Phenomenology of Physics Beyond the Standard Model in *ep* Collisions

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Abstract

The phenomenology and prospects for a discovery at the HERA *ep* collider of new bosons coupling to electron-quark pairs, as leptoquarks or squarks in supersymmetry with R-parity violation, is reviewed. Such particles could be singly produced at HERA, thus allowing a wide mass domain to be probed, and could lead to very striking final states. Moreover these could account for some slight "anomalies" recently observed in the data of both H1 and ZEUS experiments at HERA. In this paper, emphasis is put on the limitations of commonly used hypotheses in the considered models.

1 Introduction

The *ep* collider HERA is ideally suited to look for new particles coupling to lepton-quark pairs. Such particles could be leptoquark bosons, which appear in many extensions of the Standard Model (SM), or squarks in R-parity violating ($\not{R}_p$) supersymmetric (SUSY) models. Such particles could be singly produced in *ep* collisions via the fusion of the incoming lepton with a quark coming from the proton. The interest in such new bosons has been considerably renewed recently following the observation by the H1 [1] and ZEUS [2] experiments of a possible excess of events at very high masses and squared momentum transfer Q^2, above expectations from SM neutral current (NC) and charged current (CC) deep-inelastic scattering (DIS).

This paper reviews the phenomenology of leptoquarks and $\not{R}_p$SUSY at HERA. In the first section, emphasis is put on the restricted validity range of the narrow-width approximation when calculating the resonant production cross-section of leptoquarks. The importance of non s-channel contributions and of next-to-leading order corrections is also shown. The very rich phenomenology provided in *ep* collisions by resonantly produced squarks in $\not{R}_p$SUSY models is then detailed in the following section. The importance of cascade decays is stressed, and an example process which could lead to exciting final states with a hard isolated lepton, missing transverse momentum and a hard hadronic system is detailed.

A review of recent experimental results on searches for new physics at HERA, including also searches for excited fermions and for general contact interactions, can be found elsewhere in these proceedings [3]. They are based on the full e^+p statistics accumulated between 1994 and 1997, corresponding to a luminosity of $\simeq 40\text{pb}^{-1}$ per experiment.

2 Phenomenology of Leptoquarks in *ep* Collisions

Leptoquarks (LQ) are scalar or vector bosons which carry both lepton and baryon quantum numbers and thus connect in a fundamental way the leptonic and baryonic sectors of the SM. They appear naturally in many unifying theories beyond the SM such as Grand Unified Theories [4] and Superstring inspired E_6 models [5], and in some Compositeness [6] and Technicolour [7] models.

At HERA, LQs may be produced resonantly up to the kinematic limit of $\sqrt{s_{ep}} \simeq 300$GeV via the fusion of the incident lepton with a quark or antiquark coming from the proton, or exchanged in the u-channel, as illustrated in Fig. 1. The Yukawa coupling λ at the $LQ - e - q$ vertex is an unknown parameter of the model.

2.1 First Generation Leptoquarks

We first consider the case where the only SM fermions which couple to LQs belong to the first generation. Such LQs (henceforth called first generation LQs) give $e + q$ or $\nu + q'$ final states leading to individual

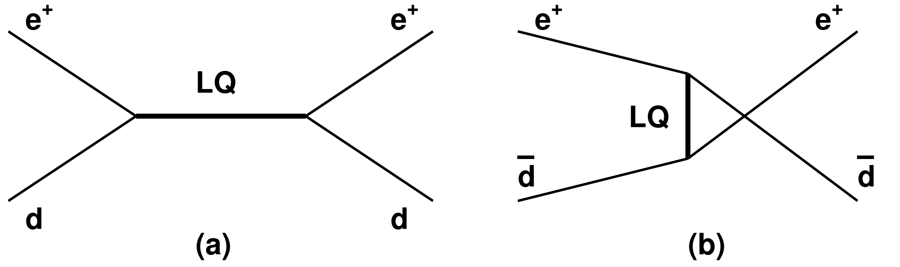


Figure 1: Example diagrams for resonant production in the s-channel (a) and exchange in the u-channel (b) of a LQ with fermion number $F = 0$. The corresponding diagrams for $|F| = 2$ LQs are obtained from those depicted by exchanging the quark and antiquark.

events indistinguishable from SM NC and CC DIS respectively. For the process $eq \to LQ \to eq$, the distribution of the transverse energy $E_{T,e}$ of the final state lepton shows a Jacobian peak at $M_{LQ}/2$, M_{LQ} being the LQ mass. Hence the strategy to search for a LQ signal in ep collisions is to look, among high Q^2 (i.e. high $E_{T,e}$) DIS event candidates, for a peak in the invariant mass M of the final $e - q$ pair.

Moreover, the significance of the LQ signal over the SM DIS background can be enhanced by exploiting the specific angular distribution of the LQ decay products. Indeed, scalar LQs produced in the s-channel decay isotropically in their rest frame leading to a flat $\mathrm{d}\sigma / \mathrm{d}y$ spectrum where $y = \frac{1}{2}(1 + \cos\theta^*)$ is the Bjorken scattering variable in DIS and θ^* is the decay polar angle of the lepton relative to the incident proton in the LQ centre of mass frame. In contrast, events resulting from the production and decay of vector LQs would be distributed according to $\mathrm{d}\sigma / \mathrm{d}y \propto (1-y)^2$. These y spectra from scalar or vector LQ production are markedly different from the $\mathrm{d}\sigma / \mathrm{d}y \propto y^{-2}$ distribution expected at fixed M for the dominant t-channel photon exchange in neutral current DIS events [1]. Hence, a LQ signal in the NC-like channel will be statistically most prominent at high y.

2.1.1 The Buchmüller-Rückl-Wyler Model

A reasonable phenomenological framework to study first generation LQs is provided by the BRW model [8]. This model is based on the most general Lagrangian that is invariant under $SU(3) \times SU(2) \times U(1)$, respects lepton and baryon number conservation, and incorporates dimensionless family diagonal couplings of LQs to left- and/or right-handed fermions. Under these assumptions LQs can be classified according to their quantum numbers into 10 different LQ isospin multiplets (5 scalar and 5 vector), half of which carry a vanishing fermion number $F = 3B + L$ (B and L denoting the baryon and lepton number respectively) and couple to $e^+ + q$ while the other half carry $|F| = 2$ and couple to $e^+ + \bar{q}$. These are listed in Table 1.

We use the nomenclature of [9] to label the different LQ states : the superscript indicates the electric charge of the LQ, while its weak isospin is denoted by the subscript. We do not use specific symbols to label the *anti-leptoquarks* which are actually produced in e^+p collisions. In addition to the underlying hypotheses of BRW, we restrict LQs couplings to only one chirality state of the lepton, given that deviations from lepton universality in helicity suppressed pseudoscalar meson decays have not been observed [10, 11]. This restriction affects only two scalar (S_0 and $S_{1/2}$) and two vector (V_0 and $V_{1/2}$) LQs. Hence we can index the LQ states with the chirality of the incoming *electron* (by convention) which could allow their production in e^-p collisions. For example the $\tilde{S}_0$ will be denoted by $\tilde{S}_{0,R}$.

In the BRW model, LQs decay exclusively into eq and/or νq and the branching ratio $\beta_e = \beta(LQ \to eq)$ is fixed by gauge invariance to 0.5 or 1 depending on the LQ type.

[1]At high momentum transfer, Z^0 exchange is no longer negligible and contributes to less pronounced differences in the y spectra between LQ signal and DIS background.

$F=-2$	Prod./Decay	β_e	$F=0$	Prod./Decay	β_e
Scalar Leptoquarks					
${}^{1/3}S_0$	$e_R^+\bar{u}_R \to e^+\bar{u}$	1/2	${}^{5/3}S_{1/2}$	$e_R^+u_R \to e^+u$	1
	$e_L^+\bar{u}_L \to e^+\bar{u}$	1		$e_L^+u_L \to e^+u$	1
${}^{4/3}\tilde{S}_0$	$e_L^+\bar{d}_L \to e^+\bar{d}$	1	${}^{2/3}S_{1/2}$	$e_L^+d_L \to e^+d$	1
${}^{4/3}S_1$	$e_R^+\bar{d}_R \to e^+\bar{d}$	1	${}^{2/3}\tilde{S}_{1/2}$	$e_R^+d_R \to e^+d$	1
${}^{1/3}S_1$	$e_R^+\bar{u}_R \to e^+\bar{u}$	1/2			
Vector Leptoquarks					
${}^{4/3}V_{1/2}$	$e_L^+\bar{d}_R \to e^+\bar{d}$	1	${}^{2/3}V_0$	$e_L^+d_R \to e^+d$	1
	$e_R^+\bar{d}_L \to e^+\bar{d}$	1		$e_R^+d_L \to e^+d$	1/2
${}^{1/3}V_{1/2}$	$e_L^+\bar{u}_R \to e^+\bar{u}$	1	${}^{5/3}\tilde{V}_0$	$e_L^+u_R \to e^+u$	1
${}^{1/3}\tilde{V}_{1/2}$	$e_R^+\bar{u}_L \to e^+\bar{u}$	1	${}^{5/3}V_1$	$e_R^+u_L \to e^+u$	1
			${}^{2/3}V_1$	$e_R^+d_L \to e^+d$	1/2

Table 1: Leptoquark isospin families in the Buchmüller-Rückl-Wyler model. For each leptoquark, the superscript corresponds to its electric charge, while the subscript denotes its weak isospin. β_e denotes the branching ratio of the LQ into $e+q$.

It is however possible to relax some of the assumptions used by BRW (especially allowing mixing between LQ multiplets, or couplings of the LQs to other particles than first generation fermions), and to build other LQ models [12] where the branching ratio β_e can be treated as a free parameter.

2.1.2 The Narrow-Width Approximation

In the s-channel, a LQ is produced at a mass $M = \sqrt{s_{ep}x}$ where x is the momentum fraction of the proton carried by the struck quark. Over a large fraction of the mass range accessible at HERA and

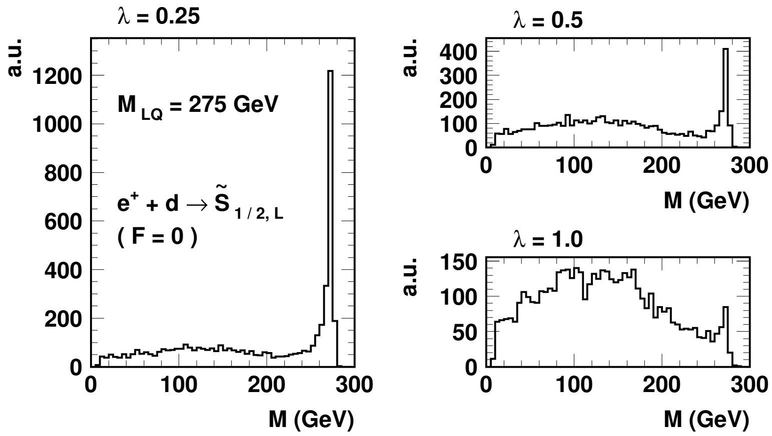


Figure 2: Distorsion of the mass spectra expected for a 275 GeV scalar $F=0$ LQ with increasing coupling.

for a reasonable coupling strength, e.g. satisfying $\lambda^2/4\pi < 1$, the intrinsic decay width of a scalar (S) or vector (V) LQ of nominal mass M_{LQ} into a lepton and a quark is expected to be small. This width is calculated as $\Gamma_S = (3/2)\Gamma_V = \lambda^2 M_{LQ}/16\pi$ which corresponds for example to $\Gamma_S \simeq 40$MeV for a scalar LQ at $M_{LQ} = 200$GeV and $\lambda = 0.1$. In the narrow-width approximation (NWA), the resonant production cross-section $\sigma_{\rm NWA}$ is proportional to $\lambda^2 q(x)$ where $q(x)$ is the density of the struck parton in

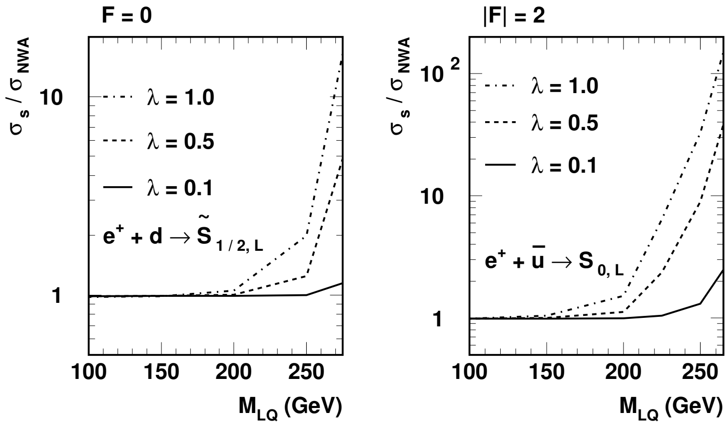


Figure 3: Ratio of the s-channel LQ production cross-section σ_s for finite LQ width to the cross-section calculated in the narrow-width approximation.

the incoming proton. However when approaching the kinematic limit (i.e. at high x) where the values of $q(x)$ are very small, the coupling strengths which can be probed with the actual integrated luminosities are too high for the NWA to be valid. The convolution of the steeply falling $q(x)$ with the Breit-Wigner distribution of finite width characterizing the resonance leads to a strong distortion of the LQ mass peak, and the mass spectrum shows very large tails towards low values, as illustrated in Fig. 2. As a result the LQ production cross-section σ_s in the s-channel for M_{LQ} approaching $\sqrt{s_{ep}}$ is considerably larger than σ_{NWA} [13], as shown in Fig. 3 for the typical range of couplings which can be probed at HERA with the current luminosity. For $\lambda = 0.5$, one can see that the deviation from NWA becomes sizeable at $M_{LQ} > 250$GeV for a LQ produced via a valence (u, d) quark (i.e for a $F = 0$ LQ), and already at $M_{LQ} > 200$GeV for a production via a sea quark (i.e. for a $|F| = 2$ LQ).

2.1.3 Different Contributions

At large LQ mass, other effects can play an important role and affect the signal cross-section. First, the u–channel contribution can become large especially for $|F| = 2$ LQs and e^+p scattering where valence quarks are involved (see Fig. 1b). However the events originating from u-channel LQ exchange would mainly be concentrated at mass values much lower than M_{LQ}. As such, kinematic cuts used in the experimental searches in order to enhance the LQ signal significance over the DIS background (i.e. a lower Q^2 cut and a lower y cut, as mentionned in the beginning of this section, which select high M events since $M^2 = yQ^2$) considerably suppress the u-channel contribution.

Finally, the interference of the LQ processes with SM γ and Z exchange can no longer be neglected for LQ masses close to or above the kinematic limit. Depending on the LQ type, this interference can be constructive or destructive[2], and it can get comparable to or greater than the pure s– and u–channel contributions. In Fig. 4 the relative magnitudes of the various terms in the high Q^2 domain are shown for the $S_{0,R}$ ($|F| = 2$) and the $\tilde{S}_{1/2,L}$ ($F = 0$) scalar leptoquarks for a coupling $\lambda = 0.5$. For the $S_{0,R}$, the (positive) interference with SM DIS begins to dominate the s–channel cross-section at $M > 220$GeV. The squared amplitude of the u-channel becomes bigger than the s–channel cross-section in the highest mass domain, but both the squared amplitudes are then negligible compared to the interference with DIS. For the $\tilde{S}_{1/2,L}$, the u–channel contribution is negligible, but the (negative) interference becomes the dominant contribution for $M > 285$GeV.

[2] The signs of the interference terms between SM gauge boson and $F = 0$ LQ contributions given in the original BRW paper [8] were found to be incorrect. The correct signs which can be inferred from [14] have been provided in the *erratum* to Ref. [8] and have been used here.

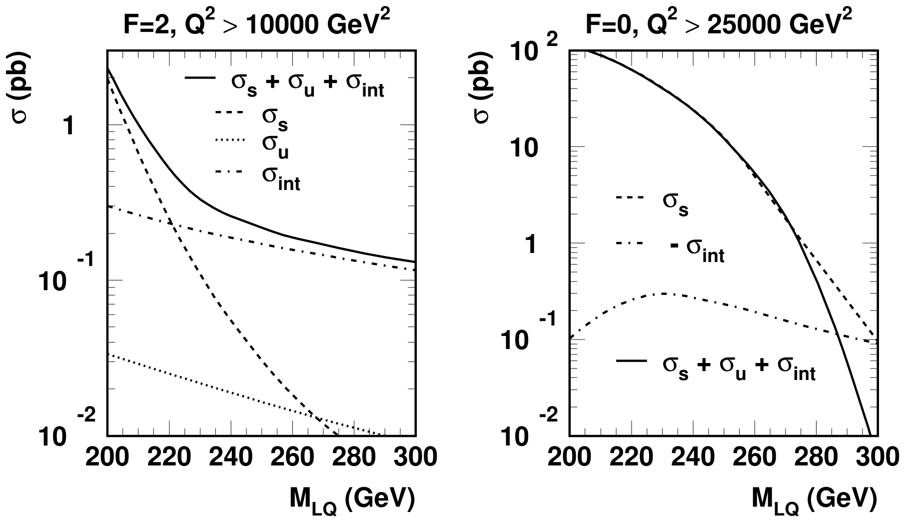


Figure 4: Contributions of the s- and u-channel processes and of their interference with SM DIS for (a) $S_{0,R}$ ($\mid F \mid= 2$) and (b) $S_{1/2,L}$ ($F = 0$). λ has been fixed to 0.5, a value which is typical for the experimental sensitivity in this mass range.

2.1.4 Next-to-Leading Order Corrections

Cross-sections for the resonant production of scalar leptoquarks at HERA including next-to-leading order (NLO) QCD corrections in ep collisions have been recently calculated in the NWA in [15]. All the accounted contributions, which include the $LQ - e - q$ vertex correction, the emission of real gluons, the virtual corrections, and the contribution of eg in the initial state, are depicted in Fig. 5. Similarly to DIS, the sum of the virtual and bremsstrahlung corrections is ultraviolet and infrared finite, and the collinear divergences due to gluon emission from the initial quark and to gluon splitting to $q\bar{q}$ pairs are absorbed in the quark and gluon parton densities. The resulting K-factors defined as $K_{NWA}(M_{LQ}) = \sigma^{NLO}_{NWA}(M_{LQ})/\sigma^{LO}_{NWA}(M_{LQ})$ lead to a sizeable enhancement of the NWA cross-section at high LQ masses. This can be seen in Fig. 6 where the evolution of the K factors as a function of the LQ mass is shown by

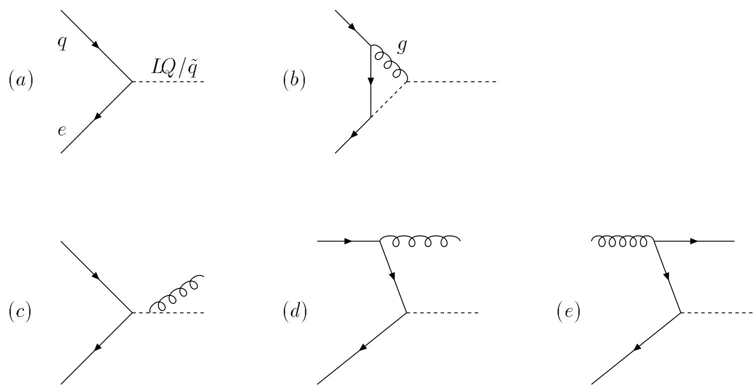


Figure 5: Next-to-Leading Order contributions to leptoquark production at HERA (from [15]).

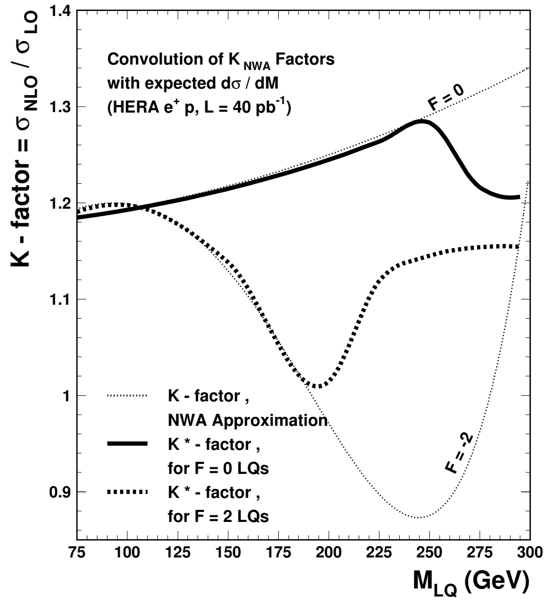


Figure 6: K-factors for $F = 0$ (upper curves) and $|F| = 2$ (lower curves) LQs. The thin dotted curves show the results of the K-factor calculation in the NWA, while the thick solid and dashed curves correspond to the convolution of these K-factors with the expected $\hat{s}$ spectrum for coupling values close to the expected HERA's sensitivity. The K-factors in the NWA have been calculated using Fortran code provided by M. Spira [15].

the dotted curves, for LQs with $F = 0$ and $|F| = 2$. However, at high LQ masses and couplings, mainly low x events are involved, as seen in Fig. 2. To get the correct K-factor for the s-channel production of high mass LQs, we thus calculate the convolution product $K^*(M_{LQ})$ of $K_{NWA}(\hat{s})$ with the spectrum $d\sigma/d\hat{s}$ of LQ events expected at M_{LQ} for coupling values close to the current HERA's sensitivity :

$$K^*(M_{LQ}) = \int d\hat{s} K_{NWA}(\hat{s}) \times \left(\frac{d\sigma}{d\hat{s}}\right)_{\lambda=\lambda_{sensitivity}(M_{LQ})}$$

$\lambda_{sensitivity}(M_{LQ})$ is evaluated using the leading-order expression of the cross-section for resonant LQ production taking into account the finite LQ width. The evolution of this convolution K^* with the LQ mass is shown in Fig. 6 as thick lines, for $F = 0$ (solid curve) and $|F| = 2$ (dashed curve) LQs. Taking into account the finite width of the LQ, the NLO corrections enhance the resonant production cross-section of a $F = 0$ LQ by up to $\simeq 30\%$ at 250 GeV. For higher masses this enhancement decreases because of the distorsion of the LQ mass spectrum. For $|F| = 2$ LQs, this enhancement remains below $\simeq 20\%$.

2.1.5 The Contact Term Approach

For LQ masses far above the kinematic limit, the contraction of the propagator in both the s- and u-channels leads to a four-fermion interaction, as depicted in Fig. 7. Such interactions are studied in the context of general contact terms, which can be used to parameterize any new physics process with a characteristic energy scale far above the kinematic limit. The effective Lagrangian reads as :

$$\begin{aligned}\mathcal{L}_{CI} \quad = \quad & \eta^q_{LL}(\bar{e}_L\gamma^\mu e_L)(\bar{q}_L\gamma_\mu q_L) + \eta^q_{LR}(\bar{e}_L\gamma^\mu e_L)(\bar{q}_R\gamma_\mu q_R) \\ & + \eta^q_{RL}(\bar{e}_R\gamma^\mu e_R)(\bar{q}_L\gamma_\mu q_L) + \eta^q_{RR}(\bar{e}_R\gamma^\mu e_R)(\bar{q}_R\gamma_\mu q_R)\end{aligned}$$

The sets of non-vanishing couplings η in the above Lagrangian describing interactions induced by the exchange of very massive LQs of the BRW model and their relations to the LQ mass and coupling are given in Table 2. This table has been adapted from [16] following [14], after discussions with the authors of [16], and sign errors of the coupling coefficients for $|F| = 2$ scalar LQs and $F = 0$ vector LQs have been corrected.

In ep collisions, Contact Interactions (CI) would interfere with NC DIS processes and lead to a distorsion of the Q^2 spectrum of NC DIS candidate events. The H1 [17] and ZEUS [18] Collaborations

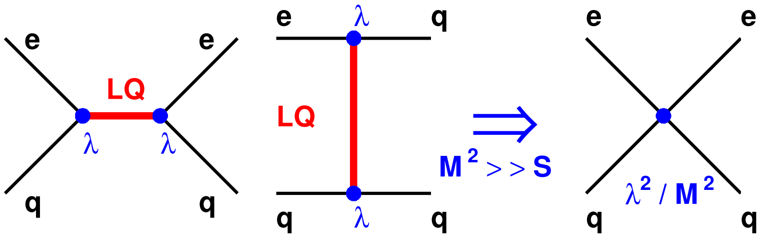


Figure 7: Contraction of the LQ propagator in the s- and u-channel exchanges, leading to a four-fermion interaction.

BRW Model, $a = (\lambda/M_{LQ})^2$

LQ	coupling to u quark (GeV^{-2})	coupling to d quark (GeV^{-2})	LQ	coupling to u quark (GeV^{-2})	coupling to d quark (GeV^{-2})
$S_{0,L}$	$\eta^u_{LL} = +\frac{1}{2}a$		$V_{0,L}$		$\eta^d_{LL} = -a$
$S_{0,R}$	$\eta^u_{RR} = +\frac{1}{2}a$		$V_{0,R}$		$\eta^d_{RR} = -a$
$\tilde{S}_{0,R}$		$\eta^d_{RR} = +\frac{1}{2}a$	$\tilde{V}_{0,R}$	$\eta^u_{RR} = -a$	
$S_{1/2,L}$	$\eta^u_{LR} = -\frac{1}{2}a$		$V_{1/2,L}$		$\eta^d_{LR} = +a$
$S_{1/2,R}$	$\eta^u_{RL} = -\frac{1}{2}a$	$\eta^d_{RL} = -\frac{1}{2}a$	$V_{1/2,R}$	$\eta^u_{RL} = +a$	$\eta^d_{RL} = +a$
$\tilde{S}_{1/2,L}$		$\eta^d_{LR} = -\frac{1}{2}a$	$\tilde{V}_{1/2,L}$	$\eta^u_{LR} = +a$	
$S_{1,L}$	$\eta^u_{LL} = +\frac{1}{2}a$	$\eta^d_{LL} = +a$	$V_{1,L}$	$\eta^u_{LL} = -2a$	$\eta^d_{LL} = -a$

Table 2: Relations between the parameters η of the Contact Interaction Lagrangian and the mass and coupling of leptoquarks in the BRW model.

searched for such distorsions in the full e^+p data collected between 1994 and 1997, using respectively a χ^2 fit of the single differential cross-section $d\sigma/dQ^2$, and a 2-dimensional likelihood analysis in (x,y). Resulting bounds on η have been translated into lower limits on M_{LQ}/λ for very massive LQs in [17] following the correspondance given in Table 2.

It should be stressed that such constraints on LQs resulting from CI analyses can not be extrapolated towards too low LQ masses. This is illustrated in Fig. 8 for the case of the $S_{1/2,L}$ LQ and a coupling $\lambda = 1$. The full line in Fig. 8a shows the squared s-channel amplitude $\mid A_s \mid^2$ integrated over $Q^2 > 25000\mathrm{GeV}^2$ as the function of the LQ mass. The dashed line represents the opposite of the interference term $I.T.$ between LQ exchange and NC DIS, this interference being destructive for this LQ and in the considered Q^2 range. In Fig. 8b, the same terms are shown when evaluated in the contact interaction approximation. As expected, this approximation gives a good estimate of the exact calculation when M_{LQ} is high, e.g. close to 1 TeV. However sizeable differences exist between the two calculations for smaller LQ masses, for both contributions. Adding the squared amplitude and the interfence term gives a "cross-section" $\sigma_{tot} = |A_s|^2 + I.T.$ which quantifies the difference between the considered model and the SM : when σ_{tot} is positive (negative) the LQ exchange would manifest itself as an excess (deficit) of NC DIS-like events compared to the SM prediction. Fig. 8c shows the relative difference of σ_{tot} in the exact and approximate calculations $\mid d\sigma/\sigma \mid = \mid (\sigma_{tot,exact} - \sigma_{tot,CI})/\sigma_{tot,exact} \mid$. For M_{LQ} between 300 and $\sim$ 450 GeV, the CI approximation completely underestimates the cross-section. The rise of $\mid d\sigma/\sigma \mid$ observed above $\sim$ 400GeV comes from the fact that, due to the destructive interference, σ_{tot} becomes negative above a given LQ mass M_0, which is smaller in the approximate than in the exact calculation as seen comparing Fig. 8a and Fig. 8b. Above $M_0(exact) \sim 450\mathrm{GeV}$ both calculations lead to a negative σ_{tot} and the agreement between them improves with increasing LQ mass. However below $\sim$ 500GeV, contracting

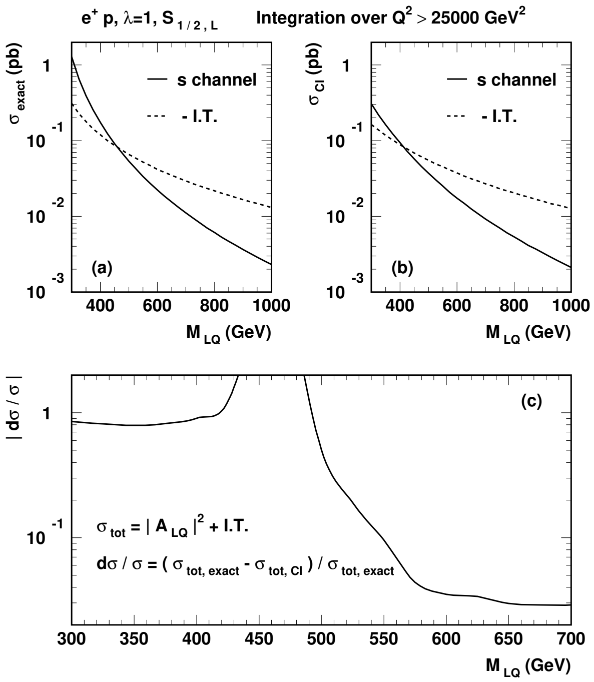


Figure 8: Squared s-channel amplitude (full line) and the opposite of the interference with NC DIS (dashed line) for the $S_{1/2,L}$ LQ and $\lambda = 1$ calulated exactly (a) and in the Contact Interaction approximation (b), as a function of the LQ mass. The relative difference of the total "cross-section" σ_{tot} in the two calculations is shown in (c).

the LQ propagator does not give a reliable estimate of the signal cross-section in the considered example. The mass value above which the CI approach can be used depends on the LQ type, and on the kinematic domain over which the cross-sections are integrated.

2.1.6 Status of LQs Searches

Recent searches for LQs at HERA using the full available e^+p luminosity are presented in detail in [19, 20]. For example, the mass spectra of the NC DIS candidates at $Q^2 > 2500\mathrm{GeV}^2$ observed by H1 are shown in Fig. 9a, before and after applying a mass-dependent lower y_{cut} optimized to enhance the LQ signal significance over the NC DIS background, as discussed in the beginning of section 2.1. Compared to the previous H1 publication [1] the full dataset was re-analysed including a new in-situ energy calibration for the electrons. This has led to slight migrations (within originally quoted systematic errors) of individual events in (M, y) compared to [1]. In the mass window considered in [1] of total width 25GeV around 200GeV, and at $y > 0.4$, 8 events are observed, while 3.0 ± 0.5 are expected from NC DIS. Out of these, 5 events originate from the $1994 - 1996$ data and 3 from the 1997 data. Hence, the "mass clustering" around $\simeq 200$GeV observed previously is not confirmed by the 1997 H1 data alone. The analyses were then used to constrain LQ models. For example, scalar LQs in the BRW model can be excluded up to 275 GeV for a coupling λ of the electromagnetic strength, i.e. $\lambda = 0.3$. Moreover, in a general LQ model, mass dependent upper limits on the branching ratio β_e were also obtained [19] assuming a fixed λ value.

At the TeVatron collider, LQs are produced by pairs, mainly via their coupling to gluons. The production cross-section is thus independent on the Yukawa coupling λ. Fig. 9b shows the domain of the (β_e, M_{LQ}) plane excluded by scalar LQ searches at TeVatron [21]. Combining $D\emptyset$ and CDF results [22], scalar LQs lighter than 242 GeV can be excluded at 95% CL for $\beta_e = 1$.

Hence the discovery of a LQ at HERA requires that the branching β_e is not too high (e.g. $\beta_e < 0.4$ for $M_{LQ} = 200$ GeV). Small values of β_e require to move away from the BRW model, considering e.g. models where mixing between different LQs multiplets is allowed, or where LQs couple to other particles than SM fermions. These can also been achieved when LQs possess Lepton Flavor Violating (LFV) couplings to eq as well as to μq (or τq) pairs, or in supersymmetry with R-parity violation. These last two cases

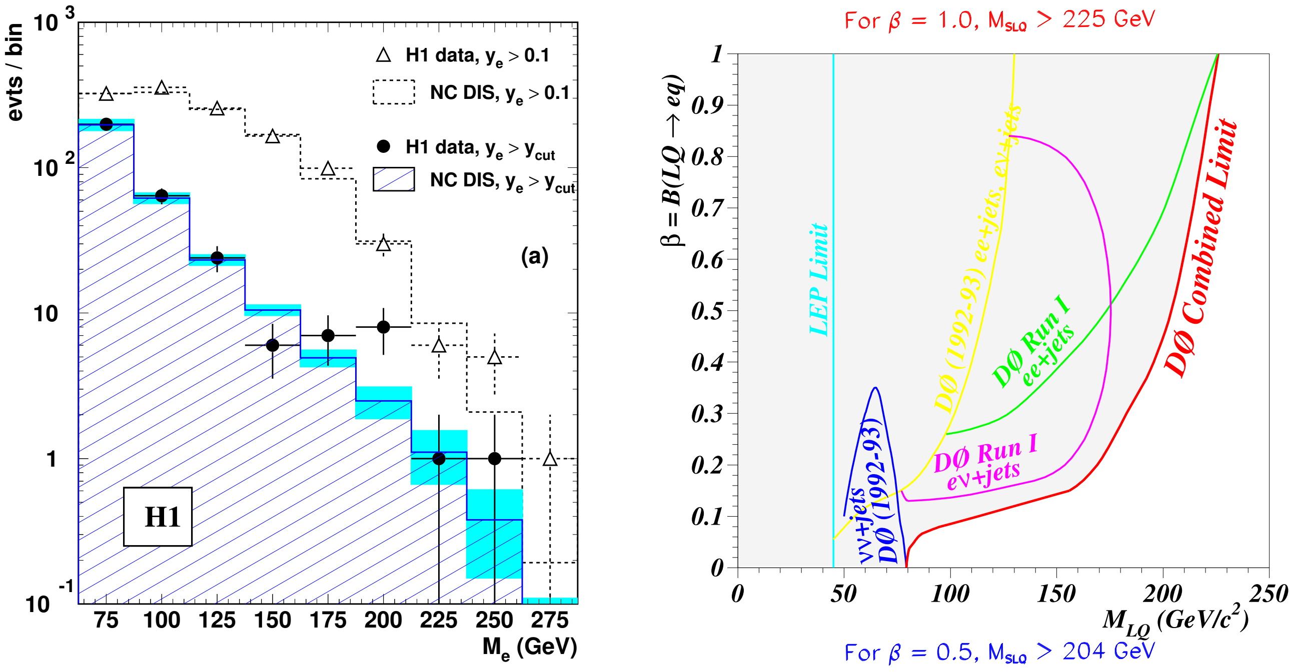


Figure 9: (a) Mass spectra [19] for NC DIS-like final states for H1 data (symbols) and DIS expectation (histograms). In (a), the NC DIS-like comparison is shown before (open triangles, white histogram) and after (closed dots, hatched histogram) a y cut designed to maximize the significance of an eventual scalar LQ signal. (b) Domain in the (β_e, M_{LQ}) plane excluded by scalar LQ searches at the TeVatron [21].

will be considered in the remaining part of this paper.

2.2 Lepton Flavor Violating Leptoquarks

At HERA, the s- or u-channel exchange of LFV LQs possessing couplings λ_{1i} and λ_{2j} (resp. λ_{3j}) to eq_i and μq_j (resp. τq_j pairs), where i and j denote the generation of the involved quarks, would lead to $\mu + jet$ (resp. $\tau + jet$) final states.

It is often assumed in LQs searches at colliders that LQs couple only within a single generation (i.e. possess family diagonal couplings), because of strong limits on flavor-changing neutral currents and rare lepton-family violating decays. Indeed very stringent limits often constrain such LQs when both quarks involved belong to the first generation. However for many other combinations (q_i, q_j) the contraints are not very severe [10]. It is thus of high interest to also study those LQs at collider experiments.

Searches for such LFV LQs at HERA are presented in [19, 23]. When the LQ mass is far above the kinematic limit, the signal cross-section is proportional to the square of $\lambda_{1i} \times \lambda_{lj} / M_{LQ}^2$ ($l = 2$ or 3). No signal has been observed so far at HERA and thus upper limits on this quantity have been obtained. It has been shown in [19] that, for both $e \leftrightarrow \mu$ and $e \leftrightarrow \tau$ transitions, HERA limits extend significantly beyond the reach of other experiments for some LQ types and some $\lambda_{1i} \times \lambda_{lj}$ couplings products.

A representation of the discovery potential of such LFV LQs, e.g. for $e \leftrightarrow \tau$ transitions, can be given in the plane λ_{3j} against the LQ mass, for a fixed value of the coupling λ_{1i}. This is shown in Fig. 10 for a LQ possessing the quantum numbers of the $S_{1/2,L}$ in the BRW model (hence only the cases $j = 1, 2$ are relevant), assuming an integrated e^+p luminosity of 250 pb^{-1}. The most stringent indirect bound constraining the $eu \leftrightarrow \tau u$ transition induced by this LQ comes from the most recent upper limit [10, 24] on the branching ratio $\tau \to \pi^0 e$ and is represented as the full and dotted lines. It can be seen that HERA

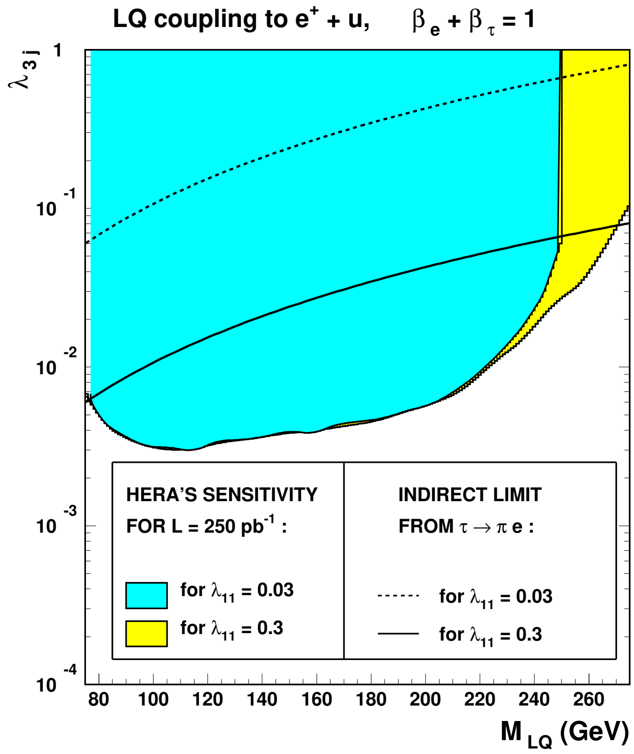


Figure 10: HERA's sensitivity for $\mathcal{L} = 250\text{pb}^{-1}$ on LQs possessing the quantum numbers of the $S_{1/2,L}$ of the BRW model and coupling both to e^+u and to τq_j pairs ($j = 1, 2$). Shadowed areas indicate the domains which could be excluded at HERA for two fixed values of the coupling λ_{11} of the LQ to e^+u. The full and dashed lines show the most stringent indirect upper limit on λ_{31} (coming from $\tau \to \pi e$) for the two cases considered. For this LQ type no indirect process constrains the product $\lambda_{32} \times \lambda_{11}$.

data would considerably extend above the currently excluded domain. Moreover, for this LQ type, no indirect process constrains the couplings product $\lambda_{32} \times \lambda_{11}$.

3 Supersymmetry with R-parity Violation in *ep* collisions

The most general SUSY theory which preserves gauge invariance of the Standard Model allows Yukawa couplings between one scalar squark ($\tilde{q}$) or slepton ($\tilde{l}$) and two known SM fermions. Such couplings induce violation of the R-parity defined as $R_p = (-1)^{3B+L+2S}$, where S denotes the spin of the particles. Moreover, couplings between a $\tilde{q}$ and a lepton and a quark, or between a $\tilde{l}$ and two leptons, violate the lepton number L, while those coupling a $\tilde{q}$ to a pair of quarks violate the baryon number B. The simultaneous violation of L and B could have dramatic consequences on the proton decay, but it is possible to build viable $\not{R}_p$SUSY models where B remains conserved. We consider here the SUSY phenomenology at HERA in presence of $\not{R}_p$ Yukawa couplings violating L only, but maintaining otherwise the minimal field content of the so-called Minimal Supersymmetric Standard Model (MSSM). The phenomenology of $\not{R}_p$SUSY at HERA was first investigated in [25] and in more detail in [26, 27, 28]. The following sections 3.1 and 3.2 present a summary of these studies.

3.1 Squark Production

Of special interest for HERA are those Yukawa vertices which couple a squark to a lepton-quark pair, allowing the resonant production of a squark similarly to that of leptoquarks. These are described in the superpotential by the terms $\lambda'_{ijk} L_i Q_j \bar{D}_k$, with i, j, k being generation indices [3]. The corresponding part

[3] In the usual superfields notation, L_i, Q_j and $\bar{D}_k$ contain respectively the left-handed lepton doublet, quark doublet and the right handed quark singlet.

of the Lagrangian, expanded in fields, reads as [25] :

$$\begin{aligned}\mathcal{L}_{L_iQ_j\bar{D}_k} &= \lambda'_{ijk}\Big[-\tilde{e}^i_L u^j_L \bar{d}^k_R - e^i_L \tilde{u}^j_L \bar{d}^k_R - (\bar{e}^i_L)^c u^j_L \tilde{d}^{k*}_R \\ &\quad +\tilde{\nu}^i_L d^j_L \bar{d}^k_R + \nu_L \tilde{d}^j_L \bar{d}^k_R + (\bar{\nu}^i_L)^c d^j_L \tilde{d}^{k*}_R\Big] + \text{h.c.}\end{aligned}$$

where the superscripts ^{c} denote the charge conjugate spinors and the * the complex conjugate of scalar fields. In ep collisions, the couplings λ'_{1jk} thus allow the resonant production of $\tilde{u}^j_L$ or $\tilde{d}^k_R$ squarks through eq fusion. For the nine possible λ'_{1jk} couplings, the corresponding single production processes are given in Table 3. We will make the simplifying assumption that one of the λ'_{1jk} coupling dominates other $R\!\!\!/_p$couplings, which has no direct incidence on the phenomenology but allows a simple presentation of HERA discovery potential.

λ'_{1jk}	Production Processes	
111	$e^+ + \bar{u} \to \tilde{d}^*_R$	$e^+ + d \to \tilde{u}_L$
112	$e^+ + \bar{u} \to \tilde{s}^*_R$	$e^+ + s \to \tilde{u}_L$
113	$e^+ + \bar{u} \to \tilde{b}^*_R$	$e^+ + b \to \tilde{u}_L$
121	$e^+ + \bar{c} \to \tilde{d}^*_R$	$e^+ + d \to \tilde{c}_L$
122	$e^+ + \bar{c} \to \tilde{s}^*_R$	$e^+ + s \to \tilde{c}_L$
123	$e^+ + \bar{c} \to \tilde{b}^*_R$	$e^+ + b \to \tilde{c}_L$
131	$e^+ + \bar{t} \to \tilde{d}^*_R$	$e^+ + d \to \tilde{t}_L$
132	$e^+ + \bar{t} \to \tilde{s}^*_R$	$e^+ + s \to \tilde{t}_L$
133	$e^+ + \bar{t} \to \tilde{b}^*_R$	$e^+ + b \to \tilde{t}_L$

Table 3: Squarks production processes at HERA with an e^+ incoming beam through $R\!\!\!/_p$couplings λ'_{1jk}.

With an e^+ incident beam, HERA is best sensitive to couplings λ'_{1j1}, where mainly $\tilde{u}^j_L$ squarks could be produced via processes involving a valence d quark. On the contrary, e^-p data allow to better probe λ'_{11k} couplings and $\tilde{d}^k_R$ squarks. Hence, different squarks and couplings can be probed depending on the charge of the incident lepton. This dichotomy has important consequences since "left" and "right"squarks have different allowed or dominant decay modes as will be seen in the following.

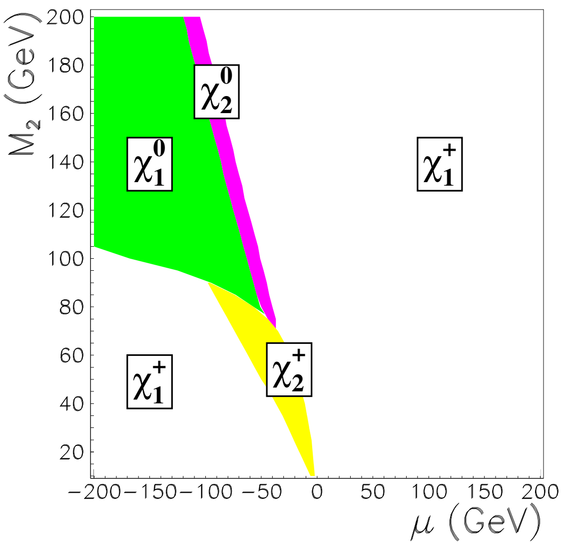
3.2 Decays and Final States

The squarks decay either via their Yukawa coupling into SM fermions, or via their gauge couplings into a quark and a neutralino χ^0_i $(i = 1, 4)$, a chargino χ^+_j $(j = 1, 2)$ or a gluino $\tilde{g}$. The former modes are henceforward called "$R\!\!\!/_p$decays" and the latter "gauge decays". The mass eigenstates χ^0_i and χ^+_j are mixed states of gauginos and higgsinos and are in general unstable. This latter point holds in $R\!\!\!/_p$ SUSY also for the Lightest Supersymmetric Particle (LSP) which decays via λ'_{1jk} into a quark, an antiquark and a lepton [25]. This is in contrast to the MSSM and has important phenomenological and possibly cosmological consequences. Gauge decays of squarks into gluinos have not been considered so far in experimental searches at HERA [29, 30, 31] where $\tilde{g}$ were assumed to be heavier than the squarks. This hypothesis is also made here. However, $\tilde{q}$ decays into $\tilde{g}$ would lead to final states similar to those induced by decays into χ's, with a higher jet multiplicity. These decays thus do not modify the phenomenology presented below.

In cases where both production and decay occur through a λ'_{1jk} coupling the squarks behave as scalar leptoquarks. The $\tilde{u}^j_L$ ressembles the $\tilde{S}_{1/2,L}$ LQ described in the BRW model and decays into $e^+ + d_k$, while the $(\tilde{d}^k_R)^*$ ressembles the $S_{0,L}$ and can decay into $e^+ + \bar{u}_j$ as well as $\bar{\nu}_e + \bar{d}^j$. The partial width for these decays is proportional to $\lambda'^2_{1jk} M_{\tilde{q}}$ so that squark $R\!\!\!/_p$decays mainly contribute at high mass for large Yukawa coupling values.

On the contrary, for small $\tilde{q}$ masses or small λ' values, gauge decays into a neutralino or a chargino will dominate in general. (Almost) only the $\tilde{q}_L$ are allowed by gauge symmetry to decay into charginos. This

Figure 11: *Dominant gauge decay of a* 150GeV $\tilde{u}_L$ *squark in the* (M_2, μ) *plane, for* $\tan\beta =$ 1. *Gluinos are assumed to be heavier than the squarks.*



is because the $SU(2)_L$ symmetry which implies in the SM that the right handed fermions do not couple to the W boson also forbids a coupling of $\tilde{q}_R$ to the $\tilde{W}$. The $\tilde{q}_R$ decays $\tilde{q}_R \rightarrow q'\chi_i^+$ involving charginos are only possible through the $\tilde{H}^\pm$ component of the $\chi^\pm$ in which case the coupling is proportional to the q' mass. Hence these decays are strongly suppressed for a $\tilde{q}_R$ of the first or second generation. On the contrary "left" squarks (especially the $\tilde{u}_L^j$ which could be produced at HERA in e^+p collisions) can dominantly decay into the lightest chargino, although the χ_1^+ is usually heavier than the χ_1^0. This is illustrated in Fig. 11, where the dominant gauge decay of a 150 GeV $\tilde{u}_L$ is shown in the plane (M_2, μ) for $\tan\beta = 1$. It can be seen that the decay into the lightest chargino dominates as soon as kinematically allowed. Hence such decays (followed by the subsequent decay of the χ^+) should not be neglected with e^+ in the initial state.

The final states resulting from squark gauge decays will finally depend on the subsequent decay of the χ. Neutralinos can undergo the $\not{R}_p$ decays $\chi_\alpha^0 \rightarrow e^\pm q\bar{q}'$ or $\chi_\alpha^0 \rightarrow \nu q\bar{q}$, the former (latter) being dominant if χ_α^0 is dominated by its photino (zino) component. When χ_α^0 decays via $\not{R}_p$ into a charged lepton, both the "right" and the "wrong" sign lepton (compared to incident beam) are equally probable leading to largely background free striking signatures for lepton number violation. On the contrary, the only $\not{R}_p$ decays for charginos are $\chi_\alpha^+ \rightarrow \nu u^j \bar{d}^k$ and $\chi_\alpha^+ \rightarrow e^+ d^k \bar{d}^j$. Neutralinos χ_α^0 with $\alpha > 1$ as well as charginos can also undergo gauge decays into a lighter χ and two SM fermions, through a real or virtual gauge boson or sfermion.

Combining all squarks and χ's decay modes, many possible final states could be observed, with one or several lepton, one or several jet(s), with or without missing transverse momentum $P_{t,miss}$. Most of those are listed in Table 4. It should be noted that some of these final states, induced only through the decays of $\tilde{q}$ into charginos, would be less easily observable in e^-p collisions where mainly "right" squarks are produced than in e^+p collisions. The branching ratios in the different channels depend on the strength of the Yukawa coupling λ', on the squark mass, as well as on the MSSM parameters $(M_2, \mu, \tan\beta)$ which determine the mass spectrum of the χ's and their couplings to sfermion-fermion pairs. Besides the striking signature $e^+p \rightarrow e^- + jets + X$ already mentioned above, quasi background free final states with two or three leptons together with a hard hadronic system constitute "golden" channels to look for the $\not{R}_p$SUSY signal. The final states listed in Table 4 have been studied by H1 Collaboration in [29] using $\simeq$ 3pb^{-1} of e^+p data. All different channels were combined and mass dependent upper limits on the Yukawa couplings λ'_{1jk} were derived, for several chosen points $(M_2, \mu, \tan\beta)$ of the MSSM parameter space. More recent analyses [30, 31] based on $\simeq$ 40pb^{-1} of e^+p data considered only the e + jet(s) channels and lower

$\tilde{q} \to \not{R}_p$:
high P_t e + 1 jet (NC DIS)
$P_{t,miss}$ + 1 jet (CC DIS)
$\tilde{q} \to$ gauge, no $P_{t,miss}$:
high P_t $e^{\pm}$, multijets (NC DIS)
high P_t $e^{\pm}$ (wrong sign) , multijets
high P_t $e^{\pm} + l^+ + l^-$ + multijets (trileptons)
$\tilde{q} \to$ gauge, $P_{t,miss}$:
$P_{t,miss}$, multijets (CC DIS, photoproduction)
high P_t lepton + 1 jet + $P_{t,miss}$ (if χ_1^0 stable, ie $\simeq \tilde{H}$)
$e^{\pm}$ + lepton + $P_{t,miss}$, multijets
lepton + $P_{t,miss}$, multijets

Table 4: Possible final states induced by resonant squark production in ep collisions. The sources of SM backgrounds which are expected to be large are indicated in parentheses.

bounds on squark masses up to $\simeq$ 275GeV could be set for an electromagnetic strength of the Yukawa coupling.

3.3 HERA's discovery potential

The sensitivity limits on the couplings λ'_{1jk} that HERA could achieve with an integrated luminosity of 500pb^{-1} is indicated in Table 5, combining all channels studied in [29]. These bounds are given at a fixed squark mass (150 GeV) and for two representative cases of the MSSM parameters, with a 40 GeV χ_1^0 dominated by its photino or zino component. The comparison with the most stringent existing limits (see [32, 33] for a recent review, and references therein) is also shown, together with the corresponding process.

	Sensitivity for $M_{\tilde{q}} = 150$GeV, $M_{\chi_1^0} = 40$GeV and $\boldsymbol{\mathcal{L} = 500\mathrm{pb}^{-1}}$			
	HERA sensitivity		Indirect limits	
	$\tilde{\gamma}$-like χ_1^0	$\tilde{Z}$-like χ_1^0	Value	Process
λ'_{111}	0.008	0.023	0.002	$\beta\beta 0\nu$ decay
λ'_{112}	0.020	0.057	0.03	CC-universality
λ'_{113}	0.026	0.072	0.03	CC-universality
λ'_{121}	0.008	0.023	0.05	APV
λ'_{122}	0.027	0.077	0.09	ν_e-mass
λ'_{123}	0.043	0.012	0.25	$D - \bar{D}$ mixing
λ'_{131}	0.007	0.024	0.05	APV
λ'_{132}	0.027	0.091	0.5	R_e^{exp}
λ'_{133}	0.068	0.230	0.003	ν_e-mass

Table 5: Expected exclusion upper limits at 95% CL on the couplings λ'_{1jk} for $M_{\tilde{q}} = 150$GeV and $M_{\chi_1^0} = 40$GeV together with the best indirect limits.

In most cases HERA would extend considerably beyond the domains presently excluded by the other experiments, apart from the cases of λ'_{111} and λ'_{133} couplings, which are severely constrained by the non-observation of neutrinoless double beta decay [34] and upper limits on the ν_e Majorana mass [35] respectively.

3.4 Other $\not{R}_p$SUSY scenarios relevant at HERA

The observation of a possible excess of NC DIS-like events at very high Q^2 motivated considerable work on $\not{R}_p$SUSY phenomenology in ep collisions. Studies of other $\not{R}_p$SUSY scenarios [36, 37] extending beyond the possibilities presented above have also been triggered by the observation by both H1 [38] and ZEUS [39] Collaborations of events with one isolated lepton, missing transverse momentum $P_{t,miss}$ and a hadronic system. Five events $e^+p \to \mu + P_{t,miss} + X$ and three events $e^+p \to e + P_{t,miss} + X$ have been observed by H1 and ZEUS experiments respectively. A summary of these observations can be found elsewhere in these proceedings [3]. Some of those events are of special interest since their hadronic final state shows large transverse momentum $P_{t,had}$ (three such events for $e^+p \to \mu + X$, two for $e^+p \to e + X$), which is not very likely for Standard Model processes leading to the observed final state. In this section we study and illustrate a scenario proposed by T. Kon et al. in [36], where the resonant production of a scalar top was proposed to account for these events, and also to eventually explain a possible simultaneous excess of events in high Q^2 NC DIS.

3.4.1 The special case of the (light) stop

It is well known that due to possible important mixing in the third generation, the supersymmetric partners of the top or bottom quarks could be the lightest squarks. At HERA the light stop $\tilde{t}_1$ could be resonantly produced via $e^+ + d \to \tilde{t}_1$ through the λ'_{131} coupling. This process differs from the general resonant $\tilde{q}$ production studied in the previous section, since in general the decay mode $\tilde{t}_1 \to t + \chi_1^0$ is kinematically forbidden. Hence, if the lightest chargino is heavier than the stop, $\tilde{t}_1 \to e^+ + d$ is the only $\tilde{t}_1$ decay mode. However, as soon as the decay into $\chi_1^+ + b$ is kinematically allowed, it will largely dominate over the $\not{R}_p$stop decay, leading to a very small branching β_e for $\tilde{t}_1 \to e^+ + d$. It was argued in [40] that this prevents the observation at HERA of a light stop produced via λ'_{131} in the simplest NC DIS-like channel, since :

- for β_e close to 1, LQ searches at the TeVatron exclude a $\tilde{t}_1$ lighter than 242 GeV;
- too small β_e values would require large couplings λ'_{131} for such a signal to be observed, in conflict with the indirect bounds on this coupling.

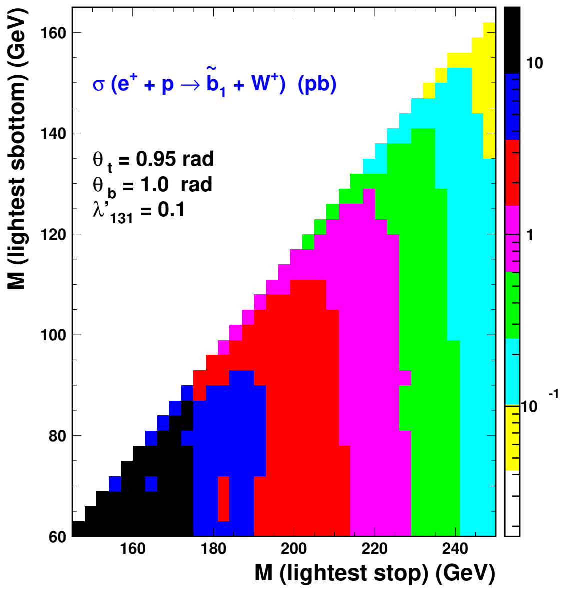


Figure 12: Cross-section for $\tilde{b}_1 + W$ production at HERA. $\tan\beta$ has been set to 5 and λ'_{131} to 0.1, i.e. below the indirect limit of 0.12 coming from Atomic Parity Violation. This cross-section approximately scales as $(\lambda'_{131} \times \cos^2\theta_t \times \cos\theta_b)^2$.

A possible way-out consists in opening other decay modes for the stop, leading to possible "intermediate" values for the branching β_e. This could be achieved if the light sbottom $\tilde{b}_1$ is lighter than the stop, so that $\tilde{t}_1 \to \tilde{b}_1 + W^+$ is allowed. At high values of M_2 and $\mid \mu \mid$, the χ^0 and χ^+ are heavy and the $\tilde{b}_1$ is the LSP. The only decay modes for the stop are $\tilde{t}_1 \to e^+ + d$ and $\tilde{t}_1 \to \tilde{b}_1 + W$, while the $\tilde{b}_1$ only decays via $R\!\!\!/_p$ into $\bar{\nu}_e + d$. The final state of $e^+ + d \to \tilde{b}_1 + W^+$ thus depends on the W decay only and consists of several jets and $P_{t,miss}$, or one lepton, one jet and $P_{t,miss}$. The cross-section for $\tilde{b}_1 + W^+$ production is shown in Fig. 12 in the $(M_{\tilde{t}_1}, M_{\tilde{b}_1})$ plane, for fixed values of λ'_{131}, θ_t and θ_b. It can be seen that sizeable cross-sections (of the order of 1 pb) can be reached, predicting few events to be observed in the leptonic decay mode of the W with the current HERA luminosity. The compatibility of the kinematics of $\tilde{b}_1 + W$ events with that of the $l + jet + P_{t,miss}$ events observed at HERA is addressed in the following paragraph.

3.4.2 High P_t Isolated Leptons Events

A light sbottom decaying only into $\bar{\nu}_e + d$ is constrained by TeVatron searches for LQs decaying to $\nu + q$, which lead to a lower mass limit of $\simeq$ 90GeV. Thus the stop should be heavier than $\simeq$ 170GeV to allow $\tilde{t}_1 \to \tilde{b}_1 + W$. Hence we consider in the following $M(\tilde{t}_1) \simeq$ 200GeV and $M(\tilde{b}_1) \simeq$ 100GeV.

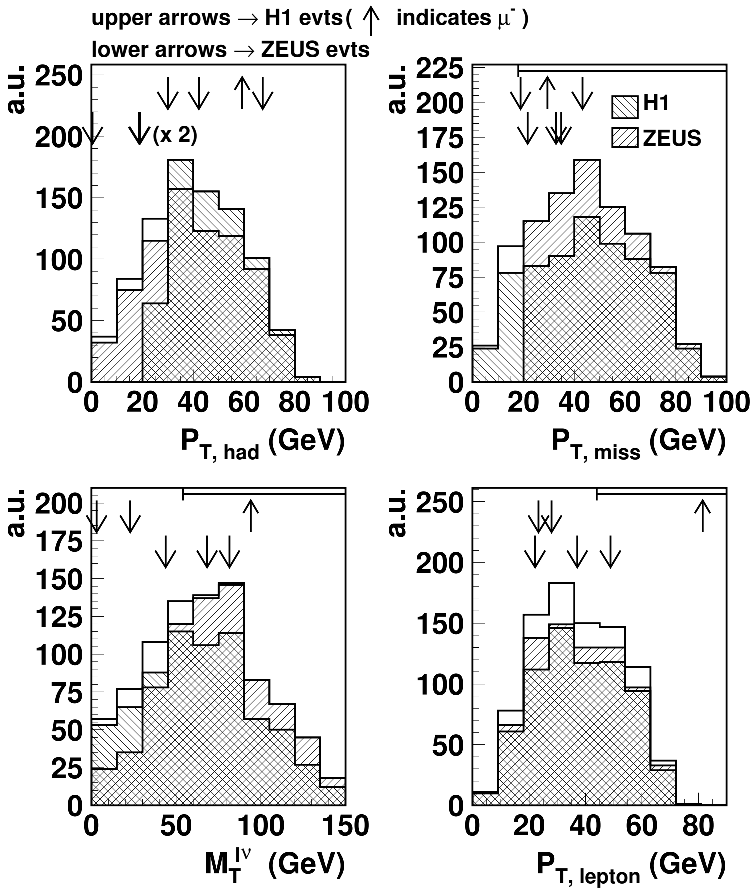


Figure 13: Expected distributions for $\tilde{b}_1 + W$ events followed by a leptonic decay of the W. The $\tilde{t}_1$ and $\tilde{b}_1$ masses have been set to 205 GeV and 100 GeV respectively. Distributions are shown without any selection cut as white histograms and requiring $P_{T,had} > 25$ GeV (used in the H1 analysis of $e^+ + p \to \mu + X$ events) or $P_{t,miss} > 20$ GeV (used in the ZEUS analysis of $e^+ + p \to e + X$ events) as hatched histograms.

The $\tilde{b}_1 + W$ production has been implemented in the package SUSYGEN3 [41], which is an extension of the SUSYGEN [42] event generator allowing to study SUSY processes also in ep collisions. It includes initial and final state parton showers and the string fragmentation is used for the non-perturbative part of the hadronization. Samples of $\tilde{b}_1 + W$ Monte-Carlo events where the W decays leptonically have been produced using SUSYGEN3 with $M_{\tilde{t}_1} = 205$GeV and $M_{\tilde{b}_1} = 100$GeV. The expected distributions for the transverse momentum of the hadronic system $P_{t,had}$, the missing transverse momentum $P_{t,miss}$, the transverse momentum of the charged lepton $P_{t,lepton}$ and the transverse mass $M_T^{l,\nu}$ between the lepton and the neutrino are shown in Fig. 13. The white histograms correspond to the distributions obtained before any selection cut, while the hatched ones show how the cuts applied in the H1 and ZEUS analyses (roughly $P_{t,had} > 25$GeV and $P_{t,miss} > 20$GeV, respectively) reduce the acceptance. For each variable, the upper (resp. lower) arrows show the position of the μ (resp. e) events observed by H1 (resp. ZEUS). In one out of the five μ events observed by H1 the scattered positron is also detected, which makes this event very likely to come from Standard Model W production. This event is thus not considered here. For another μ event the momentum of the track associated to the μ could not be measured with enough precision, hence lower limits on $P_{t,miss}$, $M_T^{l\nu}$ and $P_{t,lepton}$ are shown as horizontal lines for this event.

It can be seen that the observed events lie well within the bulk of these distributions, apart from one $e^+p \to \mu^- + X$ event observed by H1. This event could anyway not be due to $\tilde{b}_1 + W^+$ production because of the charge of the final state lepton.

Whether the "high P_t isolated lepton events" observed at HERA are accounted for by $\tilde{b}_1 + W$ production or are due to SM processes should be clarified with increasing luminosity, or by studying the SUSY signal induced by hadronic decays of the W. Meanwhile, one should wonder whether the observation of few events coming from $e^+ + d \to \tilde{b}_1 + W \to l^+ + jet + P_{t,miss}$ would not imply a too large signal in the $e^+ + d \to \tilde{t}_1 \to e^+ + d$ channel, which would be in conflict with the current measurements of high Q^2 NC DIS. Fig. 14 shows the branching ratio β_e of the $\tilde{t}_1$ to decay into $e^+ + d$ in the $(M_{\tilde{b}_1}, \theta_b)$ plane, for fixed

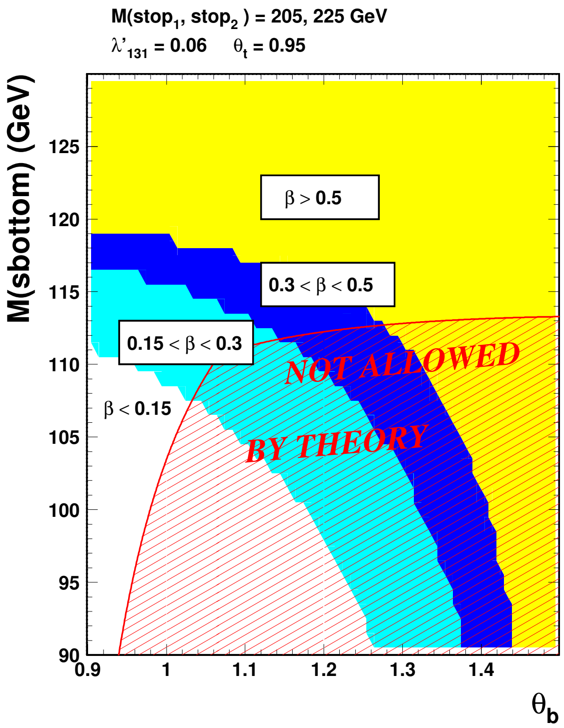


Figure 14: Iso-domains for the branching β_e of the $\tilde{t}_1$ to decay into $e^+ + d$ through λ'_{131}, in the $(M_{\tilde{b}_1}, \theta_b)$ plane, for $M_{\tilde{t}_1} = 205$ GeV, $\lambda'_{131} = 0.06$ and $\theta_t = 0.95$ rad. The hatched domain is forbidden if one assumes soft terms universality.

values of the stop mass and mixing angle, and for $\lambda'_{131} = 0.06$. Assuming soft terms universality, relations between $\tan\beta$ and stop and sbottom mixing angle and masses forbid the lowest hatched part of this plane. It can be seen that a small branching ratio into $e^+ + d$ can be insured provided that the sbottom mass remains quite small. It is thus possible to observe few events induced by $e^+ + d \to \tilde{b}_1 + W \to \nu_e d l \nu_l$

together with a reasonably small (or event not observable) signal in the $e^+ + d \to \tilde{t}_1 \to e^+ + d$ channel. Before concluding, we note that such light $\tilde{t}_1$ and $\tilde{b}_1$ contribute to the W and Z self-energies [43]. In the constrained $\not{R}_p$-MSSM model the part of the parameter space where these induced contributions to Π_W and Π_Z are not in conflict with the latest upper limit on $\Delta\rho$ appears to be quite restricted.

For completeness, we also recall the SUSY interpretation proposed in [29, 44] short after the H1 observation of the first $e^+ + p \to \mu + X$ event in 1994. The decay of the stop (or any resonantly produced squark) into a quark and χ_1^+, followed by the decay $\chi_1^+ \to \mu^+ + \nu_\mu + \chi_1^0$ could account for such events, provided that the time of flight of the χ_1^0 is large such that the χ_1^0 escapes detection.

4 Conclusions and Outlook

The discovery potential for leptoquarks or R-parity violating squarks at the HERA ep collider has been emphasized and some aspects of their phenomenology have been detailed. Although the current HERA data show a general good agreement with the Standard Model predictions, some intriguing observations still need to be clarified. The high Q^2 NC DIS data still present a slight excess of events compared to the prediction from the Standard Model. Moreover interesting events with one isolated lepton, missing transverse momentum and a hard hadronic system could be the first signs of new physics. The future HERA luminosity upgrade which should provide a five-fold increase of the statistics, will allow exciting searches to be pursued.

Acknowledgments I wish to thank the organizers of QFTHEP'99 for providing me the opportunity to emphasize the discovery potential of Physics Beyond the Standard Model in ep collisions at this very stimulating Workshop and for their warm hospitality during my stay in Moscow. I also thank my colleagues from H1 and ZEUS experiments at HERA for their help and support. I am very gratefull to A.S. Belyaev, W. Buchmüller, R. Rückl, F. Schrempp, A. Semenov and M. Spira for their help and usefull discussions.

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