Search for New Physics in $e^{\pm}q$ Contact Interactions at HERA

H1 Collaboration

Abstract

A search for physics beyond the Standard Model in neutral current deep inelastic scattering at high Q^2 is performed in $e^{\pm}p$ collisions at HERA. The full H1 data sample corresponding to an integrated luminosity of 440 pb^{-1} is used. No significant deviation from the Standard Model is observed. Limits are derived on the compositeness scale for general contact interactions, on the ratio of mass to the Yukawa coupling for heavy-leptoquark models, on the effective Plank-mass scale in models with large extra dimensions and on the quark radius.

1 Introduction

Deep inelastic neutral current scattering $ep \to eX$ at high squared momentum transfer Q^2 allows one to study the structure of eq interactions at short distances and to search for new phenomena beyond the Standard Model (SM). The concept of four-fermion contact interactions (CI) provides a convenient method to investigate the interference of any new particle field associated to large scales with the γ and Z fields of the SM.

The present analysis is a continuation of previous studies [1] and is based on $e^{\pm}p$ H1 data that correspond to the integrated luminosity of 440 pb^{-1} [2–5].

2 Analysis Method

The analysis investigates the measured cross sections $\mathrm{d}\sigma/\mathrm{d}Q^2$ and performs quantitative tests of the SM or CI models, applying a minimisation of the χ^2 function:

$$\chi^2 = \sum_i \frac{\left(\sigma_i^{\mathrm{exp}} - \sigma_i^{\mathrm{th}}\,(1 - \sum_k \Delta_{ik}(\varepsilon_k))\right)^2}{\delta_{i,stat}^2\,\sigma_i^{\mathrm{exp}}\sigma_i^{\mathrm{th}}\,(1 - \sum_k \Delta_{ik}(\varepsilon_k)) + (\delta_{i,uncor}\,\sigma_i^{\mathrm{exp}})^2} + \sum_k \varepsilon_k^2\ . \tag{1}$$

Here σ_i^{exp} and σ_i^{th} are the experimental and theoretical cross sections for the measurement point i, and $\sigma_{i,stat}$ and $\sigma_{i,uncor}$ correspond to relative statistical and uncorrelated systematic errors. The functions $\Delta_{ik}(\varepsilon_k)$ describe correlated systematic errors for point i associated to a source k. They depend on the fit parameters ε_k, which are effective pulls caused by systematics. The analysis method is described in more detail elsewhere [1, 6].

3 Models of Contact Interactions

3.1 General contact interactions

Four-fermion CI represent an effective theory which describes low-energy effects due to new physics at much higher energy scales. The most general chiral invariant Lagrangian for neutral current vector-like four-fermion contact interactions can be written in the form [7, 8]:

$$\mathcal{L}_V \;=\; \sum_q \sum_{a,b=L,R} \eta_{ab}^q\,(\bar{e}_a\gamma_\mu e_a)(\bar{q}_b\gamma^\mu q_b)\ , \tag{2}$$

where a and b indicate the left-handed and right-handed fermion helicities and q indicates the flavour of the quark. In case of general models allowing compositeness or substructure for fermion the contact interaction coefficients are defined by:

$$\eta_{ab}^q = \epsilon_{ab}\,\frac{4\pi}{\Lambda^2}. \tag{3}$$

Each particular scenario is defined by a set of coefficients ϵ_{ab}, each of which may take the values ± 1 or 0, and the compositeness scale Λ. Lower limits at 95% confidence level (CL) on $\Lambda^{\pm}$ are presented in table 1.

3.2 Leptoquarks

Leptoquarks couple to lepton–quark pairs and appear in extensions of the Standard Model which try to connect the lepton and quark sectors. They carry lepton (L), baryon (B) and a fermion number $F = L{+}3\,B$. According to the Buchmüller, Rückl and Wyler framework [9] there are 14 possible leptoquark states: seven scalar and seven vector. For high enough mass scales the leptoquark mass M_{LQ} and its coupling λ are related to the contact interaction coefficients via:

$$\eta^q_{ab} = \epsilon^q_{ab}\,\frac{\lambda^2}{M^2_{LQ}}\ , \tag{4}$$

where the coefficients ϵ^q_{ab} depend on the leptoquark type [10]. The notation, quantum numbers and lower limits at 95% confidence level (CL) on M_{LQ}/λ are presented in table 2.

3.3 Large extra dimensions

It has been suggested that the gravitational scale M_S in $4+n$ dimensional string theory may be as low as the electroweak scale of order TeV [11]. The relation to the Planck scale $M_P \sim 10^{19}$ GeV and the size R of the n compactified extra dimensions is given by $M^2_P \sim R^n\, M_S^{2+n}$. In some models with large extra dimensions the SM particles reside on a four-dimensional brane, while the spin 2 graviton propagates into the extra spatial dimensions and appears in the four-dimensional world as a tower of massive Kaluza-Klein states with a level spacing $\Delta m = 1/R$. The gravitons couple to the SM particles via the energy-momentum tensor with a tiny strength given by the inverse Planck scale. However, the summation over the enormous number of Kaluza-Klein states up to the ultraviolet cut-off scale, taken as M_S, leads to an effective contact-type interaction [12] with a coupling:

$$\eta_G = \frac{\lambda}{M^4_S}\ . \tag{5}$$

The coefficient λ depends on the details of the theory and is expected to be of order unity. However, by convention, one also allows for a negative coupling and thus sets $\lambda = \pm 1$. Lower limits at 95% confidence level (CL) on M_s are presented in table 4.

3.4 Form factors

A fermion substructure can also be formulated by assigning a finite size to the electroweak charge distributions. It is convenient to introduce electron and quark form factors $f(Q^2)$ which reduce the SM cross section at high momentum transfer [13]:

$$f(Q^2) = 1 - \frac{R^2}{6} Q^2 \,, \tag{6}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} = \frac{\mathrm{d}\sigma^{\mathrm{SM}}}{\mathrm{d}Q^2} f_e^2(Q^2)\, f_q^2(Q^2) \,, \tag{7}$$

where R is the root of the mean squared radius of the electroweak charge distribution. An upper limit at 95% CL on the quark radius $R_q < 0.65 \cdot 10^{-18}$ m, is derived assuming point-like leptons ($f_e \equiv 1$), for the present analysis of 1994-2007 $e^{\pm}p$ data.

4 Summary

Neutral current deep inelastic e^-p and e^+p scattering cross section measurements are analysed to search for new phenomena mediated through CI. The data are well described by the SM expectations. Limits on the strength parameters of various models are presented.

Lower limits at 95% CL on eq compositeness scale parameters $\Lambda^{\pm}$ are derived within a model independent analysis. They range between 3.7 TeV and 7.4 TeV depending on the chiral structure. A study of virtual leptoquark exchange yields lower limits on the ratio M_{LQ}/λ between 0.4 TeV and 1.94 TeV. Squarks in R-parity violating supersymmetry with masses satisfying $M_{\tilde{u}}/\lambda'_{1j1} < 0.94$ TeV and $M_{\tilde{d}}/\lambda'_{11k} < 0.58$ TeV can be excluded. Possible effects of low scale quantum gravity with gravitons propagating into extra spatial dimensions are searched for. Lower limits on the effective Planck scale M_S of $0.90 - 0.91$ TeV are found. A form factor approach yields an upper limit on the size of light u and d quarks of $R_q < 0.65 \cdot 10^{-18}$ m assuming point-like electrons.

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H1 Search for General Compositeness			
	$\eta_{ij}^{eq} = \epsilon_{ij}^{eq} 4\pi/\Lambda^2$	$e^{\pm}p$ (H1 prel.)	
Model	[ϵ_{LL}, ϵ_{LR}, ϵ_{RL}, ϵ_{RR}]	Λ^+ [TeV]	Λ^- [TeV]
LL	[+1, 0, 0, 0]	3.7	4.1
LR	[0, +1, 0, 0]	4.4	4.1
RL	[0, 0, +1, 0]	4.2	4.0
RR	[0, 0, 0, +1]	3.7	3.8
VV	[+1, +1, +1, +1]	5.4	7.4
AA	[+1, −1, −1, +1]	4.3	5.2
VA	[+1, −1, +1, −1]	3.3	3.6
$X1$	[+1, −1, 0, 0]	3.3	4.5
$X2$	[+1, 0, +1, 0]	5.1	5.0
$X3$	[+1, 0, 0, +1]	5.0	5.2
$X4$	[0, +1, +1, 0]	5.3	5.3
$X5$	[0, +1, 0, +1]	5.1	5.0
$X6$	[0, 0, +1, −1]	4.1	3.2
$U1$	[+1, −1, 0, 0]	4.0	4.7
$U2$	[+1, 0, +1, 0]	5.2	5.5
$U3$	[0, +1, 0, +1]	5.2	7.1
$U4$	[0, +1, +1, 0]	5.3	6.4
$U5$	[0, +1, 0, +1]	5.2	5.8
$U6$	[0, 0, +1, −1]	4.1	3.5

Table 1: Relations between couplings [ϵ_{LL},ϵ_{LR}, ϵ_{RL}, ϵ_{RR}] for the compositeness models and lower limits at 95% CL on compositeness scale parameters $\Lambda^{\pm}$. For models U1 to U6 the couplings for d quarks are zero, for all the other models the coupling structure is the same for d and u quarks. Results are given for the present analysis of 1994-2007 $e^{\pm}p$ data.

H1 Search for Heavy Leptoquarks				
	$\eta^q_{ab} = \epsilon^q_{ab} \cdot (\lambda/M_{LQ})^2$			$e^\pm p$ (H1 prel.)
LQ	ϵ^u_{ab}	ϵ^d_{ab}	F	M_{LQ}/λ [GeV]
S_0^L	$\epsilon^u_{LL} = +\frac{1}{2}$		2	940
S_0^R	$\epsilon^u_{RR} = +\frac{1}{2}$		2	830
$\tilde{S}_0^R$		$\epsilon^d_{RR} = +\frac{1}{2}$	2	400
$S_{1/2}^L$	$\epsilon^u_{LR} = -\frac{1}{2}$		0	1040
$S_{1/2}^R$	$\epsilon^u_{RL} = -\frac{1}{2}$	$\epsilon^d_{RL} = -\frac{1}{2}$	0	800
$\tilde{S}_{1/2}^L$		$\epsilon^d_{LR} = -\frac{1}{2}$	0	580
S_1^L	$\epsilon^u_{LL} = +\frac{1}{2}$	$\epsilon^d_{LL} = +1$	2	630
V_0^L		$\epsilon^d_{LL} = -1$	0	900
V_0^R		$\epsilon^d_{RR} = -1$	0	710
$\tilde{V}_0^R$	$\epsilon^u_{RR} = -1$		0	1350
$V_{1/2}^L$		$\epsilon^d_{LR} = +1$	2	510
$V_{1/2}^R$	$\epsilon^u_{RL} = +1$	$\epsilon^d_{RL} = +1$	2	1280
$\tilde{V}_{1/2}^L$	$\epsilon^u_{LR} = +1$		2	1440
V_1^L	$\epsilon^u_{LL} = -2$	$\epsilon^d_{LL} = -1$	0	1940

Table 2: Coupling coefficients η^q_{ab}, fermion number $F = L + 3B$ and 95% CL lower limits on M_{LQ}/λ for scalar (S) and vector (V) leptoquarks. Results are given for the present analysis of 1994-2007 $e^\pm p$ data. L and R denote the lepton chirality. The subscript $I = 0,\ 1/2,\ 1$ is the weak isospin. $\tilde{S}$ and $\tilde{V}$ differ by two units of hypercharge from S and V respectively. Quantum numbers and helicities refer to e^-q and $e^-\bar{q}$ states.

H1 Search for Squarks			
$\not{R}_p$ coupling		ϵ^q_{ab}	$e^{\pm}p$ (H1 prel.) $M_{\tilde{q}}/\lambda'$ [GeV]
λ'_{11k}	$e^+d \rightarrow \tilde{u}^{(k)}$	$\epsilon^u_{LL} = +\frac{1}{2}$	940
λ'_{1j1}	$e^-u \rightarrow \tilde{d}^{(j)}$	$\epsilon^d_{LR} = -\frac{1}{2}$	580

Table 3: Coefficients ϵ^q_{ab} and 95% CL lower limits on $M_{\tilde{q}}/\lambda'$ for R_p violating couplings λ'_{ijk} [14], where i, j, k are family indices, to squarks. The λ'_{11k} coupling corresponds to the S^L_0 leptoquark coupling and the λ'_{1j1} coupling corresponds to the $\tilde{S}^L_{1/2}$ leptoquark coupling shown in table 2. Results are given for the present analysis of 1994-2007 $e^{\pm}p$ data.

H1 Search for Large Extra Dimensions	
$\eta_G = \lambda/M_S^4$ coupling λ	$e^{\pm}p$ (H1 prel.) M_S [TeV]
$+1$	0.90
-1	0.91

Table 4: Lower limits for a model with large extra dimensions on the gravitational scale M_S at 95% CL assuming positive ($\lambda = +1$) or negative ($\lambda = -1$) coupling from the present analysis of 1994-2007 $e^{\pm}p$ data.

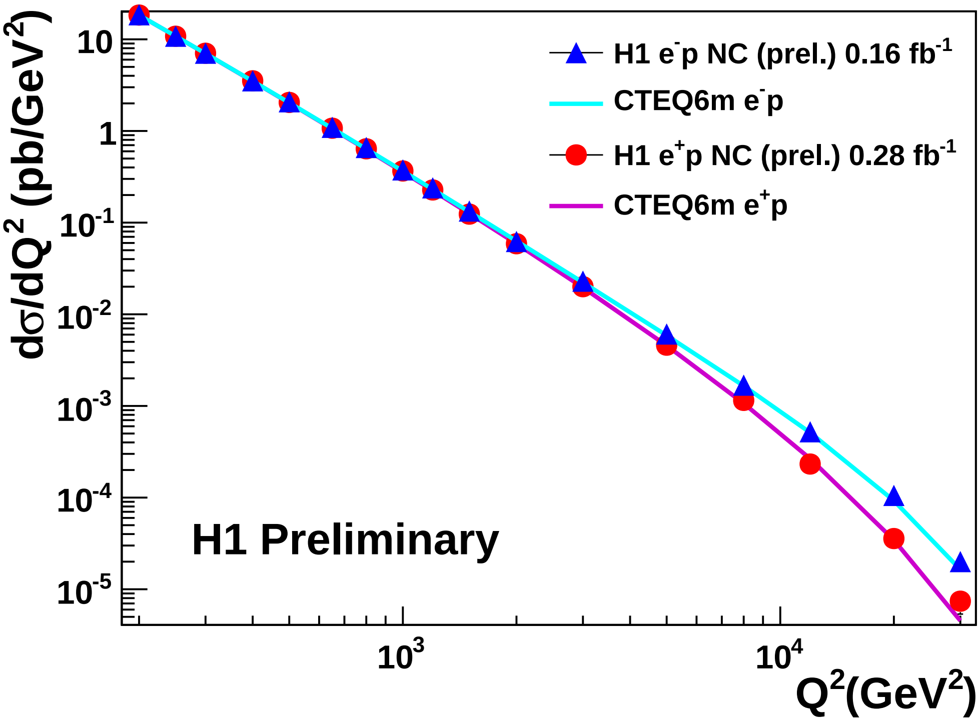

Figure 1: Cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ at $\sqrt{s} = 319$ GeV for $e^+p \to e^+X$ and $e^-p \to e^-X$ scattering. H1 data are compared with Standard Model expectations using the CTEQ6m parton distributions [15].

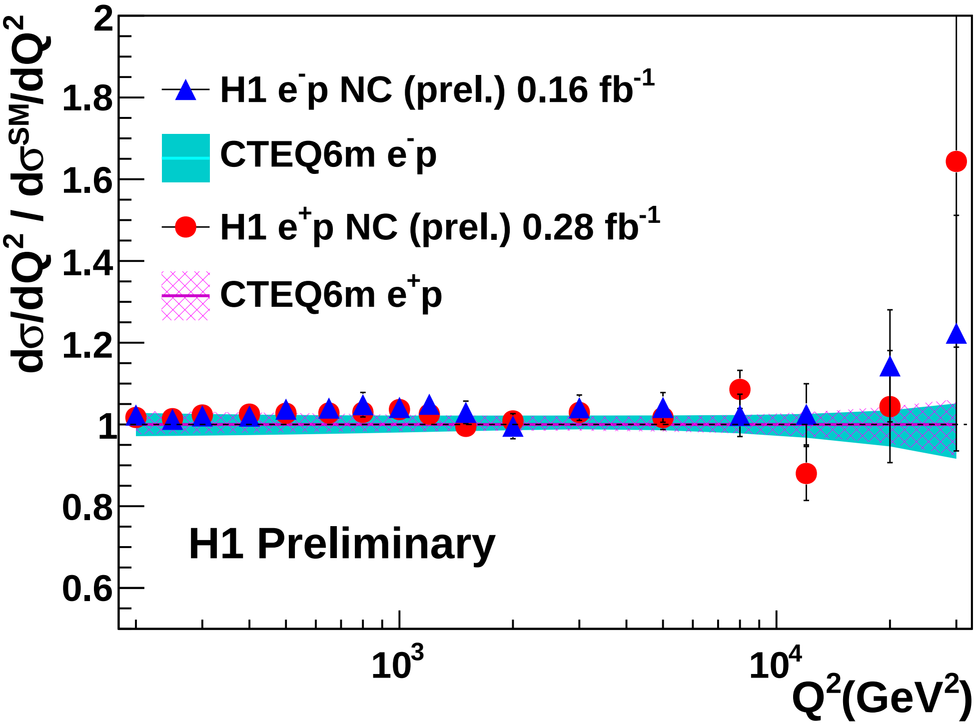

Figure 2: Ratio of the measured cross section to the Standard Model prediction determined using CTEQ6m parton distribution function [15] for $e^+p \to e^+X$ and $e^-p \to e^-X$ scattering.

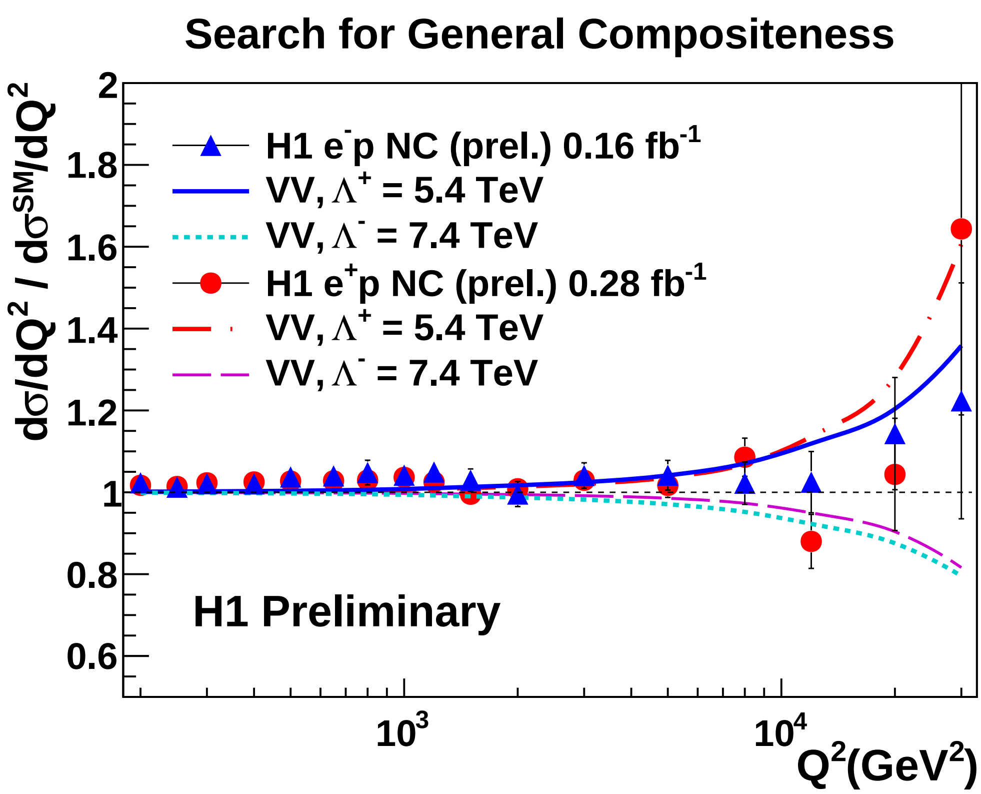

Figure 3: NC cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ at $\sqrt{s} = 319$ GeV normalised to the Standard Model expectation. H1 $e^{\pm}p$ scattering data are compared with curves corresponding to 95% CL exclusion limits obtained from the combined data for VV compositeness scales Λ^+ and Λ^- couplings.

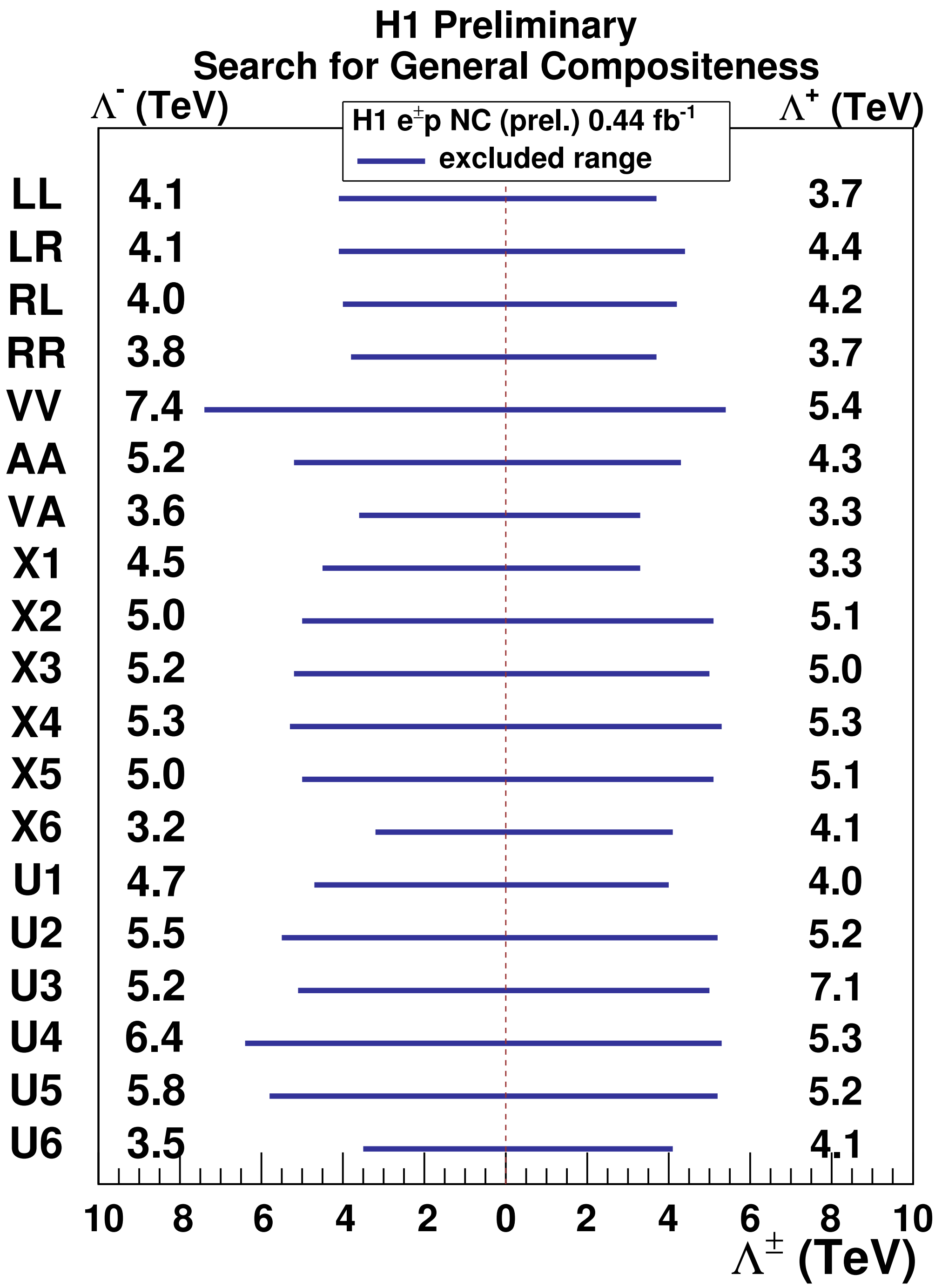

Figure 4: Exclusion regions and lower limits (95% CL) on compositeness scale parameters $\Lambda^{\pm}$ for various chiral models obtained from the combined $e^{\pm}p$ data applying a frequentist method.

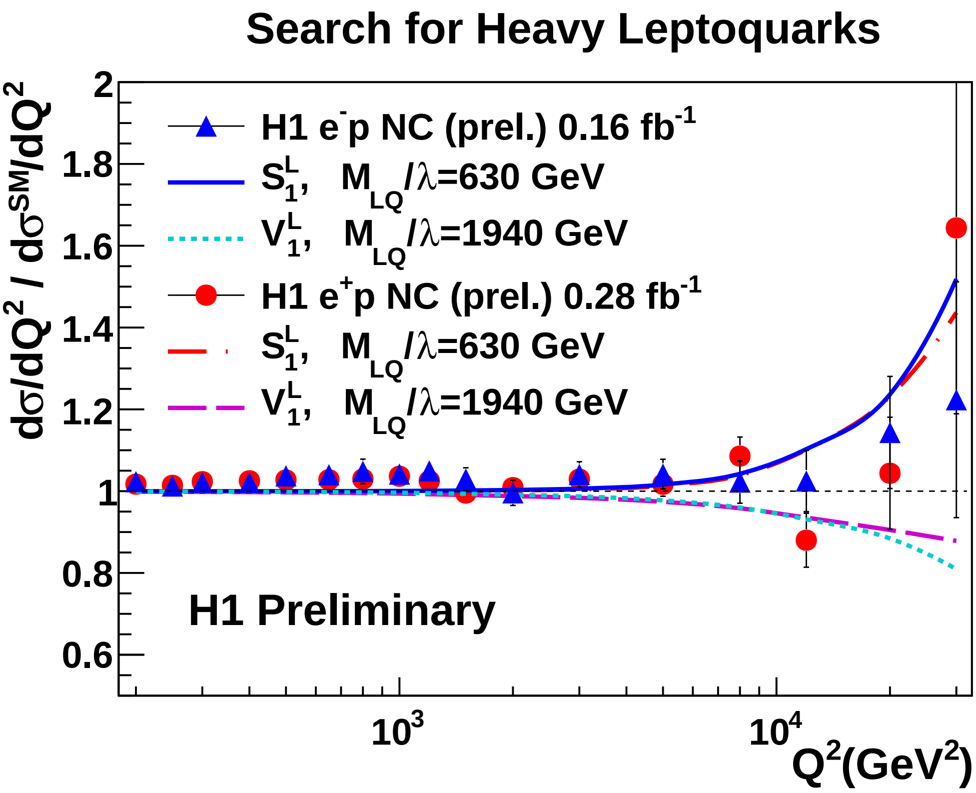

Figure 5: NC cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ at $\sqrt{s} = 319$ GeV normalised to the Standard Model expectation. H1 $e^{\pm}p$ scattering data are compared with curves corresponding to 95% CL exclusion limits obtained from combined data for M/λ of leptoquarks S_1^L and V_1^L.

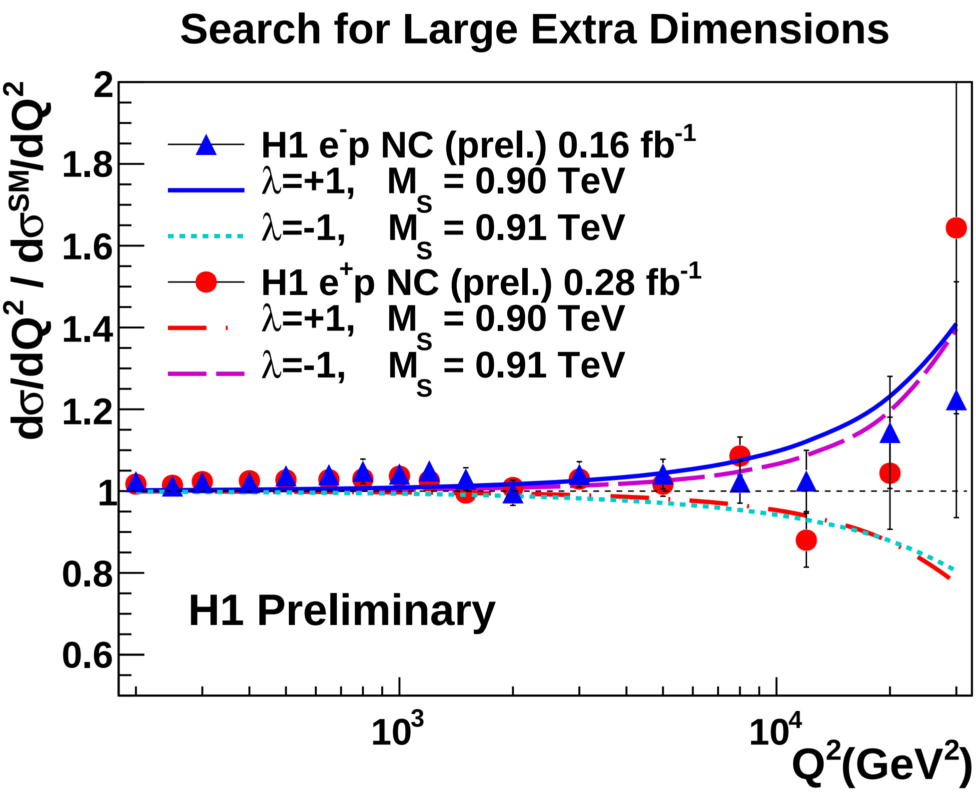

Figure 6: NC cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ at $\sqrt{s} = 319$ GeV normalised to the Standard Model expectation. H1 $e^{\pm}p$ scattering data are compared with curves corresponding to 95% CL exclusion limits obtained from combined data for gravitational scales M_S assuming positive ($\lambda = +1$) and negative ($\lambda = -1$) couplings.

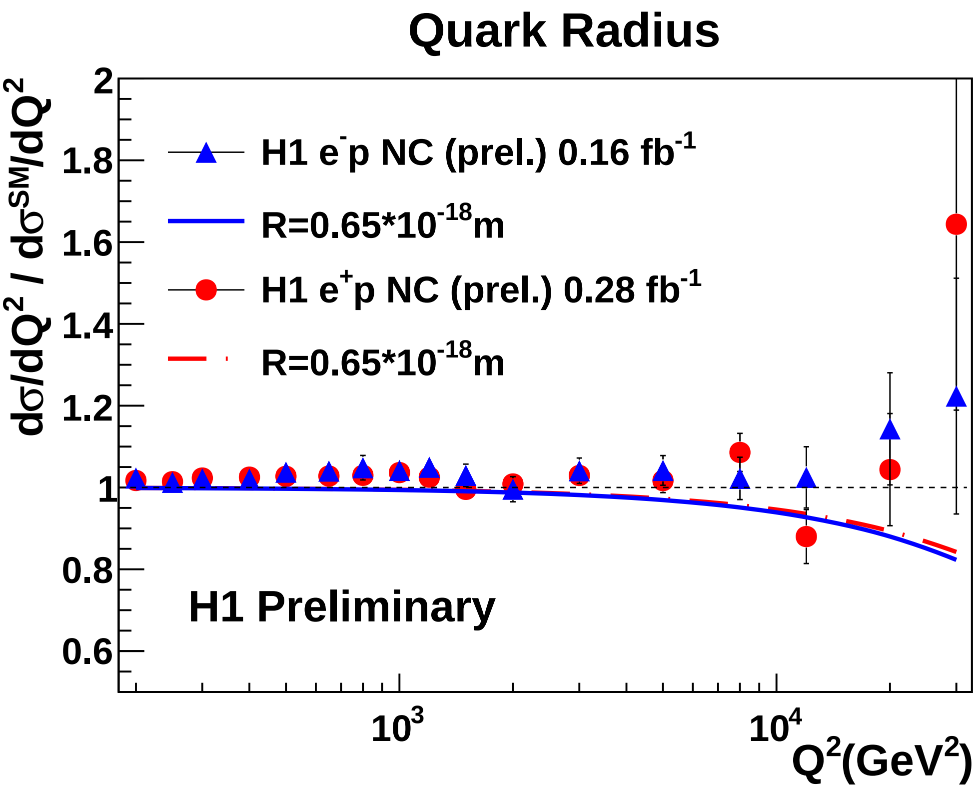

Figure 7: NC cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ at $\sqrt{s} = 319$ GeV normalised to the Standard Model expectation. H1 $e^{\pm}p$ scattering data are compared with curves corresponding to 95% CL exclusion limits obtained from combined data for R_q assuming point-like leptons.