The higgsino-singlino sector of the NMSSM: Combined constraints from dark matter and the LHC

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Aim, given the absence of significant BSM excesses at the LHC:

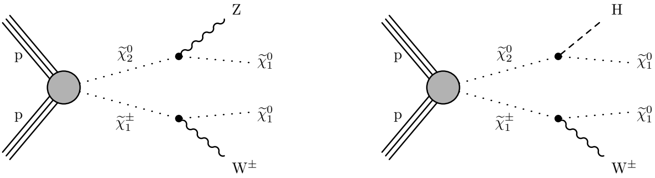
- Derive strict limits (as general as possible) on sparticle masses, here: NMSSM
- Byproduct: Pin down dark spots in present searches

Bottom up strategy:
Start with electroweakinos, the “lower ends” of realistic decay cascades
Subsequently allowed electroweakino masses and couplings can be used to constrain realistic decay cascades of squarks, stops, gluinos, . . .

Assume, as promised by Supersymmetry:
A dark matter relic density in the WMAP/Planck window,
consistent with constraints from direct DM detection

In the NMSSM, a light singlino-like LSP $\tilde{\chi}_1^0$ with some higgsino component allows for a dark matter relic density in the WMAP/Planck window consistent with constraints from direct detection experiments, notably from PandaX-II on spin dependent dark matter − neutron scattering

Constrained by searches at the LHC for electroweak production of charginos and neutralinos?

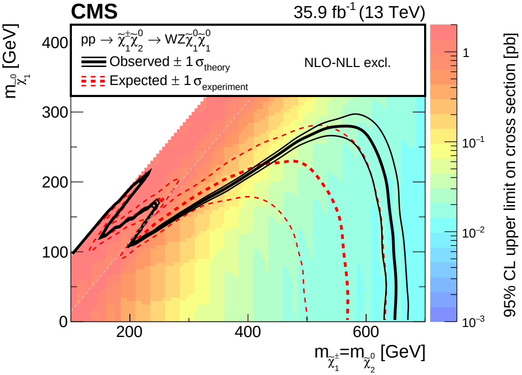


Note: In the NMSSM, “H” includes H_{SM} and mostly singlet-like H_1/A_1; due to a sum rule H_1 is automatically light if a pseudoscalar A_1 with $M_{A_1} \approx 2M_{singlino}$ reduces the singlino relic density to the WMAP/Planck value via annihilation with A_1 in the s-channel

AND: $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ (and $\tilde{\chi}_3^0$) are higgsinos, not winos!

— Light higgsinos are natural ($\leftrightarrow \mu$ parameter not far above M_Z)
— Heavier winos are motivated by a GUT relation $M_2 \approx M_3/3$ among the wino mass parameter M_2 and the gluino mass M_3, and lower bounds on $M_3 \gtrsim 2$ TeV

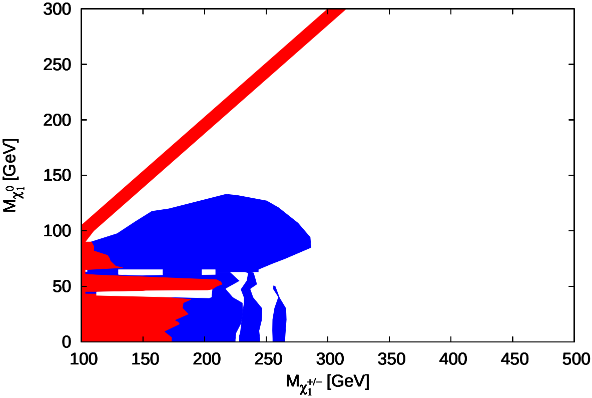
$\longrightarrow$ Higgsinos have smaller cross sections, leading to weaker bounds on cross sections × branching fractions than from wino production e.g. from CMS-SUS-17-004 (1801.03957) in the plane $M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0}$:



After a scan over viable NMSSM parameters requiring good dark matter, we recast these limits using the resulting higgsino/singlino masses and couplings

First: Simplifying (technical) assumption: Heavy sleptons (staus)

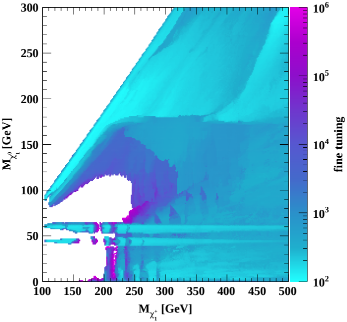
$\longrightarrow$ Strictly excluded regions in the plane $M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0}$:



Red: Excluded for arbitrary bino mass M_1, allowing for $M_1 < \mu$ ($= M_{\mathrm{h}iggsino}$)
Blue: Excluded if $M_1 > 300$ GeV as motivated by the GUT relation $M_1 \approx M_3/6$

NUH-NMSSM

Assume universal gaugino masses, universal squark=slepton masses at M_{GUT}
→ Stronger constraints,
→ The necessary amount of finetuning can be estimated
(mainly due to constraints from dark matter relic density):



→ Relatively low finetuning for $M_{\tilde{\chi}_1^0} \sim M_Z/2$, $\sim M_{H125}/2$ or $\sim M_{\tilde{\chi}_1^\pm}$ where s-channel annihilation or co-annihilation is possible
Otherwise: s-channel annihilation via A_1 with $M_{\tilde{\chi}_1^0} \sim M_{A_1}/2$

Reasons for the alleviated constraints from searches for $\tilde{\chi}^{\pm}_1 \to \tilde{\chi}^0_1 + W$, $\tilde{\chi}^0_{(2,3)} \to Z + \tilde{\chi}^0_1$:

— Smaller production cross sections (although there are two nearly degenerate higgsinos)

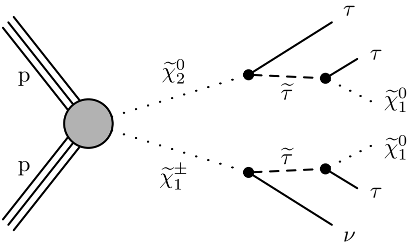
— Decays $\tilde{\chi}^0_{(2,3)} \to H_{SM} + \tilde{\chi}^0_1$, on which limits are much weaker, have branching fractions of $\sim 30 - 50\%$ (averaging over both higgsinos)

— If decays $\tilde{\chi}^0_{(2,3)} \to Z + \tilde{\chi}^0_1$ are kinematically forbidden for Z on-shell, decays $\tilde{\chi}^0_{(2,3)} \to H_1/A_1 + \tilde{\chi}^0_1$ can be dominant where H_1/A_1 are NMSSM specific light scalars/pseudo scalars; difficult to detect!
(Taking constraints on H_1/A_1 from searches at LEP/LHC and $H_{SM} \to H_1 + H_1$ into account)

Still, searches for $\tilde{\chi}^{\pm}_1 \to \tilde{\chi}^0_1 + W$, $\tilde{\chi}^0_{(2,3)} \to Z + \tilde{\chi}^0_1$ do constrain light higgsinos/singlinos except . . .

Relaxing the “simplifying (technical)” assumption (1):

Allowing for light staus:
$\longrightarrow$ Higgsinos $\tilde{\chi}_1^\pm$, $\tilde{\chi}_{2,3}^0$ prefer to decay into staus instead of the LSP $\tilde{\chi}_1^0$:



Constraints from corresponding searches by CMS in CMS-PAS-SUS-17-002, but weak for light $\tilde{\tau}$

$\longrightarrow$ No NMSSM-points get excluded by searches for charginos and neutralinos if staus are lighter than higgsinos (of mass $\sim \mu$)

Relaxing assumption (2):

Allowing for a bino lighter than higgsinos, the neutralinos are:
$\tilde{\chi}_1^0$: Singlino as before
$\tilde{\chi}_2^0$: Bino
$\tilde{\chi}_{(3,4)}^0$: Higgsinos
$\tilde{\chi}_5^0$: wino, assumed heavy

$\longrightarrow$ In the presence of a light singlet-like scalar H_1 (or A_1) with

$$M_{H_1} < M_{higgsino} - M_{bino}$$

the higgsinos can decay via the cascade

$$\tilde{\chi}_{(3,4)}^0 \to H_1 + \tilde{\chi}_2^0 \to H_1 + H_1 + \tilde{\chi}_1^0$$

and decays $\tilde{\chi}_1^\pm \to \tilde{\chi}_2^0 + W^{(*)}$ become possible

$\longrightarrow$ Constraints from existing searches for charginos and neutralinos can be circumvented

Conclusions:

— For strict constraints it seems reasonable to start with the electroweakino sector, to use subsequently for realistic decay cascades

— In the NMSSM where a singlino-like LSP can satisfy the constraints on dark matter, it is appropriate to impose these constraints;
these exclude already a sizeable region in the plane $M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0}$

— If heavy staus and bino are assumed, additional regions in this plane are definitively excluded by recent searches for neutralinos/charginos

— Dark spot 1: light staus!
(Not excluded by searches for stau pair production at the LHC)

— Dark spot 2: light bino, leading to higgsino decay cascades via light H_1/A_1
$\longrightarrow$ To include in electroweakino searches? (Difficult, of course)

— BMpoints and planes are proposed in 1806.10672

	P1	P2	P3	P4	P5	P6
$M_{\chi_1^\pm}$	265	261	219	286	276	193
$M_{\chi_1^0}$	3.2	40	62	85	107	150
$M_{\chi_2^0}$	250	244	206	261	257	197
$M_{\chi_3^0}$	285	278	236	306	293	205
M_{H_1}	56	35	59	20	3	60
M_{A_1}	76	78	63	167	205	259
$BR(\chi_2^0 \to \chi_1^0 + Z)$	0.40	0.30	0.84	0.73	0.13	0.95*
$BR(\chi_2^0 \to \chi_1^0 + H_{SM})$	0.48	0.64	0.09	0.22	0.77	0.00
$BR(\chi_2^0 \to \chi_1^0 + H_1)$	0.08	0.05	0.02	0.03	0.10	0.00
$BR(\chi_3^0 \to \chi_1^0 + Z)$	0.57	0.70	0.39	0.34	0.89	0.99*
$BR(\chi_3^0 \to \chi_1^0 + H_{SM})$	0.33	0.24	0.56	0.61	0.09	0.00
$BR(\chi_3^0 \to \chi_1^0 + H_1)$	0.06	0.02	0.03	0.05	0.02	0.00
Xsect $\to \chi_1^\pm + \chi_2^0$ [fb]	125	139	318	85	93	295
Xsect $\to \chi_1^\pm + \chi_3^0$ [fb]	128	141	258	96	115	437

Table: Masses (in GeV) and branching fractions of benchmark points of the pNMSSM. Branching fractions into Z with a star indicate off-shell decays.

	P7	P8	P9	P10	P11	P12
$M_{\chi_1^\pm}$	129	237	118	158	210	226
$M_{\chi_1^0}$	97	160	45	47	50	60
$M_{\chi_2^0}$	131	238	110	123	128	180
$M_{\chi_3^0}$	140	248	128	172	222	240
$M_{\chi_4^0}$	303	355	302	183	224	246
M_{H_1}	32	25	35	43	5	62
M_{A_1}	174	290	42	37	49	21
$BR(\chi_2^0 \to \chi_1^0 + Z)$	0.00	0.00	0.10*	0.02*	0.00	0.16
$BR(\chi_2^0 \to \chi_1^0 + H_{SM})$	0.00	0.00	0.00	0.00	0.00	0.00
$BR(\chi_2^0 \to \chi_1^0 + H_1)$	1.00	1.00	0.38	0.27	1.00	0.01
$BR(\chi_2^0 \to \chi_1^0 + A_1)$	0.00	0.00	0.52	0.71	0.00	0.02
$BR(\chi_2^0 \to \nu_\tau + \tilde{\nu}_\tau)$	0.00	0.00	0.00	0.00	0.00	0.81
$BR(\chi_3^0 \to \chi_1^0 + Z)$	0.96*	0.88*	0.33*	0.80	0.25	0.36
$BR(\chi_3^0 \to \chi_1^0 + H_{SM})$	0.00	0.00	0.00	0.09	0.39	0.39
$BR(\chi_3^0 \to \chi_1^0 + H_1)$	0.04	0.12	0.61	0.08	0.07	0.02
$BR(\chi_3^0 \to \chi_1^0 + A_1)$	0.00	0.00	0.03	0.01	0.00	0.00
$BR(\chi_3^0 \to \chi_2^0 + Z)$	0.00	0.00	0.03*	0.00	0.06	0.00
$BR(\chi_3^0 \to \chi_2^0 + H_1)$	0.00	0.00	0.00	0.02	0.23	0.00

$BR(\chi_3^0 \to \tau^\pm + \tilde{\tau}^\mp)$	0.00	0.00	0.00	0.00	0.00	0.17
$BR(\chi_3^0 \to \nu_\tau + \tilde{\nu}_\tau)$	0.00	0.00	0.00	0.00	0.00	0.06

$BR(\chi_4^0 \to \chi_1^0 + Z)$				0.44	0.86	0.23
$BR(\chi_4^0 \to \chi_1^0 + H_{SM})$				0.01	0.06	0.03
$BR(\chi_4^0 \to \chi_1^0 + H_1)$				0.01	0.02	0.00
$BR(\chi_4^0 \to \chi_1^0 + A_1)$				0.00	0.02	0.00
$BR(\chi_4^0 \to \chi_2^0 + Z)$				0.00	0.04	0.00
$BR(\chi_4^0 \to \chi_2^0 + H_1)$				0.51	0.00	0.07
$BR(\chi_4^0 \to \tau^\pm + \tilde{\tau}^\mp)$				0.00	0.00	0.56
$BR(\chi_4^0 \to \nu_\tau + \tilde{\nu}_\tau)$				0.00	0.00	0.10

Xsect $\to \chi_1^\pm + \chi_2^0$ [fb]	1319	186	3138	670	78	145
Xsect $\to \chi_1^\pm + \chi_3^0$ [fb]	1759	212	2376	829	295	241
Xsect $\to \chi_1^\pm + \chi_4^0$ [fb]	9	7	8	437	316	164