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DARK MATTER AND CONSEQUENCES OF SUSY

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1. INTRODUCTION

Supersymmetry is a natural solution to the gauge hierarchy problem that sets in for the Standard Model at the TeV scale. Thus if one supersymmeterizes the SM model particle spectra, one can build a model going past the TeV scale yet consistent with all the successes of the Standard Model below a TeV. If one assumes supersymmetry sets in at $\approx$ TeV and continues such models to higher energies one finds remarkably the grand unification of the coupling constants at the GUT scale $M_G \cong 2\times10^{16}$ GeV a result consistent with LEP data at the 1% scale. Models which yields this unification arise naturally in supergravity (SUGRA) grand unification and such models with R-parity invariance predict the existence of cold dark matter, the lightest neutralino $\tilde{\chi}_1^0$, of the right amount.

We discuss here some of the other consequences that might be expected of such SUGRA models. Already, existing experiments have begun to restrict the SUSY parameter space significantly: the amount of CDM, the Higgs mass bound ($m_h \geq 114.1$ GeV), the $b \to s + \gamma$ limits and (possibly) the $g_\mu - 2$ anomaly.

We start with the simplest model, mSUGRA, with universal soft breaking parameters and discuss what additional signatures of SUSY might be seen at

Tevatron : $B_s \to \mu^+ + \mu^-$

LC : $e^+ e^- \to \tilde{\tau}^+ + \tilde{\tau}^-$

$\to \tilde{\chi}^0_1 + \tilde{\chi}^0_2$

We then consider non-universal models [with non-universal gaugino masses and non-universal Higgs and 3rd generation masses at M_G to see how robust the mSUGRA predictions are and where non-universal soft breaking signatures may reside.

2. mSUGRA MODEL

mSUGRA model depends on 4 additional parameters and 1 sign (and as such it is the most predictive model):

m_0: scalar soft breaking mass at M_G

$m_{1/2}$: gaugino mass at M_G ($m_{\tilde{\chi}_1^0} \cong 0.4\, m_{1/2}$, $m_{\tilde{\chi}_1^\pm} \cong 0.8\, m_{1/2}$)

A_0: cubic soft breaking mass at M_G

$\tan\beta$: $\langle H_2 \rangle / \langle H_1 \rangle$ at electroweak scale

$\frac{\mu}{|\mu|}$: sign of Higgs mixing parameter in superpotential ($W^{(2)} = \mu H_1 H_2$)

We examine parameter range

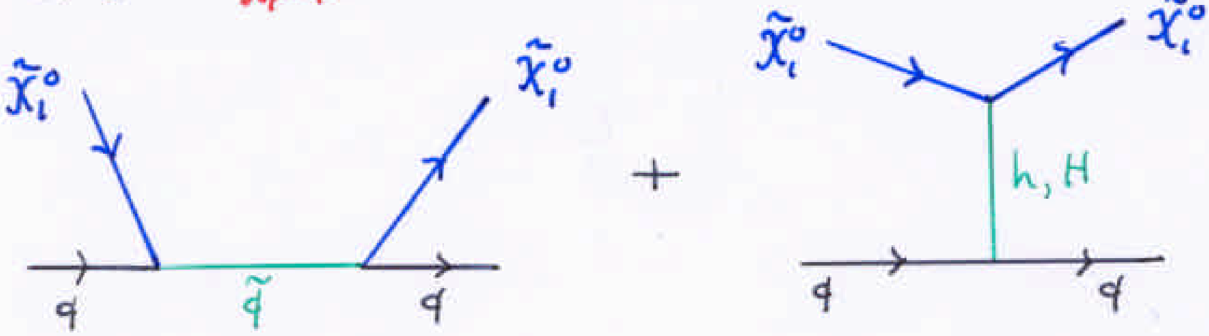
$$m_0 \lesssim 1\ \mathrm{TeV}$$

$$m_{1/2} \lesssim 1\ \mathrm{TeV}\ (m_{\tilde{g}} < 2.5\ \mathrm{GeV})$$

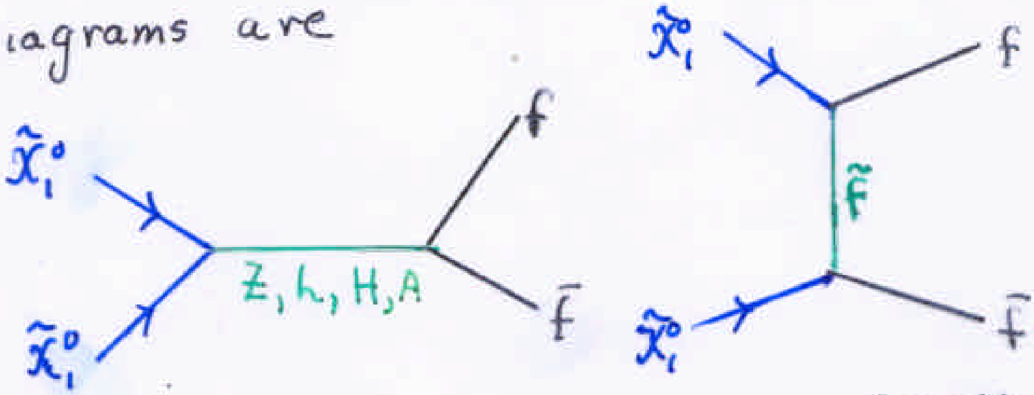
$$2 \leq \tan\beta \leq 55$$

$$|A_0| \leq 4\, m_{1/2}$$

For heavy nuclei, the spin-independent neutralino-nucleus cross section dominates, which allows one to extract the $\tilde{\chi}_1^0$-proton cross section $\sigma_{\tilde{\chi}_1^0-p}$. The basic quark diagrams are



In the early universe the $\tilde{\chi}_1^0$ annihilation diagrams are



f = SM fermion

However, if a second particle becomes nearly degenerate with the $\tilde{\chi}_1^0$ one must include it in the early universe annihilation processes, which leads to co-annihilation phenomena.

In SUGRA models, this accidental near degeneracy occurs naturally for the light stau $\tilde{\tau}_1$: For low and intermediate $\tan\beta$, the RGE give

$$m_{\tilde{e}_R}^2 = m_0^2 + 0.15\, m_{1/2}^2 \underbrace{- \sin^2\theta_W\, M_W^2 \cos 2\beta}_{\simeq (37\,\mathrm{GeV})^2}$$

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

Thus for $m_0 = 0$, the $\tilde{e}_R$ becomes degenerate with the $\tilde{\chi}_1^0$ at $m_{1/2} \simeq 370$ GeV, co-annihilation thus begins at $m_{1/2} \simeq (350\text{-}400)$ GeV. As $m_{1/2}$ increases, m_0 must be raised in lock step (to keep $m_{\tilde{e}_R} > m_{\tilde{\chi}_1^0}$. More precisely, it is the light stau, $\tilde{\tau}_1$, which is the lightest slepton and dominates the co-annihilation phenomena. However, one ends up with corridors in $m_0 - m_{1/2}$ plane with allowed relic density with m_0 closely correlated with $m_{1/2}$, m_0 increasing as $m_{1/2}$ increases, as seen above.

In order to carry out these calculations it is necessary to include a number of corrections and we list some of them here:

* Two loop gauge and one loop Yukawa RGE are used from M_G to M_{EW} and QCD RGE below for light quark contributions.
* Two loop and pole mass corrections included in calculation of m_h.
* One loop corrections to m_b and m_τ included. [Ratazzi, Sarid; Carena, Wagner, Pokorski] which are important at large $\tan\beta$.
* Large $\tan\beta$ NLO SUSY corrections to $b \to s\gamma$ [Degrassi et al.; Ciuchini et al.] included.
* All stau-neutralino co-annihilation channels included in relic density calculation including large $\tan\beta$ regime [Arnowitt, Dutta, Santoso; Ellis, Falk, Olive, Srednicki; Gomez, Vergados].

We do not include Yukawa unification or proton decay constraints as these depend sensitively on post-GUT physics, about which little is known.

The current experiments that most strongly restrict The SUSY parameter space are the following:

* Amount of cold dark matter (CDM)

Global fit to CMB and other data yields $\Omega_{CDM} h^2 = 0.139 \pm 0.026$ [Turner] and we take a 2.5σ range around the central value

$$0.07 \le \Omega_{CDM} h^2 \lesssim 0.21$$

The MAP data, due out in the near future will be able to significantly narrow this range.

* Higgs mass

The LEP lower bound

$$m_h > 114.1 \text{ GeV} \qquad \text{[LEP]}$$

is significant for lower $\tan\beta$ ($\tan\beta \lesssim 30$) but will generally become very significant if This bound were to rise just a few GeV. Unfortunately, theoretical calculations still have an error of $\simeq (2-3)$ GeV and we interpret (conservatively) the above to mean $(m_h)_{theory} > 111$ GeV. mSUGRA predicts $m_h \lesssim 130$ GeV which would make the light Higgs within the reach of the Tevatron Run IIB.

* $b \to s + \gamma$ decay

The CLEO data has statistical, systematic and theoretical error and so we take a relatively broad range around the CLEO central value:

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

It is possible that the B-factories (Belle, BABAR) will be able to narrow this range. The $b \to s + \gamma$ rate is significant for large $\tan\beta$ ($\tan\beta \gtrsim 30$) and if the lower bound is raised, the lower bound on $m_{1/2}$ will be raised.

* Muon $g_\mu - 2$

The current estimated deviation from the Standard Model is a 1.6σ effect in $a_\mu = \frac{1}{2}(g_\mu - 2)$

$$\Delta a_\mu = (27 \pm 16) \times 10^{-10} \qquad \text{[Brookhaven E821]}$$

New data, currently being analyzed, should reduce the statistical error by a factor of 2-3, and new data from Novosibirsk and Beijing should reduce the theoretical error in $a_\mu^{had}(SM)$ by a similar factor. Thus if the central value were to stay the same, this could become a $\gtrsim 4\sigma$ effect. However, new doubts have been raised concerning the size of the error in the theoretical calculation of $a_\mu^{\ell\ell}$ part mudying the waters

The three experimental constraints on m_h, $b \to s+\gamma$, $\Omega_{\tilde{\chi}_1^0} h^2$ now combine to greatly restrict the mSUGRA parameter space:

- m_h bound (for low $\tan\beta$) and $b \to s+\gamma$ constraint (for higher $\tan\beta$) produce a lower bound on $m_{1/2}$ over the entire parameter space:

$$m_{1/2} \gtrsim (300-400)\,\mathrm{GeV}$$

and consequently

$$m_{\tilde{\chi}_1^0} \gtrsim (120-160)\,\mathrm{GeV} \quad [m_{\tilde{\chi}_1^0} \cong 0.4\, m_{1/2}]$$
$$[m_{\tilde{\chi}_1^\pm} \cong 0.8\, m_{1/2}]$$

- This means that most of the parameter space is in the $\tilde{\tau}_1 - \tilde{\chi}_1^0$ co-annihilation domain in the relic density calculation i.e. in order to satisfy the relic density bound m_0 is approximately determined by $m_{1/2}$ (for fixed $\tan\beta$, A_0).

- Hence as $m_{1/2}$ increases so does m_0 and hence $\sigma_{\tilde{\chi}_1^0 - p}$ decreases.

Consider:

(1) $\mu > 0$

Figs. $m_0 - m_{1/2}$ allowed regions showing $\sigma_{\tilde{\chi}_1^0 - p}$; $A_0 = 0, \mu > 0$
$\tan\beta = 10, 50$

Note that the "dark matter allowed" band is close
the allowed parameter region independent of
ones prejudice that $\tilde{\chi}_1^0$ is the cold dark matter (C
Thus below the band the $\tilde{\tau}_1$ is the DM (i.e. the LSP
and thus be charged DM while above the band
not enough $\tilde{\chi}_1^0$ annihilate in the early
universe over closing the universe.

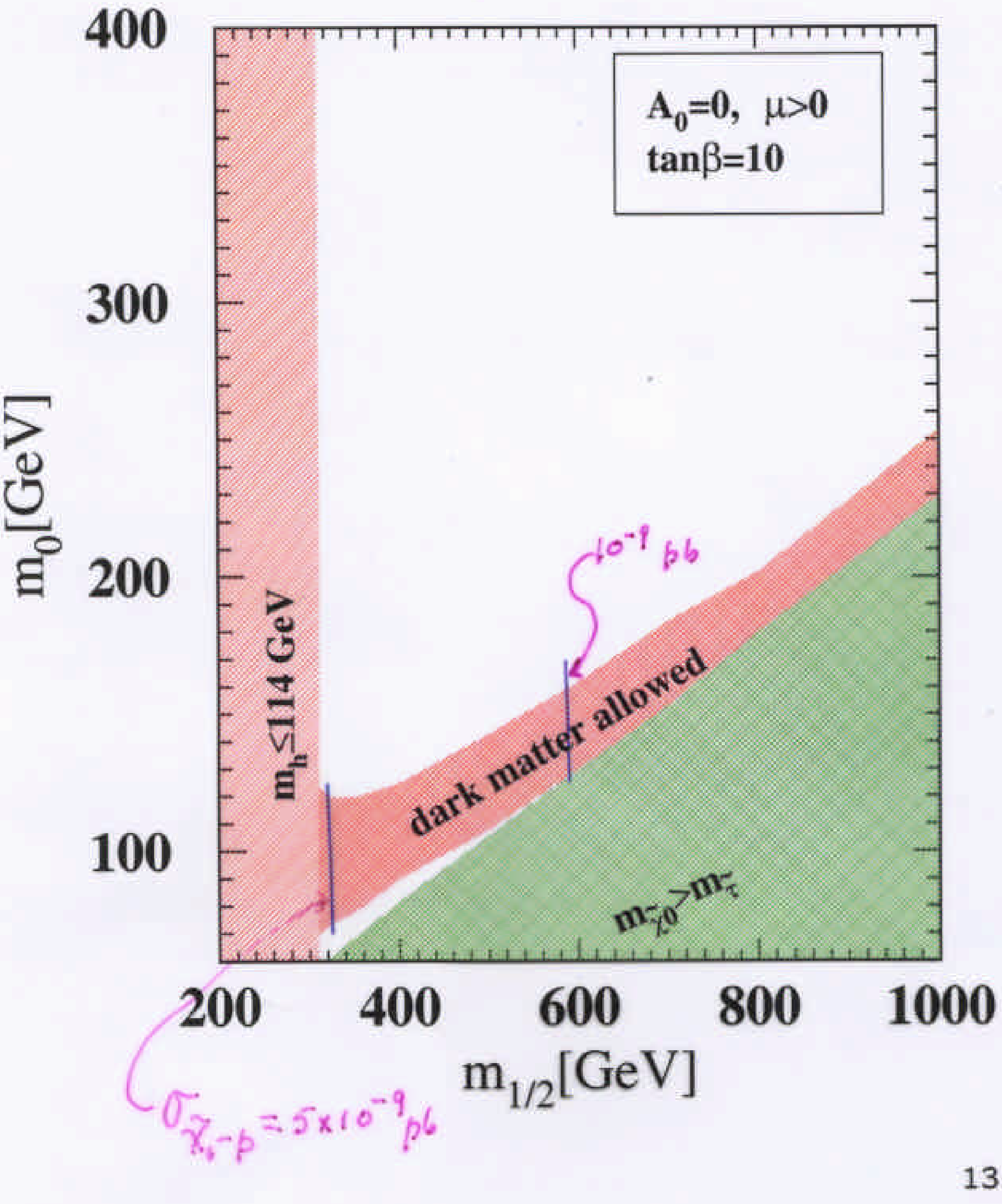
(2) $\mu < 0$

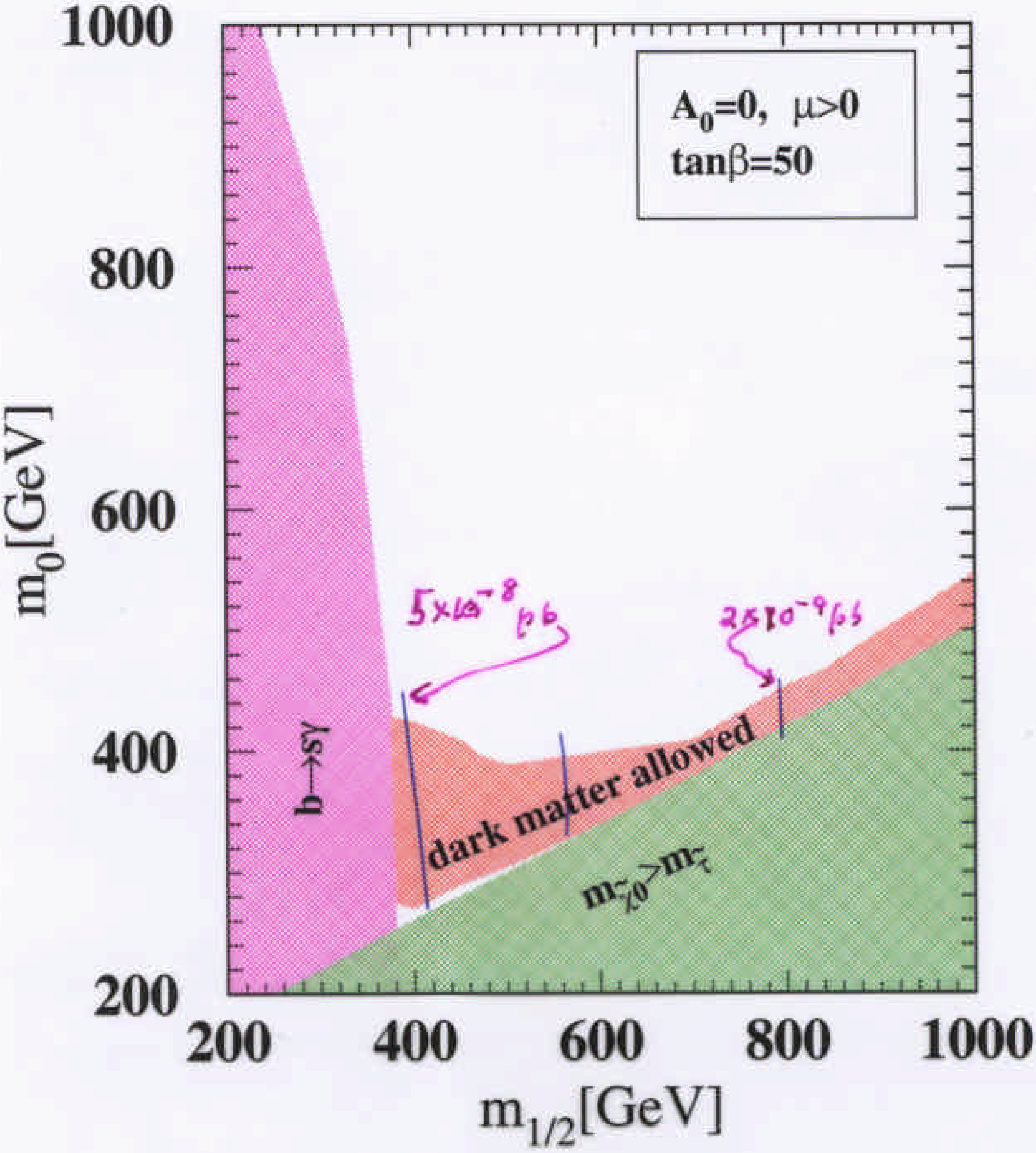
Here an accidental cancelation in $\sigma_{\tilde{\chi}_1^0 - p}$
occurs over a wide range of $\tan\beta$ [Ellis, Ferst
Olive; Arnowitt, Dutta, Santoso] giving large regions
where

$$\sigma_{\tilde{\chi}_1^0 - p} < 10^{-10}\ pb$$

an hence experimentally unacessible

Fig. $\sigma_{\tilde{\chi}_1^0 - p}$ vs. $m_{1/2}$, $\mu < 0$, $A_0 = 0$, $5 \lesssim \tan\beta \lesssim 30$

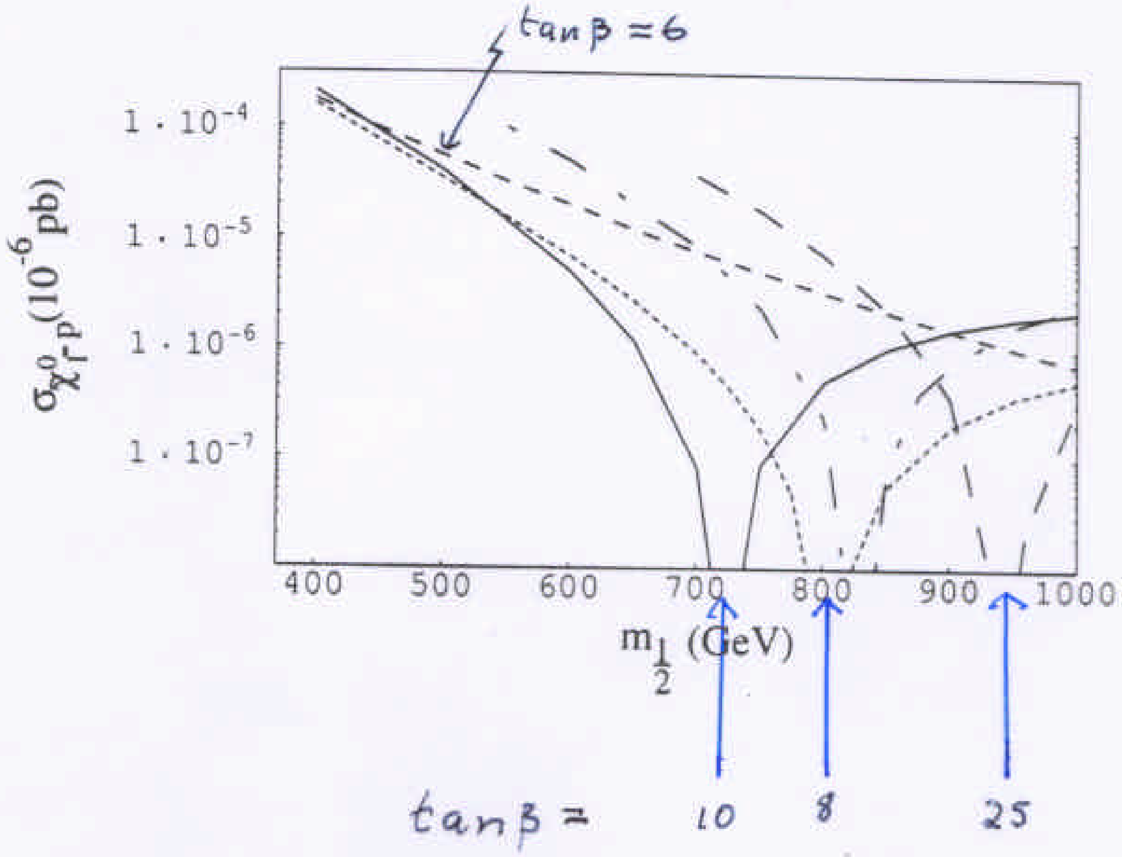

400
300
200
100
200
400
600
800
1000
m_0[GeV]
$m_{1/2}$[GeV]
A_0=0, μ>0
tanβ=10
$m_h \leq 114$ GeV
dark matter allowed
$m_{\tilde{\chi}^0} > m_{\tilde{\tau}}$
10^{-9} pb
$\sigma_{\tilde{\chi}_1-p} = 5\times10^{-9}$ pb



1000
800
600
400
200
200
400
600
800
1000
m_0[GeV]
$m_{1/2}$[GeV]
A_0=0, μ>0
tanβ=50
b→sγ
dark matter allowed
$m_{\tilde{\chi}^0} > m_{\tilde{\tau}}$
5×10⁻⁸ pb
2×10⁻⁹ pb

mSUGRA, $\mu < 0$

$\sigma_{\tilde{\chi}_1^0 - p} < 1 \times 10^{-10}$ pb for $450\,\mathrm{GeV} < m_{1/2} < 1\,\mathrm{TeV};\ 5 \lesssim \tan\beta \lesssim$



3. Muon Magnetic Moment Anomaly

Initially, with a deviation from the SM for a_μ of 2.6σ, it appeared That there was possible evidence for a breakdown of The SM in The electroweak sector. However, the discovery of a sign error in the calculation of The hadronic part of The scattering of light by light, $a_\mu^{\ell\ell}$, reduced This to a 1.6σ effect:

$$\Delta a_\mu = 27(16) \times 10^{-10}$$

corresponding to a value for $a_\mu^{\ell\ell}$ of

$$a_\mu^{\ell\ell} = (8.6 \pm 1.5) \times 10^{-10}$$ [Knecht, Nyffeler; Hayakawa, Kinoshita]

With future errors being reduced by a factor of ≈ 2-3, one might expect that an effect would still survive if the central value remained unchanged.

However, an alternate calculation of $a_\mu^{\ell\ell}$ gave

$$a_\mu^{\ell\ell} = \left[5.5^{+5.0}_{-6.0} + 3.1\,\tilde{C}\right] \times 10^{-10}$$ [Ramsey-Musolf, Wise]

where $\tilde{C} \approx \mathcal{O}(1)$ are non-leading terms. Thus, e.g if $\tilde{C} \cong 5$ the effect would be wiped out.

Leaving aside the theoretical uncertainties in the SM contribution to a_μ, the SUSY contribution in mSUGRA will generally be large [Yuan, Arnowitt, Chamseddine, Nath; Kosower, Krauss, Sakai]:

$\underline{a_\mu^{SUSY}}$

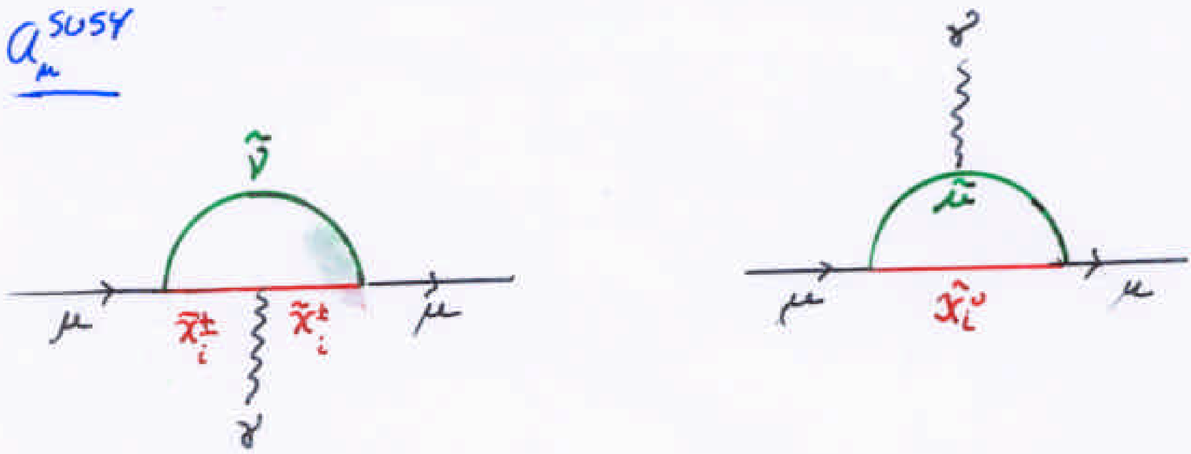
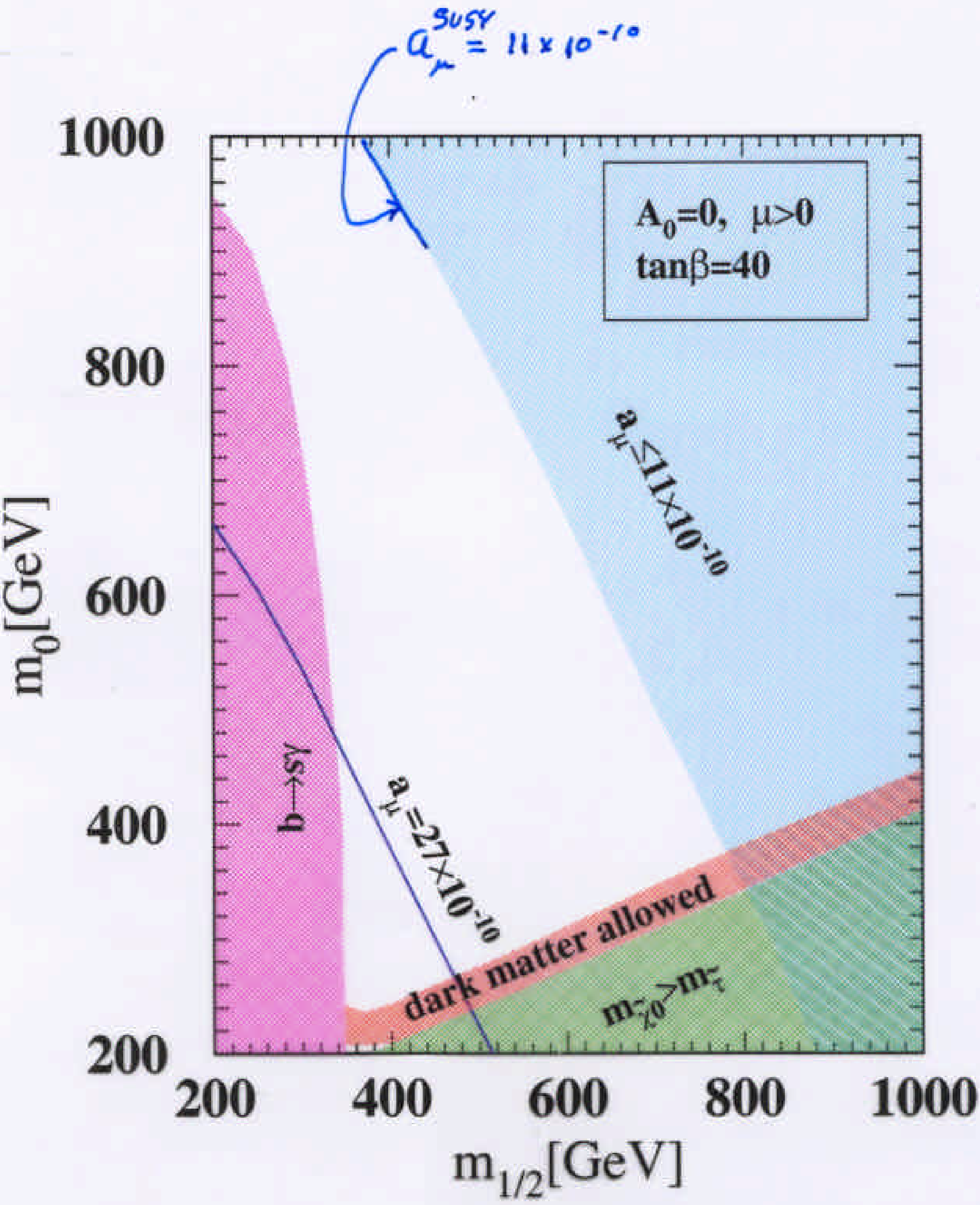


Fig. $m_0 - m_{1/2}$ plane, $A_0 = 0$, $\tan\beta = 40$, $\mu > 0$

Thus if the final numbers require a_μ^{SUSY} to be small, e.g. $a_\mu^{SUSY} \lesssim 10 \times 10^{-10}$, the SUSY squark/gluinos are in the TeV domain, while if $a_\mu^{SUSY} \gtrsim 40 \times 10^{-10}$ it would exclude mSUGRA.

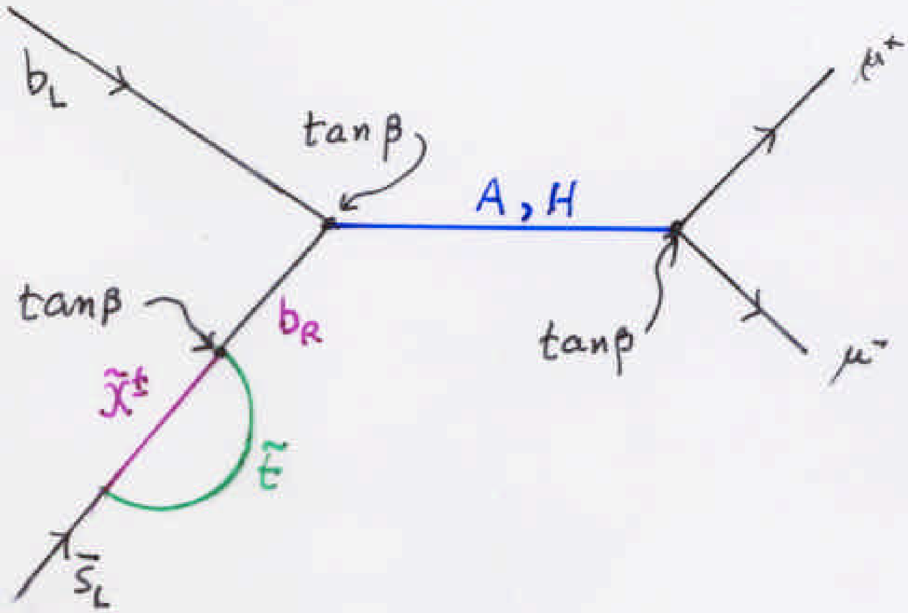

$a_\mu^{SUSY} = 11 \times 10^{-10}$
$A_0=0, \mu>0$
$\tan\beta=40$
$a_\mu \leq 11\times10^{-10}$
$b\rightarrow s\gamma$
$a_\mu=27\times10^{-10}$
dark matter allowed
$m_{\tilde{\chi}^0} > m_{\tilde{\tau}}$
m_0[GeV]
$m_{1/2}$[GeV]
200
400
600
800
1000

4. $B_s \to \mu^+ + \mu^-$ at the Tevatron

The $B_s \to \mu^+ + \mu^-$ offers an additional window for investigating the mSUGRA parameter space. [Bobeth et al.; Dedes et al.] The SM prediction for the branching ratio is quite small

$$B[B_s \to \mu^+\mu^-] = (3.1 \pm 1.4) \times 10^{-9} \text{ ; Standard Model}$$

However, the SUSY contribution can become quite large for large $\tan\beta$. An example of one of the important SUSY graphs is:



Thus in SUSY

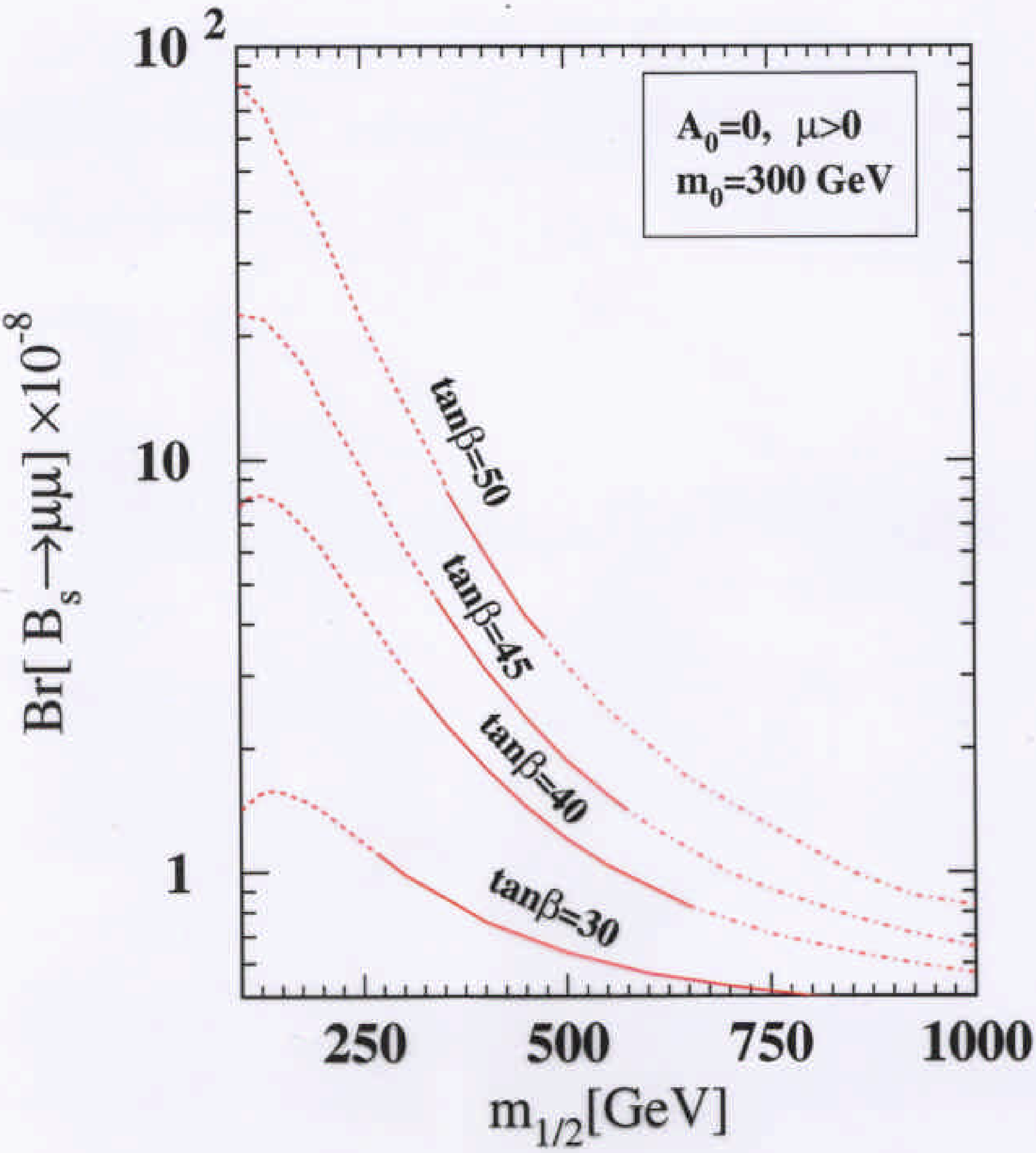
$$B[B_s \to \mu^+\mu^-] \sim (\tan\beta)^6 \quad (!)$$

This process has become interesting because it appears possible to observe it at the Tevatron Run II B [Arnowitt, Dutta, Kamon, Tanaka]. A set of cuts eliminating background (gluon splitting $g \to b\bar{b}$; fakes) leads to a sensitivity of

$$B[B_s \to \mu\mu] \gtrsim 6\times10^{-9} \quad \text{for } 15\,fb^{-1}/\text{detector}$$

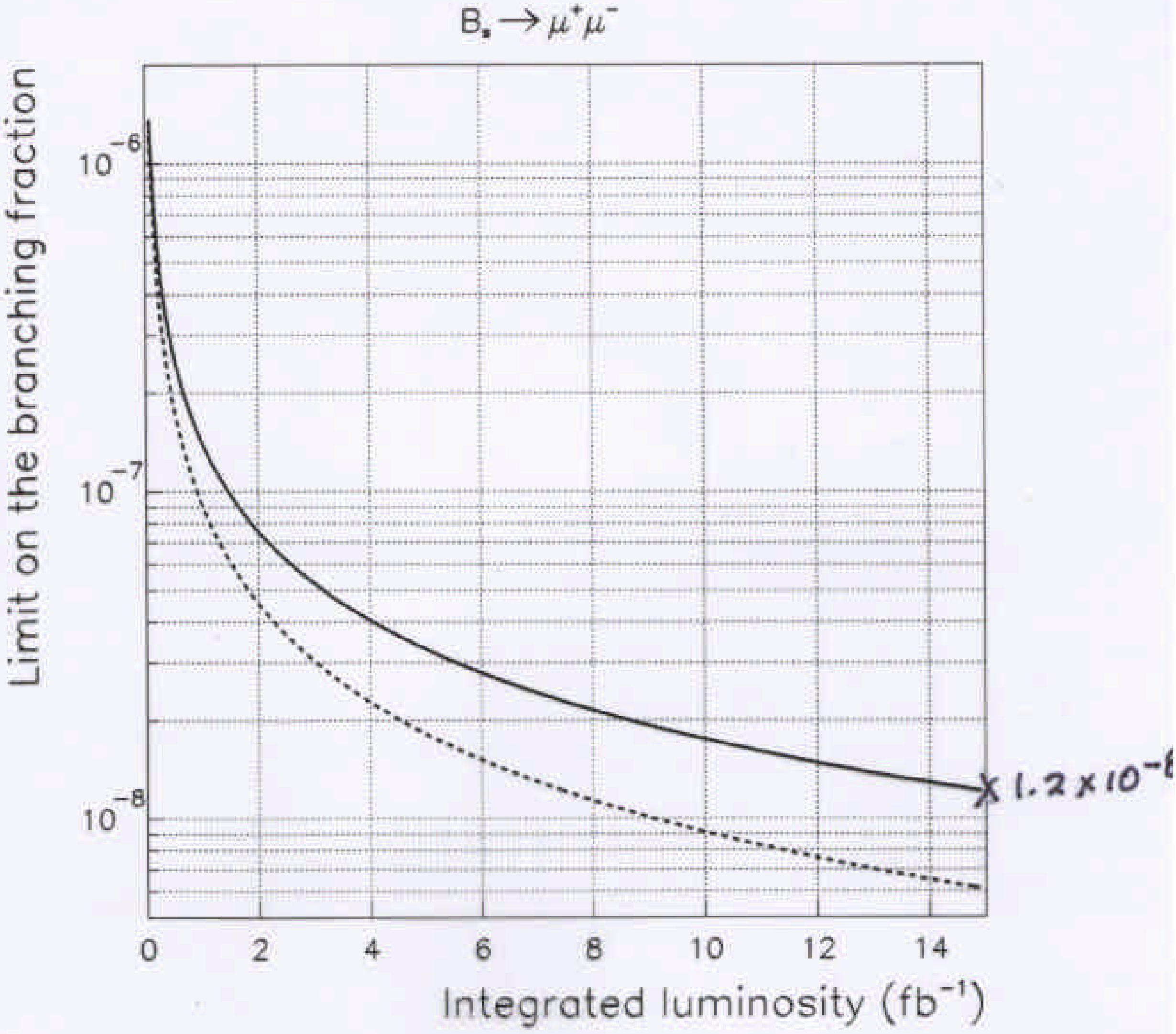
making the Tevatron sensitive to this decay for

$$\tan\beta \gtrsim 30$$



[Arnowitt, Dutta]

CDF RUN II: $B_s \to \mu^+\mu^-$



[Arnowitt, Dutta, Kamon, Tanaka]

5. LC Reach

We consider two possible linear colliders of

$$\sqrt{s} = 500 \text{ GeV} \; ; \quad \sqrt{s} = 800 \text{ GeV}$$

We've seen that the m_h and $b \to s + \gamma$ bounds already means that $m_{1/2} \gtrsim 350$-400 GeV and so for mSUGRA gluinos and squark would generally be beyond the reach of such machines. The most favorable SUSY signals are then

$$e^+ + e^- \to \tilde{\chi}^0_2 + \tilde{\chi}^0_1 \to (\ell^+ + \ell^- + \tilde{\chi}^0_1) + \tilde{\chi}^0_1$$

$$\ell = \tau, \mu, e$$

and

$$e^+ + e^- \to \tilde{\tau}_1^+ + \tilde{\tau}_1^- \to (\tau^+ + \tilde{\chi}^0_1) + (\tilde{\tau}^- + \tilde{\chi}^0_1)$$

Since in mSUGRA, $m_{\tilde{\chi}^0_2} \cong 2 m_{\tilde{\chi}^0_1}$ one has for the mass reach

$$\tfrac{1}{2} m_{\tilde{\chi}^0_2} \doteq m_{\tilde{\chi}^0_1} \lesssim \begin{cases} 165 \text{ GeV}, & \sqrt{s} = 500 \text{ GeV} \\ 265 \text{ GeV}, & \sqrt{s} = 800 \text{ GeV} \end{cases}$$

and

$$m_{\tilde{\tau}_1} \lesssim \begin{cases} 250 \text{ GeV}, & \sqrt{s} = 500 \text{ GeV} \\ 400 \text{ GeV}, & \sqrt{s} = 800 \text{ GeV} \end{cases}$$

In general $m_{\tilde{e}}, m_{\tilde{\mu}} > m_{\tilde{\tau}}$ and so $\tilde{\tau}$ will be the major signal, as $m_{\tilde{e}}, m_{\tilde{\mu}}$ not accessible for most of parameter space.

Possible backgrounds are for $\tilde{\tau}^+\tilde{\tau}^-$ production:

$$e^+ + e^- \to W^+ + W^- \to \tau^+ + \tau^- + \nu_\tau + \bar{\nu}_\tau$$
$$\to Z + Z \to (\nu + \bar{\nu}) + (\tau^+ + \tau^-)$$
$$\to \nu + \bar{\nu} + \tau^+ + \tau^- \text{ (non-resonant)}$$

Of these only the first is large, and one can essentially eliminate it by using a R 90% polarized beam. So a clean signal should be available if the $\tilde{\tau}^\pm$ are kinematically accessible. [Arnowitt, Dutta, Kamon]

6. mSUGRA PARAMETER SPACE

We now summarize the effects of all the constraints from m_h, $b \to s\gamma$, dark matter, a_μ and what might be expected from $B_s \to \mu^+\mu^-$ and the NLC. We will assume here that

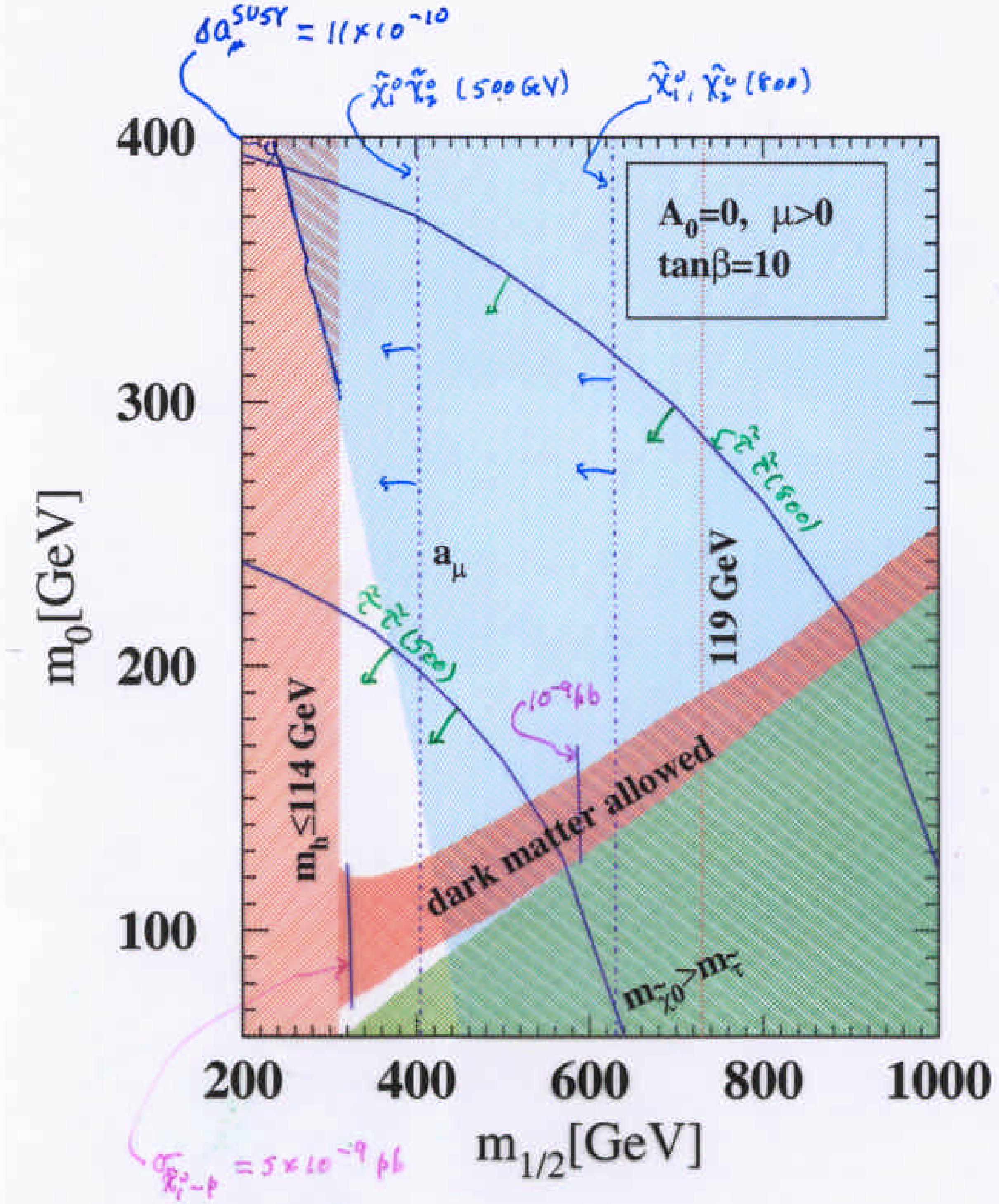
$$\Delta a_\mu = a_\mu^{SUGRA} > 11 \times 10^{-10}$$

though one may wish to relax this later.

Fig m_0-$m_{1/2}$ plane, $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$

We see for low $\tan\beta$ there is not much parameter space and even an NLC of $\sqrt{s} = 500$ GeV can cover it (though $\sqrt{s} = 800$ GeV does much better). The $\sigma_{\tilde{\chi}^0_1 - p}$ dark matter cross sections are small but of size that future experiments hope to achieve (GENIUS, Cryoarray, ZEPLIN IV, (WORE).

Of the two NLC signals the $\tilde{\chi}^0_2 - \tilde{\chi}^0_1$ is sensitive to large m_0 while the $\tilde{\tau}_1 - \tilde{\tau}_1$ signal is sensitive to relatively large $m_{1/2}$. Due to the dark matter channel constraint, the latter appears to be the more important signal.



[Arnowitt, Dutta, Kamon, Tanaka[1]]

Figs. $m_0 - m_{1/2}$ plane, $\tan\beta = 40$; $\mu > 0$; $A_0 = 0, -2m_{1/2}, +2m_{1/2}$

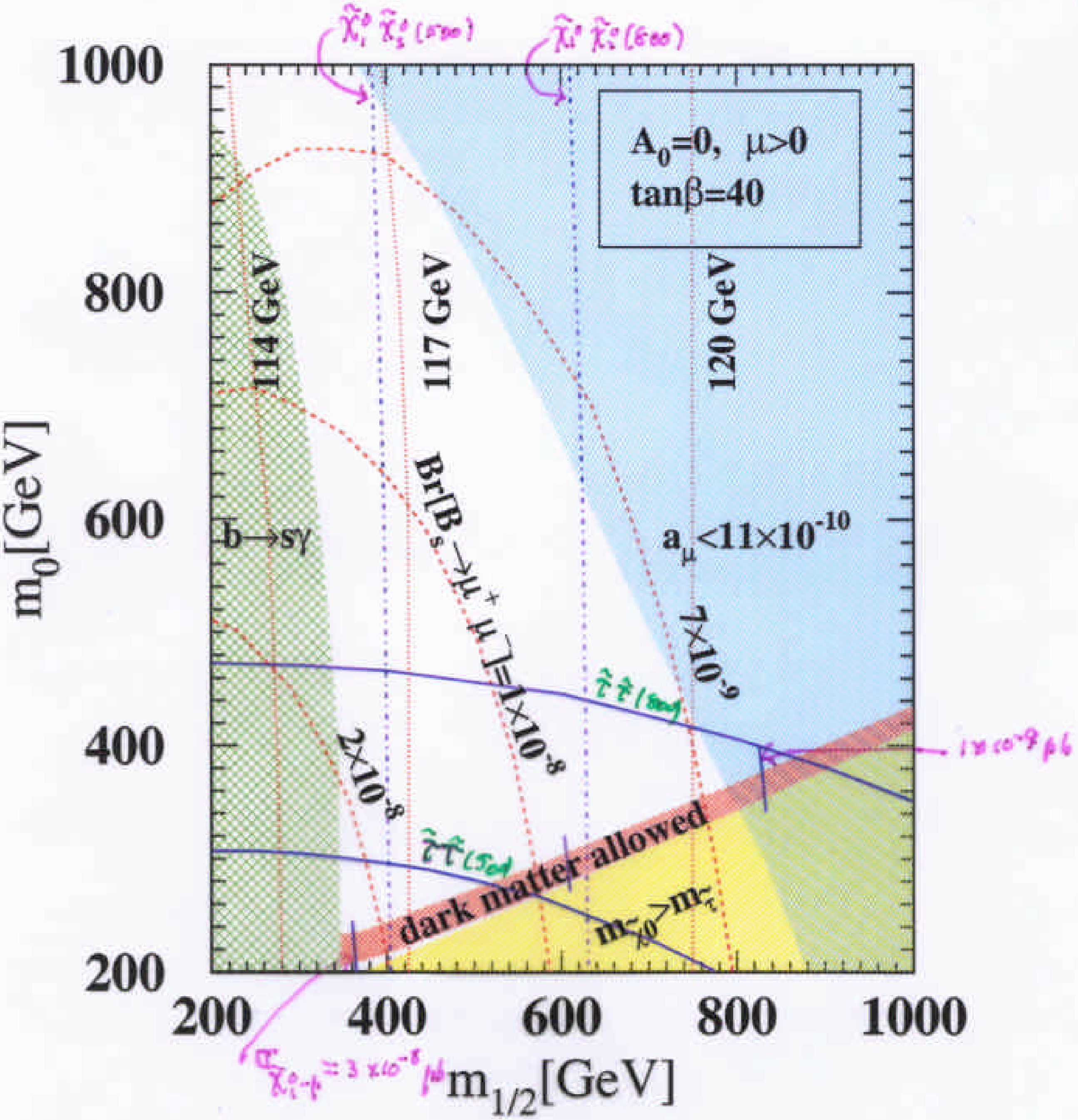
For $\tan\beta = 40$, the $B_s \to \mu\mu$ decay becomes significant, and assuming the combined CDF-D0 data is available, this would cover the full parameter space for $a_\mu > 10\times$

The NLC(500) $\tilde{\tau}\tilde{\tau}$ signal would cover only about 1/2 the parameter space, while the NLC(800) would be sensitive to the full space for $a_\mu > 10\times10^{-10}$.

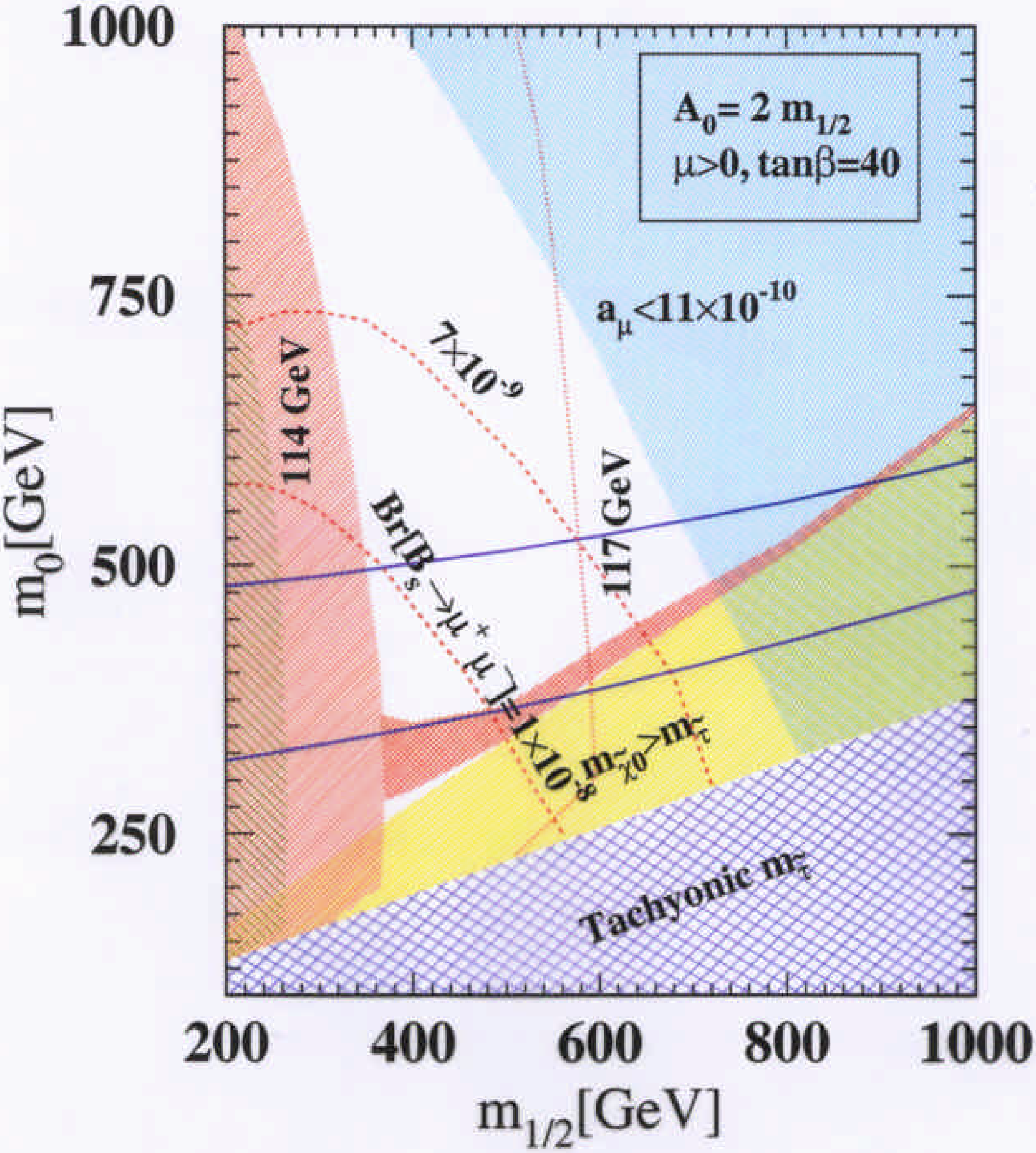
The effect of $A_0 \neq 0$ is to tilt the dark matter allowed band and raise the allowed m_0 values.

Figs. $m_0 - m_{1/2}$ plane, $\tan\beta = 50, 55$; $\mu > 0$, $A_0 = 0$

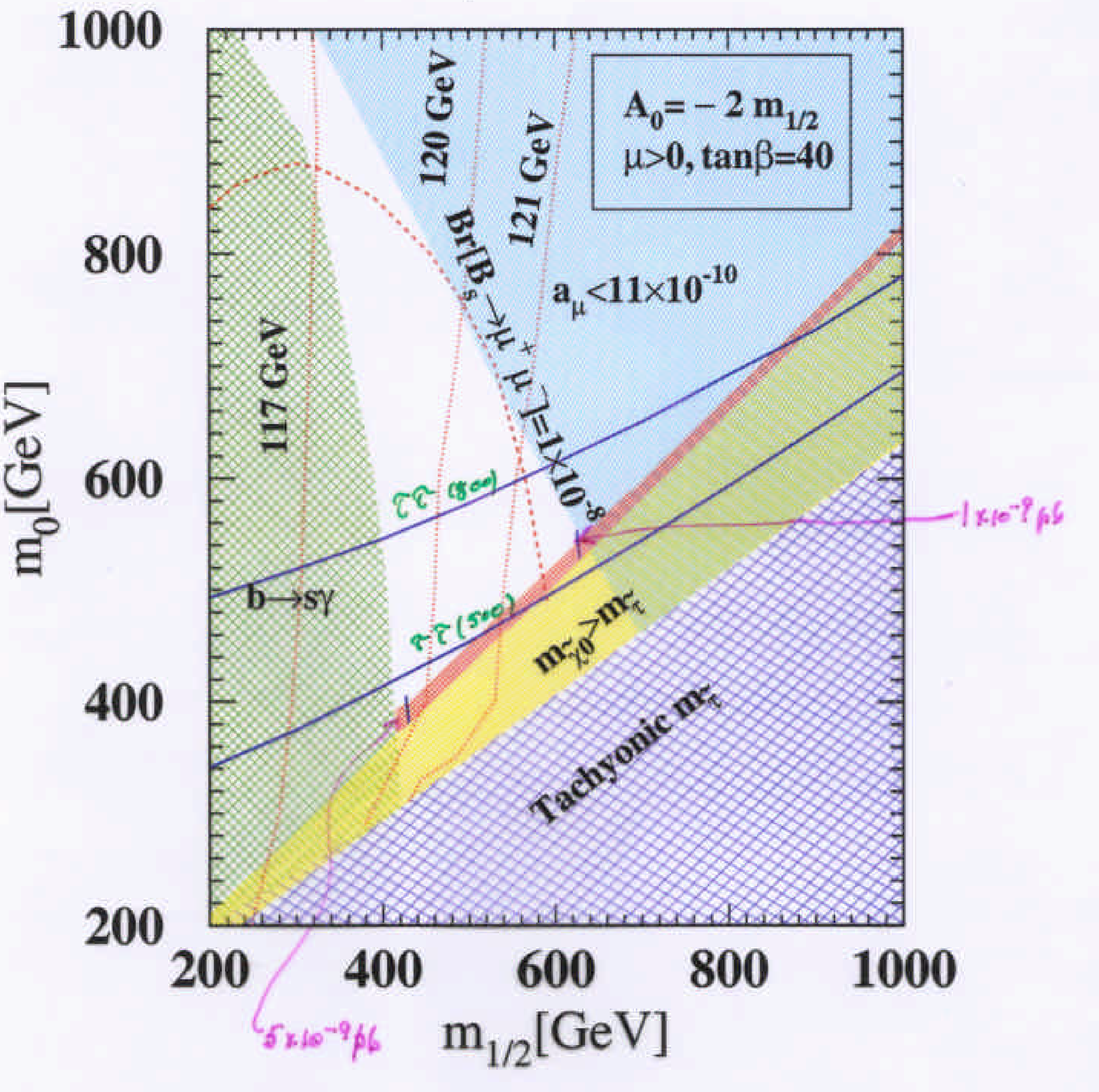
For very large $\tan\beta$, the new feature is the opening of a "bulge" in the dark matter band at low $m_{1/2}$ (due to fact A, H Higgs become light allowing rapid early universe annihilation). This increases the significance of the low $m_{1/2}$ signal of $\tilde{\chi}^0_2 - \tilde{\chi}^0_1$ of NLC(500), while the $\tau\tau$ signal disappears at $\tan\beta \simeq 55$. Again the NLC(800) can cover the entire parameter space with the $\tau\tau$ signal.



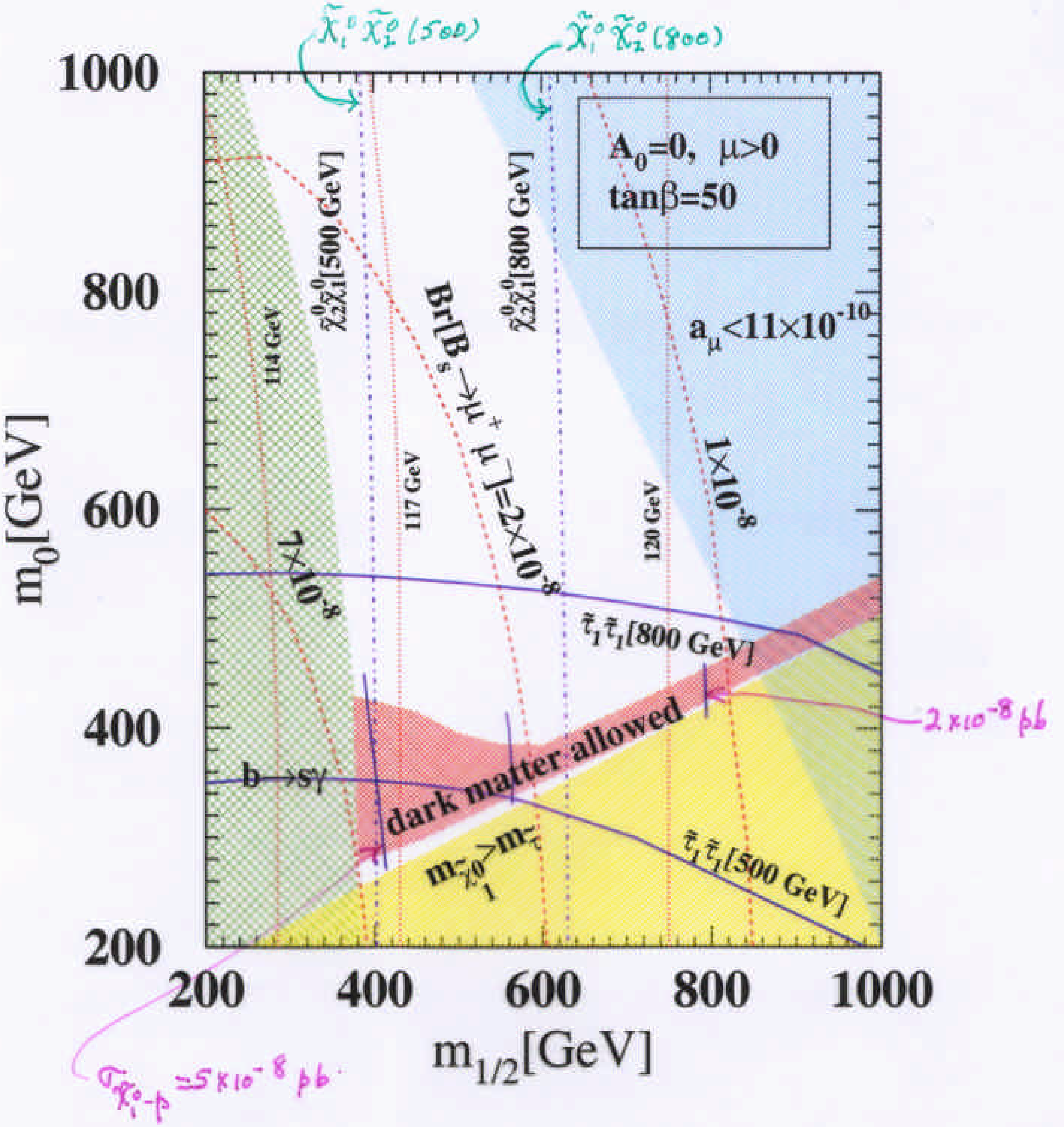
[Arnowitt, Dutta, Kamon, Tanaka]^2



[Arnowitt, Dutta, Kamon, Tanaka][4]

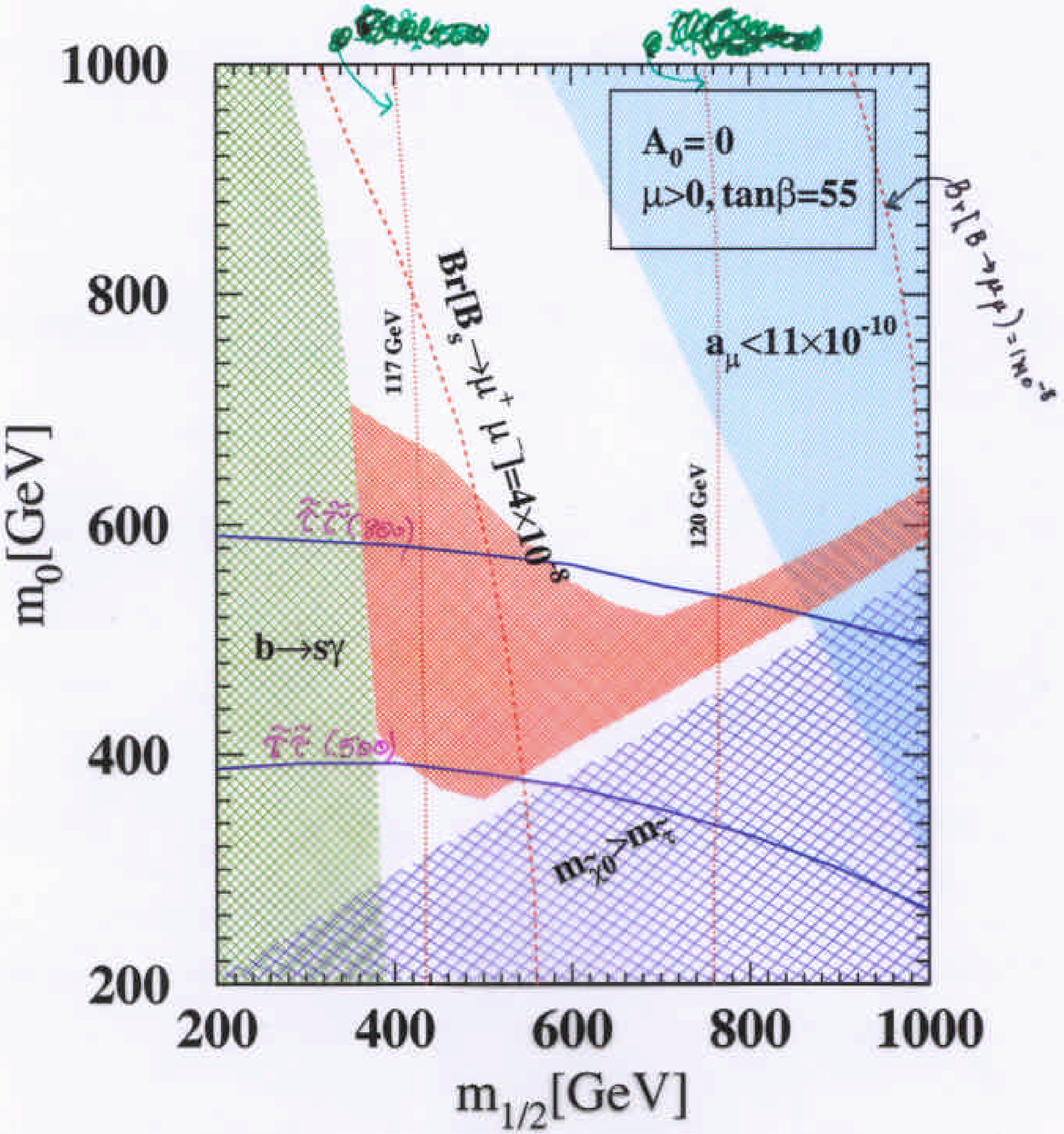


[Arnowitt, Dutta, Kamon, Tanaka]



$\tilde{\chi}_1^0\tilde{\chi}_2^0$ (500)
$\tilde{\chi}_1^0\tilde{\chi}_2^0$ (800)
A_0=0, μ>0
tanβ=50
$a_\mu<11\times10^{-10}$
$\tilde{\chi}_2^0\tilde{\chi}_1^0$[500 GeV]
$\tilde{\chi}_2^0\tilde{\chi}_1^0$[800 GeV]
114 GeV
117 GeV
120 GeV
$Br[B_s\to\mu^+\mu^-]=2\times10^{-8}$
1×10^{-8}
7×10^{-8}
$\tilde{\tau}_1\tilde{\tau}_1$[800 GeV]
$\tilde{\tau}_1\tilde{\tau}_1$[500 GeV]
dark matter allowed
$b\to s\gamma$
$m_{\tilde{\chi}_1^0}>m_{\tilde{\tau}}$
2×10^{-8} pb
$\sigma_{\tilde{\chi}_1^0-p}\simeq5\times10^{-8}$ pb
m_0[GeV]
$m_{1/2}$[GeV]
200
400
600
800
1000

$m_t = 175$ GeV ; $m_b = 4.25$ GeV



[Arnowitt, Dutta, Kamon, Tanaka] 5

6. Non-Universal Models

We examine some non-universal models to see what aspects of mSUGRA are maintained, and what new effects might show up.

Two striking effects in mSUGRA are:

* $\tilde{\chi}_1^0 - \tilde{\tau}_1$ co-annihilation (leading to narrow band of allowed region in $m_0 - m_{1/2}$ plane)
* $m_{\tilde{\chi}_1^0} \gtrsim 120$ GeV bound from $b \to s\gamma$ and m_h constraint (forbidding light $\tilde{\chi}_1^0$).

(1) Non-universal gaugino masses

Here $SU(3)_C$, $SU(2)_L$, $U(1)_Y$ gaugino masses may all be different at M_G:

$$\tilde{m}_1 \; ; \; \tilde{m}_2 = \tilde{m}_1(1+\tilde{\delta}_2) \; ; \; \tilde{m}_3 = \tilde{m}_1(1+\tilde{\delta}_3) \qquad M_G$$

$$m_{\tilde{\chi}_1^0} \cong 0.4\,\tilde{m}_1$$

* One has from RGE that $m_{\tilde{\tau}_1}^2 - m_{\tilde{\chi}_1^0}^2$ depends mainly on $U(1)$ mass $\tilde{m}_1$. Hence the $\tilde{\chi}_1^0 - \tilde{\tau}_1$ co-annihilation remains essentially unchanged

* $b\to s\gamma$ is relatively insensitive to $\tilde{m}_2$ but is very sensitive to $\tilde{m}_3$. Roughly speaking $(m_{\tilde{\chi}_1^0})_{min}$ scales inversely with $\tilde{m}_3$ i.e

$$(m_{\tilde{\chi}_1^0})_{min} \approx \left[m_{\tilde{\chi}_1^0}(\delta_3=0)\right]_{min} / (1+\tilde{\delta}_3) \; ; \; \tilde{\delta}_3 \approx \tfrac{1}{2}$$

This allows smaller $\tilde{\chi}_1^0$ to occur, more in DAMA allowed region. (However, $\sigma_{\tilde{\chi}_1^0 - p}$ does not significantly increase.)

(2) Non-universal 3rd generation $\tilde{q}/\tilde{l}$ and Higgs soft m

One can consider models with non-universal soft breaking in Higgs and 3rd generation masses at M_G:

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

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

$$m_{b_R}^2 = m_0^2(1+\delta_6) \; ; \; m_{l_L}^2 = m_0^2(1+\delta_7)$$

The parameter μ^2 governs much of the physics:

If μ^2 decreases (increases) the Higgsino content of $\tilde{\chi}$ increases (decreases) and hence the $\sigma_{\tilde{\chi}_1^0 - p}$ increases (decreases).

For small and intermediate $\tan\beta$ [R. Arnowitt, P. Na

$$\mu^2 = \frac{t^2}{t^2-1}\Big[\big(\frac{1-3D_0}{2}+\frac{1}{t^2}\big)+$$

$$\frac{1-D_0}{2}(\delta_3+\delta_4)-\frac{1+D_0}{2}\delta_2+\frac{\delta_1}{t^2}\Big]m_0^2+$$

universal parts + loop corrections.

where D_0 is small i.e. $D_0 \simeq 0.25$. Universal m_0 part not large, and so μ^2 can be raised or lowered by δ_i corrections.

$$t \equiv \tan\beta \quad ; \quad D_0 \cong 1-\left(\frac{m_t}{200\sin\beta}\right)^2$$

μ^2 decreases ($\sigma_{\tilde{\chi}_1^0-p}$ increases) if $\delta_1, \delta_3, \delta_4 < 0$, $\delta_2 > 0$

As a second effect that can happen when the Higgsino content of $\tilde{\chi}_1^0$ is increased (when μ^2 is decreased) is that the $\tilde{\chi}_1^0 - \tilde{\chi}_1^0 - Z$ is strengthen allowing a new annihilation channel to become important (in addition to the $\tilde{\tau}_1 - \tilde{\chi}_1^0$ co-annihilati channel). As a simple example we consider the case with non-universality only for H_2:

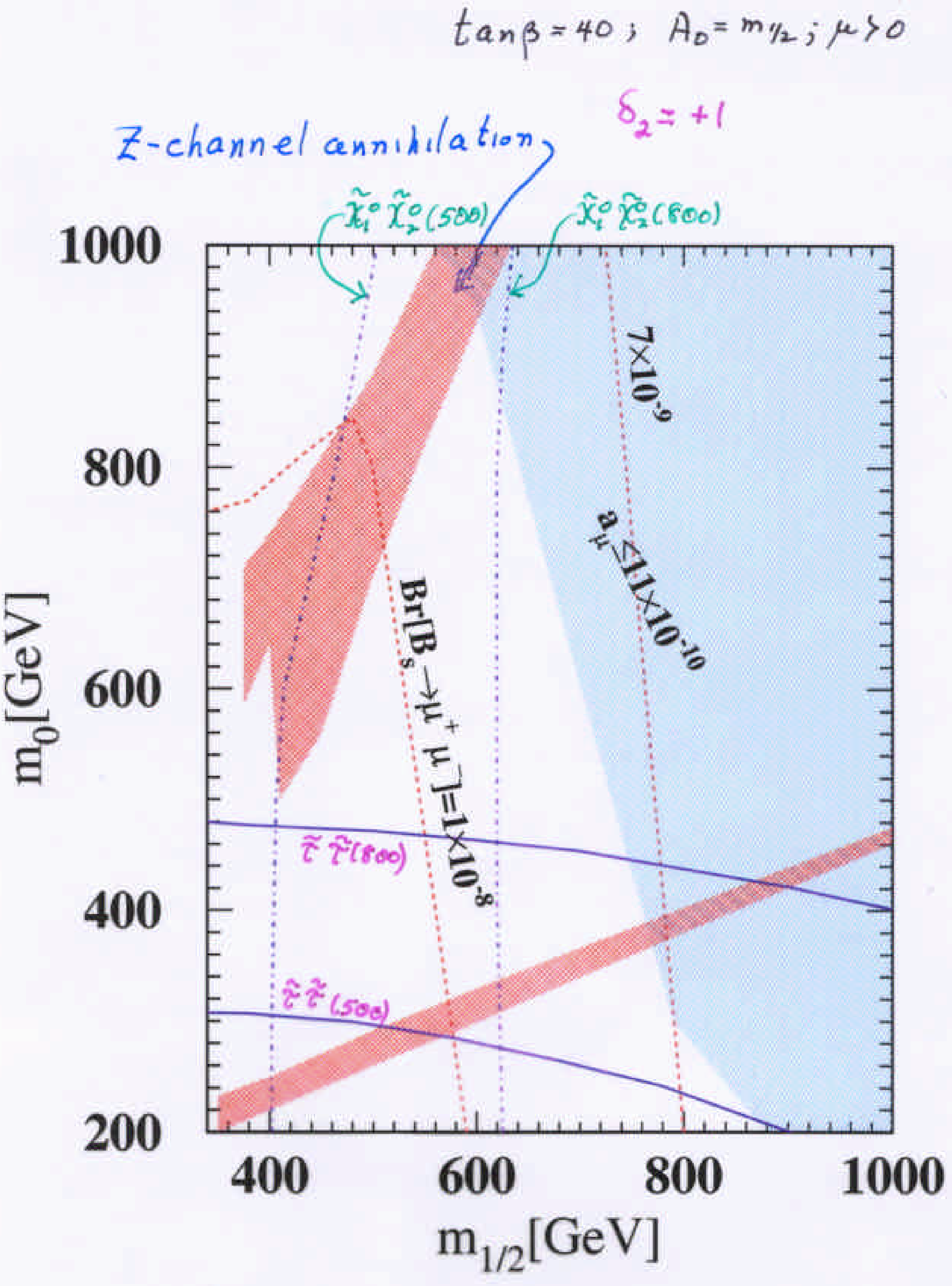
$$\delta_2 = 1 \;;\; \text{all other } \delta_i = 0$$

Fig. $m_0 - m_{1/2}$ allowed regions; $\tan\beta = 40$, $A_0 = m_{1/2}$, $\mu > 0$.

One sees the usual $\tilde{\tau}_1 - \tilde{\chi}_1^0$ co-annihilation channel plus the additional Z-channel at higher m_0. The cross sections for $\tilde{\chi}_1^0$-p scattering can become quite large the Z-channel region

Fig. $\sigma_{\tilde{\chi}_1^0 - p}$ vs $m_{1/2}$ for $\delta_2 = +1$, $\tan\beta = 40$, $A_0 = m_{1/2}$, $\mu > 0$

The cross sections rise up to the DAMA region for low $m_{1/2}$ ($m_{\tilde{\chi}_1^0} \cong 0.4\, m_{1/2}$) and so if the DAMA data is confirmed, it would point to a non-universality of this type.



$\tan\beta = 40$; $A_0 = m_{1/2}$; $\mu > 0$
$\delta_2 = +1$
Z-channel annihilation
$\tilde{\chi}_1^0 \tilde{\chi}_2^0 (500)$
$\tilde{\chi}_1^0 \tilde{\chi}_2^0 (800)$
7×10^{-9}
$a_\mu \leq 11\times10^{-10}$
$Br[B_s \to \mu^+\mu^-]=1\times10^{-8}$
$\tilde{\tau}\tilde{\tau}(800)$
$\tilde{\tau}\tilde{\tau}(500)$
m_0[GeV]
$m_{1/2}$[GeV]

Non-universal SUGRA; $\delta_2 = 1$
$\tan\beta = 40$; $A_0 = m_{1/2}$; $\mu > 0$

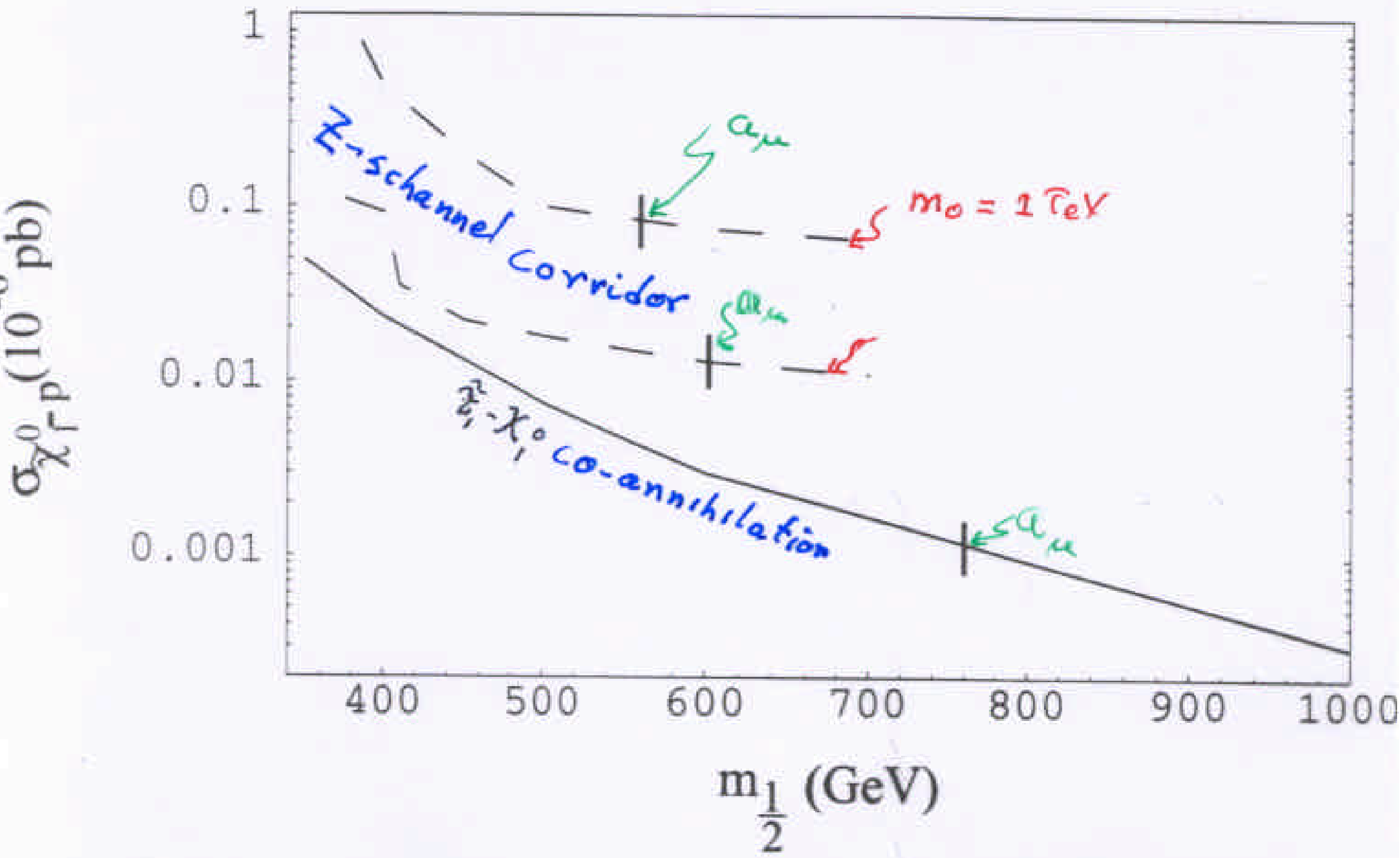


FIG. 4. $\sigma_{\tilde{\chi}_1^0 - p}$ as a function of $m_{1/2}$ ($m_{\tilde{\chi}_1^0} \cong 0.4 m_{1/2}$) for $\tan\beta = 40$, $\mu > 0$, $m_h > 111$ GeV, $A_0 = m_{1/2}$ for $\delta_2 = 1$. The lower curve is for the $\tilde{\tau}_1 - \tilde{\chi}_1^0$ co-annihilation channel, and the dashed band is for the Z s-channel annihilation allowed by non-universal soft breaking. The curves terminate at low $m_{1/2}$ due to the $b \to s\gamma$ constraint. The vertical lines show the termination at high $m_{1/2}$ due to the lower bound on a_μ of Eq. (1).

Arnowitt, Dutta, Santoso

7. Conclusions and Summary

We've examined restrictions on SUSY parameter space from existing experiments and future experiments at Tevatron ($B_s \to \mu^+\mu^-$) and possible LC ($e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$; $\tilde{\chi}_1^0\tilde{\chi}_2^0$) for mSUGRA and non-universal SUGRA:

mSUGRA

(1) $\tilde{\chi}_1^0 - \tilde{\tau}_1$ co-annihilation (narrow band in much of $m_0 - m_{1/2}$ plane)

(2) $m_{\tilde{\chi}_1^0} \gtrsim 120$ GeV from $b \to s\gamma$, m_h (forbidding light $\tilde{\chi}_1^0$)

(3) Tevatron can scan full parameter space $B_s \to \mu\mu$ for $\tan\beta \gtrsim 40$ (for $a_\mu^{SUSY} > 10 \times 10^{-10}$) with 15 fb^{-1}/det.

(4) LC at 800 GeV can scan almost all parameter space (with $e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$; $\tilde{\chi}_1^0\tilde{\chi}_2^0$)

(5) Dark Matter $\sigma_{\tilde{\chi}_1^0 - p}$ in range of planned detectors ($\gtrsim 10^{-9}$ pb) for $\mu > 0$

Non-universal SUGRA

(1) Co-annihilation $\tilde{\chi}_1^0 - \tilde{\tau}_1$ unchanged

(2) $m_{\tilde{\chi}_1^0}$ lower bound can be weakened (non-universa[l] gauginos)

(3) New Z-channel early universe annihilation at large m_0, moderate $m_{1/2}$; can increase $\sigma_{\tilde{\chi}_1^0 - p}$ towar[d] DAMA data (non-universal scalar masses)

(4) There are parameter regions in Z-channel region where LC at 500 GeV sees no SUSY except light Higgs (though Tevatron might still see $B_s \to \mu\mu$ decay).