Color-Octet Scalars At The LHC: Sgluons

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Outline

Motivation I

Supersymmetry, most complete and respected vision of physics beyond SM
In simplest $N = 1$ supersymmetric extension of SM (MSSM):
Each SM particle $\Leftrightarrow$ sparticle, differs in spin by half a unit

Successes of supersymmetry do not rest on its minimal realization.

Shortcomings of MSSM:

- SUSY must be broken and its origin is still unknown
- Experimental constraints play an increasingly restictive role in building models of SUSY breaking
- Most disturbing: Flavor problem

Traditional solution: Flavor diagonal soft-breaking parameters
Alternative: Alter low energy structure of model

Motivation II

N=1/*N*=2 hybrid model:
MSSM extended by gauge elements of N=2 SUSY

Interesting features:

- Dirac gauginos lead to suppression in flavor-violating processes

  Kribs, Poppitz, Weiner 0712.2039

- Additional matter content at electroweak scale:

  Dirac gaugino requires additional degrees of freedom:
  Provided by adding a chiral super-multiplet

Here: Phenomenology of scalar partner of Dirac gluino - sgluon

Choi, Drees, Kalinowski, Kim, EP, Zerwas 0812.3586

Plehn, Tait 0810.3919

Introduction to $N=1/N=2$ hybrid SUSY model

- Hyper-QCD sector
- Gluino sector
- Sgluon sector:
  Tree level couplings
  Loop induced couplings

Fayet Nucl.Phys. B **113** *(1976) 135*

Alvarez-Gaume, Hassan hep-ph/9701069

Benakli, Moura 0802.3672

Choi, Drees, Freitas, Zerwas 0808.2410

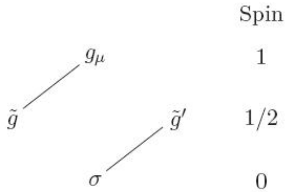
$N\!=\!1/N\!=\!2$ hybrid model: Hyper-QCD sector

MSSM: Gluinos are Majorana particles with two degrees of freedom to match gluons in vector super-multiplet.

To provide two additional degrees for Dirac gluino:

$$\underbrace{\text{vector super-multiplet} \quad + \quad \text{chiral super-multiplet}}_{\text{vector hyper-multiplet of } N=2 \text{ SUSY:}} =$$

- gluon/gluino $\hat{g} = \{g_\mu, \tilde{g}\}$
- gluino'/sgluon $\hat{g}' = \{\tilde{g}', \sigma\}$



N=2 mirror fermions are assumed to be heavy to avoid chirality problems.

$N=1/N=2$ hybrid model: Gluino sector I

Lagrangian from general N=2 action can be restricted to few relevant terms:

- Old and new gluinos are coupled minimally to gluon field:

$$\mathcal{L}_{QCD}^{g\tilde{g}\tilde{g}} = g_s\, Tr\left(\overline{\tilde{g}}\gamma_\mu[g_\mu, \tilde{g}] + \overline{\tilde{g}'}\gamma_\mu[g_\mu, \tilde{g}']\right)$$

- Quarks and squarks interact only with old gluinos

$$\mathcal{L}_{QCD}^{q\tilde{q}\tilde{g}} = -g_s\left[\overline{q_L}\tilde{g}\tilde{q}_L - \overline{q_R}\tilde{g}\tilde{q}_R + h.c.\right]$$

- Soft SUSY breaking generates masses for gluinos

$$\mathcal{L}_{QCD}^{m} = -\frac{1}{2}\left[M_3'\, Tr\left(\overline{\tilde{g}'}\tilde{g}'\right) + M_3\, Tr\left(\overline{\tilde{g}}\tilde{g}\right) + M_3^D\, Tr\left(\overline{\tilde{g}'}\tilde{g} + \overline{\tilde{g}}\tilde{g}'\right)\right]$$

$N\!=\!1/N\!=\!2$ hybrid model: Gluino sector II

Diagonalizing mass matrix

$$\mathcal{M}_G = \begin{pmatrix} M_3' & M_3^D \\ M_3^D & M_3 \end{pmatrix}$$

gives rise to 2 Majorana mass eigenstates with masses m_1 and m_2.

$M_3' = M_3 = 0,\ M_3^D \neq 0$

Mixing between states maximal
Dirac gluino $\tilde{g}_D = \tilde{g}_R + \tilde{g}_L'$ with mass $m_{\tilde{g}_D} = |M_3^D|$

$M_3' \to \pm\infty$

MSSM gluino is recovered

Coupling of Dirac gluino to quarks and squarks

$$\mathcal{L}_{QCD}^{q\tilde{q}\tilde{g}} = -g_s\left[\overline{q_L}\tilde{g}_D\tilde{q}_L + \overline{q_R}\tilde{g}_D^{c\,T}\tilde{q}_R + h.c.\right]$$

Trilinear gluon/gluino interaction is sum of individual interactions.

$N=1/N=2$ hybrid model: Sgluon sector I

Assume: Real and imaginary components of scalar field σ degenerate with mass M_σ

Tree level couplings

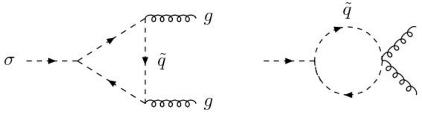
- gluinos: $\mathcal{L}_{\tilde{g}_D\tilde{g}_D\sigma} = -\sqrt{2}i\, g_s\, f^{abc}\, \overline{\tilde{g}^a_{DL}}\, \tilde{g}^b_{DR}\, \sigma^c + h.c.$
- squarks: $\mathcal{L}_{\sigma\tilde{q}\tilde{q}} = -g_s M_3^D \left[\sigma^a \frac{\lambda^a_{ij}}{\sqrt{2}} \sum_q \left(\tilde{q}^*_{Li}\tilde{q}_{Lj} - \tilde{q}^*_{Ri}\tilde{q}_{Rj}\right)\right] + h.c$
- $\sigma\sigma^* g$ and $\sigma\sigma^* gg$ couplings to gluons as required by gauge invariance

➡ Although R-parity even, single sgluon cannot be produced in pp collisions at tree level.

$N=1/N=2$ hybrid model: Sgluon sector II

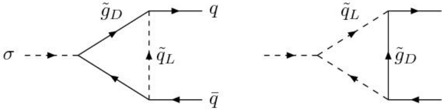
Loop induced couplings

- gluon pair



gluino loops vanish in σgg, σggg, ...

- quark pair

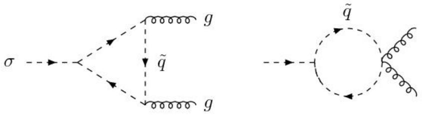


suppressed by quark mass

$N=1/N=2$ hybrid model: Sgluon sector II

Loop induced couplings

- gluon pair



gluino loops vanish in σgg, σggg, ...

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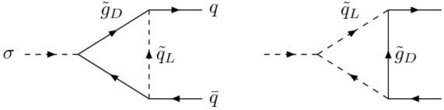


suppressed by quark mass

} vanish for degenerate L/R squarks

Phenomenology: Sgluon decays I

Tree level sgluon decays

- A pair of Dirac gluinos: $\Gamma(\sigma \to \tilde{g}_D \bar{\tilde{g}}_D) \propto M_\sigma$

  gluino modes: $\sigma \to \tilde{g}\tilde{g}$, $\sigma \to \tilde{g}\bar{q}q\tilde{\chi}$

- A pair of squarks: $\Gamma(\sigma \to \tilde{q}_a \tilde{q}_a^*) \propto \frac{|M_3^D|^2}{M_\sigma}$

  squark modes: $\sigma \to \tilde{q}\tilde{q}^*$, $\sigma \to \tilde{q}\bar{q}\tilde{\chi}$, $\sigma \to \tilde{q}^* q\tilde{\chi}$, $\sigma \to q\bar{q}\tilde{\chi}\tilde{\chi}$

➡ For σ pair production at the LHC a spectacular signature

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

$$pp \to 8\,\text{jets} + 4\,\text{LSP's}$$

Phenomenology: Sgluon decays II

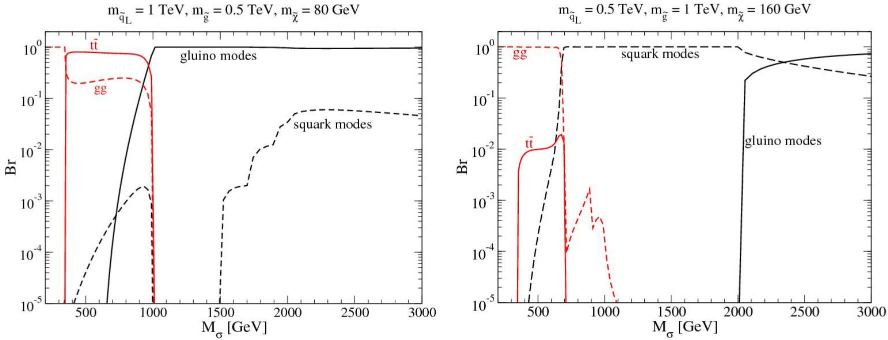
Loop induced sgluon decays

- A pair of gluons: $\Gamma(\sigma \to gg) \propto \frac{|M_3^D|^2}{M_\sigma}$
- A pair of quarks: $\Gamma(\sigma \to q\bar{q}) \propto \frac{m_q^2}{M_\sigma} \frac{|M_3^D|^2}{\left(D[|M_3^D|^2]\right)^2}$

➡ For σ pair production at the LHC a spectacular signature

$$pp \longrightarrow tt\bar{t}\bar{t}$$

Phenomenology: Branching ratios



$$m_{\tilde{q}_R} = 0.95 m_{\tilde{q}_L}, \; m_{\tilde{t}_L} = 0.9 m_{\tilde{q}_L}, \; m_{\tilde{t}_R} = 0.8 m_{\tilde{q}_L}$$

with $\tilde{t}_L$-$\tilde{t}_R$ mixing determined by $X_t = m_{\tilde{q}_L}$

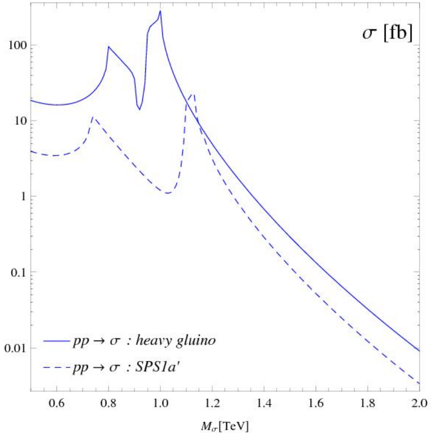
Phenomenology: Sgluon production I

Single sgluon production

$$\hat{\sigma}[gg \to \sigma] = \frac{\pi^2}{M_\sigma^3}\Gamma(\sigma \to gg)$$

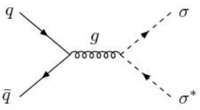
$$\begin{aligned} \sigma &\to t\bar{t} \to b\bar{b}W^+W^- \\ \sigma &\to gg \end{aligned}$$

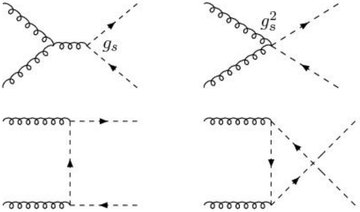
- cannot have simultaneously large cross section and large tt decay mode
- large background in gg decay mode



Phenomenology: Sgluon production II

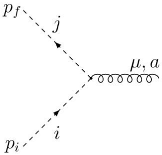
Sgluon pair production





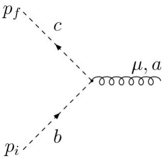
differ from squark pair production just by color factors:

Gluon-Squark-Squark



$$= -ig_s \left(\frac{\lambda^a}{2}\right)_{ji} (p_i + p_f)_\mu$$

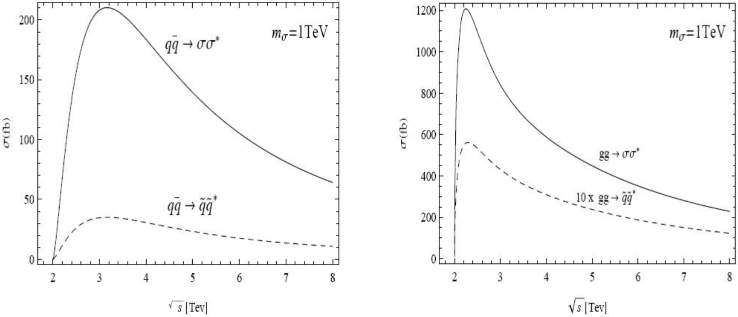
Gluon-Sgluon-Sgluon



$$= -ig_s \, f^{abc} \, (p_i + p_f)_\mu$$

Phenomenology: Sgluon production III

Parton-level cross sections

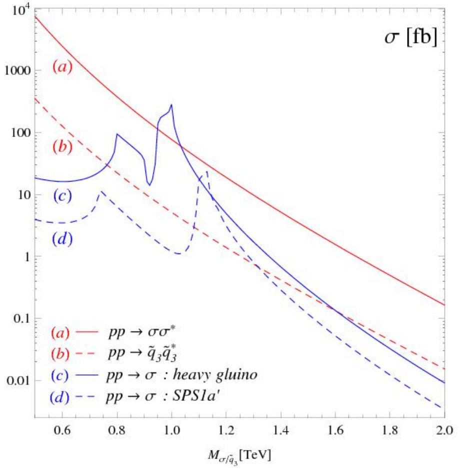


Larger cross sections for sgluon pair production reflect different strengths of couplings:

$$\frac{\sigma\left[q\bar{q} \to \sigma\sigma^*\right]}{\sigma\left[q\bar{q} \to \tilde{q}_3\tilde{q}_3^*\right]} = \frac{Tr\left(\frac{\lambda^a}{2}\ \frac{\lambda^b}{2}\right)\ f^{acd}f^{bcd}}{Tr\left(\frac{\lambda^a}{2}\ \frac{\lambda^b}{2}\right)\ Tr\left(\frac{\lambda^a}{2}\ \frac{\lambda^b}{2}\right)} = \frac{12}{2} = 6$$

Phenomenology: Sgluon production IV

Sgluon production in pp collisions



Phenomenology: Signatures I

Most spectacular

$$gg\,,\ q\bar{q} \to \sigma\sigma^* \quad \text{with} \quad \sigma \to \tilde{g}\tilde{g} \to qq\tilde{q}\tilde{q} \to qqqq + \tilde{\chi}\tilde{\chi}$$

$$pp \to 8\,\text{jets} + 4\,\text{LSP's}$$

Analyzing production and decays near mass thresholds:

- sgluon pair production: $M_\sigma \simeq 2m_{\tilde{g}} \simeq 2m_{\tilde{q}} \gg m_{\tilde{\chi}_1^0}$

$$\langle E_{\perp j}^{tot} \rangle \sim 2m_{\tilde{q}} \qquad \langle E_{\perp j} \rangle \sim m_{\tilde{q}}/4 \qquad \langle p_{\perp \tilde{\chi}} \rangle \sim m_{\tilde{q}}$$

- gluino pair production: $m_{\tilde{g}}|_{\text{MSSM}} = M_\sigma|_{\text{hybrid model}}$

$$\langle E_{\perp j}^{tot} \rangle \sim 2m_{\tilde{q}} \qquad \langle E_{\perp j} \rangle \sim m_{\tilde{q}}/2 \qquad \langle p_{\perp \tilde{\chi}} \rangle \sim \sqrt{2}m_{\tilde{q}}$$

Phenomenology: Signatures II

$M_{\sigma/\tilde{g}}$	2σ		$2\tilde{g}$		2σ	$2\tilde{g}$
	$\langle E_{\perp j}^{tot}\rangle$	$\langle E_{\perp j}\rangle$	$\langle E_{\perp j}^{tot}\rangle$	$\langle E_{\perp j}\rangle$	$\langle p_{\perp\tilde{\chi}}\rangle$	$\langle p_{\perp\tilde{\chi}}\rangle$
1.50 TeV	1.67	0.21	1.67	0.42	0.45	0.65
0.75 TeV	0.91	0.11	0.93	0.23	0.22	0.31
$M_\sigma = 2\,M_{\tilde{g}} = 8/3\,M_{\tilde{q}} = 15\,M_{\tilde{\chi}}$						

Other interesting final states:

- $pp \to \tilde{t}_1\tilde{t}_1\tilde{t}_1^*\tilde{t}_1^*$ if $m_{\tilde{q}} \lesssim m_{\tilde{g}}$ and L/R mixing significant in stop sector
- $pp \to \tilde{q}\tilde{q}^*\tilde{g}\tilde{g}$ if $M_\sigma > 2m_{\tilde{g}} \gtrsim 2m_{\tilde{q}}$
- $pp \to tt\bar{t}\bar{t}$ if two-body decays kinematically excluded, kinematic reconstruction of M_σ

Summary

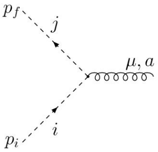
- Alternative $N=1/N=2$ realisation discussed
- Dirac gluinos and color-octet scalars, sgluons
- Spectacular signatures distinctly different from MSSM
  - Multi-jet final states with large missing transverse momentum
  - Four top quarks
  - If L/R squark mass splitting large, single sgluon production sizable
- Simplified discussion with pure Dirac gluinos and degenerate real and imaginary components of sgluon field. Relaxing theses assumptions would not change gross features.

Backup

- Feynman rules
- Formulae for decay widths
- Sgluon pair production cross sections
- Decay chains and estimates
- Monte Carlo: Jet transverse momenta

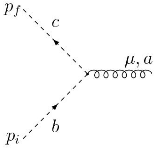
Feynman rules

Gluon-Squark-Squark



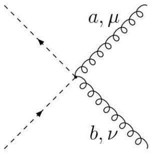
$$= -ig_s \left(\frac{\lambda^a}{2}\right)_{ji} (p_i + p_f)_\mu$$

Gluon-Sgluon-Sgluon



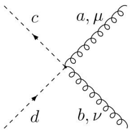
$$= -ig_s\, f^{abc} (p_i + p_f)_\mu$$

Gluon-Gluon-Squark-Squark



$$= i\, g_s^2 \left\{\frac{\lambda^a}{2}, \frac{\lambda^b}{2}\right\} g_{\mu\nu}$$

Gluon-Gluon-Sgluon-Sgluon



$$= i\, g_s^2 \left(f^{eac} f^{ebd} + f^{ead} f^{ebc}\right) g_{\mu\nu}$$

Decay widths - Tree level

$$\Gamma(\sigma \to \tilde{g}_D \bar{\tilde{g}}_D) = \frac{3\alpha_s M_\sigma}{4} \beta_{\tilde{g}} (1 + \beta_{\tilde{g}}^2)$$
$$\Gamma(\sigma \to \tilde{q}_a \tilde{q}_a^*) = \frac{\alpha_s}{4} \frac{|M_3^D|^2}{M_\sigma} \beta_{\tilde{q}_a} \,, \quad (a = L, R)$$

Non-trivial $\tilde{q}_L - \tilde{q}_R$ mixing: $\tilde{q}_1 = \cos\theta_{\tilde{q}} \tilde{q}_L + \sin\theta_{\tilde{q}} \tilde{q}_R$

$\tilde{q}_1 \tilde{q}_1^*$ and $\tilde{q}_2 \tilde{q}_2^*$: contribution suppressed by $\cos^2(2\theta_{\tilde{q}})$

$\tilde{q}_1 \tilde{q}_2^*$ and $\tilde{q}_2 \tilde{q}_1^*$: contribution suppressed by $\sin^2(2\theta_{\tilde{q}})$ and

$$\beta_{\tilde{q}_a} \to \lambda^{1/2}(1, m_{\tilde{q}_1}^2/M_\sigma^2, m_{\tilde{q}_2}^2/M_\sigma^2)$$

Decay widths - Loop induced I

$$\Gamma(\sigma \to gg) = \frac{5\alpha_s^3}{384\pi^2} \frac{|M_3^D|^2}{M_\sigma} \left| \sum_q \left[\tau_{\tilde{q}_L} f(\tau_{\tilde{q}_L}) - \tau_{\tilde{q}_R} f(\tau_{\tilde{q}_R})\right] \right|^2 ,$$

with $\tau_{\tilde{q}_{L,R}} = 4m^2_{\tilde{q}_{L,R}}/M_\sigma^2$ and

$$f(\tau) = \begin{cases} \left[\sin^{-1}\left(\frac{1}{\sqrt{\tau}}\right)\right]^2 & \text{for } \tau \geq 1\,, \\ -\frac{1}{4}\left[\ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \text{for } \tau < 1\,. \end{cases}$$

Non-trivial $\tilde{q}_L - \tilde{q}_R$ mixing: $\tilde{q}_1 = \cos\theta_{\tilde{q}}\tilde{q}_L + \sin\theta_{\tilde{q}}\tilde{q}_R$

$L, R \to 1, 2$: contribution suppressed by $\cos^2(2\theta_{\tilde{q}})$ in $|...|^2$

Decay widths - Loop induced II

$$\Gamma(\sigma \to q\bar{q}) = \frac{9\alpha_s^3}{128\pi^2}\frac{|M_3^D|^2 m_q^2}{M_\sigma}\,\beta_q\left[\left(M_\sigma^2 - 4m_q^2\right)|\mathcal{I}_S|^2 + M_\sigma^2\,|\mathcal{I}_P|^2\right]$$

$$\begin{aligned}
\mathcal{I}_S &= \int_0^1 dx \int_0^{1-x} dy \left\{(1-x-y)\left(\frac{1}{C_L} - \frac{1}{C_R}\right) + \frac{1}{9}(x+y)\left(\frac{1}{D_L} - \frac{1}{D_R}\right)\right\} \\
\mathcal{I}_P &= \int_0^1 dx \int_0^{1-x} dy \left(\frac{1}{C_L} - \frac{1}{C_R}\right) \\
C_a &= (x+y)|M_3^D|^2 + (1-x-y)m_{\tilde{q}_a}^2 - xyM_\sigma^2 - (x+y)(1-x-y)m_q^2 \\
D_a &= (1-x-y)|M_3^D|^2 + (x+y)m_{\tilde{q}_a}^2 - xyM_\sigma^2 - (x+y)(1-x-y)m_q^2
\end{aligned}$$

Non-trivial $\tilde{q}_L - \tilde{q}_R$ mixing: $\tilde{q}_1 = \cos\theta_{\tilde{q}}\tilde{q}_L + \sin\theta_{\tilde{q}}\tilde{q}_R$

$L, R \to 1, 2$: contribution suppressed by $\cos^2(2\theta_{\tilde{q}})$ in $|...|^2$

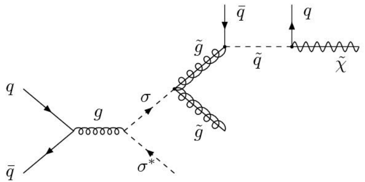
Sgluon pair production cross sections

$$\sigma[q\bar{q} \to \sigma\sigma^*] = \tfrac{4\pi\alpha_s^2}{9s}\,\beta_\sigma^3$$

$$\sigma[gg \to \sigma\sigma^*] = \frac{15\pi\alpha_s^2\beta_\sigma}{8s}\left[1 + \frac{34}{5}\,\frac{M_\sigma^2}{s} - \frac{24}{5}\left(1 - \frac{M_\sigma^2}{s}\right)\frac{M_\sigma^2}{s}\,\frac{1}{\beta_\sigma}\log\left(\frac{1+\beta_\sigma}{1-\beta_\sigma}\right)\right]$$

Decay chains and estimates

Sgluon pair production

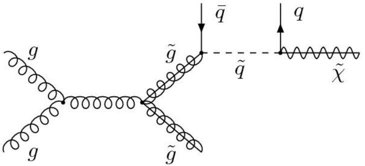


$M_\sigma \simeq 2m_{\tilde{g}} \simeq 2m_{\tilde{q}} \gg m_{\tilde{\chi}_1^0}$

$p_{\perp\bar{q}} = 0,\ p_{\perp q} = m_{\tilde{q}}/2,\ p_{\perp\tilde{\chi}} = m_{\tilde{q}}/2$

$$\begin{aligned} \langle E_{\perp j}^{tot} \rangle &= 4 \cdot m_{\tilde{q}}/2 = 2m_{\tilde{q}} \\ \langle E_{\perp j} \rangle &= 1/8 \cdot m_{\tilde{q}}/2 = m_{\tilde{q}}/4 \\ \langle p_{\perp\tilde{\chi}} \rangle &= \sqrt{4 \cdot (m_{\tilde{q}}/2)^2} = m_{\tilde{q}} \end{aligned}$$

Gluino pair production



$$\begin{aligned} \langle E_{\perp j}^{tot} \rangle &= 2 \cdot m_{\tilde{q}}/2 = m_{\tilde{q}} \\ \langle E_{\perp j} \rangle &= 1/4 \cdot m_{\tilde{q}} = m_{\tilde{q}}/4 \\ \langle p_{\perp\tilde{\chi}} \rangle &= \sqrt{2 \cdot (m_{\tilde{q}}/2)^2} = m_{\tilde{q}}/\sqrt{2} \end{aligned}$$

$m_{\tilde{g}}|_{\text{MSSM}} = M_\sigma|_{\text{hybrid model}}$

$\langle E_{\perp j}^{tot} \rangle = 2m_{\tilde{q}},\ \langle E_{\perp j} \rangle = m_{\tilde{q}}/2$

$\langle p_{\perp\tilde{\chi}} \rangle = \sqrt{2}m_{\tilde{q}}$

Monte Carlo: Jet transverse momenta

$M_{\sigma/\tilde{g}}$		2σ		$2\tilde{g}$		2σ	$2\tilde{g}$
		$\langle E_{\perp j}^{tot} \rangle$	$\langle E_{\perp j} \rangle$	$\langle E_{\perp j}^{tot} \rangle$	$\langle E_{\perp j} \rangle$	$\langle p_{\perp \tilde{\chi}} \rangle$	$\langle p_{\perp \tilde{\chi}} \rangle$
1.50 TeV	[tot]	1.67	0.21	1.67	0.42	0.45	0.65
	[high]		0.27		0.53		
	[low]		0.15		0.31		
0.75 TeV	[tot]	0.91	0.11	0.93	0.23	0.22	0.31
	[high]		0.14		0.29		
	[low]		0.08		0.17		
$M_\sigma = 2\, M_{\tilde{g}} = 8/3\, M_{\tilde{q}} = 15\, M_{\tilde{\chi}}$							