Dark Matter Direct Detection in the NMSSM

Daniel E. López-Fogliani

Universidad Autónoma de Madrid

Departamento de Física Teórica & IFT

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D. Cerdeño, C. Hugonie, D. L-F, C. Muñoz, A. Teixeira, JHEP 0412 (2004) 048.

D. Cerdeño, E. Gabrielli, D. L-F, C. Muñoz, A. Teixeira, JCAP (2007) (accepted).

Outline

Direct Detection of Neutralino Dark Matter in the NMSSM

- The NMSSM
- The Neutralino-Nucleon Cross Section
- Experimental constraints
- Analysis of Neutralino DM in the NMSSM

Conclusions

Why the NMSSM?

The NMSSM

★ Solves a problem of naturalness in the MSSM: why the μ parameter in $\mu H_1 H_2$ is of order the electroweak scale.

Superpotential

$$\boldsymbol{W} = \epsilon_{ij} \left(Y_u\, H_2^j\, Q^i\, u + Y_d\, H_1^i\, Q^j\, d + Y_e\, H_1^i\, L^j\, e \right) - \epsilon_{ij} \boldsymbol{\lambda}\, S\, H_1^i H_2^j + \frac{1}{3} \boldsymbol{\kappa} S^3$$

Higgs soft terms of the NMSSM

$$-\boldsymbol{L}_{soft}^{Higgs} = m_{H_i}^2 H_i^* H_i + \boldsymbol{m_S^2}\, S^* S + (-\epsilon_{ij} \boldsymbol{\lambda}\, \boldsymbol{A_\lambda} S H_1^i H_2^j + \tfrac{1}{3} \boldsymbol{\kappa}\, \boldsymbol{A_\kappa}\, S^3 + \mathrm{H.c.})$$

NMSSM potential

After EW Symmetry breaking: $< H_1^0 >= v_1, \quad < H_2^0 >= v_2, \quad < S >= s$

$$\mu_{\text{eff}} = \lambda s$$

$$\langle V_{\text{neutral}}^{\text{Higgs}} \rangle = \frac{g_1^2+g_2^2}{8}\left(|v_1|^2 - |v_2|^2\right)^2 + |\lambda|^2\left(|s|^2|v_1|^2 + |s|^2|v_2|^2 + |v_1|^2|v_2|^2\right)$$
$$+|\kappa|^2|s|^4 + m_{H_1}^2|v_1|^2 + m_{H_2}^2|v_2|^2 + m_S^2|s|^2$$
$$+(-\lambda\kappa^* v_1 v_2 s^{*2} - \lambda A_\lambda s v_1 v_2 + \frac{1}{3}\kappa A_\kappa s^3 + \text{H.c.})$$

Minimization of the scalar potential

Finding a minimum of V is much harder than in the MSSM ...

From the minimization of the potential with respect to the phases of the VEV's we have four combinations of signs for A_κ A_λ, s and k :

$k > 0$:

(i) $\text{sign}(s) = \text{sign}(A_\lambda) = -\text{sign}(A_\kappa)$,

(ii) $\text{sign}(s) = -\text{sign}(A_\lambda) = -\text{sign}(A_\kappa)$,
with $|A_\kappa| > 3\lambda v_1 v_2 |A_\lambda| / (-|sA_\lambda| + \kappa|s^2|)$.

(iii) $\text{sign}(s) = \text{sign}(A_\lambda) = \text{sign}(A_\kappa)$,
with $|A_\kappa| < 3\lambda v_1 v_2 |A_\lambda| / (|sA_\lambda| + \kappa|s^2|)$.

$k < 0$:

(iv) $\text{sign}(s) = \text{sign}(A_\lambda) = \text{sign}(A_\kappa)$,
with $|A_\kappa| > 3\lambda v_1 v_2 |A_\lambda| / (|sA_\lambda| - \kappa|s^2|)$.

We must also satisfy the minimization Eqs. for $|v|$

NMSSM Particle content

NMSSM Spectrum $\equiv$ MSSM + $\begin{cases} 2\,\text{Higgs}\,(\text{CP}-\text{even},\ \text{CP}-\text{odd}) \\ 1\,\text{Neutralino} \end{cases}$

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta & 0 \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta & 0 \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\lambda s & -\lambda v_2 \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\lambda s & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2\kappa s \end{pmatrix}$$

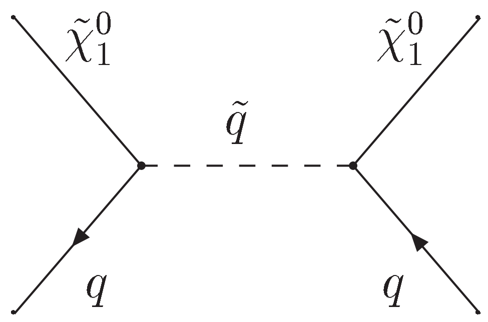
The lightest neutralino:

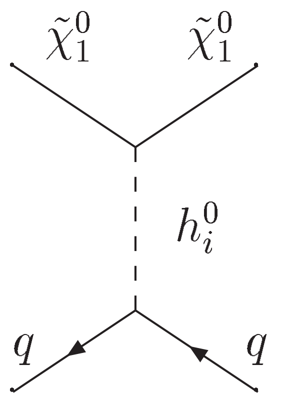
$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0 + N_{15}\tilde{S}$$

The lightest CP-even Higgs:

$$h_1^0 = S_{11}H_1^0 + S_{12}H_2^0 + S_{13}S$$

Dark matter: Direct detection in the NMSSM





$$\mathcal{L}_{\text{eff}} = \alpha_{3i}\, \bar{\tilde{\chi}}_1^0\, \tilde{\chi}_1^0\, \bar{q}_i q_i$$

$$\alpha_{3i}^{h} = \sum_{a=1}^{3} \frac{1}{m^2_{h_a^0}} C_Y^i \,\text{Re}\left[C_{HL}^a\right]$$

$$\alpha_{3i}^{\tilde{q}} = -\sum_{X=1}^{2} \frac{1}{4(m^2_{Xi} - m^2_{\tilde{\chi}_1^0})} \text{Re}\left[\left(C_R^{Xi}\right)\left(C_L^{Xi}\right)^*\right]$$

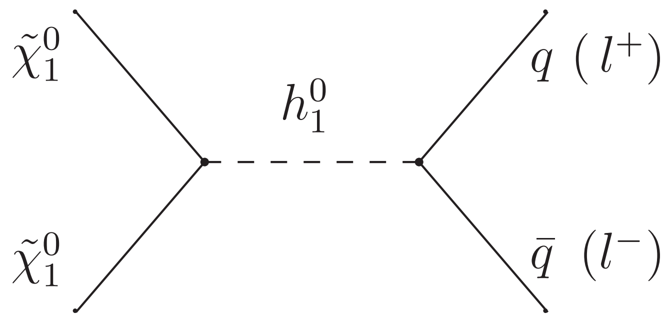
See also V. Barger et al., '07, for an analysis of MSSM singlet extensions.

Relic density

Enough $\tilde{\chi}_1^0$ can survive annihilation (and coannihilation) in order to account for observed Ω

For example: $\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \Rightarrow \begin{cases} W^\pm\, W^\pm\,,\; Z\,Z \\ h^0\, h^0\,,\; a^0\, a^0\,,\; h^0\, Z \\ \bar{q}\, q\,,\, l^+\, l^- \end{cases}$

NMSSM similar to MSSM, but additional "fingerprint"-type processes like



where $\tilde{\chi}_1^0 \leftrightsquigarrow$ singlino; $h_1^0 \leftrightsquigarrow$ singlet

BUT! **Generating large** σ **may lead to** excessive $\tilde{\chi}_1^0$-annihilation (**low** Ω)

See also Bélanger et al., '05

Constraints on the NMSSM parameter space and computation

Relevant parameters at low scale $\lambda,\ \kappa,\ \tan\beta,\ \mu,\ A_\lambda,\ A_\kappa,\ M_1,\ M_2,\ M_3\ (M_0, A_0)$

- Minimization of the potential
- Absence of Landau Pole for λ, κ, Y_t, and Y_b below M_{GUT}
- Computation of the NMSSM spectrum
- Experimental constraints from LEP
  - Neutralino
  - Higgs
  - Squark

} NMHDECAY 2.0 (Ellwanger, Hugonie)

- b $\longrightarrow$ s γ $(g_\mu - 2)$, rare B and K decays — Our code
- Dark Matter Relic density — New MicrOMEGAs
- Neutralino Nucleon Cross Section — Our code

Muon anomalous magnetic moment (a_μ)

Experimental data: $a_\mu = 11659208(6) \times 10^{-10}$

Theoretical for SM: $a_\mu = 11659180.4(5.1) \times 10^{-10}$

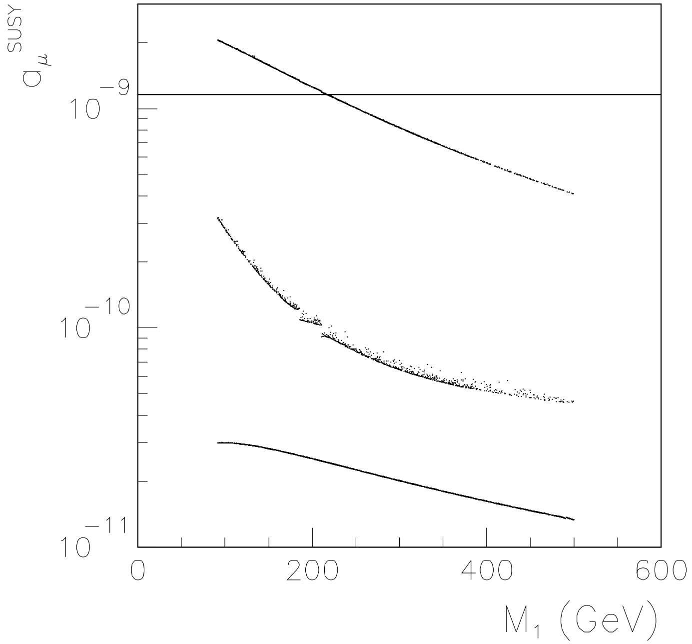
$$\Delta a_\mu = (27.6 \pm 8) \times 10^{-10}$$

At to 2σ level the SUSY contribution must be:

$$11.6 \times 10^{-10} \lesssim a_\mu^{\rm SUSY} \lesssim 43.6 \times 10^{-10}$$

SUSY contributions at 1 loop-level:

- Dominant: **Sneutrino and Chargino**
- **Charged Sleptons and Neutralino**



$\mathbf{a}_\mu^{\mathrm{SUSY}}$ **as a function of** $\mathbf{M}_1$

The horizontal solid line indicates the lower bound of the allowed 2σ interval.

Choosing typical NMSSM values $\mu = 150$ GeV,$-800 \lesssim A_\lambda \lesssim 800$ GeV, $-300 \lesssim A_\kappa \lesssim 300$ GeV, and low $\tan\beta$, $\tan\beta = 5$, in order to analyze departures from the MSSM.

From bottom to top, $m_{L,E} = 1$ TeV with $A_E = 1$ TeV,
$m_{L,E} = 150$ GeV with $A_E = 1$ TeV, $m_{L,E} = 150$ GeV with $A_E = -2.5$ TeV.

$b \longrightarrow s\,\gamma$

Experimental data [HFAG '06]: BR$(b \longrightarrow s\gamma)$= $(3.55 \pm 0.27) \times 10^{-4}$

Theoretical calculation for the SM [Gambino '05]: BR$(b \longrightarrow s\gamma)$= $(3.73 \pm 0.30) \times 10^{-4}$

SUSY contributions at 1 loop-level

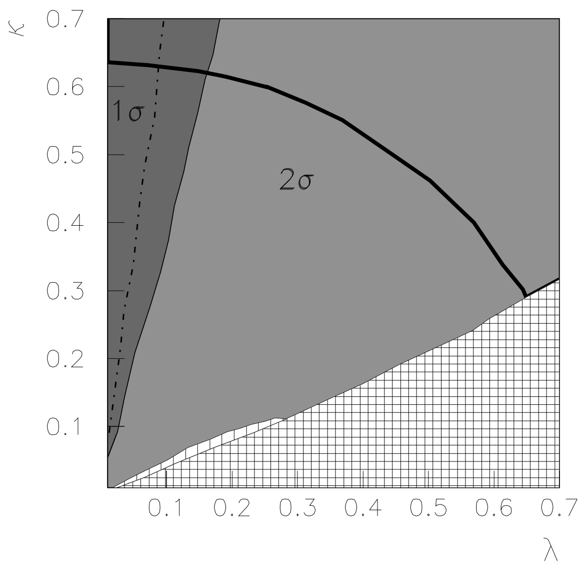
- Charged Higgs $H^{\pm}$ and up quarks u, c, t
- Chargino $\tilde{\chi}^{\pm}$ and up squarks $\tilde{u}$, $\tilde{c}$, $\tilde{t}$
- Neutralino $\tilde{\chi}^{0}$ and down squarks $\tilde{d}$, $\tilde{s}$, $\tilde{b}$
- gluino $\tilde{g}$ and down squarks $\tilde{d}$, $\tilde{s}$, $\tilde{b}$

In our analysis: dominant $H^{\pm}$-mediated contribution! [No flavour mixing other than the $V_{\rm CMK}$]

$\Rightarrow$ BR$(b \longrightarrow s\gamma) \;\propto\; 1/m^4_{H^{\pm}}$ with $m^2_{H^{\pm}} = \frac{2\mu^2}{\sin(2\beta)}\frac{\kappa}{\lambda} - v^2\lambda^2 + \frac{2\mu A_\lambda}{\sin(2\beta)} + m^2_W$

BR($b \longrightarrow s\gamma$) in the NMSSM: Results

$M_1 = 160$ GeV, $M_2 = 320$ GeV, $A_\lambda = 400$ GeV, $A_\kappa = -200$ GeV, $\mu = 130$ GeV, $\tan\beta = 5$



$b \longrightarrow s\gamma$ isocurves "mimic" $m_{H^\pm}$ isocurves

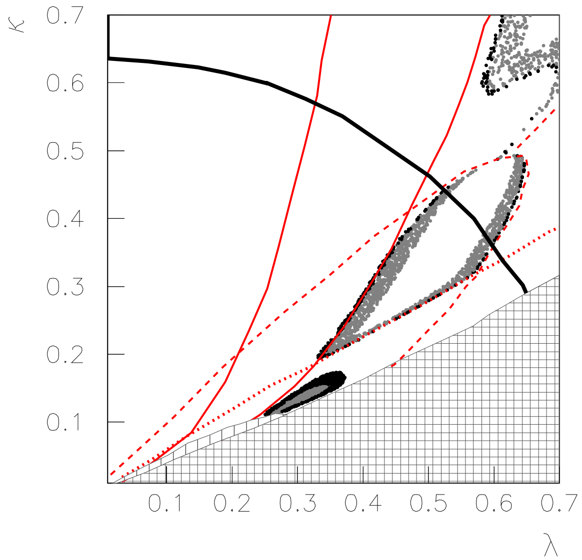
$b \longrightarrow s\gamma$ typically maximal close to tachyon "border"

Improve $b \longrightarrow s\gamma$: larger ($A_\lambda$, μ, $\tan\beta$) $\longleftrightarrow$ Worsens exclusion by LEP constraints

Relic density in the λ-κ plane

For the same parameters as the previous study

$M_1 = 160$ GeV, $M_2 = 320$ GeV, $A_\lambda = 400$ GeV, $A_\kappa = -200$ GeV, $\mu = 130$ GeV, $\tan\beta = 5$



red dots $\leftrightarrow m_{\chi_1^0} = m_{h_1^0}$; black full $\leftrightarrow m_{\chi_1^0} = m_Z, m_W$; red dashed $\leftrightarrow 2m_{\chi_1^0} = m_{h_2^0}$;

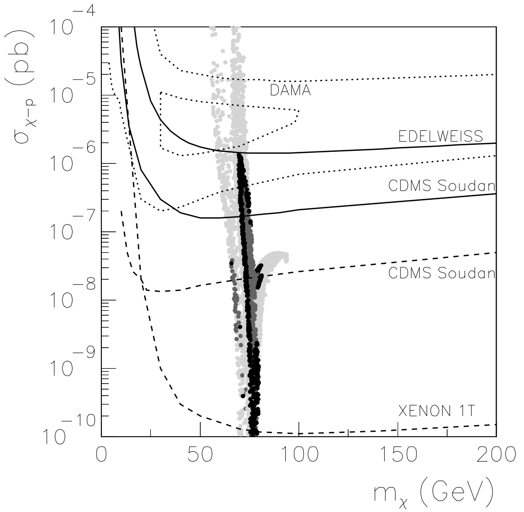
Very **light** neutral Higgs: $m_{h_1^0} \gtrsim 20$ GeV; **singlet** component: $S_{13}^2 \sim 0.99$;

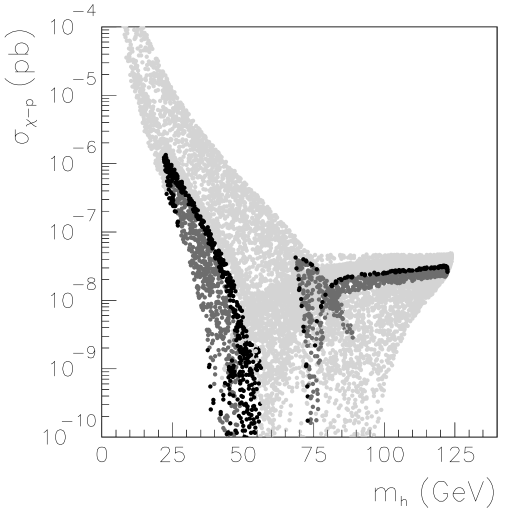
Higgsino-Bino LSP; moving to small κ with respect to $\lambda \Rightarrow$ small $m_{\chi_1^0}$ and more singlino $(N_{15}^2 \lesssim 0.35)$

Dark Matter: Ω and direct detection

For the same parameters as the previous study

$M_1 = 160$ GeV, $M_2 = 320$ GeV, $A_\lambda = 400$ GeV, $A_\kappa = -200$ GeV, $\mu = 130$ GeV, $\tan\beta = 5$





Gray $\longrightarrow$ Experimentally accepted (accelerators)

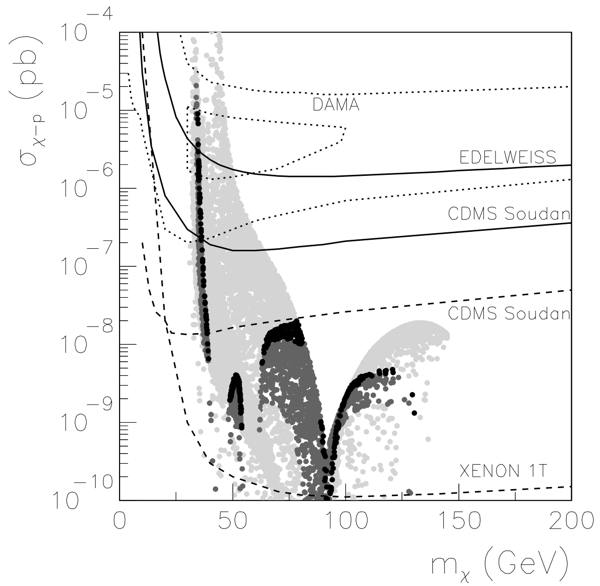
Dark Gray $\longrightarrow$ In addition fulfil $0.1 \leq \Omega h^2 \leq 0.3$

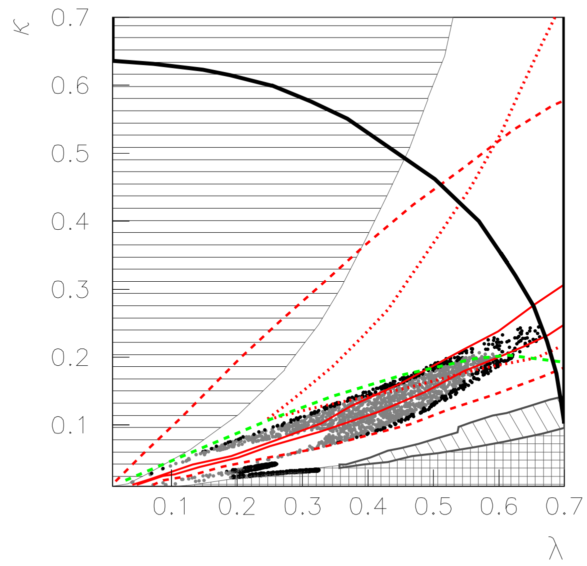
Black $\longrightarrow$ Satisfies all experimental constraints including WMAP $0.094 \lesssim \Omega h^2 \lesssim 0.129$

Large σ $\longrightarrow$ exchange of light singlet-like Higgs

NMSSM DM: further examples

$M_1 = 330$ GeV, $M_2 = 660$ GeV, $A_\lambda = 570$ GeV, $A_\kappa = -60$ GeV, $\mu = 160$ GeV, $\tan\beta = 5$





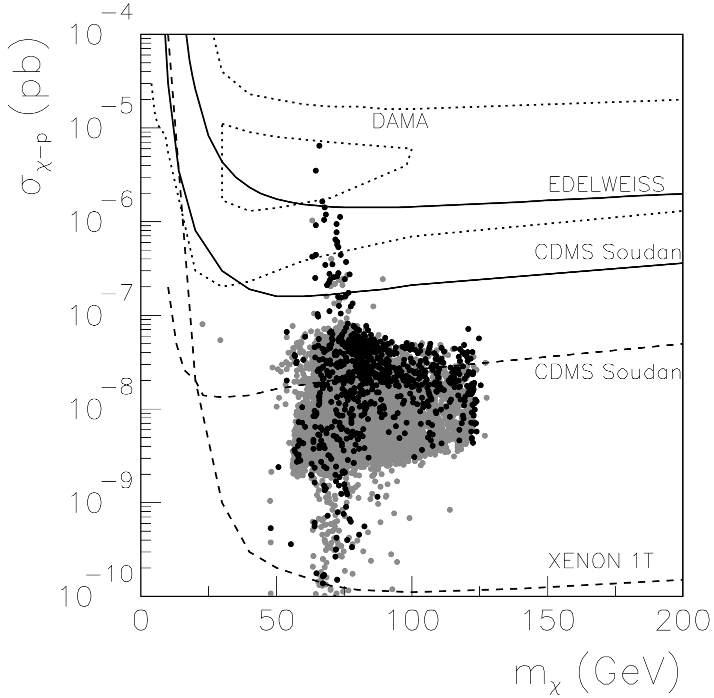
⋆ Green dash $Z_{15}^2 = .5$

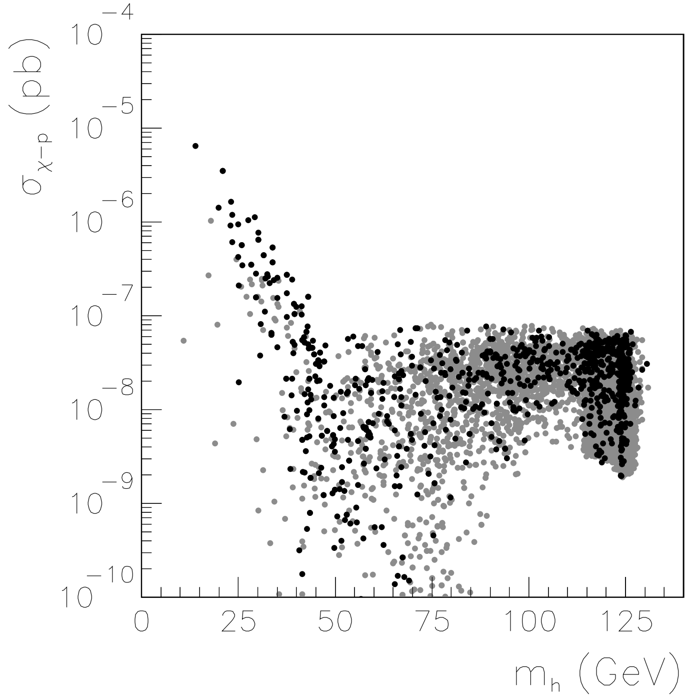
⋆ a_μ more than 2σ away $a_\mu \approx 7.2 \times 10^{-10}$

⋆ Compatible with Ω and $b \to s\gamma$ (2σ)

⋆ Within CDMS-Soudan range: $\tilde{\chi}_1^0$ singlino-like and h_1^0 singlet like.

NMSSM DM





$110 \lesssim M_2 \lesssim 430$ GeV, $-800 \lesssim A_\lambda \lesssim 800$ GeV, $-300 \lesssim A_\kappa \lesssim 300$ GeV,

$100 \lesssim \mu \lesssim 300$ GeV, $\tan\beta = 5$

Conclusions

❶ Systematic analysis of the NMSSM parameter space

Taken into account LEP constraints

BR$(b \to s\,\gamma)$ bounds (as well as others)

WMAP data on Ω

Investigated prospects for direct detection of DM

❷ In the NMSSM, large $\sigma_{\tilde{\chi}_1^0-p}$ can be obtained

Associated to t-channel exchange of very light Higgs ($m_{h_1^0} \lesssim 70$ GeV), large singlet component (escapes detection)

NMSSM nature is further evidenced in having a singlino-Higgsino LSP

❸ Impact of Ω and BR$(b \to s\,\gamma)$

Ω often relies on the same light-Higgs exchange that gives large σ

large $\sigma_{\tilde{\chi}_1^0-p} \leftrightarrow$ excessive annihilation

BR$(b \to s\,\gamma)$ typically larger in regions where DM is WMAP-compatible & within range of present detectors