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NEW PHYSICS INTERPRETATIONS OF THE HERA HIGH-Q^2 EVENTS *

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ABSTRACT

Theoretical interpretations of the excess of high-Q^2 events recently observed in deep-inelastic positron-proton scattering at HERA are reviewed. After a few remarks on the standard model predictions I discuss leptoquarks, squarks with R-parity violating couplings, and contact interactions. The relevant bounds from other experiments are summarized.

1. The data

Both HERA experiments, H1 [1] and ZEUS [2], have reported the observation of an excess of events in deep-inelastic positron-proton scattering at the center-of-mass energy $\sqrt{s} = 300$ GeV, large Bjorken-x, and high momentum transfer Q^2, relative to the expectation in the standard model. Including the new data presented at the 1997 summer conferences [3], H1 and ZEUS each observe 18 neutral current (NC) events at $Q^2 > 1.5 \cdot 10^4$ GeV^2, while H1 expects 8.0 ± 1.2 and ZEUS about 15 events. At H1, the excess is concentrated in the rather narrow energy range 187.5 GeV $\leq \sqrt{xs} \leq$ 212.5 GeV of the positron-quark subprocess, where 8 events are observed with 1.53 ± 0.29 expected. However, in the same region, ZEUS finds roughly the expected number of events. Conversely, in the region $x > 0.55$, $y = Q^2/xs > 0.25$ where ZEUS finds 5 events with 1.51 ± 0.13 expected, H1 observes no excess. A surplus of events is also observed in charged current (CC) scattering, although with smaller statistical significance. At $Q^2 > 10^4$ GeV^2, H1 and ZEUS together find 28 events, while the standard model predicts 17.7 ± 4.3.

The clustering of the H1 events at a fixed value of $M = \sqrt{xs}$ could indicate the production of a resonance with lepton+quark quantum numbers and mass $M \simeq 200$ GeV. On the other hand, ZEUS has 4 events clustered at a somewhat higher mass $M \simeq 225$ GeV. Given the experimental mass resolution of 5 and 9 GeV, respectively, it appears unlikely that both signals come from a single narrow resonance [3,5]. Alter-

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natively, the excess may be a continuum effect caused by some anomalous behaviour of parton densities or by new physics giving rise to residual interactions. Although the anomalous number of events is not large enough to clearly exclude statistical fluctuations as the origin of the excess, and the differences in the H1 and ZEUS data are somewhat puzzling, the data have provided a lot of excitement and motivation to investigate possible interpretations within and beyond the standard model.

2. Standard model

While the uncertainties in the hard electroweak subprocesses and radiative effects are negligibly small [1,2], the main theoretical uncertainty on the high-Q^2 cross sections in the standard model comes from the parton densities in the proton. The latter are obtained by extrapolation of measurements at lower Q^2 using next-to-leading order evolution equations. For presently available parametrizations the HERA collaborations have estimated this uncertainty to be about 7 % [1,2]. This is much to small to accommodate the observed effect.

Up to now, no standard model mechanism is known which could explain the observed surplus of events. Attempts [6] to add to the conventional parton densities a new valence component at very large x but low Q^2, and to feed down this enhancement to lower x by evolution to very high Q^2, fail to increase the cross sections by a sufficient amount because of the constraints put by the fixed-target data. Also the hypothesis of an intrinsic charm component [7] generated nonperturbatively does not seem to lead to a viable explanation. Moreover, no sign of a deviation from the perturbative evolution of structure functions in QCD has been found in the data up to $Q^2 \simeq 10^4$ GeV^2. Whatever mechanism is responsible for the HERA anomaly, it must have quite a rapid onset.

Thus it is rather safe to conclude that either the excess is a statistical fluctuation, or it is very likely produced by new physics beyond the standard model. The latter case immediately raises the question whether one is dealing with a (not necessarily single) resonance or with a continuum effect. In the following, we give a brief overview of the main speculations, pointing out also the implications of experimental data which appeared after this Conference.

3. Leptoquarks

The most exciting speculation is the one of a possible discovery of a new particle. Being supposedly produced as a s-channel resonance in e^+q or $e^+\bar{q}$ collisions, this new member of the particle zoo must be a boson and carry simultaneously lepton and quark quantum numbers. Such species are generically called leptoquarks. Leptoquarks appear in extensions of the standard model involving unification, technicolor, compositeness, or R-parity violating supersymmetry. In addition to the couplings to the standard model gauge bosons [8], leptoquarks have Yukawa-type couplings to lepton-quark pairs. In the generally adopted framework described in Ref. [9], the Yukawa couplings are taken to be dimensionless and $SU(3) \times SU(2) \times U(1)$ symmetric:

$$\lambda_i \bar{l}_i q S \quad \text{or} \quad \lambda_i \bar{l}_i q^c S \tag{1}$$

for scalars, and

$$\lambda_i \bar{l}_i \gamma_\mu q V^\mu \quad \text{or} \quad \lambda_i \bar{l}_i \gamma_\mu q^c V^\mu \tag{2}$$

for vector LQs. Here, c denotes charge conjugation, λ_i is the generic coupling constant, and $i = L, R$ specifies the lepton handedness. Moreover, the Yukawa couplings are assumed to conserve lepton and baryon number in order to avoid rapid proton decay, to be non-zero only within one family in order to exclude FCNC processes beyond CKM mixing, and chiral in order to escape the very strong bounds from leptonic pion decays.

The allowed states can be classified according to spin, weak isospin and fermion number. The nine possible scalar and vector leptoquarks are listed in Tab. 1. We use the notation introduced in Ref. [10] and generally employed in experimental papers: scalars are denoted by S_I, vectors by V_I, I being the weak isospin, and isomultiplets with different hypercharges are distinguished by a tilde. States in the upper half of Tab. 1 carry fermion number $F = 2$, those in the lower half have fermion number $F = 0$. Given are also the electric charges, the decay modes for first generation leptoquarks with the respective branching ratios, and the specific Yukawa couplings to be subsituted for λ_i. As a consequence of the assumption that low-mass leptoquarks have either L- or R-couplings, but not both at the same time, the branching fractions to a charged lepton final state can only be 1, 1/2, or 0.

With the above couplings the resonance cross section in ep scattering is given by

$$\sigma = N_\sigma \frac{\pi}{4s} \lambda_i^2 q_f(M^2/s, \mu^2) \ , \tag{3}$$

where $q_f(x, \mu^2)$ is the density of quarks (or antiquarks) with flavour f in the proton, and $N_\sigma = 1\,(2)$ for scalars (vectors). The relevant scale μ is expected to be of order the leptoquark mass M. The coupling constant λ_i can be read off from Tab. 1. Obviously, leptoquarks with fermion number $F = 0\,(2)$ can be produced from valence quarks in $e^+q\,(e^-q)$ fusion. This is essential for the interpretation of the HERA anomaly: the coupling strength required for $F = 0$ resonance production is much smaller than the one for $F = 2$ production.

In order to explain the observed excess of high-Q^2 events at HERA by the production and decay of a 200 GeV leptoquark, one roughly needs $\lambda_i \simeq e$ for $F = 2$ states and $\lambda_i \simeq e/10$ for $F = 0$. The factor 10 difference in λ simply reflects the factor 100 difference in the sea and valence quark densities in the region of x and Q^2 where the signal is observed. Similarly, the coupling of $F = 0$ leptoquarks to the d quark has to be twice larger than the coupling to the u quark in order to compensate

LQ		Q	Decay Mode	BR $e^{\pm} j$	Coupling $\lambda_{L,R}$	Limits Ref. [24]	HERA estimates
S_0	$\tilde{d}_R$	$-1/3$	$e_L u$ $\nu_L d$ $e_R u$	$\frac{1}{2}$ 1	g_L $-g_L$ g_R	$g_L < 0.06$ $g_R < 0.1$	0.40 0.28
$\tilde{S}_0$		$-4/3$	$e_R d$	1	g_R	$g_R < 0.1$	0.30
S_1		$+2/3$	$\nu_L u$	0	$\sqrt{2} g_L$	$g_L < 0.09$	–
		$-1/3$	$\nu_L d$ $e_L u$	$\frac{1}{2}$	$-g_L$ $-g_L$		0.40
		$-4/3$	$e_L d$	1	$-\sqrt{2} g_L$		0.21
$V_{1/2}$		$-1/3$	$\nu_L d$ $e_R u$	0 1	g_L g_R	$g_L < 0.09$	– 0.30
		$-4/3$	$e_L d$ $e_R d$	1	g_L g_R	$g_R < 0.05$	0.32 0.32
$\tilde{V}_{1/2}$		$+2/3$	$\nu_L u$	0	g_L	$g_L < 0.09$	–
		$-1/3$	$e_L u$	1	g_L		0.32
$S_{1/2}$		$-2/3$	$\nu_L \bar{u}$ $e_R \bar{d}$	0 1	g_L $-g_R$	$g_L < 0.1$	– 0.052
		$-5/3$	$e_L \bar{u}$ $e_R \bar{u}$	1	g_L g_R	$g_R < 0.09$	0.026 0.026
$\tilde{S}_{1/2}$	$\bar{\tilde{d}}_L$	$+1/3$	$\nu_L \bar{d}$	0	g_L	$g_L < 0.1$	–
	$\bar{\tilde{u}}_L$	$-2/3$	$e_L \bar{d}$	1	g_L		0.052
V_0		$-2/3$	$e_L \bar{d}$ $\nu_L \bar{u}$ $e_R \bar{d}$	$\frac{1}{2}$ 1	g_L g_L g_R	$g_L < 0.05$ $g_R < 0.09$	0.080 0.056
$\tilde{V}_0$		$-5/3$	$e_R \bar{u}$	1	g_R	$g_R < 0.09$	0.027
V_1		$+1/3$	$\nu_L \bar{d}$	0	$\sqrt{2} g_L$	$g_L < 0.04$	–
		$-2/3$	$e_L \bar{d}$ $\nu_L \bar{u}$	$\frac{1}{2}$	$-g_L$ g_L		0.080
		$-5/3$	$e_L \bar{u}$	1	$\sqrt{2} g_L$		0.019

Table 1. Scalar (S) and vector (V) leptoquarks, and their electric charges Q, decay modes, branching ratios into charged lepton + jet channels, and Yukawa couplings. Given are also the most stringent low-energy bounds and the couplings deduced from the 1994-96 HERA data. Inclusion of the 1997 data decrease the couplings by about 15%. Using the H1 data alone would roughly give the couplings shown above. Also shown are the assignments of squarks with R-parity violating couplings. (From Ref. [11].)

the factor four difference in the corresponding quark densities. These simple rules of thumb describe the main pattern in the couplings found in detailed analyses [11,12] and listed in the last column of Tab. 1.

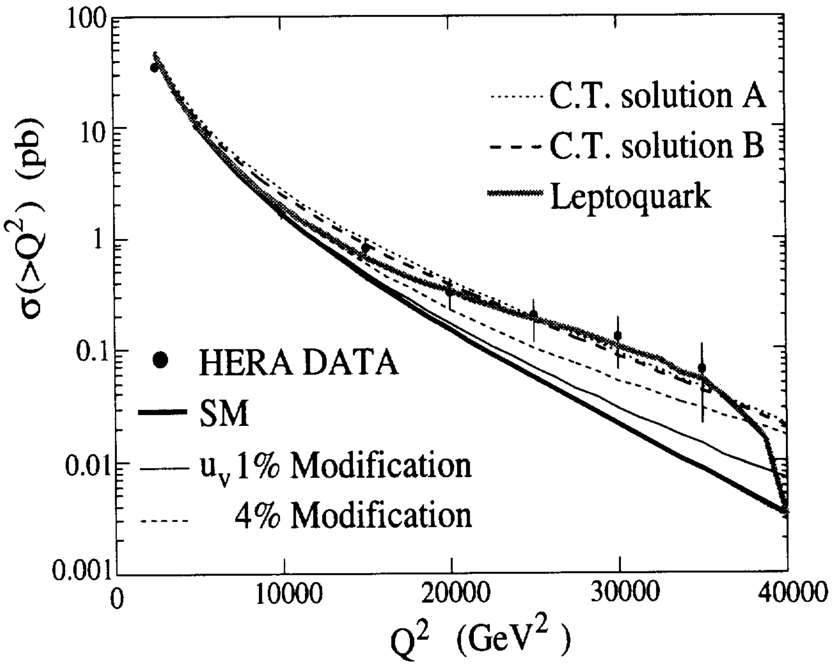

Fig. 1. Cross section integrated above a given minimum Q^2 in the standard model and in the presence of the $S^L_{1/2}$ leptoquark with $M = 200$ GeV and $\lambda_L = 0.025$ compared with the 1994 - 96 data. Also shown are effects due to an enhancement of the valence quark density and from contact interactions. (From Ref. [13].)

Fig. 1 shows the e^+p cross section integrated above a given minimum value of Q^2 in a scenario with a 200 GeV $S_{1/2}$ leptoquark in comparison with the 1994 - 96 data [1,2] and the standard model expectation. The Yukawa coupling λ_L is taken to be 0.025 in conformity with the estimate given in Tab. 1. As one can see, the leptoquark hypothesis can provide a satisfactory interpretation at least of the original data from the 1994 - 96 runs.

Having only couplings to standard model particles, leptoquarks decay exclusively to lepton-quark pairs. The partial width per channel is given by

$$\Gamma = \frac{N_\Gamma}{16\pi}\lambda_i^2 M = 350\,\mathrm{MeV}\,N_\Gamma \left(\frac{\lambda}{e}\right)^2 \left(\frac{M}{200\,\mathrm{GeV}}\right) , \qquad (4)$$

N_Γ being 1 for scalars and 2/3 for vectors. Hence, leptoquarks are very narrow for masses in the range accessible at HERA, and for couplings weaker than the electromagnetic coupling strength $e = \sqrt{4\pi\alpha}$.

Obviously, only states with charge 2/3 can be produced in e^+q fusion and subsequently decay into $\bar{\nu}_e q$. For chiral couplings $\lambda_L \neq 0$ and $\lambda_R = 0$, this leaves only the vector leptoquarks V_0 and V_1 as possible sources of CC final states. Similarly, in $e^+\bar{q}$ fusion only the charge 1/3 scalar leptoquarks S_0 and S_1 can give rise to CC events. The branching fractions into a charged lepton plus jet and neutrino plus jet are 50% each. This is a second feature which plays an important role in interpretations of the HERA events, as became very clear after the Conference when new data from different experiments came in.

The leptoquark masses and couplings are constrained by high- and low-energy experiments. Direct searches for leptoquarks have been performed at the Tevatron, at HERA and at LEP. Recently, the CDF and D0 collaborations have improved their mass limits for scalar leptoquarks considerably. D0 now excludes first generation leptoquarks with masses below 225 GeV assuming a branching ratio $B_{eq} = 1$ for decays into $e^\pm$ and a jet [14], whereas CDF quotes a limit of 213 GeV [15] (all mass limits at 95 % CL). For branching ratios less than one, the limits are weaker, e.g., $M > 176$ GeV for $B_{eq} = 0.5$ [14]. The bounds on vector states are even stronger: 298 GeV for $B_{eq} = 1$ and 270 GeV for $B_{eq} = 0.5$ [16]. The corresponding mass limits on second and third generation scalar leptoquarks are $M > 184$ GeV for $B_{\mu q} = 1$ and $M > 98$ GeV for $B_{\tau q} = 1$, respectively [17]. The above constraints follow from pair-production mainly by $q\bar{q}$ annihilation, and are therefore practically independent of the unknown Yukawa coupling λ.

In contrast, the mass limits obtained at HERA [18] depend on λ and the quantum numbers specified in Tab. 1. For $\lambda = e$ and $F = 0$ ($F = 2$) leptoquarks the upper limits from resonance production in e^-p ($0.4\ \mathrm{pb}^{-1}$) and e^+p ($2.8\ \mathrm{pb}^{-1}$) collisions at H1 reach up to 270 (245) GeV. The corresponding reach for $\lambda = 0.03$ is 170 (130) GeV, except in the case of V_0^R which is excluded up to $M = 210$ GeV. Heavy leptoquarks generate effective contact interactions [19] and can therefore be probed by a general contact term analysis. The outcome of such a test is presented in Ref. [20].

At LEP2, the most stringent, but again λ-dependent mass bound comes from the search for single-leptoquark production at $\sqrt{s} = 161$ and 172 GeV, and excludes masses for scalars with $|Q| = 5/3$ and $1/3$ below 131 GeV assuming $\lambda \geq e$ [21]. The upper limits on leptoquark masses from pair production [22], being close to half of the center of mass energy $\sqrt{s}$, are weaker than the above limit, and also way below the Tevatron bounds. Indirect constraints from t- and u-channel exchange of leptoquarks [11] in $e^+e^- \to q\bar{q}$ are approaching an interesting sensitivity. From the very recent analysis by OPAL [23] for $\sqrt{s} = 130$ to 172 GeV we infer upper limits on λ between 0.2 and 0.7 assuming $M = 200$ GeV. In addition, similarly as at HERA, bounds on contact interactions can be translated into constraints on heavy leptoquarks. States with integer isospin $I = 0$ and $I = 1$ generate equal-helicity LL and RR contact terms, while leptoquarks with $I = 1/2$ give rise to opposite-helicity RL and LR contact terms.

Finally, indirect bounds on Yukawa couplings and masses can also be derived from weak and rare processes at low energies [24]. The most restrictive bounds come from atomic parity violation and lepton and quark universality, at least for first generation leptoquarks and chiral couplings. The maximum allowed couplings for $M = 200$ GeV are given in Tab. 1 [11].

Whereas the coupling strength λ required for $F = 0$ leptoquarks to explain the observed excess of events is compatible with all existing bounds, the coupling necessary for $F = 2$ leptoquarks is already excluded by the low-energy constraints, and also at the borderline of getting in conflict with LEP2 data. Moreover, with such strong couplings, $F = 2$ leptoquarks should have shown up in e^-p scattering at HERA [25], where they can be produced off the valence quark component, despite of the low luminosity of the previous e^-p run. Furthermore, since vector leptoquarks cannot be made responsible for an excess of events at $M \simeq 200$ to 225 GeV because of the high Tevatron mass bounds, only the two scalar doublets $S_{1/2}$ and $\tilde{S}_{1/2}$ remain from the whole Tab. 1 as a possible source of the signal. However, with the advent of the new data also these solutions got into difficulties. Firstly, the Tevatron mass limits require scalar leptoquarks of the first generation with $M \simeq 200$ GeV to have branching ratios into e + jet final states less than about 0.7[a], whereas in the framework considered in Tab. 1, $S_{1/2}$ and $\tilde{S}_{1/2}$ are expected to have $B_{eq} = 1$ (or 0, but then they cannot be produced in e^+p). Secondly, the scalar doublets do not give rise to CC events. As already mentioned, among the $F = 0$ leptoquarks only the vector states V_0 and V_1 decay into $\bar{\nu}_e + jet$. However, vector leptoquarks are clearly excluded by the Tevatron mass bounds. Thirdly, any single-resonance interpretation of the high-Q^2 events has difficulties to explain the distributions in M or x simultaneously for H1 and ZEUS.

Thus it seems that the leptoquark interpretation of the HERA high-Q^2 events points at more complicated scenarios involving more than just a single leptoquark at a time, and different couplings, not just the coupling to first generation fermions with given chirality. Several possibilities have been suggested allowing for $B_{eq} < 1$, providing CC final states, and predicting a broad mass bump rather than a narrow resonance signature: $SU(2) \times U(1)$ violating, intergenerational couplings [26,27] and leptoquark mixing [28], LQ models with additional vector-like fermions [29], and squarks with R-parity violating couplings [30].

4. Squarks

The squark proposition is clearly the most interesting one, since it can be realized in a supersymmetric extension of the standard model which is attractive for many other reasons. If R-parity is violated squarks can have direct couplings to lepton-quark pairs, and therefore act as leptoquarks. However, because of the usual R-parity conserving interactions one naturally expects the branching ratio for $\tilde{q} \to e + jet$ to be smaller than unity. In addition, one can get CC-like final states, e.g., through the

[a]This follows from the D0 limits [14] alone. An even smaller branching ratio is required by the combined D0 and CDF bounds.

decay chain $\tilde{q} \to q\chi$, $\chi \to \nu + \cdots$, χ being either a neutralino or chargino. Thus it appears possible to avoid two of the main problems encountered in the simplest leptoquark models.

ijk	C	n, m	source
111	0.004	$2,\frac{1}{2}$	ν-less $\beta\beta$ decay
112 113	0.04	1,0	CC universality
121 131	0.07	1,0	atomic P-violation
122 133	0.08 0.003	$\frac{1}{2}$,0	ν_e mass
123	0.52 0.28	1,0 $\frac{1}{2}$,0	F − B asymmetry $D - \overline{D}$ mixing*
132	0.68	1,0	$R_e\ (Z_0)$

Table 2. Low-energy constraints $\lambda'_{ijk} < C\,(M_{\tilde{q}}/200\,\mathrm{GeV})^n\,(m_{\tilde{g}}/1\,\mathrm{TeV})^m$ on R-parity violating couplings relevant for e^+p scattering [34]. The limit on λ'_{123} from $D - \overline{D}$ mixing, marked by *, involves quark mixing and is thus model-dependent.

In the minimal supersymmetric extension of the standard model, one can have a renormalizable, gauge invariant operator in the superpotential that couples squarks to quarks and leptons:

$$W_{\not R} = \lambda'_{ijk} L^i_L Q^j_L \overline{D}^k_R. \tag{5}$$

Here, L and Q denote doublets of lepton and quark superfields, respectively, D stands for singlets of d-quark superfields, and i, j, and k are generation indices. This interaction term violates global invariance of R-parity, defined as $R = (-1)^{3B+L+2S}$ which is $+1$ for particles and -1 for superpartners. In general, there are other R-odd operators in the superpotential that couple sleptons to leptons and squarks to quarks. Together, they may induce rapid proton decay. This can be avoided by requiring conservation of R-parity, or a strong hierarchy in the various couplings. Generally, these two options lead to very different phenomenology.

As can be seen from (5), direct couplings to lepton-quark pairs exist for the squark singlets $\tilde{d}^k_R$ and the doublets $(\tilde{\bar{d}}^j_L,\ \tilde{\bar{u}}^j_L)$. The quantum number assignment for these squarks is identical to the assignment for the states S_0 and $\tilde{S}_{1/2}$, respectively, given in Tab. 1. Consequently, squarks can be resonance-produced at HERA [30,31]:

$$e^+ d^k_R \to \tilde{u}^j_L \qquad (\tilde{u}^j = \tilde{u}, \tilde{c}, \tilde{t}), \tag{6}$$

$$e^+ \bar{u}^j_L \to \tilde{\bar{d}}^k_R \qquad (\tilde{d}^k = \tilde{d}, \tilde{s}, \tilde{b}). \tag{7}$$

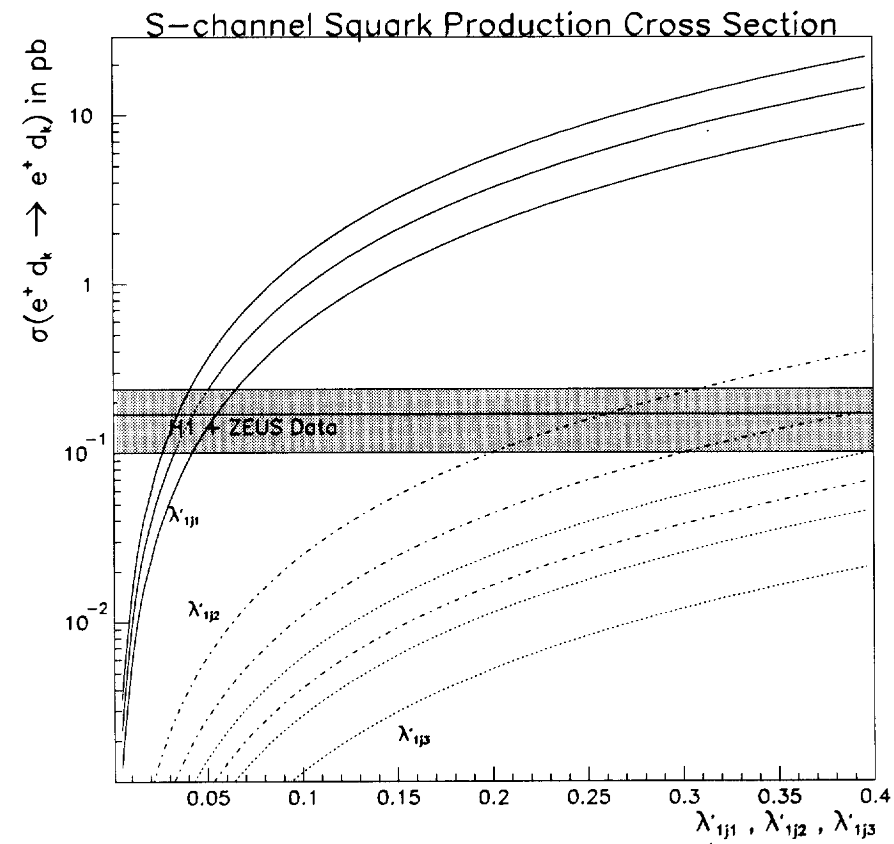

Fig. 2. Cross section for $e^+d_k \to \tilde{u}_j \to e^+d_k$ as a function of the coupling λ'_{1jk} for d valence quarks (full), s quarks (dash-dotted) and b quarks (dotted) assuming $B_{eq} = 1$. The curves from top to bottom correspond to $M_{\tilde{u}_j}$ = 200, 210, and 220 GeV. The shaded region shows the excess cross section for the 1994 - 96 HERA data for $Q^2 > 20,000$ GeV^2 (From Ref. [32].)

The cross sections are determined by the coupling constants λ'_{1jk}. Similarly as the leptoquark Yukawa couplings $\lambda_{L,R}$ from Tab. 1, these couplings are strongly constrained by existing data. The relevant bounds are summarized in Tab. 2. As already pointed out, since the excess of events was observed in e^+p but not in e^-p scattering, the process of class (7) involving the $\bar{u}$ sea is unlikely. Moreover, the coupling strength $\lambda'_{11k} \simeq e$, required for production off sea quarks, is incompatible with the existing bounds. This also applies to the $e^+\bar{c}$ channel with the marginal exception of the subprocess $e^+\bar{c} \to \bar{\tilde{t}}$ [32]. The top sea plays no role. Turning to the processes of class (6), one finds three possible explanations of the HERA anomaly [30 b]:

$$e^+d \to \tilde{c} \ \ (\lambda'_{121}), \tag{8}$$
$$e^+d \to \tilde{t} \ \ (\lambda'_{131}), \tag{9}$$

[b]For a discussion of the strange stop scenario see in particular Ref. [33]

$$e^+ s \to \tilde{t} \ \ (\lambda'_{132}). \tag{10}$$

The corresponding cross sections are plotted in Fig. 2 for $M_{\tilde{q}} = 200$ to 220 GeV, and setting $B_{eq} = 1$. As can be seen, within the limits on λ' quoted in Tab. 2 one can still afford branching ratios for $\tilde{c}, \tilde{t} \to e^+ d$ below 0.7, necessary in order to avoid the D0/CDF mass bounds. Studies [35,36] have shown that one can indeed find allowed regions in the supersymmetry parameter space in which $B_{eq} < 0.7$. This is exemplified in Fig. 3 for $B(\tilde{t} \to e^+ d)$. However,as one can see there is not too big a room for a consistent squark interpretation of the HERA anomaly.

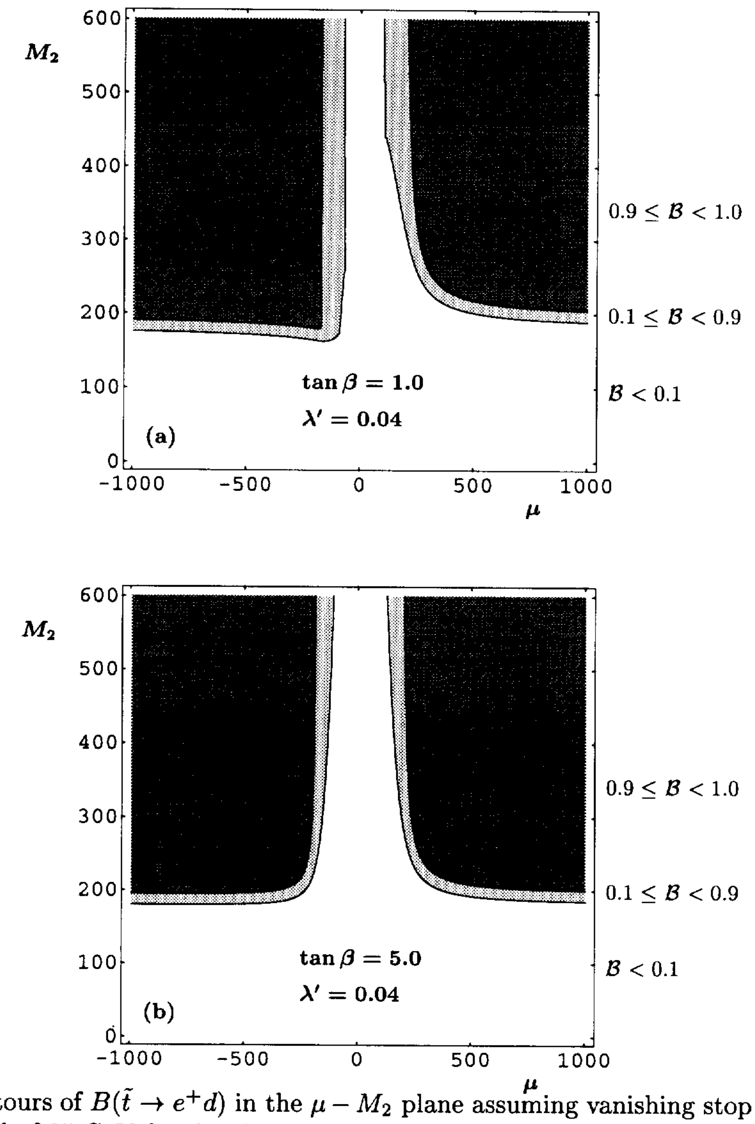

Fig. 3. Contours of $B(\tilde{t} \to e^+ d)$ in the $\mu - M_2$ plane assuming vanishing stop left-right mixing. The LEP2 bound of 85 GeV for the chargino mass is taken into account. (From Ref. [36].)

Concerning the CC events it is important to note the following. The NC events from $\tilde{t}, \tilde{c} \to e^+ d$ have the same visible particles as the DIS-NC events. This is not expected for the CC events originating from cascade decays of squarks on the one hand, and DIS-CC events on the other. More specifically, the anomalous CC events should exhibit a multijet topology.

Finally, the difficulty to interpret the excess of events as a single-resonance effect may also find a reasonable solution [37]. In the MSSM each fermion has two superpartners, $\tilde{f}_L$ and $\tilde{f}_R$, which mix in general. In the case of stop this mixing may be sizeable and lead to two mass eigenstates with a small but pronounced mass difference. Such a case is illustrated in Fig. 4. The resulting mass distribution can apparently mimic a continuum effect.

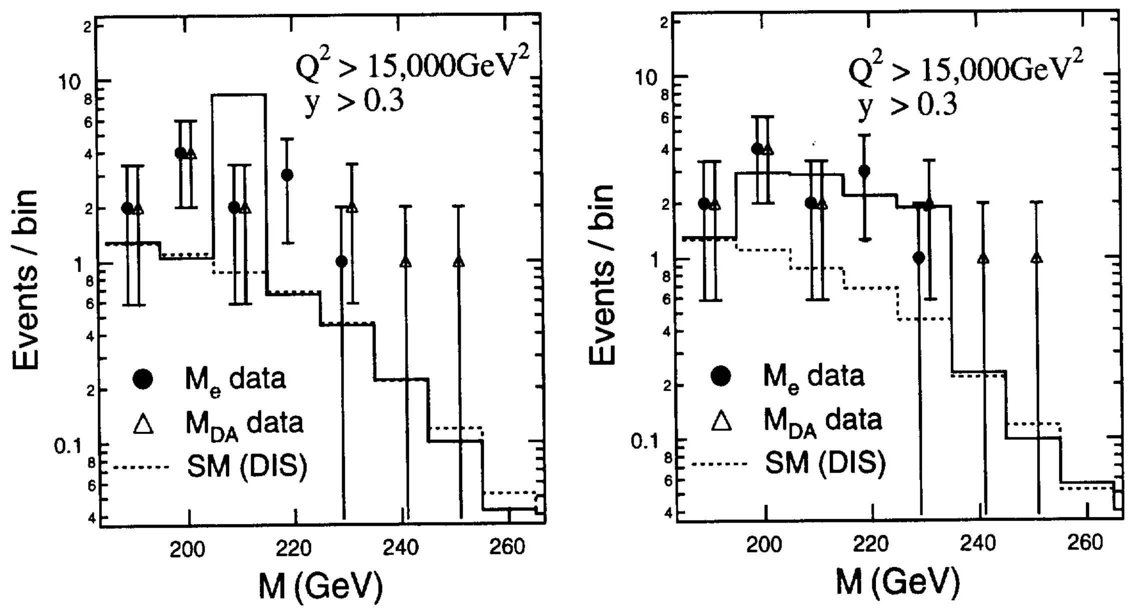

Fig. 4. Distributions in $M = \sqrt{xs}$ of the 1994 - 96 HERA data (H1 and ZEUS combined) in comparison with the distributions in a single stop scenario (left, $M_{\tilde{t}} = 210$ GeV, $\lambda'_{131} = 0.04$) and in a mixed left-right stop scenario (right, $M_{\tilde{t}_1} = 205$ GeV, $M_{\tilde{t}_2} = 225$ GeV, $\theta_t = 0.95$, $\lambda'_{131} = 0.045$). (From Ref. [37].)

5. Contact interactions

With the new 1997 HERA data it has become somewhat more likely that the observed excess of events is due to some continuum mechanism. An appropriate and very general description is provided by contact interactions. Such residual interactions could originate from the exchange of a new heavy particle, or from lepton and quark substructure. For NC lepton-quark scattering, one may use the following effective

Lagrangean:

$$\mathcal{L}_{\text{eff}} = \sum_{\substack{i,k=L,R\\ q=u,d,\cdots}} \eta^q_{ik} \frac{4\pi}{(\Lambda^q_{ik})^2} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_k \gamma_\mu q_k) \ . \tag{11}$$

At $Q^2 \ll \Lambda^2$, the interference of contact terms with the standard model amplitudes leads to an enhancement or suppression of the NC cross section depending on the sign η_{ik}. The x and Q^2 dependence of the deviations is expected to be rather smooth. In Ref. [38] it was shown that e^+p scattering is particularly sensitive to LR and RL contact terms, while e^-p scattering is better for probing LL and RR helicity structures. Furthermore, it was pointed out that destructive interference can lead to a rather sharp onset of the deviations with Q^2. An explanation of the HERA data by contact terms is possible with Λ of the order of 3 TeV [39].

Source	Limit
Tevatron (CDF)[41]	$\Lambda > 2.5 \div 6.0$ TeV
HERA (H1)[42]	$\Lambda > 1.0 \div 2.5$ TeV
LEP2 (OPAL)[23]	$\Lambda > 1.1 \div 5.2$ TeV
atomic P-violation[43]	$\Lambda > 7.4 \div 12.3$ TeV
CCFR (for $\nu_\mu \nu_\mu qq$)[44]	$\Lambda > 1.8 \div 7.9$ TeV
CKM unitarity[27]	$\Lambda > 10 \div 90$ TeV

Table 3. Bounds on the scale of contact terms.

As is obvious from (11), contact interactions in $eq \to eq$ also modify the potential in atoms and affect the crossed channels $e^+e^- \to q\bar{q}$ and $q\bar{q} \to e^+e^-$. Therefore, the existence of contact terms is strongly constrained by atomic parity violation (APV) experiments, hadron production at LEP, and Drell-Yan production at the Tevatron. Moreover, $SU(2) \times U(1)$ symmetry implies the existence of contact interactions involving neutrinos. Typical bounds on Λ from the various sources are summarized in Tab. 3. The existing constraints on $eeqq$ contact terms still allow some excess of NC events as shown in Fig. 5, provided the APV bound is avoided by choosing an P-even combination of contact terms [39]. However, an analogous explanation of the possible excess of CC events by $e\nu qq'$ contact interactions is ruled out [27]. Finally, if this interpretation of the signal in NC e^+p scattering is correct, one should observe a

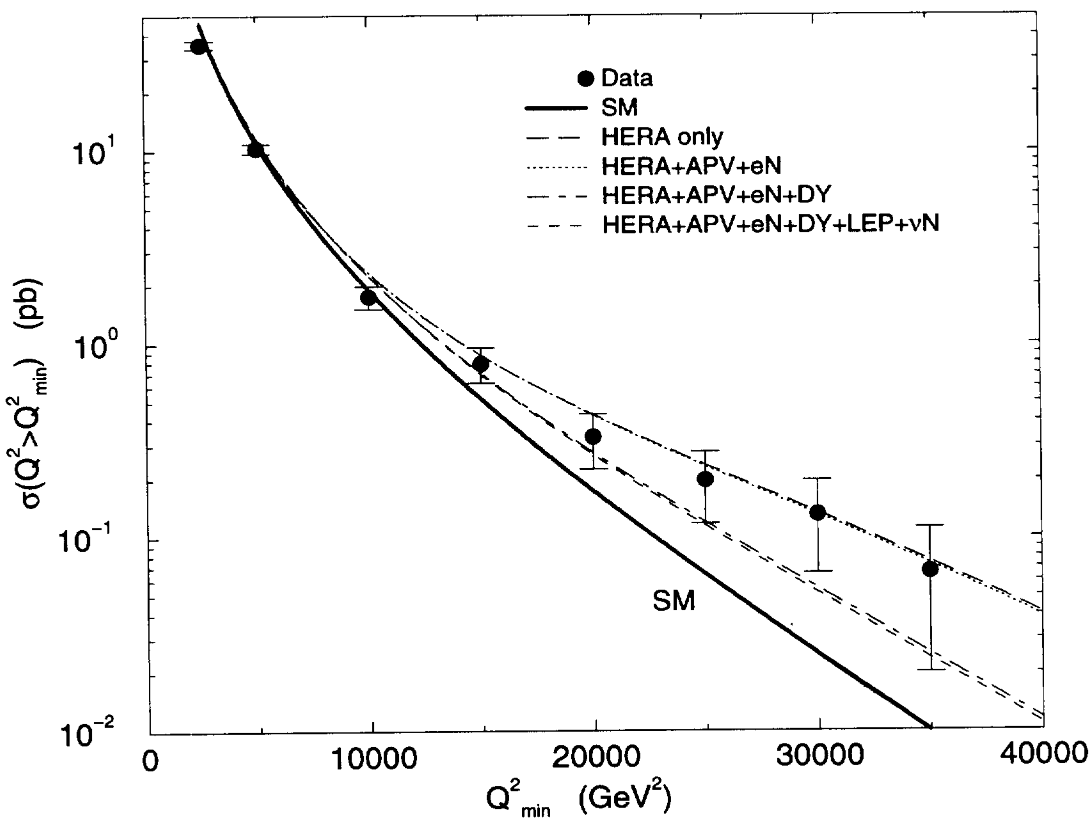

Fig. 5. Fits of contact interactions to the measured cross section $\sigma(Q^2 > Q^2_{min})$ for $e^+p \to e^+X$ including bounds from low-energy and collider experiments. (For details see Ref. [40].)

similar effect in e^-p scattering.

6. Conclusions

For the time being, it remains an open question whether or not the excess of high-Q^2 events observed at HERA is a statistical fluctuation or a physical effect. If it is a real signal, then it very likely originates from new physics beyond the standard model. Making this assumption, the present data slightly favour some continuum mechanism, but do not yet allow to rule out a resonance effect. Both kinds of interpretations are tightly constrained by measurements at LEP2 and the Tevatron, as well as by low-energy data. These bounds rule out the simplest leptoquark scenarios and do also not leave much room for the squark interpretation. Particularly difficult would be the explanation of anomalous CC events. At any rate, if the excess of high-Q^2 events is confirmed by future data, related signals should show up soon in other experiments.

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