Rapidity Gap Events for Squark Pair Production at the LHC

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Abstract. The exchange of electroweak gauginos in the $t$– or $u$–channel allows squark pair production at hadron colliders without color exchange between the squarks. This can give rise to events where little or no energy is deposited in the detector between the squark decay products. We discuss the potential for detection of such rapidity gap events at the Large Hadron Collider (LHC). We present an analysis with full event simulation using PYTHIA as well as Herwig++, but without detector simulation. We analyze the transverse energy deposited between the jets from squark decay, as well as the probability of finding a third jet in between the two hardest jets. For the mSUGRA benchmark point SPS1a we find statistically significant evidence for a color singlet exchange contribution.

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SUSY RAPIDITY GAPS

One of the main objectives of the Large Hadron Collider (LHC) is the search for supersymmetric (SUSY) particles [1]. In the energy range of the LHC we expect squark pair production to be one of the most important channels for the production of superparticles [2]. Squark pair production includes contributions with electroweak (EW) exchange particles at tree [3,4] or one-loop [5] level. The tree–level EW contributions can change the production cross section by up to 50% [4]. Moreover, EW gaugino exchange in the $t$– or $u$–channel gives rise to events with no color connection between the produced squarks.

QCD radiation then preferentially takes place in the phase space region between the respective connected initial quark and final squark, not between the two outgoing squarks. If the rapidity region between both squarks is indeed free of QCD radiation it is called a “rapidity gap”. The situation is different for the lowest order QCD contribution. The final squarks are color–connected and radiation into the region between them is expected. This difference might allow to isolate events with electroweak gaugino (color singlet [CS]) exchange, which could e.g. lead to new methods to determine their masses and couplings. The above discussion describes a single partonic reaction producing stable squarks. In reality, the squarks will decay. Even if we assume that each squark decays into a single jet, the rapidity distribution of these jets will differ from that of the squarks. Squark decay also leads to additional parton showers from final state radiation. Moreover, the underlying event produced by the beam remnants and their interactions can also deposit energy in the gap.
**NUMERICAL SIMULATION**

In the following we perform a full event simulation, including squark decays, hadronization, jet reconstruction and the “underlying event”, however without simulating the detector. To be specific, we consider rapidity–gap events for squark pair production at the LHC, where electroweak (EW) contributions at tree level are included. The production of the first two generations of squarks via $t-$ and $u-$channel diagrams is taken into account. $s-$channel contributions are neglected, since they are quite small [4], and are not expected to lead to rapidity–gap events. The mass spectrum and branching ratios of the sparticles are obtained from SPheno [6]. Analytical expressions for the squared and averaged matrix elements are given in Ref. [4]. We implemented the relevant matrix elements for QCD and as well for EW contributions in a simple parton–level simulation. Jets are reconstructed via the $k_T$ clustering algorithm of FastJet [7]. Events are analyzed using the program package root [8].

We impose the following cuts: the two highest transverse momentum jets have to satisfy: $E_T(j_i) \geq 100$ GeV; $|\eta(j_i)| \leq 5.0$ ($i = 1, 2$). We further suppress SM backgrounds by requiring a large amount of missing transverse energy: $\not{E}_T \geq 100$ GeV.

Squark pair events containing at least one $SU(2)$ singlet squark, which give rise to quite small EW contributions [4], are suppressed by requiring the existence of two like–sign charged leptons, with $p_T(\ell_i) \geq 5$ GeV; $|\eta(\ell_i)| \leq 2.4$ ($i = 1, 2$). In order to be able to define a meaningful rapidity gap, the two leading jets should be well separated in rapidity: $\Delta \eta \equiv |\eta(j_1) - \eta(j_2)| \geq 3.0$. We have to take into account that the two jets have finite radii. The “gap region” is therefore defined as: $\min[\eta(j_1), \eta(j_2)] + 0.7 \leq \eta \leq \max[\eta(j_1), \eta(j_2)] - 0.7$. One can expect that most of the particles produced during hadronization are within the cone of 0.7 of the corresponding jets [9]. The overall efficiency of our cuts relative to the entire squark pair sample is less than 1%, cf. [10]. Since we want to avoid “event pile–up”, i.e. multiple $pp$ interactions during the same bunch crossing, we assume an integrated luminosity of 40 fb$^{-1}$ at $\sqrt{s} = 14$ TeV.

Our first attempt to isolate “rapidity gap events” uses a completely inclusive quantity. We define $E_T^{gap, \text{particles}}$ as the total transverse energy deposited in the gap region; this is
FIGURE 2. Fraction of squark pair events passing a minijet veto in the rapidity–gap region, as predicted using full event simulations using Herwig++ and PYTHIA 6.4. The black curve is for the pure QCD sample, and the red (gray) curve for the QCD+EW sample.

computed from all photons and hadrons in the event (after hadronization and decay of unstable hadrons), but does not include the leptons produced in $\tilde{\chi}^0$ and $\tilde{\chi}^\pm$ decays. The distribution of $E_{\text{gap}}^{\text{particles}}$ is shown in Fig. 2 for Herwig++ and PYTHIA 6.4. In this and all following figures, black and red histograms denote pure QCD and QCD+EW predictions, respectively. We also show the statistical error for each bin.

We note that including EW contributions increases the number of events, although in most bins this effect is statistically not very significant. However, in the first bin, where the total $E_T$ is less than 5 GeV, the inclusion of these CS exchange contributions increases the number of events by a factor of $2.8 \pm 1.1$ and $2.36 \pm 0.56$ in the Herwig++ and PYTHIA 6.4 simulations, respectively. This indicates that CS exchange does lead to “gap” events where little or no energy is deposited between the two hard jets.

The difference between the two generators is as large as the effect from the CS events: PYTHIA 6.4 without CS exchange contributions predicts almost exactly the same number of events in the first bin as Herwig++ with CS exchange. PYTHIA 6.4 also predicts a $E_{\text{gap}}^{\text{particles}}$ distribution which is quite flat beyond 20 GeV, whereas the distribution predicted by Herwig++ flattens out only at about 40 GeV. One might thus be able to use the higher bins, where the effect of the CS exchange contributions is not very sizable, to decide which generator describes the data better, or to tune the Monte Carlo generators to the data. This should reduce the difference between the two predictions.

Predicting the total transverse energy flow is difficult, since this observable is strongly affected by semi– and non–perturbative effects. Thus, we discuss in the following the occurrence of relatively soft “minijets” in the gap region. Fig. 2 shows the fraction of events where the energy $E_{\text{Jet,max}}^{\text{gap}}$ of the most energetic jet in the gap region is less than the value $E_{\text{Jet,max}}^{\text{gap}}$ displayed on the $x$–axis. Since Fig. 2 shows event fractions, all curves asymptotically approach 1 at large $E_{\text{Jet,max}}^{\text{gap}}$. We assume that jets with transverse energy above $E_{\text{thresh}} = 5$ GeV can be reconstructed. If the true threshold is higher, the curves should simply be replaced by constants for $E_{\text{Jet,max}}^{\text{gap}} \leq E_{\text{thresh}}$. We expect that the underlying event by itself generates few, if any, reconstructable jets. The results here
are nevertheless still not quite immune to non–perturbative effects, since reconstructed jets may also contain a few particles stemming from the underlying event. Note also that a jet whose axis lies in the gap region might contain (mostly quite soft) particles that lie outside of this region. Conversely, even though we use a cluster algorithm, where by definition each particle belongs to some jet, some particles in the gap region might be assigned to a jet whose axis lies outside this region.

We see that PYTHIA 6.4 predicts more events without jet in the gap region than Herwig++. This is consistent with the observation that PYTHIA predicted more events with little or no energy deposited in the gap region and tends to generate fewer hard gluons than Herwig++ does, see [10]. Moreover, both PYTHIA 6.4 and Herwig++ predict a significant increase of the fraction of events without jet in the gap region once EW, CS exchange contributions are included; the effect is statistically most significant for $E_{T,\text{jet,max}}^{\text{gap}} \sim 20$ to 40 GeV. Here both generators predict an increase of the fraction of events without (sufficiently hard) jet in the gap by about 0.05. Taking a threshold energy of 30 GeV as an example, Herwig++ predicts about 1,570 out of the total of 4,032 events without jet in the gap once EW effects are included. This should allow to measure the fraction of events without jet in the gap to an accuracy of about 0.01; a shift of the jet–in–the–gap fraction by 0.05 thus corresponds to a change by about five standard deviations (statistical error only).

Unfortunately a pure SUSY QCD PYTHIA simulation leads to a fraction of events without jet of 0.45 for the same threshold energy, which is higher than the Herwig++ prediction including EW contributions. Clearly these large discrepancies between the two MC generators have to be resolved before reliable conclusions about the color flow in squark pair events can be drawn. In Ref. [10] we showed that a similar difference between the predictions of the two generators also exists for the jet–in–the–gap cross section in standard QCD. This indicates that such standard QCD events can be used during the earliest phases of LHC running to improve the event generators, hopefully to the extent that the difference between their predictions becomes significantly smaller than the effect from the EW contributions.

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