

# From the LHC to Future Colliders

9-27 February 2009

## Color-octet scalars at the LHC

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Based on: S.Y. Choi, M. Drees, JK, J.M. Kim, E. Popena, P.M. Zerwas  
Phys.Lett.B 672 ( arXiv:0812.3586)

# Motivation

Supersymmetry – the most elegant and respected proposition for the beyond SM physics

But SUSY must be broken, and the origin of its breaking is still unknown

Phenomenologically add soft SUSY breaking terms to

- keep unseen superpartners out of experimental reach
- retaining renormalisability
- and maintaining perturbatively stable hierarchy of scales

Experimental constraints, mainly from flavor and Higgs physics, limit the allowed parameter space and play an increasingly restrictive role in building models of SUSY breaking

However, successes of supersymmetry do not rest on its minimal realisation

In fact, non-minimal realisations may ameliorate the SUSY flavor problem

for example, Dirac gauginos (in contrast to Majorana in the MSSM) forbid some couplings and often lead to additional suppression in flavor-changing processes from gauginos running in the loops.

[Kribs, Poppitz, Weiner 0712.2039](#)

[Blechman, Ng 0803.3811](#)

Dirac gauginos offer an attractive alternate formulation with distinct phenomenology

Here we consider the scalar partners of the Dirac gluino – sgluons

[Plehn, Tait 0810.3919](#)

[Kane, Petrov, Shao, Wang 0805.1397](#)

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# Introduction to N=1/N=2 hybrid model

In the MSSM gluinos are Majorana particles with two degrees of freedom to match gluons in a vector super-multiplet.

To provide two additional degrees, the vector super-multiplet can be paired with an additional chiral super-multiplet to a vector hyper-multiplet of N=2 supersymmetry.

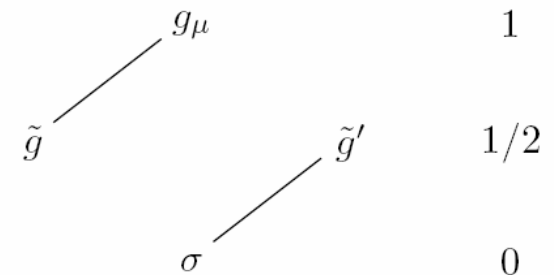
Fayet 1976

Alvarez-Gaume, Hassan hep-ph/9701069

Fox, Nelson, Weiner hep-ph/0206102

Schematically, the N=2 QCD hyper-multiplet can be decomposed into the usual N=1 color-octet:

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



N=2 mirror (s)fermions are assumed to be heavy to avoid chirality problems

# Hyper-QCD sector

Choi, Drees, Freitas, Zerwas 0808.2410

old and new gluinos are coupled minimally to the gluon field

$$\mathcal{L}_{\text{QCD}}^{g\tilde{g}\tilde{g}} = g_s \text{Tr} (\bar{\tilde{g}} \gamma^\mu [g_\mu, \tilde{g}] + \bar{\tilde{g}}' \gamma^\mu [g_\mu, \tilde{g}'])$$

quarks and squarks interact only with old gluinos

$$\mathcal{L}_{\text{QCD}}^{q\tilde{q}\tilde{g}} = -g_s [\bar{q}_L \tilde{g} \tilde{q}_L - \bar{q}_R \tilde{g} \tilde{q}_R + \text{h.c.}]$$

gluino mass term

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

The mass matrix  $\mathcal{M}_g = \begin{pmatrix} M_3' & M_3^D \\ M_3^D & M_3 \end{pmatrix}$  gives rise to two

Majorana mass eigenstates

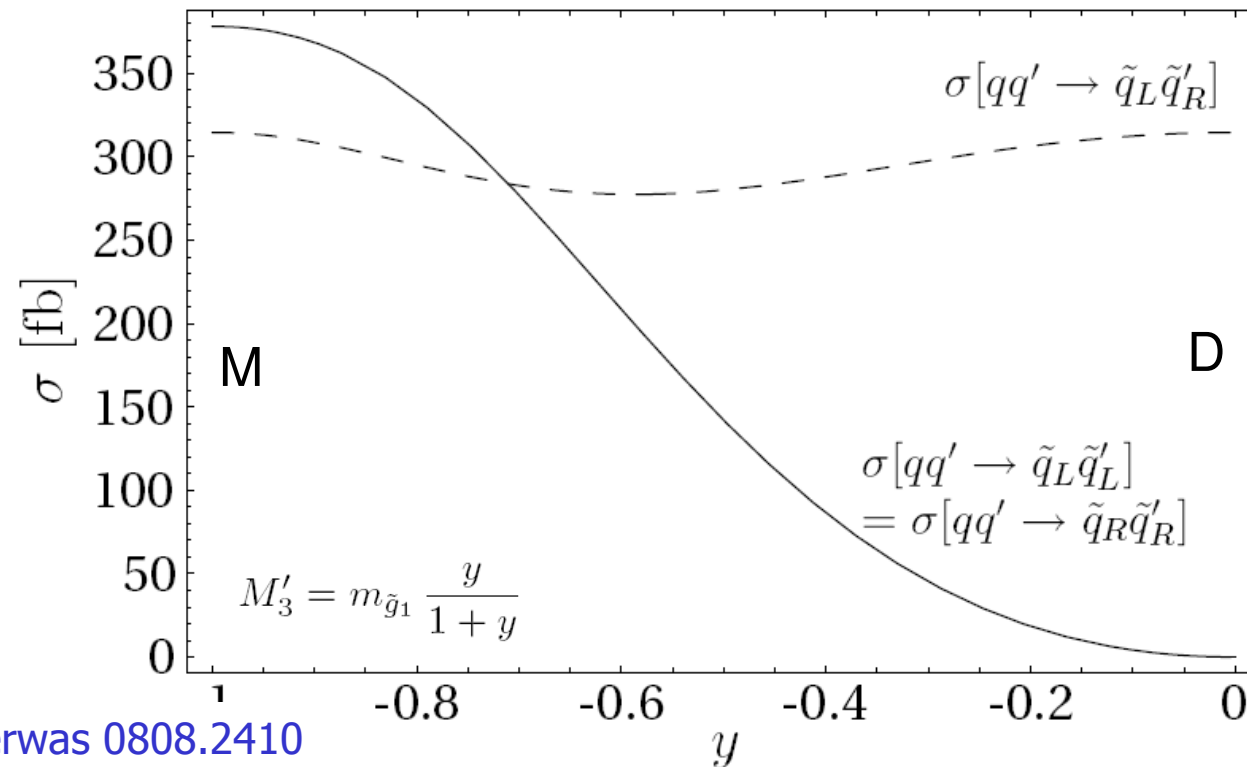
Limiting cases:  $\left\{ \begin{array}{l} \text{for } M_3' \rightarrow \pm\infty, \text{ standard MSSM gluino is recovered} \\ \text{for } M_3 = M_3' = 0, \text{ Dirac gluino } g_D = \tilde{g}_R + \tilde{g}'_L \\ \text{with mass } |M_3^D| \end{array} \right.$

Dirac gluinos: characteristically different from Majorana, e.g.

$$\text{Majorana : } \sigma[qq' \rightarrow \tilde{q}_L \tilde{q}'_L] = \sigma[qq' \rightarrow \tilde{q}_R \tilde{q}'_R] = \frac{2\pi\alpha_s^2}{9} \frac{\beta m_{\tilde{g}_1}^2}{sm_{\tilde{g}_1}^2 + (m_{\tilde{g}_1}^2 - m_{\tilde{q}}^2)^2}$$

$$\text{Dirac : } \sigma[qq' \rightarrow \tilde{q}_L \tilde{q}'_L] = \sigma[qq' \rightarrow \tilde{q}_R \tilde{q}'_R] = 0$$

$$\text{Majorana = Dirac : } \sigma[qq' \rightarrow \tilde{q}_L \tilde{q}'_R] = \frac{2\pi\alpha_s^2}{9s^2} [(s + 2(m_{\tilde{g}_1}^2 - m_{\tilde{q}}^2))L_1 - 2\beta s],$$



# Color-octet scalars: sgluons

## Tree-level couplings

- $\sigma\sigma^*g$  and  $\sigma\sigma^*gg$  couplings as required by gauge invariance
- gluinos  $-\sqrt{2}i g_s f^{abc} \overline{\tilde{g}_{DL}^a} \tilde{g}_{DR}^b \sigma^c + \text{h.c.}$
- Dirac gluino mass => trilinear scalar couplings to squarks

$$-g_s M_3^D \left[ \sigma^a \frac{\lambda_{ij}^a}{\sqrt{2}} \sum_q (\tilde{q}_{Li}^* \tilde{q}_{Lj} - \tilde{q}_{Ri}^* \tilde{q}_{Rj}) + \text{h.c.} \right]$$

vanish for degenerate L/R squarks

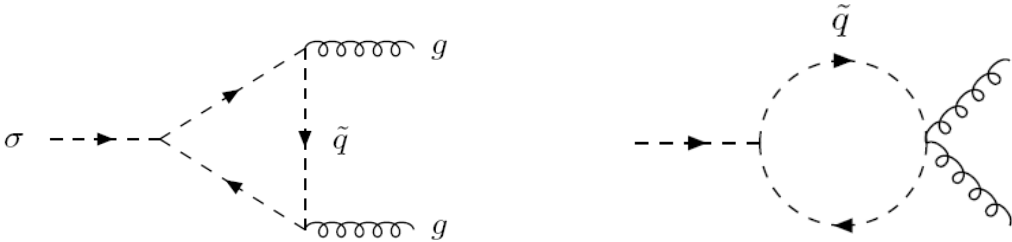


Although R-parity even, single sgluon cannot be produced in pp collisions at tree-level

# Color-octet scalars: sgluons

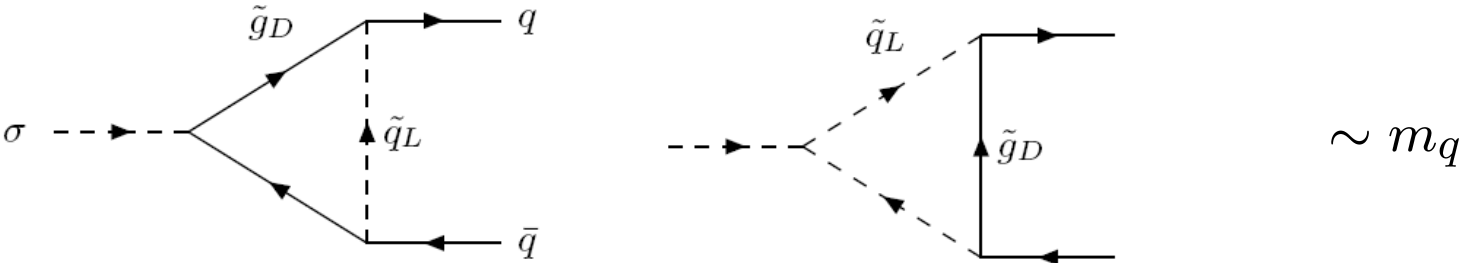
## One loop couplings

- to a gluon pair through diagrams with squarks



gluino loops vanish in  $\sigma gg, \sigma ggg, \dots$

- to a quark pair through diagrams with squark/gluino





# Phenomenology at the LHC

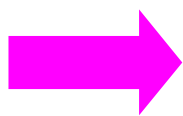
 Sgluon decays

 Sgluon production at the LHC

# Tree-level sgluon decays

At tree level sgluons can decay into:

- a pair of Dirac gluinos  $\Gamma[\sigma \rightarrow \tilde{g}_D \tilde{g}_D] = \frac{3\alpha_s M_\sigma}{4} \beta_{\tilde{g}} (1 + \beta_{\tilde{g}}^2)$
- a pair of squarks  $\Gamma[\sigma \rightarrow \tilde{q}_a \tilde{q}_a^*] = \frac{\alpha_s |M_3^D|^2}{4 M_\sigma} \beta_{\tilde{q}_a}$



$$\begin{aligned} \sigma &\rightarrow \tilde{g}\tilde{g} \rightarrow qq\tilde{q}\tilde{q} \rightarrow qqqq + \tilde{\chi}\tilde{\chi}, \\ \sigma &\rightarrow \tilde{q}\tilde{q} \rightarrow qq + \tilde{\chi}\tilde{\chi}, \end{aligned}$$

where  $\tilde{\chi}$  chargino or neutralino

For  $\sigma$  pair production at the LHC a spectacular signature

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

# Loop-induced sgluon decays

Loop-induced couplings generate decays into:

- a pair of gluons

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

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

$$\tau_{\tilde{q}_{L,R}} = 4m_{\tilde{q}_{L,R}}^2 / M_\sigma^2$$
- a pair of quarks

$$\Gamma(\sigma \rightarrow q\bar{q}) = \frac{9\alpha_s^2}{28\pi^2} \frac{|M_3^D|^2 m_q^2}{M_\sigma} \beta_q [(M_\sigma^2 - 4m_q^2) |\mathcal{I}_S|^2 + M_\sigma^2 |\mathcal{I}_P|^2]$$

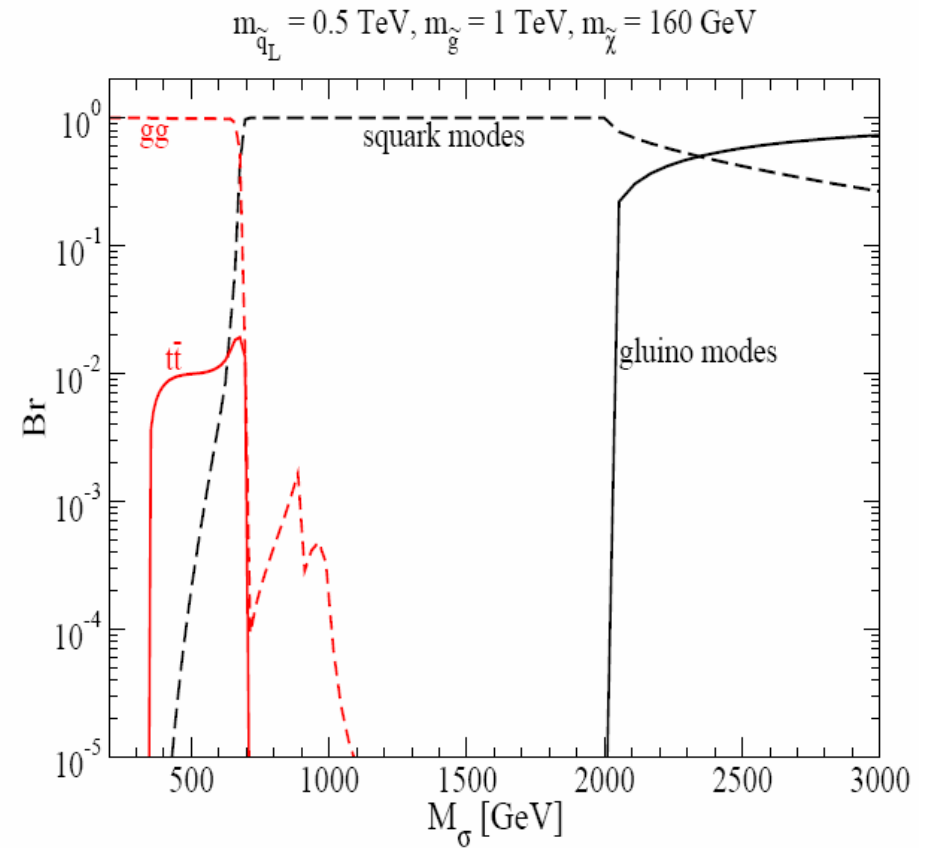
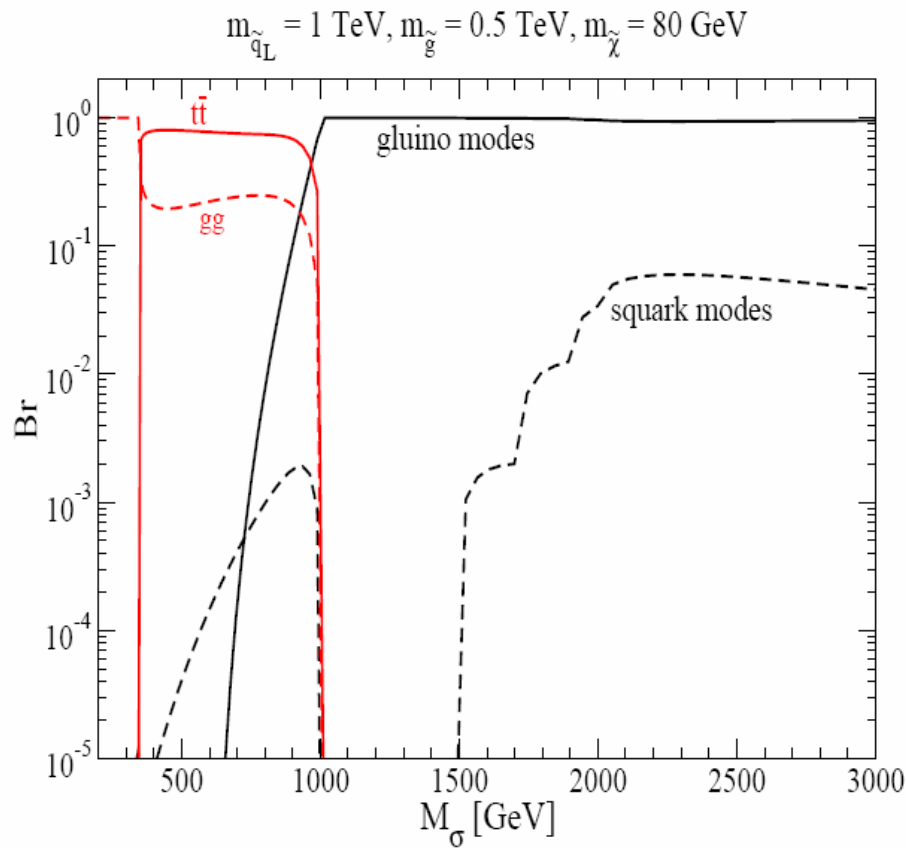
$$\mathcal{I}_P = C_{0L} - C_{0R}, \quad C_{0L,R} \equiv C_0(|M_3^D|, m_{\tilde{q}_{L,R}}, |M_3^D|; m_q^2, m_q^2, M_\sigma^2)$$

Both channels vanish for degenerate L/R squarks

For  $\sigma$  pair production at the LHC a spectacular signature

$$pp \rightarrow t\bar{t}t\bar{t}$$

# Branching ratios for sgluon decays



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

$$X_t = m_{\tilde{q}_L}$$

# Sgluon production at the LHC

■ **Single sgluon production:** resonance formation

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

In principle reconstructible in loop-induced decay modes

$$\sigma \rightarrow t\bar{t} \rightarrow b\bar{b}W^+W^-$$

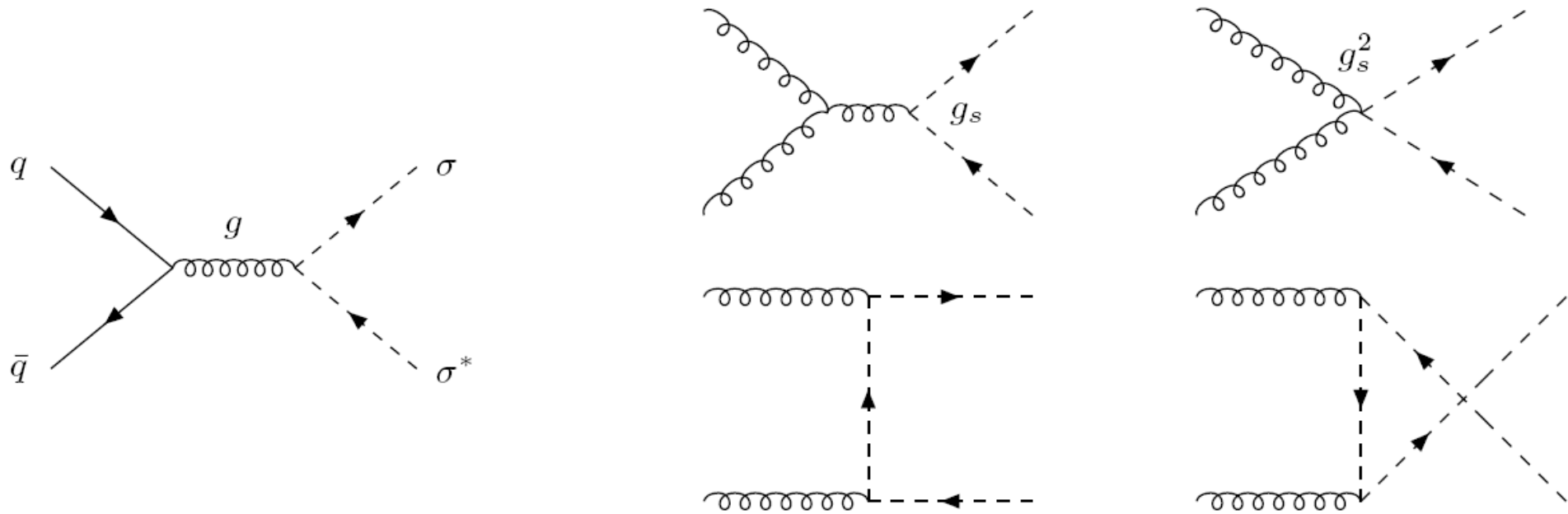
$$\sigma \rightarrow gg.$$

But

- large background in  $gg$  decay mode
- cannot have simultaneously large cross section and large  $t\bar{t}$  decay mode

# Sgluon production at the LHC

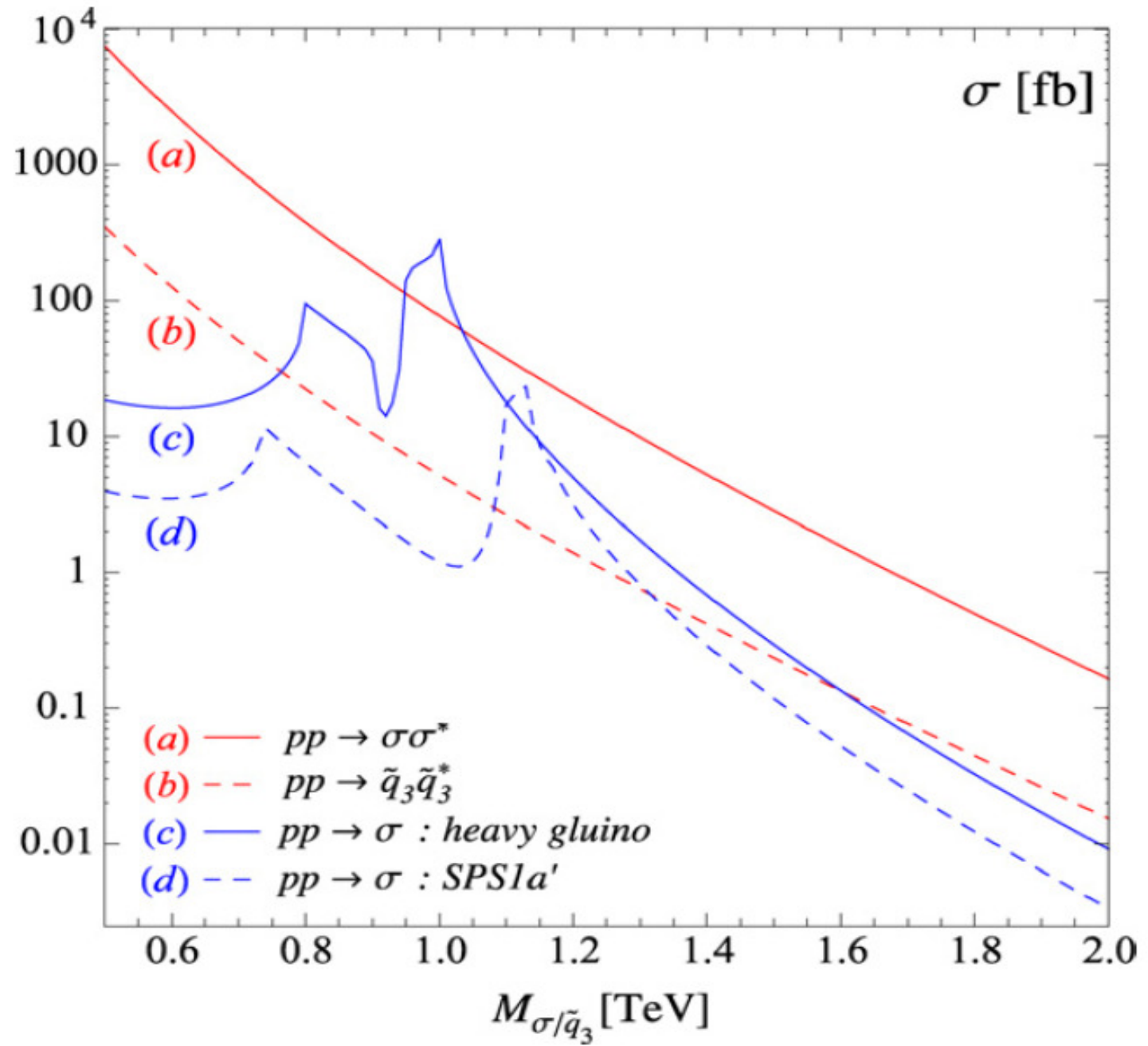
## 📖 Sgluon pair production



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

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

# Sgluon production in pp collisions



# Signatures:

Most spectacular

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

giving  $pp \rightarrow 8 \text{ jets} + 4 \text{ LSP}'s$

high sphericity  
large missing  $p_T$

$M_{\sigma/\tilde{g}}$	$2\sigma$		$2\tilde{g}$		$2\sigma$	$2\tilde{g}$
	$\langle E_{\perp j}^{tot} \rangle$	$\langle E_{\perp j} \rangle$	$\langle E_{\perp j}^{tot} \rangle$	$\langle E_{\perp j} \rangle$	$\langle p_{\perp \chi} \rangle$	$\langle p_{\perp \chi} \rangle$
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		
$M_{\sigma} = 2 M_{\tilde{g}} = 8/3 M_{\tilde{q}} = 15 M_{\chi}$						

$pp \rightarrow t\bar{t}t\bar{t}$  if  $m_{\tilde{q}} \lesssim m_{\tilde{g}}$  and L/R mixing significant in stop sector

$pp \rightarrow t\bar{t}c\bar{c}$  if flavor mixing in the up-type squark sector



# Summary

- ❏ SUSY - best scenario for physics beyond SM
- ❏ Alternative  $N=1/N=2$  realisation discussed
- ❏ Dirac gluinos and color-octet scalars
- ❏ Spectacular signatures distinctly different from MSSM
  - ❏ Multi-jet final states with high sphericity
  - ❏ Four top quarks
  - ❏ If L/R squark mass splitting large, single sgluon production sizable. Could sgluon be reconstructed?
- ❏ Simplified discussion with pure Dirac gluinos and degenerate real and imaginary components of color-octet scalar field.  
Relaxing these assumptions would not change gross features.