Phenomenology of Mixed Modulus-Anomaly Mediated SUSY Breaking Models

Ting T. Wang

Florida State University

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Outline

- Motivation for the model
- Soft terms at the unification scale
- Some phenomenology
- Measuring modular weights
- Conclusions

Based on work with Baer, Park, Tata. hep-ph/0604253.

Motivation for MM-AMSB models

- There are several mechanisms for mediating the SUSY breaking:
  - Moduli mediation
  - Anomaly mediation
  - Gauge mediation

  Most studies assume one of them is dominant.

- In some models, two mechanisms may give comparable contributions to soft SUSY breaking terms:
  - Models based on KKLT construction (Type IIB).

    Kachru, Kallosh, Linde and Trivedi. PRD68:046005,2003.

  - Kähler stablization models (Heterotic).

    Gaillard and Nelson, NPB571:3-25,2000.

    Kane, Lykken, Mrenna, Nelson, Wang and TTW, PRD**67**, 045008 (2003)

Soft Terms in Moduli SUSY Breaking Models

- The scalar potential in SUGRA is

$$V = K_{I\bar{J}} F^I \bar{F}^{\bar{J}} - 3e^K W\overline{W} + \ldots \qquad K_{I\bar{J}} = \partial^2 K / \partial Z^I \partial \overline{Z}^{\bar{J}}$$

The auxiliary fields and gravitino mass are

$$F^M = -e^{K/2} K^{M\overline{N}} (\overline{W}_{\overline{N}} + K_{\overline{N}} \overline{W}) \qquad \left\langle e^{K/2} W \right\rangle = m_{3/2}$$

- SUSY is broken when some F-terms get non-zero vevs.
- Gaugino masses:

$$M_a = \frac{1}{2} (\mathrm{Re}(f_a))^{-1} F^M \partial_M f_a$$

- Scalar masses: (assuming $\widetilde{K}_{\bar{\alpha}\beta}(h_m, h_m^*) = \delta_{\bar{\alpha}\beta} K_\alpha(h_m, h_m^*)$)

$$m_\alpha^2 = (m_{3/2}^2 + V_0) - F^{\bar{M}} F^N \partial_{\bar{M}} \partial_N \log K_\alpha$$

- Trilinear terms:

$$\widetilde{A}_{\alpha\beta\gamma} = F^M \left[Y_{\alpha\beta\gamma} \partial_M K + \partial_M Y_{\alpha\beta\gamma} - Y_{\alpha\beta\gamma} \partial_M \log K_\alpha K_\beta K_\gamma \right]$$

- In these models, we have

$$m_{soft} \sim \frac{F^T}{T} \sim m_{3/2}$$

Soft Terms in Anomaly Mediated SUSY Breaking Models

The anomaly-induced soft terms are always present in a broken supergravity theory. Suppose the F-term of the chiral compensator gets a vev:

$$\Phi = 1 + F_\Phi \theta^2$$

where $F_\Phi = m_{3/2}$, then the soft terms from super-conformal anomaly are

$$\begin{aligned} M_\lambda &= - \frac{g^2}{2} \frac{d g^{-2}}{d \ln \mu} F_\Phi \\ m^2_{\tilde{Q}} &= -\frac{1}{4} \frac{d^2 \ln Z_Q}{d(\ln \mu)^2} F_\Phi F^*_\Phi \\ A_y &= -\frac{1}{2} \sum_i \frac{d \ln Z_{Q_i}}{d \ln \mu} F_\Phi \end{aligned}$$

The scale of the soft terms is

$$m_{soft} \sim \frac{F_\Phi}{16\pi^2} = \frac{m_{3/2}}{16\pi^2}$$

Randall and Sundrum, NPB557:79-118,1999.
Giudice, Luty, Murayama and Ratazzi,JHEP 9812:027,1998.

Soft terms in KKLT models

- Turn on NS and RR fluxes in the Calabi-Yau compactification of Type IIB superstring theory. This could fix all but the Kähler modulus.
- Include non-perturbative corrections to the superpotential to fix the Kähler modulus. This leads to a SUSY preserving AdS ground state with all moduli fixed.
- Add anti-D branes to get a ds Sitter ground state. SUSY is broken by a very small amount.
- Moduli and anomaly contributions to the soft SUSY breaking terms are comparable.

Conlon, Quevedo, Suruliz, JHEP 0508:007,2005.
Choi, Falkowski, Nilles, Olechowski and Pokorski, JHEP 0411 (2004) 076.
Choi, Falkowski, Nilles and Olechowski, NPB718:113, 2005. Kitano and Nomura, PLB631:58-67,2005

Parameters in MM-AMSB Models

- The Kähler potential is

$$K = -3\ln(T+T^*) + \sum_i \frac{1}{(T+T^*)^{n_i}} Q_i^* Q_i$$

where n_i are the modular weights for the matter fields.

- The gauge kinetic functions are

$$f_a = T^{l_a}$$

- The free parameters are

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

n_i and l_a depend on how to get the SM fields from the brane configuration. We treat them phenomenologically, setting $l_a = 1$ and choosing n_i from $(0, \frac{1}{2}, 1)$.

Soft Terms at the Unification Scale

Each soft term is a summation of moduli and anomaly contributions:

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

In these formulas,

$$
\begin{aligned}
a_{ijk} &= 3 - n_i - n_j - n_k \\
c_i &= 1 - n_i \\
M_s &= \frac{m_{3/2}}{16\pi^2} \\
b_a &= \left(\frac{33}{5}, 1, -3 \right) \\
\gamma_i &= 8\pi^2 \frac{\ln Z_i}{\ln \mu} = 2 \sum_a g_a^2 C_a^2(Q_i) - \sum_{y_i} |y_i|^2 \\
\dot{\gamma}_i &= 2 \sum_a g_a^4 b_a C_a^2(Q_i) - \sum |y_i|^2 \, b_{y_i} \\
\xi_i &= \sum_{j,k} a_{ijk} \frac{y_{ijk}^2}{4} - \sum_a l_a g_a^2 C_a^2(Q_i)
\end{aligned}
$$

Light $\tilde{t}$ in MM-AMSB Models

- We use Isajet 7.74 for mass spectra calculation.
- An interesting feature is $\tilde{t}$ could be quite light due to a relatively large A_t . In the zero modular weights cases, at the high scale we have $|A_t| = 3\,|M_a|$.
- Large A_t helps suppress the $\tilde{t}$ mass through the RGE running:

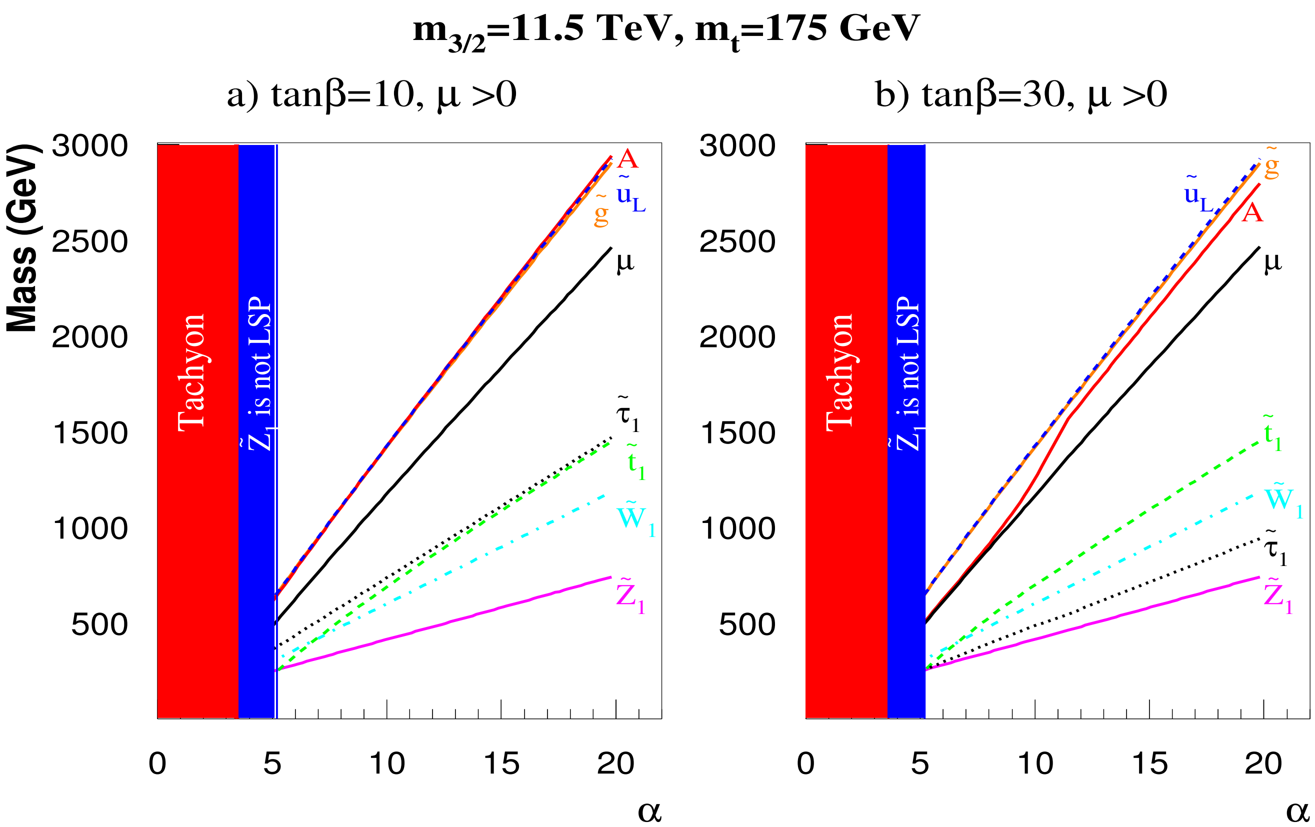
$$\frac{dm^2_{\tilde{t}_R}}{dt} = \frac{2}{16\pi^2}\left(-\frac{16}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 - \frac{2}{5}g_1^2S + 2y_t^2X_t\right)$$

$$X_t = m^2_{Q_3} + m^2_{\tilde{t}_R} + m^2_{H_u} + A_t^2$$

- Large A_t also increases the mixing of scalar tops which reduces the lighter scalar top mass.
- A light $\tilde{t}$ can enhance the strength of the first-order phase transition and therefore make the Electroweak baryogenesis successful.

Carena, Quiros, Wagner, PLB380:81-91,1996.

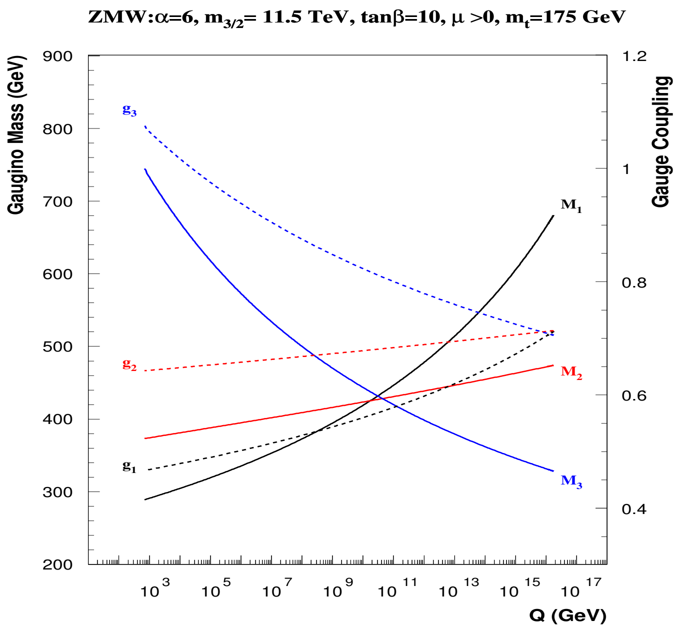
Mass Spectrum for Zero Modular Weights Cases

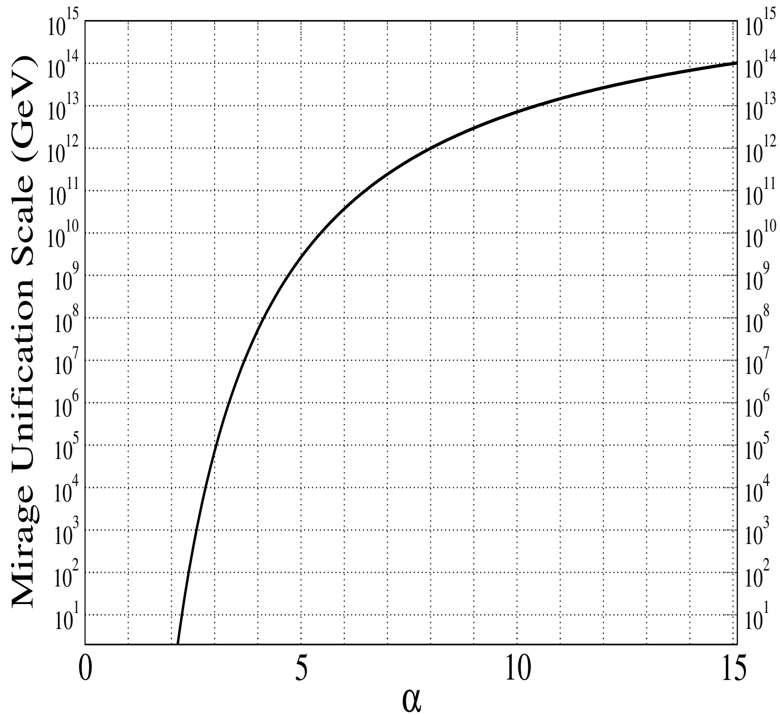


Mirage Unification: Gaugino Masses

The gaugino masses unify at an intermediate scale:

$$\mu_{mir} = M_{GUT} e^{-8\pi^2/\alpha} \qquad M_a(\mu_{mir}) = M_s \alpha$$

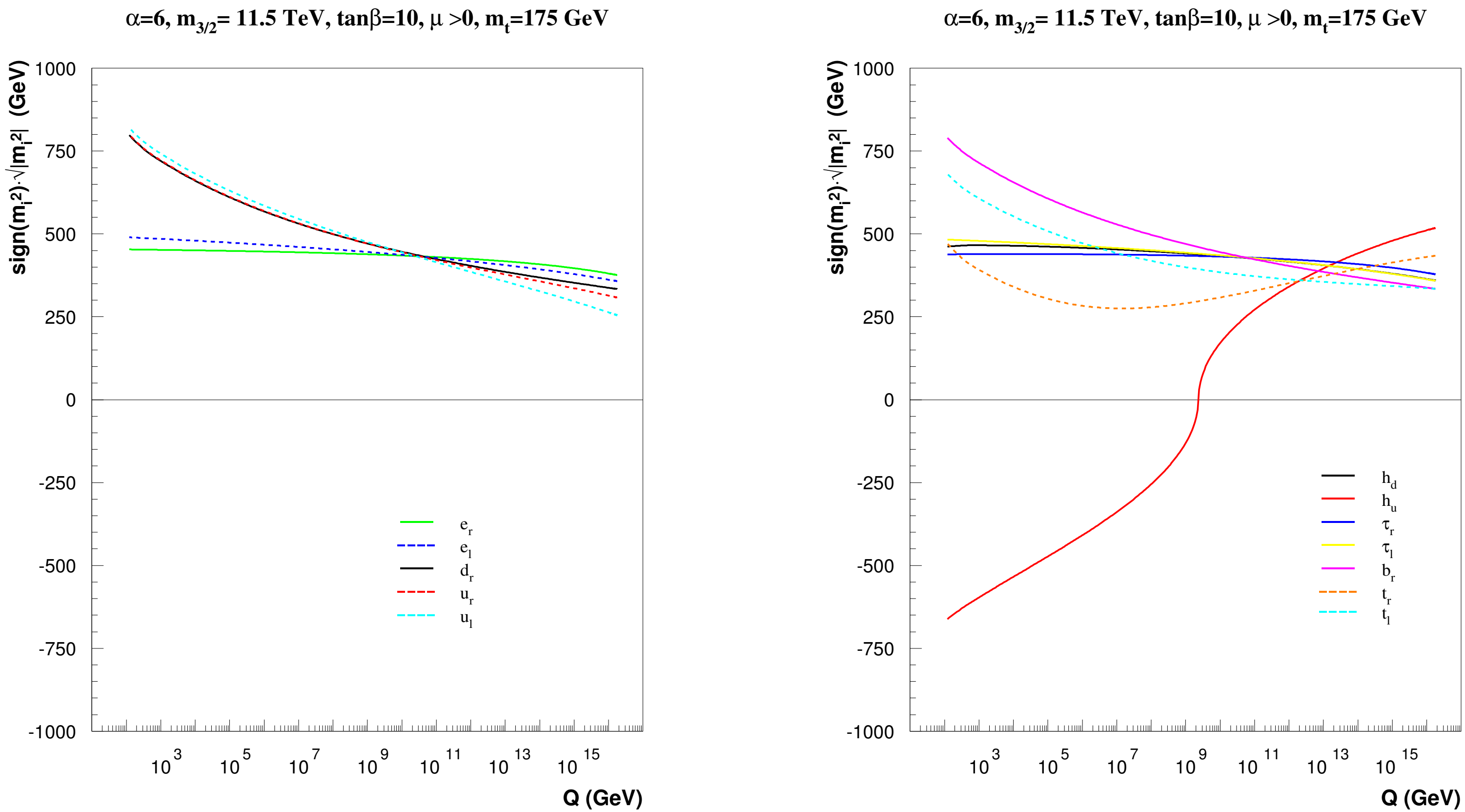




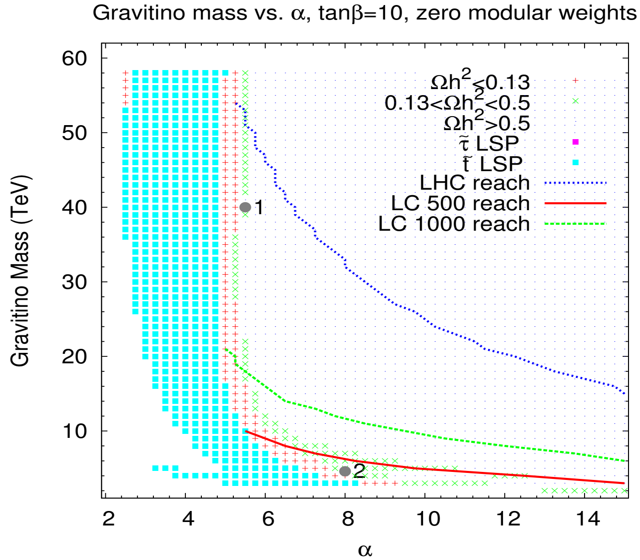
Mirage Unification: Scalar Masses

The scalar masses also unify at the same intermediate scale μ_{mir} :

$$\mu_{mir} = M_{GUT} e^{-8\pi^2/\alpha} \qquad m_i(\mu_{mir}) = M_s \alpha$$



Collider Reach and WMAP Constraints for Zero Modular Weights Cases

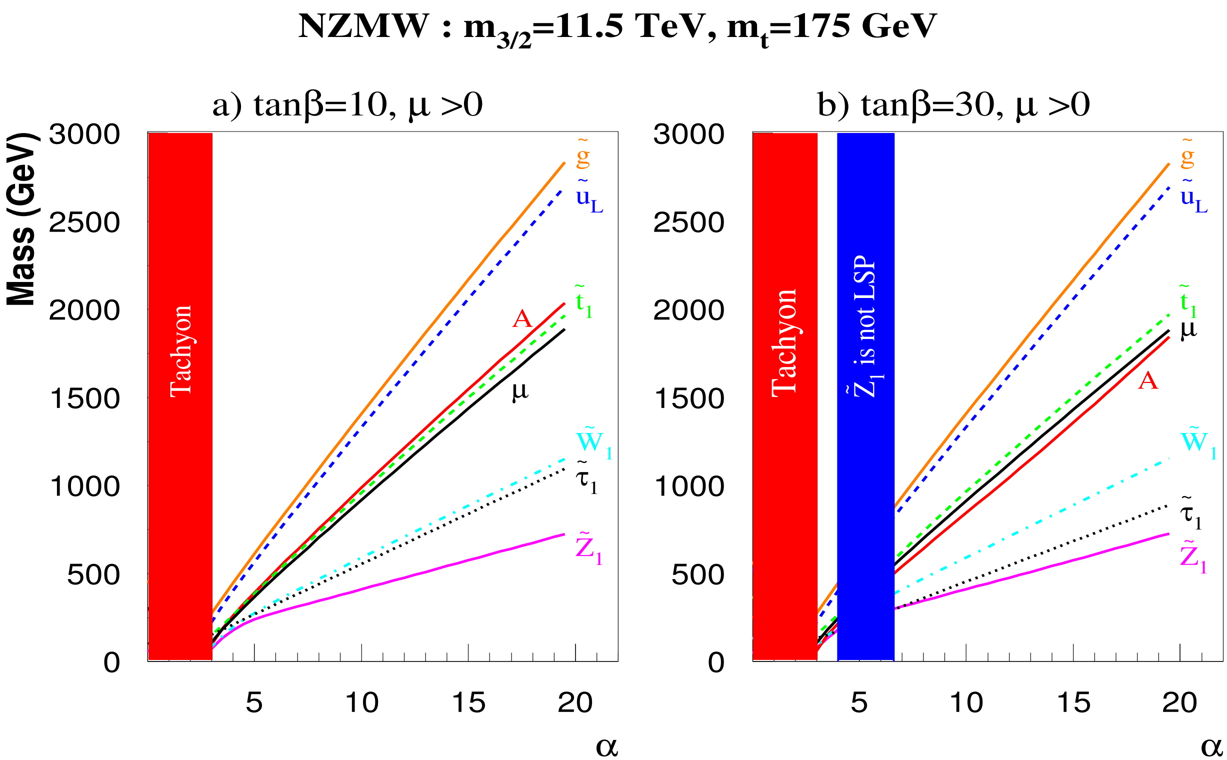


	KKLT1	KKLT2
α	5.5	8
$m_{3/2}(TeV)$	40	4.6
$\tan\beta$	10	10
μ	1753.8	371.9
$m_{\tilde{g}}$	2256.2	475.8
$m_{\tilde{u}_L}$	2273.5	470.5
$m_{\tilde{t}_1}$	1076.5	161.7
$m_{\tilde{b}_1}$	1871.4	396.0
$m_{\tilde{e}_L}$	1536.3	270.9
$m_{\tilde{e}_R}$	1438.8	247.4
$m_{\tilde{\tau}_1}$	1397.8	232.0
$m_{\widetilde{W}_1}$	1215.2	178.1
$m_{\widetilde{Z}_2}$	1244.9	183.3
$m_{\widetilde{Z}_1}$	979.1	132.3
m_A	2326.7	446.2
m_h	124.4	114.1
$\Omega_{\widetilde{Z}_1}h^2$	0.12	0.11
$BF(b \to s\gamma)$	3.3×10^{-4}	9.8×10^{-5}
Δa_μ	6.1×10^{-11}	20.1×10^{-10}
$\sigma_{sc}(\widetilde{Z}_1 p)$	7.8×10^{-11} pb	5.0×10^{-9} pb

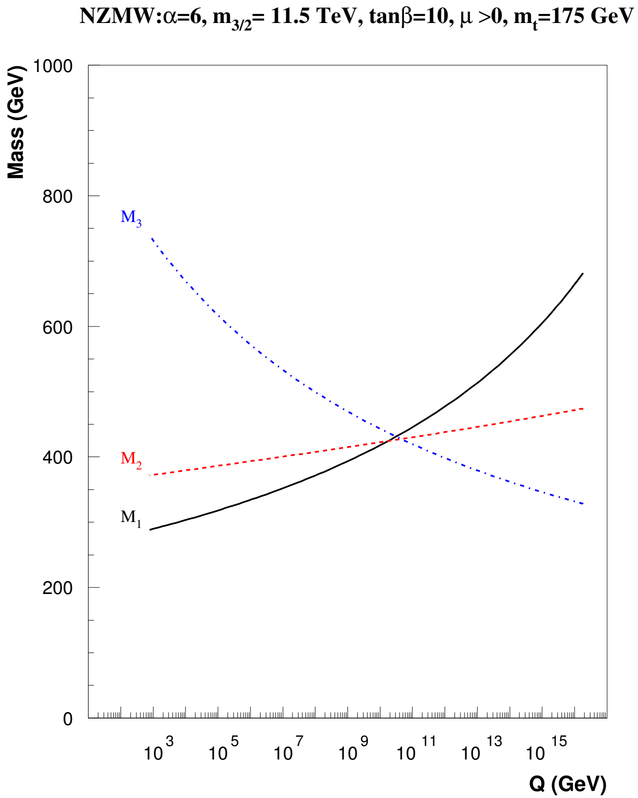
Mass Spectrum for Non-Zero Modular Weights Cases

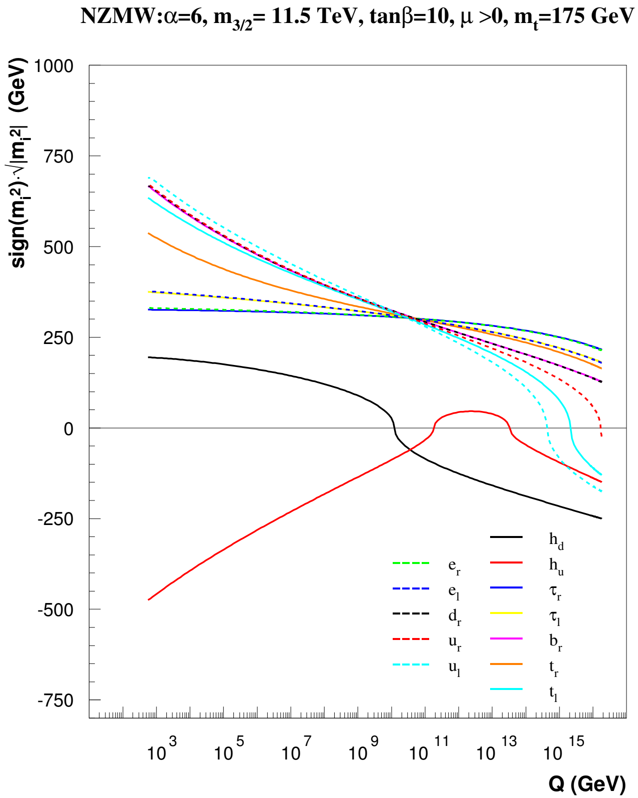
As an example for non-zero modular weights, we consider

$$n_{H_u} = n_{H_d} = 1 \qquad n_{\text{matter}} = \frac{1}{2}.$$

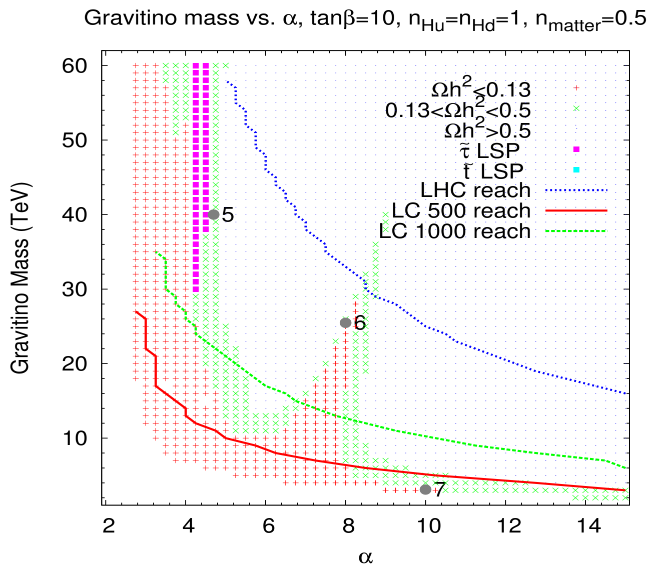


Evolution of Soft Terms in Non-Zero Modular Weights Cases





Collider Reach and WMAP Constraints for Non-Zero Modular Weights Cases



	KKLT5	KKLT6
α	4.7	8
$m_{3/2}(TeV)$	40	25.467
$\tan\beta$	10	10
μ	1023.1	1425.3
$m_{\tilde g}$	1808.8	2304.6
$m_{\tilde u_L}$	1644.1	2158.8
$m_{\tilde t_1}$	1254.5	1601.5
$m_{\tilde b_1}$	1520.5	1971.1
$m_{\tilde e_L}$	985.7	1149.0
$m_{\tilde e_R}$	886.3	993.0
$m_{\tilde \tau_1}$	879.8	982.9
$m_{\widetilde W_1}$	968.6	1077.2
$m_{\widetilde Z_2}$	990.7	1108.9
$m_{\widetilde Z_1}$	869.1	791.2
m_A	1135.3	1581.2
m_h	119.7	120.8
$\Omega_{\widetilde Z_1} h^2$	0.12	0.12
$BF(b\to s\gamma)$	3.4×10^{-4}	3.4×10^{-4}
Δa_μ	1.3×10^{-10}	9.4×10^{-11}
$\sigma_{sc}(\widetilde Z_1 p(\mathrm{pb}))$	4.4×10^{-9}	1.3×10^{-10}

Measuring Modular Weights at LHC and ILC

- At the mirage unification scale $\mu_{mir} = M_{GUT} e^{-8\pi^2/\alpha}$, we have the relations

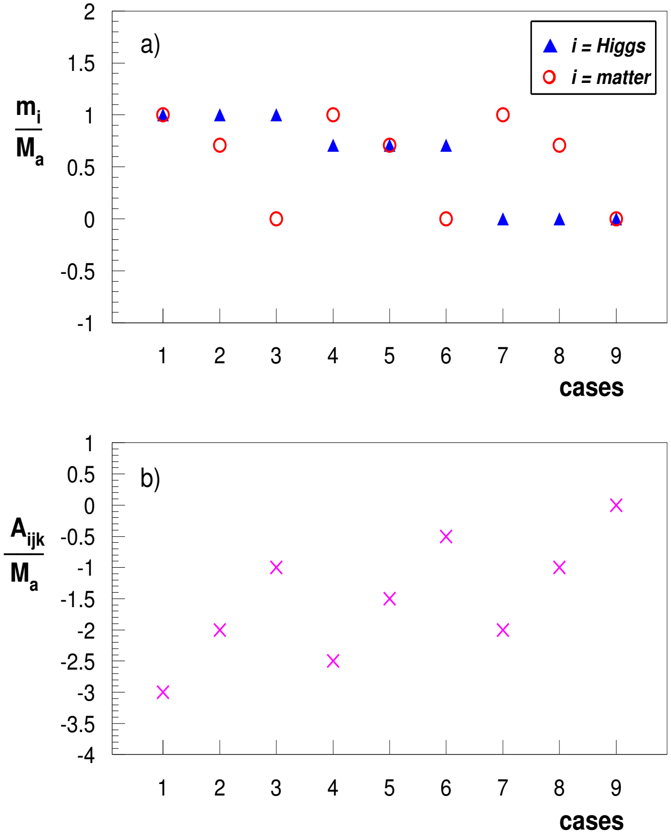
$$\left.\frac{m_i}{M_a}\right|_{\mu_{mir}} = \sqrt{1 - n_i} \qquad \left.\frac{A_{ijk}}{M_a}\right|_{\mu_{mir}} = n_i + n_j + n_k - 3$$

- Typical models have $n = 0, \frac{1}{2},$ or 1 . There are 9 combinations if modular weights are family universal and $n_{H_u} = n_{H_d}$:

case	1	2	3	4	5	6	7	8	9
n_{Higgs}	0	0	0	$1/2$	$1/2$	$1/2$	1	1	1
n_{Matter}	0	$1/2$	1	0	$1/2$	1	0	$1/2$	1

Measuring Modular Weights at the LHC and ILC

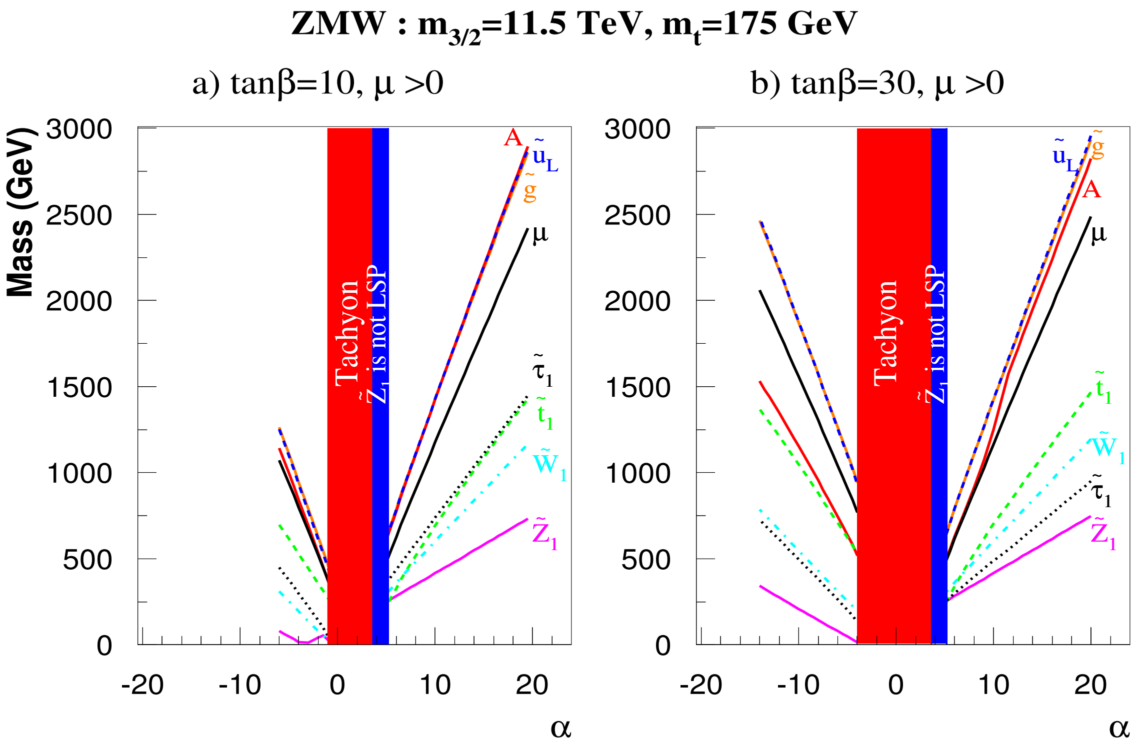
Each case gives a distinct set of mass ratios. Measurements at the LHC and ILC may allow us to determine these ratios and then extract the modular weights.



Conclusions

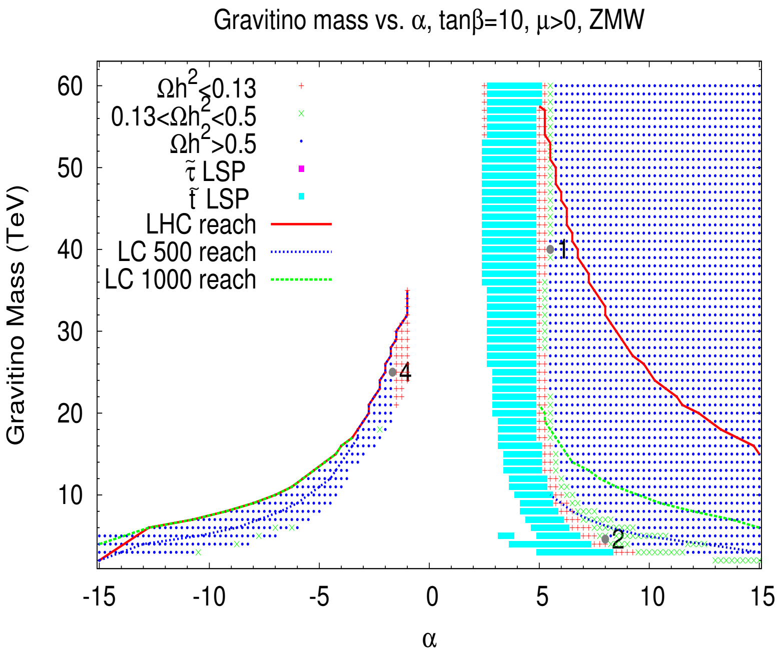
- MM-AMSB models are theoretically well motivated.
- These models solve the tachyonic slepton problem in pure AMSB.
- A large parameter space can satisfy the WMAP constraints.
- Because of the large trilinear terms, $\tilde{t}$ can be quite light. This may help the EW Baryogenesis.
- Most of the WMAP allowed parameter space is detectable at the LHC.
- It is possible to measure the modular weights by using LHC and ILC data.

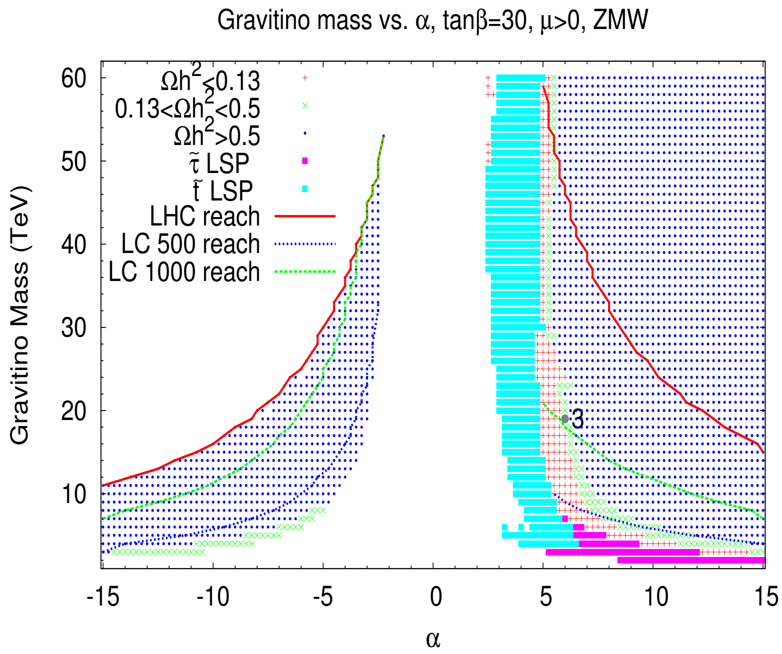
Mass Spectrum for Zero Modular Weights Cases



For low positive α , Stop-LSP and/or stau-LSP coannihilation can reduce relic density.

Collider Reach and WMAP Constraints for Zero Modular Weights Cases



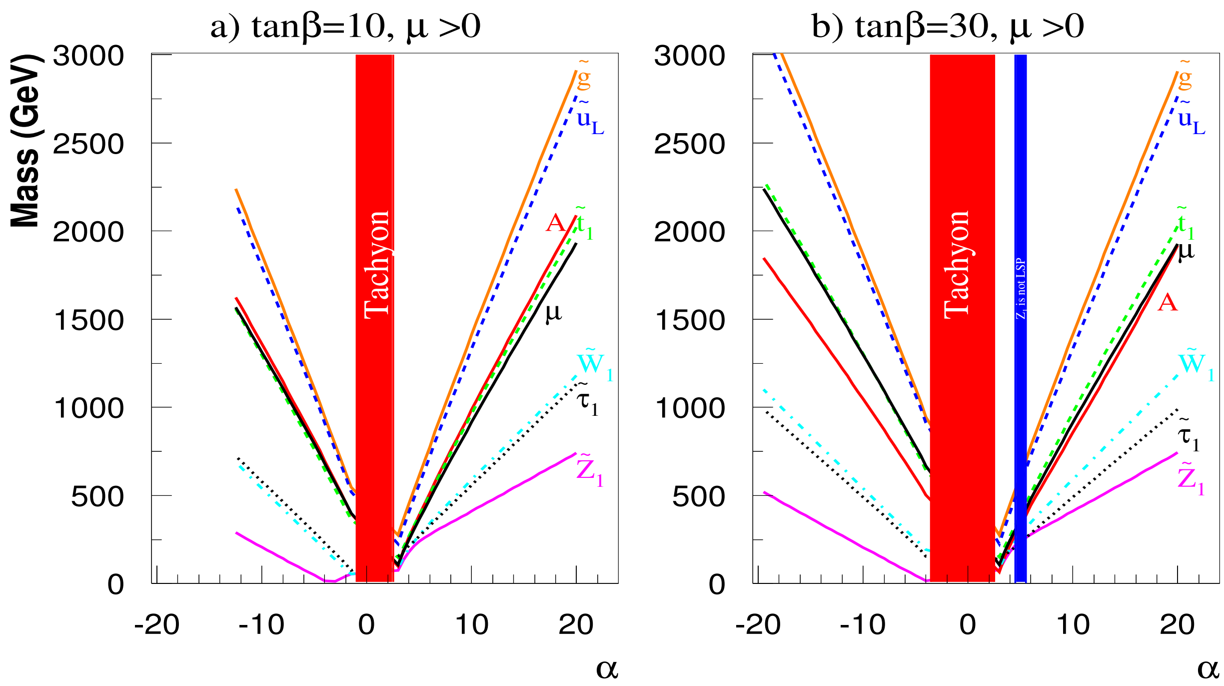


Mass Spectra for Non-Zero Modular Weights

As an example for non-zero modular weights, we consider

$$n_{H_u} = n_{H_d} = 1 \qquad n_{\mathrm{matter}} = \frac{1}{2}.$$

NZMW : $m_{3/2}$=11.5 TeV, m_t=175 GeV



Collider Reach and WMAP constraints for Non-Zero Modular Weights Cases