Dark Matter in the NMSSM

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— On the Nature of Susy Dark Matter

— Light Dark Matter in the NMSSM

On the Nature of Susy Dark Matter

Assuming GUT relations among gaugino masses M_1 and $M_3 = M_{\text{gluino}}$ (Grand Unification is one of the "goodies" of Supersymmetry!):

$$M_1 \text{ (bino) } \sim \frac{1}{6} M_3$$

LHC: $M_{\text{gluino}} \gtrsim 1.5$ TeV $\longrightarrow$ $M_1 \gtrsim 250$ GeV

Higgsinos: Masses given by $\sim \mu$
MSSM: $\mu H_u H_d$ in the superpotential
NMSSM: $\lambda S H_u H_d + \frac{\kappa}{3} S^3$ in the superpotential $\longrightarrow$ $\mu_{\text{eff}} = \lambda \langle S \rangle$

Small $\mu_{\text{(eff)}}$ preferred by low fine-tuning:

$$M_Z^2 \simeq \frac{2(m_{H_d}^2 - \tan^2\beta \; m_{H_u}^2)}{\tan^2\beta - 1} - 2\mu_{\text{(eff)}}^2$$

$\longrightarrow$ absence of cancellations if $|\mu_{\text{(eff)}}| \approx M_Z$
$\longrightarrow$ $|\mu_{\text{(eff)}}| < M_1$, higgsino-like dark matter(?)

But: higgsino-like dark matter faces problems:

— Too small relic density (Z-exchange in the s-channel)

— Too large direct detection cross section (unless $> 90\%$ "pure")

$\longrightarrow$ Should one conclude that $|\mu_{(\text{eff})}| \gtrsim M_1$, hence
No Dark Matter below 250 GeV (if M_1 "unified" with M_3)?

True in the MSSM, NOT in the NMSSM:

The lightest neutralino can be an admixture of the singlino χ_S and higgsinos, if the singlino mass term

$$M_{\chi_S} = 2\frac{\kappa}{\lambda}\mu_{\text{eff}}$$

is small enough

Note: the singlino and the CP-even/CP-odd singlet Higgs masses M_{H_S}/M_{A_S} satisfy an approximate sum rule (for $\langle S \rangle \gg M_Z$):

$$M_{\chi_S}^2 \sim M_{H_S}^2 + \frac{1}{3} M_{A_S}^2$$

Not very exact due to omitted terms, rad. corrs. and mixing effects, still:

A light singlino implies light singlet-like CP-even and CP-odd Higgs bosons

Viable? Consider constraints from

— WMAP/Planck on the relic density,

— LEP on light Higgs bosons, on $\chi_1^0 + \chi_2^0$ production, invis. Z-width $\lesssim 2$ MeV,

— XENON100 on the direct detection cross section,

— Parameters consistent with a SM-like Higgs boson near 125 GeV, incl. SM-like signal rates

And recent constraints from

— invisible/undetected decays of the SM-like H_{125} Higgs boson (if $M_{\chi_1^0} \lesssim 60$ GeV),
— searches for charginos/neutralinos at the LHC (relevant for $M_{\chi_1^0} \lesssim 60$ GeV)

Note: $M_{\chi_1^0} \sim 63$ GeV constitutes a "barrier":

— $M_{\chi_1^0} \sim 63 \pm 2$ GeV is impossible: too small relic density from H_{125}-exchange in the s-channel
— constraints from H_{125}-decays apply only for $M_{\chi_1^0} \lesssim 60$ GeV
— constraints from searches for charginos/neutralinos at the LHC are relevant only to $M_{\chi_1^0} \lesssim 60$ GeV

Singlino-higgsino-like LSP with $M_{\chi_1^0} \lesssim 60$ GeV viable at all?

(Constraints from indirect DM detection and ATLAS searches for $Z/W + E_T^{\text{miss}}$ apply to $M_{\chi_1^0} \lesssim 10$ GeV, not considered here)

Constraints from invisible/undetected H_{125} decays:

Invisible: $H_{125} \to \chi_1^0 \chi_1^0$; (weak) constraints from ZH-production:

$Z^* \to H_{125} + Z \to \chi_1^0 \chi_1^0 + e^+e^-, \mu^+\mu^-$: $\quad BR(H_{125} \to \chi_1^0 \chi_1^0) \lesssim 75\%$

Undetected: $H_{125} \to \chi_1^0 \chi_1^0$ or pair of light CP-even or CP-odd Higgs states H_1, A_1 decaying to 4b-quarks

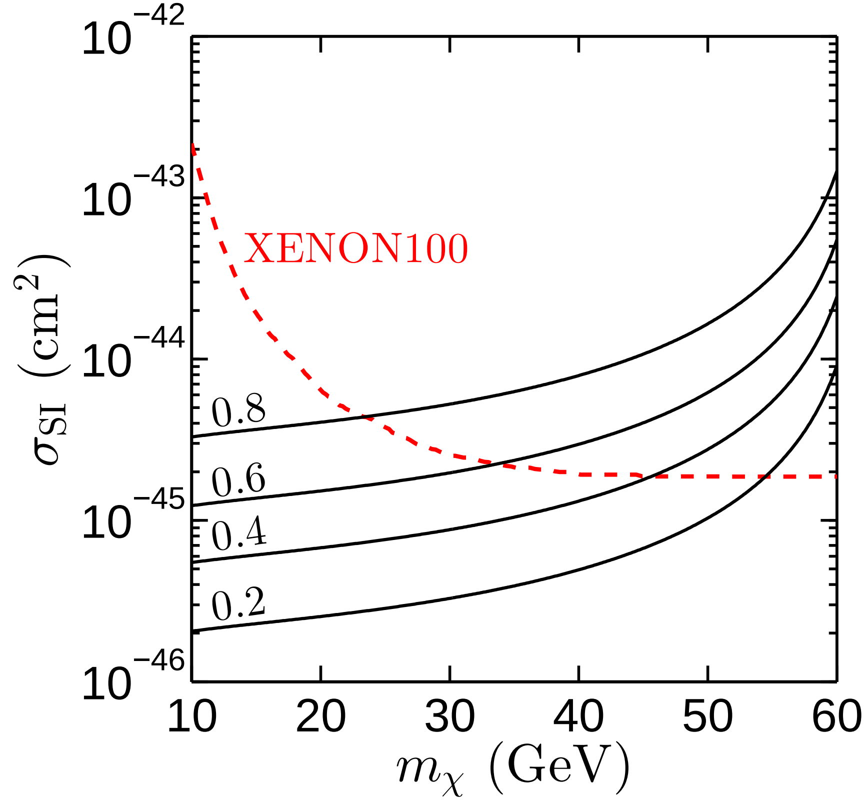
$\longrightarrow$ additional contributions to the total width $\Gamma_{\text{Tot}}(H_{125})$

$\longrightarrow$ reduction of the observed BRs of H_{125} into $\gamma\gamma$, ZZ, WW, $b\bar{b}$

$\longrightarrow$ $BR(H_{125} \to$ undetect.$)$ $\lesssim$ 30% (Belanger et al., 1302.5694)
(unless the coupling of H_{125} to ZZ/WW – relevant for VBF – is enhanced; impossible if H_{125} =mixture of SU(2) doublets and singlets)

$\longrightarrow$ Strong bounds on $H_{125} \to \chi_1^0 \chi_1^0$, $H_1 H_1$, $A_1 A_1$ for $M_{\chi_1^0}$, M_{H_1}, M_{A_1} below 60 GeV; large couplings (large λ) ruled out

Also: Upper bounds on the SI χ_1^0–proton cross section mediated by H_{125}, stronger than the ones from XENON100 for $M_{\chi_1^0} \lesssim 50$ GeV:



However: In the NMSSM, the SI χ_1^0–proton cross section can be mediated dominantly by a light mostly singlet-like CP-even Higgs boson (Vasquez et al., 1009.4380) inspite of its small couplings to quarks, since $\sigma_{\chi p}^{\rm SI} \sim M_H^{-4}$!

$\longrightarrow$ XENON100 bounds remain relevant here

Constraints from chargino/neutralino searches at the LHC:

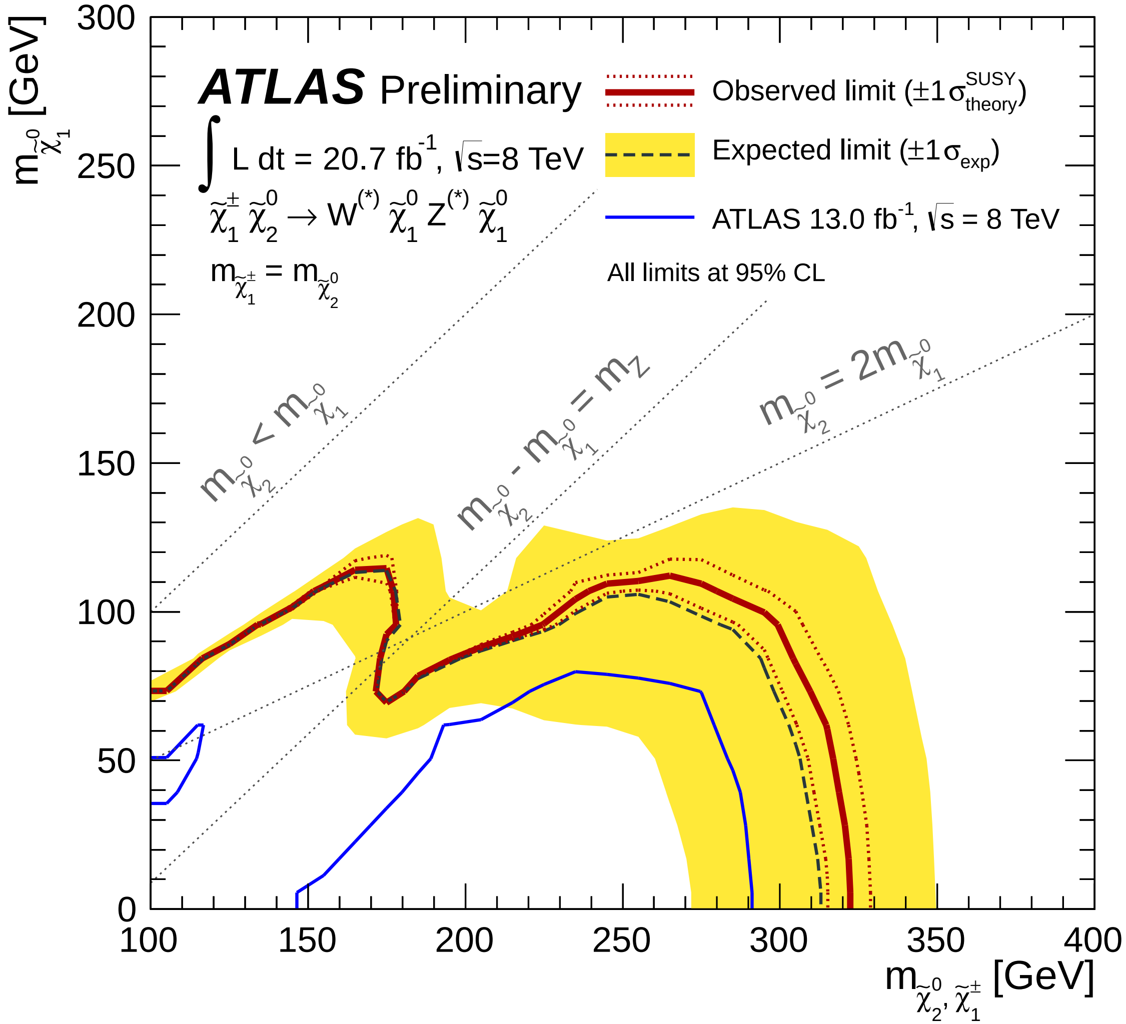
Most relevant:

$$W^* \to \chi_1^+ + \chi_2^0 \to (W_{\to lept} + \chi_1^0) + (Z_{\to 2lept} + \chi_1^0)$$

$\longrightarrow$ 3 leptons ($e^\pm$ or $\mu^\pm$) + E_T^{miss}

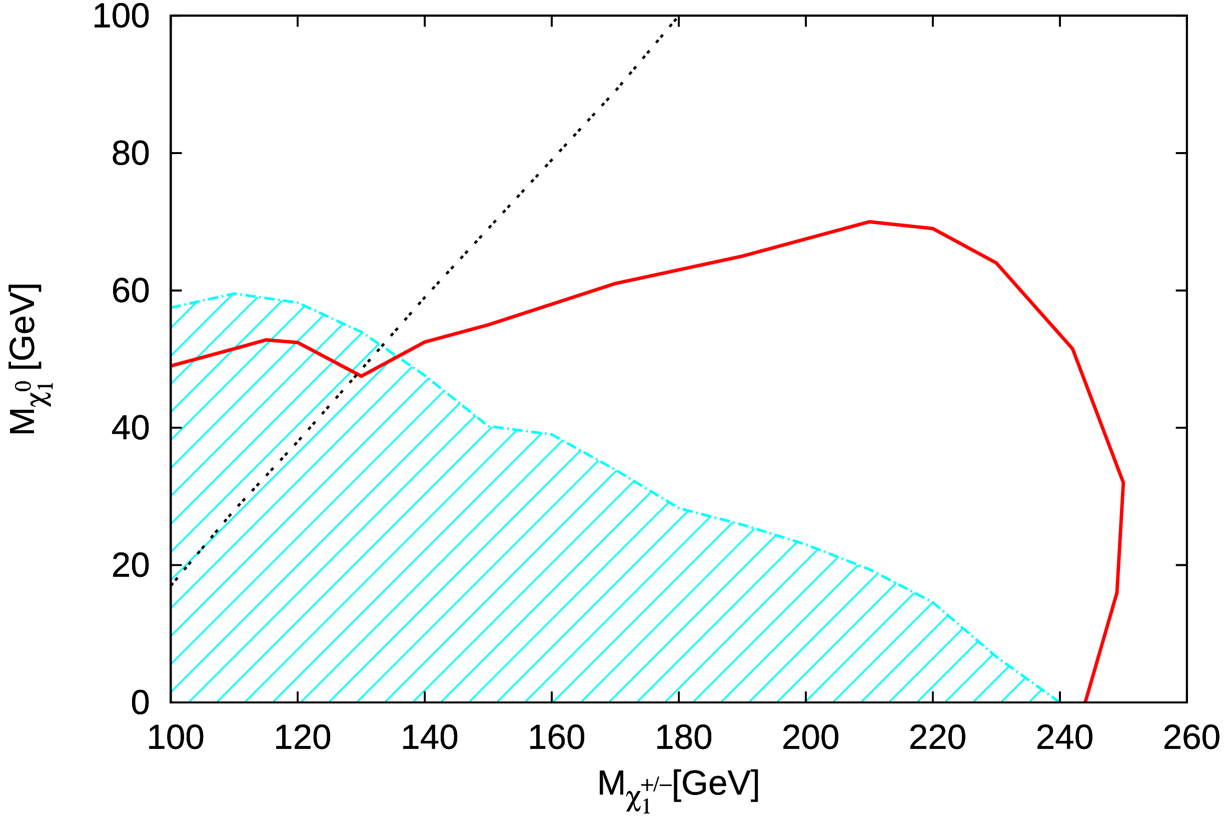
Often interpreted for χ_1^+, χ_2^0 wino-like (degenerated), χ_1^0 bino-like,
no $\chi_2^0 \to \chi_1^0$+Higgs decays ("simplified model")

From ATLAS-CONF-2013-035:



$\longrightarrow M_{\chi_1^{\pm}} \lesssim 320$ GeV for $M_{\chi_1^0} \lesssim 100$ GeV

Applying the same bounds to the singlino-higgsino scenario in the NMSSM (U.E., 1309.1665; simplified: assuming no $\chi^0_{2,3} \to \chi^0_1$+Higgs decays):



Blue hatched: excluded by LEP; red curve: excluded by ATLAS

$\longrightarrow$ $M_{\chi_1^\pm} \lesssim$ 240 GeV for $M_{\chi_1^0} \lesssim$ 60 GeV

$\longrightarrow$ Alleviation of the previous bounds since the W-higgsino^2 coupling is smaller than the W-wino^2 coupling (Clebsch Gordan coeff.), and $\chi^0_{2,3}$ have some singlino component

The BRs for $\chi^0_{2,3} \to \chi^0_1$+Higgs decays (assumed to be absent here) depend strongly on the various mixing angles/parameters;

Allowing for $\chi^0_{2,3} \to \chi^0_1$+Higgs decays with parameters consistent with Dark Matter relic density, XENON100 bounds, a 125 GeV SM-like Higgs: The BR for the dominant $\chi^0_{2,3} \to \chi^0_1 + H$ decay is

$$BR(\chi^0_2 \to \chi^0_1 + H_{125}) \sim 35\%$$

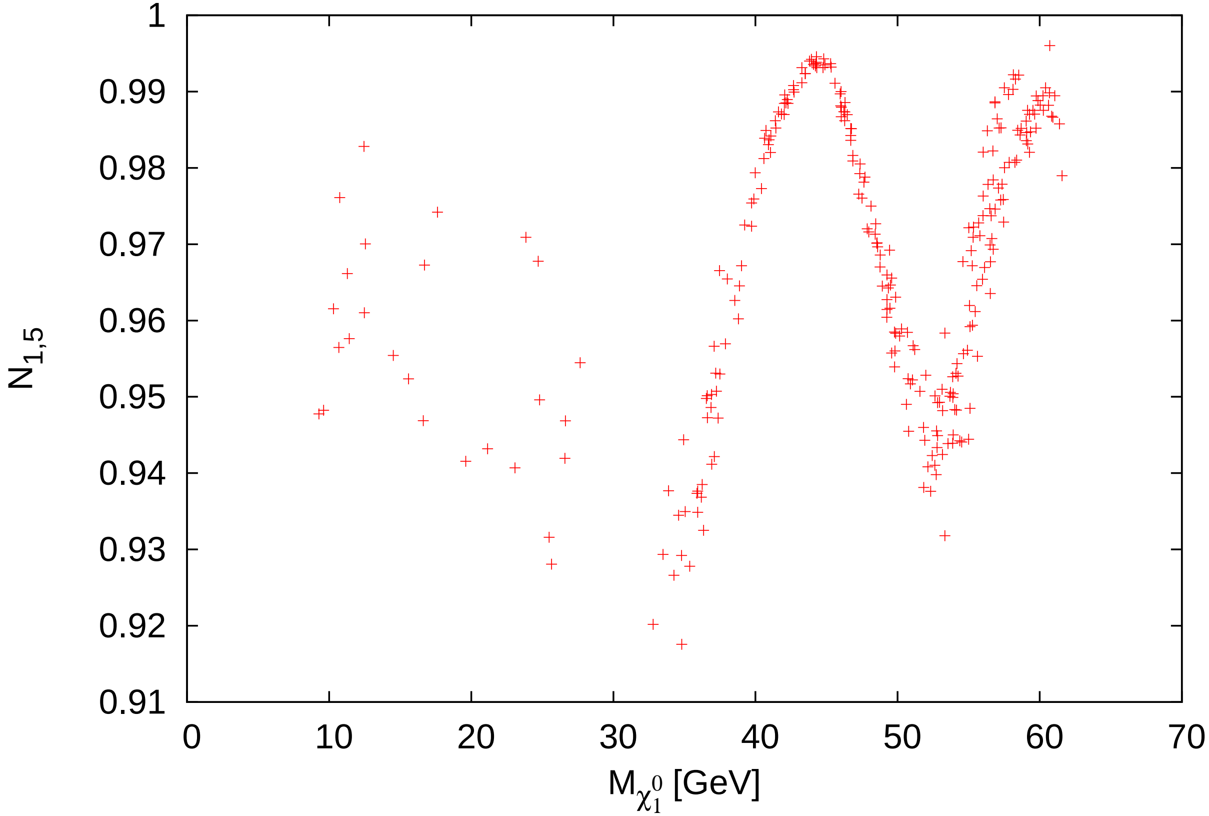
$\longrightarrow$ Further alleviation of the previous bounds:

$$M_{\chi^\pm_1} \sim \mu_{\text{eff}} \gtrsim 170 \text{ GeV for } M_{\chi^0_1} \lesssim 40 \text{ GeV}$$

Still non-trivial!

Scanning the NMSSM Parameter Space, implementing all constraints on Dark Matter (relic density, XENON100, LEP) and a 125 GeV Higgs boson (mass, signal rates from Belanger et al., 1306.2941): Viable points!
BUT: “MSSM-like” H_{125} mass (large $\tan\beta$, small λ, large A_{top})

The χ_1^0 singlet component $N_{1,5}$ as function of $M_{\chi_1^0}$:



$\longrightarrow 0.91 \lesssim N_{1,5} \lesssim 1.00$, mostly singlet-like

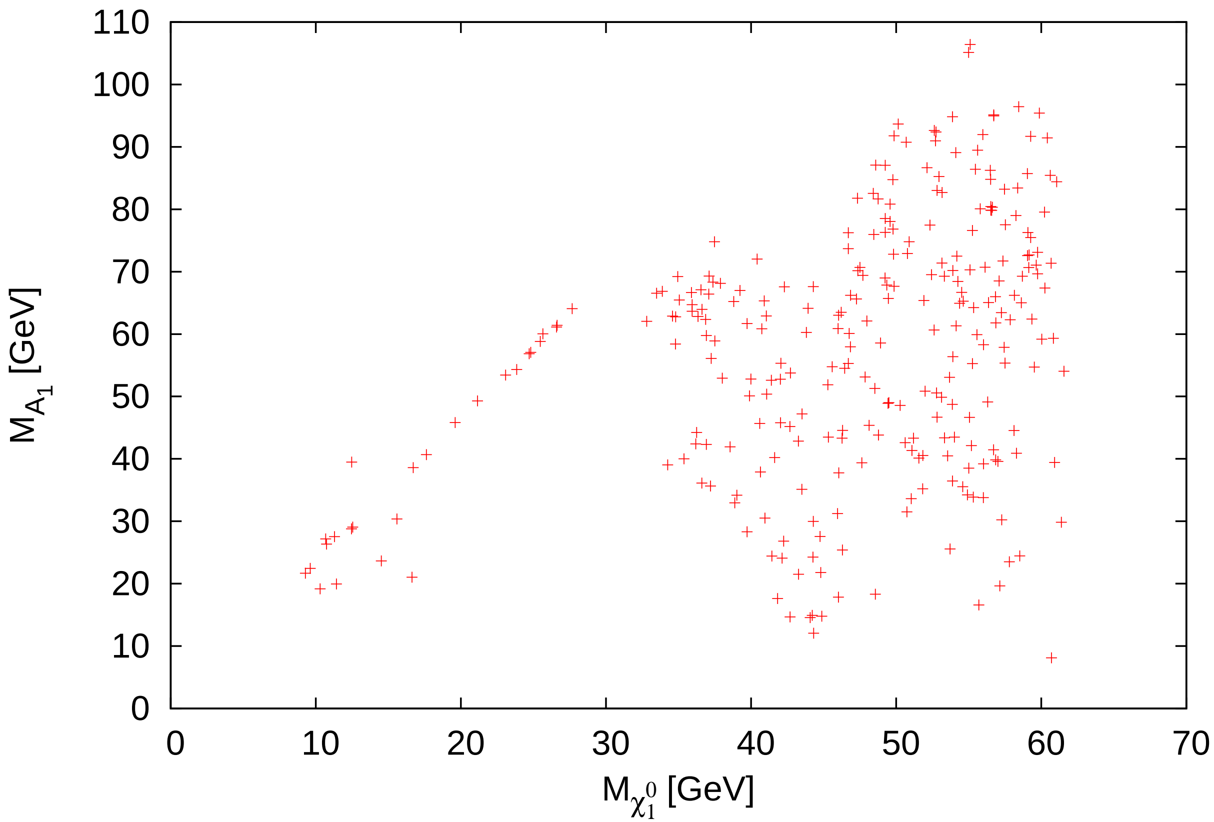
Note: In order for the relic density not to be too small due to s-channel resonances

— $N_{1,5}$ must be close to 1 for $M_{\chi_1^0}$ close to $\frac{125.7}{2} \sim 63$ GeV such that χ_1^0 decouples from H_{125}, but $N_{1,5} < 1$ for $M_{\chi_1^0}$ away from 63 GeV such that Ωh^2 is in agreement with WMAP/Planck

— $N_{1,5}$ must be close to 1 for $M_{\chi_1^0}$ close to $\frac{1}{2} M_Z \sim 45$ GeV such that χ_1^0 decouples from Z, but $N_{1,5} < 1$ for $M_{\chi_1^0}$ away from 45 GeV such that Ωh^2 is in agreement with WMAP/Planck

— And for $M_{\chi_1^0} \lesssim 30$ GeV?

The lightest CP-odd Higgs mass M_{A_1} as function of $M_{\chi_1^0}$:

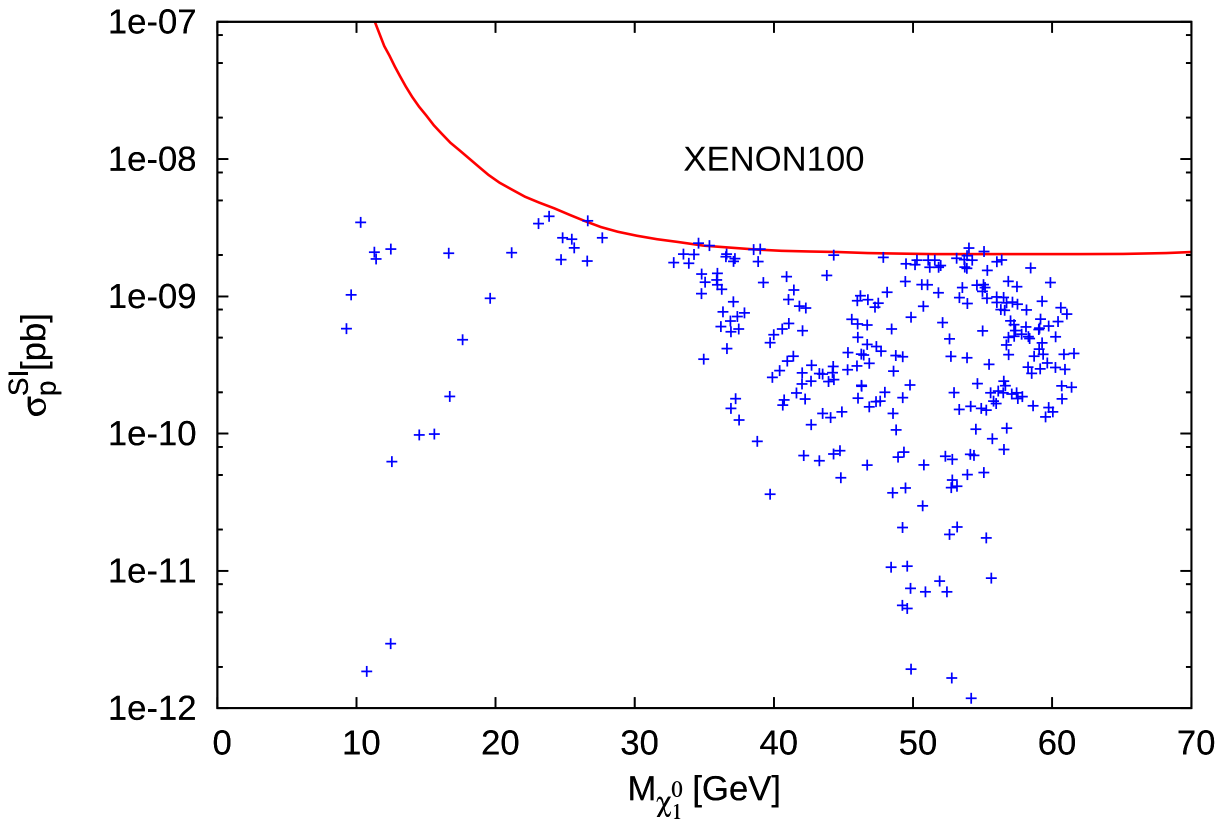


$\longrightarrow$ For $M_{\chi_1^0} \lesssim 30$ GeV we have typically $M_{A_1} \sim 2\ M_{\chi_1^0}$,

$\longrightarrow$ χ_1^0 annihilation through A_1 in the s-channel

$\longrightarrow$ 3 different χ_1^0 annihilation channels depending on $M_{\chi_1^0}$!

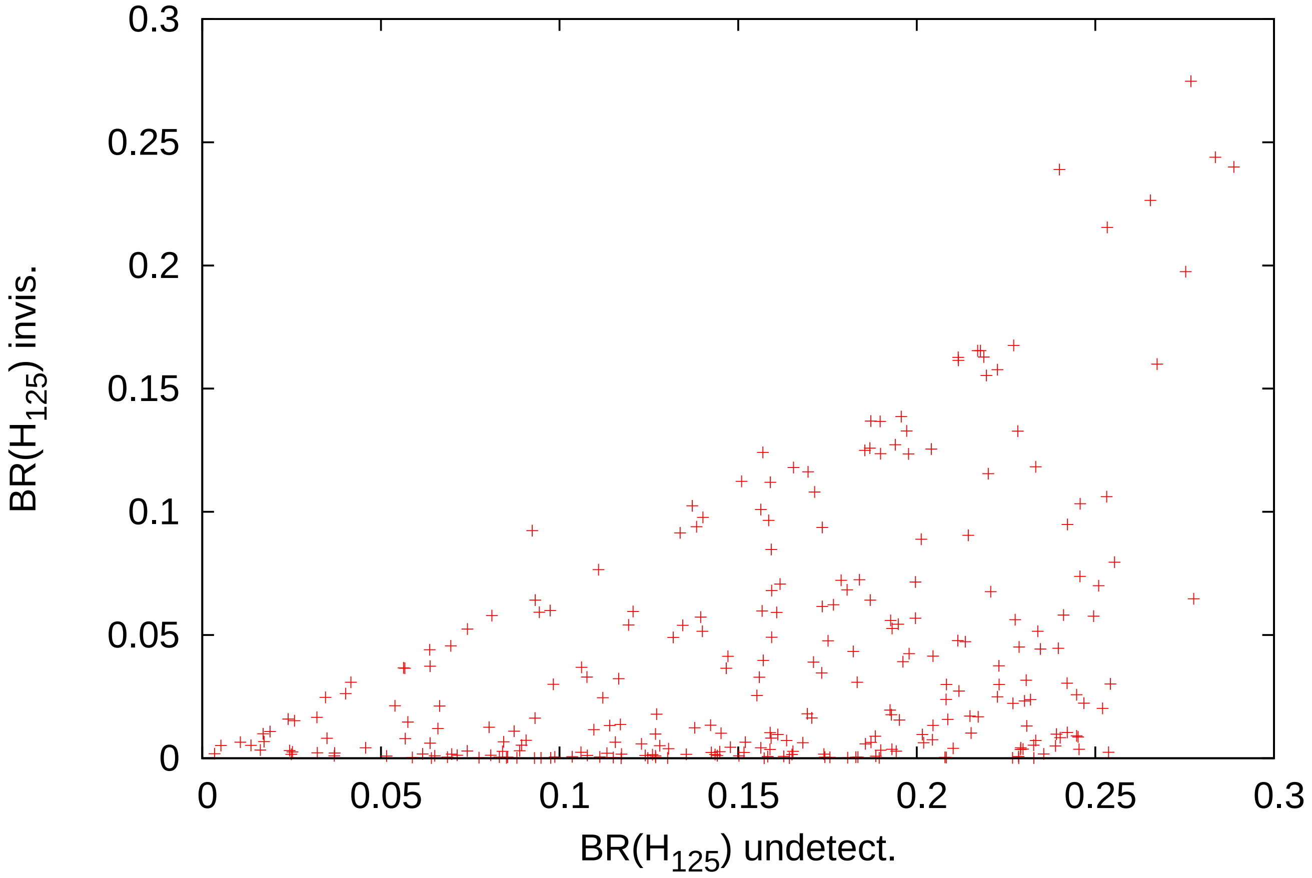
The spin-independent χ_1^0-proton cross section as function of $M_{\chi_1^0}$:



Note: much larger cross sections at low $M_{\chi_1^0} \lesssim 15$ GeV (DAMA, CoGENT) are not possible

XENON1T (about 2 orders of magnitude better) will test most – but still not all – of the parameter space

The invisible $BR(H_{125} \to \chi_1^0 \chi_1^0)$ as function of the undetected $BR(H_{125} \to \chi_1^0 \chi_1^0,\ H_1 H_1,\ A_1 A_1)$:



$\longrightarrow$ Both $H_{125} \to \chi_1^0 \chi_1^0$ and $H_{125} \to H_1 H_1,\ A_1 A_1$ can contribute sizeably to the undetected BR

Conclusions:

— A singlino-higgsino-LSP scenario in the NMSSM (large M_1, low μ_{eff}) is well motivated; very distinct from the MSSM

— Viable – even for $M_{\chi_1^0} \lesssim 60$ GeV – in spite of new recent constraints from the LHC: H_{125} signal rates, searches for neutralinos/charginos

Future tests:

— XENON1T, of course;

— Neutralino/chargino searches at the LHC; need careful interpretation!

— Stronger constraints on $BR(H_{125})_{\text{undetect.}}$ from lower bounds on H_{125} signal rates into $\gamma\gamma$ etc.?