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Pursuing Interpretations of the HERA Large-Q^2 Data

G. Altarelli[1], **J. Ellis**, **G.F. Giudice**[2], **S. Lola** and **M.L. Mangano**[3]

Theory Division, CERN, CH-1211, Genève 23, Switzerland

Abstract

We explore interpretations of the anomaly observed by H1 and ZEUS at HERA in deep-inelastic e^+p scattering at very large Q^2, in terms of possible physics beyond the Standard Model. Since the present data could be compatible with either a continuum or a resonant solution, we discuss both the possibilities of new effective interactions and the production of a narrow state of mass $M \sim 200$ GeV with leptoquark couplings. We compare these models with the measured Q^2 distributions: for the contact terms, constraints from LEP 2 and the Tevatron allow only a few choices of helicity and flavour structure that could roughly fit the HERA data. The data are instead quite consistent with the Q^2 distribution expected from a leptoquark state. We study the production cross sections of such a particle at the Tevatron and at HERA, the latter in the cases where it is produced from either a valence or a sea quark. The absence of a signal at the Tevatron disfavours the likelihood that any such leptoquark decays only into e^+q. We then focus on the possibility that the leptoquark is a squark with R-violating couplings. In view of the present experimental limits on such couplings, the most likely production channels are $e^+d \to \tilde{c}_L$ or perhaps $e^+d \to \tilde{t}$, with $e^+s \to \tilde{t}$ a more marginal possibility. We point out that the $\tilde{c}_L$ could have competing branching ratios for R-conserving and R-violating decay channels, whereas $\tilde{t}$ decays would be more likely to be dominated by one or the other. Possible tests of our preferred model include the absence both of analogous events in e^-p collisions and of charged current events, and the presence of detectable cascade decays whose kinematical signatures we discuss. This model could also make an observable contribution to $K \to \pi\bar{\nu}\nu$ and/or neutrinoless $\beta\beta$ decay. We also discuss the possible implications for the Tevatron and for $e^+e^- \to \bar{q}q$ and neutralinos at LEP 2.

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[1] Also at Università di Roma III, Rome, Italy.
[2] On leave of absence from INFN, Sez. di Padova, Italy.
[3] On leave of absence from INFN, Sez. di Pisa, Italy.

1 Introduction and Summary

The HERA experiments H1 [1] and ZEUS [2] have recently reported an excess of deep-inelastic e^+p scattering events at large values of $Q^2 > 1.5 \times 10^4$ GeV^2, in a domain not previously explored by other experiments. With a total e^+p integrated luminosity of 14 pb^{-1}, H1 [1] observes 7 events with large e^+-jet invariant masses $M = \sqrt{xs}$, clustered around $M = 200$ GeV, in which the positron is backscattered at large $y = Q^2/M^2$. Similarly, ZEUS [2] with an integrated luminosity of 20 pb^{-1} observes 5 events at comparable large values of Q^2, x and y. Although the H1 and ZEUS data are mutually consistent and the presence of the same type of excess in the two experiments is certainly impressive, the detailed features of the events are not exactly the same in H1 and ZEUS. The events of H1 are more suggestive of a resonance with e^+-quark quantum numbers than the ZEUS data points, which are more scattered in mass. The difference could, however, be due to the different methods of mass reconstruction used by the two experiments, or to fluctuations in the event characteristics. Of course, at this stage, due to the limited statistics, one cannot exclude the possibility that the whole effect is a statistical fluctuation. This will hopefully be clarified soon by the coming 1997 run. Meanwhile, it is important to explore possible interpretations of the signal, in particular with the aim of identifying additional signatures that might eventually be able to discriminate between different explanations of the reported excess.

Since the observed excess is with respect to the Standard Model expectation based on the QCD-improved parton model, the first question is whether the effect could be explained by some inadequacy of the conventional analysis without invoking new physics beyond the Standard Model. In the case of the apparent excess of jet production at large transverse energy E_T recently observed by the CDF collaboration at the Tevatron [3], it has been argued [4] that a substantial decrease in the discrepancy can be obtained by modifying the gluon parton density at large values of x where it has not been measured directly. In the HERA case [1, 2], a similar explanation is apparently not viable. In this case, the valence quark densities are the most relevant ones, and they have been measured directly [5] in the same range of x at much lower values of Q^2. Since the values of x which are relevant for the HERA excess are quite large ($x \sim 0.5$), it is possible in principle that higher-order effects of the Sudakov type, not accounted for by the standard next-to-leading-order QCD analysis of the structure function data, could affect the low-energy extraction of the partonic densities and their evolution to high Q^2 [6]. It should be remarked, however, that the most recent measurements of F_2 from the HERA experiments explore the same high-x values in a large range of Q^2 values, and no anomaly was found at large x up to $Q^2 \sim 10^4$ GeV^2 [1, 2]. The evolution logarithms could not explain the abrupt occurrence of the effect, which is undetected at $Q^2 \sim 10^4$ GeV^2 but fully visible at $Q^2 \sim 2 \times 10^4$ GeV^2. Therefore one can safely conclude that Sudakov effects cannot provide a credible explanation of the observed excess. We also note that, if the parton densities were to blame, very similar effects should be seen in both neutral and charged current channels, with both e^+ and e^- beams. This can be checked in the near future. We do not consider this alternative in the following, but concentrate on interpretations based on possible new physics.

We first discuss the possibility that the observed excess is a non-resonant continuum. Within this scenario, a rather general approach is to interpret the HERA excess as due to an effective four-fermion $\bar{e}e\bar{q}q$ contact interaction [7] with a scale Λ of order 1.5-2.5 TeV. It is interesting that a similar contact term of the $\bar{q}q\bar{q}q$ type, with a scale of exactly the same order of magnitude, could also reproduce the CDF excess in jet production at large E_T [4]. We study the contact interaction scenario for the HERA excess in some detail. In order to interfere with the electroweak gauge interactions, the contact term is taken as the local product of two mixed vector- and axial-vector currents. We study the x and Q^2 distributions that correspond to different flavours, signs and choices of helicity for the contact terms (i.e., LL, RR, LR or RL), and compare them with the HERA data. Strong bounds on the possible magnitudes of the interaction scales Λ are imposed by CDF data [9] on the Drell-Yan production of e^+e^- pairs at large invariant mass, and by LEP 2 data on hadron production [10, 11]. If we restrict our analysis to one particular term at a time, though in general one cannot exclude a superposition of different chiral structures, we find that most of the individual contact terms that could fit the HERA data are already excluded. Only for particular choices of quark flavour, sign and helicity can one obtain even rough agreement with the HERA data while escaping the existing bounds. We present examples of these models, and point out the desirability of further tests at LEP 2, where a complete analysis by all the experimental collaborations is still lacking, and at the Tevatron. It is interesting that the existence of the appropriate contact terms could be soon excluded, or their effects discovered in these experiments. We recall that the effects of contact terms should be present in both the e^+ and the e^- cases with the same intensity, and possibly also in the charged current channel, if left-handed currents are invoked.

We then focus on the possibility of a resonance with e^+q quantum numbers, namely a leptoquark. Most probably the production at HERA occurs from valence u or d quarks, since otherwise the coupling would need to be quite large, and more difficult to reconcile with existing limits [12, 13, 11, 14]. Assuming an S-wave state, one may have either a scalar or a vector leptoquark. Although we mostly consider the first option, we also include some discussion of the vector case. Defining the coupling λ for a scalar ϕ by $\lambda\phi\bar{e}_L q_R$ or $\lambda\phi\bar{e}_R q_L$, the observed excess of ~ 10 events in 34 pb^{-1}, observed with an efficiency of $\sim 80\%$, suggests values of $\lambda \sim 0.025$ or 0.04 for production from u or d quarks respectively. The corresponding natural decay width is of the order of a few MeV. We compute the Q^2 distribution predicted by leptoquark production, and show that it matches the data better than the corresponding distributions for contact terms. A scalar e^+u or e^+d state couples to the following SU(2) doublet combinations: $e^+_L(u_L, d_L)$, $(e^+_R, \bar{\nu}_R)u_R$, or $(e^+_R, \bar{\nu}_R)d_R$. This implies that a scalar with e^+u or e^+d quantum numbers can decay into $\bar{\nu}q$ final states only if it has another Yukawa interaction besides that responsible for its production. This additional interaction involves a lepton field of opposite chirality and is strongly constrained by pion decays. In its absence, a leptoquark would not be able to explain any resonant signal in the charged-current channel. The H1 collaboration has reported [1] four events in this channel, with a Standard Model background of about two, but ZEUS [2] has not reported a recent charged-current analysis. We note that the situation is different for a vector leptoquark in the e^+q case, or for a scalar leptoquark in the e^-q case. In the latter case we could, for example, have a coupling to the weak isospin singlet $e^-_L u_L - \nu_L d_L$ that indeed leads to both neutral and charged current decay modes.

Leptoquarks would be produced via QCD interactions at the Tevatron [15]. We find that a scalar leptoquark of mass $M \sim 200$ GeV has a production cross section of around 0.2 pb

[4]Note, however, that this interpretation is not strengthened by more recent data on the dijet angular distribution [8].

at the Tevatron. The cross section for vector leptoquarks is somewhat model-dependent, but expected to be much larger, as discussed later. Given the large value of the cross section, a leptoquark branching ratio $\mathcal{B}(e^+q) < 1$ into the observed e-jet channel is perhaps needed, even in the scalar case, to avoid a possible combined CDF/D0 exclusion limit. The current best limit from the Tevatron for a first-generation leptoquark is 194 GeV for $\mathcal{B}(e^+q) = 1$, recently given by the D0 collaboration [16], and the corresponding limit for $\mathcal{B}(e^+q) = \mathcal{B}(\bar{\nu}q) = 0.5$ is 143 GeV [16]. Thus any scalar with leptoquark quantum numbers might need additional decay modes beyond those given by the λ interaction introduced above for its production mechanism.

Perhaps the most appealing form of leptoquark is a squark [17] with couplings that violate R parity [18]. This possibility has been put forward in connection with the HERA events also in ref. [19]. In terms of supersymmetric chiral multiplets, the relevant coupling is given by

$$\lambda'_{ijk} L_i Q_j D^c_k \tag{1}$$

where L_i, Q_j and D^c_k are superfields of lepton doublets, quark doublets and quark singlets respectively, and i, j, k are generation indices. Leaving production from the sea aside for the moment, the processes relevant for HERA that arise from this coupling are $e^+_R d_R \to \tilde{u}_L$ or $\tilde{c}_L$ or $\tilde{t}_L$. We find that the first possibility is eliminated by existing limits on λ'_{111}, in particular those from $\beta\beta$ decay [20], whereas the latter are still permitted. In the following, we study the scharm $\tilde{c}$ and stop $\tilde{t}$ possibilities in some detail. We recall that the R-violating decays of the produced squark must compete with the ordinary R-conserving decays. Although some sizeable additional decay channels are welcome in view of the non-observation of a signal at CDF/D0, the R-conserving channels should have a moderate rate, otherwise the coupling λ'_{ijk} required to explain the HERA excess becomes dangerously large, particularly in view of upper limits on λ'_{121} coming from $\beta\beta$ [20] and $K \to \pi\bar{\nu}\nu$ [21] decays. We make a careful study of the regions of parameter space for the supersymmetric model where the balance of R-conserving and R-violating decays is favourable, for both the $\tilde{c}$ and $\tilde{t}$ cases. Such a balance is more likely in the $\tilde{c}_L$ case than for the $\tilde{t}$. In the squark scenario there would be no signal in the charged-current $\bar{\nu}q$ channel, but there could be R-conserving decay signatures, whose kinematical properties we discuss later. No signal is expected from the same sparticle with e^- beams, unless one is sensitive to production from the $\bar{d}$ sea density. A distinctive signature of the $\tilde{c}$ possibility could be the appearance of a signal in $K \to \pi\bar{\nu}\nu$ close to the present upper limit.

We have also examined possible signatures of R-violating supersymmetric interactions at LEP 2. We find that interference effects in the reactions $e^+e^- \to \bar{q}q$ are unlikely to be detectable, unless the HERA squark is produced from the sea, in which case a signal might be detectable in $\bar{s}s$ final states. However, other effects of R-parity violation could be observable, such as $e^+e^- \to \chi^0\chi^0$, where χ^0 denotes the lightest neutralino, thanks to its R-violating decays. We also discuss the compatibility of the squark explanation of the HERA events with the model recently proposed [22] to interpret the four-jet anomaly found by ALEPH [23], but not seen by the other LEP experiments [24].

q	$e^+e^- \to u\bar{u}$		$e^+e^- \to d\bar{d}$	
ij	$\eta=+1$	$\eta=-1$	$\eta=+1$	$\eta=-1$
LL	1.1	2.4	2.4	1.0
RR	1.4	1.7	2.1	1.2
LR	1.5	1.6	1.7	1.4
RL	1.7	1.4	1.6	1.5

Table 1: *Preliminary OPAL 95% CL limits [11] on the effective contact interaction scale* Λ^q_{ij} *(in TeV).*

2 Effective Contact Interactions

Whereas the H1 data are at first sight quite suggestive of the production of a resonance in the s channel, the spread in $x_{2\alpha}$ of the ZEUS data [5] seem to favour the possibility of an effective 4-fermion contact interaction, which we pursue first as a more conservative option. As is customary in the literature [7], we parametrize the contact interactions in terms of the mass scale Λ appearing in the following effective Lagrangian:

$$\mathcal{L}_4 \;=\; 4\pi \sum_{\substack{i,j=L,R\\ q=u,d}} \frac{\eta_{ij}}{(\Lambda^q_{ij})^2}\, \bar{e}_i\gamma^\mu e_i\, \bar{q}_j\gamma_\mu q_j \;. \tag{2}$$

We allow for independent couplings of u and d quarks, as well as for independent couplings of all different helicity states [6]. The parameter η_{ij} takes the values ±1, and allows for constructive and destructive interferences in the different channels.

Very tight constraints on the size of such possible interactions have been set in the past [25]. Recent preliminary results from dielectron production at the Tevatron [9] and from hadron production at LEP 2 [10, 11] restrict even further the allowed ranges of the parameters Λ^q_{ij} in (2). The most recent analysis by OPAL [11], in particular, sets the 95% CL limits on the 16 independent couplings in (2) shown in Table 1. The CDF limits [9] have only been given for the isoscalar $u+d$ quark flavour combination, and for the LL helicity combination. We have simulated the effects in hadronic collisions of the contact interactions for which the OPAL limits allow good fits of the HERA data. For these cases we extracted from the Tevatron dilepton data limits on the relevant parameters Λ^q_{ij} by analogy with the limits provided by CDF for the isoscalar LL case [9].

Since contact interactions do not generate any particular structure in the x distributions, we discuss their impact on the integrated Q^2 distributions of the HERA data, as provided in their papers and combined in their public presentations [1, 2]. We have calculated the effects of

[5] The variable $x_{2\alpha}$ is the Bjorken x variable extracted using the double-angle method [1, 2]. We discuss in the Appendix issues related to this spread and to the comparison between values of x reported by H1 [1] and ZEUS [2], in the light of possible initial-state radiation.

[6] We do not consider here scalar current couplings, because they are very strongly constrained by low-energy data on helicity-suppressed decays [12, 13].

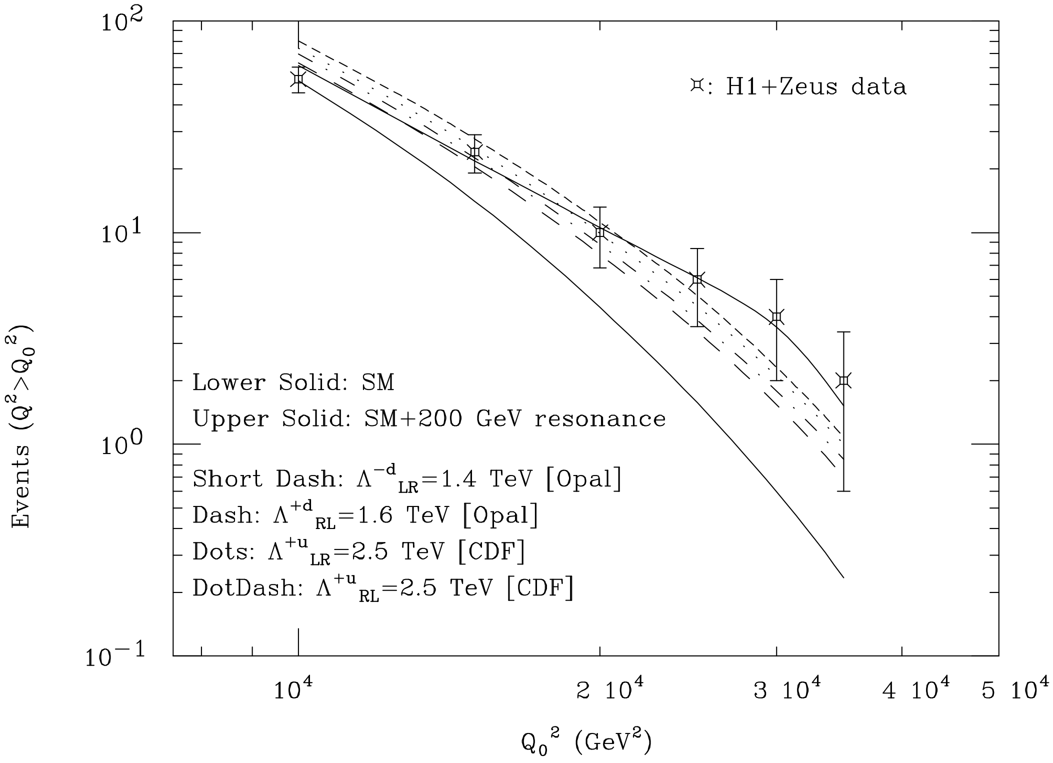

Figure 1: *HERA data for the integrated Q^2 distribution, compared to current limits on effective contact interactions from OPAL and CDF. Only the four combinations that best reproduce the HERA data are shown. The lower solid line corresponds to the prediction of the Standard Model. The upper solid curve corresponds to the decay of a 200 GeV s-channel resonance, produced at a rate compatible with the reported excess of events.*

each one of the 16 4-fermion couplings, including its interference with the Standard Model DIS processes. In the cases where the OPAL constraint allows a fit, we have applied the inferred CDF constraints on the corresponding Λ^q_{ij}, which are usually stronger.

We applied the analysis cuts of the H1 and ZEUS experiments, as described in their publications, and combined the expectations for the respective integrated luminosities and efficiencies [7]. Only a few of the 16 possible couplings are at all compatible with the HERA data, and the four best cases are presented in Fig. 1. In none of these cases is the agreement in shape between data and expectations particularly good. We note the essential rôles played by both OPAL and CDF in constraining the possible effective contact interactions: in particular, there are good fits of the HERA data for couplings with magnitudes that are at best compatible with the OPAL data alone, such as the choice $\Lambda^u_{RL} = 1.4$ TeV, with $\eta = -1$. However, this possibility is excluded by the CDF limit, which is stronger for this specific coupling, namely larger than

[7] We have verified that our Standard Model predictions, after accounting for the analysis cuts, efficiencies and integrated luminosities of the two experiments, agree with those presented in the H1 and ZEUS papers [1, 2].

3 TeV.

We conclude from this study that, while the contact interaction hypothesis cannot be entirely ruled out, the strong constraints already set by the LEP and Tevatron experiments do not allow for good fits of either the event rates or the Q^2 distributions of the H1 and ZEUS data. We remark once more that, in any case, for the contact interaction hypothesis to be tenable, the apparent resonant structure in the invariant e^+q mass distribution reported by H1 could only be the result of a statistical fluctuation, and should be washed out by higher statistics. We would also expect that a joint effort of the four LEP collaborations using the combined set of all LEP 2 data already on tape could further restrict the allowed ranges of the Λ parameters, as could a combined analysis of CDF and D0 data.

3 Leptoquarks

Since the excess found by H1 [1] occurs in a small range of e^+q invariant masses [8], it is natural to examine models containing a new boson with leptoquark quantum numbers, which may be classified according to their spin and isospin quantum numbers [26]. As discussed in the introduction, they may couple to a fermionic current constructed out of a quark and a lepton with a coupling constant λ. In the narrow-width approximation, the leading-order parton-level cross section for production of a leptoquark of spin J at HERA is given by:

$$\sigma = \frac{\pi}{4s} \lambda^2 F_J \qquad (F_0 = 1,\ F_1 = 2)\ . \tag{3}$$

The convolution of the parton cross section (3) with the parton densities of the proton [27] and with the effects of initial-state photon radiation from the positron, yields the cross sections shown in Fig. 2. We have assumed in this figure a leptoquark coupling to only one fermionic helicity, and have used $\lambda = 0.01$ as a reference value. Figure 2 shows results for all quark flavours. As is clear from the figure, all effective sea quark luminosities are significantly suppressed for masses in the 200 GeV region, where the hypothetical HERA signal lies. The cross sections for $\lambda = 0.01$ in the different production channels to produce a leptoquark with mass 200 GeV are given in Table 2. We have verified that the acceptance cuts imposed by H1 and ZEUS on their data have efficiencies of approximately 80% and 100%, respectively. Accounting for the detector efficiencies of the two experiments as quoted in their papers (of the order of 80%), for the relevant integrated luminosities, and assuming a total of 10 signal events in the combined experiments, we find that a value of λ of approximately $0.04/\sqrt{\mathcal{B}}$ is required for leptoquark production by e^+d collisions, with correspondingly larger couplings required for production by e^+ collisions with sea quarks. The cross sections for a vector leptoquark are a factor of two larger, and hence would require couplings smaller by a factor of $\sqrt{2}$. The implications of the value $\lambda \sim 0.04$ in the case of scalar quark production via an R-violating interaction will be discussed in the following section.

[8] Although the ZEUS events are more spread in invariant mass, and appear at larger values of $x_{2\alpha}$, we note that an inter-collaboration working group has found that the two data sets are compatible, and that ISR and other instrumental effects could in principle cause shifts of several % in the observed values of $x_{2\alpha}$, as discussed in the Appendix.

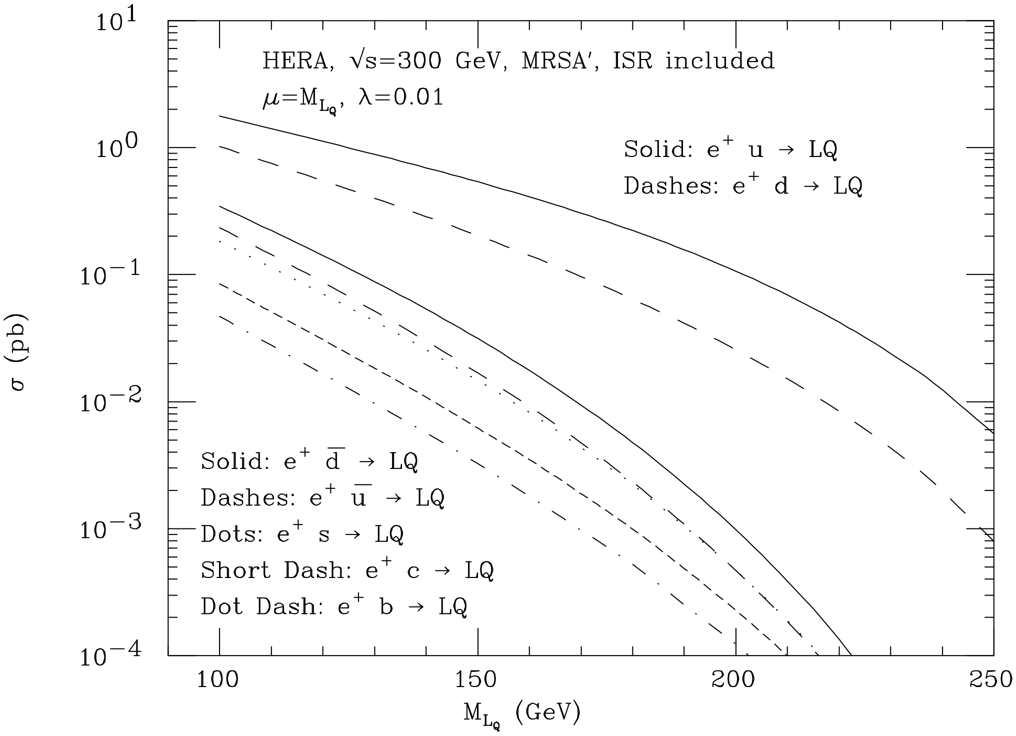

Figure 2: *Scalar leptoquark (or R-violating squark) production cross sections at HERA, including the effects of initial-state radiation (ISR). The contributions of different quark flavours in the proton are shown separately.*

σ(fb), $\lambda = 0.01$	e^+u	e^+d	$e^+\bar{d}$	$e^+\bar{u}$	e^+s	e^+c	e^+b
(with ISR)	106	25.6	0.98	0.47	0.47	0.23	0.12
(no ISR)	117	28.4	1.12	0.53	0.53	0.26	0.14

Table 2: *Production cross sections for a scalar leptoquark (or R-violating squark) of mass 200 GeV at HERA, assuming a coupling* $\lambda = 0.01$*, showing the effects of ISR.*

It is important to explore the possible implications of the existence of 200 GeV leptoquarks at the Tevatron, since there leptoquarks are produced via model-independent QCD processes with potentially large rates. The production cross section for scalar, colour-triplet particles at the Tevatron is given as a function of the mass in Fig. 3, using the MRSA$'$ [27] parton distribution function set, and a renormalization/factorization scale $\mu = m$. The lowest-order production cross section for a pair of 200 GeV leptoquarks is 0.18 pb [9]. The total integrated luminosity collected by the CDF and D0 experiments is of the order of 200 pb^{-1}, which would yield approximately 36 events if the hypothetical leptoquarks had a 100% branching ratio into electrons. The detection efficiencies for such a signal quoted by the CDF and D0 experiments are each of the order of 20%, resulting in about 7 detected events in total. Although the expected 3.5 events per experiment are not sufficient to exclude a leptoquark of 200 GeV in either CDF or D0 individually, the best current limit being 194 GeV by D0 as mentioned in the Introduction, it is likely that exclusion of a 200 GeV scalar leptoquark with 100% branching ratio into electrons at more than the 95% CL would result from the absence of a signal in a combined analysis of the data collected by CDF and D0. For this reason, in the following section we disfavour models with decay modes dominated by electrons [10] although this possibility is not yet rigorously excluded.

The case of a 200 GeV vector leptoquark is most likely totally ruled out by the Tevatron data, since the production rate can be as much as a factor of 10 larger than that of scalar leptoquarks, as shown in Fig. 3. We emphasize that in calculating this curve we have only included the light quark annihilation processes, and assumed minimal couplings to the gluons [29]. In the absence of a definite model of vector leptoquarks, their coupling to gluons is not uniquely defined, and in general leads to bad high-energy behaviour and unphysically large cross sections. This problem has been studied in detail in refs. [30, 31], where $J = 1$ leptoquark-pair production was considered for a general class of anomalous couplings. In ref. [30, 31] it was shown that, even allowing for anomalous couplings, and selecting them so as to minimize the production cross section via destructive interference, the total rate would still be a factor of two larger than that for scalar leptoquarks. In the absence of a signal, such a large rate would not be consistent with a combined CDF+D0 analysis if $\mathcal{B}(e^+q) = 1$. If one discards the possibility of such a fine-tuning in the anomalous couplings, values of $\mathcal{B}(e^+q)$ significantly below 1 could be excluded.

4 R-Parity Violation

We find it attractive to embed a hypothetical leptoquark in a well-motivated theoretical framework capable of constraining its properties and providing other experimental signatures, as is

[9]For our choice of renormalization scale, we also expect a multiplicative K factor of the order of 1.10 to 1.15 due to higher-order QCD corrections. These have been evaluated in the case of supersymmetric scalar quarks in [28]. The case of leptoquarks can be recovered by assuming a very large gluino mass. In this case, diagrams due to four-squark operators which are not present in the leptoquark case only appear in the gluon-fusion production channel, which is significantly suppressed.

[10]*A priori*, generic leptoquarks could avoid this problem by having two different Yukawa couplings, allowing νq decays as mentioned in the Introduction, or by coupling to μq or τq. However, the μq option is strongly constrained by limits on flavour-changing interactions, such as $\mu - e$ conversion on nuclei [12, 13].

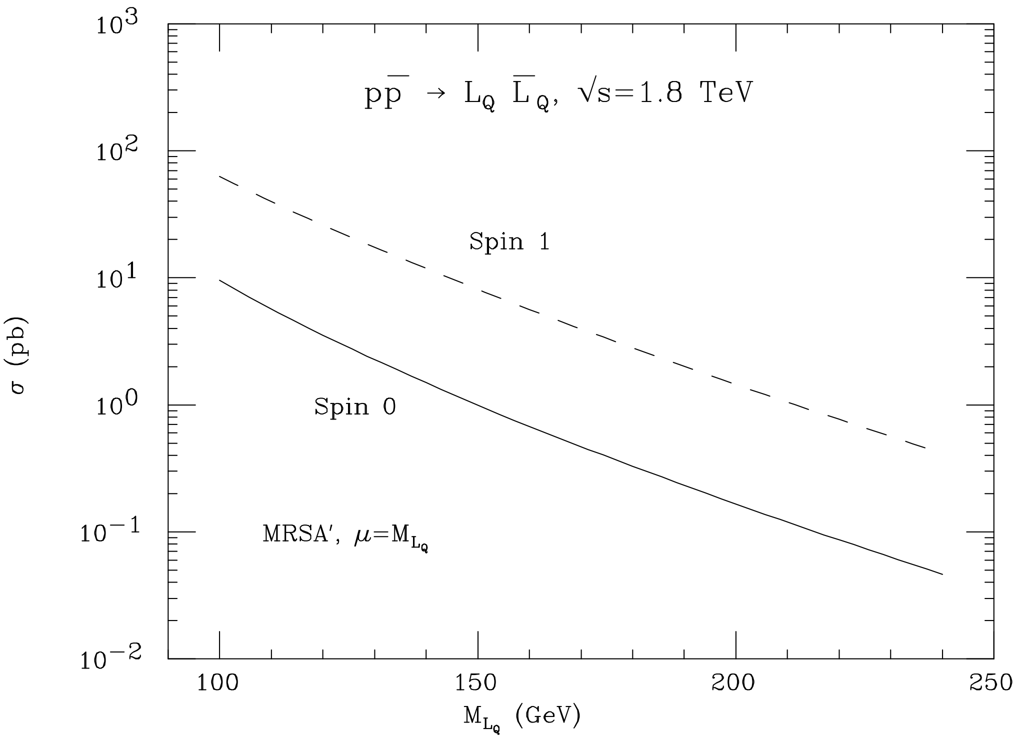

Figure 3: *Scalar and vector leptoquark production cross sections at the Tevatron. In the case of the vector leptoquark, as discussed in the text, we have only included the light $q\bar{q}$ annihilation processes.*

provided by the minimal supersymmetric extension of the Standard Model [17] with violation of R parity [18]. The corresponding superpotential can be written in the form

$$W_R \equiv \mu_i H L_i + \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k \ , \tag{4}$$

where $H, L_i, E^c_j, Q_k, (U,D)^c_l$ denote superfields for the $Y = 1/2$ Higgs doublet, left-handed lepton doublets, lepton singlets, left-handed quark doublets and quark singlets, respectively. The indices i,j,k label the three generations of quarks and leptons. Henceforth, we work in a basis for the L_i and the $Y = -1/2$ Higgs doublet $\bar{H}$ in which $\mu_i = 0$, and the only surviving bilinear term is the Higgs mixing $\mu H\bar{H}$. Furthermore, we assume the absence of the λ'' couplings, so as to avoid rapid baryon decay, and the λ couplings play no rôle in our analysis.

4.1 Production mechanisms

The squark production mechanisms permitted by the λ' couplings in (4) include e^+d collisions to form $\tilde{u}_L, \tilde{c}_L$ or $\tilde{t}_L$, which involve valence d quarks, and various collisions of the types e^+d_i ($i = 2,3$) or $e^+\bar{u}_i$ ($i = 1,2,3$) which involve sea quarks. The required magnitude of the coupling λ' is fixed by the observed product of the cross section σ and the squark branching ratio $\mathcal{B}$ for the R-parity violating mode $\tilde{q} \to e^+q'$. From the results of the previous section, summarized in Table 2, we infer that the valence production mechanism requires λ'_{1j1} ($j = 1,2,3$) to be about $0.04/\sqrt{\mathcal{B}}$, while any of the sea production mechanisms require $\lambda'_{1jk} > 0.3/\sqrt{\mathcal{B}}$ ($j,k = 1,2,3$). The latter are only marginally compatible with LEP 2 limits [11], and with previous H1 limits [14] in the cases j or $k = 1$.

The required values of the λ'_{1jk} are to be compared with the upper limits available from various other laboratory experiments [11]. It has been inferred from upper limits on neutrinoless $\beta\beta$ decay that [20]

$$|\lambda'_{111}| < 7 \times 10^{-3} \left(\frac{m_{\tilde{q}}}{200\ \mathrm{GeV}}\right)^2 \left(\frac{m_{\tilde{g}}}{1\ \mathrm{TeV}}\right)^{\frac{1}{2}} \ . \tag{5}$$

where $m_{\tilde{q}}$ is the mass of the lighter of $\tilde{u}_L$ and $\tilde{d}_R$, and $m_{\tilde{g}}$ is the gluino mass. This limit excludes any production mechanism involving only first-generation particles, and in particular the valence parton process $e^+d \to \tilde{u}_L$.

For charm squark production $e^+d \to \tilde{c}_L$, the most important constraint on the relevant coupling constant λ'_{121} comes from limits on flavour-changing neutral current processes. The simultaneous presence of several λ' couplings with different flavour indices leads in general to dangerous tree-level flavour violations. Usually one makes the most conservative assumption that only a single λ' coupling with specific flavour indices is non-negligible. However, because of the mismatch in flavour space between the up- and down-type left-handed quarks, this hypothesis cannot be simultaneously satisfied both in the up and down sectors. We will work in a basis where, in terms of the lepton (N_i, E_i) and quark (U_i, D_i) mass eigenstates, the λ' interaction term in the superpotential is written as

$$\lambda'_{ijk}(N_i V_{jl} D_l - E_i U_j) D^c_k \ , \tag{6}$$

[11] We will not consider here very stringent limits on R-parity violating interactions coming from cosmological considerations of the baryogenesis energy scale [32], since there are ways to avoid these in principle, such as baryogenesis at the electroweak scale [33].

where V_{ij} is the usual Cabibbo-Kobayashi-Maskawa matrix. We will also implicitly assume that the only sources of flavour violations are described by V and by the R-parity violating interactions. Because of the non-trivial mixing in the down sector, the λ_{ijk} couplings are bounded by $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) < 2.4 \times 10^{-9}$ [34] to be [21]

$$|\lambda'_{1jk}| < 2 \times 10^{-2} \left(\frac{m_{\tilde{d}_{k_R}}}{200 \text{ GeV}} \right) \quad \text{for } j = 1, 2,\ k = 1, 2, 3. \tag{7}$$

Therefore a $\tilde{c}_L$ interpretation of the HERA data, which implies $\lambda'_{121} \sim 0.04/\sqrt{\mathcal{B}}$, is possible if

$$m_{\tilde{d}_R} > \frac{400 \text{ GeV}}{\sqrt{\mathcal{B}}} \ . \tag{8}$$

However, this bound on $m_{\tilde{d}_R}$ can be partially relaxed if the mixing in the down sector is somewhat suppressed by the simultaneous presence of various non-vanishing coupling constants λ'_{ijk}. For instance, allowing for several λ'_{1j1} with different indices j, the bound in eq. (7) becomes

$$\sqrt{\left| \sum_j \lambda'_{1j1} \frac{V_{j1}}{V_{21}} \right| \left| \sum_l \lambda'_{1l1} \frac{V_{l2}}{V_{22}} \right|} < 2 \times 10^{-2} \left(\frac{m_{\tilde{d}_R}}{200 \text{ GeV}} \right) \ . \tag{9}$$

If λ'_{111} saturates the bound in eq. (5), then λ'_{121} can be as large as 4×10^{-2}, even with $m_{\tilde{d}_R} = 200$ GeV. We want to stress that such a cancellation is not necessarily accidental, but could arise as a consequence of a particular alignment of the R-violating interactions in flavour space. The simultaneous presence of different couplings λ'_{1j1} entails, in our basis, some flavour violation in the up sector. We expect therefore new effects in D^0–$\bar{D}^0$ mixing and in the decay modes $D^0 \to e^+e^-$, $D^+ \to \pi^+e^+e^-$. These processes at present do not set constraints on λ'_{1j1} more stringent than the one considered above [13]. We also remark that the bound in eq. (8) can also be further relaxed by analogous cancellations among various λ'_{12k} couplings with different indices k.

In any case, the $\tilde{c}_L$ interpretation of the HERA data seems to suggest that $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ is very close to its experimental bound, a prediction which can be tested in the near future in the ongoing Brookhaven experiment [34]. Notice however that, while $m_{\tilde{d}_R}$ determines the effective interaction responsible for $K^+ \to \pi^+ \nu\bar{\nu}$, the HERA process is sensitive to $m_{\tilde{c}_L}$. In the absence of a complete theory describing all supersymmetric particle masses, $m_{\tilde{d}_R}$ and $m_{\tilde{c}_L}$ are not necessarily related, and this prevents us from a definite prediction for $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$.

Notice that one mass relation can be obtained in the case of the $\tilde{c}_L$ interpretation of the HERA data, with the help of weak-SU(2) symmetry. Indeed, assuming no significant left-right squark mixing, we can predict $m_{\tilde{s}_L} = \sqrt{m^2_{\tilde{c}_L} - \cos 2\beta M_W^2} \sim 200$ to 220 GeV. The squark $\tilde{s}_L$ cannot be produced at HERA from valence parton processes, but could be observed at the Tevatron.

The last possibility of a valence production mechanism is $e^+d \to \tilde{t}_L$ via λ'_{131}. Apart from the H1 and OPAL limits mentioned earlier, this coupling constant is constrained by experiments on parity violation in atomic physics, which imply [35]

$$|\lambda'_{131}| < 4 \times 10^{-1} \left(\frac{m_{\tilde{t}_L}}{200 \text{ GeV}} \right) \ . \tag{10}$$

This certainly allows a sufficient production rate, even if $\mathcal{B}$ is significantly less than 1. In the absence of left-right stop mixing, one expects $m_{\tilde{b}_L} = \sqrt{m^2_{\tilde{t}_L} - \cos 2\beta M^2_W - m^2_t + m^2_b} \sim 100$ to 130 GeV, in which case there would be an excessive contribution to the electroweak ρ parameter: $\Delta\rho \sim 2$ to 4×10^{-3}. At present the experimental value of $\Delta\rho$ from LEP/SLD data plus m_W/m_Z measurements is $\Delta\rho_{exp} = (4.7\pm1.3)\times10^{-3}$ [36]. The Standard Model value for $m_t = 175$ GeV is $\Delta\rho_{SM} = 5.7\times10^{-3}$ and 4.9×10^{-3} for $m_H = 100$ and 300 GeV, respectively. Thus, there is little space for a new positive contribution to $\Delta\rho$. This suggests the necessity of significant left-right stop mixing, which is not unnatural and could also accommodate the lightness of the stop with respect to the other squarks. In this case, $\tilde{b}_L$ could be heavier and $\Delta\rho$ reduced. This also entails that the value of λ'_{131} inferred naively from the HERA data is smaller than the actual value by a factor of $\cos\phi_t$, where ϕ_t is the stop mixing angle.

Most sea production processes are excluded by a combination of different experimental constraints. Some of these have been discussed above; others come from contributions to the electron neutrino mass [37]

$$|\lambda'_{133}| < 5\times10^{-3}\left(\frac{m_{\tilde{q}}}{200\text{ GeV}}\right)^{\frac{1}{2}} \quad , \quad |\lambda'_{122}| < 1\times10^{-1}\left(\frac{m_{\tilde{q}}}{200\text{ GeV}}\right)^{\frac{1}{2}} \ , \tag{11}$$

which exclude sea-quark production mechanisms involving only third- (or only second-) generation particles. In eq. (11) we have assumed a common supersymmetry-breaking mass $m_{\tilde{q}}$ in the 2×2 mass matrix for the $\tilde{d}_L$–$\tilde{d}_R$ system, and taken $m_s(m_{\tilde{q}}) = 100$ MeV for the running strange quark mass. Finally, $\tilde{u}_L$ production off sea quarks of the second or third generation is constrained by limits on charged-current universality, which impose [35]

$$|\lambda'_{11k}| < 6\times10^{-2}\left(\frac{m_{\tilde{d}_{kR}}}{200\text{ GeV}}\right) \quad \text{for } k = 1,2,3. \tag{12}$$

Also, if the observed anomaly is due to the sea process $e^+\bar{u}\to\bar{\tilde{d}}_{kR}$, then an effect more than 50 times larger should have shown up in $e^-u\to\tilde{d}_{kR}$, while no anomaly has been observed in about 1 pb^{-1} of data collected in e^-p collisions [38].

The only remaining possibility for production on sea partons is $e^+s\to\tilde{t}_L$ via the λ'_{132} interaction, which is constrained, but not quite excluded, by the OPAL analysis [11]. Limits on anomalous top quark decay modes also set weak bounds on this coupling [21], but these disappear as soon as the selectron mass is not much smaller than m_t. This interaction can also give new contributions to the $b\to s\gamma$ decay rate, but these effects can be suppressed by an approximate alignment in the down sector. Therefore λ'_{132} could be as large as 0.3 and the process $e^+s\to\tilde{t}_L$ be at the origin of the HERA signal. In this case, as we will discuss in the next section, the scattering process $e^+e^-\to\bar{s}s$ has an anomalous contribution due to t-channel stop exchange which can be easily identified at future LEP 2 runs.

4.2 Decay patterns

Next we address the issue of the squark decay modes. In the case of $\tilde{c}_L$, the most important possible decay modes are the R-conserving $\tilde{c}_L\to c\chi^0_i$ $(i=1,..,4)$ and $\tilde{c}_L\to s\chi^+_j$ $(j=1,2)$, and the R-violating $\tilde{c}_L \to de^+$, where χ_i^0, χ_j^+ denote neutralinos and charginos, respectively. If R-parity violating couplings other than λ'_{121} were present, further decay modes could be allowed, although this possibility is severely constrained by limits on flavour and lepton conservation. The decay rate for the R-parity violating mode is [39, 40, 41]

$$\Gamma(\tilde{c}_L \to e^+ d) = \frac{1}{16\pi}(\lambda'_{121})^2 m_{\tilde{c}_L} \tag{13}$$

and the coupling λ'_{121} is fixed by our production assumption. It has often been found that the R-conserving modes dominate, but this is not necessarily the case. They could be either suppressed by phase space or, in the $\tilde{c}_L \to c\chi_i^0$ case, by (partial) cancellations in the neutralino couplings. The $s\chi_j^+$ decay mode can only be suppressed by phase space, so we assume that $m_{\chi_j^+} > 200$ GeV. Neglecting $\tilde{c}_{L,R}$ mixing, the decay rate for the neutralino mode is given by [40]

$$\Gamma(\tilde{c}_L \to c\chi_i^0) = \frac{g^2}{32\pi}(A_i^2 + B_i^2)\ m_{\tilde{c}_L} \left(1 - \frac{m^2_{\chi_i^0}}{m^2_{\tilde{c}_L}}\right)^2 , \tag{14}$$

where

$$A_i = \frac{m_c N_{i4}}{M_W \sin\beta}, \quad B_i = N_{i2} + \frac{1}{3}\tan\theta_W N_{i1} . \tag{15}$$

In eq. (15) the N_{ij} are the elements of the unitary matrix that diagonalises the neutralino mass matrix in the SU(2) - U(1) gaugino basis [17], and $\tan\beta$ is the ratio of Higgs vacuum expectation values. The quark-mass-suppressed A_i^2 term in eq. (14) may be neglected, and we notice that the B_i^2 term in eq. (14) is reduced either if the lightest neutralino is an approximate higgsino ($N_{11} \sim N_{12} \sim 0$) or if there is a cancellation

$$N_{12} \sim -\frac{1}{3}\tan\theta_W N_{11} . \tag{16}$$

Remarkably enough, we find that the cancellation (16) does occur in an acceptable domain of supersymmetric parameter space, given analytically by

$$m_{\chi_1^0} = \frac{4\sin^2\theta_W}{3 - 4\sin^2\theta_W} M_2 \tag{17}$$

$$\mu = \sin 2\beta X \pm \sqrt{\sin^2 2\beta X^2 + m_{\chi_1^0}(m_{\chi_1^0} + 2X)} \tag{18}$$

$$X \equiv \frac{2(1 - \sin^2\theta_W)(3 - 4\sin^2\theta_W)}{(3 - 8\sin^2\theta_W)} \frac{M_Z^2}{M_2} . \tag{19}$$

Here M_2 is the SU(2) gaugino mass, while the U(1) gaugino mass is determined by the unification relation $M_1 = (5/3)\tan^2\theta_W M_2$. Notice that such a cancellation is possible for $\tilde{c}_L \to c\chi_1^0$, but impossible, for instance, in the analogous $\tilde{d}_R$ decay, whose rate is still given by eq. (14), with $B_i = -\tan\theta_W N_{i1}$.

The results of numerical studies, see Fig. 4a, explicitly show the three regions where the $\tilde{c}_L$ R-parity violating decay modes become important. The first region occurs for M_2 and μ large enough to suppress kinematically all two-body R-parity conserving modes ($m_{\chi^0}, m_{\chi^\pm} >$

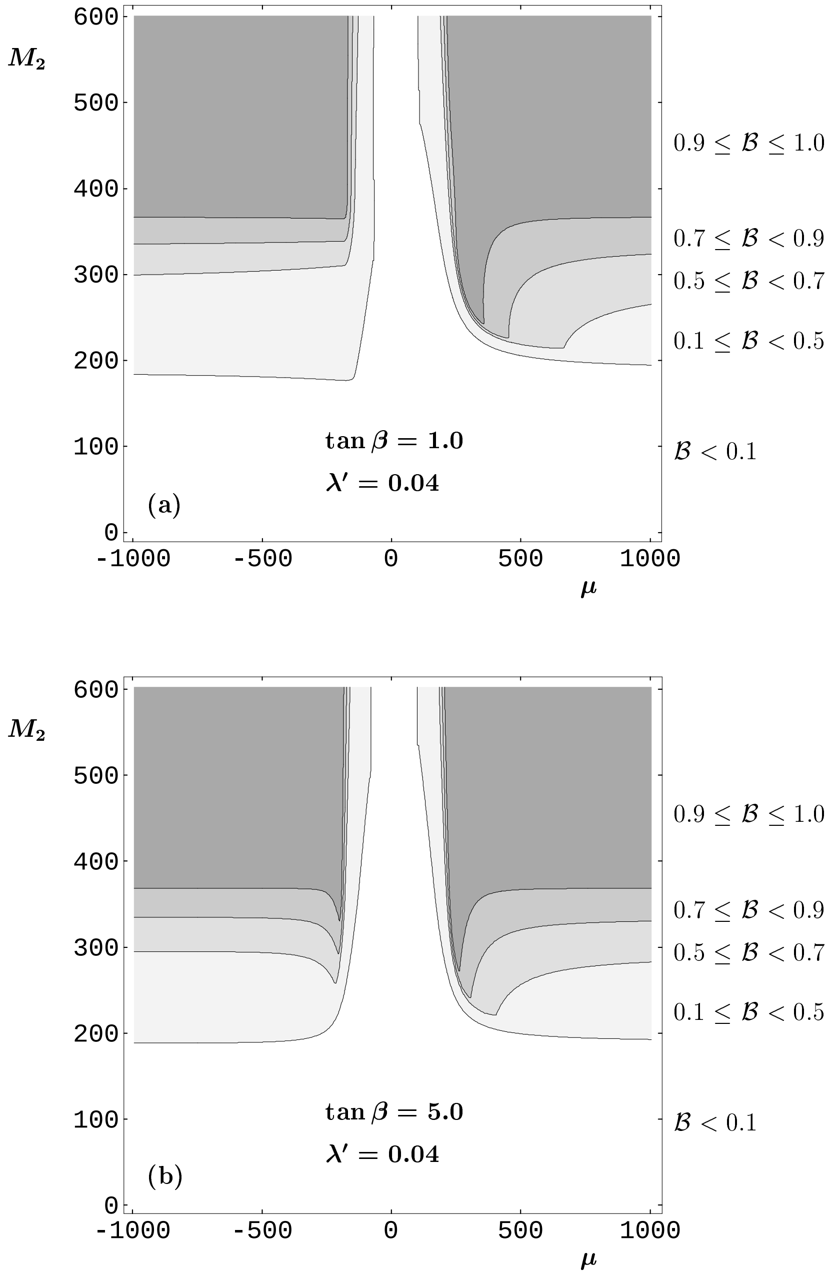

Figure 4: *Contours of $\mathcal{B}(ed)$ for the R-violating decay of $\tilde{c}_L$, in the $\mu - M_2$ plane. Here λ' has been fixed to 0.04 and $\tan\beta = 1$ (a) and 5 (b), respectively. The LEP 2 bound of 85 GeV for the chargino has also been implemented.*

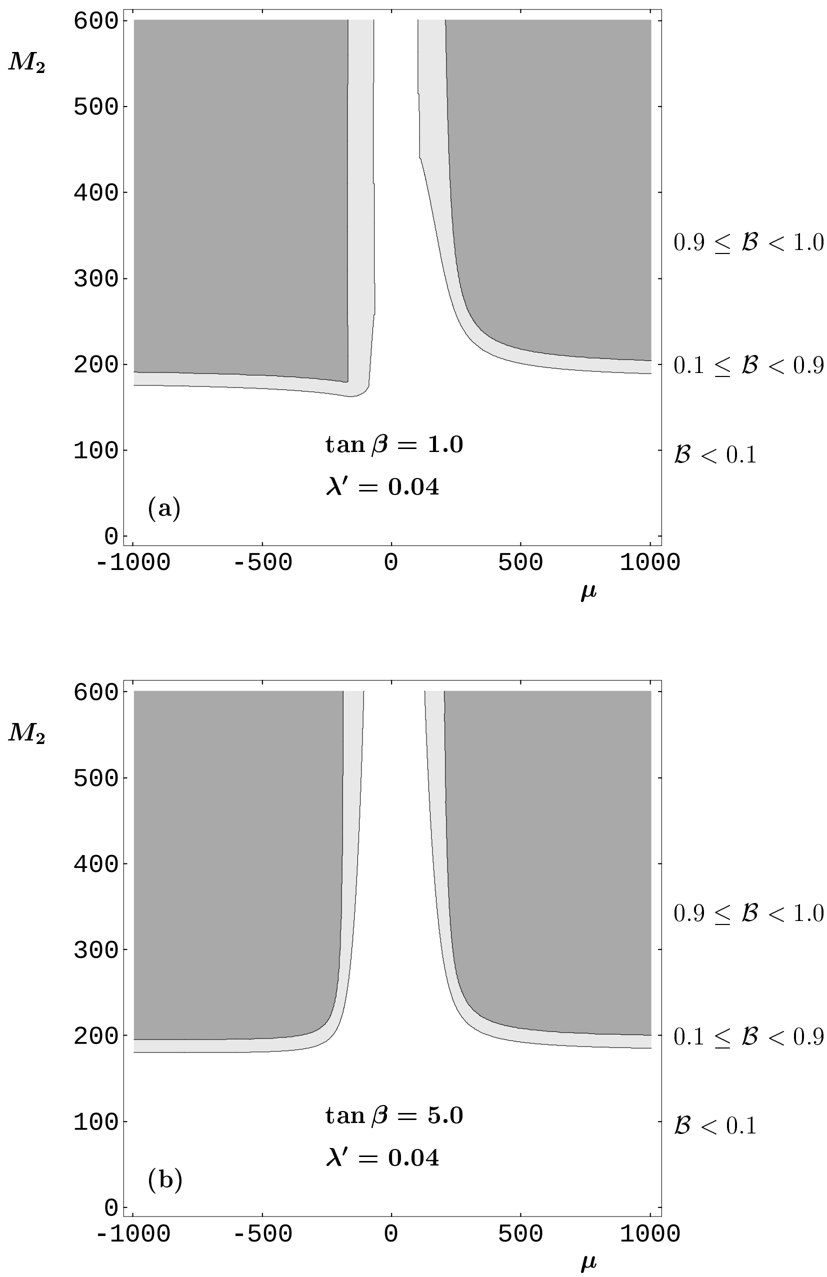

Figure 5: *Contours of $\mathcal{B}(ed)$ for the R-violating decay of $\tilde{t}_L$, in the $\mu - M_2$ plane. Here λ' has been fixed to 0.04 and $\tan\beta = 1$ (a) and 5 (b), respectively. We have assumed a vanishing stop left-right mixing. The LEP 2 bound of 85 GeV for the chargino has also been implemented.*

$m_{\tilde{c}_L}$). In this case, $\mathcal{B} = 1$ and $\tilde{c}_L$ should lie at the edge of the parameter region excluded by D0. The second region is the thin slice of parameter space where χ^0 is an approximate higgsino ($\mu << M_2$). In this case, the couplings of $\tilde{c}_L$ to the light chargino and neutralinos are suppressed, and the R-parity violating mode can compete with the R-parity conserving ones. In the third region, the decay mode $\tilde{c}_L \to c\chi^0$ is suppressed by the approximate cancellation of eq. (16). This cancellation is especially marked for tan$\beta \sim 1$, where $\mathcal{B} > 0.5$ over a large domain of μ. The extent of the cancellation region is reduced as tanβ is increased, as can be seen from Fig. 4b, which is for tan$\beta = 5$, since the region where eq. (16) is approximately satisfied becomes narrower as tanβ increases. We conclude from Fig. 4 that the detection of e^+q final states by H1 and ZEUS data should not be a surprise.

A small value of $\mathcal{B}$ could in principle be accommodated by increasing the magnitude of the λ'_{121} coupling by the corresponding factor of $1/\sqrt{\mathcal{B}}$, though the scope for this is severely limited by the bounds described above. On the other hand, if $\mathcal{B} \sim 1$, the squark should be at the verge of being discovered at the Tevatron or possibly ruled out by CDF and D0 data, as discussed in the previous section.

In the case of $\tilde{t}_L$, it is interesting to notice that the neutralino decay mode $\tilde{t}_L \to t\chi^0_i$ is kinematically closed in a natural way. In order to obtain a large value of $\mathcal{B}$, it is sufficient to require that all charginos are heavy enough to forbid the decay $\tilde{t}_L \to b\chi^+_j$ (see figs. 5a and 5b). In view of the Tevatron limits discussed in the previous section, that may pose a problem if $\mathcal{B}(eq)$ is very close to 1, we have analyzed other possible decay modes. Under the gaugino unification assumption with $m_{\chi^+_j} > m_{\tilde{t}_L}$, the three-body decay $\tilde{t}_L \to bW^+\chi^0_i$ (mediated by a virtual χ^+_j, t or $\tilde{b}_L$) has a negligible rate. Even if a slepton were much lighter than the stop, the decay modes $\tilde{t}_L \to b\ell^+\tilde{\nu}$, $b\nu\tilde{\ell}^+$ could not compete with the R-parity violating decay, for $\lambda'_{131} = 4 \times 10^{-2}$. It is usually assumed that the flavour-violating decay $\tilde{t}_L \to c\chi^0_i$ is rather suppressed in supersymmetric models. However, in theories with R-parity violation, the whole issue of flavour conservation is undermined, and we cannot exclude new unexpected effects, which could lead to large rates for $\tilde{t}_L \to c\chi^0_i$ and values of $\mathcal{B}$ considerably smaller than 1.

If the stop is produced by the sea-parton collision $e^+s \to \tilde{t}_L$, then the R-parity violating decay is fast enough to compete with the chargino mode. The R-violating branching ratio $\mathcal{B}$ depends only on the chargino masses $m_{\chi^+_j}$ and their gaugino compositions $|V_{j1}|$. We find $\mathcal{B} = 0.5$ either for a pure gaugino-like chargino ($|V_{11}| = 1$) of 150 GeV, or for a mixed chargino ($|V_{11}| = 1/\sqrt{2}$) of 120 GeV. Therefore, in this case, it is easier to escape the Tevatron limits, although a small value of $\mathcal{B}$ requires a large value of λ'_{132} and a large effect in $e^+e^- \to \bar{s}s$ at LEP 2.

It is natural to ask whether the R-violating scenario for the HERA events discussed above is compatible with the R-violating scenario proposed elsewhere [22] to interpret the four-jet excess seen by ALEPH [23] at LEP 2 [12]. The suggestion contained in ref. [22] was that ALEPH had observed the R-conserving production process $e^+e^- \to \tilde{e}_L\tilde{e}_R$, mediated by an approximate U(1) gaugino with mass M_1 between 100 and 120 GeV. The subsequent R-violating decays of each $\tilde{e}_{L,R}$ into $\bar{q}q$ produce a pair of hadronic jets via an interaction of the λ' type. This could have the 121 flavour structure advocated above for $\tilde{c}_L$ production at HERA, in which case we

[12] We are aware that the ALEPH signal [23] has not been confirmed by the other LEP collaborations [24], but reserve judgement on the final fate of the four-jet excess.

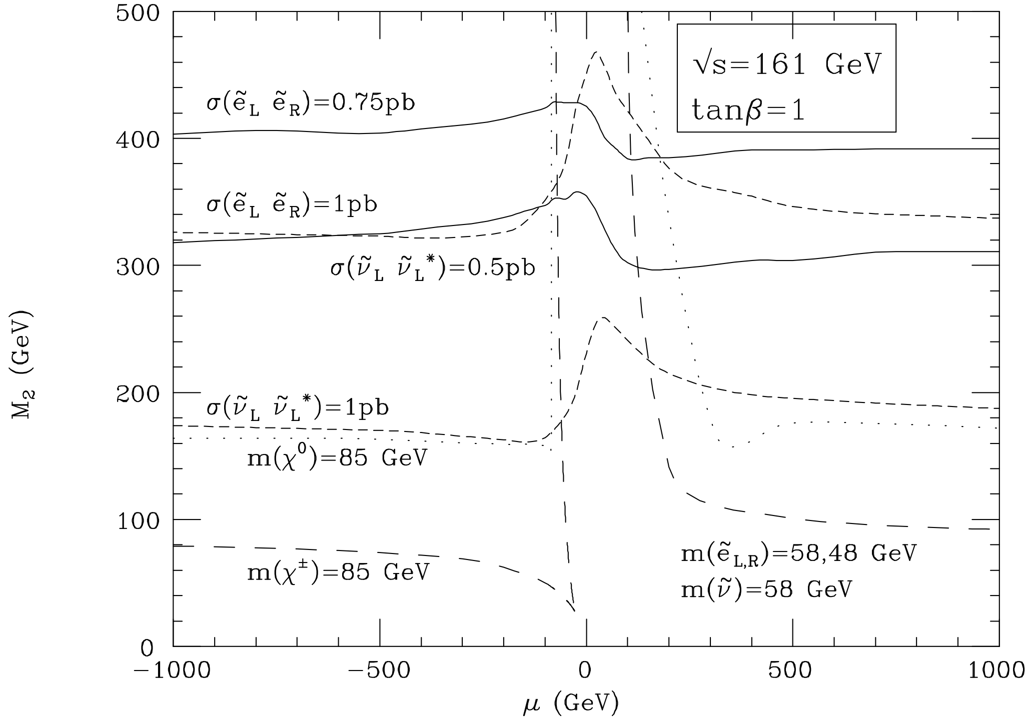

Figure 6: *Crosss section contours for $\tilde{e}_L\tilde{e}_R$ and $\bar{\tilde{\nu}}\tilde{\nu}$ production at LEP 2 ($\sqrt{s} = 161$ GeV and $\tan\beta = 1$). The calculations were performed using the programs* SUSYXS *documented in ref. [42], and include the effect of ISR. The regions corresponding to lightest chargino and neutralino masses heavier than 85 GeV lie above the dashed and dotted lines, respectively.*

predict the presence of a charm quark and an antiquark in the two dijets of the ALEPH final states. A strong constraint on this scenario comes from an adequate suppression of sneutrino pair production, which requires $\tan\beta \sim 1$ and M_2 larger than what predicted by gaugino unification. It is interesting to notice that such a choice of parameters can also lead to the approximate cancellation described in eq. (16), and therefore to a significant value for $\mathcal{B}$. We display in Fig. 6 contours of the cross sections for $\tilde{e}_L\tilde{e}_R$ and $\bar{\tilde{\nu}}\tilde{\nu}$ production at LEP 2 for $\sqrt{s} = 161$ GeV and $\tan\beta = 1$. We do not show the corresponding figure for larger values of $\tan\beta$ since, for $m_{\tilde{e}_L} = 58$ GeV, values of $\tan\beta > 1.23$ are excluded by the requirement $m_{\tilde{\nu}} > M_Z/2$. In Fig. 6 we have assumed gaugino mass unification, in order to allow the comparison with the results shown in Fig. 4. However, as mentioned above, a better agreement with the ALEPH data is actually obtained when M_2 is larger than $(3/5)\tan^{-2}\theta_W M_1$. We conclude that the R-violating interpretation of the HERA data in terms of $\tilde{c}_L$ production advocated above is not incompatible with that proposed previously [22] for the ALEPH four-jet events.

5 Tests to Discriminate between Models

In this final section we review some key experimental tests that may help to distinguish between different novel physics interpretations of the HERA large-Q^2 events.

The first comment follows from Fig. 1: the Q^2 distribution expected from effective contact interactions and resonance interpretations are different and could be distinguished clearly with a modest increase in statistics. The present data seem to favour a resonance interpretation, but it would be premature to draw firm conclusions at this stage. As for the x distributions, more statistics are again required to establish consistency with a resonant peak smeared out by ISR (see the Appendix), gluon radiation, hadronization and detector effects.

"Charged current" events due to νq decays would be expected in some leptoquark and R-violating squark scenarios at rates similar to those for the "neutral current" events seen. However, this is not the case, in particular, for the valence production $e^+d \to \tilde{c}_L/\tilde{t}$ scenario favoured above. The H1 collaboration has reported [1] four "charged current" events in a kinematic region where less than two are expected according to the Standard Model. The scenario we favour would be excluded if this signal built up into a significant signal with the advent of more data.

The recorded luminosity in e^-p collisions is rather limited, although it has already provided some constraints on scenarios in which a leptoquark (R-violating squark) is produced via e^+ collisions with a sea quark, as commented in the previous section. A much higher e^-p integrated luminosity should become available in the future. The cross section curves shown in Fig. 2 are also applicable to these collisions. It is a key prediction of our preferred $\tilde{c}_L/\tilde{t}$ model that there should be no large cross section for the production of a resonance peak in e^-p collisions.

One of the options for future HERA running is for e^+D collisions [43]. This is potentially interesting, since the HERA signal is made from e^+d collisions according to our favoured interpretation, the neutron contains twice as many d quarks as the proton, and this ratio is further enhanced at large x. The luminosity for e^+d collisions in scattering off a neutron is the same as that for e^+u collisions in a proton, and can be read off from Fig. 2. Unfortunately, the effective E_{CM} in e^+n scattering will be less than the 300 GeV currently attained with protons.

We recall that, for the reasons discussed above, the $\tilde{c}_L \to c(\chi^0 \to \bar{q}q\ell, \nu)$ decay chain may have a branching ratio comparable to the e^+q final state that we hypothesize to have been observed, and these should be observable at HERA. We note that $\ell^\pm$ final states are equally likely in χ decays, and that dominance by $\ell = \mu, \tau$ cannot be excluded. These final states would all have very clear signatures: charged leptons which may well have different flavour and/or charge from the incoming e^+, or missing energy carried away by a neutrino, each accompanied by three hadronic jets, at least one of which should contain a charmed particle.

In Figure 7 we show the shapes of the x_e [13] and Q^2 distributions for wrong-sign leptons due to R-conserving decays of squarks at HERA. We have not implemented any selection cut in preparing this figure, with the exception of a $Q^2 > 5000$ GeV requirement for the events in the x_e distribution. Small Standard Model backgrounds to these final states are expected to come from semileptonic decays of heavy quarks (charm and bottom). The separation of these backgrounds depends significantly on the lepton isolation requirements, which are related to the detector characteristics and will not be studied here. Since the distributions depend

[13] x_e is the Bjorken x variable extracted using the electron method (see refs. [1, 2]).

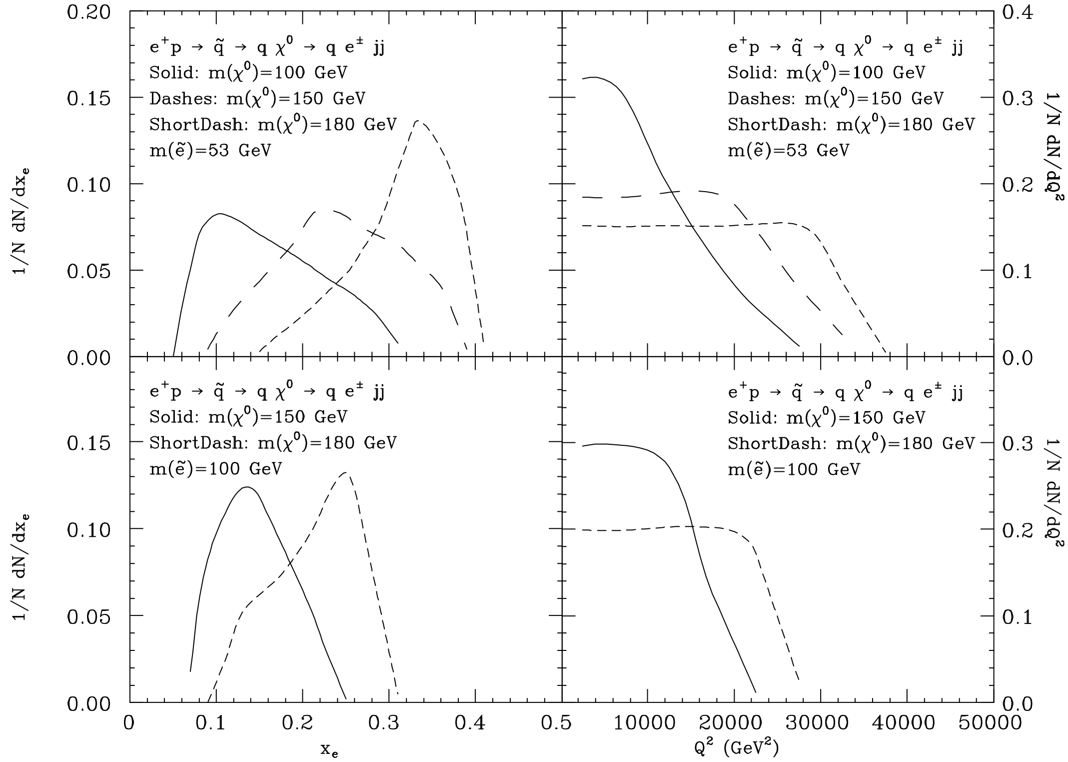

Figure 7: *Kinematical distributions of wrong-sign electrons in the R-conserving decays of squarks, followed by R-violating neutralino decay. Different combinations of neutralino and slepton masses are shown.*

significantly on the masses of the states produced in the decay chain, we consider two values of the slepton mass (53 and 100 GeV) and three values of the neutralino mass (100, 150 and 180 GeV). As expected, the figures show that the most interesting signals arise in the case of the largest neutralino masses and smaller slepton masses.

Our analysis has pointed up the urgency of a joint analysis of the CDF and D0 dielectron data, to see whether the existence of a 200 GeV leptoquark (or R-violating squark) can be probed with the available Tevatron data, and, in the absence of a signal, down to what $\mathcal{B}(eq)$ it can be excluded. If the existence of such a leptoquark (squark) is still a live issue at the time of the next Tevatron run, we expect that the data taken then should be able to probe its existence down to values of $\mathcal{B}(eq)$ that are below those of interest to the present HERA data.

The cascade decays of the squark via an R-conserving $\tilde{c}_L \to \chi^0 c$ interaction could also have distinctive signatures at the Tevatron. We show in Fig. 8 the invariant mass distribution of lepton pairs, which is independent of the relative charge of the leptons. The final states consist of two leptons (with equal probability of having same or opposite charge), a large number of jets (there are 6 energetic quarks in the final state), and no missing transverse energy [14].

[14]If there are also $\chi \to \nu\tilde{\nu}$ decays, more signatures would appear, such as $e^\pm$ + jets + missing transverse

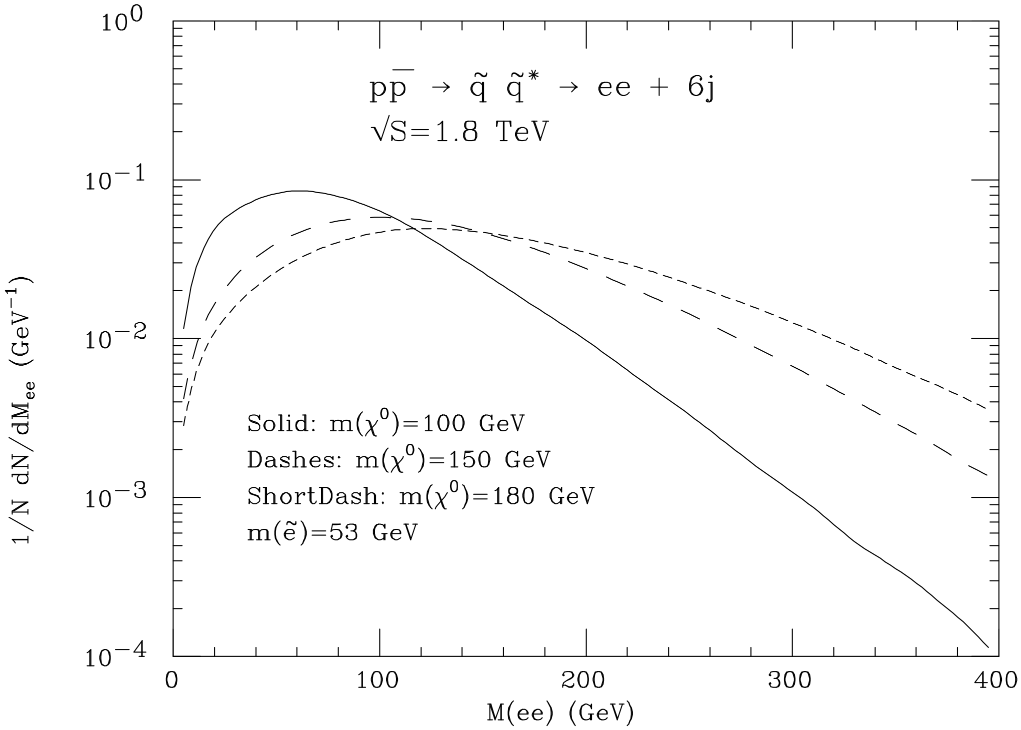

Figure 8: *Invariant mass distributions of electron pairs from the R-conserving decays of squark pairs produced at the Tevatron, followed by R-violating neutralino decays. Different combinations of neutralino masses are shown.*

Possible backgrounds come from the production and decay of top quark pairs, when the net missing transverse energy carried away by neutrinos is small and additional jet are produced by radiative processes. In the case of like-charge leptons, the $t\bar{t}$ background requires one of the leptons to come from the semileptonic decay of one of the b quarks in the final state. Once again, the precise size of the background will strongly depend on the lepton isolation requirements, and will not be estimated here.

In the case of stop production and decay via a virtual chargino, the signatures become particularly interesting, because of the presence of b jets in the final state. Transverse missing energy would also arise from the chargino decay to neutrino and slepton. In the case of $\tilde{c}_L$ decays to $c\chi^0$ there will be charm jets, which will still give rise to secondary vertices. Only higher statistics will however allow this signal to be isolated and distinguished from the secondary vertex distribution of b decays.

It is natural to ask whether a squark weighing 200 GeV might have some observable indirect effects at LEP 2, even though it could not be produced directly. An R-violating interaction λ' gives a contribution to the cross section of a generic quark-antiquark final state $\bar{f}f$ via the

energy.

exchange of a squark $\tilde{q}_L$ or $\tilde{q}_R$, which is parametrised as

$$\sigma = \sigma_{SM} + \frac{3\lambda'^4 I_1}{64\pi s} + \frac{3\lambda'^2 \alpha_{em} I_2}{4s} \left[e_e e_f + a_L^e a_{L,R}^f \frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \right] \tag{20}$$

where

$$I_1 = \frac{1+2x_{\tilde{q}}}{1+x_{\tilde{q}}} - 2x_{\tilde{q}} \ln\left(\frac{1+x_{\tilde{q}}}{x_{\tilde{q}}}\right) \tag{21}$$

$$I_2 = \frac{1}{2} - x_{\tilde{q}} + x_{\tilde{q}}^2 \ln\left(\frac{1+x_{\tilde{q}}}{x_{\tilde{q}}}\right) \tag{22}$$

with $a_{L,R}^f = (T_3^f - e^f \sin^2\theta_W)/(\sin\theta_W \cos\theta_W)$ and $x_{\tilde{q}} \equiv \frac{m_{\tilde{q}}^2}{s}$. In the case of $d\bar{d}$ production by $\tilde{c}_L$ exchange, we have $a_R^d = -e_d \tan\theta_W$, whereas in the case of $\bar{c}c$ production by $\tilde{d}_R$ exchange we have $a_L^c = (1/2 - 2/3\sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$. The contribution in eq.(20) proportional to I_1 arises from the diagram with the R-parity violating vertices, while those proportional to I_2 are interference terms with the Standard Model s-channel γ and Z exchange respectively. For $\sqrt{s} = 192$ GeV, the correction to the Standard Model cross section is ≈ 0.02 pb, which we suspect that is rather small to be observed. However, there could be an observable signal in $e^+e^- \to \bar{s}s$ due to $\tilde{t}$ exchange in the sea production scenario discussed above, which is already on the verge of exclusion by OPAL [11].

Since the lightest neutralino χ^0 decays rapidly via R-violating interactions, the reaction $e^+e^- \to \chi^0\chi^0$ should be observable at LEP 2 for m_{χ^0} below the kinematic limit, currently about 85 GeV. We do not discuss here the production cross section, which depends, e.g., on the selectron masses assumed. We have plotted in Fig. 6 the $m_{\chi^0} = 85$ GeV contours. Comparison with Figs. 4 and 5 indicates that our favoured R-violating HERA scenarios are not strongly constrained by present LEP 2 data, though future data at $\sqrt{s} = 200$ GeV might make some inroads on the parameter space.

The R-violating scenario squark mentioned in the previous section may have observable consequences for other experiments that are not *a priori* related. One example is $K \to \pi\bar{\nu}\nu$ decay [21]. We have seen that this imposes one of the most stringent constraints on the λ'_{121} coupling that we invoke. A corollary is that there may be an interesting contribution to this decay from beyond the Standard Model, waiting to be discovered just below the present level of experimental sensitivity. The magnitude of any such signal depends on the pattern of flavour mixing among R-violating couplings. In some variations, there may also be contributions to nuclear $\beta\beta$ decay lurking just below the present experimental sensitivity [20].

These examples point to a general theoretical issue raised by the possibility of R violation. General R-violating couplings do not respect the classic conditions for natural conservation of flavour in neutral interactions [44]. Perhaps these are in any case optional, and one should be content with models which fall numerically below the experimental upper limits on flavour-changing neutral interactions. On the other hand, natural respect for them played an important historical rôle in motivating the Standard Model. Therefore, it is desirable to clarify whether there are any interesting and plausible conditions under which these constraints are naturally respected by R-violating interactions [45, 46].

This example shows that interesting and relevant theoretical, as well as experimental, issues are into new light by the observation of large-Q^2 events at HERA. It may well be that these turn out to be a malign statistical fluctuation, rather than a harbinger of new physics. However, we have shown in this paper that complementary experiments may soon be able to cast light on possible interpretations in terms of physics beyond the Standard Model. In the mean time, the HERA large-Q^2 events have caused us to look anew at supersymmetry with R violation, in particular, and provided us with new reason to question the conventional R-conserving paradigm for supersymmetric phenomenology.

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Note Added

After the completion of this paper we received the articles in ref. [47, 48], which make the interesting observation that experiments on atomic parity violation pose stringent limits on the strength of any $A_eV_q = RR-LL+RL-LR$ $\bar{e}e\bar{q}q$ contact term. The present experimental value on the coefficient C_{1q} of the A_eV_q term in the effective lagrangian, as given on pages 87-92 of ref.[25], implies the following 95% CL limit on the corresponding deviation from the Standard Model $\Delta C_{1q} = \sum_{ij}(\sqrt{2}\pi\eta_{ij}\delta_i)/(G_F\Lambda_{ij}^{q2})$ (where $\delta_i = +1, -1$ for $i = R$ or $i = L$, respectively):

$$-0.099 < \Delta C_{1u} < 0.051 \qquad -0.050 < \Delta C_{1d} < 0.084 \tag{23}$$

Assuming a single non-vanishing operator at a time, this translates into

$$\Lambda_{LL}^{+u},\ \Lambda_{LR}^{+u},\ \Lambda_{RL}^{-u},\ \Lambda_{RR}^{-u} > 2.0 \text{ TeV}, \tag{24}$$

$$\Lambda_{LL}^{-u},\ \Lambda_{LR}^{-u},\ \Lambda_{RL}^{+u},\ \Lambda_{RR}^{+u} > 2.7 \text{ TeV}, \tag{25}$$

$$\Lambda_{LL}^{+d},\ \Lambda_{LR}^{+d},\ \Lambda_{RL}^{-d},\ \Lambda_{RR}^{-d} > 2.8 \text{ TeV}, \tag{26}$$

$$\Lambda_{LL}^{-d},\ \Lambda_{LR}^{-d},\ \Lambda_{RL}^{+d},\ \Lambda_{RR}^{+d} > 2.1 \text{ TeV}. \tag{27}$$

Comparing with Fig. 1 we see that these limits are quite constraining on the individual terms. But we also see from Fig. 1 that we could, for example, take $\Lambda_{RL}^{+u} = \Lambda_{LR}^{+u}$ [48], which is parity conserving, and add the corresponding contributions that are very similar in shape. In this way the limits are evaded and the fit is as good as for the separate contributions.

Appendix: Some Attempts to Understand the Possible Effects of Initial-State Radiation

In an attempt to gain more insight into the apparent spread in the invariant masses of the ZEUS events, and the fact that their masses appear at first sight to be somewhat higher than those of the H1 events, we have looked into the possible impact of initial-state radiation (ISR) [15]. In the presence of ISR, the relation between the value M_e of the reconstructed resonance mass, as determined by the electron method, is related to the true value M by

$$M_e^2 = M^2 \frac{(1 - \frac{z}{y_e})}{(1-z)^2} \tag{28}$$

where z is the fraction of the electron's longitudinal momentum lost to ISR, and y_e is the value of the conventional deep-inelastic y variable estimated using the electron method. In the case of small z, eq. (28) reduces to:

$$M_e^2 = M^2 \left[1 + z \, \left(\frac{2y_e - 1}{y_e} \right) \right] , \tag{29}$$

which corresponds to a negative shift in mass for $y_e < 1/2$, and to a positive shift for $y_e > 1/2$.

The analogous relation between $M_{2\alpha}$, the mass determined by the double-angle method, and the true value M is

$$M_{2\alpha}^2 = M^2 \frac{1}{(1-z)^2} . \tag{30}$$

In the presence of ISR, $M_{2\alpha}$ will therefore always be larger than the true value of M. In particular, $M_{2\alpha}$ will always be larger than M_e.

We recall that H1 prefers to estimate M using M_e [1], whereas ZEUS favours $M_{2\alpha}$ [2]. ISR effects could therefore lead qualitatively to M_{ZEUS} being greater than M_{H1}, as observed, and resolution differences might explain their greater spread. On the other hand, the experimental cuts allow for a fraction of electron energy lost to ISR up to $\sim 10\%$, so it is not clear whether its effect could be important quantitatively.

One can use eqs. (28) and (30) to extract a relation between the masses reconstructed with the two techniques and the true mass, under the hypothetical assumption that the measured differences are due to ISR and not to resolution effects. The following relations hold:

$$z = y_e(1-\rho) \quad , \quad \rho = \frac{M_e^2}{M_{2\alpha}^2} \tag{31}$$

$$M^2 = M_{2\alpha}^2 \left(1 - y_e + y_e\rho\right)^2 . \tag{32}$$

We applied these relations to the five ZEUS candidate events, using the values of y extracted using the double-angle techique. Four out of the five events have $x_e < x_{2\alpha}$, and are therefore compatible with the ISR interpretation. The values of z and of the true mass which we calculate using the above relations are given in Table 3.

Allowing either the highest- or lowest-mass event to be background, we find good consistency with a single mass value around 220 GeV, though this still looks higher than that quoted by H1 [1][16].

[15] It is clear that this exercise is best carried out by the experimental collaborations themselves: our intention is only to form an approximate impression of how large the effects of ISR might be.

[16] We have checked that, when applied to the H1 data, the above ISR estimation procedure makes no significant difference to their preferred mass value $M \sim 200$ GeV, which has an energy scale error of about 5 GeV.

Ev. #	z	M_e	$M_{2\alpha}$	M
1	~ 0	217	208	208
2	0.029	220	226	220
3	0.027	225	235	229
4	0.10	233	253	226
5	0.073	200	231	215

Table 3: *Estimated effect of ISR on the apparent masses of the five candidate ZEUS [2] events extracted using the* electron *(M_e) and the* double-angle *($M_{2\alpha}$) techniques, where z is the energy fraction lost to ISR as estimated from eq. (31) and M is the ISR-corrected mass defined in eq. (32). The first event gives no indication that $z > 0$, and we have retained the $M_{2\alpha}$ estimate.*

Needless to say, only an accurate analysis by ZEUS, properly accounting for the effects of experimental resolution and their correlations between the two techniques, will provide an accurate estimate of the ISR-induced corrections. As remarked in ref. [2], the differences between the values of M_e and $M_{2\alpha}$ observed in the five candidate events are also not inconsistent with the reported measurement uncertainties.

References

[1] C. Adloff *et al.*, H1 collaboration, DESY preprint 97-24, `hep-ex/9702012`, and Y. Sirois, for the H1 collaboration,
`http://dice2.desy.de/h1/www/html/hiq2.html`.

[2] J. Breitweg *et al.*, ZEUS collaboration, DESY preprint 97-25, `hep-ex/9702015`, and B. Straub, for the ZEUS collaboration,
`http://zow00.desy.de:8000/~ukatz/ZEUS_PUBLIC/hqex/hqex_highx.html`.

[3] F. Abe *et al.*, CDF collaboration, *Phys. Rev. Lett.* **77** (1996) 438.

[4] J. Huston *et al.*, *Phys. Rev. Lett.* **77** (1996) 444;
H.L. Lai *et al.*, *Phys. Rev.* **D55** (1997) 1280.

[5] A.C. Benvenuti *et al.*, BCDMS collaboration, *Phys. Lett.* **B223** (1989) 485, and *Phys. Lett.* **B237** (1990) 599.

[6] S. Catani, M.L. Mangano, P. Nason and L. Trentadue, *Nucl. Phys.* **B478** (1996) 273.

[7] E. Eichten, K. Lane and M. Peskin, *Phys. Rev. Lett.* **50** (1983) 811.

[8] F. Abe *et el.*, CDF collaboration, *Phys. Rev. Lett.* **77** (1996) 5336.

[9] A. Bodek, for the CDF collaboration, FERMILAB-Conf-96/381-E, Proc. of Cracow International Symposium on Radiative Corrections, Poland, 1996.

[10] G. Alexander *et al.*, OPAL collaboration, CERN-PPE/96-156.

[11] S. Komamiya, for the OPAL collaboration, CERN seminar, Feb. 25th, 1997, `http://www.cern.ch/Opal/plots/komamiya/koma.html`.

[12] W. Buchmüller and D. Wyler, *Phys. Lett.* **B177** (1986) 377.

[13] M. Leurer, *Phys. Rev.* **D49** (1994) 333;
S. Davidson, D. Bailey and B.A. Campbell, *Z. Phys.* **C61** (1993) 613 and references therein.

[14] S. Aid *et al.*, H1 collaboration, *Z. Phys.* **C71** (1996) 211.

[15] S. Abachi *et al.*, D0 collaboration, *Phys. Rev. Lett.* **72** (1994) 965;
F. Abe *et al.*, CDF collaboration, *Phys. Rev.* **D48** (1993) 3939.

[16] D0 collaboration, `http://d0wop.fnal.gov/public/new/lq/lq_blurb.html`.

[17] For reviews, see, for instance:
H.P. Nilles, *Phys. Rep.* **110** (1984) 1;
H.E. Haber and G.L. Kane, *Phys. Rep.* **117** (1985) 75;
G.G. Ross, *Grand Unified Theories*, (Benjamin-Cummings, Menlo Park, CA, 1985);
R. Barbieri, Riv. Nuovo Cimento **11**, (1988) 1.

[18] G. Farrar and P. Fayet, *Phys. Lett.* **B76** (1978) 575;
S. Weinberg, *Phys. Rev.* **D26** (1982) 287;
N. Sakai and T. Yanagida, *Nucl. Phys.* **B197** (1982) 133.

[19] D. Choudhury and S. Raychaudhuri, CERN preprint TH/97-26, `hep-ph/9702392`.

[20] M. Hirsch, H.V. Klapdor-Kleingrothaus and S.G. Kovalenko, *Phys. Rev. Lett.* **75** (1995) 17, and *Phys. Rev.* **D53** (1996) 1329.

[21] K. Agashe and M. Graesser, *Phys. Rev.* **D54** (1995) 4445.

[22] M. Carena, G.F. Giudice, S. Lola, and C.E.M. Wagner, preprint CERN-TH/96-352, `hep-ph/9612334`.

[23] D. Buskulic *et al.*, ALEPH collaboration, *Z. Phys.* **C71** (1996) 179,
G. Cowan, for the ALEPH collaboration, CERN seminar, Feb. 25th, 1997
`http://alephwww.cern.ch/ALPUB/seminar/Cowan-172-jam/cowan.html`.

[24] W.D. Schlatter, for the LEP Working Group on Four-Jet Final States, CERN seminar, Feb. 25th, 1997.

[25] Particle Data Group, R.M. Barnett *et al.*, *Phys. Rev.* **D54** (1996) 1.

[26] See e.g. W. Buchmüller, R. Rückl and D. Wyler, *Phys. Lett.* **B191** (1987) 442.

[27] A.D. Martin, R.G. Roberts and W.J. Stirling, *Phys. Lett.* **B354** (1995) 155.

[28] W. Beenakker, R. Hopker, M. Spira and P.M. Zerwas, `hep-ph/9610490`.

[29] J. Blümlein and R. Rückl, *Phys. Lett.* **B304** (1993) 337.

[30] J. Blümlein, E. Boos and A. Kryukov, `hep-ph/9610408`.

[31] J. Blümlein, `hep-ph/9703287`.

[32] B. Campbell, S. Davidson, J. Ellis, and K.A. Olive, *Phys. Lett.* **B256** (1991) 457;
W. Fischler, G.F. Giudice, R.G. Leigh, and S. Paban, *Phys. Lett.* **B258** (1991) 45.

[33] See *e.g.* A.G. Cohen, D.B. Kaplan, and A.E. Nelson, *Ann. Rev. Nucl. Part. Sci.* **43** (1993) 27;
V.A. Rubakov and M.E. Shaposhnikov, *Phys. Usp.* **39** (1996) 461, and references therein.

[34] S. Adler *et al.*, BNL E787 collaboration, *Phys. Rev. Lett.* **76** (1996) 1421.

[35] V. Barger, G.F. Giudice, and T. Han, *Phys. Rev.* **D40** (1989) 2987.

[36] G. Altarelli, preprint CERN-TH/96-265, `hep-ph/9611239`.

[37] R.M. Godbole, P. Roy, and X. Tata, *Nucl. Phys.* **B401** (1993) 67.

[38] S. Aid *et al.* (H1 collaboration), *Phys. Lett.* **B379** (1996) 319;
M. Derrick *et al.* (ZEUS collaboration), *Z. Phys.* **C72** (1996) 47.

[39] J.L. Hewett, Proc. 1990 Summer Study on High Energy Physics, Snowmass, Colorado.

[40] J. Butterworth and H. Dreiner, *Nucl. Phys.* **B397** (1993) 3;
H. Dreiner and P. Morawitz, *Nucl. Phys.* **B428** (1994) 31;
E. Perez, Y. Sirois and H. Dreiner, contribution to Beyond the Standard Model Group, 1995-1996 Workshop on Future Physics at HERA, see also the Summary by H. Dreiner, H.U. Martyn, S. Ritz and D. Wyler, `hep-ph/9610232`.

[41] T. Kon and T. Kobayashi, *Phys. Lett.* **B270** (1991) 81;
T. Kon, T. Kobayashi, S. Kitamura, K. Nakamura and S. Adachi, *Z. Phys.* **C61** (1994) 239;
T. Kobayashi, S. Kitamura, T. Kon, *Int. J. Mod. Phys.* **A11** (1996) 1875.

[42] M.L. Mangano, G. Ridolfi *et al.*, `hep-ph/9602203`, published in Physics at LEP 2, eds. G. Altarelli, T. Sjöstrand and F. Zwirner, CERN Report 96-01, vol. 2, p.299.

[43] M. Arneodo, A. Bialas, M.W. Krasny, T. Sloan and M. Strikman, `hep-ph/9610423`, in Future Physics at HERA, Hamburg 1995/96, p.887.

[44] S.L. Glashow and S. Weinberg, *Phys. Rev.* **D15** (1977) 1958;
E.A. Paschos, *Phys. Rev.* **D15** (1977) 1966.

[45] T. Banks, Y. Grossman, E. Nardi and Y. Nir, *Phys. Rev.* **D52** (1995) 5319.

[46] A. Chamseddine and H. Dreiner, *Nucl. Phys.* **B458** (1996) 65.

[47] K.S. Babu, C. Kolda, J. March-Russell, and F. Wilczek, `hep-ph/9703299`.

[48] V. Barger, K. Cheung, K. Hagiwara, and D. Zeppenfeld `hep-ph/9703311`.