Searches for physics beyond the Standard Model at HERA

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Abstract. This article summarizes the results of searches for new physics beyond the Standard Model at HERA performed by the ZEUS and H1 experiments. Recent results are presented on direct searches for electron-quark resonant states such as leptoquarks or squarks in R-parity violating SUSY, on indirect searches for new physics leading to *eeqq* contact interactions and on searches for single top-quark production through anomalous flavour-changing coupling in neutral-current processes. Most of the results shown are based on the full statistics collected before the luminosity upgrade of HERA and some of them were also updated with newer results made available after the workshop.

1. Introduction

The HERA collider at DESY has been operating successfully a 27.5 GeV electron or positiron beam and an 820 GeV (920 GeV) proton beam, thus providing e^-p and e^+p collisions at center-of-mass energies $\sqrt{s}$ of 300 GeV (318 GeV).
Specifically, the results presented here are based on the three following data samples:

Year	Collisions	$\sqrt{s}$ GeV	Luminosities (pb^{-1}) H1	ZEUS
1994-1997	e^+p	300	37	47
1998-1999	e^-p	318	15	17
1999-2000	e^+p	318	65	68

Unlike LEP and TeVatron, HERA has both lepton and baryon numbers in the initial state and is ideally suited to s-channel resonant formation of new particles which couple to lepton-parton pairs with masses up to the HERA center-of-mass energy. Examples of such particles are leptoquarks (LQs) and squarks in R-parity violating SUSY and corresponding searches are reviewed in sections 2 and 3.
The effects of new interactions at scales much above $\sqrt{s}$ can be studied in the context of 4-fermion contact interactions. Latest limits on various models including compositeness, leptoquarks and large extra dimensions are presented in section 4.
The anomalous rate of events with isolated high-P_T leptons and missing transverse energy observed in H1 is currently the only deviation from the Standard Model observed at HERA. Latest findings with the entire data available are presented in section 5. Interpretation of such events as single top production via flavour-changing neutral current interactions is also discussed in section 6.

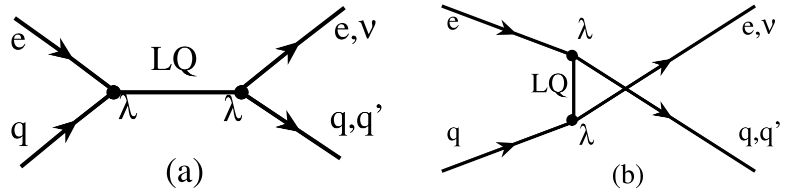

Figure 1. Diagrams for s-channel LQ production **(a)** and u-channel LQ exchange **(b)** at HERA.

The Standard Model background to most of the searches is neutral current (NC) and charged current (CC) deep inelastic scattering (DIS). The diagrams and the kinematic variables used to describe these processes can be found elsewhere in the proceedings of this workshop.

2. Leptoquarks

Leptoquarks (LQs) are scalar or vector color-triplet bosons carrying both lepton (L) and baryon (B) number and are characterized by a fermion number F=L+3B. They appear in many unifying theories beyond the Standard Model (SM) which attempt to relate the two lepton and quark families. At HERA, LQs can be resonantly produced in the s-channel or exchanged in the u-channel between the incoming lepton and a quark from the proton as shown in figure 1, where λ is the unknown Yukawa coupling. Here we only consider states coupling to first generation fermions‡ giving rise to $LQ \rightarrow eq$ and $LQ \rightarrow \nu q$ diagrams whose amplitudes interfere with those from NC and CC DIS. In the BRW LQ model[1], all the scalar and vector LQ species with $SU(3)\times SU(2)\times U(1)$ invariant couplings (7 with F=0 and 7 with F=2) are classified along with their quantum numbers. The branching ratios for LQ decays to eq (β_{eq}) and to νq ($\beta_{\nu q}$) is predicted in the model to be either 1 or 0.5 (0 or 0.5, respectively), depending on the LQ quantum numbers.

The largest sensitivity at HERA is achieved for LQ masses M_{LQ} smaller than $\sqrt{s}$. If λ is not too large (order of unity or less) the s-channel contribution largely dominates the LQ cross section. Here, a sharp resonance peak in the NC DIS (CC DIS) measured mass distribution at M_{LQ} is expected for eq (νq) LQ decays, where M_{LQ} is directly related to the proton momentum fraction x_0 of the interacting quark ($M_{LQ} = \sqrt{sx_0}$). Furthermore, the inelasticity variable y, which is directly related to the decay polar angle of the outgoing lepton, has a different distribution for scalar LQs (uniform), vector LQs ($\propto (1-y)^2$) and NC DIS (falling as $1/y^2$) and a mass dependent lower y cut can be applied to enhance the LQ signal. In this domain, the production cross section can be expressed with a narrow-width approximation $\sigma^{NWA} \propto \lambda^2 q(x_0, M_{LQ}^2)$ where $q(x_0, M_{LQ}^2)$ is the quark density evaluated at x_0 and at a virtuality scale M_{LQ}^2. Because of the large x_0 involved in the interaction, F=0 (F=2) LQs are best probed with e^+p (e^-p) data as they would couple to valence quarks in the proton.

The search for such resonances has been recently extended by H1[2] and ZEUS[3] to all the available 1994-2000 data. The mass distributions of the events form NC DIS

‡ Searches for lepton flavour violating LQ interactions have also been performed by ZEUS and H1; for details, refer to [5].

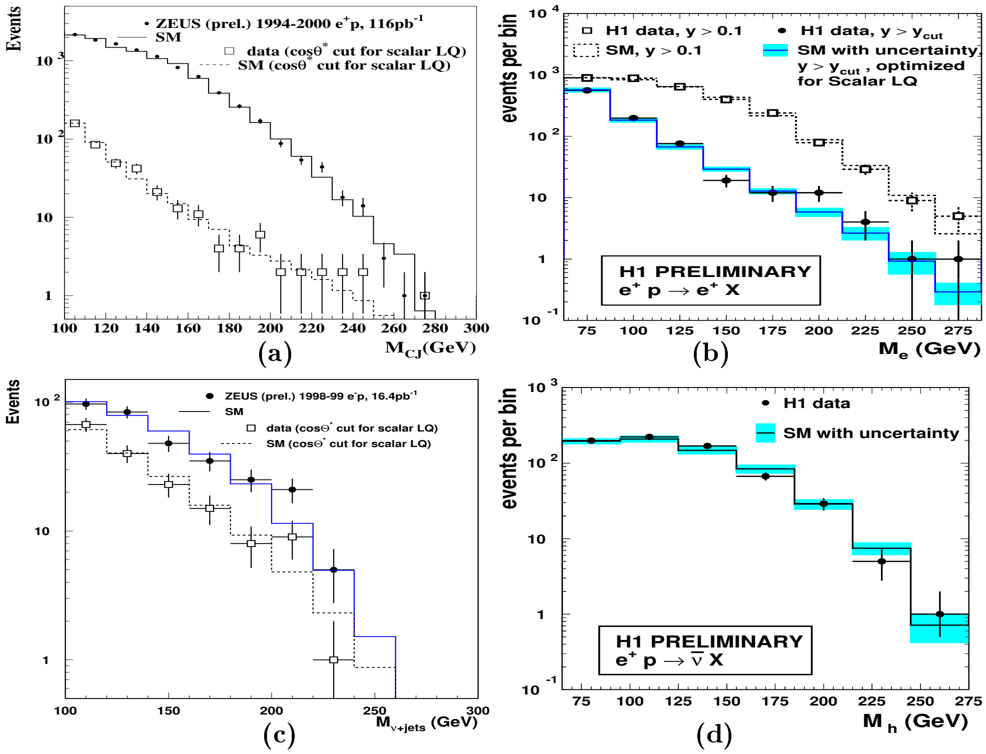

Figure 2. Mass spectra for the events from NC DIS selection of e^+p data from ZEUS **(a)** and H1 **(b)** (symbols) compared to the DIS expectations (histograms). The curves are shown before and after a y cut designed to maximize the significance for scalar LQ signal. The shaded boxes indicate the $\pm 1\sigma$ uncertainties on the DIS expectations. Similarly, figures **(c)** and **(d)** show the mass spectra for the events from CC DIS selection of e^-p data (ZEUS) and e^+p data (H1).

selection of over 100pb^{-1} of e^+p data is shown in figure 2(a) and 2(b). The mass was calculated from the energy and angle of the scattered positron (H1) or as the invariant mass between positron and jets (ZEUS). In both experiments, the distributions show a good agreement with DIS expectations before and after applying the optimized y cut to enhance the sensitivity; the observation of few events at large mass and large y by both experiments with 1994-96 e^+p data[4] has not been confirmed with more recent data and their statistical significance is now much reduced. The mass spectra from CC DIS selection are also shown in figure 2(c) for the e^-p data and in figure 2(d) for the $e+p$ data where the mass is now reconstructed from the hadronic final state only; again, good agreement is found with SM predictions.

The exclusion limits on the coupling λ as function of M_{LQ} are shown in figure 3 for all the F=0 LQs (from ZEUS e^+p data) and the F=2 LQs (from H1 e^-p data) described by the BRW model. Limits were extended above the HERA center-of-mass energy by taking into account the u-channel and interference contributions to the cross section. For a coupling λ of electromagnetic strength ($\lambda = \sqrt{4\pi\alpha_{em}} \simeq 0.3$), F=2 LQs are ruled out up to a masses of 290 GeV while F=0 LQs are excluded up to 275 GeV masses for a coupling of a strength 100 times smaller. These results are complementary to the TeVatron limits which are independent of the coupling

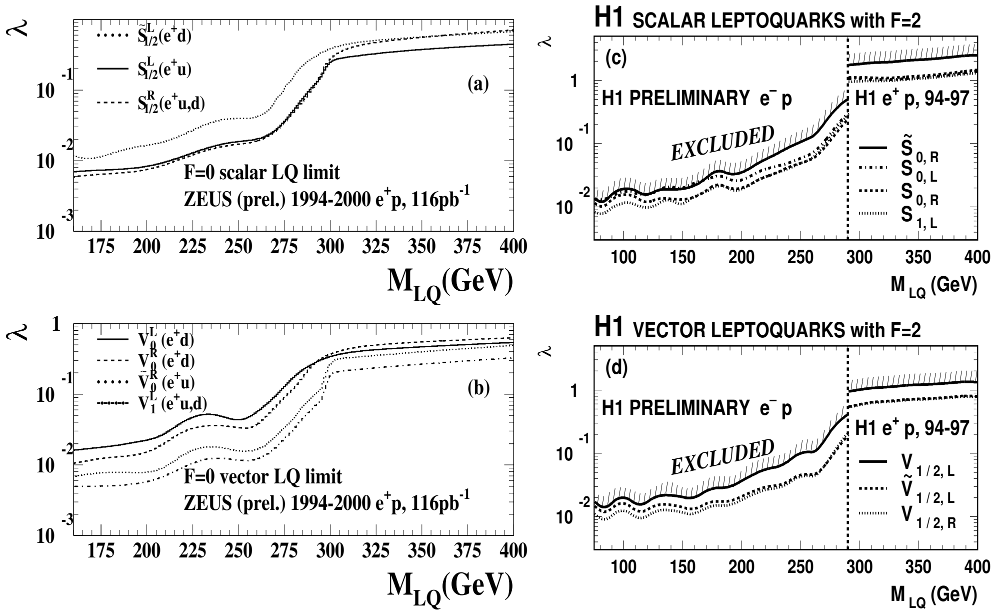

Figure 3. Exclusion limits at 95% CL on the Yukawa coupling λ as function of the LQ mass for the 14 LQs described in the BRW model: scalar F=0 **(a)**, vector F=0 **(b)**, scalar F=2 **(c)** and vector F=2 **(d)**. Domains above the curves are excluded. In figures **(c)** and **(d)**, constraints for M_{LQ} above the center-of-mass energy were obtained using the partial e^+p data sample at $\sqrt{s} = 300$GeV.

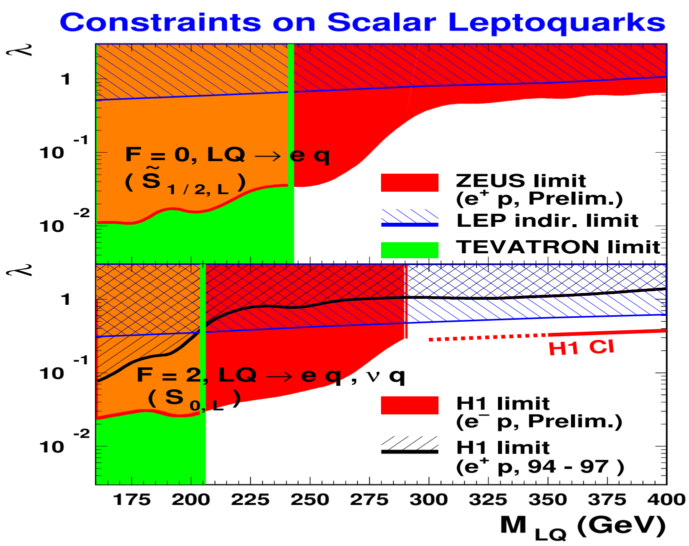

Figure 4. Exclusion limits at 95% CL on the Yukawa coupling λ for scalar F=0 (top) and F=2 (bottom) LQs. Excluded domains by LEP and TeVatron are also shown. A limit obtained by contact interaction analysis (H1 CI) is shown in the bottom figure.

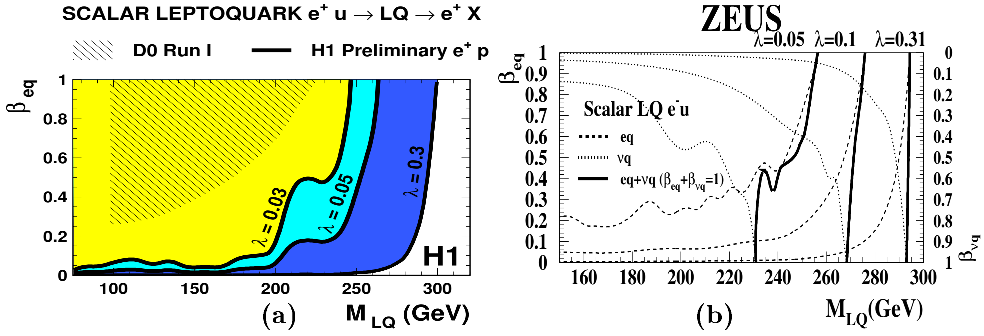

Figure 5. Mass dependent exclusion limits at 95% CL on the branching ratio β_{eq} of a scalar LQ which couples to e^+u **(a)** and e^-u **(b)** for fixed couplings λ. For each limit curve, the area to the left of the curve is excluded. For the e^-u state, limits are also shown on branching ratio to $\beta_{\nu q}$ using CC DIS data and on β_{eq} combining both NC and CC DIS data with the assumption $\beta_{eq}+\beta_{\nu q}=1$ (solid line). The hatched region in **(a)** represents the domain excluded by D0 at TeVatron.

and extend up to 225 GeV (204 GeV) for scalar LQs decaying to eq with branching $\beta_{eq}=1$ ($\beta_{eq}=1/2$). A comparison is shown in figure 4 which also includes LEP indirect limits and H1 constraints obtained from contact interaction analysis[8] which will be discussed in section 4.

Beyond the BRW ansatz, generic LQ models can be considered, where other LQ decay modes are allowed and the branching ratios β_{eq} and $\beta_{\nu q}$ are free parameters. Mass dependent exclusion limits on β_{eq} for scalar LQs with fixed couplings λ to e^+u and e^-u are shown in figure 5. It can be seen that HERA offers a unique probe for the domain at large mass and low β_{eq}, unexplored at the TeVatron. For the e^-u states, limits obtained combining both NC and CC DIS data are also shown; if the assumption $\beta_{eq}+\beta_{\nu q}=1$ is made, limits are almost independent on the individual branching ratios (thick line in figure (b)).

3. R-Parity violating supersymmetry

R-Parity violating SUSY provides an interesting theoretical framework which allow squarks ($\tilde{q}$) to be singly produced at HERA as scalar eq resonances and where the squark branching to eq is normally small.

R-parity, defined as $R_p=(-1)^{3B+L+2S}$ where S is the spin of the particle, is a multiplicative quantum number which is 1 for SM particles and -1 for their supersymmetric partners (sparticles). The most general SUSY theory preserving SM gauge invariance allows for Yukawa couplings between two SM fermions and a scalar SUSY partner of a quark (squark $\tilde{q}$) or a lepton (slepton $\tilde{l}$); these couplings induce violation of the R-parity ($\not{R}_P$). When these couplings are included in the theory, SUSY particles can be singly produced at colliders and the lightest SUSY particle (LSP) is no longer stable.

Of special interest at HERA is the $\not{R}_P$ superpotential term $\lambda'_{ijk}L_iQ_j\bar{D}_k$ where the superfields L_i Q_j and D_k denote the left-handed lepton doublets, the left handed quark doublets and the right-handed down quark singlets, together with their SUSY partners $\tilde{l}^i_L$, $\tilde{q}^j_L$ and $\tilde{d}^k_R$, and i,j,k are generation indices. In particular, λ'_{1jk} makes

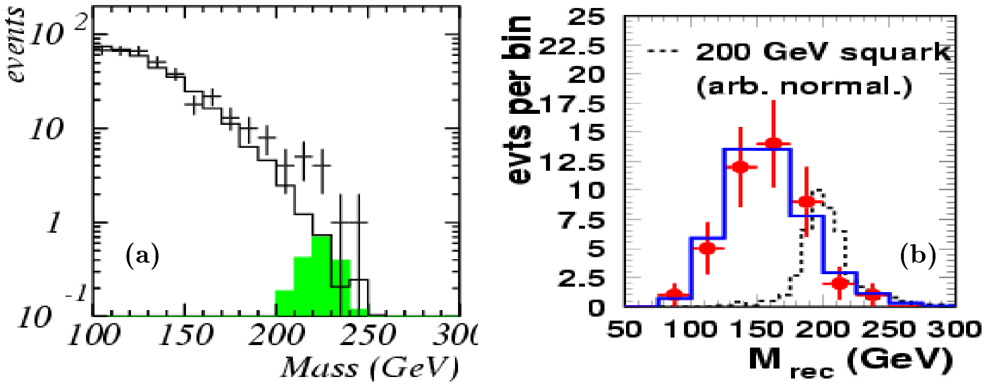

Figure 6. Observed (symbols) and expected (open histograms) mass distributions for ν+multijet events after preselection in ZEUS **(a)** and H1 **(b)**. The shaded histogram in **(a)** (dashed histogram in **(b)**) shows an hypothetical signal from a 220 GeV (200 GeV) squark.

single $\tilde{q}$ production possible through electron- or positron-quark fusion, similarly to scalar LQ production discussed earlier. With a e^+ beam, HERA is most sensitive to couplings λ'_{1j1} where $\tilde{u}^j_L$ (i.e. $\tilde{u}_L$, $\tilde{c}_L$ and $\tilde{t}_L$) are being produced by e^+d fusion.

Once produced, the squarks decay either with the same Yukawa coupling (same experimental signature as scalar LQs) or via their usual gauge couplings: $\tilde{q}\rightarrow q\chi^0_\alpha$ (α=1,4), $\tilde{q}\rightarrow q\chi^\pm_\beta$ (β=1,2) and $\tilde{q}\rightarrow q\tilde{g}$. Neutralinos χ^0, charginos $\chi^\pm$ and gluinos $\tilde{g}$ are unstable. This holds also for the lightest of them (LSP) which undergoes a $\not{R}_P$ decay through λ' coupling; for example, neutralinos can undergo the $\not{R}_P$ decays $\chi^0\rightarrow e^\pm q\bar{q}'$ or $\chi^0\rightarrow\nu q\bar{q}'$, the former decay providing a background free signature of "wrong charge" lepton. Heavier neutralinos (α>1) or charginos usually undergo a gauge decay into a lighter χ and two SM fermions, giving raise to an even larger variety of final states.

Search for squarks was presented by H1[6] and ZEUS[7] using the 1994-1997 e^+p data at $\sqrt{s}$=300 GeV. In both analyses, events were preselected into exclusive distinguishable analysis classes based on the presence of high-P_T charged leptons, missing energy and on the number of jets in the final state (H1) or on a topological quantity called *circularity*§ (ZEUS). Such classes include the LQ-like decays of the squarks via $\not{R}_P$ (event selection similar to LQ analysis) as well as the multijet, high-circularity final state topologies which cover the gauge decays of squarks. Events were further classified according to the charge of the scattered lepton (e^+ or wrong-sign e^-) and the presence of secondary electrons or muons (H1).

The ZEUS mass spectrum of ν+*multijet* events after a broad preselection is shown in figure 6(a). For masses above 200 GeV, ZEUS shows a substantial excess (15 events observed, 5.1 expected background) whose origin is still unclear. However, the excess is not confined to those regions of y and circularity characteristic of a squark signal and vanishes when the final selection is applied (the selection criteria, optimized as a function of the squark mass and of the MSSM parameters, are detailed is [7]). The corresponding mass spectrum from H1, with harder cuts applied, is shown in figure 6(b) and also shows no excess. In all the other event classes, good agreement

§ Circularity is defined in terms of the transverse momentum vectors of all final state energy clusters. It takes value 0 when all vectors are collinear and value 1 when vectors have a uniform azimuthal distribution.

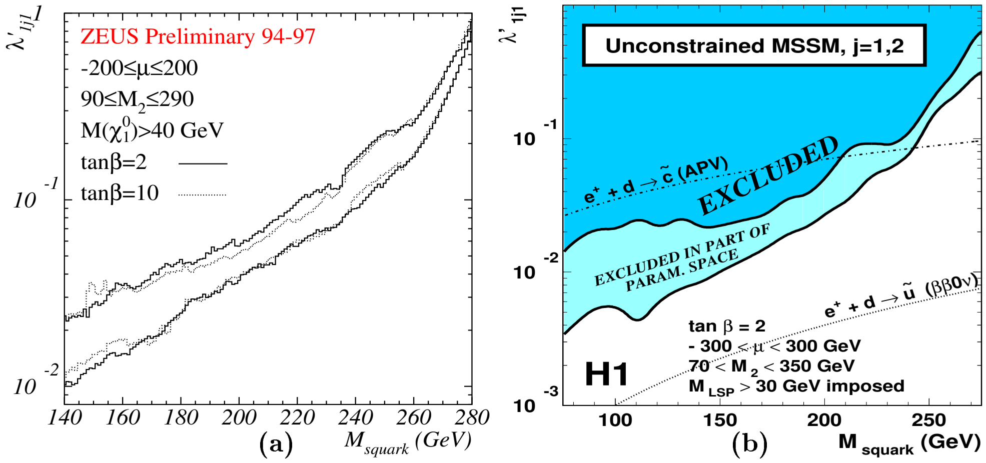

Figure 7. Upper limits at 95% CL for the coupling λ'_{1j1} as a function of the squark mass in the unconstrained MSSM obtained by ZEUS **(a)** for $\tan\beta$=2 and 10 and H1 **(b)** for $\tan\beta$=2. In both figures, a scan of the MSSM parameters μ and M_2 corresponding to the range shown in the figure is performed, and largest (lowest) limit value obtained is indicated as the upper (lower) curve. In figure **(b)**, the indirect bounds from neutrinoless double-beta decay and from atomic paity violation are also reported.

is found between data and SM expectations; in particular, no events passed the e^-+*multijet* selection in both the experiments.

Exclusion limits on λ'_{1j1} as a function of the squark mass are shown in figure 7 for an unconstrained minimal SUSY model (MSSM) where the parameters μ, M_2 and $\tan\beta$ were only used to determine the masses and couplings of the χ's, while the sfermion masses are free parameters. At most one λ'_{1j1} was assumed to be non-zero and both squarks and sleptons were assumed to be mass degenerate in the calculation of the branching ratios. A scan of the parameters μ and M_2 was performed at fixed $\tan\beta$ values in the ranges shown in the figures, where points leading to LSP masses below 30 GeV(H1) or 40 GeV (ZEUS) were not considered to avoid domains excluded by searches at LEP. For Yukawa couplings of electromagnetic strength, squark masses below ∼260 GeV are ruled out by both experiments (the case j=3, treated separately by H1 because of the large top mass and $t\to bW$ decay, leads to very similar limits at high $\tilde{q}$ masses). Note that TeVatron constraints on direct searches for scalar LQs, discussed in the previous section, are very weak when applied to this scenario because the branching $\tilde{q}\to eq$ is normally small. However, the coupling λ'_{111} is severely constrained by neutrinoless double-beta decay, while the results on λ'_{121} and λ'_{131} improve the indirect constraints from atomic parity violation experiments.

Excluded domains of the minimal supergravity (mSUGRA) model parameters $(m_0, m_{1/2})$, obtained by H1, are shown in figure 8 for $\tan\beta$=2, μ<0 and λ'_{1j1}=0.3. It can be seen that the parameter space where $M_{\tilde{u}_L}$<260 GeV is nearly fully excluded for j=1,2. In the case j=3, larger values of m_0 can be probed due to the mixing in the $\tilde{t}$ sector which leads to $\tilde{t}$ masses smaller than the other $\tilde{u}^j_L$ squarks; in this case, masses up to 245 GeV can be excluded for λ'_{131}=0.3. Limits from TeVatron and LEP SUSY searches are also shown in the figures; these limits do not depend on the coupling λ' and are comparable to the HERA limits in parts of the parameter space.

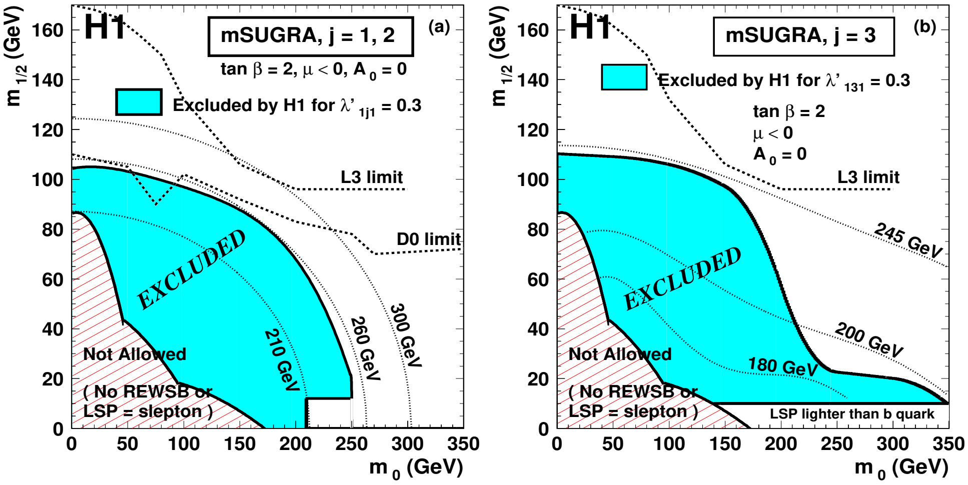

Figure 8. Domain of the plane of the mSUGRA parameters (m_0, $m_{1/2}$) excluded for for $\tan\beta$=2, μ<0 and λ'_{1j1}=0.3; figure **(a)** corresponds to j=1,2, figure **(b)** corresponds to j=3. The regions below the dashed curves are excluded by the D0 or L3 experiments. The hatched domains correspond to values of the parameters where the symmetry breaking model assumed fails, or where the LSP is a slepton. Isolines for different $\tilde{u}^j_L$ masses are shown as dotted curves. For $m_{1/2}$ below 10 GeV in figure (b), the LSP becomes lighter than b quark and thus is stable even for non vanishing λ'_{131}.

4. Contact interactions

With the increase of the accumulated luminosity, ZEUS and H1 experiments were able to measure NC DIS cross section up to values of Q^2 of about 40000 GeV^2, which corresponds to probing distance scale down to less than 1/1000 of the proton radius. If new particles or new substructures would exist at scales in the TeV range, these would alter the high-Q^2 measured cross section.

The four fermions $eeqq$ contact interaction (CI) is the most general framework to quantify the effects coming from new physics at scales much larger than $\sqrt{s}$; possible sources of such contact terms are either a substructure of fermions (here the scale is related to the size of the composite object) or exchange of new heavy particles (the scale is related to the mass and couplings of the new exchanged boson). As strong limits are placed on scalar and tensor terms, only vector CI terms need to be considered; they can be expressed as an additional term $\sum \eta^{eq}_{ij}(\bar{e}_i\gamma^\mu e_j)(\bar{q}_j\gamma_\mu q_i)$ to the SM Lagrangian, where the sum runs over the electron and quark helicities (i,j=L,R). Given the dominance of u and d quarks at high-Q^2 there are eight independent contact terms, four for each quark flavour.

ZEUS has recently presented a CI analysis of the 1994-2000 e^+p and e^-p high-Q^2 DIS data[9], corresponding to almost 130 pb^{-1} of luminosity. Similar analysis was earlier presented by H1[8] with 97pb^{-1} of e^+p and e^-p data (last part of e^+p data collected in year 2000 was not included). Both experiments found a good agreement with SM up to the highest Q^2 values and have derived limits on the various models which will be discussed in the following (refer to [9, 8] for details on the statistical treatment of the data).

In the general case (referred to as *compositeness models*), the coefficients η are related to the compositeness scale Λ through $\eta{=}\pm g^2/\Lambda^2$ where the coupling strength of the new interaction is conventionally set to $g^2{=}4\pi$. The sign of the coefficient η determines the interference effect with the SM at intermediate Q^2 which can produce an increase or a decrease of the cross section. Combining the above terms, many CI interaction models can be constructed which have different chiral structures and interference signs. ZEUS has analyzed the data in terms of 30 CI scenarios and derived lower limits on Λ. The limits at 95% CL range between 2.6 TeV and 7 TeV for the scenarios considered. Similar scenarios were also considered by H1 with limits on Λ ranging between 1.6 TeV and 9.2 TeV. These limits are competing and sometimes more stringent than those obtained at LEP and TeVatron.

If *heavy leptoquarks* would exist with masses M_{LQ} much larger than $\sqrt{s}$, the effect at HERA would be equivalent to a vector-type CI, where M_{LQ} and the coupling λ are related to the CI coefficients via $g/\Lambda{=}\lambda/M_{LQ}$. Lower 95% CL limits on the ratio M_{LQ}/λ were derived by both experiments for the 14 LQs described by the BRW model[1]. These limits lie in the range 310 GeV - 1.4 TeV (ZEUS) and 290 GeV - 1.7 TeV (H1) and are valid only within the assumption $M_{LQ}{\gg}\sqrt{s}$. An example of such limits obtained by H1 is shown in figure 4.

It has been recently suggested[10] that space-time could be characterized by n compactified *extra spatial dimensions.* While known particles, including strong and electroweak bosons, are confined to the 4-dimensional space, the spin 2 graviton propagates as a massless particle into the extra dimensions. In models where extra

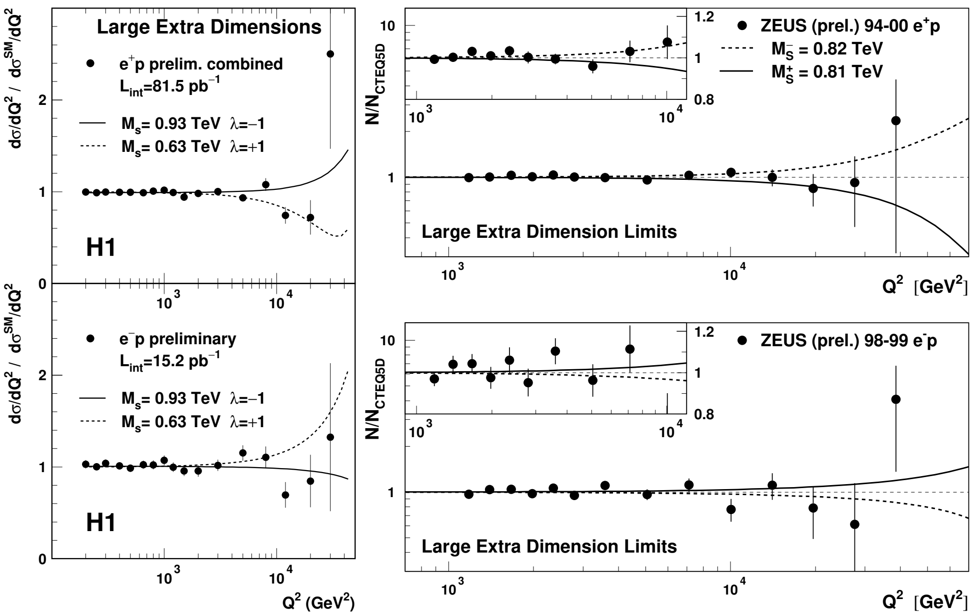

Figure 9. NC cross section $d\sigma/dQ^2$ normalized to the SM expectation for e^+p data (top) and e^-p data (bottom) as a function of Q^2 for H1 (left) and ZEUS (right). The curves in the figures show the effects of graviton exchange in large extra dimensions given by a common fit to the scale M_S with couplings λ=+1 and λ=-1. The values shown for M_S represent the 95% CL lower limits.

dimensions have very large size (large extra dimensions), gravity could be characterized by an "effective" Planck scale M_S of the order of a TeV; at such energies, gravitational intractions could become comparable in strength to the electroweak interactions. The contribution of virtual gravitons, which would appear in the 4-dimensional world as a spectrum of massive Kaluza-Klein states, to $eq \rightarrow eq$ scattering lead to an effective contact interaction with a coupling coefficient $\eta = \lambda / M_S^4$[11]; two scenarios $\lambda = \pm 1$, corresponding to different interference with SM, are conventionally considered. The combined analysis of $e^{\pm}p$ data by ZEUS (H1) yields 95% CL lower limits on M_S of 0.81 (0.63) TeV for λ=+1 and 0.82 (0.93) TeV for λ=-1. The effects of graviton exchange on the NC Q^2 distributions of ZEUS and H1 are shown in figure 9. Similar investigations of virtual graviton exchange in e^+e^- collisions provide comparable limits.

5. Events with isolated high-P_T leptons with missing P_T

Events produced in ep collisions with high-P_T isolated leptons and missing transverse momentum are promising candidates for new physics. In the SM, events from this topology are predicted from W production where the W decays leptonically $W \rightarrow l\nu$ ($l = e, \mu$). However, since the cross section for W production is small ($\sigma \sim 1$ pb), only few events are expected within present statistics. A significant excess compared to SM expectations might reflect squark production from $\not{R}_P$ interactions, top quark production followed by $t \rightarrow bW$ decay or anomalous electroweak $WW\gamma$ coupling.

From a first study of e^+p interactions at $\sqrt{s}$=300 GeV H1 found six events, one where the lepton is an e^- and five where the leptons are $\mu^{\pm}$. The number of muon events was significantly above the expectations of 0.8±0.2 events. A similar search performed by ZEUS found good agreement with the SM.

The search was recently extended by H1[12] to cover the complete 1994-2000 data and new events were found. The analysis, which was developed to maximize the acceptance for SM W production, required a missing P_T>12 GeV and the presence of an identified electron or muon track with P_T^{track}>10 GeV. Track isolation was achived by requiring the separation of that track to the nearest jet (D_{jet}) and the nearest track (D_{trk}) in the pseudorapidity-azimuth plane to be larger than 1.0 and 0.5 respectively. Additional topological cuts were also used to enhance the W signal over other sources of SM background. In the e^-p data sample no events are observed in either the electron or muon channel. In the e^+p data sample, 10 events are observed in the electron channel (one e^-, five e^+ and four tracks with unmeasured charge) and 8 events are observed in the muon channel (two μ^-, five μ^+ and one track with unmeasured charge). Corresponding expectations from SM processes are 7.9±1.9 electron events (6.1 from W production) and 2.6±0.7 muon events (2.1 from W production).

The transverse momentum of the hadronic system P_T^X and the transverse mass M_T of the H1 events are compared in figure 10(a) and 10(b) to SM W production. The events are distributed in a Jacobian peak consistent with the W mass, but are seen with high P_T^X, atypical of W production. This is also shown in figure 10(c), where the data appear to lie above the expectation at large P_T^X; at P_T^X>25 GeV (P_T^X>40 GeV), 10 (6) events are seen while only 2.8±0.7 (1.0±0.3) are expected from SM processes, 2.3 (0.9) from W production only.

ZEUS has also recently extended to the complete 1994-2000 data the search for these events topologies[13] and still observes a good agreement with the SM, even at large P_T^X values: 2 events (1 electron and 1 muon) are observed at P_T^X>25 GeV with a SM expectation of 2.4±0.2 (2.0 from W production), while no events are observed

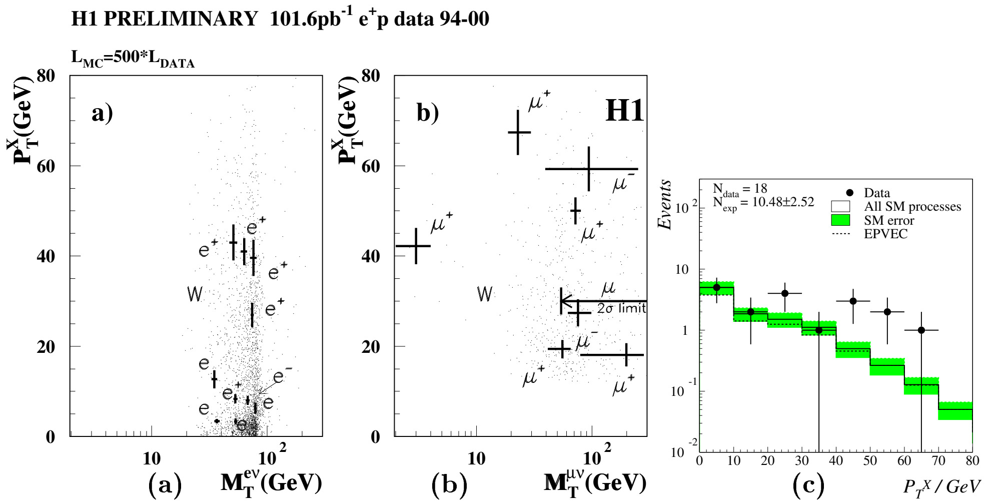

Figure 10. A comparison of the H1 isolated lepton events with the SM expectations in the electron **(a)** and muon **(b)** channels showing the distribution in the transverse momentum of the hadronic system P_T^X and transverse mass M_T formed by the lepton and the missing 4-momentum vectors (the smaller dots represent the distribution of SM W Monte Carlo events). Figure **(c)** shows the P_T^X distribution of the combined e and μ channels compared to SM (open histogram); the shaded band represents the total error on SM expectation, the dashed histogram the W component only.

for P_T^X>40 GeV with a SM expectation of 1.0±0.1 events (0.9 from W production). Although the sensitivities to W production of the two experiments are similar, ZEUS cannot confirm the H1 excess. A search in the and $W \to q\bar{q}$ and $W \to \tau\nu$ channels, attempted by H1[14], brings no comparable sensitivity. A substantial increase in the data samples seems to be required before a definitive conclusion can be drawn.

6. Search for single top production

In the SM, flavour changing NC interactions (FCNC) are forbidden at leading order. Transitions between a top quark and light u or c quark can only occur via loops, which renders the cross section extremely small. However, some models beyond the SM predict anomalous effective couplings of a top quark to a light quark and a gauge boson (of the type tuV and tcV where $V{=}\gamma, Z$) which could give rise to experimental signatures. At HERA, such couplings would lead to single top production illustrated in figure 11(a). Note that such process, given the large Z and t mass, is largely dominated t-channel exchange of a quasi real γ between the electron and a valence u quark. The sensitivity at HERA is therefore largest for the anomalous magnetic $tu\gamma$ coupling, denoted $\kappa_{tu\gamma}$.

Searches for such FCNC couplings have been carried out at LEP in single top production ($e^+e^- \to tq$) and at TeVatron in rare top decays ($t \to q\gamma, qZ$). These processes can constrain the γ and Z couplings, and the limits can apply to both u and c quarks. At HERA, such search is also motivated by the observation of high P_T lepton events discussed in the previous section; top quark decays predominantely via $t \to bW$ and, because of the large top mass, the b-quark jet would carry a large P_T^X.

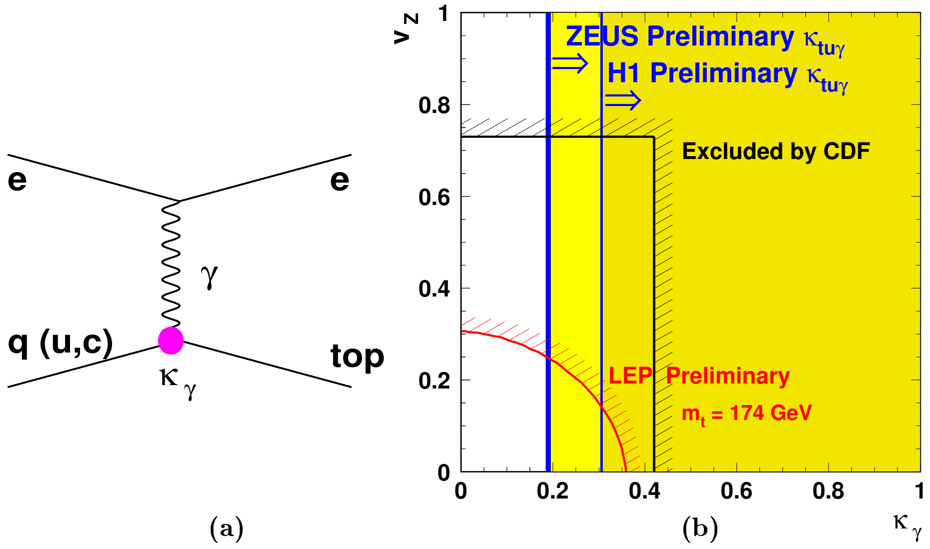

Figure 11. Example diagram for anomalous single top production via FCNC interaction at HERA **(a)** and limits on the FCNC magnetic coupling at the photon vertex (κ_γ) and the vector coupling at the Z vertex (v_Z) obtained by TeVatron (CDF), LEP, H1 and ZEUS. The HERA limits apply to the coupling $\kappa_{tu\gamma}$only.

Both ZEUS and H1 have reported results on top searches in both the leptonic and the hadronic W decay channel [13, 15].

For the leptonic W decay channel the same selection criteria as for the isolated lepton events presented in the previous section were used by both experiments. Additionally, ZEUS required P_T^X>40 GeV, yielding no events in this channel with an expectation of 1.0±0.1 events from SM background. H1 required instead P_T^X>25 GeV, the transverse mass M_T>10 GeV and discarded events where the isolated lepton had a negative charge, incompatible with top decay. H1 found 5 top candidate events (3 e^+ and 2 μ^+) with an expectation of 1.8±0.5 from SM background sources.

For the hadronic W decay channel, ZEUS required three jets of large transverse energy. For any pair of jets, a mass window centered around the W mass was applied to the their invariant mass. If any pair of jets fulfilled this requirement, a mass window centered around the top mass was also applied to the three-jet invariant mass. Using 127pb^{-1} of e^+p and e^-p data (corresponding to the whole 1995-2000 data), ZEUS found 19 candidate events while 20.0 were expected from background sources. H1 analysis applied a similar selection method: using the e^+p data at $\sqrt{s}$=300 GeV, 10 events were selected with an expectation of 8.3 from SM background. In both ZEUS and H1, no excess of events is seen in the hadronic W decay channel.

The 95% CL limits on the anomalous $\kappa_{tu\gamma}$ coupling obtained combining the results from the leptonic and the hadronic decay channels are compared in figure 11(b) with limits from TeVatron and LEP. Because of the excess in the leptonic channel, H1 limit ($\kappa_{tu\gamma}$<0.31) is weaker than ZEUS limit ($\kappa_{tu\gamma}$<0.19). In both cases, the obtained limit exclude a substantial region in $\kappa_{tu\gamma}$ not excluded by other experiments.

7. Conclusions

Extensive searches for physics beyond the standard model have been performed by ZEUS and H1 experiments at HERA. In most of the searches presented, all the data collected with electron- and positron-proton collisions up to year 2000 were analyzed. No established signal of new physics was found and limits were derived on various models which are competitive with similar searches at other colliders.

At the time of writing, a new 5-years running of HERA is starting with an upgraded machine. Integrated luminosities of the order of 1 fb^{-1} (i.e. a 10-fold increase compared to present luminosity) with polarized e^+ and e^- beams will be available. This will open new scenarios in unexplored regions and will eventually unreveal the breakdown of the Standard Model if any new physics is existing within the reach of HERA.

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