RESULTS ON SEARCHES BEYOND THE STANDARD MODEL AT HERA

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Signals of physics beyond the Standard Model at HERA have been searched for by the H1 and ZEUS collaborations. Results are reported about searches of contact interaction effects, leptoquarks, R-parity violating squarks, excited fermions and single top production. The analyses used the data set collected during the HERA phase I, consisting in about 110 (15) pb^{-1} of e^+p (e^-p) collisions per experiment. No evidence for new physics has been found and limits have been set on the parameters of the models considered.

1 Introduction

At HERA electrons or positrons of 27.5 GeV and protons of 920 GeV (820 GeV before 1998) are collided, resulting in a center-of-mass energy, $\sqrt{s}$, of 318 (300) GeV. The maximum square momentum transfer (Q^2) reached is a few times 10^4 GeV^2, which means the resolution power in probing the proton structure is of the order of 10^{-16}cm.

In the years 1994-2000 the luminosity collected by each experiment is approximately 110 pb^{-1} with e^+p and 15 pb^{-1} with e^-p collisions.

Signals for new physics have been searched by both collaborations and are reported for the following topics:

- Physics at an energy scale much higher than the HERA energy could produce deviations in the high Q^2 region. Modeling the process as a four fermion contact interaction ($eeqq$) the evidence for new physics can be investigated.

- Resonant electron-quark states can be formed, taking advantage of the unique opportunity of an initial state with definite leptonic and baryonic number provided by HERA. Leptoquarks and R-parity violating squarks are examples of such states.

- Excited states of leptons or quarks, predicted by compositeness theories, could be produced if their masses are below the HERA center-of-mass energy.
- Events with a high p_T lepton and missing transverse energy have been searched, following the first observation by H1. Single top production events at HERA would present the same topology and could be observed if an anomalous large top coupling existed.

2 Contact Interactions

Four-fermion contact interactions (CI) are an effective theory which can be used to describe virtual effects coming from physics processes at much higher energy scale. Such effects could produce deviations on the observed Q^2 distributions in Deep Inelastic Scattering (DIS) with respect to Standard Model (SM) expectations, which could result in an increase of the cross section at the largest Q^2 and an interference effect (positive or negative) with the SM in the intermediate Q^2 region [1].

As strong limits have already been placed on the scalar and tensor terms [2], only the vector $eeqq$ terms have been considered here. They can be represented as additional terms in the SM Lagrangian:

$$L_{CI} = \sum_{\alpha,\beta=L,R}^{q=u,d} \eta^q_{\alpha\beta} (\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta) \tag{1}$$

where the coefficients $\eta^q_{\alpha\beta} = \epsilon g^2_{CI}/\Lambda^2$ characterize the different CI scenarios defining their chiral properties via the sign of the interference with SM, ϵ, their strength via the coupling g_{CI} (by convention set to $g_{CI} = \sqrt{4\pi}$) and their effective mass scale via the parameter Λ (α and β are, respectively, the electron and quark helicity and q is the quark flavor).

The high Q^2 Neutral Current (NC) DIS measurements performed by both collaborations [3,4] show no deviations from the SM expectation, hence limits on the scale Λ were derived for the most common CI models. The Q^2 distribution measured by ZEUS is shown in fig. 1 for the e^+p (left top) and e^-p (left bottom) data together with the 95% CL effect of the presence of a VV-type CI scenario ($\eta_{LL} = \eta_{LR} = \eta_{RL} = \eta_{RR}$). The recently released limits obtained by H1 for several scenarios are shown in fig. 1, right plot. The limits range up to more than 5 TeV and are comparable to what obtained at LEP and Tevatron studying reactions complementary to HERA, respectively $e^+e^- \to q\bar{q}$ and Drell-Yan processes.

The specific model with Large Extra Dimensions [5] has also been considered. In such a model SM particles can propagate in the ordinary 4-dimensional space and the graviton has access to the extra dimensions which are compactified to a size below the millimeter scale. With very large extra dimensions, the effective Planck scale, M_S, could be comparable to the electroweak scale and CI-like terms with coupling coefficient $\eta_G = \lambda/M_S^4$ could be visible at HERA in the high Q^2 region [6]. Limits on the effective scale M_S have been set to ~ 0.8 TeV at 95% CL [7,8].

3 Leptoquarks

Leptoquarks (LQ) are color-triplet bosons carrying both leptonic (L) and baryonic (B) number predicted by several extensions of the SM. They could be directly produced at HERA by fusion of the initial state electron with the quark of the incoming proton with a cross section depending on the unknown Yukawa coupling λ at the LQ-electron-quark vertex.

The experimental results have been interpreted in the framework of the Buchmüller-Rückl-Wyler (BRW) model [9], where the branching ratios β_e (β_ν) for the LQ decays to eq (νq) are assumed to have fixed values (1, 1/2, 0). The BRW model classifies 14 possible scalar or vector LQ species with fermionic number $F = 3B + L = 0$ or $|F| = 2$. The $F = 0$ LQs couple to a

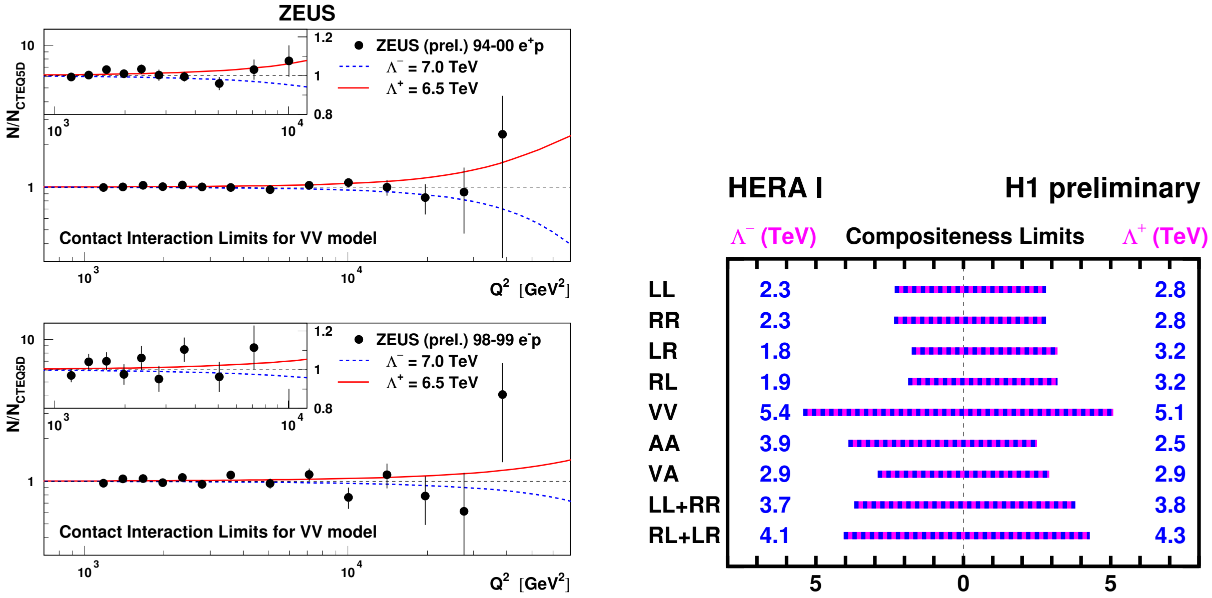

Figure 1: Left side: ZEUS Neutral Current measurements (normalized to SM expectations using the CTEQ5D parton distributions) compared with curves corresponding to 95% CL exclusion limits for the effective mass scale in the VV contact-interaction model, for positive (Λ^+) and negative (Λ^-) couplings. Right-side: H1 limits on the compositeness scale Λ resulting from the combined analysis of the e^+p and e^-p data (values outside the regions delimited by the bars are excluded at 95% CL).

particle and an anti-particle and are therefore better tested with e^+p collisions, while $|F| = 2$ LQs couple to two particles or two anti-particles and are better tested in e^-p collisions.

The LQ decay to lepton-quark pair produces a final state identical to SM DIS, but the angular distribution of the scattered lepton is different. The inelasticity variable, y, is related to the lepton decay angle in the lepton-quark rest frame, θ^*, with $cos\theta^* = 1 - 2y$. DIS events have a $1/y^2$ angular distribution, scalar LQs are flat in y and vector LQs have a $(1 - y^2)$ dependence. Therefore a cut in y is used to enhance the LQ signal over the DIS background.

No evidence of a signal has been found by either collaboration [10,11], therefore limits on the Yukawa coupling as a function of the LQ mass have been derived and shown in fig. 2 (a) for two types of scalar LQs, together with the LEP and Tevatron limits. A more general LQ model has been considered, treating the branching ratios β_e and β_ν as free parameters, with the only assumption that $\beta_e + \beta_\nu = 1$. In this case, combining NC and CC results, the limits obtained are largely independents of the branching ratios and are shown in fig. 2 (b). The comparison with the Tevatron limits shows that HERA results extend to lower masses and smaller branching ratio to νq.

4 R-parity violating squarks

R-parity is a multiplicative quantum number defined as $R_p = (-1)^{L+3B+2S}$ where L, B and S denote leptonic number, baryonic number and particle spin. It distinguishes standard particles having $R_p = +1$, from their supersymmetric partners for which $R_p = -1$.

In supersymmetric models with R-parity conservation (e.g. MSSM, the Minimal Supersymmetric Standard Model), sparticles are produced in pairs and the lightest supersymmetric particle is stable. In models where R-parity is violated [12], sparticles can be singly produced and decay back to SM particles.

The $\lambda'_{ijk} L_i Q_j D_k$ term in the supersymmetric lagrangian is of interest at HERA (L and Q are the left-handed lepton and quark doublet superfields, D is a right-handed singlet superfield

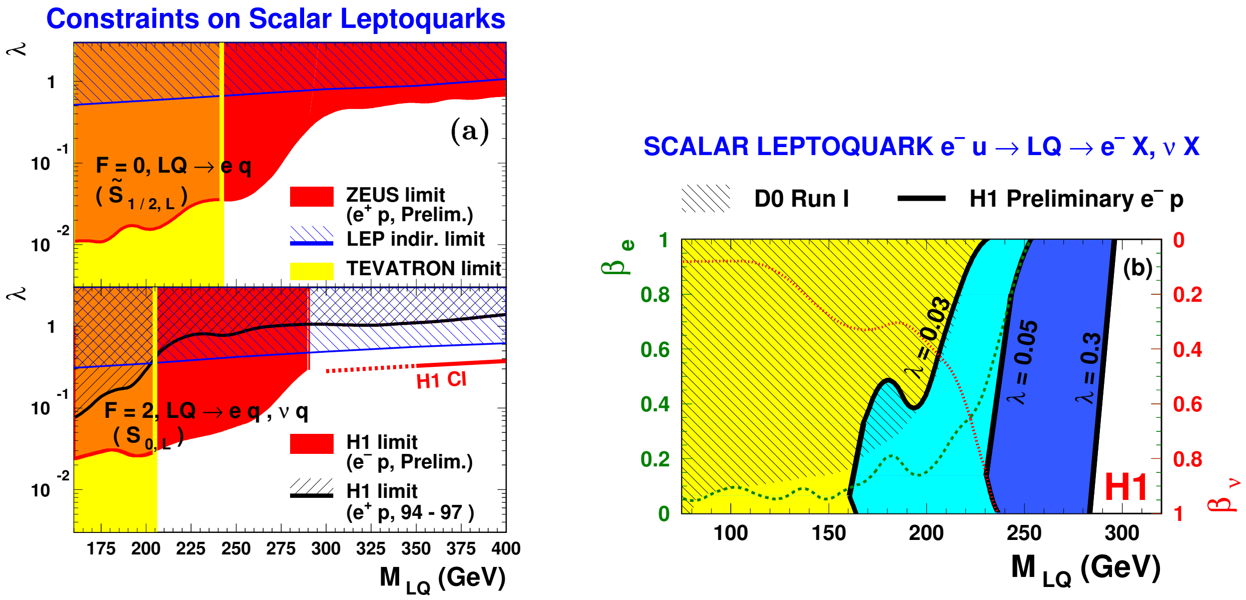

Figure 2: a): Exclusion limits at 95% CL on the Yukawa coupling λ as a function of the mass for a scalar LQ with $F = 0$ in ZEUS (upper) and with $F = 2$ in H1 (lower). The regions above the curves are excluded. LEP and Tevatron limits are also shown. b): Domains excluded by the combinations of NC and CC data for a scalar $F = 0$ LQ decaying only in eq or νq for three values of the Yukawa coupling λ. The regions on the left of the curves are excluded at 95% CL. For $\lambda = 0.05$ the part of the plane to the left of the dashed (dotted) curve is excluded by the NC (CC) analysis. Tevatron exclusion region is also shown.

of down-type quarks, λ' is the Yukawa coupling and i, j, k denote their generation), since a non-zero value of λ'_{1jk} would imply the possibility to produce single squarks via eq fusion.

The decay mechanism of a squark can then involve R-parity conserving decay to gauginos and produce many final states, made of multi-jet and leptons, which have been investigated by both collaborations [13,14]. No evidence of a signal has been found and in fig. 3 limits on the coupling as a function of the squark mass are shown for two sets of SUSY parameters.

5 Excited Fermions

The family structure and mass hierarchy of the known fermions suggests they could not be elementary particles but have a substructure, as postulated in compositeness models. A consequence of these models is the existence of excited states of leptons and quarks which could be produced at HERA, depending on the dynamics of the unknown sub-constituents.

Once produced, an excited fermion would decay to a normal fermion by radiating off a gauge boson.

The experimental results have been studied in the theoretical framework of the Hagiwara, Komamiya and Zeppenfeld model [15], where the production cross section depends on the relative coupling strengths f, f' and f_s to the SU(2), U(1) and SU(3) gauge groups.

Assuming relations between the couplings, the cross section depends only on the parameter f/Λ. The conventional assumptions used at HERA are: $f_s = 0$ and $f = \pm f'$.

Neither collaboration have found deviations from SM expectation in any of the decay channels considered [16,17] and therefore limits have been set on f/Λ. In fig. 4 the H1 limits for excited electrons and excited neutrinos are shown. The excited electron limits are new preliminary results obtained by considering all the electroweak decays $e^* \to e + \gamma$, $e^* \to eZ$, $e^* \to \nu W$ and final states resulting from Z or W hadronic decays, and using the full 1994-2000 luminosity.

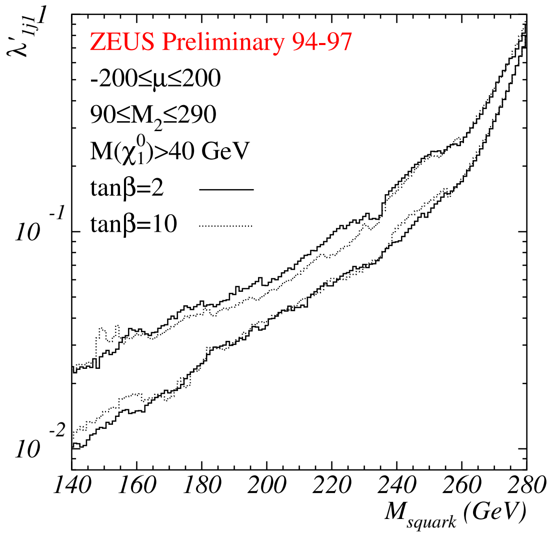

Figure 3: Minimum and maximum 95% CL limits on λ'_{1j1} versus the squark mass for $\tan\beta = 2$ (solid) and 10 (dotted), obtained in the region -200 GeV $\leq \mu \leq$ 200 GeV and 90 GeV $\leq M_2 \leq$ 290 GeV.

Table 1: Results of the search for isolated lepton events as observed by H1 and ZEUS for two values of the hadronic transverse momentum (P_T^X) cut. The H1 value in the table refers to the e^+p data only (see text for the H1 e^-p result).

	P_T^X cut	Electrons Observed/Expected (W)	Muons Observed/Expected (W)
ZEUS prel.	25	$1/1.14 \pm 0.06$ (1.10)	$1/1.29 \pm 0.16$ (0.95)
94-00 $e^{\pm}$p 130 pb^{-1}	40	$0/0.46 \pm 0.03$ (0.46)	$0/0.50 \pm 0.08$ (0.41)
H1 prel.	25	$4/1.29 \pm 0.33$ (1.05)	$6/1.54 \pm 0.41$ (1.29)
94-00 e^{+}p 102 pb^{-1}	40	$2/0.41 \pm 0.12$ (0.40)	$4/0.58 \pm 0.16$ (0.53)

The comparison to the LEP results shows that the HERA potentiality is especially good in the excited neutrino search, where the limits have been extended to masses above 200 GeV.

6 Isolated Lepton Events

In 1998 H1 reported the observation of an excess in the production of events with a high transverse momentum lepton and missing P_T [18]. Both collaborations [19,20] have analysed the complete data set available from HERA phase I, and the results are summarized in table 1, where the data are compared with the SM expectation (dominated by the W production whose cross section has been measured at HERA to be ~1 pb [21]).

It is clear that while the ZEUS result is in agreement with the SM expectations both in the electron and in the muon channel, H1 observes an excess of events. On the other hand the MC expectations are in good agreement between the two experiments.

The H1 result for the 98-99 e^-p data (14 pb^{-1}), not reported in the table, is in agreement with the SM (Observed/Expected = 0/1.8±0.4).

The invariant mass distribution of the events is compatible with W production (fig. 5 left). The excess of events is pronounced in the kinematic region at high hadronic transverse momentum, as shown in fig. 5 right.

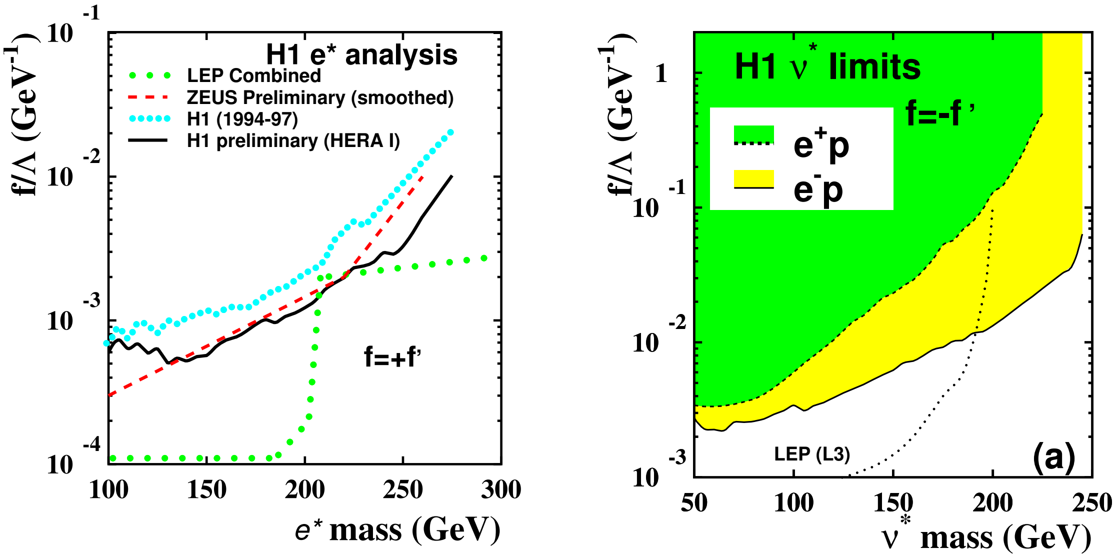

Figure 4: Exclusion limits on the coupling f/Λ at 95% CL as a function of the mass of the excited electron (left) and excited neutrino (right). LEP limits are also shown.

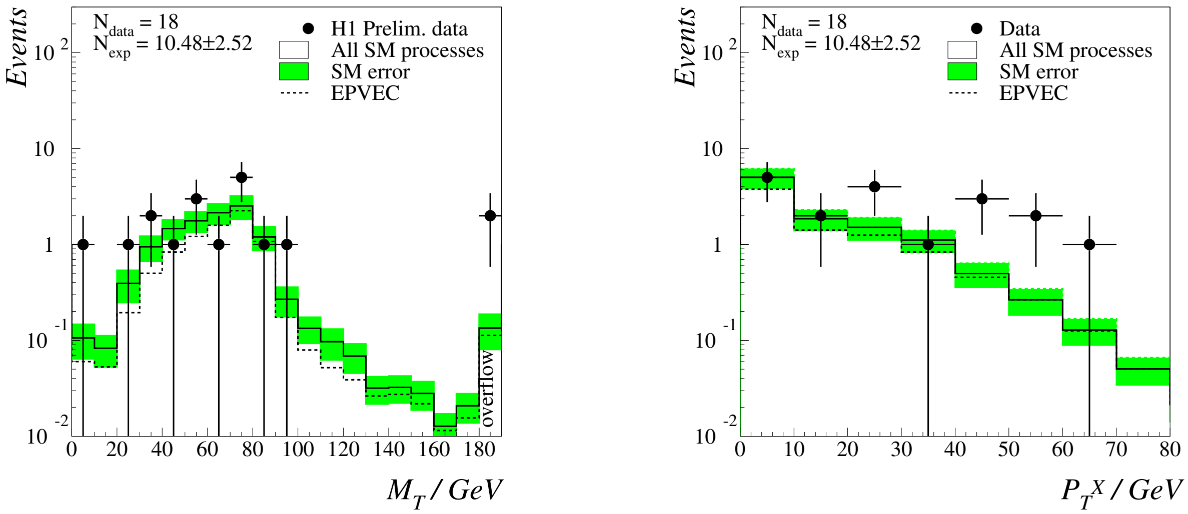

Figure 5: Transverse mass (left) and transverse hadronic momentum (right) distributions for the final e^+p data selection in the combined electron and muon channels as measured in H1. The total expectation from Standard Model is shown as full histogram together with the total error band. The dashed histogram represents the W production component.

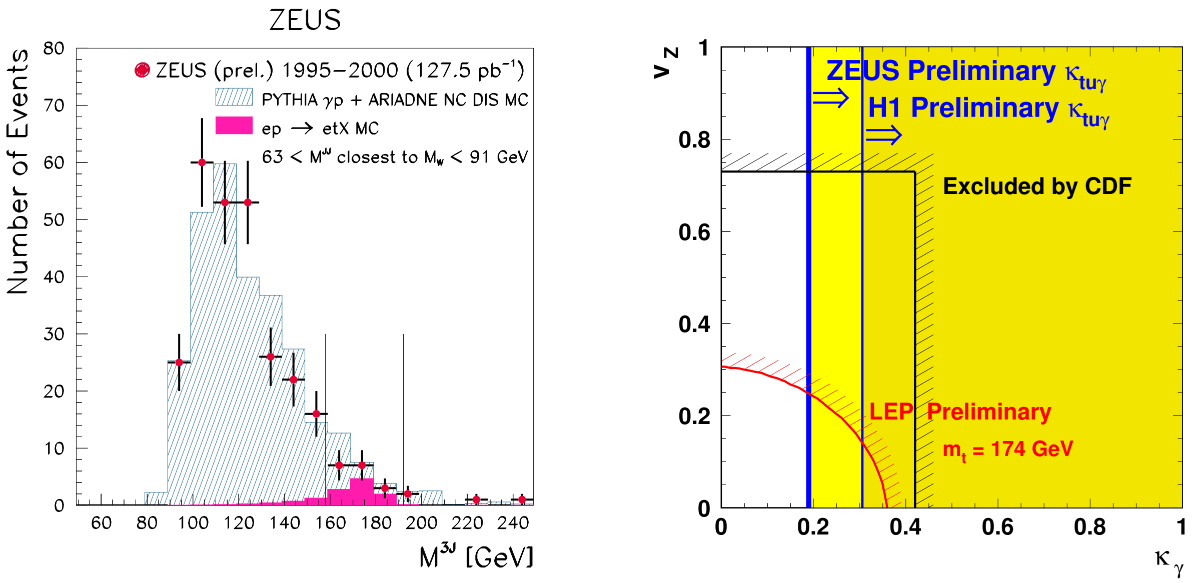

Figure 6: Left: three-jet invariant mass as reconstructed by ZEUS in the single top selection in the hadronic channel. The mass cuts applied in the final selection are shown as dashed lines. Right: limits at 95% CL on the FCNC magnetic coupling at the photon vertex, κ_γ and the vector coupling at the Z vertex, V_Z The LEP and Tevatron results are also shown. HERA results apply only to $\kappa_{tu\gamma}$.

7 Single Top Production

The signature of the events discussed in the previous section is also typical of a top quark decaying via $t \to bW \to bl\nu$. Top production at HERA would proceed via Flavor Changing Neutral Current (FCNC) events and is therefore tiny ($\sigma(ep \to etX) \sim$ 1fb at $\sqrt{s} = 300$ GeV) in the SM, because FCNC are forbidden at tree level and the contribution from loop diagrams is GIM suppressed. However SM extensions predict anomalously large top couplings which could increase the top production cross section to a sizable value.

For the leptonic decay of the W, H1 [22] observes five events (3 electrons + 2 muons) compatible with single top production, with an excess over the SM expectation (Observed/Expected = 5/1.8). ZEUS [20], instead, is in agreement with SM (Observed/Expected = 0/0.96).

The search in the hadronic decay channel has produced results consistent with the SM for both collaborations and the ZEUS invariant mass plot is shown in fig. 6 left for the three-jet event candidates. It has to be noticed that the sensitivity of the hadronic channel is lower with respect to the leptonic one. This means the H1 excess in the leptonic channel is not in contradiction with the hadronic channel result.

Combining leptonic and hadronic results a limit has been set on the magnetic coupling at the photon-top-quark vertex, which is plotted in fig. 6 right against the vector coupling at the Z-top-quark vertex.

The HERA results, plotted together with the Tevatron and LEP results, are absolutely competitive. The difference between ZEUS and H1 is simply due to the events found by H1 in the final selection.

8 Summary

The data set collected during HERA phase I has been extensively analysed by the H1 and ZEUS collaborations in the search for new physics. No evidence for new processes beyond the SM has been found. The exclusion power at HERA is similar to that at the other colliders (LEP and Tevatron).

The luminosity of the HERA II programme is needed to clarify the still outstanding isolated lepton events found by H1. In contrast to that, ZEUS data are in good agreement with SM.

The HERA II programme has reached its startup phase. The promised increase in luminosity should add up to an integrated value of about 1 fb^{-1} per experiment by the end of 2006, a factor 10 higher than the current value. This will allow an improvement of the limits currently set for contact-interactions, leptoquarks, squarks and excited fermions.

The running options with polarized $e^{\pm}$ beams will allow to enhance and/or disentangle the processes coupling to chiral leptons and to better control some background process.

Considerable efforts also on the detector side have been undertaken. Both experiments are now equipped with an improved forward tracking and vertex reconstruction capability, which will increase the sensitivity to flavor specific processes.

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