THEORETICAL INTERPRETATIONS
OF THE HERA HIGH-\(Q^2\) EVENTS

R. RÜCKL

Institut für Theoretische Physik, Universität Würzburg
D-97074 Würzburg, Germany

and

H. SPIESBERGER

Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany

ABSTRACT

Theoretical interpretations of the high-\(Q^2\) events recently observed in deep-inelastic positron-proton scattering at HERA are reviewed. We discuss leptoquarks, squarks with \(R\)-parity violating couplings, and contact interactions. Bounds from and implications on other experiments are taken into consideration.

1. The Data

Both HERA experiments, H1 and ZEUS, have reported the observation of an excess of events in deep-inelastic positron-proton scattering at large values of Bjorken-\(x\) and momentum transfer \(Q^2\), relative to the expectation in the standard model. Including the new data presented recently at the 1997 Lepton-Photon Symposium, 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 \(\pm\) 1.2 and ZEUS about 15 events. At H1, the excess is concentrated in the rather narrow mass range \(187.5\) GeV \(\leq M = \sqrt{xs} \leq 212.5\) GeV where 8 events are observed with 1.53 \(\pm\) 0.29 expected. However, in the same region, ZEUS finds roughly the expected number of events. Conversely, in the region \(x > 0.55, y = Q^2/M^2 > 0.25\) where ZEUS finds 5 events with 1.51 \(\pm\) 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 and expect 17.7 \(\pm\) 4.3.

The clustering of the H1 events at a fixed value of \(M = \sqrt{xs}\) could indicate the

\(^{a}\)Talk presented by R. Rückl at the Ringberg Workshop New Trends in HERA Physics, May 25 – 30, 1997, Tegernsee, Germany.

\(^{a}\)For a detailed discussion of the 1994-96 data see, for example, Ref. }
production of a resonance with leptoquark 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. Rather, the excess may be a continuum effect reminiscent of contact interactions. Although the anomalous number of events is not large enough to clearly exclude statistical fluctuations as the origin of the effect, and because of the puzzling differences among the H1 and ZEUS data, it is important to investigate possible interpretations within and beyond the standard model.

Leaving aside very small uncertainties in electroweak parameters and radiative corrections, the main theoretical uncertainty on the high-$Q^2$ cross sections in the standard model come from the structure functions. 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 an uncertainty of about 7\% from this source. Attempts 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. Explanations based on a strong intrinsic charm component produced by some nonperturbative effect do not seem to be more successful. In fact, up to this day no standard model mechanism is known which could explain the observed surplus of events. Moreover, no sign of a deviation from the perturbative evolution of structure functions in QCD up to $Q^2 \simeq 10^4$ GeV$^2$ has so far been found in the data. Whatever mechanism is responsible for the HERA anomaly, it must have quite a rapid onset.

Therefore, if the excess is not a statistical fluctuation, it is very likely produced by some new physics beyond the standard model. Then the question arises 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 hypotheses put forward.

2. 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. In addition to their couplings to the standard model gauge bosons, they are usually assumed to have Yukawa-type couplings to lepton-quark pairs:

$$\lambda_i\phi_{LQ}\bar{l}_i q \quad \text{or} \quad \lambda_i\phi_{LQ}\bar{l}_i q^c,$$

and similarly for vector LQs. Here, $c$ denotes charge conjugation, and $i = L, R$ specifies the lepton handedness.
With the above couplings the resonance cross section in ep scattering is given by
\[ \sigma = N \frac{\pi}{4s} \lambda^2 q_f(M^2/s, \mu^2), \]  
where \( q_f(x, \mu^2) \) is the density of quarks (or antiquarks) with flavour \( f \) in the proton, and \( N = 1 \) (2) for scalars (vectors). The relevant scale \( \mu \) is expected to be of order \( M \). Obviously, leptoquarks with fermion number \( F = 0 \) (2) are dominantly produced from valence quarks in \( e^+ q (e^- q) \) fusion.

Having only couplings to standard model particles, leptoquarks decay exclusively to lepton-quark pairs. The partial width per channel is given by
\[ \Gamma = \frac{a}{16\pi} \lambda^2 M = 350 \text{ MeV} \frac{a}{e} \left( \frac{\lambda}{e} \right)^2 \left( \frac{M}{200 \text{ GeV}} \right), \]  
a 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 \( e = \sqrt{\frac{4\pi}{e}} \).

Leptoquarks appear in extensions of the standard model involving unification, technicolor, compositeness, or R-parity violating supersymmetry. In the generally adopted framework described in Ref. [8], the Yukawa couplings are taken to be dimensionless and \( SU(3) \times SU(2) \times U(1) \) symmetric. Moreover, they 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 the CKM mixing, and chiral in order to avoid the very strong bounds from leptonic pion decays. The allowed states can be classified according to spin, weak isospin and fermion number. They are summarized in Table 1.

The leptoquark masses and couplings are constrained by high-energy data. Direct searches for leptoquarks have been performed at the Tevatron, at HERA and at LEP. Recently, both experiments, CDF and D0, have improved their mass limits for scalar leptoquarks considerably. D0 excludes first generation leptoquarks with masses below 225 GeV assuming a branching ratio \( B_{eq} = 1 \) for decays into \( e^\pm \) and a jet \( [9] \), whereas CDF quotes a limit of 213 GeV \( [10] \) (all mass limits are at 95% CL). For branching ratios less than one, the limits are weaker, e.g., \( M > 176 \text{ GeV} \) for \( B_{eq} = 0.5 \) \( [9] \). The bounds on vector states are even stronger: 298 GeV for \( B_{eq} = 1 \) and 270 GeV for \( B_{eq} = 0.5 \) \( [11] \). The corresponding bounds on second and third generation scalar leptoquarks are \( M > 184 \text{ GeV} \) for \( B_{\mu q} = 1 \) and \( M > 98 \text{ GeV} \) for \( B_{\tau q} = 1 \), respectively \( [12] \). The above constraints follow from pair-production mainly by \( q\bar{q} \) annihilation, and are therefore practically independent of the unknown Yukawa coupling \( \lambda \). In contrast, the mass limits obtained at HERA depend on \( \lambda \) and the quantum numbers specified in Table 1. For \( \lambda = e \) they range from 207 to 272 GeV \( [13] \). These limits are lowered by about 50 GeV if \( \lambda = 0.1 \). Finally, the most stringent but again \( \lambda \)-dependent mass bound at LEP2 comes from the search for single-leptoquark production and excludes
| $LQ$ | $Q$ | Decay Mode | BR $e^\pm j$ | Coupling $\lambda_{L,R}$ | Limits Ref. | HERA estimates |
|------|-----|------------|-------------|----------------|------------|---------------|
| $S_0$ | $\bar{d}_R$ | $-1/3$ | $\nu_{Ld}$ $\nu_{Ld}$ $e_{Rd}$ | $1/2$ | $g_L$ | $g_L < 0.06$ | 0.40 |
|      |       |           |             | $-g_L$ | | | |
|      |       |           |             | $g_R$ | | | 0.28 |
| $\tilde{S}_0$ | $-4/3$ | $e_{Rd}$ | 1 | $g_R$ | $g_R < 0.1$ | 0.30 |
| $S_1$ | $+2/3$ | $\nu_{Lu}$ | 0 | $\sqrt{2}g_L$ | $g_L < 0.09$ | - |
|      | $-1/3$ | $\nu_{Ld}$ $\nu_{Ld}$ $e_{Lu}$ | $1/2$ | $-g_L$ | | | 0.40 |
|      | $-4/3$ | $e_{Ld}$ $e_{Ld}$ $e_{Lu}$ | 1 | $-\sqrt{2}g_L$ | | | 0.21 |
| $V_{1/2}$ | $-1/3$ | $\nu_{Ld}$ $\nu_{Ld}$ $e_{Lu}$ | 0 | $g_L$ | | | |
|      | $-4/3$ | $e_{Ld}$ $e_{Ld}$ $e_{Lu}$ | 1 | $g_L$ | $g_R < 0.05$ | 0.32 |
|      |       |           |             | $g_R$ | | | 0.32 |
| $\tilde{V}_{1/2}$ | $+2/3$ | $\nu_{Lu}$ | 0 | $g_L$ | $g_L < 0.09$ | - |
|      | $-1/3$ | $\nu_{Lu}$ $\nu_{Lu}$ $e_{Lu}$ | 1 | $g_L$ | | | 0.32 |
| $S_{1/2}$ | $-2/3$ | $\nu_{Lu}$ $\nu_{Lu}$ $e_{Lu}$ | 0 | $g_L$ | | | - |
|      | $-5/3$ | $e_{Lu}$ $e_{Lu}$ $e_{Lu}$ | 1 | $-g_R$ | | | 0.052 |
|      |       |           |             | $g_R$ | $g_R < 0.09$ | 0.026 |
|      |       |           |             | | | 0.026 |
| $\tilde{S}_{1/2}$ | $+1/3$ | $\nu_{Lu}$ | 0 | $g_L$ | | | - |
|      | $-2/3$ | $e_{Lu}$ $e_{Lu}$ $e_{Lu}$ | 1 | $g_L$ | | | 0.052 |
| $V_0$ | $-2/3$ | $\nu_{Lu}$ $\nu_{Lu}$ $e_{Lu}$ | $1/2$ | $g_L$ | | | 0.080 |
|      |       |           |             | $g_L$ | $g_R < 0.05$ | 0.056 |
| $\tilde{V}_0$ | $-5/3$ | $e_{Lu}$ $e_{Lu}$ $e_{Lu}$ | 1 | $g_R$ | | | 0.027 |
| $V_1$ | $+1/3$ | $\nu_{Lu}$ | 0 | $\sqrt{2}g_L$ | $g_L < 0.04$ | - |
|      | $-2/3$ | $\nu_{Lu}$ $\nu_{Lu}$ $e_{Lu}$ | $1/2$ | $-g_L$ | | | 0.080 |
|      | $-5/3$ | $e_{Lu}$ $e_{Lu}$ $e_{Lu}$ | 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 possible assignments of squarks with R-parity violating couplings.
masses below 131 GeV assuming $\lambda > e$. The mass limits from leptoquark pair production roughly reach half of the center-of-mass energy $\sqrt{s}$, and are thus much weaker than the Tevatron bounds.

Indirect bounds on Yukawa couplings and masses can be derived from t/u-channel LQ-exchange in $e^+e^- \rightarrow q\bar{q}$, and from low-energy data. From the very recent analysis by OPAL we infer upper limits on $\lambda$ between 0.2 and 0.7 assuming $M = 200$ GeV. However, 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.

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 $\lambda \approx e$ for $F = 2$ states and $\lambda \approx e/10$ for $F = 0$. The factor 10 difference in $\lambda$ simply reflects the factor 100 difference in the sea and valence quark densities in the region of $x$ and $Q^2$ where the signal resides. Similarly, the coupling of $F = 0$ leptoquarks to the $d$ quark has to be two times larger than the coupling to the $u$ quark in order to compensate 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, and shown in the last column of Table 1.

Whereas the coupling strength $\lambda$ required for $F = 0$ leptoquarks 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 into conflict with LEP2 data. Moreover, with such strong couplings, $F = 2$ leptoquarks should have shown up in $e^-p$ scattering at HERA, where they can be produced off the valence quark component, despite of the low luminosity of the previous $e^-p$ run. Since vector leptoquarks cannot be made responsible for an excess of events at $M \approx 200$ 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 Table 1 as a possible interpretation. However, also these solutions have difficulties. Firstly, the Tevatron mass limits require scalar leptoquarks of the first generation with $M \approx 200$ GeV to have branching ratios into $e + jet$ final states less than about 0.7, whereas in the simple framework considered in Table 1, $S_{1/2}$ and $\tilde{S}_{1/2}$ are expected to have $B_{eq} = 1$. Secondly, the scalar doublets cannot give rise to CC events.

Thus it seems that the leptoquark interpretation of the HERA high-$Q^2$ events points to more complicated and maybe more realistic scenarios. Several possibilities have been suggested allowing for $B_{eq} < 1$ and, at the same time, providing CC final states: $SU(2) \times U(1)$ violating, intergenerational couplings, leptoquark mixing, LQ models with additional vector-like fermions, and squarks with $R$-parity violating couplings.

\[b\]This follows from the D0 limits alone. An even smaller branching ratio is required by the combined D0 and CDF bounds.
3. Squarks

Supersymmetry with $R$-parity violation provides an attractive theoretical framework in which 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 $\tilde{q} \rightarrow e + \text{jet}$ to be smaller than unity. In addition, one can get CC-like final states, e.g., through the decay chain $\tilde{q} \rightarrow q\chi \rightarrow q\nu + \cdots$, $\chi$ being either a neutralino or chargino. Thus it appears possible to avoid the two main problems encountered in the simplest leptoquark models.

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:

$$W_R = \lambda'_{ijk} L^i_L Q^j_L \overline{D}^k_R.$$  \hspace{1cm} (4)

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.

| $ijk$ | $C$ | $n,m$ | source |
|------|-----|------|--------|
| 111  | 0.004 | $2, \frac{1}{2}$ | $\nu$-less $\beta\beta$ decay |
| 112  | 0.04  | 1,0 | CC universality |
| 113  | 0.07  | 1,0 | atomic $P$-violation |
| 121  | 0.09  | $1, \frac{1}{2}$ | $\nu_e$ mass |
| 122  | 0.08  | $1, \frac{1}{2}$ | $F-B$ asymmetry |
| 133  | 0.52  | $1, 0$ | $D-\overline{D}$ mixing$^*$ |
| 132  | 0.68  | 1,0 | $R_e (Z_0)$ |

Table 2: Low-energy constraints on $R$-parity violating couplings $\lambda'_{ijk} < C (M_{\tilde{g}}/200 \text{ GeV})^n (m_{\tilde{q}}/1 \text{ TeV})^m$ relevant for $e^+p$ scattering. The limit on $\lambda'_{123}$ from $D-\overline{D}$ mixing, marked by $^*$, involves quark mixing and is thus model-dependent.
Figure 1: Cross section for $e^+d_k \rightarrow \tilde{u}_j \rightarrow e^+d_k$ as a function of the coupling $\lambda'_{1jk}$ 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 $\sigma_{exp} = (0.17 \pm 0.07)$ pb from 1994 - 96 HERA data for $Q^2 > 20,000$ GeV$^2$ (from Ref. 27).

Expanding the superfields in (4) in terms of matter fields, one finds interaction terms which allow for resonance production of squarks at HERA 26:

\begin{align}
  e^+ d_R^k &\rightarrow \tilde{u}_L^j \quad (\tilde{u}^j = \tilde{u}, \tilde{c}, \tilde{t}), \\
  e^+ \bar{u}_L^j &\rightarrow \bar{d}_R^k \quad (\bar{d}^k = \bar{d}, \bar{s}, \bar{b}).
\end{align}

The cross sections are determined by the coupling constants $\lambda'_{1jk}$. Similarly as the leptoquark Yukawa couplings $\lambda_{L,R}$ from Table 1 these couplings are strongly constrained by existing data. The relevant bounds are summarized in Table 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 (6) involving the $\bar{u}$ sea is unlikely. Moreover, the coupling strength $\lambda_{11k} \simeq e$, required for production off sea quarks, is incompatible
Figure 2: Contours of $B(\bar{t} \to e^+ d)$ 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. 31.)
with the existing bounds. This also applies to the $e^+\bar{c}$ channel with the marginal exception of the subprocess $e^+\bar{c} \rightarrow \tilde{t}^\pm$ [27]. The top sea plays no role. Turning to the processes of class (5), one finds three possible explanations of the HERA anomaly [25],

\begin{align*}
e^+d &\rightarrow \tilde{c} \, (\lambda'_{121}), \\
e^+d &\rightarrow \tilde{t} \, (\lambda'_{131}), \\
e^+s &\rightarrow \tilde{t} \, (\lambda'_{132}).
\end{align*}

The corresponding cross sections are plotted in Fig. [1] for $M_{\tilde{q}} = 200$ to 220 GeV, and setting $B_{eq} = 1$. As can be seen, within the limits on $\lambda'$ quoted in Tab. [2] one can still afford branching ratios for $\tilde{c}, \tilde{t} \rightarrow e^+d$ below 0.7, necessary in order to avoid the D0/CDF mass bounds. Studies [28, 31] 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. [2] for $B(\tilde{t} \rightarrow e^+d)$. However, there is not too big a room for a consistent squark interpretation of the HERA anomaly.

![Figure 3: Distributions in $M = \sqrt{s}$ 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. [2].](image)

Note that the NC events from $\tilde{t}, \tilde{c} \rightarrow e^+d$ have the same visible particles as the [For a discussion of the strange stop scenario see in particular Ref. [2].]
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.

Finally, the difficulty to interpret the excess of events as a single-resonance effect may also find a reasonable solution. In the MSSM each fermion has two superpartners 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. 3. The resulting mass distribution can apparently mimic a continuum effect.

4. 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. They 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:

$$\mathcal{L}_{\text{eff}} = \sum_{i, k = L, R} \eta_{ik}^q \frac{4\pi}{(\Lambda^q_{ik})^2} (\bar{e}_i \gamma^\mu e_i) (\bar{q}_k \gamma_\mu q_k).$$  \hspace{1cm} (10)

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 $\eta_{ik}^q$. The $x$ and $Q^2$ dependence of the deviations is expected to be rather smooth. In Ref. \[it\] 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 leads to a rather sharp onset of the deviations with $Q^2$. An explanation of the HERA data by contact terms is possible with $\Lambda$ of the order of 3 TeV \[it\].

As is obvious from (10), contact interactions in $eq \rightarrow eq$ also modify the potential in atoms and affect the crossed channels $e^+e^- \rightarrow q\bar{q}$ and $q\bar{q} \rightarrow e^+e^-$. 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 $\Lambda$ from the various sources are summarized in Table 3. The existing constraints on $eeqq$ contact terms still allow a reasonable fit to the excess of NC events as shown in Fig. 4, provided the APV bound is avoided by choosing an $P$-even combination of contact terms \[it\]. However, an analogous explanation of the possible excess of CC events by $evqq'$ contact interactions is ruled out \[it\]. Finally, if this interpretation of the signal in NC $e^+p$ scattering is correct, one should
Table 3: Bounds on the scale of contact terms.

| Source                              | Limit              |
|-------------------------------------|--------------------|
| Tevatron (CDF)                      | $\Lambda > 2.5 \div 6.0$ TeV |
| HERA (H1)                           | $\Lambda > 1.0 \div 2.5$ TeV |
| LEP2 (OPAL)                         | $\Lambda > 1.1 \div 5.2$ TeV |
| atomic $P$-violation                | $\Lambda > 7.4 \div 12.3$ TeV |
| CCFR (for $\nu_{\mu}\nu_{\mu}qq$)  | $\Lambda > 1.8 \div 7.9$ TeV |
| CKM unitarity                       | $\Lambda > 10 \div 90$ TeV  |

Figure 4: Fits of contact interactions to the measured cross section $\sigma(Q^2 > Q^2_{\text{min}})$ for $e^+p \rightarrow e^+X$ including bounds from low-energy and collider experiments (for details see Ref. 38).
observe a similar effect in $e^-p$ scattering.

5. Conclusions

For the time being, it is 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 an excess of CC events. At any rate, if the excess of high-$Q^2$ events is confirmed by future data it is likely that related signals will soon show up in other experiments.

6. Acknowledgments

We wish to thank J. Kalinowski and P. Zerwas for the fruitful collaboration on the subject of this talk, and T. Kon for providing us with an updated version of Fig. 3. This work was supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, Bonn, Germany, Contracts 05 7BI92P (9) and 05 7HZ91P (0). R. R. wants to thank B. Kniehl and G. Kramer for their kind invitation to and hospitality at the workshop.

7. References

1. C. Adloff et al., H1 Collaboration, Z. Phys. C74 (1997) 191.
2. J. Breitweg et al., ZEUS Collaboration, Z. Phys. C74 (1997) 207.
3. B. Straub, Talk presented at the XVIII International Symposium on Lepton Photon Interactions, July 28 – August 1, 1997, Hamburg.
4. Y. Sirois, these proceedings.
5. U. Bassler and G. Bernardi, DESY 97-136 [hep-ex/9707024].
6. S. Kuhlmann, H. L. Lai and W. K. Tung, [hep-ph/9704338]. K. S. Babu, C. Kohls, J. March-Russell and F. Wilczek, [hep-ph/9705393].
7. J. F. Gunion and R. Vogt, [hep-ph/9706252]. W. Melnitchouk and A. W. Thomas, [hep-ph/9707387].
8. W. Buchmüller, R. Rückl and D. Wyler, Phys. Lett. B191 (1987) 442.
9. B. Abbott et al., D0 Collaboration, FERMILAB-PUB-97/252-E [hep-ex/9707033].
10. F. Abe et al., CDF Collaboration, FERMILAB-PUB-97/280-E.
11. J. A. Valls, FERMILAB-CONF-97/135-E, XXXII Rencontres de Moriond, QCD and Hadronic Interactions, Les Arcs, France, 1997.
12. F. Abe et al., CDF Collaboration, Phys. Rev. Lett. 78 (1997) 2906, Phys. Rev. Lett. 75 (1995) 1012; B. Abbott et al., D0 Collaboration, paper 109 submitted to the International Europhysics Conference on High Energy Physics, Jerusalem, 1997.
13. S. Aid et al., H1 Collaboration, Phys. Lett. B369 (1996) 173; M. Derrick et al., ZEUS Collaboration, Phys. Lett. B306 (1993) 173, Z. Phys. C73 (1997) 613.
14. OPAL Collaboration, paper LP138 submitted to the XVIII International Symposium on Lepton-Photon Interactions, Hamburg, 1997.
15. B. Adeva et al., L3 Collaboration, Phys. Lett. B261 (1991) 169; G. Alexander et al., OPAL Collaboration, Phys. Lett. B263 (1991) 123; P. Abreu et al., DELPHI Collaboration, Phys. Lett. B316 (1993) 620.
16. K. Ackermans et al., OPAL Collaboration, CERN-PPE/97-101.
17. M. Leurer, Phys. Rev. D49 (1994) 333; ibid. D50 (1994) 536; S. Davidson, D. Bailey and B. Campbell, Z. Phys. C61 (1994) 613.
18. J. Kalinowski, R. Rückl, H. Spiesberger and P. M. Zerwas, Z. Phys. C74 (1997) 595.
19. G. Altarelli et al., hep-ph/9703276; J. Blümlein, Z. Phys. C74 (1997) 605; J. Kalinowski, R. Rückl, H. Spiesberger and P. M. Zerwas, Z. Phys. C74 (1997) 595; K. S. Babu, C. Kolda, J. March-Russel and F. Wilczek, Phys. Lett. B402 (1997) 367; J. L. Hewett and T. G. Rizzo, hep-ph/9703337; Z. Kunszt and W. J. Stirling, Z. Phys. C75 (1997) 453.
20. S. Aid et al., H1 Collaboration, Phys. Lett. B369 (1996) 173.
21. Z. Kunszt and W. J. Stirling, Z. Phys. C75 (1997) 453.
22. G. Altarelli, G. F. Giudice and M. L. Mangano, hep-ph/9705287.
23. K. S. Babu, C. Kolda and J. March-Russel, hep-ph/9705414.
24. J. L. Hewett and T. G. Rizzo, hep-ph/9708419.
25. D. Choudhury and S. Raychaudhuri, Phys. Lett. B401 (1997) 54; G. Altarelli et al., hep-ph/9703276; H. Dreiner and P. Morawitz, hep-ph/9703279; J. Kalinowski, R. Rückl, H. Spiesberger and P. M. Zerwas, Z. Phys. C74 (1997) 595; T. Kon and T. Kobayashi, hep-ph/9704221; J. Ellis, S. Lola and K. Sridhar, hep-ph/9705416; T. Kon, T. Matsushita and T. Kobayashi, hep-ph/9707353; M. Carena et al., hep-ph/9707458.
26. J. L. Hewett, Proceedings, 1990 Summer Study on High Energy Physics – Research Directions for the Decade (Snowmass 1990), ed. E. Berger (World Scientific, 1992); T. Kon, K. Nakamura and T. Kobayashi, Z. Phys. C45 (1990) 567, Acta Phys. Polon. B21 (1990) 315; J. Butterworth and H. Dreiner, Nucl. Phys. B397 (1993) 3; H. Dreiner, E. Perez and Y. Sirois, hep-ph/9703444.
27. H. Dreiner and P. Morawitz, hep-ph/9703279.
28. J. Ellis, S. Lola and K. Sridhar, hep-ph/9705416.
29. H. Dreiner, hep-ph/9707435, and references therein.
30. D. Choudhury and S. Raychaudhuri, Phys. Lett. B401 (1997) 54.
31. G. Altarelli et al., hep-ph/9703276.
32. T. Kon and T. Kobayashi, hep-ph/9704221 (to appear in Phys. Lett. B).
33. R. Rückl, Phys. Lett. B129 (1983) 363, Nucl. Phys. B234 (1984) 91; P. Haberl, F. Schrempp and H.-U. Martyn, in the Proceedings, Physics at HERA (Hamburg, 1991), eds. W. Buchmüller and G. Ingelman.
34. K. S. Babu, C. Kolda, J. March-Russell and F. Wilczek, Phys. Lett. B402 (1997) 367; V. Barger et al., Phys. Lett. B404 (1997) 147, hep-ph/9707412; N. Di Bartolomeo and M. Fabbrichesi, Phys. Lett. B406 (1997) 237; N. G. Deshpande, B. Dutta and X.-G. He, hep-ph/9705236; F. Cornet and J. Rico, hep-ph/9707299.
35. V. Barger et al., hep-ph/9707412.
36. X. Wu, Talk presented at the International Europhysics Conference on High Energy Physics, August 19 – 26, 1997, Jerusalem.
37. S. Aid et al., H1 Collaboration, Phys. Lett. B353 (1995) 578.
38. A. Deandrea, hep-ph/9705435.
39. E. Gallas, Talk presented at the International Europhysics Conference on High Energy Physics, August 19 – 26, 1997, Jerusalem.