SEARCHES FOR NEW PHYSICS IN ep SCATTERING AT HERA

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The latest results from the H1 and ZEUS collaborations are presented on leptoquark production and rare Standard Model processes. The data were taken in the period 1994–2005, at a centre of mass energy of up to 319 GeV. Intriguing events containing isolated leptons and missing transverse momentum, as well as multi–lepton events, are observed by H1 in regions of phase space where the SM prediction is low. Interpretations of the observed excesses in terms of physics Beyond the Standard Model are also discussed.

1 Introduction

A comprehensive physics programme is employed by the H1 and ZEUS experiments at the HERA ep collider. To date, each experiment has collected over 300 pb^{-1} of data for physics analysis, consisting of approximately equal amounts of e^+p and e^-p scattering. Together with measuring the structure of the proton, the deep inelastic collisions (DIS) produced at HERA at a centre of mass up to 319 GeV provide an ideal environment to study rare processes.

Model dependent searches are employed to set constraints on the Standard Model (SM) and look for specific new particles and physics beyond the Standard Model (BSM). The search for the production of leptoquarks at HERA, including lepton flavour violating models, is described in section 2. Model independent searches are employed at HERA to look for anomalies in the high transverse momentum (P_T) phase space sparsely populated by the SM, the results of which are presented in sections 3–5. A summary is given in section 6.

2 Leptoquark Production and Lepton Flavour Violation

The ep collsions at HERA provide a unique possibility to investigate the formation of a new particle coupling to a lepton–quark pair. In the Buchmüller, Rückl and Wyler (BRW) classification of such states, termed "leptoquarks", 7 scalar and 7 vector particles are proposed, all of which can couple to an eq pair and 4 of which can also couple to both eq and νq [1]. Leptoquarks are hence bosons of fractional charge that carry both leptonic (L) and baryonic (B) numbers, such that their fermion number ($F = 3B + L$) can be $F = 0$ or $F = 2$. A leptoquark that couples to all lepton flavours would result in the possibility of lepton flavour violating (LFV) processes in ep collisions.

A search for first generation leptoquark production, $eq \to eq$ or $eq \to \nu q$ has been performed on the HERA I data by the H1 [2] and ZEUS [3] collaborations by looking for deviations in the mass spectra of neutral current (NC) and charged current (CC) DIS interactions, the major SM background. No evidence of leptoquark production is observed, and limits on the 14 leptoquark couplings are derived as function of mass, as shown for example from H1 for $F = 0$ scalar leptoquarks in figure 1 (left), where the derived limits are compared to those from the D0 [4] and OPAL [5] experiments. Leptoquark masses up to 386 GeV are ruled out at 95% confidence level (CL) for a coupling λ of electromagnetic strength ($\lambda = \sqrt{4\pi\alpha_{em}} = 0.3$).

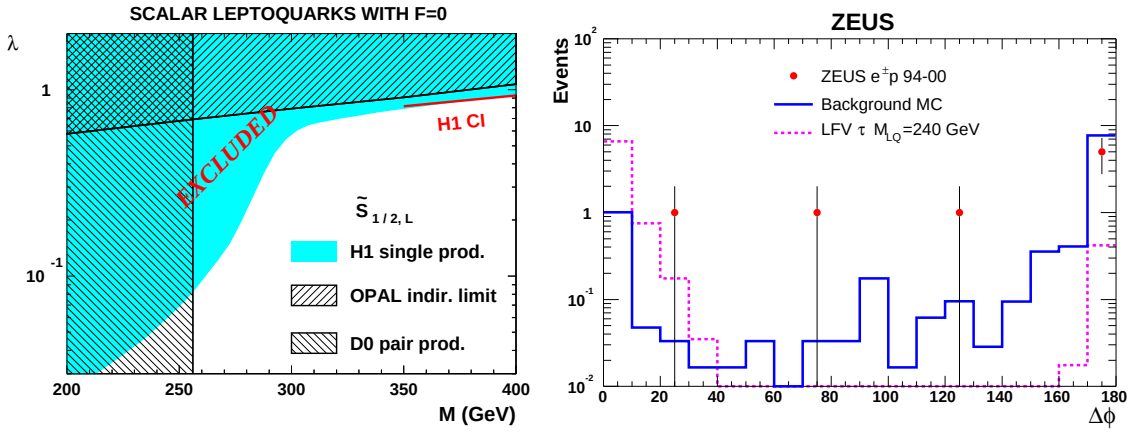

Figure 1: Left: H1 exclusion limits at 95% CL on the coupling λ as a function of leptoquark mass for $F = 0$ scalar leptoquarks in the framework of the BRW model. The derived limits are compared to those from the D0 and OPAL experiments. Right: The difference in azimuthal angle of the candidiate lepton and missing P_T, as observed at the preselection level of the ZEUS LFV leptoquark search. The data are the points, the solid histogram is the SM prediciton and the dashed line represents the signal expectation with arbitrary normalisation.

A search for LFV processes mediated by leptoquark exchange has also been performed by H1 [6] and ZEUS [7], investigating the interactions $eq \to \mu q$ and $eq \to \tau q$. The analysis has a low SM background and thus high sensitivity to such processes. Figure 1 (right) shows the $\Delta\phi$ distribution at the preselection level of the ZEUS analysis, where $\Delta\phi$ is the difference in azimuthal angle of the lepton and missing P_T in the event. A cut is subsequently made in the final selection of $\Delta\phi < 20^o$. It can be seen that good separation of the LFV leptoquark production signal and the SM background is achieved, although no evidence for LFV is observed. Similarly to the above analyses, limits are derived for the appropriate leptoquark couplings as a function of mass. The ZEUS analysis of the $eq \to \tau q$ channel, which uses 113 pb^{-1} of e^+p data, improves the existing limits from rare τ, B or K decays (see references given in [7]).

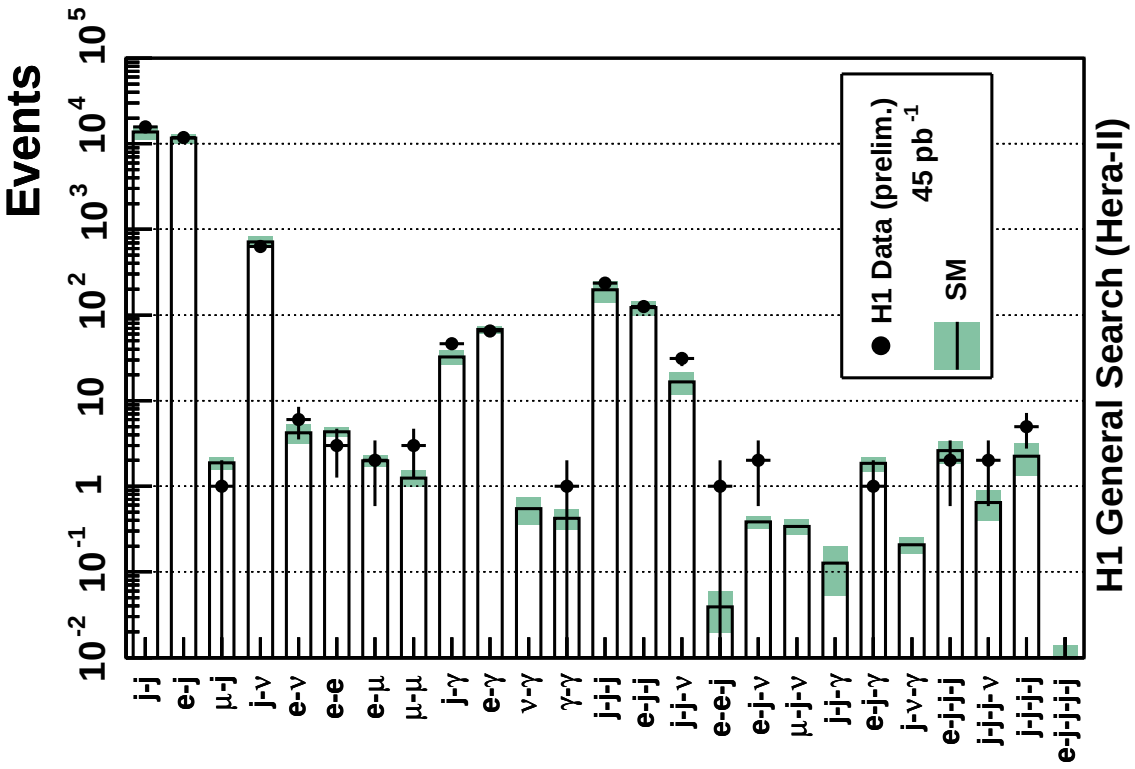

Figure 2: Event yields for all event classes with a SM expectation greater than 0.01 events in the H1 HERA II general search analysis. The data are the points, the histogram bars are the SM prediction and the shaded band is the total SM error.

3 A General Search for New Phenomena

A model independent general search for deviations from the SM has been performed by H1 [8], using a HERA I data sample corresponding to an integrated luminosity of 117 pb^{-1}. All high P_T final state configurations involving electrons (e), muons (μ), jets (j), photons (γ) or neutrinos (ν) 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, e–j, μ–j–ν, j–j–j and so on.

Data events are found in 22 such event classes and a good agreement is observed between data and the SM expectation in most event classes. A non–biased statistical method is employed to search for deviations of the data with respect to the SM. A good agreement is found in all channels, except in the μ–j–ν event class, where 4 data events are observed compared to a SM expectation of 0.8 $\pm$ 0.2 as previously reported in [9]. Additionally, in the e–j–j–j–j event class 1 event is observed in the data compared to a SM prediction of 0.026 $\pm$ 0.011.

The H1 general search has been repeated using 45 pb^{-1} of HERA II e^+p data [10], the results of which are shown in figure 2. As in the HERA I analysis, a good overall agreement is observed between the data and the SM prediction and data events are observed in 20 of the event classes. The deviation of the data with respect to the SM in the e–j–ν event class corresponds to the observed excess in this data sample as reported in [11]. The observed excesses in the e–j–ν and μ–j–ν event classes, in which the main SM contribution arises from real W production, are described in more detail in section 4.

4 Events containing Isolated Leptons and Missing Transverse Momentum

Events containing a high P_T isolated electron or muon and large missing transverse momentum have been observed at HERA [9,12,13]. The main SM contribution to such a topology comes from the production of real W bosons $ep \to eW^{\pm}X$ with subsequent leptonic decay $W \to l\nu$. An excess of HERA I (1994–2000) data events compared to the SM prediction was reported by the H1 collaboration [9], which was not confirmed by the ZEUS collaboration, although using a slightly different analysis approach [14].

The H1 analysis has been updated [11,15] to include new $e^{\pm}p$ data from the ongoing HERA II phase (2003–2005), resulting in a total analysed luminosity of 279 pb^{-1}. A total of 40 events are observed in the data, compared to a SM prediction of 34.3 $\pm$ 4.8. The hadronic transverse momentum (P_T^X) spectra of the $e^{\pm}p$ data are presented in figure 3. At large values of P_T^X an excess of e^+p data events is observed compared to the SM expectation, as can be seen in figure 3 (left). For $P_T^X > 25$ GeV a total of 15 data events are observed compared to a SM prediction of 4.6 $\pm$ 0.8. The observed excess is equivalent to a fluctuation of approximately 3.4σ. Interestingly, the excess is not observed in the current e^-p analysis, as can be seen in figure 3 (right), which includes an almost factor of 10 increase in statistics with respect to the HERA I e^-p data set. The results of the H1 analysis are summarised in table 1.

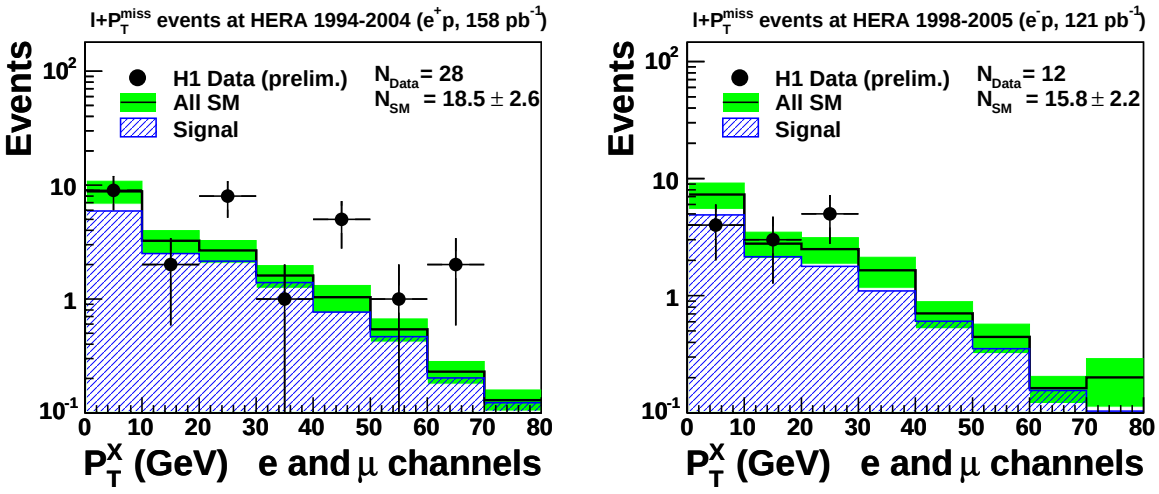

Figure 3: The hadronic transverse momentum spectra of the observed events in the H1 isolated lepton analysis. The sample is divided into the e^+p (shown on the left, $\mathcal{L}$ = 158 pb^{-1}) and e^-p (right, $\mathcal{L}$ = 121 pb^{-1}) data samples. The data are the points, the full histogram is 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.

A re-analysis of the ZEUS electron channel has been performed [16], using e^+p data from 1999–2000 in addition to HERA II e^+p data from 2003–04 (total luminosity 106 pb^{-1}), leading to a similar SM background expectation to the H1 analysis. However, the ZEUS analysis does not confirm the observed H1 excess, with only one electron candidate observed in the region $P_T^X > 25$ GeV compared to a SM prediction of 1.5 $\pm$ 0.2. It should be noted, however, that the two analyses remain different in terms of phase space; in particular the ZEUS analysis has a more restrictive polar angle range.

Both experiments have also searched for the non–standard production of single top quarks at HERA I via the Flavour Changing Neutral Current (FCNC) process, with subsequent leptonic W decay [14,17]. The analysis strategy is an extension of the isolated lepton analysis described above, where the topology, as illustrated in figure 4 (left), could explain the observed H1 excess (although this process would predict a similar signal rate in e^+p and e^-p collisions). While some

Table 1: Summary of the H1 results of searches for events with isolated electrons or muons and missing transverse momentum for the e^+p data ($\mathcal{L}$=158 pb^{-1}), e^-p data ($\mathcal{L}$=121 pb^{-1}) and the full HERA data set ($\mathcal{L}$=279 pb^{-1}), in the region $P_T^X > 25$ GeV. The number of observed events are compared to the SM prediction.

H1 Preliminary $P_T^X > 25$ GeV	e channel	μ channel	combined e & μ
1994–2004 e^+p 158 pb^{-1}	9 / 2.3 ± 0.4	6 / 2.3 ± 0.4	15 / 4.6 ± 0.8
1998–2005 e^-p 121 pb^{-1}	2 / 2.4 ± 0.5	0 / 2.0 ± 0.3	2 / 4.4 ± 0.7
1994–2005 $e^\pm p$ 279 pb^{-1}	11 / 4.7 ± 0.9	6 / 4.3 ± 0.7	17 / 9.0 ± 1.5

of the H1 events at large P_T^X show kinematics compatible with the single top hypothosis, no signal can be claimed. Figure 4 (right) shows limits derived at 95% CL by both experiments on the anomalous FCNC $\kappa_{tu\gamma}$ coupling, compared to limits derived by the CDF [18] and L3 [19] experiments. HERA has the best sensitivity to the $\kappa_{tu\gamma}$ coupling in the region where v_{tuZ} is small. The ZEUS limits are also derived with a dependence on the v_{tuZ} coupling.

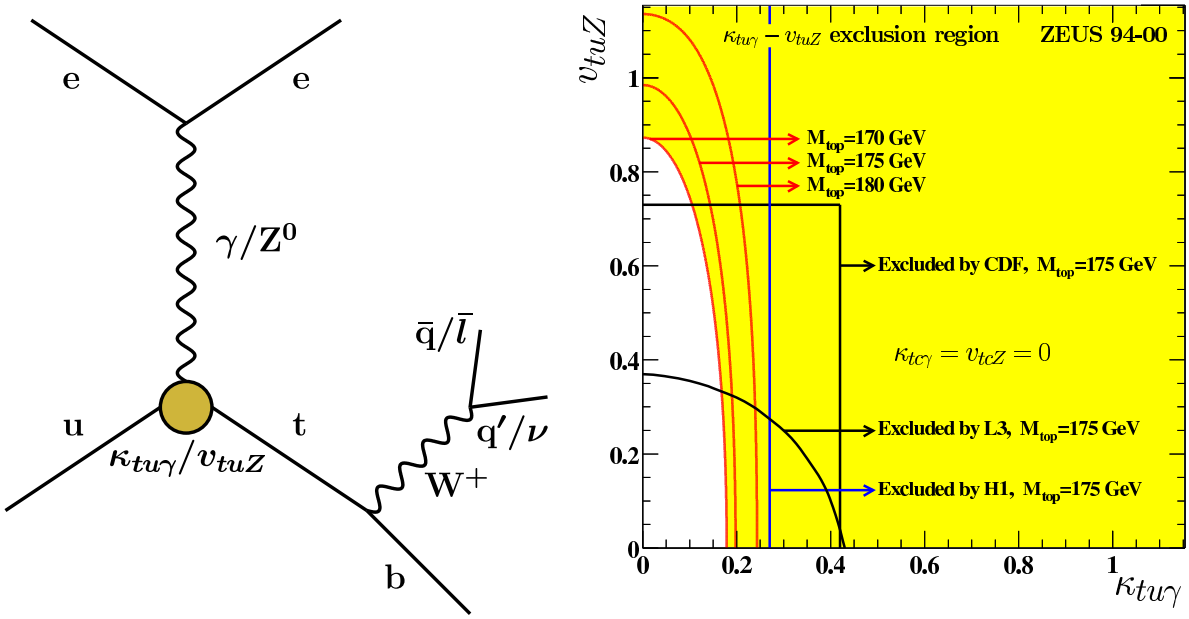

Figure 4: Left: Single top production at HERA via FCNC. Right: Exclusion limits at 95% CL on the anomalous $\kappa_{tu\gamma}$ and v_{tuZ} couplings derived by H1 and ZEUS, compared to limits derived by the CDF and the L3 experiments.

5 Multi–lepton Events

Searches for multi–electron production at high transverse momentum have been previously carried out by the H1 [20] and ZEUS [21] experiments, using the HERA I data sample. The production of high P_T muon pairs has also been studied at HERA I by both H1 [22] and ZEUS [23]. The main SM process for multi–lepton production in ep collisions is photon–photon interactions $\gamma\gamma \to l^+l^-$, where quasi real photons radiated from the incoming electron and proton interact to produce a pair of leptons. High mass events ($M_{1,2} > 100$ GeV) are observed in the in the di–electron sample of both experiments, and additionally in the H1 tri–electron sample, regions where the SM expectation is low.

H1 has recently updated the analysis to include the new HERA II data [10,24], now exploiting a total luminosity of 275 pb^{-1}. The analysis examines $e\mu$, $\mu\mu$, $e\mu$, eee and $e\mu\mu$ topologies, searching for events with at least two high P_T electrons or muons. Figure 5 shows the scalar sum of the transverse momenta of the selected events containing two or three high P_T leptons, for the positron and electron data separately, and for all HERA together. The data are found to be in good overall agreement with the SM, although interesting events are seen at high masses and, similarly to the analysis described in section 4, only in the e^+p data. The high mass events include di–electron and tri–electron events observed in the HERA I data and, more recently, electron–muon events observed in the HERA II data.

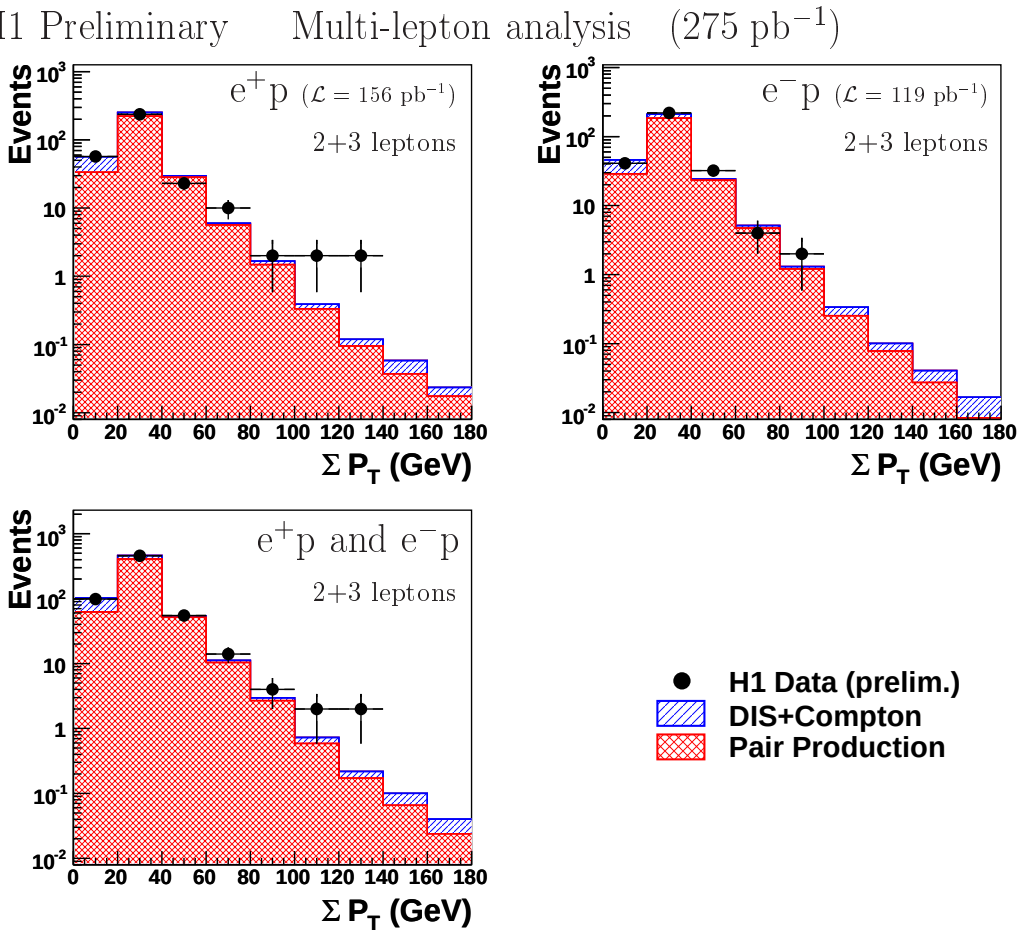

Figure 5: Distributions of the scalar sum of the transverse momenta of the combination of all di– and tri–lepton events for data taken in e^+p (upper left) and e^-p (upper right) collisions. The combination of all di– and tri–lepton events for all HERA data is shown in the lower figure. The data (points) are compared to the SM expectation (histogram), which is dominated by pair production.

The production in ep collisions of a doubly charged Higgs boson $H^{++(--)}$ could be a source of events containing multiple high P_T leptons and the observed high mass events in the H1 analysis have been investigated in this context [25]. Only one ee event satisfies the additional selection criteria and the HERA limits on the $H^{++(--)}$ coupling to ee are not competitive to those set by the OPAL experiment [26]. However, limits derived from the HERA data in the $e\mu$ decay channel of the $H^{++(--)}$ extend to higher masses beyond the reach of the previous searches performed by the CDF [27] and LEP [28] experiments and new constraints are obtained for the $H^{++(--)}$ coupling to $e\tau$.

6 Summary

Many searches for new physics have been performed at HERA by the H1 and ZEUS collaborations. No evidence for the production of leptoquarks is observed. Interesting events containing isolated leptons and missing P_T as well as multiple high P_T leptons at high masses are observed by H1. The continued data taking in the HERA II phase by both experiments will hopefully clarify the high P_T lepton events seen by H1 and further the search for new physics at HERA.

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