BEYOND THE STANDARD MODEL PHYSICS AT HERA

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Abstract

Recent results on physics beyond the Standard Model from the HERA *ep* collider are discussed, based on samples of 37 pb^{-1} and 47 pb^{-1} of data collected by the H1 and ZEUS Collaborations, respectively, during 1994–1997. Presented are limits on leptoquarks, contact interactions, supersymmetry, and excited fermions. Also discussed are an excess of events with high p_T muons and missing transverse momentum observed by the H1 Collaboration.

1 Introduction

The HERA ep collider, with a center-of-mass energy of 300 GeV, has not only expanded the study of deep inelastic scattering (DIS), but in addition provides a unique laboratory for the study of physics beyond the Standard Model. With the advent of high luminosity running during 1996, results from HERA on new physics remain quite competitive, even with such strong competition as the Tevatron [1] and LEP II. [2]

The results presented in this article are based on 37 pb^{-1} of data collected by the H1 Collaboration and 47 pb^{-1} of data collected by the ZEUS Collaboration during 1994–1997. During this time, HERA collided 27.5 GeV positrons with 820 GeV protons for a center-of-mass energy of 300 GeV. The result is values of Q^2 (the negative square of the four-momentum transfer between the positron and proton) as high as 50000 GeV^2.

The H1 and ZEUS detectors are described in detail elsewhere. [3] [4] Both are full coverage, 4π detectors with precision tracking, calorimetry, and muon identification. By convention, the forward, or positive z direction, is aligned with the proton beam, and the angle θ is defined with respect to the z-axis.

2 Leptoquarks

Leptoquarks are hypothetical particles that carry both lepton and quark number. Assuming $SU(3) \times SU(2) \times U(1)$ symmetry, first-generation leptoquarks are limited to 10 in number and share a total of 14 independent couplings. [5] Since leptoquarks are both produced from and decay into lepton-quark pairs, their event signatures are virtually indistinguishable from ordinary neutral-current (NC) and charged-current (CC) DIS. The cross section for DIS ($d\sigma/dy \propto y^{-2}$), however, can be contrasted with that for scalar ($d\sigma/dy \propto 1$) and vector ($d\sigma/dy \propto (1-y)^2$) leptoquarks, where $y = Q^2/xs$ and $x = x$-Bjorken. In addition, resonant (s-channel) leptoquark production is confined to a narrow bin in x at M^2/s.

Both H1 and ZEUS calculate limits on leptoquark production as a function of the leptoquark mass M_{LQ} by applying cuts to DIS events that preserve the mass peak in x and the high-y distribution characteristic of leptoquarks while suppressing ordinary DIS. H1 uses the positron energy and angle to determine M_{LQ}, whereas ZEUS uses the cone algorithm to find the dominant hadron jet and then calculates the hadronic jet and positron invariant mass. Both experiments compare the number of selected events against leptoquark Monte Carlos that include initial-state

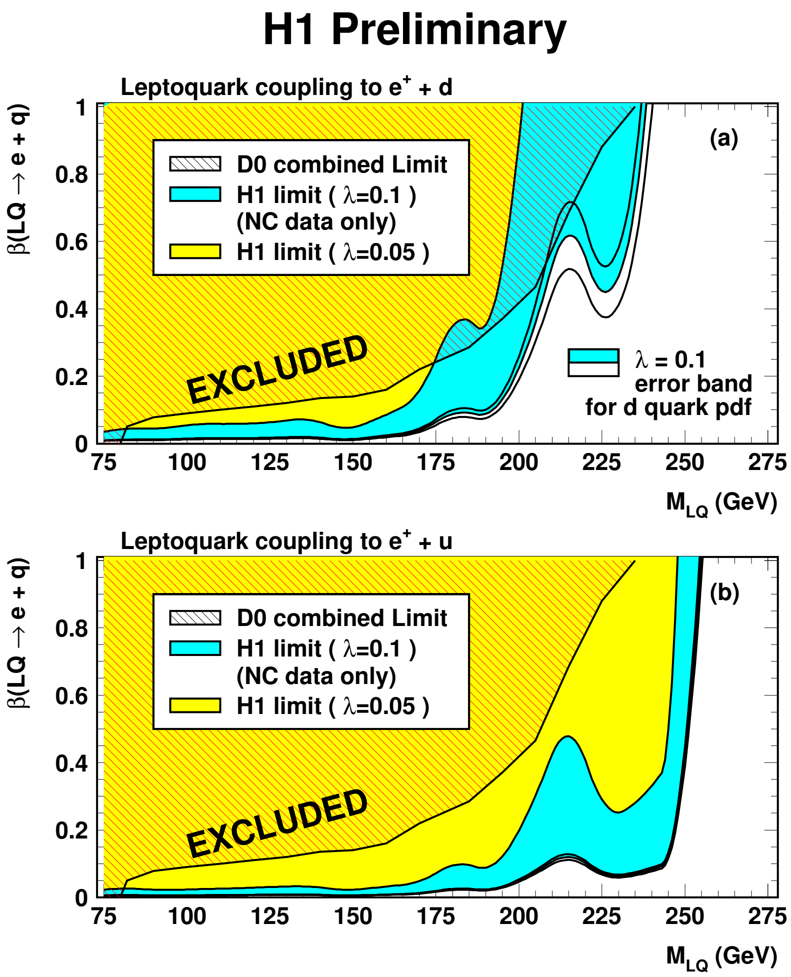

Figure 1: *Limits at 95% CL from H1 on the branching ratio for scalar leptoquarks that decay into (a)* e^+d *and (b)* e^+u *at 95% CL. The limits are compared to recent D0 results.* [6)]

radiation and first-order QCD corrections.

A sample of results from both experiments is shown in figs.1 and 2. Leptoquark searches at HERA are superior to the Tevatron at low branching ratios, as indicated by the H1 results. The ZEUS results, interpreted in terms of branching ratio times cross section, limit scalar leptoquark production at HERA to less than 0.3 pb for $180 < M_{LQ} < 290$ GeV.

3 Contact Interactions

The effect of a broad range of new physics on the NC DIS cross section can be approximated at their low energy limit by $eq \rightarrow eq$ contact interactions. The most general chiral invariant neutral-current contact interaction Lagrangian can be writ-

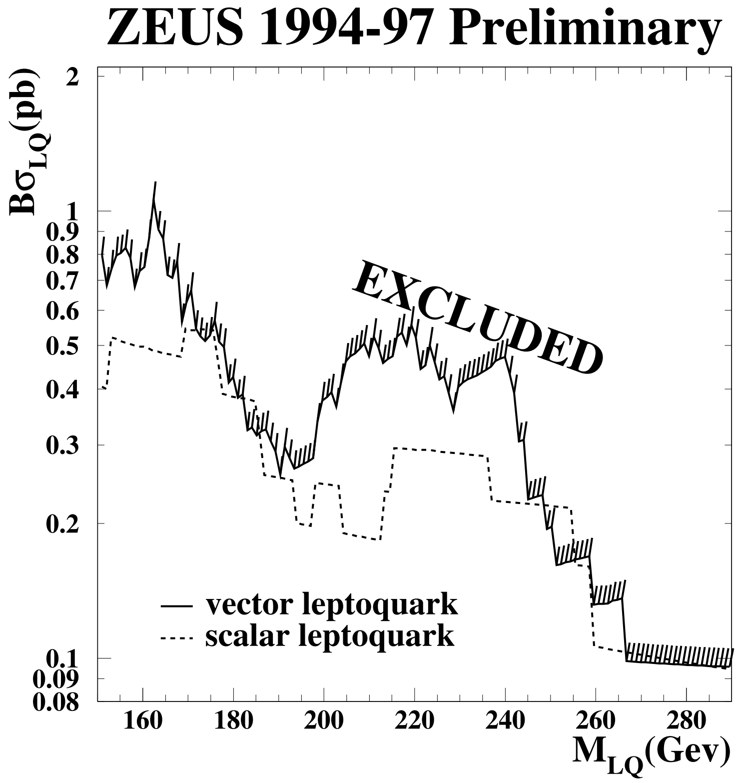

Figure 2: *Limits from ZEUS on cross section times branching ratio for scalar and vector leptoquarks at 95% CL.*

ten:

$$\begin{aligned} L = \sum_q [\ & \eta^q_{LL}\,(\bar{e}_L\gamma^\mu e_L)\,(\bar{q}_L\gamma_\mu q_L)\ +\ \eta^q_{LR}\,(\bar{e}_L\gamma^\mu e_L)\,(\bar{q}_R\gamma_\mu q_R) + \\ & \eta^q_{RL}\,(\bar{e}_R\gamma^\mu e_R)\,(\bar{q}_L\gamma_\mu q_L)\ +\ \eta^q_{RR}\,(\bar{e}_R\gamma^\mu e_R)\,(\bar{q}_R\gamma_\mu q_R)\quad] \end{aligned} \tag{1}$$

where $\eta = ag^2/\Lambda^2$, g is the coupling, Λ the effective mass, and a the relative sign of the individual terms. By convention, $g^2 = 4\pi$ and $|a| = 1$ when quoting limits on Λ. [7)]

Recent measurements of parity-violating transition amplitudes in cesium atoms imply strong limits on the individual η terms. [8)] These limits, however, do not apply to contact interactions that contain a parity-conserving combination of η terms. The models tested by H1 and ZEUS are listed in tab.1, of which all besides the LL, LR, RL, and RR models are not constrained by the atomic parity violation measurements.

The events produced by $eq \to eq$ contact interactions are indistinguishable from Standard Model NC DIS. Their effect is to alter the apparent NC DIS cross section by a large increase at large Q^2 in addition to smaller increases or decreases at moderate Q^2 due to interference with the Standard Model. To place limits on

Table 1: *The contact interaction models tested by H1 and ZEUS and the measured 95% CL limits on their couplings Λ. Each model includes a combination of two or more positron/quark couplings of equal magnitude as indicated in the columns marked "LL", "LR", etc. There are two limits for each model, corresponding to the overall sign of the couplings. The H1 limits are preliminary.*

	Up Quark Coupling				Down Quark Coupling				ZEUS Limit (TeV)		H1 Limit (TeV)	
Model	LL	LR	RL	RR	LL	LR	RL	RR	$a=-1$	$+1$	-1	$+1$
LL	$+a$				$+a$						1.2	2.4
LR		$+a$				$+a$					1.5	3.0
RL			$+a$				$+a$				1.6	3.0
RR				$+a$				$+a$			1.2	2.4
VV	$+a$	$+a$	$+a$	$+a$	$+a$	$+a$	$+a$	$+a$	5.0	4.7	2.5	4.5
AA	$+a$	$-a$	$-a$	$+a$	$+a$	$-a$	$-a$	$+a$	2.6	2.5	3.8	2.0
VA	$+a$	$-a$	$+a$	$-a$	$+a$	$-a$	$+a$	$-a$	3.7	2.6	2.8	2.6
X1	$+a$	$-a$			$+a$	$-a$			2.8	1.8		
X2	$+a$		$+a$		$+a$		$+a$		3.1	3.4		
X3	$+a$			$+a$	$+a$			$+a$	2.8	2.9		
X4		$+a$	$+a$			$+a$	$+a$		4.3	4.0		
X5		$+a$		$+a$		$+a$		$+a$	3.3	3.5		
X6			$+a$	$-a$			$+a$	$-a$	1.7	2.8		
U1	$+a$	$-a$							2.6	2.0		
U2	$+a$		$+a$						3.9	4.0		
U3	$+a$			$+a$					3.5	3.7		
U4		$+a$	$+a$						4.8	4.4		
U5		$+a$		$+a$					4.2	4.0		
U6			$+a$	$-a$					1.8	2.4		

Λ, H1 fits the cross section $d\sigma/dQ^2$ binned in Q^2 to predictions with and without each contact interaction model and determines the value of Λ that produces an appropriate increase in χ^2. In contrast, ZEUS performs an unbinned maximum likelihood fit in x and y using NC DIS Monte Carlo events to predict migration between the observed and true values. [9] Both results are summarized in tab.1 and reach limits on Λ as high as 5.0 TeV.

4 Supersymmetry

Supersymmetry (SUSY) theories relate bosons and fermions by associating to each fermion a bosonic partner and vice-versa. One of the more popular of such models is the Minimal Supersymmetric Standard Model (MSSM), [10] which, as the price for

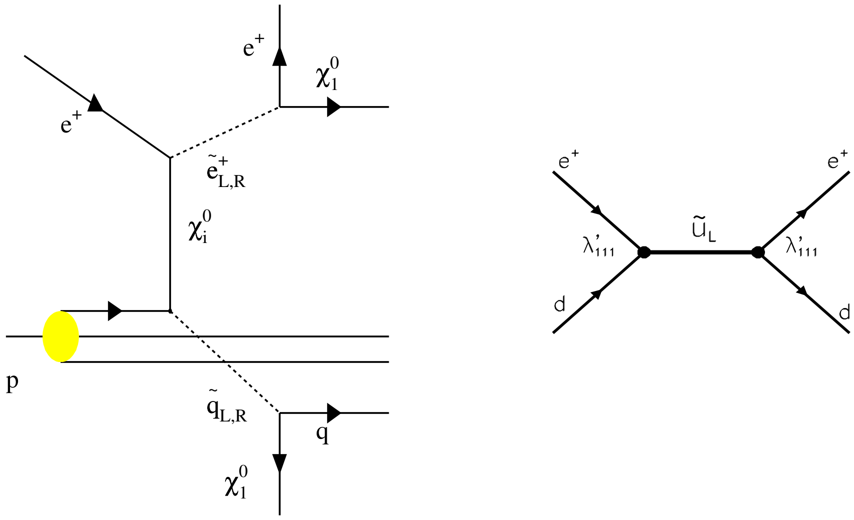

Figure 3: *Examples of Feynman diagrams at HERA for (left) R_P-conserving selectron and squark production and (right) R_P-violating single squark production.*

unifying bosons and fermions, introduces several new model parameters, including: M_1 and M_2, the mass of the $U(1)$ and $SU(2)$ gauginos, respectively; the higgsino mass parameter μ; and $\tan\beta$, the ratio of the vacuum expectation values of the model's two Higgs doublets. In addition, a new, conserved quantum number R-parity (R_P) is introduced which implies that supersymmetric particles may only be created or destroyed in pairs and that the lightest supersymmetric particle is stable.

At HERA, MSSM particles could be created in squark/slepton pairs as shown on the left in fig.3. Assuming that the lightest supersymmetric particle is a neutralino (χ_1^0), the signature of such an event is a final-state electron or positron, a hadronic system of high mass, and missing momentum from the two final state neutralinos. ZEUS has performed a search [11)] for such events by selecting events with an isolated positron or electron and missing transverse or longitudinal energy. The result was one event found with two events expected from Standard Model backgrounds, primarily W boson production. Resulting limits, translated into the squark mass and selectron mass plane, are shown in fig.4.

If the conservation of R_P is relaxed, it is possible to produce single supersymmetric particles at HERA (fig.3, right). This is attractive because it could produce a cross section similar to that of a leptoquark and in addition produce events with high-p_T leptons (described later). The cost of relaxing R_P conservation, however, is the introduction of additional complexity to the SUSY model, in particular, the couplings λ'_{ijk} between the ith generation left-handed lepton doublet, the jth generation left-handed quark doublet, and the kth generation right-handed

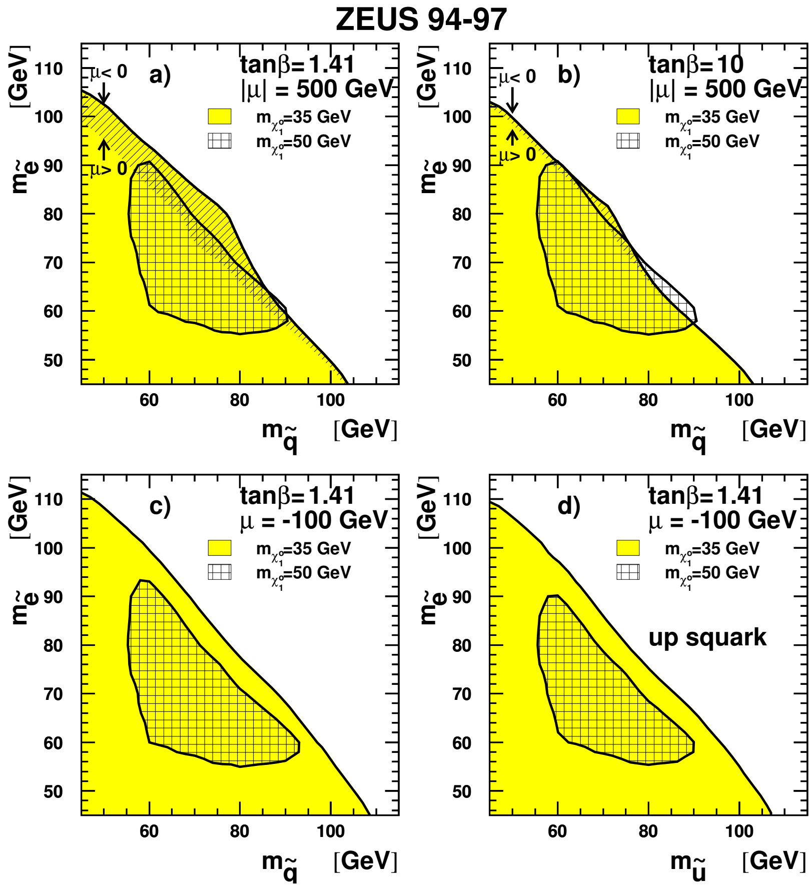

Figure 4: *ZEUS results on limits in the MSSM. Shown are excluded regions at the 95% CL in the plane defined by the selectron and squark masses, for* $m_{\chi_1^0} = 35$ *GeV (grey area) and* $m_{\chi_1^0} = 50$ *GeV (double-hatched area). In (a)* ($\tan\beta = 1.41$) *and (b)* ($\tan\beta = 10$)*, the limits are for* $|\mu| = 500$ *GeV. For* $\mu < 0$*, the excluded region also includes the single-hatched area. The limits obtained for* $\mu = -100$ *GeV and* $\tan\beta = 1.41$ *are shown (c) for both up and down squark contributions and (d) with up squarks alone.*

quark singlet. Nevertheless, if it is assumed that the lightest supersymmetric particle is a neutralino, gluinos are heavier then squarks, and one of the couplings λ'_{1jk} is dominate, than it is possible to classify supersymmetric events at HERA into four event topologies. These topologies include a combination of missing transverse energy, a high p_T electron or positron, and/or multiple jets.

The H1 collaboration has performed a search for R_P-violating supersymmetry under these assumptions by applying a series of event selection cuts tailored for each event topology. The remaining number of events in the data is compared against Monte Carlo predictions of Standard Model backgrounds and the result is used to calculate limits on the couplings λ'_{1jk} as a function of squark mass. A sample of results is shown in fig.5 with comparisons to limits obtained from measurements of double beta decay and [12] atomic parity violation. [13]

5 Excited Fermions

In models of fermion compositeness, it is possible to produce excited fermions in ep collisions that subsequently decay into an ordinary fermion and a gauge boson. The signature of such a decay would be the resonant production of a particle pair such as $e\gamma$, eZ, νW, $\nu\gamma$, νZ, eW, or qW. The method used for searching for these signatures depends on the decay mode, but follows a general strategy: decays that include an electron or gamma should include a large electromagnetic calorimetric deposit; decays that include a neutrino must have missing P_T; decays that include a W or Z should include jets that reconstruct near the boson mass. Additional cuts may be applied to remove specific Standard Model backgrounds, such as QED Compton events.

After performing these cuts, H1 is left with as many as 223 events ($e^* \to e\gamma$ channel) to as few as zero events ($\nu^* \to \nu\gamma$ channel), with efficiencies that vary between 40% and 80%. The resulting limits on production cross section are shown in fig.6. Also shown is the ZEUS analysis of the single channel $e^* \to e\gamma$. For masses above ~ 180 GeV, the H1 and ZEUS limits correspond to few, if any, events passing the cuts, and thus reach cross section limits of ~ 0.1 pb.

6 High-p_T Leptons and Missing Transverse Momentum

At HERA, W production is the primary source in the Standard Model of events with both missing transverse momentum and a high p_T (transverse momentum) lepton. The predicted cross section, however, is relatively small, which is among the reasons

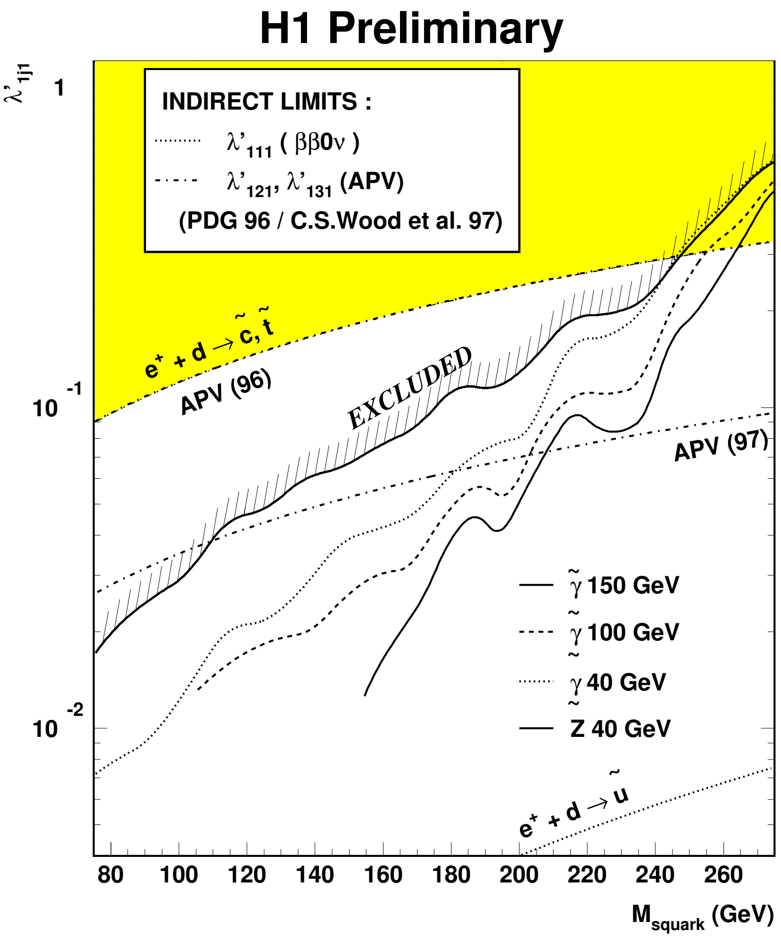

Figure 5: *H1 results on limits in R_P-violating SUSY. Plotted are lower limits on the squark-lepton-quark coupling λ'_{1jk} as a function of squark mass M_{squark}. Also shown are indirect limits on λ'_{111} and λ'_{121},λ'_{131}.* 12) 13)

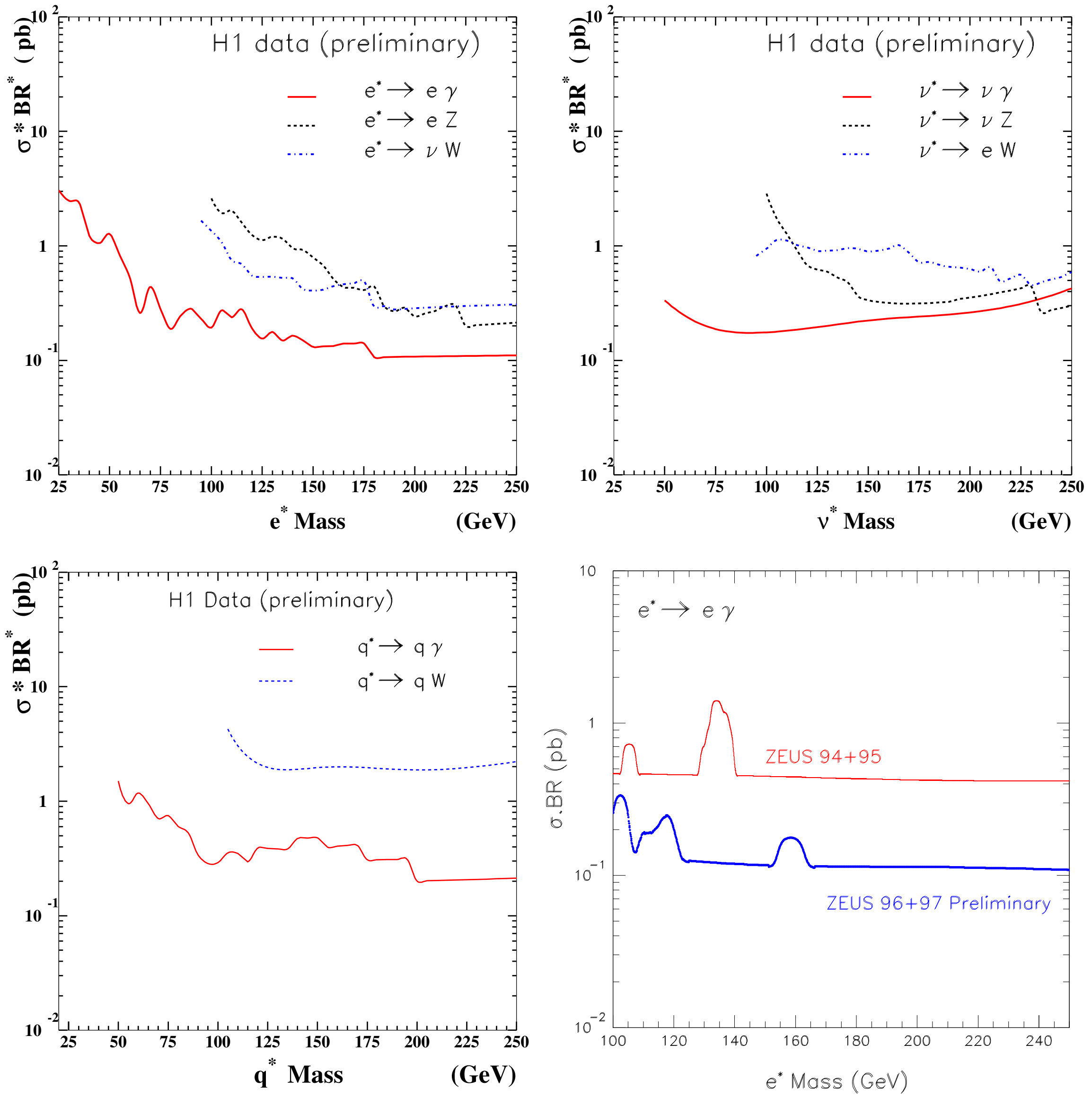

Figure 6: *Limits on the cross section times branching ratio of excited leptons at 95% CL. Shown are limits from H1 on excited electrons (top left), H1 on excited neutrinos (top right), H1 on excited quarks (bottom left), and ZEUS on excited electrons (bottom right).*

Table 2: *The number of events observed and predicted for events that pass the H1 high-p_T lepton and missing transverse momentum cuts. The limits given correspond to a 95% CL. Unless otherwise stated, the quoted numbers refer to the sum of the production of both lepton charges.*

	Electron Channel	Muon Channel
Data	$0\ e^+$, $1\ e^-$	5
W production	1.65 ± 0.47	0.53 ± 0.11
Z production	0.01 ± 0.01	0.01 ± 0.01
CC DIS	0.02 ± 0.01	0.01 ± 0.01
NC DIS	$0.51 \pm 0.10 e^+$, $0.02 \pm 0.01 e^-$	0.09 ± 0.06
Photoproduction	< 0.02	< 0.02
Heavy Quarks	< 0.04	< 0.04
Photon-Photon	$0.09 \pm 0.03 e^+$, $0.04 \pm 0.01 e^-$	$0.14^{+0.14}_{-0.07}$

the observation by the H1 Collaboration [15] of several such events has caused some excitement.

Interesting events are selected by H1 by searching events with missing transverse momentum $P_T > 25$ GeV (as measured in the calorimeter) for isolated tracks that have a transverse momentum $p_T > 10$ GeV and that have characteristics consistent with an electron or muon. In the '94–'97 data sample, five muon and one electron event were uncovered. According to Monte Carlo studies, 2.4 ± 0.5 electrons and 0.8 ± 0.2 muons are expected in the Standard Model, as tabulated in tab.2.

If these muon events were the result of W production and the subsequent decay $W \to \nu\mu$, the transverse mass M_T calculated from the combination of missing P_T (assigned to the unobserved single neutrino) and the high p_T lepton should peak near the W mass. Three muon events, however, have a combination M_T and hadronic transverse momentum P_T^X that are unlikely according to Monte Carlo expectations for W production, as shown in fig.7. Combined with the unexpected number of events, this suggests a production mechanism for muon events that is not one of the Standard Model processes considered.

The ZEUS Collaboration has performed a similar analysis of their data, the result of which is shown in tab.3 for the muon channel. No excess was observed.

7 Conclusion

The HERA ep collider is a unique laboratory for the search for physics beyond the Standard Model. Both of its experiments, H1 and ZEUS, have produced limits on:

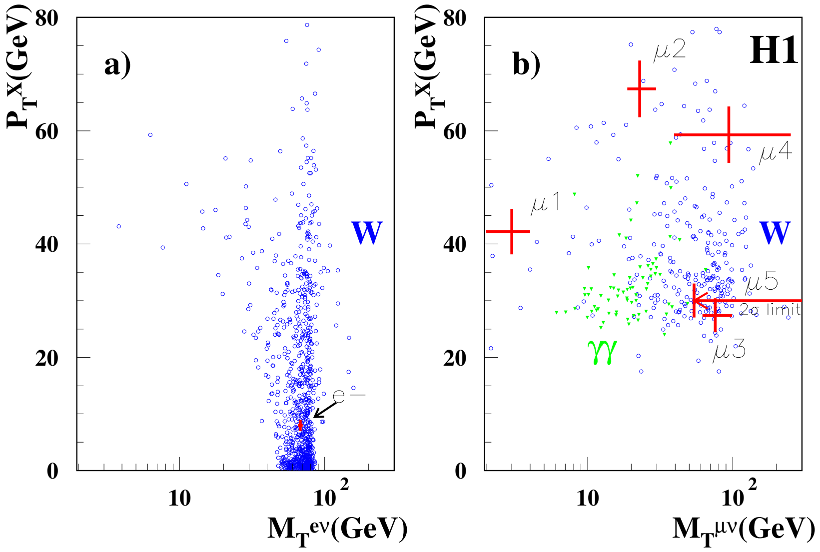

Figure 7: *The distribution of hadronic transverse momentum P_T^X versus the transverse mass $M_T^{l\nu}$ of the hadronic system and lepton for (a) electron and (b) muon events that pass the H1 high-p_T lepton and missing transverse momentum cuts. The crosses indicate the one-sigma uncertainty on the measured kinematic parameters of the six observed events (for event "μ5" the 2σ lower limit for $M_T^{l\nu}$ is shown). The dominant Standard Model contributions (dots for W production and open circles for photon-photon processes in the muon channel) are shown for a luminosity which is a factor 500 higher than in the data. In the muon channel, no significant contribution is expected at $P_T^X < 25$ GeV due to a requirement of $P_T > 25$ GeV in the calorimeter.*

Table 3: *The number of events observed and predicted in the Standard Model (SM) for muon events seen in ZEUS that pass cuts similar to those used by H1 in their high-p_T lepton and missing transverse event sample.*

Calorimeter P_T	Data	SM Monte Carlo W	SM Monte Carlo Other	Efficiency
> 20 GeV	1	0.6	1.7 ± 0.4	39%
> 30 GeV	0	0.3	0.5 ± 0.2	38%

- leptoquarks
- $eq \to eq$ contact interactions
- supersymmetry
- excited fermions

All of these results demonstrate a sensitivity that is competitive with measurements recently released by competing experiments and several results include limits that are the most restrictive yet published.

In addition, the H1 Collaboration has observed an excess of events with high-p_T muons and missing transverse momentum that are difficult to explain within the Standard Model.

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