Gluino-gluino bound state searches at LHC

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Outline

- Gluino properties
- Theory of gluino-gluino bound states
- Pseudoscalar gluinonium decays
- Old estimates for reach at LHC
- Realistic simulations
- Problems to solve
- Conclusions

What do we know about gluinos?

Almost everything. . . We know that

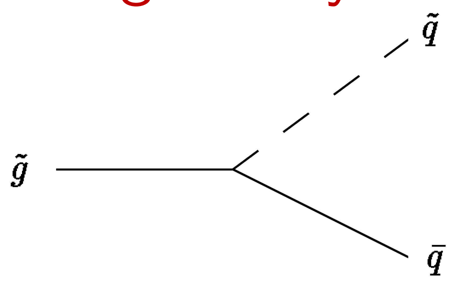
- gluinos are (Majorana) fermions, strongly coupled to gluons;
- gluinos carry a conserving quantum number (R parity);
- gluinos are coupled to all quark flavours with equal strengths;
- gluinos are **not** coupled to leptons, photons, W and Z.

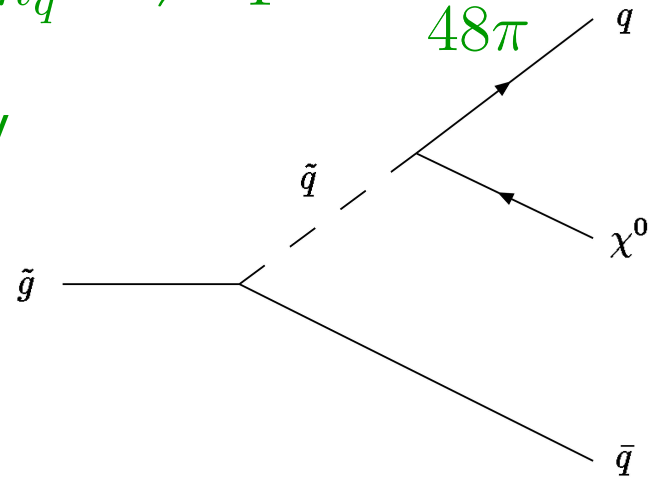
But we are not sure that they exist, and we don't know the mass $m_{\tilde{g}}$.

The main decay mode of a gluino depends on the masses:

$m_{\tilde{g}} > m_q + m_{\tilde{q}} \quad \Rightarrow \quad \Gamma \sim \alpha_s m_{\tilde{g}}$ $\qquad$ $m_{\tilde{g}} < m_q + m_{\tilde{q}} \quad \Rightarrow \quad \Gamma \sim \dfrac{\alpha \alpha_s m_{\tilde{g}}}{48\pi}$

"strong" decay $\qquad$ "weak" decay



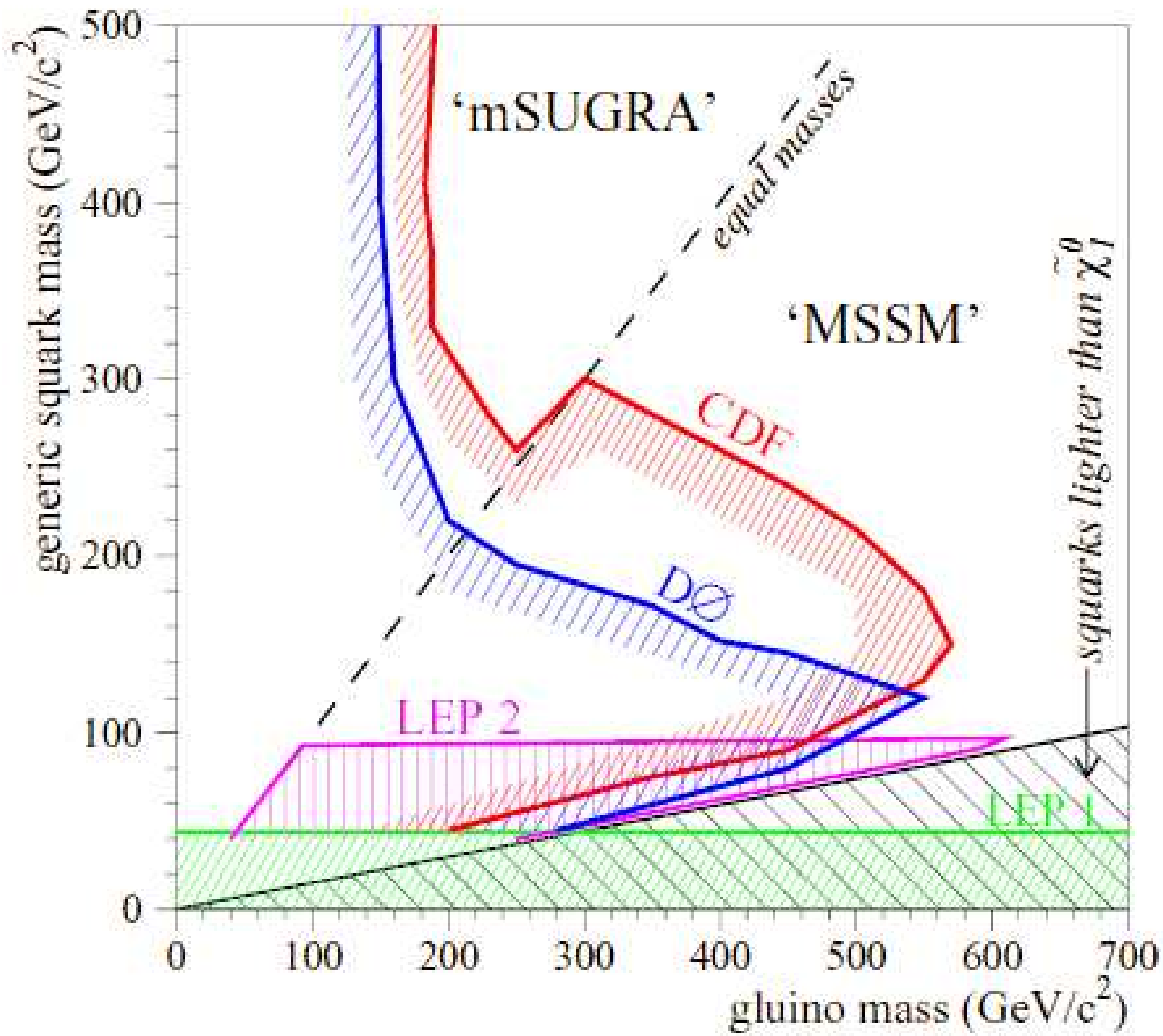


Searches so far

Latest PDG plot:

[June 16 2004]

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



Gluino-gluino bound states

Gluinos are strongly interacting fermions carrying a conserving quantum number — much like heavy quarks. One-gluon exchange potential between two gluinos is **attractive** in no less than three different colour states:

$$\begin{array}{rcl} V_{\tilde{g}\tilde{g}}(r) & = & K\dfrac{\alpha_s}{r} \\ 8 \;\times\; 8 & = & 1 \;\oplus\; 8_S \;\oplus\; 8_A \;\oplus\; 10 \;\oplus\; \overline{10} \;\oplus\; 27 \\ K & : & -3 \quad -3/2 \quad -3/2 \qquad 0 \qquad 0 \qquad 1 \\ \text{Colour structure} & : & \delta_{ab} \quad d_{abc}\epsilon^c \quad f_{abc}\epsilon^c \end{array}$$

Typical annihilation decay rates of various **gluinonium** states $(\tilde{g}\tilde{g})$ with masses $M \simeq 2m_{\tilde{g}}$ are rather large:

$$\Gamma((\tilde{g}\tilde{g}) \to gg, q\bar{q}) \simeq (1-30)\alpha_s^5 M \;\; \simeq \;\; (10-300) \times \Gamma(\tilde{g} \to q\bar{q}\tilde{\gamma})$$

hence, if $m_{\tilde{g}} < m_q + m_{\tilde{q}}$, gluinonium should exist.

[Haber, Kane **PR 117**, 75; Keung, Khare **PR D29**, 2657; Kuhn, Ono **PL B142**, 436; Goldman, Haber **Physica 15D**, 181; VK et al, **ZP C43**, 509]

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 "gold-plated" $\mu^+\mu^-$, e^+e^- or $\gamma\gamma$ decay modes
- Makes detection of bound states more difficult

❖ The two gluinos in the bound state are identical fermions:

- The full $(\tilde{g}\tilde{g})$ wave function, space×spin×colour, must change sign under interchange of the gluinos
- C-parity of $(\tilde{g}\tilde{g})$ must be $+1$

⇒ Only certain states can exist:

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

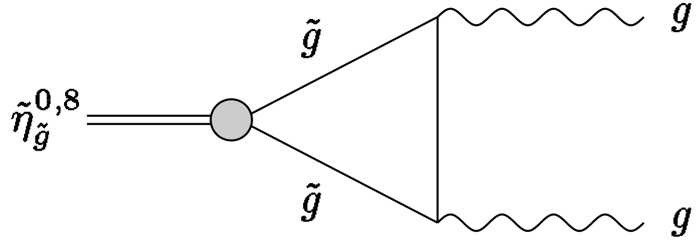
The spectrum of gluinonium

Spin-parity J^P of lowest allowed gluinonium states in three colour sectors (pseudoscalars shown in red):

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

Pseudoscalar gluinonium decay

At tree level: two-gluon decay is the only one:



$$\Gamma(\eta^1_{\tilde{g}} \to gg) = \frac{243}{8}\alpha_S^5 M \simeq 700 \text{ MeV}$$

$$\Gamma_{\text{eff}}(\eta^8_{\tilde{g}} \to gg) = \frac{243}{32}\alpha_S^5 M \simeq 180 \text{ MeV}$$

$$(\text{for } m_{\tilde{g}} = 230 \text{ GeV}, \; M \simeq 2m_{\tilde{g}} = 450 \text{ GeV})$$

- Gluinonium states are narrow resonances
- Pseudoscalars $\eta^{1,8}_{\tilde{g}}$ are strongly coupled to the gluon-gluon channel
- SM Higgs coupling to gg is smaller by a factor of ~ 70

How could we see pseudoscalar gluinonium?

As a narrow resonance in the two-gluon channel

The main problems are immediately evident:

- This channel has huge irreducible "generic" QCD background
- Two gluons can give more than two jets
- One should expect small signal-to-background ratios $\mathcal{O}(1\%)$
- Thus, the best possible experimental resolution is vital

On the brighter side:

- Other types of background should not be too important
- The signal-to-background ratio should improve (slightly) with increasing M

Early estimates for LHC

At the LHC gluon-gluon collisions dominate over $q\bar{q}$ at all invariant masses

Should be the place to look for pseudoscalar gluinonia $\eta^1_{\tilde{g}}, \eta^8_{\tilde{g}}$:

$$g + g \longrightarrow \eta_{\tilde{g}}^{1,8} \longrightarrow g + g$$

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

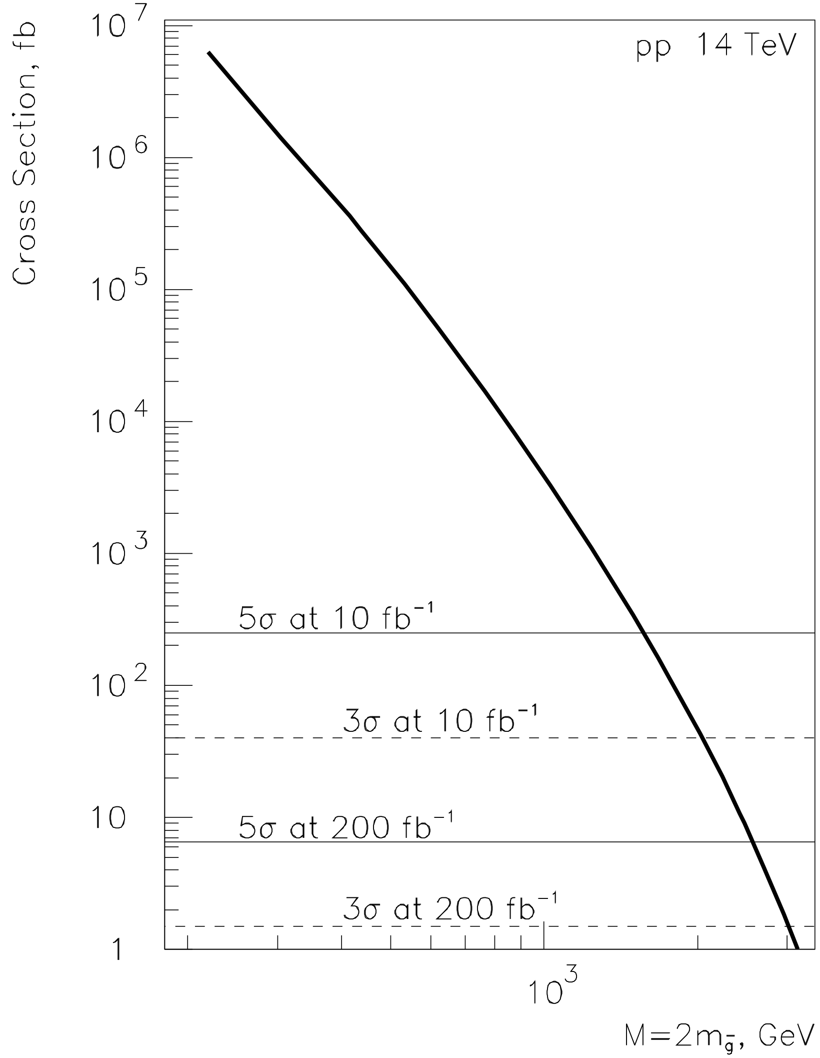
Signal-to-background ratio in $g\ g$ mode:

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

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

Optimistic view on the reach in gg mode

- The cross section is fairly large
- 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
  (see below)
- S/B ratio around 2-3%



Real ATLAS simulations

Used most recent "physics-validated" version of ATLAS software.

SIGNAL:

- Tweaked A_0 (Pseudoscalar Higgs) in PYTHIA to have necessary Γ and 100% BR to gg.
- 5000 events with $M = 450$ GeV ($\Gamma(gg) = 1.0$ GeV) $m_{\tilde{g}} \approx 230$ GeV.
- 5000 events with $M = 900$ GeV ($\Gamma(gg) = 1.1$ GeV) $m_{\tilde{g}} \approx 460$ GeV.
- 5000 events with $M = 1350$ GeV ($\Gamma(gg) = 1.2$ GeV) $m_{\tilde{g}} \approx 680$ GeV.
- Production cross sections: 120 pb, 2.3 pb, 0.2 pb respectively.
- Integrated luminosity of 1 fb^{-1} would correspond to stat. wights of 22.5, 0.47 and 0.036, respectively.

Background

QCD jet production

"Trigger-level" cut: events should contain at least one jet with P_T larger than some threshold value P_T^{min}.

- 100k events with $P_T^{min} = 70$ GeV (labelled as **j70**)
- Cross section 6.6 μb
- Roughly 50% are gg events
- Integrated luminosity of 1 fb^{-1} would correspond to stat. weight of 66000

- 100k events with $P_T^{min} = 560$ GeV (labelled as **j560**)
- Cross section 370 pb
- Only 20% are gg events, qg "elastic" scattering dominating
- Integrated luminosity of 1 fb^{-1} would correspond to stat. weight of 3.7

Analysis aims

Two distinct problems to solve:

1. Make the signal as narrow as possible
   - select suitable (2-jet?) events only
   - experimental resolution on jet energy
   - jet reconstruction details
   - quality of QCD simulation?

2. Suppress the background as much as possible
   - angular dependence
   - other discriminating variables?
   - separate gluonic and light-quark jets from each other?

Still an early stage of analysis — most of these still to be worked out...

Subprocess scattering angle $\cos\theta^*$

Main discriminating variable: $\cos\theta^*$, scattering angle in c.m.s. of the partonic $2 \to 2$ subprocess.

- Signal should be isotropic (pseudoscalar partcile decay)
- Backgroud typically has singularities $\sim (1 \pm \cos\theta^*)^{-1}$

Experimentally, we have defined $\cos\theta^*$ as:

$$\cos\theta^* = \frac{E_1\, P_z - p_{1z}\, E}{E_1\, E - p_{1z}\, P_z}$$

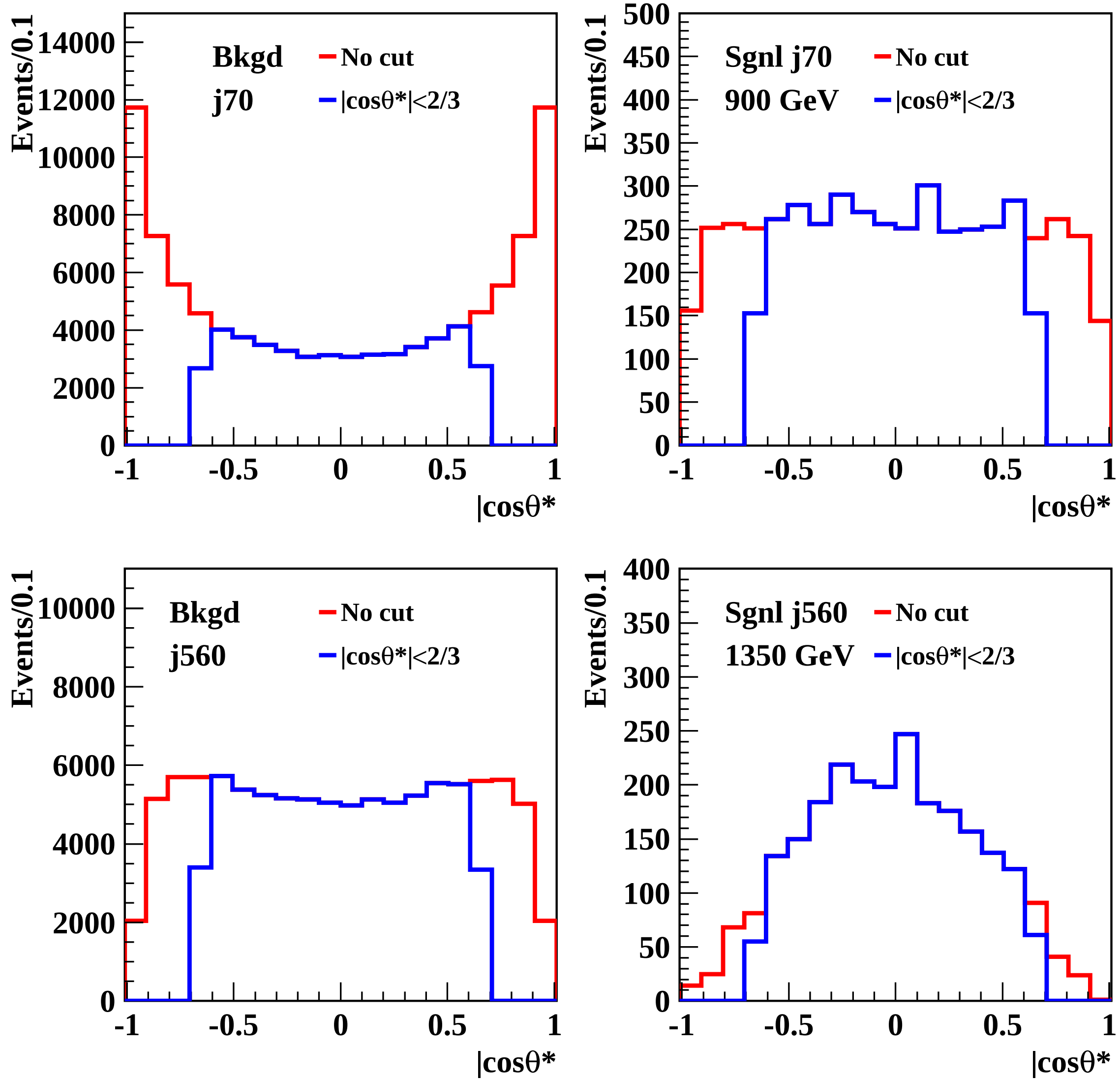
E_1, p_{1z}: jet with highest energy;

E, P_z: vector sum over **all** jets

This definition is exact for a perfect $2 \to 2$ subprocess with no masses and no overall transverse momentum. More useful definitions may be possible.

Measured $\cos\theta^*$ distributions

- Cut $|\cos\theta^*| < 2/3$ rejects 2/3 of j70 background
- Works better at high invariant masses
- Less efficient for j560 as P_T cut does a similar job
- More than 75% of signal survives



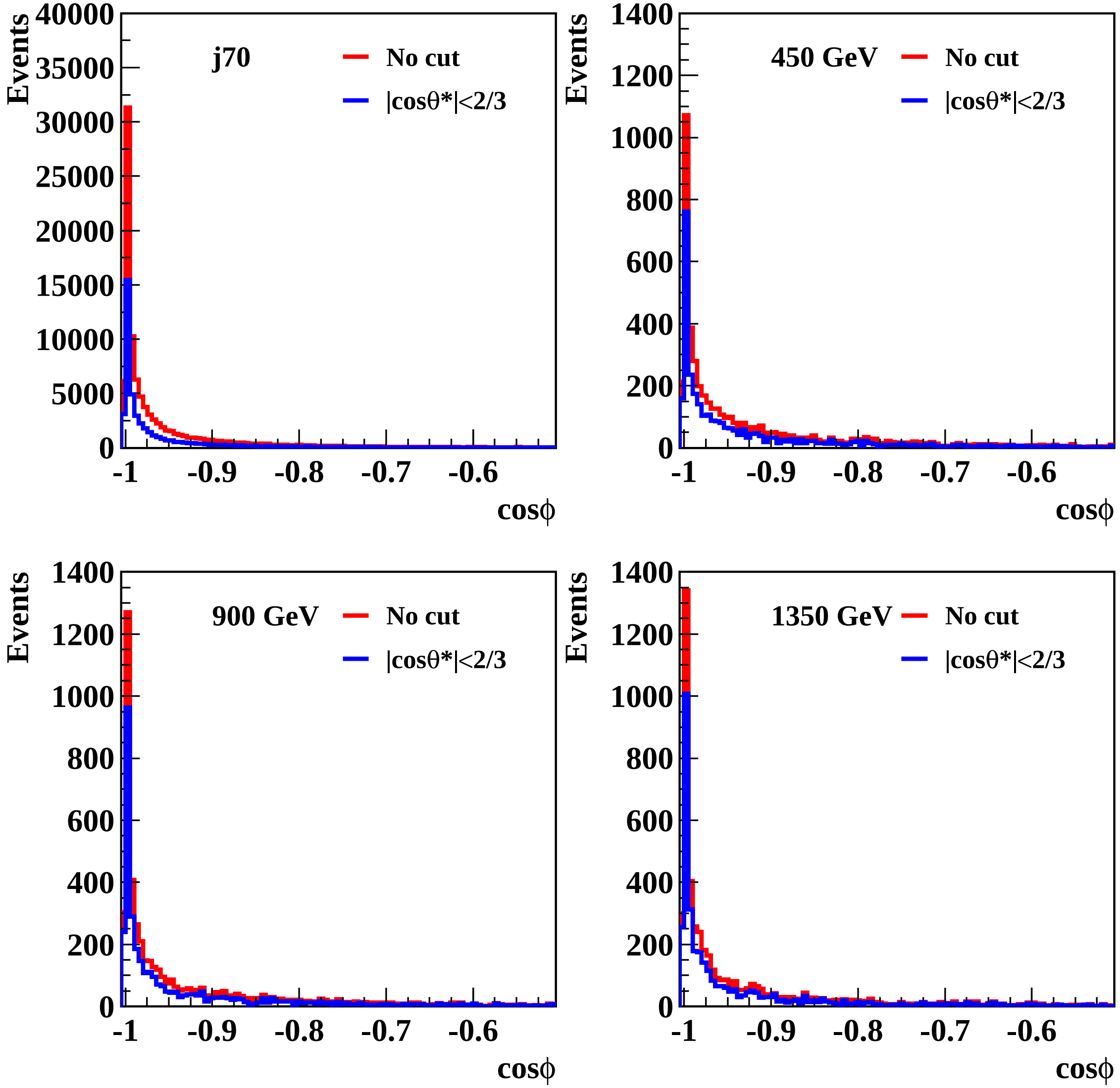
Transverse opening angle ϕ

ϕ — opening angle in transverse plane between two jets with highest P_T.

A tight cut, say, $\cos\phi < -0.98$ rejects 3-jet events.

Improves resolution, but reduces signal significance.

Not too helpful for background discrimination



Invariant mass distributions: j70

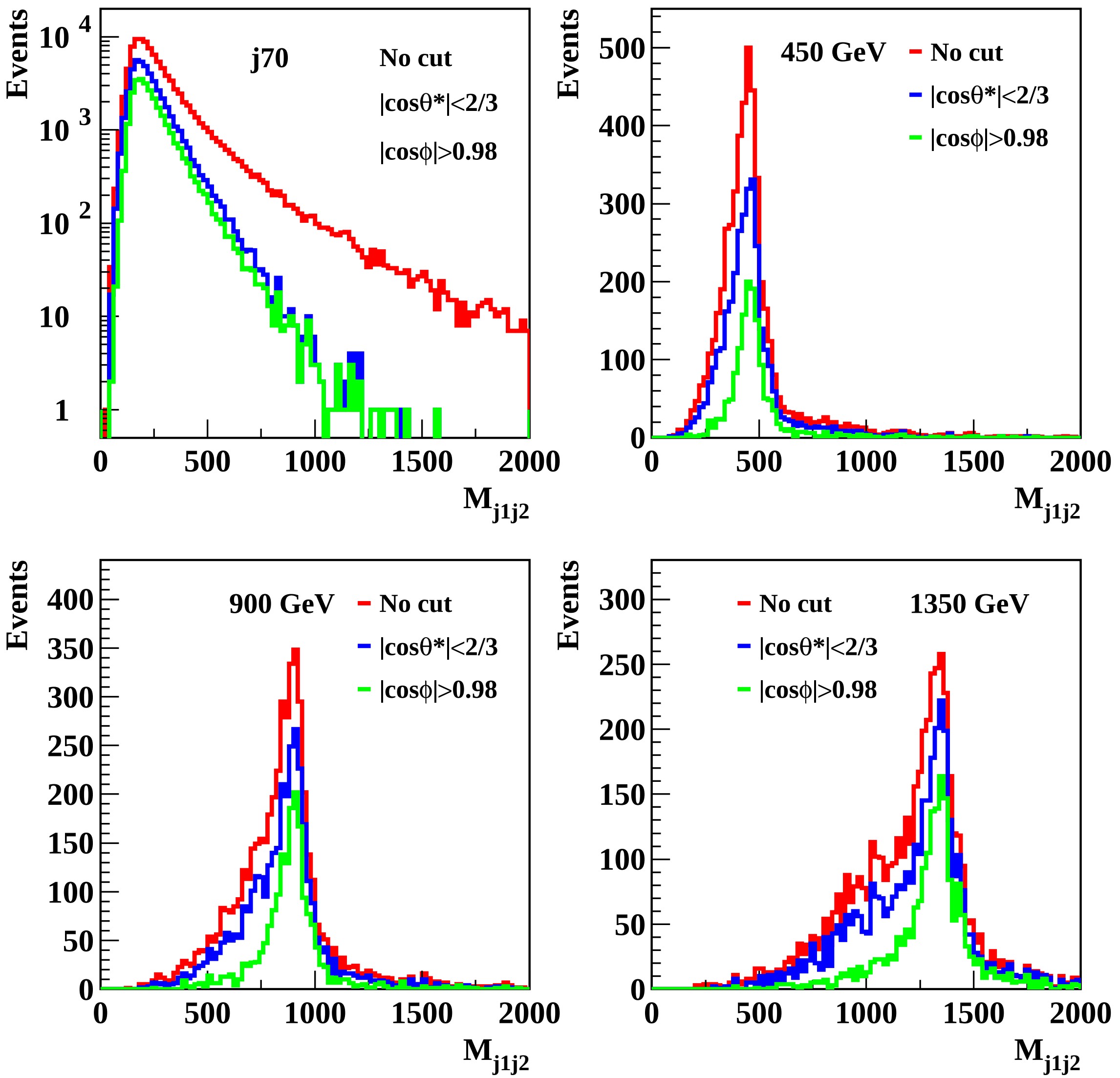
Two highest P_T ("biggest") jet invariant masses:

$\cos\theta^*$ cut suppresses **j70** background

$\cos\phi$ cut improves signal peak shape

Detector esolution is as expected

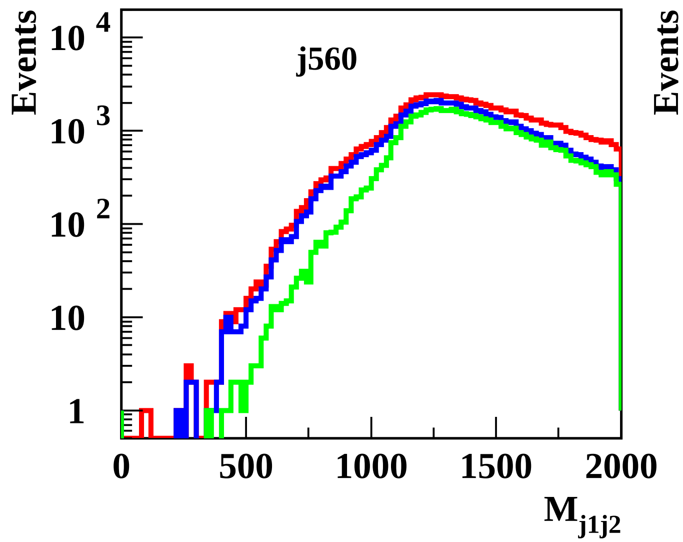
Tails due to QCD

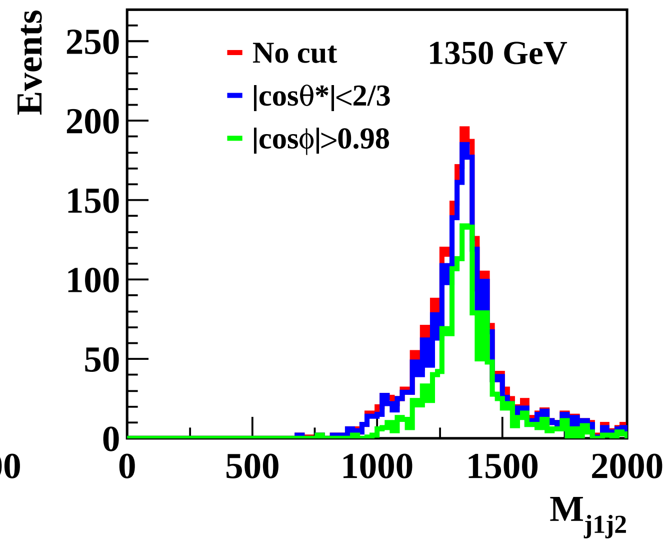


Invariant mass distributions: j560

Two highest P_T jet invariant masses:

$\cos\theta^*$ cut is less efficient for **j560** background





$\cos\phi$ cut not too useful here: rejects more signal than background

Long tails in the signal shape are due to QCD radiation:
sometimes “wrong” jets are picked up, or “right” jets are lost

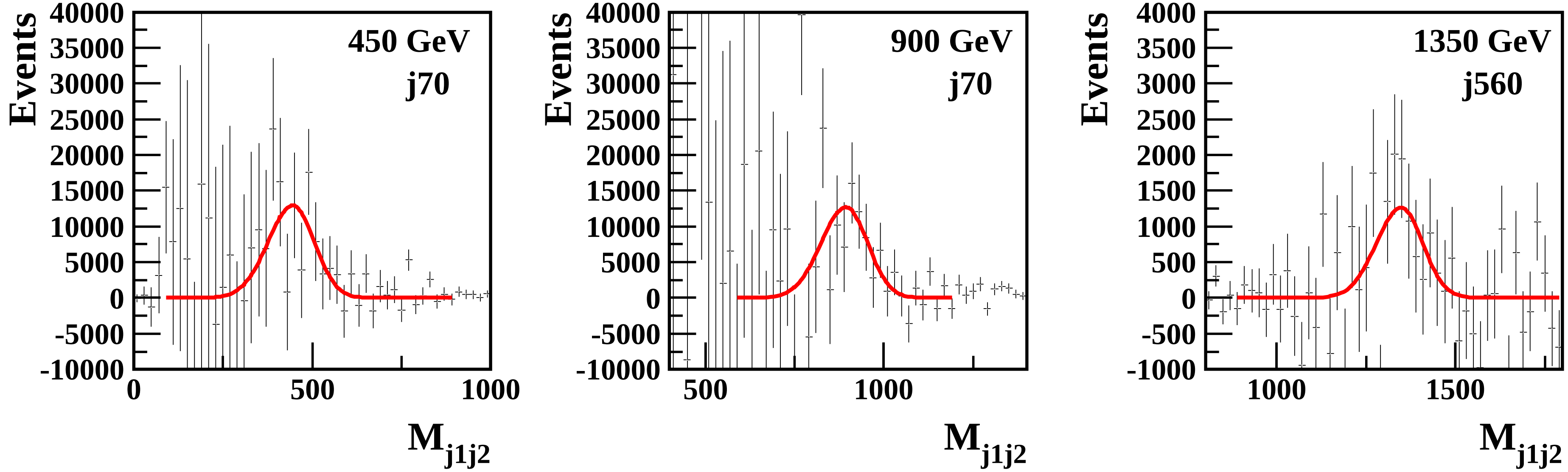
Search simulation

In the absence of full MC statistics, the following procedure was used:

- A smooth curve was fitted to the background, rescaled to the required integrated luminosity, and new, appropriate errors were generated.
- Signal was also rescaled to the required luminosity, and added to the background.
- A smooth fit was subtracted from the sum.
- The difference was fitted with a Gaussian of fixed width.

Discovering Pseudoscalar Gluinonium

This procedure is illustrated here at lowest integrated luminosity (for each mass) such, that a statistically significant signal is visible.



Mass: 446 ± 22 GeV $\quad 896 \pm 23$ GeV $\quad 1349 \pm 23$ GeV

Height: 13000 ± 3000 (4.2σ) $\quad 12700 \pm 2500$ (5.1σ) $\quad 1260 \pm 340$ (3.7σ)

Cuts not optimized yet; e.g. 900 GeV should benefit from tighter P_T cut.

Mass measured with high precision

Comparison to earlier (naive) estimates

- ATLAS detector performance in jet energy and angular resolution is good, core peak has expected width.

- Two-biggests-jet invariant mass resolution, effectively achieved at the moment, is strongly affected by QCD radiation due to problems in separating gluonic ISR and FSR.
  - Sometimes "wrong" jets have larger P_T, which results in the high-mass tail.
  - Jet splitting and soft jet radiation produces the low-mass tail.
  - Less than half of signal events end up in the core peak.

- Quark-gluon scattering background is very significant, especially at high invariant masses.

Main problems to solve — still the same

- **Suppress the background:** find criteria to suppress QCD background without losing too much signal.
  - Angular dependence (works; can be improved further).
  - Exclude quark jets if possible (jet shapes?).
  - Exploit energy/colour flow differences (if any) between S and B.
  - Other ideas?

- **Improve invariant mass resolution:** bring the tails back to core
  - Separate gluonic ISR from FSR (tried, with limited success).
  - Exploit zero P_T constraint (tried, with some success; should be done properly during reconstruction).
  - Energy/colour flow analysis.

Conclusions

- First few steps are made in full realistic simulation of pseudoscalar gluinonium searches as a narrow resonance in the two-jet system;
- Analysis is useful for some other exotics searches (e.g. technicolour);
- If observed, very good for gluino mass measurement;
- ATLAS detector performs as expected;
- QCD is more of a problem:
  - Extra high P_T jets in signal events
  - Extra soft jets in signal events
  - Big gluon-gluon and quark-gluon scattering background
- Still some way to go until the naively expected reach is achieved (and improved?)