Dirac Gaugino Phenomenology

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Overview

- Motivation for Dirac gauginos
- Bottom-up and top down model building
- Dirac gauginos and the Higgs
- Collider status

Not covered: flavour; any serious discussion of dark matter; many references to others' work.

Dirac gauginos

- In the MSSM have Majorana gauginos described by one Weyl fermion λ in adjoint rep of each gauge group, mass term $\mathcal{L} \supset -\frac{1}{2}M_\lambda \lambda\lambda + h.c.$
- To make give a Dirac mass, add an extra adjoint fermion χ to give mass term

$$\mathcal{L} \supset -m_D \chi\lambda + h.c.$$

- This also requires a scalar Σ by supersymmetry, fit in an adjoint chiral multiplet (Σ, χ).

Motivation: bottom up

- Dirac gauginos allow the relaxation of LHC search bounds as production of squarks is suppressed since no chirality flip is possible. Gluino production is enhanced a little relative to MSSM, but on other hand is greatly suppressed when $m_{\tilde{q}_{1,2}} \gg m_{\tilde{g}}$.
- They typically suppress processes such as $B \to s\gamma$ and $\Delta F = 2$ processes.
- They allow for increased naturalness: supersoft masses do not lead to large corrections to stop mass.
- They allow new Higgs couplings, permitting increased Higgs mass $\to$ compatibility with e.g. light stops.
- There would have been/could still be clear signals from accompanying adjoint scalars if light (this would have been a surprise) $\to$ interesting signatures.
- If gauginos are found at the LHC, we will have to determine whether they are Majorana or Dirac in nature, and this is very difficult to do directly: maybe only possible at ILC
- Challenge is to study how the possible spectra affect Higgs properties, because that is what we can measure!
- Also important to look at the other interesting signatures and dark matter constraints.

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Motivation: top down

Some attractive theoretical motivations:

- 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 may preserve R, Majorana does not: [Fayet, 78] suggested this as the original way to obtain gaugino masses!
- Alternatively Majorana gaugino mass may simply be too small
- Adjoint multiplets appear in <u>many</u> UV models – $N = 2$ SUSY/$N = 1$ in $d > 4$ dimensions, brane moduli in string theory, ...

Supersoftness

- A Dirac mass can be written as a holomorphic term:

$$\int d^2\theta 2\sqrt{2} m_D \theta^\alpha \mathrm{tr}(W^a_\alpha \Sigma^a) \supset -m_D(\lambda^a \chi^a) + \sqrt{2} m_D \Sigma^a D^a$$

- Divergent terms only appear in the effective action under a $d^4\theta$ integral.
- Unlike the F-term spurion $\eta = \mu\theta^2$ which is dimensionless, $m_D\theta^\alpha$ has dimension $1/2$.
- So counterterms in the effective action would have to have extra powers of Λ, e.g.

$$\int d^4\theta \theta^2 \overline{\theta}^2 \left[\frac{|m_D|^4}{\Lambda^2} + \frac{m_D^2 \mu^* + \overline{m}_D^2 \mu}{\Lambda} \right] \Phi \overline{\Phi}$$

- As $\Lambda \to \infty$ these vanish – so all counterterms involving m_D vanish – so they only lead to finite quantum corrections $\to$ "supersoftness", no logarithmic corrections to e.g. the squark/Higgs masses.
- One important exception is the tadpole, which may have a counterterm $\to$ logarithmic corrections.

$$\int d^4\theta \theta^2 \overline{\theta}^2 (m_D^2 \mu^* + \overline{m}_D^2 \mu)(\Phi + \overline{\Phi})$$

RGEs

Since the operator is holomorphic, the RGEs for the Dirac mass itself are given by

$$\beta_{m_D^{iA}} = \gamma^i_j m_D^{jA} + \frac{\beta_g}{g} m_D^{iA}.$$

It does not enter the other RGEs!
However, there is an exception: the tadpole! The Dirac mass term enters explicitly here, so it had to be computed from scratch.

$$\beta^{(i)}_{t^a} \equiv X_S^{(i)} + X_\xi^{(i)} + X_D^{(i)}$$

$$(4\pi)^2 X_\xi^{(1)} = 2\sqrt{2} g_Y m_D^{aY} \mathrm{tr}(\mathcal{Y} m^2)$$
$$(4\pi)^4 X_\xi^{(2)} = 2\sqrt{2} g_Y m_D^{aY} \mathrm{tr}(\mathcal{Y} m^2 (4g^2 C_2 - Y_2))$$

and

$$(4\pi)^2 X_D^{(1)} = 2\Big[(m_D^2)_{ef}(A^{aef} + MY^{aef}) + Y_{efk}\mu^{ka}(m_D^2)^{ef}\Big]$$
$$(4\pi)^4 X_D^{(2)} = 4(\beta^{(1)}_{m_D}/m_D)^f_g \Big[(m_D^2)_{ef}(A^{aeg} + MY^{aeg}) + Y_{efk}\mu^{ka}(m_D^2)^{eg}\Big]$$

Naturalness

Bottom line:

- Tadpole term naturally generated by running, but not dangerous in size (in fact, it is useful phenomenologically): typically $\sim g_Y m_D \overline{m^2}$ (or smaller if $\mathrm{tr}(\mathcal{Y} m^2) = 0$ and $\mu = 0$).
- Dirac gaugino masses do not enter the Higgs or stop mass RGEs $\rightarrow$ increased naturalness: finite contribution to stop mass from gluino of

$$\delta m_{\tilde{t}}^2 \overset{DG}{=} \frac{m_{D3}^2 \alpha_s}{2\pi} \log\left(\frac{m_{O_P}}{m_{D3}}\right)^2$$

Compare this to the Majorana case of

$$\delta m_{\tilde{t}}^2 \overset{MSSM}{=} \frac{4 M_3^2 \alpha_s}{3\pi} \log\left(\frac{\Lambda_{UV}}{M_3}\right)^2$$

Similar conclusions can be drawn for the Higgs mass-squared parameter etc.

D-term masses

For the phenomenology of Dirac gaugino models, a striking property is the new D-term couplings:

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

They have two main effects:

- Adjoint scalar masses and B-type masses are modified:

$$\mathcal{L} \supset \frac{1}{2} D_a^2 + \sqrt{2}(m_D \Sigma_a + \bar{m}_D \overline{\Sigma}_a) D_a$$
$$\xrightarrow{m_D \text{ real}} -\frac{1}{2} m_D^2 (\Sigma_a + \overline{\Sigma}_a)^2$$

- Trilinear terms modify Higgs mass matrix

$$\frac{1}{\sqrt{2}} g_Y m_D (S + \overline{S})(H_u^* H_u - H_d^* H_d) \supset -g_Y m_D c_{2\beta} v \,(s_R h)$$

→ Bino mass is important for the Higgs mass, cannot be decoupled!

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Status

Studying non-(N)MSSM SUSY models was typically hard due to lack of tools - and sometimes theory. However, everything is now in place and progressing fast.
On the theory side,

- Increasing numbers of people interested in this class of models (too many to mention), e.g. lepton number as R-symmetry, detailed studies of naturalness, “Goldstone gaugino” scenario, etc.
- We now understand the technical aspects well: RGEs, how the masses are generated, etc.
- We have the tools for general theories: SARAH (Dirac gauginos added in 2012), FeynRules, CalcHEP, MadGraph, MicrOmegas, PYR@TE, ...
- Significant advance in the Higgs mass calculation in general models; now implemented in SARAH [Goodsell, Nickel, Staub ’14 and ’15], ...

But in terms of LHC analyses:

- A couple of early studies (Martin and Kribs ’12; Heikinheimo, Kellerstein, Sanz ’11) of collider bounds for simplified models.
- Some work on bounds on sgluons.

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Scenarios

Once we add Dirac gaugino masses, there are still many different choices we can make $\rightarrow$ many different scenarios, e.g.

- The simplest is to extend the MSSM with adjoint chiral fields $\mathbf{S}$, $\mathbf{T}$, $\mathbf{O}$, one for each gauge group.
- The MSSM breaks R-symmetry in the Higgs sector. An alternative is to add two additional $SU(2)$ doublets R_u, R_d which pair with the Higgs but don't get a vev:

$$W_{\mathrm{MRSSM}} \supset \mu_u H_u R_u + \mu_d R_d H_d$$

- Neither of these scenarios preserve gauge coupling unification: can add some additional fields to restore natural unification.

We also have many options for the choice of couplings and soft terms:

- Could have the purist "supersoft" scenario where the only soft terms come from the Dirac gaugino mass (in particular, have no A-terms). Then $m_D \gg m_{\tilde{q}}$, the scalar adjoints are $\sim 2m_D$ but the pseudoscalar adjoints are light.
- If we break R-symmetry in the Higgs sector, we have new adjoint couplings that enhance the Higgs mass at tree level.
- We can also use the vev of the singlet to generate μ/B_μ as in the NMSSM.

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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)

Supersymmetric 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:

$$W_{\mathrm{Yukawa}} = Y_U^{ij} \mathbf{Q_i} \cdot \mathbf{H_u} \mathbf{u^c_j} + Y_D^{ij} \mathbf{Q_i} \cdot \mathbf{H_d} \mathbf{d^c_j} + Y_E^{ij} \mathbf{L_i} \cdot \mathbf{H_d} \mathbf{e^c_j}$$

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

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

- Several possible new Adjoint couplings which violate R:

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

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The Higgs sector of Dirac gaugino models

At tree level the scalar mass matrix is now 4×4! In the basis $\{h, H, S_R, T^0_R\}$ it is

$$\begin{pmatrix} M_Z^2 + \Delta_h s_{2\beta}^2 & \Delta_h s_{2\beta} c_{2\beta} & \Delta_{hS} & \Delta_{hT} \\ \Delta_h s_{2\beta} c_{2\beta} & M_A^2 - \Delta_h s_{2\beta}^2 & \Delta_{HS} & \Delta_{HT} \\ \Delta_{hS} & \Delta_{HS} & \tilde{m}_S^2 & \lambda_S \lambda_T \frac{v^2}{2} \\ \Delta_{hT} & \Delta_{HT} & \lambda_S \lambda_T \frac{v^2}{2} & \tilde{m}_T^2 \end{pmatrix}$$

where $\Delta_h = \frac{v^2}{2}(\lambda_S^2 + \lambda_T^2) - M_Z^2$.
In limit of large m_S, m_T, can integrate out adjoint scalars to obtain

$$m_h^2 \simeq M_Z^2 c_{2\beta}^2 + \frac{v^2}{2}(\lambda_S^2 + \lambda_T^2) s_{2\beta}^2$$

Can enhance the Higgs mass naturally! And λ_S, λ_T also contribute at loop level.

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Mixing

Note that we have

$$\begin{aligned} \Delta_{hs} &= v[\sqrt{2}\lambda_S \tilde{\mu} - g_Y m_{1D} c_{2\beta}] & \Delta_{ht} &= v[-\sqrt{2}\lambda_T \tilde{\mu} + g_2 m_{2D} c_{2\beta}] \\ \Delta_{HS} &= g' m_{1D} v s_{2\beta}, & \Delta_{HT} &= -g m_{2D} v s_{2\beta}, \\ v_S &= -\frac{1}{\tilde{m}^2_{SR}}\left[t_{S_R} + \frac{v}{2}\Delta_{hs}\right], & v_T &= -\frac{1}{\tilde{m}^2_{TR}}\left[t_{T^0_R} + \frac{v}{2}\Delta_{ht}\right]. \end{aligned}$$

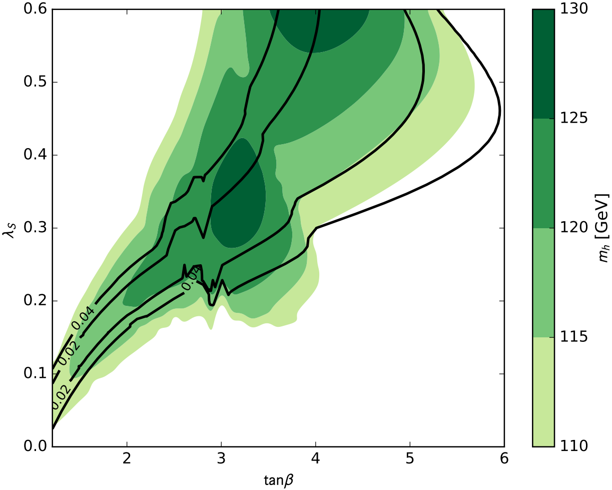
v_T shifts the W mass, so we have

$$\Delta\rho = \frac{4v_T^2}{v^2} = (4.2 \pm 2.7) \times 10^{-4} \to v_T \lesssim 4 \text{ GeV}.$$

So the triplet should be heavy ($\mathcal{O}(\text{TeV})$).
Mixing between singlet/triplet and light Higgs also lowers the Higgs mass $\to$ m_{DY}, m_{D2} cannot be arbitrarily high without tuning!

Example

Consider as an example (from my paper 1605.05313 with Benakli, Darmé and Harz) a moderately light singlet



Loop Corrections

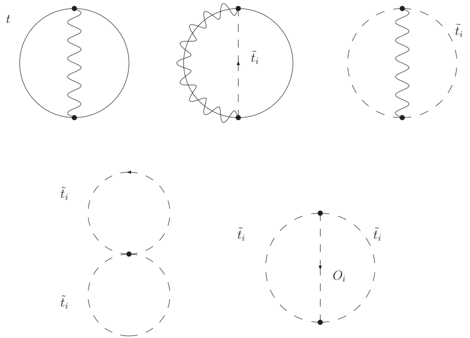
- Since squark A-terms violate R, large A-terms are inconsistent with pure Dirac gauginos.
- If λ_S, λ_T are not large enough at tree level, need significant loop corrections from stops but also S, T

Loop corrections to the Higgs mass are where most progress has been made recently:

- Can now compute up to two loops for any model in SARAH: full one loop, and at two loops all corrections in the gaugeless limit with zero external momentum.
- Remains much more to be done – in particular implementation of our solution to the Goldstone boson catastrophe from 1609.06977 (with J. Braathen).
- Also progress in analytic computations for Dirac gaugino models.

$\alpha_s \alpha_t$

The $\alpha_s \alpha_t$ corrections are universal to all Dirac gaugino models:



Have calculated anayltic results for these and written a code with J. Braathen and P. Slavich (1606.09213). This is now available in `SARAH` as options 8 and 9.

What we can obtain

We then find:

- General two loop corrections to all neutral scalars and pseudoscalars, in both $\overline{\text{DR}}$ and on-shell schemes.
- A simplified analytic formula for the case $m_{\tilde{t}_1} = m_{\tilde{t}_2} = m_{\tilde{g}} = M_S, x_i \equiv M_S^2/m_{O_i}^2$, e.g.

$$\Delta m_h^2 \approx \frac{3\, m_t^4}{4\,\pi^2 v^2} \left[\ln \frac{M_S^2}{m_t^2} + \hat{X}_t^2 - \frac{\hat{X}_t^4}{12} \right] + (\Delta m_h^2)_{2\ell}^{\text{“MSSM”}} + c_{\phi O}^2 \, (\Delta m_h^2)_{2\ell}^{O_1} + s_{\phi O}^2 \, (\Delta m_h^2)_{2\ell}^{O_2}$$

$$(\Delta m_h^2)_{2\ell}^{O_i} = - \frac{\alpha_s m_t^4}{\pi^3 v^2} \left\{ 1 - \ln \frac{M_S^2}{Q^2} + f(x_i) - \hat{X}_t^2 \left[1 - \ln \frac{m_{O_i}^2}{Q^2} + 2\, x_i\, f(x_i) \right] + \frac{\hat{X}_t^4}{6} \left[1 + 3\, x_i\, (1 + \ln x_i) - \ln \frac{m_{O_i}^2}{Q^2} + 6\, x_i^2\, f(x_i) \right] \right\}$$

- A simple analytic formula for the case $m_{\tilde{g}} \gg m_{\tilde{t}_i}$ and no stop mixing.

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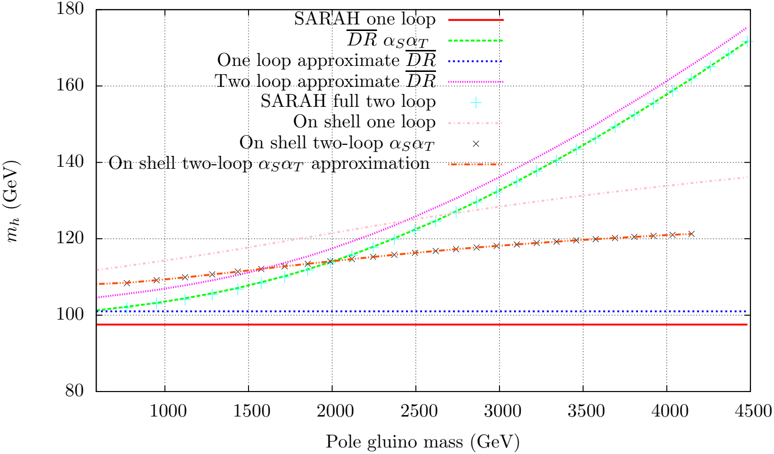
Supersoft scenario

As a cautionary note (that is understood in the MSSM too) the supersoft scenario with a $\overline{\text{DR}}$ stop mass calculation is very misleading:



The on-shell calculation is much more reliable here!

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 $\alpha_{GUT} \sim 1/24$.

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

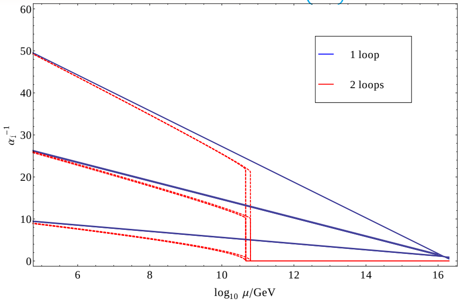
- Triumph of the MSSM (modulo two-loop discrepancy...) that we might like to preserve!!
- Adding adjoint fields does (except for $\mathbf{S}$, a singlet): $\mathbf{T}$ decreases b_2 by 2, $\mathbf{O}_g$ decreases b_3 by 3

Our choice: add

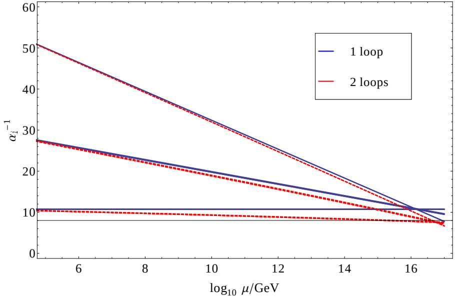
$$(\mathbf{1}, \mathbf{2})_{1/2} + (\mathbf{1}, \mathbf{2})_{-1/2} + 2 \times (\mathbf{1}, \mathbf{1})_{\pm 1}$$

This could come from $(SU(3))^3$ (would need also four SM singlets).

$SU(5)$ vs $SU(3)^3$



$$(\mathbf{3},\mathbf{2})_{-5/6} + (\bar{\mathbf{3}},\mathbf{2})_{-5/6}$$



$$(\mathbf{1},\mathbf{2})_{1/2} + (\mathbf{1},\mathbf{2})_{-1/2} + 2\times(\mathbf{1},\mathbf{1})_{\pm 1}$$

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MDGSSM

We can now define the field content of our unified scenario: the MSSM plus

Names		Spin 0	Spin 1/2	Spin 1	$(SU(3), SU(2), U(1)_Y)$	R-charge
DG-octet	$\mathbf{O}$	O	χ_g $[\equiv \tilde{g}']$		(**8**, **1**, 0)	0
DG-triplet	$\mathbf{T}$	$\{T^0, T^\pm\}$	$\{\chi_T^0, \chi_T^\pm\}$ $[\equiv \{\tilde{W}'^\pm, \tilde{W}'^0\}]$		(**1**,**3**, 0)	0
DG-singlet	$\mathbf{S}$	S	χ_S $[\equiv \tilde{B}']$		(**1**, **1**, 0)	0
Higgs-like leptons	$\mathbf{R_u}$	R_u	$\tilde{R}_u$		(**1**, **2**, -1/2)	1
	$\mathbf{R_d}$	R_d	$\tilde{R}_d$		(**1**, **2**, 1/2)	1
Fake electrons	$\hat{\mathbf{E}}(\times 2)$	$\hat{E}$	$\tilde{\hat{E}}$		(**1**, **1**,1)	0
	$\hat{\mathbf{E}}'(\times 2)$	$\hat{E}'$	$\tilde{\hat{E}}'$		(**1**, **1**,-1)	2

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Toward a GUT scenario

We can now take one of two directions:

- An extended MRSSM $\to$ removing $\mu, \mu_R, \lambda_S, \lambda_T$ and related couplings, where an R-symmetry is preserved by the Higgs sector.
- Charge the new fields under lepton number, so that we have new heavy vector-like leptons and sleptons. The superpotential and adjoint soft terms become

$$
\begin{aligned}
W \supset & (\mu + \lambda_S S) H_d H_u + 2\lambda_T H_d T H_u \\
& + (\mu_R + \lambda_{SR} S) R_u R_d + 2\lambda_{TR} R_u T R_d + (\mu_{\hat{E}\,ij} + \lambda_{SEij} S)\hat{E}_i \hat{\hat{E}}_j \\
& + Y_{\hat{E}_i} R_u H_d \hat{E}_i + Y_{\hat{\hat{E}}_i} R_d H_u \hat{\hat{E}}_i \\
& + Y^{ij}_{LFV} L_i \cdot H_d \hat{E}_j + Y^{j}_{EFV} R_u H_d E_j \\
-\Delta\mathcal{L}^{\text{scalar soft}}_{\text{adjoints}} = & m_S^2 |S|^2 + \frac{1}{2} B_S (S^2 + h.c.) + 2m_T^2 \mathrm{tr}(T^\dagger T) + (B_T \mathrm{tr}(TT) + h.c.) \\
& + 2m_O^2 \mathrm{tr}(O^\dagger O) + (B_O \mathrm{tr}(OO) + h.c.) \\
& + \left[T_S S H_u \cdot H_d + 2T_T H_d \cdot T H_u + \frac{1}{3}\kappa A_\kappa S^3 + t_S S + h.c.\right] \\
& + \left[T_{SO} S \mathrm{tr}(O^2) + T_{ST} S \mathrm{tr}(T^2) + \frac{1}{3} T_O \mathrm{tr}(O^3) + h.c.\right]
\end{aligned}
$$

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The C in CMDGSSM

We can now specify a minimal set of boundary conditions at the GUT scale:

- As in the CMSSM/mSUGRA, we have $m_0, \tan\beta$ but instead of $m_{1/2}$ we have m_D. We set $A_0 = 0$ due to ~~SUSY~~ preserving R-symmetry.
- We also choose to take non-universal Higgs masses, and so specify μ, B_μ.
- Since we have two new tadpole conditions from v_S, v_T we specify m_{S0} (singlet scalar mass) and m_{T0} (triplet scalar mass) at the GUT scale. We set the octet scalar mass equal to the triplets, and take $B_T = B_S = B_O = 0$ for minimality.
- We have the Yukawa couplings $Y_{\hat{E}i}, Y_{\hat{\hat{E}}i}, Y^{ij}_{LFV}, Y^{j}_{EFV}$ which are equivalent to lepton Yukawas; they are constrained to be $\lesssim 0.01$ and so irrelevant for spectrum-generator purposes.
- We have a choice of $\mu_R, \mu_E \rightarrow$ can either adjust for precision gauge unification; set to be equal to the Higgs mu; set at convenient values. The Higgs mass and coloured sparticle spectrum is largely independent of this choice.
- We have a choice of couplings $\lambda_S, \lambda_T, \lambda_{SR}, \lambda_{TR}, \lambda_{SEij}$: can take $N = 2$ values, or $(SU(3))^3$ values, or choose freely.

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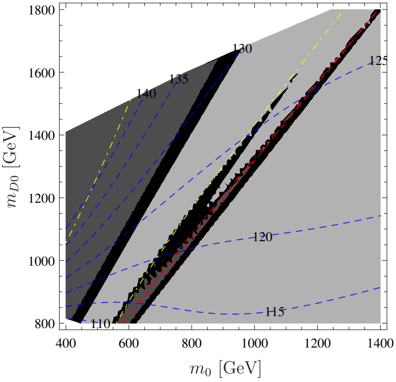
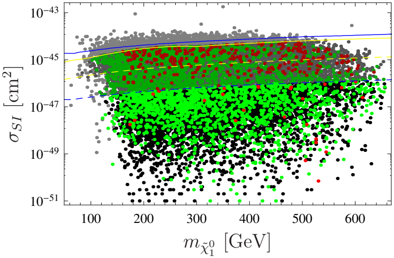
CMDGSSM and DM

From 1507.01010 with Krauss, Müller, Porod, Staub.
Taking $\tan\beta = 6$, $B_O = -1.2 \times 10^6$ GeV, $\lambda_S = 0.15$, $\lambda_T = 0.52$ at low scale:



Yellow lines: Heavy Higgs resonance;
Red dashed: pseudoscalar.



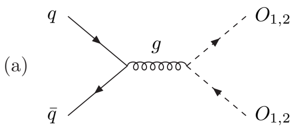
Yellow dashed line: LUX/PandaX;
Blue dashed line: XENON1T

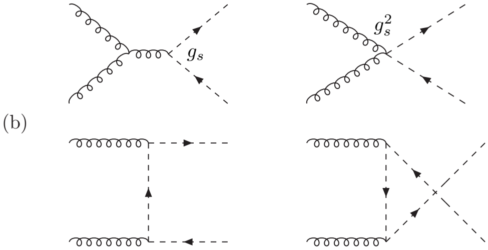
Sgluons

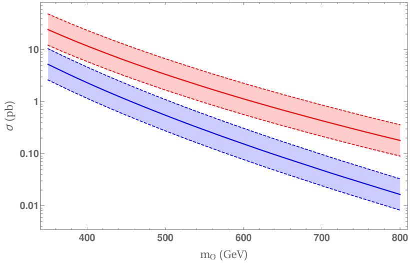
- In models with Dirac gauginos, we also have the scalar octet superpartners, the sgluons O.
- In typical explicit models (e.g. gauge mediation) the scalars are potentially the heaviest particles in the theory, but the pseudoscalar can be arbitrarily light!
- However, the scalar could be light if B_O is large $\rightarrow$ they can have very interesting phenomenology
- Current bounds are surprisingly weak, below a TeV.

Octet tree couplings

The octet scalars have the usual gauge couplings and so can be produced in pairs at tree level:







Tree level decays

They have trilinear couplings with the squarks and gauginos

$$\mathcal{L}_{Dirac} = -\int d^2\theta \frac{m_D}{4\sqrt{2}f^2}\overline{D}^2 D^\alpha (X^\dagger X) W^a_\alpha \mathbf{O}^a \supset \sqrt{2} m_D (O^a + O^{a*}) D^a_c ,$$

$$\rightarrow -2 g_s m_D T^a_{xy} \sum_{\tilde{q}_L, \tilde{q}_R} (\tilde{q}^*_{Lxi}\tilde{q}_{Lyi} - \tilde{u}^*_{Rxi}\tilde{u}_{Ryi} - \tilde{d}^*_{Rxi}\tilde{d}_{Ryi}) \left(\cos(\frac{\phi_O}{2}) O^a_1 + \sin(\frac{\phi_O}{2}) O^a_2 \right)$$

$$\mathcal{L}_{Gauge} \supset i f^{abc} \overline{O}^b \lambda^a \chi^c + h.c.$$

These lead to rapid decays if the squarks or gluinos are ligher than half the octet mass → but this would mean rather heavy octets anyway.

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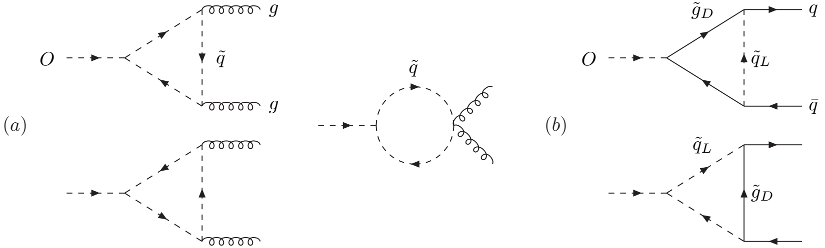
Octet loop couplings

More interestingly, the above generate couplings at one loop with the quarks and gluons, which provide the conventional decay modes:



Loop couplings

- The widths to quarks are parametrised by

$$\mathcal{L} \supset c_{1\bar{t}t}\bar{t}O_1 t + c_{2\bar{t}t} i\bar{t}O_2\gamma_5 t,$$

- i.e. they split into scalar and pseudoscalar.
- The widths to gluons are given by

$$\Gamma(O_1 \to gg) = \frac{5\alpha_s^3}{192\pi^2}\frac{m_{D3}^2}{M_{O_1}}\cos^2(\frac{\phi_O}{2})|\lambda_{g_1}|^2, \quad \Gamma(O_2 \to gg) = \frac{5\alpha_s^3}{192\pi^2}\frac{m_{D3}^2}{M_{O_2}}\sin^2(\frac{\phi_O}{2})|\lambda_{g_2}|^2.$$

- Pseudoscalars do not decay to gluons – they only decay to tops $\rightarrow$ four top events (as suggested in 1501.07580) rule them out for $m_O \lesssim$ 880 GeV.
- Scalars can still be light

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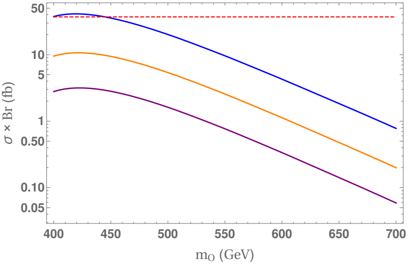
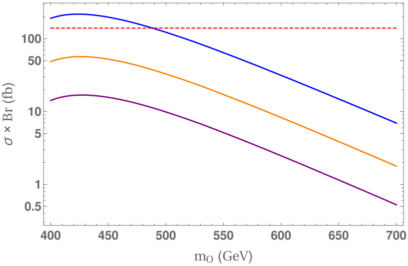
Rough four-top limits on sgluons

For squarks $\sim$ TeV and gluinos of 2.5 (top) 3, 3.5 (bottom) TeV, rough limits from four-top events are:



8 TeV data



First 13 TeV limits

These should be properly redone with recasting and new data ...

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Goldstino couplings with Dirac gauginos

Recall that the operator for the Dirac gaugino mass is a holomorphic operator:

$$\int d^2\theta 2\sqrt{2} m_D \theta^\alpha \mathrm{tr}(W_\alpha \Sigma) \to -\frac{m_D}{4\sqrt{2} f^2} \int d^2\theta\, \overline{D}^2 D^\alpha (X^\dagger X) W^a_\alpha \Sigma^a$$

By extending X from a spurion to include (now a proto-)goldstino ψ_X, we can write down all of the couplings. Up to second order in ψ_X we have:

$$\begin{aligned}
\mathcal{L}_{Dirac} = & -m_D \lambda\chi + 2|m_D| D S_R + \frac{|m_D|}{f^2}\Big[-iDS_R(\partial_\mu \psi_X \sigma^\mu \overline{\psi}_X - \psi_X \sigma^\mu \partial_\mu \overline{\psi}_X) \\
& + \frac{1}{2} S_I F_{\mu\nu} \epsilon^{\mu\nu\rho\lambda} (\psi_X \sigma_\lambda \partial_\rho \overline{\psi}_X - \overline{\psi}_X \overline{\sigma}_\lambda \partial_\rho \psi_X) + S_R F_{\mu\nu} (\psi_X \sigma^\mu \partial^\nu \overline{\psi}_X - \overline{\psi}_X \overline{\sigma}^\mu \partial^\nu \psi_X)\Big] \\
& + \Big[\frac{m_D}{f} \Big(-\psi_X \lambda F_S - S i \lambda^\alpha \sigma^\mu_{\alpha\dot{\beta}} \partial_\mu \overline{\psi}^{\dot{\beta}}_X \\
& - i S \psi^\alpha_X \sigma^\mu_{\alpha\dot{\alpha}} D_\mu \overline{\lambda}^{\dot{\alpha}} + \frac{1}{\sqrt{2}} \psi_X \chi D - \frac{i}{2\sqrt{2}} \psi^\alpha_X (\sigma^\mu \overline{\sigma}^\nu)_\alpha^{\ \beta} F_{\mu\nu} \chi_\beta \Big) \\
& + \frac{i m_D}{f^2} \Big((\chi \sigma^\mu \partial_\mu \overline{\psi}_X) \psi_X \lambda - (\chi \partial_\mu \psi_X) \lambda \sigma^\mu \overline{\psi}_X \Big) + h.c. \Big].
\end{aligned}$$

From these generic couplings, we have – in principle – everything we need for phenomenological studies.

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Observations

(a) The sgoldstino does not enter at second order.

(b) A vacuum expectation value for the adjoint scalar $v_S \equiv \langle S_R \rangle$ induces kinetic mixing between the goldstino and the gaugino

$$\mathcal{L} \supset -\frac{\sqrt{2} m_D v_S}{f} \left[i\lambda\sigma^\mu \partial_\mu \overline{\psi}_X + i\psi_X \sigma^\mu D_\mu \overline{\lambda} \right].$$

(c) The Dirac operator contains a coupling of two goldstinos to a gauge boson and the corresponding adjoint scalar. For a light enough scalar, this brings phenomenological signatures that are absent in the Majorana case – and therefore potentially interesting phenomenology.

Conventional signals

Gravitinos have been the subject of much experimental interest, involving one of two approaches:

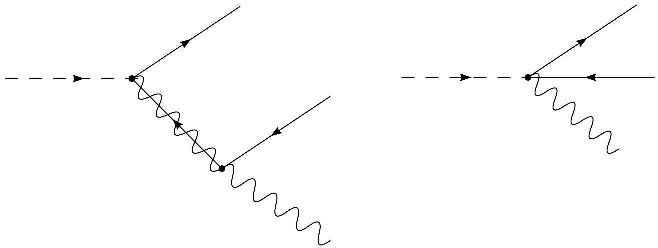
1. Consider all supersymmetric particles to be heavy and integrate them out, leaving only the SM fields and the gravitino. Place limits on $\sqrt{f}$ from the resulting higher-dimensional operators.
2. Make assumptions about the spectrum of superpartners and place limits on $\sqrt{f}$ as a function of their masses.

Approach (1) is dubious: current limit has $\sqrt{F} > 240$ GeV from monophoton searches at LEP, makes no sense given latest superparticle bounds.

Octet goldstino decays

Now let us consider the new, goldstino, decay channels:

- If the octet is heavier than the gluino, then it will decay rapidly to that:
$$\Gamma(O_i \to \tilde{g}G) = \frac{(M_{O_i}^2 - m_D^2)^4}{32\pi f^2 M_{O_i}^3}$$
- If instead the gluino and squarks are heavy, then it can decay to a gluon and two goldstini via $O \to GGg$ and $O \to G\tilde{g} \to GGg$:



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Octet goldstino couplings

- These processes involve highly non-renormalisable operators:

$$\mathcal{L}_{OGGg} = \frac{m_D}{f} \partial^\mu (G\sigma^\nu \overline{G}) G^a_{\mu\nu} O^a_1 + \frac{m_D}{2f} \epsilon^{\mu\nu\rho\lambda} \partial_\rho (G\sigma_\lambda \overline{G}) G^a_{\mu\nu} O^a_2 \,,$$

,

- Naively this looks like the decay rate should increase as m_D increases! However, we also have the couplings for the other process:

$$\mathcal{L} \supset \bigg(\frac{m_D}{\sqrt{2}f} G\sigma^{\mu\nu}\chi^a G^a_{\mu\nu} + \frac{i}{\sqrt{2}f} M^2_{O_2} O^a_2 G\chi^a - \frac{1}{\sqrt{2}f} (M^2_{O_1} - 2m^2_D) O^a_1 G\chi^a + h.c. \\ + \frac{i m_D}{\sqrt{2}f} \partial_\mu O_1 (G\sigma^\mu \overline{\lambda} - \lambda\sigma^\mu \overline{G}) + \frac{m_D}{\sqrt{2}f} \partial_\mu O_2 (\lambda\sigma^\mu \overline{G} + G\sigma^\mu \overline{\lambda}) \,.$$

- They actually interfere so that m_D can decouple; we find $(y \equiv \frac{M^2_{O_i}}{m^2_D})$

$$\Gamma(O_i \to \tilde{g} G) = \frac{(M^2_{O_i} - m^2_D)^4}{32\pi f^2 M^3_{O_i}} ,$$

$$g(y) \equiv \frac{60\,(3-y)\,(1-y)^3 \log(1-y)}{y^5} + \frac{6y^4 - 155y^3 + 480y^2 - 510y + 180}{y^4}$$

$$= \frac{2}{7}y^2 + \frac{3}{14}y^3 + \frac{1}{7}y^4 + \ldots$$

$$g(1) = 1 \,.$$

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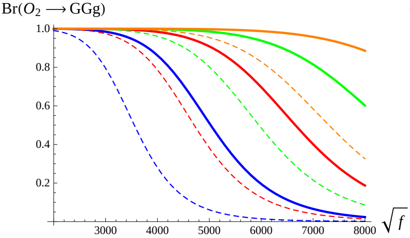
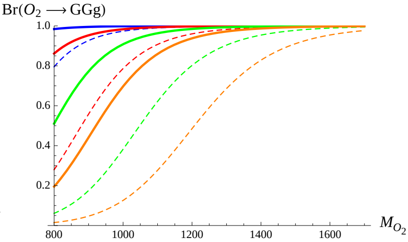
Branching ratios

So then we may have regions of parameter space where the goldstino decays of the octet are important:





Full lines are drawn for $\delta\tilde{m} = M_Z = 90$ *GeV and dotted lines for* $\delta\tilde{m} = 180$ *GeV.*
Also, we have taken $m_{\tilde{g}} = 1.7$ *TeV and* $m_{\tilde{q}} = 1.5$ *TeV.*
Left plot: (Blue, Red, Green, Orange): $M_{O_2} = (0.8$ *TeV,* 1 *TeV,* 1.2 *TeV,* 1.4 *TeV).*
Right plot: (Blue, Red, Green, Orange): $\sqrt{f} = (3$ *TeV,* 4 *TeV,* 5 *TeV,* 6 *TeV).*

Conventional searches for low-scale SUSY

- The standard search channel for low-scale SUSY-breaking is monojet/monophoton events:

$$\begin{aligned} g + g &\to G + G + g \\ g + q &\to G + G + q \\ q + \overline{q} &\to G + G + \gamma/g \end{aligned} \tag{1}$$

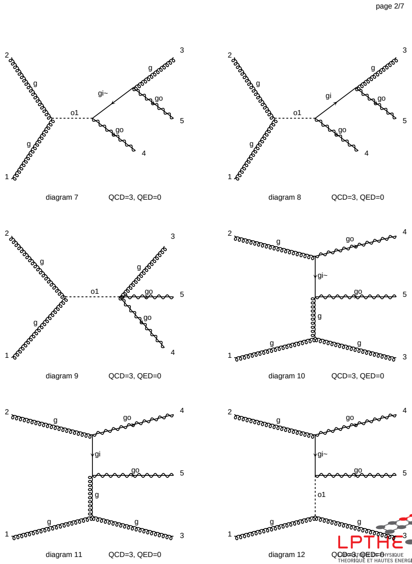
- As I mentioned earlier, either we integrate out all of the SUSY particles and look at the model-independent effective operators à la Brignole, Feruglio, Mangano, Zwirner $\rightarrow$ does not matter whether gluinos are Dirac or Majorana, but unfortunately the bounds are too weak to be consistent.
- ... or we need to revist the standard Majorana case.
- Or instead: the theory with light octets is an interesting alternative.

Conclusions

- Dirac gauginos have many advantages and remain an attractive reason for TeV-scale SUSY to still be hiding.
- The tools to study them are now available.
- The main thing missing now is detailed collider studies.
- But also many more possibilities for model scenarios.

Octet scalar monojet events

- There are many diagrams which contribute to these processes, but they are dominated at LHC by gluon fusion.
- Must include the full effective theory of scalar octet, gluino and goldstino.
- Crucially depends on the single octet production process via the loop-induced coupling.



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Implementation

- As an illustration and precursor to a full study, we have implemented the model in `Feynrules` and then `MadGraph` and `CalcHEP`.
- Calculated cross-sections at LHC13 for goldstino events when one octet scalar is light as a function of the octet scalar mass, with the total double octet production cross-section given as reference.
- Events where two sgluons are produced and at least one decays to goldstinos (as opposed to two jets) are labelled $O_1 \to jGG$ and $O_2 \to jGG$.
- $\sqrt{f} = 7.5$ TeV was chosen since then $m_{\tilde{q}} \sim m_{\tilde{g}} \sim 0.2\sqrt{f} \sim 1.5$ TeV, with the squark masses varying from a common SUSY-breaking mass as $\sqrt{m_{\tilde{q}}^2 \pm \frac{1}{2}M_Z^2}, \sqrt{m_{\tilde{q}}^2 \pm 2M_Z^2}$.
- Monojet events are labelled $p\ p \to j\ G\ G$; for these, two different, lower, values of $\sqrt{f}$ are shown, and the spectrum of other sparticles has the first two generations of squarks and the right-handed squarks of the third generation at 2 TeV, with left-handed third-generation squarks at 755 GeV.
- In all cases the gluino mass was fixed at 1500 GeV.

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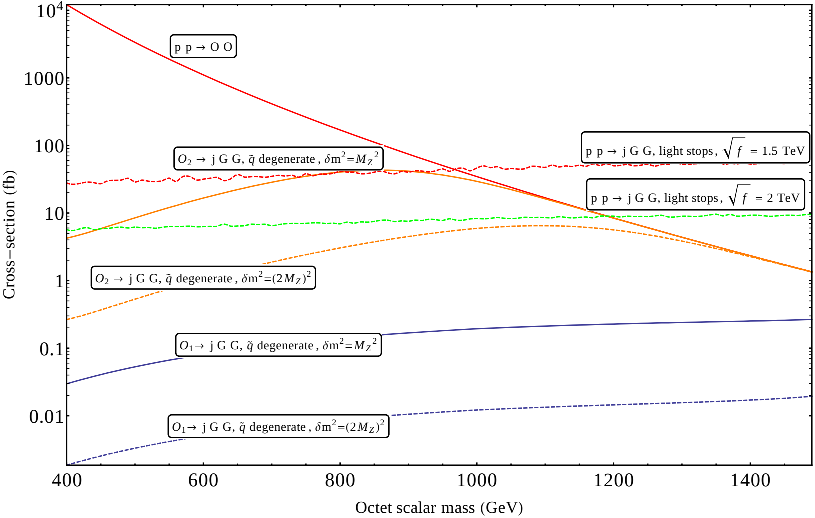
Projected cross-sections



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