Non-standard models of Gauge Mediation

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Summary

- I will discuss scenarios of gauge mediation in the presence of more than one SUSY breaking sector. [K. Benakli, C. Moura arXiv:0706.3127] [C. Cheung, Y. Nomura, J. Thaler 1002.1967] [R. Argurio, Z. Komargodski, A. Mariotti 1102.2386] [J. Thaler, Z. Thomas 1103.1631] [R. Argurio, G. Ferretti, A. Mariotti, K. Mawatari, Y. Takaesu in progress.]
- These models are characterized by a ultralight gravitino (LSP) and a number of uneaten pseudo-goldstini (NLSP, NNLSP...) of mass intermediate between that of the gravitino and of the lightest observable-sector particle (LOSP).
- One of the salient feature of the presence of extra pseudo-goldstini is a softer and more structured photon spectrum.
- For lack of time, I will concentrate on a simplified model with one pseudo-goldstino and one neutralino LOSP.

Elephant in the room:

The status of low energy SUSY is a bit worrisome... It can be summarized by saying that both [ATLAS: 1109.6572, 1109.6606, 1110.2299] and [CMS: 1109.2352] rule out conventionally decaying colored superpartners up to almost 1 TeV.

In addition, relevant to gauge mediation there is the non-observation of prompt photons in association with $\not{E}_T$ [ATLAS: 1107.0561] [CMS: 1103.0953, 1105.3152].

(These last papers are from the 2010 data sample of $\approx 35\ pb^{-1}$ but they have been updated recently.)

In any SUSY theory $m_{3/2} = F/\sqrt{3}M_{\mathrm{Planck}}$.

In gravity mediation models (mSUGRA, CMSSM...) $\sqrt{F} > 10^{11}\mathrm{GeV}$ and the gravitino plays no role in collider experiments.

In gauge mediation the gravitino is the LSP and the other $R = -1$ particles (e.g. χ) can decay into it.

By the Equivalence Theorem: Light Gravitino $\equiv$ Goldstino.

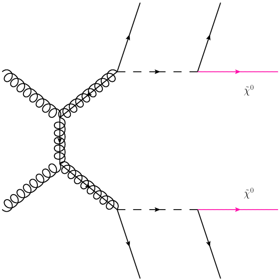
Example: if there is only one scale in the SUSY breaking sector:

$$m_{\mathrm{Soft}} \approx \alpha\sqrt{F} \approx 1\mathrm{TeV} \Rightarrow m_{3/2} \approx 1\mathrm{eV}$$

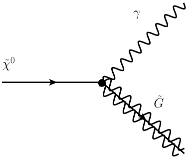
$$\Gamma(\chi \to \gamma\, G) \approx \frac{m_\chi^5}{48\pi m_{3/2}^2 M_{\rm Planck}^2}$$

(BR$=100\%$ for the lightest neutralino, ≈ 0 for the others).
Can lead to $c\tau = 10^{-10}\ m$ (prompt) $\leftrightsquigarrow$ $10^2\ m$.

In the case of prompt decay, a typical SUSY decay chain



is followed by



$$\sigma\left[\text{jets} + \not{E}_T(\chi\chi)\right] \approx \sigma\left[\text{jets} + \gamma + \gamma + \not{E}_T(GG)\right]$$

but also

$$\sigma\left[\chi\chi\right] \text{ (unobserv.)} \approx \sigma\left[\gamma + \gamma + \not{E}_T(GG)\right]$$

and even

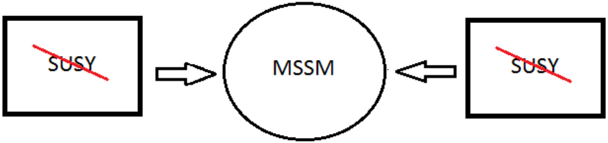
$$\sigma\left[G\chi\right] \text{ (unobserv.)} \approx \sigma\left[\gamma + \not{E}_T(GG)\right]$$

The $\chi \to \gamma\, G$ decay is a two massless-bodies decay, so the γ takes half of the energy in the χ rest frame.
Are there other options?

In a nice series of papers, starting from C. Cheung, Y. Nomura and J. Thaler [1002.1967], (see [K. Benakli, C. Moura arXiv:0706.3127] for an earlier brane-world model) it was pointed out that in the case of more than one SUSY breaking sector the physics of goldstini needs to be revised.

This was applied to models of gauge mediation in R. Argurio, Z. Komargodski and A. Mariotti [1102.2386] and the present work is a continuation of that work attempting to extract the salient phenomenological features.

Prototypical example: Two hidden sectors communicating via MSSM:



In the absence of MSSM interactions the model contains two goldstini G_1 and G_2.

One linear combination $G = \frac{F_1 G_1 + F_2 G_2}{\sqrt{F_1^2 + F_2^2}}$ is eaten by the gravitino but remains as a true goldstino in gauge mediation, by the equivalence theorem.

The other combination $G' = \frac{-F_2 G_1 + F_1 G_2}{\sqrt{F_1^2 + F_2^2}}$ acquires a model dependent mass that can be at the EW scale or larger and it is called a pseudo-goldstino.

We define $F = \sqrt{F_1^2 + F_2^2}$ so that $m_{3/2} = F/\sqrt{3} M_{\mathrm{Planck}}$ as before.

To find the couplings to the matter fields we use the spurion formalism $X_h \supset F_h\theta^2 + \sqrt{2}G_h\theta$

$$\begin{aligned}
\frac{1}{2}\int \mathrm{d}^2\theta M_h \frac{X_h}{F_h}\mathcal{W}^2 &\supset \frac{1}{2}M_h\lambda^2 + \frac{iM_h}{2\sqrt{2}F_h}\lambda\sigma^\mu\bar{\sigma}^\nu G_h F_{\mu\nu} \\
\int \mathrm{d}^4\theta {m_h}^2 \frac{X_h^\dagger X_h}{F_h^2}\Phi^\dagger\Phi &\supset {m_h}^2\phi^\dagger\phi + \frac{{m_h}^2}{F_h}(G_h\psi\phi^\dagger + \bar{G}_h\bar{\psi}\phi)
\end{aligned}$$

Rotating to the G, G' basis, setting $M = M_1 + M_2$ and $m^2 = m_1^2 + m_2^2$, we get the usual G couplings and the G' couplings enhanced/supressed by the mediation model dependent quantities

$$\begin{aligned}
K_V &= -\frac{M_1F_2}{MF_1} + \frac{M_2F_1}{MF_2} \\
K_S &= -\frac{m_1^2F_2}{m^2F_1} + \frac{m_2^2F_1}{m^2F_2}
\end{aligned}$$

to be treated as free parameters.

In general there will be different M^a, K_V^a for the different gauge groups and different m^{i2}, K_S^i for the different families:

$$\frac{im^a}{2\sqrt{2}F}(\lambda^a\sigma^\mu\bar{\sigma}^\nu G F^a_{\mu\nu} + K_V^a\lambda^a\sigma^\mu\bar{\sigma}^\nu G' F^a_{\mu\nu}) +$$
$$\frac{m^{i2}}{F}(G\psi_i\phi^{i\dagger} + \bar{G}\bar{\psi}^i\phi_i + K_S^i G'\psi_i\phi^{i\dagger} + K_S^i\bar{G}'\bar{\psi}^i\phi_i)$$

where $\lambda = \tilde{B}, \tilde{W}^3 \ldots, \psi = \tilde{H}_u^0, \tilde{H}_d^0 \ldots$ and one must rotate to the LOSP mass eigenstate

$$\begin{aligned} \chi &= -iN_1\tilde{B} - iN_2\tilde{W}^3 + N_3\tilde{H}_u^0 + N_4\tilde{H}_d^0 \\ &= -ia_\gamma\tilde{\gamma} - ia_{Z_T}\tilde{Z} + a_{Z_L}\tilde{H}' + a_H\tilde{H}'' \end{aligned}$$

The coupling of the true goldstino G can also be written as a derivative coupling to the supercurrent:

$$\frac{1}{F}(\partial_\mu G^\alpha J^\mu_\alpha + \text{ h.c.})$$

with

$$J^\mu = \frac{1}{2\sqrt{2}}\sigma^\nu\bar{\sigma}^\rho\sigma^\mu\bar{\lambda}^a F^a_{\nu\rho} + \sigma^\nu\bar{\sigma}^\mu\psi_i D_\nu\phi^{*i} - i\sigma^\mu\bar{\psi}^i W^*_i - \frac{i}{\sqrt{2}}g\phi^{*i}T^a\phi_i\sigma^\mu\bar{\lambda}^a$$

Either of the two actions leads to the same decay rates. (But for the non-derivative action the decay into Z is tricky! See e.g. [F. Luo, K. A. Olive, M. Peloso 1006.5570]. One has to consider the mixing between goldstinos and neutralinos). For the goldstino we have the e.g. well known result [S. Ambrosanio, G. L. Kane, G. D. Kribs, S. P. Martin, S. Mrenna hep-ph/9605398]

$$\Gamma(\chi \to Z\, G) = \frac{2|a_{Z_T}|^2 + |a_{Z_L}|^2}{96\pi}\frac{m_\chi^5}{m_{3/2}^2 M_{\text{Planck}}^2}\left(1 - \frac{m_Z^2}{m_\chi^2}\right)^4$$

A similar (messier) formula hold for the pseudo-goldstino.

For the pseudo-goldstino G' it's better to use the non derivative coupling as before

$$\frac{im^a}{2\sqrt{2}F} K_V^a \lambda^a \sigma^\mu \bar{\sigma}^\nu G' F_{\mu\nu}^a + \frac{m^{i2}}{F} (K_S^i G' \psi_i \phi^{i\dagger} + K_S^i \bar{G}' \bar{\psi}^i \phi_i)$$

One can, of course, use the e.o.m. backwards but one encounters a contact term $\propto (K_V - K_S) G' \lambda \psi \psi$ required to soften the UV behavior of the amplitude.

K_V and K_S are model dependent dimensionless parameters that can be of order $10 \leftrightsquigarrow 100$.

An example

Here I will only present a simplified example, to illustrate some of the physics that might arise. Let us choose $M_{\tilde{B}} \approx M_{\tilde{W}} \gg m_Z$ so that the neutralino can be chosen to be mostly a photino

1. For $K_V, K_S \gg 1$ the photino λ will decay mostly to the pseudo-goldstino G' plus γ.
2. If the photino and pseudo-goldstino have similar masses $m_\lambda \gtrsim m_{G'}$ the γ spectrum will be softer than in usual gauge mediation.

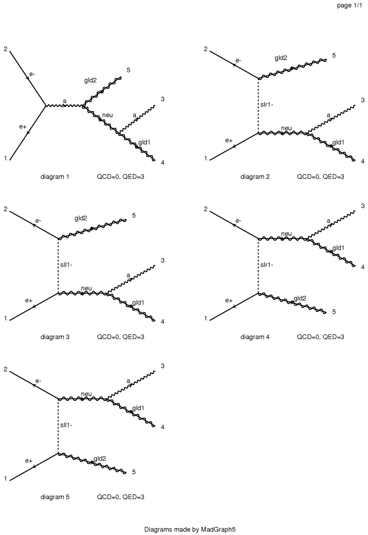
Of course, there is a tension between the two conditions since at some point the lack of phase space in 2 invalidates 1.

The nice feature of this limit is that many results can be obtained analytically for lepton colliders. For instance the amplitude for $e^+e^- \to G'\chi$, leading to $\sigma(e^+e^- \to \gamma + \not{E}_T)$ via NWA is: (m_e is the degenerate selectrons mass)

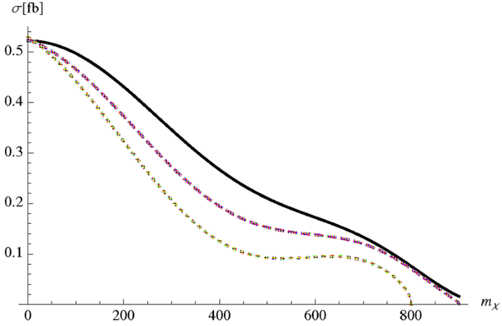
$$
\begin{aligned}
&\frac{2K_V^2 m_\chi^2}{s}\left(2tu - m_\chi^2(t+u) + 2m_{G'}m_\chi s + m_{G'}^2(2m_\chi^2 - t - u)\right) \\
&+2K_S^2 m_e^4 \left(\frac{(m_{G'}^2 - t)(m_\chi^2 - t)}{(m_e^2 - t)^2} + \frac{(m_{G'}^2 - u)(m_\chi^2 - u)}{(m_e^2 - u)^2} + \frac{2m_{G'}m_\chi s}{(m_e^2 - t)(m_e^2 - u)}\right) \\
&+\frac{4K_V K_S m_\chi^2 m_e^2 (m_{G'}^2 - t)}{t - m_e^2} + \frac{4K_V K_S m_{G'} m_\chi m_e^2 (m_\chi^2 - t)}{t - m_e^2} \\
&+\frac{4K_V K_S m_\chi^2 m_e^2 (m_{G'}^2 - u)}{u - m_e^2} + \frac{4K_V K_S m_{G'} m_\chi m_e^2 (m_\chi^2 - u)}{u - m_e^2}
\end{aligned}
$$

(Setting $K_S = K_V = 1$ and $m_{G'} = 0$ reproduces [J. L. Lopez, D. V. Nanopoulos, A. Zichichi hep-ph/9611437])

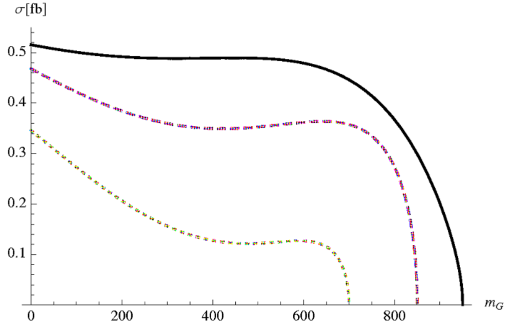
Diagrams for $\sigma(e^+e^- \to \gamma + \not{E}_T)$



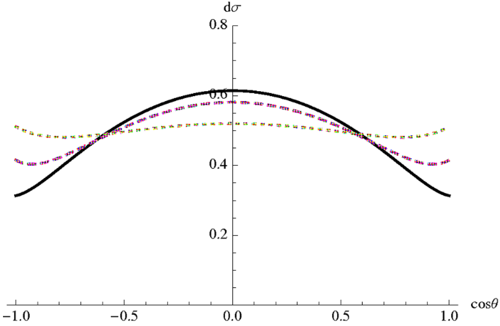
Total cross section of production of G' and χ as a function of m_χ, with $\sqrt{s} = 1000GeV$, $m_e = 500GeV$ and $m_G = 0, 100, 200GeV$ for black, dashed and dotted line respectively.

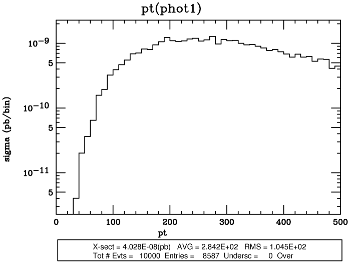


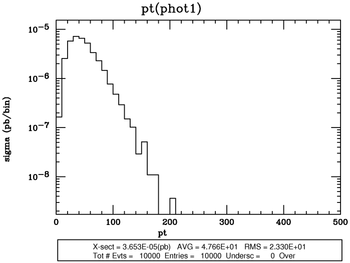
Total cross section of production of G' and χ as a function of m_G, with $\sqrt{s} = 1000 GeV$, $m_e = 500 GeV$ and $m_\chi = 50, 150, 300 GeV$ for black, dashed and dotted line respectively.



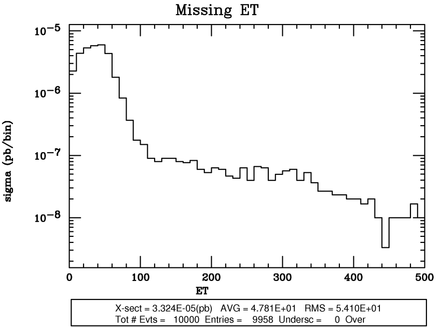
The normalized differential cross section of production of G' and χ as a function of $\cos\theta$, with $\sqrt{s} = 1000GeV$, $m_\chi = 200GeV$, $m_e = 500GeV$ and $m_G = 0, 200, 400GeV$ for black, dashed and dotted line respectively.







Last example $p + p \to \gamma + \gamma + \not{E}_T$ at 7 TeV (preliminary).
$m_{3/2} = 10^{-11}$ GeV, $m_{G'} = 370$ GeV, $m_\chi = 400$ GeV,
$m_{\text{Squarks}} = 1000$ GeV, $K_V = K_S = 100$
Note: the cross section is ridiculously small because I don't allow jets. We are in the process of doing a more realistic simulation.
Compare $d\sigma/dp_t$ of the most energetic γ for $\gamma\gamma GG$ v.s. $\gamma\gamma G'G'$



Missing energy for the process.

Conclusions

In the coming years we will receive the final verdict from the LHC experiments as to whether low energy SUSY is present or not in nature.

One must consider non-standard scenarios to make sure we are not missing anything. This is useful at this stage, as long as it is not done just to rescue one's favorite model at all costs.

The scenario with multiple goldstini is one of the many examples leading to non standard signatures worth keeping in mind.

At the end, we should remember Woody Allen:
Eighty percent of success is showing up!