Spin-dependent constraints on neutralino dark matter in (N)MSSM

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M. Badziak, M.O. and P. Szczerbiak, Phys. Lett. B70 (2017) 226; JHEP 07 (2017) 050

Outline

- Introduction
- Experimental searches for Dark Matter
  - limits on spin-independent cross-sections $\Rightarrow$ blind spots
  - new strong limits on spin-dependent cross-sections
- Bino-higgsino LSP in MSSM
- Singlino-higgsino LSP in NMSSM
- Conclusions

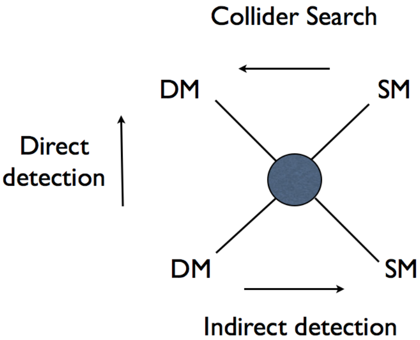
Introduction

One of the motivations for SUSY extensions of the SM: they naturally can accommodate Dark Matter (DM) particles

- In many cases Lightest Supersymmetric Particle (LSP)
  - has mass of the order of the EW scale
  - has weak-strength interactions
- $\Rightarrow$ LSP is a good candidate for DM
- Many Direct Detection (DD) and Indirect Detection (ID) experiments searching for DM particles
  - no (confirmed) positive results of these searches
- DM relic density is known with a good precision (especially with Planck data)
  - in general we have the upper bound on the LSP relic density
  - also the lower bound if LSP is to be dominant component of DM
- No DM particle discovered at LHC
- $\Rightarrow$ Strong constraints on LSP interactions and SUSY spectrum
- Can all such constraints be fulfilled in (simple) SUSY models?

Experimental searches for DM

Constraints on interactions of DM particles with SM particles



$(v \approx 0)$

and thermal relic abundance

$(v > 0)$

Experimental searches for DM

DD experiments

- searches for events of DM scattering on nuclei
- LUX, XENON, PandaX, LZ, CDMS, CRESST, PICO ...
- very strong limits on $\sigma^{\rm SI}$ and strong limits on $\sigma^{\rm SD}$

ID experiments

- searches for products of DM annihilation
- IceCube, Fermi-LAT, AMS, MAGIC, HESS, ANTARES ...
- typically less restrictive than the recent DD results

LHC experiments

- searches for production of DM particles
- limits on masses and interactions of other SUSY particles
- Higgs properties

Experimental searches for DM

Experimental bounds on σ^{SI} are much stronger than on σ^{SD}

Limits presented by LUX at Moriond 2017:

$$\sigma^{\mathrm{SI}} < 2.2 \cdot 10^{-46}\,\mathrm{cm}^2 \qquad \text{for } m_{\mathrm{LSP}} = 50\,\mathrm{GeV}$$

$$\sigma^{\mathrm{SD}} < 1.6 \cdot 10^{-41}\,\mathrm{cm}^2 \qquad \text{for } m_{\mathrm{LSP}} = 35\,\mathrm{GeV}$$

But in some cases it is easier to fulfill bounds on σ^{SI}

We consider neutralino DM in MSSM and NMSSM with decoupled squarks (and gluinos)

DM-nucleon cross sections

- spin-independent
  - mediated by scalars ~~and squarks~~
- spin-dependent
  - mediated by Z ~~and squarks~~

Blind-spots:
points in the parameter space for which DM-nucleon cross-section is very small (eg. below the neutrino background)

- possible for σ^{SI}
  - contributions from scalars may be small or may interfere destructively
- not possible for σ^{SD}
  - typically coupling to Z can not be very small because it is important also for the relic abundance of DM

$$\sigma^{\rm SI} = \frac{4\mu_{\rm red}^2}{\pi} \frac{\left[Z f^{(p)} + (A-Z) f^{(n)}\right]^2}{A^2}$$

$$f^{(N)} \approx \sum_{i=1}^{2(3)} f_{h_i}^{(N)} \equiv \sum_{i=1}^{2(3)} \frac{\alpha_{h_i\chi\chi}\alpha_{h_i NN}}{2m_{h_i}^2}$$

$$\alpha_{h_i\chi\chi} = \sqrt{2}\lambda\left(S_{i1}N_{14}N_{15} + S_{i2}N_{13}N_{15} + S_{i3}N_{13}N_{14}\right) - \sqrt{2}\kappa S_{i3}N_{15}^2$$
$$+ g_1\left(S_{i1}N_{11}N_{13} - S_{i2}N_{11}N_{14}\right) - g_2\left(S_{i1}N_{12}N_{13} - S_{i2}N_{12}N_{14}\right)$$

$$\alpha_{h_i NN} = \frac{m_N}{\sqrt{2}v}\left(\frac{S_{i1}}{\cos\beta}F_d^{(N)} + \frac{S_{i2}}{\sin\beta}F_u^{(N)}\right)$$

h_i scalar mass eigenstates
S_{ij} (N_{kl}) mixing matrix in the scalar (neutralino) sector
MSSM: $i,j = 1,2$ $\quad k,l = 1,\ldots,4$
NMSSM: $i,j = 1,2,3$ $\quad k,l = 1,\ldots,5$

$$\sigma^{\rm SD} = C\cdot 10^{-38}{\rm cm}^2 \left(N_{13}^2 - N_{14}^2\right)^2$$

If DM annihilation dominated by $\chi\chi \to Z \to t\bar{t}$ then $\Omega h^2 \sim (\sigma^{\rm SD})^{-1}$

$$\Omega h^2 \approx \left(\frac{0.05}{N_{13}^2 - N_{14}^2}\right)^2 \left[\sqrt{1-\frac{m_t^2}{m_\chi^2}} + \frac{3}{4x_f}\left(1-\frac{m_t^2}{2m_\chi^2}\right)\frac{1}{\sqrt{1-\frac{m_t^2}{m_\chi^2}}}\right]^{-1}$$

Well-tempered bino-higgsino (higgsino-bino) neutralino in MSSM

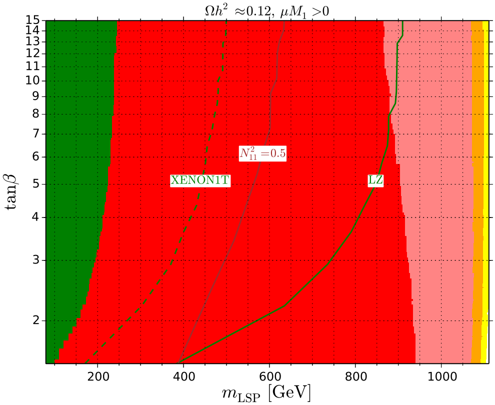
- no resonant annihilation via s-channel
- no coannihilation with particles other than charginos and neutralinos

For heavy (decoupled) H and A we find

$$\alpha_{h\chi\chi} \approx -\sqrt{2} g_1 N_{11}^2 \frac{M_Z \sin\theta_W}{\mu} \frac{m_\chi/\mu + \sin(2\beta)}{1-(m_\chi/\mu)^2}$$

$\Rightarrow$ **it is easier to explore (exclude) parts of the parameter space with $M_1\mu > 0$ because σ^{SI} is bigger**

MSSM – heavy s



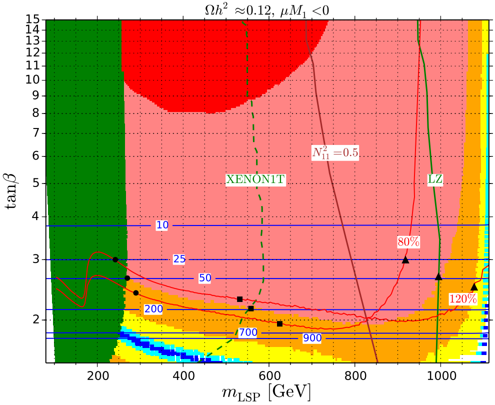
$\sigma^{\rm SI}$ excluded by
old LUX
new LUX

$\sigma^{\rm SI}$ sensitivity of
XENON1T
LZ

$\sigma^{\rm SD}$ excluded by
new LUX

For positive $M_1\mu$ much stronger constraints from experiments sensitive to $\sigma^{\rm SI}$

Almost pure higgsino with mass ~ 1100 GeV still allowed

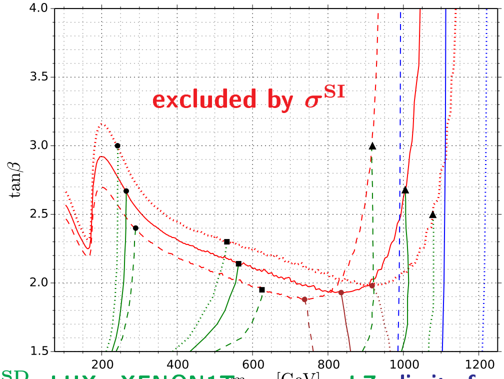


$\sigma^{\rm SI}$ below
LZ sensitivity
ν background

For negative $M_1\mu$ recent results excluded large part of the parameter space

Well-tempered bino-higgsino still allowed
but only for small values of $\tan\beta \Rightarrow$ stops must be heavy $m_{\tilde{t}} \gtrsim 50$ TeV
XENON1T sensitivity:
$\sigma^{\rm SI}$ or $\sigma^{\rm SD}$ alone may push this limit to about 200 TeV
$\sigma^{\rm SI}$ and $\sigma^{\rm SD}$ together to about 900 TeV

The exclusion/sensitivity regions change if the uncertainty in the relic abundance calculations are taken into account



Ωh^2 calculated with MicrOMEGAs:

dashed – 80%
solid – 100%
dotted – 120%

of the measured 0.12

Allowed region:
below red;
right from green;
left from blue

$\sigma^{\rm SD}$: LUX XENON1T LZ limit of pure higgsino

Present limits for bino-higgsino LSP:
$\tan\beta \lesssim$ 3.0, 2.7, 2.4 $\Rightarrow$ $m_{\tilde t} \gtrsim$ 25, 50, 90 TeV
In any case stops must be very heavy

Allowing for relatively light H and A does not help much in the case of well-tempered bino-higgsino LSP

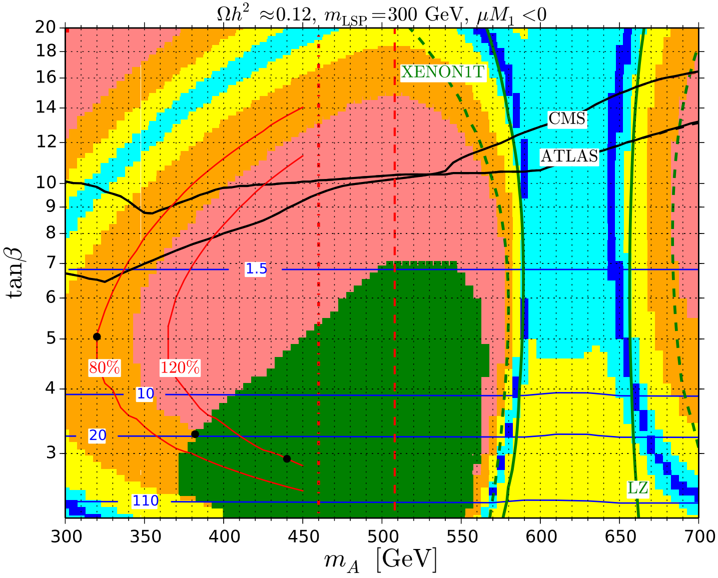
Bounds on $\tan\beta$ obtained by ATLAS and CMS searches for $H/A \to \tau\tau$ play important role

Small marginally allowed region
$m_\chi \sim$ 300 GeV, $\tan\beta \sim 7$ and $m_A \sim$ 350 GeV
likely to be excluded very soon

3 possibilities left in MSSM

- small $\tan\beta$ and very heavy stops (at least 25 TeV)
  - sensitivity of LZ to $\sigma^{\rm SD}$ enough to probe the whole region
- almost pure higgsino
- tuned SUSY spectrum (resonant annihilation)

MSSM – light H



$\Omega h^2 \approx 0.12$, $m_{\rm LSP} = 300$ GeV, $\mu M_1 < 0$
XENON1T
CMS
ATLAS
LZ
1.5
10
20
110
80%
120%
20
18
16
14
12
10
9
8
7
6
5
4
3
$\tan\beta$
300
350
400
450
500
550
600
650
700
m_A [GeV]

NMSSM

There are many new interesting possibilities in NMSSM

Especially interesting are new singlet particles:

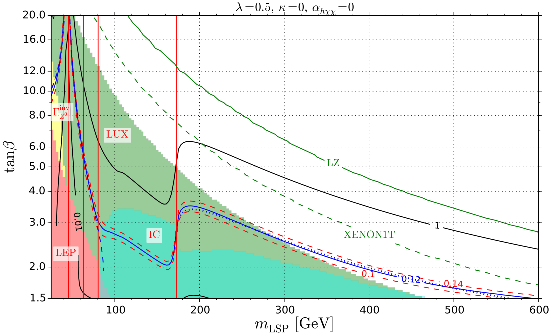
- singlino – additional component of LSP
- scalar – additional contribution to σ^{SI}
- pseudoscalar – new features of the relic abundance calculation

We concentrate on:

- singlino-higgsino LSP (all gauginos decoupled)
- LSP is thermal dominant component of DM
- blind-spots – points in the parameter space giving σ^{SI} below the neutrino background
- impact of the present and planned measurements of σ^{SD}

Simple case with negligible

- contributions from s and H exchange to $\sigma^{\rm SI}$
- mixing of h with s and H



LUX limits on $\sigma^{\rm SD}$ stronger than the corresponding limits from IceCube

Allowed regions

- small $\tan\beta$, $m_{\rm LSP} \gtrsim 300$ GeV – will be fully explored by XENON1T
- Z resonance – will be fully explored by LZ

Similar to well-tempered bino-higgsino in MSSM

If the singlet-dominated scalar is light and contributes to $\sigma^{\rm SI}$ the simple blind-point condition

$$\frac{m_\chi}{\mu} - \sin(2\beta) = 0$$

takes the form

$$\frac{\gamma + \mathcal{A}_s}{1 - \gamma \mathcal{A}_s} = -\eta$$

where

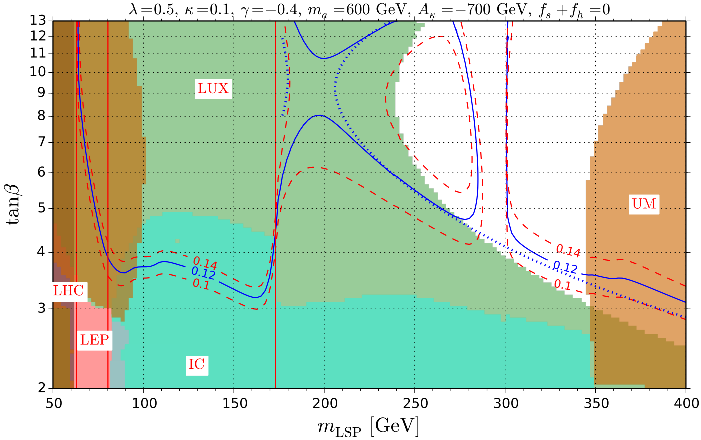
$$\mathcal{A}_s \approx -\gamma \frac{1 + c_s}{1 + c_h} \left(\frac{m_h}{m_s} \right)^2 \qquad c_{h_i} \equiv 1 + \frac{\tilde{S}_{h_i \hat{H}}}{\tilde{S}_{h_i \hat{h}}} \left(\tan\beta - \frac{1}{\tan\beta} \right)$$

$$\gamma \equiv \frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}} \qquad \eta \equiv \frac{N_{15}(N_{13}\sin\beta + N_{14}\cos\beta)}{N_{13}N_{14} - \frac{\kappa}{\lambda} N_{15}^2}$$

c_{h_i} – ratio of the couplings, normalized to the SM values, of h_i to the b quarks and to the Z^0 bosons

For $m_s < m_h$ the s-h mixing may increase m_h by up to ~ 5 GeV

Regions with large s-h mixing are allowed by all present data with resonant LSP annihilation



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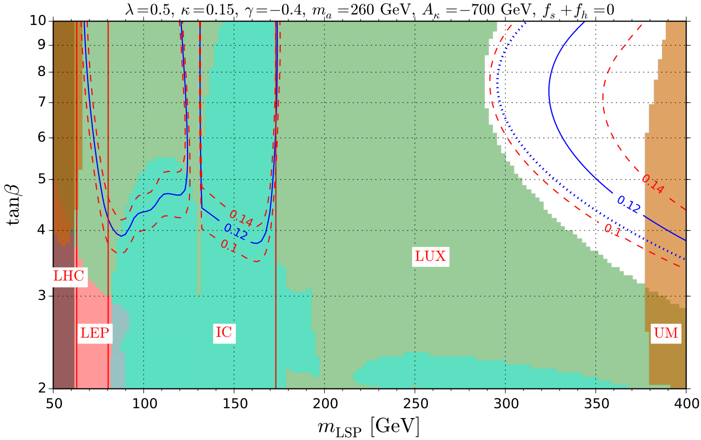
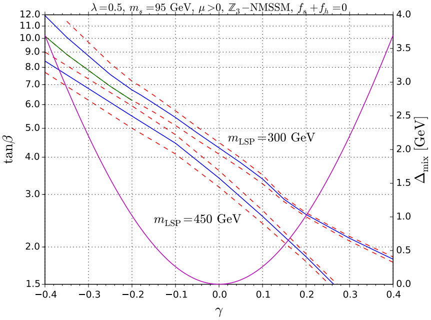


There are correlations with the properties of Higgs

Increasing the s-h mixing leads to growing change in $\tan\beta$ (necessary to keep the Blind Spot and correct value of Ωh^2)



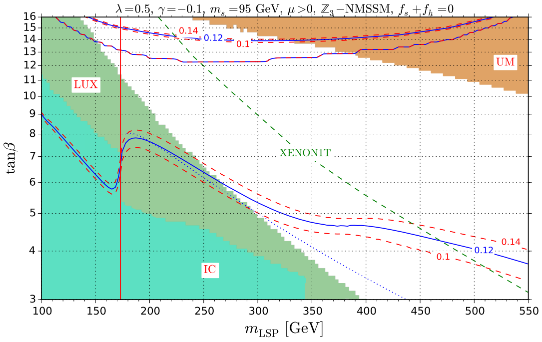
$\tan\beta$ grows (decreases) for negative (positive) mixing parameter γ

- sign of γ is correlated with BR($h \to b\bar{b}$)
- values of $\tan\beta$ and $|\gamma|$ are related with stop masses necessary to get the correct Higgs mass

$\Rightarrow$ lighter stops are allowed when $\frac{\mathrm{BR}(h\to b\bar{b})}{\mathrm{BR}(h\to ZZ)}$ is below the SM value

For smaller s-h mixing the lower bound on $m_{\rm LSP}$ even in the $\mathbb{Z}_3$-symmetric NMSSM may be relaxed to

- **about 250 GeV for moderate $\tan\beta$ (no resonant annihilation)**
- **below 150 GeV for big $\tan\beta$ (resonant annihilation with a exchanged)**



Parts of the allowed regions beyond the reach of XENON1T

(sa, ha ect. final states are important for non-resonant annihilation)

Conclusions

- Strong experimental limits on SI interactions of DM are fulfilled close to Blind Spots
- No analogous BS for SD interactions
- Regions close to BS for $\sigma^{\rm SI}$ may be explored by combining data from experiments sensitive to $\sigma^{\rm SD}$, from LHC and from the relic abundance

- MSSM: well-tempered bino-higgsino LSP allowed for
  - $m_{\rm LSP} \gtrsim 250$ GeV, small $\tan\beta$ and very heavy stops (at least 25 TeV)
    - this region of the parameter space will be covered by LZ
  - small region $m_{\rm LSP} \sim 300$ GeV, $\tan\beta \sim 8$, $m_A \sim 400$ GeV
    - region will be covered by XENON1T and LHC

- NMSSM singlino-higgsino LSP, heavy s and H scalars:
  - $m_{\rm LSP} \gtrsim 300$ GeV, $\tan\beta \lesssim 3.5$
  - $m_{\rm LSP} \lesssim 700$ GeV if λ is to be perturbative till $M_{\rm GUT}$
    - region will be covered by XENON1T
  - small region close to the Z resonance (will be covered by LZ)

Conclusions

- NMSSM singlino-higgsino LSP, light s and a:
  - light s gives more possibilities for SD blind spots
    - s as intermediate particle, s-h mixing
  - light a and s give more possibilities to obtain correct Ωh^2 without influencing σ^{SD}
    - s and a as intermediate particles, additional final states, interference
  - several kinds of allowed regions in the parameter space
    - quite wide ranges of m_{LSP} and $\tan\beta$
    - even for the $\mathbb{Z}_3$-symmetric NMSSM
  - relatively light stops allowed, especially when
    - $m_s < m_h$
    - BR($h \to b\bar{b}$) below the SM prediction
  - some parts of the allowed regions beyond XENON1T sensitivity