Light, Long-Lived Gluinos in DIS at HERA

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Abstract: A method of searching for gluinos in (3+1) jet events in deep inelastic scattering (DIS) at HERA is presented. Event shape variables that are sensitive to gluino production and the dependence of cross-sections on x and Q^2 are investigated. A parton-level Monte Carlo study for events with $Q^2 > 4$ GeV^2 shows that although standard QCD and gluino producing processes behave differently, the small size of the gluino cross-section makes a search for gluinos using this method impossible, given the present prospects for luminosity ($500\,\mathrm{pb}^{-1}$) at HERA.

1 Introduction

The supersymmetric partner of the gluon, the spin 1/2 gluino ($\tilde{g}$), is predicted by supersymmetric extensions of the Standard Model [1]. Gluino searches have placed limits on the mass $m_{\tilde{g}}$, and lifetime $\tau_{\tilde{g}}$, of the gluino, but it is not clear that a light, long-lived gluino has been experimentally excluded [2]. Like the gluon, a long-lived gluino would be a strongly interacting particle, which fragments and could be detected as a jet in multijet events. Unlike the gluon, the gluino has spin 1/2, causing gluino and gluon events to exhibit different event shapes. Rather than seeking to identify individual gluino events, a search could detect gluino production by means of an event shape distribution for a large number of events. OPAL performed such a search [3], but the results were inconclusive [4].

This paper discusses whether such a search for gluinos is possible in DIS at HERA. We first examine the dependence of gluino production on the kinematic variables x and Q^2 and discuss in which regions of phase space the gluino cross-section would be expected to be larger than its average. We then examine the distributions of three topological variables which are sensitive to the presence of gluino production. Finally, we study whether an experimental search at HERA would be able to detect gluino production using this method.

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2 Gluino and (3+1) Jet Production at HERA

Gluino production at HERA would occur to leading order in α_s^2, producing 3 jets in the detector, plus the proton remnant jet, which partly disappears into the beam pipe. The absolute DIS cross-section is not constant with respect to the kinematic variables x, Q^2. Due to the photon propagator in Fig. 1(a), there is a strong Q^2 dependence in the DIS differential cross-section, while the structure functions $F_2(x, Q^2)$ and $F_1(x, Q^2)$ grow rapidly with decreasing x [5]. Thus, the DIS cross-section is largest at small Q^2 and small x. The relative contributions of the various

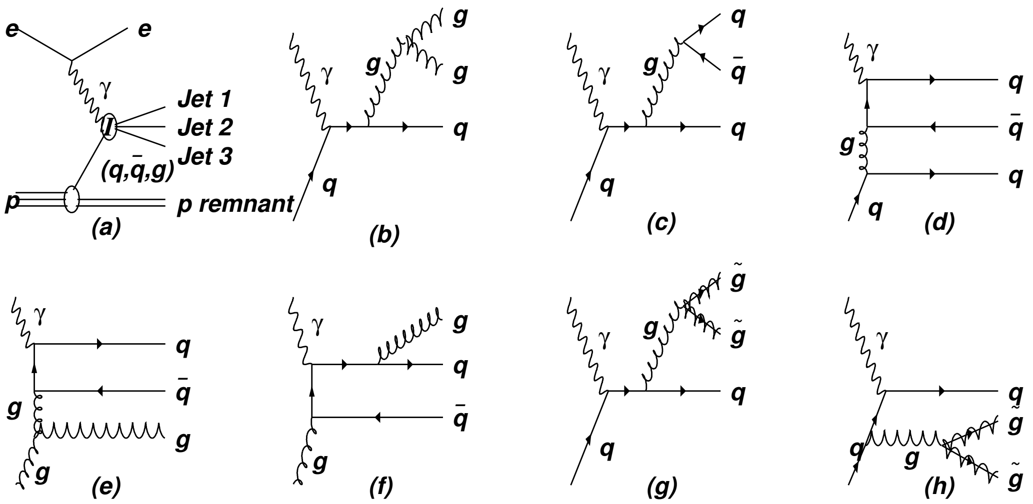

Figure 1: *(a) Generic diagram of (3+1) jet production at HERA. The vertex* I *represents a subprocess generating any of the final states: (b) qgg, (c) direct $qq\bar{q}$, (d) t-channel $qq\bar{q}$, (e) direct $q\bar{q}g$, (f) t-channel $q\bar{q}g$, (g), (h) gluino production by initial and final state gluon radiation.*

subprocesses are also dependent on x and Q^2. In Figs. 1(g) and (h), one sees that gluino production occurs only in quark-initiated events. Among the standard QCD backgrounds (Figs. 1(b)-(f)), however, there are gluon-initiated final states, such as $q\bar{q}g$ (Figs. 1(e),(f)). Because quark parton densities diminish with respect to the gluon density as x decreases, we expect the ratio of gluino events to standard QCD events to be more favourable at large x.

Figures 2(a) and (b) show the x and Q^2 dependence of the differential subprocess cross-sections and the total (3+1) jet cross-section. The deep inelastic (3+1) jet cross-section decreases with increasing x and Q^2, but the proportion of gluino events increases with increasing x. Thus, two competing factors play a role when deciding in which area of x and Q^2 space to conduct a search. A discussion of tradeoffs between statistics and signal-to-background ratio appears in Section 4.

To simulate (3+1) jet events to order α_s^2, we have used the parton-level Monte Carlo program PROJET [6] using the GRV parton densities [7]. PROJET contains the standard contributions to the (3+1) jet cross-section as well as the leading order matrix elements for gluino production in DIS. In order to avoid infra-red singularities in the cross-section due to collinear gluon radiation, PROJET uses the modified JADE jet algorithm which defines jets according to a parameter y_{cut}, requiring for each jet pair i, j that $m_{ij}^2 \geq y_{cut} W^2$. This algorithm also includes a reconstructed beam jet to account for longitudinal momentum which is partly lost into the beam pipe. To account for detector acceptance, we have required that the polar angle of the

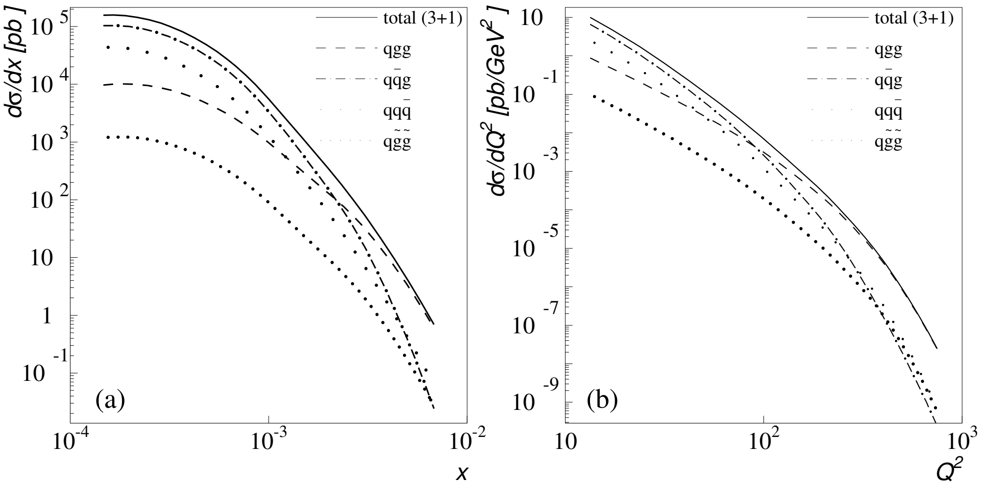

Figure 2: *Differential cross-sections of (3+1) jet QCD processes and of gluino production with respect to (a) x and (b) Q^2.*

outgoing detector jets and the outgoing electron be between $4°$ and $173°$, an angular acceptance typical for the HERA detectors. This corresponds to a range of $4\,\mathrm{GeV}^2 < Q^2 < 8 \times 10^4\,\mathrm{GeV}^2$.

Because the goal of this study is to determine whether a search for gluinos in DIS at HERA is possible at all, we make three optimistic assumptions in our calculation:

(1) All calculations are made with $y_{cut} = 0.01$. Although at $y_{cut} = 0.01$ the calculation is theoretically well defined, when analysing data it is often desirable to increase y_{cut} to decrease the influence of detector resolution and hadronisation on the jet definition. This would result in a decrease in the total (3+1) jet cross-section and a reduction of statistics.

(2) We use a parton-level Monte Carlo prediction. Directly examining the behaviour of final-state partons ignores hadronization effects and the difficulties of reconstructing original parton momenta from energy deposited in a detector. This will cause any effects of gluino production in this study to appear more clearly than they would in practice.

(3) We assume $m_{\tilde{g}} = 0$. Supersymmetric theories require a gluino mass larger than several hundred MeV [8]. Due to reductions in phase space, the gluino cross-section decreases as $m_{\tilde{g}}$ increases [9]. Our choice of $m_{\tilde{g}} = 0$ means we will be considering a cross-section which is slightly larger than what would be seen in reality.

3 Topological Signatures

We studied three event shape variables that differentiate standard QCD from QCD with gluinos:

1. η_{struck} **: The pseudorapidity of the struck quark.** Unlike standard QCD processes, gluino events must be quark initiated in leading order. Because of the relatively high quark densities at larger x, we expect the struck quark in a gluino event to carry a larger fraction of the proton's momentum. Thus, we expect that for gluino events, the pseudorapidity of the struck quark $(-\ln(\tan^{-1}(\theta_{struck}/2)))$ is generally larger than in standard QCD events, i.e. the struck quark in a gluino event is more inclined to exit the event vertex in the proton direction.

To identify the struck quark jet we reconstruct the event in the Breit frame where the virtual photon is antiparallel to the struck quark and has twice its momentum (i.e. $-p_{\gamma^*} = 2p_{struck}$). In this frame we identify the highest-energy jet with the jet formed by the struck quark. Figure 3(a) shows the predicted distribution of η_{struck} for gluino events and for the standard QCD background. As expected, more gluino events are at larger η_{struck}.

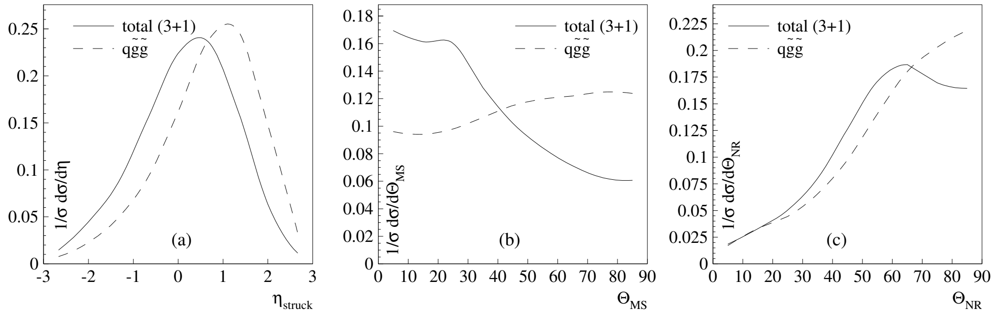

Figure 3: *Normalized differential cross-section with respect to the event shape variables (a) η_{struck}, (b) θ_{MS}, and (c) θ_{NR}. In each figure the distributions for standard QCD events and for events with gluino production are shown.*

2. θ_{MS} **: The Muñoz-Tapia-Stirling angle.** In the gluino producing diagrams, Figs. 1(g) and (h), the virtual photon always interacts directly with the parton from the proton. For the $q\bar{q}q$ and $q\bar{q}g$ final states, there are also diagrams in which the interaction between the photon and the proton proceeds by t-channel gluon exchange. Muñoz-Tapia and Stirling have defined an angle θ_{MS} which is sensitive to the presence of this exchange in photoproduction at HERA [10]; θ_{MS} is the angle between the plane formed by the highest-p_T jet and the proton beam and the plane formed by the two other jets. We have applied this angle to DIS.

In photoproduction, an electron radiates a photon along its direction of motion. When this photon interacts with a beam proton travelling antiparallel to the electron direction, the resulting event has very little transverse momentum and is boosted parallel to the beam axis. In DIS, the direction of momentum transfer need not be parallel to the beam axis. Therefore, when applying θ_{MS} to HERA DIS events, we first transform the event into the centre-of-mass frame of the virtual photon and the struck quark, where the angle θ_{MS} is defined. As prescribed in Ref. [10], we place a cut of $|\ \eta_{struck}\ | < 1$ in this system. Although η_{struck} is peaked far in the forward direction in the laboratory frame, in the centre-of-mass frame the η_{struck} is peaked at 0, and consequently this cut results in only a small loss of statistics.

Fig. 3(b) shows the differential cross-section as a function of θ_{MS} for gluino and standard QCD processes. Just as in photoproduction, θ_{MS} is (in principle) capable of differentiating between gluino and standard QCD events in DIS.

3. θ_{NR} **: The Nachtmann-Reiter angle.** The Nachtmann-Reiter angle θ_{NR} was conceived as a means of detecting the existence of the non-Abelian gluon self-coupling in QCD [11]. The angle's sensitivity to the spin of the particles produced at the secondary vertex of a radiated gluon also allows it to test for the production of spin-1/2 gluinos.

Originally, the Nachtmann-Reiter angle was defined for the case of e^+e^- annihilation as the angle between suitable directions formed from the two highest energy jets and the two lowest energy jets. We have defined θ_{NR} at HERA to be the angle between the struck quark jet and the two lower energy jets in the rest frame of the two lower energy jets. Similar angular momentum conservation and γ_5 invariance arguments apply as in the e^+e^- case.

The differential cross-section as a function of θ_{NR} is shown in Fig. 3(c). We see that for the gluino events it exhibits the same $\sin^2\theta_{NR}$ behaviour that is predicted for a virtual gluon splitting into two fermions [11]. For standard QCD events, the distribution is qualitatively different.

4 Search Strategies

To determine whether gluinos could be detected at HERA we pursued two different search strategies. First we investigated whether an experiment would be able to extract a gluino signal from a standard QCD background by imposing cuts based on the angular distributions mentioned above. Second we determined whether a χ^2 fit of the angular distributions of standard QCD plus gluino production to the angular distributions of standard QCD would be able to distinguish between the two distributions. For each method we investigated whether the result could be improved by looking in a favourable region of x and Q^2.

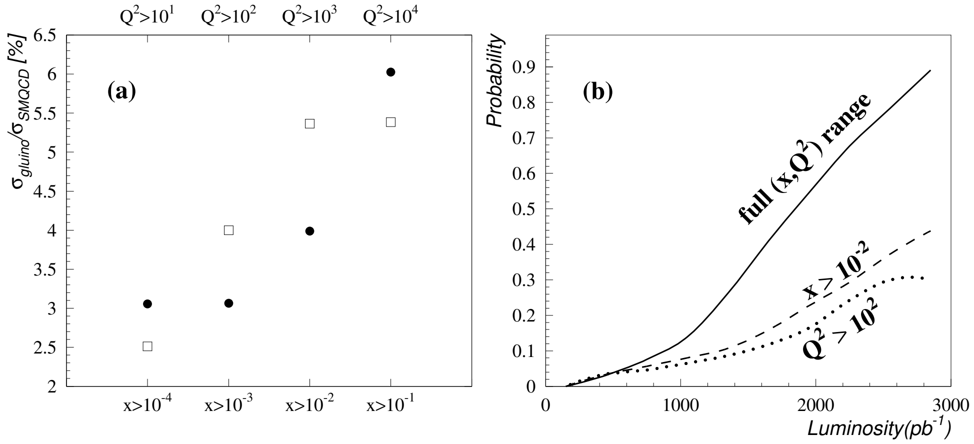

Figure 4: *(a) Signal-to-background ratio (in per cent) after event shape cuts for different regions of x (dots) and Q^2 (squares). (b) Probability that an experiment would be able to distinguish between QCD and gluino production at a 95% confidence level as a function of the available luminosity.*

The cuts made in an attempt to extract a gluino signal from the standard QCD background were derived from the distributions in Fig. 3. Our cuts are chosen to be at the point where the normalized distribution curves intersect: $\theta_{MS} \geq 50$, $\theta_{NR} \geq 70$, $\eta_{struck} \geq 1.0$. We computed the signal-to-background ratios for several values of cuts on x and Q^2. Although we vary the kinematic region where we evaluate our cuts, qualitatively the distributions change very little, and we impose the same cuts regardless of the kinematic region considered.

Figure 4(a) shows the gluino cross-section in the considered region in proportion to the standard QCD cross-section. Although the signal-to-background ratio has been improved from 1% (Fig. 2) to 6%, the uncertainties in the absolute cross-sections of QCD related processes are over 20%. Even with an unlimited statistical sample, this method would not succeed.

A χ^2 fit of the calculated signal-plus-background event shape distributions to the calculated background distribution would avoid the uncertainties inherent in the absolute cross-sections.

We divided our Monte Carlo sample into 5 bins in each of the variables η_{struck}, θ_{MS}, and θ_{NR}. Using a random number generator we simulated the statistical errors that would be seen in an experimental data sample containing QCD and gluino production events. For each value of the luminosity considered, we simulated 10000 experiments, and performed a χ^2 fit of the calculated signal ($\tilde{g}$) plus background (QCD) event shape distributions to the distribution from the calculated background (QCD).

The probability that an experiment performed would be able to distinguish standard QCD processes from standard QCD plus gluino production at a 95% confidence level is shown in Fig. 4(b). The current estimate of the lifetime integrated luminosity of HERA, $500\,\mathrm{pb}^{-1}$, is far too low to allow a search for gluinos at HERA by the above method.

5 Conclusion

We have investigated the effects of gluino production on three event shape variables that are in principle capable of differentiating between events with and without gluinos in (3+1) jet events in DIS at HERA. We have also studied the x and Q^2 dependence of the gluino production mechanism and the standard QCD subprocess mechanisms. Because the total gluino cross-section is small compared to the competing QCD background, it will not be possible using the angular distributions to determine whether or not gluinos are being produced at HERA.

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