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Cutting (Mass) Edges at LHC from Supersymmetry with Leptoquarks

J. Reuter[1 a,b] and D. Wiesler[2 a,b]

[a] *University of Edinburgh, School of Physics and Astronomy, JCMB, The King's Buildings, Mayfield Road, Edinburgh EH9 3JZ, SCOTLAND*

[b] *Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, Hermann-Herder-Str. 3, D–79104 Freiburg, GERMANY*

Abstract

Supersymmetric (SUSY) Grand Unified Theories based on exceptional gauge groups like E_6 have recently triggered a lot of interest. Aside from top-down motivations, they contain phenomenologically interesting states with leptoquark quantum numbers. Their SUSY partners, leptoquarkinos, will show up like all R-odd particles in decay cascades, but mass edges in kinematic distributions – originating from the same semi-exclusive final states – will however have major differences to the corresponding edges of ordinary squarks. This bears the opportunity to detect them at LHC, but also to be confused with other new physics models with discrete parities.

[1] j.reuter@ed.ac.uk
[2] daniel.wiesler@ed.ac.uk

1 Introduction

Supersymmetry is one of the most promising solutions of the hierarchy and fine-tuning problem, namely the vast difference between the electroweak (EW) and the Planck scale, and the very stability of this difference. It yields a mechanism for radiatively generating EW symmetry breaking, allows for an exact unification of all forces and conveys a candidate for dark matter. However, it comes with the price of having new problems, connected to the flavour sector, the stability of the proton, and new sorts of hierarchy problems known as the μ problem and doublet-triplet splitting. To address these questions, models have been developed that derive from a Planck or GUT scale exceptional gauge group like E_6 [1], and might be embedded in the context of the heterotic string. Such E_6-based models have a matter-Higgs unification, are automatically anomaly-free, include the right-handed neutrino, and solve the μ problem as an effective next-to-minimal SUSY Standard Model (NMSSM). However, one either has to solve a problem similar to doublet-triplet splitting, or use e.g. an intermediate Pati-Salam or left-right symmetric model [2], whose intermediate symmetry could either be broken by Higgs representations or orbifold compactifications [3,4]. The fundamental representation of E_6, the **27**, contains exotic states which carry both lepton and baryon number and hence act as leptoquarks. As they are left-chiral superfields (with vector-like quantum numbers with respect to the EW gauge group), they come as a pair of scalars, D and D^*, being R even, and a Dirac fermion, $\tilde{D}$, being R odd, at the EW scale. The states are called leptoquarks and leptoquarkinos, respectively. Their potential discovery at the Large Hadron Collider (LHC) may allow for a direct handle on the GUT structure of these models at the TeV scale beyond super-precise extrapolation of parameters over 13-15 orders of magnitude.

For the rest of this letter, we just take the model-building set-up above as a rough motivation how such states could come about in Nature, and further on just assume their existence together with the spectrum of an NMSSM-like model. The phenomenology of the scalar leptoquarks are very similar to that of non-supersymmetric states and will be discussed in a following publication [4]. While the pair production of the fermionic superpartners, the leptoquarkinos, is almost completely determined by QCD, their decays as R-odd particles show the very same cascade-like structures as squark and gluino decays. However, their decay products contain both non-vanishing lepton and baryon number. Hence, kinematic edge structures for the mass determination of new physics states derived from jet-lepton or jet-dilepton exclusive final states have very characteristic features which – using invalid assumptions about the underlying SUSY model – could lead to wrong particle identifications and mass determinations (The latter point is particularly relevant, if the scalar states which happen to be usually heavier than the fermions might lie outside the kinematic reach of LHC). The goal of this letter is to show the essential and important differences between standard SUSY squark cascades and leptoquarkino-triggered cascades.

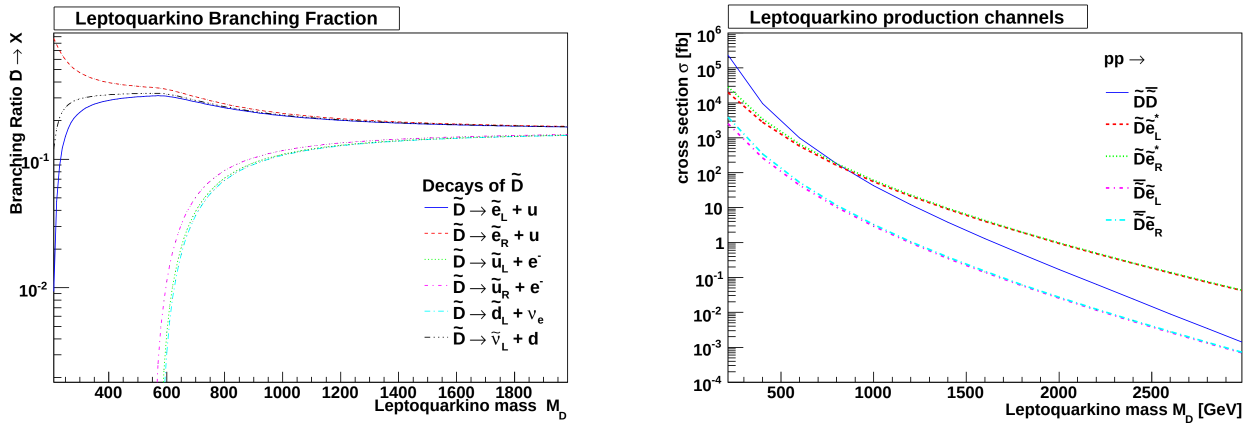

Figure 1: *Branching ratio for the leptoquarkino decay into fermion and scalar (left), leading order cross sections for single and pair production at 14 TeV (right).*

2 Physiognomy of LHC mass edges

Mass edge variables [5,6,7,8,9] have mostly been developed with a certain decay pattern in mind: left-handed squark into a quark, two leptons and the lightest neutralino via the on-shell decays of the second-to-lightest neutralino and a right-handed slepton:

$$\tilde{q}_L \to q\tilde{\chi}_2^0 \to ql^{\pm}\tilde{l}_R^{\mp} \to ql^{\pm}l^{\mp}\tilde{\chi}_1^0 \tag{1}$$

Since one is not able to distinguish experimentally which of the leptons $l^{\pm}$ and $l^{\mp}$ is nearest [1] to the quark, specifically two observables have been invented [6], which allow for a discrimination:

$$m_{ql,high} = \max\{m_{ql^+}, m_{ql^-}\} \tag{2}$$

$$m_{ql,low} = \min\{m_{ql^+}, m_{ql^-}\} \tag{3}$$

As squarks are pair-produced at the LHC, they decay via the above or even simpler patterns leading to final states with two hard partonic jets[2], two or more OSSF (opposite sign, same flavour) leptons[3] and most importantly large portions of missing transverse energy.

Leptoquarkinos, if existent, are abundantly produced at the LHC, since they are massive colored isosinglet fermions [1]. The leading order cross sections basically depend only on the

[1] in terms of the decay cascade

[2] At this point we neglect the polluting effects of initial and final state radiation, since we require these objects to have a minimum transverse momentum of at least 50 GeV. More hard jets are in principle possible, in e.g. gluino pair production, but cannot serve as backgrounds to leptoquarkino signals with a fixed baryon number.

[3] OSDF (opposite sign different flavour) leptons are also possible due to the Majorana nature of decaying neutralinos.

mass for pair production, and the Yukawa coupling for single production, respectively (see RHS of Fig. 1). The Yukawa coupling is without knowledge of the complete GUT model arbitrary, but was taken here to be of the size of the electromagnetic coupling ($y = 0.312$). The LHS of Fig. 1 shows the branching fractions of the decaying leptoquarkino (for varying masses) into a fermion/sfermion pair. As the decay into squarks and leptons is kinematically forbidden for low leptoquarkino masses (and still heavily phase-space suppressed for increasing masses), the sleptons dominate as intermediate states in cascades. Consequently, a typical leptoquarkino decay looks as follows,

$$\tilde{D} \to q\tilde{l}^{-}_{R/L} \to ql^{-}\tilde{\chi}^{0}_{1} \tag{4}$$

whereas a second-to-lightest neutralino in the decay chain starts to become important for heavier masses with different intermediate states, e.g.:

$$\tilde{D} \to \tilde{q}^{-}_{R/L}l^{-} \to ql^{-}\tilde{\chi}^{0}_{2} \to ql^{-}l^{\pm}l^{\mp}\tilde{\chi}^{0}_{1}\,. \tag{5}$$

The influence of this second type of cascade will be discussed later on.

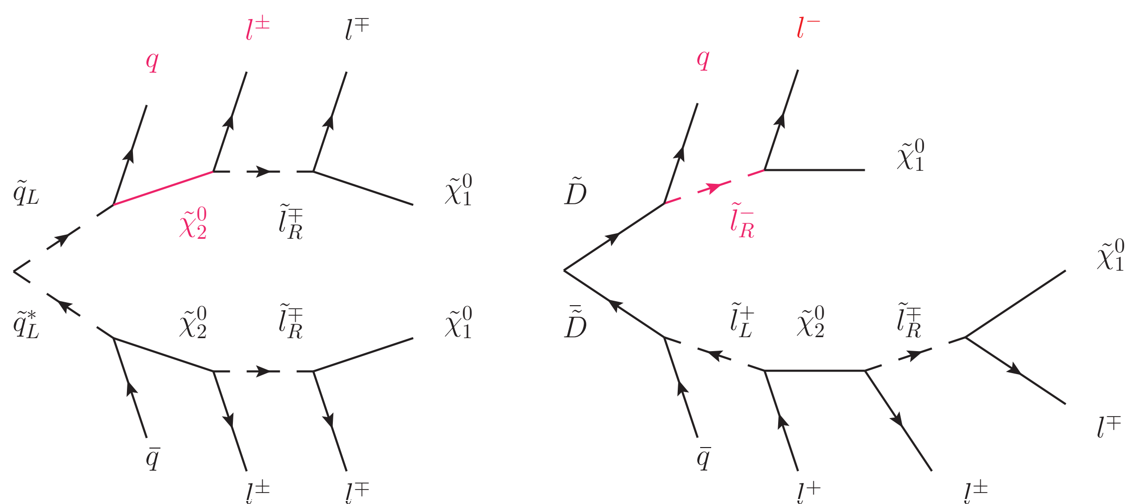

Figure 2: *Examples for decay cascades under investigation: squark (left) and leptoquarkino (right) pair production*

Leptoquarkinos produced in pairs thus show the same final states as squarks, namely two hard partonic jets, two or more leptons and large missing transverse energy in the detector, accounting for the undetected neutralinos. At first, we stick to the case of only two OSSF leptons being present.

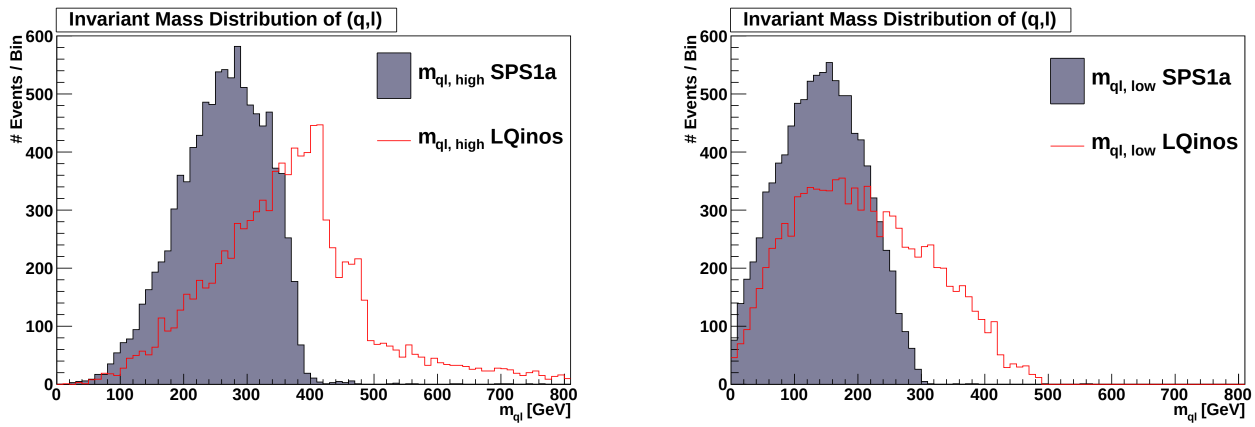

Figure 3: *Anatomy of leptoquarkino mass edges for* $m_{ql,high}$ *and* $m_{ql,low}$ *with* $m_D = 600$ GeV

2.1 Case I: two final state leptons

At this stage, recent analysis methods for those lepton-quark mass edges described above applied to events including leptoquarkino cascades show strong discrepancies to well-known results from standard SUSY signals. The difference emerges due to the intermediate on-shell scalar (squark or slepton) between the quark and lepton compared to a Majorana fermion as e.g. the neutralino in the MSSM: there are no possible spin correlations between lepton and quark, as they are connected through a scalar propagator. As a result, their invariant mass spectrum is equivalent to the dilepton spectrum in standard MSSM models (stemming from a scalar slepton propagator), in that it linearly rises from zero to its maximum at the endpoint, where it instantly falls down to zero. These edges are given by the masses of the intermediate and mother particles:

$$m_{ql}^{max} = \left[\frac{(m^2_{\tilde{e}_{R(L)}} - m^2_{\tilde{\chi}^0_1})(m^2_{\tilde{D}_1} - m^2_{\tilde{e}_{R(L)}})}{m^2_{\tilde{e}_{R(L)}}}\right]^{\frac{1}{2}}$$
$$= 433\ \ (496)\ \ \text{GeV} \qquad (6)$$

The values in parentheses are given for an intermediate left-handed slepton, which is slightly phase-space suppressed. The overall signal consists of the sum of both contributions leading to the shape visible in Figures 3 and 4. For the comparison of ordinary squark with leptoquarkino cascades we used the parameter point *SPS1a* [10] for the MSSM as well a model containing leptoquarks[4] and -inos with varying masses augmented by squarks and sleptons with the same masses as the *SPS1a* data point ($m_{\tilde{u}_L} = 567$ GeV, $m_{\tilde{u}_R} = 547$ GeV, $m_{\tilde{l}_L} = 204$ GeV, $m_{\tilde{l}_R} = 145$ GeV, $m_{\tilde{\chi}^0_1} = 97$ GeV, $m_{\tilde{\chi}^0_2} = 181$ GeV). For each model, a data set of 10K unweighted events

[4]The scalars are considered heavier than fermions (masses well above 1 TeV), since this is usually the case and their presence would most likely alter the shape in that a resonant peak structure would dominate the spectrum.

was generated using a hard-coded implementation of these E_6-inspired SUSY models into the event generator WHIZARD [11], which is particularly well suited for LHC beyond the SM studies [12]. While a complete validation of the model implementation using the WHIZARD interface to the FEYNRULES package [13] is under way, the part of the implementation relevant for this letter has been extensively tested.

Returning to the cascade, there still remains the problem of observability: experimentally there is no possibility to select the correct partonic jet and corresponding lepton, which are then to be combined to the invariant mass spectrum. While in MSSM models this would come about due to the presence of the Majorana fermion decay into two OSSF leptons, in the leptoquarkino case two OSSF leptons are to be collected from different cascades, one originating from the leptoquarkino and the other from its antiparticle, respectively. The observables $m_{ql,low}$ and $m_{ql,high}$, shown in Fig. 3, thus display the tremendous discrepancy, especially the latter one with its sharply falling edge shape, intrinsic to the nature of the scalar intermediate sparticle.

The issue of combinatorics can however be addressed by combining the softest jet and the hardest lepton to form an invariant mass spectrum in a single event. This has proven to be useful [14] in terms of resembling the actual shape and thus the most accurate position of the theoretical edge:

$$m^*_{ql} = m(\min_E\{q_1, q_2\}, \max_E\{l^+, l^-\}) \tag{7}$$

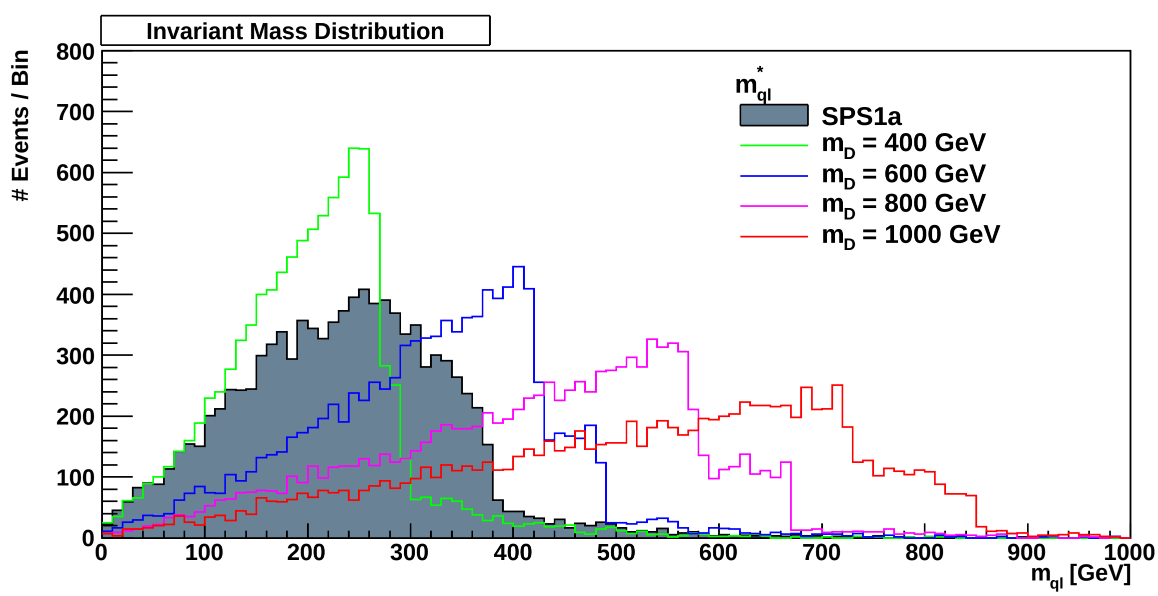

Figure 4: *Mass scan for m^*_{ql} as described in the text.*

In Figure 4, this observable is given for four different leptoquarkino masses ranging from 400

GeV to 1000 GeV and, as comparison, it is also plotted for MSSM-like SUSY ‘backgrounds’. The deviation is apparent and (at least before detector effects) already visible by eye.

2.2 Case II: four final state leptons

As for the case with four final state leptons, a decay pattern as in Figure 2 is responsible and thus the following (new) double on-shell decay chain:

$$\tilde{D} \to q l_1^- \tilde{\chi}_2^0 \to q l_1^- l_2^\pm l_2^\mp \tilde{\chi}_1^0 \,. \tag{8}$$

Here, in the last step the decay into a different lepton flavour was chosen for convenience in discrimination at parton level. Experimentally, a discrimination can be achieved by applying the so-called flavour subtraction to the dilepton invariant mass spectrum. Since the position and shape of the edge depends on all masses of the particles inherent in the cascade, an intermediate second-to-lightest neutralino leads to a partially displaced endpoint. This is to be understood in terms of Eq. (6), where the shift leads to maxima at $m_{ql}^{max} = 162$ GeV, 265 GeV, 364 GeV, and 460 GeV for $m_D = 400$ GeV, 600 GeV, 800 GeV, and 1000 GeV, respectively. Remember that in *SPS1a*, the decay of the left-handed squark into the lightest neutralino is suppressed mainly due to weak $SU(2)_L$ symmetry, which in turn, for larger masses of the exotic leptoquarkino, leads to an enhancement of this chain compared to the exclusive two-lepton signals discussed above.

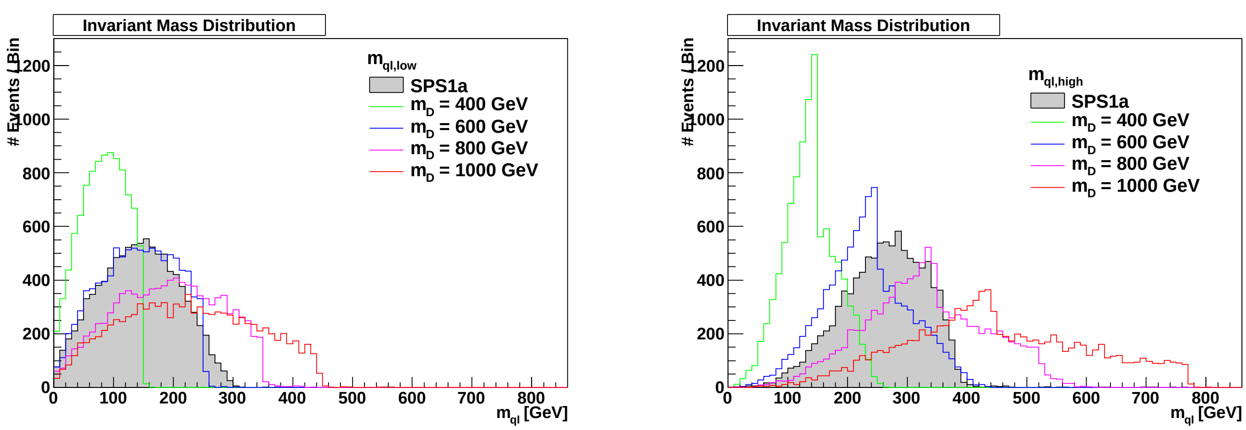

Figure 5: *leptoquarkino signals for differing masses compared to SPS1a 'background' for* $m_{ql,high}$ *and* $m_{ql,low}$

3 Conclusions

In this letter, we showed in the context of a quite general setup of GUT-inspired SUSY models containing non-standard SUSY states how the physiognomy of standard kinematic variables for mass determination of cascade states can be altered. This happened as the lack of spin correlations does not distort the shape of those observables. However, the missing spin correlations do not come from a complete change of the underlying model paradigm (e.g. assuming Universal Extra Dimensions, UED) but from a slight variation or extension of the standard SUSY scenario. The potential for a possible confusion in the model discrimination is specifically given in the case that the corresponding scalar partners are too heavy to show up as resonances at LHC. Angular jet-lepton correlations might serve as a powerful tool to discriminate these models from e.g. UED and are being currently investigated. This might serve as a prime example to show that a model discrimination at LHC is only possible by fitting all achievable observables from as many channels as possible to the underlying model assumptions.

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