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GLUINO SIGNATURES AT THE $p\bar{p}$ COLLIDER

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ABSTRACT

Gluino pairs may be copiously produced at the CERN $p\bar{p}$ Collider. We present rate estimates implementing appropriate experimental cuts on missing transverse momenta and the transverse energy of jets from $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ decay. We discuss the p_T distributions of jets from $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ decay and the fractions of apparent one-, two-, three-, and four-jet events coming from $\tilde{g}\tilde{g}$ production. Gluinos with masses $\lesssim 40$ GeV could provide an observable signature in present $p\bar{p}$ Collider data.

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Supersymmetry (SUSY) is the most promising framework for explaining the hierarchical ratio between m_W and the Planck mass or the grand unification scale, and for unifying gravity with particle physics¹⁾. One of the immediate consequences of simple SUSY is the existence of supersymmetric partners of all the known quarks, leptons, and gauge bosons. Whilst SUSY requires that the couplings between quarks and gluons and their partner squarks and gluinos should be $O(\alpha_s)$, the sparticle masses are model-dependent and could be anywhere between a few GeV and $O(1)$ TeV¹⁾. The present experimental lower limit on the gluino mass is a few GeV²⁾. If their masses are not too large, the strongly interacting squarks and especially gluinos should be copiously produced at $p\bar{p}$ colliders. Existing perturbative QCD calculations³⁾ suggest that present CERN $p\bar{p}$ Collider experiments should be sensitive to gluinos weighing up to 40 or 50 GeV.

In this paper we study signatures of gluino production as a function of the possible gluino mass⁴⁾. The gluino is expected⁵⁾ to decay predominantly into $q\bar{q}\tilde{\gamma}$, where the photino $\tilde{\gamma}$ is anticipated to be the lightest sparticle. Being stable, weakly interacting, and neutral, the $\tilde{\gamma}$ escapes from the experimental apparatus like a neutrino, providing a signature of missing transverse momentum⁶⁾ (Fig. 1) with no associated charged lepton. Present collider experiments can detect missing transverse momenta p_T^{miss} larger than about 15 GeV⁶⁾. We show that although the total $\tilde{g}\tilde{g}$ production cross-sections are reduced by requiring $p_T^{\text{miss}} > 15$ GeV and by demanding, in addition, the presence of at least one q or $\bar{q}$ jet with transverse momentum $> p_T^{\text{cut}} = O(30)$ GeV (Fig. 2), the reduction in cross-section is less dramatic for more massive gluinos, and if gluinos have masses less than about 40 GeV they should be detectable in present collider data. We estimate in Figs. 3 and 4 the fractions of one-, two-, three-, and four-jet events which are detectable under realistic experimental conditions, using cuts similar to those used by UA1 in the reduction of their data presented in Ref. 7. Whilst the total rate of missing transverse momentum events itself depends on the gluino mass $m_{\tilde{g}}$, it is desirable to find a quantity derived from the observable jet parameters which estimates $m_{\tilde{g}}$ correctly. We find that the minimum mass⁸⁾ [or cluster transverse mass⁹⁾] previously discussed in connection with diffractive $t \rightarrow b\mu\nu$ decay can also be used to estimate $m_{\tilde{g}}$ quite accurately, despite the danger of confusing jets from the decays of different gluinos, and the fact that gluinos are not in general produced with negligible p_T .

There are three essential ingredients in our calculations:

- a) differential cross-sections for the QCD subprocesses $gg \rightarrow \tilde{g}\tilde{g}$ and $q\bar{q} \rightarrow \tilde{g}\tilde{g}$, which we take from Ref. 3;
- b) the gluon structure function in the proton, which we take from the CDHS parametrization evolved using the Altarelli-Parisi equations as described in Ref. 10;
- c) distributions for $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ decay which we compute using a decay matrix element squared,

$$|M|^2 \propto (p_{\tilde{g}} \cdot p_{\bar{q}})(p_{\tilde{\gamma}} \cdot p_q) + (p_q \cdot p_{\tilde{\gamma}})(p_{\tilde{g}} \cdot p_{\bar{q}}), \quad (1)$$

although our results are largely insensitive to this assumption, phase-space decay giving similar results. We neglect the masses of the final-state quarks and photino: in many models¹⁾ $m_{\tilde{\gamma}} = O(1/10)m_{\tilde{g}}$, which is less than 5 GeV for the range of $m_{\tilde{g}}$ of interest here.

*) This signature is more general than the specific SUSY process that we discuss here, since all SUSY decay chains are expected to terminate with a stable neutral sparticle.

After convolution of the above three processes we obtained the distributions of p_T^{miss} for different gluino masses presented in Fig. 1. We see that whereas the total cross-section for $\tilde{g}$ production decreases rapidly with increasing $m_{\tilde{g}}$, the number of events with large p_T^{miss} decreases more slowly. The signature for $\tilde{g}\tilde{g}$ production is therefore large p_T^{miss} with no charged leptons. The missing transverse momentum should be larger than the experimental resolution of a detector such as UA1, which surrounds the interaction point almost hermetically and is therefore particularly well suited to measure p_T^{miss} . The experimental resolution for measuring p_T^{miss} is typically 5 GeV⁶⁾, so to determine the “detectable” SUSY cross-section we adopted a cut $p_T^{\text{miss}} > 15$ GeV, and cross-sections with this cut applied are shown in Fig. 2. We see that with the present integrated luminosity of about 100 nb⁻¹, $\tilde{g}\tilde{g}$ production is in principle detectable (≥ 10 events expected) for $m_{\tilde{g}}$ up to 50 GeV. With an increase in luminosity by a factor of 10, gluino masses up to 65 GeV should be accessible.

In the present data the SUSY event signature of missing transverse momentum is compromised by the trigger requirement that at least one jet be seen in the apparatus⁶⁾, and that the transverse energy exceed about 30 GeV. The trigger is fully efficient above 30 GeV, but has some efficiency down to 20 GeV. To illustrate the effects of this jet trigger on the SUSY signature, we have plotted in Fig. 2 the transverse momentum of the largest p_T jet as a function of $m_{\tilde{g}}$. We see that triggering on events containing a jet with $p_T > p_T^{\text{cut}} = O(30)$ GeV reduces the cross-sections for low gluino masses, but that their effects are less important for higher gluino masses. Figure 3 (4) shows that the gluino signature should still be measurable for $m_{\tilde{g}} \lesssim 40$ GeV with the present integrated luminosity even if one makes a trigger cut: $p_T^{\text{cut}} = 20$ (30) GeV, and $m_{\tilde{g}} \lesssim 65$ GeV with an order of magnitude more luminosity.

The rapidity distributions for q and $\bar{q}$ jets from $\tilde{g}$ decay are quite peaked around $y = 0$, and very few jets are produced with $|y| > 3$. We would expect the q and $\bar{q}$ jets from $\tilde{g}$ decay to resemble those seen in e^+e^- annihilation, so that their charged multiplicities would typically exceed 2.

Whilst an idealized $\tilde{g}\tilde{g}$ production and decay event yields four final-state jets from the two $(q\bar{q})$ combinations, some of these jets may coalesce if their azimuthal angular separation $\Delta\phi$ and rapidity difference Δy are small, or be lost if their p_T is too small to be picked up by an experimental jet-finding algorithm. Accordingly we have calculated the fractions of observable one-, two-, three-, and four-jet events, taking only jets with $p_T > 10$ GeV and coalescing jets with $[(\Delta\phi)^2 + (\Delta y)^2]^{\frac{1}{2}} < 1$. Following UA1⁷⁾, we present cross-sections with

$$p_T^{\text{miss}} > \sigma : \sigma \equiv 0.7 \sqrt{\sum_{\text{jet}} E_T + 20 \text{ GeV}} \quad (2)$$

corresponding to a 4σ imbalance in p_T for a detector with transverse momentum resolution $\Delta p_T = 0.7 \sqrt{E_T}$ with 20 GeV being the average E_T of the $p(\bar{p})$ debris. The results are shown with a jet trigger $p_T^{\text{cut}} = 20$ GeV in Fig. 3, and with $p_T^{\text{cut}} = 30$ GeV in Fig. 4. We see that relatively few events still exhibit the idealized four-jet topology, whilst most events have fewer observable jets. The azimuthal angle of the missing p_T vector is only weakly correlated with the azimuthal angles of the observable jets, except for small $m_{\tilde{g}}$. This means, for example, that the missing p_T in two-jet events will not in general be collinear, in contrast to events where b or c quarks decay into energetic neutrinos. The second set of cuts applied by UA1, namely demanding a missing p_T vector of magnitude greater than 2σ which is separated in azimuthal angle by $> 100^\circ$, is almost equivalent to the 4σ cut (2) for one-jet events, but considerably more destructive to the supersymmetric signature in multi-jet events.

Although the collider sensitivity to $m_{\tilde{g}} \lesssim 40$ to 50 GeV takes us considerably beyond the present²⁾ experimental limit of a few GeV, it does not explore all the theoretically allowed range¹⁾, which extends up to $O(1)$ TeV. This range could, however, be explored by the next generation of colliders, at present under discussion, such as the Superconducting Super Collider and the Juratron. Perturbative QCD calculations of the $\tilde{g}\tilde{g}$ cross-section indicate that gluinos with masses up to $O(1)$ TeV should be observable at a collider with 20 TeV in the centre of mass. We have explored the experimental signatures of gluinos with masses up to 1 TeV and have found that their experimental signatures should be considerably cleaner than in the present energy regime. This is because the transverse energy resolution of calorimeters such as UA1 increases⁶⁾ as $\Delta E_T \cong 0.7 \sqrt{E_T} \propto \sqrt{m_{\tilde{g}}}$, whilst the typical p_T^{miss} scales as $m_{\tilde{g}}$. Therefore a cut of $p_T^{\text{miss}} > 50$ GeV should provide a clean sample of genuine events with missing p_T without greatly reducing the total SUSY cross-section. Details of our studies of $\tilde{g}$ production at multi-TeV hadron colliders and the separation from heavy quark decays with missing neutrinos will be presented elsewhere¹¹⁾.

Suppose that either now or in the future a missing transverse momentum signal is established with event topologies compatible with $\tilde{g}\tilde{g}$ production and decay. Clearly the total SUSY cross-section itself depends on the gluino mass, but how can one estimate the unknown gluino mass using the observable q and $\bar{q}$ jet parameters, despite the absence of information about the two missing photinos? This problem is analogous to that of estimating the mass of a heavy quark seen to decay semileptonically, such as $t \rightarrow b\mu\nu$. It has been proposed that one estimate the masses of t -quark hadrons produced diffractively with $p_T \ll m_t$ by computing for each event the minimum mass⁸⁾ [or cluster transverse mass⁹⁾] defined by

$$m^* \equiv [m_{\text{vis}}^2 + 2p_T^{\text{miss}2} + 2p_T^{\text{miss}}(m_{\text{vis}}^2 + p_T^{\text{miss}2})^{\frac{1}{2}}]^{\frac{1}{2}} \quad (3)$$

where m_{vis} is the invariant mass of the visible decay products (b jet and μ in the t -quark case, q and $\bar{q}$ jet in our case). The distribution in $\xi \equiv m^*/m_{t \text{ or } \tilde{g}}$ peaks at $\xi \approx 1$ as $(1 - \xi^2)^{-\frac{1}{2}}$, and is relatively insensitive to p_T smearing at production and to experimental cuts⁸⁾. We have three problems in $\tilde{g}\tilde{g}$ production which were absent in the t -quark case, namely: i) the fact that perturbative QCD does not necessarily produce the $\tilde{g}$ with negligible p_T ; ii) the possibility of confusing which jets are the decay products of which gluino; and iii) the possibility that two or more jets may coalesce. However, because the parton-parton collision luminosities fall as the subprocess centre-of-mass energy $\sqrt{\hat{s}}$ decreases, and because point-like cross-sections fall as $\hat{s}^{-1}$, most of the $\tilde{g}\tilde{g}$ pairs are produced with invariant masses $\sqrt{\hat{s}}$ close to $2 m_{\tilde{g}}$, and hence the gluinos have $p_T \lesssim O(m_{\tilde{g}})$. We were therefore encouraged to compute the distribution in minimum mass (2) from Monte Carlo $\tilde{g}\tilde{g}$ and $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ four-jet events and found that its mean correctly reproduced $m_{\tilde{g}}$. In real life, one does not know which jet $i = 1$ to 4 comes from which gluino decay. We have studied this confusion problem by computing $m^*(ij)$ for each pair of jets and for the complementary pair $m^*(kl)$, taking the combinations (ij) and (kl) which minimize

$$|m^*(ij) - m^*(kl)| / |m^*(ij) + m^*(kl)| \quad (4)$$

and calculating the mean value of $m_{\tilde{g}}^? \equiv \frac{1}{2} [m^*(ij) + m^*(kl)]$ for this particular combination. We find that the mean value of $m_{\tilde{g}}^?$ exceeds the true value of $m_{\tilde{g}}$ by about 10% even after requiring $p_T^{\text{miss}} > 15$ GeV. Therefore this simple extension of the minimum mass (2) approach already provides a

crude measure of the gluino mass, although the decay jet distributions could undoubtedly be exploited in more sophisticated ways.

We conclude that the production cross-sections for gluinos are sufficiently large, and their decay signatures are sufficiently clean, that present $p\bar{p}$ Collider data can be used to search for gluinos weighing up to 40 GeV. Future collider experiments could¹⁰⁾ explore all the theoretically expected mass range up to $O(1)$ TeV.

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Figure captions

- Fig. 1** The perturbative QCD cross-sections in $p\bar{p}$ collisions at 540 GeV for $\tilde{g}\tilde{g}$ production followed by $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ decay, as functions of the gluino mass $m_{\tilde{g}}$ and the missing transverse momentum p_T^{miss} , binned in units of 5 GeV.
- Fig. 2** The cross-sections for $\tilde{g}\tilde{g}$ production followed by $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ decay, as a function of $m_{\tilde{g}}$ and of the largest jet p_T , binned in units of 5 GeV.
- Fig. 3** The total and topological cross-sections for $\tilde{g}\tilde{g}$ production followed by $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ decay giving one-, two-, three-, or four-jet final states with $p_T^{\text{miss}} > 4 \times 0.7 \sqrt{E_T}$, with the added requirement that the largest p_T jet have $p_T > p_T^{\text{cut}} = 20$ GeV. Jets with $[(\Delta\phi)^2 + (\Delta y)^2]^{\frac{1}{2}} < 1$ have been coalesced, and jets with $p_T < 10$ GeV have been discarded.
- Fig. 4** As for Fig. 3, with the additional trigger requirement that the jet with the largest p_T have $p_T > p_T^{\text{cut}} = 30$ GeV.

Fig. 1

Fig. 2

Fig. 3

Fig. 4