Direct detection constraints on well-tempered dark matter in MSSM and NMSSM

Paweł Szczerbiak

University of Warsaw

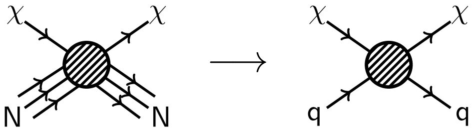
COSMO 2017

August 30, 2017, Paris, France

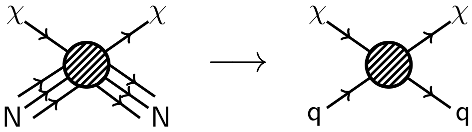
In collaboration with M. Badziak, M. Olechowski

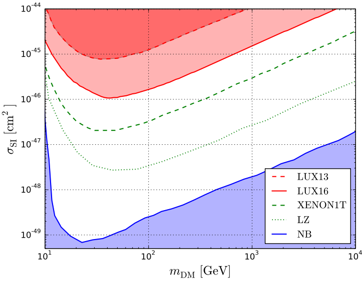
Based on: 1: Phys. Lett. B **770** (2017) 226-235
2: JHEP **1707** (2017) 050

Motivation: direct detection of dark matter

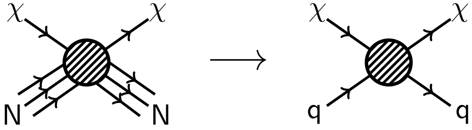


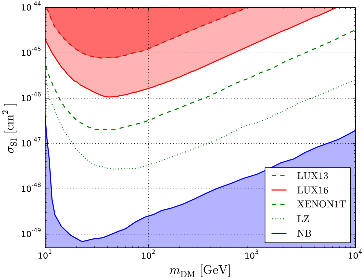
Motivation: direct detection of dark matter

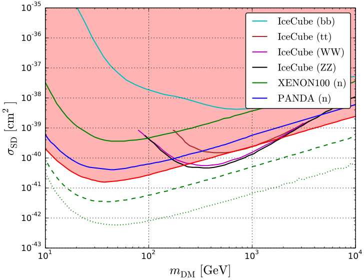




Motivation: direct detection of dark matter







Constraints

Constraint 1:

$$\Omega h^2 \approx 0.12$$

Constraints

Constraint 1:

$$\Omega h^2 \approx 0.12$$

Constraint 2:

$$\sigma_{\rm SI} \sim \left(\frac{\alpha_{\chi\chi h}\alpha_{hNN}}{2m_h^2} + \frac{\alpha_{\chi\chi H}\alpha_{HNN}}{2m_H^2} + \cdots \right)^2$$

$$\sigma_{\rm SD} \sim (N_{13}^2 - N_{14}^2)^2$$

Constraints

Constraint 1:

$$\Omega h^2 \approx 0.12$$

Constraint 2:

$$\sigma_{\mathrm{SI}} \sim \left(\frac{\alpha_{\chi\chi h}\alpha_{hNN}}{2m_h^2} + \frac{\alpha_{\chi\chi H}\alpha_{HNN}}{2m_H^2} + \cdots \right)^2$$

$$\sigma_{\mathrm{SD}} \sim (N_{13}^2 - N_{14}^2)^2$$

$$N_{13}^2 - N_{14}^2 = \frac{\left[1 - (m_\chi/\mu)^2\right](1 - N_{11(15)}^2)\cos 2\beta}{1 + (m_\chi/\mu)^2 + 2\,(m_\chi/\mu)\sin 2\beta}$$

Constraints

Constraint 1:

$$\Omega h^2 \approx 0.12$$

Constraint 2:

$$\sigma_{\rm SI} \sim \left(\frac{\alpha_{\chi\chi h}\alpha_{hNN}}{2m_h^2} + \frac{\alpha_{\chi\chi H}\alpha_{HNN}}{2m_H^2} + \cdots \right)^2$$

$$\sigma_{\rm SD} \sim (N_{13}^2 - N_{14}^2)^2$$

$$N_{13}^2 - N_{14}^2 = \frac{\left[1 - (m_\chi/\mu)^2\right](1 - N_{11(15)}^2)\cos 2\beta}{1 + (m_\chi/\mu)^2 + 2\,(m_\chi/\mu)\sin 2\beta}$$

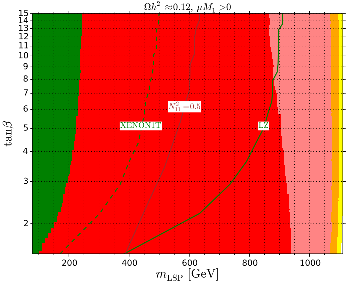
SI blind spots possible

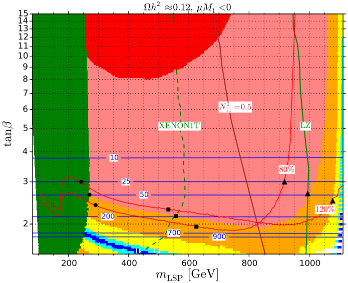
SD blind spots only for $\tan\beta = 1$ or pure states

Well-tempered bino-Higgsino in MSSM – heavy H

$$\alpha_{h\chi\chi}\alpha_{hNN} \sim \frac{N_{11}^2}{\mu}\,\frac{m_\chi/\mu + \sin 2\beta}{1-(m_\chi/\mu)^2} \qquad \alpha_{H\chi\chi}\alpha_{HNN} \sim 0$$

$$\sigma_{\mathrm{SI}} = 0 \quad \Longrightarrow \quad \frac{m_\chi}{\mu} + \sin 2\beta \approx 0$$

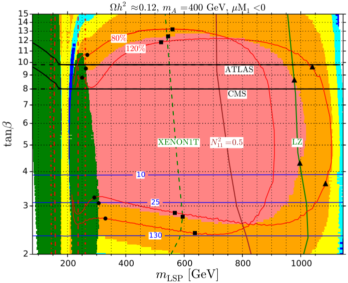


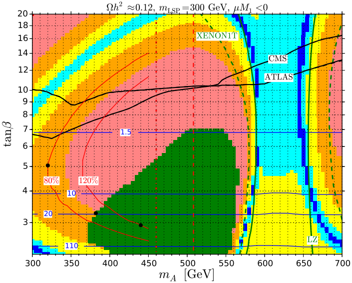


Well-tempered bino-Higgsino in MSSM – light H

$$\alpha_{h\chi\chi}\alpha_{hNN} \sim \frac{N_{11}^2}{\mu}\,\frac{m_\chi/\mu + \sin 2\beta}{1-(m_\chi/\mu)^2} \qquad \alpha_{H\chi\chi}\alpha_{HNN} \sim \frac{N_{11}^2}{\mu}\,\frac{\tan\beta}{1-(m_\chi/\mu)^2}$$

$$\sigma_{\rm SI} = 0 \quad \Longrightarrow \quad \frac{m_\chi}{\mu} + \sin 2\beta \approx -\frac{m_h^2}{m_H^2}\,\frac{\tan\beta}{2}$$





The NMSSM model

$$W = \lambda S H_u H_d + \xi_F S + \frac{1}{2}\mu' S^2 + \frac{1}{3}\kappa S^3$$

$$-\mathcal{L}_{\rm soft} \supset m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2$$

$$+A_\lambda \lambda H_u H_d S + \frac{1}{3} A_\kappa \kappa S^3 + m_3^2 H_u H_d + \frac{1}{2} m_S'^2 S^2 + \xi_S S + h.c.$$

5 additional parameters with respect to $\mathbb{Z}_3$-NMSSM.

The NMSSM model

$$W = \lambda S H_u H_d + \xi_F S + \frac{1}{2}\mu' S^2 + \frac{1}{3}\kappa S^3$$

$$-\mathcal{L}_{\rm soft} \supset m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2$$

$$+A_\lambda \lambda H_u H_d S + \frac{1}{3} A_\kappa \kappa S^3 + m_3^2 H_u H_d + \frac{1}{2} m_S'^2 S^2 + \xi_S S + h.c.$$

5 additional parameters with respect to $\mathbb{Z}_3$-NMSSM.

Scalar sector:

$$\begin{pmatrix} \hat{h} \\ \hat{H} \\ \hat{s} \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta & 0 \\ \sin\beta & -\cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} H_d \\ H_u \\ S \end{pmatrix}$$

Mass eigenstates: $h_i = \tilde{S}_{ij} \hat{H}_j \qquad h_i = h,\ H,\ s$

Blind spots for singlino-Higgsino LSP in NMSSM

Approximations/assumptions:

1. $N_{11} \approx 0 \approx N_{12}$ gauginos decoupled
2. $m_H \gg m_h$ heavy H

Blind spots for singlino-Higgsino LSP in NMSSM

Approximations/assumptions:

1. $N_{11} \approx 0 \approx N_{12}$ gauginos decoupled
2. $m_H \gg m_h$ heavy H

Considered cases:

1. Only h exchange
   - no mixing among scalars
   - with scalar mixing
2. h and H exchange
   - no mixing with s
   - mixing with s, $m_s \gg m_h$
3. h and s exchange
   - leading effect from H

Blind spots for singlino-Higgsino LSP in NMSSM

Approximations/assumptions:

1. $N_{11} \approx 0 \approx N_{12}$ — gauginos decoupled
2. $m_H \gg m_h$ — heavy H

Considered cases:

1. Only h exchange
   - no mixing among scalars $\frac{m_\chi}{\mu} - \sin 2\beta = 0$ (MSSM-like)
   - with scalar mixing
2. h and H exchange
   - no mixing with s $\frac{m_\chi}{\mu} - \sin 2\beta = \frac{\tan\beta}{2}\left(\frac{m_h}{m_H}\right)^2$ (MSSM-like)
   - mixing with s, $m_s \gg m_h$
3. h and s exchange
   - leading effect from H

Blind spots for singlino-Higgsino LSP in NMSSM

Approximations/assumptions:

1. $N_{11} \approx 0 \approx N_{12}$ — gauginos decoupled
2. $m_H \gg m_h$ — heavy H

Considered cases:

1. Only h exchange in this talk
   - no mixing among scalars $\frac{m_\chi}{\mu} - \sin 2\beta = 0$ (MSSM-like)
   - with scalar mixing
2. h and H exchange
   - no mixing with s $\frac{m_\chi}{\mu} - \sin 2\beta = \frac{\tan\beta}{2}\left(\frac{m_h}{m_H}\right)^2$ (MSSM-like)
   - mixing with s, $m_s \gg m_h$
3. h and s exchange in this talk
   - leading effect from H

General NMSSM – only h exchange (no scalar mixing)

Blind spot condition:

$$\frac{m_\chi}{\mu} - \sin 2\beta \approx 0$$

General NMSSM – only h exchange (no scalar mixing)

Blind spot condition:

$$\frac{m_\chi}{\mu} - \sin 2\beta \approx 0$$

Two generic mechanisms:

- resonance with Z^0 boson ($m_\chi \sim 45$ GeV):

$$\Omega h^2 \approx 0.1 \left(\frac{0.3}{N_{13}^2 - N_{14}^2} \right)^2 \frac{m_Z^2}{4 m_\chi^2} \left[\left(\frac{4 m_\chi^2}{m_Z^2} - 1 + \frac{\bar{v}^2}{4} \right)^2 + \frac{\Gamma_Z^2}{m_Z^2} \right]$$

- annihilation into $t\bar{t}$ ($m_\chi \gtrsim 170$ GeV):

$$\Omega h^2 \approx 0.1 \left(\frac{0.05}{N_{13}^2 - N_{14}^2} \right)^2 \left[\sqrt{1 - \frac{m_t^2}{m_\chi^2}} + \frac{3}{4} \frac{1}{x_f} \left(1 - \frac{m_t^2}{2 m_\chi^2} \right) \frac{1}{\sqrt{1 - \frac{m_t^2}{m_\chi^2}}} \right]^{-1/2}$$

General NMSSM – only h exchange (no scalar mixing)

Blind spot condition:

$$\frac{m_\chi}{\mu} - \sin 2\beta \approx 0$$

Two generic mechanisms:

- resonance with Z^0 boson ($m_\chi \sim 45$ GeV):

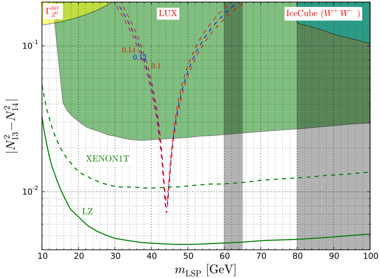
$$\Omega h^2 \approx 0.1 \left(\frac{0.3}{N_{13}^2 - N_{14}^2} \right)^2 \frac{m_Z^2}{4 m_\chi^2} \left[\left(\frac{4 m_\chi^2}{m_Z^2} - 1 + \frac{\bar{v}^2}{4} \right)^2 + \frac{\Gamma_Z^2}{m_Z^2} \right]$$

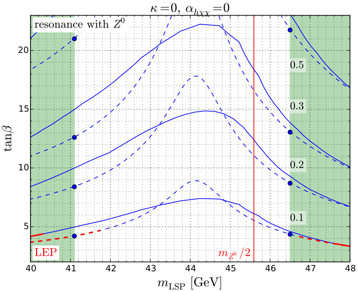
- annihilation into $t\bar{t}$ ($m_\chi \gtrsim 170$ GeV):

$$\Omega h^2 \approx 0.1 \left(\frac{0.05}{N_{13}^2 - N_{14}^2} \right)^2 \left[\sqrt{1 - \frac{m_t^2}{m_\chi^2}} + \frac{3}{4} \frac{1}{x_f} \left(1 - \frac{m_t^2}{2 m_\chi^2} \right) \frac{1}{\sqrt{1 - \frac{m_t^2}{m_\chi^2}}} \right]^{-1/2}$$

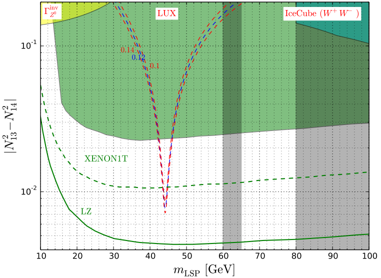
$$\sigma_{\rm SD} \sim (N_{13}^2 - N_{14}^2)^2$$

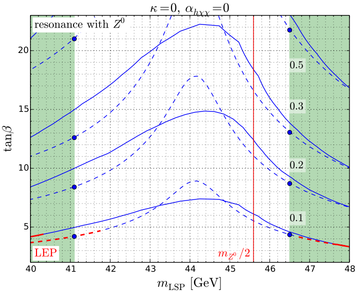
General NMSSM – only *h* exchange (no scalar mixing)

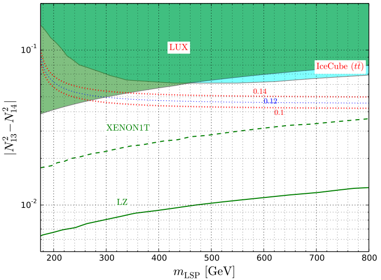


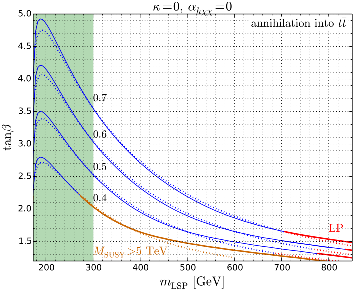


General NMSSM – only *h* exchange (no scalar mixing)





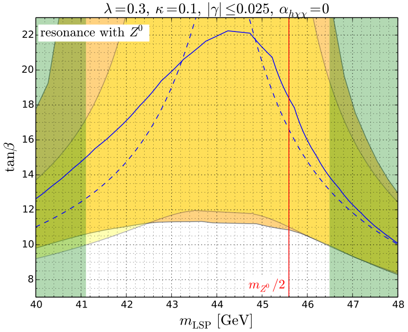


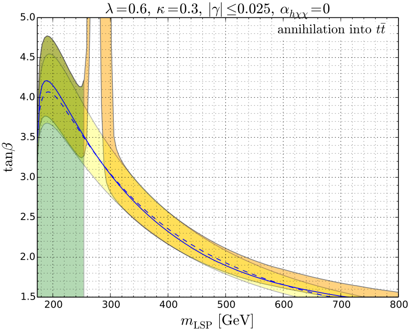


General NMSSM – only h exchange (with scalar mixing)

Blind spot condition ($\gamma \equiv \frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}}$):

$$\frac{m_\chi}{\mu} - \sin 2\beta \approx \gamma \frac{\kappa}{\lambda} \left(\frac{\mu}{\lambda v}\right) \left(1 - \left(\frac{m_\chi}{\mu}\right)^2\right)$$





General NMSSM – h and s exchange

- Let us introduce:

$$\mathcal{A}_s \equiv \frac{\alpha_{sNN}}{\alpha_{hNN}} \frac{\tilde{S}_{s\hat{s}}}{\tilde{S}_{h\hat{h}}} \left(\frac{m_h}{m_s}\right)^2 \qquad \gamma \equiv \frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}}$$

General NMSSM – h and s exchange

- Let us introduce:

$$\mathcal{A}_s \equiv \frac{\alpha_{sNN}}{\alpha_{hNN}} \frac{\tilde{S}_{s\hat{s}}}{\tilde{S}_{h\hat{h}}} \left(\frac{m_h}{m_s}\right)^2 \qquad \gamma \equiv \frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}}$$

- Blind spot condition:

$$\frac{m_\chi}{\mu} - \sin 2\beta \approx \frac{\gamma + \mathcal{A}_s}{1 - \gamma \mathcal{A}_s} \frac{\kappa}{\lambda} \left(\frac{\mu}{\lambda v}\right) \left(1 - \left(\frac{m_\chi}{\mu}\right)^2\right)$$

General NMSSM – h and s exchange

- Let us introduce:

$$\mathcal{A}_s \equiv \frac{\alpha_{sNN}}{\alpha_{hNN}} \frac{\tilde{S}_{s\hat{s}}}{\tilde{S}_{h\hat{h}}} \left(\frac{m_h}{m_s}\right)^2 \qquad \gamma \equiv \frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}}$$

- Blind spot condition:

$$\frac{m_\chi}{\mu} - \sin 2\beta \approx \frac{\gamma + \mathcal{A}_s}{1 - \gamma \mathcal{A}_s} \frac{\kappa}{\lambda} \left(\frac{\mu}{\lambda v}\right) \left(1 - \left(\frac{m_\chi}{\mu}\right)^2\right)$$

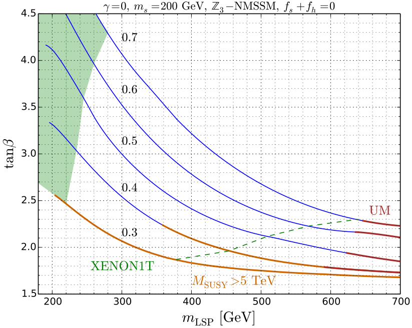
- Conclusions:
  - because $m_s < m_h$, the RHS can be one order of magnitude larger as compared to the case of only h exchange
  - in general NMSSM we can have $\Omega h^2 \approx 0.12$ and other experimental bounds fulfilled even for $\Delta_{\mathrm{mix}} \sim 4$ GeV, where $\gamma \sim \sqrt{\Delta_{\mathrm{mix}}}$, $m_h = \hat{M}_{hh} + \Delta_{\mathrm{mix}}$.

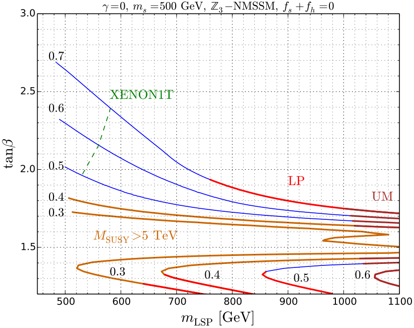
$\mathbb{Z}_3$-NMSSM – only h exchange (heavy singlet)

$$\frac{m_\chi}{\mu} - \sin 2\beta \approx \gamma \frac{\kappa}{\lambda} \left(\frac{\mu}{\lambda v}\right) \left(1 - \left(\frac{m_\chi}{\mu}\right)^2\right)$$

$$\mathrm{sgn}(m_\chi \mu) = \mathrm{sgn}(\kappa) \qquad |\kappa| < \tfrac{1}{2}\lambda \text{ (for singlino-like LSP)}$$

$$m_s^2 + \tfrac{1}{3} m_a^2 \approx m_{\mathrm{LSP}}^2 + \gamma^2 (m_s^2 - m_h^2) \quad \Rightarrow \quad m_{\mathrm{LSP}} > m_s$$



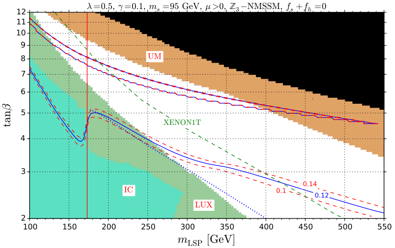


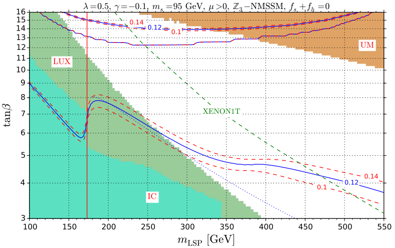
$\mathbb{Z}_3$-NMSSM – h and s exchange (light singlet)

$$\frac{m_\chi}{\mu} - \sin 2\beta \approx \frac{\gamma + \mathcal{A}_s}{1 - \gamma \mathcal{A}_s} \frac{\kappa}{\lambda} \frac{\mu}{\lambda v_h} \left(1 - \left(\frac{m_\chi}{\mu} \right)^2 \right)$$

$$m_a \approx 2 m_{\rm LSP} \quad \Rightarrow \quad m_s^2 + \tfrac{1}{3} m_{\rm LSP}^2 + \gamma^2 \left(m_h^2 - m_s^2 \right) \approx \Delta_{\hat{s}\hat{s}} + \tfrac{1}{3} \Delta_{\hat{a}\hat{a}}$$

$$m_s^2 \approx m_{\rm LSP}^2 \left[\left(\frac{\lambda \tan\beta}{2\pi} \right)^2 \ln \left(\frac{2 M_{\rm SUSY}}{m_{\rm LSP} \tan\beta} \right) - \frac{1}{3} \right]$$

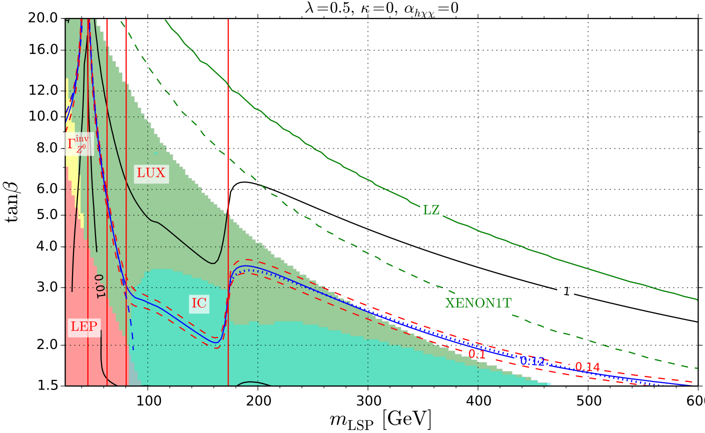




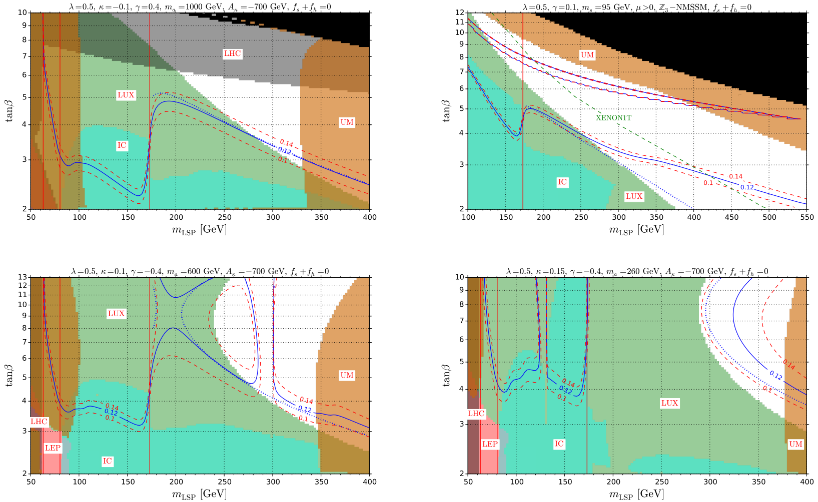
Conclusions

- We derived current constraints and prospects for SD direct detection for SI blind spots for bino-Higgsino LSP in MSSM and for singlino-Higgsino LSP in NMSSM.
- For bino-Higgsino, if H is decoupled, current DD limits set a lower bound $m_{\tilde{t}} \gtrsim 25$ TeV. For $H \sim 400$ GeV light stops are possible and this scenario will be tested in near future.
- For singlino-Higgsino the allowed parameter space is still large. If m_H, $m_s \gg m_h$ the allowed mass regions are $m_{\rm LSP} \sim 41 - 46$ and $300 - 800$ GeV and will be almost entirely probed by XENON1T.
- In $\mathbb{Z}_3$-NMSSM additional annihilation channels and resonanse with a relax the SD bounds. In particular, $m_{\rm LSP} \gtrsim 400$ GeV may not be explored by XENON1T.
- In the above scenarios, future SD limits will play a crucial role in probing the parameter space.

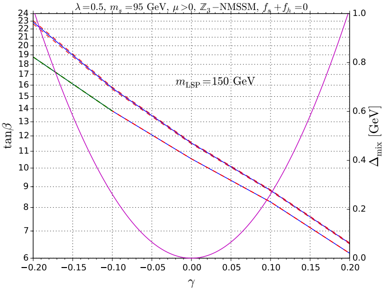
Backup slides: General NMSSM – only *h* exchange

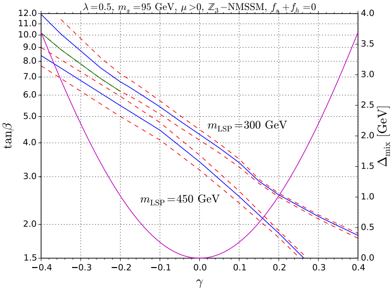


Backup slides: General NMSSM – *h* and *s* exchange



Backup slides: $\mathbb{Z}_3$-NMSSM – h and s exchange





Backup slides: Higgs sector

- Convenient basis ($\hat{H} = \mathcal{O}_\beta H$):

$$\begin{pmatrix} \hat{h} \\ \hat{H} \\ \hat{s} \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta & 0 \\ \sin\beta & -\cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} H_d \\ H_u \\ S \end{pmatrix}$$

- Mass eigenstates:

$$h_i = \tilde{S}_{ij} \hat{H}_j = S_{ij} H_j \quad \Longrightarrow \quad \tilde{S} = S \cdot \mathcal{O}_\beta$$

Explicitly:

$$h_i = \tilde{S}_{h_i \hat{h}} \hat{h} + \tilde{S}_{h_i \hat{H}} \hat{H} + \tilde{S}_{h_i \hat{s}} \hat{s}$$

$$h_i \equiv h, H, s$$

Backup slides: Higgs sector

- Diagonalization ($\Lambda \equiv A_\lambda + \langle \partial_S^2 f \rangle$):

$$\begin{pmatrix} M^2_{\hat{h}\hat{h}} & M^2_{\hat{h}\hat{H}} & M^2_{\hat{h}\hat{s}} \\ M^2_{\hat{h}\hat{H}} & M^2_{\hat{H}\hat{H}} & M^2_{\hat{H}\hat{s}} \\ M^2_{\hat{h}\hat{s}} & M^2_{\hat{H}\hat{s}} & M^2_{\hat{s}\hat{s}} \end{pmatrix}$$

$$\begin{cases} M^2_{\hat{h}\hat{H}} = \frac{1}{2}(M_Z^2 - \lambda^2 v^2)\sin 4\beta \\ M^2_{\hat{H}\hat{s}} = \lambda v \Lambda \cos 2\beta \\ M^2_{\hat{h}\hat{s}} = \lambda v (2\mu - \Lambda \sin 2\beta) \end{cases}$$

  Diagonal elements, $M^2_{\hat{h}\hat{h}}$, $M^2_{\hat{H}\hat{H}}$, $M^2_{\hat{s}\hat{s}}$, are more complicated. We trade them for physical scalar masses (m_h, m_s, m_H).

- For a given $m_h \simeq 125$ GeV, m_s, m_H, μ, λ, Λ, $\tan\beta$ we can find numerically $\tilde{S}_{ij}$.

Backup slides: XENON1T – May 2017