CRACOW EPIPHANY CONFERENCE
ON HADRON INTERACTIONS
AT THE DAWN OF THE LHC

Dedicated to the memory of Jan Kwieciński

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Color-octet scalars at the LHC

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Outline

- Motivation
- Introduction to N=1/N=2 hybrid model
  - the gluino sector
  - the color-octet scalars (sgluons)
- Phenomenology of sgluons at the LHC
  - decays
  - production at the LHC
- Summary

Based on: Choi, Drees, JK, Kim, Popenda, Zerwas - arXiv:0812.3586

Motivation

This year the LHC experiments will start taking data

- the outcome far more important than any other in the past
- all future projects: ILC, superB, super..., depend on LHC discoveries
- huge responsibility to provide quick and reliable answers

The biggest question: the nature of the electroweak symmetry breaking

In the SM: Higgs mechanism ⟹ Higgs particle – the only missing piece of the SM

Although very successful, the SM is not the ultimate theory

- the Higgs sector unnatural
  why EW scale << M_{Pl} – the hierarchy problem
- matter-antimatter asymmetry
- dark matter/energy

→ Hints for new physics at a TeV scale

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

Motivation for (weak-scale) SUSY

- naturalness => new TeV scale that cuts off quadratically divergent contributions from SM particles
- predicts a light Higgs M_h< 130 GeV

  as suggested by data M_h< 180 GeV
- Predicts gauge coupling unification
- provides a dark matter candidate: neutralino, sneutrino, ..
- introduces new sources of CP violation
- consistent with EW data

In the simplest realisation each SM particle is paired with a sparticle that differs in spin by ½:

- quarks – squarks
- gluons – gluinos
- leptons – sleptons
- Higgses – higgsinos
- .....

But SUSY must be broken, and its origin 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

......

Introduction to N=1/N=2 hybrid model

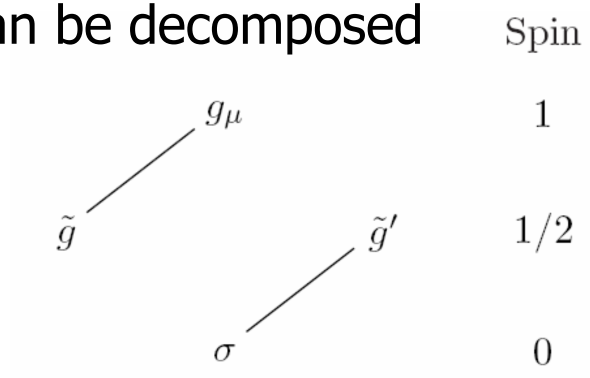
In the MSSM gluinos are Majorana particles with two degrees of freedom to match gluons in a vector super-multiplet.

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

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

quarks and squarks interact only with old gluinos

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

gluino mass term

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

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:

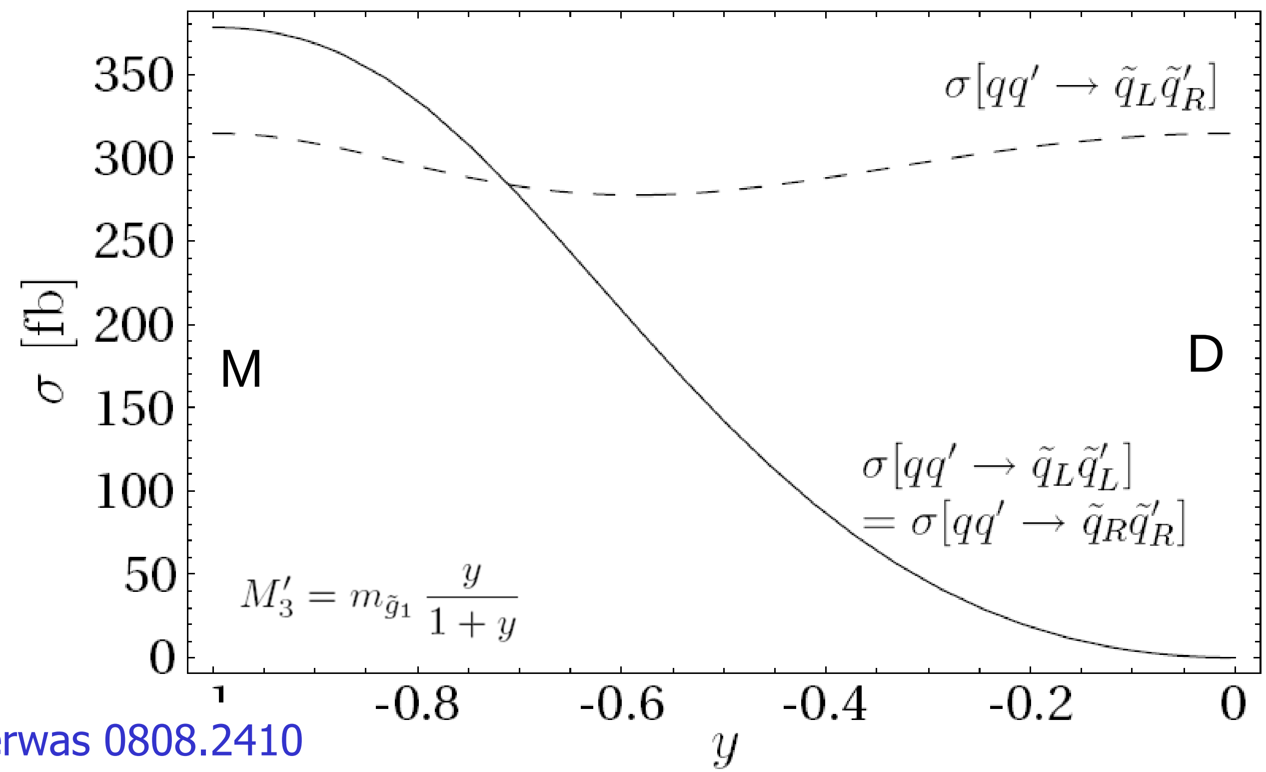
- for $M_3' \to \pm\infty$, standard MSSM gluino is recovered
- for $M_3 = M_3' = 0$, Dirac gluino $g_D = \tilde{g}_R + \tilde{g}'_L$ with mass M_3^D

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

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

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

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



Choi, Drees, Freitas, Zerwas 0808.2410

Color-octet scalars: sgluons

Tree-level couplings to

- gluinos $-\sqrt{2}i\, g_s\, f^{abc}\, \overline{\tilde{g}^a_{DL}}\, \tilde{g}^b_{DR}\, \sigma^c + \mathrm{h.c.}$
- squarks $-\, g_s M_3^D \left[\sigma^a \frac{\lambda^a_{ij}}{\sqrt{2}} \sum_q (\tilde{q}^*_{Li}\tilde{q}_{Lj} - \tilde{q}^*_{Ri}\tilde{q}_{Rj}) + \mathrm{h.c.} \right]$

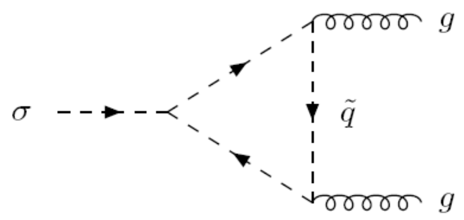
  vanish for degenerate L/R squarks
- and $\sigma\sigma^* g$ and $\sigma\sigma^* gg$ couplings to gluons as required by gauge invariance

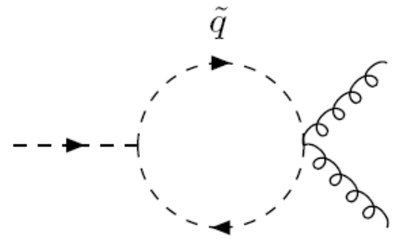
Although R-parity even, single sgluon cannot be produced in pp collisions at tree-level

Color-octet scalars: sgluons

At one loop couplings to

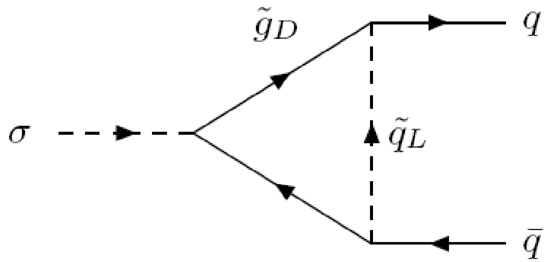
- A gluon pair through diagrams with squarks

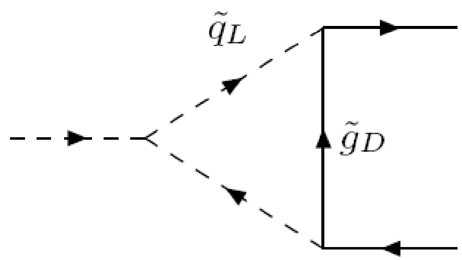




gluino loops vanish in $\sigma gg,\ \sigma ggg,\ \ldots$

- A quark pair through diagrams with squark/gluino





Phenomenology at the LHC

- Sgluon decays
- Sgluon production at the LHC

Tree-level sgluon decays

into:

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

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

$$\sigma \to \tilde{q}\tilde{q} \to qq + \tilde{\chi}\tilde{\chi} ,$$

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

For σ pair production at the LHC a spectacular signature

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

Loop-induced sgluon decays

into:

- A pair of gluons

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

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

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

- A pair of quarks

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

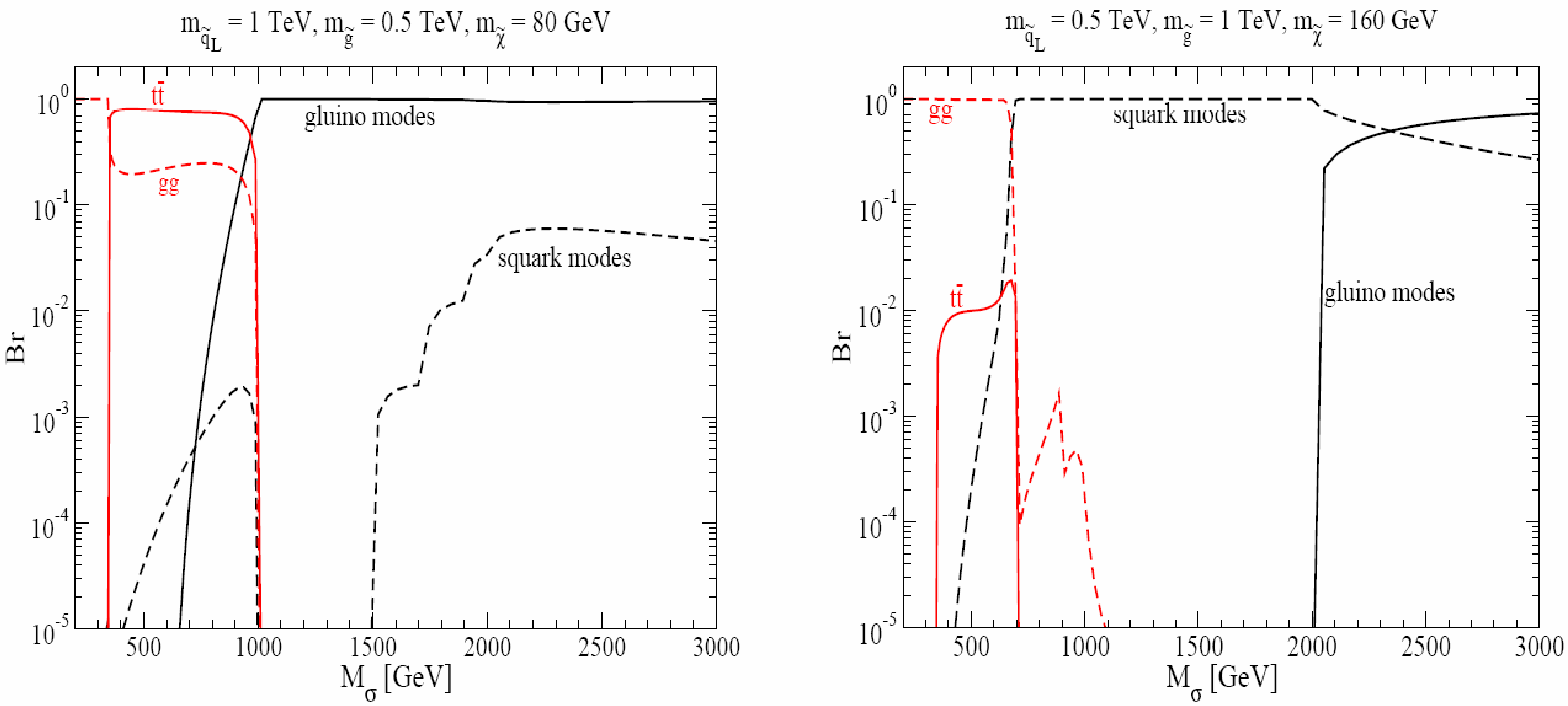
$$\mathcal{I}_P = C_{0L} - C_{0R}, \quad C_{0L,R} \equiv C_0(|M_3^D|, m_{\tilde{q}_{L,R}}, |M_3^D|; m_q^2, m_q^2, M_\sigma^2)$$

Both channels vanish for degenerate L/R squarks

For σ pair production at the LHC a spectacular signature

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

Branching ratios for sgluon decays



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

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

Sgluon production at the LHC

- Single sgluon production

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

In principle reconstructible in loop-induced decay modes

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

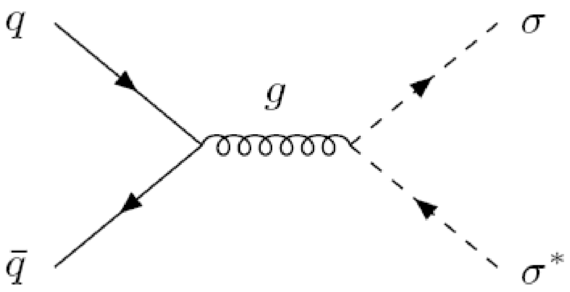
$$\sigma \to gg \,.$$

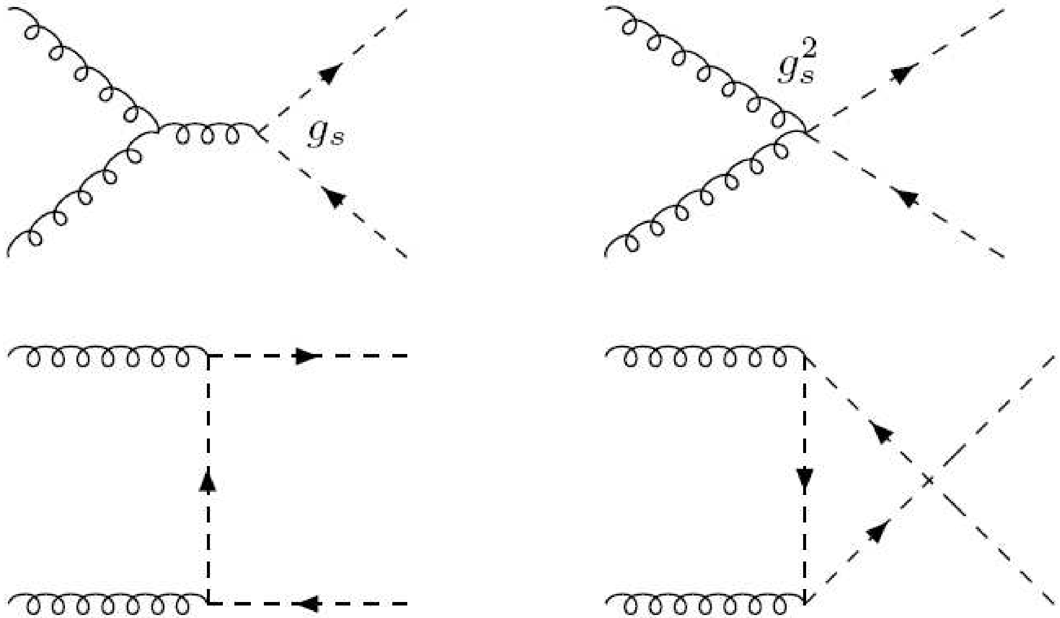
But

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

Sgluon production at the LHC

- Sgluon pair production

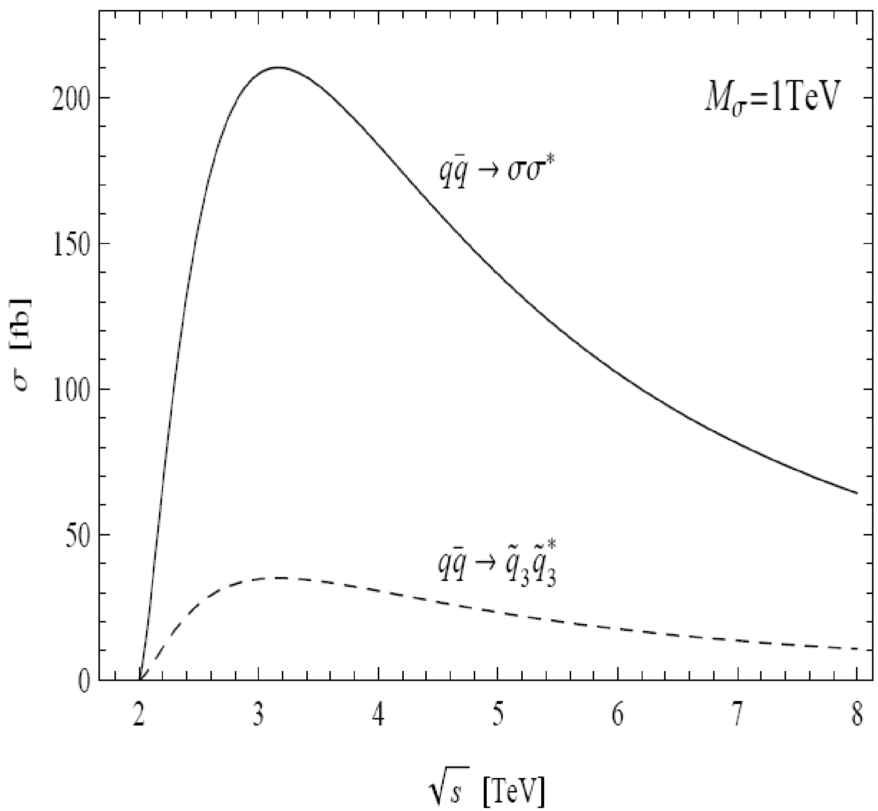


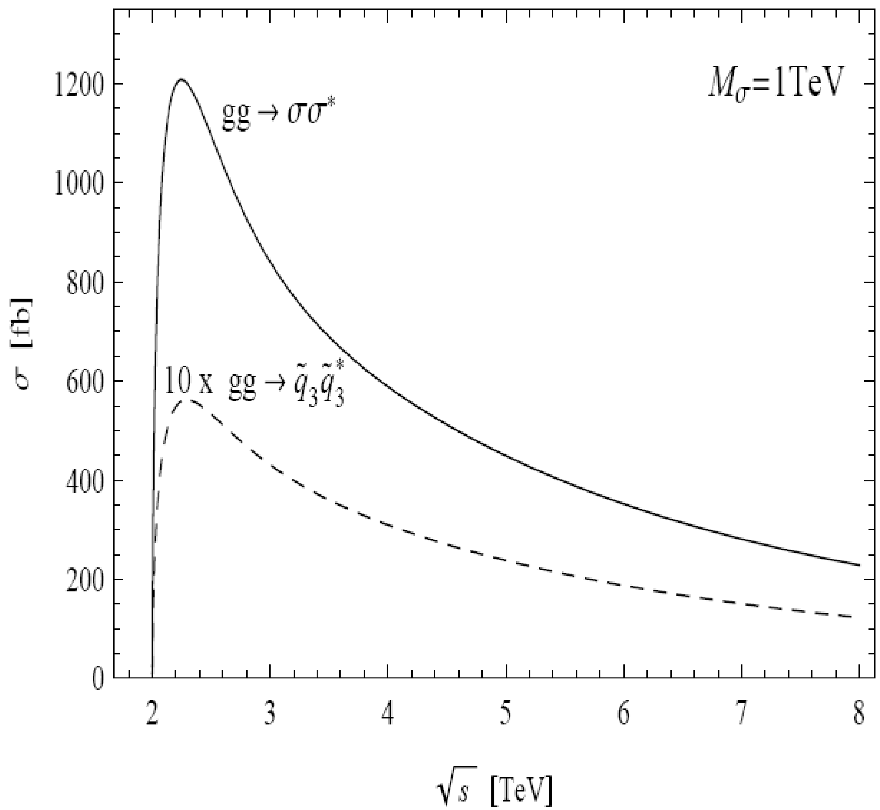


$$\sigma[q\bar{q} \to \sigma\sigma^*] = \frac{4\pi\alpha_s^2}{9s}\,\beta_\sigma^3\,,$$

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

Parton-level cross sections

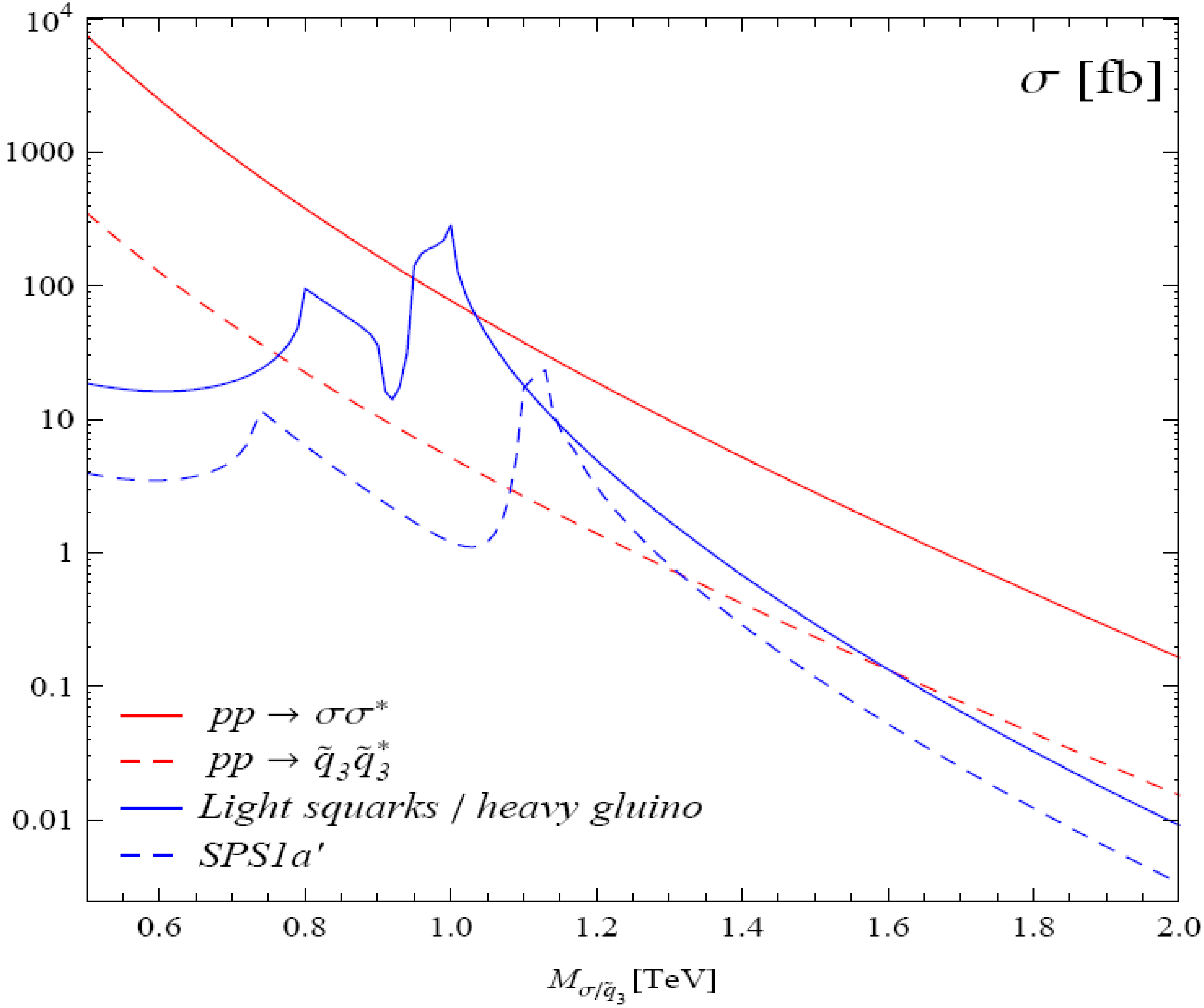




Larger cross section for sgluon-pair production reflects the different strengths of the couplings: octet for sgluons, triplet for squarks, e.g.

$$\frac{\sigma\left[q\bar{q} \longrightarrow \sigma\sigma^*\right]}{\sigma\left[q\bar{q} \longrightarrow \tilde{q}_3\tilde{q}_3^*\right]} = \frac{\mathrm{tr}\left(\frac{\lambda^a}{2}\,\frac{\lambda^b}{2}\right)\,\mathrm{tr}\left(F^a F^b\right)}{\mathrm{tr}\left(\frac{\lambda^a}{2}\,\frac{\lambda^b}{2}\right)\,\mathrm{tr}\left(\frac{\lambda^a}{2}\,\frac{\lambda^b}{2}\right)} = \frac{12}{2} = 6$$

Sgluon production in pp collisions



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Signatures:

- Most spectacular

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

giving $pp \longrightarrow 8\,\mathrm{jets} + 4\,\mathrm{LSP's}$

high sphericity
large missing p_T

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

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

- $pp \longrightarrow t\bar{t}c\bar{c}$ 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.