SEARCH FOR BEYOND THE STANDARD MODEL PHYSICS AT HERA

E. GALLO

INFN Firenze,
Via Sansone 1,
50019 Sesto Fiorentino, Italy,
E-mail: gallo@fi.infn.it

The H1 and ZEUS Collaborations have almost completed a rich program of searches for physics beyond the Standard Model using the data collected in the HERA I period. The main highlights, such as leptoquarks and signatures with isolated leptons at high energy, are reviewed.

1. Introduction

The H1 and ZEUS Collaborations have each collected of the order of $110 \div 130\ pb^{-1}$ of e^+p and $15\ pb^{-1}$ of e^-p collisions data in the HERA I running period. These data have been used for a wide spectrum of searches for physics beyond the Standard Model (SM). In these proceedings some of the highlights are presented, together with some of the prospects for the HERA II running.

2. Leptoquarks

Leptoquarks (LQ) are scalar or vector triplet bosons, carrying both lepton (L) and baryon (B) number, and are foreseen in many extensions of the SM. HERA is the ideal accelerator to look for leptoquarks, as, for large masses, they are produced from the fusion of the electron/positron beam with a valence u, d-quark in the proton. The Buchmüller-Rückl-Wyler model classify them in 14 different types, according *i.e.* to their quark flavour content (up or down), their fermion number (7 with $F = 3B + L$=0 and 7 with $F = 2$), their spin (7 scalar and 7 vector), and their decay (eq or νq). For masses $M_{LQ} < \sqrt{s} = 300, 318$ GeV, leptoquarks are produced mainly in the s-channel. The cross-section, in the narrow-width-approximation, is proportional to $\lambda^2 q(x, Q^2)$, where λ is the Yukawa-coupling of the leptoquark to the lepton and quark and the quark density $q(x, Q^2)$ is evaluated at Bjorken $x = M_{LQ}^2/s$ and photon virtuality $Q^2 = M_{LQ}^2$. The signature is therefore a narrow resonance decaying into electron+jet or neutrino+jet, with mass peaking at $M_{LQ} \simeq \sqrt{xs}$. The final state is in principle not distinguishable from the SM DIS processes $ep \to eX$ (NC) or $ep \to \nu X$ (CC), however the inelasticity y distribution, which is related to the scattering angle in the $eq(\nu q)$ rest frame, is different for LQs ($d\sigma/dy \sim y$ for scalar, $\sim (1-y)^2$ for vectors) and for DIS ($\sim 1/y^2$). For $M_{LQ} \gg \sqrt{s}$, the effect of the leptoquark exchange can be treated as a contact-interaction term.

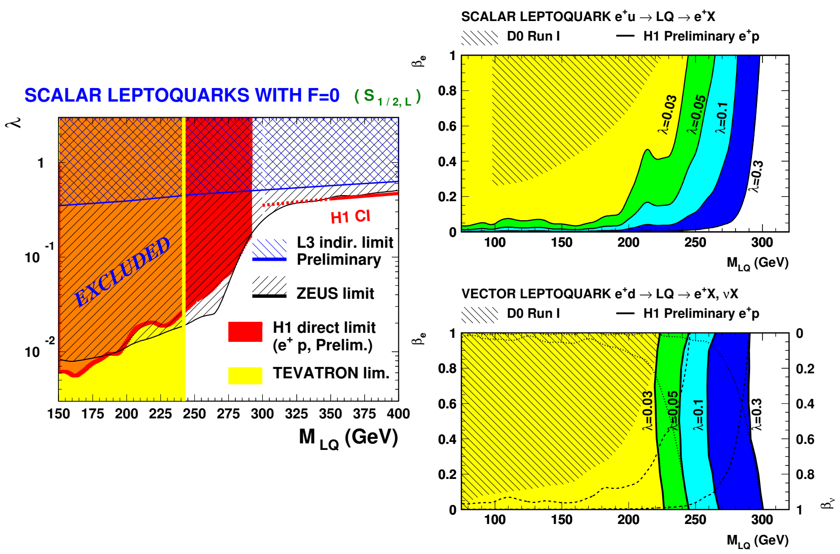

Figure 1. Example of limits on leptoquark production from the HERA I data, compared also to LEP and Tevatron results. The left plot shows the limit of the Yukawa coupling λ as a function of the LQ mass for the $S_{1/2}^L$ type leptoquark. The right plot shows the limit on the branching ratio β_e versus the LQ mass.

Both H1 and ZEUS have performed sophisticated fits of the SM+LQ+interference cross-section to their high Q^2 and high$-x$ data, using the two-dimensional information in the $x - y$ plane[1]. No evidence of a leptoquark signal has been found in the data. H1 has used the neutral current data at high Q^2, while ZEUS has also done a fit to the charged current data, providing strong limits for the 4 types of leptoquark decaying both to eq and to νq. An example of these limits is shown for the $S_{1/2}^L$

leptoquark (produced in e^+p, *i.e.* $F = 0$) in Fig. 1 (left), where the limits of the coupling λ versus the LQ mass is presented for H1 and ZEUS, in comparison to L3 and the Tevatron combined analysis.

In the mass region between 240 and 300 GeV, HERA set the most stringent limits, excluding couplings in the range of $10^{-2} \div 10^{-1}$. At LEP, the strongest limits come from indirect searches from the reaction $e^+e^- \to q\bar{q}$ and are competitive only in the contact-interaction region for few types of leptoquarks. At Tevatron, leptoquarks are produced in pairs and the cross-section is independent from the Yukawa coupling λ, as shown in the figure. However their limits depend on the branching ratio β_e to electron and quark in the final state, as illustrated in Figure 1 (right). HERA has better sensitivity than D0 for small branching ratios and there is still a window open for discovery for small values of λ and β_e. The search for leptoquarks remain therefore a *must* also for the HERA II searches, which will complement the Tevatron II results in this field.

3. Lepton Flavour Violation

As there is now clear evidence for oscillations in the neutrino sector, it is natural to look for flavour violation interactions in the charged leptonic sector (LFV). HERA is basically background-free for reactions of the type $eq \to \mu X$ or $eq \to \tau X$, which are predicted by many extensions of the SM, like leptoquarks coupling also to the second and third generation, here taken as a possible model.

ZEUS has recently[2] presented a new analysis in the τ channel, which makes use of a new τ identification technique for the hadronic decay[3]. In this method, variables which are chosen to discriminate between QCD and τ-jets, making use of the fact that taus are low-multiplicity and collimated jets, are combined with a multi-observable discrimination technique. The signal efficiency is therefore improved with respect to previous analyses. The LFV signature is a τ, either decaying to electron, muon or hadrons, aligned with the missing transverse momentum in the event.

No event with such a signature was selected by ZEUS in the 99-00 e^+p data. The result is used to set limits on the production of leptoquarks which decay to $e\tau$. An example, for the two leptoquark types $\tilde{S}^L_{1/2}$ and V^R_0, is shown in Figure 2, where the limit of the Yukawa coupling λ_{eq}, assuming that it is equal to the coupling $\lambda_{\tau q}$, is presented as a function of the LQ mass. For couplings of the order of the electromagnetic interaction, $\lambda = 0.3$, leptoquarks with LFV are excluded in the range $279 \div 299$ GeV.

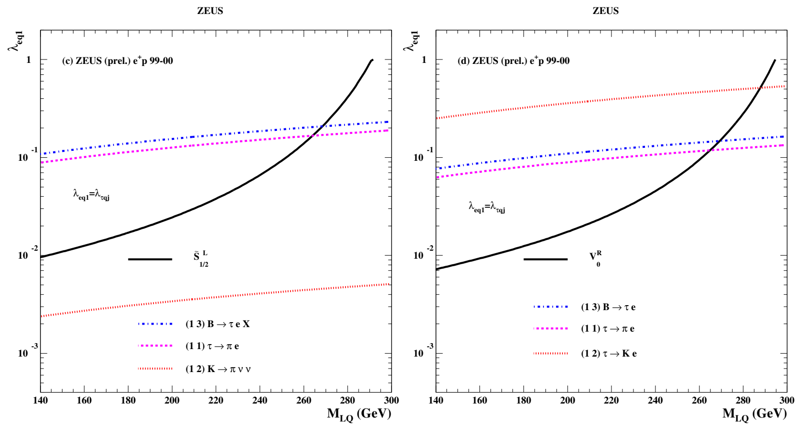

Figure 2. Example of limits on lepton flavour violation production from the ZEUS data, compared also to limits extracted from rare decays.

The limits are also shown in comparison to results obtained indirectly from rare decays of B, K mesons and taus. ZEUS sets the strongest limits in a wide region, especially when a heavy quark in the finally state is involved.

4. $R-$parity violating supersymmetry

The Minimal Supersymmetric Model (MSSM) is widely accepted as a possible extension of the SM. In SUSY models, every particle has its own supersymmetric partner and their spin S differ by 1/2. A new quantity, the R-parity, defined as $R_p = (-1)^{3B+L+2S}$, is $+1$ for particle and -1 for sparticle. While HERA is not competitive with LEP and Tevatron for reactions which require the conservation of R_p, it can instead look for R_p-violating reactions. In this case the Lagrangian has 3 additional terms:

$$L = \lambda_{ijk} L_i L_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j \tilde{D}_k + \lambda''_{ijk} U_i D_j \tilde{D}_k. \quad (1)$$

While LEP is more sensitive to the first term and Tevatron to the last, HERA can search for reactions with the term λ', involving the coupling of squarks to an electron and a quark.

An example in e^+p interaction is the process $e^+d \to \tilde{u}^j_L$, where the squark u^j_L can decay to: e^+d, giving a signature identical to the one expected by a leptoquark; or via a gauge decay to $q\chi^0_\alpha$, $q\tilde{g}$ or $q\chi^+_\beta$. The neutralinos $\chi^0_{1,2,3,4}$, the charginos $\chi^+_{1,2}$ and the gluino $\tilde{g}$ are unstable and can decay via $R-$parity violating coupling. For instance the decay $\chi^0 \to e^\pm q\bar{q}$,

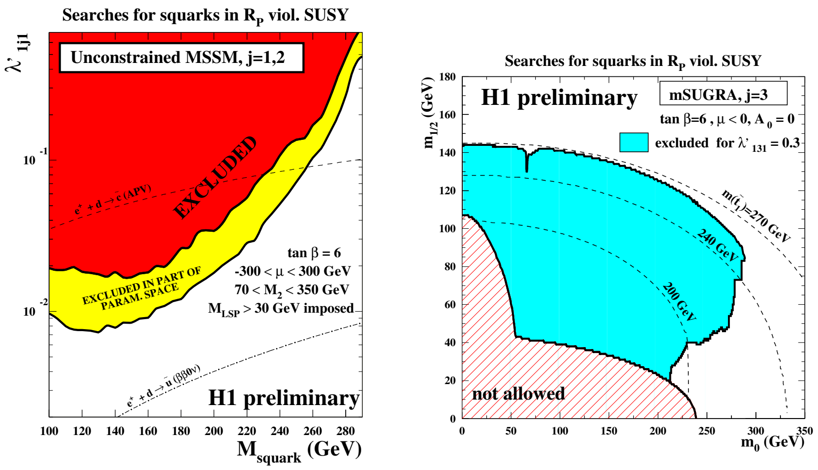

Figure 3. Limits on R_p-violating squark production for $\tilde{u}, \tilde{c}$ squarks in the unconstrained MSSM model (left) and on the stop production in the mSugra model (right).

gives in the final state a total signature of 3 jets and an electron or positron, half of the time of opposite sign compared to the initial beam lepton, which is a background-free process.

The H1 Collaboration has analyzed the 98-00 data and searched for squarks in seven different topologies, according to all possible decays[4]. No evidence was found for a signal, therefore limits on squark production were determined. The limits were derived scanning a wide range of the SUSY parameters μ, M_2 and for two values of the $\tan\beta$ parameters (2,6). However the limits do not depend strongly on these variations, as shown by the grey band in Figure 3 (left). In general $\tilde{u}_L, \tilde{c}_L$ squarks with masses below 240 GeV are ruled out for $\lambda'_{111}, \lambda'_{121} = 0.3$, respectively.

H1 has also calculated limits in the framework of the Minimal Supergravity Model (mSUGRA). An example is shown for the stop quark in Figure 3 (right), where the exclusion region in the two mSUGRA parameters $m_0, m_{1/2}$ is shown for $\lambda'_{131} = 0.3$. The excluded area corresponds approximately to a value of the $\tilde{t}_L$-mass of 270 GeV, as shown by the dashed line in the figure. The present Tevatron limits are around 130 GeV and the sensitivity of Tevatron Run II is around 250 GeV, showing the importance of HERA II for stop searches.

5. Isolated leptons and missing p_T events at HERA

The H1 collaboration has observed regularly, during the HERA I running, an excess of events characterized by an isolated lepton e, μ at high trasverse energy, missing transverse momentum p_T and high transverse momentum of the remaining hadronic system p_T^X. Both H1 and ZEUS have published their final results on this study, which are summarized in Table 1[5].

Table 1. Summary of isolated lepton search at H1 and ZEUS.

	Electron obs./exp	Muon obs./exp.	Tau obs./exp.
H1 $p_T^X > 25$ GeV	4 / 1.49	6 / 1.44	-
H1 $p_T^X > 40$ GeV	3 / 0.54	3 / 0.55	-
ZEUS $p_T^X > 25$ GeV	2 / 2.90	5 / 2.75	2 / 0.20
ZEUS $p_T^X > 40$ GeV	0 / 0.94	0 / 0.95	1 / 0.07

The main SM expectation in the table comes from the production of a W radiated from a quark line, and then decaying into a lepton and a neutrino, giving therefore the observed topology. However, while for the SM expectation the p_T^X distribution peaks at low values, for H1 there is a clear excess of events at $p_T^X > 40$ GeV, where 6 events are observed in the $\mu + e$-channels, while less than 1 event is expected. The ZEUS experiment does not confirm the result and observes no events for $p_T^X > 40$ GeV.

A possible process beyond the SM which could give this signature is the flavour-changing neutral-current (FCNC) reaction $eu \to (e)t \to (e)bW$ (where the scattered electron is seen in the detector only for high Q^2). Top decays could be produced in the SM via CC processes like $eg \to \nu tb$, however the cross-section is less than 1 fb and not measurable with the present integrated luminosity. Any excess of this kind of events could then be due to FCNC reactions. Both ZEUS and H1 have performed a search optimized for single-top production, both in the leptonic- and hadronic-decay of the W. In the leptonic channel, H1 observes 5 events compatible with a single-top signal, while 1.8 are expected from the SM contribution; no deviation is observed in the hadronic channel, where however the contribution from the SM QCD background is high. ZEUS observes no deviation in both channels, setting therefore strong limits on the FCNC couplings.

ZEUS has calculated the limit taking into account both the $tu\gamma$ and the tuZ contribution at leading order, as shown in Figure 4 (right). H1 has calculated the limit using the NLO order cross-section and neglecting the Z contribution: the excess in the leptonic channel is cause of the slighlty

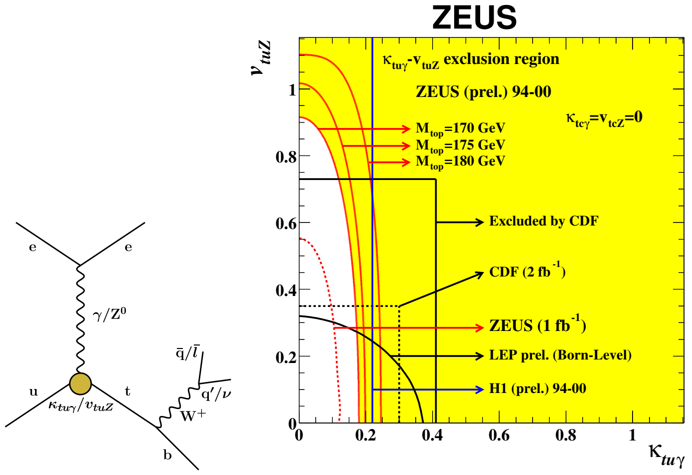

Figure 4. Diagram for FCNC top production at HERA (left) and limit (right) the FCNC couplings obtained by H1, ZEUS, CDF and the combined LEP preliminary result. The dashed lines show also the prospects on the limits at HERA II and Tevatron II, assuming that no deviation from the SM is observed.

weaker limit in $k_{tu\gamma}$ compared to ZEUS. The limits are compared to the ones derived by the LEP experiments, looking for the decay $e^+e^- \to tu$[a], and to the CDF contraints derived from the branching ratios $t \to q\gamma$, $t \to qZ$. The strongest limit on the γ coupling, $k_{tu\gamma} < 0.174$, comes from ZEUS.

At HERA II, the search for this kind of events will be one of the high priority studies. Even hoping to see still an excess, an absence of this signal will provide very strong limits on the FCNC couplings, as shown in Figure 4 for an expected integrated luminosity of 1 fb^{-1}.

The ZEUS experiment has extended the previous search to the hadronic τ-decays[b]. The same technique described in Section 3 has been used to separate the taus from the QCD jets. The results[3] are summarized in Table 1, where, with some surprise, 2 outstanding events with $p_T^X > 25$ GeV remain after all cuts, with a SM expectation of 0.20 ± 0.05[c]. Note that,

[a] The charm contribution has been put to zero in this comparison, as in the HERA high$-x$ regime of interest to this process the charm-density is negligible compared to the u-density. The LEP and CDF results have therefore been rescaled by a factor $\sqrt{2}$. Another factor of $\sqrt{2}$, compensating the previous one, derives from the different Lagrangian convention used by HERA and LEP/Tevatron.
[b] The decays $\tau \to e\nu, \tau \to \mu\nu$ are included in the previous search.
[c] The results here reported are an update of what presented at the Workshop, with the recently published results.

due to the low efficiency of selecting τ-hadronic decays, the cross-section corresponding to these 2 events is far higher than the single-top cross-section already excluded by the e, μ and hadronic-channels. A possible beyond the SM explanation of these τ events requires that there is no W-production involved. It is possible, in SUSY models with large $\tan\beta$, that the stop decays with preference to a τ, *i.e.* $\tilde{t} \to \tau\tilde{\nu}_\tau b, \tilde{\tau}\nu_\tau b$, with subsequent decays, giving the observed topology.

6. Multi-lepton events at HERA

Also the study of events with two or more leptons (e or μ) at high-energy, can provide information on new possible processes beyond the SM. H1 has recently published the final results on this search, ZEUS has presented preliminary results, both use the full HERA I data-sets[6].

For the multi-electron search, both experiments require two well-reconstructed *central* electrons[d], well inside the acceptance of the tracking chambers ($20° < \theta_e < 150°$ for H1 and $17° < \theta_e < 164°$ for ZEUS), and with transverse energy $p_T^e > 10$ GeV. At high-Q^2 values, the scattered electron can be observed in the detector, giving a topology of 3-e in the final states: the third electron is allowed in a wider angular region ($5° < \theta_e < 175°$). In general both H1 and ZEUS observe, in all distributions, a good agreement with the SM prediction, which is dominated by the Bethe-Heitler reaction $\gamma\gamma \to l^+l^-$.

Table 2. Summary of multi-electron search at H1 and ZEUS for $M_{12} > 100$ GeV.

	DATA H1	SM H1	DATA ZEUS	SM ZEUS
$2e$	3	0.30 ± 0.04	2	0.77 ± 0.08
$3e$	3	0.23 ± 0.04	0	0.37 ± 0.04

H1 observes in total 108 $2e$ events and 17 $3e$ events, in good agreement with the SM predictions of 117.1 ± 8.8 and 20.3 ± 2.1, respectively. However, the invariant mass distribution, M_{12}, of the two highest-p_T^e electrons, shows 6 outstanding events at mass greater than 100 GeV, 3 with 2 electrons and 3 with 3 electrons, while 0.53 events in total are expected. The M_{12} distribution is shown in Figure 5 and the predicted number of events is shown in Table 2. The figure also shows that the events at high mass

[d]The term electron here refers to both electrons and positrons, unless specified.

have a different topology in the $2e$- and in the $3e$-case: while in the $2e$-case the two electrons with high invariant mass have also high transverse momentum, this is not the case for the $3e$-events, suggesting that, if it is new physics, it could be of different origin.

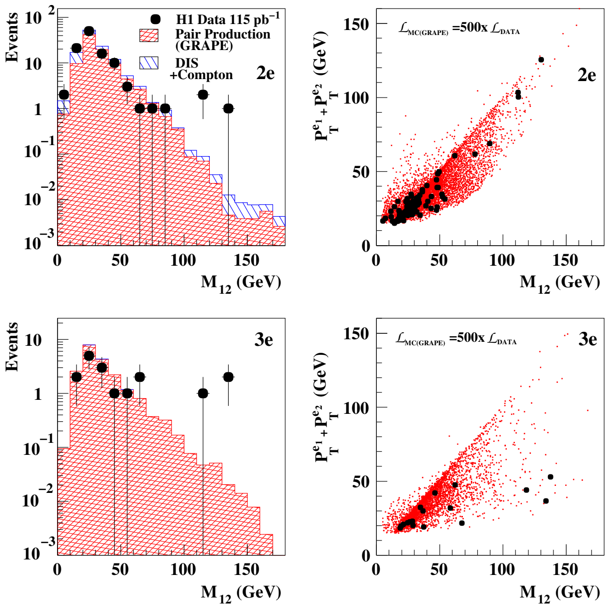

Figure 5. Invariant mass distribution of the two highest-p_T^e electrons in the H1 data, for the $2e$- and $3e$- samples separately, compared to the sum of the SM expectations. The two plots on the left show the correlation between the mass and the sum of the transverse momentum of the two highest-p_T^e electrons.

The ZEUS collaboration has looked for a similar topology in the HERA I data. In total 191 $2e$-events and 26 $3e$-events are selected, in broad agreement with the SM prediction of 213.9 ± 3.9 and 34.7 ± 0.5, respectively. However no deviation is observed at high mass, where two $2e$-events have $M_{12} > 100$ GeV, while 1.2 are expected in total (see Table 2). In addition, no deviation from the SM is observed in the muon-channel by both experiments.

A possible explanation of the 6 outstanding events observed by H1 is the production of doubly-charged Higgs. A $H^{++}(H^{--})$ can be produced at HERA, radiated from the positron(electron) line. It decays then in two leptons of the same positive (negative) sign. Although there are already very strong limits from OPAL, a dedicated search was done by H1, optimizing the selection cuts for this signal. Only one of the 6 events survive these criteria, making unlikely that these events can be explained by doubly-charged Higgs production. The analysis is instead used to set limits on this process, excluding H^{++}/H^{--}-masses of 131 GeV for a value of the Yukawa coupling of the Higgs to the electrons of 0.3. Also this search will be an important chapter of the HERA II program, with expected sensitivities that compete with the present limits from LEP.

7. Summary

The H1 and ZEUS Collaboration have looked for signature beyond the SM model in many processes, ranging from s-channel resonances like leptoquarks, squarks and excited fermions, to contact-interactions and to special signatures in the final state like those with high-transverse-momentum leptons. It is natural to ask if anything was forgotten: for this purpose H1 has performed a model-independent search[7], selecting all events with at least two objects (electrons, photons, muons, jets, and neutrinos *i.e.* missing p_T) at high trasverse energy ($E_T > 20$ GeV). The number of selected events has been compared to the expectation, calculated from the sum of the Monte Carlo prediction of various models. The largest deviation is observed in the $\mu - jet - \nu$ channel, corresponding to the events with isolated muons, high p_T^X and high missing p_T, as described in Section 5. All other observations are compatible with all previous analyses and no other anomaly is found. With the higher integrated luminosity promised for HERA II, it will be exciting to confirm or solve the remaining puzzles from the 1994-2000 running period.

References

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