A few selected HERA results are presented and the prospects for future measurements with high luminosity are discussed, which will become available after the planned luminosity upgrade of the HERA storage ring planned for 2000.
1 Present HERA Performance

The electron - proton storage ring HERA at DESY, colliding 27.5 GeV electrons or positrons on 820 GeV protons, started operation in 1992. The instantaneous and integrated luminosities have been steadily increased as shown in Fig. 1. During the first two years of operation, when electrons were colliding on protons, the electron beam current was limited by breakdowns of the beam lifetime. These limitations were not present after the machine switched to positrons during the 1993/1994 winter shut-down. Operation in 1997 was very successful providing an increased instantaneous luminosity and a long duration of the running period. In total integrated luminosities of 2 pb⁻¹ (e⁻ p collisions, 1992 and 1993) and 71 pb⁻¹ (e⁺ p collisions, since 1994) have been delivered to the colliding beam experiments H1 and ZEUS.

Table 1 compares the machine parameters which were achieved in 1997 to the original design parameters. The maximum luminosity of $1.4 \times 10^{31} \text{cm}^{-2} \text{s}^{-1}$ is close to the original design goal ($1.5 \times 10^{31} \text{cm}^{-2} \text{s}^{-1}$).

The accelerator is now operated in a two year cycle. Short winter shut-downs of one to two months in 1996/97 and 1998/99 alternate with long winter shut-downs in the following year. The major activity for HERA during the present winter shut-down is a modification of the vacuum system of the electron ring in order to allow high current electron running. The expected integrated luminosities per experiment (e⁻ p collisions) for the next two years are about 15 pb⁻¹ in 1998 (short running period) and >35 pb⁻¹ in 1999 (long running period). The luminosity upgrade and installation of spin rotators in the south (ZEUS) and north (H1) straight sections are planned for the 1999/2000 winter shut-down.

2 The HERA Luminosity Upgrade

The aim of the HERA luminosity upgrade is to increase the design luminosity from $1.5 \times 10^{31} \text{cm}^{-2} \text{s}^{-1}$ to about $7 \times 10^{31} \text{cm}^{-2} \text{s}^{-1}$ as shown in table 1. An integrated luminosity of about 1 fb⁻¹ per experiment is expected to be delivered to the colliding beam experiments in the running period 2000 - 2005. The luminosity increase will be achieved by stronger focusing of both the electron and proton beam. The final focusing magnets have to be moved closer to the interaction point (IP). This necessitates an earlier separation of both beams at the interaction region, which requires new superconducting beam magnets to be placed inside the H1 and ZEUS detectors. The design of the new interaction region is challenging, because of a significant increase of the synchrotron radiation emitted near the IP. Details of the luminosity upgrade can be found in [1]. In table 1 the electron beam energy of 30 GeV was chosen as
### HERA Parameters

| Parameter                              | 1997         | Design       | Upgrade      |
|----------------------------------------|--------------|--------------|--------------|
| p beam energy (GeV)                    | 820          | 820          | 820          |
| e beam energy (GeV)                    | 27.5         | 30           | 30           |
| Number of bunches (proton/electron)    | 180/189      | 210          | 180/189      |
| Number of protons/bunch                | $7.7 \times 10^{10}$ | $10 \times 10^{10}$ | $10 \times 10^{10}$ |
| Number of electrons/bunch              | $2.9 \times 10^{10}$ | $3.6 \times 10^{10}$ | $4.2 \times 10^{10}$ |
| Proton current (mA)                    | 105          | 160          | 140          |
| Electron current (mA)                  | 43           | 58           | 58           |
| Hor. proton emittance (nm rad)         | 5.5          | 5.7          | 5.7          |
| Hor. electron emittance (nm rad)       | 40           | 39           | 22           |
| Proton beta function x/y (m)           | 7/0.5        | 10/1         | 2.45/0.18    |
| Electron beta function x/y (m)         | 1/0.7        | 2/0.7        | 0.63/0.26    |
| beam size $\sigma_x \times \sigma_y$ ($\mu$m) | 200 × 54 | 247 × 78 | 118 × 32 |
| Synchrotron radiation at IP (kW)       | 6.9          | 9.7          | 25           |
| Specific luminosity (cm$^{-2}$ s$^{-1}$ mA$^{-2}$) | $7.6 \times 10^{29}$ | $3.4 \times 10^{29}$ | $1.6 \times 10^{30}$ |
| Luminosity (cm$^{-2}$ s$^{-1}$)        | $1.4 \times 10^{31}$ | $1.5 \times 10^{31}$ | $7.4 \times 10^{31}$ |

Table 1: HERA parameters achieved in 1997, compared to the original design and the luminosity upgrade program. * Increase to 920 GeV is being studied. † Maximum energy assumed for layout of IP.

the maximum energy for background calculations and the design of the new interaction region. The actual electron energy will be slightly lower, because of constraints on the reliability and power of the RF system. There are plans for an increase of the proton beam energy from 820 to 920 GeV. First tests were successfully performed during the machine development period in December 1997. If further tests scheduled during the re-commissioning in 1998 are successful too, the beam energy may already be increased for the 1998 running period.

### 3 Detector Modifications

Both collaborations have made several modifications of their detectors during the last years. H1 installed a new backward tracking detector and a new rear calorimeter. Small electromagnetic calorimeters near the beam pipe (BPC) for tagging very low $Q^2$ electrons were added to both detectors. In addition small Si trackers were placed in front of the BPCs in order to improve the measurement of the scattered electron. H1 installed a Si micro vertex detector with backward wheels. During the 1997/98 shut-down ZEUS implemented a forward plug calorimeter (FPC) for a better measurement of the proton remnant and very forward jets. These modifications, except the ZEUS FPC and the H1 barrel Si micro vertex detector, aim at improving the acceptance for electrons scattered at very small angle, and hence extending the kinematic region to very low $x$ and $Q^2$ physics.

Several detector modifications have been proposed for the HERA luminosity upgrade: H1 is planning an upgrade of the central and forward tracking and an upgrade of the trigger; ZEUS will install a Si micro vertex detector with forward wheels. Both collaborations have to modify their luminosity monitors and leading proton spectrometers. The compensating solenoids will be removed. The acceptance at very small angles will be slightly reduced because of the final focusing magnet inside the detector volumes, i.e. detector components at very small angles (BPC and FPC) will have to be removed.
4 Selected Recent Results and Prospects

In the following, a few selected recent results are presented and compared to expected future measurements, which were studied at the Workshop on Future Physics at HERA \[2\].

4.1 Measurement of $F_2$ Structure Function

One of the main objectives of deep inelastic scattering at HERA is a precision measurement of the proton structure function $F_2$ in a wide range of $x$ and $Q^2$. The explored kinematic range in the $x,Q^2$ plane is shown in Fig. 2 and compared to fixed target experiments. The HERA experiments have increased the $x$ and $Q^2$ ranges by two orders of magnitude each. During the last few years the kinematic range was extended to very low $x$ and $Q^2$ by improving the detector acceptance at low scattering angles as described in the previous section. At large $x$ and $Q^2$ the measurements are limited by the available statistics. The measured $F_2(x,Q^2)$ structure function as a function of $Q^2$ is shown in Fig. 3 for fixed values of $x$. Strong scaling violations are observed, which decrease as $x$ increases. The data are well described by QCD using NLO DGLAP evolution in the full kinematic range \[3\].

High luminosity data ($L \geq 300\,\text{pb}^{-1}$) will provide a precision measurement of $F_2(x,Q^2)$ at the few percent level over the full accessible kinematic region from $x \sim 10^{-5}$ to $Q^2 \sim 50000\,\text{GeV}^2$. $F_2$ is also expected to be the most precise way to determine the strong coupling constant $\alpha_s$ and the gluon distribution $xg$ from $F_2$ scaling violations at the 1% level \[5\].

![Figure 2: Kinematic region of deep inelastic scattering.](image)

![Figure 3: Structure function $F_2$ as a function of $Q^2$ for fixed values of $x$.](image)

4.2 Charm Contribution to Proton Structure Function

The charm contribution to the proton structure function, $F_{2c}$, can be measured directly by tagging charm in the hadronic final state. Both H1 and ZEUS so far used the decay $D^* \rightarrow D^0\pi \rightarrow K\pi\pi$ for this measurement. The differential cross section $d^2\sigma_{c\bar{c}}/dx dQ^2$ was measured in the phase space region of $|\eta^{D^*}| < 1.5, p_T^{D^*} > 1.5\,\text{GeV}$, $80 < W < 210\,\text{GeV}$ and $3 < Q^2 < \ldots$.
170 GeV$^2$ (in case of ZEUS). The measured data are in agreement with the expectation of photon-gluon fusion as the primary production mechanism and disagree with processes in which the charmed hadrons would originate from charm quarks inside the proton. The contribution from charm to the proton structure function, $F^c_2$, was determined from the measured differential cross section by integrating and extrapolating outside the measured $\eta^{D^*}$ and $p^{D^*}_t$ ranges. The results shown in Fig. 4 are in good agreement with the NLO perturbative QCD calculation using the gluon distributions obtained from the $F_2$ scaling violation of the ZEUS data shown as band in Fig. 4. The $F^c_2$ contribution accounts for about 25% of the $F_2$ structure function for $Q^2 \lesssim 7$ GeV$^2$.

The present results provide a consistency check of perturbative QCD although they are limited by the available statistics and systematic uncertainties. About 160,000 tagged charm events, compared to the present data sample of a few hundred events, are expected for an integrated luminosity of 500 pb$^{-1}$ and improved tracking (including silicon micro vertex detectors), which will allow a detailed study of the dynamics of charm production. The large integrated luminosity anticipated will also give access to the bottom structure function $F_2^{bb}$.

### 4.3 Events with Isolated Lepton and Missing $p_t$

Both collaborations searched for events with isolated leptons and missing transverse momentum. The H1 analysis is based on the 1994 to 1997 summer data sample, which corresponds to an integrated luminosity of 24.7 pb$^{-1}$. The basic requirement for the event selection was a missing transverse momentum of $p_T^{med} > 25$ GeV measured in the calorimeter. Beam gas background, cosmic and halo muon events were rejected by requiring a reconstructed vertex in the interaction region and by using a set of topological and timing filters. The events were required to have a track with transverse momentum higher than 10 GeV and polar angle greater than 10$^\circ$. After these cuts 336 events were left. Five of these events have a well isolated track;

![Graph](image-url)

Figure 4: $F^c_2$ as a function of $x$ for different $Q^2$ bins. The shaded band represents the NLO calculation using the gluon density extracted from the ZEUS NLO fit with charm masses ranging from 1.35 to 1.70 GeV.

3 events contain an isolated muon, 1 event contains an isolated electron and 1 event contains both an isolated positron and an isolated muon.

The main Standard Model process expected to yield sizeable rates of events with missing transverse momentum and a high $p_T$ isolated lepton is the production and subsequent leptonic decay of a $W$ boson. The expected number of events is $1.34 \pm 0.20$ with isolated electron and $0.41 \pm 0.07$ with an isolated muon. The event rate coming from other sources, e.g. production of heavy quark pair (charm or bottom) and production of $\tau$ pairs, was estimated to be less than 0.05 events.

Fig. 5 compares the hadronic transverse momentum $p_X^T$ and transverse mass $M_{T\nu}$ with the expected distribution of $W$ events. The Monte Carlo corresponds to a 500 times higher luminosity than the data.

A similar analysis was carried out by the ZEUS collaboration. The main selection criteria were: energy of the electron candidate $> 15$ GeV and missing $p_T > 19$ GeV. For muon candidates a minimum ionizing particle with track momentum greater than 5 GeV and missing $p_T > 18$ GeV was required. In addition, there were cuts on the polar angle and quality of the track.

Using the full 1994 to 1997 data sample of 46.6 pb$^{-1}$, 4 events with an isolated electron and no events with isolated muon were found. The number of expected events in the electron channel are: $2.2 \pm 0.02$ from $W$ production, $0.32 \pm 0.14$ from neutral current deep inelastic scattering, $0.65 \pm 0.17$ from charged current deep inelastic scattering, $0.27 \pm 0.27$ from elastic and inelastic $\gamma \gamma \rightarrow e^+e^-$ production, and $< 0.06$ from elastic and inelastic $\gamma \gamma \rightarrow \tau^+\tau^-$ production. In the muon channel $0.46 \pm 0.02$ events are expected from $W$ production, $< 0.06$ from NC DIS, $0.37 \pm 0.13$ from CC DIS, $0.41 \pm 0.18$ from elastic and inelastic $\gamma \gamma \rightarrow \mu^+\mu^-$ production, and $0.06 \pm 0.06$ from elastic and inelastic photoproduction $(\gamma \gamma \rightarrow \mu^+\mu^-)$. For both channels the observed rate of events is consistent with $W$ production. In the $\mu$-channel a limit on the $W$ cross section of $\sigma(W)(p_T^{had} > 30 \text{ GeV})< 1.2 \text{ pb}^{-1}$ at 95% CL was obtained.
4.4 Determination of the $W$ Boson Mass

The cross section for charged current electron proton scattering can be written as a function of the $W$ boson mass ($m_W$):

$$\frac{d^2\sigma_{e^-p}}{dx\,dQ^2} = \frac{G_F^2}{2\pi x} \left( \frac{m_W^2}{m_W^2 + Q^2} \right)^2 \sum_{i=1}^{3} \left[ x u_i(x, Q^2) + (1 - y)^2 x d_i(x, Q^2) \right],$$

with $G_F = \frac{\pi\alpha}{\sqrt{2}m_W(1-m_t^2/M_Z^2)} \frac{1}{1-\Delta_R(m_t)}$, where the mass of the top-quark ($m_t$) enters via radiative corrections. Fitting the cross section to the measured CC cross section with $m_W$ as the only free parameter, the following results were obtained for the $W$ mass: H1: $84^{+9+5}_{-6-4}$ GeV (including 1994 data, 3.1 pb$^{-1}$) [8], ZEUS: $79^{+8+6}_{-7-3}$ GeV (including 1994 data, 3.7 pb$^{-1}$) [9] and ZEUS: $78.6^{+3.5+3.3}_{-2.4-3.0}$ GeV (including 1997 data, 46.6 pb$^{-1}$). These results, although $W$ production in the $t$-channel, are consistent with the LEP and Tevatron measurements, but currently much less precise.

A detailed study of the expected sensitivity for $m_W$ with high luminosity and polarized electron/positron beam was done by R. Beyer et al. [10]. The CC and NC cross sections will be measured as a function of $Q^2$ and compared to the Standard Model prediction with $m_W$ and $m_t$ as free parameters. There is only a weak logarithmic dependence on the Higgs boson mass, since it enters via loops. The CC cross section is more sensitive to $m_W$, as its normalization directly depends on $m_W$, whereas in the case of NC it is the shape of the cross section as a function of $Q^2$. The sensitivity of the measurement is significantly improved with polarized electron or positron beams. A beam polarization of 70% is roughly equivalent to a factor of 4 increase in integrated luminosity for unpolarized beams.

The expected error on $m_W$ was studied by varying the relative systematic uncertainty from 0 to 5%. The goal is a relative systematic error of 1%. A 1% determination of the luminosity has already been achieved. A 2% measurement error of the polarization is conceivable and adequate, since it enters through a factor $(1 + |P|)$ in the cross section. The largest experimental uncertainty will be the absolute energy scale of the calorimeter, which is presently 1 to 2% for electrons and 3% for hadrons. High luminosity data samples will allow to impose constraints on the reconstruction of the final state. Similar to the present CC analysis, the CC data will be cross checked with NC events.

Fig. 6 shows the expected measurement of $m_W$. The 1 σ contour is represented by the shaded ellipse. The resulting precisions will be $\delta m_W = \pm 300$ MeV and $\delta m_t = \pm 50$ GeV. Assuming a top-quark mass measurement of CDF and D0 with 5 GeV uncertainty, the expected error is $\delta m_W = \pm 55$ MeV for each experiment assuming a 1% systematic error. The accuracy deteriorates to $\pm 81$ MeV for a 2% systematic uncertainty. The expected precision is similar to the expected combined LEP2 measurement error of $< 50$ MeV for 500 pb$^{-1}$ [11].
4.5 Search for anomalous $WW\gamma$ Couplings

In general, the cross section for $ep \rightarrow eWX$ can be written as sum of the contributions from the Standard Model, the anomalous coupling and an interference term: $\sigma_{\text{tot}} = \sigma_{\text{SM}} + a\sigma_{\text{int}} + a^2\sigma_{\text{an}}$, where $a = \Delta\kappa, \lambda$ are the anomalous couplings of the three-boson vertex $WW\gamma$. At HERA a measurement of the anomalous couplings was done by ZEUS using an integrated luminosity of about $10\,\text{pb}^{-1}$, resulting in limits of $\Delta\kappa < 7(\lambda = 0)$ and $|\lambda| < 11.7(\Delta\kappa = 0)$ at 95% CL [12].

Fig. 7 [13] compares the 95% CL sensitivity limits that can be achieved at HERA with an integrated luminosity of $1\,\text{fb}^{-1}$ to projected limits [14] from LEP2, Tevatron and LHC. HERA results on $\Delta\kappa$ will be competitive to LEP2 and Tevatron measurements.

![Figure 7: Expected 95% CL limits for $WW\gamma$ couplings determined from single $W$ production at HERA, $WW$ production at LEP2 and $W\gamma$ production at the Tevatron and LHC.](image-url)
4.6 Search for Selectron and Squark Production

A search for selectron and squark production at HERA $ep \rightarrow \tilde{e}_{L,R} \tilde{q}_{L,R} X$ was first performed by H1 using the 1994-1995 data sample ($\mathcal{L} = 6.4$ pb$^{-1}$) [13]. ZEUS extended the sensitivity by using the 1994-1996 data sample, corresponding to $\mathcal{L} = (20.0 \pm 0.2)$ pb$^{-1}$ [16]. Selectron, squark event candidates were selected requiring a well identified electron, the hadronic system and the electron not back-to-back in azimuth, and missing momentum in the final state. Two events survived the selection, in agreement with the expected Standard Model backgrounds of $2.74 \pm 0.47$ events.

Limits on supersymmetric models were calculated assuming that the right and left-handed selectrons have the same mass $m_{\tilde{e}}$ and all quarks (except stop) have the same mass $m_{\tilde{q}}$ and there is no mixing between the L-R scalar fermions. Fig. 8 shows the region excluded by ZEUS in the plane defined by $m_{\tilde{e}}$ and $m_{\tilde{q}}$ for fixed values of $m_{\chi_0^1}$. For a selectron of $m_{\tilde{e}} = 80$ GeV (the LEP2 limit [17]) and a neutralino of $m_{\chi_0^1} = 40$ GeV, squarks up to $m_{\tilde{q}} \simeq 60$ GeV are excluded. These limits on squark masses are complementary to those from CDF and D0 [18], because the HERA results make no assumptions on the gluino mass.

Fig. 9 compares the excluded regions in the $M_2$ versus $\mu$ plane, for fixed selectron and squark mass, with limits from chargino and neutralino searches at LEP [19].

High luminosity data will increase the sensitivity to higher masses, e.g. limits of $(m_{\tilde{e}} + m_{\tilde{q}})/2 = 97$ GeV for $M_2 = 130$ GeV [20].

5 Conclusions

Electron proton collisions at HERA provide a unique environment for the study of QCD and electroweak aspects of the Standard Model. So far these measurements were mainly done at low and medium $x$ and $Q^2$. High $Q^2$ physics has just begun. The obtained results on searches beyond the Standard Model are competitive with other measurements. In 1998/1999 a $e^-p$ data sample of about $50$ pb$^{-1}$ is expected. The present...
physics program will continue which the full detector upgrades. In addition, comparisons of $e^-p$ and $e^+p$ cross sections will be performed. After the upgrade of the machine in 2000, a factor of $\approx 5$ increase in luminosity and a total integrated luminosity from 5 years running of $\approx 1 \text{ fb}^{-1}$ per experiment is expected, which will provide a very rich physics program.

References

[1] HERA Luminosity Upgrade, editor U. Schneekloth, in preparation, [http://www.desy.de/hera/lumiup/lumi.html](http://www.desy.de/hera/lumiup/lumi.html)

[2] Proceedings of the 1995/96 Workshop 'Future Physics at HERA', ed. G. Ingelman, A. De Roeck and R. Klanner (1996), [http://www.desy.de:8888/~heraws96](http://www.desy.de:8888/~heraws96)

[3] ZEUS Collab., M. Derrick et al., Z.Phys. C72 (1996) 593.

[4] B.W. Harris, J. Smith, Nucl.Phys. B452 (1995) 109.

[5] M. Botje et al., Proceedings of HERA Workshop, vol. 1, p.33.

[6] K. Daum et al., Proceedings of HERA Workshop, vol. 1, p.89.

[7] H1 Collaboration, submitted to EPS, Jerusalem (1997), A708.

[8] H1 Collab., S. Aid et al., Phys.Lett.B379 (1996) 319.

[9] ZEUS Collab., M. Derrick et al., Z.Phys. C72 (1996) 47.

[10] R. Beyer et al., Proceedings of HERA Workshop, vol. 1, p.140.

[11] M.A. Thomson, Proceedings of '97 Electroweak Int. & Unified Theor., Moriond (1997).

[12] D.S. Waters, Proceedings of Int.Conf. on High Energy Phys., Warsaw (1996), vol. 2, p.1048.

[13] V. Noyes, Proceedings of HERA Workshop, vol. 1, p.190.

[14] H. Aihara et al. published in ELECTROWEAK SYMMETRY BREAKING AND NEW PHYSICS AT THE TEV SCALE, eds. T. Barklow, S. Dawson, H.E. Haber, J.L. Siegrist, World Scientific, 1996.

[15] H1 Collab., S. Aid et al., Phys.Lett.B380 (1996) 461.

[16] ZEUS Collaboration, submitted to EPS, Jerusalem (1997), N-689.

[17] OPAL Collab., G. Alexander et al., CERN/PPE 96-182, ALEPH Collab., CERN/PPE 97-041.

[18] CDF Collab., F. Abe et al., Phys.Rev.Lett. 69 (1992) 3439, D0 Collab., S. Abachi et al., Phys.Rev.Lett. 75 (1995) 618.

[19] ALEPH Collab., CERN/PPE 96-083.

[20] P. Schleper, Proceedings of HERA Workshop, vol. 1, p.275.