ELECTROWEAK PHYSICS AND SEARCHES FOR NEW PHYSICS AT HERA

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Abstract

The charged and neutral current cross sections of deep inelastic *ep* scattering at HERA are presented. For the first time, these cross sections are also measured with longitudinally polarised electron (positron) beams. The cross sections are compared to the standard model expectations. No deviations are found. Recent results on further searches for physics beyond the standard model in the full HERA data set are reported. The data have been analysed searching for contact interactions, leptoquarks, squarks and light gravitinos in R-parity violating sypersymmetric models. A dedicated search for events with isolated leptons and missing transverse momentum is also reported.

1 Introduction

At the HERA collider electrons (positrons) and protons collide at a center-of-mass energy of about $\sqrt{s} = 320$ GeV (300 GeV before 1998). From 1994-2000 (HERA I), integrated luminosities of about 100 pb^{-1} of e^+ p and 15 pb^{-1} of e^- p scattering data were collected by each of the two experiments H1 and ZEUS.

After an upgrade to run with high luminosity and with polarised leptons 60 pb^{-1} of e^+p data and 100 pb^{-1} of e^-p data with an average polarisation of 40% and helicity $\pm$ 1 have been collected since 2003 (HERA II).

The data were used to measure the charged and neutral cross sections with and without polarisation and to search for new physics beyond the Standard Model (SM).

2 Electroweak measurements

At HERA both neutral current (NC) interactions $ep \to ep$ via γ or Z^0-exchange, or charged current (CC) interaction $ep \to e\nu$ via $W^\pm$ exchange are observed. The cross sections are described in terms of Q^2, the four momentum transfer squared, Bjorken x and the inelasticity y. These variables are related through $Q^2 = sxy$.

Fig. 1 shows the Q^2 dependence of the NC and CC cross sections for e^+p and e^-p data measured in HERA I. [1] The data are well described by the SM as shown here with the CTEQ6D parametrisation for the parton densities in the proton. At low Q^2 the NC cross section exceeds the CC cross section by more than two orders of magnitude due to the dominating photon exchange with the propagator term $\sim 1/Q^4$. In contrast the CC cross section which is proportional to $M_W^2/(Q^2+M_W^2)$ approaches a constant at low Q^2. The CC and NC cross sections are of comparable size at $Q^2 \sim 10^4$ GeV^2, where the photon and the Z^0 exchange contributions to the NC cross sections are of similar size to those of the $W^\pm$ exchange. These measurements thus illustrate unification of the electromagnetic and the weak interactions in deep inelastic scattering.

Small differences between e^+ and e^- scattering can be observed in both cross sections. The difference between the e^+ and e^- scattering in the NC cross section is due to γZ interference. The difference of the CC cross sections arises from the difference between the up and down quark distributions and the less favourable helicity factor $(1-y)^2$ in the e^+p cross section:

$$\bar{\sigma}^+_{CC} \sim x\bar{u} + (1-y)^2 xd \tag{1}$$

$$\bar{\sigma}^-_{CC} \sim xu + (1-y)^2 x\bar{d} \tag{2}$$

[1] The e^+p data have been combined after scaling the 94-97 data to $\sqrt{s} =$ 319 GeV.

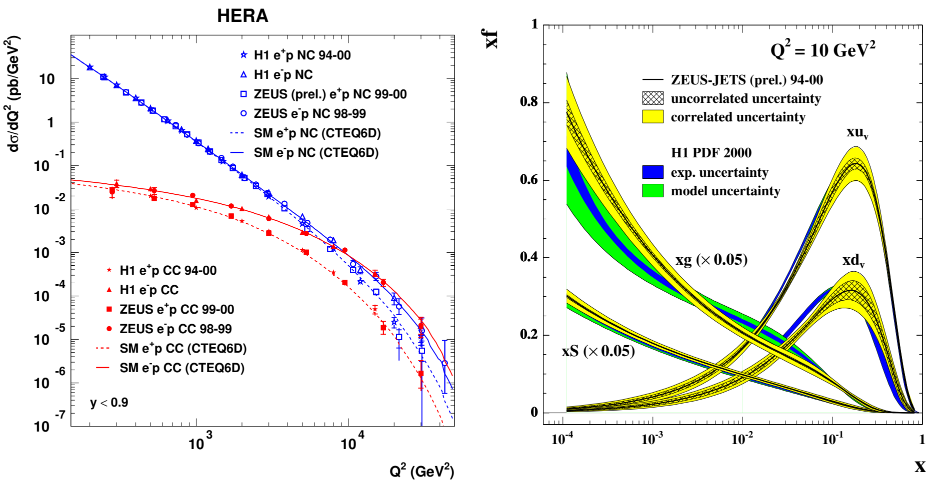

Figure 1: l*left: NC and CC $e^{\pm}p$ scattering cross sections as a function of Q^2 right: parton density functions*

The high precision and the wide kinematic range covered by the HERA DIS data, over four orders of magnitude in x and Q^2, allows the determination of the parton density functions (PDFs) in an NLO QCD fit using the DGLAP evolution equations as shown in Fig.1. The ZEUS fit uses in addition e^+p deep inelastic inclusive jet cross sections and direct photoproduction dijet cross sections to further constrain the gluon density [1]. The PDFs extracted by both experiments agree and are in agreement with global fits. In a complementary measurement to the fits, the H1 collaboration extracted the u and d quark distributions in x and Q^2 bins where they contribute at least 70% to the cross section [2]. The results are in good agreement with the fits.

The longitudinally polarised leptons available in HERA II are used to measure the polarisation dependence of the total charged current cross section. Due to the non-existence of right handed currents in the SM a linear dependence of the CC cross section on the polarisation is expected:

$$\sigma^{\pm}_{CC} = (1 \pm P)\sigma^{(P=0)}_{CC} \tag{3}$$

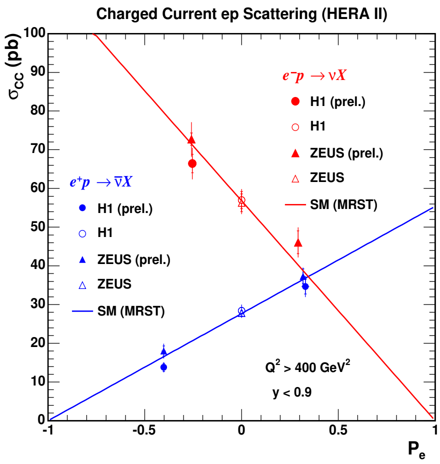

Figure 2: *CC cross sections as a function of polarisation.*

Fig.2 shows the total charged current cross section as a function of the polarisation for e^+p and e^-p scattering. The data agree well with the expectations from the SM and with a linear fit. Hence no sign for a right handed weak current is observed.

3 Physics beyond the SM

The precise CC and NC cross section measurements and the high statistics available allow to look for new particles or processes that would lead to deviations of the cross sections from the standard model predictions. The *ep* collider HERA is ideally suited to search for new particles coupling to electron-quark (positron-quark) pairs.

3.1 Contact interactions

To search for new particles associated to a large scale ($M_X >> \sqrt{s}$) the possible interference of a new particle with the γ or Z field of the $e^{\pm}p$ NC scattering pro-

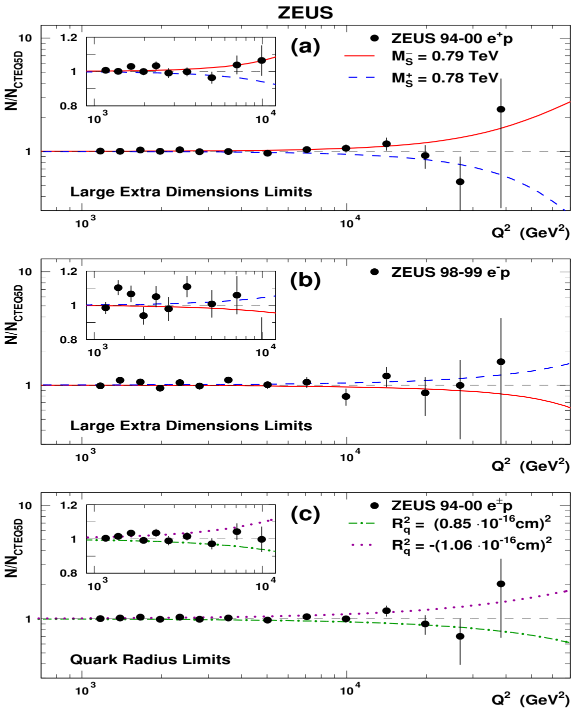

Figure 3: *ZEUS* $e^{\pm}p$ *(a),(b) data compared with 95% C.L. exclusion limits for the effective Planck mass scale in models with large extra dimensions. (c) Exclusion limits for the effective mean-square radius of the electroweak charge of the quark. Results are normalized to the SM expectations calculated using the CTEQ5D parton distributions.*

cess is parametrized and the effect on the NC cross section has been calculated, see Fig.3.

Since no deviations of the NC cross section from the SM are found various limits were derived: the effective mass scale in *eeqq* contact interactions Λ is above 1.6 to 5.5 TeV (depending on the parametrisation); the ratio of leptoquark mass to the Yukawa coupling M_{LQ}/λ_{LQ} for heavy leptoquark models is above 0.3-1.4 TeV and mass scale parameters in models with large extra dimensions below 0.79 TeV are excluded [3), 4)]. The limit on the quark charge radius, in the classical form factor approximation, is $0.85 \cdot 10^{-18}$ cm.

3.2 Leptoquarks

Leptoquarks (LQ) are bosons that carry both lepton (L) and baryon (B) numbers and have lepton-quark couplings. Their fermion number ($F = 3B + L$) can be $F = 0$ or $|F| = 2$. Such bosons arise naturally in unified theories that arrange quarks and leptons in common multiplets such as GUT like theories, technicolor, compositness.

HERA provides a unique facility for resonant production of first generation leptoquarks with $M_{LQ} = \sqrt{s_{ep}x}$ decaying into a lepton and a jet, with the lepton being either an electron or a neutrino. In the Buchmüller-Rückl-Wyler model [7] the resonance-decay branching ratios β_e, β_ν are fixed to 0, 0.5 or 1, in generic models β is a free parameter.

Searches for narrow width resonances have been performed by both experiments [5], [6]. No evidence for a resonance were found in either the eq or the νq topology. Limits were derived that depend only very weakly on β. The excluded mass regions depend on the leptoquark type and the coupling. For a coupling constant of electromagnetic strength ($\lambda \simeq \sqrt{4\pi\alpha_{em}}$) mass limits ranging from 275 to 325 GeV were set. These limits extend beyond the mass domain covered at the Tevatron, where however coupling independent bounds can be set.

The recent observations of neutrino oscillations have shown that lepton-flavor violation (LFV) does occur in the neutrino sector. The LFV induced in the charged-lepton sector by neutrino oscillations cannot be measured at existing colliders due to the low expected rate. However, there are many extensions of the SM such as GUT, SUSY and compositness that predict possible $e \to \mu$ or $e \to \tau$ transitions mediated by leptoquarks at detectable rates. The presence of such processes, which can be detected almost without background, would clearly be a signal of physics beyond the SM.

A search for LFV interactions $ep \to \mu X$ and $ep \to \tau X$ has been performed by both experiments using the entire HERA I data sample [8], [9]. No evidence for LFV was found and limits on M_{LQ} and the couplings $\lambda_{\mu q}$, $\lambda_{\tau q}$ were set. For $M_{LQ} = 250$ GeV, upper limits on $\lambda_{eq_1}\sqrt{\beta_{\mu q}}$ ($\lambda_{eq_1}\sqrt{\beta_{\tau q}}$) in the range 0.010-0.12 (0.013-0.15) were set.

3.3 Supersymmetry

Supersymmetry (SUSY) [10] is an attractive concept which remedies some shortcomings of the SM. It introduces fermion-boson symmetry by associating a bosonic (fermionic) supersymmetric partner to each fermionic (bosonic) SM particle, differing in its spin by half a unit. Particles carry the number $R_p = (-1)^{L+3B+2S}$ where B denotes the baryon number, L the lepton number and S the spin of a particle. The masses of the new particles are related to the symmetry breaking mechanism. Various models exist that differ in the description of the SUSY breaking mechanism and on whether R_p is conserved or violated. If R_p might be violated SUSY particles can be singly produced and the lightest supersymmetric particle (LSP) is not stable.

If R_p is violated squarks can be resonantly produced in lepton quark fusion at HERA via a Yukawa coupling λ'. H1 searched for such processes taking into account direct and indirect R-parity violating decay modes [11]. No evidence for squark production is found in the multi-lepton and multi-jet final state topologies investigated. Mass dependent limits on the R_p violating couplings λ'_{1jk} are derived within a phenomenological version of the Minimal Supersymmetric Standard Model (MSSM). The existence of $\tilde{u}_L$-type and $\tilde{d}_R$-type squarks of all three generations with masses up to 275 GeV and 280 GeV respectively is excluded at the 95% CL for a Yukawa coupling of electromagnetic strength ($\lambda \sim \sqrt{4\pi\alpha_{em}}$) in a large part of the MSSM parameter space. These mass limits extend considerably beyond the reach of other collider experiments. Recently a squark search has been carried out by ZEUS restricted to the case of the stop and to a few decay modes [12]. Similar limits were observed.

Exclusion limits of 285 (275) GeV for $\tilde{d}_R$-type ($\tilde{u}_L$-type) squarks for $\lambda \sim \sqrt{4\pi\alpha_{em}}$ were also derived in the more restricted minimal Supergravity Model (mSUGRA) for which the limits obtained are partly competitive with and complementary to those derived at the LEP and Tevatron colliders.

In Gauge Mediated Supersymmetry Breaking (GMSB) models, new "messenger" fields are introduced which couple to the source of supersymmetry breaking. The breaking is then transmitted to the SM fields and their superpartners by gauge interactions. The gravitino, $\tilde{G}$, is the lightest supersymmetric particle and can be as light as 10^{-3} eV. At HERA, single neutralinos could be resonantly produced via t-channel selectron exchange. Both collaboration searched for R_p violating SUSY in a GMSB scenario at HERA [13], [14]. For the case that the $\tilde{\chi}^0_1$ is the next-to-lightest supersymmetric particle and that the decay $\tilde{\chi}^0_1 \to \gamma\tilde{G}$ into a stable gravitino occurs with an unobservably small lifetime. The resulting experimental signature is a photon, a jet originating from the scattered quark and missing transverse momentum due to the escaping gravitino. No deviations from the SM were found and constraints on GMSB models are derived for different values of the R_p violating coupling. For small mass differences between the neutralino $\tilde{\chi}^0_1$ and the supersymmetric partner of the left-handed electron $\tilde{e}_L$, neutralinos with masses up to 112 GeV are ruled out at the 95% confidence level for R-parity-violating couplings λ' equal to 1. Similarly, for large mass differences, massed of $\tilde{e}_L$ up to 164 GeV are excluded.

3.4 Isolated leptons

A search for events with a high energy isolated electron or muon and missing transverse momentum has been performed by both experiments for the HERA I and HERA II data sets. In the transverse plane, it is required that the hadronic final state and the lepton are not back-to-back, which reduces genuine background from deep inelastic scattering and ensures that the missing transverse momentum is due to an invisible particle (ν). For the remaining hadronic final state the transverse momentum (p_T^X) is measured.

Within the SM such events are expected to be mainly due to W boson production with subsequent leptonic decay. Searches have been performed by both experiments in the decay channels into electrons, muons and taus [15], [17], [16].

In the HERA I analyses an overall good agreement between data and the SM expectation was found at both experiments, see Tab.1. However, requiring $p_T^X > 25$ GeV, 5 electron and 6 muon events were observed by the H1 experiment compared to an expectation of 1.76 ± 0.30 and 1.68 ± 0.30 respectively. This excess is not confirmed by ZEUS [16]

To enhance the limited statistics isolated lepton events were investigated in the recent HERA II data set by both collaborations [18], [19]. ZEUS modified his search to be more closely comparable to the H1 analysis than previous ZEUS searches. Fig. 4 shows the transverse momentum spectrum of events with isolated leptons (electron and muon channels combined) in the H1 HERA I+II data set . H1 found 11 events in the high p_T^X region ($p_T^X > 25$ GeV) compared to an expectation of 3.2 ± 0.6 with an isolated electron and 6 compared to an expectation of 3.2 ± 0.5 with an isolated muon, see Tab.1. ZEUS found 1 event in the electron channel compared to 1.50 $\pm$0.18 expected which is consistent with the SM.

3.5 Anomalous single top production

A search for single-top production $ep \to etX$ has been made by both experiments. Since the centre of mass energy in the ep collision at HERA is well above the top production threshold, single top production is kinematically possible. However, in the SM the dominant process for single top production is the charged current reaction $e^+p \to \bar{\nu}t\bar{b}X(e^-p \to \bar{t}bX)$. This process has a tiny cross section of less than 1 fb. However, in several extensions of the SM, the top quark is predicted to undergo flavour changing neutral current (FCNC) interactions, which could lead to a sizeable top production cross section. FCNC interactions are for example present in models which contain an extended Higgs sector [22] or SUSY [23]. An observation of top quarks at HERA would thus be a clear indication of physics beyond the SM.

Table 1: *HERA event yields in the search for isolated leptons with missing transverse momentum. The numbers are given for the electron and muon channel for different cuts* p_T^X.

data set	Electron obs./exp.	Muon obs./exp.	Combined
H1 94-00 L($e^{\pm}$) = 118 pb^{-1}			
Full sample	11 / 11.54 ± 1.50	8 / 2.94 ± 0.50	19 / 14.48 ± 2.0
$P_T^X > 25$ GeV	5 / 1.76 ± 0.30	6 / 1.68 ± 0.30	11 / 3.44 ± 0.6
H1 94-05 L($e^{\pm}$) = 211 pb^{-1}			
all data	25 / 20.4 ± 2.9	9 / 4.5 ± 1.1	34 / 25.7 ± 4.0
$P_T^X > 25$ GeV	11 / 3.2 ± 0.6	6 / 3.2 ± 0.5	17 / 6.4 ± 1.1
ZEUS (prel.) 99-04 L(e^{+}) = 106 pb^{-1}			
$P_T^X > 25$ GeV	1 / 1.50 ± 0.18		

Both experiments searched for decays of top quarks into a b quark and a W boson in the leptonic and hadronic decay channels of the W. ZEUS observed no event in the leptonic channel and no excess over the SM in the hadronic channels therefore limits were set on FCNC interactions of the type tqV. The contribution of the charm quark, which has only a small density in the proton at high Bjorken x, was ignored by setting $\kappa_{tc\gamma} = \nu_{tcZ} = 0$. Only the anomalous couplings involving a u quark $\kappa_{tu\gamma}$ and ν_{tuZ} were considered. By combining the results from both the leptonic and hadronic channels, an upper limit of $\kappa_{tu\gamma}$ derived see Fig.4, corresponding to a limit on the cross section for single-top production of $\sigma(ep \to etX) < 0.225$ pb at 95% C.L..

H1 observed 5 events in the leptonic channel while 1.31±0.22 events are expected, in the hadronic channel no excess above the expectation for SM processes is found. Assuming that the observed events are due to a statistical fluctuation, an upper limit of 0.55 pb on the single top cross section is set.

4 Conclusions

Results on the electroweak measurements and searches for physics beyond the Standard Model (BSM) at HERA have been presented. Exploring the full HERA I data set no signal of BSM physics has been observed, but some interesting deviations were found to be followed up in the future.

First results from HERA II have been presented confirming the HERA I observations. The HERA II start-up is promising. With the new incoming data (700 pb^{-1} until 2007) the sensitivity to new physics will increase.

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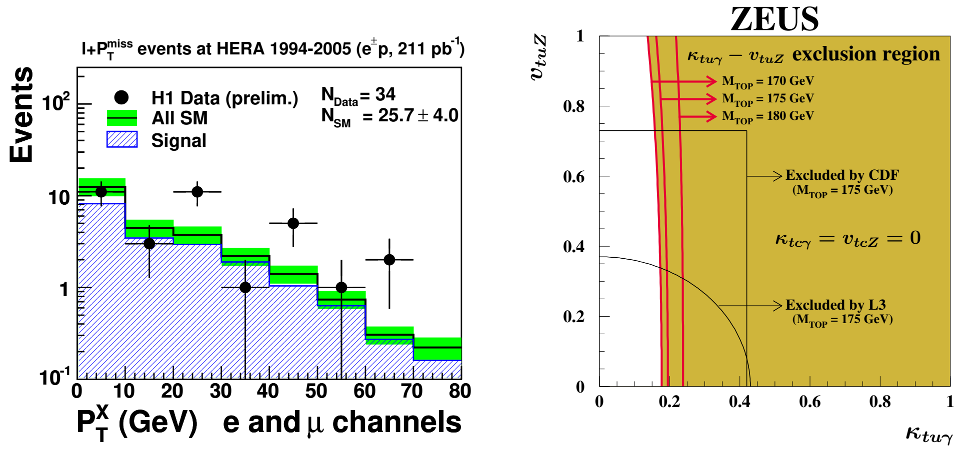

Figure 4: **left:** *Transverse momentum distribution in the electron and muon channels combined of events with isolated leptons is compared to SM expectation (open histogram). The signal component of the SM expectation, dominated by real W production, is given by the hatched histogram. The total error on the SM expectation is given by the shaded band.* **right:** *FCNC exclusion region at 95% C.L. in the* $\kappa_{tu\gamma}$-ν_{tuZ} *plane for three values of* M_{top} *(170, 175 and 180 GeV) assuming* $\kappa_{tc\gamma} = \nu_{tcZ} = 0$*. The CDF and L3 exclusion limits are also shown.*