Dirac Gauginos, Gauge Mediation and Unification

Based on K. Benakli and MDG: 0811.4409, 0905.1043 (with also G. Belanger, C. Moura and A. Pukhov) 0909.0017 and 1003.4957

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Overview

- Motivation for Dirac Gauginos
- Dirac Gauginos and Gauge Mediation
- Model Building

Chiral Adjoint Fields

- MSSM chiral superfields are in singlet, fundamental and antifundametal reps; vector superfields are in adjoint reps.
- To allow Dirac masses for the gauginos, must add chiral adjoint field:

$$\mathbf{\Sigma} = \Sigma + \sqrt{2}\theta^{\alpha}(\chi)_{\alpha} + (\theta\theta)F_{\Sigma} + ... \to \mathcal{L} \supset -m_D\chi\lambda$$

- $\to$ Adjoint superfields will contain fermions to partner gauginos, but scalars too.
- $N \geqslant 2$ supersymmetry - chiral adjoint is superpartner of vectors
- Seiberg dualities (e.g. ISS):

$$Q_i\tilde{Q}_j = \mu X_{ij} = \mu\delta_{ij}\mathrm{tr}X_{ii} + \mu(X_{ij} - \delta_{ij}\mathrm{tr}X_{ii})$$

Motivation

- Nelson-Seiberg Theorem: existence of R symmetry (chiral symmetry under which bosons are also charged: $\Phi \to e^{i\alpha R_\Phi}\Phi$, $\theta \to e^{i\alpha}\theta$, $W \to e^{2i\alpha}W$) required for F-term SUSY breaking
- Many ~~SUSY~~ models preserve R symmetry (e.g. original O'Raifertaigh model)
- Dirac gaugino mass preserves R provided $R[\mathbf{S}, \mathbf{T}, \mathbf{O}_g] = 0$, Majorana does not: [Fayet, 78] suggested this as the original way to obtain gaugino masses!
- Alternatively Majorana gaugino mass may be too small (e.g. from many O'Raifeartaigh models [Komargodsky and Shih, 2008], [Abel, Jaeckel, Khoze 09])
- May also have non-flavour blind mediation [Kribs, Poppitz and Weiner, 07]
- Moreover, if gauginos are found at the LHC, we will have to determine whether they are Majorana or Dirac in nature!
- ...so can we make predictions of the range of parameters to look for?

Unification

- MSSM one-loop beta-function coefficients are $(b_3, b_2, b_1 = (5/3)b_Y) = (3, -1, -11)$, lead to unification of couplings at 10^{16} GeV with perturbative couplings $\alpha_{GUT} \sim 1/24$.

$$\frac{1}{g_i^2(\mu)} = \frac{1}{g_i^2(M_{SUSY})} + \frac{b_i}{8\pi^2} \log \mu/M_{SUSY}$$

- Triumph of the MSSM (modulo two-loop discrepancy...) that we would like to preserve!!
- Adding complete GUT multiplets (as in gauge mediation) does not alter this (beta-function coefficients decreased by $(1, 1, 1)$ per pair of $SU(5)$ messengers).
- Adding adjoint fields does (except for $\mathbf{S}$, a singlet): $\mathbf{T}$ decreases b_2 by 2, $\mathbf{O}_g$ decreases b_3 by 3
- If we want to preserve gauge unification must also add other states

Messengers to the Rescue

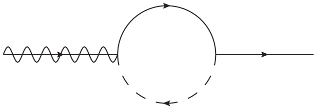
- Gauge mediation requires messenger fields - these could also restore gauge unification!
- Require at least 2 pairs of messengers in (anti) fundamental of $SU(2)$ and $SU(3)$ for adjoint scalar masses (see later)
- Easy to find sets of messengers that satisfy this, e.g.

$$
\begin{array}{rcl}
4 \times [(1,1)_1 + (1,1)_{-1}] & \text{at} & m_1 = 3\ 10^{12}\text{GeV} \\
4 \times [(1,2)_{1/2} + (1,\overline{2})_{-1/2}] & \text{at} & m_2 = 1.3\ 10^{13}\text{GeV} \\
2 \times [(3,1)_{1/3} + (\overline{3},1)_{-1/3}] & \text{at} & m_3 = 10^{13}\text{GeV} \\
M_U \sim 9.9 \cdot 10^{17}\text{GeV} & & \alpha_U^{-1} \sim 4.77
\end{array}
$$

- High messenger scale required to allow perturbativity up to GUT scale

Dirac Gauginos in Gauge Mediation

- Dirac masses in gauge mediation:



- Can have F or D term breaking (c.f. Majorana case)
- Lowest order operators are

$$\int d^2\theta \frac{a}{M^3} \mathrm{tr}(W^\alpha \Sigma) \overline{D}^2 D_\alpha (\mathbf{X}^\dagger \mathbf{X}) + \frac{b}{M} \mathrm{tr}(W^\alpha \mathbf{\Sigma}) W'_\alpha$$

- $a, b \sim \frac{\lambda_X g}{(4\pi)^2}$, $m_D \sim \frac{\lambda_X g}{(4\pi)^2} \frac{F^2}{M^3}, \frac{\lambda_X g}{(4\pi)^2} \frac{D}{M}$ in gauge mediation
- Clearly if $F/M^2, D/M^2 \ll 1$ then F-terms lead to very small masses (c.f. sfermion masses $m_{\tilde{f}} \sim \frac{g^2 F}{(4\pi)^2 M}$)
- For high messenger scale must allow D term breaking (c.f. semi-direct gauge mediation in $4-1$ model)

Gaugino Masses from Kinetic Mixing

- NB for $U(1)$s there is an additional Dirac gaugino mass operator:

$$\mathcal{L} \supset -\int d^2\theta \frac{c}{M} W^\alpha W'_\alpha \mathbf{X} \to -c\frac{F}{M}\lambda^\alpha \lambda'_\alpha$$

- Suppose we consider the kinetic mixing as a function of X:

$$\mathcal{L} \supset \frac{1}{2}\chi(X) F^{\mu\nu} F'_{\mu\nu} \supset \int d^2\theta \frac{1}{2}\chi_h(X) W^\alpha W'_\alpha + c.c.$$

- The leading order mass can then be calculated in the SUSY limit by analytic continuation again:

$$m_D = -\frac{1}{2} g g' \partial_X (\chi_h)\Big|_{F=0} F = -\frac{1}{2} g^2 \frac{\partial}{\partial \log X}(\chi_h)\Big|_{X=M} \frac{F}{M}$$

- For D-terms have similar expression, but now differentiate with respect to the adjoint: $\langle W'_\alpha \rangle = \theta_\alpha D'$, so

$$m_D = -\frac{1}{2\sqrt{2}} g g' \partial_\Sigma (\chi_h)\Big|_{\Sigma=0} D'$$

- NB kinetic mixing may in fact vanish and still have a gaugino mass!

Gaugino Masses from Kinetic Mixing II

- Interestingly can extend to $SU(N)$ gauginos:

$$-\frac{1}{2}\int d^2\theta W'^{\alpha} W^I_{\alpha}\Sigma^I \partial_{\Sigma^I}\chi_h(\Sigma^I) = -\frac{1}{2}\int d^2\theta 2 W'^{\alpha} \mathrm{tr}(W_{\alpha}\mathbf{\Sigma})\partial_{\Sigma^I}\chi_h(\Sigma^I)$$

- Gives a gauge mediation expression

$$m_D = \left| -\frac{1}{2}\frac{D'}{\sqrt{2}}\frac{g g'}{16\pi^2}\partial_{\Sigma^I}\mathrm{tr}\left(Q' R(T^I) \log|\mathcal{M}|^2/\mu^2 \right)\Big|_{X^I=0} \right|$$

- Also note: if kinetic mixing with hypercharge is not zero, in presence of D-terms this is dangerous!

$$\int d^2\theta \chi_h W^{\alpha}_Y W'_{\alpha} \to \mathcal{L} \supset \chi D_Y D'$$

- $D_Y = -g_Y \sum_i Y_i |\phi_i|^2$ so

$$\delta m^2_{\tilde{f}} = \chi D' g_Y Y_f = D' Y_f g_Y^2 g' \mathrm{tr}\left(\frac{YQ'}{16\pi^2}\log|\mathcal{M}|^2/\mu^2\right)$$

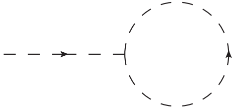
- Not suppressed by messenger mass!
- For F-terms corrections to hypercharge D_Y usually suppressed by insisting on messenger parity

Non-standard Soft Terms

- There are additional non-standard terms that <u>may</u> also be soft:

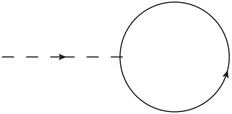
$$-\mathcal{L}^{\text{Non-standard}}_{\text{Breaking}} = t^i \phi_i + \frac{1}{2} r_i^{jk} \phi^i \phi_j \phi_k + m_D^{ia} \psi_i \lambda_a + \text{h.c.}$$

- Quadratic divergences <u>may</u> only appear in scalar tadpoles



- Gauge invariance ensures such terms only appear for singlets - a $U(1)$ adjoint!
- If SUSY is spontaneously broken then quadratic divergences cancel
- Note that there is a supersymmetric term that mimics r_i^{jk}:

$$W \supset \frac{1}{2} \mu^{ij} \Phi_i \Phi_j + \frac{1}{6} y^{ijk} \Phi_i \Phi_j \Phi_k$$
$$\rightarrow \mathcal{L} \supset -\frac{1}{2} y^{jkl} \mu_{il} \phi^i \phi_j \phi_k - \frac{1}{2} \mu^{ij} \chi_i \chi_j - \frac{1}{6} y^{ijk} \phi_i \chi_j \chi_k$$



- In that case fermion loop cancels the divergence:

Non-standard terms II

- For spontaneously broken SUSY, all of the non-standard terms actually come from a holomorphic coupling:

$$\int d^2\theta 2\sqrt{2} m_D \theta^\alpha \mathrm{tr}(W_\alpha \Sigma) \supset -m_D(\lambda_a \psi_a) + \sqrt{2} m_D \Sigma_a D_a$$

- This translates into

$$\mathcal{L} \supset -m_{bD}\sqrt{2} g_b \Sigma_a \phi^\dagger R^a_b \phi$$

- So $r_i^{i\Sigma_a} = m_{bD}\sqrt{2} g_b R^a_b(i)$
- This is preserved by the RGEs!
- Also no $R^{\Sigma\Sigma}_{\Sigma}$ terms because

$$D_a \supset -i f^{abc}\Sigma^b(\Sigma^\dagger)^c \to \mathcal{L} \supset -i m_D \sqrt{2} g \Sigma_a \Sigma_b (\Sigma^\dagger)_c f^{abc} = 0$$

- So all of these terms are determined by the Dirac gaugino mass!

Higgs Sector

- One motivation: allow ~~SUSY~~ sector to preserve R-symmetry
- Then Σ must have R-charge zero, since $\theta^\alpha \to e^{i\epsilon}\theta^\alpha : \lambda^\alpha \to e^{i\epsilon}\lambda^\alpha$ and thus for $\lambda^\alpha\chi_\alpha$ to exist, $\chi_\alpha \to e^{-i\epsilon}\chi_\alpha$. Then Σ must transform like $\theta^\alpha\chi_\alpha$ since $\mathbf{\Sigma} = \Sigma + \sqrt{2}\theta^\alpha\chi_\alpha + ...$
- However, R-symmetry is extension of chiral symmetry (LH and RH fermions transform oppositely, but the superpartner scalars also transform)
- No surprise that the MSSM Higgs sector breaks R
- Must either extend Higgs sector ([Amigo, Blechman, Fox and Poppitz, 08]) or
- Explicitly break R in visible sector
- Reasonable since exist no continous global symmetries due to gravity; can be broken by small SUGRA effects

New Couplings

Here are the most general renormalisable superpotential couplings:

- SUSY couplings contained in superpotential:
  $W = W_{\mathrm{Yukawa}} + W_{\mathrm{Higgs}} + W_{\mathrm{Adjoint}}$
- No new Yukawas:

$$W_{\mathrm{Yukawa}} = Y_U^{ij}\mathbf{Q_i}\cdot\mathbf{H_u}\mathbf{u_j^c} + Y_D^{ij}\mathbf{Q_i}\cdot\mathbf{H_d}\mathbf{d_j^c} + Y_E^{ij}\mathbf{L_i}\cdot\mathbf{H_d}\mathbf{e_j^c}$$

- Two new Higgs couplings:

$$W_{\mathrm{Higgs}} = \mu\mathbf{H_u}\cdot\mathbf{H_d} + \lambda_S\mathbf{S}\mathbf{H_d}\cdot\mathbf{H_u} + 2\lambda_T\mathbf{H_d}\cdot\mathbf{T}\mathbf{H_u}$$

- Several new adjoint-only couplings, BUT all of these violate R and so we shall set to zero:

$$W_{\mathrm{Adjoint}} = L\mathbf{S} + \frac{M_S}{2}\mathbf{S}^2 + \frac{\kappa_S}{3}\mathbf{S}^3 + M_T\mathrm{tr}(\mathbf{TT}) + \lambda_{ST}\mathbf{S}\mathrm{tr}(\mathbf{TT}) + M_O\mathrm{tr}(\mathbf{OO}) + \lambda_{SO}\mathbf{S}\mathrm{tr}(\mathbf{OO}) + \frac{\kappa_O}{3}\mathrm{tr}(\mathbf{OOO}).$$

Effective Higgs Potential

- In gauge mediation typically heaviest fields are S, T, O $\rightarrow$ integrate out. Higgs potential simplifies:

$$
\begin{aligned}
V_{eff} \quad = \quad & (m_{H_u}^2 + \mu^2)|H_u|^2 + (m_{H_d}^2 + \mu^2)|H_d|^2 - [m_{12}^2 H_u \cdot H_d + h.c.] \\
& + \frac{1}{2}\Big[\frac{1}{4}(g^2 + g'^2) + \lambda_1\Big](|H_d|^2)^2 + \frac{1}{2}\Big[\frac{1}{4}(g^2 + g'^2) + \lambda_2\Big](|H_u|^2)^2 \\
& + \Big[\frac{1}{4}(g^2 - g'^2) + \lambda_3\Big]|H_d|^2|H_u|^2 + \Big[-\frac{1}{2}g^2 + \lambda_4\Big](H_d \cdot H_u)(H_d^* \cdot H_u^*)
\end{aligned}
$$

where

$$
\lambda_3 = 2\lambda_T^2, \qquad \lambda_4 = \lambda_S^2 - \lambda_T^2, \qquad \lambda_1 = \lambda_2 = 0
$$

- Allows increased Higgs mass
- Also the origin of the potential may be a maximum rather than saddlepoint as in MSSM
- Furthermore, leading logarithmic corrections to $\lambda_1, \lambda_2, \lambda_3 \propto \frac{\lambda_{S,T}^4}{16\pi^2} \log \frac{m_{S,T}^2}{v^2}$
- EW precision variables restrict λ_T at tree level, less restrictive at large mass

Model Building Constraints

- Want to now obtain the low energy parameters from specific high energy choices of spurions, messengers and couplings
- Dirac masses require D-terms
- However, D-terms only generate sfermion masses at order D^2/M^3 at two loops
- At three-loop order, get

$$m_{\tilde{f}}^2 = \sum_{b=1}^{3} C_{\tilde{f}}^b \frac{(m_{bD})^2 \alpha_b}{\pi} \log \left(\frac{m_{\Sigma_P}^{(b)}}{m_{bD}} \right)^2$$

- Very small mass for selectrons - inverted “small gaugino mass” problem!!
- Solution: include also (R-symmetric) F-terms
- Find messenger couplings constrained by hypercharge tadpoles, singlet tadpoles, and adjoint scalar masses

Tadpoles

- Recall hypercharge tadpole induced by kinetic mixing:

$$\Delta m_{\tilde{f}}^2 = -g_Y^2 Y_f g' D' \frac{1}{8\pi^2} \sum_r 2\mathrm{tr}(\hat{e}\hat{Y}) \log M^r/\Lambda$$

- For large D', dangerous even if suppressed by a few loops
- Require $\mathrm{tr}(Q Q' \log |M|^2) = 0$
- Restricts us to degenerate sets of messengers Q_i, $\tilde{Q}_{\bar{j}}$ in fundamental, antifundamental pairs (c.f. Extraordinary Gauge Mediation [Cheung, Fitzpatrick and Shih, 2008])

$$\mathcal{L}_F^{Mess} = \int d^2\theta [M_{\mathrm{mess}}^{(a)} \mathrm{tr}(\mathbf{Q}_{\mathbf{ia}} \tilde{\mathbf{Q}}_{\bar{\mathbf{j}}\mathbf{a}}) \delta_{i\bar{j}} + \lambda_{i\bar{j}}^{(ab)} \mathrm{tr}(\mathbf{Q}_{\mathbf{ia}} \mathbf{\Sigma}_b \tilde{\mathbf{Q}}_{\bar{\mathbf{j}}\mathbf{a}}) + \kappa_{i\bar{j}}^{(a)} \mathrm{tr}(\mathbf{Q}_{\mathbf{ia}} \tilde{\mathbf{Q}}_{\bar{\mathbf{j}}\mathbf{a}}) \mathbf{X}].$$

- D-term couplings

$$\mathcal{L}_D^{Mess} = D[\textstyle\sum_{i,a} e_i^{(a)} \mathrm{tr}(Q_{ia} Q_{ia}^\dagger - \tilde{Q}_{ia} \tilde{Q}_{ia}^\dagger)]$$

- Define matrix $\hat{e}_{i\bar{j}} \equiv e_i \delta_{i\bar{j}}$

Singlet Tadpoles

- Tadpoles induced at one loop for singlet:

$$V \supset \frac{|F|^2}{32\pi^2 M_{\text{mess}}}\left[\Sigma \text{tr}(\lambda\{\kappa, \kappa^\dagger\}) + \Sigma^\dagger \text{tr}(\lambda^\dagger\{\kappa, \kappa^\dagger\})\right] + \frac{D^2}{16\pi^2 M_{\text{mess}}}\text{tr}(\Sigma\lambda\hat{e}^2 + \Sigma^\dagger\lambda^\dagger\hat{e}^2).$$

- This imposes

$$\text{tr}(\lambda\{\kappa, \kappa^\dagger\}) = 0$$
$$\text{tr}(\lambda\hat{e}^2) = 0$$

Adjoint Scalar Masses

- Adjoint scalar masses generated at one loop, size $m_\Sigma \sim \lambda D/M, \lambda F/M > m_D, m_{\tilde{f}}$
- Two types of mass

$$-\mathcal{L} \supset m_\Sigma^2 2^\delta \mathrm{tr}(\Sigma^\dagger \Sigma) + \frac{1}{2} B_\Sigma 2^\delta \mathrm{tr}(\Sigma^2 + (\Sigma^\dagger)^2)$$

- The propagating degrees of freedom are the real and imaginary components:

$$-\mathcal{L} \supset 2^\delta \mathrm{tr}\left(\frac{1}{2}(m^2 + B)\Sigma_P^2 + \frac{1}{2}(m^2 - B)\Sigma_M^2\right)$$

- Physical masses are $m_{\Sigma_P}^2, m_{\Sigma_M}^2 = m_\Sigma^2 \pm B_\Sigma$
- Tachyon unless $m_\Sigma^2 \geqslant B_\Sigma$!!!
- Minimal gauge mediation has $m_\Sigma^2 = 0$!

Adjoint Scalar Masses: F Term Models

$$m_\Sigma^2 = 2^{-\delta}\frac{1}{16\pi^2}\frac{F^\dagger F}{M_{\rm mess}^2}\frac{1}{6}{\rm tr}\left(2[\lambda,\lambda^\dagger][\kappa,\kappa^\dagger]+[\lambda,\kappa]([\lambda,\kappa])^\dagger\right)$$

$$B_\Sigma = -2\times 2^{-\delta}\frac{1}{16\pi^2}\frac{F^\dagger F}{M_{\rm mess}^2}\times\frac{1}{6}{\rm tr}\left(\kappa^\dagger(\kappa\lambda^2+\lambda\kappa\lambda+\lambda^2\kappa)\right)$$

For specific choice

$$\lambda = y\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix},\qquad \kappa = \begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix}$$

we find no tachyons, and

$$\mathcal{L}\supset -\frac{y^2}{96\pi^2}\frac{\Sigma^\dagger\Sigma}{M_{\rm mess}^2}\left[{\rm tr}(\frac{1}{2}|\Sigma+\overline{\Sigma}|^2+\frac{3}{2}|\Sigma-\overline{\Sigma}|^2)\right].$$

NB in this model the F term preserves R symmetry
For two pairs of messengers, essentially <u>only</u> choice!

Adjoint Scalar Masses: D Term Models

- Dirac gaugino mass given by $m_{bD} = \frac{2^{-\delta}}{\sqrt{2}} g_b \mathrm{tr}(\lambda^{(ab)} \hat{e}^{(a)}) \frac{2}{(4\pi)^2} \frac{D}{M_{\mathrm{mess}}}$
- Adjoint masses given by

$$m_\Sigma^2 = 2^{-\delta} \frac{1}{96\pi^2} \frac{D^2}{M_{\mathrm{mess}}^2} \mathrm{tr}\left([\hat{e}, \lambda]([\hat{e}, \lambda])^\dagger \right) + 2^{-\delta} \frac{3D}{64\pi^2} \mathrm{tr}(\hat{e}[\lambda, \lambda^\dagger])$$

$$B_\Sigma = -2 \times 2^{-\delta} \frac{1}{96\pi^2} \frac{D^2}{M_{\mathrm{mess}}^2} \mathrm{tr}\left(2\lambda^2 \hat{e}^2 + \lambda \hat{e} \lambda \hat{e} \right)$$

- To avoid tachyons need $[\hat{e}, \lambda] \neq 0$ - i.e. the couplings do not respect the $U(1)'$

Two important choices of couplings:

1. $\mathcal{V}(x, \theta) \equiv \frac{1}{\sqrt{4x^2-2}} \begin{pmatrix} 1 + ix & e^{i\theta}\sqrt{3(x^2-1)} \\ e^{-i\theta}\sqrt{3(x^2-1)} & -1 + ix \end{pmatrix}$
   Find $B_\Sigma = 0$, $m_\Sigma^2 > 0$ for $x^2 > 1$.
2. $\mathcal{U}(x) \equiv \frac{1}{\sqrt{1+x^2}} \begin{pmatrix} 1 & ix \\ -ix & -1 \end{pmatrix}$

Find

$$m_S^2 = \frac{|y|^2 D^2}{16\pi^2 M_{\mathrm{mess}}^2} \frac{1}{3} \frac{4x^2}{1+x^2}, \; B_S = -\frac{|y|^2 D^2}{16\pi^2 M_{\mathrm{mess}}^2} \frac{2}{3} \frac{3+x^2}{1+x^2}$$

i.e. need $2x^2 \geqslant (x^2+3)$.

Renormalisation I

- Soft terms generated at the messenger scale must be run down to low energies
- Several new parameters and couplings, including the non-standard soft terms
- Equations for sgluon mass:

$$\frac{d}{dt} m_O^2 = \frac{1}{16\pi^2}\left[-24 g_3^2 m_{3D}^2 \right]$$
$$\frac{d}{dt} B_O = \frac{1}{16\pi^2}\left[-12 g_3^2 B_O \right]$$

- If running from a high scale, strong coupling causes B_O to run much more strongly than m_O and may regenerate a tachyon at low energies!
- Hence for $SU(3)$ adjoints we choose messenger couplings of form $V(x, 0)$, where $B_O = 0$ at one loop at high scale

Renormalisation II

- If we have a GUT model, then we must run messenger couplings from the GUT scale:

$$\frac{d\lambda^{i\tilde{j}}}{dt} = \frac{-2g^2\lambda^{i\tilde{j}}}{16\pi^2}[2C_2(R) + C_2(G)] + \frac{1}{16\pi^2}[2C_2(R)\lambda\lambda^\dagger\lambda + I(R)\lambda \mathrm{tr}(\lambda\lambda^\dagger)].$$

- i.e. generic choices of λ will change their structure on RG running
- This could be a disaster - could allow singlet tadpoles etc
- Clearly if λ is proportional to a unitary matrix then we avoid this problem

Sample Models

	Model-I		Model-II		Model-III	
Parameter	Input					
$F(\mathrm{GeV}^2)$	7.5×10^{17}		5.5×10^{17}		1.3×10^{18}	
$D(\mathrm{GeV}^2)$	7.5×10^{17}		5.5×10^{17}		1.1×10^{18}	
x_U	2		1.9		2	
x_V	1.5		1.1		1	
y_{S1}	0		0		0	
y_{S2}	0.317		0.709		0.224	
y_{S3}	0.211		0.473		0.149	
y_T	0.819		1.83		0.549	
y_O	0.819		1.83		0.142	
	input	output	input	output	input	output
y_t	0.32	0.993	0.315	0.991	0.33	0.991
y_b	0.16	0.691	0.158	0.688	0.165	0.693
y_τ	0.2	0.295	0.193	0.288	0.206	0.297
λ_S	0.0868	0.0767	0.0993	0.0769	0.123	0.106
λ_T	0.112	0.152	0.128	0.113	0.129	0.223
$\mu(\mathrm{GeV})$	310	296	101	98	330	301
$B_\mu(\mathrm{GeV}^2)$	-4490	-4320	-2209	-2180	-18200	-16400
	Output					
$\tan\beta$	28.7		28.6		28.8	
$\Delta\rho$	2.18×10^{-6}		7.67×10^{-5}		0.000525	
α_Y	0.0105					
α_2	0.0332					
α_3	0.092					

Table: Model parameters.

Sample Spectra

Field	Model — I	Model — II	Model — III
m_{D1}	127	134	161
m_{D2}	217	308	472
m_{D3}	1190	1710	828
S_P	1350	1100	1720
S_M	5320	5370	6770
T_P	3590	2190	1190
T_M	5890	4910	6500
O_P	5870	4020	1090
O_M	5870	4020	1090
Q_3	523	508	442
$Q_{1,2}$	617	554	791
U_3	656	583	810
$U_{1,2}$	786	657	1160
D_3	477	469	369
$D_{1,2}$	535	504	587
L_3	623	459	1070
$L_{1,2}$	652	480	1130
E_3	956	703	1650
$E_{1,2}$	995	730	1720
H_u	308 i	127 i	311 i
H_d	198	237	621
A	352	250	689
h	117	115	117
H	351	248	692

Table: Low energy soft masses in GeV, with the exception that A, h and H are the physical Pseudoscalar, lightest scalar and heavy scalar Higgs masses respectively.

Conclusions

- Have assembled all the ingredients for constructing a class of models involving Dirac gaugino masses through gauge mediation
- It is straightforward to find models that unify gauge couplings
- Strong constraints are placed on messenger couplings through adjoint scalar masses
- RGE effects can be very important

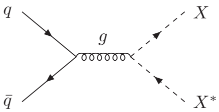
Future Possibilities

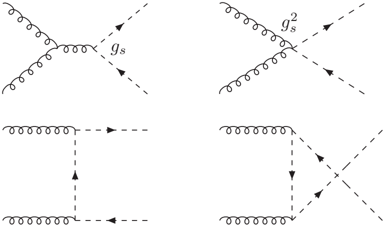
Many possible avenues for future work:

- Modifications of Higgs sector (current choice is "MSSM in disguise"...) e.g. MSSM without μ-term, NMSSM-type models...
- Calculation of two-loop effects
- Implementation in "Dirac Gaugino Soft Susy"
- Models to realise messenger mass patterns
- Explicit ~~SUSY~~ sectors (e.g. $4-1$ model)
- Gravity mediation, embedding in string models, Dirac gravitinos,....

Collider Signatures

- May be difficult to distinguish directly Dirac and Majorana gauginos except at $e^- e^-$ collider
- Indirectly we do obtain spectacular signals from the adjoint scalars





- Decay as (tree level):

$$X \to \tilde{g}\tilde{g} \to q q \tilde{q}\tilde{q} \to q q q q + \tilde{\chi}\tilde{\chi}$$
$$X \to \tilde{q}\tilde{q} \to q q + \tilde{\chi}\tilde{\chi}$$

and (one loop):

$$X \to t\bar{t}$$