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Discovering baryon-number violating neutralino decays at the LHC

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Recently there has been much interest in the use of single-jet mass and jet substructure to identify boosted particles decaying hadronically at the LHC. We develop these ideas to address the challenging case of a neutralino decaying to three quarks in models with baryonic violation of R-parity. These decays have previously been found to be swamped by QCD backgrounds. We demonstrate for the first time that such a decay might be observed directly at the LHC with high significance, by exploiting characteristics of the scales at which its composite jet breaks up into subjets.

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The LHC potential for the discovery of supersymmetry broken at the TeV scale [1, 2, 3, 4, 5] has generated much interest. Certainly, the potential prize is great: TeV-scale supersymmetry could solve several puzzling problems and answer a number of open questions in modern particle physics, such as the fine-tuning of the Higgs mass, the unification of forces at high energies and the nature of dark matter. Effort has mainly been concentrated on investigations into the discovery reach and possibility of parameter measurements in the Minimal Supersymmetric Standard Model (MSSM) and various more constrained versions featuring a weakly-interacting and stable Lightest Supersymmetric Particle (LSP), which gives a missing-energy signature. Candidates for the LSP include the lightest neutralino, $\tilde{\chi}_1^0$, and the gravitino.

However, the gauge symmetries of the Standard Model (SM) also allow for dimension-four terms in the superpotential of the forms

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k,$$

which violate the R-parity that is imposed in the MSSM. Non-zero values for the couplings λ could imply drastically different phenomenologies for supersymmetry at the LHC, allowing for the decay of the LSP, or any heavier sparticle, directly to SM particles. At first glance this seems at odds with supersymmetric dark matter, but recent studies show that a gravitino LSP can be sufficiently long-lived to be a good dark matter candidate even in the presence of large R-parity-violating (RPV) couplings, with very specific signatures predicted for astrophysical gamma-ray measurements and for the LHC [6, 7, 8, 9].

Broadly speaking, we can classify the RPV models in terms of the dominant coupling λ and the identity of the Next-to-Lightest Supersymmetric Particle (NLSP), assuming that the gravitino is the LSP. The lepton-number-violating (LV) couplings λ and λ' generally give MSSM-like signatures with missing energy from neutrinos and/or extra leptons in the decays of the NLSP. The exception is a slepton/sneutrino NLSP that decays into two quarks via a dominant λ' coupling. Scenarios such as these should be easy to extract from the SM backgrounds, as shown for a neutralino NLSP in [10].

However, dominant baryon-number-violating (BV) couplings λ'' are more difficult to deal with, due to the large hadronic activity expected at the LHC, which threatens to drown decays such as $\tilde{\chi}_1^0 \to qqq$. The QCD background for jets with $p_T > 500$ GeV and a $\tilde{\chi}_1^0$ mass of $\mathcal{O}(100$ GeV) is about two orders of magnitude higher than the signal. The background's non-trivial shape means that it would be hard to establish whether a small deviation from the expected background is a signal of something new, or simply a defect in one's understanding of the background. Some success has been reported by relying on the production of a high-p_T lepton in the decay chain leading to the NLSP [10, 11, 12], but ideally one would wish to demonstrate the feasibility of signal isolation and mass measurement in a less model-dependent manner. Otherwise, one might fear that supersymmetry could escape discovery at the LHC by cloaking itself in BV decays.

In this Letter we investigate that problem by looking for jets from the decays of very boosted sparticles via BV couplings. Such decays give rise to a composite jet made up of two or more collimated subjets, with a jet mass related to that of the original sparticle, with specific properties predicted for the scale at which the main jet separates into subjets. Similar techniques have previously been used by the authors for analysing WW scattering [13, 14], for detecting massive boson decays in MSSM scenarios [15] and in Higgs searches [16]. In addition, a number of other techniques for separating hadronic decays of heavy particles from QCD backgrounds have been suggested by other groups [17, 18, 19, 20, 21, 22, 23]. The present article tackles a new and more difficult problem: how to identify a hadronic resonance of *unknown* mass in a scale invariant manner. The techniques presented here in a supersymmetric scenario with RPV clearly have applications to any hadronically-decaying massive-particle resonance that can be produced far above threshold, and are promising for broad use in the challenging LHC searches for hadronic decays of new particles.

We focus our investigation on the CMSSM benchmark point SPS1a [24], which features a neutralino with mass $m_{\tilde{\chi}_1^0} = 96.1$ GeV. We also look at two other

CMSSM points with larger sparticle masses and lower cross sections, that lie along the corresponding benchmark line [24]. RPV is incorporated by setting the coupling $\lambda''_{112} = 0.001$. Whereas the choice of benchmark point gives an optimistic value for the supersymmetric cross section, which for SPS1a is 47 pb at leading order, the dominant RPV coupling is chosen to be difficult: no heavy flavours are present to help tag the correct jets and the coupling is chosen to be relatively large, so that decays do not lead to displaced vertices [25]. We note that the gluino and squark masses at the SPS1a point are $\sim 600, 550$ GeV, respectively, which are both $\gg m_{\tilde{\chi}_1^0}$, and hence yield highly-boosted NLSPs in their decays.

In order to simulate sparticle pair-production events at the LHC with RPV decays, we use the Herwig 6.510 Monte Carlo event generator [26, 27, 28, 29] with CTEQ 6L [30] PDFs, and use Jimmy 4.31 [31] for the simulation of multiple interactions [32]. This is interfaced to the FastJet 2.4.0 [33, 34] jet-finder package using the Rivet [35] framework. Our background sample, consisting of QCD $2 \to 2$ events, $t\bar{t}$, W+jet, Z+jet and $WW/WZ/ZZ$ production is simulated with the same setup. The leading-logarithmic parton shower approximation that is used has been shown to model jet substructure well in a wide variety of processes [36, 37, 38, 39, 40, 41].

For both signal and background we generate a number of events equivalent to 1 fb^{-1} of LHC data at 14 TeV CM energy. No attempt is made at detector simulation through finite calorimeter granularity, but we do impose a geometrical acceptance cut on jets of $|\eta| < 2.5$.

To illustrate the types of approach that can be taken with subjet studies, we shall consider two complementary analyses. The first will be based on the k_T algorithm [42, 43] and will require substructure in two jets, i.e., one for each neutralino expected in an event. The other, based on the Cambridge/Aachen (C/A) algorithm [44, 45], will examine the substructure of just the hardest jet.

The (inclusive) k_T algorithm defines distances $d_{kl} \equiv \min(p_{Tk}^2, p_{Tl}^2)(\Delta R_{kl}^2/R^2)$, $d_{kB} \equiv p_{Tk}^2$, and sequentially merges the pair of objects k, l with smallest d_{kl}, unless there is a smaller d_{kB}, in which case k becomes a jet. The constant R sets the angular reach of the jets. Since the k_T distance is just the relative transverse momentum between objects, the mergers of interest for a decayed heavy-particle tend to be the last ones. This was exploited in [13, 14, 15], where a dimensionful cut was placed on the d_{kl} scale of the last merging in the jet, d_1, in order to preferentially select boosted W bosons over QCD jets, which, for a given mass, have smaller d_1.

However, our case differs from [13, 14, 15] in two respects. First, we are searching for an object of unknown mass, which means that we should avoid biasing the search with a dimensionful substructure cut. A good alternative is to cut on a dimensionless variable normalised to the jet mass m_j, $y_i = d_i R^2/m_j^2$. Secondly, the neutralino has a three-body decay, in contrast to a W-boson's two-body decay. This suggests that one should cut on the properties of the last *two* mergings, i.e. on y_1 and y_2. Their distributions are illustrated in Fig. 1. The left panel shows QCD jets with $p_T > 400$ GeV, while the right panel shows jets matched to neutralinos for the SPS1a benchmark point, with the jet within $\Delta R < 0.3$ of the neutralino, having $p_T > 400$ GeV and mass 90 GeV $< m_j <$ 120 GeV. Even after the hard cut on jet p_T, there are clear differences between neutralino jets and the QCD background.

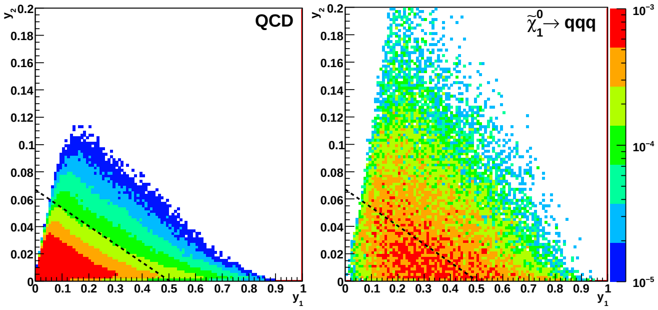

FIG. 1: The y-values from the k_T algorithm with $R = 0.4$ for the last and next-to-last merging for QCD jets (left), and jets matched to neutralinos (right). Also shown is the proposed cut line. Both distributions are normalized to unity.

For our full analysis with the k_T algorithm, we take $R = 0.4$ and use the following two cuts: i) at least three jets with $p_T > 400, 300, 100$ GeV and ii) two of the jets should be “neutralino candidates”, each with $p_T > 300$ and $y_2 > -0.13 y_1 + 0.067$. The choice of R is a compromise between capturing sufficient signal, favouring large R, and not smearing the mass peak with particles from the underlying event, favouring small R [46]. The third-jet cut is motivated by the expected presence of an acompanying jet from the squark or gluino decay, and we have verified that Herwig's simulation of the fraction of QCD events with a relatively soft third jet is consistent with NLO calculations [47]. The requirement of high p_T should ensure high trigger efficiency, as well as good collimation of the neutralino jets.

The mass distribution for the neutralino candidate jets is shown in Fig. 2 (left). The QCD background is still dominant after the cuts, but the neutralino is clearly visible as a perturbation on the rapidly falling background. This analysis reconstructs 5.6% of all neutralinos with $p_T > 400$ GeV in a 20 GeV mass window around the nominal mass; for QCD jets it accepts 0.071% of all jets with $p_T > 400$ GeV in the same window.

Even though we have introduced only dimensionless jet substructure cuts in the above analysis, the background distribution also has a peak near the neutralino mass. This is a consequence of higher-order perturbative effects [19, 48] and the peak position is determined by their interplay with the jet p_T and substructure cuts.

To avoid this issue, we consider the C/A algorithm, which successively recombines the pair of objects closest in ΔR_{kl}, until all objects are separated by more than R,

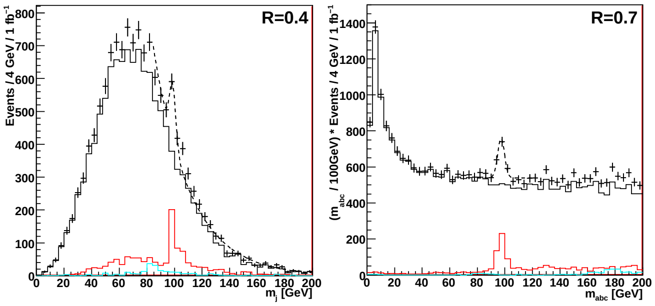

FIG. 2: Jet mass distribution (points with error bars) for the k_T algorithm (left) and C/A algorithm (right) after all cuts. Also shown are the contributions from QCD (black), supersymmetric events (red) and other SM backgrounds (cyan).

at which point they are the jets.

Because the ordering of C/A mergings knows nothing about the momentum scales, one cannot rely on the properties of the last mergings to tag relevant substructure. Instead we recurse through all mergings storing those that are sufficiently symmetric, $z \equiv \min(p_{Tk}, p_{Tl})/(p_{Tk} + p_{Tl}) > z_{\min}$, ignoring in the recursion the softer of the two subjets when $z < z_{\min}$, and from this we identify the two that have the largest JADE-type distance, $d^J_{kl} = p_{Tk} p_{Tl} \Delta R^2_{kl}$ (related to m^2_{kl} if k and l are massless). If the one with smaller d^J (labeled "bc") is contained within the other (labeled "a(bc)"), and $\mu \equiv m_{bc}/m_{abc} > \mu_{\min}$, then we consider "abc" to be a neutralino candidate. The cut on z causes one to ignore the soft splittings that dominate QCD branching and are largely responsible for producing the peak in the mass distribution of QCD jets. The cut on μ ensures the presence of a three-body decay structure inside the jet.

The full C/A-based analysis proceeds as follows: i) we use $R = 0.7$ and require at least three jets with $p_T > 500, 300, 100$ GeV, and $|\Delta\eta_{13}| < 1.5$, ii) the hardest jet is taken to be a neutralino candidate if it passes the substructure cuts with $z_{\min} = 0.15$ and $\mu_{\min} = 0.25$. For the events that pass the cuts, we plot in Fig. 2 (right) the distribution of m_{abc}, weighted with $m_{abc}/100$ GeV. Expectations from QCD are that this distribution should be rather flat for $m_{\min} \lesssim m_j \lesssim p_T R\sqrt{z_{\min}}$, where $m_{\min}$ is some small value governed by higher orders. This is indeed what we observe, and for a range of choices of R value and p_T cut the signal is found to lie in this interval. This analysis reconstructs 15.4% of all neutralinos with $p_T > 500$ GeV in a 20 GeV mass window around the nominal mass; for QCD jets 0.23% of all jets with $p_T > 500$ GeV are accepted in this mass window.

For both analyses we estimate the significance of the signal based on the number of signal and background events in the five highest signal bins, a range of 20 GeV around the peak, a choice consistent with the 7% mass resolution seen in ATLAS detector simulations [14]. This ignores the effect of the 'looking-elsewere' problem, but should demonstrate the potential of such a search. The results are shown in Fig. 3 (left) for various neutralino masses along the SPS1a benchmark line. Even in the highest-mass case studied, the significance is well above the 5-σ discovery 'threshold' with 1 fb^{-1} of statistics.

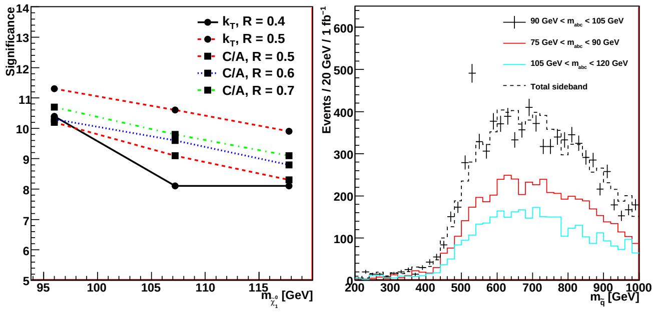

FIG. 3: Estimated sensitivity for 1 fb^{-1} as a function of $\tilde\chi^0_1$ mass for various choices of jet algorithm and size R (left), jet mass distribution for a squark search using the C/A algorithm with $R = 0.5$ and background estimation by sidebands (right).

Analysis	$m_{\tilde\chi^0_1}$	χ^2/ndf	$m_{\tilde q_R}$	χ^2/ndf
k_T, R=0.4	98.6 ± 0.4	2.66	—	—
C/A, R=0.5	97.7 ± 0.5	1.03	522.3 ± 1.3	1.32
C/A, R=0.7	97.3 ± 0.4	0.94	524.7 ± 1.2	0.62

TABLE I: Neutralino and squark mass fits for SPS1a. The nominal masses are $m_{\tilde\chi^0_1} = 96.1$ GeV and $m_{\tilde q_R} = 520$ GeV.

With evidence for a resonance peak, the next step is to estimate the mass of the resonance. We fit the jet-mass distributions with a background plus Gaussian signal distribution. For the k_T analysis we use an exponential background in the interval $[80, 200]$ GeV, while for the C/A analysis we use a uniform background in the interval $[80, 120]$ GeV. The results of this naive fit, which ignores the experimental jet mass resolution, are shown in Table I for the SPS1a benchmark point. Improvements on the systematic errors inherent in this method are possible by calibrating the jet mass against the known masses of the W boson or top quark, for which a reasonably clean measurement should be possible in events in which one top quark decays leptonically. Improvements in the mass measurement are also possible through filtering of jets, as demonstrated in [16].

In Fig. 3 (right) we also demonstrate the potential of our method for reconstructing the squark mass. By selecting events from the C/A analysis in the signal band 90 GeV $< m_{abc} <$ 105 GeV and combining the neutralino candidate with the third hardest jet in the event, we arrive at the distribution in black, with a clear peak around 520 GeV. The interpretation of the peak is checked by plotting the sideband distributions, picking events from 75 GeV $< m_{abc} <$ 90 GeV (red) and 105 GeV $< m_{abc} <$ 120 GeV (cyan). These show no sign of a peak. By subtracting the sidebands, normalized to the number of signal band events (dashed line), and fitting the remaining peak with a Gaussian we arrive at the squark mass estimates in Table I.

The effects of pile-up, intrinsic resolution and granularity of the detector will all have additional impact on the discovery of a neutralino resonance and the measurement of its mass at the LHC, but initial studies with realistic detector simulations indicate that the efficiencies and resolutions assumed here are not unreasonable [14].

In conclusion, we see that using sophisticated jet clustering algorithms such as k_T and C/A gives us the possibility of discovering baryon-number violating decays of the type $\tilde{\chi}_1^0 \to qqq$, without the assumption of additonal features such as hard leptons, and even when using only the substructure the hardest jet in the event. We have further found that the neutralino mass can be measured to a precision of a few GeV in these R-parity-violating scenarios, most likely limited by the experimental jet mass resolution, and that one can identify the squark resonance. Realizing the potential outlined in the above analyses is a challenge that merits experimental study.

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