Neutralino Dark Matter in mSUGRA: the Light Higgs Pole Window

Jean-Loïc Kneur (LPTA Montpellier)

with Abdelhak Djouadi and Manuel Drees

(hep-ph/0504090)

SUSY 2005, Durham, July 18-23, 2005

1. Introduction

2. Updated Theoretical and Experimental Constraints on mSUGRA

3. Scanning of mSUGRA parameter space:

(Reopening) the light Higgs pole window

4. Phenomenological perspectives at present and future colliders

5. Conclusions

1. Introduction

mSUGRA model most widely studied of MSSM, with virtues:

-only a handful of parameters;

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}(\mu).$$

-stable gauge hierarchy (for $m_{sparticles}$ not $\gg$ 1 TeV);

-radiative electroweak symmetry breaking (EWSB),

not much FCNC problems, etc;

-a very plausible (neutralino) Dark Matter candidate;

Yet, recently a perception that mSUGRA parameter space got "squeezed" (specially after WMAP): only four favored (relatively small) regions...

But, rather than "size of allowed regions" e.g. in $(m_0, m_{1/2})$ plane, perhaps more meaningful to look at min (max) mass bounds allowed by constraints, scanning ALL parameters..

$\longrightarrow$ Direct experimental limits from colliders can still be saturated in many cases, even after WMAP..
(Djouadi, Drees, JLK '05, LCWS05 contribution 220)

• Here, re-opening the light h-pole D.M. window:

Due essentially to recent re-evaluation of Higgs masses + increase in top mass central value, (Er..before newest CDF+D0 m_t (hep-ex/0507), but see later..)

a 5th acceptable WMAP region (besides the "bulk", $\tilde{\tau}$-co-annihilation, focus point and A-pole) with

$2m_{\tilde{\chi}_1^0} \lesssim m_h$ (near resonant s-channel h-exchange) in a quite significant region of mSUGRA parameter space

(considered years ago, but assumed almost excluded by LEP2 limits on m_h and $m_{\tilde{\chi}_1^0}[\simeq m_{\tilde{\chi}_1^\pm}/2]$..)

(NB noticed previously (after WMAP) by Baer et al '03-'04, but we study systematically its occurrence in full mSUGRA parameter space, +discuss some phenomenological consequences)

→ indeed, main interesting consequences:
strong UPPER mass bounds on

- gluino,
- lighter chargino
- and LSP

Quite good prospects for LHC, and ILC!

2. (Updated) Theoretical and Experimental Constraints

Th. constraint: consistent EWSB

Electroweak symmetry breaking (EWSB) triggered by the soft breaking terms $m_{H_u}^2$, $m_{H_d}^2$

Consistent EWSB in MSSM: typically $m_{H_u}^2(Q)$ driven < 0 by RG evolution $\propto Y_t^2$ from Q_{GUT} to Q_{EWSB}

with $|\mu|$ determined as function of other parameters by minimization of scalar potential

$\rightarrow$ not always consistent sol. for μ

Note: μ very sensitive to Rad. Corr., m_t,.. via RGE:

e.g. $\quad d\,(m_{H_u}^2) \propto Y_t^2\, d\,(\ln Q)$;

and $\mu^2 \sim -m_{H_u}^2 - m_Z^2/2 \qquad$ for $\tan\beta \gg 1$

Moreover CCB (Charge and/or Color breaking) minima of V_{eff}, deeper than true EWSB minimum, may occur. (relevant for large A_0 in mSUGRA)

New theoretical developments in MSSM mass calculation

Recent detailed comparisons (e.g. S. Kraml et al '04; Allanach, Djouadi, JLK, Porod, Slavich '04) of latest versions of the public codes:

–SuSpect 2.3, (A. Djouadi, JLK, G. Moultaka) (used here)
–SoftSusy 1.8.7 (B. Allanach)
–SPheno 2.2.1 (W. Porod)
–Isajet/sugra 7.71 (H. Baer, F. Paige, S. Protopescu, X. Tata)

• in particular, the first three (latest version) codes include a two-loop computation of Higgs masses and EWSB conditions performed in the $\overline{DR}$ renormalization scheme

• The full one-loop corrections are taken from

Pierce-Bagger-Matchev- Zhang (PBMZ) '96

• The leading two-loop corrections (in the limit of zero external momentum) in the self-energies are taken from

Brignole-Dedes-Degrassi-Slavich-Zwirner (BDDSZ) '01–'03

• Note: scale and scheme (comparing with OS scheme FeynHiggs results) dependences measure higher order theoretical uncertainties.

Experimental constraints on mSUGRA

- LEP/Tevatron limits on sparticle masses/pair production

NB very latest '05 Tevatron limits not included, but harmless to the relevant h-pole region (needs rather large m_0, see later)

Higgs mass constraints:

- $M_A \gg M_h \to h =$ SM-like, $\sin^2(\beta - \alpha) \sim 1$
$\to M_h \gtrsim 114$ GeV (LEP-combined)
Also considered ~ 3 GeV th. uncertainty, i.e. $M_h \gtrsim 111$ GeV

-light A: $\sin^2(\beta - \alpha) \sim 0 \to M_{h,A} \gtrsim 90$ GeV ($e^+e^- \to hA$)

-in between: we fit for $\{\sin^2(\beta - \alpha), M_h\}$ cf. LEP exclusion plot

Electroweak precision data

potentially dangerous: largest R.C. contributions to $\Delta\rho \equiv \rho - 1$: IF sparticles with large mass splittings.

$$\to \Delta\rho(\tilde{b}, \tilde{t}) + \Delta\rho(\tilde{\tau}, \tilde{\nu}) < 2.2 \cdot 10^{-3}$$

in fact, safe for most of mSUGRA parameter space
(i.e. small or superseded by other constraints)

- $g_\mu - 2$ constraints: SUSY contributions

Charginos+ sneutrino (dominant); Neutralinos + smuon

We consider, respectively, either:
$-5.7 \cdot 10^{-10} < \Delta a_\mu^{SUSY} < 47 \cdot 10^{-10}$
(conservative, combined e^+e^-+ τ-decay data, 2 σ)

or: $10.6 \cdot 10^{-10} < \Delta a_\mu^{SUSY} < 43.6 \cdot 10^{-10}$
(more "aggressive", but now $\sim$ consensual: e^+e^- data only)
STILL constraining for mSUGRA ($\mu < 0$ not favored)

- $b \to s\gamma$ constraints:

SUSY contributions (LO): Charginos + stops; H^+ + top
+NLO (enhanced by large $\tan\beta$ and/or large $\ln(M_{susy}/M_W)$)
(Degrassi, Gambino, Guidice '00)
NB we use LO+NLO code by P. Gambino

we take: $2.65 \leq 10^4 \cdot B.R.(b \to s\gamma) \leq 4.45$

+ constraint on amplitude sign! ($\simeq$ constraints on BR($b \to s\, l^+ l^-$) (i.e. requires SM sign, cf. Gambino et al '04)

BUT, $b \to s\gamma$ constraint easily evaded if e.g. small 2–3 gen. squark mixing (Borzumati et al '00, Okumura,Roszkowski '04)

$\to$ We consider two case: with AND w/o this constraint

Experimental "evidences"

• Dark Matter relic density:

$0.087 < \Omega h^2 < 0.138$, conservative (99% C.L.) WMAP

IF LSP $= \chi_0$, relic density:

$\Omega_\chi h^2 \sim [\sigma(\chi_0 \chi_0 \to all) + co - annihilation\ processes]^{-1}$

NB Ωh^2 calculation performed by "private" code (M. Drees)

• LEP2 '2000 "evidence" for SM-like h with $M_h \simeq 115$ GeV
Nowadays only $\sim 1.7\sigma$..

Anyway, we indicate regions of mSUGRA /
113 GeV $< M_h <$ 117 GeV
and $\sin^2(\beta - \alpha) \geq 0.95$

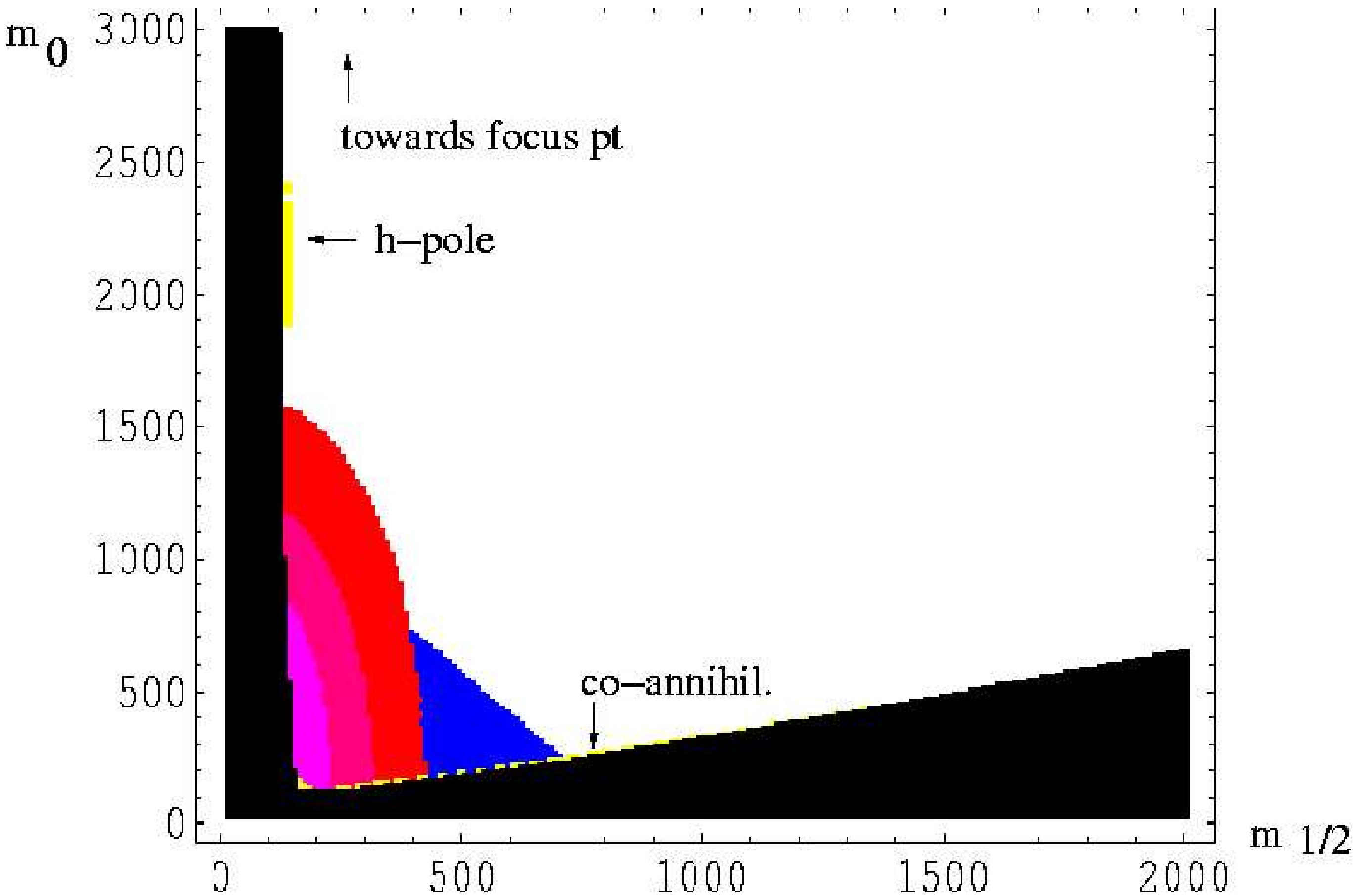
Finally, study effects of top mass uncertainties on all this:

we take 171 GeV $< m_t <$ 185 GeV

(i.e. 90 % C.L. range of former m_t results, but $m_t = 178$ GeV is 1-σ from newest central value.. (D0 run I+CDF run II))

3. Scanning mSUGRA parameter space:

Re-opening the light h-pole D.M. window

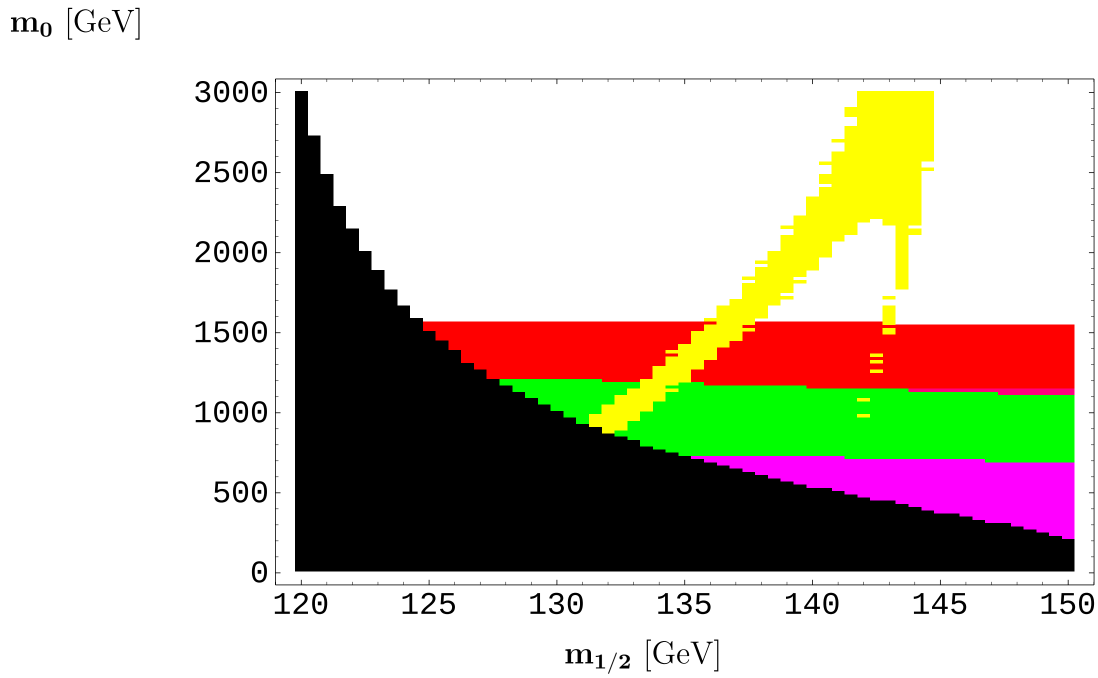


$A_0 = 0$, $\tan\beta = 30$, $m_t = 178$ GeV.

Dark: ruled out by consistent EWSB + Neutralino LSP. Purple: LEP excluded $M_h < 111$ GeV, Pink: 111 GeV $< M_h <$ 114 GeV (here coincides with (hidden) Green: ruled out by $b \to s\gamma$ constraints). Red and blue areas: respectively LEP evidence for a light MSSM Higgs $M_h \sim 115$ GeV and 90% C.L. evidence of a SUSY signal in $(g-2)_\mu$ with e^+e^- data only.

Yellow strips: favored by WMAP, $0.087 \leq \Omega_{\chi_1^0} h^2 \leq 0.138$.

Here's a closer view on the $2m_{\tilde{\chi}_1^0} \lesssim m_h$ (near resonant s-channel h-exchange) region



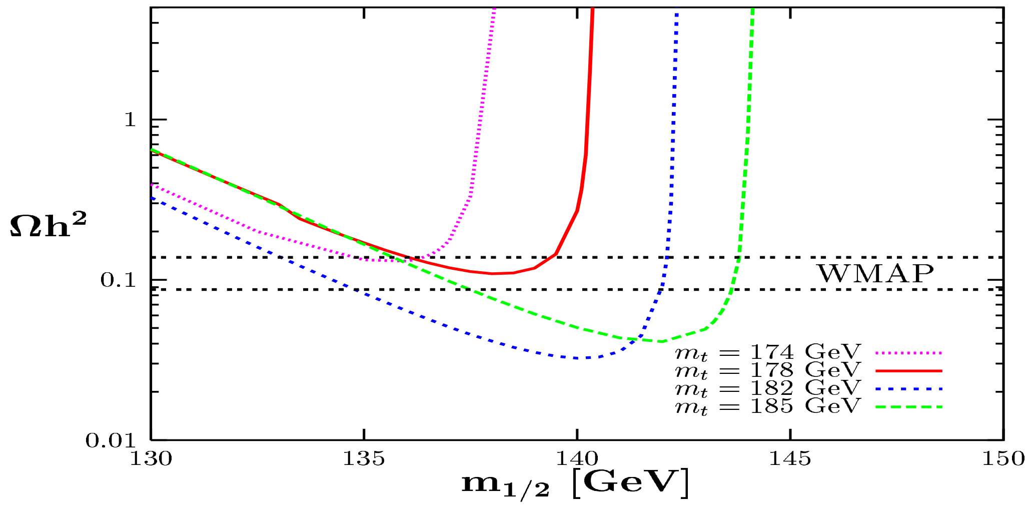
$A_0 = 0$, $\tan\beta = 30$, $m_t = 178$ GeV.

Dark: ruled out by consistent EWSB + Neutralino LSP. Purple and green: ruled out by, respectively, $M_h > 114$ GeV and $b \to s\gamma$ constraints. Red areas: respectively LEP evidence for a light MSSM Higgs $M_h \sim 115$ GeV. Yellow bands: range favored by WMAP, $0.087 \leq \Omega_{\chi_1^0} h^2 \leq 0.138$.

NB requires proper thermal averaging of s-channel x-section near resonance (Griest, Seckel '91)

Rk 1: the (thermally averaged) x-section drops very quickly once $m_{\tilde{\chi}_1^0} > m_h/2$, since the (positive) kinetic energy can only move the LSPs away from the $h-$pole.

This explains the asymmetric two strips.



i) $m_t = 174$ GeV, $m_0 = -A_0 = 1.5$ TeV, $\tan\beta = 30$; $M_h \sim 116$ GeV; *ii)* $m_t = 178$ GeV, $m_0 = 1.5$ TeV, $A_0 = -1$ TeV, $\tan\beta = 30$; $M_h \sim 117$ GeV; *iii)* $m_t = 182$ GeV, $m_0 = 1$ TeV, $A_0 = -1$ TeV, $\tan\beta = 10$; $M_h \sim 115$ GeV; *iv)* $m_t = 185$ GeV, $m_0 = 1$ TeV, $A_0 = 0$, $\tan\beta = 20$; $M_h \sim 116$ GeV.

Rk 2: depth of min of $\Omega_{\tilde{\chi}_1^0} h^2$ determined by:

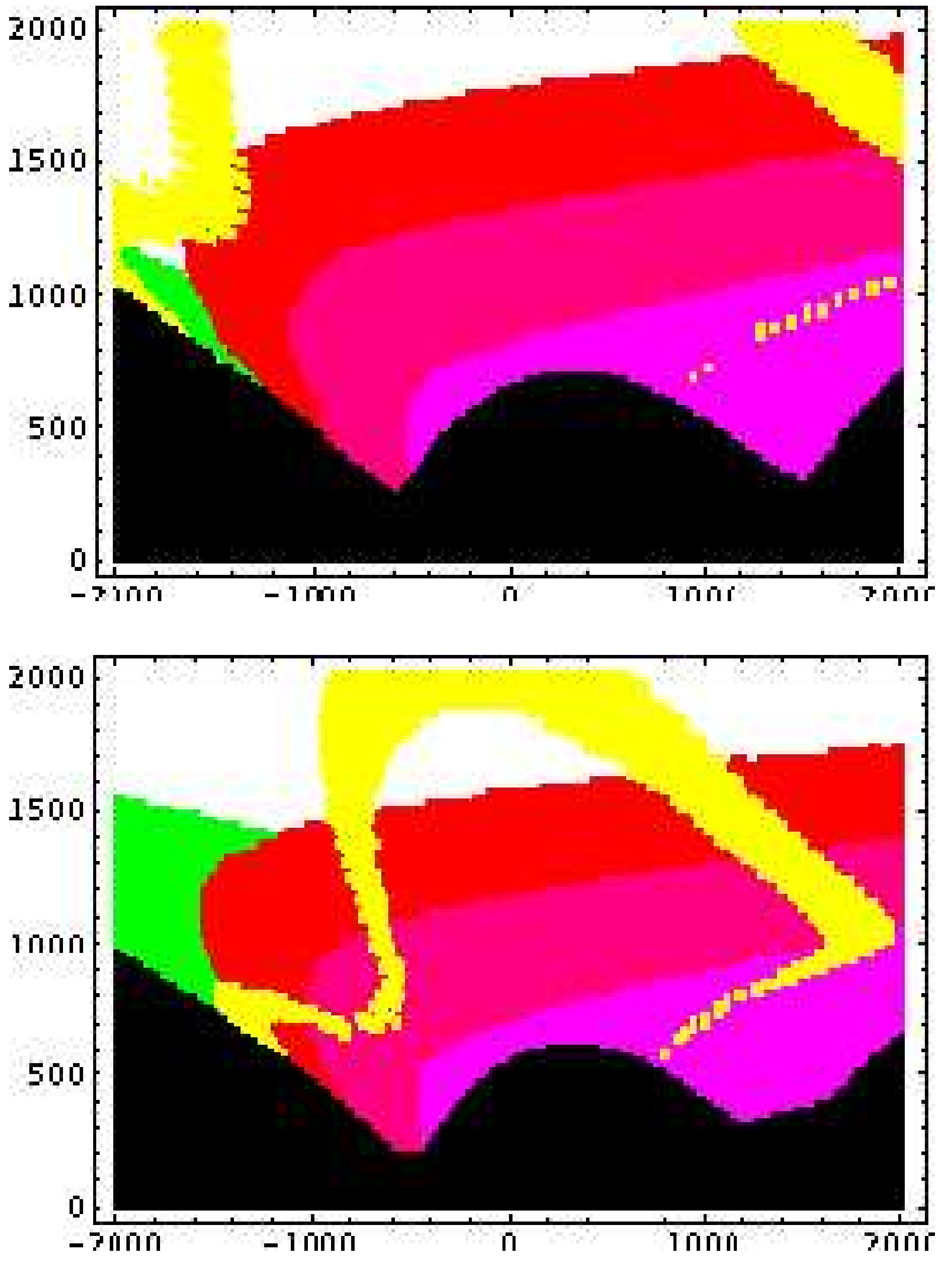
$$g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} \propto \frac{M_Z(2\mu\cos\beta + M_1)}{\mu^2 - M_1^2},$$

(assuming $\sin\beta \simeq 1$ and $M_1 \cos\beta \ll |\mu|$, $M_1 \simeq 0.4 m_{1/2}$)

thus $g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} \searrow$ with $|\mu| \nearrow$, i.e. $m_t \nearrow$, and/or $|A_0| \nearrow$, and/or $m_0 \nearrow$.

All this explains the origin of the two branches, whenever the min is below the WMAP range.

Actually, $2m_{\tilde{\chi}_1^0} \lesssim m_h$ (near resonant s-channel h-exchange) in a quite significant region of full mSUGRA parameter space



Constraints on the (A_0, m_0) plane for $m_{1/2} = 140$ GeV, $\mu > 0$, $\tan\beta = 10$ (top) and 30 (bottom). $m_t = 178$ GeV.

Quantity	Range I	Range II
$m_{\tilde{e}_R} \simeq m_{\tilde{\mu}_R}$ [GeV]	[708, –]	[299, 1300]
$m_{\tilde{e}_L} \simeq m_{\tilde{\mu}_L}$ [GeV]	[713, –]	[311, 1300]
$m_{\tilde{\tau}_1}$ [GeV]	[627, –]	[98.8, 934]
$m_{\tilde{\tau}_2}$ [GeV]	[714, –]	[306, 1130]
$m_{\tilde{\nu}_\tau}$ [GeV]	[708, –]	[281, 1130]
$m_{\tilde{\chi}_1^\pm}$ [GeV]	[105, 122]	[105, 115]
$m_{\tilde{\chi}_2^\pm}$ [GeV]	[295, 1820]	[297, 580]
$m_{\tilde{\chi}_1^0}$ [GeV]	[52.9, 60.7]	[53.4, 58.4]
$m_{\tilde{\chi}_2^0}$ [GeV]	[105, 122]	[105, 115]
$m_{\tilde{\chi}_3^0}$ [GeV]	[280, 1820]	[280, 574]
$m_{\tilde{\chi}_4^0}$ [GeV]	[293, 1820]	[294, 578]
$m_{\tilde{g}}$ [GeV]	[383, 482]	[365, 433]
$m_{\tilde{d}_R} \simeq m_{\tilde{s}_R}$ [GeV]	[774, –]	[431, 1340]
$m_{\tilde{d}_L} \simeq m_{\tilde{s}_L}$ [GeV]	[782, –]	[446, 1350]
$m_{\tilde{b}_1}$ [GeV]	[607, –]	[302, 920]
$m_{\tilde{b}_2}$ [GeV]	[772, –]	[408, 1030]
$m_{\tilde{t}_1}$ [GeV]	[110, –]	[102, 791]
$m_{\tilde{t}_2}$ [GeV]	[645, –]	[417, 930]
m_h [GeV]	[114, 122]	[114, 119]
m_H [GeV]	[228, –]	[216, 825]
$m_{H^\pm}$ [GeV]	[246, –]	[234, 830]
$\sigma(\tilde{\chi}_1^0 p \to \tilde{\chi}_1^0 p)$ [pb]	[3.1 10^{-11}, 1.4 10^{-7}]	[6.6 10^{-10}, 2.0 10^{-7}]

Table 1: Lower and UPPER bounds on sparticle and Higgs masses in mSUGRA under two different sets of assumptions. requires $m_h > 2m_{LSP}$!.
Set I: loose $g_\mu - 2$ constraint + $b \to s\gamma$ constraint.
Set II: "more aggressive" $g_\mu - 2$ constraint, NO $b \to s\gamma$ constraint.

All limits obtained by scanning full parameter space for 171 GeV $\leq m_t \leq$ 185 GeV.

4. Phenomenology of h-pole regions: perspectives at colliders

acceptable (WMAP) relic density in quite large regions of m_0 and A_0, while $m_{1/2} \sim 130 - 150$ GeV.

constraint set I (loose $g_\mu - 2 + b \to s\gamma$): favors rather heavy sfermions and Higgses $(H, A, H^\pm)$

(small $m_{1/2} \leftrightarrow$ large m_0 required to satisfy LEP Higgs and $b \to s\gamma$ constraints)

- Tevatron: no good prospects
(best may be $\tilde{t}_1$ (pair) production, but only for small $\tan\beta$)

LHC: $\sigma(\tilde{g}\tilde{g}) > 10\ pb$ (i.e. 10^5 events/yr for low luminosity)

$\sigma(\tilde{\chi}_2^0 \chi_1^\pm) > 1\ pb$: detectable, in principle, over most of parameter space

sfermions (except $\tilde{t}_1$) too heavy to be produced even at ILC

- Very good prospects for $\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^0 \tilde{\chi}_2^0)$ at ILC

- "smoking gun" signature:
$Z\, h$ production followed by invisible decay $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$

(though, $Br(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) \lesssim 1\%$ in h-pole region..)

Constraint set II: (i.e. "agressive" $g_\mu - 2(e^+e^-)$, NO $b \to s\gamma$)

dramatically reduces MIN sfermion masses,
because large $|A_0|$ allowed, reducing MIN m_0.

Requiring $g_\mu - 2$ (e^+e^- data only) imposes stringent upper bounds on all sparticle +Higgs masses

(which are strengthened even more in the h-pole window)

-reduced upper bounds on all gaugino-like states

slepton pair production possible at ILC

- Also, Direct Dark Matter detection: upper limit on

$\sigma(\tilde{\chi}_1^0 p \to \tilde{\chi}_1^0 p)$ close to the near future sensitivity

(but only for large $\tan\beta$)

SUMMARY

- (resurrection of) a 5th WMAP region:

"light h-pole" with $2m_{\tilde{\chi}_1^0} \lesssim M_h$

Due to recent re-evaluation of M_h, + needs large top mass (NB so newest CDF+D0 m_t values go in wrong direction, but do not close it!)

- Special emphasize on min/max allowed sparticle masses: (more meaningful than "size of allowed parameter space")

$\longrightarrow$ stringent UPPER bounds on masses of gaugino states:

gluino, lighter chargino and LSP masses

-quite stringent upper bounds on most sparticles, when combined with "agressive" (e^+e^- data) $g_\mu - 2$

- **The h-pole region could be soon covered by sparticle searches at LHC**

(unlike the other favored WMAP regions, which are difficult to probe comprehensively at LHC or ILC)

If $\chi^\pm$ and h found at LHC, precise $m_{\tilde{\chi}_1^0}$ and M_h measurements (at ILC) needed to check if h-pole indeed gives correct $\Omega\, h^2$