Skalarne gluony i dirakowskie gluina w LHC

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w oparciu o: S.Y. Choi, M. Drees, JK, J.M. Kim, E. Popenda, P.M. Zerwas
Phys.Lett.B 672 (arXiv:0812.3586)

Plan

- Motywacja
- Wprowadzenie do hybrydowego modelu N=1/N=2 SUSY
  - sector gluinowy
  - sektor skalarnych gluonów (sgluons)
- Fenomenologia w LHC
  - rozpady
  - produkcja
- Podsumowanie

Motivation

This year the LHC experiments will start taking data

- great expectations for new physics
- be ready for unexpected
- all future projects: ILC, superB, super…, will depend on LHC discoveries

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
  as suggested by EW precision data
- 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
- .....

If SUSY particles produced at the LHC, it will be crucial to verify that they are superpartners:

measure their spins, couplings, quantum numbers

For colored superpartners production rates largely determined by the QCD structure – will not depend strongly on other BSM features

If gluinos are seen – Majorana or Dirac ?

Need a model to differentiate

Actually Dirac gauginos might be welcome …..

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

And the Dirac gluinos bring in scalar gluons – **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 N=1 vector super-multiplet

$$W^a_\alpha = \tilde{g}^a_\alpha + D^a \theta_\alpha + (\sigma^{\mu\nu})_\alpha{}^\beta \theta_\beta G^a_{\mu\nu} + \ldots$$

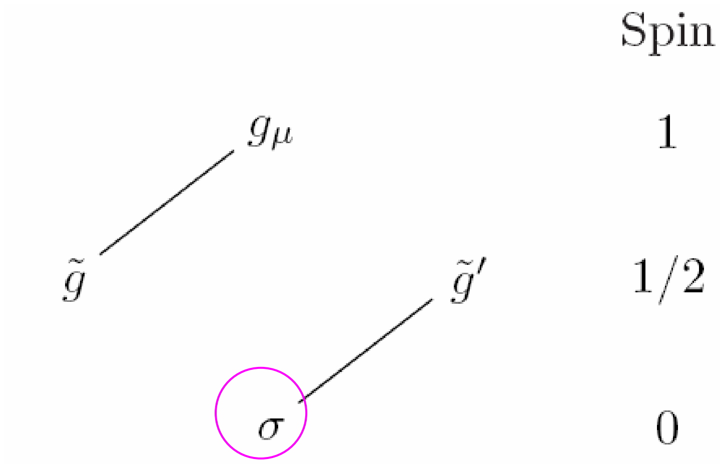
can be paired with an additional N=1 chiral super-multiplet

$$\Phi^a = \sigma^a + \sqrt{2}\theta\, \tilde{g}'^a + \theta\theta\, F^a$$

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:



Sgluons are R-parity even

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

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

$$g_\mu = \frac{1}{\sqrt{2}} g_\mu^a \lambda^a$$

quarks and squarks interact only with old gluinos

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

gluino mass term

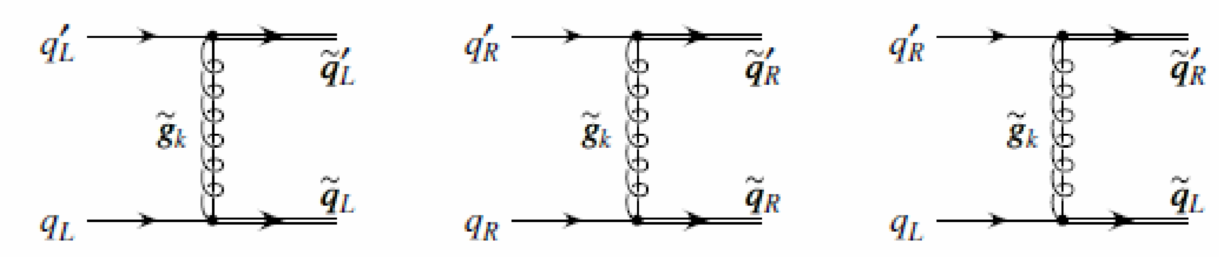
$$\mathcal{L}_{\rm QCD}^{m} = -\frac{1}{2}\left[M_3'\,{\rm Tr}(\overline{\tilde{g}'}\tilde{g}') + M_3\,{\rm Tr}(\overline{\tilde{g}}\tilde{g}) + M_3^D\,{\rm Tr}(\overline{\tilde{g}'}\tilde{g} + \overline{\tilde{g}}\tilde{g}')\right]$$

In the $\tilde{g}', \tilde{g}$ basis, the mass matrix $\mathcal{M}_g = \begin{pmatrix} M_3' & M_3^D \\ M_3^D & M_3 \end{pmatrix}$

It gives rise to two Majorana mass eigenstates

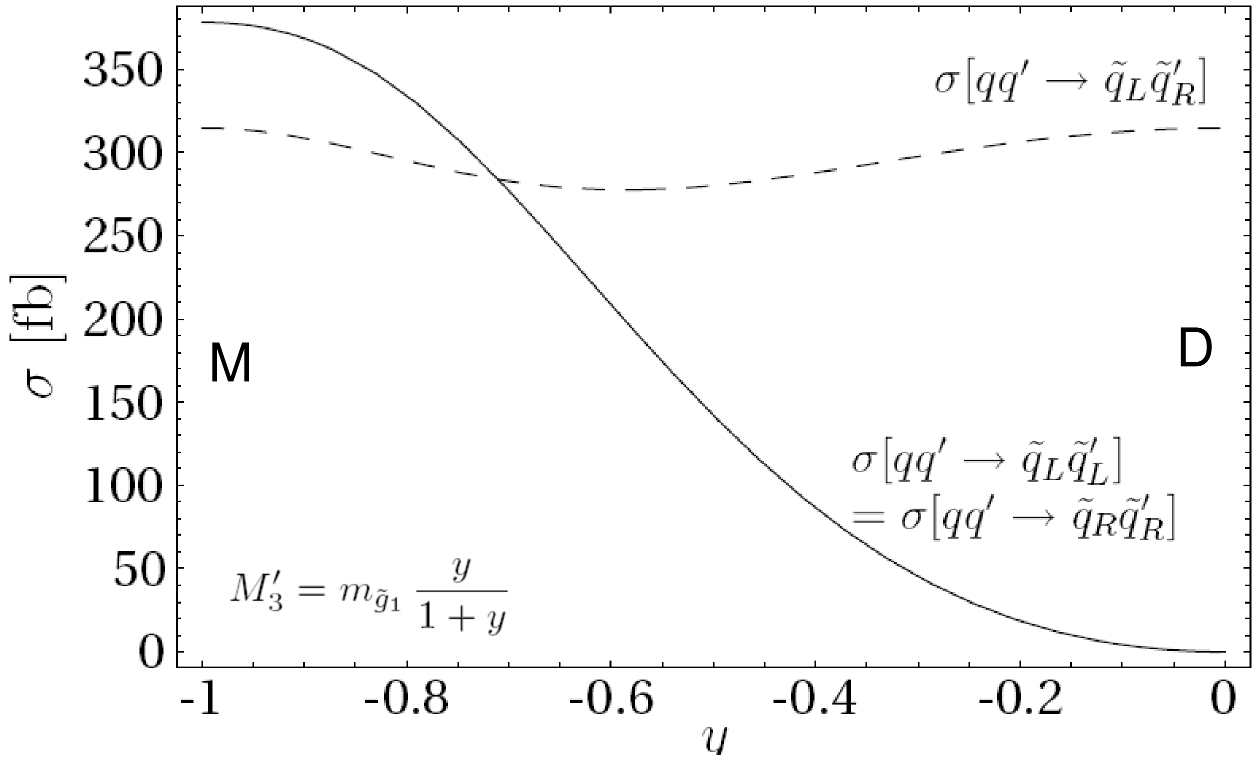
Limiting cases:
- for $M_3' \to \pm\infty$, standard MSSM gluino is recovered
- for $M_3 = M_3' = 0$, Dirac gluino $\tilde{g}_D = \tilde{g}_R + \tilde{g}_L'$ with mass $|M_3^D|$

Dirac gluinos: characteristically different from Majorana, e.g. consider squark pair production:



$$\sigma[qq' \to \tilde{q}_L \tilde{q}'_L] = \sigma[qq' \to \tilde{q}_R \tilde{q}'_R] = \begin{cases} \dfrac{2\pi\alpha_s^2}{9} \dfrac{\beta m_{\tilde{g}1}^2}{s m_{\tilde{g}_1}^2 + (m_{\tilde{g}_1}^2 - m_{\tilde{q}}^2)^2} & \text{for Majorana} \\ 0 & \text{for Dirac} \end{cases}$$

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



$\sqrt{s} = 2000$ GeV

$m_{\tilde{q}} = 500$ GeV

$m_{\tilde{g}1} = 600$ GeV

Choi, Drees, Freitas, Zerwas 0808.2410

Color-octet scalars: sgluons

Tree-level couplings

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

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

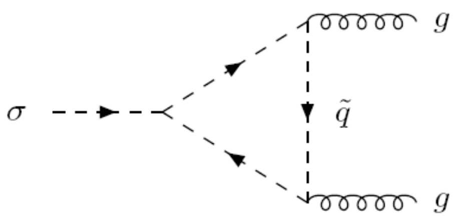
vanish for degenerate L/R squarks

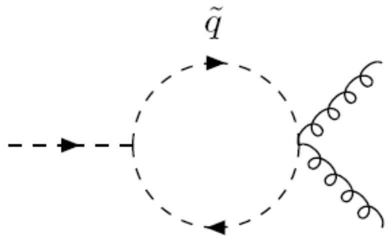
Although R-parity even, single sgluon cannot be produced in pp collisions at tree-level

Color-octet scalars: sgluons

One-loop couplings

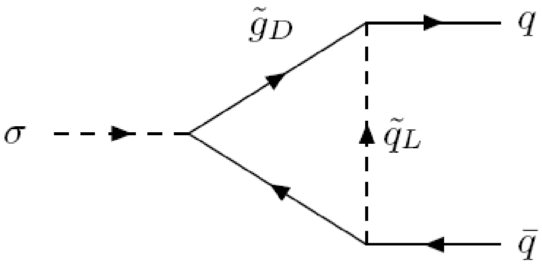
- to a gluon pair through diagrams with squarks

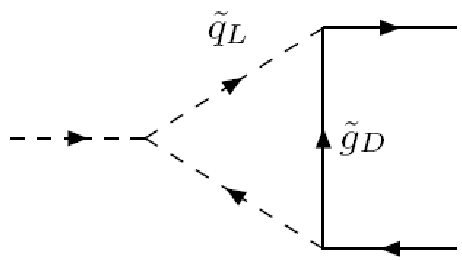




gluino loops vanish in $\sigma gg,\ \sigma ggg,\ \ldots$

- to a quark pair through diagrams with squark/gluino





$\sim m_q$

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 $$\Gamma[\sigma \to \tilde{g}_D \bar{\tilde{g}}_D] = \frac{3\alpha_s M_\sigma}{4} \beta_{\tilde{g}} \, (1 + \beta_{\tilde{g}}^2)$$
- 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

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

Loop-induced sgluon decays

Loop-induced couplings generate decays into:

- a pair of gluons

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

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

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

- a pair of quarks

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

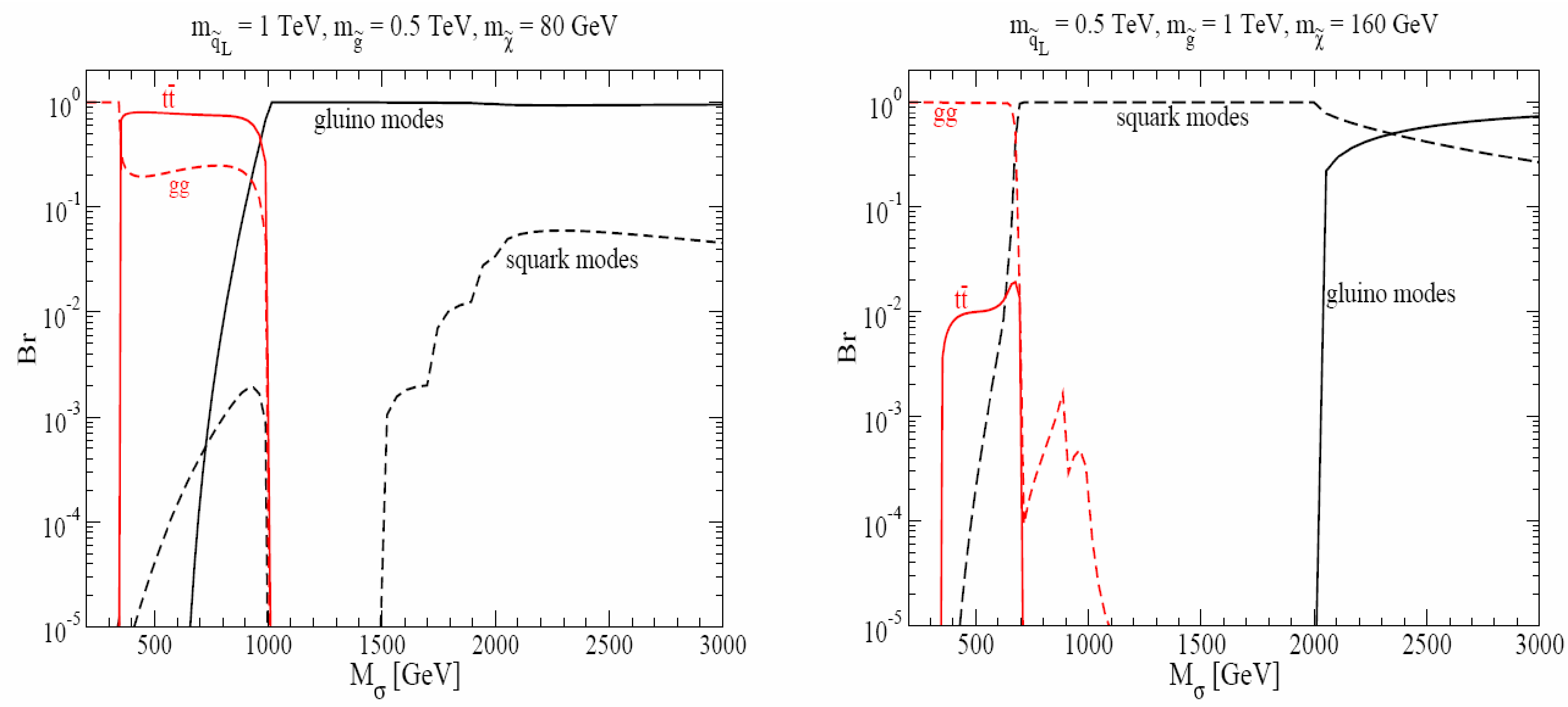
$$\mathcal{I}_P = C_{0L} - C_{0R}, \quad C_{0L,R} \equiv C_0(|M_3^D|, m_{\tilde{q}_{L,R}}, |M_3^D|; m_q^2, m_q^2, M_\sigma^2)$$

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**: resonance formation

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

In principle reconstructible in loop-induced decay modes

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

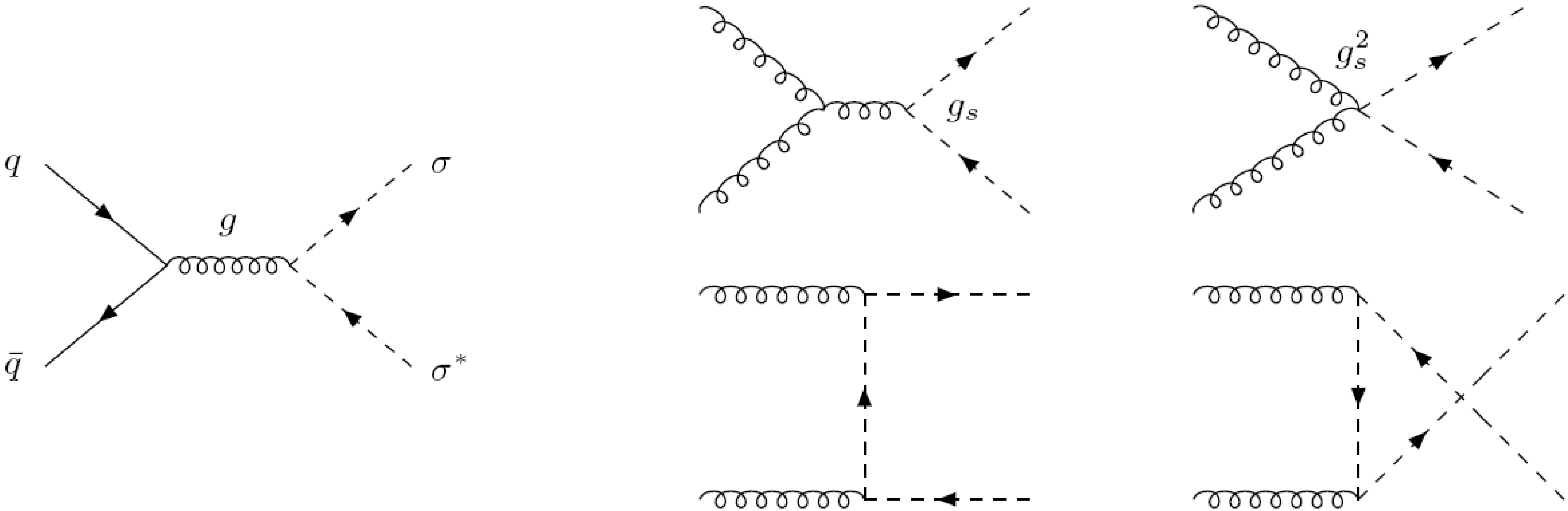
$$\sigma \longrightarrow gg\,.$$

But

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

Sgluon production at the LHC

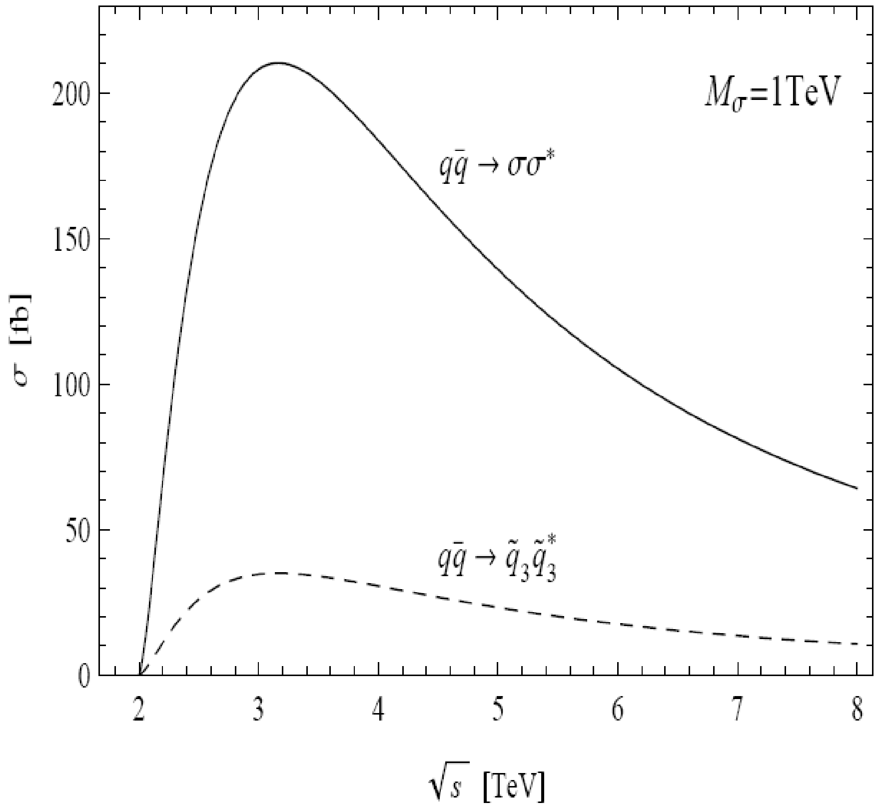
- Sgluon pair production

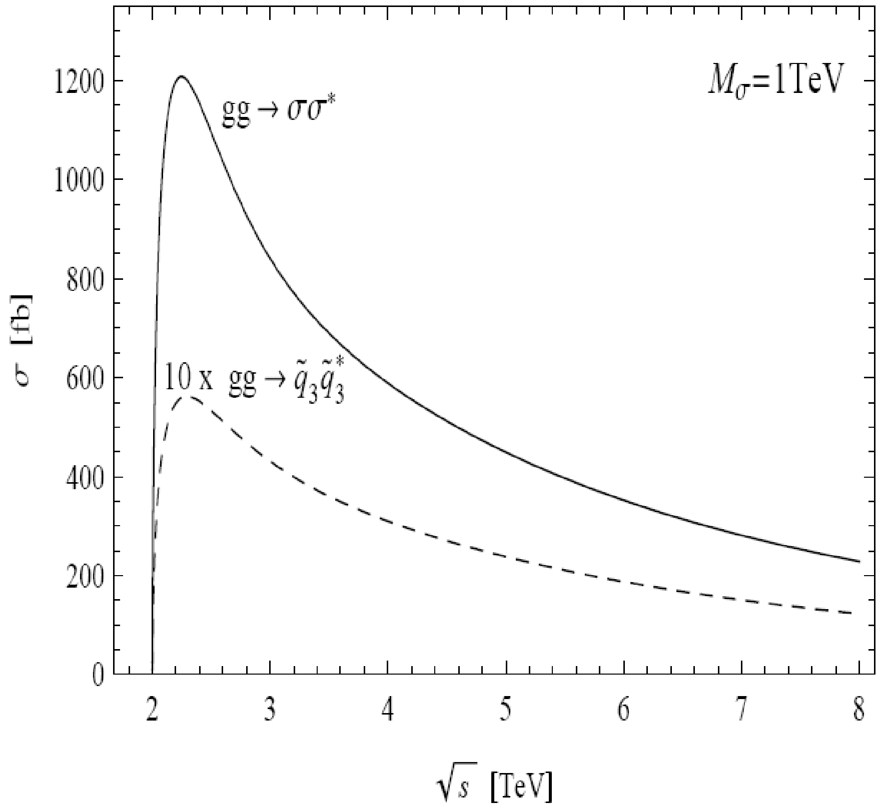


$$\sigma[q\bar{q} \to \sigma\sigma^*] \; = \; \frac{4\pi\alpha_s^2}{9s}\,\beta_\sigma^3\,,$$

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

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.

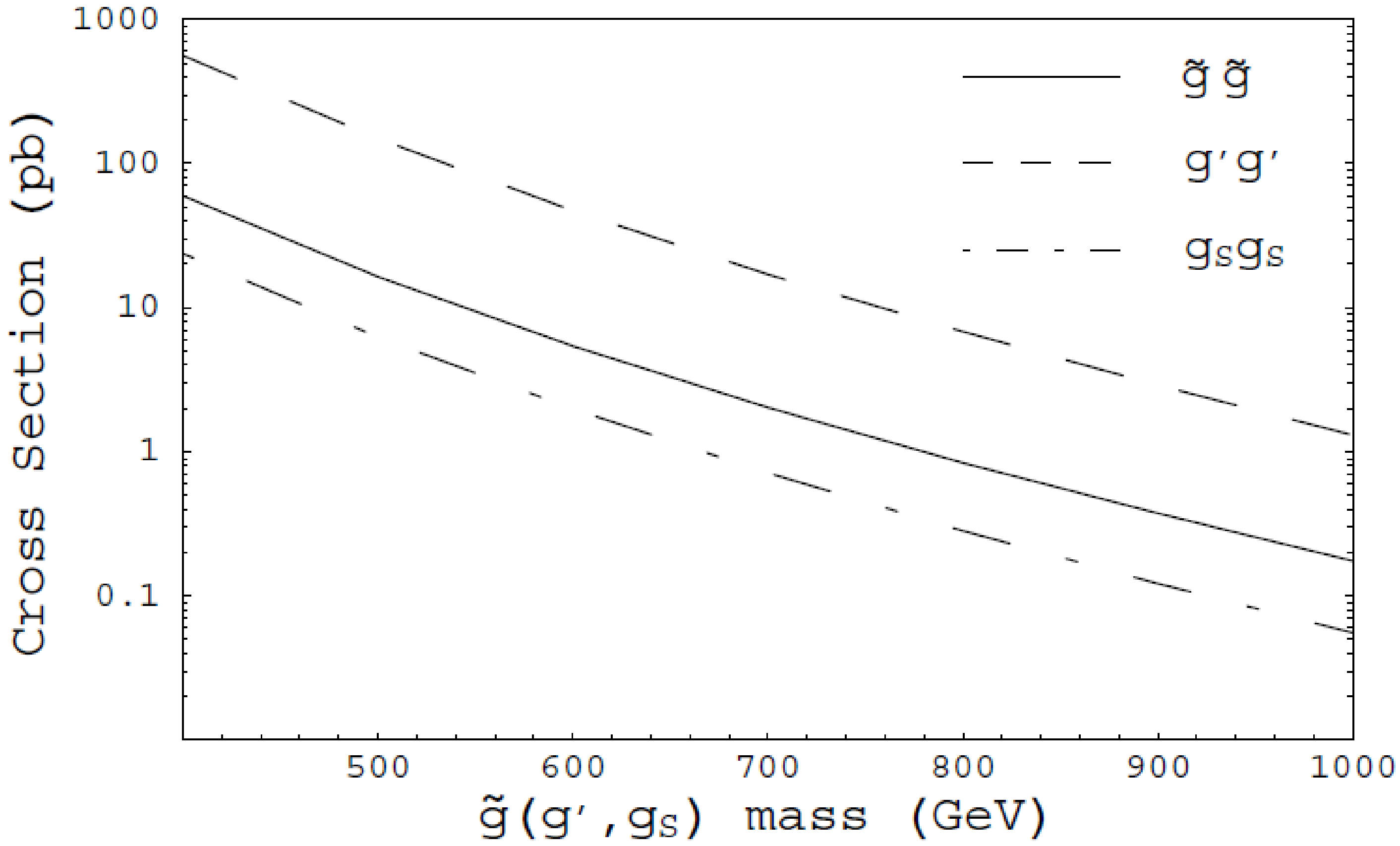
$$\frac{\sigma\left[q\bar{q} \longrightarrow \sigma\sigma^*\right]}{\sigma\left[q\bar{q} \longrightarrow \tilde{q}_3\tilde{q}_3^*\right]} = \frac{\mathrm{tr}\left(\frac{\lambda^a}{2}\,\frac{\lambda^b}{2}\right)\,\mathrm{tr}\left(F^aF^b\right)}{\mathrm{tr}\left(\frac{\lambda^a}{2}\,\frac{\lambda^b}{2}\right)\,\mathrm{tr}\left(\frac{\lambda^a}{2}\,\frac{\lambda^b}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

Kane,Petrov, Shao, Wang, arXiv:0805.1397

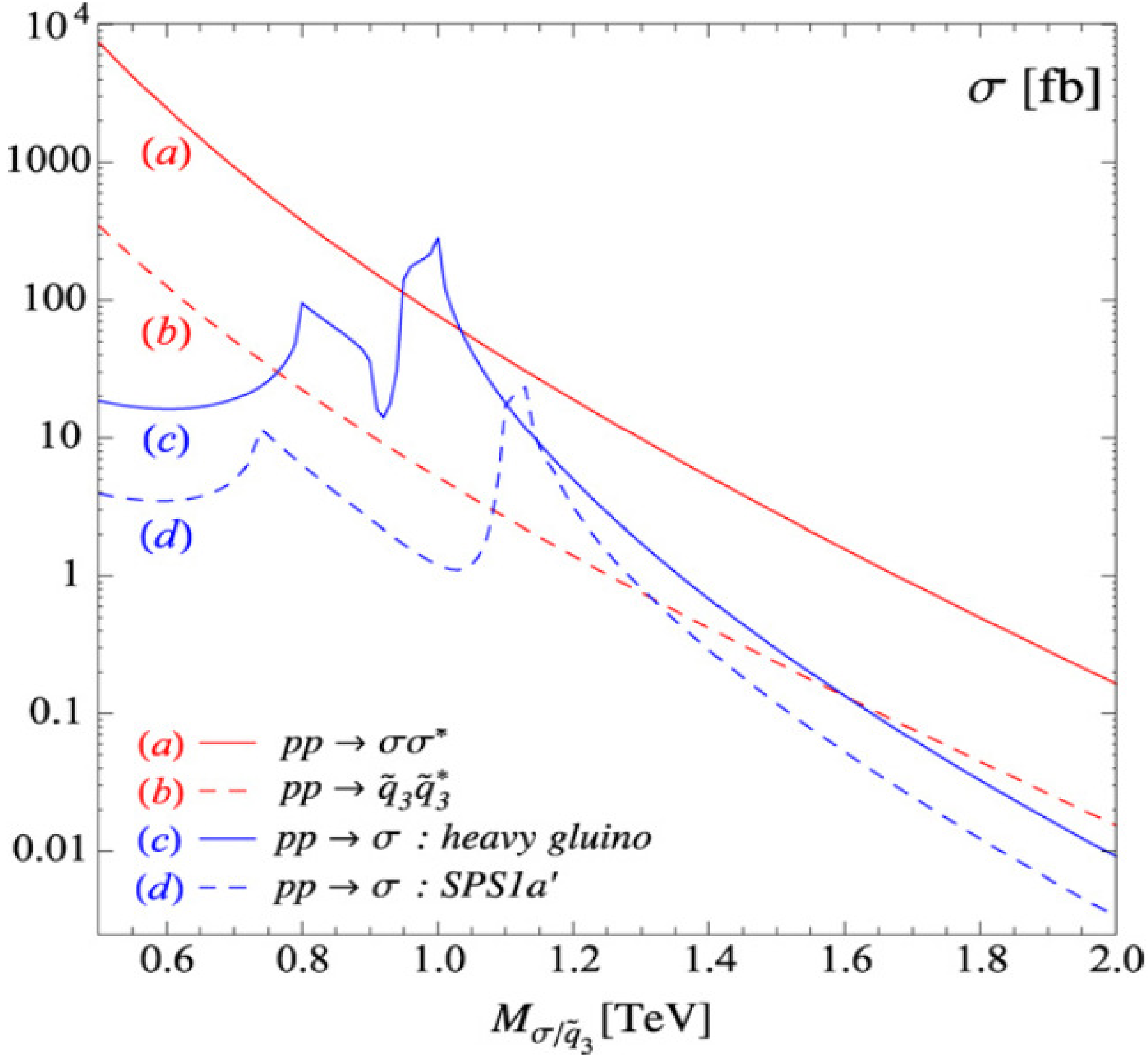
$$\hat{\sigma}_{gg\to gsgs}(\hat{s}, m_{gs}) = \frac{\pi\alpha_s^2}{\hat{s}}\left[\left(\frac{15}{16} + \frac{51 m_{gs}^2}{8\hat{s}}\right)\beta + \frac{9 m_{gs}^2}{2\hat{s}^2}\left(\hat{s} - m_{gs}^2\right)\log\frac{1-\beta}{1+\beta}\right],$$

$$\hat{\sigma}_{gg\to\tilde{g}\tilde{g}}(\hat{s}, m_{\tilde{g}}) = \frac{\pi\alpha_s^2}{\hat{s}}\left[-\left(3 + \frac{51 m_{\tilde{g}}^2}{4\hat{s}}\right)\beta + \frac{9}{4}\left(1 + \frac{4 m_{\tilde{g}}^2}{\hat{s}} - \frac{4 m_{\tilde{g}}^4}{\hat{s}^2}\right)\log\frac{1+\beta}{1-\beta}\right],$$

$$\hat{\sigma}_{gg\to gVgV}(\hat{s}, m_{g'}) = \frac{\pi\alpha_s^2}{\hat{s}}\left[\left(9\frac{\hat{s}}{m_{g'}^2} + \frac{117}{8} + \frac{153}{4}\frac{m_{gV}^2}{\hat{s}}\right)\beta + 9\left(1 + 3\frac{m_{g'}^2}{\hat{s}} - 3\frac{m_{gV}^4}{\hat{s}^2}\right)\log\frac{1-\beta}{1+\beta}\right]$$



Sgluon production in pp collisions



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.

Dirac gluino mass:

SUSY breaking from hidden-sector spurion

$$\mathcal{L}_{SB} = \int d^2\theta \frac{\sqrt{2}}{M_0} W'^{\alpha} W_{\alpha}^a \Phi^a + h.c.$$

$$W_{\alpha}^a = \tilde{g}_{\alpha}^a + D^a \theta_{\alpha} + \ldots$$

$$\Phi^a = \sigma^a + \sqrt{2}\theta\, \tilde{g}'^a + \theta\theta\, F^a$$

When the spurion gets vev $\langle W'_{\alpha} \rangle = D' \theta_{\alpha}$

$$\mathcal{L}_{SB} \to -M_3^D \tilde{g}^a \tilde{g}'^a + \sqrt{2}\sigma^a D^a$$

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

$$M_3^D = D'/M_0$$