Dirac Gauginos

Based on K. Benakli and MDG: 0811.4409, 0905.1043 (with also G. Belanger, C. Moura and A. Pukhov), 0909.0017 and 1003.4957; and S. Abel and MDG: 1102.0014

Mark D. Goodsell

DESY, Hamburg

LAPTH,
10^{th} March 2011

Overview

- Motivation for Dirac gauginos
- Model building: bottom up
- Dirac gauginos and Gauge Mediation
- Top down models and unification
- Dirac gauginos and (deconstructed) gaugino mediation

Motivation: bottom up

- If gauginos are found at the LHC, we will have to determine whether they are Majorana or Dirac in nature
- This is very difficult to do directly: maybe only possible at ILC
- There may be clear signals from accompanying adjoint scalars if light
- Otherwise: challenge is to study the possible spectra from different models
- Can they look like e.g. minimal gauge mediation? Will the gauginos be heavier than the sfermions? Can the (N)LSP be a (pseudo-)Dirac gaugino?...

Motivation: top down

Some attractive theoretical motivations:

- Nelson-Seiberg Theorem: existence of R symmetry (chiral symmetry under which bosons are also charged: $\Phi \rightarrow e^{i\alpha R_\Phi}\Phi$, $\theta \rightarrow e^{i\alpha}\theta$, $W \rightarrow e^{2i\alpha}W$) required for F-term SUSY breaking
- Many ~~SUSY~~ models preserve R symmetry (e.g. original O'Raifertaigh model)
- Dirac gaugino mass may preserve R , 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]

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:

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

- $\rightarrow$ Adjoint superfields will contain fermions to partner gauginos, but scalars too.
- $N \geqslant 2$ supersymmetry - chiral adjoint is superpartner of vectors
- Higher dimensional models:

$$\partial^5_{[\mu} A^5_{\nu]} - [A^5_{\mu}, A^5_{\nu}] = \begin{cases} \partial^4_{[\mu} A^4_{\nu]} - [A^4_{\mu}, A^4_{\nu}] \\ \partial^4_{\mu} A_5 - [A^4_{\mu}, A_5] \end{cases}$$

- $\rightarrow$Current in warped models
- Seiberg dualities (e.g. ISS):

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

MSSM with Adjoints

Names		Spin 0	Spin 1/2	Spin 1	$SU(3), SU(2), U(1)_Y$
Quarks	$\mathbf{Q}$	$\tilde{Q} = (\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)		(**3**, **2**, 1/6)
	$\mathbf{u^c}$	$\tilde{u}^c_L$	u^c_L		($\bar{\mathbf{3}}$, **1**, -2/3)
(×3 families)	$\mathbf{d^c}$	$\tilde{d}^c_L$	u^c_L		($\bar{\mathbf{3}}$, **1**, 1/3)
Leptons	$\mathbf{L}$	$(\tilde{\nu}_{eL}, \tilde{e}_L)$	(ν_{eL}, e_L)		(**1**, **2**, -1/2)
(×3 families)	$\mathbf{e^c}$	$\tilde{e}^c_L$	e^c_L		(**1**, **1**, 1)
Higgs	$\mathbf{H_u}$	(H^+_u, H^0_u)	$(\tilde{H}^+_u, \tilde{H}^0_u)$		(**1**, **2**, 1/2)
	$\mathbf{H_d}$	(H^0_d, H^-_d)	$(\tilde{H}^0_d, \tilde{H}^-_d)$		(**1**, **2**, -1/2)
Gluons	$\mathbf{W}_{3\alpha}$		$\lambda_{3\alpha}$ $[\equiv \tilde{g}_\alpha]$	g	(**8**, **1**, 0)
W	$\mathbf{W}_{2\alpha}$		$\lambda_{2\alpha}$ $[\equiv \tilde{W}^\pm, \tilde{W}^0]$	$W^\pm, W^0$	(**1**, **3**, 0)
B	$\mathbf{W}_{1\alpha}$		$\lambda_{1\alpha}$ $[\equiv \tilde{B}]$	B	(**1**, **1**, 0)
DG-octet	$\mathbf{O_g}$	O_g $[\equiv \Sigma_g]$	χ_g $[\equiv \tilde{g}']$		(**8**, **1**, 0)
DG-triplet	$\mathbf{T}$	$\{T^0, T^\pm\}$ $[\equiv \{\Sigma^W_0, \Sigma^\pm_W\}]$	$\{\chi^0_T, \chi^\pm_T\}$ $[\equiv \{\tilde{W}'^\pm, \tilde{W}'^0\}]$		(**1**,**3**, 0)
DG-singlet	$\mathbf{S}$	S $[\equiv \Sigma_B]$	χ_S $[\equiv \tilde{B}']$		(**1**, **1**, 0)

Building Models of Dirac Gauginos

- Want to extend MSSM by adding Dirac gaugino masses but minimal number of new fields and parameters inspired by problem of small Majorana masses
- If we want to exclude a Majorana mass altogether, need a symmetry forbidding $-\frac{M}{2}\lambda^\alpha\lambda_\alpha$ in effective Lagrangian.
- Since λ_α is lowest component of chiral superfield W_α, this transforms in the same way.
- To allow the kinetic term $\int d^2\theta \frac{1}{4} W^\alpha W_\alpha$, so must $d^2\theta \rightarrow$ an R-symmetry.
- Then Σ 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 Σ must transform like $\theta^\alpha\chi_\alpha$ since $\mathbf{\Sigma} = \Sigma + \sqrt{2}\theta^\alpha\chi_\alpha + ...$
- BUT exist no continous global symmetries $\rightarrow$ discrete or broken?

Dirac vs Majorana masses

- R-symmetry is extension of chiral symmetry (LH and RH fermions transform oppositely, but the superpartner scalars also transform), so no surprise that the MSSM Higgs sector breaks R
- Must either extend Higgs sector ([Amigo, Blechman, Fox and Poppitz, 08]) or allow small Majorana masses
- These will be generated anyway if we include gravity and cancel cosmological constant:

$$0 = V = |F|^2 + V_F^{hid} - 3m_{3/2}^2 M_P^2 \rightarrow m_{3/2} = |F|/\sqrt{3}M_P \qquad (1)$$

- Leads to

$$m_{1/2}^i = \frac{\alpha^i b^i}{4\pi} m_{3/2} = \frac{\alpha^i b^i}{4\pi} \frac{|F|}{\sqrt{3}M_P}$$

- $B\mu$ also violates R; could come from Higgs sector superpotential or gravity etc. Our (minimal) approach: add μ, $B\mu$ as required.
- Can also avoid $B\mu$ [Davies, March-Russell and McCullough, 11].

Supersymmetric 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:

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

- Two new Higgs couplings (c.f. NMSSM):

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

- Several new Adjoint couplings, but violate R so shall set to zero:

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

"Standard" Soft Terms

"Standard" soft terms take the form:

$$-\mathcal{L}^{\text{Standard}}_{\text{Breaking}} = (m^2)^j_i \phi^i \phi_j + (\frac{1}{6} a^{ijk}\phi_i\phi_j\phi_k + \frac{1}{2} b^{ij}\phi_i\phi_j + \frac{1}{2} M_a \lambda_a \lambda_a + h.c.)$$

So we have the MSSM terms plus new m^2 and B-type terms:

$$\begin{aligned} -\Delta\mathcal{L}^{DG-\text{Adjoint}}_{\text{soft}} &= m_S^2|S|^2 + \frac{1}{2}B_S(S^2 + h.c.) + 2m_T^2 \text{tr}(T^\dagger T) + B_T(\text{tr}(TT) + h.c.) \\ &\quad + 2m_O^2 \text{tr}(O^\dagger O) + B_O(\text{tr}(OO) + h.c.) \end{aligned}$$

The adjoint scalar A-terms (including the possible scalar tadpole) are given by

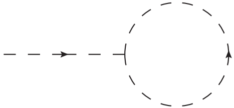
$$\begin{aligned} -\Delta\mathcal{L}^{A}_{\text{soft}} =& A_S\lambda_S S H_d \cdot H_u + 2A_T\lambda_T H_d \cdot T H_u + t^S S + \frac{1}{3}\kappa_S A_{\kappa_S} S^3 \\ &+ \lambda_{ST} A_{ST} S\text{tr}(TT) + \lambda_{SO} A_{SO} S\text{tr}(OO) + \frac{1}{3}\kappa_O A_{\kappa_O} \text{tr}(OOO) \\ &+ h.c. \end{aligned}$$

Non-standard Soft Terms

- There are additional non-standard terms that may also be soft:

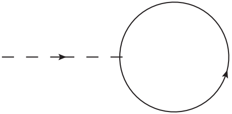
$$-\mathcal{L}^{\text{Non-standard}}_{\text{Breaking}} = t^i \phi_i + \frac{1}{2} r_i^{jk} \phi^i \phi_j \phi_k + m_D^{ia} \chi_i \lambda_a + h.c.$$

- 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_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 soft terms II

The possible non-standard soft terms are

$$
\begin{aligned}
&-\mathcal{L}^{\text{Non-standard}} \\
=&m_{1D}\chi_S\lambda_Y + 2m_{2D}\mathrm{tr}(\chi_T\lambda_2) + 2m_{3D}\mathrm{tr}(\chi_O\lambda_3) \\
&+ \tilde{Q}_i^\dagger r_{\tilde{Q}_i}^{S\tilde{Q}_j} S\tilde{Q}_j + \tilde{L}_i^\dagger r_{\tilde{L}_i}^{S\tilde{L}_j} S\tilde{L}_j + \tilde{u}_j r_{\tilde{u}_i}^{S\tilde{u}_j} S\tilde{u}_i^\dagger + \tilde{d}_j r_{\tilde{d}_i}^{S\tilde{d}_j} S\tilde{d}_i^\dagger + \tilde{e}_j r_{\tilde{e}_i}^{S\tilde{e}_j} S\tilde{e}_i^\dagger \\
&+ \tilde{H_u}^\dagger r_{\tilde{H_u}}^{S\tilde{H_u}} S\tilde{H_u} + \tilde{H_d}^\dagger r_{\tilde{H_d}}^{S\tilde{H_d}} S\tilde{H_d} \\
&+ (\tilde{Q}_i^\dagger r_{\tilde{Q}_i}^{T_a\tilde{Q}_j} T_a\tilde{Q}_j) + (\tilde{L}_i^\dagger r_{\tilde{L}_i}^{T_a\tilde{L}_j} T_a\tilde{L}_j) + (\tilde{H_u}^\dagger r_{\tilde{H_u}}^{T_a\tilde{H_u}} T_a\tilde{H_u}) + (\tilde{H_d}^\dagger r_{\tilde{H_d}}^{T_a\tilde{H_d}} T_a\tilde{H_d}) \\
&+ (\tilde{Q}_i^\dagger r_{\tilde{Q}_i}^{O_a\tilde{Q}_j} O_a\tilde{Q}_j) + (\tilde{u}_j r_{\tilde{u}_i}^{O_a\tilde{u}_j} O_a\tilde{u}_i^\dagger) + (\tilde{d}_j r_{\tilde{d}_i}^{O_a\tilde{d}_j} O_a\tilde{d}_i^\dagger) \\
&+ r_S^{SS} S^\dagger S^2 + r_S^{T^aT^b} S^\dagger \mathrm{tr}(T^aT^b) + r_{T^b}^{ST^a} S\mathrm{tr}((T^b)^\dagger T^a) + r_{T^c}^{T^aT^b}\mathrm{tr}(T^aT^b(T^c)^\dagger) \\
&+ r_{O^c}^{O^aO^b}\mathrm{tr}((O^c)^\dagger O^aO^b) + r_S^{O^aO^b} S^\dagger\mathrm{tr}(O^aO^b) + r_{O^b}^{SO^a} S\mathrm{tr}((O^b)^\dagger O^a) \\
&+ \mathrm{h.c.}
\end{aligned}
$$

Each of these should have a new RGE!!!!

Non-standard terms III

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

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

- 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

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

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

Electroweak Symmetry Breaking

- New couplings may affect EWSB
- In particular, depending on $W(S)$ singlet may behave like n/NMSSM or variants
- Our main assumption is $W(S) = 0$ but we can easily set $W(S) \neq 0$, $\mu = 0$ without significantly changing conclusions
- Parametrise ~~SUSY~~ by spurions $\mathbf{M}_i = 1 + 2\theta\theta M_i$, $\mathbf{m}_{\alpha iD} = \theta_\alpha m_{iD}$:

$$\mathcal{L}_{gauge} = \int d^4x d^2\theta \, [\, \frac{1}{4}\mathbf{M}_1 \mathbf{W}_1^\alpha \mathbf{W}_{1\alpha} + \frac{1}{2}\mathbf{M}_2 \mathrm{tr}(\mathbf{W}_2^\alpha \mathbf{W}_{2\alpha}) + \frac{1}{2}\mathbf{M}_3 \mathrm{tr}(\mathbf{W}_3^\alpha \mathbf{W}_{3\alpha}) + \sqrt{2}\mathbf{m}_{1D}^\alpha \mathbf{W}_{1\alpha}\mathbf{S} + 2\sqrt{2}\mathbf{m}_{2D}^\alpha \mathrm{tr}(\mathbf{W}_{2\alpha}\mathbf{T}) + 2\sqrt{2}\mathbf{m}_{3D}^\alpha \mathrm{tr}(\mathbf{W}_{3\alpha}\mathbf{O}_g) \,]$$

- and

$$-\Delta\mathcal{L}_{soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + B_\mu (H_u \cdot H_d + h.c.) + m_S^2 |S|^2 + \frac{1}{2} B_S (S^2 + h.c.) + 2 m_T^2 \mathrm{tr}(T^\dagger T) + B_T(\mathrm{tr}(TT) + h.c.) + A_S \lambda_S (S H_d \cdot H_u + h.c.) + 2 A_T \lambda_T (H_d \cdot T H_u + h.c.)$$

Electroweak Symmetry Breaking II

Neutral scalar potential:

$$
\begin{aligned}
V_{EW} \quad = \quad & (m_{H_u}^2 + \mu^2)|H_u^0|^2 + (m_{H_d}^2 + \mu^2)|H_d^0|^2 - B_\mu (H_u^0 H_d^0 + h.c.) + \frac{g^2 + g'^2}{8}(|H_u^0|^2 - |H_d^0|^2)^2 \\
& +(\lambda_S^2 + \lambda_T^2)|H_u^0 H_d^0|^2 \\
& + \frac{1}{2}(M_S^2 + m_S^2 + 4m_{1D}^2 + B_S)S_R^2 + \frac{1}{2}(M_S^2 + m_S^2 - B_S)S_I^2 \\
& + \frac{1}{2}(M_T^2 + m_T^2 + 4m_{2D}^2 + B_T)T_R^2 + \frac{1}{2}(M_T^2 + m_T^2 - B_T)T_I^2 \\
& + \left[\frac{\lambda_S^2}{2}(S_R^2 + S_I^2) + \frac{\lambda_T^2}{2}(T_I^2 + T_R^2) - \sqrt{2}\mu(\lambda_S S_R - \lambda_T T_R) - \lambda_S \lambda_T (S_I T_I + S_R T_R)\right] \\
& \quad \times \left[|H_u^0|^2 + |H_d^0|^2\right] \\
& + g' m_{1D} S_R (|H_u^0|^2 - |H_d^0|^2) + g m_{2D} T_R (|H_u^0|^2 - |H_d^0|^2) \\
& + \frac{\lambda_S}{\sqrt{2}}(M_S + A_S)S_R(H_{dR}^0 H_{uR}^0 - H_{dI}^0 H_{uI}^0) + \frac{\lambda_S}{\sqrt{2}}(M_S - A_S)S_I(H_{dR}^0 H_{uI}^0 + H_{dI}^0 H_{uR}^0) \\
& - \frac{\lambda_T}{\sqrt{2}}(M_T + A_T)T_R(H_{dR}^0 H_{uR}^0 - H_{dI}^0 H_{uI}^0) - \frac{\lambda_T}{\sqrt{2}}(M_T - A_T)T_I(H_{dR}^0 H_{uI}^0 + H_{dI}^0 H_{uR}^0)
\end{aligned}
$$

Electroweak Symmetry Breaking III

Find

$$v_s \simeq \frac{v^2}{2(M_S^2 + m_S^2 + 4m_{1D}^2 + B_S)} \left[g' m_{1D} c_{2\beta} + \sqrt{2}\mu\lambda_S - \frac{\lambda_S}{\sqrt{2}}(M_S + A_S) s_{2\beta} \right]$$

$$v_t \simeq \frac{v^2}{2(M_T^2 + m_T^2 + 4m_{2D}^2 + B_T)} \left[g m_{2D} c_{2\beta} - \sqrt{2}\mu\lambda_T + \frac{\lambda_T}{\sqrt{2}}(M_T + A_T) s_{2\beta} \right]$$

- EW precision experiments tell us that $\Delta\rho = \frac{M_W^2}{M_Z^2 \hat{c}_Z^2} - 1 = 0.0004^{+0.0008}_{-0.0004}$
- Here $\Delta\rho \approx 4(v_t/v)^2$, restricts $v_t \lesssim 3\ \mathrm{GeV}$
- Satisfied for large $m_T \gtrsim 1\ \mathrm{TeV}$
- Shall assume large soft masses for m_S, m_T - c.f. gauge mediation scenario

Effective Higgs Potential

- In limit of large m_S, m_T, can integrate out S, T. Higgs potential simplifies:

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

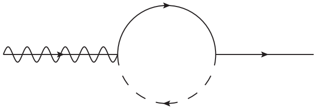
where

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

- Allows increased Higgs mass, MSSM without μ term
- Also the origin of the potential may be a maximum rather than saddlepoint as in MSSM
- Furthermore, leading logarithmic corrections to $\lambda_1, \lambda_2, \lambda_3 \propto \frac{\lambda^4_{S,T}}{16\pi^2} \log \frac{m^2_{S,T}}{v^2}$

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

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

- $a, b \sim \frac{\lambda_X g}{(4\pi)^2}$, $m_D \sim \frac{\lambda_X g}{(4\pi)^2} \frac{F^2}{M^3}, \frac{\lambda_X g}{(4\pi)^2} \frac{D}{M}$ 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. [Dumitrescu, Komargodski and Sudano, 10])

General Gauge Mediation I

Meade, Seiberg and Shih [08]:

- Hidden sector only interacts with the visible one through gauge couplings at lowest order

$$\mathcal{L}_{int} = 2g \int d^4\theta \mathcal{J}\mathcal{V} = g(JD - \lambda j - \bar{\lambda}\bar{j} - j^\mu V_\mu)$$

- Gauge current superfield:

$$\mathcal{J} = J + i\theta j - i\overline{\theta}\overline{j} - \theta\sigma\bar{\theta}j_\mu + \frac{1}{2}\theta\theta\bar{\theta}\bar{\sigma}^\mu\partial_\mu j - \frac{1}{2}\bar{\theta}\bar{\theta}\theta\sigma^\mu\partial_\mu\bar{j} - \frac{1}{4}\theta\theta\bar{\theta}\bar{\theta}\Box J$$

- e.g. for fundamentals with standard Kähler potential:

$$\mathcal{L} \supset \int d^4\theta Q^\dagger e^{2gV} Q = 2g \int d^4\theta (Q^\dagger Q) V$$

$$\begin{aligned} J &= Q^\dagger Q \\ j_\alpha &= -i\sqrt{2}Q^\dagger q_\alpha \\ \bar{j}_{\dot{\alpha}} &= i\sqrt{2}Q\overline{q}_{\dot{\alpha}} \\ j_\mu &= i(Q\partial_\mu Q^\dagger - Q^\dagger\partial_\mu Q) + q\sigma_\mu\overline{q} \end{aligned}$$

General Gauge Mediation II

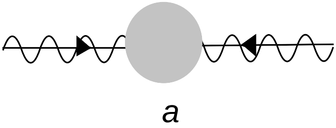
- Quantities determined by correlators:

$$\langle J(p)J(-p)\rangle = \tilde{C}_0(p^2/M^2; M/\Lambda)$$
$$\langle j_\alpha(p)\bar{j}_{\dot\beta}(-p)\rangle = -\sigma^\mu_{\alpha\dot\beta} p_\mu \tilde{C}_{1/2}(p^2/M^2; M/\Lambda)$$
$$\langle j_\mu(p)j_\nu(-p)\rangle = -(p^2\eta_{\mu\nu} - p_\mu p_\nu)\tilde{C}_1(p^2/M^2; M/\Lambda)$$
$$\langle j_\alpha(p)j_\beta(-p)\rangle = \epsilon_{\alpha\beta} M \tilde{B}_{1/2}(p^2/M^2)$$

- Prefactors are determined by Lorentz invariance and dimensional analysis
- In SUSY limit, $\tilde{C}_0 = \tilde{C}_{1/2} = \tilde{C}_1$, $\tilde{B}_{1/2} = 0$.

General Gauge Mediation III

- Quantities we want to compute are the gaugino and sfermion masses in the effective action (GGM says little about Higgs sector)
- i.e. must calculate 2-point amputated 1PI diagrams
- Find everything determined by current correlators:



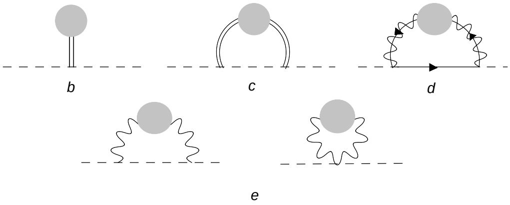
$$p^2\langle\overline{\lambda\lambda}\rangle$$
$$\sim g^2p^2\langle\overline{\lambda\lambda}(\textstyle\int j\lambda)(\int j\lambda)\rangle$$
$$\sim g^2\langle jj\rangle$$

Explicitly given by:

$$m_M = g^2 M\tilde{B}_{1/2}(0)$$

General Gauge Mediation IV

Similarly for sfermion masses



$$m_{\tilde{f}}^2 = g_1^2 Y_f \xi + \sum_{r=1}^{3} g_r^4 C_2(f;r) A_r \qquad \text{where}$$

$$A_r = -\int \frac{d^4p}{(2\pi)^4} \frac{1}{p^2} \left(3\tilde{C}_1^{(r)}(p^2/M^2) - 4\tilde{C}_{1/2}^{(r)}(p^2/M^2) + \tilde{C}_0^{(r)}(p^2/M^2) \right)$$

Leads to two sum rules (since the masses are proportional to $C_2(f;r)$ and mixed anomaly cancellation):

$$\mathrm{tr}[Ym^2] = \mathrm{tr}[(B-L)m^2] = 0.$$

General Gauge Mediation With Adjoints I

- Can we treat adjoints as part of the hidden sector and use the formulae above? For adjoint $\mathbf{\Sigma}(= \Sigma + \sqrt{2}\theta\chi + \theta\theta F_\Sigma + ...)$, gauge current is

$$\mathcal{J}_\Sigma = [\mathbf{\Sigma}, \mathbf{\Sigma}^\dagger]$$

- Maybe: we cannot write any renormalisable superpotential coupling of adjoints to visible fields because of gauge invariance

$$W \supset \lambda A \mathbf{\Sigma} B \to W \supset \mu A B$$

- Except for the Higgs sector (see earlier)
- No! How do we treat Dirac gaugino masses? Do not have to have any majorana component!
- Further problem: $C_{1/2}$ can develop a singularity in infra-red!
- Solution: define more currents
- Will the sum rules still be obeyed?

General Gauge Mediation With Adjoints II

- To define currents, must consider how adjoints couple to messenger sector:

$$W \supset \lambda_\Sigma \mathbf{\Sigma} \mathcal{J}_2 \rightarrow \mathcal{L} \supset \lambda_X \left[\chi j_2 + \overline{\chi}\overline{j}_2 + \Sigma F_2 + \bar{\Sigma}\overline{F}_2 \right]$$

- $\mathcal{J}_2 (= J_2 + \sqrt{2}\theta j_2 + \theta\theta F_2 + \ldots)$ is chiral superfield (usually composite)
- Can use this to calculate Dirac gaugino, sfermion and adjoint scalar masses

Dirac Gaugino Masses

- Define correlators

$$\langle j_\alpha(p) j_{2\beta}(-p)\rangle = \epsilon_{\alpha\beta} M \tilde{H}_{1/2}(p^2/M^2)$$
$$\langle j_{2\alpha}(p) j_{2\beta}(-p)\rangle = \epsilon_{\alpha\beta} M \tilde{I}_{1/2}(p^2/M^2)$$

- Now have terms in effective Lagrangian

$$\delta\mathcal{L}_{eff} = - g\lambda_\Sigma M \tilde{H}_{1/2}(0)\chi\lambda - \lambda_X^2 M \tilde{I}_{1/2}(0)\chi\chi - \frac{1}{2} g^2 M \tilde{B}_{1/2}(0)\lambda\lambda + \text{c.c.}$$

- Read off gaugino masses

$$m_\pm = \frac{1}{2} M \left[\hat{M}_\Sigma^0 + \lambda_X^2 \tilde{I}_{1/2}(0) + g^2 \tilde{B}_{1/2}(0) \pm \sqrt{\left(\hat{M}_X^0 + \lambda_X^2 \tilde{I}_{1/2}(0) - g^2 \tilde{B}_{1/2}(0)\right)^2 + 4 g^2 \lambda_X^2 \tilde{H}_{1/2}^2(0)} \right]$$

Sfermion Masses I

- Can use same correlators as before, **but**
- Due to tree level massless field, $C_{1/2}$ develops pole

$$\tilde{C}_{1/2}(p^2) \supset -\frac{1}{p^2}\bar{\sigma}^{\mu}_{\dot{\beta}\alpha}p_\mu|\lambda_X|^2\frac{1}{2}\int d^4x e^{ip\cdot x}\langle j_\alpha(x)\left(\int d^4z_1 j_2 \chi\right)\left(\int d^4 z_2 \bar{j}_2\bar{\chi}\right)\bar{j}_{\dot{\beta}}(0)\rangle$$
$$\supset \sim \frac{1}{p^2}|\lambda_X|^2|\tilde{H}(p)|^2$$

- $C_{1/2}$ essentially is correction to ‣ gaugino propagator - need to resum

$$A_r = -\int\frac{d^4p}{(2\pi)^4}\frac{1}{p^2}\left(3\tilde{C}_1^{(r)}(p^2/M^2) - \frac{4\tilde{C}_{1/2}^{(r)}(p^2/M^2)}{1+g_r^2\tilde{C}_{1/2}^{(r)}(p^2/M^2)} + \tilde{C}_0^{(r)}(p^2/M^2)\right)$$

- With this correction, see that the sfermion masses must be finite and the sum rules are preserved

Adjoint Scalar Masses

- Adjoint scalar masses generated at one loop:

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

- 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 $m_\Sigma^2 = 0$!
- Size of one loop mass $m_\Sigma \sim \lambda D/M, \lambda F/M > m_D, m_{\tilde{f}}$ (c.f. earlier assumptions for m_S, m_T)

Adjoint Scalar Masses in GGM

- Can use same formalism to parametrise adjoint masses: new correlators!

$$\langle F_2(p)F_2^\dagger(-p)\rangle \equiv M^2\tilde{F}_0(p^2/M^2)$$
$$\langle F_2(p)F_2(-p)\rangle \equiv M^2\tilde{F}_0'(p^2/M^2)$$

- These generate effective Lagrangian terms

$$\delta\mathcal{L}_{eff} \supset -\lambda_\Sigma^2 M^2\tilde{F}_0(0)\Sigma\overline{\Sigma} - \lambda_\Sigma^2\frac{M^2}{2}\tilde{F}_0'(0)(\Sigma^2+\overline{\Sigma}^2) \qquad (2)$$

- Giving masses

$$m_\pm^2 = \lambda_\Sigma^2\frac{M^2}{2}\left(\tilde{F}_0(0) \pm |\tilde{F}_0'(0)|\right)$$

- In all models found previously, $|\tilde{F}_0'(0)| > |\tilde{F}_0(0)|$ and there was a tachyon: see later!

Sfermion Masses II

- In many models of gauge mediated D-term SUSY breaking, sfermion mass squareds $\mathcal{O}(D^4/M^6)$ - too small
- With Dirac gauginos and λ_Σ not too small, generate $\mathcal{O}(D^2/M^2)$ mass squared at three loops
- Can use current correlator formalism to derive three loop (supersoft) sfermion masses at this order:

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

- Would lead to selectron (N)LSP

F-terms vs D-terms

- Recall that for F-terms the gaugino mass is $m_D \sim g\lambda_\Sigma \frac{F^2}{M^3}$, so have the hierarchies

$$F - \text{terms}: \quad m_D \sim g\lambda_\Sigma \frac{F^2}{M^3} \ll m_{\tilde{f}} \sim g^2 \frac{F}{M} < m_\Sigma \sim \lambda_\Sigma \frac{F}{M}$$

$$D - \text{terms}: \quad m_{\tilde{f}} \sim g^3 \lambda_\Sigma \frac{D}{M} < m_D \sim g\lambda_\Sigma \frac{D}{M} < m_\Sigma \sim \lambda_\Sigma \frac{D}{M}$$

- If we want a “natural” spectrum for EWSB etc then should include both F and D terms with $F \sim D$
- Find messenger couplings constrained by hypercharge tadpoles, singlet tadpoles, and adjoint scalar masses

Tadpoles

- Recall hypercharge tadpole induced by kinetic mixing:

$$\Delta m_{\tilde{f}}^2 = -g_Y^3 Y_f g' D' \frac{1}{8\pi^2} \sum_r 2\mathrm{tr}(\hat{e}\hat{Y}) \log M^r/\Lambda$$

- Very dangerous for large D'
- Require $\mathrm{tr}(QQ' \log |M|^2) = 0$
- This constrains acceptable messenger couplings

Messenger Couplings

- Restricted to degenerate sets of messengers $Q_i, \tilde{Q}_{\bar{j}}$ in fundamental, antifundamental pairs (similar to Extraordinary Gauge Mediation [Cheung, Fitzpatrick and Shih, 2008])

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

- $\langle \mathbf{X} \rangle = (\theta\theta) F$
- D-term couplings

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

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

Singlet Tadpoles

- Tadpoles induced at one loop for singlet:

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

- This imposes

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

Adjoint Scalar Masses: F Term Models

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

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

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

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

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

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

- 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

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

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:

$$
\begin{aligned}
\frac{d}{dt} m_O^2 &= \frac{1}{16\pi^2}\Big[-24 g_3^2 m_{3D}^2\Big] \\
\frac{d}{dt} B_O &= \frac{1}{16\pi^2}\Big[-12 g_3^2 B_O\Big]
\end{aligned}
$$

- 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. <u>generic choices of λ will change their structure on RG running</u>
- This could generate tadpoles for the singlet
- Clearly if we λ is proportional to a unitary matrix then we avoid this problem

Renormalisation III: Higgs

The soft terms for the Higgs run as

$$\begin{aligned}
16\pi^2 \frac{d}{dt} m_{H_u}^2 =& 6|y_t|^2[m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2] \\
&+ 2\lambda_S^2[m_{H_u}^2 + m_S^2 + m_{H_d}^2] + 6\lambda_T^2[m_{H_u}^2 + m_T^2 + m_{H_d}^2] \\
&+ g_Y^2 \mathrm{Tr}(Ym^2) \\
&- 4\lambda_S^2 m_{D1}^2 - 12\lambda_T^2 m_{D2}^2 \\
16\pi^2 \frac{d}{dt} m_{H_d}^2 =& 6|y_b|^2[m_{Q_3}^2 + m_{D_3}^2 + m_{H_d}^2] \\
&+ 2|y_\tau|^2[m_{L_3}^2 + m_{E_3}^2 + m_{H_d}^2] \\
&+ 2\lambda_S^2[m_{H_u}^2 + m_S^2 + m_{H_d}^2] + 6\lambda_T^2[m_{H_u}^2 + m_T^2 + m_{H_d}^2] \\
&- g_Y^2 \mathrm{Tr}(Ym^2) \\
&- 4\lambda_S^2 m_{D1}^2 - 12\lambda_T^2 m_{D2}^2 \\
16\pi^2 \frac{d}{dt} B_\mu =& B_\mu[3|y_t|^2 + 3|y_b|^2 + |y_\tau|^2 - 3g_2^2 - y_Y^2] \\
&+ 2B_\mu\lambda_S^2 + 6B_\mu\lambda_T^2
\end{aligned}$$

The new couplings can have a strong effect on driving electroweak symmetry breaking.

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

Three alternatives

1. Abandon matter and gauge unification
2. Add extra “bachelor” states to make up complete GUT adjoint multiplets [Fox, Nelson and Weiner, 02], allows matter and gauge unification
3. Add minimal extra states to restore gauge unification

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

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 to Part I

- Dirac gauginos can solve problem of R-symmetry breaking vs SUSY breaking
- Can also lead to increased Higgs mass
- 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, particularly for adjoint scalars (and Higgs)

Gaugino Mediation

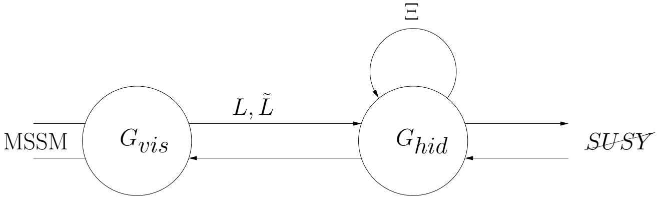
- In minimal gauge mediation there is a relationship between gaugino, sfermion masses and the (effective) number of messengers:

$$N_{eff} \equiv \frac{\Lambda_G^2}{\Lambda_S^2} \quad \text{where } M_\lambda \propto \Lambda_G, \; M_{\tilde{q}} \propto \Lambda_S$$

- Thus have $\Lambda_G \geqslant \Lambda_S$, gauginos typically heavier than sfermions
- Can we reverse this? (with F-term SUSY breaking)
- Need a way to suppress scalar masses - if the suppression is large enough, then can have sfermion masses only through gaugino loops $\rightarrow$ gaugino mediation

Deconstructed Gaugino Mediation

[Cheng, Kaplan, Schmalz and Skiba, 01]



$$W = W_{\text{MSSM}} + W_{\text{higgsing}} + W_{\text{mess}} + W_{\not{\text{SUSY}}}$$

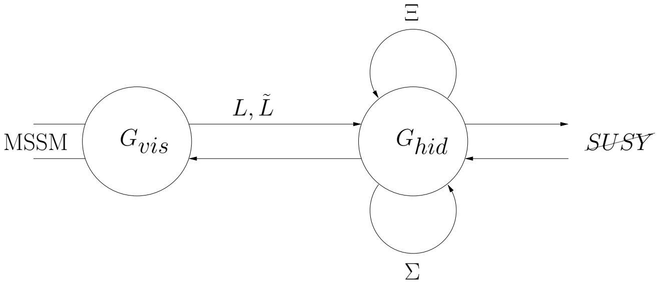
$$W_{\text{higgsing}} = K\left(\frac{1}{5} L\tilde{L} - \mu_\ell^2\right) + L\Xi\tilde{L} \tag{3}$$

- Gaugino masses M_λ at one loop for G_{hid}, scalar masses at <u>three</u> loops
- Then L gets a vev $\langle L \rangle = \langle \tilde{l} \rangle = \mu_\ell \rightarrow$ one combination of gauginos $\lambda_{\text{vis}} + \lambda_{\text{hid}}$ gets mass μg, one remains light with mass M_λ
- Now have scalar masses at two loops but suppressed by μ_ℓ / M!

$$M_\lambda \sim N g^2 \frac{F}{M} \qquad M_{\tilde{q}} \sim \sqrt{N} \frac{\mu_\ell}{M} g^2 \frac{F}{M}$$

easyDiracGauginos

Can now do the same but with Dirac gauginos:



$$
\begin{aligned}
W =& W_{\rm MSSM} + W_{\rm higgsing} + W_{\rm mess} + W_{\not{SUSY}} \\
W_{\rm higgsing} =& K\left(\frac{1}{5} L\tilde{L} - \mu_\ell^2\right) + L\Xi\tilde{L} + m\Xi\Sigma \\
W_{\rm mess} =& S f_1\tilde{f}_2 + M(f_1\tilde{f}_1 + f_2\tilde{f}_2) + h_1 f_1 \Sigma\tilde{f}_1 + h_2 f_2\Sigma\tilde{f}_2
\end{aligned}
$$

- Now can overcome the F/M^2 suppression of gaugino masses by screening!

$$
m_D \sim g\lambda_\Sigma \frac{F^2}{M^3}, \qquad m_{\tilde{f}} \sim g^2 \frac{\mu_\ell}{M}\frac{F}{M} < m_\Sigma \sim \lambda_\Sigma \frac{F}{M}
$$

Dynamical completion

- Can now add explicit SUSY breaking sector that preserves R - such as ISS!
- In fact, the whole model (with a few changes) can come from strongly coupled theory in UV
- Adapt idea of [Green, Katz and Komargodski, 10]: start with UV theory and gauge singlets

$$W^{(elec)} = m_I^J Q^I \tilde{Q}_J + S_I^J Q^I \tilde{Q}_J$$

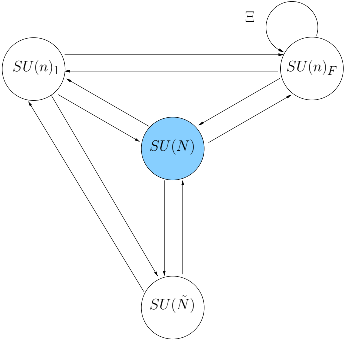
- In IR, the dual theory has mesons, but due to the singlets some are integrated out:

$$W^{(mag)} = -\mu m_I^J \Phi_J^I + \mu S_I^J \Phi_J^I + q \Phi \tilde{q}$$

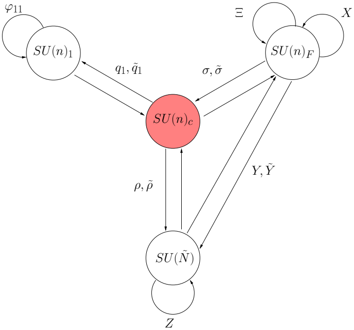
- Some magnetic quarks become the link fields while others become messengers!
- To get Dirac gauginos, we need to add a fundamental adjoint to the UV node and a term $W^{el} \supset h_\xi Q \Xi \tilde{Q}$, gives

$$W^{(mag)} = q_1 \varphi_{11} \tilde{q}_1 + \sigma X \tilde{\sigma} + m \Xi X + \rho Z \tilde{\rho} + \sigma Y \tilde{\rho} + \rho \tilde{Y} \tilde{\sigma} - \mu_1^2 \varphi_{11} - \mu_2^2 X - \mu_3^2 Z$$

Prototype example

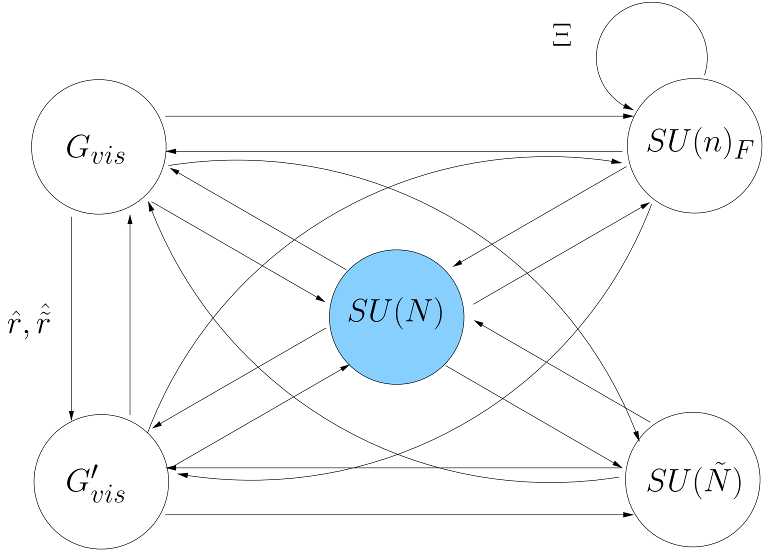


UV

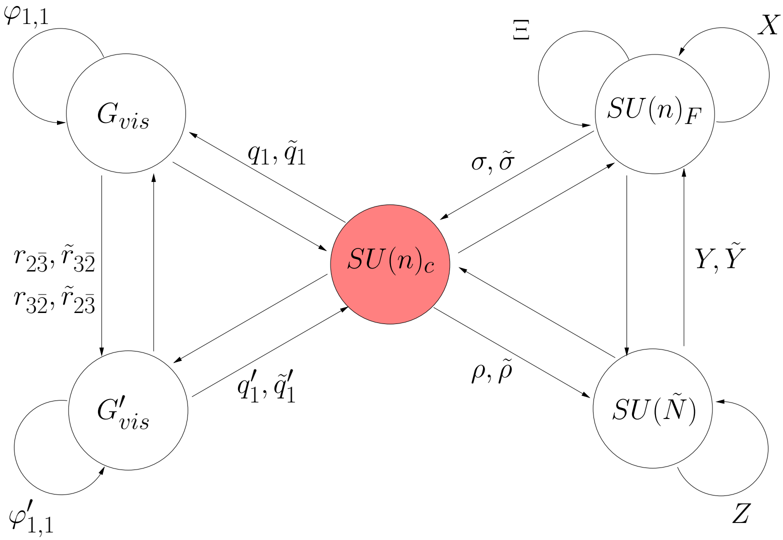


IR

An ISS-type model - UV



An ISS-type model - IR



Conclusions

- Models of Dirac gauginos can be useful to solve problems of gauge mediation and SUSY breaking, and can arise naturally in many different contexts (strong dynamics, higher dimensions, string theory, ...)
- They are more constrained than their Majorana counterparts
- Now possible to build a variety of realistic models
- $\rightarrow$the parameter space of gaugino/gauge mediation may be large - much work remains to be done exploring this!

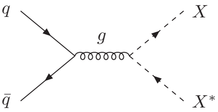
Future Possibilities

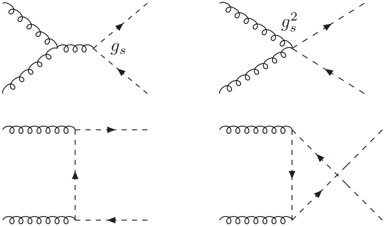
Many possible avenues for future work:

- Warped models
- Gauge messengers
- Modifications of Higgs sector (current choice is “MSSM in disguise”...) e.g. MSSM without μ-term, NMSSM-type models, SOHDM, ...
- Calculation of two-loop effects
- Implementation in “Dirac Gaugino Soft Susy”
- Models to realise messenger mass patterns
- Explicit D-term ~~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):

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

and (one loop):

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