Detecting Dark Matter in NUHM Models

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with Keith Olive (UMN) and John Ellis (CERN)

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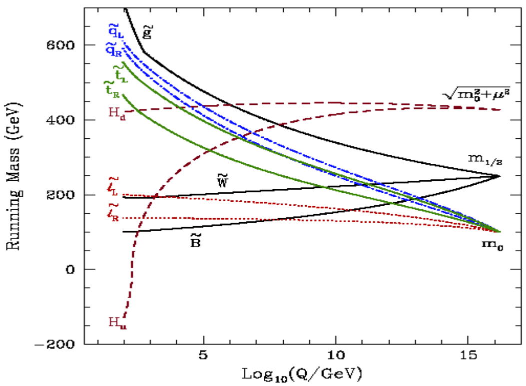
Universality

FCNC suppression: universality of matter fields that share quantum numbers (sfermion generations)

minimal Supergravity: Higgses+sfermions, gauginos

SUSY GUTs: varying degrees of universality

- SO(10): Higgses, scalars, gauginos
- SU(5): some masses equal



Mirage mediation: universality below GUT scale

Some string scenarios for SUSY breaking – maybe no universality at any scale!

Non-Universal Higgs Masses

D. Matalliotakis and H. P. Nilles, Nucl. Phys. B **435** (1995) 115 [arXiv:hep-ph/9407251]; M. Olechowski and S. Pokorski, Phys. Lett. B **344**, 201 (1995) [arXiv:hep-ph/9407404]; V. Berezinsky, A. Bottino, J. Ellis, N. Fornengo, G. Mignola and S. Scopel, *Astropart. Phys.* **5** (1996) 1, hep-ph/9508249; M. Drees, M. Nojiri, D. Roy and Y. Yamada, *Phys. Rev.* **D 56** (1997) 276, [Erratum-ibid. **D 64** (1997) 039901], hep-ph/9701219; M. Drees, Y. Kim, M. Nojiri, D. Toya, K. Hasuko and T. Kobayashi, *Phys. Rev.* **D 63** (2001) 035008, hep-ph/0007202; P. Nath and R. Arnowitt, *Phys. Rev.* **D 56** (1997) 2820, hep-ph/9701301; J. R. Ellis, T. Falk, G. Ganis, K. A. Olive and M. Schmitt, Phys. Rev. D **58** (1998) 095002 [arXiv:hep-ph/9801445]; J. R. Ellis, T. Falk, G. Ganis and K. A. Olive, Phys. Rev. D **62** (2000) 075010 [arXiv:hep-ph/0004169]; A. Bottino, F. Donato, N. Fornengo and S. Scopel, *Phys. Rev.* **D 63** (2001) 125003, hep-ph/0010203; S. Profumo, *Phys. Rev.* **D 68** (2003) 015006, hep-ph/0304071; D. Cerdeno and C. Munoz, *JHEP* **0410** (2004) 015, hep-ph/0405057;

J. Ellis, K. Olive and Y. Santoso, Phys. Lett. B **539**, 107 (2002) [arXiv:hep-ph/0204192]; J. R. Ellis, T. Falk, K. A. Olive and Y. Santoso, Nucl. Phys. B **652**, 259 (2003) [arXiv:hep-ph/0210205].

H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, Phys. Rev. D **71**, 095008 (2005) [arXiv:hep-ph/0412059]. H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, *JHEP* **0507** (2005) 065, hep-ph/0504001.

CMSSM → NUHM

CMSSM GUT-scale inputs:

$$m_0,\ m_{1/2} \text{ and } A_0 \text{ and the sign of } \mu$$

Use electroweak vacuum conditions:

$$m_A^2(Q) = m_1^2(Q) + m_2^2(Q) + 2\mu^2(Q) + \Delta_A(Q)$$

$$\mu^2 = \frac{m_1^2 - m_2^2 \tan^2\beta + \frac{1}{2} m_Z^2 (1 - \tan^2\beta) + \Delta_\mu^{(1)}}{\tan^2\beta - 1 + \Delta_\mu^{(2)}},$$

$$Q = (m_{\tilde{\tau}_R} m_{\tilde{\tau}_L})^{1/2}$$

$$m_A \equiv m_A(Q)$$

$$\mu \equiv \mu(m_Z)$$

$$m_1^2(Q) = m_1^2 + c_1,$$

$$m_2^2(Q) = m_2^2 + c_2,$$

$$\mu^2(Q) = \mu^2 + c_\mu,$$

CMSSM → NUHM

CMSSM – Higgs masses determined by $m_1^2(M_{GUT}) = m_2^2(M_{GUT}) = m_0^2$

NUHM1 – One extra free parameter: $m_1^2 = m_2^2$

$$
\begin{aligned}
m_1^2(\tan^2\beta + 1 + \Delta_\mu^{(2)}) = m_2^2(\tan^2\beta + 1 - \Delta_\mu^{(2)}) + m_Z^2(\tan^2\beta - 1) - 2\Delta_\mu^{(1)} \\
+\big(m_A^2 - (\Delta_A(Q) + c_1 + c_2 + 2c_\mu)\big)(\tan^2\beta - 1 + \Delta_\mu^{(2)}).
\end{aligned}
$$

$$
m_1^2 = m_2^2 \tan^2\beta + \mu^2(\tan^2\beta - 1 + \Delta_\mu^{(2)}) + \frac{1}{2} m_Z^2(\tan^2\beta - 1) - \Delta_\mu^{(1)}.
$$

NUHM2 – No constraint at GUT scale:

$$
\begin{aligned}
m_1^2(1 + \tan^2\beta) &= m_A^2(Q)\tan^2\beta - \mu^2(\tan^2\beta + 1 - \Delta_\mu^{(2)}) - (c_1 + c_2 + 2c_\mu)\tan^2\beta \\
&\quad -\Delta_A(Q)\tan^2\beta - \frac{1}{2} m_{\mathrm{B}Z}^2(1 - \tan^2\beta) - \Delta_\mu^{(1)}
\end{aligned}
$$

$$
\begin{aligned}
m_2^2(1 + \tan^2\beta) &= m_A^2(Q) - \mu^2(\tan^2\beta + 1 + \Delta_\mu^{(2)}) - (c_1 + c_2 + 2c_\mu) \\
&\quad -\Delta_A(Q) + \frac{1}{2} m_{\mathrm{B}Z}^2(1 - \tan^2\beta) + \Delta_\mu^{(1)}.
\end{aligned}
$$

DD-Relevant Parameters

Neutralino mass eigenstates:

$$\chi = Z_{\chi 1}\tilde{B} + Z_{\chi 2}\tilde{W} + Z_{\chi 3}\tilde{H}_1 + Z_{\chi 4}\tilde{H}_2.$$

$$(\tilde{W}^3, \tilde{B}, \tilde{H}_1^0, \tilde{H}_2^0)\begin{pmatrix} M_2 & 0 & \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_2 v_2}{\sqrt{2}} \\ 0 & M_1 & \frac{g_1 v_1}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} \\ \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_1 v_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g_2 v_2}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix}\begin{pmatrix} \tilde{W}^3 \\ \tilde{B} \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

Squark Mixing: $diag(m_1^2, m_2^2) \equiv \eta M^2 \eta^{-1}$

$$\begin{pmatrix} \cos\theta_f & \sin\theta_f e^{i\gamma_f} \\ -\sin\theta_f e^{-i\gamma_f} & \cos\theta_f \end{pmatrix} \equiv \begin{pmatrix} \eta_{11} & \eta_{12} \\ \eta_{21} & \eta_{22} \end{pmatrix}$$

DD Processes

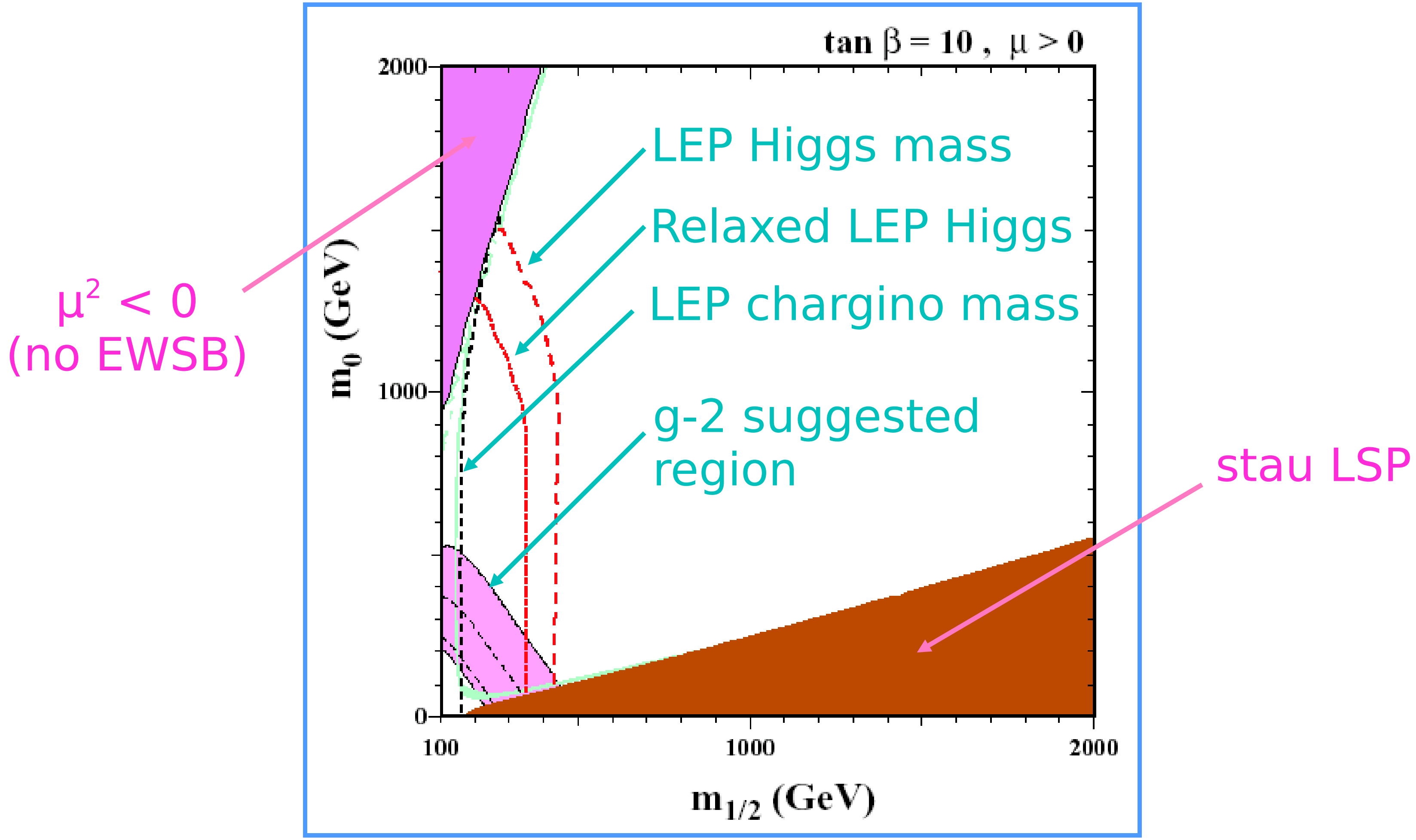
Neutralino-nucleon interaction Lagrangian:

$$\mathcal{L} = \alpha_{2i}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}_i\gamma_{\mu}\gamma^{5}q_i + \alpha_{3i}\bar{\chi}\chi\bar{q}_i q_i$$

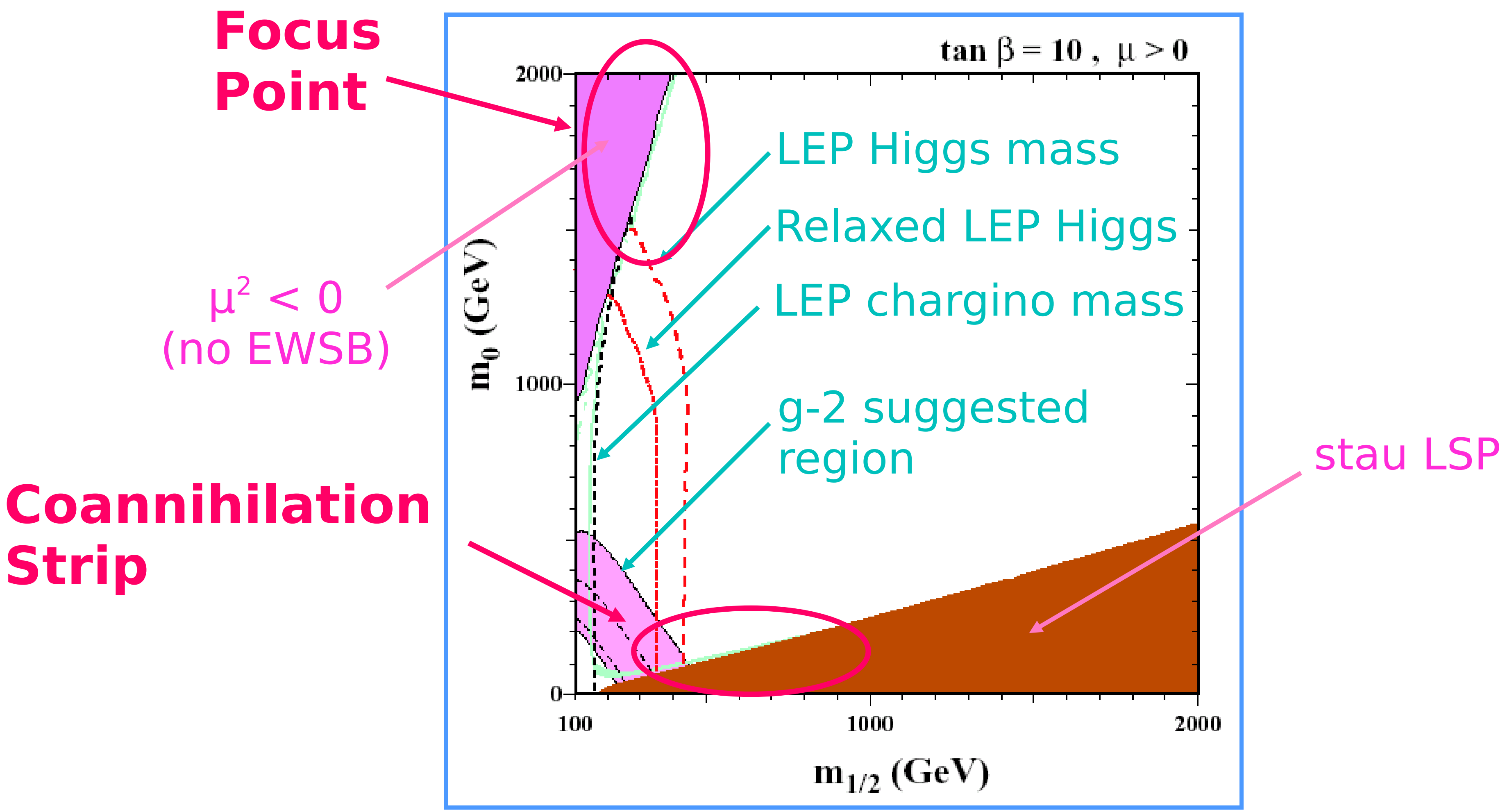
$$\begin{aligned}
\alpha_{2i} &= \frac{1}{4(m_{1i}^2 - m_\chi^2)}\left[|X_i|^2 + |Y_i|^2\right] + \frac{1}{4(m_{2i}^2 - m_\chi^2)}\left[|W_i|^2 + |V_i|^2\right] \\
&\quad - \frac{g^2}{4m_Z^2\cos^2\theta_W}\left[|Z_{\chi 3}|^2 - |Z_{\chi 4}|^2\right]\frac{T_{3i}}{2}
\end{aligned}$$

$$\begin{aligned}
\alpha_{3i} &= -\frac{1}{2(m_{1i}^2 - m_\chi^2)}\mathrm{Re}\left[(X_i)(Y_i)^*\right] - \frac{1}{2(m_{2i}^2 - m_\chi^2)}\mathrm{Re}\left[(W_i)(V_i)^*\right] \\
&\quad - \frac{g m_{q_i}}{4 m_W B_i}\left\{\left(\frac{D_i^2}{m_{H_2}^2} + \frac{C_i^2}{m_{H_1}^2}\right)\mathrm{Re}\left[\delta_{2i}\left(gZ_{\chi 2} - g' Z_{\chi 1}\right)\right]\right. \\
&\quad \left. + D_i C_i\left(\frac{1}{m_{H_2}^2} - \frac{1}{m_{H_1}^2}\right)\mathrm{Re}\left[\delta_{1i}\left(gZ_{\chi 2} - g' Z_{\chi 1}\right)\right]\right\},
\end{aligned}$$

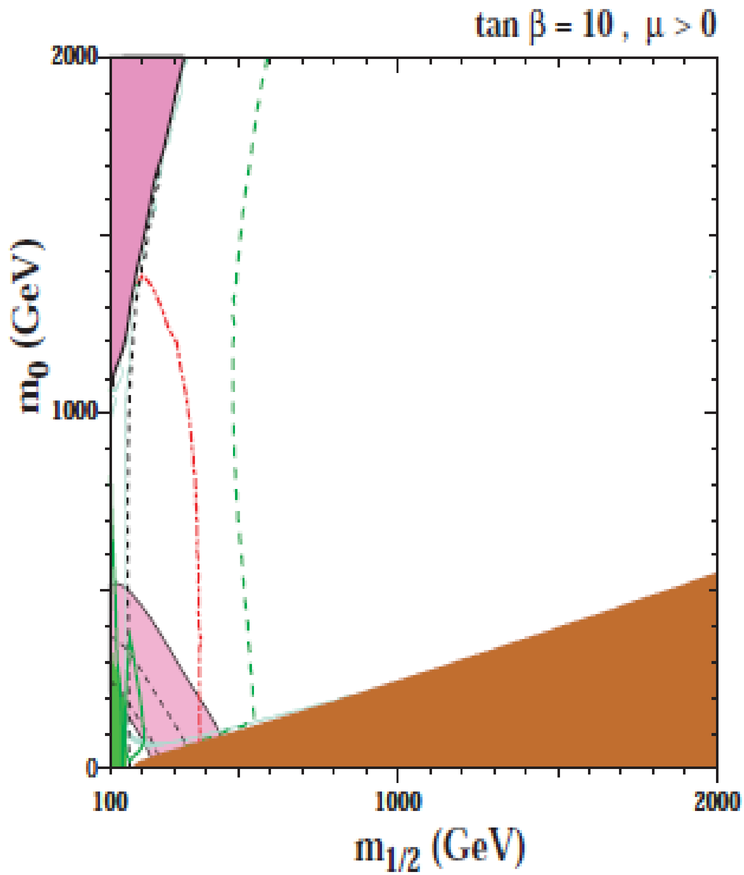
CMSSM

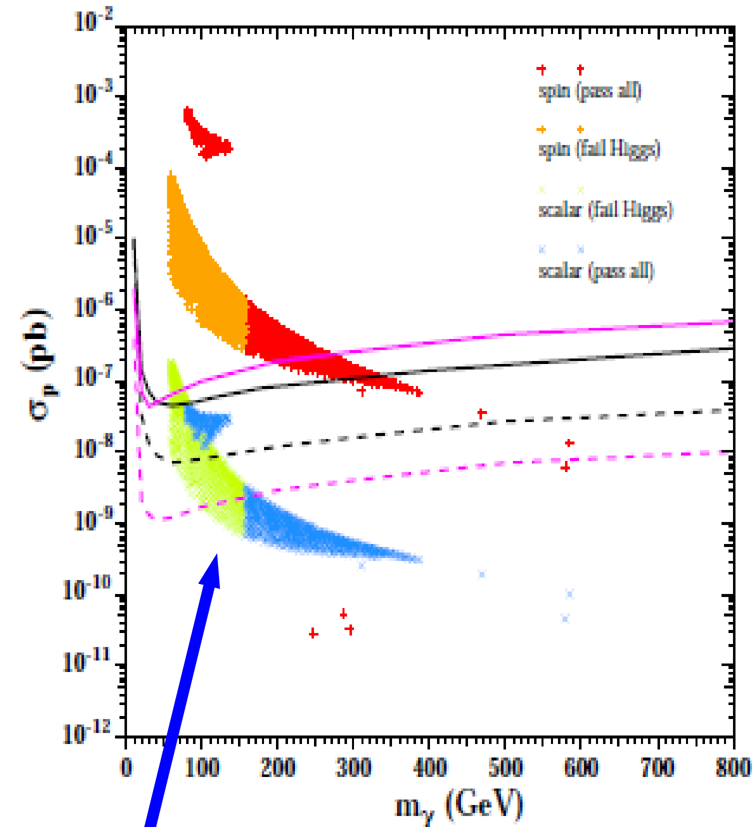

tan β = 10 , μ > 0
LEP Higgs mass
Relaxed LEP Higgs
LEP chargino mass
g-2 suggested region
μ² < 0
(no EWSB)
stau LSP
2000
1000
0
100
1000
2000
m₀ (GeV)
m1/2 (GeV)

CMSSM


Focus Point
μ² < 0 (no EWSB)
Coannihilation Strip
tan β = 10 , μ > 0
2000
1000
0
m0 (GeV)
100
1000
2000
m1/2 (GeV)
LEP Higgs mass
Relaxed LEP Higgs
LEP chargino mass
g-2 suggested region
stau LSP

CMSSM

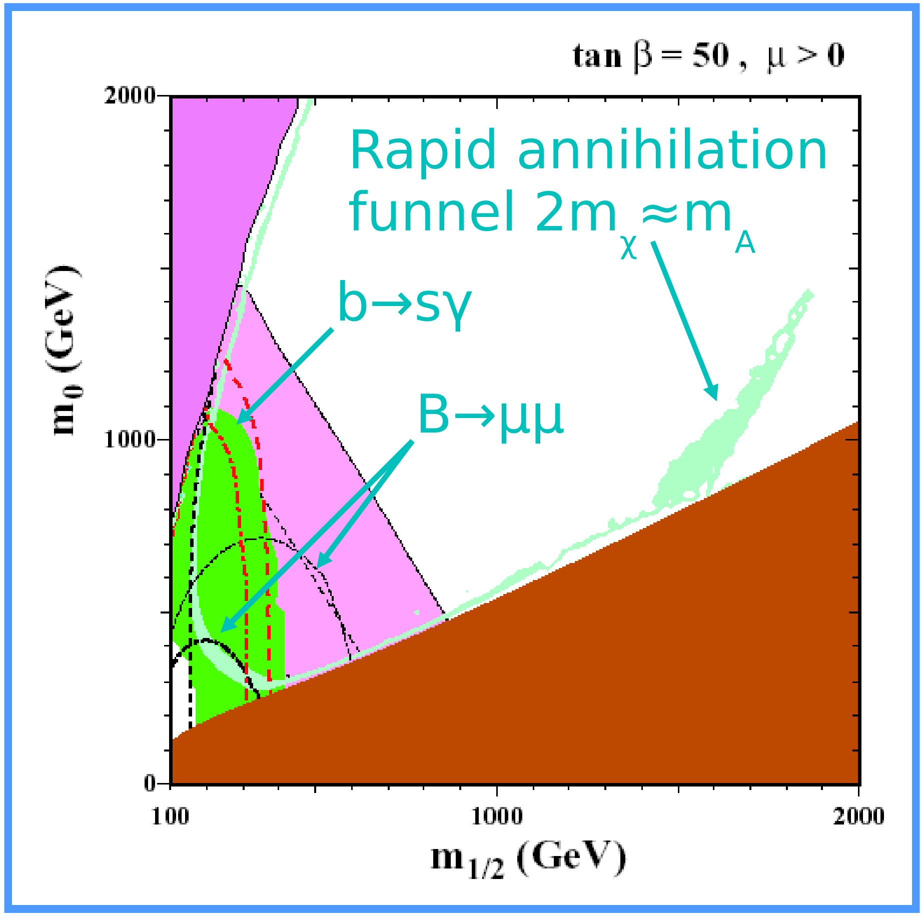




If $\Omega_\chi < \Omega_{DM}^{WMAP}$ then

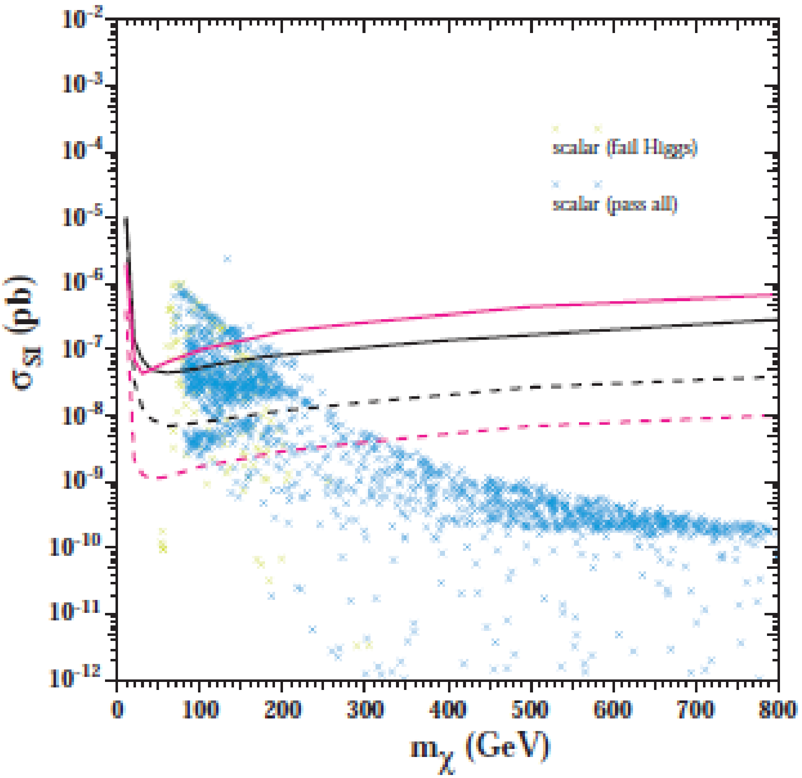
$$\sigma = \sigma_0 \frac{\Omega_\chi}{\Omega_{DM}^{WMAP}}$$

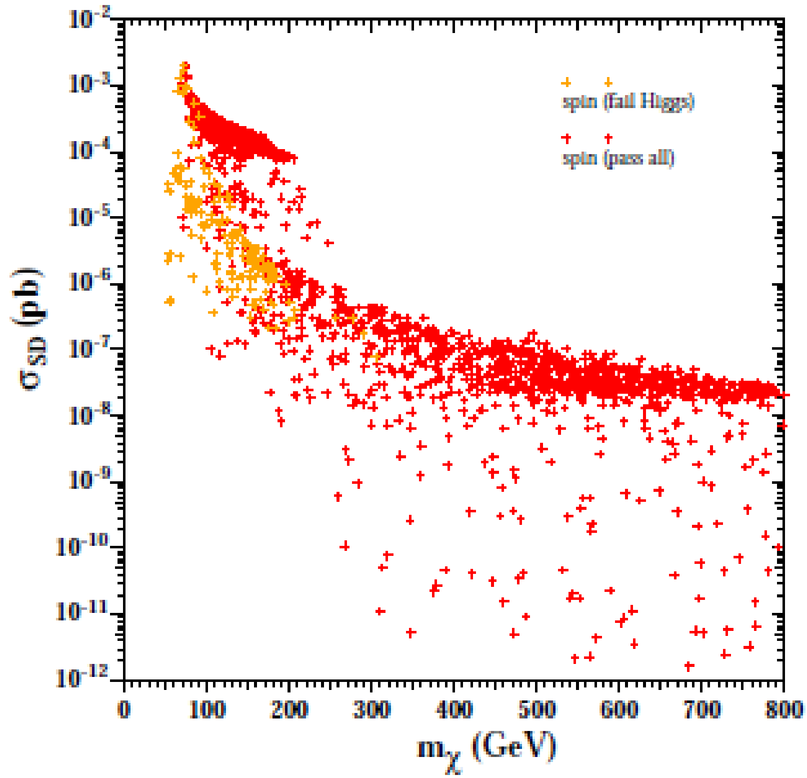
CMSSM



tan β = 50 , μ > 0
Rapid annihilation
funnel 2m χ ≈m A
b→sγ
B→μμ
2000
1000
0
100
1000
2000
m0 (GeV)
m1/2 (GeV)

CMSSM

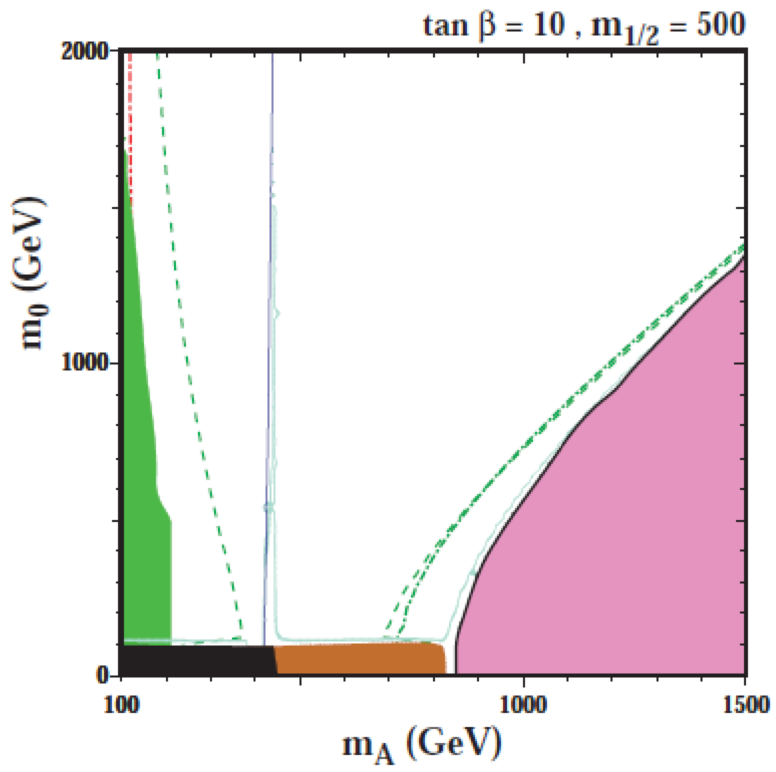




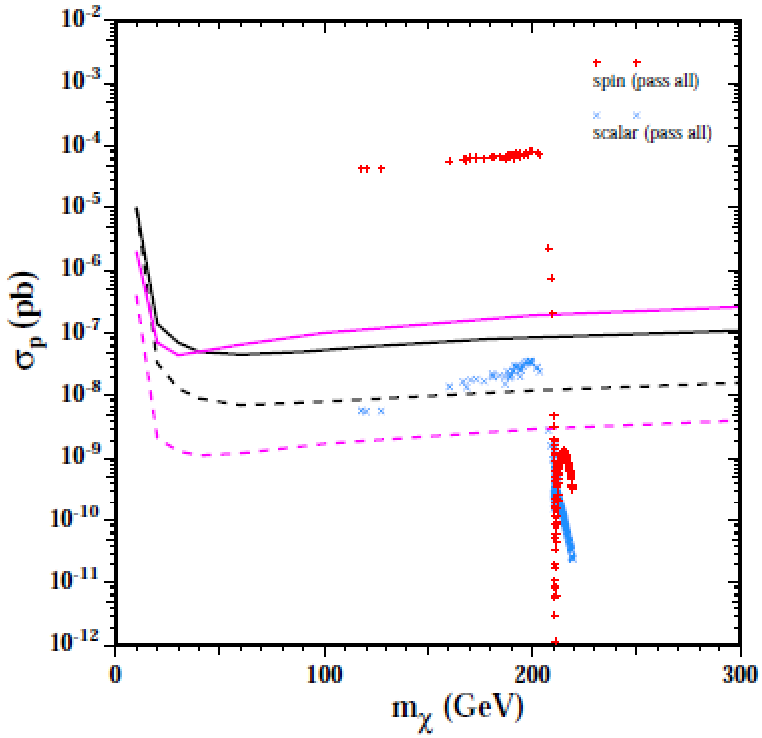
$5 \leq \tan\beta \leq 55,\ 0 \leq m_{1/2} \leq 2000\ GeV,\ 100\ GeV \leq m_0 \leq 2000\ GeV$

$-3m_{1/2} \leq A_0 \leq 3m_{1/2}$ *We consider* $\mu < 0$ *only for* $\tan\beta < 30$.

NUHM1

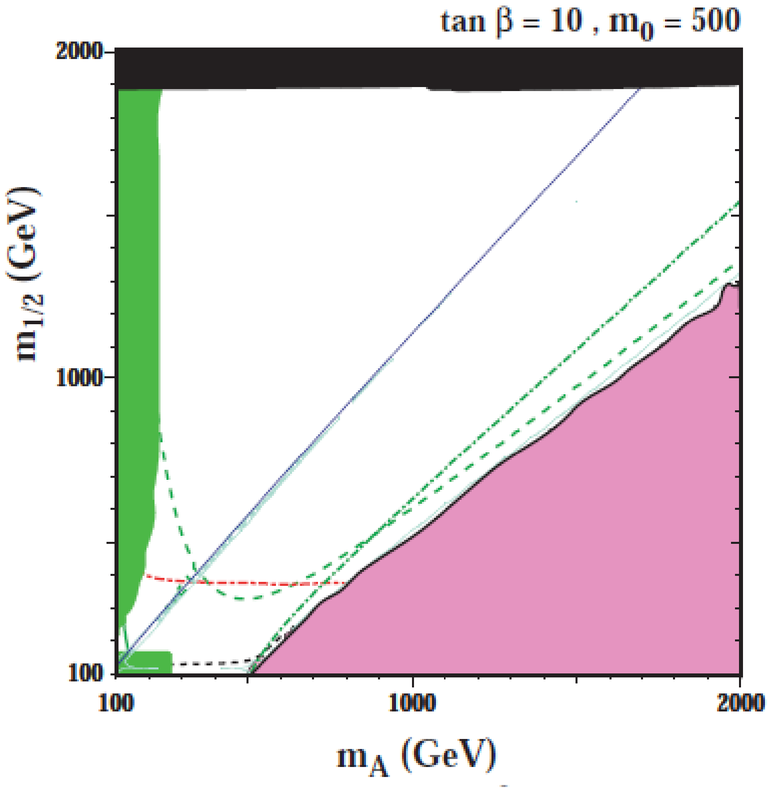


tan β = 10 , m1/2 = 500
m0 (GeV)
mA (GeV)
2000
1000
0
100
1000
1500

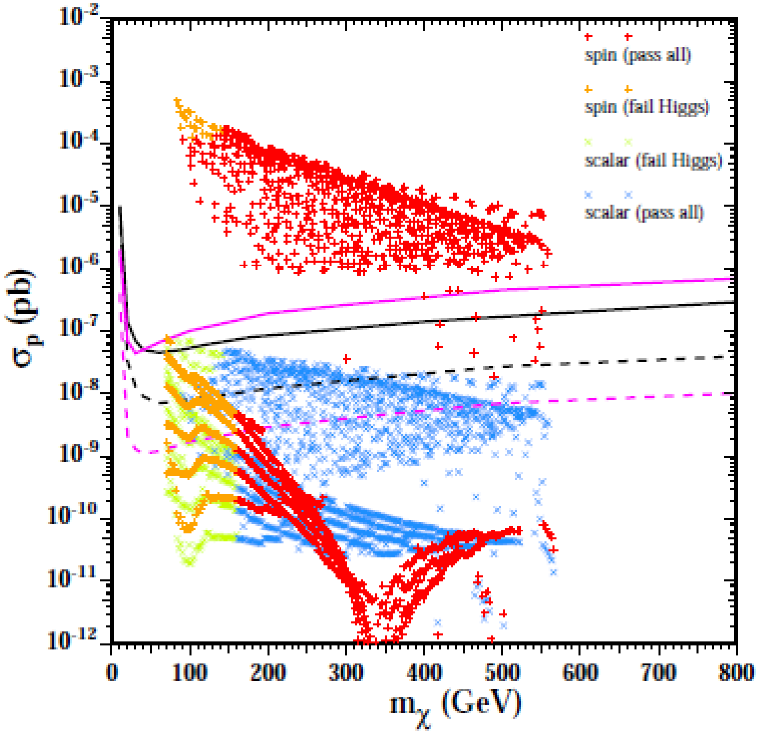


spin (pass all)
scalar (pass all)
σp (pb)
mχ (GeV)
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
0
100
200
300

NUHM1

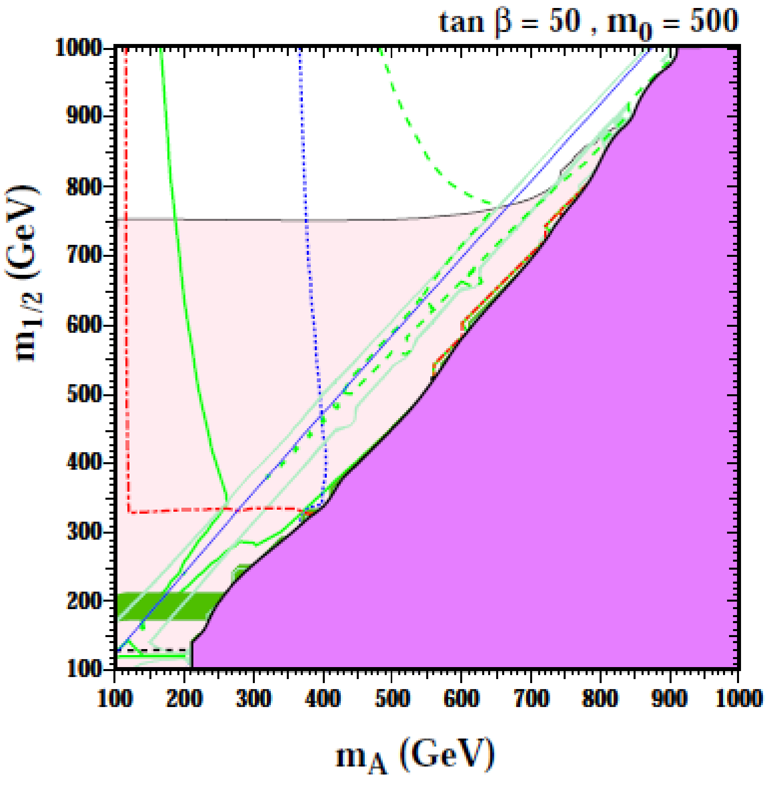


tan β = 10 , m0 = 500
m1/2 (GeV)
mA (GeV)
2000
1000
100
100
1000
2000

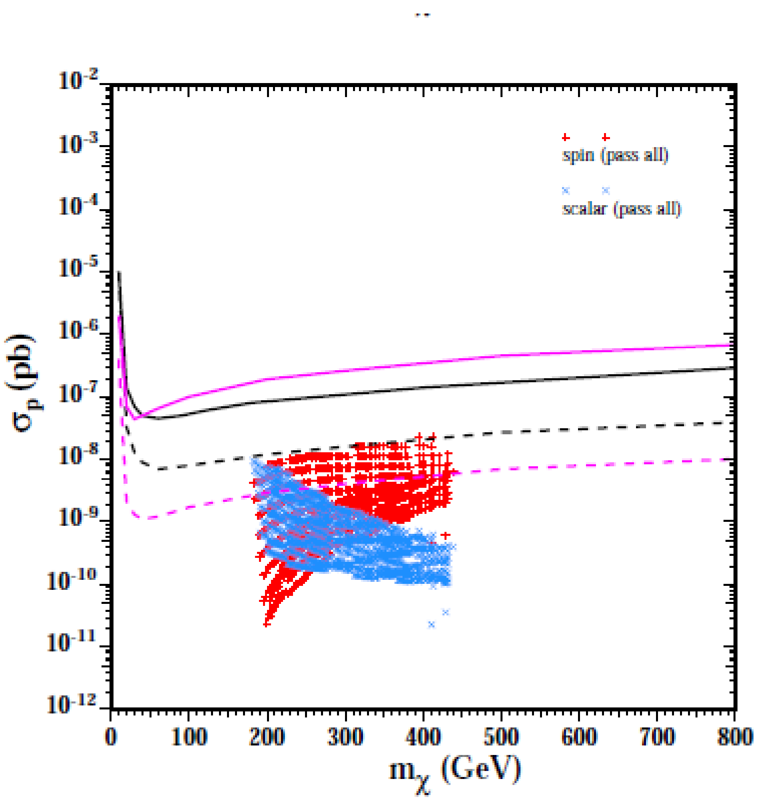


spin (pass all)
spin (fail Higgs)
scalar (fail Higgs)
scalar (pass all)
σp (pb)
mχ (GeV)
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
0
100
200
300
400
500
600
700
800

NUHM1

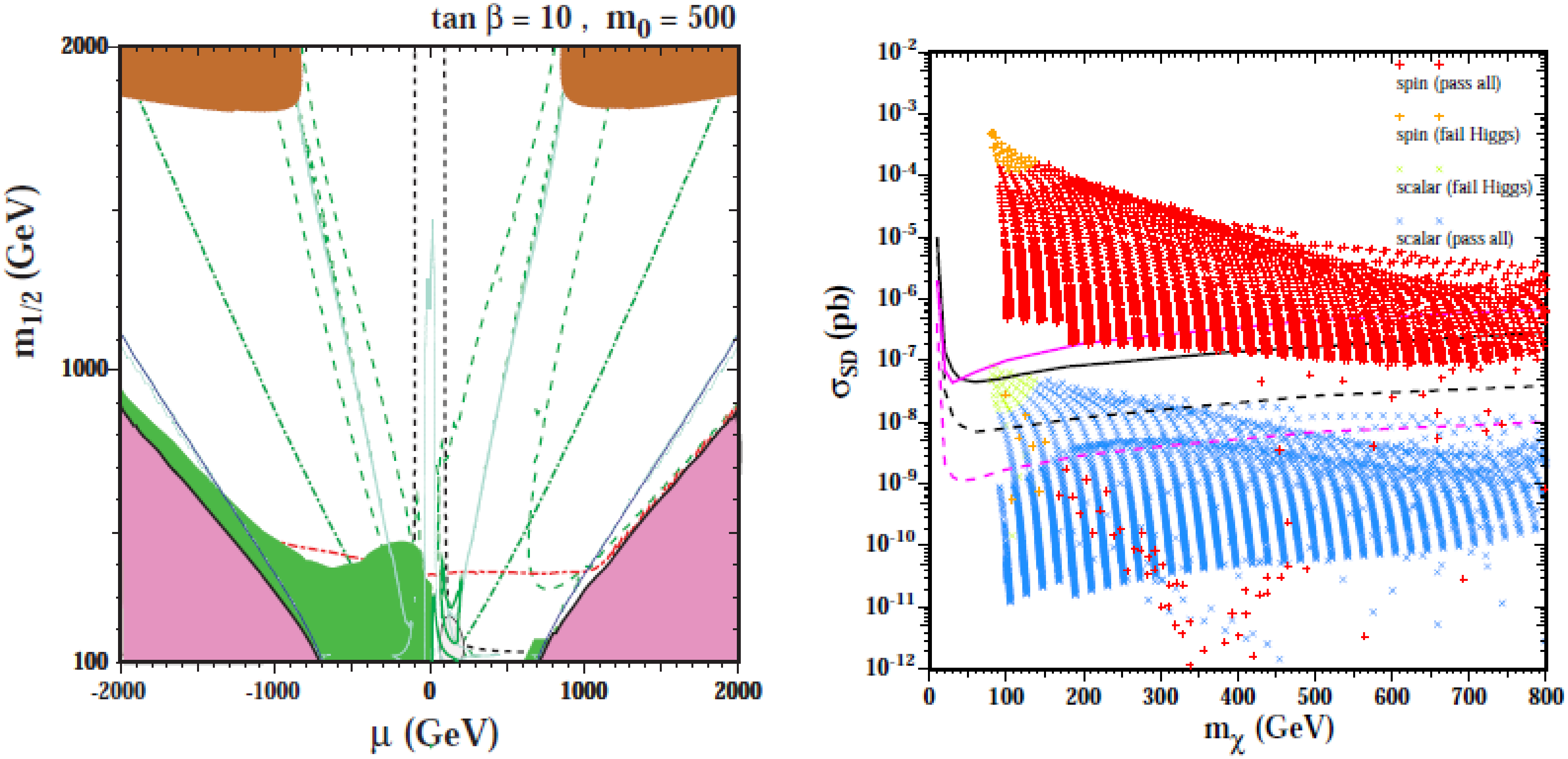


tan β = 50 , m0 = 500
m1/2 (GeV)
mA (GeV)
100
200
300
400
500
600
700
800
900
1000



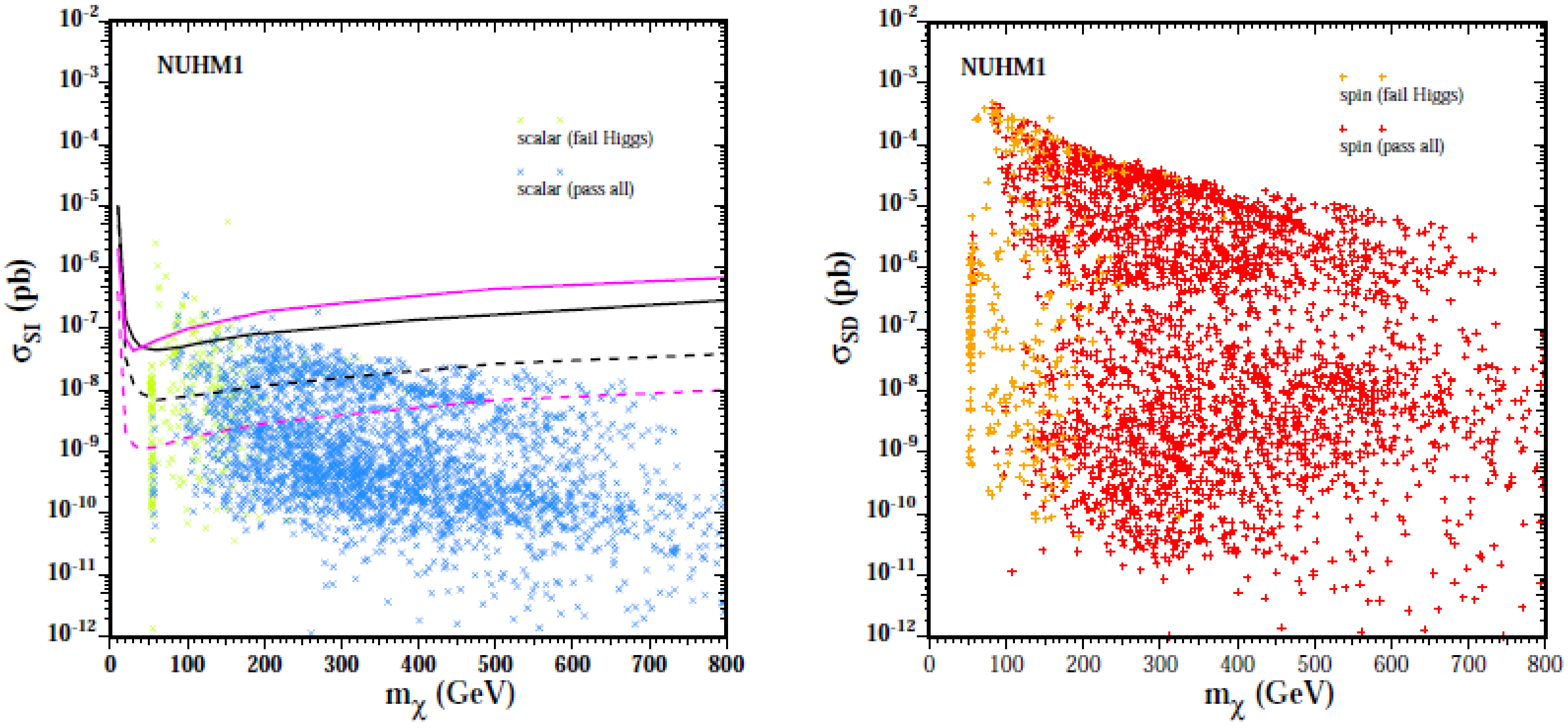
spin (pass all)
scalar (pass all)
σp (pb)
mχ (GeV)
0
100
200
300
400
500
600
700
800

NUHM1



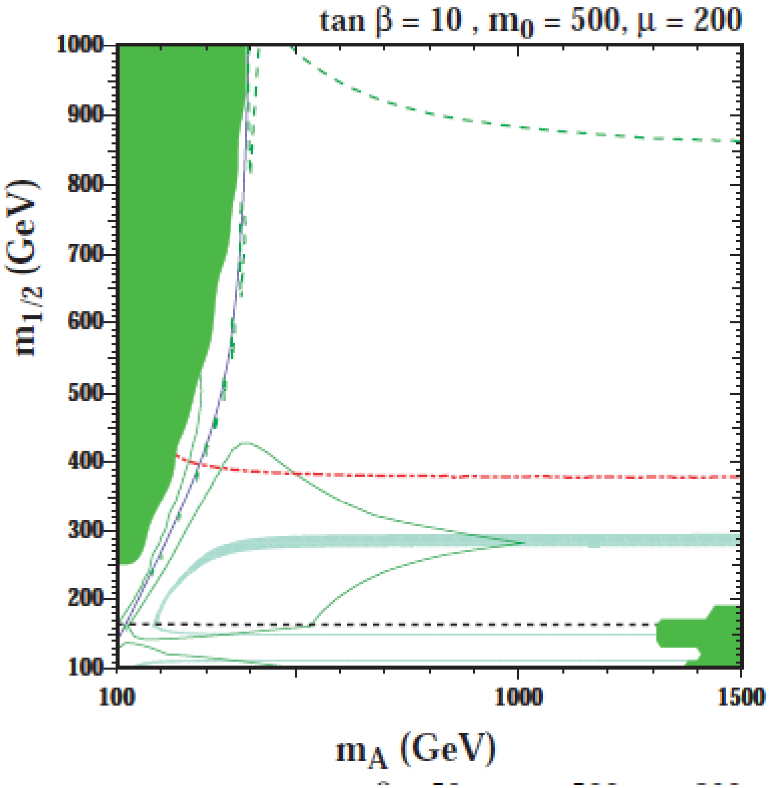
tan β = 10 , m0 = 500
m1/2 (GeV)
μ (GeV)
2000
1000
100
-2000
-1000
0
1000
2000
σSD (pb)
mχ (GeV)
spin (pass all)
spin (fail Higgs)
scalar (fail Higgs)
scalar (pass all)
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
0
100
200
300
400
500
600
700
800

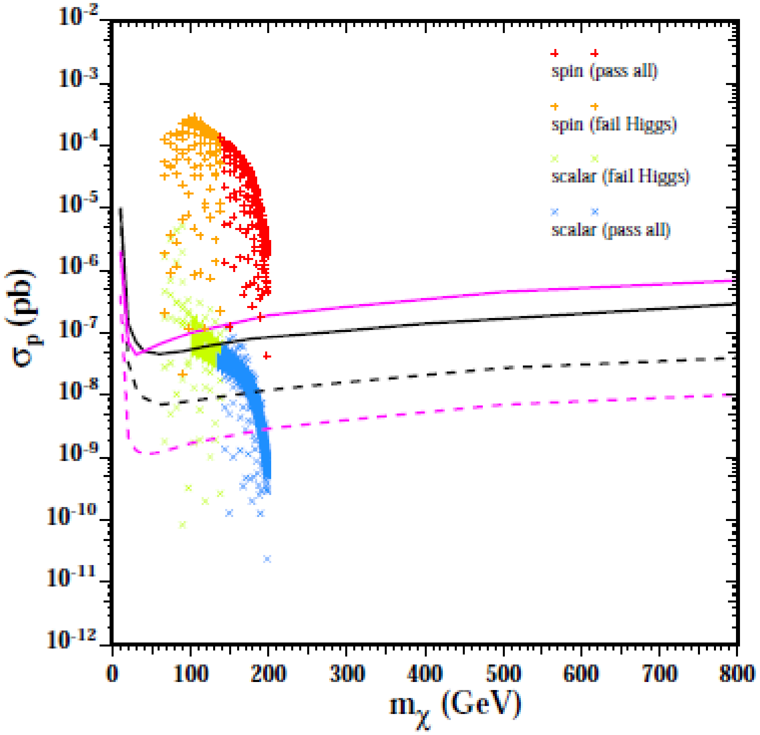
NUHM1



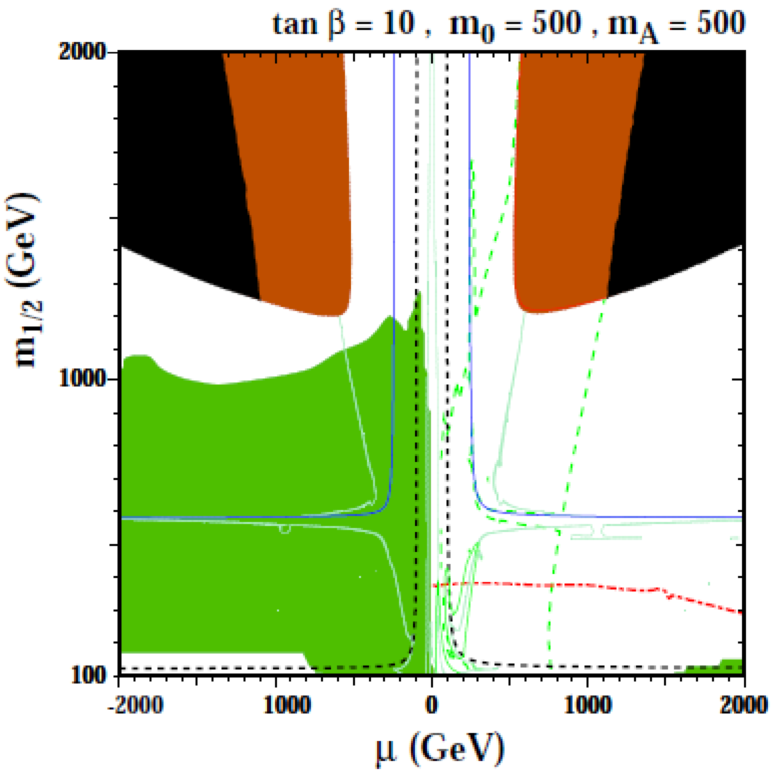
In both plots, we scan $5 \leq \tan\beta \leq 55$, *0* $\leq m_{1/2} \leq 2000$ *GeV, 100 GeV* $\leq m_0 \leq 2000$ *GeV, and* $-3m_{1/2} \leq A_0 \leq 3m_{1/2}$. *The common GUT-scale value of* $m_1 = m_2$ *is in the range* $(-2000, 2000)$ *GeV.*

NUHM2

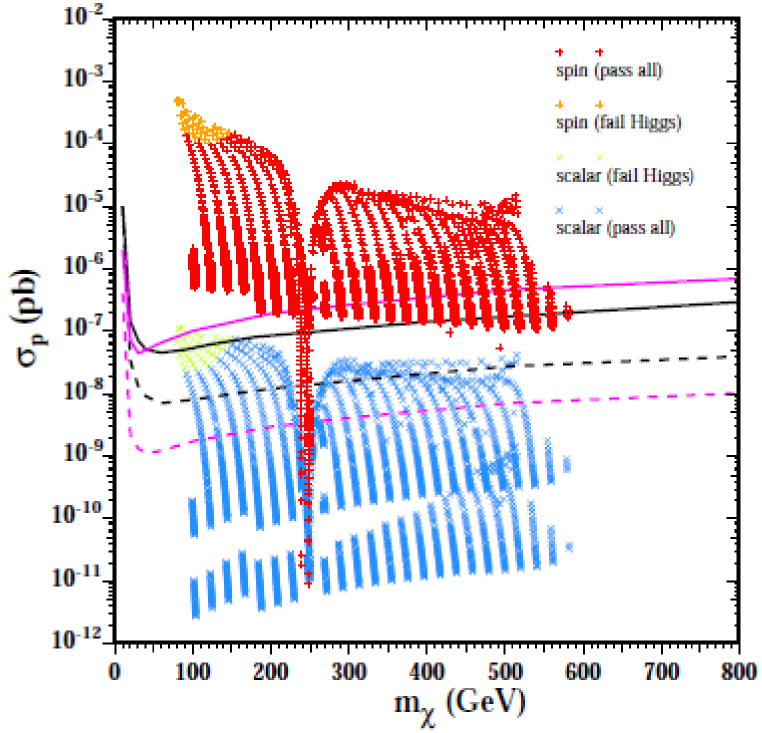

tan β = 10 , m0 = 500, μ = 200
1000
900
800
700
600
500
400
300
200
100
m1/2 (GeV)
100
1000
1500
mA (GeV)


spin (pass all)
spin (fail Higgs)
scalar (fail Higgs)
scalar (pass all)
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
σp (pb)
0
100
200
300
400
500
600
700
800
mχ (GeV)

NUHM2

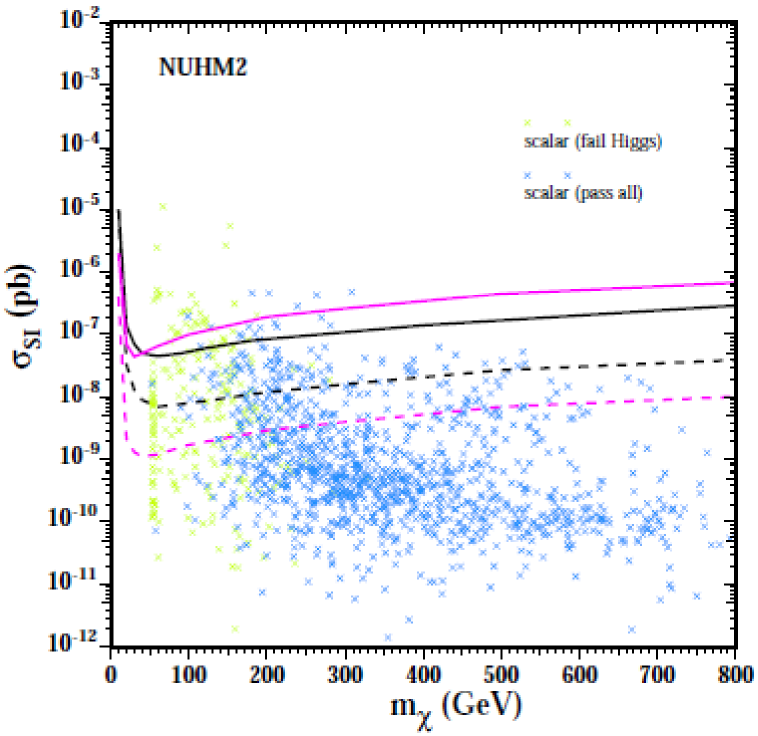


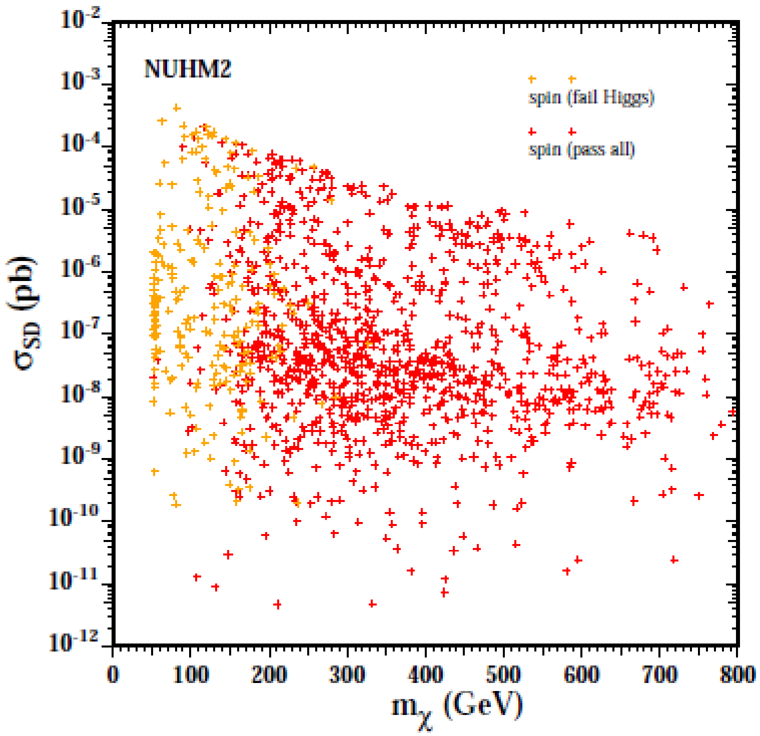
tan β = 10 , m0 = 500 , mA = 500
2000
1000
100
m1/2 (GeV)
-2000
1000
0
1000
2000
μ (GeV)



spin (pass all)
spin (fail Higgs)
scalar (fail Higgs)
scalar (pass all)
σp (pb)
mχ (GeV)
0
100
200
300
400
500
600
700
800

NUHM2





In both scans, we scan $5 \leq \tan\beta \leq 55$, $0 \leq m_{1/2} \leq 2000$ *GeV*, 100 *GeV* $\leq m_0 \leq 2000$ *GeV*, $-3m_{1/2} \leq A_0 \leq 3m_{1/2}$, *and the GUT-scale values of* m_1 *and* m_2 *are each in the range* $(-2000, 2000)$ *GeV.*

Summary

- Additional cosmologically-viable regions of parameter space lead to broader ranges of DM scattering rates than are possible in the CMSSM
  - Larger cross sections at larger mass (crossover regions with substantial Higgsino component)
  - Smaller cross sections at smaller mass (relic density suppressed by some mechanism?)
- If we observe SI scattering by heavy WIMP (not CMSSM), could be in crossover region...
- If LHC establishes light LSP but we don't see SI scattering, could mean Higgsino-like LSP