SEARCHES FOR NEW PHENOMENA AT HERA

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Recent results on searches for physics beyond the Standard model at the HERA ep-collider at DESY are presented. Possible signals of leptoquark production, manifestations of fermion compositeness, of the exchange of gravitons in large compactified extra-dimensions and outstanding event topologies are considered. The search results presented here make use of some of the most recent data taken by the H1 and ZEUS collaborations, corresponding to about 40 pb^{-1} per experiment of e^+p data at $\sqrt{s} = 300$ GeV and about 15 pb^{-1} of e^-p data at $\sqrt{s} = 318$ GeV. No significant signal beyond Standard Model expectations has been observed and constraints for possible new physics models have been derived, extending existing bounds.

1 Introduction

The HERA ep-collider offers the unique opportunity to look for new particles coupling to lepton-quark pairs such as leptoquark bosons, or to probe in effective four-fermion contact interactions lepton-quark compositeness or possible virtual contributions of very massive new fields interfering with Standard Model (SM) Deep Inelastic Scattering (DIS). Furthermore high energy ep-collisions provide an excellent environment to search for excited states of fermions, whose existence would be a natural consequence of models with composite leptons and quarks.
Recent search results for such new physics are reported here, as well as a search for rare event topologies with high p_T leptons and missing energy.

In 1994–1997 HERA collided 27.5 GeV positrons on 820 GeV protons. In 1998 the proton energy was raised to 920 GeV, which meant an increase of the center of mass energy from 300 GeV to 318 GeV. In 1998 and the first months of 1999 HERA ran with electrons. Results from H1 and ZEUS for both the e^+p and e^-p data are presented here. Due to the sensitivity of many exotic processes to the lepton charge, e^+p and e^-p studies are often complementary. In May 1999 HERA switched back to e^+p running, and a first look at about 18 pb^{-1} of these data taken in 1999 was made by ZEUS.

2 Contact Interactions

Contact Interactions (CI) can be used to parameterize any new physics process appearing at an energy scale Λ much above the center of mass energy $\sqrt{s}$. At HERA $eeqq$ four-fermion terms would interfere (constructively or destructively) with the SM Neutral Current (NC) DIS process, where the incoming lepton interacts with a quark coming from the proton via the t-channel exchange of a virtual gauge boson. Such an interference would have an effect on the distributions of the Lorentz invariant variables Q^2, x and y (related via $Q^2 = xys$); hence the analysis strategy is to look for distortions of the Q^2 distribution with respect to the DIS expectation.

The H1 [1] and ZEUS [2] collaborations searched for such distortions in the e^+p data sample, collected in 1994–97, using, respectively, a χ^2 fit of the single differential cross-section $d\sigma/dQ^2$ and a 2-dimensional likelihood analysis in (x, y). The data have been interpreted variously in terms of effective compositeness Lagrangians with various chiral structures, the exchange of heavy leptoquarks, the effect of low scale quantum gravity and a a classical quark form factor.

The general contact interaction Lagrangian for neutral current vector interactions can be written as:

$$\mathcal{L}_{CI} = \sum_{\substack{a,b=L,R \\ q=u,d}} \eta^q_{ab} (\bar{e}_a \gamma^\mu e_a)(\bar{q}_b \gamma_\mu q_b) \tag{1}$$

with $\eta^q_{ab} = \epsilon^q_{ab}(g/\Lambda)^2$ depending on the model. Λ is the effective mass scale, g the coupling strength and ϵ^q_{ab} are the relative signs ± 1 of the coupling for each quark flavour and electron/quark chiralities and their combinations determine the models.

Considering the case of a possible fermion compositeness or substructure, both experiments H1 and ZEUS have constrained the compositeness scale parameters $\Lambda^\pm$, setting $g^2 = 4\pi$ and $\epsilon = \pm 1$ for various scenarios of the chiral structure of the CI. The derived limits ranging from 1.3 to 5 TeV are displayed in Fig. 1(left) and compared to published limits from other experiments.

H1 has also interpreted the CI in terms of a quark radius by applying a multiplicative form factor to the SM differential cross-section $d\sigma/dQ^2$. It leads to an upper limit on the quark radius of 1.7×10^{-16} cm.

Limits on heavy leptoquark exchange were derived also by H1, constraining the LQ mass, M_{LQ} and its coupling to eq, λ. Limits on M_{LQ}/λ lie in the range of 220 – 1060 GeV, depending on the leptoquark type.

A new interpretation of CI is the possible contribution of virtual graviton exchange in models with large extra-dimensions, where gravity in the 4+n dimensions may become strong at the electroweak

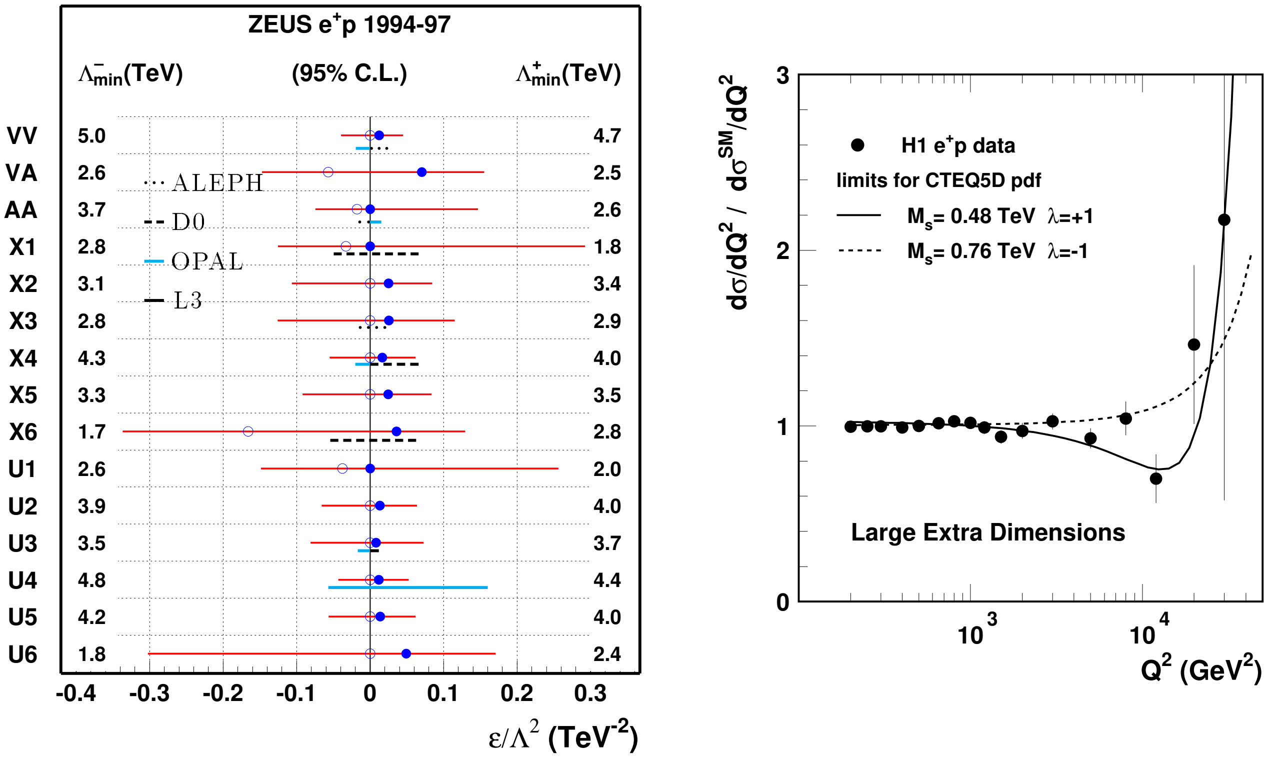

Figure 1: Left: Summary of upper limits on the compositeness scale parameters ϵ/Λ^2 as derived by ZEUS. Full/open circles represent the best fit for ϵ/Λ^2 for $\epsilon = \pm 1$, and the end of the bars are the 95% CL upper limits, which are converted to values for $\Lambda^\pm$ For comparison published limits of other experiments are also given[3,4,5,6]. Right: NC cross section $d\sigma/dQ^2$ normalised to the Standard Model expectation using CTEQ5D parton distribution[7]. H1 data are compared to the effect of graviton exchange with positive ($\lambda = +1$) and negative ($\lambda = -1$) interference. The errors represent statistics and uncorrelated experimental systematics added in quadrature.

scale[8]. Only the massless spin-2 gravitons propagate in the extra-dimensions. After compactification of the n extra dimensions, they appear in the 4-dim world as a spectrum of Kaluza-Klein (KK) states, and the exchange of the whole tower of these KK states between SM particles can be represented by an effective CI coupling λ/M_s^4. Fitting $d\sigma/dQ^2$ to a formula including the contribution of graviton exchange with λ/M_S^4 as free parameter leads to 95% CL lower limits on the effective mass scale: $M_S > 0.48$ TeV for $\lambda = +1$ and $M_S > 0.72$ TeV for $\lambda = -1$. The sensitivity of the H1 data to graviton exchange is shown in Fig. 1(right).

3 Leptoquarks

Leptoquarks (LQ) are scalar or vector color-triplet bosons, carrying both lepton (L) and baryon (B) number, and appear in many extensions to the SM. At HERA, LQs with fermion number $F = 3B+L = 0$ (2) could be resonantly produced via fusion of the incoming positron (electron) and a quark from the proton. For a given charge of the incoming lepton also leptoquarks with the other fermion number can be produced by scattering off an antiquark, but with a lower cross-section, corresponding to the lower antiquark density.

Assuming that LQ couplings respect $SU(2) \times SU(3) \times U(1)$ gauge invariance, Buchmüller, Rückl and Wyler (BRW)[9] proposed a model in which the LQs decay exclusively into $e + q$ or $\nu + q$ with a branching $\beta_e = \beta(LQ \rightarrow eq) = 1$ or 0.5. Other models can also be considered where the branching β_e is a free parameter.

Both collaborations have published results on searches for LQ's coupling only to first generation fermions from the 94–97 e^+p data sample[10,11]. Furthermore ZEUS showed preliminary results on the analysis of the 98/99 e^-p data[12], complementing the e^+p analysis since the incoming e^+ or e^- mainly probes LQs of different F. The H1 results from the analysis of the 98/99 e^-p data are presented here for the first time.

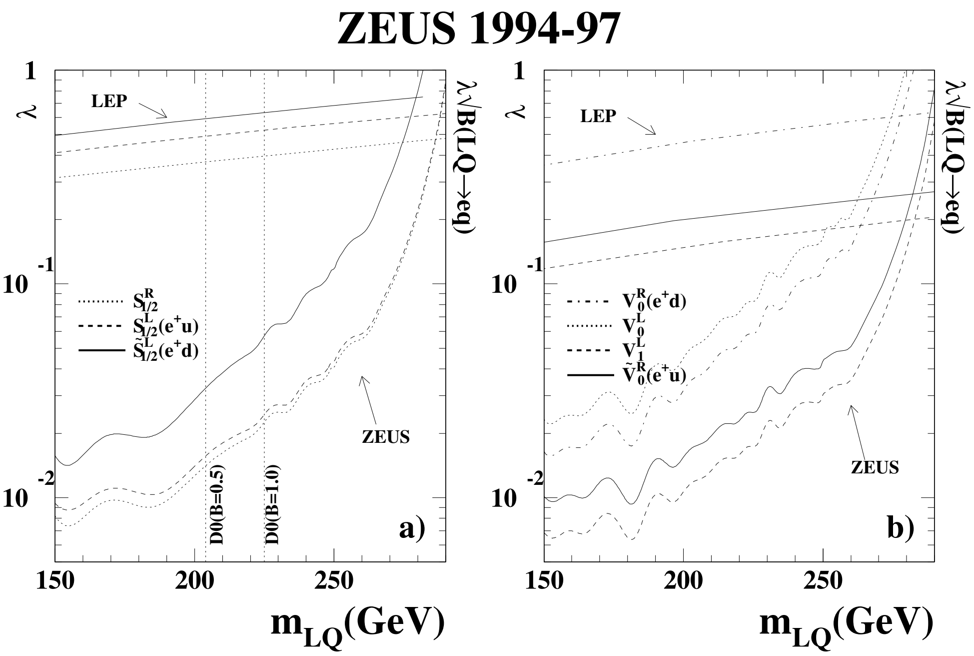

Figure 2: Coupling limits as a function of leptoquark mass for $F = 0$ leptoquarks. The results are compared to limits from LEP[14] and the TeVatron[15]. The areas above the ZEUS and LEP lines are excluded, while the areas left to the TeVatron lines are excluded. Limits on scalar (vector) leptoquarks are shown in a, (b).

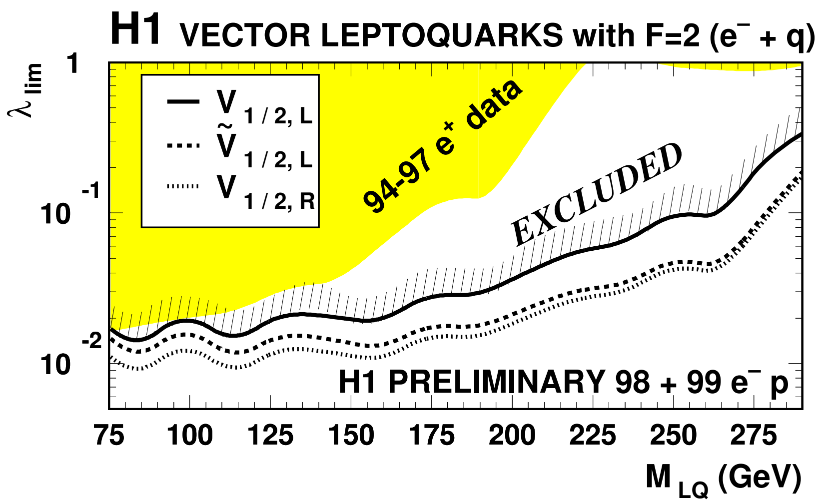

Figure 3: Exclusion limits at 95% CL on the Yukawa coupling λ as a function of the LQ mass for vector LQs with $F = 2$.

A first generation LQ would manifest itself as an excess of NC DIS-like events at high y. The searches of H1 and ZEUS have been performed in the framework of the BRW model using the e^+p data sample taken in $94 - 97$ and the full e^-p data sample from 98/99. No significant deviation from the SM has been observed, apart from a slight excess in H1 e^+p data for invariant masses around 200 GeV, mainly due to events previously reported in the $94-96$ data. The resulting mass dependent limits, on the Yukawa coupling λ of the LQ to the $e-q$ pair are shown in Fig. 2 for $F = 0$ and in Fig. 3 for $F = 2$ leptoquarks. The former are results of the ZEUS analysis of the $94 - 97$ data sample, while the latter corresponds to the analysis of the e^-p data of H1. For a coupling of the electro-magnetic strength (i.e. $\lambda = 0.3$) scalar $F = 0$ LQ masses below 280 GeV are ruled out at 95% CL, and masses up to 290 GeV are ruled out at 95% CL for $|F| = 2$ LQs. Fig. 3 shows that the sensitivity to $|F| = 2$ LQs achieved from the e^-p data is better than the one provided by the higher statistics e^+p sample.

The case of LQs decaying to νq as well as to eq has also been addressed by both collaborations [11,16] using the e^+p data sample. No signal has been observed in the Charged Current (CC) DIS sample and the CC channel has been used to better constrain such LQs [11].

A first look on 18 pb^{-1} of e^+p data taken in 1999 was performed by ZEUS. The distribution of selected high Q^2 events in the variables x_{DA} and y_{DA} is shown in Fig. 4. x_{DA}, y_{DA} stands for the kinematical variables x and y, reconstructed from the angles of the scattered electron and hadronic final state (*double angle method*). In such a plot the existence of a LQ of mass M would show itself as a clustering of events at high y around a given x ($M = \sqrt{xs}$). No such effect is observed in this low statistics sample.

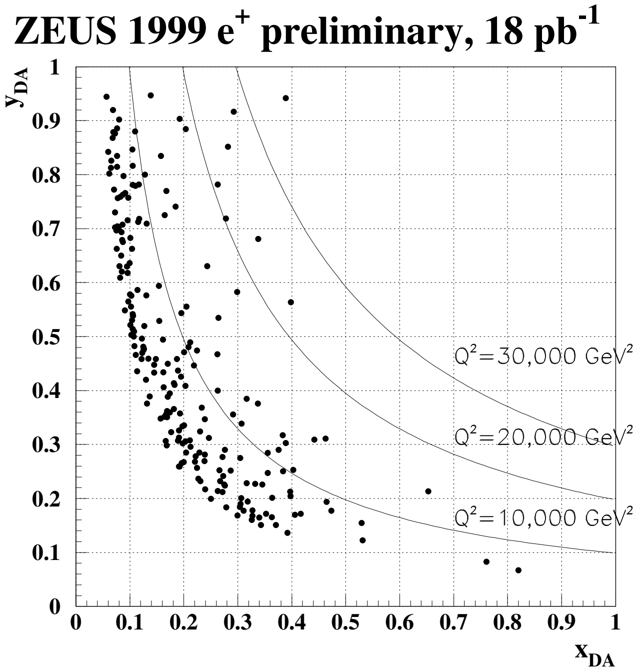

Figure 4: y_{DA} vs x_{DA} for selected high Q^2 NC DIS like events (see text).

Moving away from the BRW model, mass dependent limits on the branching β_e have been derived by the H1 collaboration from the e^+p data [11] and from the e^-p data. The latter are shown in Fig. 5 for the case of a generic scalar LQ coupling to $e^- + u$ for $\lambda = 0.1$ and $\lambda = 0.05$. The domain covered by H1 extends significantly beyond the region excluded by the $D0$ experiment, especially for low values of β_e.

Limits for lepton flavour violating scenarios have been published by H1 for couplings to μq or τq [11], and preliminary results exist from ZEUS for couplings to μq [13]. No $e^+p \to \mu + jet$ event compatible with LQ kinematics was found by neither experiment. Upper bounds on the product $\lambda \times \sqrt{\beta_\mu}$, β_μ denoting the branching ratio $\beta(LQ \to \mu + q)$, have been obtained by ZEUS as a function of the LQ mass. Scalar (vector) LQs decaying only into eq and μq are excluded up to 278 (285) GeV when the coupling at the vertices $LQ - e - q$ and $LQ - \mu - q$ are both of electro-magnetic strength. H1 also performed a search for $\tau + jet$ signatures, where the τ decays hadronically. Also in this case no event compatible with LQ kinematics has been observed and limits on LQs decaying into eq and τq have been derived, showing the important potential of HERA for LQs decaying with a small branching ratio into eq and a high branching ratio into τq. The case of very high mass ($M_{LQ} \gg \sqrt{s}$) lepton flavour violating LQs was also addressed by H1. For both $e \leftrightarrow \mu$ and $e \leftrightarrow \tau$ transitions, direct constraints obtained by H1 were compared to the most stringent indirect bounds. For some cases H1 limits extend significantly beyond the reach of other experiments [11].

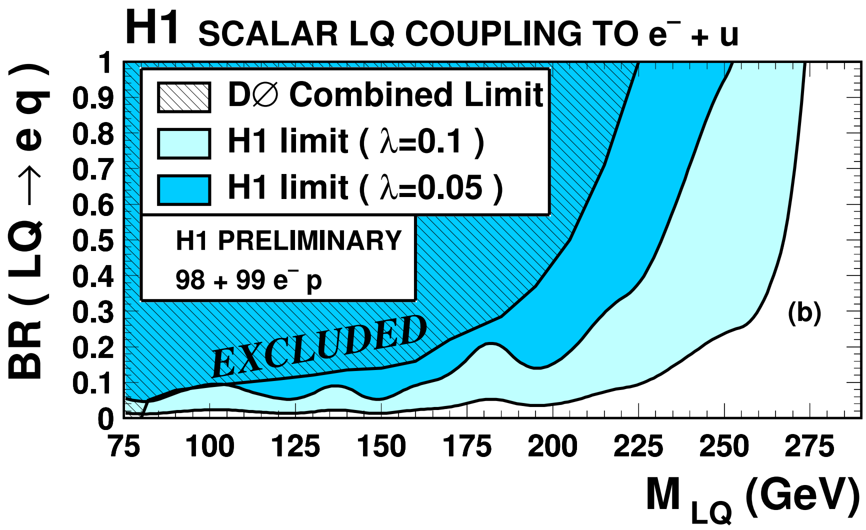

Figure 5: Mass dependent exclusion limits at 95% CL on the branching ratio β_e of the LQ to decay into eq for scalar LQs with $F = |2|$ produced as e^-u resonance.

4 Isolated Leptons

The first event having a muon with high transverse momentum, p_t, in combination with large missing transverse momentum in the calorimeter, P_T, was observed in the 1994 data sample of H1. Both collaborations have searched for further events of this type in their full $94-97$ and $98/99$ e^-p data samples, and ZEUS has also had a first look into 18 pb^{-1} of e^+p data taken in 1999. The number of events fulfilling the selection criteria and the expectation from SM processes for the two experiments are shown in Table 1. The dominant SM process yielding events with an isolated lepton and missing P_T is W production followed by a leptonic decay of the W and $\gamma\gamma \to \mu^+\mu^-$ events. With the selection criteria of $P_T > 25$ GeV and requiring at least one track with $p_t > 10$ GeV, H1 observes six events with the high momentum track exhibiting outstanding features in terms of large distances in the $\eta - \phi$ plane to the closest track, $D_{track} \geq 0.5$, and to the closest jet, $D_{jet} \geq 1$. All six events satisfy the criteria for lepton identification, five events have a muon and one has an electron in the final state. For the case of the muon events significantly less events are expected from SM processes.

The kinematics of these events was compared to the expectations due to the SM processes and it was found that for three of the muons the p_T of the hadronic final state is very large, which makes an interpretation in terms of W-production rather unlikely. (An interpretation as lepton flavour violating LQs is not favoured, since the events are not compatible with the kinematic constraints for LQ induced $eq \to \mu q$ processes.) Clearly much more luminosity is needed to understand the origin of these events.

ZEUS performed a similar analysis, selecting events containing an isolated lepton with $P_t > 10$ GeV and missing p_T in the calorimeter of $P_T > 20$ GeV. The number of events observed in the different periods of data taking are again presented in Table 1, including preliminary results from 18 pb^{-1} of 1999 e^+p data. In total seven e-events are observed where 6.1 ± 0.9 are expected and 4 μ-events where 3.7 ± 0.4 are expected, hence no deviation from SM expectations is observed. Properties of the muon events such as acoplanarity and missing P_T in the calorimeter are in agreement with expectations from SM W and $\mu\mu$ events.

5 Excited Fermions

Excited fermions (f^*) would be a clear evidence for fermionic substructure. f^*'s produced singly via the t-channel exchange of a gauge boson have been searched for at HERA, and results have been interpreted in the framework of the phenomenological model proposed by Hagiwara, Komamiya and Zeppenfeld [17]. e^* have been searched for by ZEUS [21] and H1 [22] through $e^* \to f + V$ with $V = \gamma, Z, W$,

Table 1: Number of events with an isolated lepton and large missing P_T in the calorimeter observed by H1[18,19] and ZEUS[13,20], compared to the SM expectations.

HERA mode year	e^+p (300 GeV) 94–97	e^-p (320 GeV) 98/99 **preliminary**	e^+p (320 GeV) 99 **preliminary**
H1 lumi	37pb^{-1}	14pb^{-1}	
events	observed (expected)	observed (expected)	
H1 e	1 (2.4 ± 0.5)	0 (0.37 ± 0.07)	
H1 μ	5 (0.8 ± 02)	0 (0.14 ± 0.04)	
ZEUS lumi	48pb^{-1}	16pb^{-1}	18pb^{-1}
events	observed (expected)	observed (expected)	observed (expected)
ZEUS e	3 (3.5 ± 0.7)	2 (0.8 ± 0.4)	2 (1.8 ± 0.4)
ZEUS μ	0 (2.0 ± 0.4)	0 (0.8 ± 0.1)	4 (0.9 ± 0.1)

the electroweak bosons decaying hadronically or via $W \to e\nu$, $Z \to e^+e^-$, $Z \to \nu\bar{\nu}$. The e^+p data showed no deviation from the SM in all analysed channels. Assuming an equal coupling f of the $e^* - e$ pair to $U(1)$ and $SU(2)$ bosons, upper bounds on f/Λ where Λ denotes the compositeness scale have been obtained as a function of the e^* mass. ZEUS limits shown in Fig. 6(left) exclude e^* masses below 229 GeV at 95% CL for $f/\Lambda = 1/M(e^*)$, and these bounds extend beyond the domain covered by single e^* production at LEP.

ZEUS [21] also searched for $\nu^* \to \nu\gamma$ using e^-p data, which provide a higher sensitivity than the e^+p dataset due to a higher ν^* production cross-section. ν^* lighter than 161 GeV are excluded for $f/\Lambda = 1/M(\nu^*)$, as can be seen in Fig. 6(right). Searches for q^* were reported in [22] and q^* constraints have been set for vanishing coupling f_s of the q^* to the gluon, complementary to the stringent bounds obtained at the TeVatron where q^* production requires $f_s \neq 0$.

6 Conclusion and Outlook

H1 and ZEUS searched for evidence of new physics for many different scenarios, involving either leptoquarks, new effective four-fermion contact interactions and excited leptons. Possible contributions of the exchange of gravitons in theories with compact extra-dimensions was considered for the first time at HERA. In general the data show good agreement with Standard Model predictions and exclusion limits for new physics have been derived, which are complementary or in some cases extend beyond the reach of other colliders. However the observation of some slight deviations at HERA still require clarification. Hence, the 60 pb^{-1} per experiment of e^+p data which are expected to be taken this year and the five-fold increase of luminosity and e-beam polarisation expected for year 2001 will be of great importance and will allow for exciting searches.

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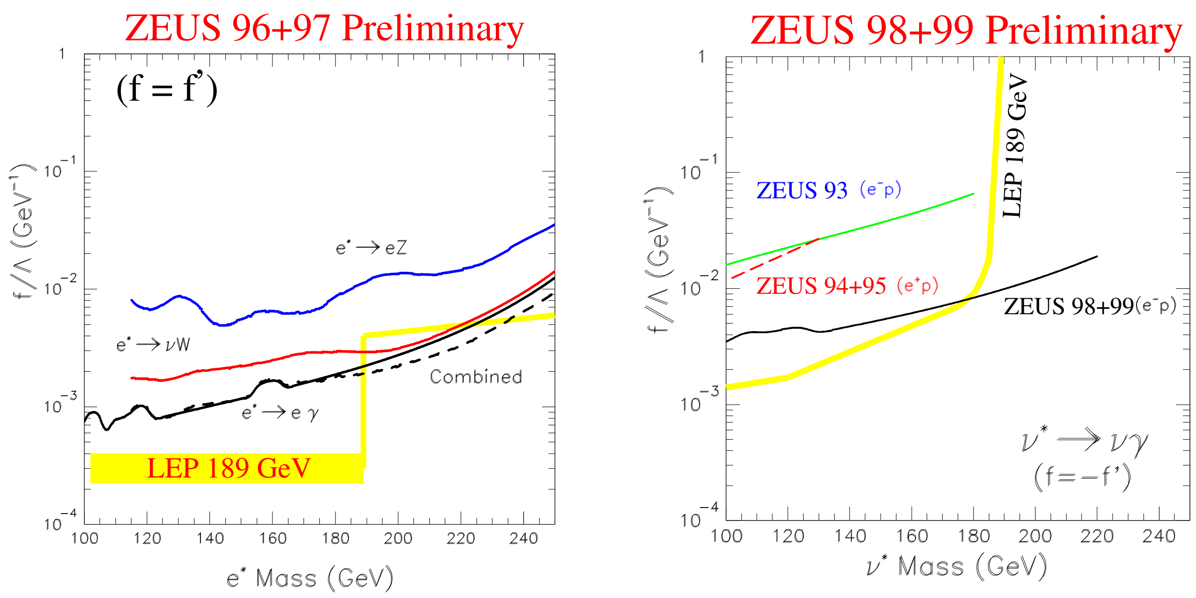

Figure 6: Upper limits at 95% CL on f/Λ as a function of the excited lepton mass for e^* (left) and ν^* (right) production. The dashed curve represents the limit obtained combining $e^* \to e\gamma$, $e^* \to eZ$ and $e^* \to \nu W$.

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