Spin-dependent constraints on blind spots for singlino-Higgsino dark matter in the NMSSM

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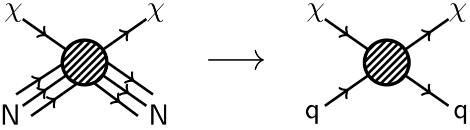
Based on: 1: arXiv:1705.00227
2: JHEP **1603** (2016) 179

Motivation: direct detection of dark matter



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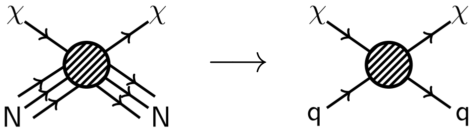

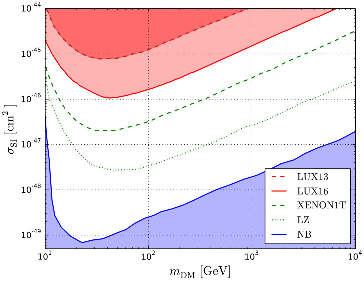

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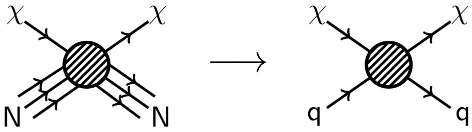

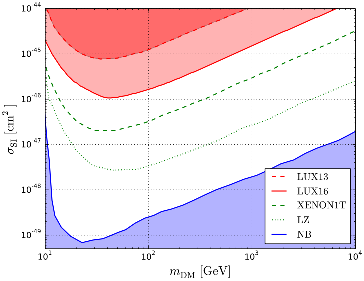

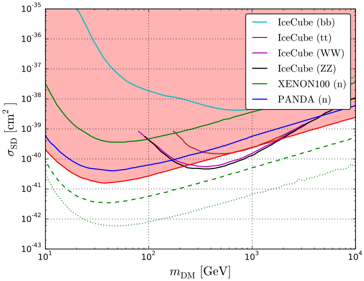

Spin-independent (SI) cross section in NMSSM

- Neutralino-nucleon interaction:

$$\chi_1^0 N \longrightarrow \chi_1^0 N \qquad (N = p, n)$$

- Cross section:

$$\sigma_{SI} = \frac{4\mu_{\rm red}^2}{\pi} f_N^2$$

- In the case of ideally elastic scalars exchange in t channel:

$$f_N \simeq \sum_{i=1}^{M} f_{N,h_i} = \sum_{i=1}^{M} \frac{\alpha_{\chi\chi h_i} \alpha_{h_i NN}}{2m_{h_i}^2}$$

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In (N)MSSM:

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

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

The NMSSM model

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

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

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

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

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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 in NMSSM

Approximations/assumptions:

1. $N_{11} \approx 0 \approx N_{12}$ gauginos decoupled
2. $m_H \gg m_h$ heavy H
3. $F_d^{(N)} \approx F_u^{(N)}$

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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, $m_s \gg m_h$
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   - leading effect from H
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Constraint 1:

$$\sigma_{\mathrm{SD}}^{(N)} = C^{(N)} \cdot 10^{-38}\ \mathrm{cm}^2\ (N_{13}^2 - N_{14}^2)^2$$

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SD blind spots for:

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Constraint 2:

$$\Omega h^2 = \Omega_{\mathrm{exp}} h^2 \approx 0.12$$

Blind spots in NMSSM – only h exchange

- Let us introduce:

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

where $|\gamma| \sim \sqrt{|\Delta_{\rm mix}|}$ and $m_h = \hat{M}_{hh} + \Delta_{\rm mix}$.

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- For small $|\gamma|$ blind spot requires small $|\eta|$ and hence:
  - strongly singlino(Higgsino)-dominated LSP
  - mixed LSP with very small λ

Relic density – only h exchange (no scalar mixing)

Because $\alpha_{h\chi\chi} = 0$ the h exchange is negligible.

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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):

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

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

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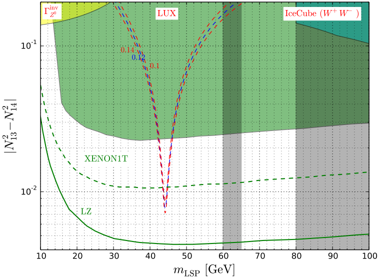

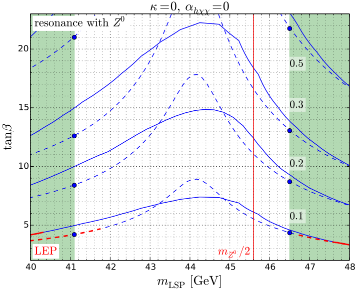

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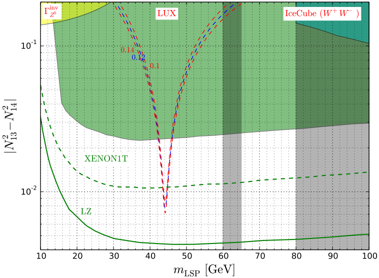

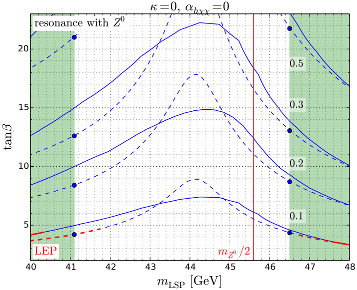

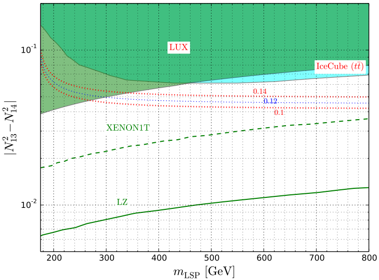

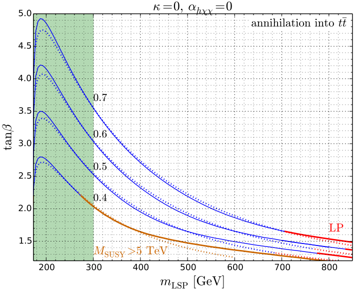

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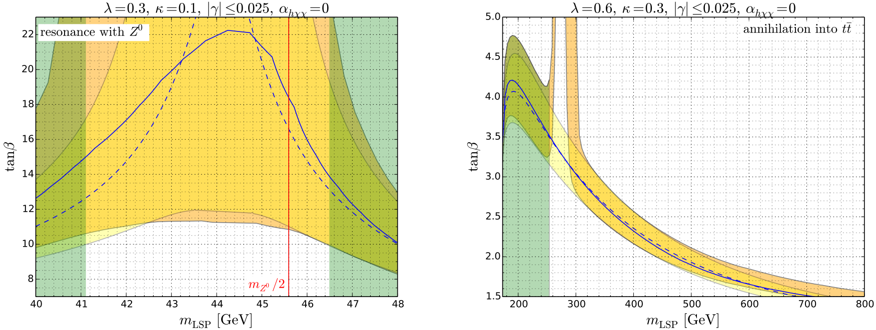

Blind spots in NMSSM – h and s exchange

- Let us introduce:

$$\mathcal{A}_s \equiv \frac{\alpha_{sNN}}{\alpha_{hNN}} \frac{\tilde{S}_{s\hat{s}}}{\tilde{S}_{h\hat{h}}} \left(\frac{m_h}{m_s}\right)^2 \approx -\gamma \frac{1+c_s}{1+c_h} \left(\frac{m_h}{m_s}\right)^2$$

$$c_i \equiv 1 + \frac{\tilde{S}_{i\hat{H}}}{\tilde{S}_{i\hat{h}}} \left(\tan\beta - \frac{1}{\tan\beta}\right)$$

For $\tan\beta \gg 1$, c_i is the ratio of $h_i b\bar{b}$ and $h_i ZZ$ couplings normalized to the SM values.

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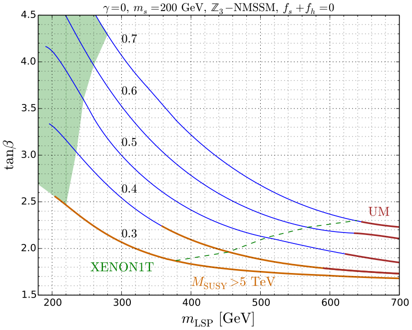
- Conclusions:
  - because $m_s < m_h$, the LHS can be one order of magnitude larger as compared to the case of only h exchange
  - in general NMSSM we can have $\Omega h^2 \approx 0.12$ and other experimental bounds fulfilled even for $\Delta_{\rm mix} \sim 4$ GeV

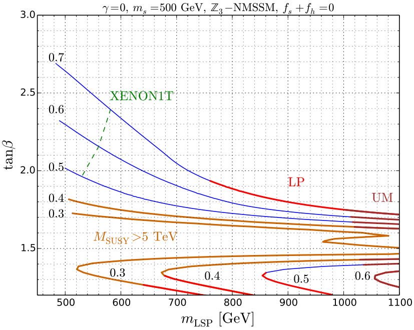
$\mathbb{Z}_3$-NMSSM – only h exchange (heavy singlet)

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

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

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



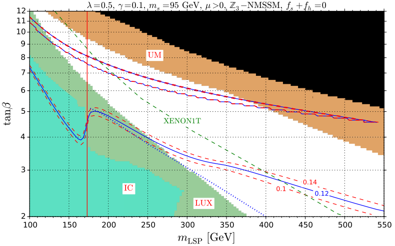


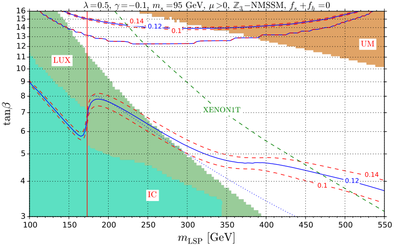
$\mathbb{Z}_3$-NMSSM – h and s exchange (light singlet)

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

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

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

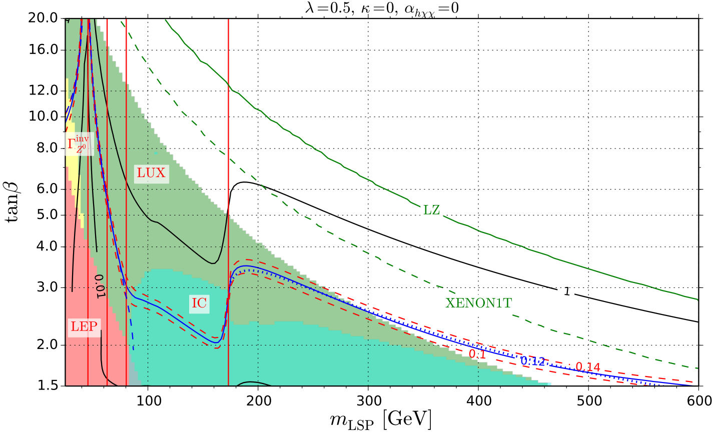




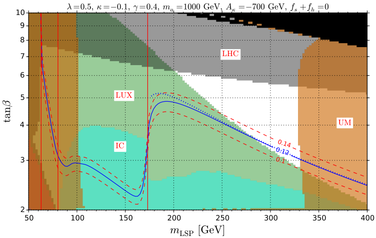
Conclusions

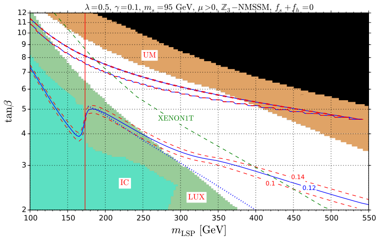
- We derived current constraints and prospects for SD direct detection for SI blind spots in NMSSM with thermal singlino-Higgsino LSP.
- If m_H, $m_s \gg m_h$ the allowed mass regions are $m_{\rm LSP} \sim 41 - 46$ and $300 - 800$ GeV and will be almost entirely probed by XENON1T.
- If m_s is small, in general NMSSM it is possible to obtain sizeable linear correction to the Higgs mass $\Delta_{\rm mix} \sim 4$ GeV with all considered experimental bounds fulfilled.
- In $\mathbb{Z}_3$-NMSSM we have $m_{\rm LSP} > m_s$ and additional annihilation channels (mainly *sa*) and resonanse with *a* relax the SD bounds. In particular, $m_{\rm LSP} \gtrsim 400$ GeV may not be explored by XENON1T.

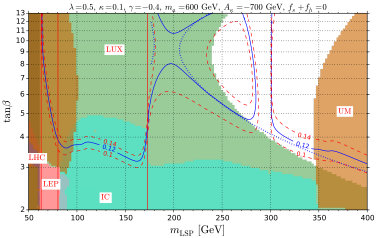
Backup slides: Relic density – only *h* exchange

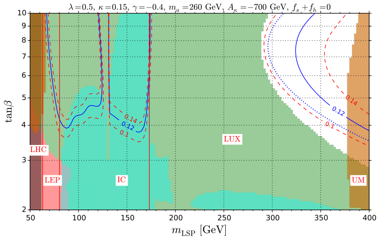


Backup slides: Relic density – *h* and *s* exchange

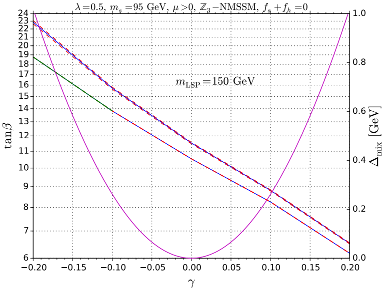


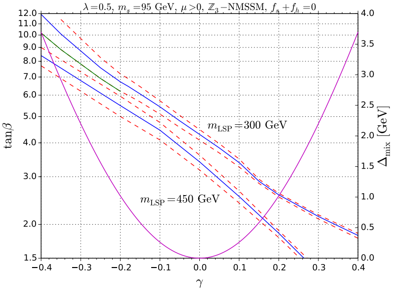






Backup slides: $\mathbb{Z}_3$-NMSSM – h and s exchange





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

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

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

  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: neutralino sector

- Mass matrix (after gaugino decoupling):

$$\begin{pmatrix} 0 & -\mu & -\lambda v \sin\beta \\ -\mu & 0 & -\lambda v \cos\beta \\ -\lambda v \sin\beta & -\lambda v \cos\beta & \langle \partial_S^2 f \rangle \end{pmatrix}$$

- LSP components (after trading $\langle \partial_S^2 f \rangle$ for m_{LSP}):

$$\frac{N_{13}}{N_{15}} = \frac{\lambda v}{\mu} \frac{(m_{\mathrm{LSP}}/\mu)\sin\beta - \cos\beta}{1 - (m_{\mathrm{LSP}}/\mu)^2}$$

$$\frac{N_{14}}{N_{15}} = \frac{\lambda v}{\mu} \frac{(m_{\mathrm{LSP}}/\mu)\cos\beta - \sin\beta}{1 - (m_{\mathrm{LSP}}/\mu)^2}$$

Backup slides: large $\tan\beta$

- Tree level couplings of h_i to b, t and W/Z:

$$C_{h_i b\bar{b}} = \tilde{S}_{i\hat{h}} + \tilde{S}_{i\hat{H}} \tan\beta$$

$$C_{h_i t\bar{t}} = \tilde{S}_{i\hat{h}} - \tilde{S}_{i\hat{H}} \cot\beta$$

$$C_{h_i VV} = \tilde{S}_{i\hat{h}}$$

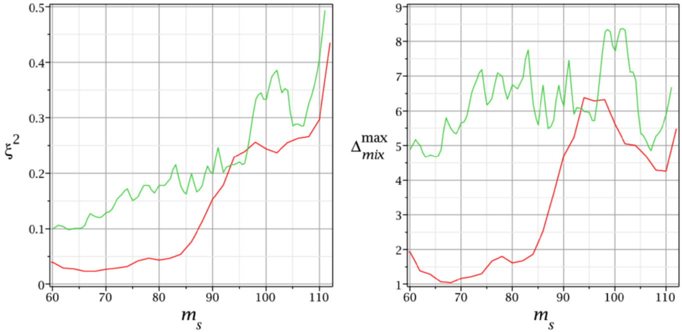
- If $m_s < m_h$, we can hide s from LEP in the limit of large $\tan\beta$ (and hence small λ). 1304.5437
- Important observables measured by LEP:

$$\xi^2_{sb\bar{b}} \equiv C^2_{sb\bar{b}} \frac{\mathrm{BR}(s \to b\bar{b})}{\mathrm{BR}^{\mathrm{SM}}(h \to b\bar{b})}\,, \quad \xi^2_{sjj} \equiv C^2_{sb\bar{b}}\, \mathrm{BR}(s \to jj)$$

Backup slides: large $\tan\beta$

$$\xi^2_{sb\bar{b}} \approx c_s^2 \tilde{S}^2_{s\hat{h}} \frac{\mathrm{BR}(s \to b\bar{b})}{\mathrm{BR}^{\mathrm{SM}}(h \to b\bar{b})}, \quad \xi^2_{sjj} \approx c_s^2 \tilde{S}^2_{s\hat{h}}\, \mathrm{BR}(s \to jj)$$

$$c_s \approx 1 + \frac{\tilde{S}_{s\hat{H}}}{\tilde{S}_{s\hat{h}}} \tan\beta$$



1304.5437 M. Badziak, M. Olechowski, S. Pokorski

Backup slides: blind spots in MSSM

- Higgs mass matrix eigenstates:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_u \\ H_d \end{pmatrix}$$

For heavy H: $\sin\alpha \approx -\cos\beta$.

- Traditional blind spots $\boxed{1211.4873}$: $m_H \to \infty$

$$\frac{m_\chi}{\mu} + \sin 2\beta = 0$$

- Generalized blind spots $\boxed{1404.0392}$: $m_H \gg m_h$

$$\frac{m_\chi}{\mu} + \sin 2\beta = -\frac{\tan\beta}{2}\left(\frac{m_h}{m_H}\right)^2$$

In both cases m_χ and μ have opposite sign.

Backup slides: blind spots in NMSSM – h and H exchange

- Let us introduce:

$$\mathcal{A}_H \equiv \frac{\alpha_{HNN}}{\alpha_{hNN}} \frac{\tilde{S}_{H\hat{H}}}{\tilde{S}_{h\hat{h}}} \left(\frac{m_h}{m_H}\right)^2 \approx \left(\frac{m_h}{m_H}\right)^2 \frac{\tan\beta}{2}$$

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

$$\frac{m_\chi}{\mu} - \sin 2\beta = \mathcal{A}_H \left[1 - \frac{\lambda v \Lambda}{m_s^2} \eta^{-1} \left(\frac{m_\chi}{\mu} - \sin 2\beta\right)\right]$$

- Conclusions:
  - sizable effect only for $\tan\beta \gg 1$
  - $\mathcal{A}_H$ is always positive
  - slightly more points in mixed LSP region