Search for excited fermions and leptoquarks at HERA

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Abstract. Recent results on searches for new particles at the electron-proton collider HERA are reported. Based on roughly $40\,\mathrm{pb}^{-1}$ of e^+p data taken in the years 1994–1997, the H1 and ZEUS collaborations have derived new exclusion limits for the direct production of excited fermion states and of leptoquarks in different decay channels, including lepton-flavor violating decays. The results of searches for contact interactions further constrain the parameter space for such particles and their couplings in the high-mass regime, where direct production is kinematically prohibited. Also preliminary analyses of the e^-p data taken in 1998 and 1999 do not find signals of new physics.

1. Introduction

Between mid–1994 and the end of 1997 the electron-proton collider HERA at DESY has been operated with positrons (e^+) at an energy of $E_e = 27.5\,\mathrm{GeV}$ and protons (p) of $E_p = 820\,\mathrm{GeV}$, yielding a center–of–mass energy of $\sqrt{s} = 300\,\mathrm{GeV}$. In this period, ZEUS and H1 have collected e^+p data samples corresponding to integrated luminosities of $47.7\,\mathrm{pb}^{-1}$ and $37\,\mathrm{pb}^{-1}$, respectively. In 1998 and the first half of 1999, each experiment has taken about $15\,\mathrm{pb}^{-1}$ of e^-p data at $\sqrt{s} = 318\,\mathrm{GeV}$. This paper describes the status of searches for signals of excited fermions, leptoquarks

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and contact interactions in these data samples. Many of the results are still preliminary, and some have only become available after this BEYOND99 conference but are included here to provide an up-to-date overview of recent experimental results. Searches at HERA for R-parity violating supersymmetry and for the production of isolated leptons with high transverse momentum (P_t) are covered in [1].

2. Excited fermions

If electrons or quarks are composite, heavy excited fermion states (f^*) could be produced in ep reactions at HERA by t-channel exchange of photons, Z or W bosons as shown in the diagram of Fig. 1. The observation of such states would be an indication of fermion substructure.

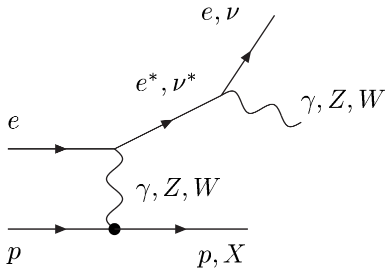


Figure 1. Feynman graph of the production and subsequent decay of excited electrons or neutrinos in ep reactions. Note that alternatively also an excited quark could be produced at the boson-proton vertex. In the case of e^* production, elastic reactions $ep \to e^* p$ are possible.

The ZEUS [2] and H1 [3] collaborations have searched for excited electrons (e^*), neutrinos (ν^*) and quarks (q^*) under the assumption that they decay into standard fermions and electroweak gauge bosons in one of the modes summarized in Tab. 1. The main selection cuts for the e^* and ν^* searches required events consistent with the presence of both a high-P_t final-state lepton (either an electron identified in the central detector or large missing transverse momentum indicating a neutrino) and of the gauge boson from the f^* decay (either identified directly in the case of a photon, or via the hadronic or leptonic decay products in the case of W and Z bosons). H1 also searched for excited quark states in events with a high-P_t jet and either a photon or an electron and missing transverse momentum ($\not{P}_t$). The backgrounds from various Standard Model (SM) processes (mainly neutral current (NC) and charged current (CC) deep-inelastic scattering (DIS), QED Compton scattering (QEDC), photoproduction of high-P_t jets (PHP) and prompt photons, on-shell production of W and Z bosons, and lepton-pair production in Bethe-Heitler ($\gamma\gamma$) processes, see Tab. 1) are estimated from MC simulations. The signal reactions are simulated using cross sections calculated according to the model by Hagiwara, Zeppenfeld and Komamiya (HZK) [4] for spin-1/2 excited fermions.

No indication of a signal above SM background has been found. As an example, Fig. 2 shows the distribution of the invariant $e\gamma$ mass in the

Table 1. Decay modes, event signatures and main SM background sources considered in the e^*, ν^* and q^* searches by ZEUS [2] and H1 [3].

f^* decay	signature	main SM background	studied by
$e^* \to e + \gamma$	$e + \gamma$	QEDC, NC	H1, ZEUS
$e^* \to e + Z \to e + q\bar{q}$	e + 2jets	NC	H1, ZEUS
$e^* \to e + Z \to e + e^+e^-$	$3e$	$\gamma\gamma$, NC	H1
$e^* \to e + Z \to e + \nu\bar{\nu}$	$e + \not{P}_t$	NC, CC, $\gamma\gamma$, W	H1
$e^* \to \nu + W \to \nu + q\bar{q}'$	$\not{P}_t$ + 2jets	CC, PHP	H1, ZEUS
$e^* \to \nu + W \to \nu + e\nu$	$e + \not{P}_t$	NC, CC, $\gamma\gamma$, W	H1
$\nu^* \to \nu + \gamma$	$\gamma + \not{P}_t$	CC, NC	H1, ZEUS
$\nu^* \to e + W \to e + q\bar{q}'$	e + 2jets	NC	H1
$\nu^* \to e + W \to e + e\nu$	$2e + \not{P}_t$	$\gamma\gamma$, QEDC, W	H1
$\nu^* \to \nu + Z \to \nu + q\bar{q}$	$\not{P}_t$ + 2jets	CC, PHP	H1
$\nu^* \to \nu + Z \to \nu + e^+e^-$	$2e + \not{P}_t$	$\gamma\gamma$, QEDC, W	H1
$q^* \to q + \gamma$	γ+jet	prompt γ	H1
$q^* \to q' + W \to q' + e\nu$	$e + \not{P}_t$+jet	NC, CC, W	H1

event sample selected in the ZEUS search for $e^* \to e\gamma$ decays. For f^* masses $M_{f^*} \gtrsim 100\,\text{GeV}$ the searches are almost background-free, yielding upper limits at 95% C.L. on the cross section times branching ratio ($\sigma \cdot \text{BR}$) of typically 0.1–1 pb. The HZK model is used to relate these limits to exclusion plots of f/Λ vs. M_{f^*}, where Λ is the characteristic mass scale and f determines the coupling at the f^*-fermion-boson vertex. In the HZK model, there are three independent couplings, of which the one to gluons (f_s) is irrelevant for f^* production at HERA and those to the U(1) and SU(2) gauge fields are assumed to be related by $f \equiv |f'_{U(1)}| = |f_{SU(2)}|$. The HERA limits shown in Fig. 3 are by almost one order of magnitude stronger than those based on the 1993–1995 data [6,7] and exclude f/Λ values above

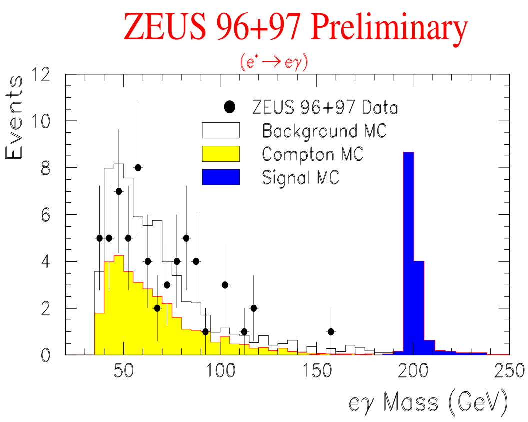


Figure 2. Spectrum of the invariant $e\gamma$ mass of ZEUS candidates for e^* production and subsequent decay $e^* \to e\gamma$. The points with error bars represent the data, the open (light-shaded) histogram the total SM background (the contribution from QED Compton scattering). The dark-shaded histogram illustrates the signal expected for a hypothetical e^* with a mass of 200 GeV.

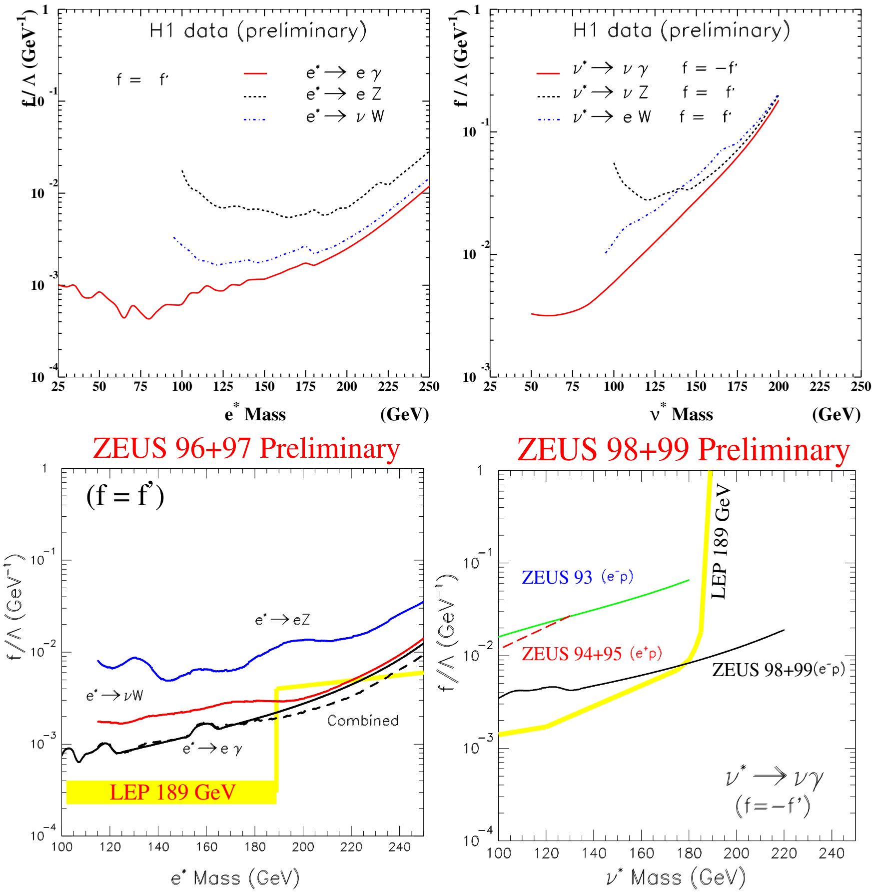


Figure 3. Limits at 95% C.L. on f/Λ from H1 (top) and ZEUS (bottom) searches for excited electrons (left) and excited neutrinos (right). The shaded bands denoted "LEP 189 GeV" indicate the exclusion limits from [5], with the band width approximating the amplitude of their small-scale variations.

$\mathcal{O}(10^{-3} \ldots 10^{-2}\,\mathrm{GeV}^{-1})$ for f^* masses between 25 and 220 GeV; this also applies to the H1 results on q^* (not shown). Assuming $f/\Lambda = 1/M_{f^*}$, the results exclude the existence of e^* with masses between 25 and 229 GeV, and of ν^* between 25 and 161 GeV. The ν^* limits are dominated by the recent e^-p results (from ZEUS) since the expected ν^* cross section is more than an order of magnitude larger for e^-p than for e^+p scattering. The comparison with the latest LEP limits [5] in Fig. 3 demonstrates that the HERA searches, in particular in the ν^* channel, advance into new discovery windows which are not (yet) accessible to other experiments. The H1 limits for q^* (assuming f_s=0) complement those from Tevatron where q^* production requires non-zero f_s.

3. Leptoquarks

Leptoquarks (LQ's) are hypothesized bosons coupling to lepton-quark pairs. They could be resonantly produced in ep reactions according to the diagram shown in Fig. 4. Buchmüller, Rückl and Wyler (BRW) [8] have classified LQ's which (i) conserve the SM gauge symmetries, (ii) only couple to quarks, leptons and SM gauge bosons and (iii) only have flavor-diagonal couplings, in ten different states characterized by their fermion number ($|F|$=2 or F=0), spin (scalar (S) or vector (V)) and weak isospin. Premise (ii) implies that LQ's only decay into $\ell^\pm q$ or $\nu q'$ pairs with given branching ratios. In many recent LQ searches, this assumption is dropped and a variable branching ratio $\beta_\ell = \mathrm{BR}(\mathrm{LQ} \to \ell^\pm q)$ is assigned to the LQ's (accounting e.g. for the case of R_P-violating squarks [1]).

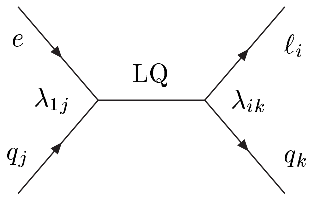
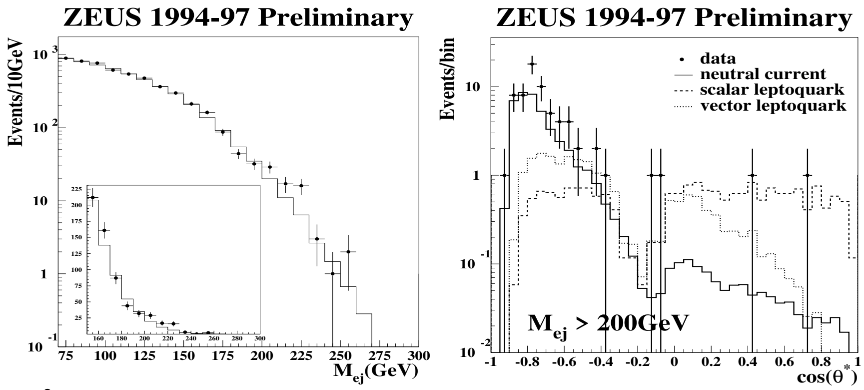


Figure 4. Feynman graph of the resonant production of a F=2 LQ in electron-quark scattering. The subscripts of the Yukawa couplings at production and decay vertex of the LQ indicate the generations of the leptons and quarks involved.

3.1. First-generation leptoquarks

LQ's coupling only to first-generation leptons can be produced at HERA in reactions of the type $ep \to \mathrm{LQ} + X \to eq + X$ ($\nu_e q' + X$), yielding the same event topologies as NC (CC) DIS at high eq invariant mass. The distinctive LQ signature is a resonant distribution of $\sqrt{xs}$ around the LQ mass, M_{LQ}, where $\sqrt{s}$ is the ep center-of-mass energy and the Bjorken variable x is the fraction of the proton momentum carried by the struck quark. Furthermore, the LQ decay angular distribution implies harder distributions of $y = s/(xQ^2)$ than for DIS (Q^2 is the negative square of the four-momentum transfer between e and p). LQ production at HERA has received particular attention after H1 [9] and ZEUS [10] have reported an excess of events of NC DIS at high x and Q^2 in their 1994–1996 data.

ZEUS [11–13] and H1 [14] have searched in the available DIS data for deviations from the SM prediction consistent with a LQ signal. The distributions of $M_e = \sqrt{x_e s}$ (derived from energy and angle of the scattered electron, H1) and M_{ej} (invariant e-jet mass, ZEUS) are shown in Fig. 5. The excess in the H1 data is still present at $M_e \approx 200\,\mathrm{GeV}$ but has not been corroborated by the 1997 data. Also ZEUS observes an excess at $M_{ej} \gtrsim 200\,\mathrm{GeV}$; however, the decay angular distribution does not support a LQ interpretation (see Fig. 5). No significant deviations from the SM predictions are observed in CC DIS [12,14] and in the new e^-p data [13].



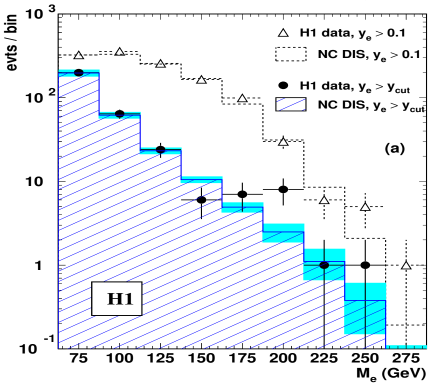


Figure 5. Distributions of M_{ej} (top left, ZEUS) and M_e (bottom, H1) in the e^+p NC data. The symbols with statistical error bars represent the data, the histograms the DIS MC. The H1 data are shown before (open triangles) and after (full dots, hatched histogram) a cut $y>y_{\min}(M_e)$. The shaded area indicates the uncertainty of the SM prediction. The polar angle distribution in the eq center-of-mass system is shown in the top right plot for ZEUS events with $M_{ej}>200$ GeV.

Using a MC simulation of signal events according to the BRW cross sections, upper limits on $\sigma \cdot$ BR for LQ production have been set. The ZEUS exclusion plots for NC-type LQ decays in e^+p and e^-p scattering are shown in Fig. 6; the H1 e^+p results (not shown) are similar but extend to higher $M_{\rm LQ}$ since u-channel LQ exchange and DIS-LQ interference are taken into account in addition to s-channel LQ formation. Assuming fixed β_e according to BRW, upper limits on the coupling $\lambda=\lambda_{1j}$ are derived as functions of $M_{\rm LQ}$ for different LQ types (Fig. 7 shows the H1 result for scalar LQ's). Note that the e^+p data are much more sensitive to $F=0$ LQ's, which can be produced from valence quarks, than to $|F|=2$ LQ's. $M_{\rm LQ}$ limits which are independent of λ are obtained by the Tevatron experiments from searches for LQ pair production in $p\bar{p}$ reactions. The combined CDF and DØ limit is $M_{\rm LQ}>242$ GeV [15] for scalar LQ's with $\beta_e=1$ and is expected to be even higher for vector LQ's. H1 has presented the LQ limits as functions of β_e and $M_{\rm LQ}$ for fixed values of λ_{1j} (Fig. 8), thus allowing a direct comparison to the LQ exclusion region from DØ [16]. The HERA experiments have a unique discovery potential at low β_e and high $M_{\rm LQ}$; future high-statistics HERA data is needed in order to clarify whether the anomalies observed in the e^+p data are an indication of LQ production.

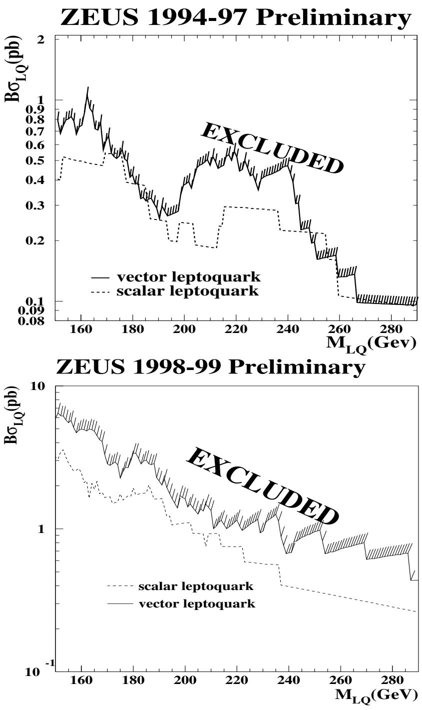


Figure 6. ZEUS limits at 95% C.L. on $\sigma \cdot \beta$ for scalar (dotted lines) and vector (full lines) LQ's, from the e^+p [11] (top) and the e^-p [13] (bottom) data.

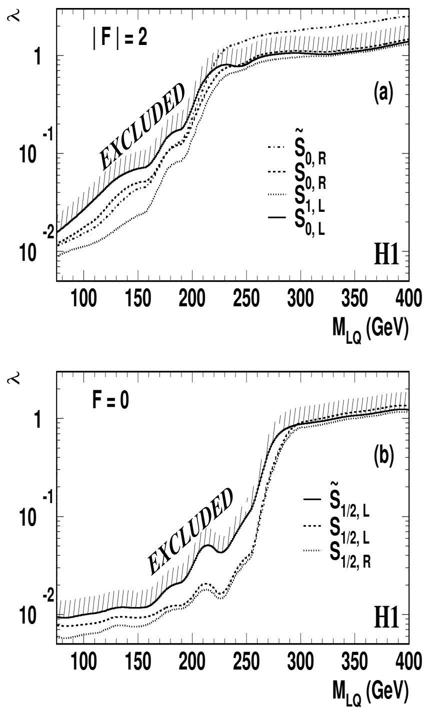


Figure 7. H1 limits at 95% C.L. on $\lambda = \lambda_{1j}$ for different scalar LQ's with $|F|$=2 (top) and F=0 (bottom). Only NC-type data are used for these limits.

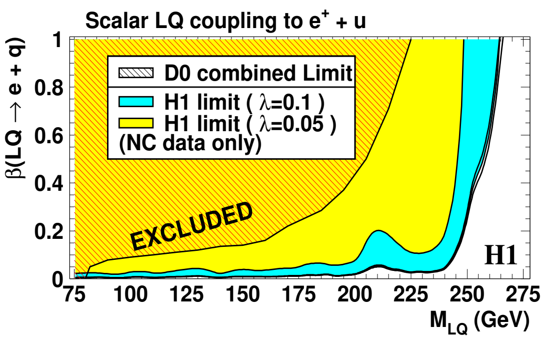


Figure 8. H1 exclusion limits on β_e as functions of $M_{\rm LQ}$, for scalar F=0 LQ's coupling to u quarks, for different fixed values of λ_{1j}. The cross-hatched area indicates the region excluded by DØ [16]. Only NC-type data have been used for this plot.

3.2. Lepton-flavor violating leptoquarks

H1 has searched for instances of the reaction $ep \to {\rm LQ} + X \to \tau q + X$, with subsequent hadronic τ decays [14]. The event selection requires the presence of a narrow hadronic jet with small track multiplicity, which is azimuthally opposite to the direction of the net transverse momentum that

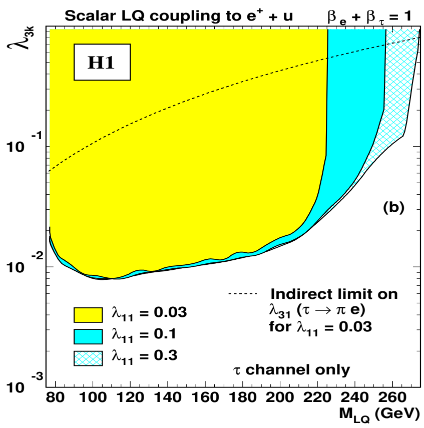


Figure 9. H1 exclusion limits at 95% C.L. on λ_{3k} for different fixed values of λ_{1j}. Scalar LQ's which only couple to e and τ ($\beta_e + \beta_\tau = 1$) are assumed. Also indicated is an indirect limit derived from the non-observation of the lepton-flavor violating decay $\tau \to e\pi$.

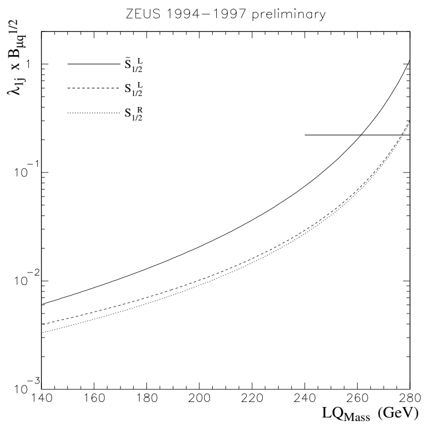


Figure 10. ZEUS exclusion limits at 95% C.L. on $\lambda_{1j} \cdot \mathrm{BR}(LQ \to \mu q)$ for three types of scalar LQ's coupling to electrons and muons and to d, u, and d and u quarks, respectively (top to bottom). The horizontal line indicates electromagnetic coupling strength.

has to exceed 10 GeV. No events fulfilling these criteria have been observed, allowing to set limits on the LQ-τ coupling λ_{3k} for fixed values of λ_{1j} (Fig. 9). These limits are stronger than those derived from lepton-flavor violating decays of τ's. The limits from searches for LQ's decaying to τ's at Tevatron are $M_{\mathrm{LQ}} > 99$ GeV (CDF [17]) and > 94 GeV (DØ [18]).

ZEUS has performed a search for lepton flavor violation in the μ channel, $ep \to \mathrm{LQ} + X \to \mu q + X$ [19]. The selection requires event topologies similar to high-Q^2 NC DIS reactions, except that the scattered e is replaced by a μ. No such event is found, with an expected background of 0.3 events predominantly from Bethe-Heitler muon pair production. Upper limits are set on $\lambda_{1j} \cdot \mathrm{BR}(LQ \to \mu q)$ (Fig. 10). Assuming couplings of electromagnetic strength, $\lambda_{1j} = \lambda_{3k} = \sqrt{4\pi\alpha}$, these limits correspond to $M_{\mathrm{LQ}} > 262$–285 GeV, depending on the LQ type.

4. Contact interactions

Contact interactions (CI) provide an effective phenomenology to describe the cross section modification of ep NC DIS due to new physics at mass scales far beyond the HERA center-of-mass energy, e.g. s- and u-channel exchange of LQ's or exchange interactions in presence of a common substructure of electrons and quarks. The Lagrangian of the vector $eeqq$ CI investigated at HERA is characterized by an overall strength $\epsilon g^2/\Lambda^2$ (where

Table 2. CI combinations considered in the ZEUS [20] and H1 [21] analyses, and the corresponding 95% C.L. lower limits on Λ derived from the NC DIS data.

CI	$\eta^u_{\rm LL}$	$\eta^u_{\rm LR}$	$\eta^u_{\rm RL}$	$\eta^u_{\rm RR}$	$\eta^d_{\rm LL}$	$\eta^d_{\rm LR}$	$\eta^d_{\rm RL}$	$\eta^d_{\rm RR}$	Λ limit [TeV] ZEUS $\epsilon=-1$	ZEUS $+1$	H1 -1	H1 $+1$
VV	+	+	+	+	+	+	+	+	5.0	4.7	1.9	5.0
AA	+	−	−	+	+	−	−	+	3.7	2.6	3.4	2.0
VA	+	−	+	−	+	−	+	−	2.6	2.5	2.6	2.6
X1	+	−	0	0	+	−	0	0	2.8	1.8	—	—
X2	+	0	+	0	+	0	+	0	3.1	3.4	—	—
X3	+	0	0	+	+	0	0	+	2.8	2.9	1.3	3.1
X4	0	+	+	0	0	+	+	0	4.3	4.0	1.8	4.1
X5	0	+	0	+	0	+	0	+	3.3	3.5	—	—
X6	0	0	+	−	0	0	+	−	1.7	2.8	—	—
U1	+	−	0	0	0	0	0	0	2.6	2.0	—	—
U2	+	0	+	0	0	0	0	0	3.9	4.0	—	—
U3	+	0	0	+	0	0	0	0	3.5	3.7	—	—
U4	0	+	+	0	0	0	0	0	4.8	4.4	—	—
U5	0	+	0	+	0	0	0	0	4.2	4.0	—	—
U6	0	0	+	−	0	0	0	0	1.8	2.4	—	—
LL	+	0	0	0	+	0	0	0	—	—	1.2	2.3
LR	0	+	0	0	0	+	0	0	—	—	1.5	3.0
RL	0	0	+	0	0	0	+	0	—	—	1.5	3.0
RR	0	0	0	+	0	0	0	+	—	—	1.2	2.3

$g^2 = 4\pi$ by convention, Λ is the effective mass scale and ϵ is an overall sign) and by a set of chiral couplings η^q_{ab}, where $q = u, d$ and $a, b = L, R$ denote the handedness of the couplings to leptons and quarks. Depending on ϵ, the CI-SM interference ($\propto Q^2/\Lambda^2$) enhances or decreases the cross section at intermediate Q^2, whereas the pure CI part ($\propto Q^4/\Lambda^4$) increases the cross section at highest Q^2. No indications for the presence of CI have been found in correspondig searches by ZEUS [20] and H1 [21]. The CI patterns investigated and the resulting 95% C.L. limits on Λ are summarized in Tab. 2. Some of the CI scenarios are investigated for the first time, for others the limits reported by the LEP and Tevatron experiments are mostly stronger than those in Tab. 2 (see [20] and references therein). Limits of $\mathcal{O}(10\,\mathrm{TeV})$ can furthermore be derived from atomic parity violation measurements (APV) [22,23] for parity-violating CI scenarios (the last four rows in Tab. 2). H1 has converted the appropriate u and d combinations of the purely chiral limits (LL etc.) into limits on $M_{\rm LQ}/\lambda_{1j}$ for different LQ species, ranging from $\approx 200\,\mathrm{GeV}$ to almost $1\,\mathrm{TeV}$ (valid for $M_{\rm LQ} \gg \sqrt{s}$); however, it should be noted that stronger limits are obtained from APV.

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