Neutralino blind spots in NMSSM with light singlet scalar

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based on: M. Badziak, M.O. and P. Szczerbiak, work in progress

Outline

- Motivation
- Higgs sector in NMSSM
  - contribution to m_h from mixing with the singlet scalar
- Direct Detection of Dark Matter particles
- Neutralino-nucleon cross section in NMSSM
- Direct Detection blind spots in NMSSM
  - only 125 GeV Higgs exchange
  - contribution from the light singlet scalar
  - numerical results
- Conclusions

Motivation

125 GeV Higgs allowed but not very natural in MSSM

Higgs boson mass in MSSM and its extensions

$$m_h^2 = M_Z^2 \cos^2 2\beta + (\delta m_h^2)^{\rm rad} + (\delta m_h^2)^{\rm non-MSSM}$$

$$(\delta m_h^2)^{\rm rad} \approx \frac{3 g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2} - \frac{1}{12}\frac{X_t^4}{M_{\rm SUSY}^4}\right]$$

- $M_{\rm SUSY} \gtrsim$ 5 TeV – for vanishing stop mixing $X_t^2 = 0$
- $M_{\rm SUSY} \gtrsim$ 700 GeV – for optimal stop mixing $X_t^2 \approx 6 M_{\rm SUSY}^2$

$\sim$ 5 GeV non-MSSM contribution to the Higgs mass
may allow for about 2 times lower SUSY scale (less fine tuning)

Self-interacting singlet S used to generate the effective μ-term

$$W_{\rm NMSSM} = \lambda S H_u H_d + f(S)$$

with $f(S) = \frac{1}{3}\kappa S^3 + \frac{1}{2}\mu' S^2 + \xi_S S$.

Soft terms in the Higgs sector:

$$-\mathcal{L}_{\rm soft} \supset m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2$$
$$+ (A_\lambda \lambda S H_u H_d + m_3^2 H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \frac{1}{2} m_S'^2 S^2 + \xi_S' S + \text{h.c.})$$

There are versions of NMSSM with less parameters

- **"$\mathbb{Z}_3$–invariant" NMSSM:** $\mu' = \xi_S' = m_3^2 = m_S'^2 = \xi_S = 0$

The Higgs squared mass matrix in the basis
$(\hat{h} = \cos\beta H_d + \sin\beta H_u, \hat{H} = \sin\beta H_d - \cos\beta H_u, \hat{s} = S)$
($\hat{h}$ has the same couplings as the SM Higgs)

$$\hat{M}^2 = \begin{pmatrix} \hat{M}^2_{hh} & \cdots & \cdots \\ \frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta & \hat{M}^2_{HH} & \cdots \\ \lambda v(2\mu - \Lambda \sin 2\beta) & \lambda v \Lambda \cos 2\beta & \hat{M}^2_{ss} \end{pmatrix}$$

$\hat{M}^2_{hh} = M_Z^2 \cos^2 2\beta + (\delta m_h^2)^{\rm rad} + \lambda^2 v^2 \, \sin^2 2\beta$
$\Lambda = A_\lambda + \langle \partial_S^2 f(S) \rangle$

The mass eigenstates h, H, s, are given by the mixing matrix $\tilde{S}$:

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

Higgs sector in NMSSM

The mass of the SM-like Higgs h:

$$m_h^2 = M_Z^2 \cos^2 2\beta + (\delta m_h^2)^{\rm rad} + \lambda^2 v^2 \sin^2 2\beta + (\delta m_h^2)^{\rm mix}$$

NMSSM contributions:

- tree-level contribution due to $\lambda S H_u H_d$ interaction
- contribution due to mixing among $\hat{h}$, $\hat{s}$, $\hat{H}$ states – mainly $\hat{h}$-$\hat{s}$

The most popular approach:

- small $\tan\beta$ (close to 1, usually < 3)
- big λ (because tree-level MSSM term $M_Z^2 \cos^2 2\beta$ is small)

New proposal: increase m_h by the mixing contribution

- moderate and large values of $\tan\beta$ especially interesting because they give big tree-level MSSM term $M_Z^2 \cos^2 2\beta$
- usually small λ is preferred

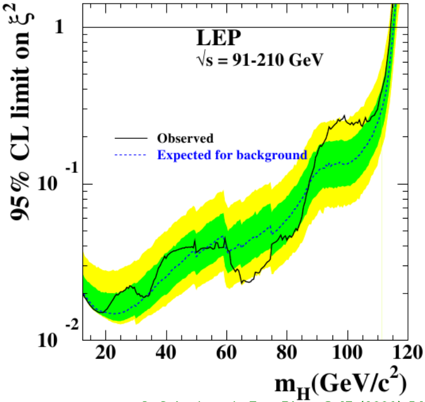
M. Badziak, M.O., S. Pokorski, JHEP 1306 (2013) 043

Higgs sector in NMSSM

$\Delta_{\rm mix} \equiv m_h - \sqrt{\hat{M}^2_{hh}}$ **is positive when** $m_s < m_h$

LEP found some excess of the Higgs-like events for a scalar mass close to 95 GeV

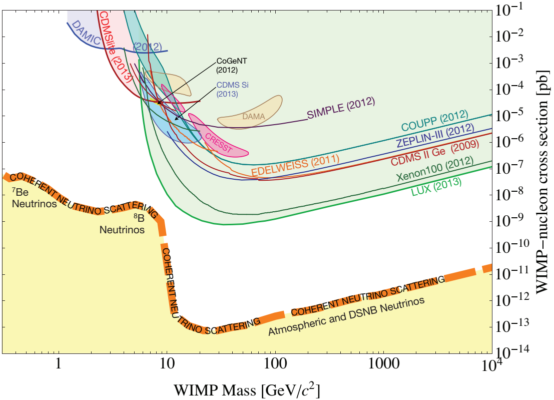
. . . and deficit of such events for a scalar mass close to 70 GeV



S. Schael et al. Eur. Phys. C 47 (2006) 547

Similar excess in $\gamma\gamma$ channel shown in preliminary results by CMS

Present experimental situation:



J. Billard, L. Strigari, E. Figueroa-Feliciano, Phys. Rev. D 89 (2014) 2, 023524

Future experiments, (XENON1T, LZ, XENONnT, DARWIN), will be more and more sensitive filling the gap between the present bounds and the neutrino background

Neutralino-nucleon cross section in NMSSM

Formulae for neutralino-nucleus spin-independent cross section in NMSSM are quite complicated

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

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

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

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

Neutralino-nucleon cross section in NMSSM

Approximations:

- sfermions are very heavy
  $\Rightarrow \sigma_{\mathrm{SI}}$ is dominated by the exchange of the Higgs scalars
- gauginos are very heavy
  $\Rightarrow$ the LSP is a singlino-higgsino mixture
- $F_d^{(N)} \approx F_u^{(N)}$

$$\alpha_{h_i\chi\chi} \approx \sqrt{2}\lambda \Big[\tilde{S}_{i\hat{h}} N_{15} \left(N_{13}\sin\beta + N_{14}\cos\beta\right) + \tilde{S}_{i\hat{H}} N_{15} \left(N_{14}\sin\beta - N_{13}\cos\beta\right) + \tilde{S}_{i\hat{s}} \left(N_{13}N_{14} - (\kappa/\lambda) N_{15}^2\right)\Big]$$

$$\alpha_{h_iNN} \approx \frac{m_N F^{(N)}}{\sqrt{2}v} \left[2\tilde{S}_{i\hat{h}} + \tilde{S}_{i\hat{H}} \left(\tan\beta - \frac{1}{\tan\beta}\right)\right]$$

H is heavy but:

- mixing of $\hat{H}$ with the light scalars may be important for their couplings
- exchange of H may give substantial contribution to σ_{SI} (not considered in this talk)

The spin-independent scattering cross-section for a singlino-higgsino neutralino

$$\sigma_{\rm SI} \approx k \cdot 10^{-45}\ {\rm cm}^2 \left(\frac{\lambda}{0.1}\right)^2 \frac{N_{15}^2(1 - N_{15}^2)}{(0.5)^2}$$

may (easily) be above the present experimental bounds.

However, in some parts of the parameter space $\sigma_{\rm SI}$ is exceptionally small ($k \ll 1$)

There are blind spots: $\sigma_{\rm SI} \approx 0$

From experimental point of view it is enough if $\sigma_{\rm SI}$ is smaller than the neutrino background.

In the most general NMSSM there are only two new parameters relevant for σ_{SI}: κ/λ and $\langle \partial_S^2 f \rangle$

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

$\langle \partial_S^2 f \rangle$, in the (3×3) neutralino mass matrix in (general) NMSSM may be traded for m_χ.

κ can not be arbitrarily big (because of Landau poles)

There are relations in different versions of NMSSM
For example in "$\mathbb{Z}_3$-invariant" NMSSM

$$\frac{\kappa}{\lambda} = \frac{1}{2}\left[(m_\chi/\mu) + (\lambda v/\mu)^2\,\frac{(m_\chi/\mu) - \sin 2\beta}{1 - (m_\chi/\mu)^2}\right]$$

Blind spots in MSSM

- "old" blind spots ($m_H \to \infty$)

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

  - $\mathrm{sgn}(m_\chi) = -\mathrm{sgn}(\mu)$
    (m_χ - eigenvalue of neutralino mass matrix - may be negative)
  - $\tan\beta \sim 1$ for mixed or higgsino-dominated LSP
  - LSP strongly bino-dominated for bigger $\tan\beta$

- "new" blind spots ($m_H \gg m_h$)

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

  - small m_h/m_H may be (partially) compensated by large $\tan\beta$

Blind spots in NMSSM – only 125 GeV Higgs exchange

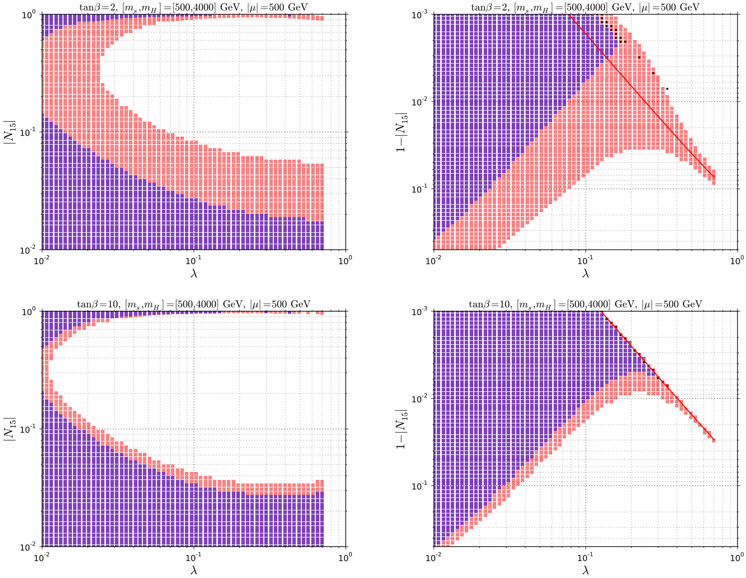
The blind spot condition with only h exchange contributing to $\sigma_{\rm SI}$:

$$\frac{m_\chi}{\mu} - \sin 2\beta = -\frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}}\frac{\mu}{\lambda v}\left[1-\left(\frac{m_\chi}{\mu}\right)^2\right]\left(\frac{N_{13}}{N_{15}}\frac{N_{14}}{N_{15}}-\frac{\kappa}{\lambda}\right) - \frac{\tilde{S}_{h\hat{H}}}{\tilde{S}_{h\hat{h}}}\cos 2\beta$$

- $-$: one coupling $\lambda H_u H_d S$
  - MSSM: H_u and H_d have opposite hypercharges
- The parameters translate to physical quantities for which there are (experimental) bounds
  - for example: $\frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}} \approx \mathrm{sgn}(\Lambda \sin 2\beta - 2\mu)\frac{\sqrt{2|\Delta_{\rm mix}|m_h}}{m_s}$
  - $|\Delta_{\rm mix}|$ should be small because $\Delta_{\rm mix} < 0$ for $m_s > m_h$
- $(N_{13}/N_{15})(N_{14}/N_{15})$ may be expressed in terms of the LSP mass (with sign) and the parameters of the scalar sector
  - For example: $\frac{N_{13}}{N_{15}} = \frac{\lambda v}{\mu}\frac{(m_\chi/\mu)\sin\beta - \cos\beta}{1-(m_\chi/\mu)^2}$

Blind spots in NMSSM – only 125 GeV Higgs exchange

$m_\chi \mu > 0$ $m_\chi \mu < 0$ $m_s = 500\,\mathrm{GeV}$ $|\Delta_{\mathrm{mix}}| < 1\,\mathrm{GeV}$



$\tan\beta = 2$

$\tan\beta = 10$

Blind spots in NMSSM – h and s exchange

The blind spot condition with h and s exchange:

$$\frac{m_\chi}{\mu} - \sin 2\beta \approx -\frac{\frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}} + \mathcal{A}_s}{1 + \mathcal{A}_s \frac{\tilde{S}_{s\hat{h}}}{\tilde{S}_{h\hat{h}}}} \frac{\mu}{\lambda v} \left[1 - \left(\frac{m_\chi}{\mu}\right)^2\right] \left(\frac{N_{13}}{N_{15}} \frac{N_{14}}{N_{15}} - \frac{\kappa}{\lambda}\right)$$

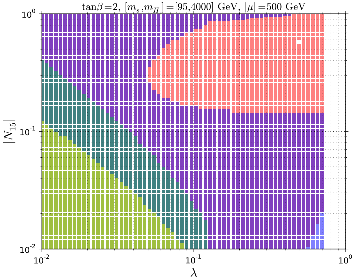
$$\mathcal{A}_s \approx \frac{\tilde{S}_{s\hat{h}}}{\tilde{S}_{h\hat{h}}} \frac{1 + c_s}{1 + c_h} \left(\frac{m_h}{m_s}\right)^2 \qquad \frac{\tilde{S}_{s\hat{h}}}{\tilde{S}_{h\hat{h}}} \approx -\frac{\tilde{S}_{h\hat{s}}}{\tilde{S}_{h\hat{h}}}$$

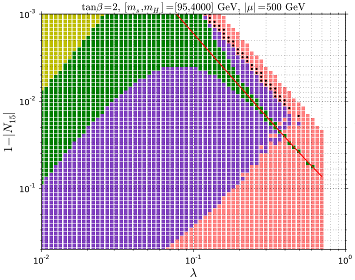
$$c_{h_i} \equiv 1 + \frac{\tilde{S}_{h_i\hat{H}}}{\tilde{S}_{h_i\hat{h}}} \left(\tan\beta - \frac{1}{\tan\beta}\right) = \frac{g_{h_i bb}/g_{h_{\rm SM} bb}}{g_{h_i ZZ}/g_{h_{\rm SM} ZZ}}$$

New contributions are related to the couplings of h and s

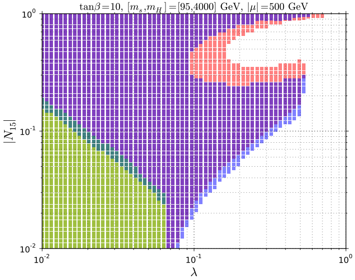
Blind spots in NMSSM – $\boldsymbol{h}$ and $\boldsymbol{s}$ exchange

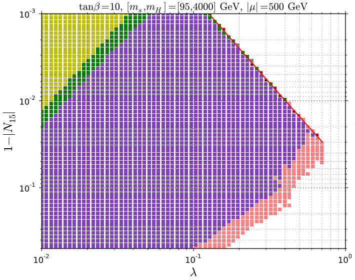
$m_\chi \mu > 0$ $\quad$ $m_\chi \mu < 0$ $\quad$ $m_s = 95\,\mathrm{GeV}$ $\quad$ $\Delta_{\mathrm{mix}} > 0$





$\tan\beta = 2$





$\tan\beta = 10$

We are interested in regions of the parameters space giving big positive contribution from the mixing to the SM-like Higgs: $\Delta_{\rm mix}$

The features of models with big $\Delta_{\rm mix}$ depend on the singlet-dominated scalar mass m_s

Of course the diagonal mass matrix contribution to the SM-like Higgs mass must also be big

Let us discuss and compare 4 representative cases:

	$\tan\beta$	λ	m_s
small $\tan\beta$, “LEP deficit” scalar	2	0.6	70 GeV
small $\tan\beta$, “LEP excess” scalar	2	0.6	95 GeV
moderate $\tan\beta$, “LEP deficit” scalar	10	0.1	70 GeV
moderate $\tan\beta$, “LEP excess” scalar	10	0.1	95 GeV

Blind spots in NMSSM – h and s exchange

Are blind spots possible when $\Delta_{\rm mix}$ is substantial?

Yes

- not for (strongly) higgsino-dominated LSP
- bigger higgsino component allowed for $c_s > 1$
- substantial $\Delta_{\rm mix}$ possible when
  - $c_s \sim 1$ for $m_s \sim 95\,\mathrm{GeV}$

$$\Delta_{\rm mix} > 4\,\mathrm{GeV} \quad \Rightarrow \quad c_s \gtrsim 0.5$$

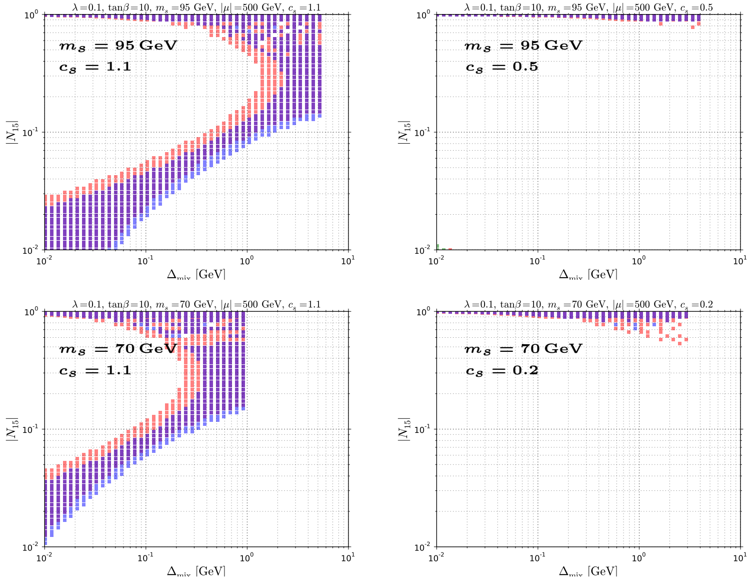
$$\Delta_{\rm mix} > 5\,\mathrm{GeV} \quad \Rightarrow \quad c_s \gtrsim 0.9$$

  - $|c_s|$ must be small for $m_s \sim 70\,\mathrm{GeV}$

$$\Delta_{\rm mix} > 3\,\mathrm{GeV} \quad \Rightarrow \quad |c_s| \lesssim 0.2 \div 0.4$$

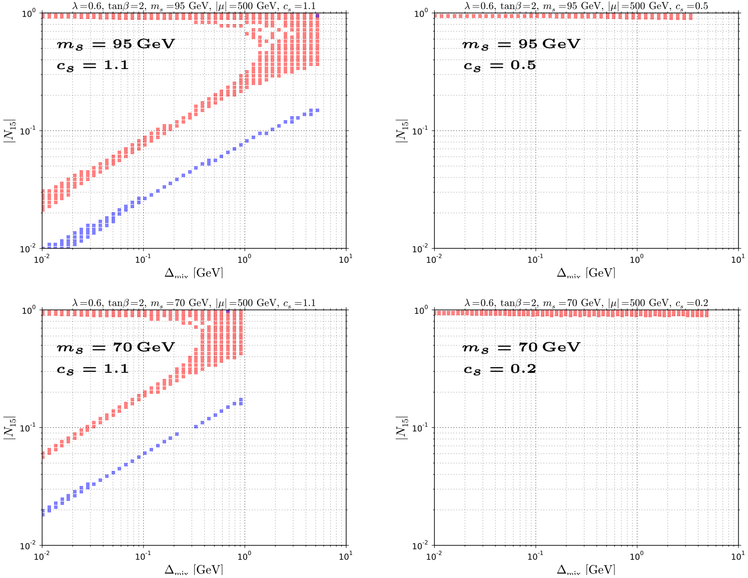
Blind spots in NMSSM – h and s exchange

$\tan\beta = 10 \qquad \lambda = 0.1$



Blind spots in NMSSM – h and s exchange

$\tan\beta = 2 \qquad \lambda = 0.6$



Blind spots in NMSSM – h and s exchange

There are versions of the NMSSM model with fewer parameters than in the most general case

For example in "$\mathbb{Z}_8$–invariant" NMSSM

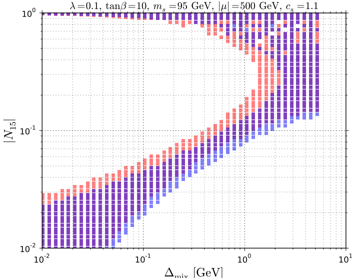
$$\mu' = 0 \qquad \Rightarrow \qquad \frac{\kappa}{\lambda} = \frac{1}{2}\left[(m_\chi/\mu) + (\lambda v/\mu)^2 \frac{(m_\chi/\mu) - \sin 2\beta}{1-(m_\chi/\mu)^2}\right]$$

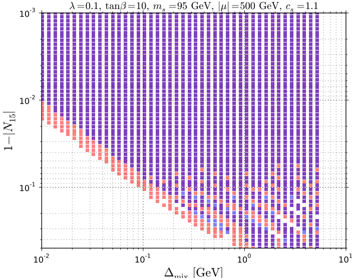
It is much more difficult to get blind spots and big mixing contribution to the Higgs mass
$\Delta_{\rm mix} > 5$ GeV may be obtained when

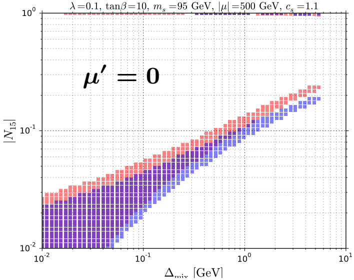
- the singlet scalar mass is close to 95 GeV
- c_s is somewhat bigger than 1
- LSP composition is (almost) fixed

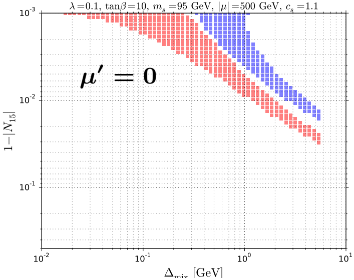
Blind spots in NMSSM – h and s exchange

$\tan\beta = 10 \qquad \lambda = 0.1 \qquad m_s = 95\,\mathrm{GeV} \qquad c_s = 1.1$









Conclusions

- General NMSSM $\Rightarrow$ new possibilities to obtain blind spots for direct detection of singlino-higgsino DM
  - due to the singlet component of the 125 GeV Higgs
  - due to the singlet-dominated scalar exchange
- There are blind spot regions with substantial contribution from the mixing to the SM-like Higgs mass
  $\Rightarrow$ correlations among other physical parameters
  - BS only for strongly singlino-dominated LSP if $c_s \lesssim 1$ necessary for $\Delta_{\rm mix} \sim 3$ for $m_s \sim 70$ GeV
  - BS also for mixed singlino-higgsino (also well-tempered) LSP with $\Delta_{\rm mix}$ up to ~6 GeV if $c_s \gtrsim 1$ and $m_s \sim 95$ GeV
- BS with big $\Delta_{\rm mix}$ favour
  - moderate $\tan\beta$ with small λ over small $\tan\beta$ with large λ
  - light scalar with mass corresponding to the LEP excess
- Specific NMSSM models give stronger relations among the physical parameters
- More detailed results to be published soon