Dirac gaugino masses without supersoftness

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The gaugino partners of the gauge bosons are usually given Majorana masses by soft SUSY breaking:

$$\mathcal{L}_{\rm Majorana} \;=\; -\frac{1}{2} M_a \lambda^a \lambda^a .$$

However, by introducing new chiral superfields $A^a \supset (\phi^a, \psi^a)$ in the adjoint rep, can have SUSY-breaking Dirac gaugino masses:

$$\mathcal{L}_{\rm Dirac} \;=\; -m_{Da} \psi^a \lambda^a .$$

These have a long history as “non-standard” SUSY breaking:

Fayet 1978; Polchinski,Susskind 1982; Hall,Randall 1991; Jack,Jones 1999; Fox,Nelson,Weiner 2002; Kribs,Poppitz,Weiner 2007; Benakli,Goodsell 2008,2010; Choi,Drees,Freitas,Zerwas 2008; Plehn,Tait 2008, Kribs,Okui,Roy 2010, Carpenter 2010; Benakli,Goodsell,Staub,Porod 2010,2014, Abel,Goodsell 2011; Goodsell 2012; Kribs,A.Martin 2012,2013; Csaki,Goodman,Pavesi,Shirman 2013; Benakli 2014; Nelson,Roy 2015; Carpenter,Goodman 2015; Alves,Galloway,McCullough,Weiner 2015; . . .

"Supersoft" operator (Fox, Nelson, Weiner 0206096) gives Dirac gaugino masses:

$$\mathcal{L} = \frac{1}{M} \int d^2\theta \, \mathcal{W}'^{\alpha} \mathcal{W}^a_\alpha A^a$$

where $\mathcal{W}'^{\alpha} = \langle D \rangle \theta^\alpha$ is a D-term spurion for SUSY breaking, and $\mathcal{W}^a_\alpha = \lambda^a_\alpha + \ldots$ are the MSSM gauge group field strength superfields.

The result is Dirac gaugino masses accompanied by "supersoft" scalar interactions:

$$\begin{aligned} \mathcal{L} &= -m_{Da}(\psi^a \lambda^a + \text{c.c.}) \\ &\quad -m_{Da}^2(\phi^a + \phi^{a*})^2 - \sqrt{2} g_a m_{Da} (\phi^a + \phi^{a*})(\tilde{q}_i^* t^a \tilde{q}_i) \end{aligned}$$

where $\tilde{q}_i$ are the MSSM scalars, and

$$m_{Da} = \langle D \rangle / M.$$

Supersoft SUSY breaking has many interesting properties. . .

Supersoft theories of Dirac gauginos predict:

- Relation between the Dirac gaugino mass, the real scalar adjoint mass, and the non-holomorphic SUSY-breaking term $\phi^a \tilde{q}_i^* \tilde{q}_i$ coupling is maintained by RG running. (Jack and Jones, 9909570)
- No UV divergent corrections to soft parameters; scalars do not get positive corrections to (mass)^2 from RG running involving gauginos.
- Real scalar adjoint gets a tree-level mass $2m_{Da}$, but imaginary scalar adjoint remains massless. ("Lemon-twist" operator can make it tachyonic.)
- No Higgs quartic interactions $(g^2 + g'^2)/8$ in the low-energy effective MSSM Lagrangian. Integrating out the scalar adjoints removes them. Problematic for $M_h = 125$ GeV.
- Supersafe from CP- and flavor-violation constraints. (Kribs, Poppitz, Weiner 0712.2039)
- Supersafe from early detection at LHC. (Kribs, A. Martin, 1203.4821)

In this talk, I explore an alternative form of Dirac gaugino masses, without supersoftness.

Dirac gaugino masses can also arise from an F-term VEV spurion $X = \theta\theta\langle F\rangle$:

$$\boxed{\mathcal{L} = -\frac{1}{M^3}\int d^4\theta \, X^* X \, \mathcal{W}_a^\alpha \, \nabla_\alpha A^a \; = \; -m_{Da}\psi^a\lambda^a}$$

where

$$m_{Da} = \sqrt{2}\langle F\rangle^2/M^3.$$

Note there are no accompanying supersoft scalar interactions here.

Technical aside: $$\nabla_\alpha\Phi = e^{-V} D_\alpha(e^V\Phi)$$

where $V = 2g_a V^a t^a$, with t^a the matrix generator for the rep of Φ, and

$$D_\alpha = \frac{\partial}{\partial\theta^\alpha} - i(\sigma^\mu\theta^\dagger)_\alpha\partial_\mu$$

is the "chiral covariant derivative".

Confession: I do not know how to make a UV completion to a complete SUSY-breaking model where this type of Dirac gaugino mass can generically dominate.

A set of model-building criteria:

- The F-term spurion X carries a conserved charge not shared by MSSM fields. Only X^*X can appear, not X or X^* separately.
- All terms communicating SUSY-breaking to the MSSM sector are suppressed by $1/M^3$. Terms like $\frac{1}{M^2}\int d^4\theta\, X^*X\, \Phi^*\Phi$ do not appear.
- No MSSM quark or lepton superfield couplings to spurions. No flavor violation.

Then the complete set of SUSY-breaking terms are the $\frac{1}{M^3}\int d^4\theta$ integrals of:

$XX^*\, \mathcal{W}^{\alpha a}\, \nabla_\alpha A^a$ = Dirac gaugino mass,

$XX^*\, A^a\, \nabla_\alpha \mathcal{W}^{\alpha a}$ = supersoft scalar interactions,

$XX^*\, \mathcal{W}^{\alpha a}\, \mathcal{W}^a_\alpha$ = Majorana gaugino mass,

$$XX^*\, \nabla^\alpha A^a\, \nabla_\alpha A^a, \qquad XX^*\, A^a\, \nabla^\alpha \nabla_\alpha A^a,$$

$$XX^*\, \nabla^\alpha H_u\, \nabla_\alpha H_d, \qquad XX^*\, H_u\, \nabla^\alpha \nabla_\alpha H_d, \qquad XX^*\, H_d\, \nabla^\alpha \nabla_\alpha H_u.$$

The μ problem is solved by the Higgs terms:

$$\frac{c_1}{2M^3} \int d^4\theta \, X X^* \, \nabla^\alpha H_u \, \nabla_\alpha H_d \quad = \quad -\tilde{\mu} \tilde{H}_u \tilde{H}_d$$

is a mass term for the Higgsinos **only**, with $\tilde{\mu} = c_1 \langle F \rangle^2 / M^3$.

There are also separate μ terms for the H_u and H_d scalars:

$$\begin{aligned}
\frac{c_2}{4M^3} \int d^4\theta \, X X^* H_u \, \nabla^\alpha \nabla_\alpha H_d \quad &= \quad \mu_u H_u F_{H_d} \; \rightarrow \; -|\mu_u|^2 |H_u|^2 + \ldots \\
\frac{c_3}{4M^3} \int d^4\theta \, X X^* H_d \, \nabla^\alpha \nabla_\alpha H_u \quad &= \quad \mu_d H_d F_{H_u} \; \rightarrow \; -|\mu_d|^2 |H_d|^2 + \ldots
\end{aligned}$$

where $\mu_u = c_2 \langle F \rangle^2 / M^3$ and $\mu_d = c_3 \langle F \rangle^2 / M^3$.

So, the MSSM gets 3 distinct μ parameters, all naturally of order the Dirac gaugino masses.

Nelson and Roy 1501.03251 did an analogous thing in the Supersoft case. This decouples the Higgsino mass from the MSSM Higgs VEV naturalness problem.

The usual supersymmetric μ can be obtained by taking the particular combination $c_1 = c_2 = c_3$, which amounts to the single term:

$$\frac{1}{4M^3} \int d^4\theta \, X X^* \, D^\alpha D_\alpha (H_u H_d),$$

leading to:

$$\tilde{\mu} \; = \; \mu_u \; = \; \mu_d .$$

But, in general, this particular combination is not special.

Similarly,

$$\frac{c_4}{4M^3}\int d^4\theta\, XX^*\, \nabla^\alpha A^a\, \nabla_\alpha A^a \quad = \quad -\frac{1}{2}\mu_a \psi^a \psi^a$$

is a Majorana mass for the adjoint chiral fermions, with $\mu_a = c_4 \langle F\rangle^2/M^3$.

The other term:

$$\frac{c_5}{4M^3}\int d^4\theta\, XX^*\, A^a\, \nabla^\alpha \nabla_\alpha A^a \quad = \quad m_a \phi^a F_a \;\; \rightarrow \;\; -m_a^2 |\phi^a|^2$$

gives the same **positive** (mass)^2 to both the real and imaginary parts of the adjoint scalar, with $m_a = c_5 \langle F\rangle^2/M^3$.

This eliminates the problem of a massless or tachyonic scalar adjoint.

The particular linear combination:

$$\frac{1}{4M^3}\int d^4\theta\, XX^*\, D^\alpha D_\alpha (A^a A^a)$$

would give a supersymmetric mass to the chiral adjoint superfield, with $\mu_a = m_a$.

Another of the possible terms written above was:

$$\frac{1}{M^3}\int d^4\theta\, X X^*\, A^a\, \nabla_\alpha \mathcal{W}^{\alpha a} + \text{c.c.} \quad = \quad m_{Ra} D^a(\phi^a + \phi^{a*})$$

where $m_{Ra} = 2\langle F\rangle^2/M^3$. After combining this with the rest of the Lagrangian involving the D^a auxiliary field, and integrating it out:

$$\mathcal{L} \;=\; -\frac{1}{2}\Big[m_{Ra}(\phi^a + \phi^{a*}) + g_a q_i^* t^a q_i\Big]^2$$

This is the scalar-only part of the supersoft operator, **without** the Dirac gaugino mass.

In the F-term VEV framework, it is independent of the Dirac gaugino mass, and can vanish at the scale M.

The gaugino masses obtained in this framework are general:

$$\mathcal{L} \;=\; -\frac{1}{2}\begin{pmatrix}\lambda^a & \psi^a\end{pmatrix}\begin{pmatrix}M_a & m_{Da}\\ m_{Da} & \mu_a\end{pmatrix}\begin{pmatrix}\lambda^a\\ \psi^a\end{pmatrix}$$

Each of M_a and m_{Da} and μ_a are $\langle F\rangle^2/M^3$ multiplied by dimensionless couplings in this framework, so any hierarchy is possible, or they could be all of comparable size.

If $m_{Da} \gg M_a, \mu_a$, then the gauginos are Dirac-like. I will assume this in the rest of the talk, and consider simple features of the RG evolution and the low-energy spectrum.

Gauge coupling unification

If we add vector-like fields $L+\overline{L}$ and $2\times(e+\overline{e})$, then the gauge couplings will unify. (Fox, Nelson, Weiner 2012.)

At 1-loop order:

$$\begin{aligned} 16\pi^2\,\beta(g_1) &= \frac{42}{5}g_1^3, \\ 16\pi^2\,\beta(g_2) &= 4g_2^3, \\ 16\pi^2\,\beta(g_3) &= 0, \end{aligned}$$

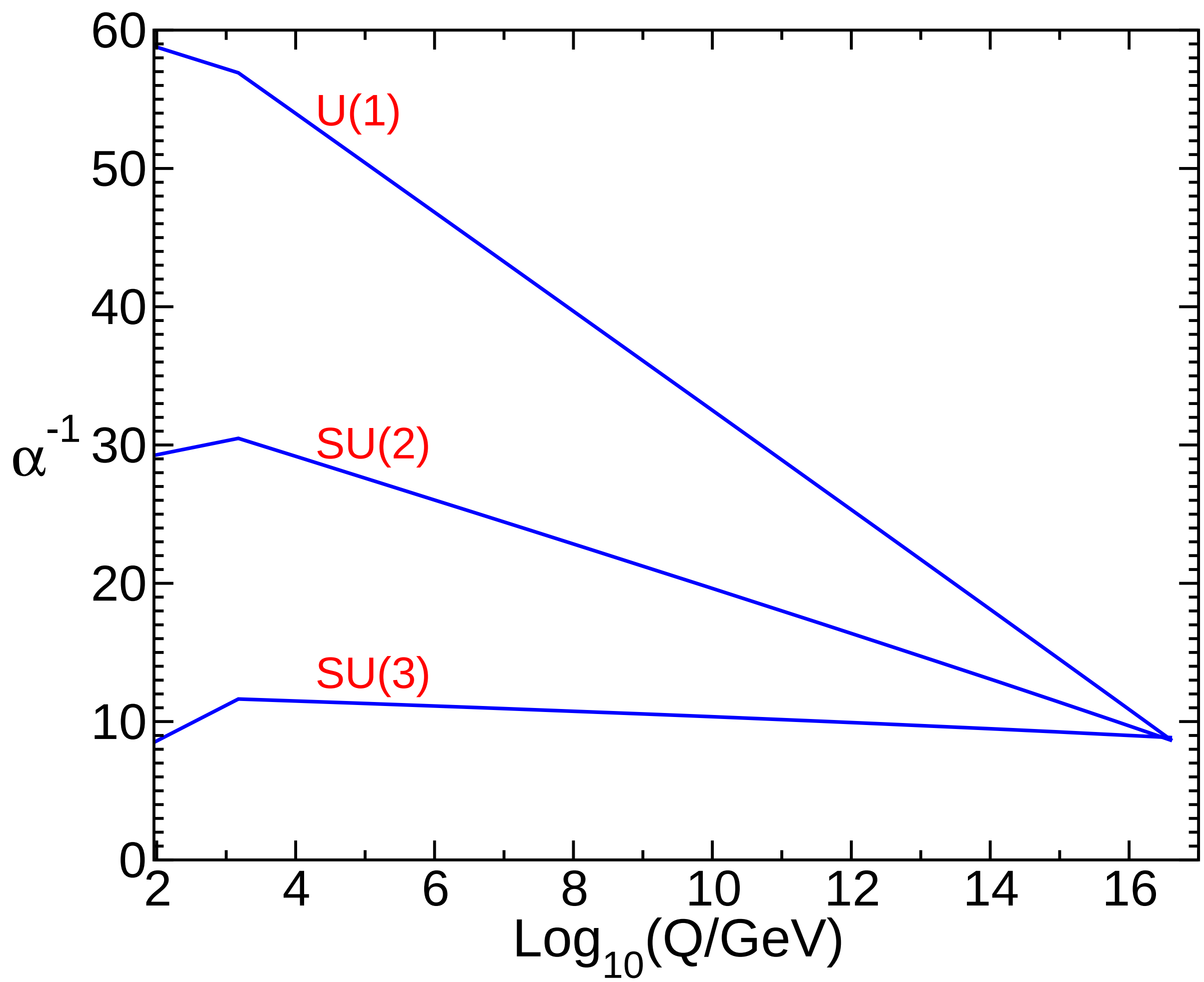
g_3 runs slowly

and the Dirac gaugino masses run as:

$$\begin{aligned} 16\pi^2\,\beta(m_{D1}) &= \frac{42}{5}g_1^2 m_{D1}, \\ 16\pi^2\,\beta(m_{D2}) &= 2g_2^2 m_{D2}, \\ 16\pi^2\,\beta(m_{D3}) &= -6g_3^2 m_{D3}. \end{aligned}$$

m_{D3} grows fast in IR

Running of gauge couplings with MSSM + Dirac gauginos and vector-like $L + \overline{L}$ and $2 \times (e + \overline{e})$ at the weak scale:



If Dirac gaugino masses, m_{Da}, dominate SUSY breaking in the visible sector effective theory, will generate non-holomorphic (scalar)^3 terms through 1-loop RG evolution:

$$\mathcal{L} \quad = \quad -r_a(\phi_a + \phi_a^*)(\tilde{q}_i^* t^a \tilde{q}_i).$$

Normalize the couplings r_a by

$$r_a = \sqrt{2} g_a m_{Da} R_a,$$

so that in the supersoft case, $R_a = 1$.

From Jack+Jones 9909570, can obtain:

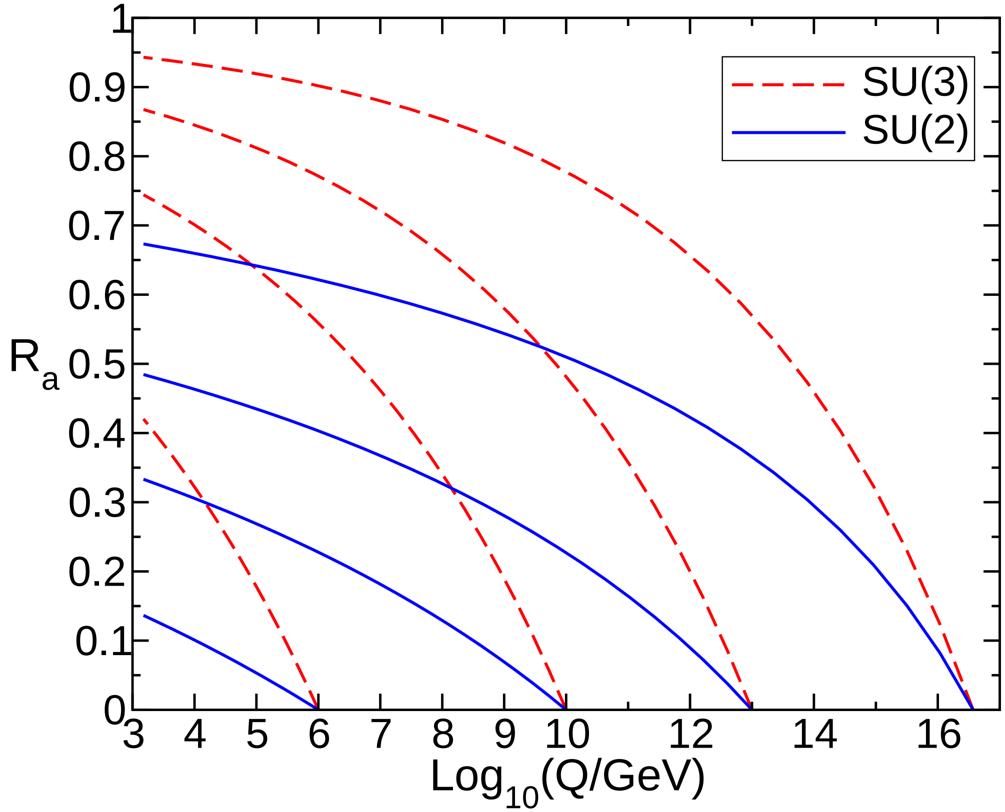
$$16\pi^2\, \beta(R_a) \quad = \quad 4g_a^2 C_a(R_a - 1)$$

where $C_a = 0, 2, 3$ for $U(1)_Y$, $SU(2)_L$, and $SU(3)_c$.

The supersoft case $R_a = 1$ is an IR fixed point of the RG evolution, for the non-Abelian groups. For $U(1)_Y$, there is no running of R_1. If it vanishes at the input scale, it will remain 0 (at 1-loop order).

Some RG trajectories of $\phi_a \tilde{q}_i^* \tilde{q}_i$ coupling parameter R_a, for $SU(3)_c$ and $SU(2)_L$.

Assuming $R_a = 0$ at input scales 10^6 and 10^{10} and 10^{13} and 3×10^{16} GeV:



$R_a = 1$ is the supersoft special case fixed point.

For the MSSM scalars, the 1-loop RG running is:

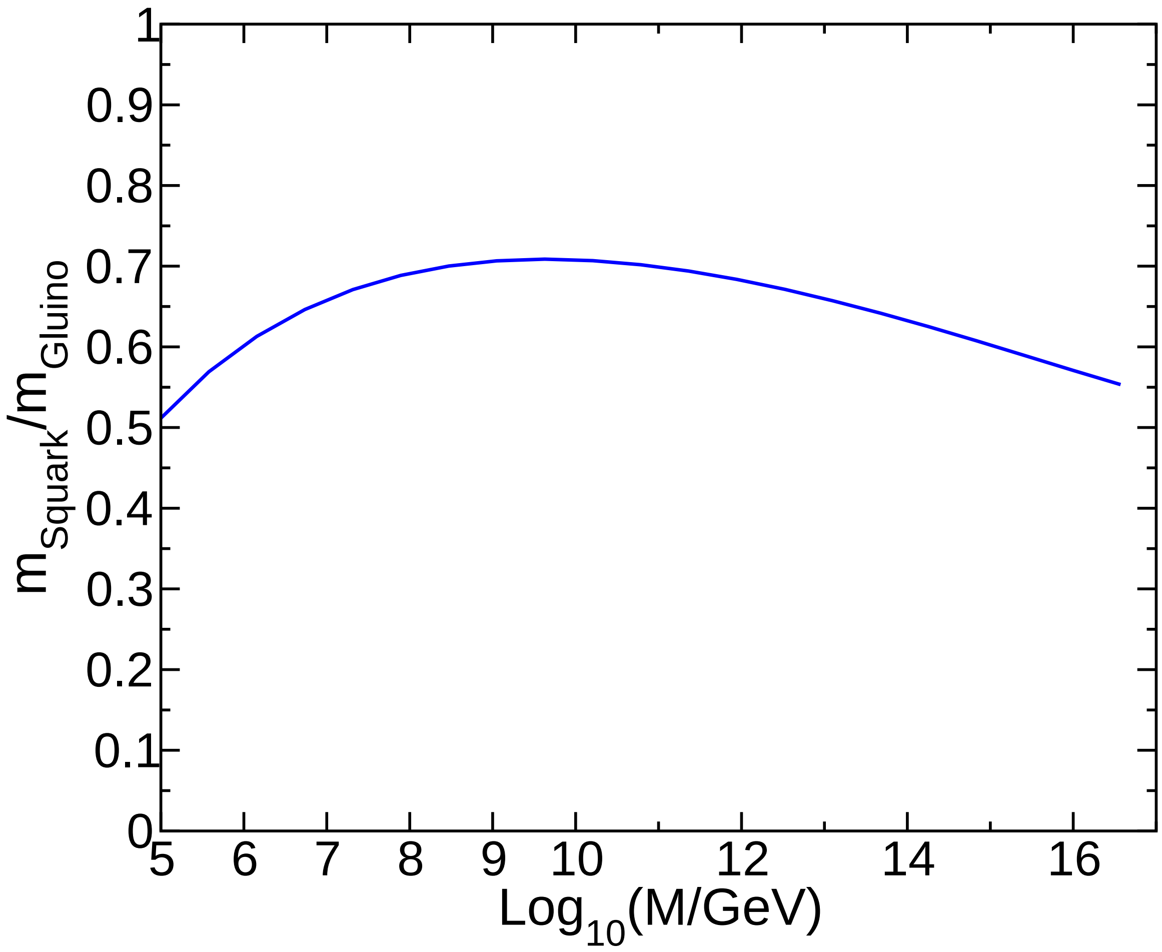
$$16\pi^2\,\beta(m_i^2) \quad = \quad 8g_a^2 C_a(i)(R_a^2 - 1)m_{Da}^2 + \text{(usual MSSM Yukawa terms)}$$

where $C_3(i) = 4/3$ for squarks, $C_2(i) = 3/4$ for doublets, and $C_1(i) = \frac{3}{5}Y_i^2$ for scalars with weak hypercharge Y_i.

For the supersoft case $R_a = 1$, the Dirac gaugino masses do not contribute to MSSM scalar running.

For $|R_a| < 1$, there is a positive RG contribution to MSSM scalar masses.

If Dirac gaugino masses dominate over all other forms of SUSY breaking, get prediction for the tree-level ratio $m_{\rm squark}/m_{\rm gluino}$ as a function of the input scale M:



Summary

Using F-term VEV for SUSY breaking, coupling to MSSM sector with assumed $1/M^3$ suppression, can have:

- SUSY breaking Dirac gaugino mass, without supersoftness
- Higgs quartic couplings not diminished
- Tree-level positive scalar adjoint squared masses
- Positive RG contributions to Higgs, sfermion masses from Dirac gaugino masses
- 3 distinct μ parameters for Higgsinos and Higgs scalars H_u, H_d

with mass scales all of order $\langle F \rangle^2/M^3$.

Can this be realized in some reasonable UV completion?

What about anomaly mediation contributions to gaugino Majorana masses?

Gravitino mass is:

$$m_{3/2} \sim \langle F \rangle / M_{\text{Planck}}.$$

and anomaly mediation gives:

$$M_a = m_{3/2} \beta(g_a)/g_a.$$

So:

- If the mediation scale is the Planck scale $M = M_{\text{Planck}}$, then $m_{3/2} =$ few $\times\ 10^{10}$ GeV, and Majorana gaugino masses will dominate over the Dirac gaugino masses.
- For the Dirac gaugino masses to dominate over the AMSB Majorana masses, need $M \lesssim 10^{13}$ GeV.