Electroweak and beyond the Standard Model results from HERA

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The latest results from the $e^{\pm}p$ HERA collider both within the Standard (electroweak) Model and beyond are reviewed. Most of the results are based on the full HERA data sample, which corresponds to an integrated luminosity of about $0.5\,\mathrm{fb}^{-1}$ per experiment (H1 or ZEUS).

1. INTRODUCTION

The electron-proton collider HERA ended its data taking on June 30, 2007. Over its lifetime of more than 15 years of operation, it has allowed each experiment, H1 and ZEUS, to collect an integrated luminosity of about $100\,\mathrm{pb}^{-1}$ and $20\,\mathrm{pb}^{-1}$ in positron-proton and electron-proton collisions respectively in the first phase (HERA-1) from 1992 to 2000. In the second phase (HERA-2) from 2003 to 2007, the positron and electron samples have increased by a factor of 2 and 10 respectively. In addition, spin rotators installed at the H1 and ZEUS interaction regions have provided longitudinal electron and positron polarization at HERA-2.

The results reviewed in the talk concern both the electroweak (EW) measurements in the Standard Model (SM) and searches beyond the SM. They are based either on the dominant inclusive Deep Inelastic Scattering (DIS) processes of neutral and charged current interactions or on rare exclusive processes such as single W and lepton pair productions. The advantage in the former case is high statistics and in the latter case clean and well defined final states.

While the emphasis is put on presenting the latest results, some early results are also shown in a few cases in order to illustrate the progress that has been made over the years and the impact of the increased data samples.

2. DOMINANT INCLUSIVE DIS PROCESSES

At HERA, both the neutral current (NC) and the charged current (CC) interactions can be studied. The cross sections of these processes may be written in the following simplified form:

$$\sigma_{\rm NC} \propto \frac{\alpha^2}{Q^4}\Phi_{\rm NC}({\rm PDFs}, v_q, a_q, P_e)\,, \tag{1}$$

$$\sigma^{\pm}_{\rm CC} \propto G_F^2 \frac{1 \pm P_e}{\left(1+\frac{Q^2}{M_W^2}\right)^2}\Phi_{\rm CC}({\rm PDFs})\,, \tag{2}$$

where α and G_F are the fine structure constant and Fermi constant for electromagnetic and weak interactions respectively, v_q and a_q are vector and axial-vector couplings of the Z boson to light quarks q (u,d), P_e is the polarization value of the electron beam, Q^2 is the four-momentum transfer squared, M_W the propagator mass of the W boson, and $\Phi_{\rm NC,CC}$ are the structure function terms for NC and CC processes respectively, which provide the primary constraint on the parton distribution functions (PDFs) of the proton.

In NC interactions at high Q^2, when Z exchange and γZ interference become increasingly important, the NC cross section depends both on v_q and a_q and on the beam polarization P_e. However, these dependencies cannot be factorized, contrary to the P_e dependence of the CC cross section. In addition, from the Q^2 dependence and the normalization of the CC cross section, one can determine the propagator mass of the W boson and the Fermi constant G_F respectively.

2.1. The propagator mass of the W boson

The first evidence of the massive W boson at HERA was obtained from the observed deviation of the CC cross section from a linear dependence on the beam energy based on the very first data of the H1 collaboration taken in 1993 corresponding to an integrated luminosity of $0.35\,\mathrm{pb}^{-1}$ [1]. The electron beam of 26.7 GeV in collision with the proton beam of 820 GeV resulted in a center of mass energy $\sqrt{s}$ of 296 GeV.[1] This is equivalent to an electron beam with energy of almost 50 TeV hitting a fixed target.

The first quantitative determination of the propagator mass of the W boson, $M_W = 76 \pm 16_{\rm stat} \pm 13_{\rm syst}$ GeV, was derived from the Q^2 dependence of the CC cross section $d\sigma_{\rm CC}/dQ^2$ with an e^-p data sample of $0.54\,\mathrm{pb}^{-1}$ [2]. Together with the NC cross section $d\sigma_{\rm NC}/dQ^2$, it was shown that the Q^2 dependence of the NC and CC cross sections are very different. At low Q^2 the electromagnetic interaction is much stronger than the weak interaction. The difference diminishes, however, as Q^2 increases, and the cross sections become comparable when Q^2 values reach the W and Z boson mass squared, demonstrating the EW unification in DIS.

The propagator mass determination in the space-like regime at HERA is complementary to other measurements using time-like production of W bosons at the Tevatron and at LEP and constitutes an important experimental consistency check of the SM.

Based on an e^-p (e^+p) sample of $0.29\,\mathrm{pb}^{-1}$ ($2.7\,\mathrm{pb}^{-1}$), H1 has performed a similar determination of the W propagator mass: $M_W^{e^-p} = 78^{+11+4}_{-9-3}$ GeV ($M_W^{e^+p} = 97^{+18+5}_{-15-10}$ GeV), where the first error is statistical and the second systematic [3]. It is interesting to note that the precision is better with the e^-p data, albeit with a smaller integrated luminosity. This is because the W^- (W^+) exchange probes mostly the u (d) quark in the proton resulting in a much larger CC cross section in e^-p interactions.

With an increased e^+p data sample of $47.7\,\mathrm{pb}^{-1}$ taken in 1994-1997 by ZEUS, a simultaneous fit of M_W and G_F was performed resulting in $M_W = 80.8^{+4.9+5.0+1.4}_{-4.5-4.3-1.3}$ GeV, where the three errors correspond to the statistical, systematic and PDFs uncertainty respectively [4]. When fixing G_F to the world average value [5], ZEUS obtained $M_W = 81.4^{+2.7}_{-2.6} \pm 2.0^{+3.3}_{-3.0}$ GeV, where the last error from the PDFs dominates over the statistical and other systematic errors.

In all above results, the correlation between the EW parameters with the PDFs was not fully taken into account. A first analysis which considered such a correlation was performed by H1, using the complete high Q^2 NC and CC cross section data and all available low Q^2 data from HERA-1 [6]. The result on the propagator mass was $M_W = 82.87 \pm 1.82^{+0.30}_{-0.16}$ GeV, where the first error is experimental and the second the model uncertainty [6]. Within the SM, a much more precise W mass determination, $M_W = 80.786 \pm 0.205^{+0.063}_{-0.098}$ GeV, was obtained using the SM constraint between M_W, G_F and other EW parameters

$$G_F = \frac{\pi\alpha}{\sqrt{2}} \frac{M_Z^2}{(M_Z^2 - M_W^2)M_W^2} \frac{1}{1-\Delta r}\,, \qquad (3)$$

where M_Z is the mass of the Z boson, and Δr represents radiative corrections which contain among others a quadratic top quark mass term and a logarithmic Higgs mass term [6].

The ten-fold increase of the e^-p data from HERA-2 should substantially improve the final precision of the W mass determination from HERA.

2.2. The light quark couplings to the Z boson

Using the same HERA-1 data sample, H1 has also performed a combined EW-PDF fit in which the four light quark couplings v_u, a_u, v_d and a_d to Z have been determined taking into account their correlation with the PDFs [6]. The resulting precision is comparable with those from CDF and the combined LEP/SLD EW fit. In addition, the HERA data can resolve the sign ambiguity seen in some of the other determinations.

[1] From 1994 on, the electron beam energy was increased to 27.5 GeV and from 1998 on, the proton beam energy was also increased to 920 GeV resulting in $\sqrt{s} = 300$ GeV and $\sqrt{s} = 318$ GeV.

The polarized electron beam at HERA-2 is expected to give additional sensitivity to these couplings in particular the vector couplings. Indeed, including new preliminary NC cross section measurements based on part of the analyzed HERA-2 data, a new fit has substantially improved the precision [7]. The comparison for the u quark couplings with the results of CDF [8] and LEP/SLD [9] is shown in Fig. 1.

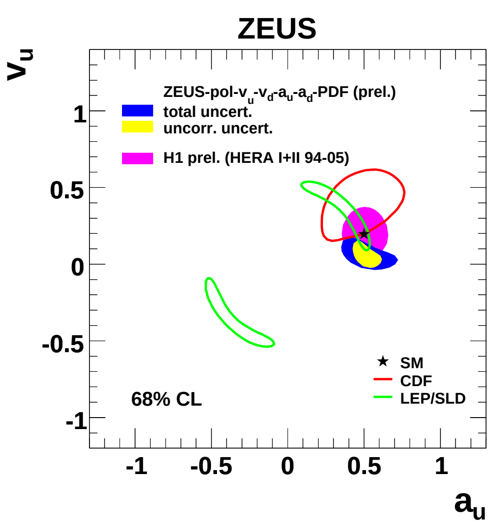

Figure 1. HERA results at 68% confidence level (CL) on u quark couplings to Z in comparison with those from CDF and LEP/SLD.

2.3. Parity violation in NC DIS at high Q^2

In the early HERA-1 data with unpolarized electron beam, different NC cross sections at high Q^2 between e^-p and e^+p interactions were observed, exhibiting the γZ interference and Z exchange contribution at high Q^2. With the polarized electron beam at HERA-2, additional differences in the cross sections between the left-handed polarization (P_L) and the right-handed polarization (P_R) are expected for the weak interaction of Z exchange. A polarization asymmetry $A^\pm$ for $e^\pm$ beams can thus be introduced

$$A^\pm = \frac{2}{P_R - P_L} \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)} \,. \tag{4}$$

The preliminary results combining the H1 and ZEUS HERA-2 data are shown in Fig. 2 [10]. This is the first observation of parity violation in NC DIS at HERA.

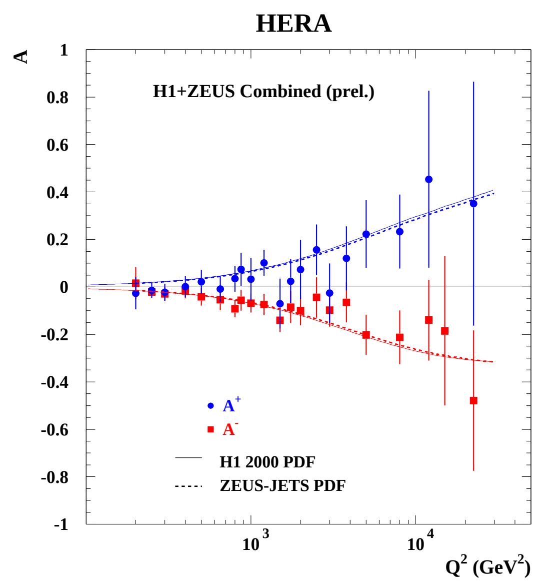

Figure 2. Measurements of $A^\pm$ by H1 and ZEUS. The error bars denote the total uncertainty which is dominated by the uncorrelated error contributions. The curves describe the theoretical predictions in NLO QCD as obtained in PDF fits to the H1 inclusive data and to the inclusive and jet ZEUS data, respectively. Both fits have been performed using the unpolarized HERA-1 data.

2.4. Limits on finite quark radius and contact interactions

NC interactions at high Q^2 at HERA provide an important test of the SM at the high energy frontier. Indeed, the SM Q^2 spectrum is expected to be modified if the interacting electron and quark have a finite size:

$$\frac{d\sigma_{\rm NC}}{dQ^2} = \frac{d\sigma_{\rm NC}^{\rm SM}}{dQ^2} f_e^2(Q^2) f_q^2(Q^2) \,, \tag{5}$$

where $f(Q^2) = 1 - \frac{\langle r^2 \rangle}{6} Q^2$ is the electron or quark form factor, $\langle r^2 \rangle$ being the mean squared radius of the EW charge distribution. Assuming a point-like electron, i.e. setting $f_e \equiv 1$ as it has been well constrained elsewhere [11], and using the full HERA (preliminary HERA-2 and published HERA-1) data, an upper limit on the radius of the light u and d quarks, $R_q = \sqrt{\langle r_q^2 \rangle} < 0.75 \cdot 10^{-18}\,\mathrm{m}$, at 95% CL has been derived by H1 [12]. The limit $R_q < 0.62 \cdot 10^{-18}\,\mathrm{m}$ from ZEUS is similar [13].

New interactions between e and q involving mass scales Λ above the center of mass energy can also modify the SM NC cross section at high Q^2 via virtual effects. Such interactions can be modeled as four-fermion contact interactions as an effective theory by additional terms in the SM Lagrangian

$$\mathcal{L} = \sum \eta_{ij}^{eq} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_j \gamma_\mu q_j)\,, \tag{6}$$

where the sum runs over electron and quark helicities and quark flavors. In Eq.(6), only vector currents are considered as strong limits have already been placed on scalar and tensor contact interactions. The coupling η_{ij}^{eq} may be written as $\eta_{ij}^{eq} = \epsilon_{ij}^{eq} \frac{4\pi}{\Lambda^2}$, where the coefficient ϵ_{ij}^{eq} may take the values ± 1 or zero. In the HERA contact interaction analyses, 19 different chiral structures have been considered. The preliminary results from ZEUS are shown in Fig. 3 [13]. The typical excluded scale is $\Lambda > 5\,\mathrm{TeV}$ at 95% CL. Comparable limits were achieved by H1 [14].

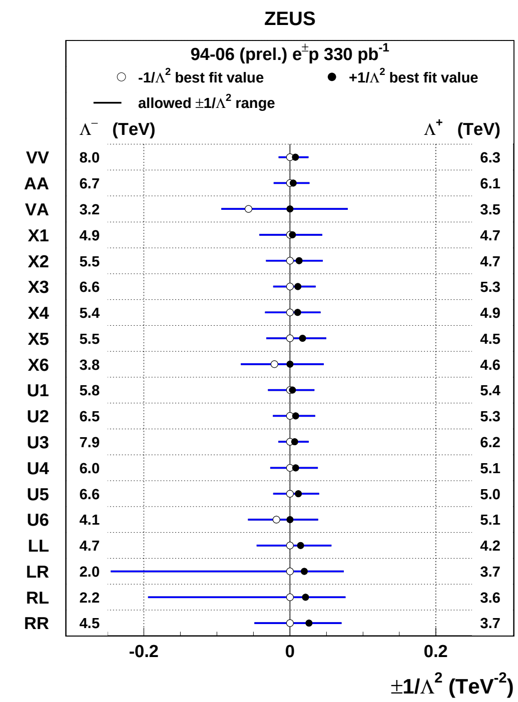

Figure 3. Confidence intervals of $\pm 1/\Lambda^2$ at 95% CL for the studied contact interaction scenarios. The numbers at the right and left margins are the corresponding lower limits on the mass scale Λ^+ ($\eta > 0$) and Λ^- ($\eta < 0$) respectively.

2.5. Total CC cross sections and constraint on right-handed currents

According to Eq.(2), the CC cross section of purely weak interactions is expected to have a linear dependence on the beam polarization P_e. The (preliminary) measurements of the total CC cross section for $Q^2 > 400\,\mathrm{GeV}^2$ and inelasticity $y < 0.9$ with polarized HERA-2 data are shown in Fig. 4 together with the corresponding cross sections of the published HERA-1 data with unpolarized beams [15]. The measurements are in good agreement with the expected linear dependence.

In the SM, only the left-handed W boson participates in the weak interaction, and the corresponding cross sections thus vanish for $P_e = -1$ (e^+p) and $P_e = 1$ (e^-p). The production of right-handed CC would result in a deviation from zero at these polarization values. The contribution of a right-handed CC can be derived from linear fits to the measured cross sections and from extrapolating the results of the fits to $P_e = \pm 1$. The upper limit on the right-handed CC cross sections can be further translated into lower mass limits on a right-handed W [15].

2.6. Other searches in inclusive DIS processes

Many searches for new particles such as leptoquarks (LQs), squarks (the supersymmetric partners of quarks) and excited states of fermions have been carried out at HERA, since the very

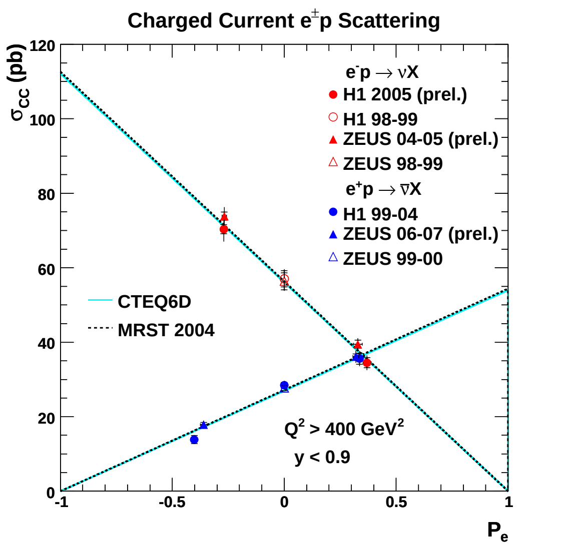

Figure 4. The dependence of the measured total CC cross sections on the $e^{\pm}$ beam polarization in comparison with the expectations from CTEQ6D [16] and MRST 2004 [17].

beginning of data taking. Both H1 and ZEUS have performed their first search using the data of 1992 of less than 30 nb^{-1} [18]. Indeed, the HERA *ep* collider is an ideal machine to look for resonant production of new particles (LQs, squarks), which couple via Yukawa couplings directly to a lepton and a parton, up to the center of mass energy. [2] This is in contrast to the pair-production in e^+e^- at the LEP or in $p\bar{p}$ at the Tevatron collider, in which case the mass reach for a direct search is up to half of the center of mass energy.

The search for the first generation LQs considers its decay into an electron and a quark or into a neutrino and a quark. These LQ decays lead to final states identical to DIS events. One cannot distinguish them on an event by event basis, but has to rely on different angular distributions, e.g. flat for scalar LQs and steeply falling for DIS events.

In the history of the HERA running, one of the most exciting moments happened in 1997 when both H1 and ZEUS reported an excess of high Q^2 events based on their 1994-1996 data of less than 20 pb^{-1} [19]. The excess generated in a short period of time a huge number of speculations on possible new physics including resonant production of LQs or squarks. However, the later high statistics data samples collected by both experiments did not confirm the excess, and constraints on LQ production were derived.

An example for the existing constraints using the full HERA data sample from H1 on a scalar LQ, which decays exclusively into an electron and a quark, is presented in Fig. 5 [20]. The new preliminary limit significantly improves the previous limit from HERA-1 [21]. For moderate Yukawa coupling values λ of about $0.03-0.6$, it also extends well beyond the direct limit from the Tevatron [22] and the indirect limit from LEP [23].

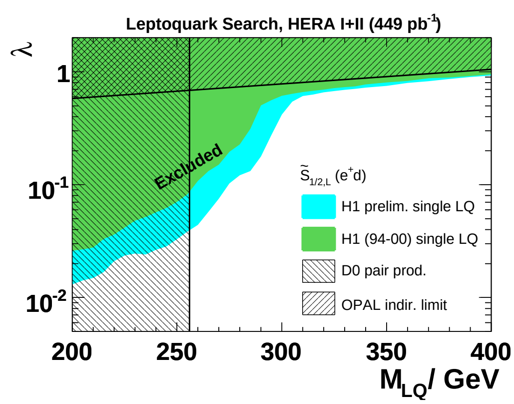

Figure 5. Example of mass-dependent upper bounds on the Yukawa coupling λ of a first generation leptoquark coupling to *ed* ($\tilde{S}_{1/2,L}(ed)$).

Searches for LQs coupling to first and second generation fermions have also been performed [24]. In this case, the final state lepton is different from the incident electron (lepton flavor violating processes), and the searches are thus essentially background free. The corresponding

[2] Beyond the kinematic limit, the search sensitivity arises from *u*-channel virtual exchange of new particles coupling to lepton-quark pairs.

constraints are also more stringent than those on the first generation LQs.

In supersymmetric (SUSY) models where the so-called R-parity (R_p) is not conserved, squarks could be resonantly produced at HERA similar to LQs. In addition to the LQ-like decays, squarks also undergo decays into gauginos (the supersymmetric partners of gauge bosons). A dedicated search requires a large number of final states to be analyzed. This has been pioneered by H1 in [25], where the full HERA-1 data have been used to set constraints on SUSY models. A similar analysis looking for the SUSY partner of the top quark has been performed by ZEUS [26].

The observed replication of three fermion families suggests the possibility that these fermions may be composite particles, consisting of combinations of more fundamental entities. The observation of excited states of leptons or quarks would be a clear signal that these particles are composite rather than elementary. At HERA, excited electrons, quarks and neutrinos (e^*, q^*, ν^*) with masses up to the kinematic limit of the center of mass energy could be produced directly via t-channel exchange of a gauge boson.

The full HERA $e^{\pm}p$ data sample collected by H1 has been used to search for excited electrons via the decays $e* \to e\gamma$, $e^* \to eZ$ and $e^* \to \nu W$ [27]. A similar preliminary search has also been performed for excited quarks via the decays $q^* \to q\gamma$ and $q^* \to qW$ [28]. The search for excited neutrinos decaying via $\nu^* \to \nu\gamma$, $\nu^* \to \nu Z$ and $\nu^* \to eW$ has been made using only e^-p collisions as the corresponding cross section in e^+p is much smaller [29]. No evidence for excited fermions has been found, and limits on the characteristic couplings have been derived [27,28,29].

3. RARE EXCLUSIVE PROCESSES

The large data sample of HERA has made it possible to use rare exclusive processes with well measured and isolated final states for performing EW measurements and for searching for deviations from the SM. Two examples are multi-lepton events with high transverse momenta (P_T) and isolated lepton events with large missing transverse momentum ($\not{P}_T$).

3.1. Multi-lepton events at high P_T

Using the full HERA data, H1 has completed [30] a study on the multi-lepton events of which an excess was reported earlier based on HERA-1 data [31]. Seven final state topologies ee, $\mu\mu$, $e\mu$, eee, $e\mu\mu$, $ee\mu$ and $eeee$ have been analyzed. In all topologies, the predicted event rate agrees with the number of observed events [30]. However, when a comparison is made requiring for the invariant mass of the two highest P_T leptons $M_{12} > 100\,\text{GeV}$, an excess is observed in most of the topologies (Table 1), although the number of observed events remains statistically limited. Demanding $\sum P_T > 100\,\text{GeV}$ for the leptons, 5 (0) events are observed in the e^+p (e^-p) sample with 0.96 ± 0.12 (0.64 ± 0.09) expected. Also shown in Table 1 are preliminary results from ZEUS on di-electron and tri-electron samples [32]. In both samples no excess has been observed.

3.2. Search for doubly-charged Higgs bosons

Motivated by the observed excess of the multi-lepton events discussed above, a search for doubly-charged Higgs bosons ($H^{\pm\pm}$) has been performed by H1 using the HERA-1 data [33]. The search looks for events with a singly produced $H^{\pm\pm}$ decaying into a high mass pair of same charge leptons, one of them being an electron. No evidence for $H^{\pm\pm}$ production is observed; out of the observed multi-lepton events from the HERA-1 data, only one di-electron event is compatible with the $H^{\pm\pm}$ signature. Mass dependent upper limits are derived on the Yukawa coupling h_{el} of the Higgs boson to an electron-lepton pair. Assuming that the doubly-charged Higgs decays only into an electron and a muon via a coupling of electromagnetic strength $h_{e\mu} = \sqrt{4\pi\alpha_{em}} = 0.3$, a lower limit of 141 GeV on the $H^{\pm\pm}$ mass is obtained at 95% CL. For a doubly-charged Higgs decaying only into an electron and a tau and a coupling $h_{e\tau} = 0.3$, masses below 112 GeV are ruled out.

Table 1
The number of observed events and SM expectations in different multi-lepton topologies for $M_{12} > 100\,\mathrm{GeV}$. The numbers shown in parentheses correspond to the contribution from the dominant pair production in $\gamma\gamma$ interactions.

Topology	H1		ZEUS	
	Data	SM (pair)	Data	SM (pair)
ee	3	1.34 ± 0.20 (0.83)	2	1.7 ± 0.2 (0.9)
$e\mu$	1	0.59 ± 0.06 (0.59)		
eee	3	0.66 ± 0.09 (0.66)	2	1.0 ± 0.1 (1.0)
$\mu\mu$	1	0.17 ± 0.07 (0.17)		
$e\mu\mu$	2	0.16 ± 0.05 (0.16)		

Table 2
The number of observed events and SM expectations for three types of leptons in $e^{\pm}p$ data samples for $P_T^X > 25\,\mathrm{GeV}$. The SM signal (dominated by W production) is shown in percentage in parentheses.

Dataset	Lepton	H1 [36]		ZEUS [37]	
		Data	Exp (signal)	Data	Exp (signal)
e^+p	e	9	4.32 ± 0.71 (82%)	3	4.0 ± 0.6 (77%)
	μ	8	3.70 ± 0.63 (92%)	3	3.4 ± 0.5 (81%)
	τ	0	0.82 ± 0.12 (46%)		
e^-p	e	1	3.18 ± 0.58 (70%)	3	3.2 ± 0.5 (69%)
	μ	0	2.40 ± 0.41 (92%)	2	2.3 ± 0.4 (85%)
	τ	1	0.68 ± 0.11 (31%)		

3.3. Isolated lepton events at large missing P_T

Since the observation of the first isolated muon event with large $\not{P}_T$ by H1 in 1994 [34], searches have been pursued and extended by H1 and ZEUS to all three types of leptons and with increasingly larger data samples [35]. The results [36,37] [3] with the full HERA data are summarized in Table 2. H1 has observed an excess in both the e and the μ channel. The excess is, however, not confirmed by ZEUS. ZEUS has, on the other hand, observed 2 isolated τ lepton events with a hadronic final state (X) at large transverse momentum ($P_T^X > 25\,\mathrm{GeV}$) for 0.20 ± 0.05 expected, based on the HERA-1 data, of which 49% is contributed by the SM signal events from single W production with a genuine isolated τ and missing transverse momentum in the final state. The corresponding signal contribution (purity) for the e and μ channels is also shown in Table 2.

3.4. Single W production cross section

From the previous section, we noticed that the isolated lepton events with large $\not{P}_T$ are dominated by the SM W production. It is possible, using the same sample, to further enhance the W signal with additional selection cuts and to measure the W production cross section.

The extracted production cross section from ZEUS [37] is $\sigma(ep \to lWX) = 0.89^{+0.25}_{-0.22}(\mathrm{stat}) \pm 0.10(\mathrm{syst})\,\mathrm{pb}$ at $\sqrt{s} = 316\,\mathrm{GeV}$ corresponding to the luminosity weighted mean of center of mass energies of the different data samples. The corresponding theoretical expectation is 1.2 pb which has an error of 15% due to the uncertainty of the next to leading order corrections.

The corresponding measurement from H1 $\sigma(ep \to lWX) = 1.14 \pm 0.25(\mathrm{stat}) \pm 0.14(\mathrm{syst})\,\mathrm{pb}$ is quoted for $\sqrt{s} = 317\,\mathrm{GeV}$ and is in agreement

[3] The preliminary results of H1 shown at the workshop have been replaced by the published one. The same is true for the results shown in sections 3.4 and 4.

with the prediction of 1.27 ± 0.19 pb [36].

Both measurements from ZEUS and H1 have a significance of about five standard deviations.

3.5. W polarization fractions at HERA

To test the compatibility of the observed W decays with the SM, a measurement of the W boson polarization is performed by H1 [36]. The measurement is based on the $\cos\theta^*$ distribution in the decay $W \to e/\mu + \nu$, where θ^* is defined as the angle between the W boson momentum in the lab frame and that of the charged decay lepton in the W boson rest frame. The angular distribution is expected to have three distinct terms, $3/4F_0(-1 - \cos^2\theta^*)$, $3/8F_-(1 - \cos\theta^*)^2$ and $3/8F_+(1 + \cos\theta^*)^2$ with F_0, F_- and F_+ corresponding to the longitudinal, left-handed and right-handed fractions respectively, of which only two are independent as $F_0 + F_- + F_+ \equiv 1$.

The results on the polarization fractions F_0 and F_- are obtained from a simultaneous fit to the measured angular distribution and shown in Fig. 6. The measurement is found in good agreement with the SM and compatible with anomalous single top production via flavor changing neutral current (FCNC, sec. 3.6).

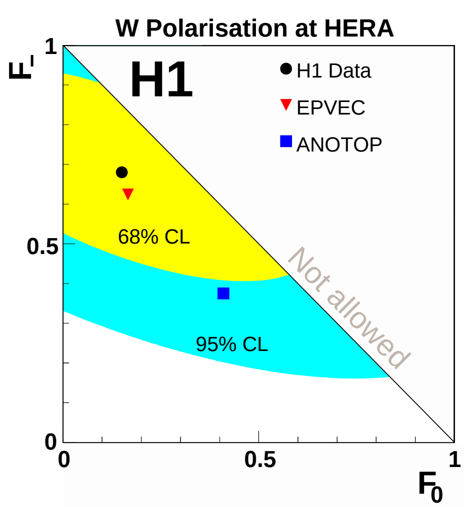

Figure 6. Preliminary W boson polarization (point) at 1 and 2σ CL (contours). Also shown are the values for the SM prediction (triangle) and anomalous single top production via FCNC (square).

3.6. Single top production

The production of single top quarks is kinematically possible at HERA. The signature of a top decay to b and W with subsequent decay of the W in the leptonic electron and muon channels would be a lepton and missing transverse momentum. This signature coincides with that of the observed isolated lepton events discussed above. The search is performed for anomalous top quark production in an FCNC process involving the coupling $\kappa_{tu\gamma}$. The dominant process for SM single top production at HERA has a cross section of less than 1 fb and is treated as background.

The limits from HERA [38,39] are compared with other experiments [40,41] in Fig. 7. The H1 limit is based on the full HERA data, whereas the ZEUS limits are obtained from the HERA-1 data taking into account not only $\kappa_{tu\gamma}$ but also v_{tuZ} both in top production and decay. ZEUS also studied the dependence of the limits on the top mass. It is found that the limits are more stringent for a smaller top mass value, as expected.

4. GENERIC SEARCH AT HIGH P_T

Different from specific searches presented so far, a generic and model-independent search for deviations from the SM prediction for all high transverse momentum final state configuration involving electrons (e), muons (μ), jets (j), photons (γ) or neutrinos (ν) was performed by H1 first using the HERA-1 data [42] and now including the HERA-2 data [43]. Events are classified in different classes. Each event class contains at least two final state objects (e, μ, j, γ, ν) with $P_T > 20$ GeV in the polar angle range $10^\circ < \theta < 140^\circ$. All event classes with observed data events or with a SM expectation greater than 0.01 event are shown for all H1 e^+p data in Fig. 8. In a further step, a statistical algorithm is used to search for deviations from the SM in the distributions of the scalar sum of transverse momenta or invariant mass of final state particles.

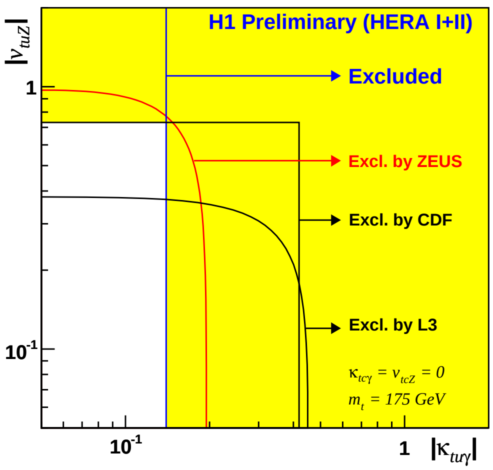

Figure 7. Exclusion limits at 95% CL on the anomalous $\kappa_{tu\gamma}$ and v_{tuZ} couplings obtained by the H1, ZEUS, CDF and L3 experiments. The charm quark couplings $\kappa_{tc\gamma}$ and v_{tcZ} are neglected, and the limits are shown assuming a top mass $m_t = 175\,\text{GeV}$.

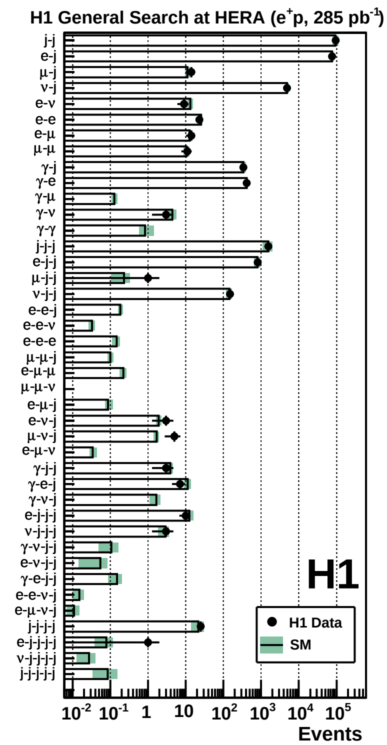

Figure 8. The data and the SM expectation for all event classes with observed data events or a SM expectation greater than 0.01 event. The error bands on the predictions include model uncertainties and experimental systematic errors added in quadrature.

5. SUMMARY

The HERA ep collider is first of all a precision QCD machine providing dominant constraints for parton distribution functions at low x. It is also a high energy collider complementary to LEP e^+e^- and the Tevatron $p\bar{p}$ colliders allowing rich electroweak measurements as well as many searches for new particles to be performed.

There is a good prospect to achieve much improved electroweak results in the next two years or so before the next Ringberg workshop. The W propagator measurement will be mainly improved using the ten-fold increases in the e^-p data sample at HERA-2. The light quark couplings to the Z boson will be further constrained using the complete polarized HERA-2 data.

Most searches are now based on the full HERA data although some of them are still in preliminary form. In essentially all cases, no significant deviation with the SM expectation is observed, with one possible exception, namely the excess observed by H1 on the isolated electron and muon events with large missing transverse energy, which has around 2.4 standard deviations. This excess is, however, not confirmed by a similar analysis from ZEUS. The various limits derived from the HERA data are often comparable to or more stringent than those from LEP and the Tevatron experiments.

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