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LEPTOQUARKS AND THE HERA HIGH- Q^2 EVENTS*

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ABSTRACT

The excess of high- Q^2 events recently observed in deep-inelastic positron-proton scattering at HERA has refuelled speculations on physics beyond the standard model, in particular on low-mass leptoquark-type particles. We review the theoretical framework for leptoquark interactions, and their production and decay at HERA. Bounds on leptoquark masses and couplings, and implications on other experiments are also discussed.

1. The data

Both HERA experiments, H1¹ and ZEUS², 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. The e^+p center-of-mass energy has been $\sqrt{s} = 300$ GeV. Including the new data presented recently at the 1997 Lepton-Photon Symposium³ † H1 and ZEUS each observe 18 neutral current (NC) events at $Q^2 > 1.5 \cdot 10^4$ GeV², while H1 expects 8.0 ± 1.2 and ZEUS about 15 events. At H1, the excess is concentrated in the rather narrow mass range $187.5 \text{ GeV} \leq M = \sqrt{xs} \leq 212.5 \text{ GeV}$ 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 $x > 0.55$, $y = Q^2/M^2 > 0.25$ 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

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†For a detailed discussion of the 1994-96 data see, for example, Ref. ⁴.

statistical significance. At $Q^2 > 10^4 \text{ GeV}^2$, H1 and ZEUS together find 28 events and expect 17.7 ± 4.3 .

The clustering of the H1 events at a fixed value of $M = \sqrt{xs}$ suggests the production of a resonance with leptoquark quantum numbers and mass $M \simeq 200 \text{ GeV}$. On the other hand, ZEUS has 4 events clustered at a somewhat higher mass $M \simeq 225 \text{ GeV}$. 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}. Rather, the excess may be a continuum effect resulting from contact interactions. Although the anomalous number of events is not large enough to clearly exclude statistical fluctuations as their origin, and the differences among the H1 and ZEUS data are somewhat puzzling, it is important to investigate possible interpretations within and beyond the standard model.

2. Standard model and new physics

Leaving aside the very small uncertainties in electroweak parameters and radiative corrections^{1,2}, the main theoretical uncertainty on the high- Q^2 cross sections in the standard model comes from 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 this uncertainty to be about 7%^{1,2}. Attempts⁶ 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 component⁷ generated by some non-perturbative mechanism do not seem to be more successful. In fact, up to this day no standard model effect is known which could explain the observed surplus of events. Moreover, so far no hint of a deviation from the perturbative evolution of structure functions in QCD up to $Q^2 \simeq 10^4 \text{ GeV}^2$ has been found in the data. 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. This immediately raises the question whether one is dealing with a (not necessarily single) resonance or with a continuum effect. Clearly, the most exciting speculation is the existence 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 the following short overview, we focus on the leptoquark hypothesis[‡]. Alternative interpretations of the HERA anomaly have been discussed by other speakers at this Workshop. In particular, we refer to the contribution to

[‡]See also the discussion by T. Rizzo in these proceedings, Ref. ⁸.

these proceedings by H. Dreiner on squarks with R -parity violating couplings⁹. The case of contact interactions is considered, for example, in Ref.¹⁰.

3. Phenomenological framework

Leptoquarks appear in extensions of the standard model involving unification, technicolor, compositeness, or R -parity violating supersymmetry. In addition to their couplings to the standard model gauge bosons[§], leptoquarks have Yukawa-type couplings to lepton-quark pairs. In the generally adopted framework described in Ref.¹², 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 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.¹³ 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 Yukawa couplings generically called $\lambda_{L,R}$. The indices L, R refer to the chirality of the lepton. 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, 0.5, or 0.

The Yukawa couplings of the leptoquark states summarized in Tab. 1 are given by the effective Lagrangeans¹²

$$\begin{aligned} \mathcal{L}_{\text{eff}}^S &= (g_L \bar{q}_L^c i\tau_2 l_L + g_R \bar{u}_R^c e_R) S_0 + g_R \bar{d}_R^c e_R \tilde{S}_0 + g_L \bar{q}_L^c i\tau_2 \vec{l}_L \vec{S}_1 \\ &+ (g_L \bar{u}_R l_L + g_R \bar{q}_L i\tau_2 e_R) S_{1/2} + g_L \bar{d}_R l_L \tilde{S}_{1/2} , \end{aligned} \quad (1)$$

$$\begin{aligned} \mathcal{L}_{\text{eff}}^V &= (g_L \bar{d}_R^c \gamma_\mu e_L + g_R \bar{q}_L^c \gamma_\mu e_R) V_{1/2}^\mu + g_L \bar{u}_R^c \gamma_\mu l_L \tilde{V}_{1/2}^\mu \\ &+ (g_L \bar{q}_L \gamma_\mu l_L + g_R \bar{d}_R \gamma_\mu e_R) V_0^\mu + g_R \bar{u}_R \gamma_\mu e_R \tilde{V}_0^\mu \\ &+ g_L \bar{q}_L \vec{\tau} \gamma_\mu l_L \vec{V}_1^\mu . \end{aligned} \quad (2)$$

Here, c denotes charge conjugation, q_L and l_L are the left-handed quark and lepton

[§]The explicit form can be found, e.g., in Ref.¹¹.

LQ	Q	Decay Mode	BR $e^\pm j$	Coupling $\lambda_{L,R}$	Limits Ref. ¹⁴	HERA estimates
S_0	$-1/3$	$e_L u$	$\frac{1}{2}$	g_L	$g_L < 0.06$	0.40
		$\nu_L d$		$-g_L$		
		$e_R u$	1	g_R		
\tilde{S}_0	$-4/3$	$e_R d$	1	g_R	$g_R < 0.1$	0.30
	$+2/3$	$\nu_L u$	0	$\sqrt{2}g_L$		—
S_1	$-1/3$	$\nu_L d$	$\frac{1}{2}$	$-g_L$	$g_L < 0.09$	0.40
		$e_L u$		$-g_L$		
	$-4/3$	$e_L d$	1	$-\sqrt{2}g_L$		
$V_{1/2}$	$-1/3$	$\nu_L d$	0	g_L	$g_L < 0.09$	—
		$e_R u$	1	g_R		0.30
	$-4/3$	$e_L d$	1	g_L		$g_R < 0.05$
	$e_R d$		g_R	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
$S_{1/2}$	$-2/3$	$\nu_L \bar{u}$	0	g_L	$g_L < 0.1$	—
		$e_R \bar{d}$	1	$-g_R$		0.052
	$-5/3$	$e_L \bar{u}$	1	g_L		$g_R < 0.09$
	$e_R \bar{u}$		g_R	0.026		
$\tilde{S}_{1/2}$	$+1/3$	$\nu_L \bar{d}$	0	g_L	$g_L < 0.1$	—
	$-2/3$	$e_L \bar{d}$	1	g_L		0.052
V_0	$-2/3$	$e_L \bar{d}$	$\frac{1}{2}$	g_L	$g_L < 0.05$	0.080
		$\nu_L \bar{u}$		g_L		
		$e_R \bar{d}$	1	g_R		
\tilde{V}_0	$-5/3$	$e_R \bar{u}$	1	g_R	$g_R < 0.09$	0.027
	$+1/3$	$\nu_L \bar{d}$	0	$\sqrt{2}g_L$		—
V_1	$-2/3$	$\nu_L \bar{u}$	$\frac{1}{2}$	g_L	$g_L < 0.04$	0.080
		$e_L \bar{d}$		$-g_L$		
	$-5/3$	$e_L \bar{u}$	1	$\sqrt{2}g_L$		

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 ¹⁵. Inclusion of the 1997 data decrease the couplings by about 15%. Using the H1 data alone would roughly give the couplings shown above.

weak isospin doublets, and u_R , d_R and e_R the right-handed singlets.

4. Production and decay

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

$$\sigma = N_\sigma \frac{\pi}{4s} \lambda_{L,R}^2 q_f(M^2/s, \mu^2) , \quad (3)$$

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 of the leptoquark mass M . The coupling constant $\lambda_{L,R}$ 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.

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

$$\Gamma = \frac{N_\Gamma}{16\pi} \lambda_{L,R}^2 M = 350 \text{ MeV } N_\Gamma \left(\frac{\lambda}{e}\right)^2 \left(\frac{M}{200 \text{ GeV}}\right) , \quad (4)$$

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 data.

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 $\lambda_{L,R} \simeq e$ for $F = 2$ states and $\lambda_{L,R} \simeq e/10$ 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 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^{15,16}, and shown in the last column of Tab. 1.

Figure 1 (taken from Ref.¹⁷) 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

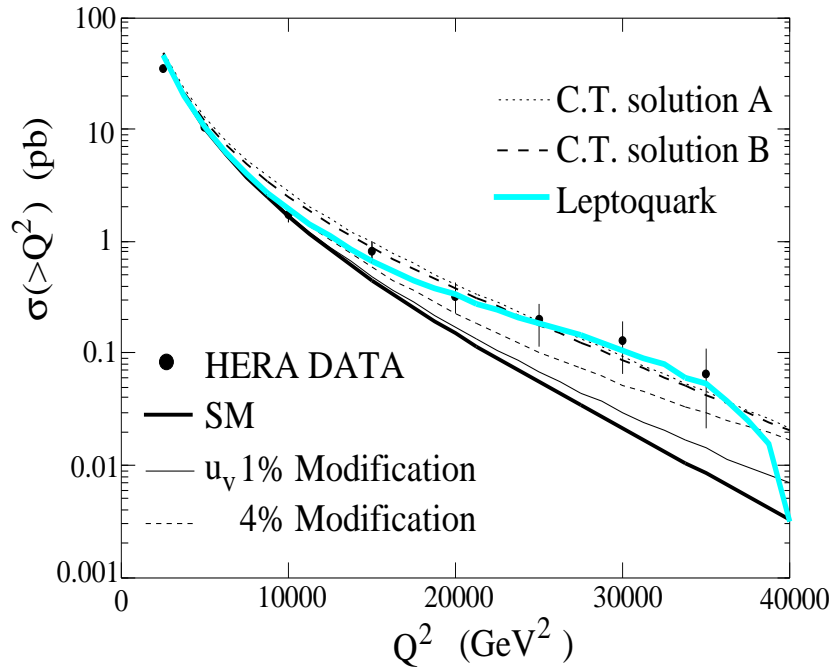


Figure 1: Cross section integrated above a given minimum Q^2 in the standard model and in the presence of the $S_{1/2}^L$ leptoquark with $M = 200$ GeV and $\lambda_L = 0.025$ compared with the 1994 - 96 data. Also shown are effects due to an enhancement of the valence quark density and due to contact interactions. (From ¹⁷.)

λ_L is taken to be 0.025 in conformity with the estimate given in Tab. 1. As one can see, the leptoquark hypothesis has provided quite a satisfactory interpretation of the data from the 1994 - 96 runs.

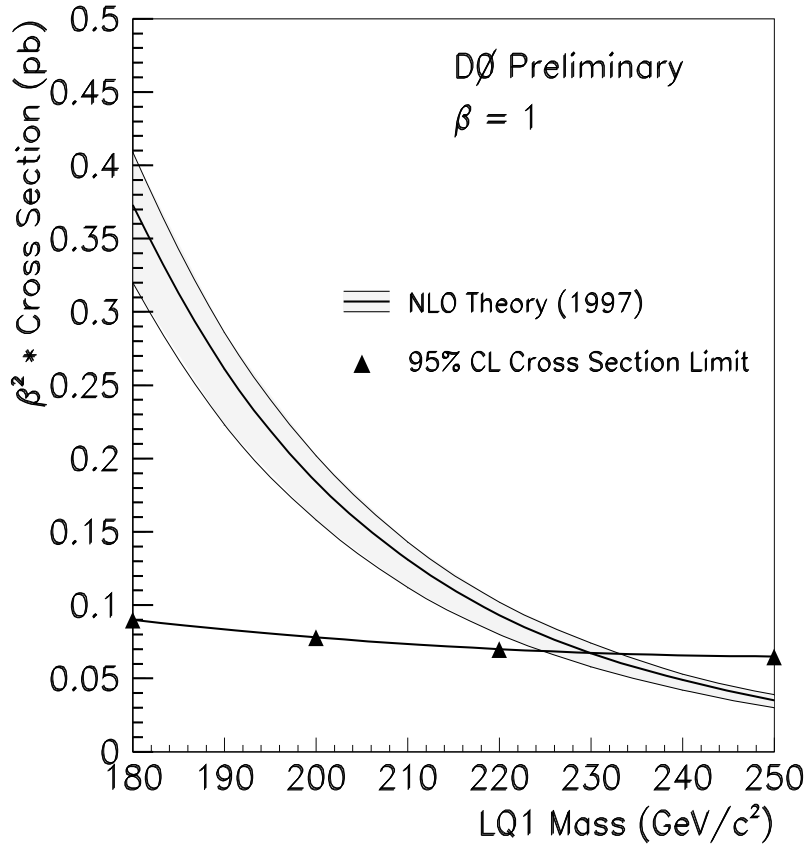


Figure 2: The D0 95 % CL limit on the production cross section times branching ratio into the $eejj$ channel ($\beta = B_{eq}$) for first generation leptoquarks. The band shows the NLO theoretical prediction ²⁰. (From ¹⁹.)

5. Bounds

The leptoquark masses and couplings are constrained by a number of low- and high-energy experiments. Direct searches for leptoquarks have been performed at the Tevatron, at HERA and at LEP. Recently, ¶ both collaborations 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 ¹⁹, whereas CDF quotes a limit of 213 GeV ²¹ (all

¶See also the discussions by S. Eno and J. Conway in these proceedings, Ref. ¹⁸.

mass limits are at 95 % CL). For branching ratios less than one, the limits are weaker, e.g., $M > 176$ GeV for $B_{eq} = 0.5$ ¹⁹. Figure 2 shows the D0 limit on the production cross section times the branching ratio β^2 for the search channel $eejj$, β being the branching fraction B_{eq} . Even stronger bounds hold for vector leptoquarks: 298 GeV for $B_{eq} = 1$ and 270 GeV for $B_{eq} = 0.5$ ²². 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 ²³. 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 bounds obtained at HERA ^{24,25} 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 pb^{-1}) and e^+p (2.8 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. Figure 3 shows the detailed H1 bounds in the (λ, M) -plane for all leptoquark species listed in Tab. 1. Heavy leptoquarks generate effective contact interactions ²⁶ and can therefore be probed by a general contact term analysis. The outcome of such a test is presented in Ref. ²⁷.

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 $\lambda \geq e$ ²⁸. The upper limits on leptoquark masses from pair production ²⁹, 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 in $e^+e^- \rightarrow q\bar{q}$ are approaching an interesting sensitivity. From the very recent analysis by OPAL ³⁰ for $\sqrt{s} = 130$ to 172 GeV we infer upper limits on λ between 0.2 and 0.7 assuming $M = 200$ GeV. We come back to this interesting search for virtual effects in section 7. 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. These rules may also be cast into the standard form of the effective Lagrangian ³¹

$$\begin{aligned} \mathcal{L}_{\text{eff}} &= \sum_{i,k=L,R} \frac{g_i^2}{M^2} \alpha_{ik}^q (\bar{e}_i \gamma^\mu e_i) (\bar{q}_k \gamma_\mu q_k) \\ &:= \sum_{i,k=L,R} \eta_{ik} \frac{4\pi}{\Lambda_{ik}^2} (\bar{e}_i \gamma^\mu e_i) (\bar{q}_k \gamma_\mu q_k) . \end{aligned} \quad (5)$$

The coefficients α_{ik}^q for $u\bar{u}$ and $d\bar{d}$ final states are listed in Tab. 2 ¹⁵. Denoting the signs of α_{ik}^q by η_{ik} , the scales Λ_{ik} of the contact interactions are related to the individual masses and couplings of the leptoquarks by $\Lambda_{ik}^2 = 4\pi M^2 / g_i^2 |\alpha_{ik}^q|$.

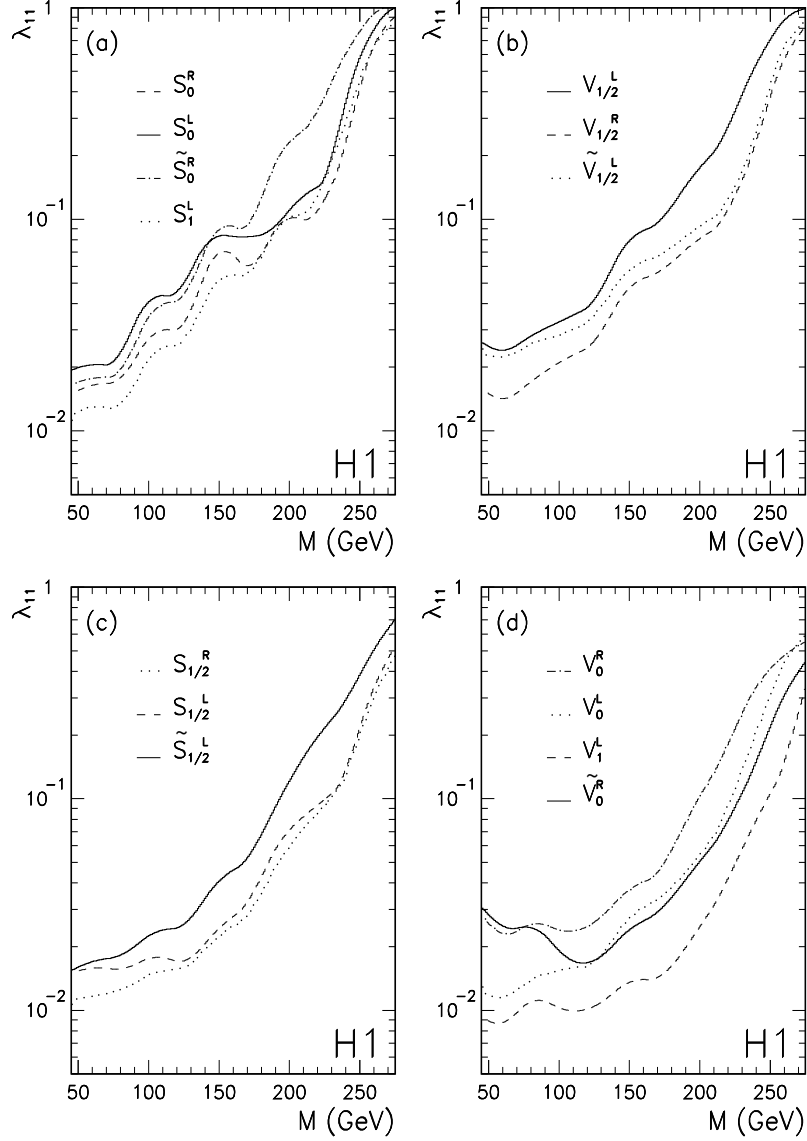


Figure 3: H1 upper limits at 95% CL from e^-p and e^+p combined for scalar and vector leptoquarks with fermion number 2 (a,b) and 0 (c, d). The upper indices L, R refer to the models $\lambda = \lambda_L, \lambda_R = 0$ and $\lambda = \lambda_R, \lambda_L = 0$, respectively. The limits on λ_L for S_0, S_1, V_0 and V_1 result from $e + X$ and $\nu + X$ final states. (From ²⁴.)

α_{ik}^q	$u\bar{u}$ final state				$d\bar{d}$ final state			
	RR	LL	RL	LR	RR	LL	RL	LR
S_0	$\frac{1}{2}$	$\frac{1}{2}$						
\tilde{S}_0					$\frac{1}{2}$			
S_1		$\frac{1}{2}$				1		
$V_{1/2}$			1				1	1
$\tilde{V}_{1/2}$				1				
$S_{1/2}$			$-\frac{1}{2}$	$-\frac{1}{2}$			$-\frac{1}{2}$	
$\tilde{S}_{1/2}$								$-\frac{1}{2}$
V_0					-1	-1		
\tilde{V}_0	-1							
V_1		-2				-1		

Table 2: The coefficients α_{ik}^q in the Lagrangian Eq. 5 for contact interactions generated by heavy leptoquark exchange, and in the corresponding helicity amplitudes Eqs. 10 and 11 ¹⁵.

Finally, indirect bounds on Yukawa couplings and masses can also be derived from low-energy data ¹⁴. 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 ¹⁵.

6. Difficulties and remedies

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 ^{24,25}, despite of the low luminosity of the previous e^-p run. The point is that in e^-p the $F = 2$ states can be produced off the valence quark component of the proton. As can be seen from Figs. 3a and b, the existing HERA bounds indeed rule out an interpretation of the high- Q^2 anomaly in terms of $F = 2$ leptoquarks with $M \simeq 200$ GeV.

Furthermore, since vector leptoquarks cannot be 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, also these solutions have 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, 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 excluded. 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 quite 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. The task is clear: find a model which predicts a sufficiently small branching fraction for $S \rightarrow eq$, to wit $B_{eq} < 0.5$, a sufficiently large branching into $S \rightarrow \nu q$, and a broad mass bump rather than a narrow resonance signature. Several possibilities have been suggested: $SU(2) \times U(1)$ violating, intergenerational couplings^{32,33} and leptoquark mixing³⁴, LQ models with additional vector-like fermions^{35,8}, and squarks with R -parity violating couplings^{36,9}.

The latter proposition is clearly the most interesting one, since it can be realized in a supersymmetric extension of the standard model which is welcome for many other reasons. In the minimal supersymmetric standard model, one can have a renormalizable, gauge invariant operator in the superpotential that violates R -parity conservation and couples squarks to quarks and leptons. In such models, squarks act as leptoquarks. More precisely, direct couplings to lepton-quark pairs exist for the singlets \tilde{d}_R^n and the doublets $(\tilde{d}_L^n, \tilde{u}_L^n)$, n being the generation index. 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, much of what has been said about leptoquark production and virtual exchange can be carried over to the squark scenario. In particular, squarks can be resonance-produced at HERA^{36,37}:

$$e^+ d_R^m \rightarrow \tilde{u}_L^m \quad (\tilde{u}^m = \tilde{u}, \tilde{c}, \tilde{t}), \quad (6)$$

$$e^+ \tilde{u}_L^m \rightarrow \tilde{d}_R^m \quad (\tilde{d}^m = \tilde{d}, \tilde{s}, \tilde{b}). \quad (7)$$

However, because of the usual R -parity conserving interactions one naturally expects the branching ratio for $\tilde{q} \rightarrow e + jet$ to be smaller than unity. In addition, one can get CC-like final states, e.g., through the decay chain $\tilde{q} \rightarrow q\chi \rightarrow q\nu + \dots$, χ being either a neutralino or chargino. Thus it appears possible to avoid two of the main problems encountered in the generic leptoquark models. Taking into account the relevant experimental constraints on masses and Yukawa couplings³⁸, one finds three allowed channels:

$$e^+ d_R \rightarrow \tilde{c}_L, \quad e^+ d_R \rightarrow \tilde{t}_L, \quad e^+ s_R \rightarrow \tilde{t}_L. \quad (8)$$

^{||}This value follows from the D0 limit¹⁹ alone. An even smaller branching ratio is required by the combined D0 and CDF bounds.

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. In this way the difficulty to interpret the excess of events as a single-resonance effect may also find a reasonable solution³⁹. For a detailed review of the squark interpretation of the HERA high- Q^2 events we refer to the contribution by H. Dreiner⁹.

7. Related predictions

Leptoquarks (squarks) which couple in the s -channel in $eq \rightarrow eq$ contribute via t/u -channel exchange to the crossed reactions $e^+e^- \rightarrow q\bar{q}$ ¹⁵ and $q\bar{q} \rightarrow e^+e^-$ ⁴⁰. Therefore, the leptoquark (squark) hypothesis can in principle be tested at LEP2 and at the Tevatron probing the same Yukawa couplings as at HERA. Effects on Drell-Yan production in hadronic collisions have been studied in Ref.⁴⁰ with emphasis on the experimental prospects at the LHC.

The angular distribution and integrated cross section for hadron production in e^+e^- annihilation in the presence of any of the leptoquarks of Tab. 1 can be found in Ref.¹⁵. Here, we give the results under the assumption that only a single state contributes:

$$\frac{d\sigma}{d\cos\theta}(e^+e^- \rightarrow q\bar{q}) = \frac{3}{32\pi s} \left\{ (|f_{RR}|^2 + |f_{LL}|^2) u^2 + (|f_{RL}|^2 + |f_{LR}|^2) t^2 \right\}, \quad (9)$$

where

$$f_{ik} = \frac{Q_{ik}^{eq}}{s} - \frac{g_i^2 \alpha_{ik}^q}{t - M^2} \quad (10)$$

for $F = 0$ leptoquarks (or the squark doublets $(\tilde{d}_L^n, \tilde{u}_L^n)$), and

$$f_{ik} = \frac{Q_{ik}^{eq}}{s} - \frac{g_i^2 \alpha_{ik}^q}{u - M^2} \quad (11)$$

for $F = 2$ leptoquarks (or the squark singlets \tilde{d}_R^n). The indices $i, k = R, L$ refer to the handedness of the electron and quark in the process $e_i^- e^+ \rightarrow q_k \bar{q}$. The generalized charges in the standard γ, Z exchange amplitudes have been abbreviated by Q_{ik}^{eq} where

$$Q_{ik}^{eq} = e^2 Q_e Q_q + \frac{g_i^e g_k^q}{1 - m_Z^2/s} \quad (12)$$

with the left/right Z charges of the fermions defined as

$$g_L^f = \frac{e}{s_W c_W} [I_3^f - s_W^2 Q_f],$$

$$g_R^f = \frac{e}{s_W c_W} [-s_W^2 Q_f]$$

and $s_W = \sin \Theta_W$, $c_W = \cos \Theta_W$. The Mandelstam variables t, u can be expressed by the production angle θ : $t = -s(1 - \cos \theta)/2$, $u = -s(1 + \cos \theta)/2$; they are both negative so that the amplitudes for LQ exchange do not change the sign when θ is varied from the forward to the backward direction. Similarly, as in the case of contact interaction, Eq. 5 and Tab. 2, leptoquarks with integer isospin contribute to equal-helicity LL and RR amplitudes, while leptoquarks with $I = 1/2$ contribute to opposite-helicity amplitudes RL and LR .

For small Yukawa couplings, the leptoquark contributions are dominated by the interference with the standard model amplitudes leading to an enhancement or suppression of the integrated cross section relative to the standard model expectation. Furthermore, the effects scale with $g_{L,R}^2$ and, for large LQ-masses, with $1/M^2$. For scalar leptoquarks with couplings $g_{L,R} = 0.1$, Fig. 4 shows the relative change of the total cross section of hadron production at LEP2 for $\sqrt{s} = 192$ GeV¹⁵. Similar results are obtained for vector states. Generally, the effect is smaller for scalar leptoquarks than for vectors, and for isospin doublets than for singlets and triplets. It is interesting to note that the species $S_{1/2}$ and $\tilde{S}_{1/2}$ which play a particularly important role in the interpretation of the HERA high- Q^2 events, give the smallest effect of all leptoquarks at LEP2, to wit $|\Delta| = O(10^{-4})$ for $g_L \simeq 0.03$ and $M = 200$ GeV. The impact on cross sections for individual quark flavours is of course somewhat stronger. On the other hand, if the excess of events at HERA was due to the production of a $F = 2$ leptoquark in positron-antiquark scattering, the effect of leptoquark exchange implied at LEP2 should be observable since the Yukawa couplings would be larger in this case, $g_{L,R} \simeq 0.3$. This is also suggested by the recent OPAL analysis³⁰ for $\sqrt{s} = 130$ to 172 GeV shown in Fig. 5, which is already sensitive to the $F = 2$ scalars S_0 , \tilde{S}_0 and S_1 for $M \simeq 200$ GeV and $g_{L,R}$ between about 0.3 and 0.5.

8. 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 a continuum mechanism, but do not yet allow to exclude 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, but leave some room for extended leptoquark models and, most importantly, for a squark interpretation. Particularly difficult is the explanation of anomalous CC events. At any rate, if the excess of high- Q^2 events is confirmed by future data related signals are likely to show up soon in other experiments.

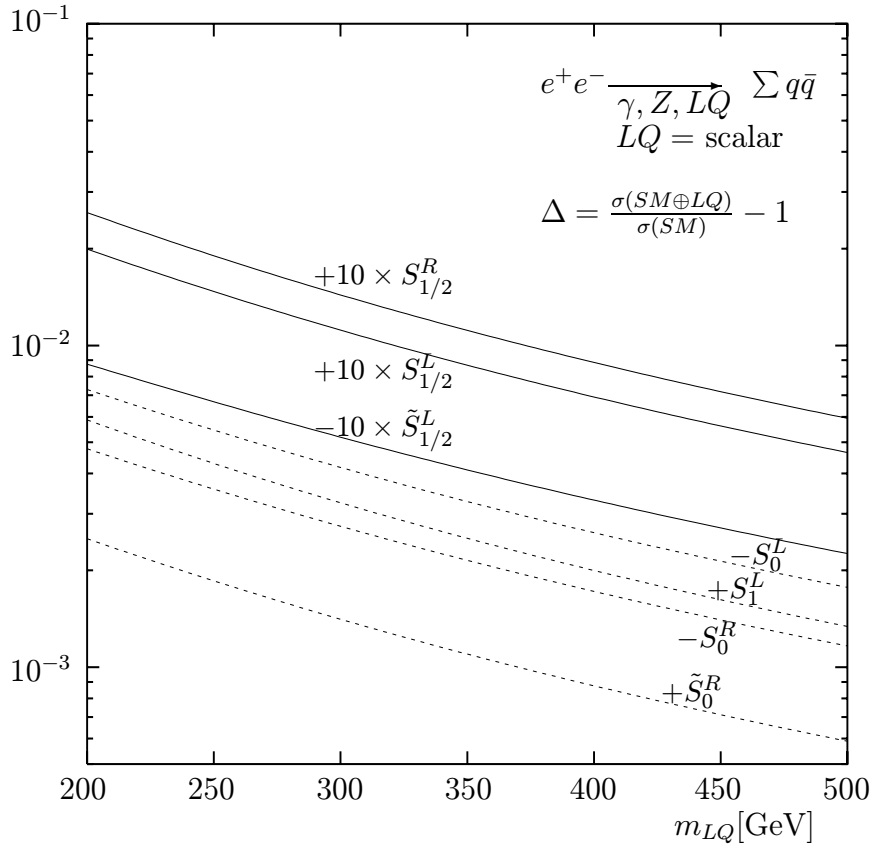


Figure 4: Effect of t/u -channel exchange of scalar leptoquarks on the total hadronic cross section at LEP2 for $\sqrt{s} = 192$ GeV¹⁵. The couplings have been fixed arbitrarily to $(g_L, g_R) = (0.1, 0)$ or $(0, 0.1)$ indicated by the upper indices L, R , respectively.

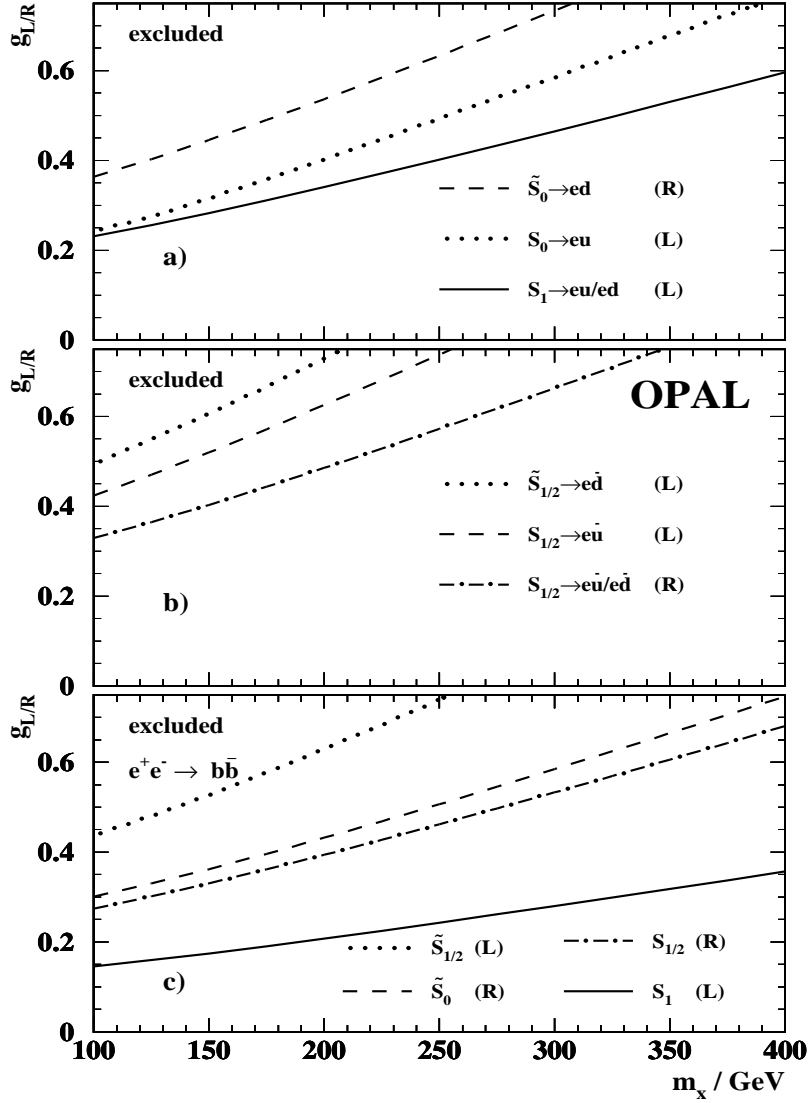


Figure 5: OPAL 95% confidence exclusion limits on $g_{L,R}$ as a function of the mass m_X for scalar leptoquarks: (a) and (b) are derived from $e^+e^- \rightarrow \sum q\bar{q}$, (c) from $e^+e^- \rightarrow b\bar{b}$. Excluded are the regions above the curves. (From ³⁰.)

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