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

Mark D. Goodsell

DESY, Hamburg

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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 antifundamental reps; vector superfields are in adjoint reps.
- To allow Dirac masses for the gauginos, must add chiral adjoint field:

\[
\Sigma = \Sigma + \sqrt{2}\theta^\alpha (\chi)_\alpha + (\theta\theta)F_\Sigma + \ldots \rightarrow \mathcal{L} \supset -m_D\chi\lambda
\]

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

\[
Q_i \tilde{Q}_j = \mu X_{ij} = \mu \delta_{ij} \text{tr}X_{ii} + \mu (X_{ij} - \delta_{ij} \text{tr}X_{ii})
\]
Motivation

- Nelson-Seiberg Theorem: existence of R symmetry (chiral symmetry under which bosons are also charged: $\Phi \rightarrow e^{i\alpha R} \Phi$, $\theta \rightarrow e^{i\alpha} \theta$, $W \rightarrow e^{2i\alpha} W$) required for F-term SUSY breaking
- Many SUSY models preserve R symmetry (e.g. original O’Raifertaigh model)
- Dirac gaugino mass preserves R provided $R[S, T, O_g] = 0$, 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?
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 \( \alpha_{\text{GUT}} \sim 1/24 \).

\[
\frac{1}{g_i^2(\mu)} = \frac{1}{g_i^2(M_{\text{SUSY}})} + \frac{b_i}{8\pi^2} \log \frac{\mu}{M_{\text{SUSY}}}
\]

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 \( S \), a singlet): \( T \) decreases \( b_2 \) by 2, \( O_g \) 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.
  
  \[ 4 \times [(1, 1)_1 + (1, 1)_{-1}] \quad \text{at} \quad m_1 = 3 \times 10^{12}\text{GeV} \]
  \[ 4 \times [(1, 2)_{1/2} + (1, \bar{2})_{-1/2}] \quad \text{at} \quad m_2 = 1.3 \times 10^{13}\text{GeV} \]
  \[ 2 \times [(3, 1)_{1/3} + (\bar{3}, 1)_{-1/3}] \quad \text{at} \quad m_3 = 10^{13}\text{GeV} \]
  \[ M_U \sim 9.9 \times 10^{17}\text{GeV} \]
  \[ \alpha_U^{-1} \sim 4.77 \]

- High messenger scale required to allow perturbativity up to GUT scale
Dirac Gauginos in Gauge Mediation

- Dirac masses in gauge mediation:

\[ \int d^2\theta \frac{a}{M^3} \text{tr}(W^\alpha \Sigma) \bar{D}^2 D_\alpha (X^\dagger X) + \frac{b}{M} \text{tr}(W^\alpha \Sigma) W'_\alpha \]

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

\[ a, b \sim \frac{\lambda_X g}{(4\pi)^2}, \quad m_D \sim \frac{\lambda_X g}{(4\pi)^2} \frac{F^2}{M^3}, \quad \frac{\lambda_X g}{(4\pi)^2} \frac{D}{M} \] 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:

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

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

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

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

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

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

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

- 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:

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

- Gives a gauge mediation expression

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

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

$$ \int d^2 \theta \chi_h W^\alpha Y W'^\alpha \rightarrow L \supset \chi D Y D' $$

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

$$ \delta m_f^2 = \chi D' g_Y Y_f = D' Y_f g_Y^2 g' \text{tr} ( \frac{Y Q'}{16 \pi^2} \log |M|^2 / \mu^2 ) $$

- 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 may also be soft:

\[-\mathcal{L}_{\text{Breaking}}^{\text{Non-standard}} = t^i \phi_i + \frac{1}{2} r^{ijk}_i \phi_j \phi_k + m^i_\Delta \psi_i \lambda_a + h.c.\]

- Quadratic divergences may 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 $r^{ijk}_i$:

\[
\mathcal{W} \supset \frac{1}{2} \mu^{ij} \Phi_i \Phi_j + \frac{1}{6} y^{ijk} \Phi_i \Phi_j \Phi_k
\]

\[
\rightarrow \mathcal{L} \supset - \frac{1}{2} y^{ijkl} \mu_{ij} \Phi_i \Phi_j \Phi_k - \frac{1}{2} \mu^{ij} \chi_i \chi_j - \frac{1}{6} y^{ijk} \Phi_i \chi_j \chi_k
\]

- 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:

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

• This translates into

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

• So \( r^i_{\Sigma^a} = m_{bD} \sqrt{2}g_b R^a_b (i) \)

• This is preserved by the RGEs!

• Also no \( R^{\Sigma \Sigma}_\Sigma \) terms because

\[
D_a \supset -i f^{a b c} \Sigma^b (\Sigma^\dagger)^c \rightarrow \mathcal{L} \supset -i m_D \sqrt{2}g \Sigma_a \Sigma_b (\Sigma^\dagger)^c f^{a b c} = 0
\]

• So all of these terms are determined by the Dirac gaugino mass!
Higgs Sector

• One motivation: allow SUSY sector to preserve R-symmetry

• Then $\Sigma$ must have R-charge zero, since $\theta^{\alpha} \rightarrow e^{i\epsilon} \theta^{\alpha}$ : $\lambda^{\alpha} \rightarrow e^{i\epsilon} \lambda^{\alpha}$ and thus for $\lambda^{\alpha} \chi_{\alpha}$ to exist, $\chi_{\alpha} \rightarrow e^{-i\epsilon} \chi_{\alpha}$. Then $\Sigma$ must transform like $\theta^{\alpha} \chi_{\alpha}$ since $\Sigma = \Sigma + \sqrt{2} \theta^{\alpha} \chi_{\alpha} + \ldots$.

• 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:
  \[ W = W_{\text{Yukawa}} + W_{\text{Higgs}} + W_{\text{Adjoint}} \]

- No new Yukawas:
  \[ W_{\text{Yukawa}} = \gamma_{ij}^u Q_i \cdot H_u u_j^c + \gamma_{ij}^d Q_i \cdot H_d d_j^c + \gamma_{ij}^e L_i \cdot H_d e_j^c \]

- Two new Higgs couplings:
  \[ W_{\text{Higgs}} = \mu H_u \cdot H_d + \lambda_S S H_d \cdot H_u + 2\lambda_T H_d \cdot T H_u \]

- Several new adjoint-only couplings, BUT all of these violate \( \mathcal{R} \) and so we shall set to zero:
  \[ W_{\text{Adjoint}} = L S + \frac{M_S}{2} S^2 + \frac{\kappa_S}{3} S^3 + M_T \text{tr}(T T) + \lambda_S T \text{Str}(T T) \]
  \[ + M_O \text{tr}(O O) + \lambda_S O \text{Str}(O O) + \frac{\kappa_O}{3} \text{tr}(O O O) \].
Effective Higgs Potential

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

$$V_{\text{eff}} = \left( m_{H_u}^2 + \mu^2 \right) |H_u|^2 + \left( m_{H_d}^2 + \mu^2 \right) |H_d|^2 - [m_{12}^2 H_u \cdot H_d + \text{h.c.}]$$

$$+ \frac{1}{2} \left[ \frac{1}{4} \left( g^2 + g'^2 \right) + \lambda_1 \right] (|H_d|^2)^2 + \frac{1}{2} \left[ \frac{1}{4} \left( g^2 + g'^2 \right) + \lambda_2 \right] (|H_u|^2)^2$$

$$+ \left[ \frac{1}{4} \left( g^2 - g'^2 \right) + \lambda_3 \right] |H_d|^2 |H_u|^2 + \left[ - \frac{1}{2} g^2 + \lambda_4 \right] (H_d \cdot H_u) (H_d^* \cdot H_u^*)$$

where

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

- 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 $\lambda_1, \lambda_2, \lambda_3 \propto \frac{\lambda_4^4 S, T}{16 \pi^2} \log \frac{m_{S, T}^2}{v^2}$
- EW precision variables restrict $\lambda_T$ 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

$$m_\tilde{f}^2 = \sum_{b=1}^{3} C^b_f \frac{(m_b D)^2 \alpha_b}{\pi} \log \left( \frac{m^{(b)}_{\Sigma_p}}{m_b D} \right)^2$$

- 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:

\[
\Delta m_f^2 = -g_Y^2 Y_f g'D' \frac{1}{8\pi^2} \sum_r 2\text{tr} (\hat{e}\tilde{Y}) \log \frac{M_r}{\Lambda}
\]

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

\[
L_{\text{Mess}}^F = \int d^2 \theta [M_{\text{mess}}^{(a)} \text{tr}(Q_{ia} \tilde{Q}_{ja}) \delta_{i\bar{j}} + \lambda_{i\bar{j}}^{(ab)} \text{tr}(Q_{ia} \Sigma_b \tilde{Q}_{ja}) + \kappa_{i\bar{j}}^{(a)} \text{tr}(Q_{ia} \tilde{Q}_{ja} X)].
\]

- D-term couplings

\[
L_{\text{Mess}}^D = \sum_{i,a} e_{i}^{(a)} \text{tr}(Q_{ia} Q_{ia}^\dagger - \tilde{Q}_{ia} \tilde{Q}_{ia}^\dagger)
\]

- 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

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

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

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

- Physical masses are \[ m_{\Sigma_P}^2, m_{\Sigma_M}^2 = m_\Sigma^2 \pm B_\Sigma \]

- Tachyon unless \[ m_\Sigma^2 \geq B_\Sigma \]

- Minimal gauge mediation has \[ m_\Sigma^2 = 0 \]
Adjoint Scalar Masses: F Term Models

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

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

For specific choice

\[
\lambda = y \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \kappa = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}
\]

we find no tachyons, and

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

NB in this model the F term preserves R symmetry
For two pairs of messengers, essentially only choice!
Adjoint Scalar Masses: D Term Models

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

- Adjoint masses given by
  \[ m_{\Sigma}^2 = 2^{-\delta} \frac{1}{96\pi^2} \frac{D^2}{M_{\text{mess}}^2} \text{tr}\left([\hat{e}, \lambda]([\hat{e}, \lambda]^\dagger)\right) + 2^{-\delta} \frac{3D}{64\pi^2} \text{tr}(\hat{e} [\lambda, \lambda^\dagger]) \]
  \[ B_{\Sigma} = -2 \times 2^{-\delta} \frac{1}{96\pi^2} \frac{D^2}{M_{\text{mess}}^2} \text{tr}\left(2\lambda^2 \hat{e}^2 + \lambda \hat{e} \lambda \hat{e}\right) \]

- 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. \(\mathcal{V}(x, \theta) \equiv \frac{1}{\sqrt{4x^2-2}} \left( \begin{array}{cc} 1 + ix & e^{i\theta} \sqrt{3(x^2 - 1)} \\ e^{-i\theta} \sqrt{3(x^2 - 1)} & -1 + ix \end{array} \right) \)

   Find \(B_{\Sigma} = 0, m_{\Sigma}^2 > 0\) for \(x^2 > 1\).

2. \(\mathcal{U}(x) \equiv \frac{1}{\sqrt{1+x^2}} \left( \begin{array}{cc} 1 & ix \\ -ix & -1 \end{array} \right) \)

   Find

   \[ m_{S}^2 = \frac{|y|^2 D^2}{16\pi^2 M_{\text{mess}}^2} \frac{1}{3} \frac{4x^2}{1 + x^2}, B_{S} = -\frac{|y|^2 D^2}{16\pi^2 M_{\text{mess}}^2} \frac{2}{3} \frac{3 + x^2}{1 + x^2} \]

   i.e. need \(2x^2 \geq (x^2 + 3)\).
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:
  \[
  \frac{d}{dt} m_O^2 = \frac{1}{16\pi^2} \left[ -24g_3^2 m_{3D}^2 \right]
  \]
  \[
  \frac{d}{dt} B_O = \frac{1}{16\pi^2} \left[ -12g_3^2 B_O \right]
  \]
- 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:

\[
\frac{d\lambda^{ij}}{dt} = -2g^2\lambda^{ij} \frac{2C_2(R) + C_2(G)}{16\pi^2} + \frac{1}{16\pi^2} [2C_2(R)\lambda\lambda^\dagger\lambda + I(R)\lambda\text{tr}(\lambda\lambda^\dagger)].
\]

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

| Parameter | Model-I | Model-II | Model-III |
|-----------|---------|----------|-----------|
| $F (\text{GeV}^2)$ | $7.5 \times 10^{17}$ | $5.5 \times 10^{17}$ | $1.3 \times 10^{18}$ |
| $D (\text{GeV}^2)$ | $7.5 \times 10^{17}$ | $5.5 \times 10^{17}$ | $1.1 \times 10^{18}$ |
| $\chi_{U}$ | 2 | 1.9 | 2 |
| $\chi_{V}$ | 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 |
| $y_{\tau}$ | 0.2 | 0.295 | 0.193 | 0.288 | 0.206 | 0.297 |
| $\lambda_{S}$ | 0.0868 | 0.0767 | 0.0993 | 0.0769 | 0.123 | 0.106 |
| $\lambda_{T}$ | 0.112 | 0.152 | 0.128 | 0.113 | 0.129 | 0.223 |
| $\mu (\text{GeV})$ | 310 | 296 | 101 | 98 | 330 | 301 |
| $B_{H} (\text{GeV}^2)$ | -4490 | -4320 | -2209 | -2180 | -18200 | -16400 |

| Output | |
|-------|--|
| $\tan \beta$ | 28.7 |
| $\Delta \rho$ | $2.18 \times 10^{-6}$ |
| $\alpha_{Y}$ | 0.0105 |
| $\alpha_{2}$ | 0.0332 |
| $\alpha_{3}$ | 0.092 |

**Table:** Model parameters.
### Sample Spectra

| Field | Model – I | Model – II | Model – III |
|-------|-----------|------------|-------------|
| $m_{D_1}$ | 127 | 134 | 161 |
| $m_{D_2}$ | 217 | 308 | 472 |
| $m_{D_3}$ | 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
Many possible avenues for future work:

- Modifications of Higgs sector (current choice is “MSSM in disguise”...) e.g. MSSM without $\mu$-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

\[ q \rightarrow \tilde{g} \tilde{g} \rightarrow q \bar{q} q \bar{q} \rightarrow q q q q + \tilde{\chi} \tilde{\chi} \]
\[ X \rightarrow t \bar{t} \]

and (one loop):

\[ X \rightarrow q \bar{q} \rightarrow q q + \tilde{\chi} \tilde{\chi} \]