Color-octet scalars of N=2 SUSY at the LHC

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based on Choi, Drees, Kalinowski, JMK, Popenda, and Zerwas
arXiv:0812.3586
Minimal Supersymmetric Standard Model (MSSM)

- One fermionic generator is assumed. (N=1)
  - Each SM particle (+one more Higgs) has its superpartner (supermultiplet)
- R-parity conservation is assumed.
  - Pairwise production of superparticles!
    - Lightest Supersymmetric Particle (LSP) stable!
- Electrically neutral, colorless Majorana fermion is assumed to be the LSP.
- SUSY breaking sector is manifested as free parameters.
  - Different parameter set gives different collider signals.
- Typical LHC signals are [e.g. The ATLAS Collaboration, arXiv:0901.0512]:
  - Pairwise production of $\tilde{q}, \tilde{g}$ → cascade decays
  - 2-4 hard jets (+softer QCD jets) + missing $E_T$ from LSP.
N=1/N=2 Hybrid Model

- **Motivations**: Demands for Dirac gaugino [Choi, Drees, Freitas, Zerwas]; “Supersoft” SUSY breaking [Fox, Nelson, Weiner]; String-inspired Brane models [Antoniadis et al.]; ...

- Matter fermions are chiral
  - We adopt N=1/N=2 hybrid scheme; i.e. N=2 mirror (s)fermions to be very heavy, and expanding N=2 only in the gauge sector.

- N=2 QCD hypermultiplet: \( \hat{g}(\{g_\mu, \tilde{g}\}) + \hat{g}'(\{\sigma, \tilde{g}'\}) \)

Furthermore, we assume
- pure Dirac gluino;
- Degenerate scalar/pseudoscalar component of \( \sigma \).
Color-octet Scalar gluon, $\sigma$

- R-parity even $\Rightarrow$ single production possible (in principle)!
- Mass given by superpotential: $W \supset \frac{1}{2} M_3' \hat{g}'^a \hat{g}'^a$
  + soft breaking terms: $\mathcal{L} \supset -m_\sigma^2 |\sigma|^2 - m_{\sigma\sigma}^2 \sigma \bar{\sigma}$.
- Interactions are
  SUSY breaking trilinear interaction with squarks:
  $\mathcal{L} \supset -g_S M_3^D \sigma^a \lambda_{ij}^a \sqrt{2} \sum q (\bar{\tilde{q}}_L^i \tilde{q}_L^j - \bar{\tilde{q}}_R^i \tilde{q}_R^j)$
  + Gauge interaction with gluons/gluinos: E.g.
  $\mathcal{L} \supset -\sqrt{2} i g_S f^{abc} \bar{\hat{g}}^a_{DL} \hat{g}^b_{DR} \sigma^c$
  $\Rightarrow$ At tree level, decays to gluino or squark pairs!
Coupling to gluons/quarks through triangle loop: E.g.

⇒ At one-loop level, decays to top-quarks or gluon pairs!
\( \sigma \) production

The relevant Feynmann diagrams:

(a) \( \bar{q} \rightarrow g \rightarrow \sigma^* \rightarrow \sigma \)

(b) \( \text{Identical (modulo color factors) to squark-pair production.} \)
The $\sigma\sigma^*$ cross sections exceed those of squarks:

\[
\frac{\sigma[gg \to \sigma\sigma^*]}{\sigma[gg \to \tilde{q}_3\tilde{q}_3^*]} = \begin{cases} 
\frac{\text{tr}([F^a,F^b][F^a,F^b])}{\text{tr}([\frac{1}{2}\lambda^a,\frac{1}{2}\lambda^b][\frac{1}{2}\lambda^a,\frac{1}{2}\lambda^b])} = \frac{216}{28/3} \approx 23, & \text{for } \beta \to 0, \\
\frac{\text{tr}(2F^aF^bF^a + F^aF^bF^aF^b)}{\text{tr}(2\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2} + \frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2})} = \frac{180}{10} = 18, & \text{for } \beta \to 1, \\
\frac{\text{tr}(\frac{1}{2}\frac{1}{2}) \text{tr}(F^aF^b)}{\text{tr}(\frac{1}{2}\frac{1}{2}) \text{tr}(\frac{1}{2}\frac{1}{2})} = \frac{12}{2} = 6, & \text{for any } \beta.
\end{cases}
\]
The partonic branching ratio:

\[ \bar{q}q \rightarrow \sigma\sigma^* \]

\[ \bar{q}q \rightarrow \tilde{q}\tilde{q}^* \]

\[ m_\sigma = 1 \text{ TeV} \]

\[ gg \rightarrow \sigma\sigma^* \]

\[ 10 \times gg \rightarrow \tilde{q}\tilde{q}^* \]

\[ m_\sigma = 1 \text{ TeV} \]
σ productions at the LHC:

⇒ Sizable σ event rate can be generated!
Recall: $\exists$ SUSY breaking trilinear interaction with squarks + gauge interaction with gluinos.

**At tree level**

- $\sigma \rightarrow \tilde{g}\tilde{g}(\rightarrow qq\tilde{q}\tilde{q} \rightarrow qqqq + \tilde{\chi}\tilde{\chi})$, with
  $$\Gamma[\sigma \rightarrow \bar{g}_D g_D] = \frac{3\alpha_s M_\sigma}{4} \beta_\tilde{g} (1 + \beta_\tilde{g}^2).$$
- $\sigma \rightarrow \tilde{q}\tilde{q}(\rightarrow qq + \tilde{\chi}\tilde{\chi})$, with
  $$\Gamma[\sigma \rightarrow \bar{q}\tilde{q}^*] = \frac{\alpha_s}{4} \frac{|M_3^D|^2}{M_\sigma} \beta_{\tilde{q}}.$$

**At one-loop level:**

- $\sigma \rightarrow t\bar{t}(\rightarrow b\bar{b}W^+W^-)$, with
  $$\Gamma(\sigma \rightarrow q\bar{q}) = \frac{9\alpha_s^3}{128\pi^2} \frac{|M_3^D|^2 m_q^2}{M_\sigma} \beta_q \left[ (M_\sigma^2 - 4m_q^2) |I_S|^2 + M_\sigma^2 |I_P|^2 \right].$$
  ($I_S, I_P$: effective scalar (S), pseudoscalar (P) couplings.)
- $\sigma \rightarrow gg$, with
  $$\Gamma(\sigma \rightarrow gg) = \frac{5\alpha_s^3}{384\pi^2} \frac{|M_3^D|^2}{M_\sigma} \left| \sum_q \left[ \tau_{\bar{q}_L} f(\tau_{\bar{q}_L}) - \tau_{\bar{q}_R} f(\tau_{\bar{q}_R}) \right] \right|^2.$$
  ($\tau_{\bar{q}_{L,R}} = 4m_{\bar{q}_{L,R}}^2/M_\sigma^2$; $f(\tau) = -\frac{1}{2} \int_0^1 \frac{dx}{x} \ln(1 - 4x(1 - x)/\tau)$.)
The decay branching ratios:

\[(m_{\tilde{q}_R} = 0.95 m_{\tilde{q}_L}; m_{\tilde{t}_L} = 0.9 m_{\tilde{q}_L}; m_{\tilde{t}_R} = 0.8 m_{\tilde{q}_L})\]

- Two-body final states dominate.
- Above thresholds, the partial width into gluinos always dominate.
Signals at the LHC

- Above all thresholds:
  \[ pp \rightarrow \tilde{g}\tilde{g}\tilde{g}\tilde{g} \rightarrow \text{(isotropically distributed, hard) 8 jets + 4 LSP's}. \]
  \[ \Rightarrow \text{Easily distinguishable!} \]

- If \( m_{\tilde{q}} \lesssim m_{\tilde{g}} \) & \( \exists \text{significant L-R mixing:} \)
  \[ pp \rightarrow \tilde{t}_1\tilde{t}_1^*\tilde{t}_1^* \rightarrow 4 \text{ LSP's + many hard jets}. \]

- If \( M_\sigma > 2m_{\tilde{g}} \gtrsim 2m_{\tilde{q}} \):
  \[ pp \rightarrow \tilde{q}\tilde{q}^*\tilde{g}\tilde{g} \rightarrow 4 \text{ LSP's + many hard jets}. \]

- If kinematically allowed:
  \[ pp \rightarrow tttt \]
  \[ \Rightarrow \text{Direct } M_\sigma \text{ reconstruction might be possible!} \]
Summary

- N=2 gauge hypermultiplet includes color-octet scalar, $\sigma$.
- The signals at the LHC from $\sigma$ are very different from those of MSSM.
- Depending on the mass spectra, either multi-jet with high sphericity and large missing $E_T$, or four top quarks should be observed.