# Search for two-gluino bound states

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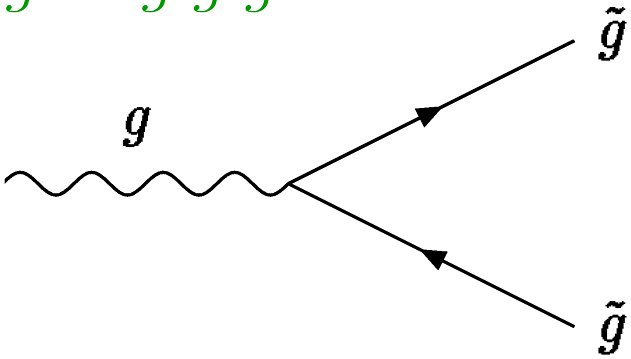
# What are gluinos?

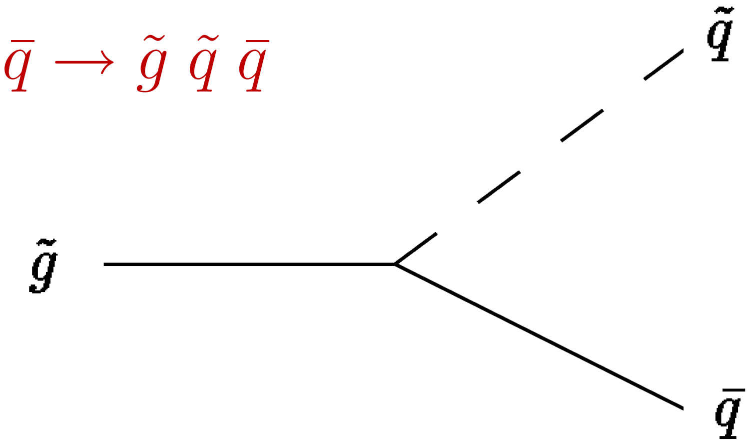
**Gluinos are supersymmetric partners of gluons:**

- gluon $g$ has spin 1, gluino $\tilde{g}$ has spin $1/2$
- gluino must be self-conjugate (Majorana) fermion to have just 2 degrees of freedom
- gluino couplings can be derived from corresponding gluon couplings:

$g\ g\ g \longrightarrow \tilde{g}\ \tilde{g}\ g$




$g\ q\ \bar{q} \longrightarrow \tilde{g}\ \tilde{q}\ \bar{q}$




Coupling strength is the usual $\alpha_s$, irrespective of SUSY breaking.

# Why talk about gluinos here?

Why talk about gluinos on a meeting dedicated to quarks and gluons?

Because quarks and gluons don't have a relative closer than gluinos!

- **Just like quarks:**
  - gluinos are fermions
  - gluinos are coupled to gluons
  - gluinos carry a conserving quantum number ($R$ parity)
- **Just like gluons:**
  - gluinos are colour octets
  - gluinos are coupled to all quark flavours with equal strengths
  - gluinos are **not** coupled to leptons, photons, $W$,$Z$

# What do we know about gluinos?

We know the quantum numbers and couplings, but we don't know its mass $m_{\tilde g}$ (in the absence of a good model for SUSY breaking).

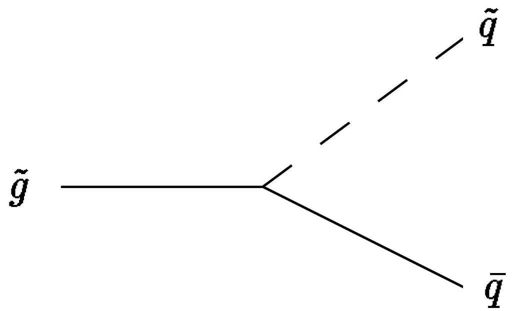
And we don't know whether it exists or not.

But if it exists, we can predict all its properties.

Most important: what is the main decay mode of a gluino?

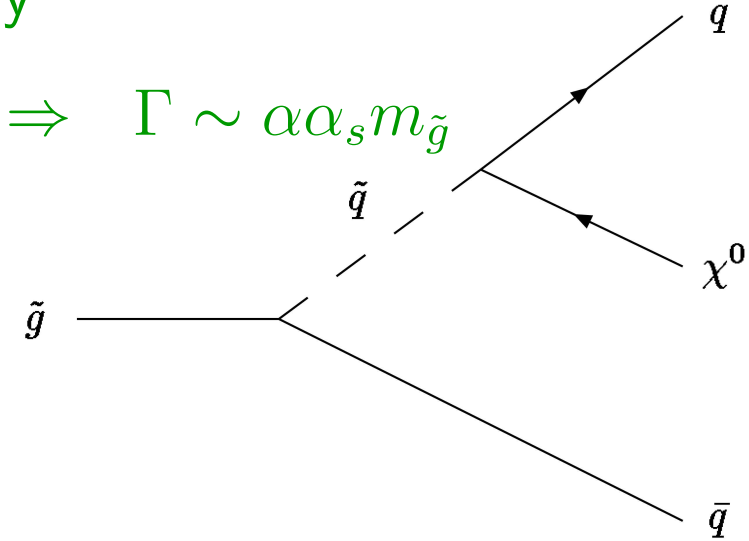
"strong" decay

$$m_{\tilde g} > m_{\tilde q} \quad \Rightarrow \quad \Gamma \sim \alpha_s m_{\tilde g}$$




"weak" decay

$$m_{\tilde g} < m_{\tilde q} \quad \Rightarrow \quad \Gamma \sim \alpha\alpha_s m_{\tilde g}$$

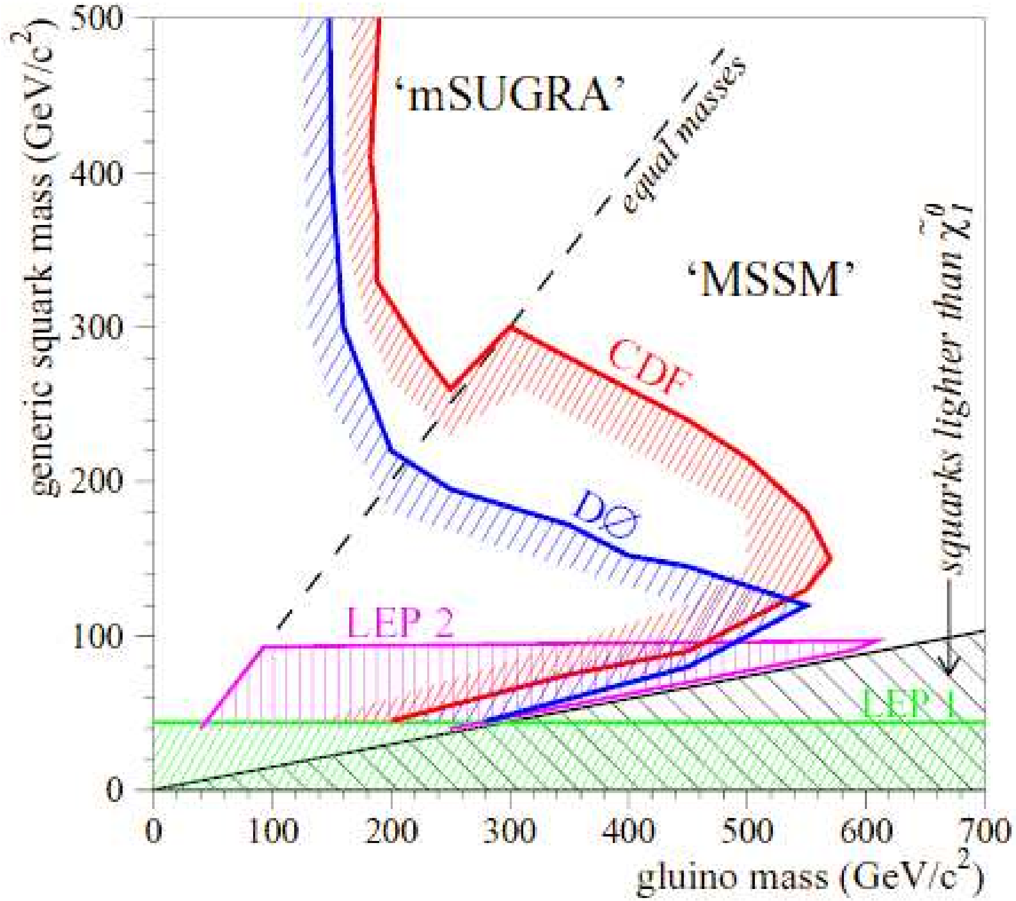


# What do the experiments say?

As always with SUSY, results of experimental searches are model-dependent.

**Latest PDG plot:** [**PR D66**, 910]

- It is significanly easier to look for gluinos if they are heavier than squarks.
- Weakly decaying gluinos are more difficult to find.
- **BUT**: weakly decaying gluinos should live long enough to form quarkonium-like bound states.



# Gluino-gluino bound states?

Gluinos: strongly interacting fermions carrying a conserving quantum number really do resemble quarks. One-gluon exchange potential

$$V_{\tilde{g}\tilde{g}}(r) = K\frac{\alpha_s}{r}$$

can be attractive in no less than three different colour states:

$$\begin{array}{ccccccccccccc} 8 \times 8 & = & 1 & \oplus & 8_S & \oplus & 8_A & \oplus & 10 & \oplus & \overline{10} & \oplus & 27 \\ K & : & -3 & & -3/2 & & -3/2 & & 0 & & 0 & & 1 \\ \text{Structure} & : & \delta_{ab} & & d_{abc}\epsilon^c & & f_{abc}\epsilon^c & & & & & & \end{array}$$

A typical annihilation decay rate of **gluinonium** $(\tilde{g}\tilde{g})$ with mass $M = 2m_{\tilde{g}}$:

$$\Gamma((\tilde{g}\tilde{g}) \to gg) \simeq \alpha_s^5 M$$

which is larger than a free gluino in-the-flight decay rate, if $m_{\tilde{g}} < m_{\tilde{q}}$ (when all numerical constants are taken into account).

[Haber, Kane **PR 117**, 75; Keung, Khare **PR D29**, 2657; Kuhn, Ono **PL B142**, 436; Goldman, Haber **Physica 15D**, 181]

# Is gluinonium “the next heavy quarkonium”?

**Not exactly, but in certain aspects it gets very close.**

Differences:

- Gluino is not (directly) coupled to leptons/$\gamma/Z/W$
  - Only hadronic decays
  - No "golden-plated" $\mu^+\mu^-$, $e^+e^-$, $\gamma\gamma$ decay modes
  - Makes detection of bound states more difficult
- Gluino is a Majorana (rather that Dirac) fermion
  1. The $(\tilde{g}\tilde{g})$ wavefunction, space×spin×colour, must change sign under interchange of the gluinos
  2. $C$-parity of $(\tilde{g}\tilde{g})$ must be $+1$

1+2 ⇒ Only certain states can exist:

$$\begin{aligned} L+S &= \text{even} \quad \text{for } 1, 8S \\ L+S &= \text{odd} \quad \text{for } 8A \end{aligned}$$

# So, what's the spectrum?

Spin-parity $J^P$ of lowest allowed gluinonium states in the three sectors:

| | $1$ | $8_S$ | $8_A$ |
|---|---|---|---|
| $^1S_0$ | $0^-$ $(\eta^0_{\tilde{g}})$ | $0^-$ $(\eta^8_{\tilde{g}})$ | — |
| $^3S_1$ | — | — | $1^-$ $(\psi^8_{\tilde{g}})$ |
| $^1P_1$ | — | — | $1^+$ |
| $^3P_0$ | $0^+$ | $0^+$ | — |
| $^3P_1$ | $1^+$ | $1^+$ | — |
| $^3P_2$ | $2^+$ | $2^+$ | — |

# Colour-octet bound states?

The typical "Bohr radius" of these states is tiny:

$$r_B \simeq (\alpha_s\, m_{\tilde{g}}/2)^{-1} \simeq (10\ \mathrm{GeV})^{-1} \simeq 0.02\ \mathrm{fm}$$

Hence, $8_S$ and $8_A$ coloured states should behave a bit like heavy gluons and form colourless hadrons with gluons and quark (antiquark) pairs.

This may lead to:

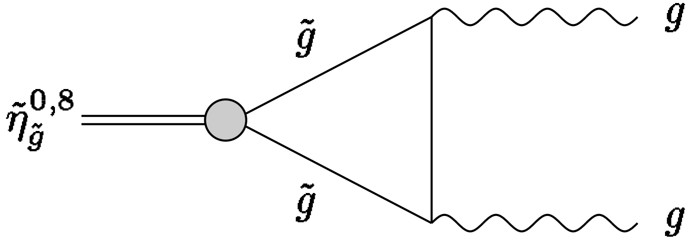
- an $\mathcal{O}(1\ \mathrm{GeV})$ overhead on gluinonium mass in these channels
- a complicated spectrum of "radiative" transitions between the three sectors, like

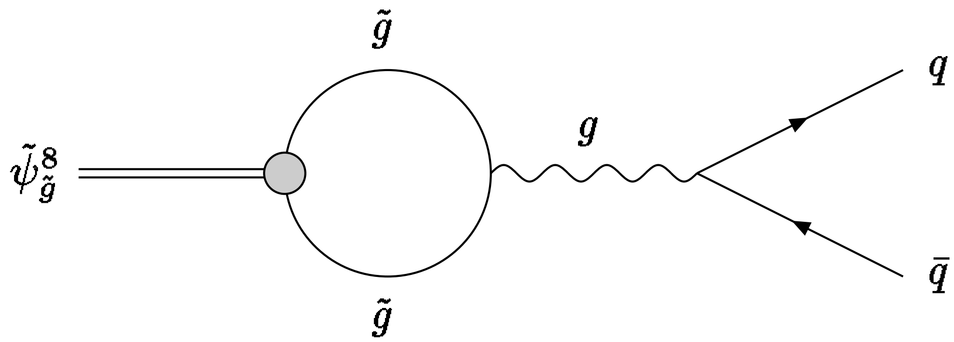
$$\psi^8_{\tilde{g}} + \{q\bar{q}\}_8 \longrightarrow \eta^0_{\tilde{g}} + 2\pi$$

but all this may be virtually impossible to observe if the gluino is heavy, as the experimental resolution will smear everything out.

# What are gluinonium decay modes?

Depending on the quantum numbers, one of these two dominate:




$$\Gamma(\eta^0_{\tilde{g}} \to g\,g) \;=\; \frac{243}{8}\alpha_S^5 M \simeq 200\ \mathrm{MeV} \qquad (\text{for } m_{\tilde{g}} = 225\ \mathrm{GeV},\ M \simeq 2m_{\tilde{g}})$$

$$\Gamma(\eta^8_{\tilde{g}} \to g\,g) \;=\; \frac{243}{32}\alpha_S^5 M \simeq\ 50\ \mathrm{MeV} \qquad \Gamma(\psi^8_{\tilde{g}} \to q\bar{q}) \;=\; N_q \frac{27}{64}\alpha_S^5 M \simeq\ 20\ \mathrm{MeV}$$

[VK et al, **ZP C43**, 509]

So, these are narrow resonances, with strong coupling to respective hadronic channels.

# How could we see them?

- As narrow resonances in the two-gluon channel
- As narrow resonances in the quark-antiquark channel

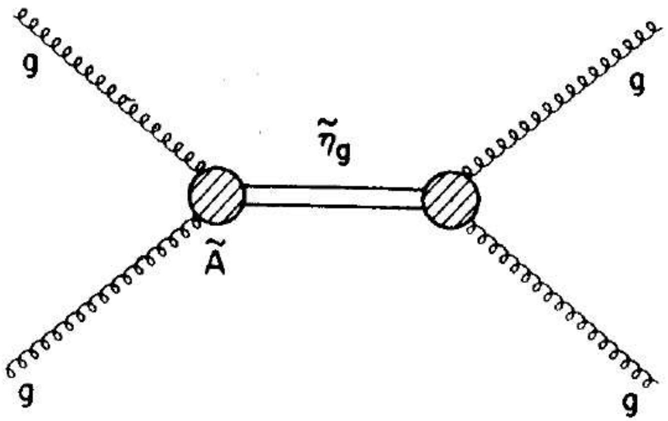
**The main problem is immediately evident:**

- These channels have huge irreducible "generic" QCD backgroungs
- Other, reducible backgroungs should not be too important
- One should expect tiny signal-to-background ratios $\mathcal{O}(1\%)$ or smaller
- Thus, the best possible experimental resolution is vital

# Where should we look?

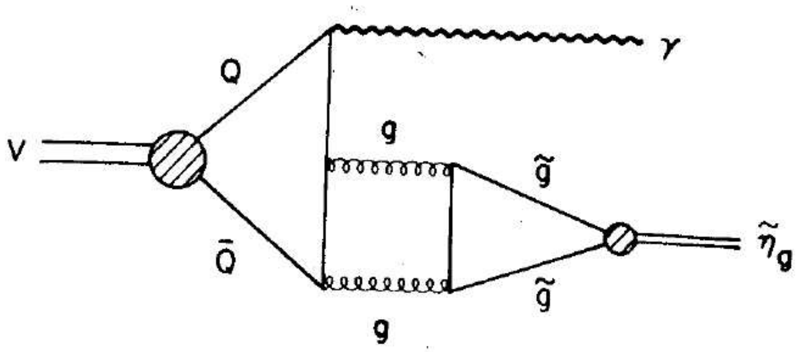
**A few examples of processes which may have a chance:**

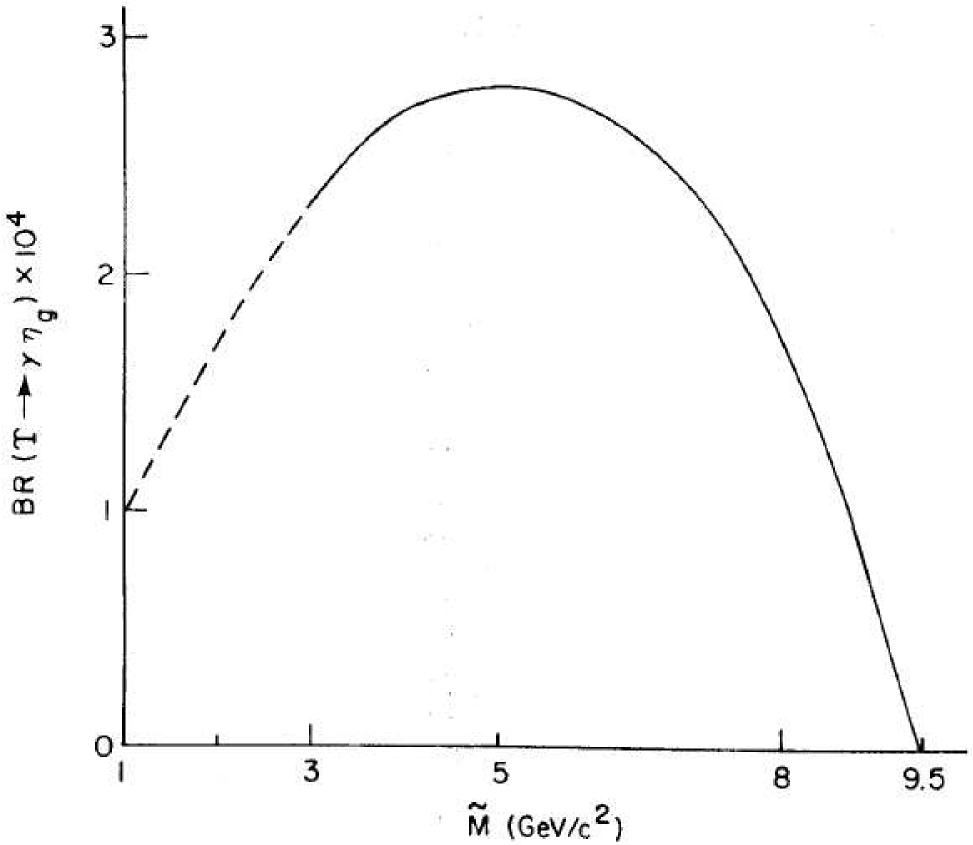
- $e^+e^-$ machines: Radiative decays of quarkonium
- Tevatron: as a peak in two (flavour-tagged?) jet invariant mass distribution
- LHC: as a peak in two (gluon) jet invariant mass distribution



# What if gluino is very light?

Radiative decays of quarkonium:




CUSB experiment looked for resonant $\gamma$ in $\Upsilon$ decays:

$$e^+e^- \to \Upsilon \to \gamma + \mathrm{hadrons}$$

Re-analysed with gluinonium in mind:

Excludes gluinonium with masses between 3 and 7 GeV.

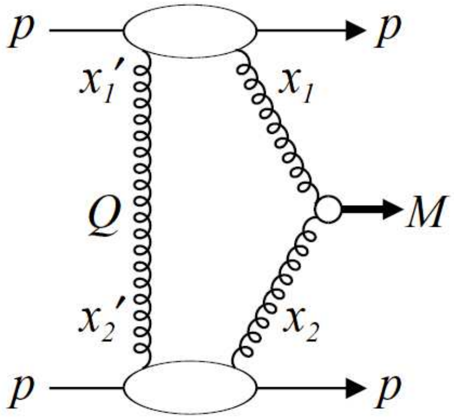
[Cakir, Farrar **PRD 50**, 3268]

# What if there is a window between 25-35 GeV?

Possible allowed window for a (quasi)-stable glino with $m_{\tilde{g}} = 25 - 35$ GeV

[Mafi, Raby **PRD 62**, 035003]

Gluinonium may be observed at LHC as an $s$-channel resonance in diffractive gluon-gluon scattering [Khoze et al, **EPJ C23**, 311]




- Special selection rules imply that lowest possible states are $^3P$
- Effective width is small, S/B ratio does not look too promising:

$$\frac{S}{B} \simeq 1.5 \cdot 10^{-3} \left(\frac{1\ \mathrm{GeV}}{\Delta}\right)\left(\frac{M}{60\ \mathrm{GeV}}\right) \qquad [\Delta = \text{ resolution}]$$

# Tevatron: vector octet state?

At the Tevatron highest invariant masses can be reached in quark-antiquark annihilation subprocess

Good place to look for the vector, colour octet gluinonium $\psi^8_{\tilde{g}}$:

$$q + \bar{q} \to \psi^8_{\tilde{g}} \to Q + \bar{Q}$$

To get rid of the gluon-gluon jet background, heavy-flavour-tagged jets could be used

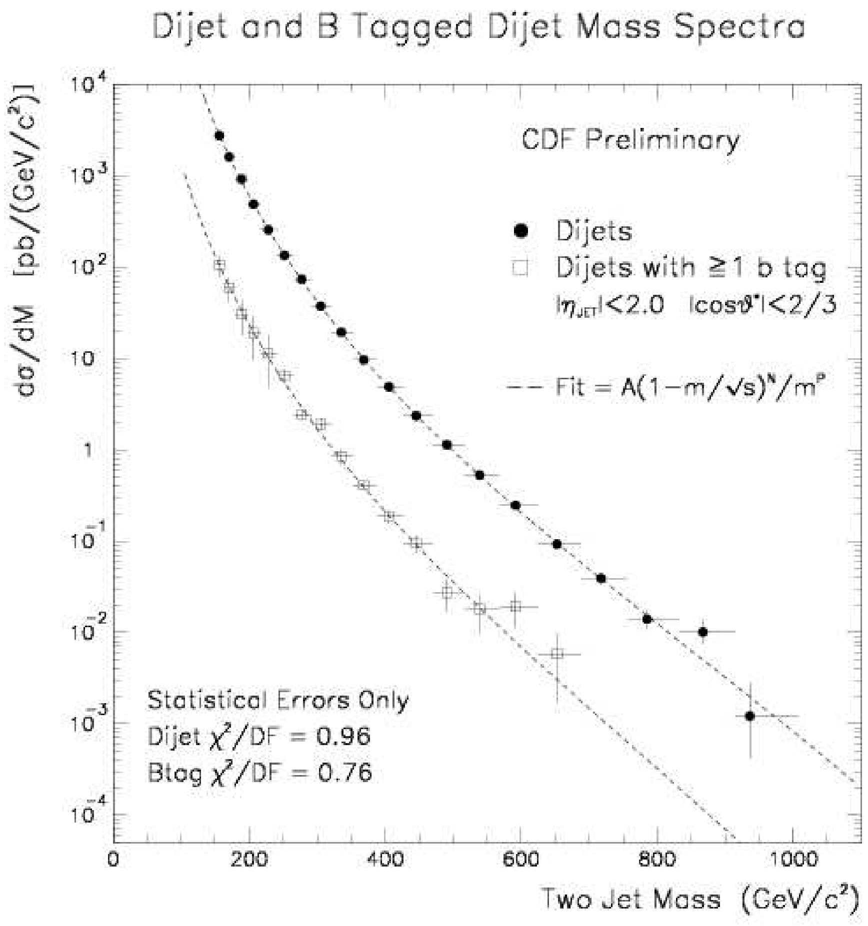
Signal-to-background ratio in this case is somewhat better:

$$\frac{S}{B} \simeq 1.5\pi\alpha_s^3 \left(\frac{M}{\Delta}\right) \simeq 0.1 \left(\frac{30\ \mathrm{GeV}}{\Delta}\right) \left(\frac{M}{600\ \mathrm{GeV}}\right)$$

[VK et al, **PR D53**, 6653]

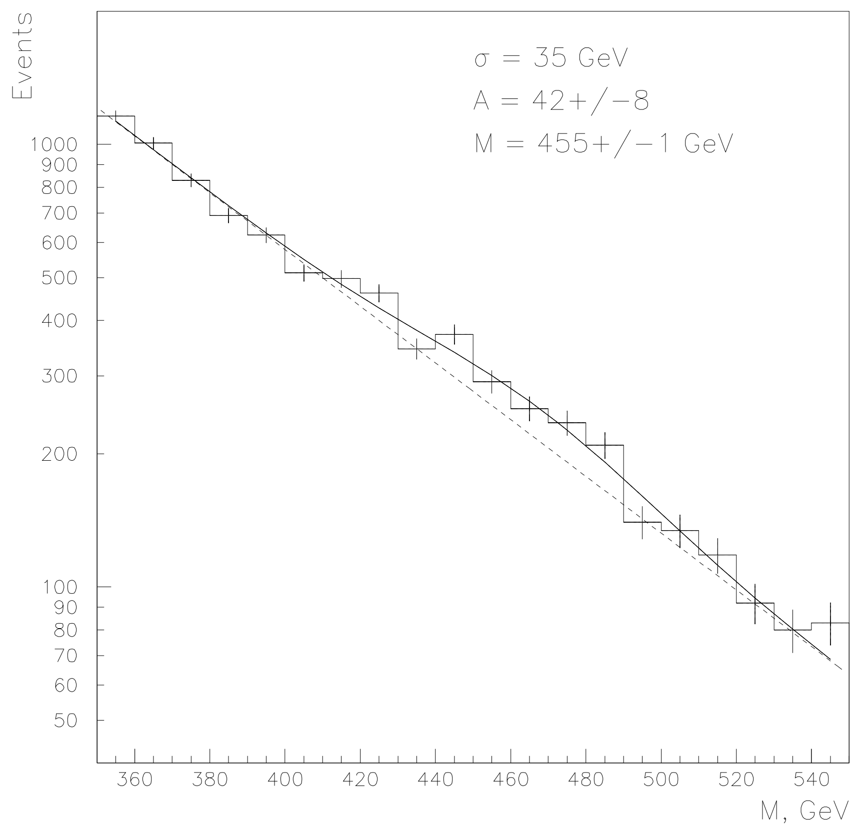
# Tevatron I: results and simulations

Data from CDF: Two-jet invariant masses, untagged and $b$-tagged




[Fermilab-Conf-95-275-E]

A simple simulation for Tevatron II $\mathcal{L} = 1$ fb$^{-1}$, $c, b$-tagged




Smeared PYTHIA, $M$=450 GeV

# LHC: is resolution good enough?

At the LHC gluon-gluon collisions dominate at all invariant masses

Good place to look for pseudoscalar gluinonia $\eta^0_{\tilde{g}}, \eta^8_{\tilde{g}}$:

$$g + g \longrightarrow \eta^{0,8}_{\tilde{g}} \longrightarrow g + g$$

The gluon-gluon jet background is now irreducible, but tight angular cuts excluding high $|\cos\theta^*|$ should help

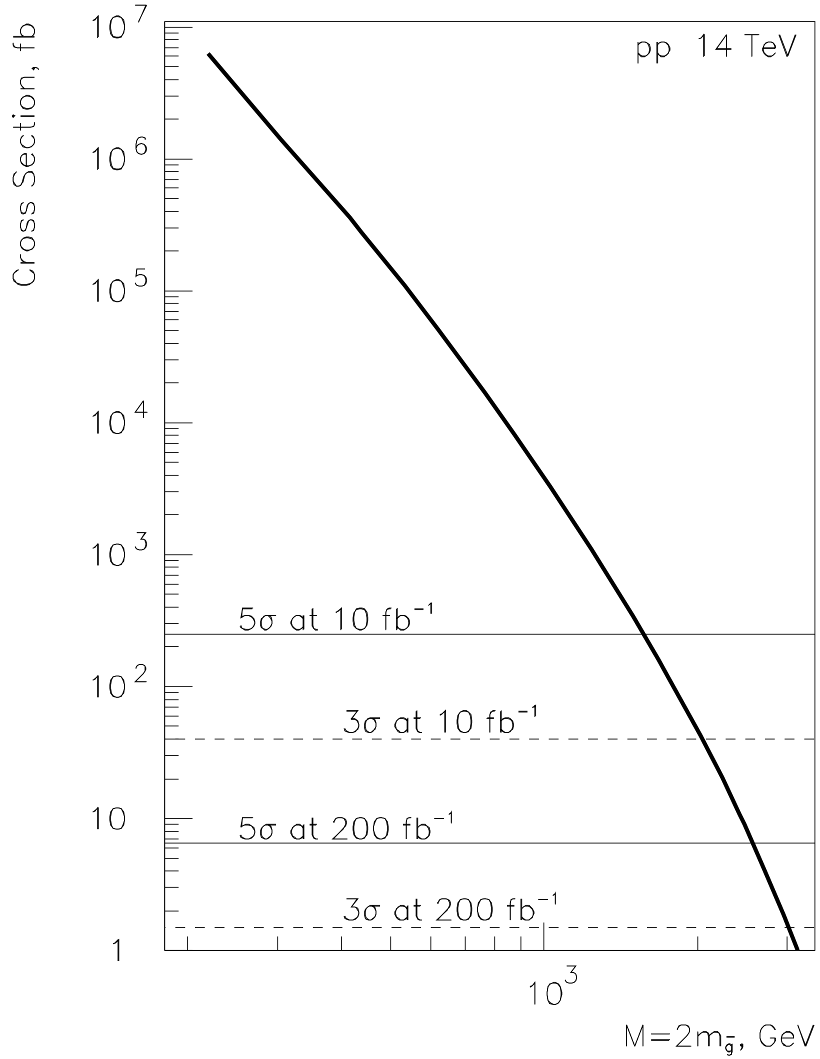
Signal-to-background ratio in this case is not hopeless:

$$\frac{S}{B} \simeq 0.2\pi\alpha_s^3 \left(\frac{M}{\Delta}\right) \simeq 0.02 \left(\frac{30\ \mathrm{GeV}}{\Delta}\right) \left(\frac{M}{600\ \mathrm{GeV}}\right)$$

[VK et al, **PR D53**, 6653]

# LHC: what are the expectations?

- Total effective width of all $gg$-coupled $(\tilde{g}\tilde{g})$ states is $\mathcal{O}(1\text{ GeV})$
- At high masses, resolution $\Delta \sim \sqrt{M}$
- Rough estimates:
  $\Delta = 32$ GeV at $M = 600$ GeV
  $\Delta = 50$ GeV at $M = 2000$ GeV
- Cut $|\cos\theta^*| < 2/3$ applied
- S/B ratio around 1-2%
- For $\mathcal{L} = 200\text{ fb}^{-1}$ may reach
  $M = 3$ TeV $\Rightarrow m_{\tilde{g}} = 1.5$ TeV



# So what?

- Bound states: complementing single gluino searches with very different phenomenology
- Reach may be comparable to single gluino searches
- On hadronic colliders, high statistics and good resolution are the keys (aren't they for anything in this business?)
- Half of the parameter space covered $[m_{\tilde{g}} < m_{\tilde{q}}]$
- Should be carried out even if (or especially if) single gluinos are detected
- Probably the most precise way of measuring the gluino mass $m_{\tilde{g}} = M/2$
- Real, dedicated searches for gluino-gluino bound states have not started yet
- I'll do my best to change this, but it may take years...