Dynamical Solution to the μ/B_μ Problem in Gauge Mediated Supersymmetry Breaking

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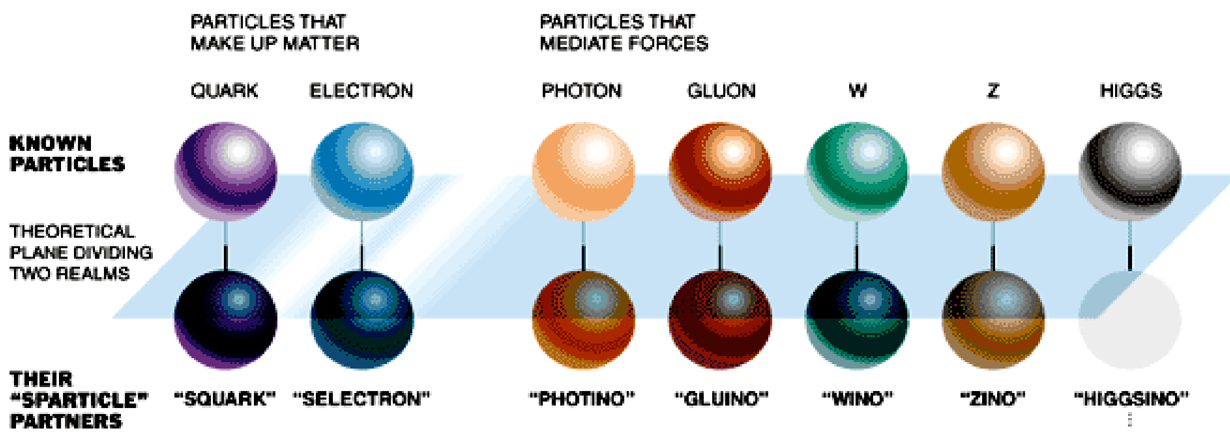
supersymmetry

fermions **bosons**



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

No new dimensionless couplings. Couplings of supersymmetric particles equal to couplings of Standard Model ones.
Two Higgs doublets necessary. Ratio of vacuum expectation values denoted by $\tan\beta$

Minimal Supersymmetric Standard Model

SM particle	SUSY partner	G_{SM}
(S = 1/2)	(S = 0)	
$Q = (t, b)_L$	$(\tilde{t}, \tilde{b})_L$	(3,2,1/6)
$L = (\nu, l)_L$	$(\tilde{\nu}, \tilde{l})_L$	(1,2,-1/2)
$U = \left(t^C\right)_L$	$\tilde{t}^*_R$	($\bar{3}$,1,-2/3)
$D = \left(b^C\right)_L$	$\tilde{b}^*_R$	($\bar{3}$,1,1/3)
$E = \left(l^C\right)_L$	$\tilde{l}^*_R$	(1,1,1)
(S = 1)	(S = 1/2)	
B_μ	$\tilde{B}$	(1,1,0)
W_μ	$\tilde{W}$	(1,3,0)
g_μ	$\tilde{g}$	(8,1,0)

The Higgs problem

- Problem: What to do with the Higgs field ?
- In the Standard Model masses for the up and down (and lepton) fields are obtained with Yukawa couplings involving H and $H^\dagger$ respectively.
- Impossible to recover this from the Yukawas derived from $P[\Phi]$, since no dependence on $\bar{\Phi}$ is admitted.
- Another problem: In the SM all anomalies cancel,

$$\begin{aligned} \sum_{quarks} Y_i &= 0; \qquad \sum_{left} Y_i = 0; \\ \sum_i Y_i^3 &= 0; \qquad \sum_i Y_i = 0 \end{aligned} \tag{38}$$

- In all these sums, whenever a right-handed field appear, its charge conjugate is considered.
- A Higgsino doublet spoils anomaly cancellation !

Solution to the problem

- Solution: Add a second doublet with opposite hypercharge.
- Anomalies cancel automatically, since the fermions of the second Higgs superfield act as the vector mirrors of the ones of the first one.
- Use the second Higgs doublet to construct masses for the down quarks and leptons.

$$W[\Phi] = h_u QUH_u + h_d QDH_d + h_l LEH_d$$

- Once these two Higgs doublets are introduced, a mass term may be written

$$\delta W[\Phi] = \mu H_u H_d$$

- μ is only renormalized by wave functions of H_u and H_d

Structure of Supersymmetry Breaking Parameters

- Although there are few supersymmetry breaking parameters in the gaugino and Higgsino sector, there are many in the scalar sector.
- For instance, there are 45 scalar states and all these scalar masses might be different. In addition, one can add complex scalar mass parameters that mix squark and sleptons of different generations: $\mathcal{L}_{\rm mix} = m^2_{ij} \tilde{f}^*_i \tilde{f}_j + h.c.$
- In addition, one can add A-terms that also mix squarks and sleptons of different generations.
- In general, in the presence of such terms, if the scalar masses are of the order of the weak scale, one can induce contributions to flavor changing neutral currents by interchanging gauginos and scalars.
- This leads to problematic phenomenological consequences.

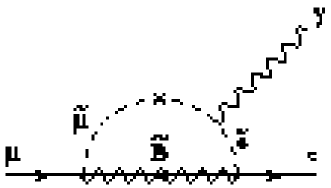
Flavor Changing Neutral Currents

- Two particularly constraining examples of flavor changing neutral currents induced by off-diagonal soft supersymmetry breaking parameters

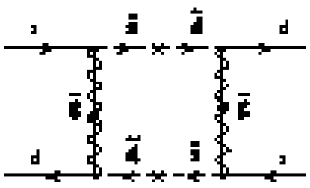
- Contribution to the mixing in the Kaon sector, as well as to the rate of decay of a muon into an electron and a photon.

- While the second is in good agreement with the SM predictions, the first one has never been observed.

- Rate of these processes suppressed as a power of supersymmetric particle masses and they become negligible *only if relevant masses are larger than 10 TeV*



(a)



(b)

Solution to the Flavor Problem

- There are two possible solutions to the flavor problem
- The first one is to push the masses of the scalars, in particular to the first and second generation scalars, to very large values, larger than *or of the order of 10 TeV.*
- Some people have taken the extreme attitude of pushing them to values of order of the GUT scale. This is fine, but supersymmetry is then broken in a hard way and the solution to the hierarchy problem is lost.
- A second possibility is to demand that the scalar mass parameters are approximately flavor diagonal in the basis in which the fermions mass matrices are diagonal. All flavor violation is induced by either CKM mixing angles, or by very small off-diagonal mass terms.
- This latter possibility is a most attractive one because it allows to keep SUSY particles with masses of the order of the weak scale.

Renormalization Group Evolution

- One interesting thing is that the gaugino masses evolve in the same way as the gauge couplings:
  $d(M_i/\alpha_i)/dt = 0, \quad dM_i = -b_i \alpha_i M_i / 4\pi, \qquad d\alpha_i/dt = -b_i \alpha_i^2 / 4\pi$

- The scalar fields masses evolve in a more complicated way.
  $4\pi dm_i^2/dt = -C_a^i 4 M_a^2 \alpha_a + |Y_{ijk}|^2 [(m_i^2 + m_j^2 + m_k^2 + A_{ijk}^2)]/4\pi$
- There is a positive contribution coming from the gaugino masses and a negative contribution proportional to the Yukawa couplings.
- Colored particles are affected by positive, strongly coupled corrections and tend to be the heaviest ones.
- Weakly interacting particles tend to be lighter, particular those affected by large Yukawas.
- There scalar field H_u is both weakly interacting and couples with the top quark Yukawa. Its mass naturally becomes negative.

Electroweak Symmetry Breaking and the μ Problem

- Negative values of the soft supersymmetry breaking mass parameter induce electroweak symmetry breaking. The total Higgs masses receive a SUSY contribution

$$\mu^2 + m_{H_i}^2$$

- Electroweak symmetry breaking therefore demands a relation between these two contributions

$$\mu^2 + \frac{M_Z^2}{2} = \frac{m_{H_d}^2 - \tan^2\beta\, m_{H_u}^2}{\tan^2\beta - 1}, \qquad \tan\beta = \frac{v_u}{v_d}$$

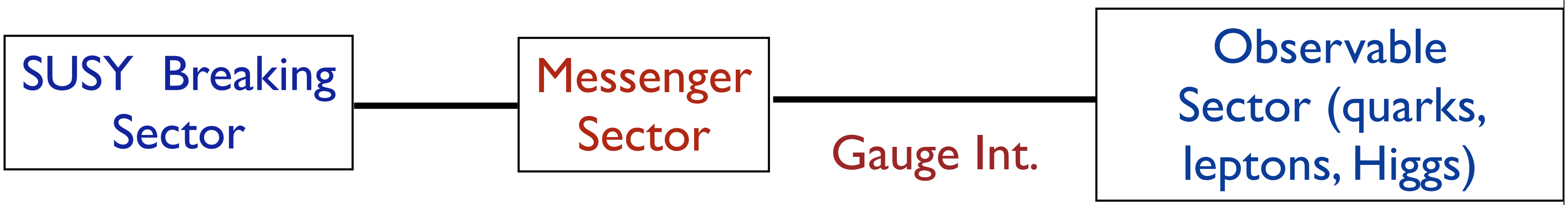
- Therefore, μ must be of the order of the SUSY breaking parameters
- Also, the mixing term $-(B_\mu H_u H_d + h.c.)$ appearing in the potential

$$\sin 2\beta = \frac{2B_\mu}{2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2}$$

must be of the same order. Is there a natural framework to solve the flavor problem, inducing weak scale values for μ and B_μ ?

Gauge Mediated SUSY Breaking

- Supersymmetry breaking is transmitted to the observable sector via (flavor blind) gauge interactions



- Messenger sector in complete representations of SU(5) and vector-like.

$$(5, \bar{5}) \equiv (3, 2) + (\bar{3}, \bar{2})$$

- Minimal model: One

$$W = \lambda \, S \; 3 \; \bar{3} + \gamma \; S \; 2 \; \bar{2}, \qquad < S >= S + F_S \theta^2,$$

with S a singlet field parametrizing SUSY breaking and the messenger mass

Spectrum of Sparticles (more details later)

- Gaugino masses fulfill the standard unification relations,

$$M_i \propto \frac{\alpha_i}{4\pi}\frac{F_S}{S}, \qquad\qquad \frac{M_i}{M_j} = \frac{\alpha_i}{\alpha_j}$$

- Scalar masses at the messenger scale are also governed by their color structure. For instance,

$$m_{\tilde{q},H} \propto \frac{\alpha_{3,2}}{4\pi}\frac{F_S}{S},$$

- This implies that, independently of the messenger scale, there are large negative corrections to the Higgs mass parameter, triggering EWSB

- The requirement of a weak scale spectrum demands

$$\Lambda \equiv \frac{F_S}{S} = \mathcal{O}(10^5\ \mathrm{GeV})$$

- The scale of SUSY breaking has important consequences, for instance it determines the gravitino mass and interactions (and therefore the nature of the LSP). Lightest superpartner tends to be a Bino.

Gravitino

- When standard symmetries are broken spontaneously, a massless boson appears for every broken generator.
- If the symmetry is local, this bosons are absorbed into the longitudinal components of the gauge bosons, which become massive.
- The same is true in supersymmetry. But now, a massless fermion appears, called the Goldstino.
- In the case of local supersymmetry, this Goldstino is absorbed into the Gravitino, which acquires mass $m_{\tilde{G}} = F/M_{Pl}$, with F the order parameter of SUSY breaking.
- The coupling of the Goldstino (gravitino) to matter is proportional to $1/\sqrt{F} = 1/\sqrt{m_{\tilde{G}} M_{Pl}}$, and couples particles with their superpartners.
- Masses of supersymmetric particles is of order F/M, where M is the scale at which SUSY is transmitted.

Decay Width of NLSP into Gravitino

- In low energy supersymmetry breaking models, the SUSY breaking scale $10\text{TeV} \leq \sqrt{F} \leq 10^3$ TeV.
- The gravitino mass is very small in this case $10^{-1}\text{eV} \leq m_{\tilde{G}} \leq 10^3$ eV.
- Since the gravitino is the lightest supersymmetric particle, then the lightest SM superpartner will decay into it.
- It is easy to extract the decay width on dimensional grounds
- Just assume that the lightest SM partner is a photino, for instance, and it decays into an almost massless gravitino and a photon. Then,

$$\Gamma(\tilde{\gamma} \to \gamma \tilde{G}) \simeq \frac{m_{\tilde{\gamma}}^5}{16\pi F^2} \simeq \frac{m_{\tilde{\gamma}}^5}{16\pi m_{\tilde{G}}^2 M_{Pl}^2} \tag{2}$$

where we have used the fact that $[F] = 2$.

Generation of μ :Giudice-Masiero mechanism

- Assume exact Peccei-Quinn symmetry forbidding μ
- Then, introduce higher dimensional operators in Kahler function

$$\Delta\mathcal{L} = \int d^4\theta \; H_u H_d \left(c_1 \frac{X}{M} + c_2 \frac{X^\dagger X}{M^2} \right) + h.c.$$

- where $X = X + F_X \theta^2$ is the SUSY breaking chiral superfield. Then,

$$\mu = \frac{c_1 F_X}{M}, \qquad B_\mu = \frac{c_2 F_X^2}{M^2}$$

- But in theories of gauge mediation, as we have seen

$$\frac{B_\mu}{\mu} \simeq \frac{F_X}{M} \simeq 100 \text{ TeV}$$

- It is therefore required that c_2 is suppressed. Different alternatives have been proposed to make it work. I will concentrate on a slightly different strategy.

Singlet Mechanism for the generation of μ

- A natural solution would be possible by introducing a singlet

  $$W = \lambda\, N H_u H_d - \tfrac{\kappa}{3} N^3 + h_u Q U H_u + \ldots$$

  and a Z_3 symmetry which ensures the absence of bilinear and linear terms. This symmetry could also help preventing the presence of S and of Yukawas with the messenger sector.

- At the messenger scale, the soft supersymmetry breaking term

  $$m_N^2 = 0, \qquad A_\lambda = 0 \qquad A_\kappa = 0$$

- Since N is a singlet, its mass term is, in principle, driven to negative values at lower energies via Yukawa interactions, inducing a non-vanishing expectation value for N. Then,

  $$\mu = \lambda\, v_N$$
  $$B_\mu = \lambda < F_N > + A_\lambda \mu$$

  $$F_N = \kappa\, v_N^2 - \frac{\lambda\, v^2}{2} \sin 2\beta$$

Problem with this Solution

- The main problem is that the Higgs mass parameter becomes rapidly negative, turning the “negative Yukawa effects” on the singlet mass into positive ones

$$16\pi^2 \frac{dm_N^2}{dt} = 4\lambda^2 \left(m_{H_u}^2 + m_{H_d}^2 + m_N^2 + A_\lambda^2\right) + 4\kappa^2 \left(3m_N^2 + A_\kappa^2\right)$$

- Then, the singlet never acquires a sufficiently large v.e.v. rendering the mechanism invalid, independently of the messenger scale

de Gouvea, Murayama’99

- The main source of the problem is related to the large values of the stop masses compare to the Higgs masses. Can this be avoided ?
- Consider a simple generalization of the messenger sector with two singlets, $W = \lambda_i \; S_i \; 3\bar{3} + \gamma_i \; S_i \; 2\bar{2}$ Dine, Mason’08
- Now, doublets and triplets transmit different SUSY breaking effects

$$\Lambda_q = \frac{\lambda_i F_i}{\lambda_i S_i}, \qquad \Lambda_l = \frac{\gamma_i F_i}{\gamma_i S_i}$$

This extra degree of freedom is enough to improve the situation

Method to extract Supersymmetry Breaking terms

Giudice, Rattazzi '98

Let us start with the effective superpotential

$W = \sum_I S_I \bar{\Phi}_I \Phi_I$

where Φ_I are the messenger fields, and S_I are singlet fields parametrizing SUSY breaking

$$< S_I >= S_I + F_I \theta^2 \begin{cases} \mathrm{I - Messenger\ Fermion\ Mass} = S_I \\ \\ \mathrm{I - Scalar\ Squared\ Masses} = S_I^2 \pm F_I \end{cases}$$

One can now parametrize the gauge superfield kinetic term

$\mathcal{L}_G = \int d^2\theta \; f_j \; W^i_\alpha W^\alpha_j, \qquad < \mathrm{Re}(f_j) > = \alpha_j^{-1}/4\pi, \qquad M_j = -F_{f_j}/(2 f_j)$

Then, for $F_I \ll S_I^2$, the gaugino mass $\qquad M_j = -\frac{1}{2} \frac{\partial \; ln f_j}{\partial \; ln S_I} \frac{F_I}{S_I}$

Similarly, for the scalar fields

$\mathcal{L} = \int d^4\theta Z_Q \Phi_Q \bar{\Phi}_Q,$

where Q are arbitrary chiral superfields. Then, its soft mass is given by

$m_Q^2 = -\frac{\partial^2 \ln Z_Q}{\partial S_J \partial S_I^\dagger} \frac{F_J F_I^\dagger}{S_J S_I^\dagger}$

Finally, if we define trilinear and bilinear terms by

$V = A_Q \Phi_Q \frac{\partial W}{\partial \Phi_Q}$

Then, $A_Q = \frac{\partial \ln Z_Q}{\partial \ln S_I} \frac{F_I}{S_I}$

One could easily show that the RG evolution of Z_Q is

$\frac{dZ_Q}{dt} = \frac{c_Q^j}{\pi} \alpha_j$

with $c_Q^j = N(N-1)/2$ for $SU(N)$ and $c_Q = Y^2/4$ for $U(1)_Y$.

Minimal Messenger Sector

Let us introduce two superfields belonging to 5, $\bar{5}$ of SU(5), $(3,2)+(\bar{3},\bar{2})$

Doublets and triplets couple to different S_I's : S_l and S_q, respectively

$$\frac{1}{\alpha_j(S_l)} = \frac{1}{\alpha_j(M_G)} + \frac{b_j}{4\pi} \ln\left(\frac{M_G^2}{|S_l|^2}\right)$$
$$\frac{1}{\alpha_j(S_q)} = \frac{1}{\alpha_j(S_l)} + \frac{b_j^{3\bar{3}}}{4\pi} \ln\left(\frac{|S_l|^2}{|S_q|^2}\right)$$
$$\frac{1}{\alpha_j(\mu)} = \frac{1}{\alpha_j(M_G)} + \frac{b_j^{\mathrm{MSSM}}}{4\pi} \ln\left(\frac{|S_q|^2}{\mu^2}\right)$$

	Full theory	MSSM + 3 $\bar{3}$	MSSM
b_3	-2	-2	-3
b_2	2	1	1
b_1	38/5	7	33/5

Using the holomorphicity of $f_j(S_I,\mu)$, we obtain

$$M_j(\mu) = \frac{B_2^j\alpha_j(\mu)}{4\pi}\frac{F_l}{S_l} + \frac{B_3^j\alpha_j(\mu)}{4\pi}\frac{F_q}{S_q},$$

where $B_{3,2}^i$ are the triplet and doublet beta-function contributions.

$$M_3(\mu) = \frac{\alpha_3(\mu)}{4\pi}\frac{F_q}{S_q}, \qquad M_2(\mu) = \frac{\alpha_2(\mu)}{4\pi}\frac{F_l}{S_l}, \qquad M_3(\mu) = \frac{\alpha_1(\mu)}{4\pi}\left(\frac{3F_l}{5S_l} + \frac{2F_q}{5S_q}\right)$$

Scalar Masses

Analogously, and ignoring Yukawa effects,

$$\ln\left(\frac{Z_Q}{Z_Q(M_G)}\right) = -\frac{2c^i_Q}{b_i}\ln\left(\frac{\alpha_i(M_G)}{\alpha_i(S_l)}\right) - \frac{2c^i_Q}{b^{3\bar{3}}_i}\ln\left(\frac{\alpha_i(S_l)}{\alpha_i(S_q)}\right) - \frac{2c^i_Q}{b_i}\ln\left(\frac{\alpha_i(S_q)}{\alpha_i(\mu)}\right)$$

At the messenger scale, $S_q \simeq S_l$

$$m^2_Q = 2\left[C^Q_3\left(\frac{\alpha_3}{4\pi}\right)^2\Lambda^2_q + C^Q_2\left(\frac{\alpha_2}{4\pi}\right)^2\Lambda^2_l + C^Q_1\left(\frac{\alpha_1}{4\pi}\right)^2\left(\frac{2}{5}\Lambda^2_q + \frac{3}{5}\Lambda^2_l\right)\right]$$

$$\boxed{\Lambda_q = \frac{\langle F_q\rangle}{\langle S_q\rangle}, \qquad \Lambda_l = \frac{\langle F_l\rangle}{\langle S_l\rangle}.}$$

Finally, all bilinear and trilinear mass terms vanish at the messenger scale

$$A_Q = 0 \qquad (A_f, A_N, B_\mu = 0)$$

Complete formulae, including RG evolution, C.W., hep-ph/9801376

Comments

- One can now introduce a parameter

$$\eta = \frac{\Lambda_l}{\Lambda_q}$$

- The relations,

$$\frac{d(M_i/\alpha_i)}{dt} = 0 \qquad\qquad \frac{M_2}{M_3} = \eta\frac{\alpha_2}{\alpha_3}$$

  hold for any value of η

- For values of this parameter larger than one the gluino and wino masses become closer in magnitude

- Similarly, and more importantly, the weakly interacting scalar masses become closer to the strongly interacting ones.

- Consequently, $m^2_{H_u}$ is not driven to large negative values, enabling the evolution of m^2_N to negative values

General considerations

- Requiring the model to predict, for a given value of the couplings, the precise value of μ that leads to consistency with electroweak symmetry breaking is quite restrictive

- For values of η close to one, there is no solution. For very large values of this parameter, there is in general no electroweak symmetry breaking. Values larger than one, but of order one are preferred.

- Small values of B_μ lead to relatively large values of $\tan\beta$

- The model still correlates the gaugino masses with the corresponding squark and slepton masses

- In general, to generate sufficiently large values of μ in low energy gauge mediated supersymmetry breaking, due to the small running, a heavy spectrum of gauginos, squarks and sleptons required.

- Lightest neutralinos and charginos are therefore mostly admixtures of Higgsinos and singlinos.

Neutralino Mass Matrix

For large values of the gaugino masses, masses are proportional to the Higgs vacuum expectation values, and naturally of the weak scale

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_{\rm W} M_{\rm Z} & s_\beta s_{\rm W} M_{\rm Z} & 0 \\ 0 & M_2 & c_\beta c_{\rm W} M_{\rm Z} & -s_\beta c_{\rm W} M_{\rm Z} & 0 \\ -c_\beta s_{\rm W} M_{\rm Z} & c_\beta c_{\rm W} M_{\rm Z} & 0 & \lambda v_{\rm s} & \lambda v_2 \\ s_\beta s_{\rm W} M_{\rm Z} & -s_\beta c_{\rm W} M_{\rm Z} & \lambda v_{\rm s} & 0 & \lambda v_1 \\ 0 & 0 & \lambda v_2 & \lambda v_1 & 2\kappa v_s \end{pmatrix},$$

Lightest chargino mass is approximately equal to μ in this case. In many of the examples we considered, singlino becomes relatively heavy and lightest charginos and neutralinos become close in mass.

Higgs Spectrum

- Mass of would be CP-odd Higgs boson tends to be large, as well as that of the associated charged Higgs

$$m_A^2 = \frac{2\mu(A_\lambda + \frac{\kappa}{\lambda}\mu) + \delta_A}{\sin 2\beta}$$

$$\delta_A \approx \frac{3}{16\pi^2}\frac{h_t^2 A_t \mu}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2}\left[m_{\tilde{t}_1}^2\left(\ln\frac{m_{\tilde{t}_1}^2}{m_t^2} - 1\right) - m_{\tilde{t}_2}^2\left(\ln\frac{m_{\tilde{t}_2}^2}{m_t^2} - 1\right)\right]$$

- Still, a light CP-odd scalar, mainly single-like remains in the spectrum, particularly in low energy mediation

$$m_{a_1}^2 = 3v_N\left(\frac{3\lambda A_\lambda \cos^2\theta_A}{2\sin 2\beta} + \kappa A_\kappa \sin^2\theta_A\right) + \mathcal{O}\left(\frac{A_\lambda}{v}, \frac{A_\kappa}{v}\right),$$

$$a_1 = \cos\theta_A\, A_{MSSM} + \sin\theta_A\, A_N$$

$$\tan\theta_A = \frac{v_N}{v\sin 2\beta} + \mathcal{O}(\frac{A_\lambda}{v}, \frac{A_\kappa}{v}) \qquad \theta_A \approx \frac{\pi}{2}$$

- This can induce new Higgs decays and change the associated phenomenology

CP-even Higgs Bosons

- Singlet like CP-even Higgs boson acquires a mass approximately equal to

$$m_{H_2}^2 = 4\,\kappa^2\, v_N^2$$

- This is, in general, larger than the would be MSSM lightest CP-even Higgs. Both states mix, with a term equal to $2\,\lambda\, v\, v_N$

- Then, for large values of $\tan\beta$ and large $v_N \gg v$, and ignoring relatively small stop mixing effects, one gets,

$$m_{H_1}^2 = M_Z^2 - \frac{\lambda^2 v^2}{\kappa^2} + \text{loop corrections}$$

what impliest rather heavy stops in order to avoid LEP bounds.

- For high energy gauge mediated models, the SU(2) singlet stop may be lighter than 1 TeV, but then the heaviest stop should be heavier than a few TeV

- The lightest CP-even Higgs is SM-like but, as emphasized before, it may decay into two CP-odd Higgs bosons.

Energy Scale, Spectrum and Collider Phenomenology

- We considered low scale, intermediate scale and high scale gauge mediated models. The three are distinguished by the length of the RG running. In the latest cases we assume negligible hidden sector effects.
- We considered nine characteristic points, within the perturbative region for the three cases considered

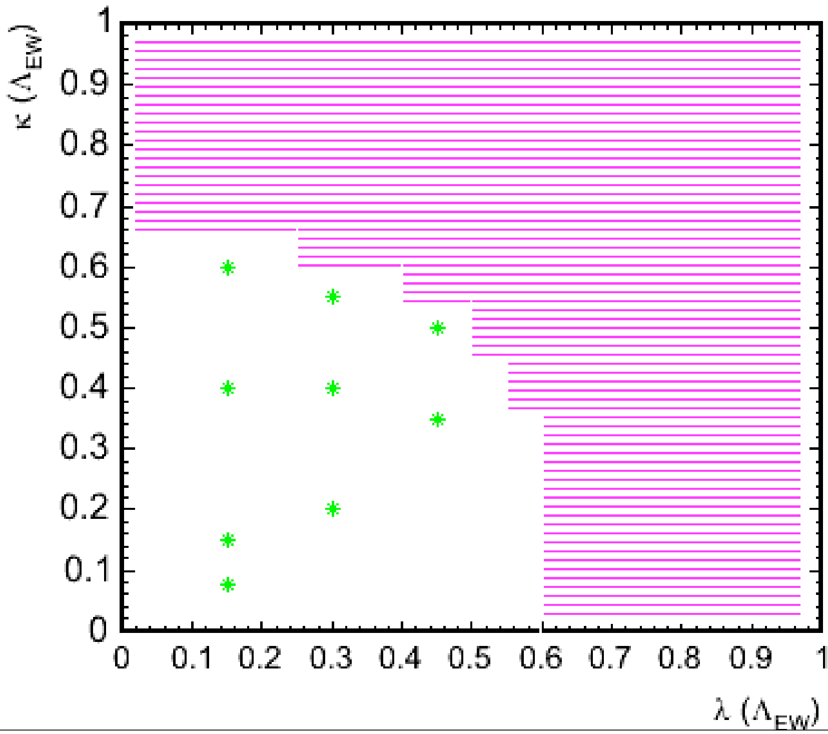


Table 1: Parameters of the low-scale general gauge mediation.

	Input Parameters			
Pts	$\lambda(\Lambda_{EW})$	$\kappa(\Lambda_{EW})$	Λ_M (GeV)	η
A1	0.15	0.075	2.50×10^5	2.1160
A2	0.15	0.15	5.00×10^5	2.2708
A3	0.15	0.40	5.00×10^6	2.5151
A4	0.15	0.60	2.00×10^7	2.7869
A5	0.30	0.20	2.50×10^5	1.9356
A6	0.30	0.40	2.50×10^5	2.1383
A7	0.30	0.55	5.00×10^5	2.2800
A8	0.45	0.35	2.00×10^6	2.2509
A9	0.45	0.50	2.50×10^5	2.1083

	Soft SUSY-breaking Parameters at the EW Scale (GeV or GeV^2)					
Pts	$M_{1,2,3}$	$m^2_{H_d}$	$m^2_{H_u}$	m^2_N	A_λ	A_κ
A1	888.7, 2225.8, 3518.0	-1.88×10^6	-7.58×10^6	-1.55×10^4	-5.0	0.7
A2	1087.3, 2768.7, 4076.2	-5.61×10^6	-1.04×10^7	-2.24×10^4	-34.0	1.0
A3	3561.3, 9274.7, 12311.1	-9.01×10^7	-1.18×10^8	-2.07×10^5	-268.9	5.0
A4	3792.8, 10085.2, 12069.8	-8.80×10^7	-1.15×10^8	-3.55×10^5	-241.4	7.3
A5	1176.0, 2881.1, 4978.1	-1.71×10^5	-1.71×10^7	-9.29×10^4	7.7	4.1
A6	906.6, 2276.4, 3560.4	-2.63×10^6	-7.72×10^6	-5.66×10^4	-13.3	2.8
A7	1055.3, 2689.6, 3943.7	-4.27×10^6	-9.83×10^6	-8.27×10^4	-24.0	3.8
A8	2070.8, 5262.9, 7810.5	3.62×10^7	-5.04×10^7	-1.93×10^6	219.1	37.9
A9	898.7, 2248.9, 3567.5	3.14×10^6	-8.05×10^6	-2.20×10^5	45.6	8.3

	Output Parameters				
Pts	h_t, h_b	Λ_q (GeV)	$\tan\beta$	μ (GeV)	B_μ (GeV^2)
A1	0.949, 0.753	3.90×10^5	43.57	173.8	1.41×10^4
A2	0.948, 0.833	4.52×10^5	48.44	105.1	7.38×10^3
A3	0.948, 0.880	1.37×10^6	51.05	121.8	6.55×10^3
A4	0.948, 0.882	1.34×10^6	52.41	106.0	1.92×10^4
A5	0.949, 0.637	5.46×10^5	36.93	321.8	7.11×10^4
A6	0.948, 0.780	3.95×10^5	45.30	124.2	1.88×10^4
A7	0.948, 0.809	4.38×10^5	46.89	109.9	1.94×10^4
A8	0.950, 0.307	8.68×10^5	17.80	1276.6	1.54×10^6
A9	0.949, 0.533	2.50×10^5	30.87	296.7	1.11×10^5

Table 2: Mass spectrum of particles and superparticles in the low-scale general gauge mediation.

	Particle Masses (TeV)			
Pts	$m_{\tilde{g}}$	$m_{\tilde{t}_{1,2}}$	$m_{\tilde{b}_{1,2}}$	$m_{\tilde{\tau}_{1,2}}$
A1	3.44	5.55, 6.36	5.86, 6.35	0.80, 2.84
A2	3.95	6.37, 7.36	6.60, 7.35	0.89, 3.53
A3	11.17	18.63, 22.24	19.08, 22.24	2.27, 11.90
A4	10.98	17.78, 22.18	18.26, 22.18	1.67, 12.98
A5	4.76	7.89, 8.98	8.54, 8.97	1.14, 3.69
A6	3.48	5.62, 6.42	5.89, 6.42	0.80, 2.90
A7	3.83	6.16, 7.14	6.43, 7.14	0.88, 3.43
A8	7.30	12.01, 14.72	14.15, 14.72	2.33, 6.85
A9	3.49	5.63, 6.57	6.23, 6.57	0.92, 2.88

	Particle Masses (GeV)			
Pts	$m_{\chi_1^c}$	$m_{\chi_1^0}$	$m_{h_{1,2,3}}$	$m_{a_{1,2}}$
A1	173.4	155.8	118.3, 187.3, 1751.6	15.7, 1751.6
A2	105.0	103.7	136.6, 211.1, 1616.8	20.3, 1616.8
A3	121.7	121.7	152.6, 644.3, 3544.8	71.3, 3544.8
A4	106.0	105.8	152.4, 843.6, 3564.4	98.0, 3564.3
A5	321.4	311.1	117.4, 433.3, 2825.2	53.8, 2825.1
A6	123.9	119.8	133.1, 331.2, 1656.8	43.3, 1656.7
A7	109.7	107.1	137.5, 401.8, 1754.8	54.3, 1754.6
A8	1276.2	1272.4	116.2, 1973.2, 6596.7	337.4, 6596.6
A9	296.1	289.8	121.9, 659.6, 2430.1	96.1, 2429.9

Table 3: Parameters of the intermediate-scale general gauge mediation.

	Input Parameters			
Pts	$\lambda(\Lambda_{EW})$	$\kappa(\Lambda_{EW})$	Λ_M (GeV)	η
B1	0.15	0.075	1.00×10^{11}	4.180
B2	0.15	0.15	1.00×10^{11}	4.512
B3	0.15	0.40	1.00×10^{11}	4.292
B4	0.15	0.60	1.00×10^{11}	4.126
B5	0.30	0.20	1.00×10^{11}	3.981
B6	0.30	0.40	1.00×10^{11}	4.360
B7	0.30	0.55	1.00×10^{11}	4.620
B8	0.45	0.35	1.00×10^{11}	4.019
B9	0.45	0.50	1.00×10^{11}	4.542

	Soft SUSY-breaking Parameters at the EW Scale (GeV or GeV^2)					
Pts	$M_{1,2,3}$	$m^2_{H_d}$	$m^2_{H_u}$	m^2_N	A_λ	A_κ
B1	781.9, 2225.5, 1762.6	7.98×10^6	-2.23×10^6	-1.42×10^5	379.6	11.6
B2	443.3, 1274.9, 935.4	1.82×10^6	-4.37×10^5	-4.41×10^4	177.8	6.2
B3	1177.2, 3362.9, 2593.9	2.41×10^6	-4.34×10^6	-2.19×10^5	215.8	13.1
B4	2138.5, 6076.2, 4875.4	3.85×10^6	-1.76×10^7	-4.93×10^5	229.8	19.5
B5	1360.7, 3846.7, 3199.0	2.63×10^7	-9.56×10^6	-1.66×10^6	649.5	80.0
B6	762.0, 2181.3, 1656.3	7.41×10^6	-1.89×10^6	-5.00×10^5	357.5	42.7
B7	475.6, 1371.9, 983.1	2.46×10^6	-5.17×10^5	-1.73×10^5	205.9	24.4
B8	1678.7, 4752.2, 3914.6	3.95×10^7	-1.66×10^7	-5.37×10^6	730.5	214.8
B9	747.1, 2150.0,1567.1	7.86×10^6	-1.96×10^6	-1.04×10^5	356.4	92.8

	Output Parameters				
Pts	h_t, h_b	Λ_q (GeV)	tanβ	μ (GeV)	B_μ (GeV^2)
B1	0.950, 0.331	1.98×10^5	19.11	541.4	3.51×10^5
B2	0.949, 0.550	1.05×10^5	31.88	150.3	4.91×10^4
B3	0.949, 0.780	2.91×10^5	45.17	126.0	6.92×10^4
B4	0.948, 0.832	5.47×10^5	48.15	126.2	9.22×10^4
B5	0.953, 0.183	3.59×10^5	10.57	1406.6	2.22×10^6
B6	0.949, 0.340	1.86×10^5	19.62	384.5	3.33×10^5
B7	0.949, 0.465	1.10×10^5	26.97	163.5	8.23×10^4
B8	0.957, 0.125	4.39×10^5	7.16	2188.5	5.30×10^6
B9	0.953, 0.173	1.76×10^5	10.03	673.5	7.40×10^5

Table 4: Mass spectrum of particles and superparticles in the intermediate-scale general gauge mediation.

	Particle Masses (TeV)			
Pts	$m_{\tilde{g}}$	$m_{\tilde{t}_{1,2}}$	$m_{\tilde{b}_{1,2}}$	$m_{\tilde{\tau}_{1,2}}$
B1	1.82	1.98, 4.03	3.23, 4.02	0.90, 3.07
B2	1.00	0.98, 2.16	1.56, 2.16	0.32, 1.74
B3	2.61	2.84, 5.58	3.59, 5.58	1.00, 4.49
B4	4.72	5.52, 10.16	6.42, 10.16	2.11, 8.07
B5	3.19	3.69, 7.21	6.04, 7.21	1.75, 5.34
B6	1.72	1.79, 3.86	3.02, 3.85	0.87, 3.01
B7	1.05	1.00, 2.33	1.71, 2.32	0.45, 1.88
B8	3.86	4.42, 8.87	7.44, 8.87	2.20, 6.60
B9	1.63	1.60, 3.76	2.96, 3.75	0.97, 2.98

	Particle Masses (GeV)			
Pts	$m_{\chi_1^c}$	$m_{\chi_1^0}$	$m_{h_{1,2,3}}$	$m_{a_{1,2}}$
B1	540.3	520.5	121.4, 536.5, 2931.9	97.1, 2931.9
B2	149.4	144.7	121.1, 297.6, 1416.9	54.0, 1416.9
B3	125.9	124.4	135.3, 663.8, 2367.7	115.8, 2367.6
B4	126.1	125.4	142.2, 997.6, 3227.7	172.5, 3227.6
B5	1405.5	1342.6	120.6, 1843.4, 5383.5	473.7, 5383.4
B6	383.7	380.6	126.1, 1009.0, 2803.2	192.7, 2136.1
B7	162.6	159.3	122.0, 590.0, 1623.6	150.5, 1623.3
B8	2187.3	1676.5	117.7, 3331.0, 6768.7	1045.5, 6768.5
B9	671.8	658.9	118.6, 1464.2, 2911.0	457.8, 2910.5

Table 5: Parameters of the high-scale general gauge mediation.

	Input Parameters			
Pts	$\lambda(\Lambda_{EW})$	$\kappa(\Lambda_{EW})$	Λ_M (GeV)	η
C1	0.15	0.075	1.00×10^{15}	4.695
C2	0.15	0.15	1.00×10^{15}	4.980
C3	0.15	0.40	1.00×10^{15}	5.060
C4	0.15	0.60	1.00×10^{15}	4.930
C5	0.30	0.20	1.00×10^{15}	4.639
C6	0.30	0.40	1.00×10^{15}	5.110
C7	0.30	0.55	1.00×10^{15}	5.240
C8	0.45	0.35	1.00×10^{15}	4.755
C9	0.45	0.50	1.00×10^{15}	5.560

	Soft SUSY-breaking Parameters at the EW Scale (GeV or GeV^2)					
Pts	$M_{1,2,3}$	$m^2_{H_d}$	$m^2_{H_u}$	m^2_N	A_λ	A_κ
C1	864.5, 2506.8, 1749.5	1.26×10^7	-2.73×10^6	-2.96×10^5	742.4	32.1
C2	628.2, 1834.5, 1207.0	5.67×10^6	-9.95×10^5	-1.54×10^5	498.5	22.8
C3	833.5, 2438.6, 1579.2	3.85×10^6	-1.57×10^6	-2.01×10^5	392.7	24.6
C4	1469.9, 4287.5, 2849.6	3.34×10^6	-5.76×10^6	-3.79×10^5	466.2	33.2
C5	1103.6, 3195.32, 2257.0	2.07×10^7	-5.90×10^6	-1.86×10^6	877.1	161.5
C6	742.4, 2174.7, 1394.5	9.02×10^6	-1.59×10^6	-7.82×10^5	608.1	101.4
C7	705.1, 2071.2, 1295.2	7.34×10^6	-1.24×10^6	-5.69×10^5	549.1	84.3
C8	1981.9, 5755.8, 3966.3	6.35×10^7	-2.35×10^7	-1.21×10^7	1332.5	611.7
C9	781.5, 2310.7, 1361.8	9.85×10^6	-2.04×10^6	-1.67×10^6	586.9	222.2

	Output Parameters				
Pts	h_t, h_b	Λ_q (GeV)	$\tan\beta$	μ (GeV)	B_μ (GeV^2)
C1	0.951, 0.220	1.98×10^5	12.63	792.6	8.99×10^5
C2	0.949, 0.391	1.37×10^5	22.64	285.4	2.23×10^5
C3	0.948, 0.702	1.79×10^5	40.79	122.3	8.75×10^4
C4	0.948, 0.794	3.23×10^5	46.05	112.8	1.03×10^5
C5	0.958, 0.124	2.56×10^5	7.10	1524.2	2.87×10^6
C6	0.951, 0.233	1.58×10^5	13.47	492.5	6.20×10^5
C7	0.949, 0.342	1.47×10^5	19.86	306.8	3.38×10^5
C8	0.967, 0.087	4.49×10^5	4.99	3406.1	1.35×10^7
C9	0.958, 0.123	1.54×10^5	7.09	891.2	1.39×10^6

Table 6: Mass spectrum of particles and superparticles in the high-scale general gauge mediation.

	Particle Masses (TeV)			
Pts	$m_{\tilde{g}}$	$m_{\tilde{t}_{1,2}}$	$m_{\tilde{b}_{1,2}}$	$m_{\tilde{\tau}_{1,2}}$
C1	1.80	1.17, 4.37	3.33, 4.37	1.18, 3.68
C2	1.27	0.61, 3.07	2.15, 3.06	0.68, 2.67
C3	1.63	0.68, 3.82	2.08, 3.81	0.89, 3.43
C4	2.84	1.54, 6.61	3.14, 6.61	2.08, 5.95
C5	2.29	1.48, 5.62	4.37, 5.61	1.59, 4.71
C6	1.46	0.52, 3.65	2.64, 3.65	1.00, 3.19
C7	1.36	0.31, 3.41	2.36, 3.40	0.84, 3.02
C8	3.90	2.07, 9.98	7.71, 9.98	2.89, 8.48
C9	1.43	0.71, 3.76	2.64, 3.76	1.14, 3.40

	Particle Masses (GeV)			
Pts	$m_{\chi_1^c}$	$m_{\chi_1^0}$	$m_{h_{1,2,3}}$	$m_{a_{1,2}}$
C1	791.3	768.6	120.7, 777.4, 3665.7	194.8, 3665.7
C2	284.6	280.6	122.2, 559.6, 2443.0	139.6, 2442.9
C3	122.1	119.9	126.8, 639.4, 2207.5	155.3, 2207.4
C4	112.7	111.6	134.2, 878.8, 2792.8	211.2, 2792.7
C5	1522.3	1101.0	116.6, 1972.0, 4872.1	698.9, 4871.9
C6	491.3	486.7	121.2, 1274.9, 3068.7	446.3, 3068.4
C7	306.0	303.1	120.4, 1086.4, 2765.9	376.0, 2765.6
C8	3404.4	1981.1	120.1, 5084.2, 8909.4	2193.7, 8909.2
C9	889.0	771.4	117.2, 1884.6, 3306.1	806.7, 3305.3

Table 7: Composition of light Higgs bosons ($\leq$ 115GeV). Here "Re" and "Im" denote the real and imaginary components of the neutral Higgs fields, respectively. All light Higgs bosons appearing in this paper are CP-odd, related to the explicitly breaking of the global $U(1)_R$ symmetry. However, all of them can satisfy the current experimental bounds since they are extremely singlet-like.

Composition of Light Higgs Bosons (LHB)				
Pts	LHBs	Im(H_d)	Im(H_u)	Im(N)
A1	a_1	-1.2×10^{-3}	-8.8×10^{-4}	0.999999
A2	a_1	-2.0×10^{-3}	-1.1×10^{-5}	0.999998
A3	a_1	-2.2×10^{-3}	9.4×10^{-4}	0.999997
A4	a_1	-2.1×10^{-3}	-7.5×10^{-5}	0.999998
A5	a_1	-2.0×10^{-4}	3.3×10^{-5}	> 0.9999995
A6	a_1	1.3×10^{-4}	-1.7×10^{-6}	> 0.9999995
A7	a_1	1.1×10^{-4}	6.1×10^{-5}	> 0.9999995
A9	a_1	4.6×10^{-3}	1.2×10^{-4}	0.999989
B1	a_1	-7.0×10^{-5}	-1.0×10^{-5}	> 0.9999995
B2	a_1	3.8×10^{-4}	1.7×10^{-5}	> 0.9999995

Table 8: Composition of the lightest neutralino or the NLSP in the low-scale general gauge mediation.

Composition of Lightest Neutralinos					
Pts	$\tilde{B}$	$\tilde{W}^0$	$\tilde{H}_d$	$\tilde{H}_u$	$\tilde{N}$
A1	0.021	-0.017	-0.451	-0.515	0.728
A2	-0.026	0.020	0.678	0.713	-0.173
A3	0.009	-0.006	0.710	-0.704	-0.024
A4	0.009	-0.006	0.710	-0.704	-0.019
A5	-0.020	0.017	0.658	0.687	-0.308
A6	-0.030	0.024	0.671	0.721	-0.172
A7	-0.027	0.020	0.679	0.722	-0.124
A8	-0.009	0.009	0.703	0.706	-0.083
A9	-0.026	0.022	0.686	0.711	-0.152

Collider Signatures

- Low scale supersymmetry breaking all squarks and sleptons too heavy to be produced at the Tevatron or LHC.

- Light charginos and neutralinos Higgsino-like and close in mass.

- Gravitino lightest SUSY particle

$$
\begin{aligned}
\chi_1^0 &\rightarrow Z\tilde{G}: \quad ZZ + X + \not{E} \\
\chi_1^0 &\rightarrow h_1\tilde{G}: \quad h_1h_1 + X + \not{E}
\end{aligned}
$$

$$
\begin{aligned}
\Gamma(\chi_1^0 \rightarrow Z\tilde{G}) &\approx \frac{1}{2}|c_{\tilde{H}_d}\cos\beta + c_{\tilde{H}_u}\sin\beta|^2 \frac{m_{\chi_1^0}^5}{16\pi F^2}\left(1 - \frac{m_Z^2}{m_{\chi_1^0}^2}\right)^4, \\
\Gamma(\chi_1^0 \rightarrow h_1\tilde{G}) &\approx \frac{1}{2}|c_{\tilde{H}_d}\sin\alpha - c_{\tilde{H}_u}\cos\alpha|^2 \frac{m_{\chi_1^0}^5}{16\pi F^2}\left(1 - \frac{m_{h_1}^2}{m_{\chi_1^0}^2}\right)^4.
\end{aligned}
$$

Displayed vertices: few mms to ms

- Observe that the Higgs, in some of the cases studied, tends to decay into two CP-odd Higgs bosons of intermediate mass, about half of Mz.

- Such a Higgs can also be studied in standard production channels at the Tevatron and the LHC

- Intermediate scale scenarios: Lighter gluino, still heavy scalars.

- NLSP is long lived at detector level. Small gap between chargino and neutralino make trilepton signals impractical. Best channels:

$$\tilde{g} \to qq'\chi_i^0, \qquad \tilde{g} \to qq'\chi_i^c.$$

- High scale scenario: Gluino and lightest stop at the reach of LHC. Stop mainly right-handed, which can decay into charginos or neutralinos

$$pp \to \tilde{g}\tilde{g}. \qquad \begin{array}{ccccc} \tilde{g} & \to & t\tilde{t}_1 & \to & tt\chi_1^0, \\ \tilde{g} & \to & t\tilde{t}_1 & \to & tb\chi_1^c. \end{array}$$

- Four top signatures, plus missing energy. They deserved to be study in much more detail !

Unification of Couplings

- The value of gauge couplings evolve with scale according to the corresponding RG equations:

$$\frac{1}{\alpha_i(Q)} = \frac{b_i}{2\pi} \ln\left(\frac{Q}{M_Z}\right) + \frac{1}{\alpha_i(M_Z)} \tag{8}$$

- Unification of gauge couplings would occur if there is a given scale at which couplings converge.

$$\frac{1}{\alpha_3(M_Z)} = \frac{b_3 - b_2}{b_1 - b_2}\frac{1}{\alpha_1(M_Z)} + \frac{b_3 - b_1}{b_2 - b_1}\frac{1}{\alpha_2(M_Z)} \tag{9}$$

- This leads to a relation between $\alpha_3(M_Z)$ and $\sin^2\theta_W(M_Z) = \alpha_1^{SM}/\left(\alpha_1^{SM} + \alpha_2^{SM}\right)$.

Results for the MSSM

- Only hint comes from Unification of Couplings

$$\alpha_3(M_Z) \simeq 0.125 - \frac{19\ \alpha_3^2(M_Z)}{28\pi} \ln\left(\frac{T_{\rm SUSY}}{M_Z}\right)$$

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Carena, Pokorski, C.W.'93

$$T_{\rm SUSY} \simeq |\mu| \left(\frac{M_{\tilde{W}}}{M_{\tilde{g}}}\right)^{3/2}$$

- Valules of $T_{\rm SUSY}$ of order 1 TeV preferred. For this, gluino mass should be of the order of the wino mass. Standard relation leads to large values of the strong gauge coupling, which may be only accomodated with GUT threshold effects.

Additional Thresholds

- In this case, gluino becomes of the order or lighter than wino, which improves the unification prediction
- However, additional threshold exists, associated with the messenger sector $\Delta\alpha_3(M_Z) \simeq \frac{9}{14\pi}\,\alpha_3(M_Z)^2\,\ln\left(\frac{\langle S_q\rangle}{\langle S_l\rangle}\right)$,

which should be added to

$$\begin{aligned}\Delta\alpha_3(M_Z) &\simeq -\frac{19}{28\pi}\,\alpha_3(M_Z)^2\,\ln\left(\frac{|\mu|}{M_Z}\left(\frac{M_2}{M_3}\right)^{3/2}\right)\\ &= -\frac{19}{28\pi}\alpha_3(M_Z)^2\ln\left(\frac{|\mu|}{M_Z}\left(\frac{\eta\,\alpha_2}{\alpha_3}\right)^{3/2}\right)\end{aligned}$$

- In the case that $\Lambda_l/\Lambda_q \sim \langle F_l\rangle/\langle F_q\rangle \simeq \eta,$ then $\langle S_q\rangle/\langle S_l\rangle \sim 1$

$$\Delta_\eta\alpha_3(M_Z) \simeq -\frac{57}{56\pi}\,\alpha_3^2(M_Z)\,\ln\eta$$

- Alternatively, for $\langle F_q\rangle \sim \langle F_l\rangle$ and $\Delta_\eta\alpha_3(M_Z) \simeq -\frac{21}{56\pi}\,\alpha_3^2(M_Z)\,\ln\eta.$
- In both cases, corrections are negative, leading to a better unification prediction than in the $\eta = 1$ case

CP-Violating Phases

- It is easy to count the number of phases that may be elliminated by field redefinition in this model
- One can show that a physical phase, beyond the one appearing in the SM appears, and may be related to the relative phase of the gaugino masses

$$arg\,(M_2^* M_3)$$

- New phases are necessary in order to implement the mechanism of electroweak baryogenesis
- Heavy scalars help in preventing problems with electric dipole moments
- Claim in the literature that, under precisely these conditions, constraints may be avoided even for lighter scalars in our framework.

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Conclusions

- The so-called μ-Problem in supersymmetric theories is intimately related to electroweak symmetry breaking
- A relation between a supersymmetric mass parameter and supersymmetry breaking terms must be enforced
- This solution should appear in a framework that leads to a solution to the flavor problem. Gauge mediation provides such a framework.
- We have explored the possibility of solving the problem in a simple modification of minimal gauge mediation
- Heavy scalars and gauginos are required, and there are interesting phenomenological consequences
- Unification conditions are improved and a physical phase appears in the spectrum
- Dark matter, among other questions, must be explored

Backup Slides

Higgs Fields

- Two Higgs fields with opposite hypercharge.

(S = 0)	(S = 1/2)	
H_1	$\tilde{H}_1$	(1,2,-1/2)
H_2	$\tilde{H}_2$	(1,2,1/2)

- Both Higgs fields acquire v.e.v. New parameter, $\tan\beta = v_2/v_1$.
- It is important to observe that the quantum numbers of H_1 are exactly the same as the ones of the lepton superfield L.
- This means that one can extend the superpotential $P[\Phi]$ to contain terms that replace H_1 by L.

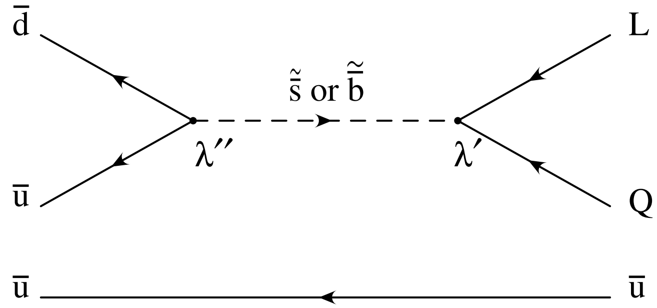
Baryon and Lepton Number Violation

- General superpotential contains, apart from the Yukawa couplings of the Higgs to lepton and quark fields, new couplings:

$$P[\Phi]_{\rm new} = \lambda' \, LQD + \lambda \, LLE + \lambda'' \, UDD \tag{41}$$

- Assigning every lepton chiral (antichiral) superfield lepton number 1 (-1) and every quark chiral (antichiral) superfield baryon number 1/3 (-1/3) one obtains :
  - Interactions in $P[\Phi]$ conserve baryon and lepton number.
  - Interactions in $P[\Phi]_{\rm new}$ violate either baryon or lepton number.
- One of the most dangerous consequences of these new interaction is to induce proton decay, unless couplings are very small and/or sfermions are very heavy.

Proton Decay



- Both lepton and baryon number violating couplings involved.
- Proton: Lightest baryon. Lighter fermions: Leptons

R-Parity

- A solution to the proton decay problem is to introduce a discrete symmetry, called R-Parity. In the language of component fields,

$$R_P = (-1)^{3B+2S+L} \tag{42}$$

- All Standard Model particles have $R_P = 1$.
- All supersymmetric partners have $R_P = -1$.
- All interactions with odd number of supersymmetric particles, like the Yukawa couplings induced by $P[\Phi]_{\rm new}$ are forbidden.
- Supersymmetric particles should be produced in pairs.
- The lightest supersymmetric particle is stable.
- Good dark matter candidate. Missing energy at colliders.