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HERA DATA AND LEPTOQUARKS IN SUPERSYMMETRY

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I present a concise review of the possible evidence for new physics at HERA and of the recent work towards a theoretical interpretation of the signal. It is not clear yet if the excess observed at large Q^2 is a resonance or a continuum (this tells much about the quality of the signal). I discuss both possibilities. For the continuum case one considers either modifications of the quark structure functions or contact terms. In the case of a resonance, a leptoquark, the most attractive possibility that is being studied is in terms of s-quarks with R-parity violation. In writing this script I updated the available information to include the new data and the literature presented up to August 1, 1997.

1. Introduction

The HERA experiments H1 [1] and ZEUS [2], recently updated in ref. [3], have reported an excess of deep-inelastic e^+p scattering events at large values of $Q^2 \gtrsim 1.5 \times 10^4 \text{ GeV}^2$, in a domain not previously explored by other experiments. The total e^+p integrated luminosity was of $14.2 + 9.5 = 23.7 \text{ pb}^{-1}$, at H1 and of $20.1 + 13.4 = 33.5 \text{ pb}^{-1}$ at ZEUS. The first figure refers to the data before the '97 run [1] [2], while the second one refers to part of the continuing '97 run, whose results were presented at the LP'97 Symposium in Hamburg at the end of July [3]. In the past, both experiments collected about 1 pb^{-1} each with an e^- beam. A very schematic description of the situation is as follows. At $Q^2 \gtrsim 1.5 \cdot 10^4 \text{ GeV}^2$ in the neutral current channel (NC), H1 observes $12+6 = 18$ events while about $5+3 = 8$ were expected and ZEUS observes $12 + 6 = 18$ events with about $9 + 6 = 15$ expected. In the charged current channel (CC), in the same range of Q^2 , H1 observes $4+2 = 6$ events while about $1.8+1.2 = 3$ were expected and ZEUS observes 3

$+ 2 = 5$ events with about $1.2 + 0.8 = 2$ expected. The distribution of the first H1 data suggested a resonance in the NC channel. In the interval $187.5 < M < 212.5 \text{ GeV}$, which corresponds to $x \simeq 0.4$, and $y > 0.4$, H1 in total finds $7 + 1 = 8$ events with about $1 + 0.5 = 1.5$ expected. But in correspondence of the H1 peak ZEUS observes a total of 3 events, just about the expected number. In the domain $x > 0.55$ and $y > 0.25$ ZEUS observes $3 + 2$ events with about $1.2 + 0.8 = 2$ expected. But in the same domain H1 observes only 1 event in total, more or less as expected.

We see that with new statistics the evidence for the signal remain meager. The perplexing features of the original data did not improve. First, there is a problem of rates. With more integrated luminosity than for H1, ZEUS sees about the same number of events in both the NC and CC channels. Second, H1 is suggestive of a resonance (although the evidence is now less than it was) while ZEUS indicates a large x continuum (here also the new data are not more encouraging). The difference could in part, but appar-

ently not completely [4], 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. All these issues will hopefully be clarified by the continuation of data taking. 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.

2. Structure Functions

Since the observed excess is with respect to the Standard Model (SM) 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 SM. In the somewhat analogous case of the apparent excess of jet production at large transverse energy E_T recently observed by the CDF collaboration at the Tevatron [5], it has been argued [6] 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. New results [7] on large p_T photons appear to cast doubts on this explanation because these data support the old gluon density and not the newly proposed one. In the HERA case, a similar explanation appears impossible, at least for the H1 data. Here quark densities are involved and they are well known at the same x but smaller Q^2 [8], [9], and indeed the theory fits the data well there. Since the QCD evolution is believed to be safe in the relevant region of x , the proposed strategy is to have, at small Q^2 , a new component in the quark densities at very large x , beyond the measured region, which is then driven at smaller x by the evolution and contributes to HERA when Q^2 is sufficiently large [8]. One possible candidate for a non perturbative effect at large x is intrinsic charm [10]. However it turns out that a large enough effect is only con-

ceivable at very large x , $x \gtrsim 0.75$, which is too large even for ZEUS. The compatibility with the Tevatron is also an important constraint. This is because ep scattering is linear in the quark densities, while $p\bar{p}$ is quadratic, so that a factor of 1.5-2 at HERA implies a large effect also at the Tevatron. In addition, many possibilities including intrinsic charm (unless $\bar{c} \neq c$ at the relevant x values [11]) are excluded from the HERA data in the CC channel [12]. In conclusion, it is a fact that nobody sofar was able to even roughly fit the data. This possibility is to be kept in mind if eventually the data will drift towards the SM and only a small excess at particularly large x and Q^2 is left with comparable effects in NC and CC, with e^+ or e^- beams.

3. Contact Terms

Still considering the possibility that the observed excess is a non-resonant continuum, a rather general approach in terms of new physics is to interpret the HERA excess as due to an effective four-fermion $\bar{e}e\bar{q}q$ contact interaction [13] with a scale Λ of order a few 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 [5]. (Note, however, that this interpretation is not strengthened by more recent data on the dijet angular distribution [14]). One has studied in detail [15] [16] vector contact terms of the general form

$$\Delta L = \frac{4\pi\eta_{ij}}{(\Lambda_{ij}^\eta)^2} \bar{e}_i\gamma^\mu e_i \bar{q}_j\gamma_\mu q_j. \quad (1)$$

with $i, j = L, R$ and η a \pm sign. Strong limits on these contact terms are provided by LEP2 [17] (LEP1 limits also have been considered but are less constraining [18,19]), Tevatron [20] and atomic parity violation (APV) experiments [21]. The constraints are even more stringent for scalar or tensor contact terms. APV limits essentially exclude all relevant $A_e V_q$ component. The CDF limits on Drell-Yan production are particularly constraining. Data exist

both for electron and muon pairs up to pair masses of about 500 GeV and show a remarkable $e - \mu$ universality and agreement with the SM. New LEP limits (especially from LEP2) have been presented [17]. In general it would be possible to obtain a reasonably good fit of the HERA data, consistent with the APV and the LEP limits, if one could skip the CDF limits [22]. But, for example, a parity conserving combination $(\bar{e}_L \gamma^\mu e_L)(\bar{u}_R \gamma_\mu u_R) + (\bar{e}_R \gamma^\mu e_R)(\bar{u}_L \gamma_\mu u_L)$ with $\Lambda_{LR}^+ = \Lambda_{RL}^+ \sim 4$ TeV still leads to a marginal fit to the HERA data and is compatible with all existing limits [22,23]. Because we expect contact terms to satisfy $SU(2) \otimes U(1)$, as they reflect physics at large energy scales, the above phenomenological form is to be modified into $\bar{L}_L \gamma_\mu L_L (\bar{u}_R \gamma^\mu u_R + \bar{d}_R \gamma^\mu d_R) + \bar{e}_R \gamma_\mu e_R \bar{Q}_L \gamma^\mu Q_L$, where L and Q are doublets [24]. This form is both gauge invariant and parity conserving. We took into account the requirement that contact terms corresponding to CC are too constrained to appear. More general fits have also been performed [22].

In conclusion, contact terms are severely constrained but not excluded. The problem of generating the phenomenologically required contact terms from some form of new physics at larger energies is far from trivial [24,25]. Note also that contact terms require values of $g^2/\Lambda^2 \sim 4\pi/(3-4 \text{ TeV})^2$, which would imply a very strong nearby interaction. Alternatively, for g^2 of the order of the $SU(3) \otimes SU(2) \otimes U(1)$ couplings, Λ would fall below 1 TeV, where the contact term description is inadequate. We recall that the effects of contact terms should be present in both the e^+ and the e^- cases with comparable intensity. Definitely contact terms cannot produce a CC signal [26], as we shall see, and no events with isolated muons and missing energy.

4. Leptoquarks

I now focus on the possibility of a resonance with e^+q quantum numbers, namely a leptoquark [15,27–32], of mass $M \sim 190 - 210$ GeV, according to H1. The most obvious possibility is that

the production at HERA occurs from valence u or d quarks, since otherwise the coupling would need to be quite larger, and more difficult to reconcile with existing limits. However production from the sea is also considered. Assuming an S -wave state, one may have either a scalar or a vector leptoquark. I only consider here the first option, because vector leptoquarks are more difficult to reconcile with their apparent absence at the Tevatron. The coupling λ for a scalar ϕ is defined by $\lambda\phi\bar{e}_L q_R$ or $\lambda\phi\bar{e}_R q_L$. The corresponding width is given by $\Gamma = \lambda^2 M_\phi / 16\pi$, and the production cross section on a free quark is given in lowest order by $\sigma = \frac{\pi}{4s} \lambda^2$.

Including also the new '97 run results, the combined H1 and ZEUS data, interpreted in terms of scalar leptoquarks lead to the following list of couplings [15,33,34]:

$$\begin{aligned} e^+u & \quad \lambda\sqrt{B} \sim 0.017 - 0.025 \\ e^+d & \quad \lambda\sqrt{B} \sim 0.025 - 0.033 \\ e^+s & \quad \lambda\sqrt{B} \sim 0.15 - 0.25 \end{aligned} \quad (2)$$

where B is the branching ratio into the e-q mode. By s the strange sea is meant. For comparison note that the electric charge is $e = \sqrt{4\pi\alpha} \sim 0.3$. Production via $e^+\bar{u}$ or $e^+\bar{d}$ is excluded by the fact that in these cases the production in e^-u or e^-d would be so copious that it should have shown up in the small luminosity already collected in the e^-p mode. The estimate of λ in the strange sea case is merely indicative due to the large uncertainties on the value of the small sea densities at the relatively large values of x relevant to the HERA data. The width is in all cases narrow with respect to the resolution: for $B \sim 1/2$ we have $\Gamma \sim 4 - 16$ MeV for valence and 350 - 1000 MeV for sea densities.

It is important to notice that improved data from CDF and D0 [7] on one side and from APV [21] and LEP [17] on the other considerably reduce the window for leptoquarks. Consistency with the Tevatron, where scalar leptoquarks are produced via model-independent (and λ -independent) QCD processes with potentially

large rates, demands a value of B sizeably smaller than 1. In fact, the most recent NLO estimates of the squark and leptoquark production cross sections [35,36] allow to estimate that at 200 GeV approximately 6–7 events with e^+e^-jj final states should be present in the combined CDF and D0 data sets. For $B = 1$ the CDF limit is 210 GeV, the latest D0 limit is 225 GeV at 95%CL. The combined CDF+D0 limit is 240 GeV at 95%CL [7]. We see that for consistency one should impose:

$$B \lesssim 0.5 - 0.7 \quad (3)$$

Finally, 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.

There are also lower limits on B , different for production off valence or sea quarks, so that only a definite window for B is left in all cases. For production off valence the best limit arises from APV [21], while for the sea case it is obtained from recent LEP2 data [17].

One obtains a limit from APV because the s -channel exchange amplitude for a leptoquark is equivalent at low energies to an $(\bar{e}q)(\bar{q}e)$ contact term with amplitude proportional to λ^2/M^2 . After Fierz rearrangement a component on the relevant APV amplitude $A_e V_q$ is generated, hence the limit on λ . The results are [26]

$$\begin{aligned} e^+u & \quad \lambda \lesssim 0.058 \\ e^+d & \quad \lambda \lesssim 0.055 \end{aligned} \quad (4)$$

The above limits are for $M = 200$ GeV (they scale in proportion to M) and are obtained from the quoted error on the new APV measurement on Cs. This error being mainly theoretical, one could perhaps take a more conservative attitude and somewhat relax the limit. Comparing with the values for $\lambda\sqrt{B}$ indicated by HERA, given in eq.(2), one obtains lower limits on B :

$$e^+u \quad B \gtrsim 0.1 - 0.2$$

$$e^+d \quad B \gtrsim 0.2 - 0.4 \quad (5)$$

For production off the strange sea quark the upper limit on λ is obtained from LEP2 [17], in that the t -channel exchange of the leptoquark contributes to the process $e^+e^- \rightarrow s\bar{s}$ (similar limits for valence quarks are not sufficiently constraining, because the values of λ required by HERA are considerably smaller). Recently new results have been presented by ALEPH, DELPHI and OPAL [17]. The best limit is from ALEPH:

$$e^+s \quad \lambda \lesssim 0.6 \quad (6)$$

(OPAL finds $\lambda \lesssim 0.7$, DELPHI $\lambda \lesssim 0.9$). This, given eq.(2), corresponds to

$$e^+s \quad B \gtrsim 0.05 - 0.2 \quad (7)$$

Recalling the Tevatron upper limits on B , given in eq.(3), we see from eqs. (5) and (7) that only a definite window for B is left in all cases.

Note that one given leptoquark cannot be present both in e^+p and in e^-p (unless it is produced from strange quarks).

5. S-quarks with R-parity Violation

I now consider specifically leptoquarks and SUSY [15,19,37–42]. In general, in SUSY one could consider leptoquark models without R-parity violation. It is sufficient to introduce together with scalar leptoquarks also the associated spin-1/2 leptoquarkinos [37]. In this way one has not to give up the possibility that neutralinos provide the necessary cold dark matter in the universe. We find it more attractive to embed a hypothetical leptoquark in the minimal supersymmetric extension of the SM [43] with violation of R parity [44]. The connection with the HERA events has been more recently invoked in ref. [15,39,41]. The corresponding superpotential can be written in the form

$$W_R \equiv \mu_i H L_i + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c +$$

$$\lambda''_{ijk} U_i^c D_j^c D_k^c, \quad (8)$$

where $H, L_i, E_j^c, Q_k, (U, D)_i^c$ 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. 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.

The squark production mechanisms permitted by the λ' couplings in (8) 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. A careful analysis [15] leads to the result that the only processes that survive after taking into account existing low energy limits are

$$\begin{aligned} e_R^+ d_R &\rightarrow \tilde{c}_L \\ e_R^+ d_R &\rightarrow \tilde{t}_L \\ e_R^+ s_R &\rightarrow \tilde{t}_L \end{aligned} \quad (9)$$

For example $e_R^+ d_R \rightarrow \tilde{u}_L$ is forbidden by data on neutrinoless double beta decay which imply [45]

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

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.

It is interesting to note [39] that the left s-top could be a superposition of two mass eigenstates \tilde{t}_1, \tilde{t}_2 , with a difference of mass that can be large as it is proportional to m_t :

$$\tilde{t}_L = \cos \theta_t \tilde{t}_1 + \sin \theta_t \tilde{t}_2 \quad (11)$$

where θ_t is the mixing angle. With $m_1 \sim 200 \text{ GeV}$, $m_2 \sim 230 \text{ GeV}$ and $\sin^2 \theta_t \sim 2/3$ one can obtain a broad mass distribution, more similar to the combined H1 and ZEUS data. (But with the present data one has to swallow that H1

only observes \tilde{t}_1 while ZEUS only sees \tilde{t}_2 !). However, the presence of two light leptoquarks makes the APV limit more stringent. In fact it becomes

$$B > B_\infty [1 + \tan^2 \theta_t \frac{m_1^2}{m_2^2}] \quad (12)$$

Thus, for the above mass and mixing choices, the above quoted APV limit [B_∞ is given in eq. (5)] must be relaxed invoking a larger theoretical uncertainty on the Cs measurement.

Let us now discuss [15] if it is reasonable to expect that \tilde{c} and \tilde{t} decay satisfy the bounds on the branching ratio B . A virtue of s-quarks as leptoquark is that competition of R-violating and normal decays ensures that in general $B < 1$.

In the case of \tilde{c}_L , the most important possible decay modes are the R -conserving channels $\tilde{c}_L \rightarrow c\chi_i^0$ ($i = 1, \dots, 4$) and $\tilde{c}_L \rightarrow s\chi_j^+$ ($j = 1, 2$), and the R -violating channel $\tilde{c}_L \rightarrow de^+$, where χ_i^0, χ_j^+ denote neutralinos and charginos, respectively. In this case it has been shown [15] that, if one assumes that $m_{\chi_j^+} > 200 \text{ GeV}$, then, in a sizeable domain of the parameter space, the neutralino mode can be sufficiently suppressed so that $B \sim 1/2$ as required (for example, the couplings of a higgsino-like neutralino are suppressed by the small charm mass).

In the case of \tilde{t}_L , it is interesting to notice that the neutralino decay mode $\tilde{t}_L \rightarrow t\chi_i^0$ is kinematically closed in a natural way. Thus, in order to obtain a large value of B in the case of s-top production off d-quarks, in spite of the small value of λ , it is sufficient to require that all charginos are heavy enough to forbid the decay $\tilde{t}_L \rightarrow b\chi_j^+$. However, we do not really want to obtain B too close to 1, so that in this case some amount of fine tuning is required. Or, with charginos heavy, one could invoke other decay channels as, for example, $\tilde{t} \rightarrow \tilde{b}W^+$ [46]. But the large splitting needed between \tilde{t} and \tilde{b} implies problems with the ρ -parameter of electroweak precision tests, unless large mixings in both the s-top and s-bottom sectors are involved and their values suitably chosen. In the case of s-top production off s-quarks, val-

ues around $B \sim 1/2$ are rather natural because of the larger value of λ , which is of the order of the gauge couplings [15,19].

The interpretation of HERA events in terms of s-quarks with R-parity violation requires a very peculiar family and flavour structure [47]. The flavour problem is that there are very strong limits on products of couplings from absence of FCNC. The unification problem is that nucleon stability poses even stronger limits on products of λ couplings that differ by the exchange of quarks and leptons which are treated on the same footing in GUTS. However it was found that the unification problem can be solved and the required pattern can be embedded in a grand unification framework [47]. The already intricate problem of the mysterious texture of masses and couplings is however terribly enhanced in these scenarios.

6. Charged Current Events

In the Introduction, I have mentioned that in the CC channel at $Q^2 \gtrsim 1.5 \cdot 10^4 \text{ GeV}^2$ H1 and ZEUS see a total of 11 events with 5 expected. The statistics is even more limited than in the NC case, so one cannot at the moment derive any firm conclusion on the existence and on the nature of an excess in that channel. However, the presence or absence of a simultaneous CC signal is extremely significant for the identification of the underlying physical effect (as it would also be the case for the result of a comparable run with an e^- beam, which however is further away in time). In view of this, I now briefly discuss the implications for the CC channel of the various proposed solutions of the HERA effect [26,46,48,49]. It is found that in most of the cases the CC signal is not expected to arise. But if it is present at a comparable rate as for the NC signal, the corresponding indications are very selective.

To see that contact terms cannot work recall that for them it is natural to assume the validity of the $SU(2) \otimes U(1)$ symmetry, because they are associated with physics at a large energy scale. In the $SU(2) \otimes U(1)$ limit, restricting us to fam-

ily diagonal quark currents in order to minimise problems with the occurrence of flavour changing neutral currents, the only possible vector contact term with valence quarks (and no Cabibbo suppression) is of the form

$$\Delta L_{CC} = \frac{4\pi\eta}{\Lambda_\eta^2} \bar{e}_L \gamma^\mu \nu_L \bar{u}_L \gamma_\mu d'_L + \text{h.c.} \quad (13)$$

i.e. the product of two isovector currents. Here d'_L is the left-handed d-quark current eigenstate, related to the mass eigenstate by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. It is simple to see that such terms cannot have a sufficient magnitude. In fact the scale Λ associated with this operator is too strongly constrained to produce any measurable effect at HERA. The constraints arise from at least two experimental facts: lepton-hadron universality of weak charged currents and electron-muon universality in charged-pion decays. The corresponding lower limits on Λ exceed 10 TeV in all cases [26].

The possible scalar or tensor currents arising from an $SU(2) \otimes U(1)$ invariant theory which can contribute to valence-parton CC processes are

$$\begin{aligned} \mathcal{L} = & \frac{4\pi}{\Lambda_S^2} (\bar{e}_R \nu_L) (\bar{u}_R d_L) + \frac{4\pi}{\Lambda_{S'}^2} (\bar{e}_R \nu_L) (\bar{u}_L d_R) + \\ & \frac{4\pi}{\Lambda_T^2} (\bar{e}_R \sigma^{\mu\nu} \nu_L) (\bar{u}_R \sigma_{\mu\nu} d_L) , \end{aligned} \quad (14)$$

while the operator $(\bar{e}_R \sigma^{\mu\nu} \nu_L) (\bar{u}_L \sigma_{\mu\nu} d_R)$ identically vanishes. The scalar interactions are strongly limited by $e-\mu$ universality in pion decays [50], because they do not lead to electron-helicity suppression, in contrast with the SM case. The lower limit on Λ is about 500 TeV [50]. The tensor interaction can be dressed into a scalar interaction of effective strength [51]

$$\frac{1}{\Lambda_{S \text{ eff}}^2} \simeq -\frac{\alpha}{\pi} \log \left(\frac{\Lambda_T^2}{M_W^2} \right) \frac{1}{\Lambda_T^2} , \quad (15)$$

with the exchange of a photon between the electron and the quark fields. The upper limit re-

mains sufficiently strong to prevent these terms from contributing as well.

Considering now also CC processes involving sea quarks [26], we can introduce a contact term for second generation quarks

$$\Delta L_{CC} = \frac{4\pi\eta}{\Lambda_\eta^{(2)2}} (\bar{e}_L \gamma^\mu \nu_L) (\bar{c}_L \gamma_\mu s'_L) + h.c. \quad (16)$$

Clearly since the strange sea in the proton is small one needs relatively small values of Λ in order to produce a sufficiently large effect. A detailed study shows that one needs $\Lambda \sim 0.8 - 1$ TeV with $\eta = -1$ in order to obtain an increase by a factor of two with respect to the SM at $Q^2 \gtrsim 15000$ GeV². But bounds on the scales $\Lambda_\eta^{(2)}$ derived from lepton universality in D decays [26,52] and, independently, from the unitarity of the CKM matrix, forbid such low values.

In conclusion it appears very difficult to accommodate a CC signal at HERA in the framework of contact terms.

Let us now consider a scalar leptoquark resonance that is coupled both to e^+d and to $\bar{\nu}u$ so that it can generate both NC and CC events from valence (note that e^+u has charge $+5/3$ and cannot go into $\bar{\nu}q$). Assuming that the symmetry under $SU(2) \otimes U(1)$ is conserved, the virtual leptoquark exchange gives a CC contribution to the low-energy effective Lagrangian of the form

$$\mathcal{L} = \frac{\lambda_u \lambda_d}{M^2} (\bar{e}_R d_L) (\bar{u}_R \nu_L) + h.c. \quad (17)$$

Here λ_u and λ_d are the (real) couplings of a leptoquark with mass M to the $\bar{\nu}_L u_R$ and $\bar{e}_R d_L$ currents, respectively. This interaction corresponds to the transition $e_L^+ d_L \rightarrow \bar{\nu}_R u_R$ which has $T = -1/2$ both in the initial and final states. At low energies, the leptoquark exchange induces a contribution to $\pi \rightarrow e\bar{\nu}$ which is not helicity suppressed. It is simple to verify that this clearly excludes any observable CC signal. An alternative is to break $SU(2) \otimes U(1)$ and assume that

the leptoquark exchange induces an effective interaction of the form

$$\mathcal{L} = \frac{\lambda_u \lambda_d}{M^2} (\bar{e}_L d_R) (\bar{u}_R \nu_L) + h.c. \quad (18)$$

Note that in the transition $e_R^+ d_R \rightarrow \bar{\nu}_R u_R$ the initial state has $T = +1/2$ while the final state has $T = -1/2$. In this case the low energy effective interaction gives a contribution to $\pi \rightarrow e\bar{\nu}$ which is helicity suppressed and so can be acceptable, as it can be checked. Since $SU(2) \otimes U(1)$ is broken only by the Higgs vacuum expectation value (VEV), the leptoquark couplings could violate gauge invariance if the leptoquark couples to the quark-lepton current through some higher-dimensional operator [26] and/or if the breaking induces a mixing between two leptoquarks of different electroweak properties [48].

Another viable alternative is a leptoquark which couples simultaneously to the $\bar{e}_R^{(1)} q_L^{(1)}$ and $\bar{\ell}_L^{(i)} u_R^{(2)}$ currents ($i = 1, 2, 3$). Here we have specified the generation indices of the different fields. If CC events were observed at HERA and such a leptoquark was responsible for them, we expect the striking signature of leptonic D decays with rates much larger than in the SM. In the case of a leptoquark produced in the e^+s channel, the possibility of a $\bar{\nu}c$ final state is still allowed. This leads to a remarkable signature in leptonic D_s decays

$$BR(D_s^- \rightarrow e^- \bar{\nu}) \simeq 6 \times 10^{-3} \frac{\mathcal{B}_{\nu c}}{(1 - \mathcal{B}_{\nu c})^3} \left(\frac{200 \text{ GeV}}{M} \right)^4 \quad i = 1, 2. \quad (19)$$

We are not aware of any existing experimental limit on this quantity.

To conclude, we recall that a leptoquark with branching ratio equal to 1 in e^+q is excluded by the recent Tevatron limits. Therefore on one hand some branching fraction in the CC channel is needed. On the other hand, we find that there

is limited space for the possibility that a lepto-quark can generate a CC signal at HERA with one single parton quark in the final state. This occurrence would indicate $SU(2) \otimes U(1)$ violating couplings or couplings to a current containing the charm quark.

A few mechanisms for producing CC final states from \tilde{c} or \tilde{t} have been proposed [26,46,49]. In all cases \tilde{c} or \tilde{t} lead to multiparton final states. Since apparently the CC candidates are all with one single jet, some strict requirements on the masses of the participating particles must be imposed so that some partons are too soft to be visible while others coalesce into a single visible jet. Consider for example the chain [26]

$$\tilde{c} \rightarrow c\chi^0 \rightarrow cv\tilde{\nu} \rightarrow cvd\bar{s} \quad (20)$$

where in the last step the R-violating coupling $\tilde{\nu} \rightarrow d\bar{s}$ is involved which, by gauge symmetry and supersymmetry, has the same coupling λ as the $ed \rightarrow \tilde{c}$ coupling. In order for the c quark to be invisible the neutralino mass must be sufficiently close to the \tilde{c} mass. For the d and \bar{s} partons to coalesce in a single jet, the s-neutrino mass must be small, close to the LEP2 limit (actually if the ALEPH 4-jet events were true, they could be a manifestation of light s-neutrinos or s-leptons). A similar chain could also lead to charged leptons plus missing energy in the final state.

In a different mechanism without light s-leptons one can use s-bottom decays, like in the chain [49].

$$\tilde{t} \rightarrow b\chi^+ \rightarrow bc\tilde{b} \rightarrow bcv\bar{d} \quad (21)$$

Here too the coupling $\tilde{b} \rightarrow d\bar{\nu}$ is implied by the $ed \rightarrow \tilde{t}$ coupling. In this case, in order not to observe the b and c quark jets in the final state, one needs that the masses of \tilde{t} , charginos and s-bottom are close and in decreasing order.

In conclusion, s-quarks with R-parity violating decays could produce CC events or events with charged leptons and missing energy. The obser-

vation of such events would make the model much more constrained.

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