SEARCHES FOR NEW PHYSICS AT HERA

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The latest results from the H1 and ZEUS collaborations are presented on rare Standard Model processes and searches for physics Beyond the Standard Model. Intriguing events containing high transverse momentum leptons are observed by H1 and many competitive limits are set by both collaborations on the production of new particles in a variety of supersymmetry scenarios.

1 Introduction

A comprehensive physics programme is employed by the H1 and ZEUS experiments at the HERA ep collider. Together with measuring the structure of the proton, the deep inelastic collisions (DIS) produced at HERA, at a centre of mass up to 318 GeV, provide an ideal environment to study rare processes, set constraints on the Standard Model (SM) and search 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, 3]. 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 in [3], which was not confirmed by the ZEUS collaboration, although using a slightly different analysis approach [4].

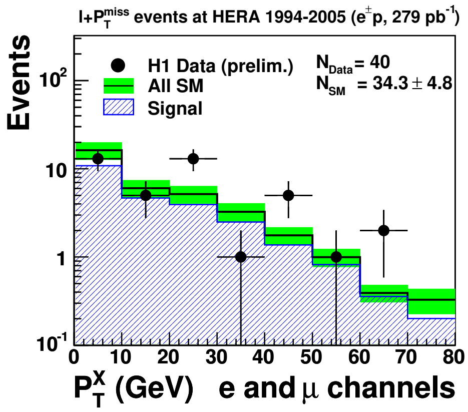

Figure 1: The hadronic transverse momentum spectrum of the observed events in the complete H1 HERA $e^{\pm}p$ data sample ($\mathcal{L} = 279$ pb^{-1}) compared to the SM expectation [5].

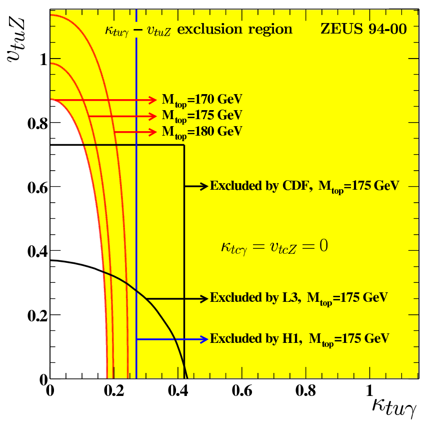

Figure 2: The ZEUS [4] and H1 [7] exclusion limits at 95% CL on the anomalous $\kappa_{tu\gamma}$ coupling compared to limits derived by the CDF [8] and the L3 [9] experiments.

The H1 analysis has been updated to include new $e^{\pm}p$ data from the ongoing HERA II phase (since 2003), resulting in a total analysed luminosity of 279 pb^{-1} [5]. A total of 40 events are observed in the data, compared to a SM prediction of 34.3 ± 4.8[1]. At large values of hadronic transverse momentum P_T^X an excess of data events is observed over the SM expectation, as can be seen in figure 1. Additionally, the observed H1 excess is only present in the e^+p data, where for $P_T^X > 25$ GeV a total of 15 data events are observed compared to a SM prediction of 4.6 ± 0.8. A re-analysis of the ZEUS electron channel has been performed [6], 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 similar backgrounds as in the H1 analysis. However, the ZEUS analysis does not confirm the H1 excess, where only one electron candidate is observed in the region $P_T^X > 25$ GeV.

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, where

[1] These numbers are updated with respect to those presented at St. Petersburg; for full details see the second reference in [5].

the analysis strategy is an extension of the isolated lepton analysis [4, 7]. Some of the H1 events at large P_T^X show kinematics compatible with the single top hypothosis, but no signal can be claimed. Figure 2 shows limits derived at 95% confidence level (CL) by both experiments on the anomalous FCNC $\kappa_{tu\gamma}$ coupling. It can be seen that HERA has the best sensitivity to the $\kappa_{tu\gamma}$ coupling in the region where v_{tuZ} is small.

2.2 Multi-lepton Events

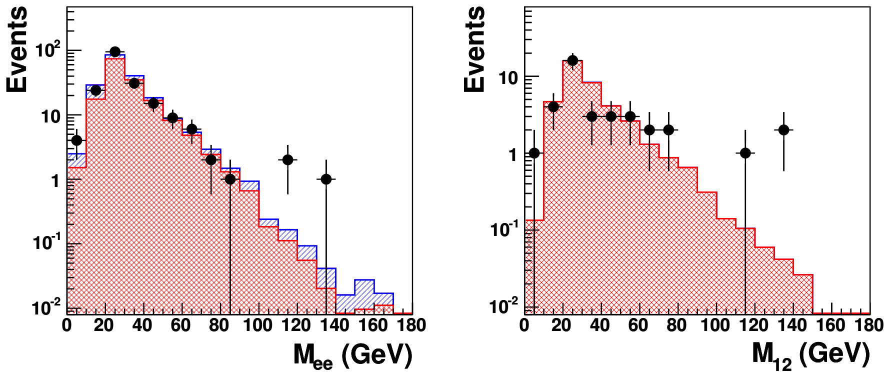

Figure 3: Distributions of the invariant mass of the two highest P_T electons in the di–electron (left) and tri–electron (right) H1 analyses compared to the SM expectation, which is dominated by pair production [13].

Searches for multi–electron production at high transverse momentum have been previously carried out by the H1 [10] and ZEUS experiments [11], using the HERA I data sample. H1 has additionally studied the production of high P_T muon pairs [12]. The main SM process for multi–lepton production in ep collisions is photon–photon interactions $\gamma\gamma \rightarrow l^+l^-$, 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 with the new HERA II data, now exploiting a total luminosity of 209 pb^{-1} [13]. 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 3 shows the invariant mass distribution of the H1 di–electron (left) and tri–electron (right) samples. The data are found to be in good overall agreement with the SM, although interesting events are seen at high masses; in the electron di–electron and tri–electron channels in the HERA I data and more recently in the electron–muon channels in the HERA II data.

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 [14]. 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 [15]. 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 [16] and LEP [17] experiments and new constraints were obtained for the $H^{++(--)}$ coupling to $e\tau$.

2.3 A General Search for New Phenomena

A model independent general search for deviations from the SM has been performed by H1 using a HERA I data sample corresponding to an integrated luminosity of 117 pb^{-1} [18]. 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 good agreement is observed between data and the SM expectation in most event classes, as can be seen in figure 4. 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 ± 0.2 as previously reported in [3]. 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 ± 0.011.

3 Searches for Physics Beyond the Standard Model

3.1 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

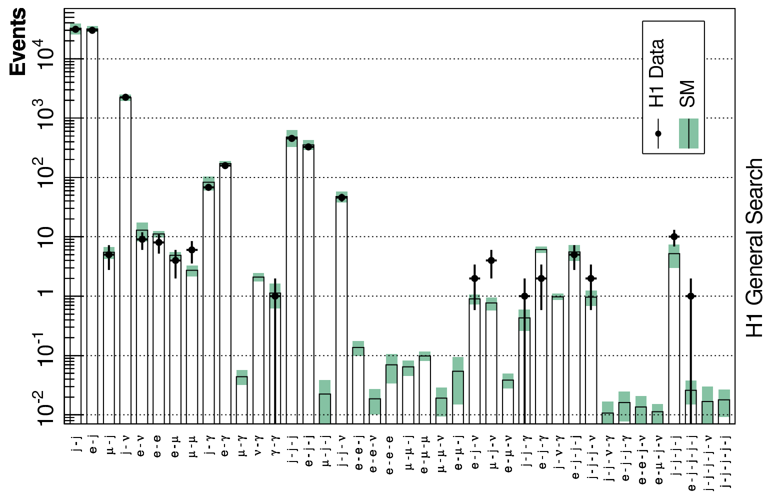

Figure 4: The data and the SM expectation for all event classes with a SM expectation greater than 0.01 events in the H1 general search analysis [18].

are proposed, all of which can couple to an eq pair and 4 of which can also couple to both eq and νq [19].

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 [20] and ZEUS [21] 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 5. In the H1 (ZEUS) analysis, leptoquark masses up to 325 (386) GeV are ruled out at 95% CL for a coupling λ of electromagnetic strength ($\lambda = \sqrt{4\pi\alpha_{em}} = 0.3$).

A search for lepton flavour violating (LFV) processes mediated by leptoquark exchange has also been performed by H1 [22] and ZEUS [23], investigating the interactions $eq \to \mu q$ and $eq \to \tau q$. No evidence for LFV is observed and, similarly to the above analyses, limits are derived for the appropriate leptoquark couplings as a function of mass. An example is shown in figure 6 from the ZEUS analysis of the $eq \to \tau q$ channel using 113 pb^{-1} of e^+p data, where the ZEUS results improve the existing limits from rare τ, B or K decays (see references given in [23]).

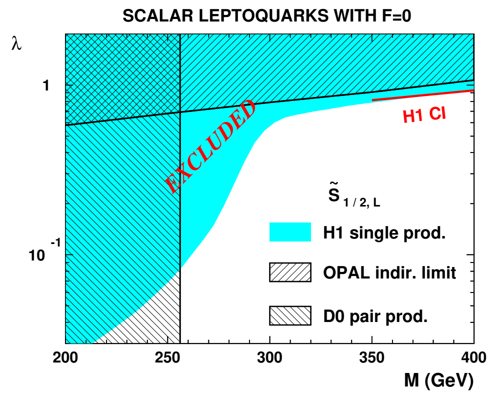

Figure 5: H1 exclusion limits at 95% CL on the coupling λ as a function of leptoquark mass for $F = 0$ scalar leptoquarks in the framework of the BRW model [20].

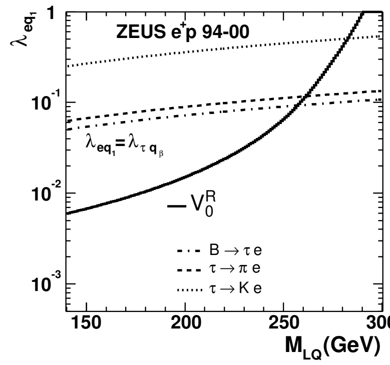

Figure 6: ZEUS exclusion limits at 95% CL on the coupling λ as a function of leptoquark mass for the vector leptoquark V_0^R in the τ decay channel [23].

3.2 R–Parity Violating SUSY and the Search for Bosonic Stop Decays

H1 has previously performed a search for squarks ($\tilde{q}$), the scalar supersymmeteric (SUSY) partners of quarks, in models with R–parity violation ($\not{R}_p$) [24]. The search rules out squarks of all flavours with masses up to 275 GeV for a coupling of electromagnetic strength in the Minimal Supersymmetric Standard Model (MSSM) framework. A similar analysis recently performed by the ZEUS collaboration set comparable limits in a search for stop quark ($\tilde{t}$) production in MSSM $\not{R}_p$ SUSY [25].

In the afforementioned analyses all squarks are assumed to be degenerate. A complementary analysis, based on the assumption $M_{\tilde{t}} > M_{\tilde{b}}$ has been performed by the H1 collaboration using e^+p data corresponding to an integrated luminosity of 106 pb^{-1}. In this case, the stop produced in $\not{R}_p$ fusion via the λ' coupling decays bosonically $\tilde{t} \to \tilde{b}W$ [26]. The $\not{R}_p$ decay of the sbottom quark $\tilde{b} \to d\bar{\nu}_e$ and leptonic and hadronic W decays are considered. The $\not{R}_p$ decay $\tilde{t} \to eq$ is also examined for completeness. The bosonic stop decay leads to three different final state topologies depending on the decay of the W boson; a jet, a lepton (electron or muon)[2] and missing transverse momentum

[2] The W decay into $\nu_\tau\tau$, where $\tau \to$ hadrons $+\nu$ is not investgated in this analysis.

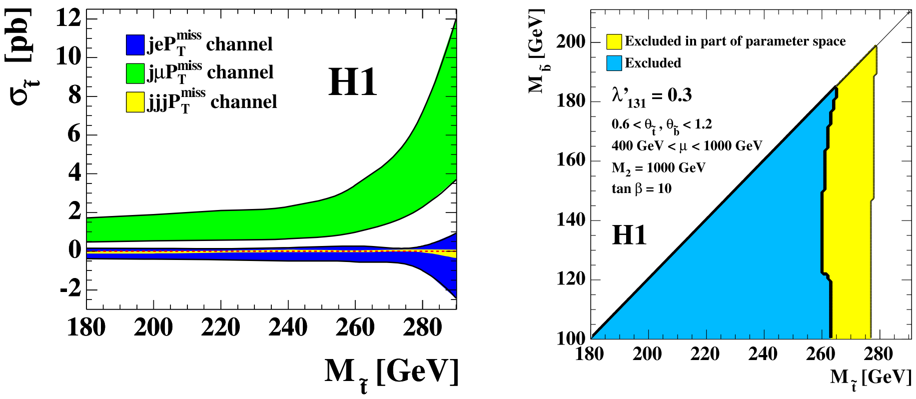

Figure 7: Left: Bands representing the allowed stop cross section regions $\sigma_{\tilde{t}} \pm \Delta\sigma_{\tilde{t}}$ as a function of the stop mass, obtained from the analysis of each bosonic stop decay channel. Right: Exclusion limits at the 95% CL in the $(M_{\tilde{t}},\, M_{\tilde{b}})$ plane for $\lambda'_{131} = 0.3$ [26].

($je\not{P}_\perp$ channel and $j\mu\not{P}_\perp$ channel) or, if the W decays to jets, three jets and missing transverse momentum ($jjj\not{P}_\perp$ channel). A slight excess of events compared to the SM prediction is observed in the $j\mu\not{P}_\perp$ channel, confirming the results of the dedicated H1 analysis to such a topology [3].

Assuming the presence of a stop mass $M_{\tilde{t}}$ decaying bosonically, the observed event yields are used to determine the allowed range for a stop production cross section $\sigma_{\tilde{t}}$, as illustrated in figure 7 (left). It can be seen that the excess in the $j\mu\not{P}_\perp$ channel is not supported by the other channels, and hence no evidence for stop production is observed. The results from the different channels are combined to derive constraints on stop quarks decaying bosonically in the MSSM. The resulting limits projected on the $(M_{\tilde{t}},\, M_{\tilde{b}})$ plane for $\lambda'_{131} = 0.3$ are shown in figure 7 (right), where for $M_{\tilde{b}} = 100$ GeV stop masses up to 275 GeV are ruled out at 95% CL.

3.3 Search for Gaugino Production and Events Containing Light Gravitinos

If squarks are very heavy, $\not{R}_p$ SUSY phenomena can manifest in ep collisions by gaugino production via t–channel slepton exchange. A search for gauginos is performed by the ZEUS collaboration, where the interaction proceeds via t–channel exchange of a selectron

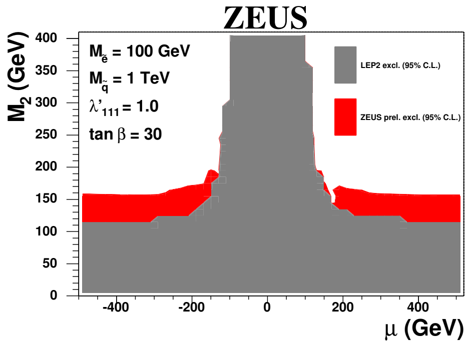

Figure 8: Excluded regions at the 95% CL in the (M_2, μ) plane from the ZEUS search for gaugino production [27], compared to results from the LEP experiments ALEPH and DELPHI [28].

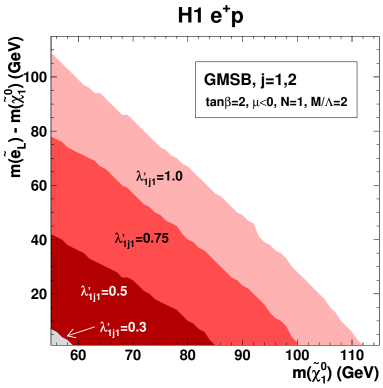

Figure 9: Excluded regions at the 95% CL in the $(m(\tilde{e}_L) - m(\tilde{\chi}_1^0),\, m(\tilde{\chi}_1^0))$ plane from H1 for various values of the coupling λ'_{1j1} (j = 1,2) [29].

and production of a neutralino $\tilde{\chi}_1^0$ [27]. The neutralino subsequently cascade decays into two quarks and an electron, positron or neutrino and hence the main SM background arises from di–jets in NC and CC DIS. No deviation from the SM is observed, and exclusion limits in the (M_2, μ) plane for gaugino production are derived at 95% CL, as shown in figure 8. These limits extend previous limits set by the LEP experiments [28].

In other, so called Gauge Mediated Supersymmetry Breaking (GMSB) models, the lightest SUSY particle (LSP) is the gravitino $\tilde{G}$ and the next–to–lightest SUSY particle (NLSP) can be the lightest neutralino $\tilde{\chi}_1^0$, which decays to the stable gravitino and a photon. This specific decay channel of the neutralino is investigated by the H1 [29] and ZEUS [30] collaborations as a search for light gravitino production, that is resonant single neutralino production $\tilde{\chi}_1^0$ via t–channel selectron exchange, $e^{\pm}p \to \tilde{\chi}_1^0 q'$, where it is assumed the $\tilde{\chi}_1^0$ is the NLSP and the subsequent decay $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ occurs with an unobservably small lifetime. The experimental signature is thus a photon, a jet from the struck quark and missing transverse momentum due to the gravitino and hence the main SM background is due to radiative CC DIS. No significant deviation from the SM is observed by either H1 or ZEUS and the results are used to derive constraints on GMSB models for different values of the $\not{R}_p$ coupling λ'_{1j1} for fixed values of the relevant

SUSY parameters. Figure 9 displays excluded regions in the $(m(\tilde{e}_L) - m(\tilde{\chi}_1^0),\ m(\tilde{\chi}_1^0))$ plane derived from e^+p HERA data from H1 for various values of λ'_{1j1}. For small mass differences between the neutralino and selectron, neutralino masses up to 112 GeV are ruled out at 95% CL for an $\not{R}_p$ coupling $\lambda'_{1j1} = 1.0$. The results presented in this section are the first constraints from HERA on SUSY models independent of the squark sector.

4 Conclusions

Many searches for new physics have been performed at HERA by the H1 and ZEUS collaborations, some including data from the new HERA II phase. Interesting events containing isolated leptons and missing P_T and multiple high P_T leptons at high masses have been observed by H1. No evidence is seen by either collaboration in searches for a large selection of exotic particles and competitive limits have been derived on such BSM scenarios. The continued data taking in the HERA II phase by both H1 and ZEUS 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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