Submitted to the 29th International Conference on High-Energy Physics ICHEP98,
Vancouver, Canada, July 1998

Search for Contact Interactions in Neutral Current Scattering at HERA

H1 Collaboration

Abstract

The neutral current reaction $e^+p \to e^+\,\mathrm{hadrons}$ has been measured with the H1 detector at HERA up to very high momentum transfers of $Q^2 = 30,000\ \mathrm{GeV}^2$. The data correspond to an integrated luminosity of 37 pb^{-1}. The differential cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ is compared to the Standard Model expectation and analyzed to search for $(\bar{e}\,e)(\bar{q}\,q)$ contact interactions. No significant signal is observed and limits on lepton–quark compositeness scales and virtual leptoquark exchange are presented.

Abstract: 584
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1 Introduction

The HERA collider allows to study deep inelastic neutral current scattering $e^+p \to e^+ \, \mathrm{hadrons}$ at very high momentum transfers Q^2, thus probing the structure of $e\,q$ interactions at very short distances of $r_{eq} \lesssim 10^{-16}$ cm. The differential cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ can be used to search for indications of new physics beyond the Standard Model, *e.g.* $(e\,q)$ compositeness or leptoquarks mediated through contact interactions. So far no significant deviations from Standard Model expectations have been observed.

Experiment The data have been collected with the H1 detector during 1994 – 1997 and correspond to an integrated luminosity of $\mathcal{L} = 37.0 \ \mathrm{pb}^{-1}$, representing a tenfold increase compared to the previous analysis [1]. Positrons with $E_e = 27.5$ GeV collide with 820 GeV protons at a center of mass energy of $\sqrt{s} = 300$ GeV. The cross section is determined from a purely inclusive measurement of the final state lepton with energy E'_e and polar angle θ_e. The kinematic quantities are calculated via $Q^2 = 4\,E_e\,E'_e\,\cos^2(\theta_e/2)$ and $y = 1 - E'_e/E_e\,\sin^2(\theta_e/2)$. The absolute energy uncertainty varies between 1% in the backward region ($\theta_e > 90°$) and 3% in the forward region. The lepton scattering angle is known to within 3 mrad. The data are corrected for detector effects and QED radiation and represent the cross section within the kinematic phase space $Q^2 > 180 \ \mathrm{GeV}^2$, $y < 0.9$ and $E'_e > 11$ GeV. An overall uncertainty due to the luminosity determination of 1.8%, the uncorrelated systematics as well as the correlated experimental systematic errors from the lepton energy and scattering angle are included in the contact interaction analysis. Details of the cross section measurement are described elsewhere [2]. It should, however, be noticed that the luminosity error used in the present analysis is lower than the one quoted in [2], due to an improved understanding of the systematic uncertainties. The differential cross section for $Q^2 = 180 - 30,000 \ \mathrm{GeV}^2$ is shown in figure 1.

The Standard Model cross section is given by

$$\frac{d^2\sigma(e^+p \to e^+h)}{dx\,dQ^2} = \frac{2\,\pi\,\alpha^2}{x\,Q^4} \left\{ Y_+\,F_2(x,Q^2) - y^2\,F_L(x,Q^2) - Y_-\,x\,F_3(x,Q^2) \right\} , \quad (1)$$

where $x = Q^2/y\,s$ is the Bjorken variable and $Y_\pm = 1 \pm (1-y)^2$. The generalized proton structure functions $F_i(x,Q^2)$ include electroweak effects and can be expressed through parton densities. The contribution of $F_L(x,Q^2)$ is expected to be negligible in the chosen kinematic region and will be discarded. Using the CTEQ4D parton parametrisation [3] in the DIS scheme gives a very good description of the data, see figure 1. A fit yields $\chi^2 = 11.9/14$ df with a normalisation of $\int \mathrm{d}\sigma^{SM} / \int \mathrm{d}\sigma = 0.988$. There is still a slight excess over the Standard Model expectation at $Q^2 \gtrsim 15,000 \ \mathrm{GeV}^2$, as reported earlier for a lower statistics data sample [4].

Contact Interaction Phenomenology New currents or heavy bosons may produce indirect effects through the interference of a *virtual* particle exchange with the γ and Z fields of the Standard Model. For particle masses well above the available production energy, such indirect signatures may be investigated by searching for a 4–fermion pointlike $(\bar{e}\,e)(\bar{q}\,q)$ contact interaction. The dependence of s, t and u channel amplitudes on couplings $g_{X\to i,\,f}$ to states i, f and mass M_X reduce to an effective coupling with dimension $[\mathrm{mass}^{-2}]$

$$\eta_{if} \equiv \frac{g_{X\to i}\,g_{X\to f}}{M_X^2} . \quad (2)$$

The most general chiral invariant contact interaction Lagrangian for neutral current vector interactions can be written in the form [5]

$$\begin{aligned} \mathcal{L}^{NC}_{\mathrm{contact}} = \sum_{q=u,\,d} & \{\eta^q_{LL}\,(\bar{e}_L\gamma_\mu e_L)(\bar{q}_L\gamma^\mu q_L) + \eta^q_{LR}\,(\bar{e}_L\gamma_\mu e_L)(\bar{q}_R\gamma^\mu q_R) \\ & + \eta^q_{RL}\,(\bar{e}_R\gamma_\mu e_R)(\bar{q}_L\gamma^\mu q_L) + \eta^q_{RR}\,(\bar{e}_R\gamma_\mu e_R)(\bar{q}_R\gamma^\mu q_R)\} , \end{aligned} \quad (3)$$

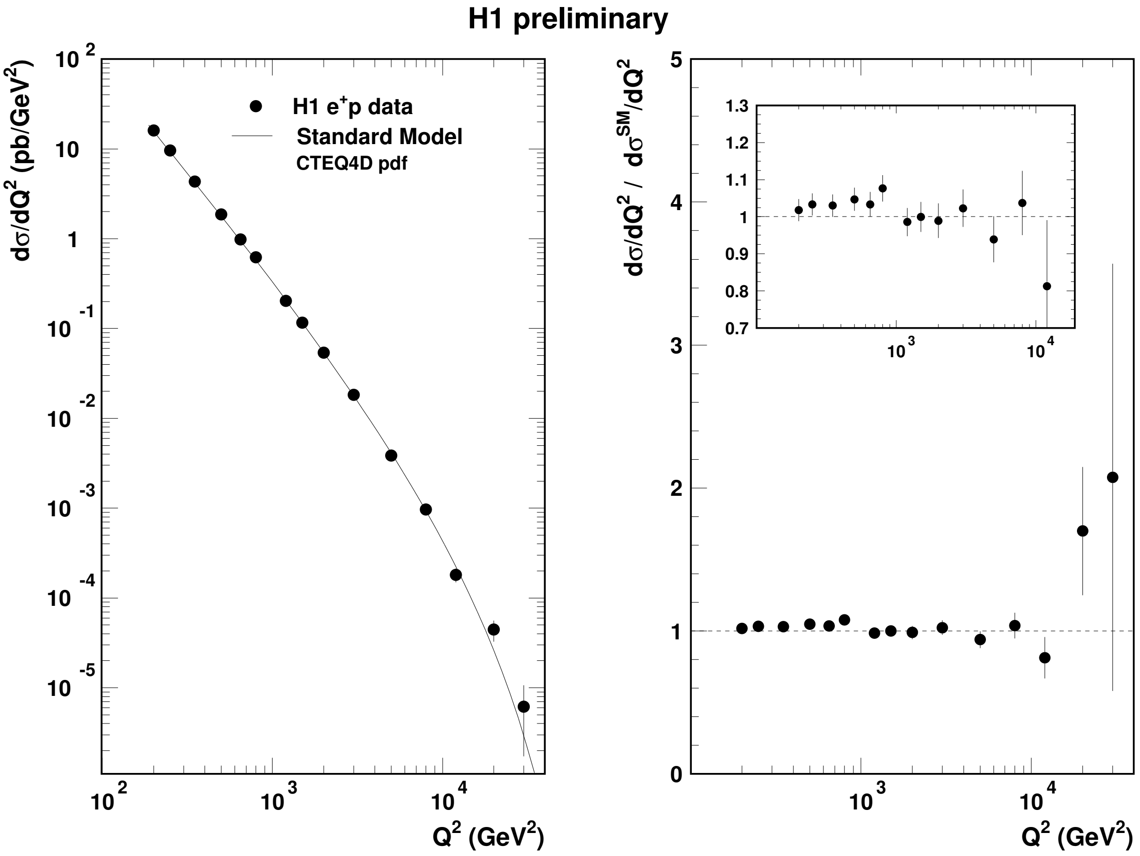

Figure 1: Differential NC cross section $\mathrm{d}\sigma(e^+p \to e^+\,\mathrm{hadrons})/\mathrm{d}Q^2$. H1 data (•) are compared with the Standard Model expectation (—) using the CTEQ4D parton distributions. The errors represent statistics and uncorrelated experimental systematics. The overall normalisation uncertainty of 1.8% is not included.

where the indices L and R denote the left–handed and right–handed fermion helicities and the sum extends over *up* and *down* quarks and antiquarks q. Scalar and tensor interactions are strongly suppressed at HERA and therefore not considered in this analysis. The ansatz eq. (3) can be easily applied to any new phenomena [5], *e. g.* $(e\,q)$ compositeness, leptoquarks or new gauge bosons, by an appropriate choice of the coupling coefficients η_{if}.

2 Compositeness Scales

In the Standard Model the fundamental particles – leptons, quarks and gauge bosons – are assumed to be pointlike. A possible fermion compositeness or substructure can be expressed by defining the coupling coefficients of eq. (2) as $\eta_{if} \equiv \pm\, g^2/\Lambda_{if}^{\pm\,2}$, where the signs indicate positive and negative interference with the Standard Model currents, g is the coupling strength conventionally chosen as $g^2/4\,\pi = 1$ and Λ is the compositeness scale. The following models are investigated: pure chiral couplings $LL,\ LR,\ RL$ and RR and mixtures $VV = LL + LR + RL + RR$, $AA = LL - LR - RL + RR$ and $VA = LL - LR + RL - RR$. Both u and d quarks are assumed to contribute with the same scale.

It is appropriate to analyze the differential cross section in terms of the coupling coefficients $\eta = 4\,\pi/\Lambda^2$ and leaving the sign of interference free. The dominant correlated systematic errors, *i. e.* the experimental uncertainty of the lepton energy scale and the scattering angle, are

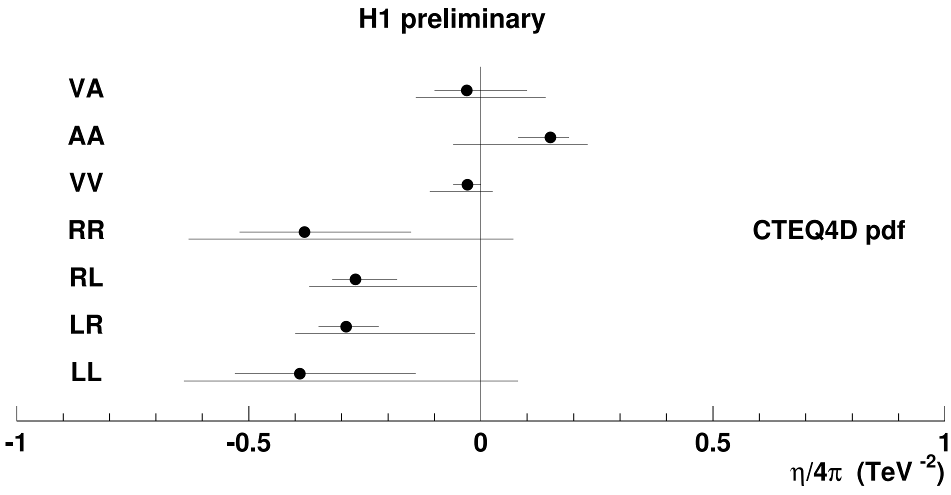

Figure 2: Fit results of the parameter $\eta/4\,\pi$ for various compositeness models using the CTEQ4D parton distributions. The upper (–•–) and lower (—) bars represent the 68% and 95% cl intervals respectively, taking into account the statistical and systematic experimental uncertainties.

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coupling	$\eta/4\,\pi$ [TeV^{-2}]	Λ^{+} [TeV]	Λ^{-} [TeV]
LL	$-0.390\,^{+0.249}_{-0.142}$	2.4	1.2
LR	$-0.293\,^{+0.076}_{-0.055}$	3.0	1.5
RL	$-0.265\,^{+0.080}_{-0.058}$	3.0	1.6
RR	$-0.385\,^{+0.234}_{-0.139}$	2.4	1.2
VV	$-0.029\,^{+0.029}_{-0.036}$	4.5	2.5
AA	$0.151\,^{+0.041}_{-0.073}$	2.0	3.8
VA	$-0.034\,^{+0.183}_{-0.062}$	2.6	2.8

Table 1: Fit results for various chiral structures of the parameter $\eta/4\,\pi$ using the CTEQ4D parton distributions and 95% cl lower limits on compositeness scale parameters $\Lambda^{\pm}$, taking the most conservative values from a variation of different parton distributions.

taken into account in the fit procedure. The results of the χ^2 fits are shown in figure 2 and compiled in table 1. The data are particularly sensitive to the VV, AA and VA models, where all chiral structures contribute with different relative signs. The VA combination can also be tested in atomic parity violation experiments at low momentum transfer, from which strong indirect bounds have been obtained [6]. Note that the LL and RR models and the LR and RL models are almost indistinguishable in deep inelastic e^+p scattering. The pure chiral couplings prefer negative values of η. This is a consequence of the trend of the data $(\mathrm{d}\sigma/\mathrm{d}Q^2)\,/\,(\mathrm{d}\sigma^{SM}/\mathrm{d}Q^2)$ being slightly low around $Q^2 \simeq 4,000 - 12,000\ \mathrm{GeV}^2$ followed by an upward fluctuation at higher Q^2 (see figure 1), which favour a negative interference term. However, the χ^2 distributions are rather broad and asymmetric around the minimum values. This is illustrated in figure 3 for the models under study using different parton distributions. The couplings η are compatible with the Standard Model within two standard deviations.

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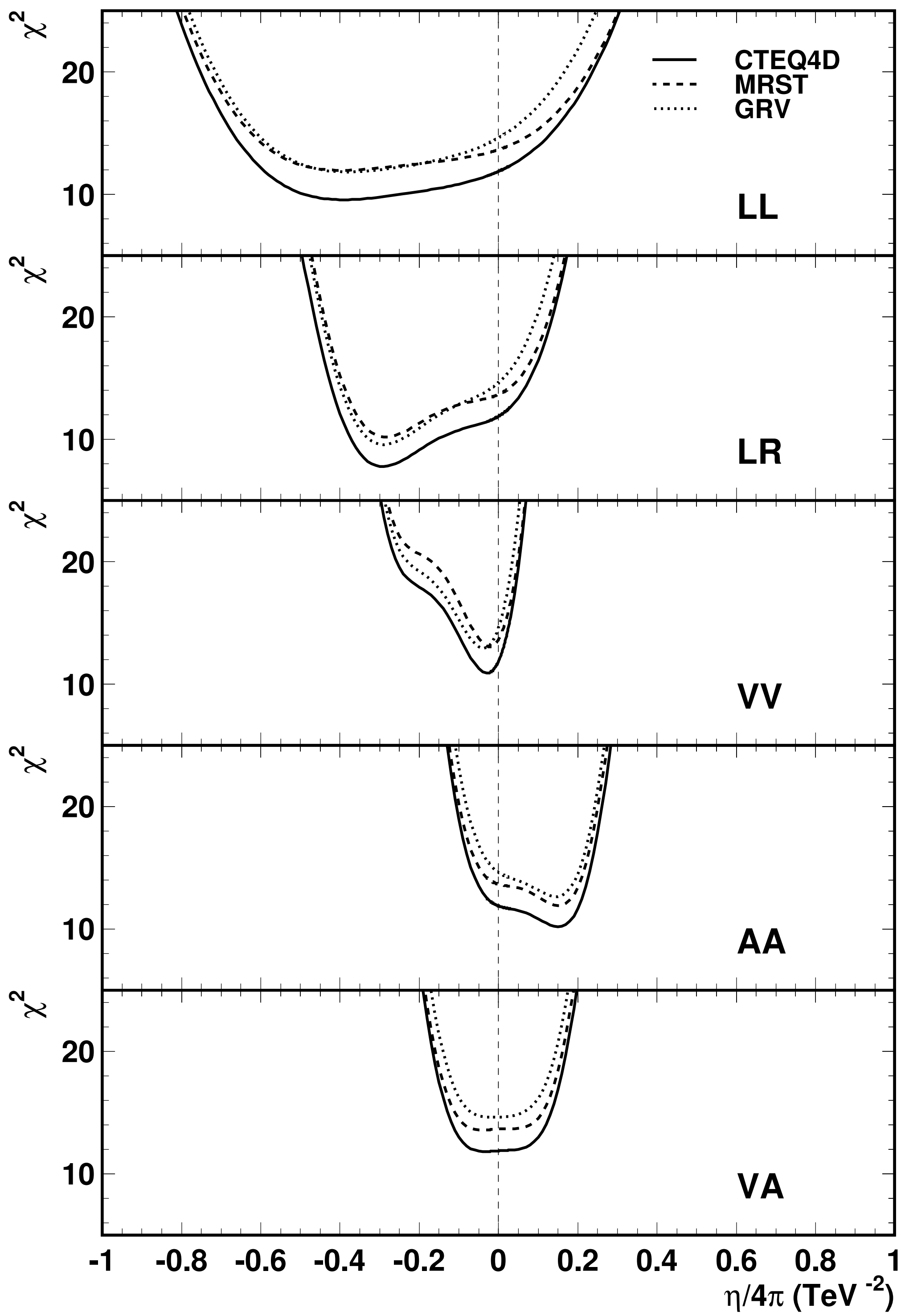

Figure 3: Distributions of χ^2 versus $\eta/4\,\pi$ from fits to various compositeness models using CTEQ4D, MRST and GRV 94 parton distributions. The LL and RR models and the LR and RL models are almost indistinguishable in deep inelastic e^+p scattering. The fits include the statistical and systematic experimental uncertainties.

Limits on the compositeness scale parameters are derived by fitting Λ^+ and Λ^- with the appropriate interference signs and taking the corresponding changes in χ^2 with respect to the fit to the Standard Model, which provides a good description of the data. Choosing different parton distributions for the cross section calculation, *e. g.* MRST or GRV 94 [3], does not change the shape of the Q^2 spectrum significantly, but rather the normalisation by up to 1.2%. The limits on $\Lambda^\pm$ change by $\sim 0.2 - 0.8$ TeV in either direction compared to the CTEQ4D parton densities. The most conservative values of $\Lambda^\pm$ obtained from a variation of the parton distributions are quoted in table 1. The limits on compositeness scale parameters vary between 1.2 TeV and 4.5 TeV depending on the chiral structure of the model.

As an illustration of the sensitivity of the data to compositeness scales figure 4 shows the fit results and the 95% cl contributions of $\Lambda^\pm$ for the LR and VV models.

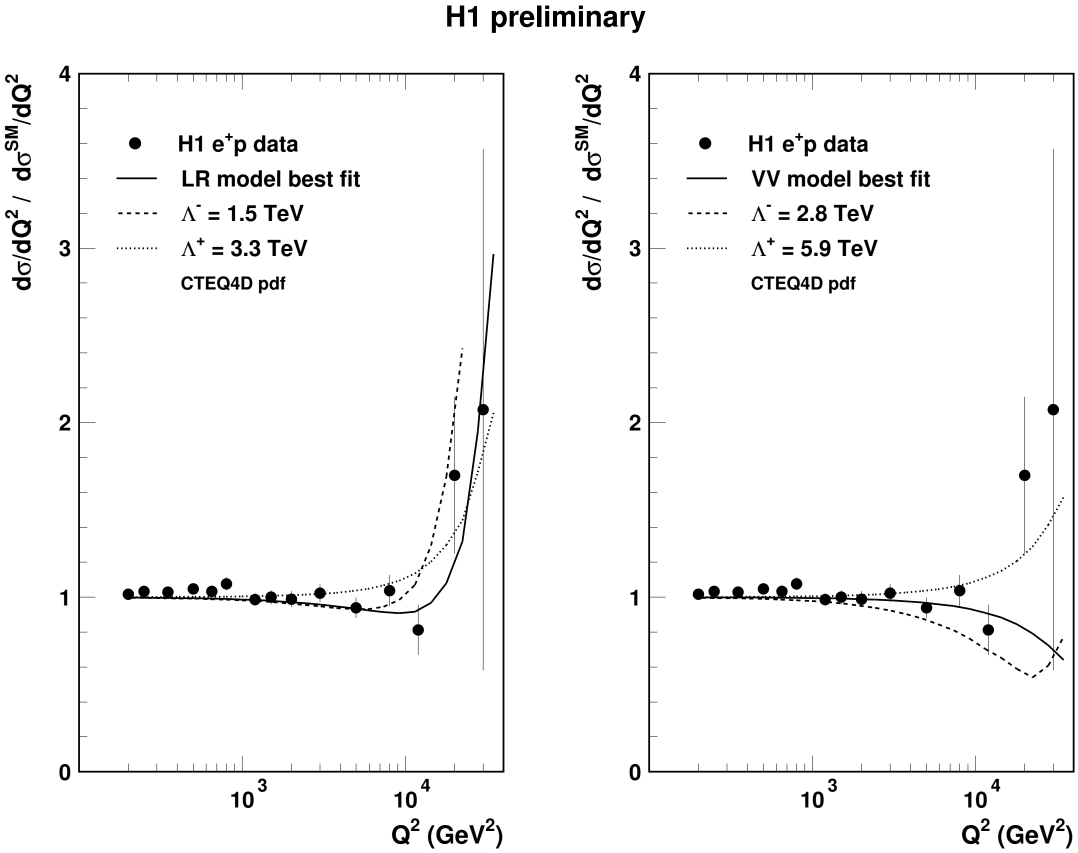

Figure 4: NC cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ normalised to the Standard Model expectation using CTEQ4D parton distributions. H1 data (•) are compared with fits to the LR (left) and VV (right) model (—) and with the 95% cl contributions of Λ^+ $(\cdots)$ and Λ^- $(--)$. The errors represent statistics and uncorrelated experimental systematics. The overall normalisation uncertainty of 1.8% is not included.

3 Leptoquarks

Leptoquarks are colour triplet bosons of spin 0 or 1, carrying lepton (L) and baryon (B) number and fractional electric charge. They couple to lepton–quark pairs and appear in extensions of the Standard Model which try to establish a connection between leptons and quarks. Leptons and quarks may be arranged in common multiplets, like in Grand Unified Theories or superstring motivated E_6 models, or they may have a common substructure as in composite models. A fermion number $F = L + 3\,B$ is defined, which takes the values $F = 2$ for leptoquarks coupling to $e^-\,q$ and $F = 0$ for leptoquarks coupling to $e^-\,\bar{q}$. For positrons the fermion number F changes by two units. Consequently $F = 0$ leptoquarks are easier accessible in e^+p scattering, while electron beams are more sensitive to $F = 2$ leptoquarks, since at moderate x values quarks are more abundant in the proton than antiquarks.

The leptoquark mass M_{LQ} and its coupling λ is related to the contact interaction coefficients of eq. (2) via $g/M_X = \lambda/M_{LQ}$. The notation and the coupling coefficients η_{if} for leptoquarks are given in table 2 (from ref. [5]). The only unknown parameter is the ratio M_{LQ}/λ. Note that vector leptoquarks have positive coupling coefficients, while scalar leptoquarks have negative coupling coefficients, being a factor of 2 smaller in magnitude.

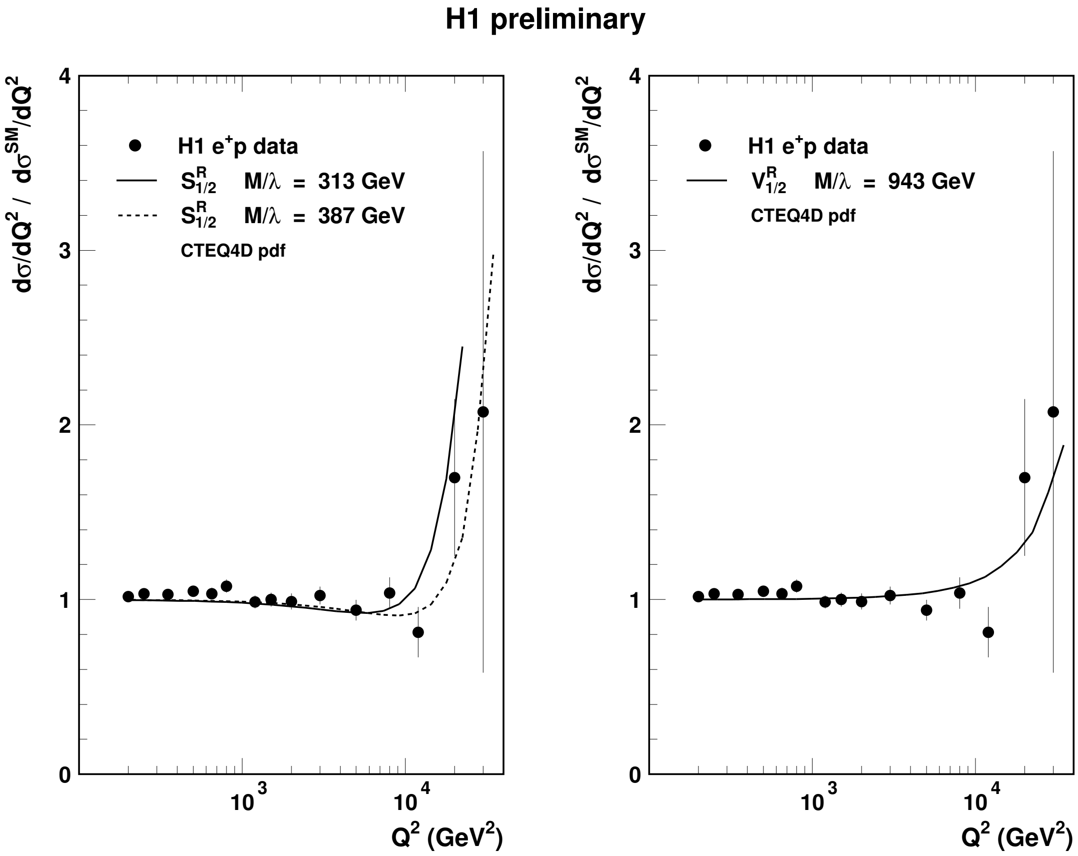

Figure 5: NC cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ normalised to the Standard Model expectation using CTEQ4D parton distributions. H1 data (•) are compared with 95% cl contributions (—) of the leptoquarks $S^R_{1/2}$ (left) and $V^R_{1/2}$ (right). Also shown is a fit $(--)$ to the scalar leptoquark $S^R_{1/2}$ with $M_{LQ}/\lambda = 387$ GeV. The errors represent statistics and uncorrelated experimental systematics. The overall normalisation uncertainty of 1.8% is not included.

As an example of the sensitivity of the data to virtual leptoquark exchange figure 5 shows the allowed contributions to the Standard Model expectation for the scalar leptoquark $S^R_{1/2}$ and the vector leptoquark $V^R_{1/2}$. It is interesting to note that a hypothetical scalar leptoquark $S^R_{1/2}$ can be accommodated by the data with almost 2 standard deviations significance if $M_{LQ}/\lambda = 387$ GeV. This leptoquark type has RL couplings to the *up* and *down* quarks and negative interference with the Standard Model currents. Such a behaviour can be understood from the results of the compositeness scale analysis, which favour a negative scale parameter $1/\Lambda^2_{RL}$.

On the other hand, the corresponding vector leptoquark $V^R_{1/2}$ with positively interfering RL couplings to u and d quarks gives no finite value for M_{LQ}/λ, but only lower limits.

The differential cross section analysis shows no evidence for a virtual leptoquark signal. The resulting lower limits on M_{LQ}/λ are summarized in table 2. They include all experimental systematics and represent the most conservative values obtained from a variation of different parton densities. In general vector leptoquarks which couple to u quarks provide the most restrictive limits of $M_{LQ}/\lambda \sim \mathcal{O}(1\ \mathrm{TeV})$. It should be emphasized that upper bounds on the coupling strength λ can only be set for leptoquark masses exceeding the accessible center of mass energy of HERA. Masses around 300 GeV are excluded for almost all types of leptoquarks with a coupling of $\lambda \gtrsim 1$.

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leptoquark	coupling to u quark $[\mathrm{GeV}^{-2}]$	coupling to d quark $[\mathrm{GeV}^{-2}]$	F	M_{LQ}/λ [GeV]
S^L_0	$\eta^u_{LL} = -\frac{1}{2}\,(\lambda/M_{LQ})^2$		2	255
S^R_0	$\eta^u_{RR} = -\frac{1}{2}\,(\lambda/M_{LQ})^2$		2	220
$\tilde{S}^R_0$		$\eta^d_{RR} = -\frac{1}{2}\,(\lambda/M_{LQ})^2$	2	368
$S^L_{1/2}$	$\eta^u_{LR} = -\frac{1}{2}\,(\lambda/M_{LQ})^2$		0	298
$S^R_{1/2}$	$\eta^u_{RL} = -\frac{1}{2}\,(\lambda/M_{LQ})^2$	$\eta^d_{RL} = -\frac{1}{2}\,(\lambda/M_{LQ})^2$	0	310
$\tilde{S}^L_{1/2}$		$\eta^d_{LR} = -\frac{1}{2}\,(\lambda/M_{LQ})^2$	0	412
S^L_1	$\eta^u_{LL} = -\frac{1}{2}\,(\lambda/M_{LQ})^2$	$\eta^d_{LL} = -1\,(\lambda/M_{LQ})^2$	2	395
V^L_0		$\eta^d_{LL} = +1\,(\lambda/M_{LQ})^2$	0	262
V^R_0		$\eta^d_{RR} = +1\,(\lambda/M_{LQ})^2$	0	299
$\tilde{V}^R_0$	$\eta^u_{RR} = +1\,(\lambda/M_{LQ})^2$		0	793
$V^L_{1/2}$		$\eta^d_{LR} = +1\,(\lambda/M_{LQ})^2$	2	355
$V^R_{1/2}$	$\eta^u_{RL} = +1\,(\lambda/M_{LQ})^2$	$\eta^d_{RL} = +1\,(\lambda/M_{LQ})^2$	2	902
$\tilde{V}^L_{1/2}$	$\eta^u_{LR} = +1\,(\lambda/M_{LQ})^2$		2	993
V^L_1	$\eta^u_{LL} = +2\,(\lambda/M_{LQ})^2$	$\eta^d_{LL} = +1\,(\lambda/M_{LQ})^2$	0	1103

Table 2: Coupling coefficients η^q_{if}, fermion number F and 95% cl lower limits on M_{LQ}/λ for scalar (S) and vector (V) leptoquarks, taking the most conservative values from a variation of different parton distributions. The notation indicates the lepton chirality *L, R* and weak isospin $I = 0,\ 1/2,\ 1$. $\tilde{S}$ and $\tilde{V}$ differ by two units of hypercharge from S and V. Note that limits on the coupling λ are only meaningful for leptoquark masses $M_{LQ} > \sqrt{s}$.

4 Conclusion

The neutral current reaction $e^+p \to e^+\,\mathrm{hadrons}$ has been measured at high momentum transfers Q^2 between $180\ \mathrm{GeV}^2$ and $30,000\ \mathrm{GeV}^2$. The differential cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ is well described over six orders of magnitude by the Standard Model expectation. The data have been analyzed to search for new phenomena mediated through $(\bar{e}\, e)(\bar{q}\, q)$ contact interactions. No significant signal for compositeness and virtual leptoquark exchange has been found.

Limits on $(e\, q)$ compositeness or substructure have been derived within a model independent analysis. The lower limits of the scale parameters $\Lambda^{\pm}$ range between 1.2 TeV and 4.5 TeV for a coupling strength $g^2/4\,\pi = 1$, depending on the chiral structure of the model. These values are compatible and of similar size like those obtained by the ZEUS [7] and LEP [8] collaborations. More stringent, model dependent bounds have been extracted from atomic parity violation experiments at very low momentum transfer [6].

A leptoquark analysis yields lower limits on M_{LQ}/λ which approach 1 TeV for vector leptoquarks with couplings to *up* quarks. Corresponding bounds on the coupling λ can be derived for leptoquark masses $M_{LQ} > \sqrt{s}$ exceeding the center of mass energy. These measurements complement the direct searches for leptoquarks at HERA [9, 10]. Supplementary information comes from low energy atomic parity violation experiments and leptonic π decays, which provide more stringent, but model dependent limits [6, 11].

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