LIGHT-GLUINO PRODUCTION AT LEP

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If gluinos are light, they will be produced in electron-positron annihilation at LEP, not only by radiation in pairs off quarks and antiquarks, but also without accompanying quark and antiquark jets. We here discuss the latter process, pair production of gluinos, in a model with soft supersymmetry breaking, allowing for mixing between the squarks. In much of the parameter space of the Minimal Supersymmetric Model (MSSM) the cross section corresponds to a $Z$ branching ratio above $10^{-5}$, even up to $10^{-4}$. A non-observation of gluinos at this level restricts the allowed MSSM parameter space.

1 Introduction

Moderately heavy gluinos, decaying to a photino, would be produced in hadronic collisions, and lead to events with missing energy (the photinos). Recent searches for gluinos by the CDF Collaboration have thus established a lower mass bound of the order of 140 GeV/$c^2$ [1]. This bound depends on the assumed decay mode of the gluino, it is valid for the case of direct decay to the lightest supersymmetric particle, $\tilde{g} \rightarrow q\tilde{\chi}$. The analysis is insensitive to light gluinos, $m_{\tilde{g}} \lesssim O(40 \text{ GeV}/c^2)$. However, various other experiments, in particular those at the CERN SPS [2] exclude, for short-lived gluinos, most of the region below 40 GeV/$c^2$, except for a narrow range around a few GeV/$c^2$ [3].

The existence of this low-mass gluino window has been given some attention recently [2, 3], and it is argued that data on $\alpha_s(m_Z)$ favour a light gluino [4]. It is easy to imagine that the gluino mass is induced radiatively, in which case it would naturally be light [5]. The importance of searching for light gluinos has repeatedly been stressed by Farrar [6, 7]. Clearly, if the gluino is very light, it should be produced at LEP, either by radiation in pairs off a quark [6, 8], or in pairs via the triangle diagram [9, 10, 11].

In the former case, there is some uncertainty about how difficult it would be to isolate the final four-jet state, because of the QCD background [12]. For the latter mechanism, the cross section has recently been re-evaluated, taking into account a heavy top quark mass and the effects of chiral mixing [13].

Light gluinos have actually been ruled out for some ranges of mass and lifetime by a variety of experiments. A recent survey has been compiled by Farrar [8] and is schematically reproduced as Fig. 1. The CUSB experiment [14] was sensitive to gluinos of any lifetime longer than the hadronization time scale, while others, like ARGUS [15] and UA1 [16] were only sensitive to gluinos decaying within the detector. The experiment by Bernstein et al. [16] searched for single charged particles resulting from the decays of neutral particles of lifetimes between $10^{-8}$ and $2 \cdot 10^{-6}$ sec. Their result has been interpreted in terms of excluded gluino masses and lifetimes by Farrar [8].

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Such plots are sometimes given in terms of squark masses instead of lifetimes. If the gluino decays to a massless photino, then the lifetime is related to the lightest relevant squark mass by

$$\tau \simeq 4 \cdot 10^{-8} \text{ sec} \left[ \frac{m_\tilde{g}}{1 \text{ TeV/c}^2} \right]^4 \left[ \frac{1 \text{ GeV/c}^2}{m_\tilde{g}} \right]^5. \quad (1.1)$$

The model considered in ref. [13] is in part given by the (soft) supersymmetry breaking part of the Lagrangian, which is given in terms of component fields as

$$L_{\text{Soft}} = \left\{ \frac{g m_d A_d}{\sqrt{2} m_W \cos \beta} Q^T c H_1 \tilde{d}^\dagger + \frac{g m_u A_u}{\sqrt{2} m_W \sin \beta} Q^T c H_2 \tilde{u}^R + \text{h.c.} \right\} - \tilde{M}_t^2 Q^T Q - \tilde{m}_u^2 \tilde{u}^R \tilde{u}^R - \tilde{m}_d^2 \tilde{d}^R \tilde{d}^R + \frac{m_\tilde{g}}{2} \sum_{a=1}^8 \left( \psi_{g_a} \bar{\psi}_{g_a} + \bar{\psi}_{g_a} \psi_{g_a} \right). \quad (1.2)$$

Subscripts $u$ (or $U$) and $d$ (or $D$) refer generically to up and down-type quarks.

The gluino mass is given explicitly by $m_\tilde{g}$, whereas squark masses depend not only on the mass parameters $\tilde{M}_t$, $\tilde{m}_u$ and $\tilde{m}_d$, but also on $m_u$, $m_d$, $m_Z$, $m_W$, $A_u$, $A_d$, $\mu$ and $\beta$. Here, $\mu$ is the coupling between the two Higgs doublets, and $\tan \beta$ the ratio of the two Higgs vacuum expectation values. The somewhat lengthy mass formulas are [18, 19]:

$$m_{\tilde{u},1,2}^2 = m_u^2 + \frac{1}{2} \left( \tilde{M}_t^2 + \tilde{m}_u^2 \right) + \frac{m_\tilde{g}^2}{4} \cos(2\beta)$$

$$m_{\tilde{d},1,2}^2 = m_d^2 + \frac{1}{2} \left( \tilde{M}_t^2 + \tilde{m}_d^2 \right) - \frac{m_\tilde{g}^2}{4} \cos(2\beta) \quad (1.3)$$

Figure 1: Excluded regions of gluino mass and lifetime.
Figure 2: The two classes of Feynman diagrams for $e^+ e^- \rightarrow \tilde{g} \tilde{g}$.

$$\pm \sqrt{\left[ \frac{1}{2} \left( M_{\tilde{L}}^2 - m_{\tilde{D}}^2 \right) + \frac{1}{2} \left( -\frac{2}{3} m_{\tilde{W}}^2 + \frac{1}{6} m_{\tilde{Z}}^2 \right) \cos(2\beta) \right] + m_{\tilde{d}}^2 |A_d + \mu \tan \beta|^2}$$  (1.4)

It should be noted that the above Lagrangian represents a model which is different from the recently considered “constrained” models based on Grand Unification and supergravity \cite{20}, the gluino mass is here not tied to the other gaugino masses.

2 The $e^+ e^- \rightarrow \tilde{g} \tilde{g}$ Cross Section

In the decay of the $Z$, or more generally in electron-positron annihilation, the pair production of gluinos can proceed via the two generic diagrams (a) and (b) of Fig. 2, where the internal lines of the triangles are quarks and squarks.

The amplitude for

$$e^+ e^- \rightarrow \tilde{g} \tilde{g}$$  (2.1)

will be proportional to the gluino current which can be written as a sum of contributions from the different quark flavours associated with the triangle diagrams, with the $u$-quark contribution

$$\tilde{G}_u^\mu = \left( \tilde{G}_{uu1}^\mu + \tilde{G}_{uu2}^\mu \right) + \left( \tilde{G}_{11u}^\mu + \tilde{G}_{22u}^\mu + \tilde{G}_{12u}^\mu + \tilde{G}_{21u}^\mu \right) + \text{crossed terms}.$$  (2.2)

The different labels refer to the quark and squark propagators of the triangle diagram.

We find that the cross section is proportional to the square of the sum of two partial amplitudes, corresponding to the contributions of the two diagrams (a) and (b). This is possible, since there is
essentially only one invariant amplitude \( \mathfrak{1} \). The integrated cross section thus takes the form

\[
\sigma = \frac{g^2 \pi^3}{12 E \cos^2 \theta_W} \left( \sqrt{E^2 - m_Z^2} \right)^3 \left( g_V^2 + g_A^2 \right) \left( s - m_Z^2 \right)^2 + \Gamma_Z^2 m_Z^2 \sum (A_a + A_b) \right|^2 ,
\] (2.3)

with \( E \) the beam energy and the sum running over quark flavours \( q \). The two partial amplitudes correspond to diagrams (a) and (b) and are given in ref. \([13]\).

Actually, since there is only one invariant amplitude, whose structure is determined by the fact that it describes the annihilation of two massless fermions to a pair of self-conjugate fermions \( \mathfrak{3} \), the angular distribution is given by the familiar \( 1 + \cos^2 \theta \).

### 3 Conditions for Vanishing Cross Section

In order to better understand what is required for the cross section to be large, let us first state the conditions that must be satisfied in order for it to vanish.

The gluino pair production cross section would vanish if the following conditions were both satisfied \([11]\):

1. mass degeneracy in each quark isospin doublet, \( m_d = m_u \) (this is violated),
2. mass degeneracy in each squark isospin doublet, i.e., \( m_{\tilde{d}_1} = m_{\tilde{d}_2} = m_{\tilde{u}_1} = m_{\tilde{u}_2} \), for each generation.

For comparison, in the case of no axial coupling to the \( Z \), i.e., in the QED limit, the cross section would vanish if there is \( \mathfrak{1} \):

- mass degeneracy in each squark chiral doublet, i.e., \( m_{\tilde{u}_1} = m_{\tilde{u}_2} \), and \( m_{\tilde{d}_1} = m_{\tilde{d}_2} \) for each generation.

This condition is less strong than item (2) above.

The magnitude of the cross section will depend on how strongly these conditions (1) and (2) are violated. Especially for the third generation, item (1) is violated. This is generally believed to imply that the squark isospin doublets are not degenerated either. However, in a consistent MSSM, the squark masses can not be specified as free parameters, they emerge as dependent on the more fundamental parameters of the Lagrangian.

One may ask whether it is possible for all squark masses to be degenerate. From eqs. (1.3) and (1.4), this is seen to require

\[
A_u + \mu \cot \beta = A_d + \mu \tan \beta = 0 \tag{3.1}
\]

and (invoking \( m_W^2 = \cos^2 \theta_W m_Z^2 \))

\[
\cos(2\beta) = \frac{m_u^2 - m_d^2}{m_W^2} \tag{3.2}
\]

The last condition clearly cannot be satisfied for a realistic top quark mass, so we conclude that there will inevitably be a contribution to the gluino pair-production cross section from the third generation.
For the purpose of developing some intuition for how large the gluino pair production cross section would be at LEP, we show in Fig. 3 the ratio

\[ R = \frac{\sigma(e^+e^- \rightarrow \tilde{g}\tilde{g})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

(4.1) vs. maximal squark mass splitting \( \delta m_{\tilde{q}} \). The plot is based on a scan of the MSSM parameter space.

Figure 3: Cross section ratios \( R = \frac{\sigma(e^+e^- \rightarrow \tilde{g}\tilde{g})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \) at the Z resonance. The figure shows the result of a scan of parameter space, against the largest resulting squark mass difference. For gluino, bottom and top quark masses given by \( m_{\tilde{g}} = 3.5 \text{ GeV}/c^2 \), \( m_b = 4.8 \text{ GeV}/c^2 \), and \( m_t = 170 \text{ GeV}/c^2 \). All encountered cross section ratios are represented by dots in this scatter plot. The horizontal axis gives the largest resulting squark mass difference. The cross section ratios are seen to be typically between \( 10^{-4} \) and \( 10^{-2} \). The \( Z \) branching ratio is obtained upon multiplying by 3.3%. Parameter sets that lead to any one of the squarks being light, \( m_{\tilde{q}} < 45 \text{ GeV}/c^2 \), are left out, since such light squarks would have been detected at LEP [21].

The band structures are ascribed to the discreteness of the sampling, as well as the rather complex dependence the cross section has on the many parameters. If the squark masses are taken as free parameters, then the cross section displays narrow valleys in the space of squark masses. Some of these valleys are related to the regions of vanishing cross sections quoted in Sect. 3, but there are also regions of low cross section not directly related to the conditions of Sect. 3, as illustrated in Fig. 4.
The value for the gluino mass, \( m_{\tilde{g}} = 3.5 \text{ GeV}/c^2 \), has been chosen as representative of the "light-gluino window". Actually, the cross section has only a very weak dependence on the gluino mass, as long as it is well below the kinematical threshold \([22]\).

Figure 4: Cross section ratio \( R \) as a function of squark masses \( m_{\tilde{d}_1} \) and \( m_{\tilde{d}_2} \), for two values of \( m_{\tilde{u}} \), and with \( m_{\tilde{u}_1} = 1 \text{ TeV}/c^2 \) and \( m_{\tilde{u}_2} = 100 \text{ GeV}/c^2 \).

5 Discussion

Even though the cross section for producing light gluinos could be rather large at LEP, their actual discovery might be difficult. First of all, we note that their contribution to the total \( Z \) width, \( 2490 \text{ MeV} \cdot R \), would lead to a small surplus of two-jet events, as compared with three-jet events, and thus a minute reduction of \( \alpha_s \).

For the purpose of discussing the signatures of gluino jets, let us consider the following cases separately: (i) the gluinos are unstable and decay within the detector, \( \tau_{\tilde{g}} \leq \mathcal{O}(10^{-9} \text{ sec}) \) (corresponding to a squark mass of \( m_{\tilde{q}} \leq 2 \text{ TeV}/c^2 \)), or (ii) the gluinos are long-lived or stable, and do not decay inside the detector.

If the gluinos do not decay within the detector, their discovery would be very difficult. They would fragment to jets consisting of ordinary hadrons and a leading \( R \)-hadron. The lightest \( R \)-hadron is believed to be the gluinoball, \( R_0 \), consisting of \( \tilde{g}g \) \([6, 7]\). This will presumably interact a few times in the calorimeter, depositing a major fraction of its energy. Such events would therefore be hard or impossible to distinguish from ordinary \( q\bar{q} \) events.
The more hopeful situation is when the gluinos decay within the detector, such that the resulting events will have missing energy due to the escaping neutralino. This is the standard SUSY signal. The most serious background will presumably be from $b \bar{b}$ events, where some energy is carried away by neutrinos. But the semileptonic decay of the $b$ also results in a charged lepton, which in principle should distinguish these events from the gluino events.

Another kind of background would be $q \bar{q}$ events in which not all the energy of the neutralinos is detected. Again, this appears to be a less serious problem, but a dedicated Monte Carlo study might be necessary in order to fully understand these backgrounds.

In summary, the pair production of light gluinos, without accompanying quark jets, is in $Z$ decay large enough to be measurable in much of the MSSM parameter space, and should therefore be searched for vigorously.

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