Phenomenology of Mixed Modulus-Anomaly Mediated SUSY Breaking Models

Xerxes Tata
University of Hawaii

Based on work with Howard Baer, Eun-Kyung Park and Ting Wang

JHEP **08**, 041 (2006), Phys. Lett. **B641**, 447 (2006), and work in progress.

Motivation and Framework

Phenomenology depends on how SUSY breaking effects are communicated to MSSM fields

- ⋆ Modulus (Gravity)-mediation+ assumptions mSUGRA Model $\Longrightarrow$ Universality (usually bino-like neutralino or gravitino LSP)
- ⋆ Gauge-mediation GMSB Models $\Longrightarrow m_i \propto g_i^2$ (light gravitino LSP)
- ⋆ Anomaly-mediation AMSB Models $\Longrightarrow m_i \propto \beta_i$ wino-like neutralino LSP

Modulus + Anomaly Mediation

Mixed Modulus-Anomaly Mediated Supersymmetry Breaking (MM-AMSB)

WHY MM-AMSB?

MM-AMSB structure of MSSM soft SUSY breaking terms arises if the moduli of type IIB superstring are stabilized because space curls up with fluxes (non-zero field strengths) along the extra dimensions.

Kachru, Kallosh, Trivedi and Linde's 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.

Three Step Construction

1. Compactification with fluxes stabilizes shape moduli and dilation fields and makes them heavy, but preserves SUSY
2. Size modulus T stabilized by a non-perturbative mechanism; $m_T \gg m_{3/2}$, AdS space.
3. Introduce anti-D3 brane; makes vacuum energy positive; breaks SUSY.

$$m_{\mathrm{SUSY}} = F_T/T \ll m_{3/2}$$

No concrete realization of KKLT idea with an explicit C-Y space and choice of fluxes that leads to a ground state with all the required properties (e.g. SM, dS spacetime)!

MSSM SUSY breaking modulus-mediated contributions, $m_{\rm SUSY} \ll m_{3/2}$, so may be comparable or smaller than loop AMSB ones.

In original KKLT construction, $m_{3/2} \simeq m_{\rm SUSY} \ln(\frac{M_P}{m_{3/2}})$.

Nevertheless the KKLT construction motivated model builders to consider what the structure of the soft SUSY breaking contributions to the MSSM might look like if such a construction becomes possible. The discovery of a realistic string vacuum would, for better or worse, of course fix everything!

PHENOMENOLOGICAL APPROACH.

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

Generalize the non-perturbative superpotential and also the "lifting potential" that gave positive vacuum energy:

$$\frac{F_T}{T} = \mathrm{coeff} \times \frac{m_{3/2}}{\ln \frac{M_P}{m_{3/2}}} \sim \mathrm{coeff} \times \frac{m_{3/2}}{4\pi^2}.$$

The ratio between anomaly and modulus mediated SUSY breaking contributions then depends on this generalization.

Parametrize this ratio by α. Since it is a ratio of products of VEVs, α can take either sign.

Warning: There are two conventions for α in the literature!

$$\alpha_{\mathrm{Our}} = \alpha_{\mathrm{FLM}} = \frac{16\pi^2}{\ln(M_P/m_{3/2})}\frac{1}{\alpha_{\mathrm{Choi}}}$$

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) for matter on D7 (D3) branes.
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 with wino-like neutralino LSP.

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, $m_{H_u}^2$ can be modest at weak scale. (Lebedev,Nilles, Ratz; Choi et al; Kitano, Nomura).

In general, we lose the scale independence of the AMSB model.

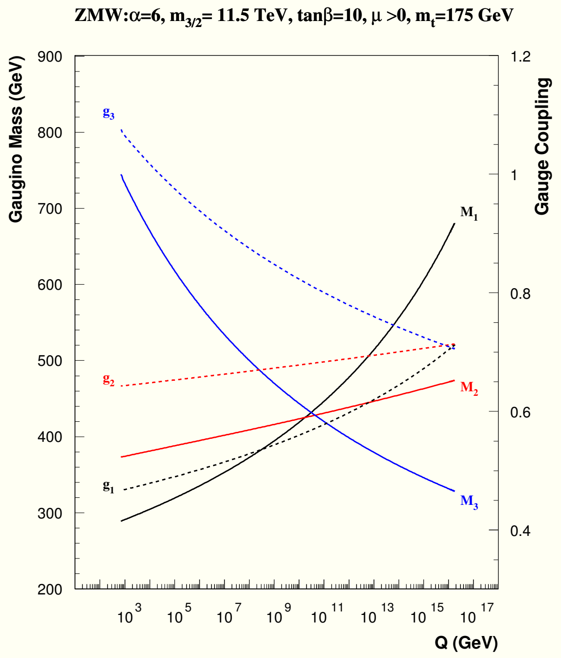
For $l_a = 1$, the cases

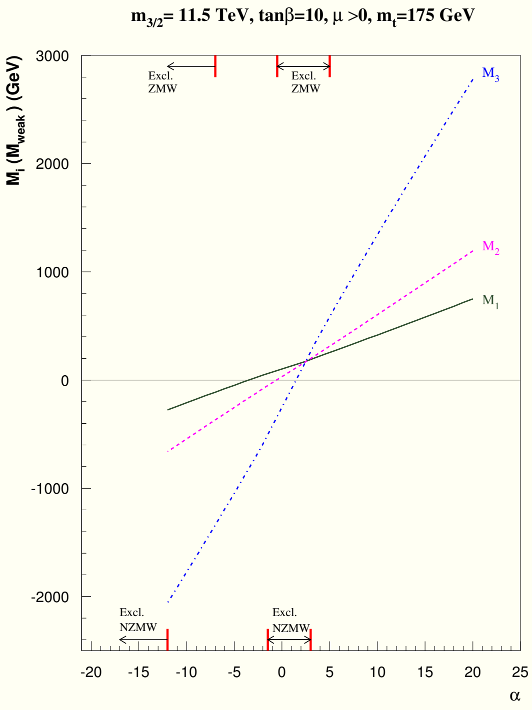
$n_{\rm matter} = \frac{1}{2}$, $n_{\rm Higgs} = 1$ (and $n_{\rm matter} = 1$, $n_{\rm Higgs} = 0$) is special, as we will see.

For the most part, 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).

True Unification and Mirage Unification

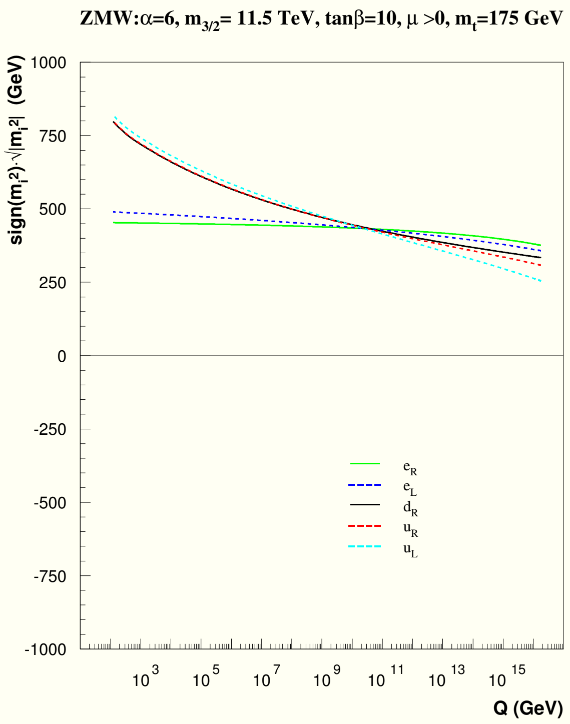


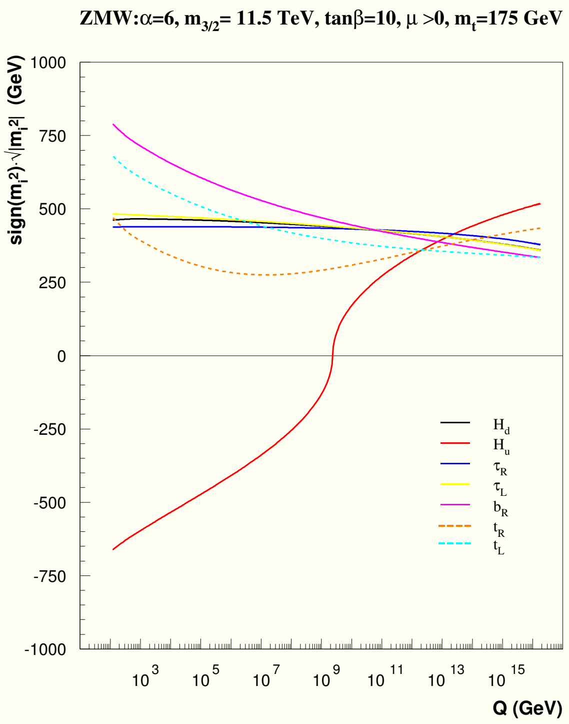


Low mirage unification scale

If $M_1\mathrm{weak} = \pm M_2\mathrm{weak}$, potential for agreement with relic density via Mixed Wino DM (MWDM) / Bino-Wino Coannihilation (BWCA).

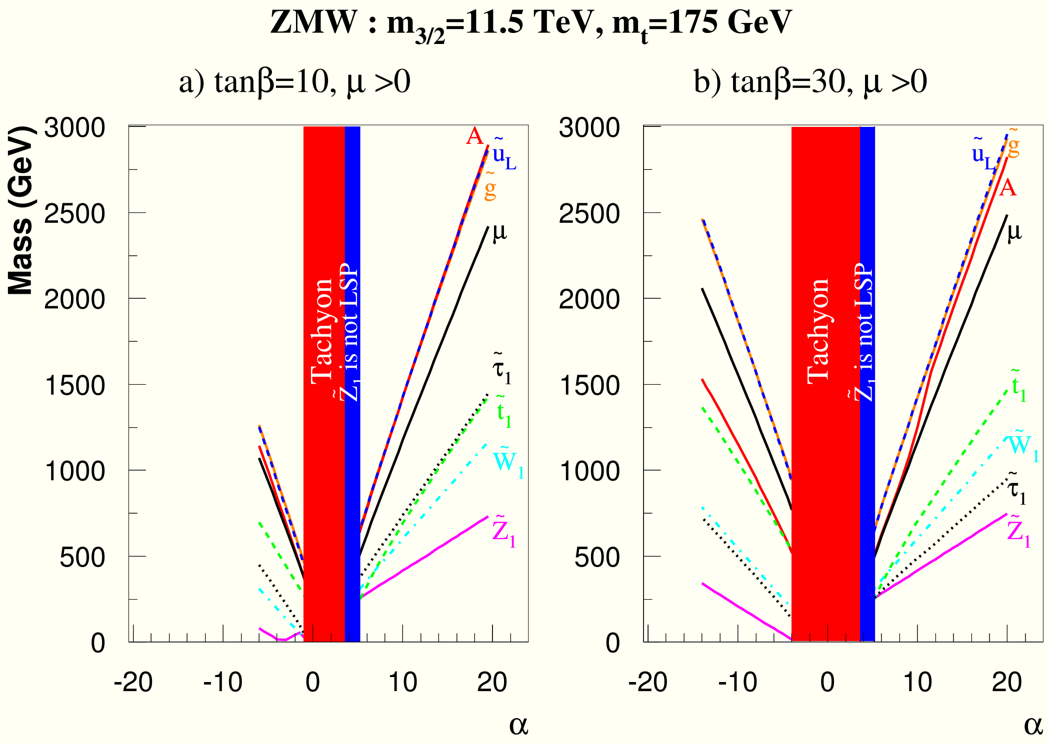
ZMW Model



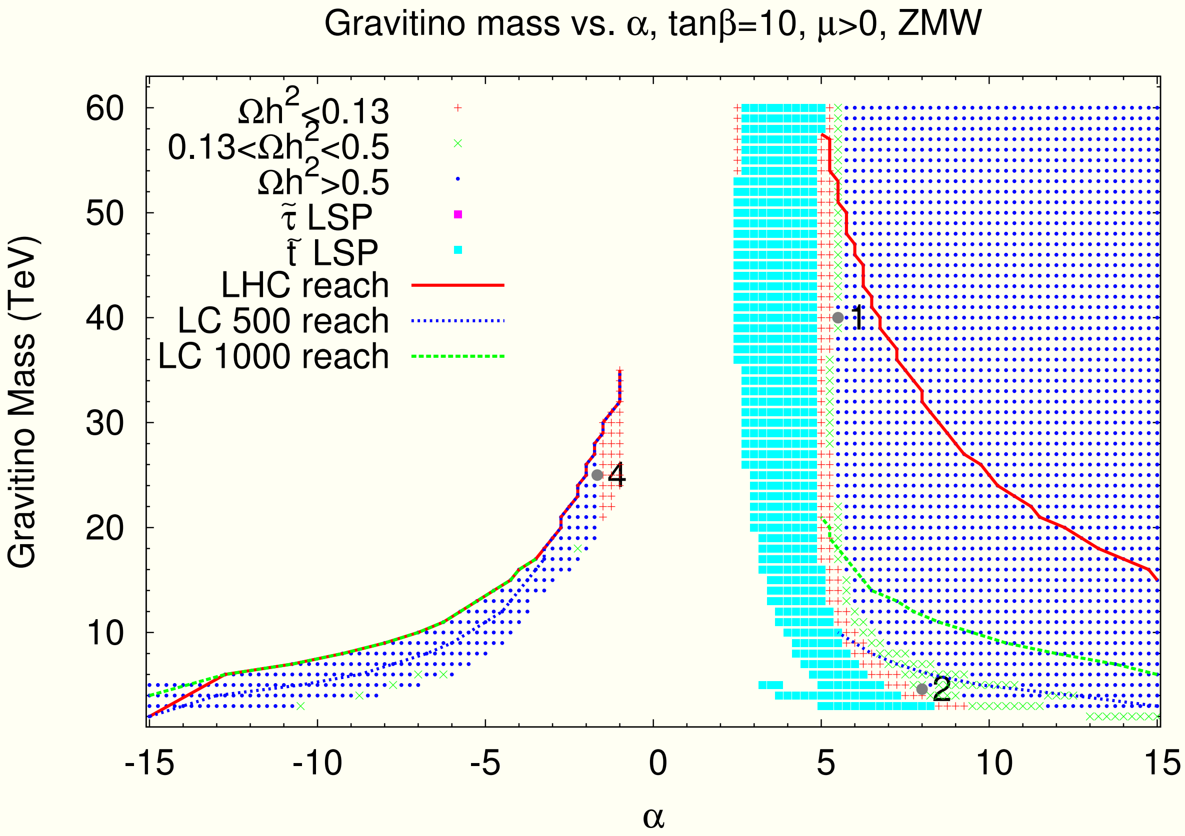


Mirage unification for scalar masses also, but spoiled by Yukawa couplings (NZMW model is an exception). Note low value of $m_{\tilde{t}_R}$. Anticipate light $\tilde{t}_1$.

ZMW Model Mass Spectrum



For low positive α, $m_{\tilde{t}_1} \sim m_{\widetilde{Z}_1}$, and for large $\tan\beta$ $m_{\tilde{\tau}_1} \sim m_{\widetilde{Z}_1}$ also. Stop and stau co-annihilation mechanisms operative. For negative α in first frame, we have BWCA. No MWDM possible as for the required α, $\tilde{t}_1 =$ LSP.



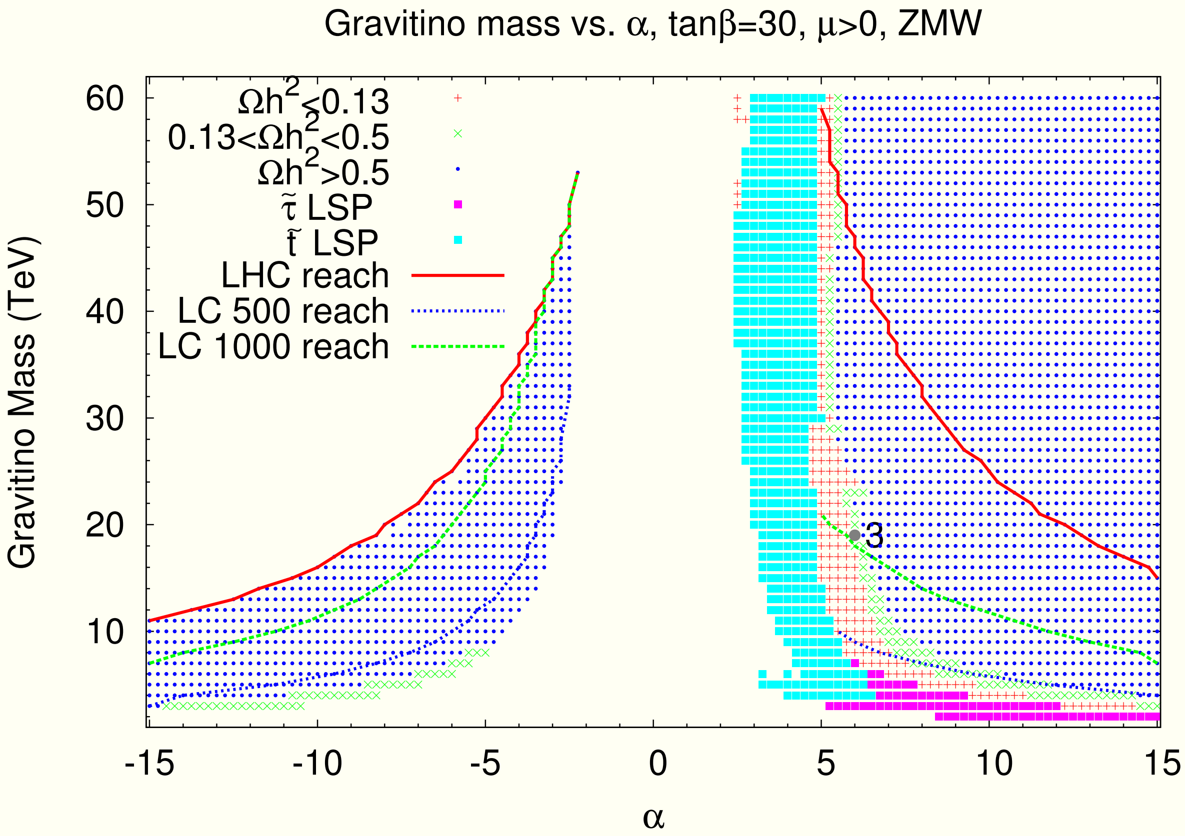
Stop coannihilation region.

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

⇒ Electroweak baryogenesis? (Carena, Quiros, Wagner; Balázs, Carena, Wagner)



Stop and stau coannihilation regions.

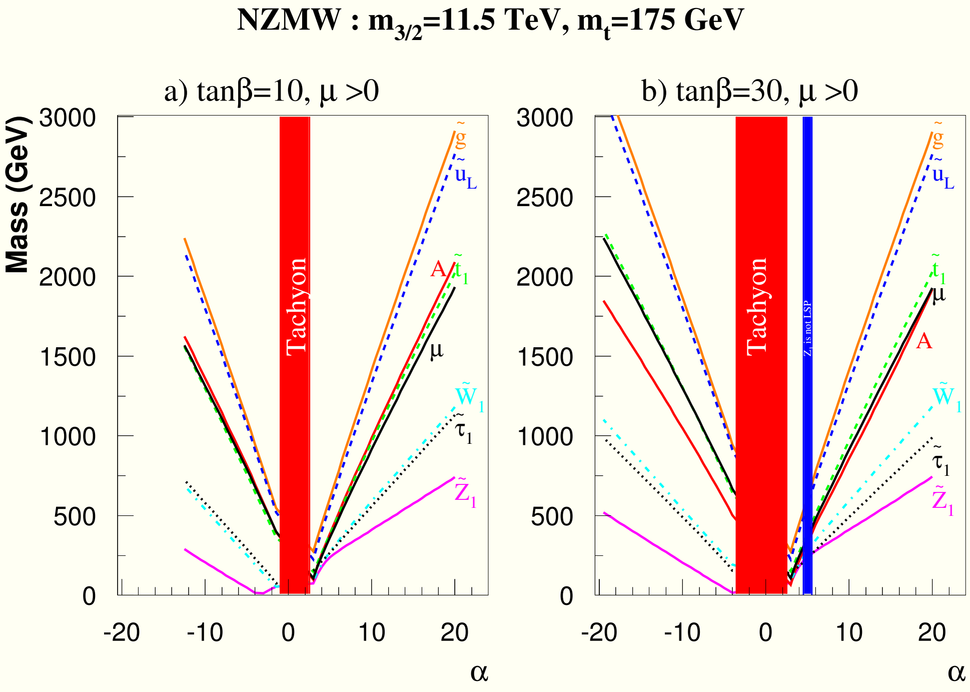
BWCA region disappears.

LHC Covers most of the WMAP allowed planes except for large $m_{3/2}$ near $\alpha \sim 5-6$.

- ⋆ Point 1: Heavy spectrum; stop coannihilation important for relic density; LHC signals will be events with 2-4 hard jets plus $E_T^{\rm miss}$ with enrichment of b-jets.
- ⋆ Point 2: Light spectrum; $m_{\tilde{t}_1} = 161$ GeV accessible at Tevatron, though mass gap is only 30 GeV; $\widetilde{W}_1 \to \tilde{t}_1 b$! 100 pb sparticle cross section at LHC; several mass edges; sparticle mass measurements?
- ⋆ Point 3: Medium spectrum; Enhanced $\widetilde{Z}_2$ decays to taus; $B(\widetilde{W}_1 \to \tilde{t}_1 b)$ ∼47%.
- ⋆ Point 4: Similar squark and gluino spectrum as Point 3, except that $\tilde{t}_1$ is not lighter than $\widetilde{W}_1$; relic density via BWCA, so $m_{\widetilde{W}_1} \simeq m_{\widetilde{Z}_2} \sim m_{\widetilde{Z}_1}$. The small mass gap may make decay products of $\widetilde{W}_1$, $\widetilde{Z}_2$ harder to see at a hadron collider.

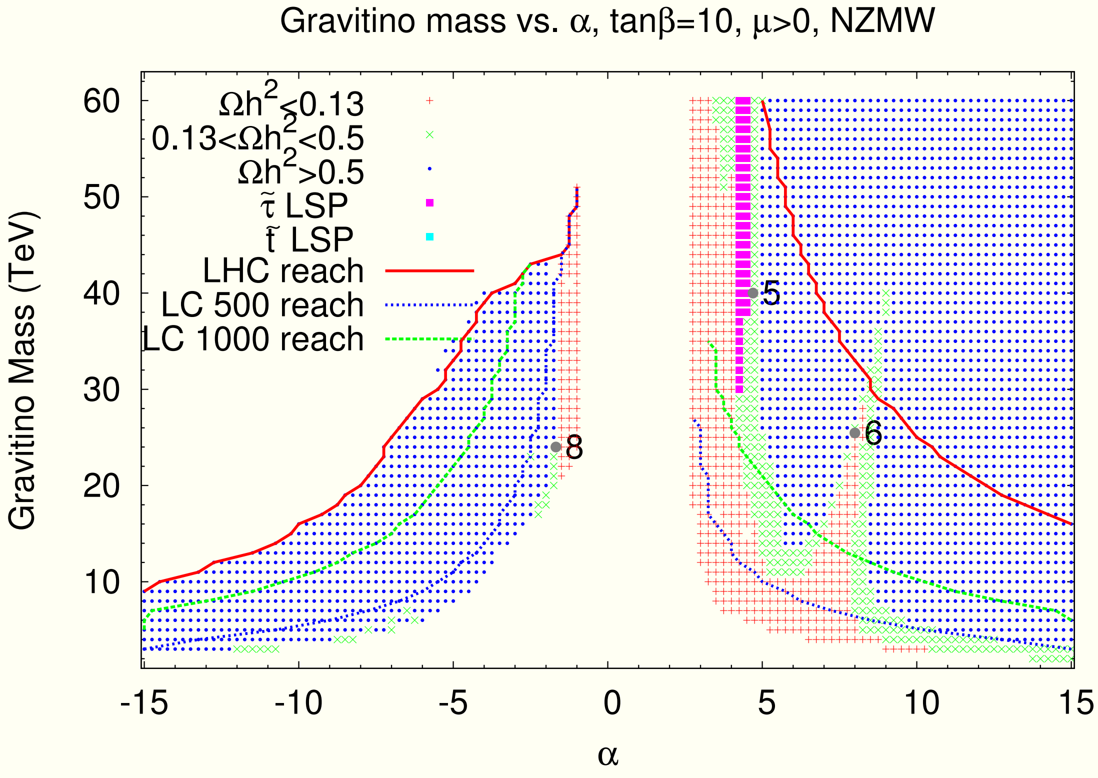
NZMW Model: $n_{\rm matter} = 1/2,\ n_{\rm Higgs} = 1$

Now, the modulus-mediated contribution to A(GUT) $\sim M_s$, so stop is not as light as in ZMW case.



Stau NLSP $\Longrightarrow$ Stau co-annihilation; Higgs funnel annihilation

Also, BWCA for $\alpha < 0$, $\tan\beta \sim 10$.



Stau coannihilation, Higgs funnel and BWCA regions clearly seen.

Also, mixed bino-wino-higgsino region (via low $|M_3|$). [Lower $|M_3| \Rightarrow$ Reduced $|\mu|$.]

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

LHC reach qualitatively similar to ZMW case.

Direct and Indirect DM detection

Many experiments for direct and indirect WIMP detection.

Direct Detection

Stage 2 (CDMS2): SI $\sigma(\widetilde{Z}_1 p) > 3 \times 10^{-8}$ pb
Stage 3 (SuperCDMS, XENON): 10^{-9} pb
Stage 3' (WARP 1400) Warm Argon Project 10^{-10} 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.

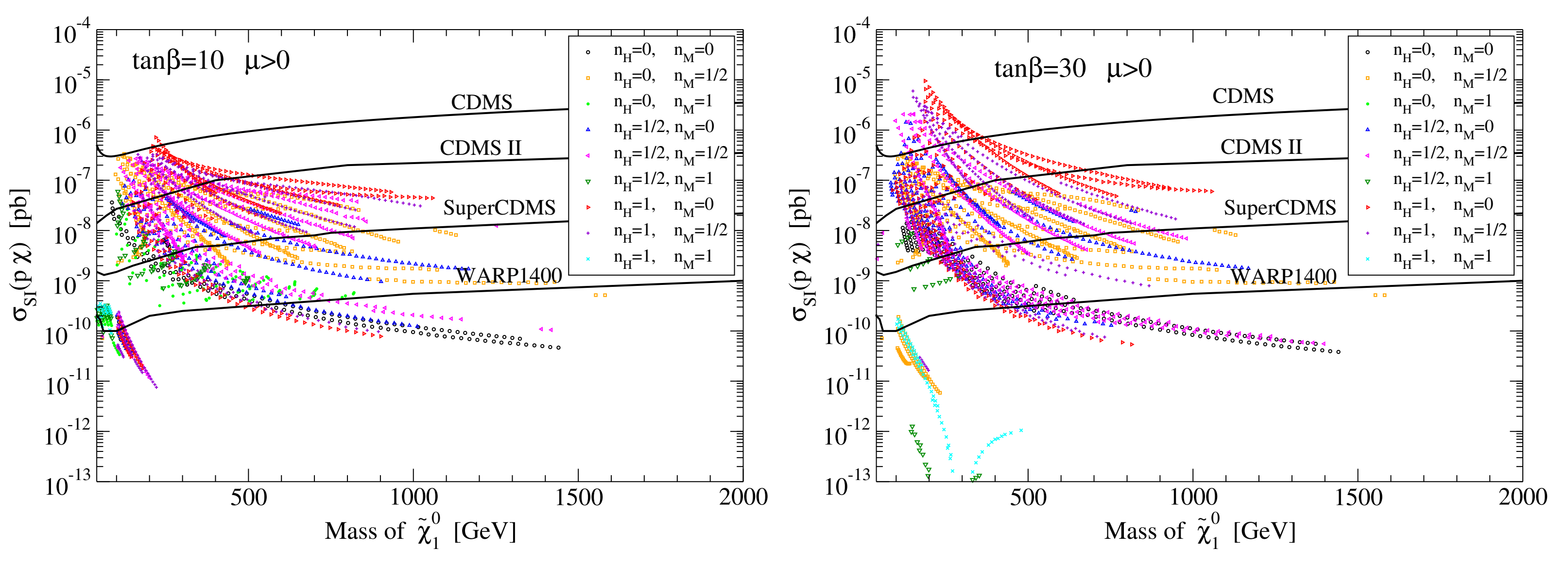
Eight Case studies (4 ZMW, / 4 NZMW)

Direct detection (Stage 2): No observable signals anticipated.
Direct detection (Stage 3): Observable signals if LSP has significant higgsino components or is close to Higgs funnel (2, 5, 7)
IceCube: No observable signals anticipated
GLAST: Observable signals in many cases (2-8)
e^+, $\bar{p}$: Observable signals near Higgs funnel(6, 7)
GAPS: Observable signal near Higgs funnel region/bulk region (2, 6, 7)
γ and antiparticle signals sensitive to halo profile. Our projections are on the optimistic side.

Generally, no DM signals in stau, stop co-annihilation regions or BWCA region anticipated as LSP is a bino.

General exploration of direct detection signal

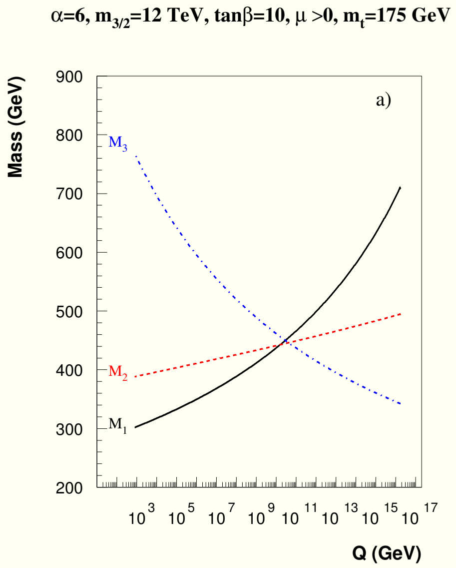
Requiring consistency with WMAP frequently yields a bigger direct detection cross section if annihilation rate is enhanced by adjusting the higgsino, and



Required $\Omega_{\widetilde{Z}_1} h^2 < 0.13$, $m_{\widetilde{W}_1} > 103.5$ GeV, $m_h > 110$ GeV.

DETERMINATION OF MODULAR WEIGHTS AT COLLIDERS

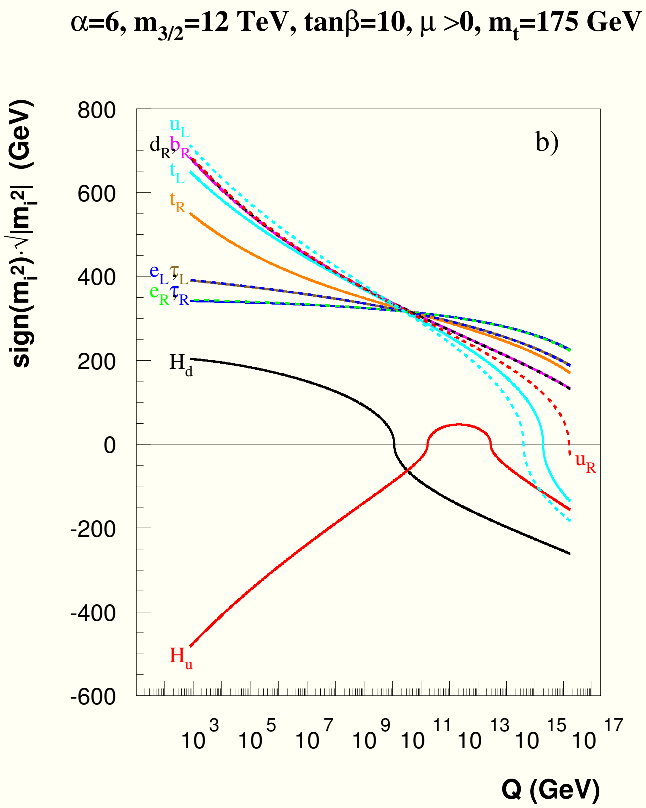
Expect mirage unification of gaugino mass parameters if $l_a \equiv l$ are universal.



If we can determine the gaugino mass parameters at the weak scale, and extrapolate these to high scale using 1-loop RGEs, these should unify at $\mu_{\rm mirage} = M_{\rm GUT} e^{-\frac{8\pi^2}{(l\alpha)}} \Rightarrow (l\alpha)$ determined.

The unified value of the gaugino mass, $M_a(\mu_{\rm mirage}) = M_s \times (l\alpha)$, then gives us M_s.

If the extrapolated values of $m_{\tilde{e}_L}$, $m_{\tilde{e}_R}$, $m_{\tilde{\nu}}$, or first generation squark parameters converge at $\mu_{\rm mirage}$, then we would have a striking confirmation of this picture!


α=6, $m_{3/2}$=12 TeV, tanβ=10, μ >0, m_t=175 GeV

$$\left.\frac{m_i}{M_a}\right|_{\mu_{\rm mirage}} = \frac{\sqrt{c_i}}{l} \Rightarrow$$

Information about matter modular weights (assumed universal for FCNC/GUTS).

CAN WE SEPARATE c_i AND l VALUES?

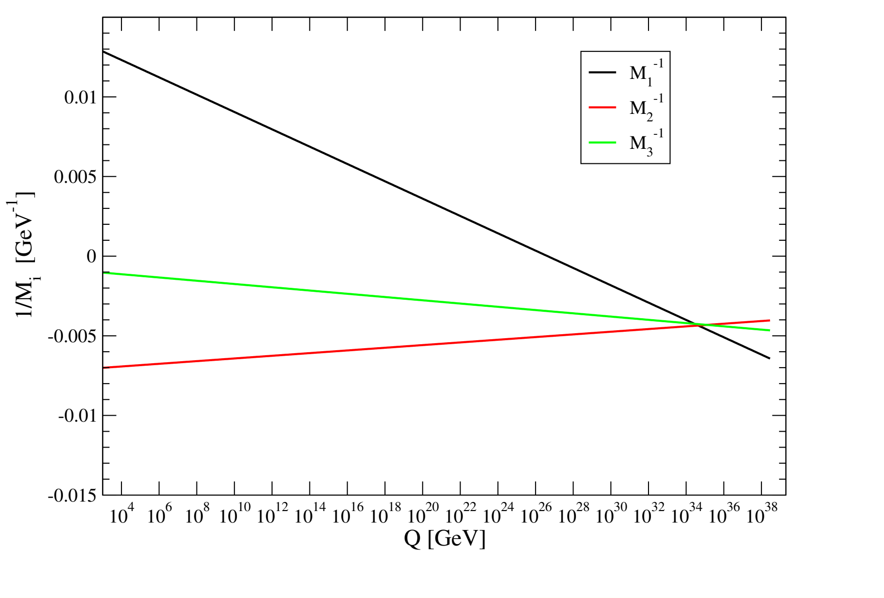
As long as the Yukawa couplings are negligible, the answer is NO! Boundary conditions depend only on, $M_s,\ (l\alpha)$ and c_i/l^2.

We would this need determination of third generation parameters, as well as ability to extrapolate these to high scales.

I think that this is much more difficult. But we have not made a detailed study.

Remember that $\mu_{\rm mirage} = M_{\rm GUT} e^{-\frac{8\pi^2}{(l\alpha)}}$

Can we test mirage unification and determine modular weights for $\alpha < 0$, where $\mu_{\rm mirage} > M_{\rm GUT}$?



Scalar unification in a similar manner.

Conclusions

- ⋆ MM-AMSB new, consistent, theoretically-motivated and phenomenologically viable framework. Fewer parameters than mSUGRA if the (discrete) modular weights are fixed.
- ⋆ 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 serve to discriminate between these various possibilities.

- ⋆ Heavy gravitino $\Longrightarrow$ Good for cosmology.
- ⋆ Very 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. LC1000 reach may exceed LHC reach, depending on what LHC ultimately probes if $n_{\rm matter} = 1$, $n_{\rm Higgs} = 0$ (Preliminary).
- ⋆ Mirage unification of soft SUSY breaking parameters (readily testable for gaugino masses and first generation scalars if sparticles are accessible).
- ⋆ Possibility of direct determination of modular weights at the LHC and ILC, assuming sleptons and charginos are accessible at ILC.