# EXCLUSIVE SEARCHES AT HERA

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The latest results from the H1 and ZEUS collaborations on exclusive searches for rare Standard Model processes and physics Beyond the Standard Model are presented. Intriguing events containing high transverse momentum leptons are observed by H1. The ZEUS searches for similar event topologies are also presented. Competitive limits on excited neutrinos and lepton flavour violation are set by the H1 collaboration. A generalised search by H1 for events containing high $P_T$ objects is also presented.

## 1 Introduction

Both the H1 and ZEUS experiments pursue a comprehensive physics programme at the HERA $ep$ collider. In addition to measurements of the structure of the proton, deep inelastic scattering at HERA at a centre-of-mass energy of up to 318 GeV provides an ideal environment for the study of rare processes, for setting constraints on the Standard Model (SM) and for searches for new particles and physics Beyond the Standard Model (BSM).

## 2 Rare Standard Model Processes

### *2.1 Events Containing Isolated Leptons and Missing Transverse Momentum*

Events containing a high transverse momentum ($P_T$) isolated electron or muon and large missing transverse momentum have been observed at HERA [1,2]. The dominant SM mechanism for producing such topologies is the production of real $W$ bosons, $ep \rightarrow eW^{\pm}X$, with subsequent leptonic decay $W \rightarrow l\nu$. An excess in the HERA I (1994-2000) data sample was reported by the H1 collaboration [2], whereas such an excess was not confirmed by the ZEUS collaboration in a similar search [3].

The H1 analysis has been updated to include new $e^{\pm}$p data from the ongoing HERA II (2003-2007) running period [4,5], resulting in a total analysed luminosity of 442 pb$^{-1}$. A total of 56 events are observed in the data, compared to a SM prediction of $54.9 \pm 7.6$. The hadronic transverse momentum ($P_T^X$) spectra of the $e^{\pm}$ data are presented in figure 1. At large values of $P_T^X$ ($> 25$ GeV ) 18 $e^+p$ data events are observed compared to the SM prediction of $7.8 \pm 1.3$. The observed excess is equivalent to a fluctuation of approximately $3\sigma$. The excess in not observed in the $e^-p$ analysis.

A similar analysis has been performed by the ZEUS collaboration on 432 pb$^{-1}$ of $e^{\pm}$ taken in the 1996-2000 and 2003-2007 running periods [6,7]. The SM expectations of the ZEUS search are similar to the H1 search, however the ZEUS analysis does not observe an excess in $e^+p$

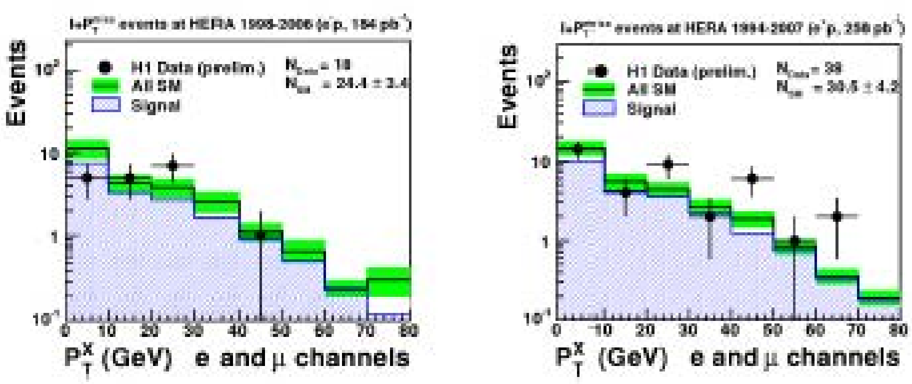


Figure 1: The hadronic transverse momentum spectra of the observed events in the H1 isolated lepton analysis. The sample is divided into $e^-p$ (shown on the left for $\mathcal{L}$ = 184 pb$^{-1}$) and $e^+p$ (right for $\mathcal{L}$ = 258 pb$^{-1}$) data samples. The data are shown as points, the filled histogram is the SM expectation and the shaded band is the total SM error. The signal component, dominated by real $W$ production, is shown by the hatched histogram.

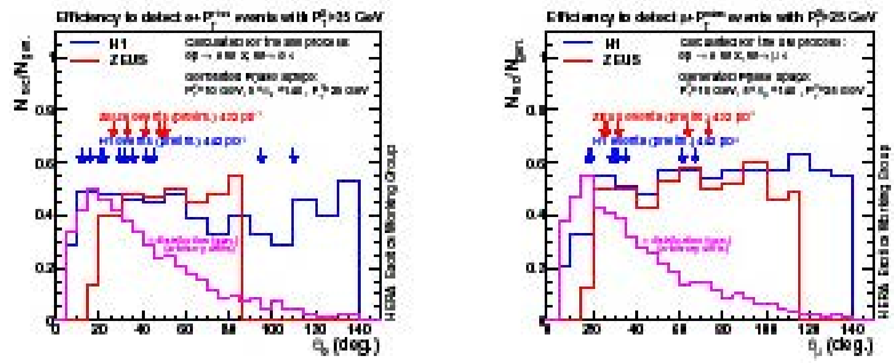


Figure 2: The efficiency of the H1 and ZEUS isolated lepton searches for $ep \rightarrow eWX$ (left $W \rightarrow e\nu_e$, right $W \rightarrow \mu\nu_\mu$) events with $P_T^X > 25$ GeV as a function of the lepton polar angle ($\theta_{e,\mu}$). The arrows in the figures denote the H1 and ZEUS candidate events. The generated spectrum for $ep \rightarrow eWX$ Monte Carlo is also shown.

data; with only one electron candidate observed in the $P_T^X > 25$ GeV region compared to a SM prediction of $1.5 \pm 0.2$ and three muon candidates observed compared to a SM prediction of $3.1 \pm 0.5$. The ZEUS data also agrees well with the SM predictions for the $e^-p$ data with 5(2) electrons (muons) observed compared to the expectation of $3.8 \pm 0.6$ ($2.2 \pm 0.3$) events.

H1 and ZEUS have formed a combined working group to clarify differences between the searches of the two collaborations. Comparisons of the efficiencies of the two searches as a function of $P_T^X$ show that the ZEUS and H1 have similar efficiency for selecting $e^{\pm}p \rightarrow e^{\pm}WX$ events at high values of $P_T^X$. The more restricted phase space of the ZEUS search leads to a slightly lower efficiency than the H1 search. It can be seen in figure 2 that in regions of the lepton polar angle $\theta_{e,\mu}$ common to both searches the efficiencies of the two searches are similar. H1 and ZEUS candidate events are illustrated by arrows on the figures, it can be seen that the majority of the H1 candidates lie within the ZEUS search acceptance, indicating that the ZEUS search is also sensitive to physics which could be responsible for the H1 excess.

### *2.2 Multi-lepton Events*

Searches for multi-electron and multi-muon production at high transverse momentum have been previously carried out by the H1 experiment [8,9]. The most recent H1 search was performed using 275 pb$^{-1}$ data taken during the HERA I and HERA II running periods. The main SM process for multi-lepton production in $ep$ collisions is photon-photon interaction $\gamma\gamma \rightarrow l^+l^-$,

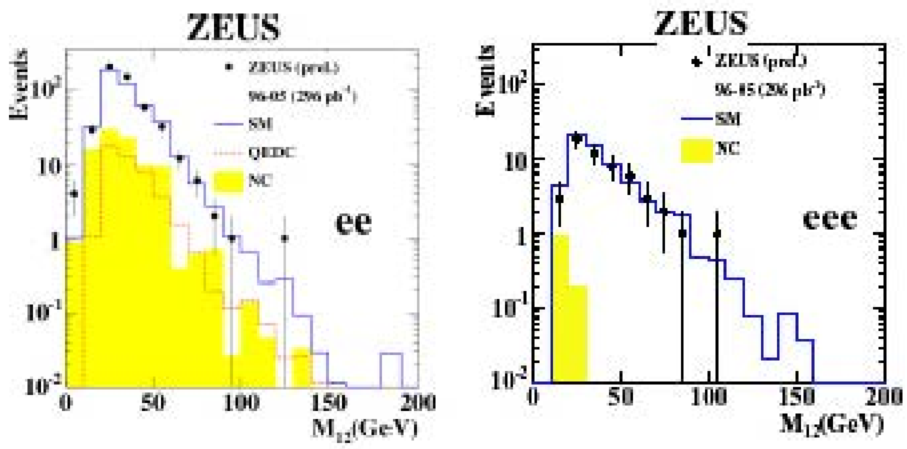


Figure 3: Comparison of the distribution of the invariant mass $M_{12}$ of the two highest $P_T$ electrons in the ZEUS multi-electron search to the SM expectation. The comparison is shown for the $ee$ (left) and $eee$ (right) topologies.

where quasi-real photons radiated from the incoming electron and proton interact to produce a pair of leptons. The H1 search studied $ee$, $\mu\mu$, $e\mu$, $eee$ and $e\mu\mu$ topologies, searching for events containing at least two high $P_T$ leptons. The data are found to be overall in good agreement with the SM. Events are observed at masses greater than 100 GeV in $e^+p$ data.

The ZEUS collaboration has recently made a new search for multi-electron events using 296 pb$^{-1}$ $e^{\pm}p$ data from the HERA I and HERA II running periods [10]. The invariant mass ($M_{12}$) distributions for the two highest $P_T$ electrons in the $ee$ and $eee$ topologies are shown in Figure 3, where overall good agreement with the SM expectations is observed. $M_{12} > 100$ GeV events are observed in both the $ee$ and $eee$ topologies; the number of such events observed is in agreement with the SM expectation.

## 3 Searches for Physics Beyond the Standard Model

### *3.1 General Search for New Phenomena*

A model-independent search for deviations from the SM was previously performed by H1 [11,12], using HERA I data. This search has been repeated by H1 [13] using 159 pb$^{-1}$ of $e^-p$ data. High $P_T$ final state configurations involving electrons ($e$), muons ($\mu$), jets ($j$), photons ($\gamma$) or neutrinos ($\nu$) are considered. All final state configurations containing at least two such objects with $P_T > 20$ GeV in the central region of the detector are investigated and classified into exclusive event classes, $\mu - j, e - j\nu, j - j - j$ etc.

The yields for the different classes are shown in Figure 4; data events are found in 21 event classes and good agreement is observed between data and the SM expectations in most event classes. A non-biased statistical method is used to search for deviations of the data with respect to the SM in the summed scalar transverse momentum ($\sum P_T$) and total invariant mass ($M_{\rm all}$) distributions sensitive to new physics. Good agreement is observed in all event classes. The distribution of the probability of obtaining a result at least as different from the SM as the obtained spectrum ($\hat{P}$) for scans of $\sum P_T$ in the different event classes is also shown in Figure 4. The data distribution is consistent with the SM.

### *3.2 Excited Neutrinos*

The fermion mass hierarchy can naturally be explained if the SM fermions are composite, in which case excited states may exist. A minimal extension [14,15,16] of the SM can incorporate

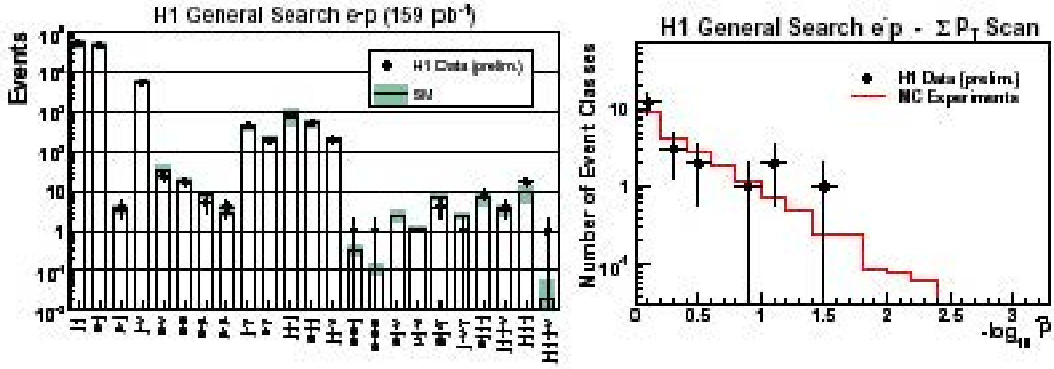


Figure 4: The yields (left) for the different event classes in the H1 general search compared to the SM predictions. The $\hat{P}$ value distrbution for $\sum P_T$ scans in the different event classes is also shown (right).

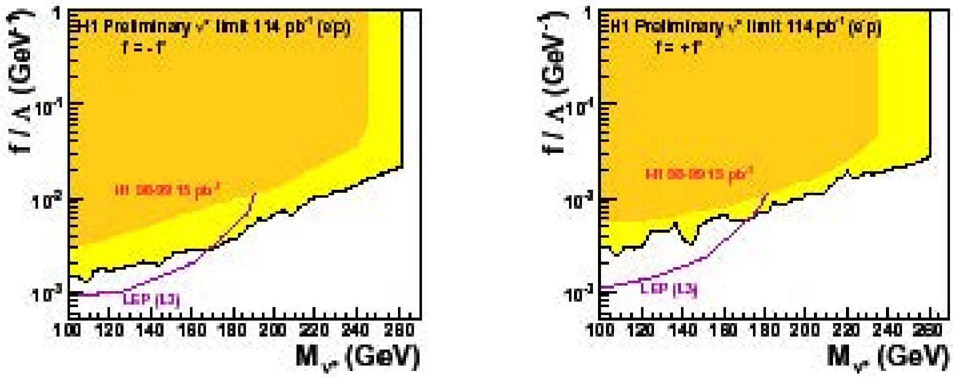


Figure 5: The limits obtained for the ratio $f/\Lambda$ as a function of the excited neutrino mass within two assumptions: $f = -f'$ (left) and $f = +f'$(right).

excited fermions such as excited neutrinos ($\nu^*$). Considering only electroweak interactions, the excitation part of the lagrangian is

$$L_{F^*F} = \frac{1}{2\Lambda}\overline{F_R^*}\sigma^{\mu\nu}\left[gf\frac{\vec{\tau}}{2}\delta_\mu \vec{W_\nu} + g'f'\frac{Y}{2}\delta_\mu B_\nu\right]F_L + \text{h.c.}, \tag{1}$$

where the new weights $f$ and $f'$ multiply the SM coupling constants $g$ and $g'$ corresponding to the weak SU(2) and electromagnetic U(1) sectors respectively. The corresponding gauge boson fields are denoted by $W$ and $B$. The matrix $\sigma_{\mu\nu} = (i/2)[\gamma^{mu}, \gamma^\nu]$, $\tau$ are the Pauli matrices, and $Y$ is the hypercharge. The compositeness scale $\Lambda$, together with $f$ and $f'$, determines the production cross section. Excited neutrinos can be produced in $ep$ collisions at HERA via the $t$-channel charged current (CC) reaction $e^{\pm}p \to \nu^* X$. The cross section is much larger in $e^-p$ collisions than in $e^+p$ collsions due to helicity enhancement specific to CC-like processes. H1 have recently presented a new search on 114 pb$^{-1}$ of $e^-p$ data [17], a dataset almost an order of magnitude larger than previously published HERA analyses [18].

Excited neutrinos are searched for in the decay channels $\nu^* \to \nu\gamma$, $\nu^* \to eW$ and $\nu^* \to \nu Z$. The $W$ and $Z$ bosons are reconstructed in the hadronic decay channel. No signal was observed in any channel. Limits on the production cross section are calculated and translated into exclusion limits in the plane ($f/\Lambda$,$M_{\nu^*}$), under the assumption $f = f'$ or $f = -f'$ (Figure 5). For $f = -f'$ (maximal $\gamma\nu\nu^*$ coupling) and assuming $f/\Lambda = 1/M_{\nu^*}$, $\nu^*$s with masses less than 188 GeV are excluded at 95% CL. The results confirm the unique sensitivity at HERA to excited neutrinos with masses beyond the reach of LEP.

### 3.3 Leptoquark Production and Lepton Flavour Violation

Particle interactions in the SM conserve lepton flavour, although there is no underlying symmetry supporting this feature. Experimental evidence for lepton flavour violation (LFV) in solar and atmospheric neutrino oscillations has been reported [19,20]. The experiemental bounds on neutrino masses imply very small LFV effects in the charged lepton sector. The observation of such effects would clearly indicate new phenomena beyond the SM.

At HERA, LFV processes $ep \rightarrow \mu X$ or $ep \rightarrow \tau X$ lead to final states with a muon or tau and hadronic system $X$. The LFV process can proceed via the exchange of a leptoquark (LQ), a boson with both lepton and baryon quantum number. Leptoquarks arise naturally as a colour triplet scalar or vector boson in many extensions of the SM such as grand unified theories, supersymmetry, compositeness and technicolor. The H1 collaboration has recently performed a new search for LFV phenomena using 66.5 pb$^{-1}$ $e^+p$ data and 13.7 pb$^{-1}$ $e^-p$ data [21].

The LFV processes $ep \rightarrow \mu X$ and $ep \rightarrow ep\tau X$ can be attributed to LQs produced predominantly by electron-quark fusion. LQs are classified into 14 types with respect to the quantum numbers spin, isospin and chirality within the framework of the Buchmüller-Rückl-Wyler (BRW) model [22]. Leptoquarks carry both lepton (L) and Baryon (B) quantum numbers. The fermion number $F = L + 3B$ is assumed to be conserved, taking values of $F = 2$ for $e^-q$ processes and $F = 0$ for $e^+q$ processes. For LQ masses ($m_{LQ}$) well below the $e^{\pm}p$ centre-of-mass energy, the $s$ channel production of $F = 2$ ($F = 0$) LQs in $e^-p$ ($e^+p$) collisions dominates. For $m_{LQ}$ greater than the centre-of-mass energy the $s$ and $u$ channel processes become of equal importance. The BRW model assumes lepton flavour conservation such that the LQs produced in $ep$ collisions decay only to $eX$ or $\nu_e X$ final states. A general extension of the BRW model allows for the decay of LQs to final states containing a lepton of different flavour ($\mu$ or $\tau$) and a jet. Non-zero couplings to an electron-quark pair and to a muon(tau)-quark pair are assumed.

In the H1 analysis, high $P_T$ muon and tau signatures are searched for. In the muon case, the signature is an isolated high $P_T$ muon back-to-back to the hadronic system in the transverse plane. In the tau case electronic, muonic and hadronic tau decays are all considered. In the case of electronic tau decays large missing momentum is expected, in the muonic decay the signature is very similar to the muon case and in the hadronic decay the signal topology is a di-jet event with no leptons. The tau-jet is characterised by a narrow energy deposit in the calorimeter and low track multiplicity. The tau-jet candidates are selected via a neural net algorithm [23].

Only one candidate event was found, in the $e^+p$ data, in the hadronic $\tau$ decay channel. This observation is in agreement with the SM and no evidence for LFV was found. Limits on couplings to 14 different LQs as a function of $m_{LQ}$ are derived. An example of the limits under the assumption that the tau- and electron-first generation quark couplings are equal is shown in Figure 6. The H1 results are directly comparable to previous limits set by ZEUS [24] and are found to be similar. At hadron colliders LQs are mainly produced in pairs independently of coupling, thus searches cannot constrain LFV couplings. Lower mass limits on the second (third) generation leptoquarks extend up to 250 GeV (150 GeV), depending on the assumptions made [25,26]. Similarly lower mass bounds from $e^+e^-$ annihilation reach values of 100 GeV [27].

## 4 Summary

Many searches for new physics have been performed at HERA by the H1 and ZEUS collaborations. No evidence for lepton flavour violation or $\nu^*$s is observed. Interesting events containing isolated leptons and missing $P_T$ as well as the multiple high $P_T$ leptons at high masses are observed by H1. H1-ZEUS working groups have been formed to clarify the high $P_T$ lepton excess observed by H1 and to extend the reach of BSM searches at HERA to its uttermost.

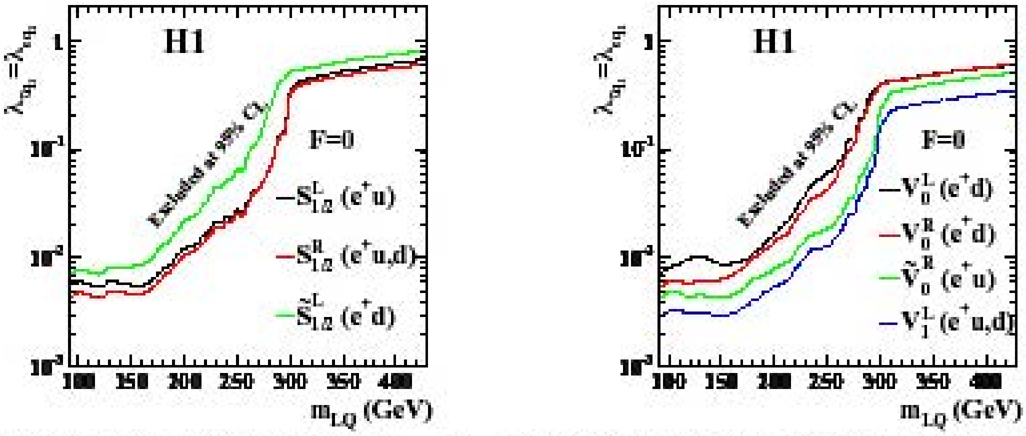


Figure 6: Limits on the coupling constants $\lambda_{eq_1} = \lambda_{\nu q_1}$ as a function of the leptoquark mass $m_{LQ}$ for F=0 scalar (left) and vector (right) leptoquarks. Regions above the lines are excluded at 95% CL. The notation $q_1$ indicates that only processes involving first generation quarks are considered.

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