		
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$ $\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	1-2 e,μ 3 e,μ	4 b 1 b	E_T^{miss} E_T^{miss}	36.1 139	ī2 0.32-0.88 ī2 Forbidden 0.86	m(. m(ř	$\tilde{\chi}_{1}^{0} = 0$ GeV, m(\tilde{r}_{1})-m($\tilde{\chi}_{1}^{0}$)= 180 Ge $\tilde{\eta}^{0} = 360$ GeV, m(\tilde{r}_{1})-m($\tilde{\chi}_{1}^{0}$)= 40 GeV			
	${\widetilde {\mathcal X}}_1^\pm {\widetilde {\mathcal X}}_2^0$ via WZ	2-3 e, μ ee, μμ	≥ 1	E_T^{miss} E_T^{miss}	36.1 139	$rac{\tilde{\chi}_1^4}{\tilde{\chi}_1^4} / rac{\chi_0^4}{\chi_1^2} = 0.205$		$m(\tilde{\chi}_{1}^{\pm})=0$ $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}$	1403.5294, 1806.02293 ATLAS-CONF-2019-014		
ct <	$\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp}$ via WW $\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{2}^{0}$ via Wh $\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp}$ via $\tilde{\ell}_{L} / \tilde{\chi}$	2 e, μ 0-1 e, μ 2 e, μ	$2 b/2 \gamma$	E_T^{miss} E_T^{miss} E_T^{miss}	139 139 139	\$\tilde{k}_1^+\$ 0.42 \$\tilde{k}_1^+\$ \$\tilde{k}_2^+\$ \$\tilde{k}_1^+\$ \$\tilde{k}_2^+\$ \$\tilde{k}_1^+\$ \$\tilde{k}_2^+\$	0	$m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{0})=70 \text{ GeV}$ $m(\tilde{\ell}, \tilde{v})=0.5(m(\tilde{\chi}_{1}^{+})+m(\tilde{\chi}_{1}^{0}))$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-019, ATLAS-CONF-2019-XYZ ATLAS-CONF-2019-008		
dire	$ \tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_{1}^{0} \\ \tilde{\ell}_{L,R} \tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0} $	2 τ 2 e, μ 2 e, μ	0 jets ≥ 1	E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss}	139 139 139	τ [τ̃ _L , τ̃ _{R,L}] 0.16-0.3 0.12-0.39 ℓ 0.256 0.7		$m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\ell})-m(\tilde{\chi}_{1}^{0})=10 \text{ GeV}$	ATLAS-CONF-2019-018 ATLAS-CONF-2019-008 ATLAS-CONF-2019-014		
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e,μ 4 e,μ	$\ge 3 b$ 0 jets	$E_T^{ m miss}$ $E_T^{ m miss}$	36.1 36.1	H 0.13-0.23 0.29-0.88 H 0.3		$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G})=1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$	1806.04030 1804.03602		
lived cles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{ m miss}$	36.1	$rac{ ilde{\chi}^{*}_{1}}{ ilde{\chi}^{1}_{1}}$ 0.46		Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019		
Long- parti	Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$		Multiple Multiple		36.1 36.1	\tilde{g} \tilde{g} [$\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}$]	2.0 2.05 2.4	$m(\tilde{\chi}_1^0)=100 \text{ GeV}$	1902.01636,1808.04095 1710.04901,1808.04095		
	LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$ $\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	eμ,eτ,μτ 4 e,μ	0 jets	E_T^{miss}	3.2 36.1	\tilde{v}_{r} $\tilde{\chi}_{1}^{+}/\tilde{\chi}_{2}^{0} [\lambda_{l33} \neq 0, \lambda_{12k} \neq 0]$ 0.82	1.9 1.33	λ'_{311} =0.11, $\lambda_{132/133/233}$ =0.07 m($\tilde{\chi}_{1}^{0}$)=100 GeV	1607.08079 1804.03602		
RPV	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	4	-5 large- <i>R</i> j Multiple	ets	36.1 36.1	$ \begin{array}{c} \tilde{g} & [m(\tilde{x}_{1}^{0})=200 \; {\rm GeV}, 1100 \; {\rm GeV}] \\ \tilde{g} & [\mathcal{X}'_{112}=2e{-}4, 2e{-}5] \end{array} $	1.3 1.9 05 2.0	Large λ_{112}'' m($\tilde{\chi}_1^0$)=200 GeV, bino-like	1804.03568 ATLAS-CONF-2018-003		
	$ \widetilde{t}\widetilde{t}, \ \widetilde{t} \to t\widetilde{\chi}^0_1, \ \widetilde{\chi}^0_1 \to tbs $ $ \widetilde{t}_1\widetilde{t}_1, \ \widetilde{t}_1 \to bs $		Multiple 2 jets + 2	b	36.1 36.7	$ \begin{array}{c} \ddot{s} & [\lambda''_{333}=2e\cdot4, 1e\cdot2] & 0.55 & 1 \\ \hline \tilde{t}_1 & [qq, bs] & 0.42 & 0.61 \end{array} $	05	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003 1710.07171		
	$t_1t_1, t_1 \rightarrow q\ell$	2 e, μ 1 μ	2 b DV		36.1 136	$ \vec{t}_1 = [1e \cdot 10 < \lambda'_{23k} < 1e \cdot 8, 3e \cdot 10 < \lambda'_{23k} < 3e \cdot 9] $	0.4-1.45 0 1.6	$\frac{BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%}{BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_t = 1}$	1710.05544 ATLAS-CONF-2019-006		
Only phen	Only a selection of the available mass limits on new states or 10^{-1} 1 Mass scale [TeV]										

Symptom Checklist

ATLAS SUSY Searches* - 95% CL Lower Limits

Patient Label

Name: <u>SUSY</u>

July 2019 Model Signature (<i>f. du</i> iff				` <i>ſ. dt</i> . [fb=					$\sqrt{s} = 13 \text{ TeV}$					
	Model		ignata	je j	2 41 [10		<u> </u>							
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$	0 e, μ mono-iet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	36.1 36.1	 <i>q</i> [2x, 8x Degen.] <i>q</i> [1x, 8x Degen.] 0.43 	0.71	1.55		$m(\tilde{\chi}_{1}^{0}) < 100 \text{ Ge}^{1}$ $m(\tilde{\chi}_{1}^{0}) = 5.$				
seuce	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_{1}^{0}$	0 e, µ	2-6 jets	E_T^{miss}	36.1	ĝ			2.0	$m(\tilde{\chi}_1^0)$	The first two-generation squark mass low			
earc	~ ~ ~ 0	0	4 1-4-			Ř	Forbidden	0.95-1.6		m()**				
lusive Si	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\chi_1^{\circ}$	3 е, µ ее, µµ	4 jets 2 jets	E_T^{miss}	36.1 36.1	s ž		1.2	1.85	m(s.,	bounds are around 1.6 lev.			
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$	0 <i>e</i> , μ	7-11 jets	$E_T^{\rm miss}$	36.1	Ĩ ~			1.8	m(X)	The aluino mass low bound is around 2.0 TeV			
Incl	$\tilde{a} \tilde{a} \rightarrow v \tilde{v}^0$	0-1 e. μ	3 h	E_{-}^{miss}	139 79.8	g ÿ		1.15	2 25	$m(\tilde{g}) \cdot m(\tilde{\chi}_1^0) = $				
	88,8-4471	SS <i>e</i> , <i>µ</i>	6 jets	-7	139	° Š		1.25	2120	$m(\tilde{g})-m(\tilde{\chi}_1^0)=300 \text{ GeV}$				
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$		Multiple		36.1	b ₁ Forbidden	0.9			$m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=1$				
			Multiple Multiple		36.1 139	b ₁ Forbido b ₁ Forbido	len 0.58-0.82 len 0.74		$m(\tilde{\chi}^0_1)=20$	$(\tilde{\chi}_{1}^{+})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=BR(t\tilde{\chi}_{1}^{+})=0.5$ 0 GeV, m $(\tilde{\chi}_{1}^{+})=300 \text{ GeV}, BR(t\tilde{\chi}_{1}^{+})=0.5$				
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 \rightarrow b h \tilde{\chi}_1^0$	0 e, µ	6 b	E_T^{miss}	139		(0.23-1.35	Δπ	$h(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0})$				
ctior	-0 -0					<u>b</u> 1 0.23-0	0.48			$\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{GeV}, m$	The stop and shottom mass low bounds			
nbo.	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow Wb \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow Wb \tilde{\chi}_1^0$	0-2 e, μ 1 e. μ	0-2 jets/1-2 3 iets/1 /	$E = E_T^{miss}$ $E = E_T^{miss}$	36.1 139	t ₁ 7.	0.44-0.59							
gen.	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 bv, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 l	E_T^{miss}	36.1	Ĩ ₁		1.16			are around 1 TeV respectively			
3 rd ($\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	2 <i>c</i>	E_T^{miss}	36.1	ĩ ĩ	0.85			n, m(7, 7) m(7b)	are around r rev, respectively.			
		0 <i>e</i> , <i>µ</i>	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1 = 0.43$	40			$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=$				
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e, μ	4 <i>b</i>	$E_T^{\rm miss}$	36.1	ĩ ₂	0.32-0.88		m	$(\tilde{\chi}_{1}^{0})=0$ GeV, m (\tilde{t}_{1}) -m $(\tilde{\chi}_{1}^{0})=180$ Ge				
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, µ	1 <i>b</i>	E_T^{miss}	139	ĩ ₂ Forbio	dden 0.86		m(i	\tilde{x}_{1}^{0})=360 GeV, m(\tilde{t}_{1})-m(\tilde{x}_{1}^{0})= 40 GeV				
	$\hat{\chi}_1^{\pm}\hat{\chi}_2^0$ via WZ	2-3 е, µ ее, µµ	> 1	E_T^{miss} E_T^{miss}	36.1 139	$ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{0}^{0} \\ \tilde{x}_{-}^{\pm}/\tilde{x}_{0}^{0} = 0.205 $	0.6			$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^0)=5$ GeV	1403.5294, 1806.02293 ATLAS-CONE-2019-014			
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}$ via WW	2 e, µ		E_T^{miss}	139	$\tilde{\chi}_{1}^{\pm}$ 0.42				$m(\tilde{\chi}_{1}^{0})=0$	ATLAS-CONF-2019-008			
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh	0-1 e, µ	$2 b/2 \gamma$	E_T^{miss}	139	$\tilde{X}_{1}^{\pm}/\tilde{X}_{2}^{0}$ Forbidden	0.74			$m(\tilde{\chi}_1^0)=70 \text{ GeV}$ A	TLAS-CONF-2019-019, ATLAS-CONF-2019-XYZ			
rec	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}$ via $\tilde{\ell}_{L}/\tilde{\nu}$	2 e, µ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$	1.0			$m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$	ATLAS-CONF-2019-008			
di E	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \chi_1^{\circ}$ $\tilde{\ell}, \tilde{\tau} \tilde{\ell}, \tilde{\tau} \rightarrow \ell \tilde{\nu}^0$	2τ 2e.u	0 iets	E_T^{miss}	139	7 [TL, TR,L] 0.16-0.3 0.12-0.3	9 0.7			m(X''_1)=0	ATLAS-CONF-2019-018			
	υL,RυL,R, υ—υι Ι	2 e, μ	≥ 1	E_T^{miss}	139	<i>t ℓ</i> 0.256	0.7							
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ	$\geq 3 b$	E_T^{miss} E^{miss}	36.1	<i>й</i> 0.13-0.23	0.29-0.88			211 11 12 12 12	ie die de la			
_		+ε,μ	0 1013	T	50.1	n 0.3		_		\mathbb{N}				
lived	Direct $\tilde{\chi}_1^* \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\perp$	Disapp. trk	1 jet	$E_T^{\rm mass}$	36.1	$\begin{array}{c} \chi_{1}^{*} \\ \tilde{\chi}_{1}^{\pm} \end{array} = 0.15 \end{array}$	46							
ng-	Stable g R-hadron		Multiple		36.1	ğ			2.0		1302.01030,1000.04030			
D d	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g} = [\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}]$								
	LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	\tilde{v}_{τ}				he intere	esting question: can we solve			
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{+} / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e, μ	0 jets	E_T^{miss}	36.1	$\bar{\chi}_{1}^{x}/\bar{\chi}_{2}^{v} = [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$	0.82	1.33			String question: ean we solve			
>	$gg, g \rightarrow qq\chi_1, \chi_1 \rightarrow qqq$	4-5 large-k jets Multiple			36.1	$\begin{array}{c} g & [m(\mathcal{X}_1)=200 \text{ GeV}, 1100 \text{ GeV}] \\ \overline{g} & [\mathcal{X}_{112}'=2e{-}4, 2e{-}5] \end{array}$	1.0	5	the electroweak symmetry breaking					
ВР	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple 36			36.1	ĝ [l ^{''} ₃₂₃ =2e-4, 1e-2]	0.55 1.0	5						
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$	0	2 jets + 2	b	36.7	$\tilde{t}_1 [qq, bs]$ 0.42	0.61	0.4.4.45						
	$t_1 t_1, t_1 \rightarrow q\ell$	2 e, μ 1 μ	2 b DV		36.1 136	$\frac{1}{4}$ [1010 $\frac{1}{4} [1010 \frac{1}{4}] [1010 \frac{1}{4}] [1010 \frac{1}{4} [1010 \frac{1}{4}] [1010 \frac{1}{4}]$								
								_						
$2n y $ a selection of the available mass limits on new states or 10^{-1} 1 Mass scale [TeV]														

simplified models, c.f. refs. for the assumptions made.

ATLAS Preliminary

Electroweak fine tuning & Naturalness

Electroweak symmetry breaking condition

$$\frac{1}{2}m_Z^2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

• The potential of scalar Higgs doublets includes mass terms μ_{r}^{2} and the potential must be unstable in order to trigger $SU(2)_{L} \times U(1)_{V}$ symmetry breaking.

- μ^2 must be cancelled by negative soft SUSY break terms
- Requires fine tuning if $|\mu| \gg m_Z$

Fine tuning measure definition:

$$\Delta_{\mathcal{O}} = \max_{i} \left| \frac{\partial \ln \mathcal{O}}{\partial \ln p_{i}} \right|, \qquad \begin{array}{c} \mathcal{O} \text{ is a physical observable ;} \\ p_{i} \text{ is the input parameter at EW scale.} \end{array}$$

Define:
$$\Delta_Z \equiv \max_i \left| \frac{\partial \ln m_Z^2}{\partial \ln p_i} \right|$$
 for tuning in EW symmetry breaking.
 $\Delta_h \equiv \max_i \left| \frac{\partial \ln m_h^2}{\partial \ln p_i} \right|$ for the tuning of SM-like Higgs boson mass.

Both quantities Δ_Z and Δ_h should be small in a natural SUSY theory.

Points: • Small μ • Large enough tree level Higgs mass

Naturalness & Dark matter

Light Higgsinos are natural, but are no good dark matter (DM) candidates.

- Relic density too small.
- Large direct detection rates (spin-dependent via Z-exchange).

MSSM

$$W_{\text{MSSM}} = W_{\text{Yukawa}} + \mu \hat{H}_u \cdot \hat{H}_d$$

 Bino LSP Relic density too large
 Higgsino-Bino mixing rates unless m_{LSP} ≥ 700 GeV



NMSSM

$$W_{\rm NMSSM} = W_{\rm Yukawa} + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

- μ is achieved by EW symmetry breaking $\mu_{\text{eff}} = \lambda \langle \hat{S} \rangle$ naturally at EW scale
- The SM-like Higgs boson mass $m_{h_{125}}^2 \approx m_Z^2 \cos^2 2\beta + \Delta_t$ $+ \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2}{\kappa^2} v^2 (\lambda - \kappa \sin 2\beta)^2.$

Additional contribution compared with MSSM

• The Singlino is a good DM candidate

Observed relic density through annihilation via

- Singlet-like CP-odd Higgs A_1 funnel
- Z or CP-even Higgs funnel
- Coannihilation with Higgsino

In R parity conserved SUSY model, if Lightest SUSY Particle is $\tilde{\chi}_1^0$, it can act as a DM candidate. It's property depends on the magnitude of its component N_{1i} .

In the gauge-eigenstate basis:

$$\psi^{0} = (\widetilde{B}, \widetilde{W}^{0}, \widetilde{H}_{d}^{0}, \widetilde{H}_{u}^{0}, \widetilde{S})$$

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2} (\psi^{0})^{\mathrm{T}} \mathcal{M}_{0} \psi^{0} + \text{c.c.}$$

$$\mathcal{M}_{0} = \begin{pmatrix} M_{1} & 0 & -\frac{g_{1}v_{d}}{\sqrt{2}} & \frac{g_{1}v_{u}}{\sqrt{2}} & 0 \\ M_{2} & \frac{g_{2}v_{d}}{\sqrt{2}} & -\frac{g_{2}v_{u}}{\sqrt{2}} & 0 \\ 0 & -\mu & -\lambda v_{u} \\ 0 & -\lambda v_{d} \\ 2\kappa v_{s} \end{pmatrix}$$

Mass eigenstate (Majorana Fermion):

$$\widetilde{\chi}_i^0 = \sum_{j=1}^5 N_{ij} \psi_j$$

 $\begin{array}{l} 0.0959 < \Omega h^2 < 0.1439 \\ \Delta_Z < 50 \ \& \ \Delta_h < 50 \\ \mbox{LHC Run I Data} \\ \mbox{DM direct detection Data (2016)} \end{array}$





Bino DM in nNMSSM

- $m_{\widetilde{\chi}} \le 200 \text{ GeV}$
- DM annihilation mechanisms :
 - 1. Z/h_1 funnel; $\sigma(\tilde{\chi}_1^0 \tilde{\chi}_1^0 \xrightarrow{Z/h_1} X X') \propto \left| \frac{C_{Z/h_1 \tilde{\chi}_1^0 \tilde{\chi}_1^0} C_{Z/h_1 X X'}}{s - m_{h_1}^2 + i\Gamma_{h_1} m_{h_1}} \right|^2$ $C_{h_1 \tilde{\chi}_1^0 \tilde{\chi}_1^0} \simeq \sqrt{2} \lambda N_{13} N_{15} - g_1 N_{11} N_{14} + g_2 N_{12} N_{14},$ $C_{Z \tilde{\chi}_1^0 \tilde{\chi}_1^0} = \frac{g_2}{2 \cos \theta_W} (-|N_{13}|^2 + |N_{14}|^2)$ in Wino and Singlino decouple limit, $N_{13} \propto \frac{v_u}{\mu} \quad N_{14} \propto (v_d \mu + v_u m_{\tilde{\chi}})/\mu^2$ relic density provide an upper limit on μ
 - 2. $\widetilde{\chi}\widetilde{\chi} \to h_1h_2$ via *t*-channel exchange of a neutralino. $m_{\widetilde{\chi}} \simeq (m_{h_1} + m_{h_2})/2$ $\sigma(\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \xrightarrow{\widetilde{\chi}_i^0} XX') \propto C_{h_1\widetilde{\chi}_i^0\widetilde{\chi}_1^0}^2 C_{h_2\widetilde{\chi}_i^0\widetilde{\chi}_1^0}^2$
 - 3. Coannihilation with slepton.



Singlino DM in nNMSSM

- $m_{\tilde{\chi}} < 450 \text{ GeV}$
- DM annihilation mechanisms :
 - 1. Z/h_1 funnel;
 - 2. $\widetilde{\chi}\widetilde{\chi} \to h_1h_2$ via *t*-channel exchange of a neutralino.
 - 3. Coannihilation with slepton.
 - 4. Coannihilation with Higgsino

in the Bino and Wino decouple limit, $2|\kappa| \lesssim \lambda, \ m_{\tilde{\chi}} \lesssim \mu, \ m_{\tilde{\chi}} > 100 \text{ GeV}.$

5. CP-odd Higgs
$$A_1^{(\star)}$$
 funnel.

Singlet sum rule $m_{\widetilde{\chi}}^2 \simeq m_{h_s}^2 + \frac{1}{3}m_{A_1}^2$

- singlet Higgs boson mass prefers to smaller than 125 GeV.
- m_{A_1} prefers to smaller than $\sqrt{3}m_{\widetilde{\chi}}$
- If m_{h_s} is small, $\widetilde{\chi}\widetilde{\chi} \to A_1^{\star} \to A_1 h_s$



Higgsino DM in nNMSSM

- $m_{\tilde{\chi}} \sim 85 \text{ GeV}$
- Large λ induce sizable mixing between Higgsino and Singlino in the neutralino mass matrix. Singlino component is around 30%.
- This scenario is tightly restricted by DM direct detections

Spin-independent cross section

$$\sigma_{\tilde{\chi}-(n)}^{SI} = \frac{4\mu_r^2}{\pi} \left| f^{(n)} \right|^2$$
$$f^{(n)} \approx \sum_{i=1}^3 f_{h_i}^{(n)} = \sum_{i=1}^3 \frac{C_{h_i \tilde{\chi}_1^0 \tilde{\chi}_1^0} C_{h_i n n}}{2m_{h_i}^2}$$

Spin-dependent cross section

$$\sigma_{\tilde{\chi}-n/p}^{SD}/\text{pb} \simeq C^{n/p} \times 10^{-4} \times \left(\frac{|N_{13}|^2 - |N_{14}|^2}{0.1}\right)^2$$





Heavy slepton case:



The black curve assumes Wino-like $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$ production cross section, Not Higgsino-like Wino-like cross section is about 3 to 4 times larger than Higgsino's Higgsino-like $\tilde{\chi}_1^{\pm}$ with mass $\sim \mu$

Higgsino-like χ_1 with mass $\sim \mu$ Higgsino-like $\tilde{\chi}_{2,3}^0$ with masses $\sim \mu \pm \Delta_{\pm}$ $(\Delta_{\pm} \sim 10 \text{ GeV} \text{ due to mixing})$

arXiv: 1801.03957



		Signa			
Search	WZ	WH	ΖŽ	ZĤ	HH
1ℓ 2b		\checkmark			
4b					\checkmark
2ℓ on-Z	\checkmark		\checkmark	\checkmark	
2ℓ soft	\checkmark				
$\geq 3\ell$	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark
$H(\gamma\gamma)$		\checkmark		\checkmark	\checkmark



Heavy slepton case:



Light slepton case: $p_{\tilde{\chi}_{1}^{\pm}} \qquad \tilde{\ell}_{\tilde{\ell}}^{\nu} \qquad \tilde{\chi}_{1}^{0}$ $p_{\tilde{\chi}_{2}^{0}} \qquad \tilde{\ell}_{\ell}^{\nu} \qquad \tilde{\chi}_{1}^{0}$ $BR(\tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0}) = 1$

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Higgsino-like $\widetilde{\chi}_{1}^{\pm}$ with mass $\sim \mu$ Higgsino-like $\widetilde{\chi}_{2,3}^{0}$ with masses $\sim \mu \pm \Delta_{\pm}$ $(\Delta_{\pm} \sim 10 \text{ GeV}$ due to mixing)

arXiv: 1801.03957



Combine them together though the **CLs** method



Impacts on nNMSSM



Bino DM in nNMSSM 1. Z/h_1 funnel; 2. $\tilde{\chi}\tilde{\chi} \rightarrow h_1h_2$ via t-channel exchange of a neutralino. 3. Coannihilation with slepton. $\sigma_{\tilde{\chi}-n}^{SI}$ too large $3\ell + E_T^{miss}$ too large

If relax the fine-tuning constraint, some parameter space region still can survive. Such parameter space will test by the upcoming DM direct detection, unless the blind-spot.

CLHCP-2019, October 23-27 Dalian

Impacts on nNMSSM



Singlino DM in nNMSSM

- 1. Z/h_1 funnel; 2. $\tilde{\chi}\tilde{\chi} \rightarrow h_1h_2$ via *t*-channel exchange of a neutralino.
- 3. Coannihilation with slepton.
- 4. Coannihilation with Higgsino
- 5. CP-odd Higgs A_1^{\star} funnel.

The surviving region:

- $m_{\widetilde{\chi}_1^0} \simeq m_{\widetilde{\chi}_1^\pm} \in (90, 440) \text{ GeV}$
- Singlino decouple case: $N_{15}^2 > 99\%$
 - Can not be detectable
- Singlino-Higgsino mixing case:

 $\begin{array}{l} 90 \ {\rm GeV} < m_{\widetilde{\chi}_1^0} < 220 \ {\rm GeV} \\ {\rm A \ singlet-like \ Higgs \ lighter \ than \ 125 \ GeV} \\ {\rm Detectable \ SI \ DM-nucleon \ Xsect} \\ \sigma_{\widetilde{\chi}-n}^{\rm SI} > 10^{-47} \ {\rm cm}^2 \end{array}$

Impacts on nNMSSM



Higgsino DM in nNMSSM

Higgsino can not be a DM candidate under the current experimental limits.

 $\sigma^{
m SD}_{\widetilde{\chi}-{
m n}}$ too large

LHC Data full cover the blindspot region

Status of the nNMSSM

Naturalness



- In the NMSSM, a Singlino-like LSP can satisfy the constraints on DM.
- The surviving parameter space allows relative small μ , which naturally trigger the Electroweak symmetry breaking.
 - Singlino decoupled case prefers large $\tan \beta$, while RGE not.
- In our work, the research of 3rd generation sparticles is not fine enough:
 - The value of stau parameters are same to the first two generations'. While the constraint on stau pair production is much weaker than selectron's and smuon's.
 - 2. Stop and sbottom searches at LHC are not take into consideration.

Status of the nNMSSM

Naturalness in DM phenomenology



- Singlino-like DM is natural in getting relic density
- there is cancellation effect in DM-nucleon scatter rate for Singlino-Higgsino mixing case:
 - 1. Blind-spot needed in the σ^{SI} ;
 - 2. $|N_{13}|^2 \approx |N_{14}|^2$ needed in the σ^{SD} .
- Singlino-Higgsino sector forms a secluded DM scenario for Singlino decoupled case:
 - 1. Higgsino act as mediator between DM and SM particles to get correct relic density.
 - 2. Singlet nature of DM keeps small direct detection rates.
- Compressed mass spectrum: final state particles are too soft!!! Recursive Jigsaw Reconstruction (RJR) technique may help us testing this region.

Status of the nNMSSM

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Fine-tuned structure in DM-nucleon scatter

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 - 2. Singlet nature of DM keeps small direct detection rates.
- Compressed mass spectrum: final state particles are too soft!!! Recursive Jigsaw Reconstruction (RJR) technique may help us testing this region.

Hard & Long & Many DM searches find the expensive inequality:

$$\frac{\langle \sigma v \rangle}{\sigma^{\rm SI}} \ge 10^9$$

- Zhaofeng Kang(康略峰), 9/6/2019, Chengdu

Summary

Light Higgsino in the NMSSM remains an natural scenario for a light supersymmetric "WIMP" consistent the dark matter relic density, constraints from direct detection and CMS Sparticle search.

A light μ in this framework is favored in predicting:

- Electroweak symmetry breaking
- SM-like Higgs boson mass
- DM relic density

While, low DM-nucleon scatter rate in a SUSY theory need some unknown mechanism to protect the naturalness of the theory.

Singlino DM candidate in natural NMSSM tell us there are two choices:

- 1. Blindspot: both SI and SD
- 2. Secluded DM scenario



Status of natural NMSSM in light of LHC 13 TeV and XENON-1T Result



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Henan Normal University

October 24, 2019 Dalian

In collaboration with Junjie Cao, Yangle He, Liang Shang and Yang Zhang Based on PRD 99, 075020 (2019). arXiv:1810.09143

Backup

To examine the nNMSSM in a wider model scope and with more experimental constaint, we scan the following parameter space:

$\begin{array}{ll} 0 < \lambda < 0.75, 0 < \kappa < 0.75, 2 < \tan \beta < 60, A_{\kappa} \le 2 \text{ TeV}, \\ 100 \text{ GeV} \le \mu \le 1 \text{ TeV}, 50 \text{ GeV} \le M_A \le 2 \text{ TeV}, \end{array}$	Stop mass and mixing for getting obvious loop correction for 125 GeV SM-like Higgs boson	
100 GeV $\leq M_{Q_3}, M_{U_3} \leq 2$ TeV, $ A_t \leq \min(3\sqrt{M_{Q_3}^2 + M_{U_3}^2}, 5 \text{ TeV})$	Common slepton soft breaking mass	
$100 \text{ GeV} \le M_{\widetilde{\ell}} \le 1.2 \text{ TeV},$	in slepton sector	
$20 \text{ GeV} \le M_1 \le 800 \text{ GeV}, 100 \text{ GeV} \le M_2 \le 1.2 \text{ TeV},$	Gaugino soft mass setting	

The mass of the gluino and the first two generation squarks are fixed to 2 TeV.

Constraints:

- B-physics constraints: such as the precise measurements of B → X_sγ, B_s → μ⁺μ₋
 B_d → X_sμ⁺μ⁻, and mass difference ΔM_d, ΔM_s
- Constraints on the Higgs sector included in the packages HiggsBounds and HiggsSignal.
- Electroweak precision test
- DM relic density: PLANCK 2015

- DM direct detection:
 - Xenon-1T 2018 data for Spin-independent Xsect;

General Higgs parameters setting to

get correct Higgs Physics

- LUX 2017 data for Spin-dependent Xsect.
- $\Delta_Z < 50, \ \Delta_h < 50$
- LHC Run-II: CMS 36 fb^{-1} data

Backup

WorkFlow:



• Scan Algorithm: Monte-Carlo Markov Chain

• Likelihood:
$$L = L_{\Omega} \times L_{m_h}$$

 $L_{\Omega} = \exp\left[-\frac{(\Omega_{\rm th} - \Omega_{\rm obs})^2}{2 (\delta \Omega)^2}\right] L_{m_h} = \exp\left[-\frac{(m_{th} - m_{obs})^2}{2 (\delta m_h)^2}\right]$