Collider and Dark Matter Searches in Models with Non-Universal SUSY Breaking Parameters

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Based largely on work with Howard Baer, A. Belyaev, T. Krupovnickas, A. Mustafayev, Eun-Kyung Park, S. Profumo and Ting Wang

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The determination of the relic density of CDM

$$\Omega_{CDM}h^2 = 0.111^{+0.006}_{-0.01}$$

is a serious constraint on any new theory with a stable WIMP, in particular R-parity conserving supersymmetry.

Assuming that the LSP is a neutralino, we strictly conclude that

$$\Omega_{\widetilde{Z}_1}h^2 \lesssim 0.123 \quad (2\sigma).$$

Generic SUSY models are bang-on if sparticles are light and the LSP is bino-like with $m_{\rm SUSY} \sim \mathcal{O}(100)$ GeV ("bulk" region).

This bulk region is being constrained by direct searches and constraints on rare processes, which force the SUSY scale to go up, and hence, $v\sigma(annihilation) \sim 1/m^2_{SUSY}$ to come down, ⇒ neutralio relic density is too large.

Seek mechanisms to jack up the LSP annihilation rate.

Jacking up the annihilation cross section

- ⋆ Co-annihilation with charge or coloured sparticle – charged/coloured sparticles annihilate efficiently, so as long as thermal equilibrium is maintained, LSP and co-annihilating partner density related by Boltzmann factor. (co-annihilation region)
- ⋆ Resonance enhancement if $2m_{\widetilde{Z}_1} \simeq m_\phi$, where $\phi = A, H$ or even h. Not as fine-tuned as it seems because resonances can be wide, and because LSP has thermal motion. (Higgs funnel)
- ⋆ Increase higgsino content of LSP since higgsinos couple to Z (small μ hyperbolic branch/focus point region)
- ⋆ Increase wino content of LSP because winos have big couplings to Z and W (need non-universal gaugino masses at GUT scale – so not an option in many popular models.)

CLEARLY THE COMPOSITION OF THE LSP HAS IMPLICATIONS FOR DIRECT AND INDIRECT DETECTION EXPERIMENTS

Implications for colliders

- ⋆ Co-annihilation clearly implies a relatively light charged/coloured sparticle.
- ⋆ Within mSUGRA, the Higgs funnel is possible only for rather large values of $\tan\beta$ ⇒ large bottom Yukawas⇒ altered sparticle cascade decay patterns.
- ⋆ Within mSUGRA, small $|\mu|$ HB/FP region occurs for $m_0 \gg m_{1/2}$ ⇒ scalars are essentially decoupled from even the LHC (sensitivity to m_t).
- ⋆ Within mSUGRA, the wino content of LSP is never large.

RELAXING UNIVERSALITY OF SUSY BREAKING PARAMETERS, OBVIATES LAST THREE CONCLUSIONS.

CAN WE TELL BY COMBINING COLLIDER SIGNALS WITH SIGNALS FROM DARK MATTER SEARCHES THAT WE ARE IN A NON-UNIVERSAL SCENARIOS

CAN WE DISTINGUISH BETWEEN VARIOUS NON-UNIVERSALITIES?

Direct and Indirect DM detection

Direct Detection

Stage 2 (CDMS2): SI $\sigma(\widetilde{Z}_1 p) > 3 \times 10^{-8}$ pb
Stage 3 (CDMS3, XENON): 10^{-9} pb

Indirect Detection

IceCube: 40 events/km^2/yr with $E_\mu > 50$ GeV,
GLAST: 10^{-10} events/cm^2/s with $E_\gamma > 1$ GeV,
Pamela: 2×10^{-9} events/GeV/cm^2/s/sr for positrons,
Pamela: 3×10^{-9} events/GeV/cm^2/s/sr for antiprotons,
GAPS: 3×10^{-13} events/GeV/cm^2/s/sr for antideuterons, $0.1 < T_{\overline{D}} < 0.25$ GeV.

Use Isatools for evaluating direct detection rates; DarkSUSY for indirect detection rates.

NON-UNIVERSAL HIGGS MASS PARAMETERS

FCNC constraints suggest particles with same gauge quantum numbers are (roughly) degenerate ⇒ intergenerational universality of sfermion masses; $m(\tilde{u}_L) = m(\tilde{c}_L) = m(_{\mathrm{L}})$, etc.

Simple anstätz: Maintain high scale sfermion mass universality, but,

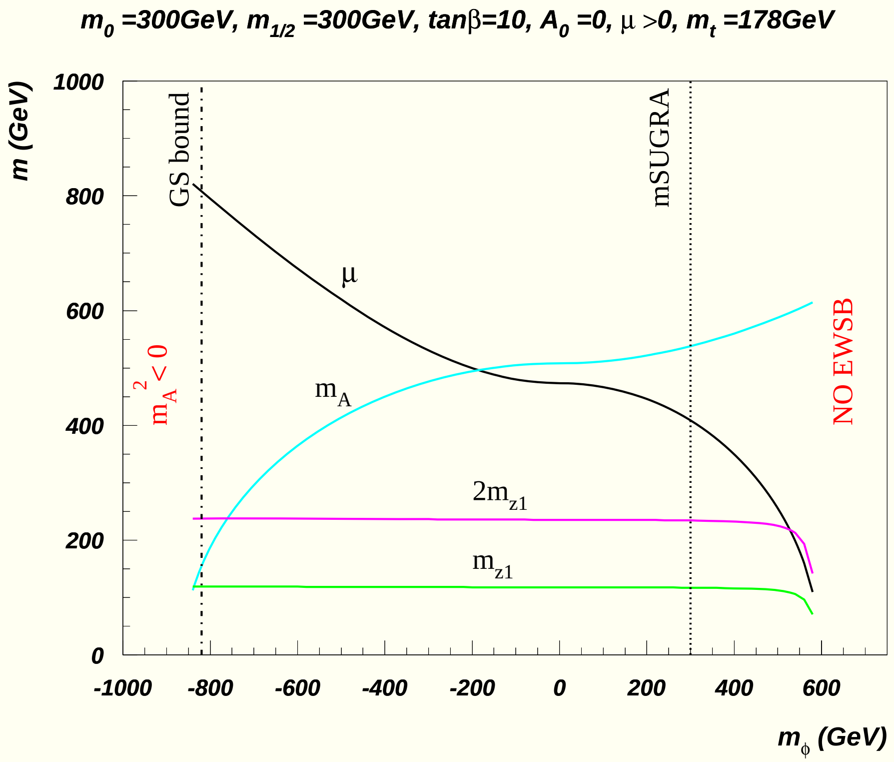
$$m^2_{H_u}(\mathrm{GUT}), m^2_{H_d}(\mathrm{GUT}) \neq m_0^2$$

$$m^2_{H_u} = m^2_{H_d} \equiv sign(m_\phi)|m^2_\phi| \text{ (NUHM1 model)}$$
$$m^2_{H_u} \neq m^2_{H_d} \text{ (NUHM2 model)}$$

NUHM1 model completely specified by

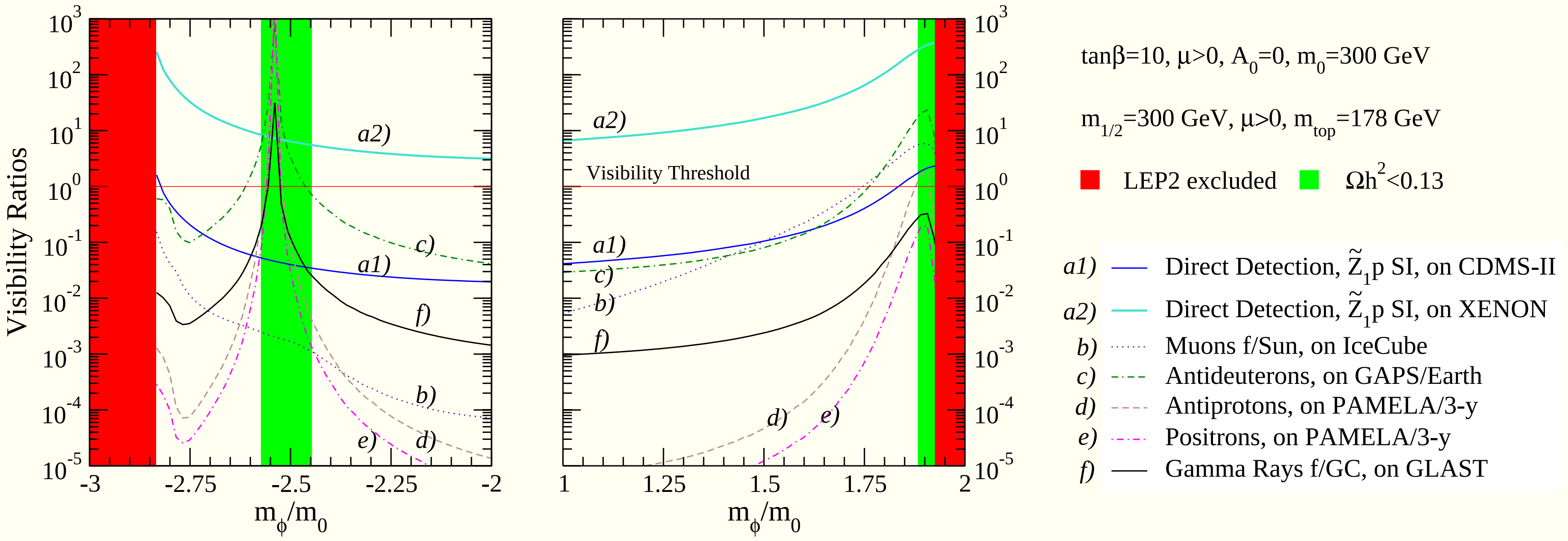
$$m_0,\ m_\phi,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$$

What does the NUHM model buy us?



Small μ for large $m_\phi > m_0$ Higgs funnel anihilation for $m_\phi < 0$

Dark Matter detection prospects for NUHM1

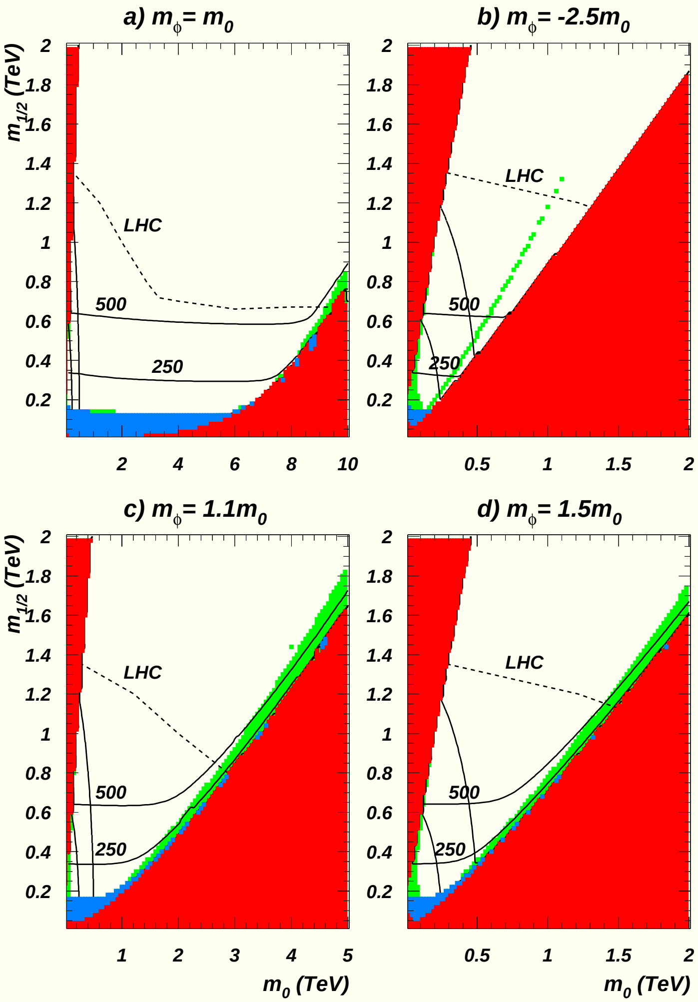


Higgs funnel for modest $\tan\beta$

small μ for low value of m_0

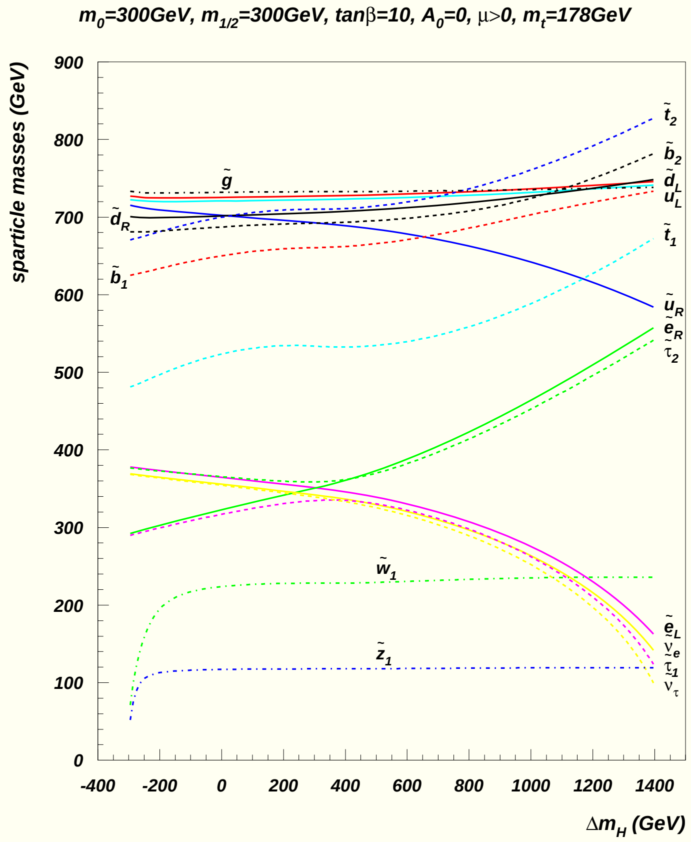
Burkert Halo profile (conservative antiparticle signals)

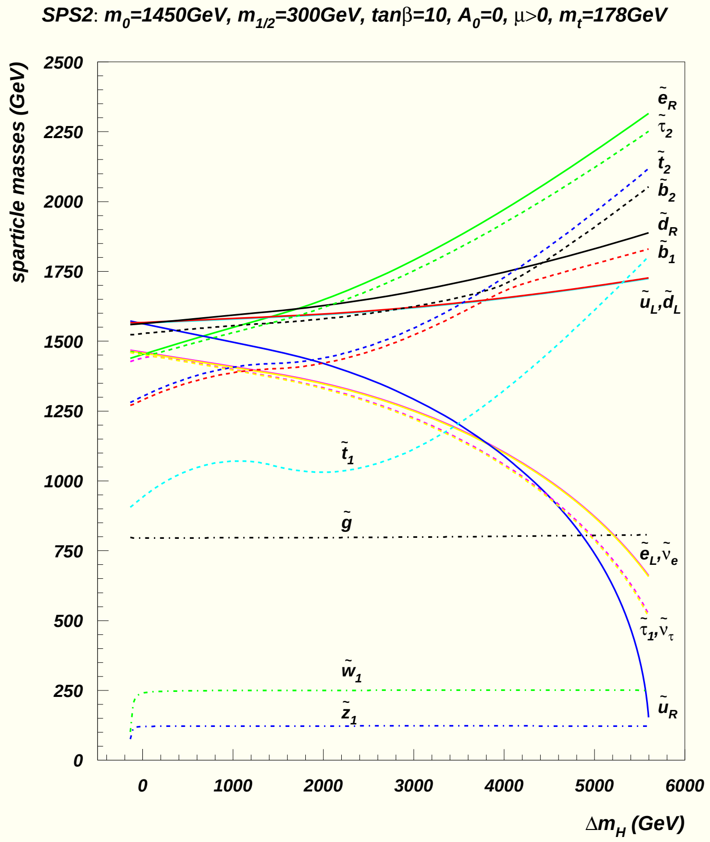
Collider Prospects



LHC covers most of Higgs funnel; Squarks accessible in frame d.

NUHM2 can lead to funny SUSY spectra because $S \neq 0$.





"Pseudo-bulk" region annihilation via LEFT staus; part of negative Δm_H region already probed at CDMS 2004!

"Pseudo-bulk" region annihilation via $\tilde{u}_R$, $\tilde{c}_R$ in right frame.

Non-Universal Gaugino Masses

GUT scale Universality ⇒ $M_3(\mathrm{weak}) \sim 3.5 M_2(\mathrm{weak}) \sim 7 M_1(\mathrm{weak})$ ⇒ Bino-like LSP in many models.

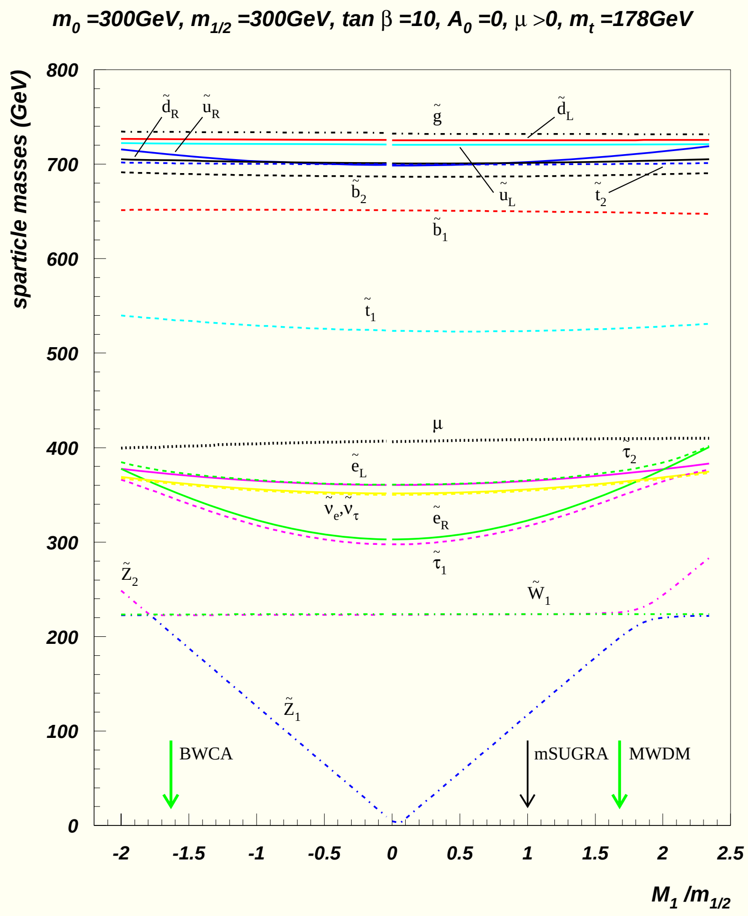
If $M_1(\mathrm{weak}) = M_2(\mathrm{weak})$, we have a photino LSP....rapidly annihilate to WW pairs. For $M_1(\mathrm{weak}) \simeq M_2(\mathrm{weak})$, we will have mixed wino dark matter (MWDM).

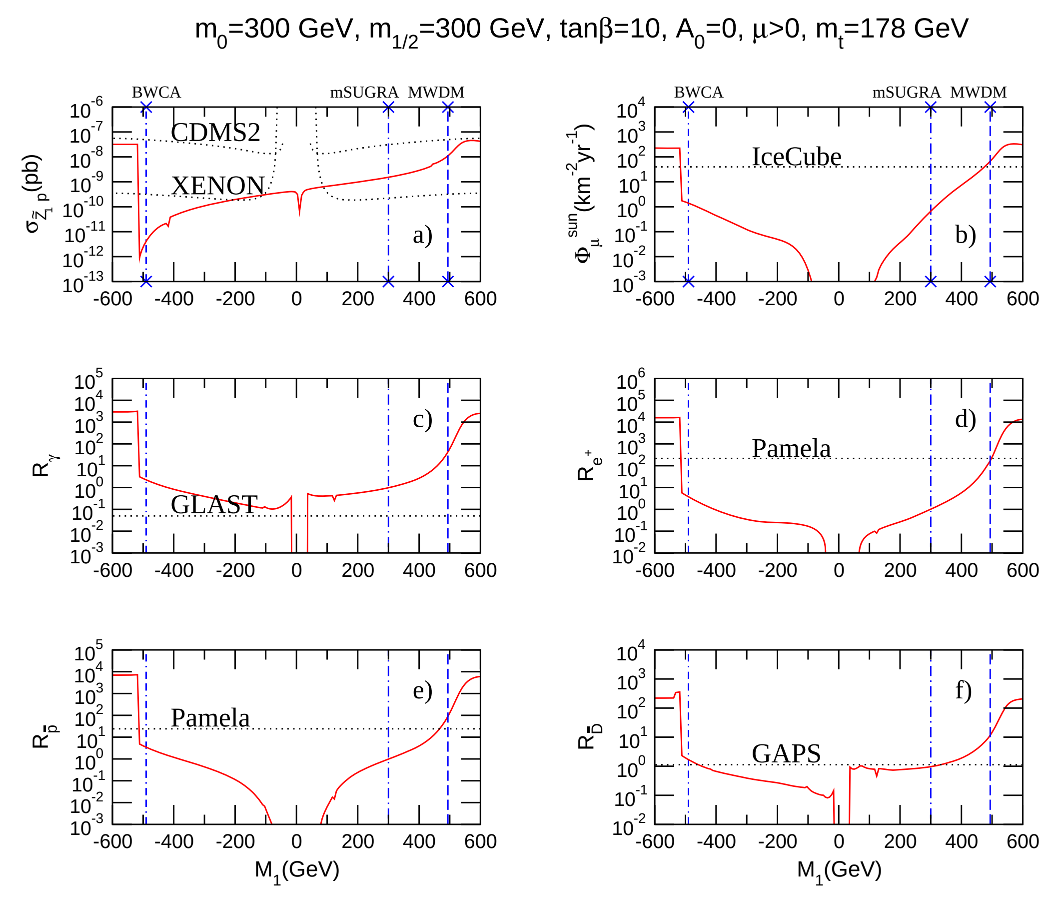
If $M_1(\mathrm{weak}) \simeq -M_2(\mathrm{weak})$, very little bino-wino mixing. But bino and wino states have about the same physical mass. ⇒ bino-wino coannihilation (BWCA).

$$m_0, m_{1/2}, M_1 \text{ or } M_2, A_0, \tan\beta, sign(\mu)$$

Although we take a phenomenlogical approach here, BWCA is realized in a mixed modulus-anomaly mediated SUSY breaking model based on string compactification with fluxes in extra dimensions. (T. Wang at SUSY 2006.)

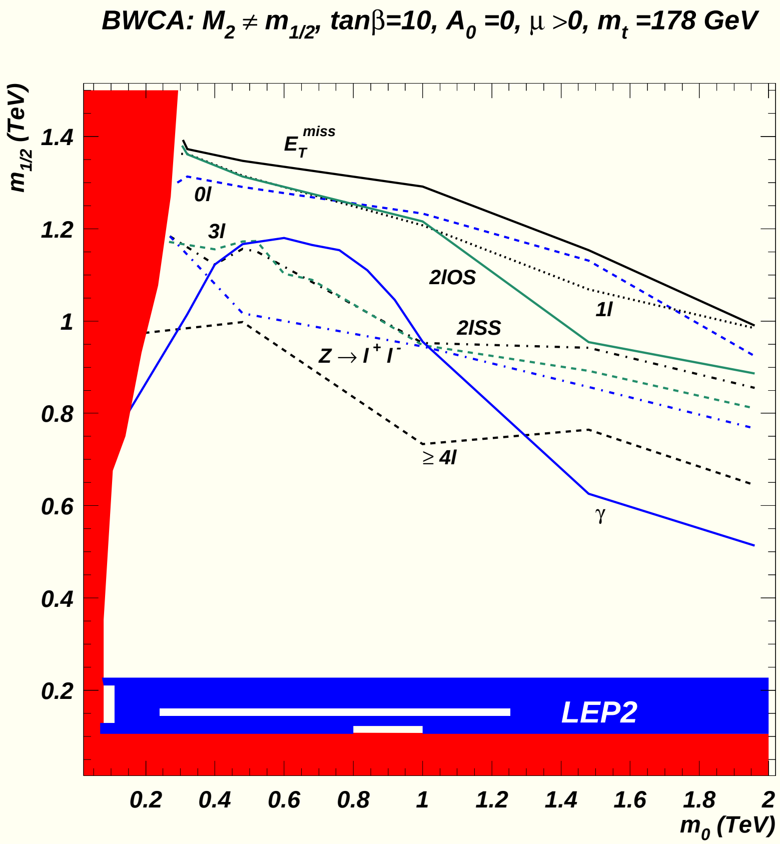
Illustrate in situation where we vary M_1 from its unified value.





Gamma ray and anti-particle detection rates are for adiabatically contracted N03 distribution for halo dark matter ⇒ Optimistic projections for these.

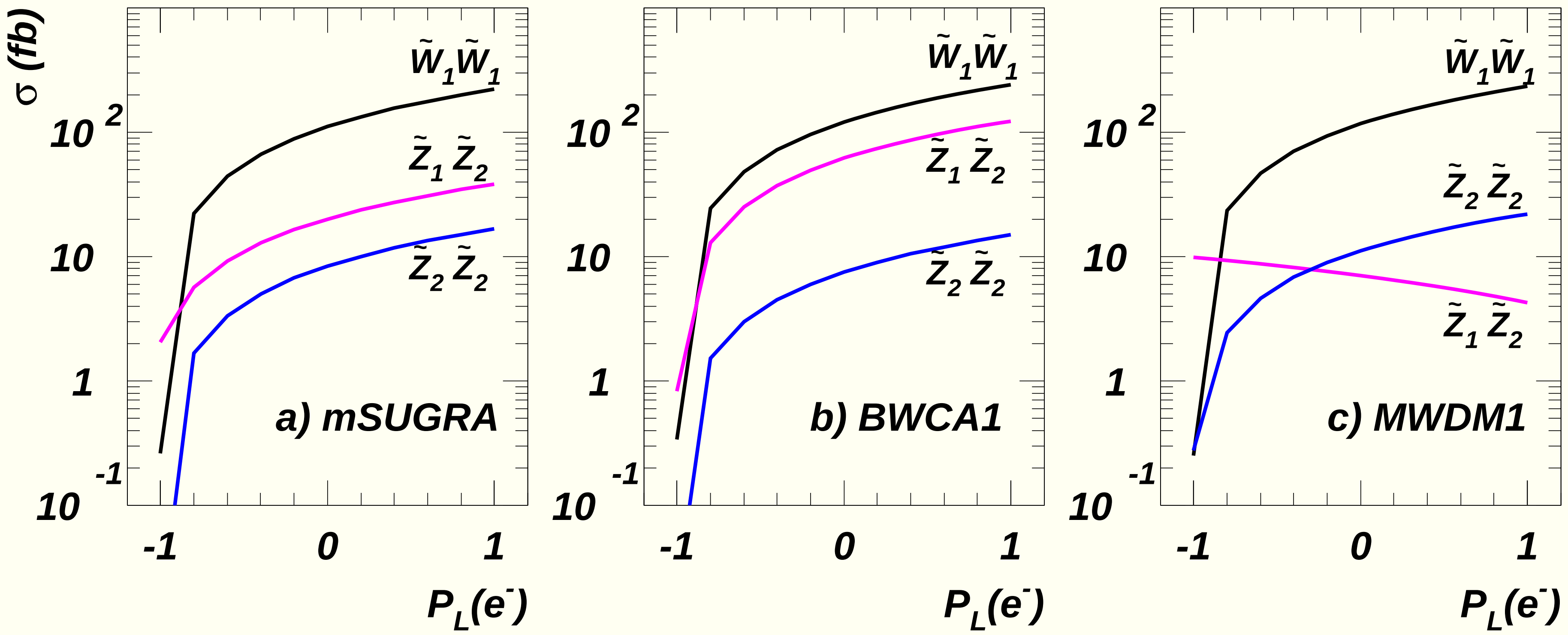
Small $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} \Rightarrow$ enhanced $\widetilde{Z}_2 \to \widetilde{Z}_1\gamma$ rate, $\sim 10-20\%$ in these scenarios.
(Vector boson-gaugino loops decouple in BWCA case, but not in MWDM case.)



Observable rate for photon signals at LHC.

Observable dilepton mass edges with small $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ at LHC.

Distinction between mSUGRA, MWDM and BWCA “easy” at Linear colliders.



Large size of $\widetilde{Z}_1\widetilde{Z}_2$ cross section in BWCA directly traced to $M_1/M_2 < 0$.

$\gamma +\not{E}_T$ events from $\widetilde{Z}_1\widetilde{Z}_2$ production and $\gamma\gamma +\not{E}_T$, jj or $\bar{\ell}\ell + \gamma + \not{E}_T$ events from $\widetilde{Z}_2\widetilde{Z}_2$ production.

M_3 different from $M_1 = M_2$

How can gluinos make a difference to the relic density?

Small $M_3(\mathrm{GUT}) \Rightarrow$ smaller evolution of squark mass squared as well as A_t parameters from gauge-gaugino loops $\Rightarrow$ smaller values for $X_t = m_{Q_3}^2 + m_{\mathrm{R}}^2 + m_{H_u^2} + A_t^2$.

Then, because

$$\frac{dm_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2 M_1^2 - 3g_2^2 M_2^2 + \frac{3}{10}g_1^2 S + 3f_t^2 X_t\right),$$

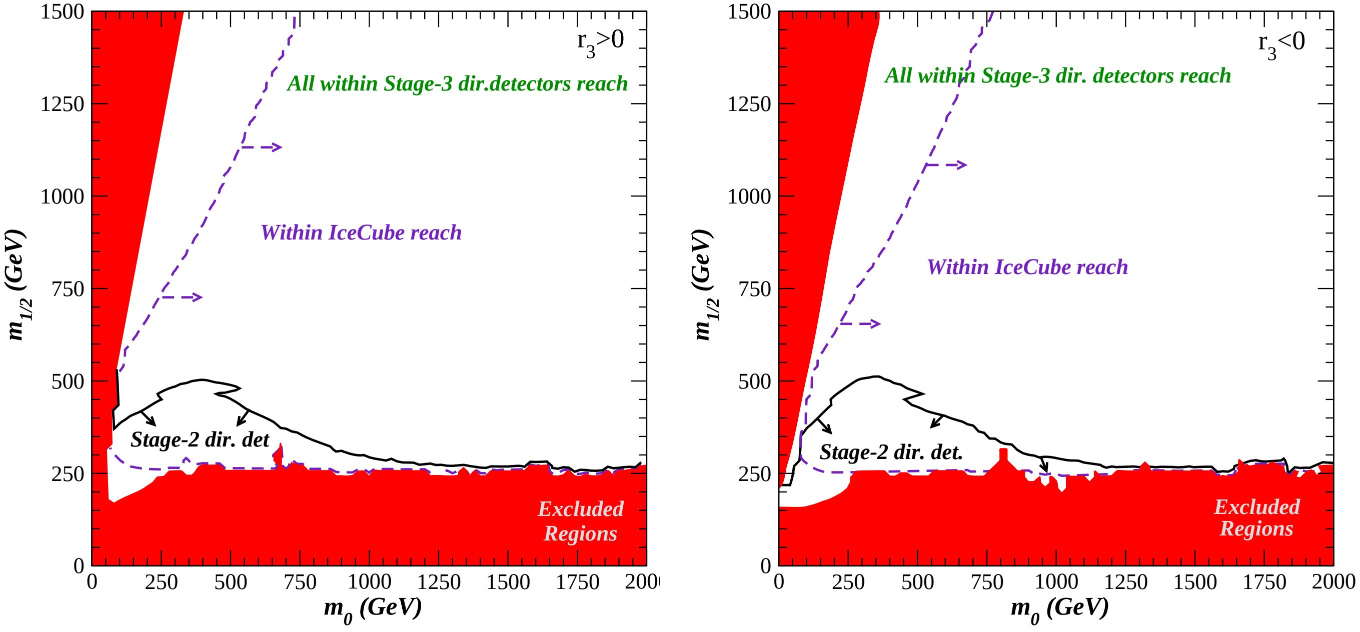
small X_t means $m_{H_u}^2$ evolves to LESS NEGATIVE values. Finally, because

$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{(\tan^2\beta - 1)} - \frac{M_Z^2}{2}$$

small $M_3(\mathrm{GUT}) \Rightarrow$ reduced μ!

Belanger *et al.*; Mambrini and Nezri.

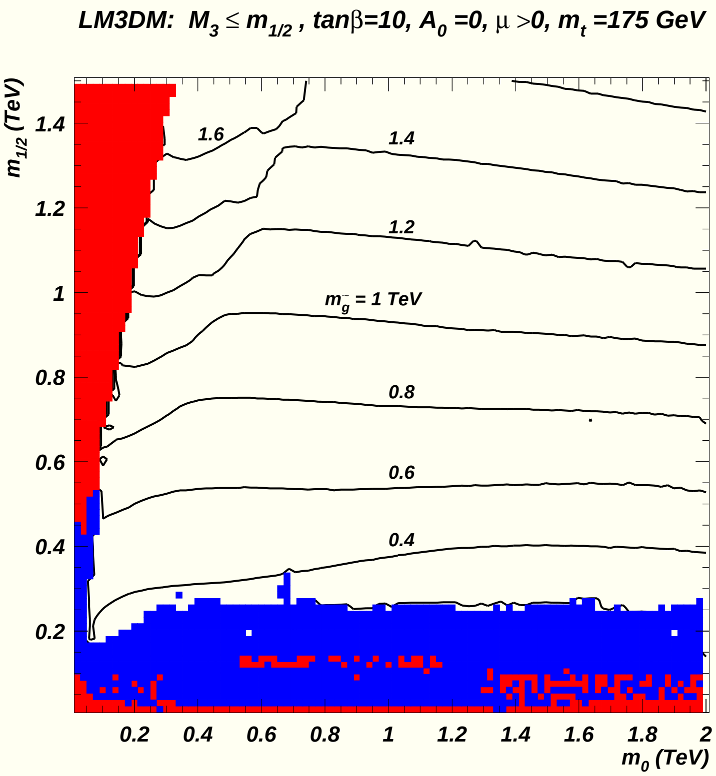
Even for low m_0, $m_{1/2}$, by adjusting $M_3(\mathrm{GUT})$, we can find the hyperbolic branch region, and so get the right relic density.

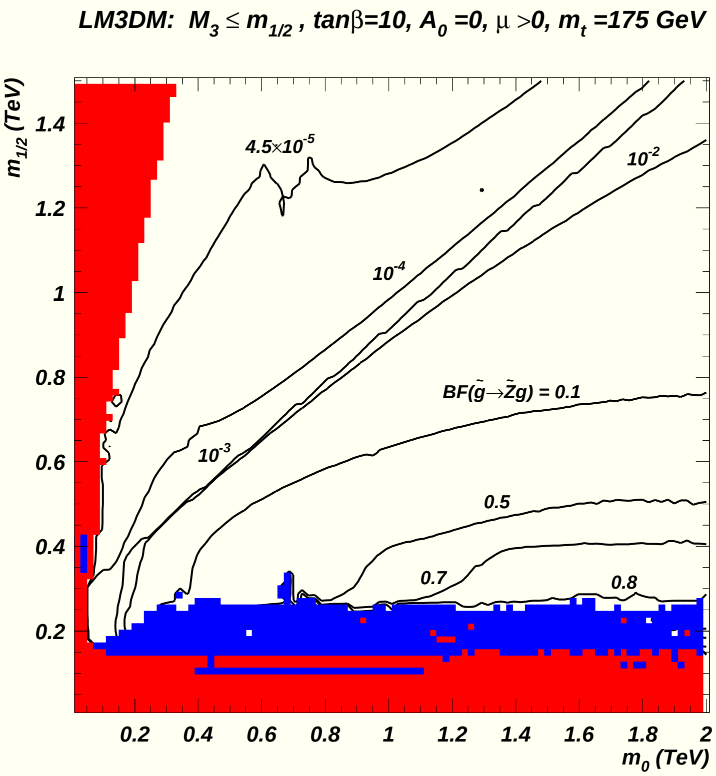


Small $|\mu| \Rightarrow$ Good DM detection.

Small $M_3 \Rightarrow$ Lighter gluinos (and also squarks) relative to uncoloured sparticles.

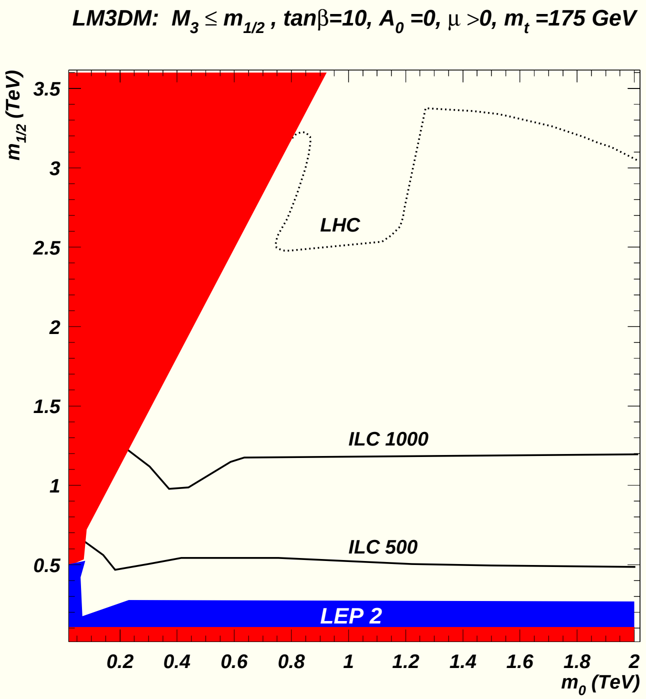
Enhanced Radiative decays of the gluino.





Opportunity for Tevatron???? Low jet multiplicity events.

LHC will overwhelm e^+e^- colliders for reach.



M_3 is everywhere adjusted to reproduce central value of the relic density.

Dilepton mass edges.

ILC contours are composites of stau and chargino contours.

All inos may be accessible at ILC ⇒ detailed study of ino sector.

Squarks may be accessible at especially a TeV collider, and since $\tilde{q} \to q\tilde{g}$, gluino studies at ILC!

Distinguishing Dark Matter Possibilities I

Feature	Models	Restriction	Stage 2/3	IceCube
Small $\vert\mu\vert$	mSUGRA NUHM1 NUHM2 LM3DM	large m_0	y/Y	Y
Higgs Funnel	mSUGRA NUHM1 NUHM2	Large $\tan\beta$	y/Y	N
BWCA		$M_1 \simeq -M_2$	N/y	N
MWDM		$M_1 \simeq M_2$	1/2y/Y	Y
Pseudo-bulk	NUHM2		Like mSUGRA with bino LSP	Like mSUGRA with bino LSP

Distinguishing Dark Matter Possibilities II

Feature	Models	Collider characteristics
Small $\|\mu\|$	mSUGRA	Sfermions decoupled, $m_{\widetilde{W}_1} \simeq m_{\widetilde{Z}_2} \simeq m_{\widetilde{Z}_1}$
	NUHM1/2	Possibly light sfermions, Long decay chains
	LM3DM	$m_{\tilde{g}} : M_1$, light squarks; ino reconstruction at ILC;
		enhanced radiative $\tilde{g}$ decays
Higgs Funnel	mSUGRA	3rd gen favoured in decays cascades
	NUHM1	Light $A,\ H,\ H^{\pm}$, but $\|\mu\|$ large
	NUHM2	μ, m_A free, cascade decays to all the Higgs possible
BWCA		enhanced radiative $\widetilde{Z}_2$ decays; mass edges;
		enhanced $\widetilde{Z}_1\widetilde{Z}_2$ production at ILC
MWDM		enhanced radiative $\widetilde{Z}_2$ decays; ino reconstruction
Pseudo-bulk	NUHM2	light $\tilde{\tau}_1 \simeq \tilde{\tau}_L$ or light $\tilde{u}_R,\ \tilde{c}_R$

Mixed Modulus-Anomaly Mediated SUSY Breaking (MM-AMSB) structure of MSSM soft SUSY breaking terms arises when extra dimensions of type IIB superstring curl up with fluxes (non-zero field strengths) along these extra dimensions.

Kachru, Kallosh, Trivedi and Linde Toy scenario

- ⋆ Stable ground state in controlled approximation (fluxes + gaugino condensation on $D7$ brane)
- ⋆ de Sitter universe (anti $D3$ brane)
- ⋆ Small SUSY breaking due to $\overline{D3}$ brane.

No concrete realization of KKLT idea with an explicit C-Y space and choice of fluxes that leads to ground state with required properties!

Phenomenological approach.

MSSM Soft terms analysed and some implications explored by,

Choi, Falkowski, Nilles, Olechowski, Pokorski
Choi, Jeong, Okumura; Falkowski, Lebedev, Mambrini; Kitano, Nomura.

Parameter Space

MSSM sparticle mass scale $\sim \frac{m_{3/2}}{16\pi^2} \equiv M_s$

Ratio of modulus-mediated and anomaly-mediated contributions set by a phenomenological parameter α

Modulus-mediated contributions depend on location of fields in extra dimensions. These contributions depend on "modular weights" of the fields, determined by where these fields are located.

Matter modular weights n_i= 0 (1)
Gauge kinetic function indices l_a= 1 (0) on $D7$ ($D3$) branes.

Model completely specified by

$$m_{3/2},\ \alpha,\ \tan\beta,\ sign(\mu),\ n_i,\ l_a$$

Radiative EWSB determines μ^2 as usual.

Soft SUSY Breaking Terms

The soft terms renormalized at $Q \sim M_{\rm GUT}$ are given by,

$$\begin{aligned} M_a &= M_s\left(\ell_a\alpha + b_a g_a^2\right), \\ A_{ijk} &= M_s\left(-a_{ijk}\alpha + \gamma_i + \gamma_j + \gamma_k\right), \\ m_i^2 &= M_s^2\left(c_i\alpha^2 + 4\alpha\xi_i - \dot\gamma_i\right), \end{aligned}$$

with

$$c_i = 1 - n_i,$$

$$a_{ijk} = 3 - n_i - n_j - n_k,$$

$$\xi_i = \sum_{j,k} a_{ijk}\frac{y_{ijk}^2}{4} - \sum_a l_a g_a^2 C_2^a(f_i), \text{and } \dot\gamma_i = 8\pi^2\frac{\partial\gamma_i}{\partial\log\mu}$$

Note that if $n_i = 0$, $A_{ijk}^2 \sim 9m_i^2$ for the modulus-mediated contribution. Large A-parameters!

$\alpha = 0$ gives us the AMSB Model.

For large $|\alpha|$, AMSB terms subdominant. With universal l_a (n_i) we will have common gaugino (scalar) masses.

Generation-independent modular weights for MSSM multiplets ensures FCNC OK.

Models potentially have smaller fine tuning: even for heavy stop, $m^2_{H_u}$ can be modest at weak scale. (Lebedev,Nilles, Ratz; Choi et al; Kitano, Nomura).

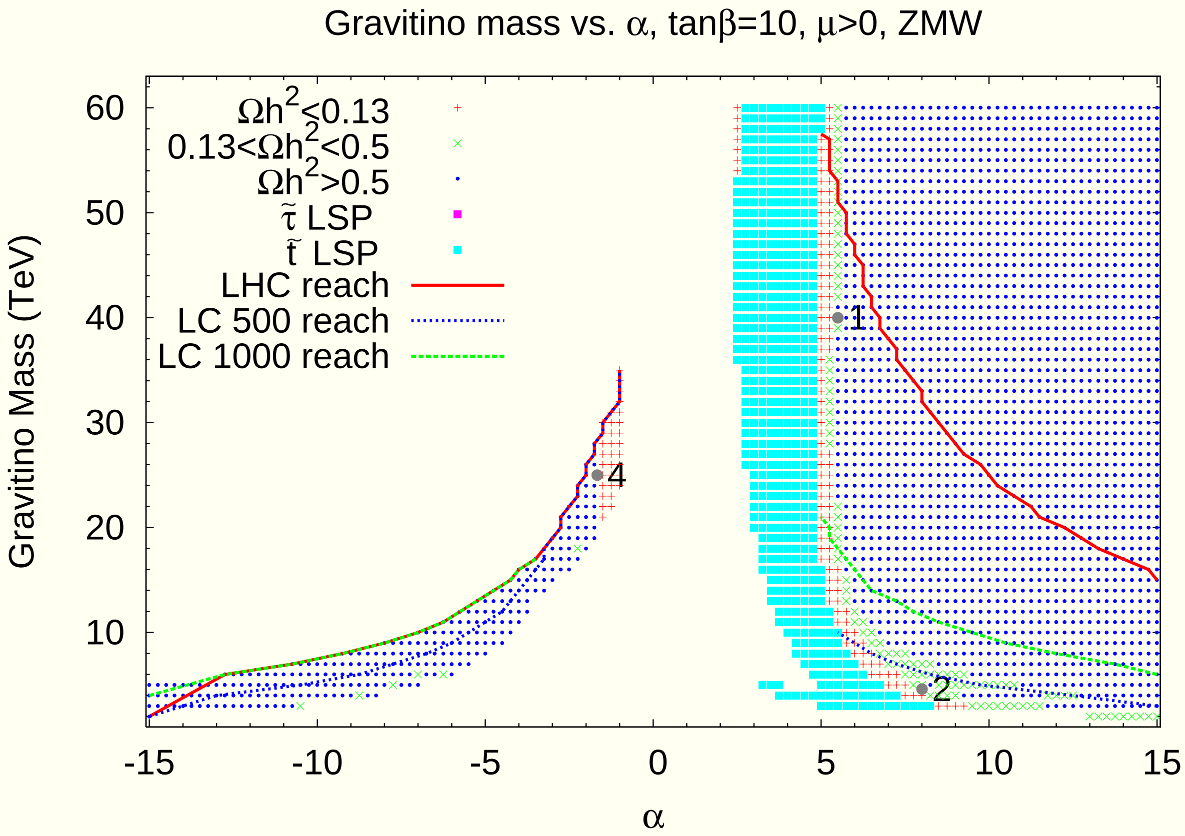
SSB parameters show apparent unification at "Mirage Unification Scale" (aside from Yukawa coupling effects). However, for $l_a = 1$, and

$n_{\rm matter} = \frac{1}{2}$, $n_{\rm Higgs} = 1$ (or $n_{\rm matter} = 1$, $n_{\rm Higgs} = 0$), mirage unfification always obtains. (Choi et al.; Kitano-Nomura)

We will always fix $l_a = 1$ and examine two cases:

★ $n_i = 0$; Zero Modular Weight (ZMW).

★ $n_{\rm matter} = 1/2$, $n_{\rm Higgs} = 1$, Non-Zero Modular Weight (NZMW).



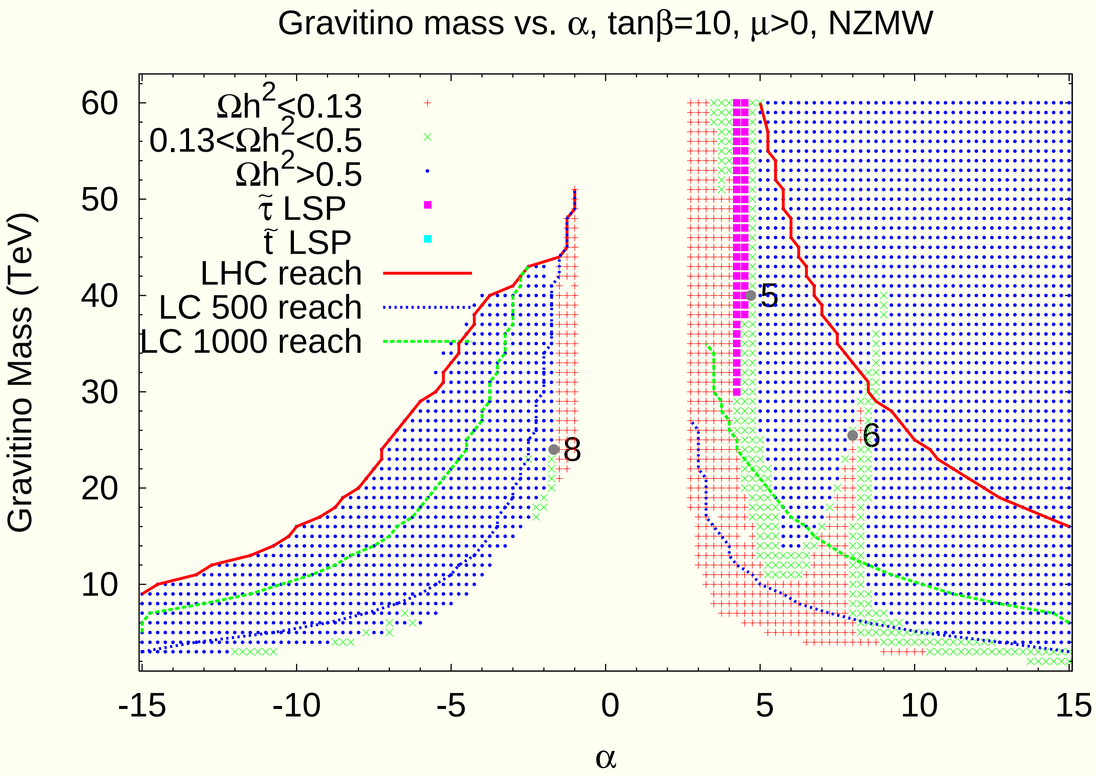
Stop coannihilation region.

Mixed higgsino region at low positive alpha.

BWCA for $\alpha < 0$. No MWDM region.

In the neighbourhood of Point 2, $m_{\tilde t_1} < m_t$, $m_h \lesssim 120$ GeV

$\Rightarrow$ Electroweak baryogenesis? (Carena, Quiros, Wagner; Balázs, Carena, Wagner)



Stau coannihilation, Higgs funnel and BWCA regions clearly seen.

Also, mixed bino-wino-higgsino region (via low $|M_3|$).

Bulk region at low $m_{3/2}$.

LHC reach qualitatively similar to ZMW case.

MM-AMSB Summary

- ⋆ MM-AMSB new, consistent, theoretically-motivated and phenomenologically viable framework. Fewer parameters than mSUGRA if the (discrete) modular weights are fixed. NZMW choice of modular weights appears to have an RG invariant spectrum, just as in the AMSB model.
- ⋆ Novel mass patterns possible; Unconventional $M_1 : M_2 : M_3$; $\tilde{t}_1$ very light, especially for ZMW model (possibly even accessible at the Tevatron).
- ⋆ Top-down framework that can give $M_1(\mathrm{weak}) \sim -M_2(\mathrm{weak})$ that was phenomenologically identified as a possibility for obtaining the right CDM relic density; also potentially gives reduced $|\mu|$ via relative reduction of M_3. Correct relic density possible via a variety of mechanisms including, bulk annihilation, Higgs funnel, stop or stau coannihilation, low $|\mu|$ via reduced M_3 and BWCA. MWDM and low $|\mu|$ via non-universal Higgs mass parameters was not possible for cases that we investigated. Collider and DM searches will discriminate between these various possibilities.

- ⋆ Heavy gravitino $\Longrightarrow$ Good for cosmology.
- ⋆ Large part of parameter space consistent with measured CDM relic density will be probed at LHC; over part of this space, precision measurements will be possible at a 1 TeV e^+e^- LC. Importantly, LC experiments will explore charginos and neutralinos in the BWCA region; these may be difficult to explore at the LHC on account of the small mass gap.
- ⋆ Mirage unification of soft SUSY breaking parameters (readily testable for gaugino masses if sparticles are accessible).
- ⋆ Direct determination of modular weights appears to be possible.

(For details, see Ting Wang at SUSY 2006.)