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NEUTRALINO-PROTON CROSS SECTIONS

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1. INTRODUCTION

Gravity mediated supergravity models with R-parity invariance automatically possess a dark matter candidate, the lightest supersymmetric particle (LSP), which in most models is the neutralino, $\tilde{\chi}_1^0$. Experiments to directly test the existance of the $\tilde{\chi}_1^0$ in the halo of the Milky Way look $\tilde{\chi}_1^0$ scattering by terrestial nuclear targets. For heavy nuclei, the spin independent scattering dominates, allowing one to determine the $\tilde{\chi}_1^0$-proton cross section $\sigma_{\tilde{\chi}_1^0-p}$. Current experiments are sensitive to halo $\tilde{\chi}_1^0$ of (DAMA, CDMS):

$$\sigma_{\tilde{\chi}_1^0-p} \gtrsim 1\times10^{-6}\ pb$$

and future detectors plan to achieve a sensitivity of (GENIUS, Cryoarray):

$$\sigma_{\tilde{\chi}_1^0-p} \gtrsim (10^{-9}-10^{-10})\ pb$$

We consider here two questions:

* What is the range of SUSY parameters current detectors are sensitive to?
* What is the smallest values of $\sigma_{\tilde{\chi}^0_1-p}$ theory is predicting?

The answer to these questions depends in part on what models one considers:

* We examine here models based on grand unification at $M_G \cong 2\times10^{16}$ GeV with radiative breaking of $SU(2)\times U(1)$ at the electroweak scale

and also in part on the choice of imput parameters and range of SUSY parameters (i.e. assumptions on "naturalness" conditions)

* Range of imput parameters can produce factors $\simeq 3$ in $\sigma_{\tilde{\chi}^0_1-p}$

There are a number of models based on grand unification of the gauge coupling constants at $M_G \cong 2\times10^{16}$ GeV:

Minimal Supergravity GUT (mSUGRA)
Universal soft breaking at M_G

Nonuniversal Soft Breaking Models
Nonuniversal scalar masses in Higgs and third generation at M_G

There are "string inspired" models

D-brane Models (IIB Orientifolds)
Nonuniversal gaugino masses at M_G
$SU(2)_L$ doublet masses different from singlet scalar masses at M_G

Horava-Witten M-Theory (Calabi-Yau)
Universal gaugino masses at M_G
Generation nonuniversality of scalar masses at M_G

Theory allows one to calculate both the detection cross section, $\sigma_{\tilde{\chi}_1^0-p}$, and the relic density $\Omega_{\tilde{\chi}_1^0} h^2$:

$$\Omega_{\tilde{\chi}_1^0} h^2 = 2.48 \times 10^{-11} \left(\frac{T_{\tilde{\chi}_1^0}}{T_\gamma}\right)^3 \left(\frac{T_\gamma}{2.73}\right)^3 \frac{N_F^{1/2}}{\int_0^{x_f} dx \langle \sigma_{ann} v \rangle}$$

where

$\Omega_{\tilde{\chi}_1^0} = \rho_{\tilde{\chi}_1^0} / \rho_c$; $\rho_c = 3H_0^2/8\pi G_N$; $h = H_0/100$

and

σ_{ann} = early universe annihilation cross section

Astronomical data gives:

$H_0 = 70 \pm 7$ km/s Mpc [Freedman]

$\Omega_m \cong 0.3 \pm 0.1$ [Dodelson, Knox; Mohr et al., Lineweaver; Efstathiou]

and using $\Omega_b \cong 0.05$ one has

$$\Omega_{\tilde{\chi}_1^0} = 0.25 \pm 0.10$$

Combining errors in quadrature gives

$$\Omega_{\tilde{\chi}_1^0} h^2 = 0.12 \pm 0.05$$

We assume here a $\simeq 2\sigma$ range

$$0.02 \leq \Omega_{\tilde{\chi}_1^0} h^2 \leq 0.25$$

2. Calculational Details

In order to get reasonably accurate theoretical answers, necessary to include a number of corrections and constraints. Summarize some of these now:

Parameter space (mSUGRA)

$m_0 \leq 1$ TeV

$m_{1/2} \leq 600$ GeV ($m_{\tilde{g}} \lesssim 1.5$ TeV; $m_{\tilde{\chi}^0_1} \lesssim 240$ GeV)

$2 \leq \tan\beta \leq 50$; $\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$

($\sigma_{\tilde{\chi}^0_1 - p}$ increases with $\tan\beta$; SO(10) $\tan\beta \simeq 40$)

$|A_0/m_0| \leq 5$ (default)

Theoretical analysis

(i) Run 1-loop Yukawa and 2-loop gauge RGE from $M_G = 2\times10^{16}$ GeV down to electroweak scale, iterating to get a consistent SUSY spectrum

(ii) QCD RGE corrections included for contributions dominated by light quarks

(iii) 1-loop, 2-loop and pole mass corrections to Higgs mass m_h.

(iv) L-R mixing in sfermion mass matrices (Important for large $\tan\beta$ in 3rd generation)

(v) 1-loop correction to m_b, m_τ (Important for large $\tan\beta$)

(vi) LO and (approximate) NLO corrections to $b \to s + \gamma$ decay.

We do not impose $b-\tau$ (or $b-\tau-t$) Yukawa unification as this depends sensitively on unknown post-GUT physics. Thus this does not naturally occur in string models where SU(5) (or SO(10)) are broken by Wilson lines.

Accelerator bounds

LEP: * $m_h > 104$ GeV ; $\tan\beta = 3$

* $m_h > 100$ GeV ; $\tan\beta = 5$

$m_{\chi_1^\pm} > 102$ GeV

Tevatron: $m_{\tilde{g}} \gtrsim 270$ GeV $(m_{\tilde{q}} \simeq m_{\tilde{g}})$

CLEO: * $1.8 \times 10^{-4} \leq B(B \to X_s \gamma) \leq 4.5 \times 10^{-4}$

Properties of proton

Theory gives naturally the $\tilde{\chi}^0_1$-quark cross section and one must convert this to $\tilde{\chi}^0_1$-proton scattering to compare with experiment. One need the quantities [Ellis, Flores; Drees, Nojiri]:

$$\sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\langle p|\bar{u}u + \bar{d}d|p\rangle$$

$$\sigma_0 = \frac{1}{2}(m_u + m_d)\langle p|\bar{u}u + \bar{d}d - 2\bar{s}s|p\rangle$$

$$r = \frac{m_s}{\frac{1}{2}(m_u + m_d)}$$

We use in the following

$$\sigma_{\pi N} = 65 \text{ MeV [Ollson; Pavan et al.]}$$

$$\sigma_0 = 30 \text{ MeV [Bottino et al.]}$$

$$r = 24.4 \pm 1.5 \text{ [Leutwyler]}$$

Other choices can change $\sigma_{\tilde{\chi}^0_1-p}$ by about a factor ≈ 3.

3. mSUGRA MODEL

The mSUGRA model depends on 4 parameters and one sign. Since there is now a considerable amount of constraints from data, it has become relatively predictive. The parameters are:

m_0: universal scalar mass at M_G

$m_{1/2}$: universal gaugino mass at M_G
(alternately: $m_{\tilde{\chi}_1^0} \cong 0.4 m_{1/2}$; $m_{\tilde{g}} \cong 2.8 m_{1/2}$)

A_0: universal cubic soft breaking mass

$\tan\beta$: $= \langle H_2 \rangle / \langle H_1 \rangle$

$\frac{\mu}{|\mu|}$: sign of Higgs mixing parameter ($W_\mu = \mu H_1 H_2$)

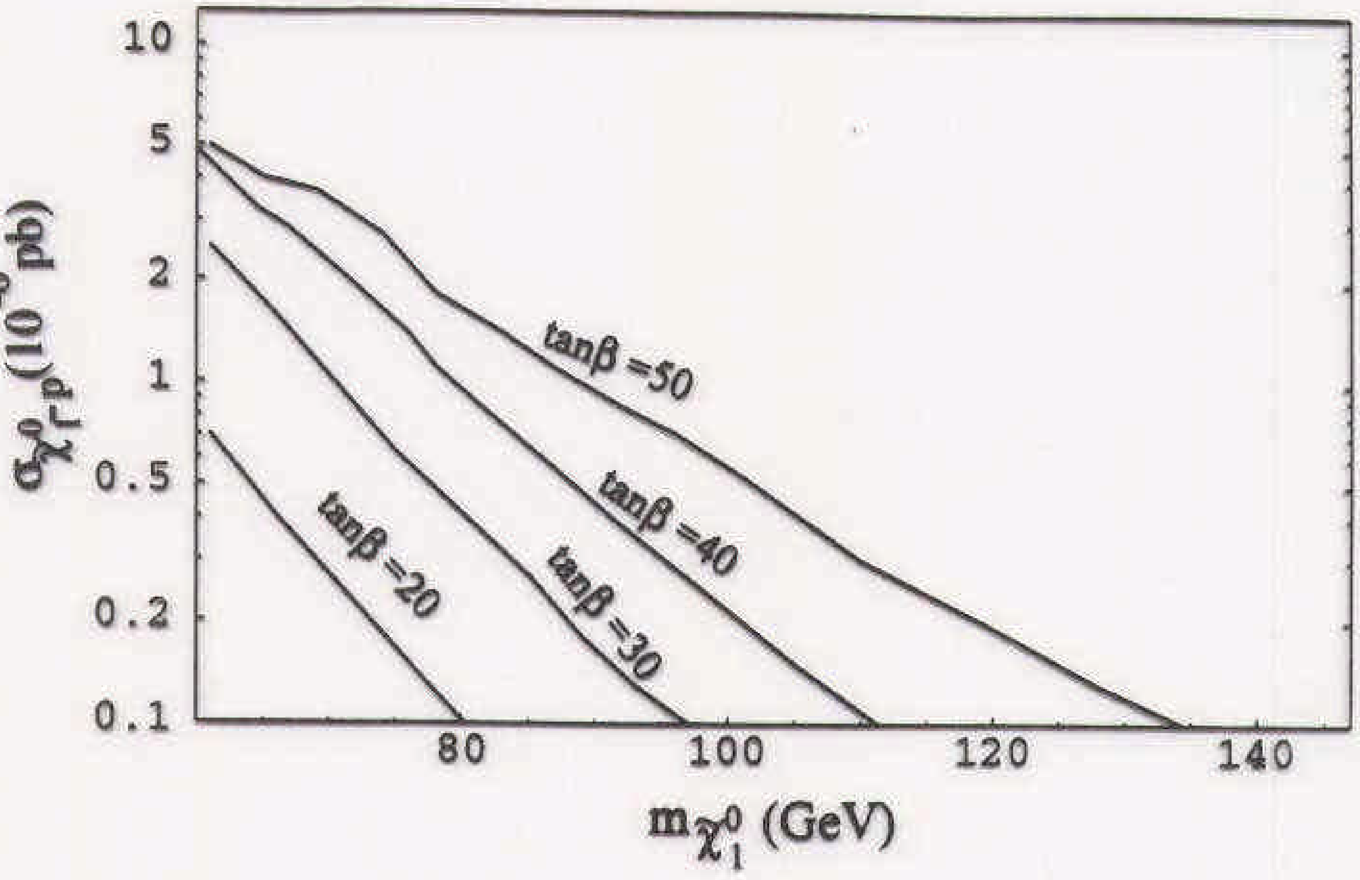
Maximum cross section:

$\sigma_{\tilde{\chi}_1^0 - p}$ is an increasing function of $\tan\beta$ and a decreasing function of $m_{1/2}$, m_0

Thus maximum cross sections should occur at large $\tan\beta$ and small $m_{\tilde{\chi}_1^0}$.

Fig. $(\sigma_{\tilde{\chi}_1^0 - p})_{max}$ obtained by varying A_0 over parameter space for $\tan\beta = 20, 30, 40, 50$.

Maximum $\sigma_{\tilde{\chi}_1^0-p}$ for $\tan\beta = 20, 30, 40, 50$ (mSUGRA)



One sees that current sensitivity of

$\sigma_{\tilde{\chi}^0_1 - p} \gtrsim 1 \times 10^{-6}\,pb$ is sampling mSUGRA for

$$\tan\beta \gtrsim 25 \quad ; \quad m_{\tilde{\chi}^0_1} \lesssim 90\ \mathrm{GeV}$$

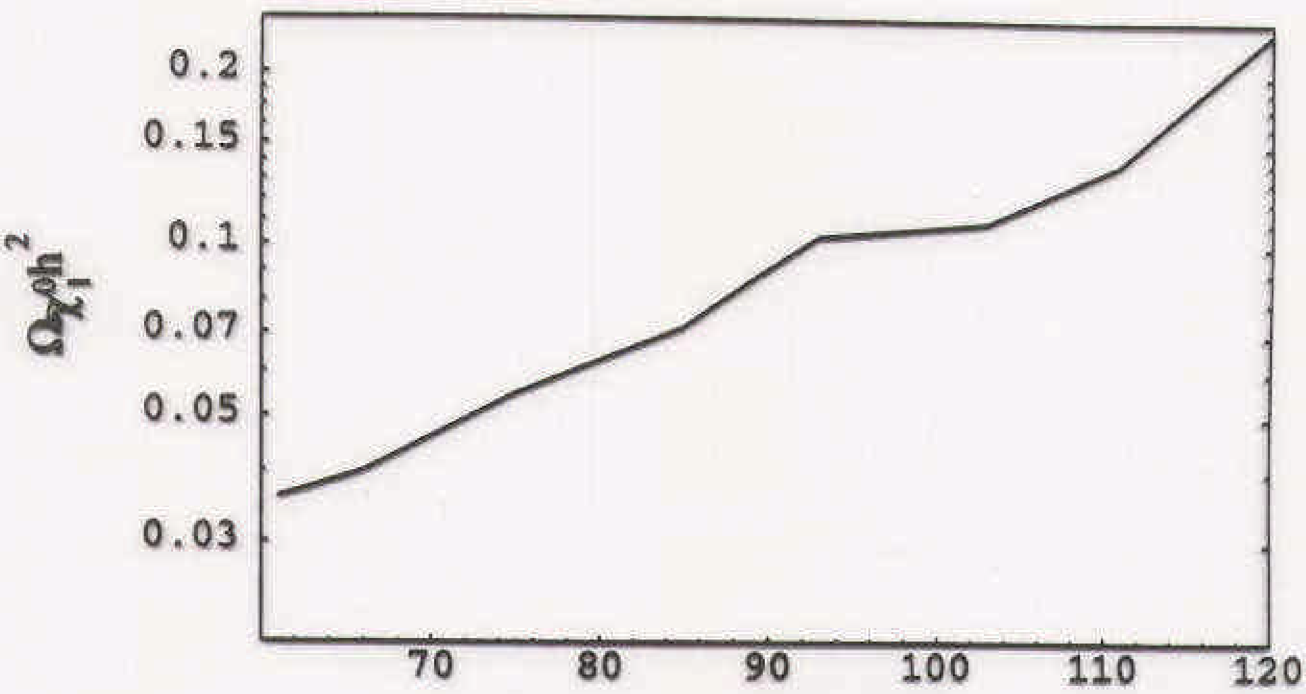
The early universe σ_{ann} decreases with $m_{1/2}$
and hence $\Omega_{\tilde{\chi}^0_1} h^2$ increases with $m_{1/2}$

Fig $\Omega_{\tilde{\chi}^0_1} h^2$ as function of $m_{\tilde{\chi}^0_1}$ for $\tan\beta = 30$ when
$\sigma_{\tilde{\chi}^0_1 - p}$ is at maximum.

Thus current sensitivity is sampling low $\Omega_{\tilde{\chi}^0_1} h^2$
i.e.

$$\Omega_{\tilde{\chi}^0_1} h^2 \lesssim 0.1$$

$\Omega_{\tilde{\chi}_1^0} h^2$ for $(\sigma_{\chi_1^0 - p})_{max}$; $\tan\beta = 30$



Minimum cross section ($m_{\tilde{\chi}_1^0} \lesssim 150$ GeV):

In this region there is no coannihilation, and the lowest cross sections occur at the smallest $\tan\beta$.

Fig. Minimum $\sigma_{\tilde{\chi}_1^0 - p}$ as function of $m_{\tilde{\chi}_1^0}$ for $\tan\beta = 3$.

One sees that for this domain

$$\sigma_{\tilde{\chi}_1^0 - p} \gtrsim 4 \times 10^{-9}\ pb \quad ; \quad m_{\tilde{\chi}_1^0} \lesssim 140\ GeV$$

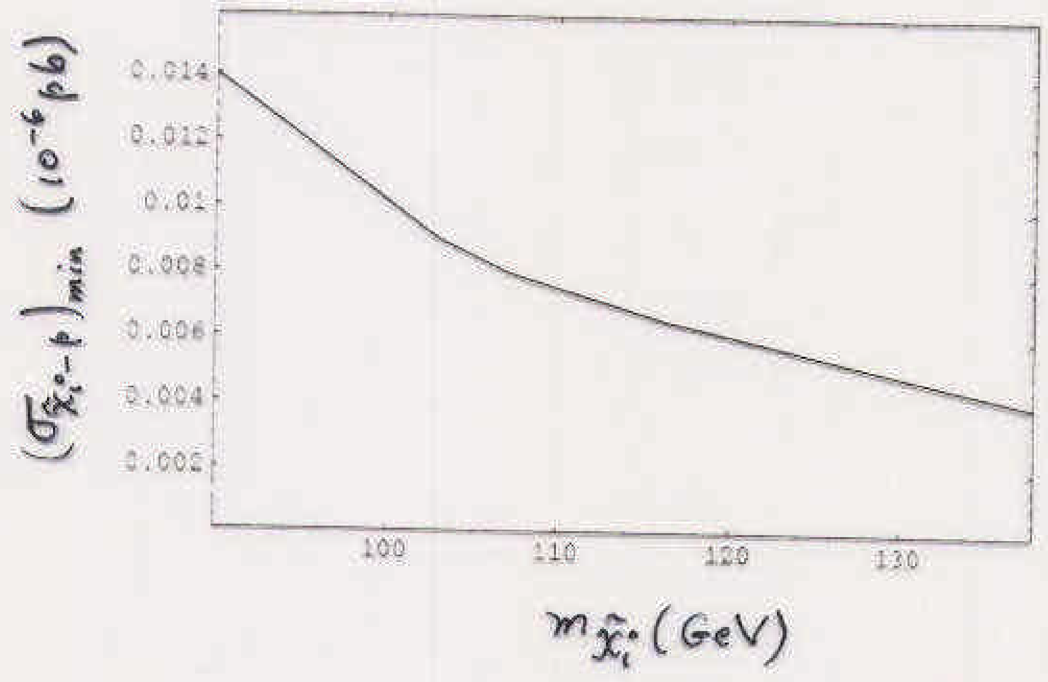
which would be accessible to planned detectors (e.g. GENIUS).

Coannihilation ($m_{\tilde{\chi}_1^0} \gtrsim 150$ GeV):

Coannihilation in the early universe occurs when a second SUSY particle becomes nearly degenerate with the LSP (i.e. $\tilde{\chi}_1^0$). The effect is significant in mSUGRA due to two "peculiarities":

mSUGRA: $(\sigma_{\tilde{\chi}_1^0-p})_{min}$; $\tan\beta = 3$

$m_{1/2} < 345$ GeV



(1) $\tilde{\chi}_1^0$ is Majorana spinor and so its early universe annihilation cross section $\sigma_{\tilde{\chi}_1^0\tilde{\chi}_1^0}$ is suppressed relative to sleptons ($\tilde{l}_R$):

$$\sigma_{\tilde{\chi}_1^0\tilde{\chi}_1^0} \simeq \frac{1}{10}\left(\sigma_{\tilde{\chi}_1^0\tilde{l}_R},\ \sigma_{\tilde{l}_R\tilde{l}_R}\right)$$

(2) Accidental near degeneracy between $\tilde{l}_R$ and $\tilde{\chi}_1^0$ in a small region of parameter space. Thus low $\tan\beta$:

$$m_{\tilde{e}_R}^2 = m_0^2 + \frac{6}{5}\frac{\alpha_G}{4\pi} f_1 m_{1/2}^2 - \sin^2\theta_W M_W^2 \cos 2\beta$$

$$f_1 = \frac{1}{\beta_1}\left[1 - \frac{1}{(1+\beta_1 t)^2}\right]$$

$$m_{\tilde{\chi}_1^0} \cong \frac{\alpha_1}{\alpha_G} m_{1/2}$$

or numerically:

$$m_{\tilde{e}_R}^2 \cong m_0^2 + \underline{0.15}\, m_{1/2}^2 + (40\ \mathrm{GeV})^2$$

$$m_{\tilde{\chi}_1^0}^2 \cong \underline{0.16}\, m_{1/2}^2$$

Thus by chosing m_0 one can make $m_{e_R} > m_{\tilde{\chi}_1^0}$ but nearly degenerate in a narrow "chimney" in $m_0 - m_{1/2}$ space

Fig. $m_0 - m_{1/2}$ allowed region for $A_0 = m_{1/2}$, $\mu < 0$ $\tan\beta = 3, 5, 10, 20$ [Ellis, Falk, Ganis, Olive].

$A = m_{1/2}\,;\ \mu < 0$

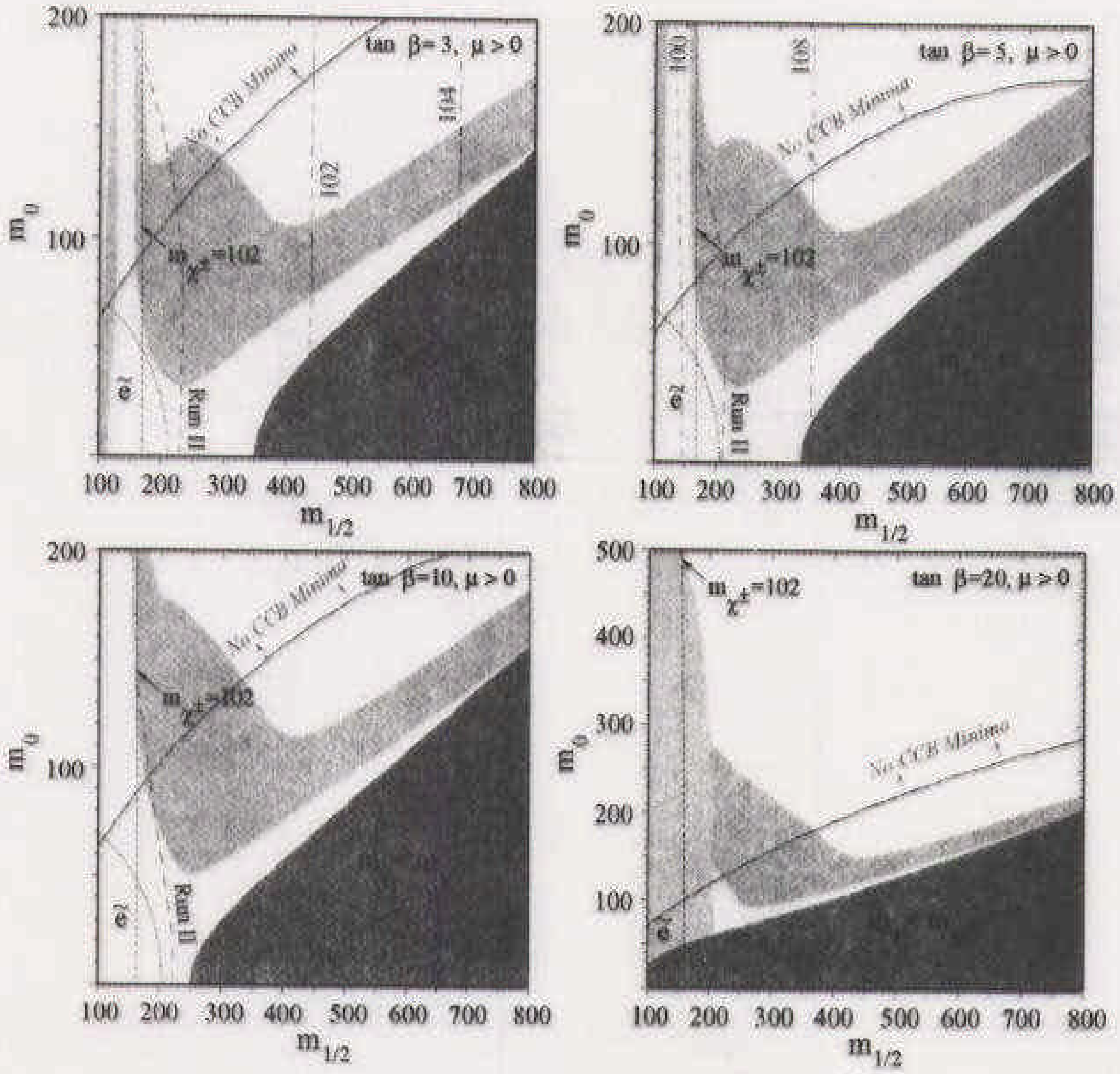


Figure 9: *The $m_{1/2}, m_0$ plane for $\mu > 0$, $A = -m_{1/2}$ and $\tan\beta =$ (a) 3, (b) 5, (c) 10 and (d) 20. The significances of the curves and shadings are the same as in Fig. 8. The light-shaded region in panel (d) is excluded by the $b \to s\gamma$ constraint. The long dashed curves in panels (a), (b) and (c) represent the anticipated limits from trilepton searches at Run II of the Tevatron [2].*

[Ellis, Falk, Ganis, Olive]

One sees that coannihilation begins at:

$m_{1/2} \gtrsim 400$ GeV ($m_{\tilde{\chi}_1^0} \simeq 160$ GeV)

The region of coannihilation is narrow, i.e.

$\Delta m_0 \simeq 25$ GeV

It is interesting to see what happens at high $\tan\beta$. We consider first: $\mu < 0$.

Fig. Allowed region in $m_0 - m_{1/2}$ plane for $\tan\beta = 40$, $\mu < 0$, $A_0 = m_{1/2}$, $2m_{1/2}$, $4m_{1/2}$ (bottom to top).

For large $\tan\beta$, the $\tilde{\tau}_1$ is lightest slepton and due to large L-R mixing is considerably lighter than other sleptons. One has

Only coannihilation region left and allowed region sensitive to A_0

Region to left of minimum $m_{1/2}$ excluded by $b \to s\gamma$ constraint

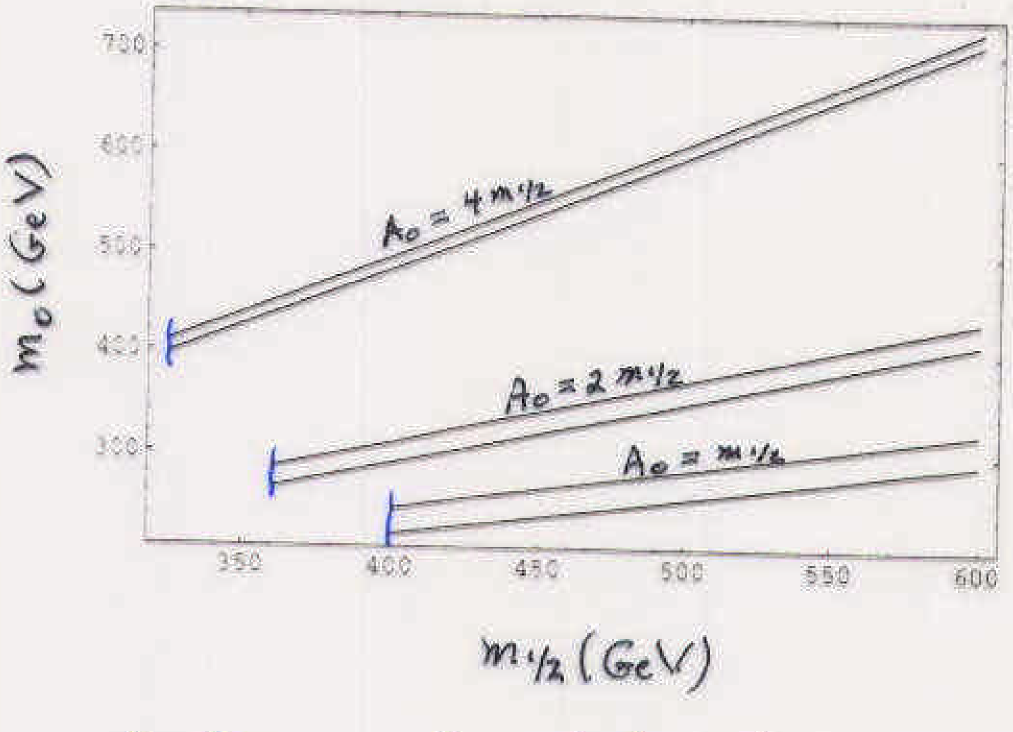
Minimum $m_{1/2}$ decreases with increasing A_0

Thickness of coannihilation chimney decreases with increasing A_0.

mSUGRA: $\tan\beta = 40$; $A_0 = m_{1/2}, 2m_{1/2}, 4m_{1/2}$

$m_0 - m_{1/2}$ allowed regions

$\mu < 0$



| : low $m_{1/2}$ bound due to $b \to s + \gamma$ constraint

The minimum $\sigma_{\tilde{\chi}_1^0-p}$ still arises from smallest allowed $\tan\beta$. However $\sigma_{\tilde{\chi}_1^0-p}$ decreases with increasing A_0 for large $\tan\beta$:

Fig. $\sigma_{\tilde{\chi}_1^0-p}$ as a function of $m_{1/2}$ for $A_0 = 4m_{1/2}$ (lower), $A_0 = 2m_{1/2}$ (upper), $\tan\beta = 40$, $\mu < 0$

and for large $m_{1/2}$, small and large $\tan\beta$ curves approach each other (in coannihilation region):

Fig. $\sigma_{\tilde{\chi}_1^0-p}$ as a function of $m_{1/2}$ for $A_0 = 4m_{1/2}$, $\tan\beta = 40$ (upper), $\tan\beta = 3$ (lower), $\mu < 0$.

Thus:

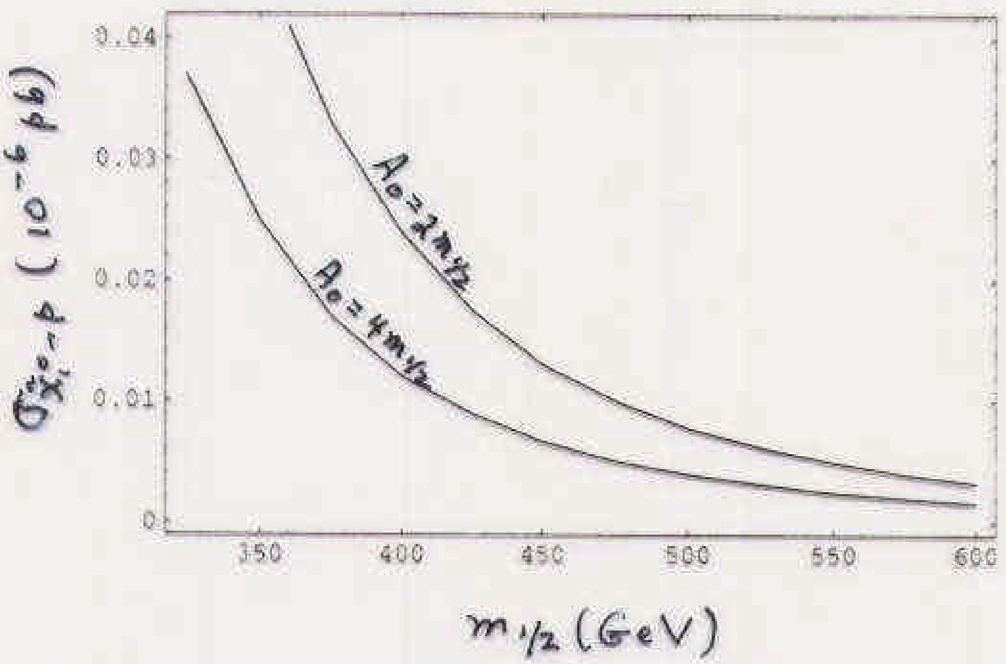
$$\sigma_{\tilde{\chi}_1^0-p} \gtrsim 1\times10^{-9}\,\text{pb} \;;\; m_{1/2} < 600 \text{ GeV}$$

$(m_{\tilde{\chi}_1^0} < 240 \text{ GeV})$

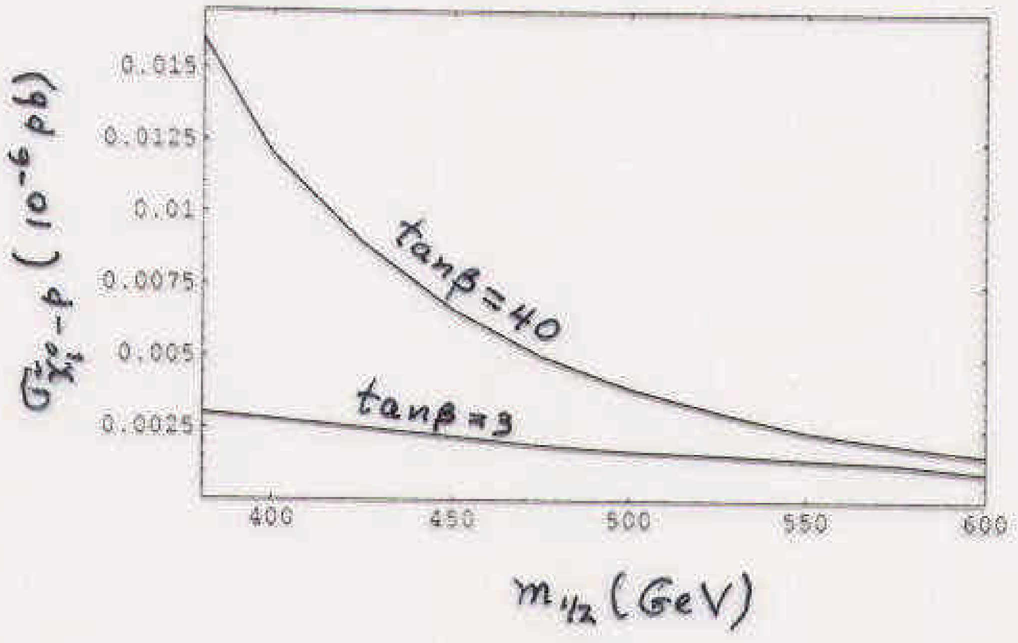
$\mu < 0$

and the region should be accessible to proposed detectors (e.g. GENIUS).

mSUGRA: $\tan\beta = 40$, $A_0 = 2m_{1/2}, 4m_{1/2}$
$\mu < 0$



mSUGRA: $A_0 = 4m_{1/2}$;
$\tan\beta = 40, 3$
$\mu < 0$



We consider next $\mu > 0$: As pointed out by Ellis, Ferstl and Olive, an "accidental" cancellation can occur in part of the parameter space in the coannihilation region which can greatly reduce $\sigma_{\tilde{\chi}^0_1-p}$. This can be seen in following figures:

Fig. $\sigma_{\tilde{\chi}^0_1-p}$ for $\tan\beta = 5, 10, 20$; $\mu > 0$, $m_{1/2} > 300$ GeV

One sees:

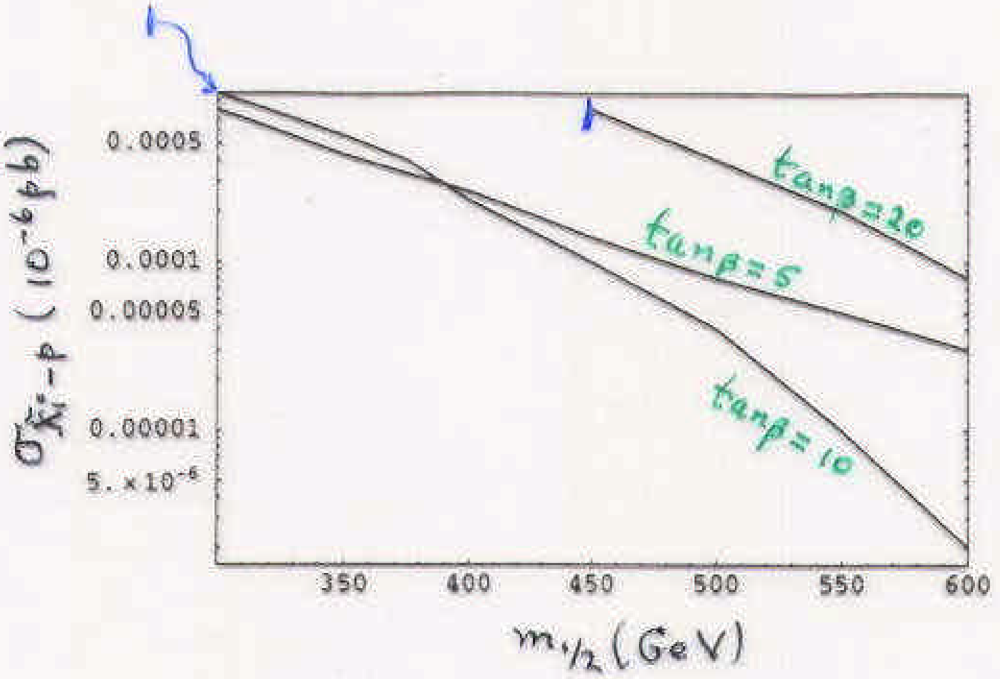
* $\sigma_{\tilde{\chi}^0_1-p} < 10^{-10}$ pb for $4 \lesssim \tan\beta < 20$; $\mu > 0$
$m_{1/2} \gtrsim 450$ GeV ($m_{\tilde{g}} > 1.1$ TeV)

* $(\sigma_{\tilde{\chi}^0_1-p})_{min} \simeq 1 \times 10^{-12}$ pb ; $\tan\beta \simeq 10$, $m_{1/2} \lesssim 600$ GeV
$\mu > 0$

In this region, proposed detectors would not be able to detect halo $\tilde{\chi}^0_1$ wimps. However (assuming mSUGRA is a valid theory), the absence of detection of wimps would imply that the squarks and gluino lie $\gtrsim 1$ TeV, which could be verified at the LHC.

$\sigma_{\tilde{\chi}_1^0 - p}$ for $\tan\beta = 5, 10, 20$; $\mu > 0$

$m_{1/2} > 300$ GeV



| = lower bound due to $b \to s + \gamma$ constraint

4. NONUNIVERSAL SUGRA MODELS

In most discussions of nonuniversal SUGRA models, universality of first two generations of squark/slepton masses at M_G is maintained (to suppress FCNC) allowing Higgs and third generation masses to become nonuniversal. One can parameterize this situation as follows:

$$m_{H_1}^2 = m_0^2(1+\delta_1)\,;\; m_{H_2}^2 = m_0^2(1+\delta_2)$$

$$m_{q_L}^2 = m_0^2(1+\delta_3)\,;\; m_{t_R}^2 = m_0^2(1+\delta_4)\,;\; m_{\tau_R}^2 = m_0^2(1+\delta_5)$$

$$m_{b_R}^2 = m_0^2(1+\delta_6)\,;\; m_{\ell_L}^2 = m_0^2(1+\delta_7)\quad;\; Q = M_G$$

[If one imposes $SU(5)$ or $SO(10)$ symmetry then $\delta_3 = \delta_4 = \delta_5$ and $\delta_6 = \delta_7$.]

In following we limit the δ_i:

$$-1 \le \delta_i \le +1$$

and maintain gauge and gaugino unification at M_G.

While there are a large number of new parameters, one can get an understanding of what effects they produce from the following:

The $\tilde{\chi}_1^0$ is a mixture of gaugino (mostly Bino) and higgsino parts:

$$\tilde{\chi}_1^0 = \alpha \tilde{W}_3 + \beta \tilde{B} + \gamma \tilde{H}_1 + \delta \tilde{H}_2$$

The dominant spin independent $\tilde{\chi}_1^0 - p$ cross section is proportional to The interference between the gaugino and higgino amplitudes and This interference is governed by μ^2:

As μ^2 decreases interference and hence $\sigma_{\tilde{\chi}_1^0 - p}$ increases

Now radiative breaking of $SU(2) \times U(1)$ determines μ^2 at the electroweak scale. For low $\tan\beta$ an analytic form exists for μ^2 (with similar structure holding at high $\tan\beta$):

$$\mu^2 = \frac{t^2}{t^2-1}\left[\left(\frac{1-3D_0}{2} - \frac{1}{t^2}\right) + \left(\frac{1-D_0}{2}(\delta_3+\delta_4) - \frac{1+D_0}{2}\delta_2 + \frac{\delta_1}{t^2}\right)\right] m_0^2$$

+ universal parts + loop corrections

where

$t \equiv \tan\beta$; $D_0 \cong 1 - (m_t/200\sin\beta)^2 \leq 0.2$

Hence

μ^2 is reduced, $\sigma_{\tilde{\chi}_1^0-p}$ is increased, for $\delta_3, \delta_4\ \delta_1 < 0$, $\delta_2 > 0$.

μ^2 is increased, $\sigma_{\tilde{\chi}_1^0-p}$ is reduced, for $\delta_3, \delta_4, \delta_1 > 0$, $\delta_2 < 0$.

The Higgs and squark nonuniversalities enter coherently, roughly in combination: $\delta_3+\delta_4-\delta_2$

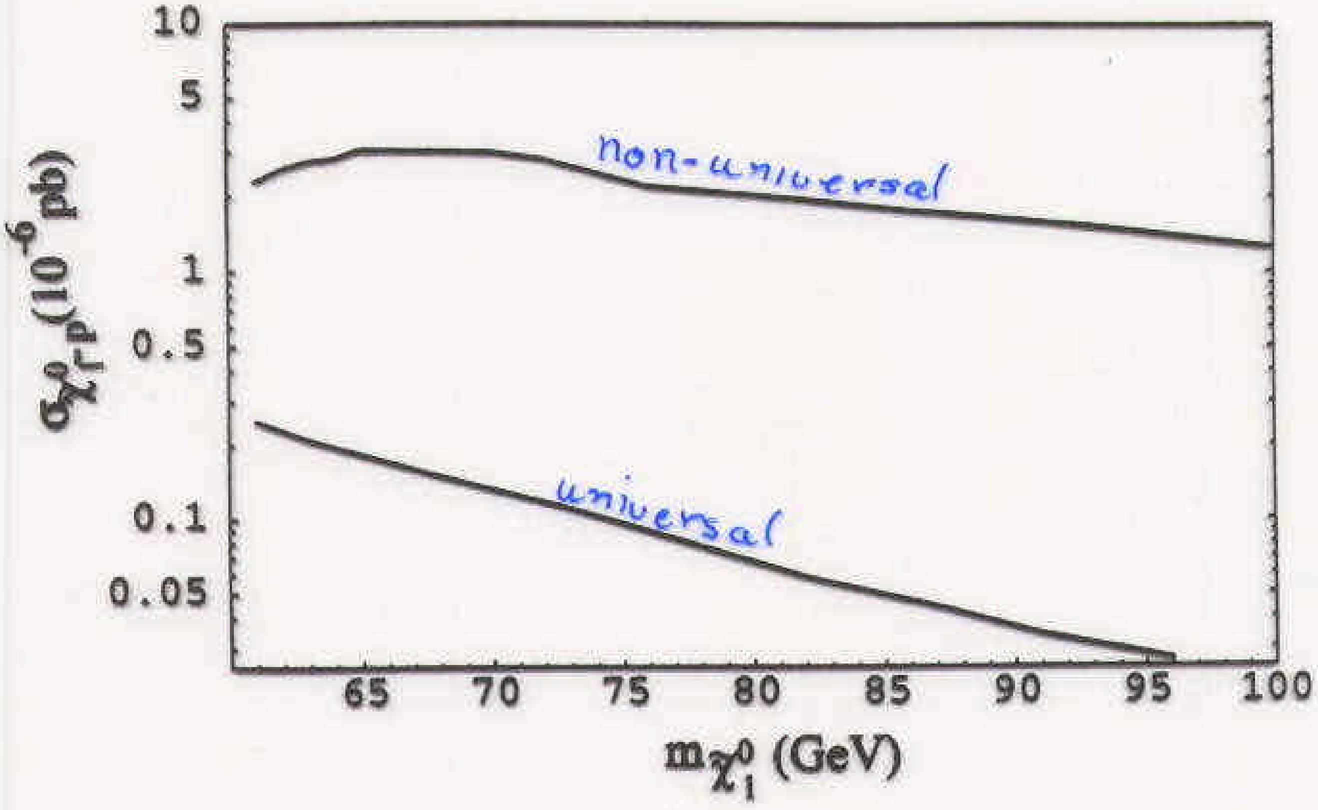
Thus one can get significantly larger cross sections in nonuniversal models:

Fig. Maximum $\sigma_{\tilde{\chi}_1^0-p}$ for $\tan\beta=7$, universal (lower) nonuniversal (upper) curve.

$\sigma_{\tilde{\chi}_1^0-p}$ can increase by factor of 10 - 100 due to nonuniversal soft breaking.

Maximum $\sigma_{\tilde{\chi}_1^0-p}$; $\tan\beta = 7$, $\mu < 0$

$\delta_3, \delta_4, \delta_1 < 0$; $\delta_2 > 0$



As a consequence, current detectors can probe nonuniversal models to lower $\tan\beta$:

Fig. Maximum $\sigma_{\tilde{\chi}_1^0 - p}$ as a function of $m_{\tilde{\chi}_1^0}$ for $\tan\beta = 7, 5$ for nonuniversal soft breaking

Thus current detectors can probe part of the parameter space for

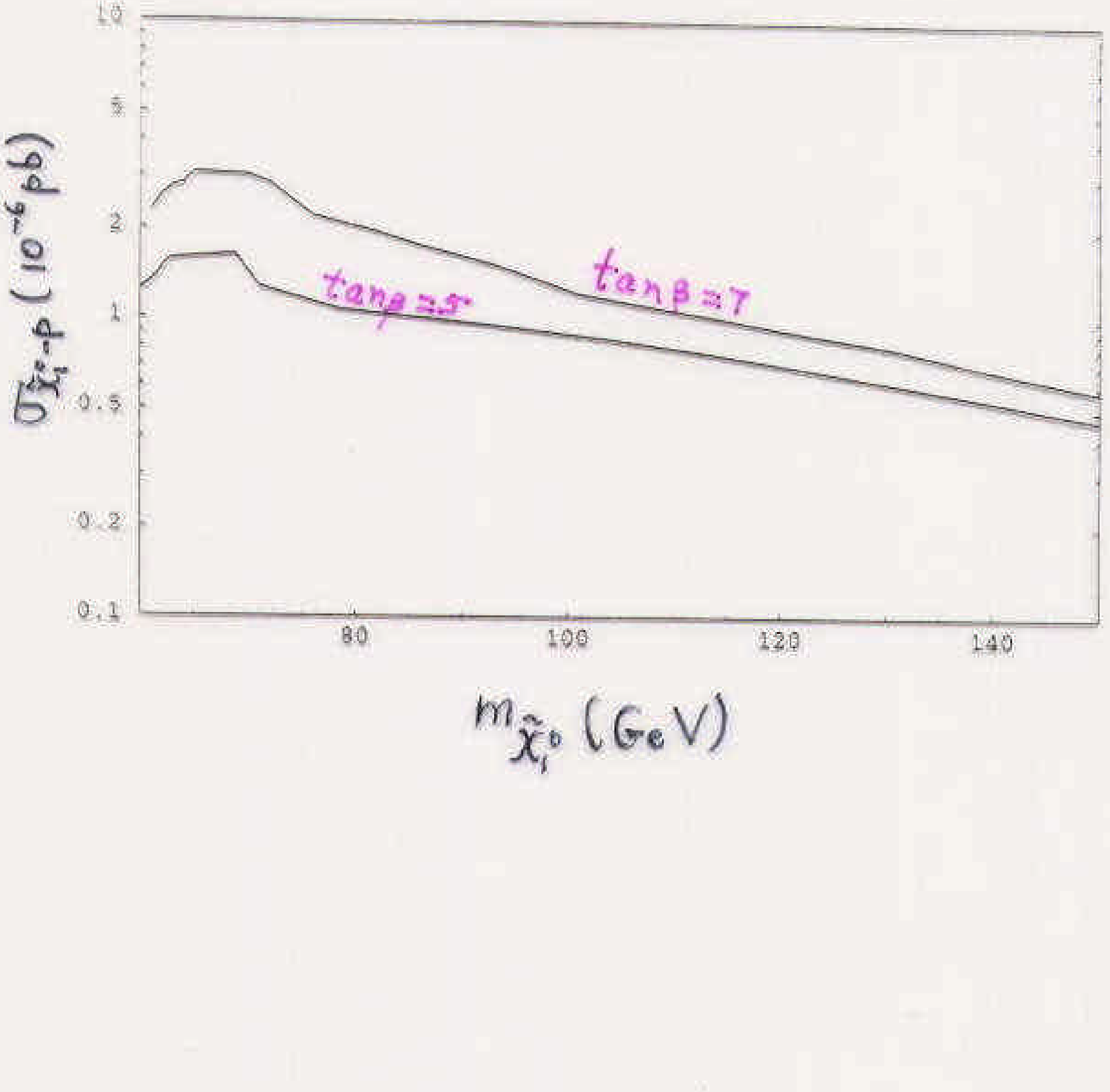
$\tan\beta \gtrsim 4$; nonuniversal models

The minimum $\sigma_{\tilde{\chi}_1^0 - p}$ occurs (as before) for lowest $\tan\beta$:

Fig. $(\sigma_{\tilde{\chi}_1^0 - p})_{min}$ as a function of $m_{\tilde{\chi}_1^0}$ for $\tan\beta = 3$ as other parameters are varied across parameter space in region below coannihilation.

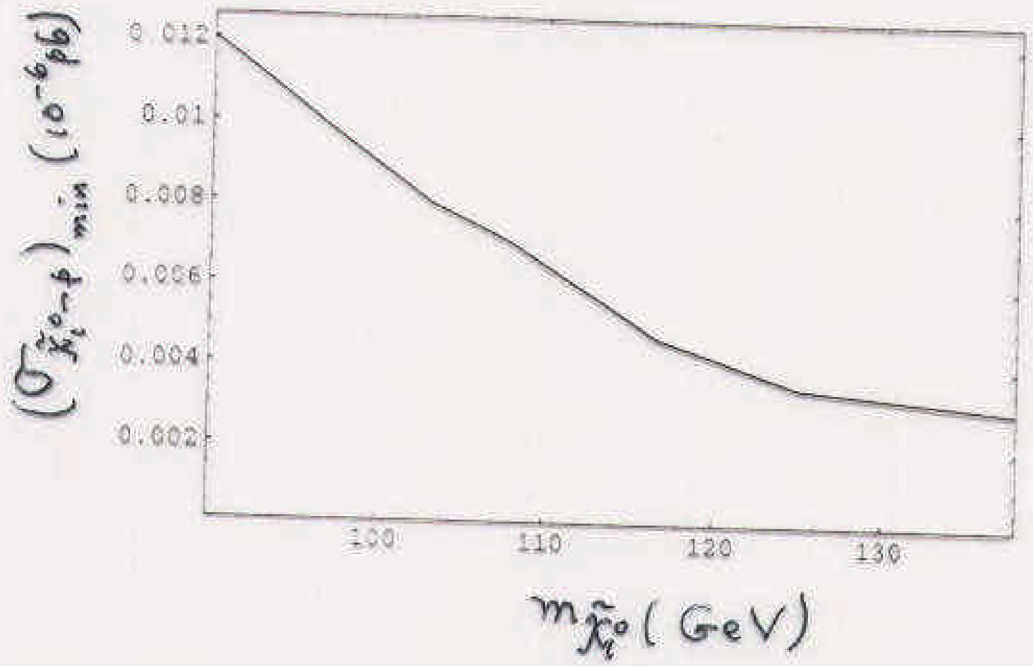
Nonuniversal soft breaking

$\left(\sigma_{\tilde{\chi}_1^0-p}\right)_{max}$ vs. $m_{\tilde{\chi}_1^0}$



Nonuniversal Soft Breaking

$(\sigma_{\tilde{\chi}_1^0-p})_{min}$; $\tan\beta=3$



The coannihilation region for the nonuniversal models has not been fully examined ($m_{\tilde{e}_R}$ can be made independently light) but over much of parameter space one finds results similar to mSUGRA i.e.

$$\sigma_{\tilde{\chi}_1^0 - p} \gtrsim 10^{-9}\ \mathrm{pb} \quad ; \quad m_{1/2} \leq 600\ \mathrm{GeV} ; \mu < 0$$

which again would be accessible to proposed detectors.

CONCLUSIONS

In all of the SUGRA-type models considered, there are regions of parameter space with $\tilde{\chi}^0_1 - p$ cross sections of size that could be observed with current detectors. Thus current detectors sample part of the parameter space of

$\tan\beta \gtrsim 25$; $m_{\tilde{\chi}^0_1} \lesssim 90$ GeV ; $\Omega_{\tilde{\chi}^0_1} h^2 \lesssim 0.1$; mSUGRA

$\tan\beta \gtrsim 4$; nonuniversal soft breaking

$\tan\beta \gtrsim 15$; D-brane models

nonuniversality allowing significantly larger cross sections than mSUGRA.

The experimental bounds on m_h (for low $\tan\beta$) and from $b \to s + \gamma$ (particularly for high $\tan\beta$) are playing an important role in eliminating parameter space, and coannihilation has extended the allowed parameter space to larger m_0, $m_{1/2}$.

For $\mu < 0$, $b \to s\gamma$ constraint is less powerful unless $\tan\beta$ is large. Then it leaves only the coannihilation bands (for $A > 0$) and these bands are sensitive to the value of A_0 and become increasingly narrow as A_0 increases. One finds generally

$$\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-9}\,pb\ ;\ m_{1/2} \le 600\,\mathrm{GeV}\ ;\ \mu < 0$$
$$(m_{\tilde{g}} \le 1.5\,\mathrm{GeV},\ m_{\tilde{\chi}_1^0} \le 240\,\mathrm{GeV})$$

This is three orders of magnitude below current detector sensitivity, but within the range planned in future detectors (such as GENIUS).

For $\mu > 0$, $b \to s\gamma$ constraint eliminates more of the parameter space, particularly at high $\tan\beta$. For mSUGRA, an accidental cancellation occurs which allows $\sigma_{\tilde{\chi}_1^0-p}$ to become quite small:

$$\sigma_{\tilde{\chi}_1^0-p} < 10^{-10}\,pb \ \text{for}\ 4 \lesssim \tan\beta \le 20;\ \mu > 0$$
$$m_{1/2} \gtrsim 450\,\mathrm{GeV}$$
$$(m_{\tilde{g}} \ge 1.1\,\mathrm{TeV})$$

and can get as small as

$$\sigma_{\tilde{\chi}_1^0-p} \cong 1\times10^{-12}\,pb\ ;\ \tan\beta \simeq 10,\ m_{1/2} = 600\,\mathrm{GeV}$$
$$\mu > 0$$