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Search for Compositeness, Leptoquarks and Large Extra Dimensions in e^-q and e^+q Contact Interactions at HERA

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Abstract

Deep-inelastic $e^{\pm}p$ scattering at high momentum transfer Q^2 is used to search for eq contact interactions associated to scales not directly accessible at HERA. The cross section measurements $\mathrm{d}\sigma/\mathrm{dQ}^2$, corresponding to luminosities of $15.2\ \mathrm{pb}^{-1}$ of e^-p data and $81.5\ \mathrm{pb}^{-1}$ of e^+p data, are well described by the Standard Model and are analysed to set constraints on new phenomena. For conventional contact interactions lower bounds can be set on eq compositeness scales $\Lambda^{\pm}$ at $1.6 - 9.2\ \mathrm{TeV}$ and on leptoquarks with a ratio mass over coupling M/λ of $0.3 - 1.7\ \mathrm{TeV}$. A search for low scale gravitational effects through the exchange of Kaluza-Klein excitations of gravitons in models with large extra dimensions results in lower limits on the effective Planck scale M_S of $0.63\ \mathrm{TeV}$ and $0.93\ \mathrm{TeV}$ for positive and negative coupling, respectively.

Abstract: 951, 952
Parallel session: 11, 3
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1 Introduction

Deep inelastic neutral current scattering $ep \to eX$ at very high squared momentum transfer Q^2 allows to study the structure of eq interactions at short distances and to search for new phenomena beyond the Standard Model. A convenient tool to investigate the interference of a new point-like particle with the γ and Z fields is the concept of four-fermion contact interaction. This paper considers conventional contact interactions, such as general models of compositeness and the exchange of heavy leptoquarks, as well as low scale quantum gravity effects, which may be mediated via gravitons coupling to Standard Model particles and propagating into large extra spatial dimensions.

The preliminary results presented here are based on recent e^-p and e^+p cross section measurements and are combined with a previous contact term analysis of e^+p scattering [1].

2 Data and analysis method

The data have been collected with the H1 detector at HERA and correspond altogether to integrated luminosities of $15.2\ \mathrm{pb}^{-1}$ of e^-p collisions taken in 1998/99 at $\sqrt{s} = 318\ \mathrm{GeV}$, $45.9\ \mathrm{pb}^{-1}$ of e^+p collisions taken in 1999/2000 at $\sqrt{s} = 318\ \mathrm{GeV}$, and $35.6\ \mathrm{pb}^{-1}$ of e^+p scattering recorded during 1994/97 at a lower center of mass energy $\sqrt{s} = 300\ \mathrm{GeV}$. Details of the cross section measurements can be found elsewhere [2].

The present contact interaction analysis uses the same methods as described in ref. [1]. The differential cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ is compared to the Standard Model prediction and deviations expressed in terms of model parameters are searched for. The experimental and theoretical uncertainties, in particular the impact of different parton distributions, are properly considered in the χ^2 analysis and the derivation of scale limits. The cross sections $\mathrm{d}\sigma(e^-p \to e^-X)/\mathrm{d}Q^2$ and $\mathrm{d}\sigma(e^+p \to e^-X)/\mathrm{d}Q^2$ of the new data, shown in figure 1, are well described by the Standard Model in the range of $Q^2 = 200 - 30,000\ \mathrm{GeV}^2$. Fits to the Standard Model expectation yield $\chi^2 = 14.5/16\ \mathrm{dof}$ with a normalisation $f_n = 1.010$ for the e^-p data and $\chi^2 = 13.2/16\ \mathrm{dof}$ with $f_n = 0.991$ for the e^+p data. The phenomenological models under investigation and their analytical treatment are discussed in ref. [1]. In the combined analysis all three data sets are treated as independent samples with individual normalisation and measurement uncertainties.

3 Compositeness

The most general chiral invariant Lagrangian for neutral current vector-like contact interactions can be written in the form [3, 4]

$$\mathcal{L}_V = \sum_{a,b=L,R} \eta^q_{ab}\, (\bar{e}_a \gamma_\mu e_a)(\bar{q}_b \gamma^\mu q_b) \ . \qquad (1)$$

For each quark flavour $q = u,\, d$ there are four coupling coefficients $\eta^q_{ab} = \epsilon(g/\Lambda^q_{ab})^2$, where a and b indicate the $L,\ R$ fermion helicities, g is the overall coupling strength, Λ^q_{ab} is a scale parameter and ϵ determines the interference sign with the Standard Model currents. In the study of possible fermion compositeness or substructure it is convenient to choose a coupling of $g^2 = 4\,\pi$ and to assume a common scale Λ for all quarks. Various scenarios of chiral structures are selected by the choice of $\epsilon = \pm 1$ or 0.

Lower limits on compositeness scale parameters $\Lambda^\pm$, associated to positive or negative interference, are summarised in table 1. As example fits of the e^-p and e^+p cross sections to the VV model are shown in figure 3. The e^-p data exhibit despite the lower luminosity for some models, *e.g.* AA^+, a higher sensitivity than the e^+p data and both lepton polarities complement each other. A combined analysis of all $e^\pm p$ data sets yields a substantial improvement on lower limits of compositeness scale parameters compared to the previous publication [1]. The results are listed in table 1 and displayed in figure 2. Limits on Λ^+ range between 3.5 and 9.2 GeV and on Λ^- between 1.6 and 5.8 GeV depending on the chiral structure. The results of direct searches for (eq) compositeness are competitive with those of other experiments at HERA [5], LEP [6] and TEVATRON [7].

4 Leptoquarks

Leptoquarks couple to lepton–quark pairs and appear in extensions of the Standard Model which try to establish a connection between leptons and quarks. They are colour triplet scalar or vector bosons, carrying lepton (L) and baryon (B) number. A fermion number $F = L + 3\,B$ is preserved, which takes *e.g.* values of $F = 2$ for e^-q and $F = 0$ for e^+q states. One therefore expects different sensitivities to particular leptoquark types from both lepton beam polarities. The leptoquark mass M_{LQ} and its coupling λ are related to the contact interaction coefficients via $g/\Lambda = \lambda/M_{LQ}$. The notation and the couplings to u and d quarks are given in table 2.

As example figure 4 shows possible contributions of the leptoquarks S_1^L and V_1^L to the e^-p cross section and of the leptoquarks $S_{1/2}^R$ and $V_{1/2}^R$ to the e^+p cross section. Each pair of leptoquarks couples with the same chiral structure but different strength and sign to u and d quarks. Limits on the ratio M_{LQ}/λ of all leptoquark species are summarised in table 2. In some cases, *e.g.* S_1^L and V_1^L, the e^-p data give more restrictive results than e^+p scattering despite the lower luminosity. The combined analysis of all $e^\pm p$ data sets helps to further constrain the leptoquark bounds reaching values of $M_{LQ}/\lambda \simeq 1.7$ TeV. It should be emphasised 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 far above 300 GeV are excluded for all types of leptoquarks (except $\tilde{S}_0^R$) with a coupling of $\lambda \gtrsim 1$. These results complement the direct leptoquark searches at HERA [8] and are competitive with limits derived in e^+e^- experiments [6].

5 Large extra dimensions

It has recently been suggested that the gravitational scale in $4+n$ dimensional string theory may be as low as the electroweak scale [9]. In models with large extra dimensions the spin 2 graviton propagates into the extra spatial dimensions and appears in the 4-dimensional world as a spectrum of massive Kaluza-Klein states. The exchange of a whole Kaluza-Klein tower between

Standard Model particles leads to an effective contact interaction with a coupling coefficient $\eta_G = \lambda/M_S^4$ [10]. By convention the coupling strength is set to $\lambda = \pm 1$.

Possible effects of Kaluza-Klein graviton exchange on the cross section measurements are shown in figure 5. Lower limits on the scale parameter M_S, derived from fits to the $\mathrm{d}\sigma/\mathrm{d}Q^2$ distribution including gravitational effects, are summarised in table 3. For the e^-p data stronger bounds are obtained for positive coupling than for negative coupling. The opposite behaviour is observed in e^+p scattering. Again, both lepton polarities complement each other and a combined analysis of all $e^\pm p$ data yields limits on M_S of 0.63 TeV for positive coupling $\lambda = +1$ and 0.93 TeV for negative coupling $\lambda = -1$. The effect of a common gravitational scale M_S on the combined e^+p and the e^-p scattering data is illustrated in figure 6. Similar investigations of virtual graviton exchange in e^+e^- annihilation provide comparable limits [11].

6 Conclusions

Neutral current deep inelastic e^-p and e^+p cross section measurements are analysed to search for new phenomena mediated through $(\bar{e}e)(\bar{q}q)$ contact interactions. No significant signal for compositeness, virtual leptoquark or graviton exchange is observed. Both lepton charges provide complementary information and a combined analysis yields improved limits on scales of new physics.

Limits on (eq) compositeness scale parameters $\Lambda^\pm$ are derived within a model independent analysis. They range between 1.6 TeV and 9.2 TeV depending on the chiral structure and sign of interference.

A study of virtual leptoquark exchange yields lower limits on the ratio M_{LQ}/λ between 0.3 TeV and 1.7 TeV. These measurements extend the direct leptoquark searches at HERA to high masses $M_{LQ} > \sqrt{s}$.

Possible effects of low scale quantum gravity with gravitons coupling to Standard Model particles and propagating into extra spatial dimensions are searched for. Lower limits on the effective Planck scale M_S of 0.63 TeV and 0.93 TeV for positive and negative coupling, respectively, are found.

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Table 1: Compositeness scale parameters $\Lambda^\pm$ (95% CL lower limits) for various chiral structures. Preliminary results are given for e^-p data at $\sqrt{s} = 318\,\mathrm{GeV}$, for e^+p data at $\sqrt{s} = 318\,\mathrm{GeV}$ and for a combined analysis also including e^+p data at $\sqrt{s} = 300\,\mathrm{GeV}$ from [1].

	$e^-p\ (318\,\mathrm{GeV})$		$e^+p\ (318\,\mathrm{GeV})$		all e^+p & e^-p	
coupling	Λ^+ [TeV]	Λ^- [TeV]	Λ^+ [TeV]	Λ^- [TeV]	Λ^+ [TeV]	Λ^- [TeV]
LL	3.1	1.4	3.0	1.5	4.3	1.6
LR	1.7	1.4	4.7	1.9	5.4	1.8
RL	1.7	1.4	4.6	1.9	5.4	1.9
RR	3.0	1.5	3.1	1.5	4.3	1.6
VV	4.5	2.6	7.4	2.4	9.2	3.0
AA	4.0	1.7	2.5	5.4	3.5	5.8
VA	2.7	2.5	3.6	3.8	3.9	4.0
$LL+RR$	4.2	2.2	4.1	1.6	5.9	2.0
$LR+RL$	2.2	1.6	6.4	2.1	7.4	2.1

Table 2: Coupling coefficients η^q_{ab}, fermion number F and 95% CL lower limits on M_{LQ}/λ for scalar (S) and vector (V) leptoquarks, including systematics from different parton distributions. Preliminary results are given for e^-p data at $\sqrt{s} = 318$ GeV, e^+p data at $\sqrt{s} = 318$ GeV and for a combined analysis also including e^+p data at $\sqrt{s} = 300$ GeV from [1]. 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. Quantum numbers and helicities are given for e^-q and $e^-\bar{q}$ states. Limits on the coupling λ are only meaningful for leptoquark masses $M_{LQ} > \sqrt{s}$.

LQ	η^u $[\lambda^2/M^2_{LQ}]$	η^d $[\lambda^2/M^2_{LQ}]$	F	e^-p (318 GeV) M_{LQ}/λ [GeV]	e^+p (318 GeV) M_{LQ}/λ [GeV]	all e^+p & e^-p M_{LQ}/λ [GeV]
S^L_0	$\eta^u_{LL} = +\frac{1}{2}$		2	720	760	1070
S^R_0	$\eta^u_{RR} = +\frac{1}{2}$		2	650	690	960
$\tilde{S}^R_0$		$\eta^d_{RR} = +\frac{1}{2}$	2	270	260	290
$S^L_{1/2}$	$\eta^u_{LR} = -\frac{1}{2}$		0	280	350	380
$S^R_{1/2}$	$\eta^u_{RL} = -\frac{1}{2}$	$\eta^d_{RL} = -\frac{1}{2}$	0	280	390	380
$\tilde{S}^L_{1/2}$		$\eta^d_{LR} = -\frac{1}{2}$	0	270	570	650
S^L_1	$\eta^u_{LL} = +\frac{1}{2}$	$\eta^d_{LL} = +1$	2	580	520	690
V^L_0		$\eta^d_{LL} = -1$	0	640	780	1030
V^R_0		$\eta^d_{RR} = -1$	0	540	640	810
$\tilde{V}^R_0$	$\eta^u_{RR} = -1$		0	550	410	530
$V^L_{1/2}$		$\eta^d_{LR} = +1$	2	320	480	480
$V^R_{1/2}$	$\eta^u_{RL} = +1$	$\eta^d_{RL} = +1$	2	490	1310	1510
$\tilde{V}^L_{1/2}$	$\eta^u_{LR} = +1$		2	500	1460	1690
V^L_1	$\eta^u_{LL} = -2$	$\eta^d_{LL} = -1$	0	740	520	680

Table 3: Preliminary results of lower limits (95% CL) on the gravitational scale M_S with positive ($\lambda = +1$) and negative ($\lambda = -1$) coupling for e^-p data at $\sqrt{s} = 318$ GeV, e^+p data at $\sqrt{s} = 318$ GeV and a combined analysis also including e^+p data at $\sqrt{s} = 300$ GeV from [1].

coupling	e^-p (318 GeV) M_S [TeV]	e^+p (318 GeV) M_S [TeV]	all e^+p & e^-p M_S [TeV]
$\lambda = +1$	0.68	0.50	0.63
$\lambda = -1$	0.48	0.89	0.93

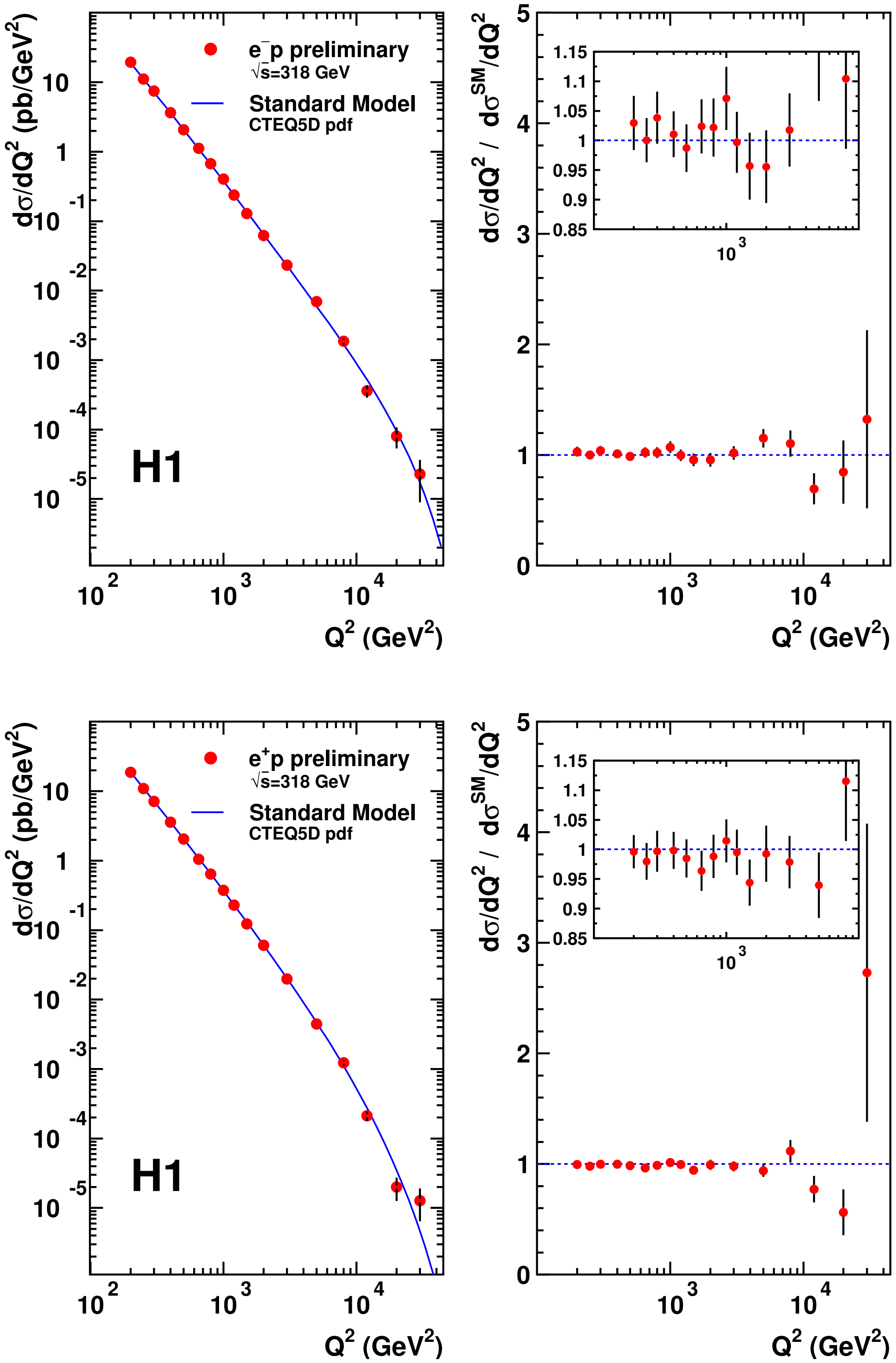

Figure 1: Differential cross sections $\mathrm{d}\sigma/\mathrm{d}Q^2$ at $\sqrt{s} = 318$ GeV for $e^-p \rightarrow e^-X$ (top) and $e^+p \rightarrow e^+X$ (bottom) scattering. H1 data are compared with Standard Model expectations using CTEQ5D parton distributions. The errors include statistics and uncorrelated experimental systematics. The normalisation uncertainties are 3% (e^-p data) and 1.5% (e^+p data).

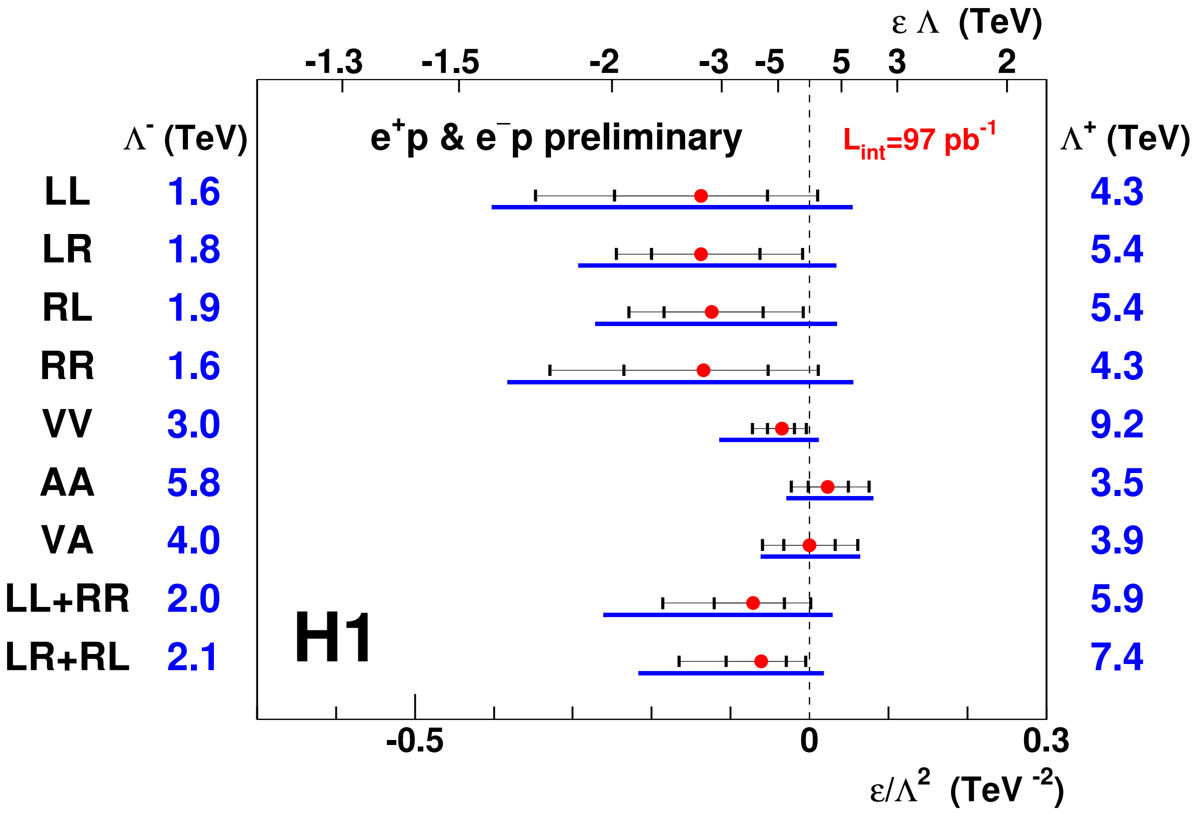

Figure 2: Analysis results of the parameter ϵ/Λ^2 for compositeness models using the combined e^+p ($\mathcal{L} = 81.5$ pb^{-1}) and e^-p ($\mathcal{L} = 15.2$ pb^{-1}) data. The thick horizontal bars indicate the 95% CL limits on Λ^+ and Λ^- including parton distribution uncertainties; values outside these regions are excluded. The corresponding thin horizontal bars show the fit results for ϵ/Λ^2 using CTEQ5D parton distributions; inner and outer error bars represent one and two standard deviations respectively. The scale for $\epsilon\,\Lambda$ is shown for convenience.

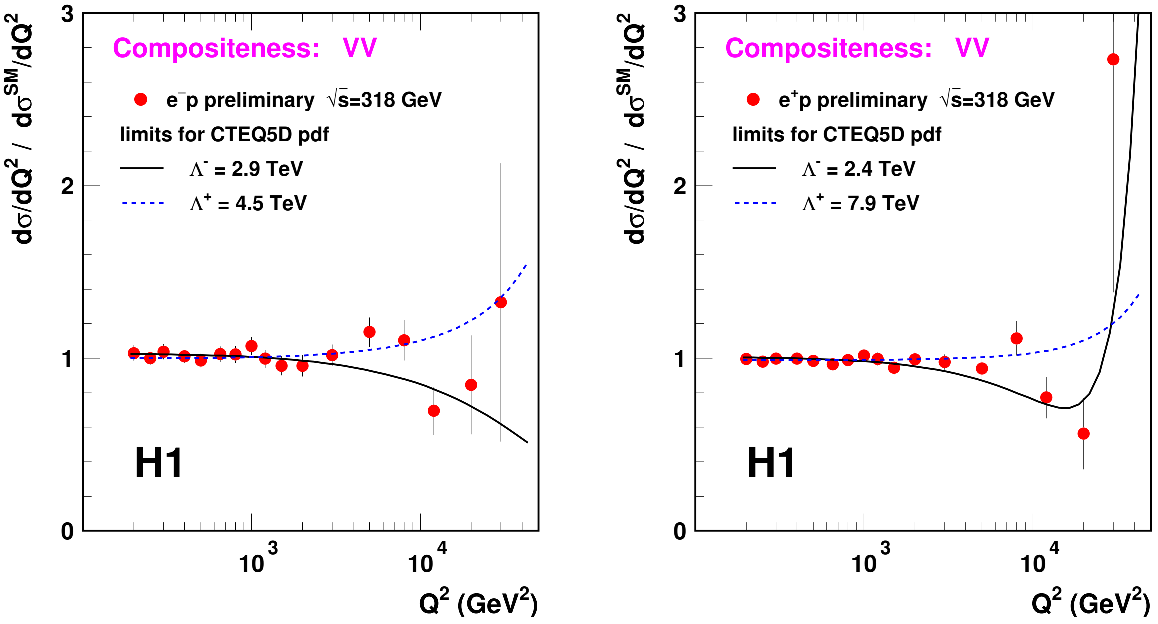

Figure 3: NC cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ at $\sqrt{s} = 318\ \mathrm{GeV}$ normalised to the Standard Model expectation using CTEQ5D parton distributions. H1 data of e^-p and e^+p scattering are compared with fits to VV compositeness models corresponding to 95% CL exclusion limits of Λ^+ and Λ^-. The errors represent statistics and uncorrelated experimental systematics.

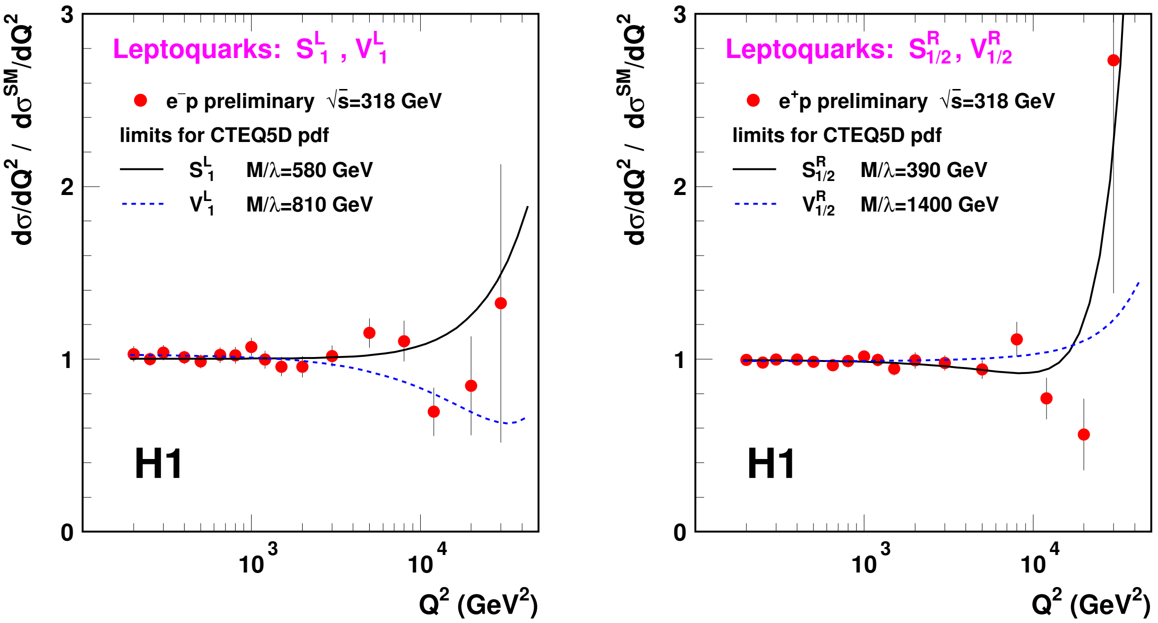

Figure 4: NC cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ at $\sqrt{s} = 318\ \mathrm{GeV}$ normalised to the Standard Model expectation using CTEQ5D parton distributions. H1 data compared with 95% CL exclusion limits of leptoquarks: e^-p scattering with S_1^L and V_1^L and e^+p scattering with $S_{1/2}^R$ and $V_{1/2}^R$. The errors represent statistics and uncorrelated experimental systematics.

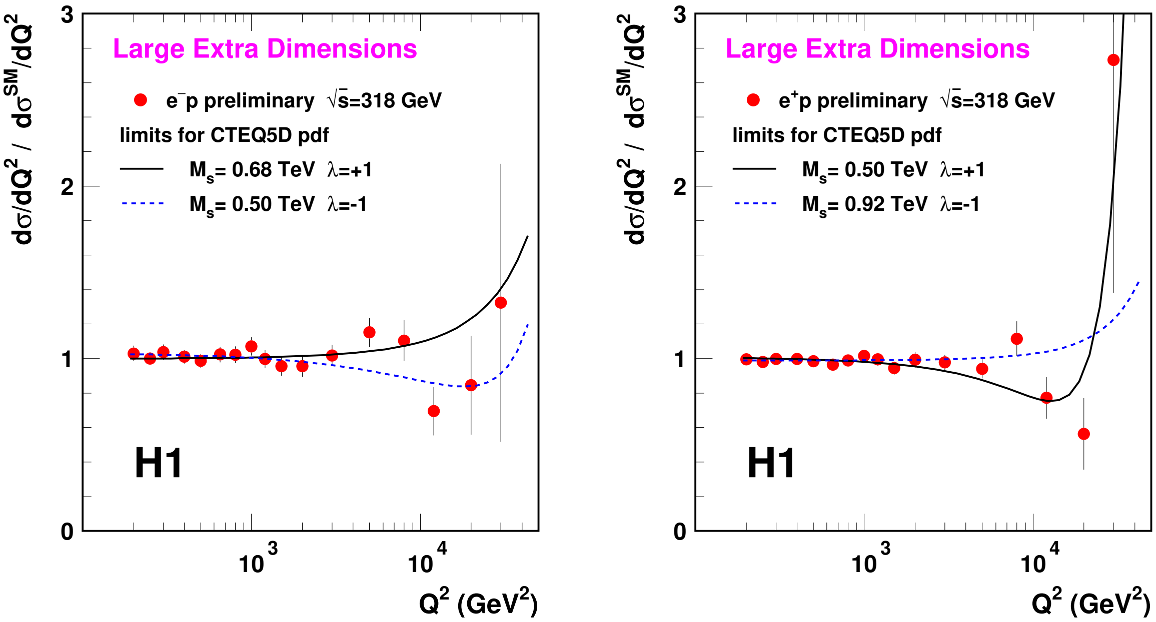

Figure 5: NC cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ at $\sqrt{s} = 318$ GeV normalised to the Standard Model expectation using CTEQ5D parton distributions. H1 data of e^-p and e^+p scattering are compared to gravitational effects of large extra dimensions at scales M_S (95% CL lower limits) with positive ($\lambda = +1$) and negative ($\lambda = -1$) coupling. The errors represent statistics and uncorrelated experimental systematics.

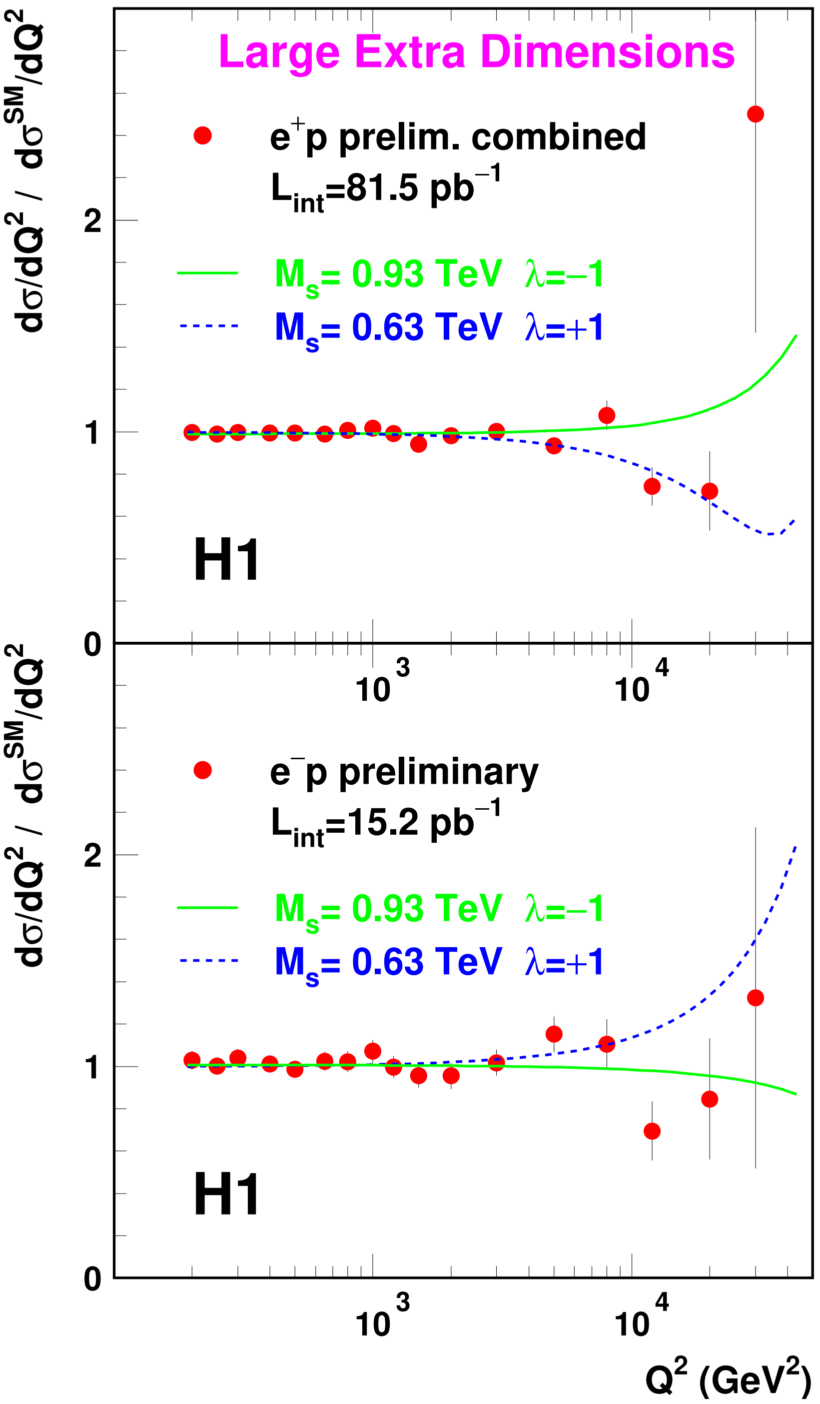

Figure 6: NC cross sections $\mathrm{d}\sigma/\mathrm{d}Q^2$ normalised to the Standard Model expectation for the combined e^+p and the e^-p scattering data. The curves show the effects of graviton exchange in large extra dimensions given by a common fit to the scale M_S (95% CL lower limits) with couplings $\lambda = +1$ and $\lambda = -1$. The errors represent statistics and uncorrelated experimental systematics.