MODEL-DEPENDENT SEARCHES FOR NEW PHYSICS AT HERA

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Some of the searches for phenomena and particles beyond the Standard Model performed at HERA relying on specific theoretical models and using almost all the collected luminosity are discussed here. They particularly concern leptoquarks, lepton flavour violation, excited fermions, the anomalous top coupling and contact interactions, with improved limits on the quark radius.

1 Introduction

The HERA collider delivered luminosity for 15 years colliding e^+ (e^-) with p at a centre-of-mass energy $\sqrt{s} \simeq$ 300-320 GeV. The data taking started in 1992 and continued until 2000 (HERA I phase). Then a substantial upgrade program involved both the machine and the experiments and the data taking was resumed in 2003 and continued until 2007 (HERA II phase), during which longitudinally polarised $e^{\pm}$ were available in most of data. The two general purpose experiments H1 and ZEUS ended data taking in summer 2007, after collecting a total integrated luminosity of about 1 fb^{-1}. At HERA an extensive program of searches for new particles and phenomena beyond the Standard Model (SM) has been carried out in a unique ep environment. The focus in this paper will be on recent results of searches inspired or driven by specific theoretical models.

2 Leptoquarks

Starting from the symmetry between the quark and the lepton sectors many extensions of the SM predict bosons with fractional electromagnetic charge and both lepton and baryon numbers. A widely used model for leptoquarks is the phenomenological model of Buchmüller-Rückl-Wyler (BRW) [1] which assumes invariance under $SU(3)_C \times SU(2)_L \times U(1)_Y$, conservation of the lepton number L and the baryon number B and a set of 7 scalar and 7 vector leptoquarks (4 decaying into both eq and νq) classified according to the fermion number $F = 3B + L = 0, 2$ and coupling to either left handed or right handed leptons, but not to both, with fixed branching ratio into $e\nu$ (1, 1/2), νq (0, 1/2). At HERA, leptoquarks can be resonantly produced in the s channel or exchanged in the u channel between the incoming lepton and the quark from the proton. The resonant production shows up as a peak in the mass spectrum or an enhancement in x distribution at the value corresponding to the mass M of the leptoquark: $x = M^2/s$. As a consequence of quark densities in the proton, e^-p and e^+p collisions offer respectively best sensitivities to $F = 2$ and $F = 0$ leptoquarks.

The availability of polarisation of both signs within the HERA II sample has the advantage of enhancing the sensitivity to individual leptoquarks species. H1 searched for leptoquarks

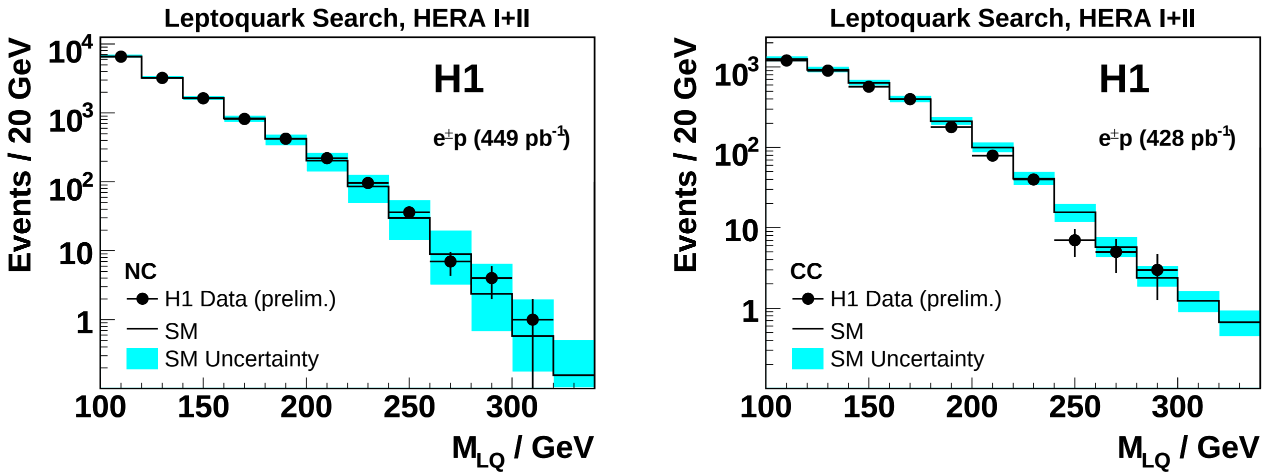

Figure 1: Mass spectra of HERA I + II $e^{\pm}p$ data for Neutral Current (left) and Charged Current (right) events in the H1 leptoquark search. Data points are compared to Standard Model (SM) expectations.

studying the inclusive Neutral Current and Charged Current Deep Inelastic Scattering high Q^2 $e^{\pm}p$ samples from HERA I and HERA II and using an integrated luminosity of 482 pb^{-1}.

No excess was seen in the $e - jet$, $\nu - jet$ mass spectra (fig. 1) and limits were set on the couplings and masses of the different leptoquark types [2] (fig. 2).

3 Lepton Flavour Violation

Leptoquarks can couple to different fermion generations and mediate lepton flavour violation processes in family non diagonal models.
H1 searched for $F = 2$ leptoquarks coupling to eq and μq using $e^- p$ HERA II data and an integrated luminosity of 158 pb^{-1}. No evidence for leptoquarks mediating lepton flavour violation was obtained and limits were set on couplings and masses of leptoquarks coupling to 1st and 2nd generation fermions (fig. 2). For an electromagnetic type coupling masses below 291-433 GeV can be excluded depending on the leptoquark type [3].

4 Excited leptons

To try to explain the hierarchy problem, models of compositeness introduce substructures to SM fermions, implying the existence of fermion excited states. Couplings between excited fermions and SM fermions can be described with phenomenological gauge mediated models [4,?,?]. Excited fermion states have spin and isospin 1/2 with both left-handed (F_L^*) and right-handed (F_R^*) components in weak iso-doublets. They can decay into fermions and gauge bosons. Magnetic type transitions between SM fermions F and excited states F^* can take place. Weight factors f, f' and f_s are used to set the coupling strength to the three gauge groups (U(1), SU(2) and SU(3)) . The branching ratios of excited lepton decays can be fixed by assuming a specific relation between f and f' and then the production cross section depends only on f/Λ where Λ is the compositeness scale.

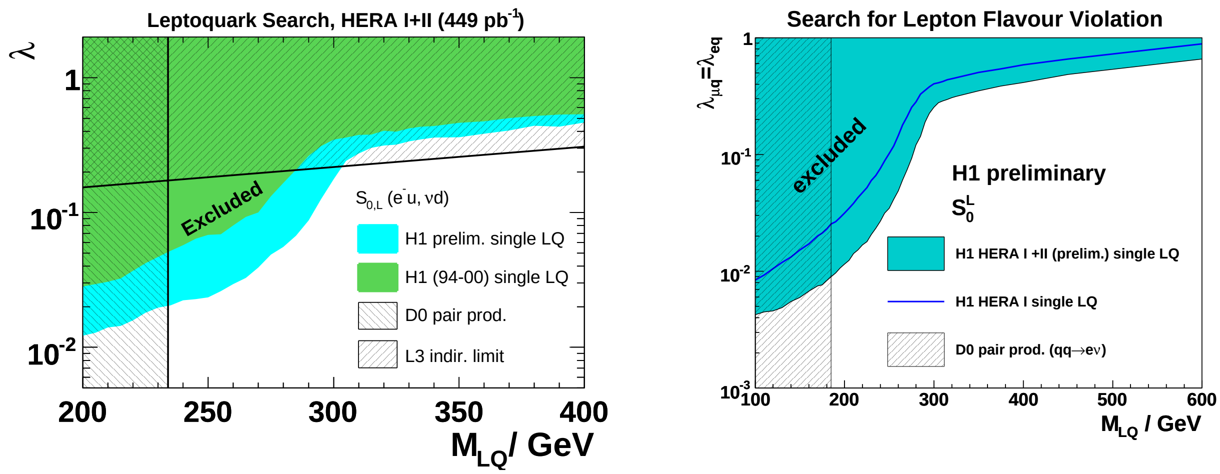

Figure 2: H1 exclusion limits at 95 % C.L. on the coupling λ as a function of the mass for the scalar leptoquark coupling to the first generation S_L^0 (left). H1 exclusion limits at 95 % C.L. on the coupling $\lambda_{\mu q} = \lambda_{eq}$ as a function of the mass for the scalar leptoquark mediating lepton flavour violation S_L^0 (right).

H1 searched for $e^* \to e\gamma$, $e^* \to eZ$ with $Z \to q\bar{q}$, and $e^* \to \nu W$ with $W \to qq'$ using $e^{\pm}p$ data and an integrated luminosity of 475 pb^{-1}. No evidence for e^* production was observed. Improved limits with respect to LEP and Tevatron were set [7].

Due to the helicity structure of electroweak interactions and the valence quark densities in the proton, signals for excited neutrinos are expected to be stronger in e^-p rather than in e^+p data. H1 searched for $\nu^* \to \nu\gamma$, $\nu^* \to \nu Z$ with $Z \to q\bar{q}$, and $\nu^* \to eW$ with $W \to qq'$ using e^-p data and an integrated luminosity of 184 pb^{-1}. No evidence was found and new limits were set [8](fig. **??**). Masses were excluded in the range up to 213 GeV ($f = -f'$) and 196 GeV ($f = f'$). The H1 analysis has entered regions of masses not previously explored.

5 Anomalous top coupling

At HERA top quarks can only be singly produced. SM single-top production proceeds via the Charged Current reaction $ep \to \nu t\bar{b}$X. As the SM cross section at HERA is less than 1 fb any observed single-top event must come from physics beyond the SM. In a Flavour Changing Neutral Current reaction the incoming lepton exchanges a γ or Z with an up-type quark in the proton, yielding a top quark in the final state most sensitive to a coupling of the type $tq\gamma$. The u-quark dominates at large x and therefore the production of single top quark is related to the coupling $tu\gamma$. H1 searched for single top events in a sample of isolated leptons with high p_t using $e^{\pm}p$ data and an integrated luminosity of 482 pb^{-1}. The analysis searched for anomalous production of t decaying into b and W with subsequent decay of W into an electron or a muon. A multivariate discrimination, based on a phase space density estimator with a range searching algorithm was used to separate the signal from the SM background (mostly real W production). The upper limit on the cross section set by H1 [9] is $\sigma_{ep \to etX} < 0.16$ pb, leading to the most stringent limit to date on $k_{tu\gamma} <0.14$ at 95 % C.L. (fig.4).

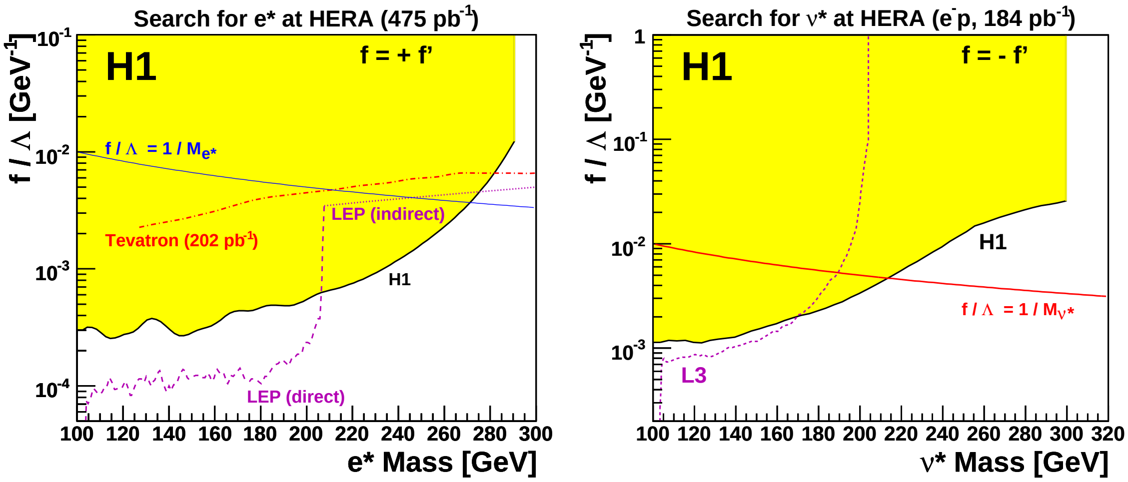

Figure 3: H1 exclusion limits at 95 % C.L. on the coupling f/Λ as a function of the mass of the e^* for gauge mediated interactions, with the assumption $f = +f'$ (left). H1 exclusion limits at 95 % C.L. on the coupling f/Λ as a function of the mass of the ν^* assuming $f = -f'$ (right).

6 Contact interactions and quark radius

Four-fermion contact interactions describe effects from processes at much higher scales, which could alter the SM distributions at high Q^2 and interfere with the predictions at intermediate Q^2. These effects modify the tree level amplitude $eq \to eq$. Let us focus on vector terms (as scalar and tensor terms are already costrained by previous searches). The Lagrangian can be written as:

$$L_{CI} = \sum_{\alpha,\beta=L,R}^{q=u,d} \eta^q_{\alpha\beta}(\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta) \tag{1}$$

The equation:

$$\eta_{\alpha\beta} = \epsilon \frac{g^2_{CI}}{\Lambda^2} \tag{2}$$

where $g_{CI} = 4\pi$ $\epsilon = \pm$ 1 defines the structure of the model.

Contact interaction effects could come from the exchange of extra gauge bosons (Z'), the production or exchange of leptoquarks or squarks, compositeness, gravitational effects (extra-dimensions) or from a finite quark radius.

ZEUS analysed inclusive Neutral Current Deep Inelastic $e^{\pm}p$ data from HERA I and HERA II corresponding to an integrated luminosity of 330 pb^{-1}, comparing the data to SM predictions and performing a QCD fit where experimental and theoretical uncertainties are taken into account [10]. Besides general model independent limits on contact interactions (values of the scale Λ_{eeqq} in the range 2.0-8.0 TeV) depending on the chiral structure, limits were also set on the heavy leptoquark (beyond the available CM energy) couplings to the first generation (M_{LQ}/λ in the range 0.29-2.08 TeV).

In some $4+n$ dimensional string theories [11,12,13] compactified extra dimensions have size $R \simeq 1$ mm. The effective Planck scale M_S related to the Planck scale $M_P \simeq 10^{19}$ GeV: $M_P^2 = M_S^{2+n} R^n$ can be as small as 1 TeV. Graviton can propagate into the extra dimension, visible in the or-

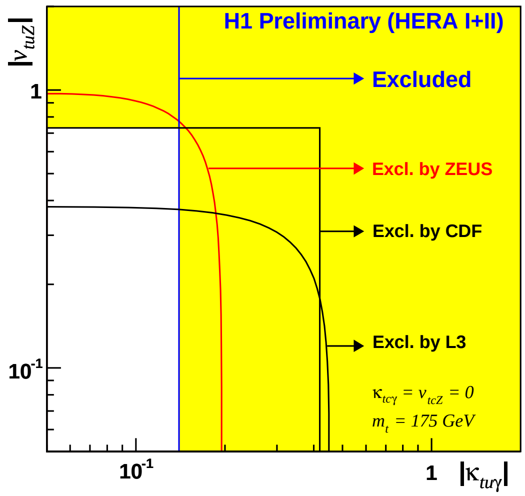

Figure 4: Exclusion limits at 95 % C.L. on the anomalous top coupling $k_{tu\gamma}$ from H1 and ZEUS compared to limits from LEP and Tevatron (anomalous couplings to charm are neglected, the top mass is set to 175 GeV).

dinary 4 dimensions as a Kaluza-Klein tower of excited states with spacing $\Delta m = \frac{1}{R}$. Such states can be summed up to M_S, give sizeable effects, equivalent to a contact interaction term $\eta^G \simeq \frac{\pm\lambda}{M_S^4}$ where $\lambda \simeq 1$ [14]. The interference with the SM can be constructive or destructive.
Constraints were derived by ZEUS for such extra dimension scales: $M_S > 0.9$ TeV for $\lambda = -1$ and $M_S > 0.88$ TeV for $\lambda = +1$.
As far as the finite size of the quark is concerned in a classical approach to the quark substructure a charge distribution of radius R_q in the quark can be described using a form factor:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot (1 - \frac{R_q^2}{6} \cdot Q^2)^2) \tag{3}$$

This effect leads to a decrease of cross sections at high Q^2. An upper limit on quark radius was extracted from the ZEUS analysis: $R_q < 0.62 \cdot 10^{-16}$ cm. A study of high Q^2 Neutral Currents single differential cross section by H1 using the complete HERA I and HERA II data and an integrated luminosity of 270 pb^{-1} (e^+p) and 165 pb^{-1} (e^-p) [15] led to a limit: $R_q < 0.74 \cdot 10^{-16}$ cm at 95 % C.L. (fig. 5).

7 Conclusions

The complete statistics of 15 years of data taking is being exploited by H1 and ZEUS to improve the sensitivity of the searches for new physics in the unique HERA environment. H1 and ZEUS at HERA have performed a number of model dependent searches finding no evidence for leptoquarks or lepton flavor violation, for excited electrons or excited neutrinos. Looking for single top production new limits on the anomalous top coupling are set. Limits on the contact interaction scales and quark radius have been updated fitting the Deep Inelastic Scattering

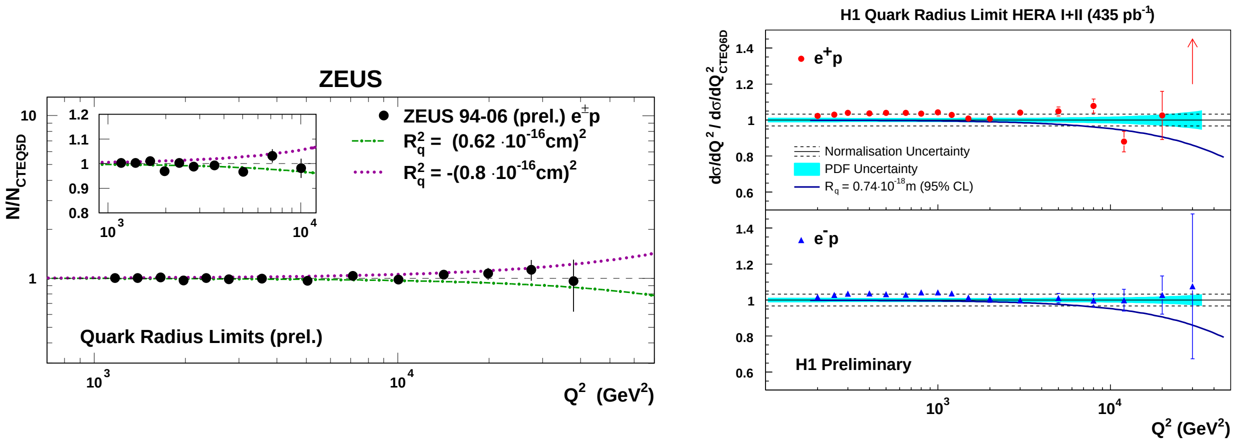

Figure 5: Ratio of inclusive neutral current deep inelastic scattering data obtained by ZEUS in $e^{\pm}$ (left) and single differential cross sections obtained by H1 in e^+p (top right) e^-p (bottom right) to SM expectations as a function of Q^2, compared with 95 % C.L. limits on the effective mean square radius of the electroweak charge of the quark.

differential cross sections at high Q^2. For some of these searches the two collaborations are going to provide a combination of H1 and ZEUS data.

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