"Anomaly Mediated Supersymmetry Breaking"

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AMSTERDAM ~~AUGUST~~ JULY! 2002

Also:

F. de Campos, M.A. Diaz, O.J.P. Eboli, M.B. Magro and P.G. Mercadante hep-ph/0110049

K. Huitu, J. Laamanen and P.N. Pandita, hep-ph/0203186

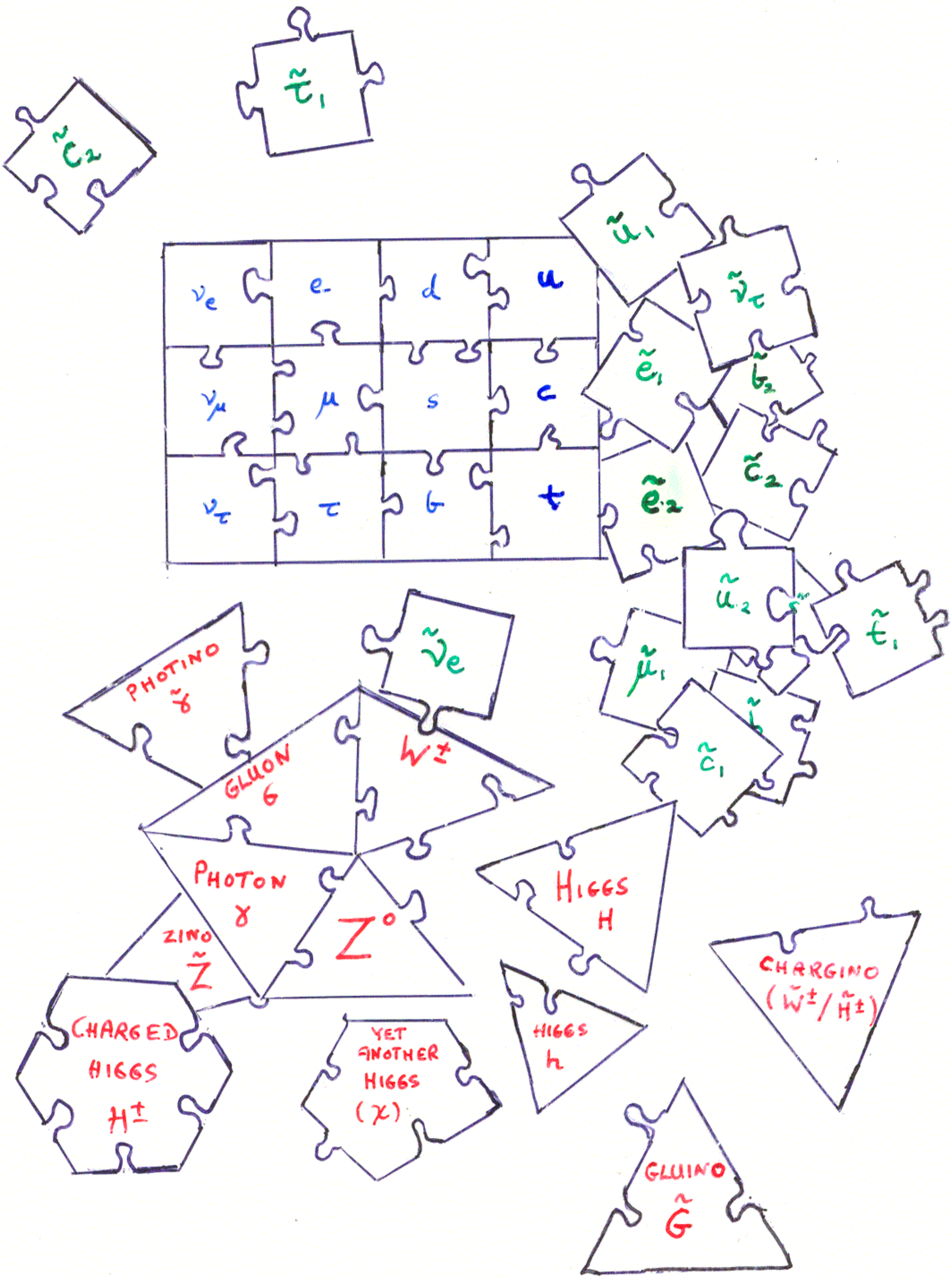
Outline

1. Anomaly Mediated Supersymmetry Breaking
2. FI terms and the tachyonic sleptons
3. Neutrino masses and Yukawa textures
4. AMSB and R-parity violation

The MSSM is the SM with superpartners for everybody: and arbitrary soft masses and ϕ^3 scalar couplings to break supersymmetry.....

The resulting theory has 125 parameters!

THE SUPERSYMMETRIC STANDARD MODEL



The CMSSM

The usual working assumption is that at gauge unification we have

$$\begin{aligned} \text{SCALAR MASSES UNIFY} &\rightarrow m_0^2 \\ \text{SOFT } \phi^3 \text{ TERMS UNIFY} &\rightarrow AY^{ijk} \\ \text{GAUGINO MASSES UNIFY} &\rightarrow M \end{aligned}$$

THERE IS NO CONVINCING THEORETICAL BASIS FOR THIS

THE AMSB SOLUTION

Remarkably the soft β-function equations can be integrated:

$$
\begin{aligned}
M_i &= m_{\frac{3}{2}} \beta_{g_i}/g_i \\
h &= -m_{\frac{3}{2}} \beta_Y \\
m^2 &= \tfrac{1}{2} m_{\frac{3}{2}} m^*_{\frac{3}{2}} \mu \frac{d}{d\mu} \gamma \\
b &= -m_{\frac{3}{2}} \beta_\mu
\end{aligned}
$$

GAUGINOS

ϕ^3

$\phi\phi^*$

These results are exactly RG invariant. They are obtained if the only source of breaking is a vev for an auxiliary field in the supergravity multiplet itself: the AMSB scenario ($m_{\frac{3}{2}}$ is the gravitino mass). To obtain an acceptable vacuum it is necessary to assume another source for b.

The Gaugino masses

In the AMSB scenario:

$$M_i = m_0 \frac{\beta_i}{g_i} = m_0 b_i \frac{\alpha_i}{4\pi}$$

With $b_i = (\frac{33}{5}, 1, -3)$ this gives

$$M_1 : M_2 : M_3 = 0.3 : 0.1 : 1,$$

to be compared with the usual assumption that $M_1 = M_2 = M_3$ at gauge unification, which gives

$$M_1 : M_2 : M_3 = 0.14 : 0.28 : 1,$$

Thus in the AMSB scenario, there is likely to be an approximately degenerate triplet of light winos (a chargino and a neutralino).

$$\tilde{W}^{\pm} \rightarrow \tilde{W}^{0} + \pi^{\pm}$$

LSP

Gaugino mass sum rule Huitu et al

In both AMSB and the CMSSM there is a sum rule relating the chargino and neutralino masses:

$$2\sum_{i=1,2}(M_{\chi_i^{\pm}})^2 - \sum_{j=1\cdots4}(M_{\chi_j^0})^2 = f(g_i)M_3^2 + 4M_W^2 - 2M_Z^2$$

In AMSB type models it is negative while in the CMSSM it is positive.

Huitu et al present sum rules and IR focus point analysis in a range of AMSB scenarios: more later (if time).

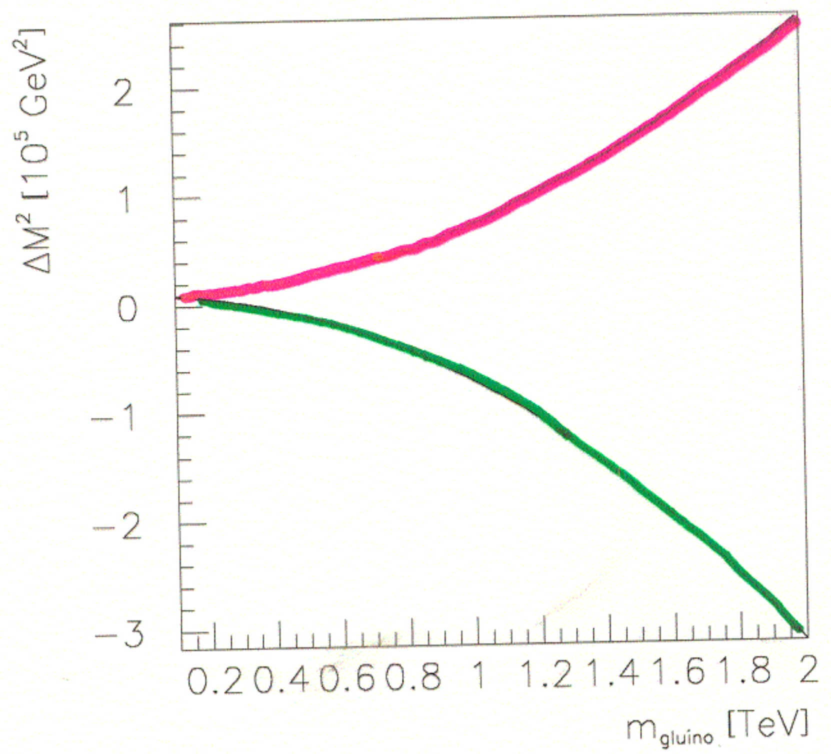


Figure 1: ΔM^2 v. gluino mass for CMSSM and AMSB

The Slepton Mass Problem

The first generation has negligible Yukawa couplings so

$$
\begin{aligned}
4\pi\gamma_{e^c} &= -\tfrac{6}{5}\alpha_1 \\
4\pi\gamma_E &= -\tfrac{3}{2}\alpha_2 - \tfrac{3}{10}\alpha_1
\end{aligned}
$$

which gives

$$
\begin{aligned}
4\pi m_{e^c}^2 &= -\tfrac{6}{10}|m_{\frac{3}{2}}|^2\beta_{\alpha_1} \\
4\pi m_E^2 &= -|m_{\frac{3}{2}}|^2\left(\tfrac{3}{4}\beta_{\alpha_2} + \tfrac{3}{20}\beta_{\alpha_1}\right)
\end{aligned}
$$

The squarks are saved by asymptotic freedom, i.e. because $\beta_{\alpha_3} < 0$.

Solution explored most has been adding a universal soft breaking:

$$m^2 = \frac{1}{2}|m_{\frac{3}{2}}|^2\mu\frac{d}{d\mu}\gamma + \overline{m}_0^2$$

Defect: no longer RG invariant.

The FI Solution

J J
AH, K, M, N
H, M, [redacted] P

$$(\hat{m}^2)^i{}_j = (m^2_{AMSB})^i{}_j + m_0^2 \delta^i{}_j.$$

is not RG invariant, but if we replace it with:

$$(\hat{m}^2)^i{}_j = (m^2_{AMSB})^i{}_j + m_0^2 \sum_{a=1}^{N} k_a (Y_a)^i{}_j$$

then $\hat{m}^2$ *is* RG invariant, as long as

$$\begin{aligned} (Y_a)^i{}_l Y^{ljk} + (Y_a)^j{}_l Y^{ilk} + (Y_a)^k{}_l Y^{ijl} &= 0 \\ \mathrm{tr}[Y_a C(R_\alpha)] &= 0 \end{aligned}$$

This just means that each Y_a corresponds to a U_1 invariance of the superpotential W and also has vanishing mixed anomaly with each MSSM gauge group factor. This apparent miracle occurs because in fact this modification to m^2_{AMSB} is precisely that introduced by a set of Fayet-Iliopoulos (FI) D-terms.

In the MSSM, there is a non-zero FI-term, but this cannot alone solve the slepton problem because its $(\text{mass})^2$ contributions to the LH and RH sleptons have opposite signs, being dictated by the hypercharge of the relevant field. But in fact the MSSM admits an additional (generation independent) anomaly-free U_1, which we call U_1' such that the mixed anomalies $U_1'(SU_3)^2$, $U_1'(SU_2)^2$, $U_1'(U_1)^2$, and $(U_1')^2 U_1$ all cancel. We can choose U_1' to be U_1^{B-L} or some linear combination of U_1^{B-L} and U_1. In fact we chose to require $\mathrm{Tr}(YY') = 0$, leading to the following table:

Table 1: Table of U_1 and U_1' hypercharges.

	Q	L	t^c	b^c	τ^c	H_1	H_2	(S_i)
Y	$\frac{1}{6}$	$-\frac{1}{2}$	$-\frac{2}{3}$	$\frac{1}{3}$	1	$-\frac{1}{2}$	$\frac{1}{2}$	(0)
Y'	$\frac{7}{3}$	-7	$\frac{5}{3}$	$-\frac{19}{3}$	3	4	-4	(s_i)

We can then write:

$$
\begin{aligned}
\overline{m}_Q^2 &= m_Q^2 + \frac{1}{6}\zeta_1 + \zeta_2 Y'_Q, \\
\overline{m}_{t^c}^2 &= m_{t^c}^2 - \frac{2}{3}\zeta_1 + \zeta_2 Y'_{t^c}, \\
\overline{m}_{b^c}^2 &= m_{b^c}^2 + \frac{1}{3}\zeta_1 + \zeta_2 Y'_{b^c}, \\
\overline{m}_L^2 &= m_L^2 - \frac{1}{2}\zeta_1 + \zeta_2 Y'_L, \\
\overline{m}_{\tau^c}^2 &= m_{\tau^c}^2 + \zeta_1 + \zeta_2 Y'_{\tau^c} \\
\overline{m}_{H_1}^2 &= m_{H_1}^2 - \frac{1}{2}\zeta_1 + 4\zeta_2 Y'_L, \\
\overline{m}_{H_2}^2 &= m_{H_2}^2 + \frac{1}{2}\zeta_1 - \zeta_2 Y'_L,
\end{aligned}
$$

and there is a good slice of parameter space [illegible]h that both $-\frac{1}{2}\zeta_1 - 7\zeta_2$ and $\zeta_1 + 3\zeta_2$ are positive

NO FLAVOUR PROBLEM!

AUTOMATIC R-PARITY CONSERVATION

The MASS SPECTRUM

$m_{\tilde{\nu}}$	112			
$m_{\tilde{u}_{L,R}}$	930	851		
$m_{\tilde{d}_{L,R}}$	935	1045		
$m_{\tilde{e}_{L,R}}$	139	339	NB	
$m_{\tilde{t}_{1,2}}$	575	861		
$m_{\tilde{b}_{1,2}}$	825	1040		
$m_{\tilde{\tau}_{1,2}}$	137	339		
$m_{\tilde{\chi}^{\pm}_{1,2}}$	104	649		
m_A	453			
$m_{h,H}$	115	455		
$m_{\chi_{1 \cdots 4}}$	103	366	648	658
$m_{H^{\pm}}$	461			
$m_{\tilde{g}}$	1007			

Table 2: Mass spectrum for $m_0 = 40\text{TeV}$, $\tan\beta = 5$, $\zeta_1 = 0.2, \zeta_2 = -0.02$

Results in red are sensitive to the singlet sector, if one is used to cancel the anomalies: in the table it is assumed that the extra U_1 decouples completely, apart from the FI-term

Mass Sum Rules

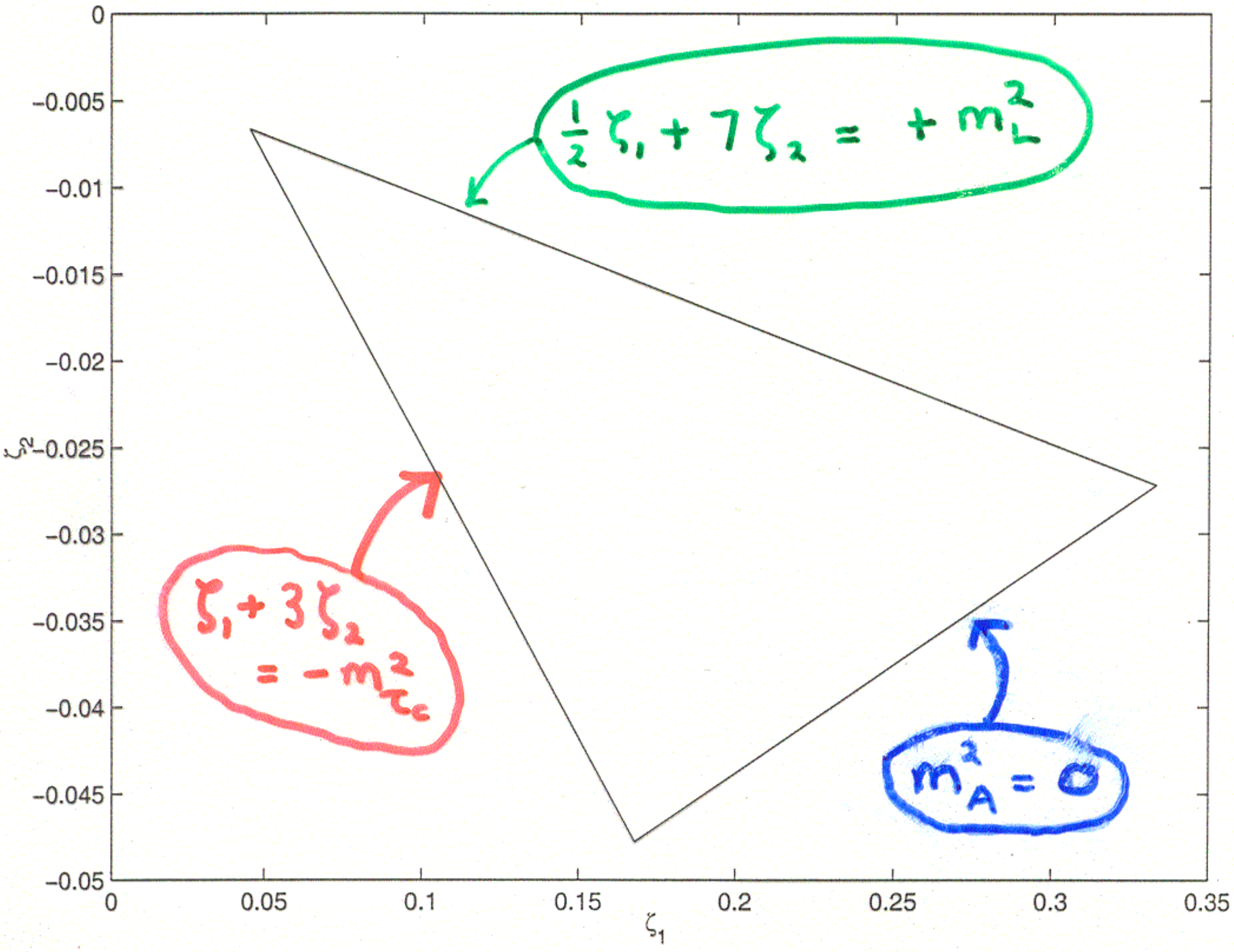
The following sum rules for the physical masses are independent of $\zeta_{1,2}$:

$$
\begin{aligned}
m^2_{\tilde t_1} + m^2_{\tilde t_2} + m^2_{\tilde b_1} + m^2_{\tilde b_2} - 2m_t^2 &= 2.79\,(m_{\tilde g})^2\,\mathrm{TeV}^2 \\
m^2_{\tilde \tau_1} + m^2_{\tilde \tau_2} + m^2_{\tilde t_1} + m^2_{\tilde t_2} - m_t^2 &= 1.15\,(m_{\tilde g})^2\,\mathrm{TeV}^2.
\end{aligned}
$$

$$
\begin{aligned}
m^2_{\tilde e_L} + 2m^2_{\tilde u_L} + m^2_{\tilde d_L} &= 2.63\,(m_{\tilde g})^2\,\mathrm{TeV}^2, \\
m^2_{\tilde u_R} + m^2_{\tilde d_R} + m^2_{\tilde u_L} + m^2_{\tilde d_L} &= 3.56\,(m_{\tilde g})^2\,\mathrm{TeV}^2, \\
m^2_{\tilde u_L} + m^2_{\tilde d_L} - m^2_{\tilde u_R} - m^2_{\tilde e_R} &= 0.90\,(m_{\tilde g})^2\,\mathrm{TeV}^2.
\end{aligned}
$$

$$
\begin{aligned}
m_A^2 - 2\sec 2\beta\left(m^2_{\tilde e_L} + m^2_{\tilde e_R}\right) &= 0.49\,(m_{\tilde g})^2\,\mathrm{TeV}^2, \\
m_A^2 - 2\sec 2\beta\left(m^2_{\tilde \tau_1} + m^2_{\tilde \tau_2} - 2m_\tau^2\right) &= 0.49\,(m_{\tilde g})^2\,\mathrm{TeV}^2.
\end{aligned}
$$

Allowed values of ζ_1 and ζ_2



Massive Neutrinos?

If we incorporate massive neutrinos via the seesaw mechanism, i.e. add to the superpotential:

$$W_\nu = \sum_{i,a} \tfrac{1}{2}\nu_a^c (M_{\nu^c})_{ab}\nu_b^c + H_2 L_i Y_\nu \nu_a^c$$

then $B-L$ is broken and we no longer have a generation-independent U_1' at our disposal. A possible fix is to introduce a U_1' with generation-dependent charges, so that only one or more tree-level Yukawa couplings are allowed.

We suppose that the rest originate via the FN mechanism: effective field theory terms of the form e.g. $H_2 Q_i u_j (\theta/M_U)^{a_{ij}}$ where θ is a MSSM singlet field with U_1'-charge q_θ that gets a vev, so that $\langle\theta\rangle/M_U \sim \lambda$.

The obvious way to introduce the ν_c is with *zero* U_1' charge; an attractive alternative is to have only two ν_c with equal and opposite U_1' charges, so that

$$M_{\nu_c} = \begin{pmatrix} 0 & M_1^\nu \\ M_1^\nu & 0 \end{pmatrix}$$

This means that one light neutrino will be massless.

YUKAWA TEXTURES and the CKM matrix

The CKM matrix exhibits the Wolfenstein texture, i.e.

$$CKM = \begin{pmatrix} 0.97 & 0.22 & 0.003 \\ -0.22 & 0.97 & 0.04 \\ 0.004 & -0.04 & 1 \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

where $\lambda \sim 0.22$. Moreover the quark and lepton masses satisfy

$$\begin{aligned} m_\tau : m_\mu : m_e &= m_b : m_s : m_d = 1 : \lambda^2 : \lambda^4 \\ m_t : m_c : m_u &= 1 : \lambda^4 : \lambda^8 \end{aligned}$$

What form of Yukawa textures will give these results? Can we assign U_1' charges so that we get mixed anomaly cancellation (to preserve the AMSB solution) and produce such a Yukawa texture? One solution is

$$Y_t \sim \begin{pmatrix} \lambda^8 & \lambda^5 & \lambda^3 \\ \lambda^7 & \lambda^4 & \lambda^2 \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix}, Y_b \sim \lambda^{\alpha_b} \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda & 1 & 1 \end{pmatrix}.$$

Then defining $Y_t^{\text{diag}} = U_t^\dagger Y_t V_t$ (similarly for Y_b, Y_τ), we indeed find that the CKM matrix $CKM = U_t^\dagger U_b$. is of CKM_W form.

An alternative form which has advantages visavis FCNC suppression is the *democratic* form

EKK
JJW

$$Y_t \sim \begin{pmatrix} \lambda^8 & \lambda^4 & 1+\mathcal{O}(\lambda^2) \\ \lambda^8 & \lambda^4 & 1+\mathcal{O}(\lambda^2) \\ \lambda^8 & \lambda^4 & 1+\mathcal{O}(\lambda^2) \end{pmatrix},$$

$$Y_b, \sim \begin{pmatrix} \lambda^4 & \lambda^2 & 1+\mathcal{O}(\lambda^2) \\ \lambda^4 & \lambda^2 & 1+\mathcal{O}(\lambda^2) \\ \lambda^4 & \lambda^2 & 1+\mathcal{O}(\lambda^2) \end{pmatrix}, \quad Y_\tau \sim \begin{pmatrix} \lambda^4 & \lambda^2 & 1 \\ \lambda^4 & \lambda^2 & 1 \\ \lambda^4 & \lambda^2 & 1 \end{pmatrix}$$

which leads to

$$CKM \sim \begin{pmatrix} 1 & 1 & \lambda^2 \\ 1 & 1 & \lambda^2 \\ \lambda^2 & \lambda^2 & 1 \end{pmatrix}$$

which is not of the form of the standard Wolfenstein parametrisation, but does reproduce the most significant feature, that is the smallness of the couplings to the third generation.

Flavour Changing Neutral Currents

We have a potential problem because of relations like

$$\overline{m}^2_{\tau^c} = m^2_{\tau^c} + \zeta_1 + \zeta_2 Y'_{\tau^c}.$$

the U'_1 hypercharge Y'_{τ^c} is different for the 3 generations and so if we rotate the sleptons to the lepton mass diagonal basis we will introduce off diagonal terms above.

But for the *democratic* texture:

- the LH fields have identical U'_1 charges, so a rotation on them does not introduce FCNCs.
- The quark/lepton textures are diagonalised by rotating (to a good approximation) the LH fields only.

R-parity violation deCampos et al

de Campos et al consider the inclusion of bilinear R-parity violation, i.e.

$$W \to W + \sum_i L_i H_2.$$

(This doesn't help with the tachyonic slepton problem). Main features:

- At the one-loop level, the soft RG equations are unchanged.

- Mixing between the SM and susy particles: e.g. the neutral gauginos and neutrinos mix, giving rise to neutrino masses, which can be consistent with the present observations; see Figure 2.

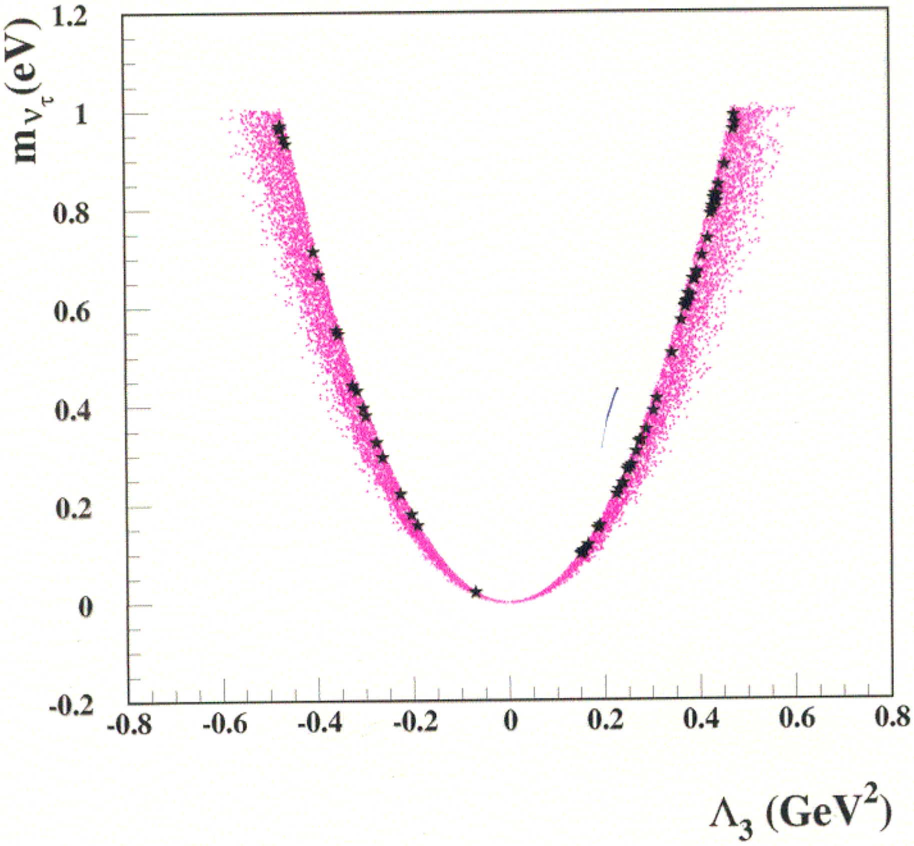


Figure 2: Tau neutrino mass as a function of Λ_3 for $5 < \tan\beta < 20$, $100 < m_0 < 1000$ GeV, $m_{3/2} = 32$ TeV and $\mu < 0$.

- There is also mixing between the scalar leptons and the charged Higgs, as well as, between sneutrinos and neutral Higgses.

Massive Neutrinos

$$W_\nu = \sum_{i,a} \tfrac{1}{2}\nu_a^c (M_{\nu^c})_{ab}\nu_b^c + H_2 L_i Y_\nu \nu_a^c$$

leads to a light neutrino mass matrix of the form

$$m_\nu = m_D M_{\nu^c}^{-1} (m_D)^T$$

where $m_D = v_2 Y_\nu$ is the Dirac ν-mass matrix, with m_D being generated by the FN mechanism.

The obvious way to introduce the ν_c is with *zero* U_1' charge; an attractive alternative is to have only two ν_c with equal and opposite U_1' charges, so that

$$M_{\nu_c} = \begin{pmatrix} 0 & M_1^\nu \\ M_1^\nu & 0 \end{pmatrix}$$

This means that one light neutrino will be massless; Introducing an appropriate θ_ν a spectrum of the form

$$m_{\nu_1} = 0, \quad m_{\nu_3} \sim 10 m_{\nu_2} \sim 5 \times 10^{-2}\mathrm{eV}$$

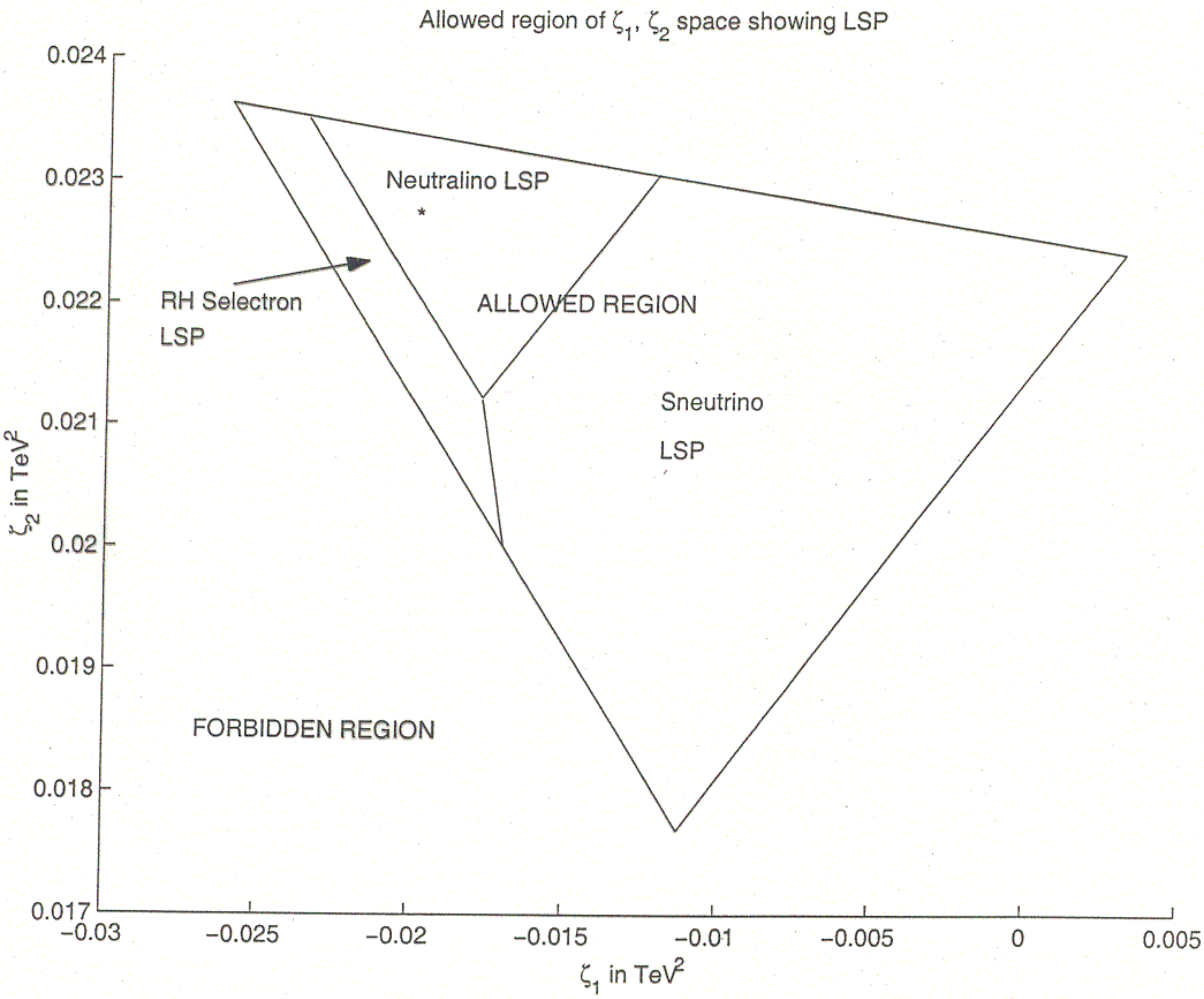
can be arranged, with large 12 and 23 mixing, and small 13 mixing, as favoured by analysis of solar and atmospheric oscillations.

The MASS SPECTRUM

With $\tan\beta = 5$, gravitino mass $m_0 = 40\mathrm{TeV}$, $\zeta_1 = -0.02$ and $\zeta_2 = 0.0227$, we find $|\mu| = 570\mathrm{GeV}$, and choosing sign $\mu = -1$ we obtain the following spectrum:

$$\begin{aligned}
m_{\tilde{t}_1} &= 869, \quad m_{\tilde{t}_2} = 484, \, m_{\tilde{b}_1} = 825, \, m_{\tilde{b}_2} = 1082 \\
m_{\tilde{\tau}_1} &= 148, \, m_{\tilde{\tau}_2} = 442, \, m_{\tilde{u}_L,\tilde{c}_L} = 931, \, m_{\tilde{u}_R} = 908, \\
m_{\tilde{c}_R} &= 856, \, m_{\tilde{d}_L,\tilde{s}_L} = 934, \, m_{\tilde{d}_R} = 998, \, m_{\tilde{s}_R} = 1042 \\
m_{\tilde{e}_L,\tilde{\mu}_L} &= 149, \, m_{\tilde{e}_R} = 117, \, m_{\tilde{\mu}_R} = 323, \, m_{\tilde{\nu}_e,\tilde{\nu}_\mu} = 126 \\
m_{\tilde{\nu}_\tau} &= 125, \, m_{h,H} = 122, 166, m_A = 161, \, m_{H^\pm} = 181 \\
m_{\tilde{\chi}^\pm_{1,2}} &= 112, 575, \\
m_{\tilde{\chi}_{1\cdots 4}} &= 111, 369, 579, 579, \, m_{\tilde{g}} = 1007,
\end{aligned}$$

where all masses are given in GeV.


Allowed region of ζ1, ζ2 space showing LSP
0.024
0.023
0.022
0.021
0.02
0.019
0.018
0.017
ζ2 in TeV2
Neutralino LSP
RH Selectron
LSP
ALLOWED REGION
Sneutrino
LSP
FORBIDDEN REGION
-0.03
-0.025
-0.02
-0.015
-0.01
-0.005
0
0.005
ζ1 in TeV2

Conclusions

- All the RG functions of a supersymmetric theory can be expressed in terms of β_g, γ (except for the FI β-function.)
- The AMSB framework (with FI terms) offers a distinctive, few-parameter form of the sparticle spectrum.
- More work needed on: FCNC, The μ-problem, neutrino masses, leptonic flavor violation, Charge/colour breaking vacua, finite temperatures, ...