# Electroweak Physics at HERA: Introduction and Summary

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**Abstract:** A high luminosity upgrade of HERA will allow the measurement of standard model parameters and the neutral current couplings of quarks. These results will have to be consistent with other precision measurements or indicate traces of new physics. The analysis of $W$ production will complement future results of LEP 2 and the Tevatron. We summarize the main results and conclusions obtained by the working group on *Electroweak Physics* concerning the potential of future experimentation at HERA.

## 1 Introduction

The DESY $ep$ collider HERA is a unique place to explore the structure of the proton, in particular at low Bjorken $x$ and large momentum transfer $Q^2$ and at the same time to probe the theory of electroweak interactions in the regime of large spacelike $Q^2$, extending previous measurements at fixed target experiments by more than two orders of magnitude. This is complementary to what can be accessed at LEP and hadron colliders in searches for deviations from the standard model (SM). In the 1987 [1] and 1991 [2] HERA workshop proceedings and elsewhere [3], comprehensive reviews on electroweak physics at HERA [4, 5] and the influence of radiative corrections [6, 7] have been published. In the meantime HERA has started and proved to work reliably. The detectors have shown to operate successfully and to be able to stand the special environment of an $ep$ machine.

The experience collected in the first years of experimentation at HERA allowed us to consider in the present workshop in some detail experimental problems, like systematic uncertainties due to the energy scale, the luminosity measurement or the measurement of the polarization, as well as limited acceptance and efficiencies. In this respect, the contributions to this workshop go beyond earlier studies.

The principal goal of the present workshop, on *Future Physics at HERA*, is to explore the physics potential attainable by possible machine and detector upgrades with respect to the various options under discussion: (i) high (1 TeV) versus design (820 GeV) proton energy; (ii) fixed-target versus collider mode; (iii) light or heavy nuclei versus protons; (iv) polarized versus unpolarized protons; (v) polarized versus unpolarized electrons and positrons; and (vi) high (1 $\mathrm{fb}^{-1}$) versus design (250 $\mathrm{pb}^{-1}$) luminosity. Working group 2 has analyzed these options and concentrated on the interesting cases for *Electroweak Physics*. In this introductory report, we shall summarize the main results obtained by the various subgroups and draw conclusions.

Prior to presenting an overview of the various subgroup activities and reporting the key results, we preselect from the upgrade options enumerated above those which will prove most useful for the study of electroweak physics at HERA, and argue why the residual options will have marginal advantage or even disadvantage. In order to suppress the impact of the (well-tested) electromagnetic interaction in neutral-current (NC) deep inelastic scattering and to gain sensitivity to the $W$-boson mass in charged-current (CC) deep inelastic scattering, large values of $Q^2$ and thus centre-of-mass energy $\sqrt{s}$ are required. Increasing the proton energy $E_p$ by 22% while keeping the lepton energy $E_e$ fixed, as in option (i), will only increase $\sqrt{s}$ by 10%, and will insignificantly improve the electroweak-physics potential. By the same token, the fixed-target mode of option (ii) will reduce the centre-of-mass energy to $\sqrt{s} = 7.6$ GeV, assuming the design lepton energy of $E_e = 30$ GeV, and will so render the study of electroweak physics much more difficult. Clearly, in order to perform precision tests of the electroweak theory, we will need as much luminosity per experimental setup as possible, so that option (vi) must receive high priority. Also, to disentangle the helicity structure of the weak NC and, in particular, to measure the vector and axial-vector couplings of quarks to the $Z$-boson, beams of longitudinally polarized electrons and positrons must be available with appropriate luminosities [8], as in option (v). On the other hand, options (iii) and (iv) are not useful for our purposes, since the structure functions of nuclei and polarized protons are at present poorly known, which would jeopardize electroweak precision tests. In addition, the total available luminosity would be distributed among too many different experimental setups and probably decreased due to the additional construction periods. In conclusion, options (v) and (vi) will be crucial for electroweak studies.

At HERA, investigations of electroweak physics may be classified according to two categories of processes: First, there is the more conventional measurement of inclusive deep inelastic scattering. Due to reasonably high cross sections, not only the measurement of total cross sections and their ratios, but also of differential cross sections, will allow us to envisage precision tests of the electroweak standard model. Experiments may be interpreted in terms of a measurement of the basic standard model parameters, e.g. the mass of the $W$ boson, $m_W$, or the top-quark mass, $m_t$. The potential of HERA for this kind of analysis was investigated in Ref. [9] and is summarized in section 2.1. Confronting within the standard model measurements obtained at HERA with results from other experiments will constitute one important test of our present understanding of the electroweak interactions. Another type of test of the standard model is possible by measuring quantities which are not free parameters in the standard model Lagrangian and comparing the experimental results with corresponding theoretical predictions. In particular, the measurement of NC couplings of quarks is a test of this kind and was studied in Ref. [10] (section 2.2). More general quantities generalizing the standard model Lagrangian, like the $\rho$-parameter or the $S$, $T$, $U$ parameters have been considered earlier in Ref. [3]. Finally, an analysis aiming to assess the sensitivity for additional heavy charged gauge bosons $W'$ (section 2.4) starts to overlap with the activities of the working group *Beyond the Standard Model*.

The second class of processes with a potential to study electroweak physics comprises scattering processes into exclusive final states. The aim to measure processes like Higgs-boson production (see section 2.7), the production of $b$-quarks or, most interestingly, of $W$ and $Z$ bosons (section 2.5), and to compare corresponding experimental results with the predictions of the standard model is an experimental challenge by itself. In the latter case, in order to quantify the results of such measurements testing the validity of the standard model in the gauge sector, it has become customary to generalize the standard model Lagrangian by introducing non-standard, so-called anomalous, couplings. Eventually, the information obtained by studying these processes will be concentrated in statements about these anomalous 3-boson couplings, $\Delta\kappa_V$ and $\lambda_V$ for $WWV$ ($V = \gamma$, $Z$) and $h_i^V$ for $Z\gamma V$.

Theoretical uncertainties due to an incomplete knowledge of the structure function input, as well as unknown higher-order QCD corrections and uncertainties in the scale of $\alpha_S$, deserve particular attention since they could severely limit the usefulness of electroweak physics analyses of deep inelastic scattering [9, 11]. Each of the subgroups has therefore undertaken particular efforts to demonstrate that already with the present knowledge about structure functions sensible measurements can indeed be performed. With high luminosity available, future measurements at HERA are bound to improve the situation.

# 2 Summaries of the individual contributions

## 2.1 Electroweak precision tests

The most obvious question about the possible contribution of HERA for electroweak physics tests is to which extent the basic standard model parameters $m_W$, $m_t$ and $m_H$ can be constrained by precision measurements of deep inelastic scattering cross sections. From earlier work it is known that measurements at HERA without any additional input from other experiments are very similar to a measurement of $G_\mu$, the $\mu$ decay constant, but at $\langle Q^2 \rangle = O(3000\,\mathrm{GeV}^2)$.

In the report of the subgroup on *Electroweak Precision Tests*, it is pointed out that, although an interpretation of deep inelastic scattering measurements in terms of either $m_W$ or $m_t$ results in rather large errors, HERA data will put a rather stringent constraint on the interrelation of these two parameters. Fig. 1 presents results for a measurement with 1000 pb$^{-1}$ of data from polarized neutral and charged current electron proton scattering. The corresponding $2\sigma$-contour is represented by the shaded ellipse. Projecting it onto the axes results in precisions of $\delta m_t = \pm 50\,\mathrm{GeV}$ and $\delta m_W = \pm 290\,\mathrm{MeV}$. These values are more than a factor of 2 better than what can be obtained from charged current scattering alone with the smaller luminosity of 250 pb$^{-1}$ (see the large ellipse in the figure). Anticipating future direct high precision measurements of $m_t$ and $m_W$, a comparison with these data will provide a stringent test of the standard model. One way to quantify the measurement is to combine HERA data on neutral and charged current data with a direct top mass measurement of $\pm 5\,\mathrm{GeV}$. Such a test yields $\delta m_W = \pm 60\,\mathrm{MeV}$. This scenario assumes a value of $1\,\%$ relative systematic uncertainty, which represents a serious experimental challenge. The figure also shows the relation between $m_W$ and $m_t$ following from the $G_\mu$ constraint. The upper full line is for a Higgs mass of $m_H = 100\,\mathrm{GeV}$, the lower dashed one for $m_H = 800\,\mathrm{GeV}$. Note that the confidence ellipses derived from HERA measurements are also obtained for a fixed Higgs mass value which was chosen to be 100 GeV. They would be shifted downwards much the same as the lines describing the $G_\mu$ constraint for

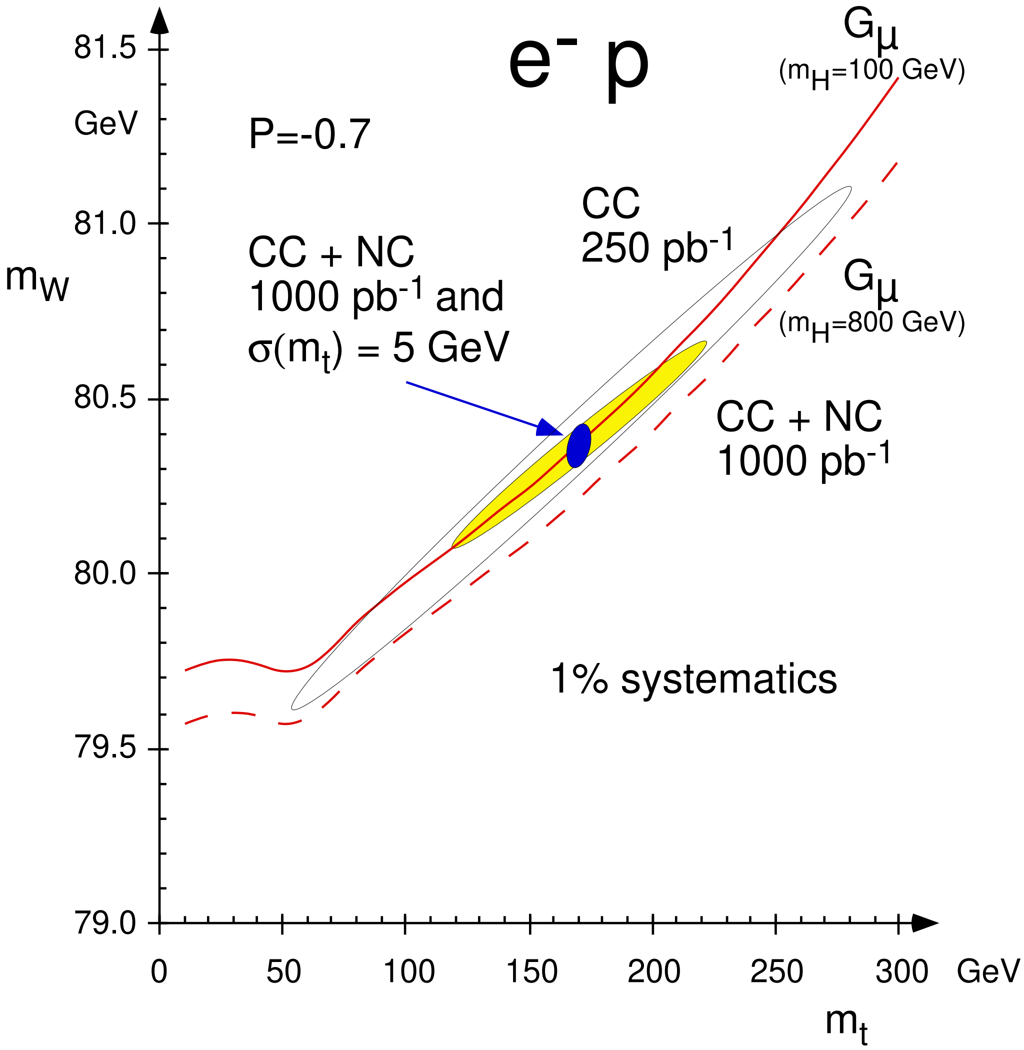


Figure 1: *$1\sigma$-confidence contours in the $(m_W, m_t)$ plane from polarized electron scattering ($P = -0.7$), utilizing charged current scattering at HERA alone with an integrated luminosity of 250 $pb^{-1}$ (large ellipse), neutral and charged current scattering at HERA with 1000 $pb^{-1}$ (shaded ellipse), and the combination of the latter HERA measurements with a direct top mass measurement with precision $\sigma(m_t) = 5\,GeV$ (full ellipse). The $m_W$-$m_t$ relation following from the $G_\mu$-constraint is also shown for two values of $m_H$.*

a Higgs mass of $m_H = 800\,\mathrm{GeV}$. It is obvious from this figure that with such a high precision one would be able to constrain the allowed range of Higgs masses provided one has available a second precise measurement of the $W$ boson mass.

Rather than taking into account a more or less well-motivated fixed size of experimental systematic errors, the *Electroweak Precision Tests* subgroup decided to investigate the dependence of the measurement error on $m_W$ on the systematic uncertainty in a range up to conservative values of 5 %. Future experiments are expected to reduce this value of systematic uncertainty, as well as uncertainties from parton distribution functions, considerably.

Comparing different scenarios of beam setups (electrons versus positrons and degree of longitudinal polarization), it turned out that experiments with left-handed electrons alone would give the highest precision from both NC and CC scattering. This is essentially a consequence of the need to have as much data as possible and thus the process with the highest cross section is preferred.

## 2.2 NC couplings of quarks

Measurements of NC and CC cross sections with longitudinally polarized electrons and positrons would provide enough information to disentangle the neutral current couplings of the light $u$ and $d$ quarks. This is demonstrated in the contribution of the subgroup on *Measurement of NC Couplings*. The analyses are based on the NC and CC cross sections. In a scenario with $1000\,\mathrm{pb}^{-1}$ divided equally between the four charge/polarization combinations, all four $u$ and $d$-type vector and axial-vector couplings can be measured with resulting fractional errors on $a_u$, $v_u$, $a_d$ and $v_d$ of 6 %, 13 %, 17 % and 17 %, respectively (see Fig. 2). Even higher precisions could be achieved by constraining two of the couplings to their standard model values. These results are comparable with the heavy quark couplings determined at LEP 1.

These studies are based on full Monte Carlo simulations taking into account the present knowledge of the ZEUS detector performance and the current analysis methods. Future upgrades to the detector and improvements in the understanding of calibration of existing detector components will serve to improve the precision of the measurements. In addition, a detailed investigation of uncertainties from parton distribution functions, entering into the analyses basically via ratios of $u$ and $d$-type quark densities, and a comparison with the experimental errors have shown that this latter source of uncertainty will not be the limiting factor in determining NC couplings of quarks at HERA.

In the light of the intriguing $R_b$ anomaly which has been presented by the four LEP experiments [12], the question was raised whether HERA would be able to provide complementary information. From earlier workshops it is known that the total rate of $b$-quark production is not at all small. However, the contribution due to photon-$Z$ interference and pure $Z$-exchange is tiny (order 50 events for $100\,\mathrm{pb}^{-1}$) [13] and much too small to be helpful for electroweak physics.

## 2.3 $W'$

The potential of HERA for the discovery of additional heavy neutral or charged gauge bosons had been studied carefully in earlier workshops. In Ref. [14] it has been pointed out that

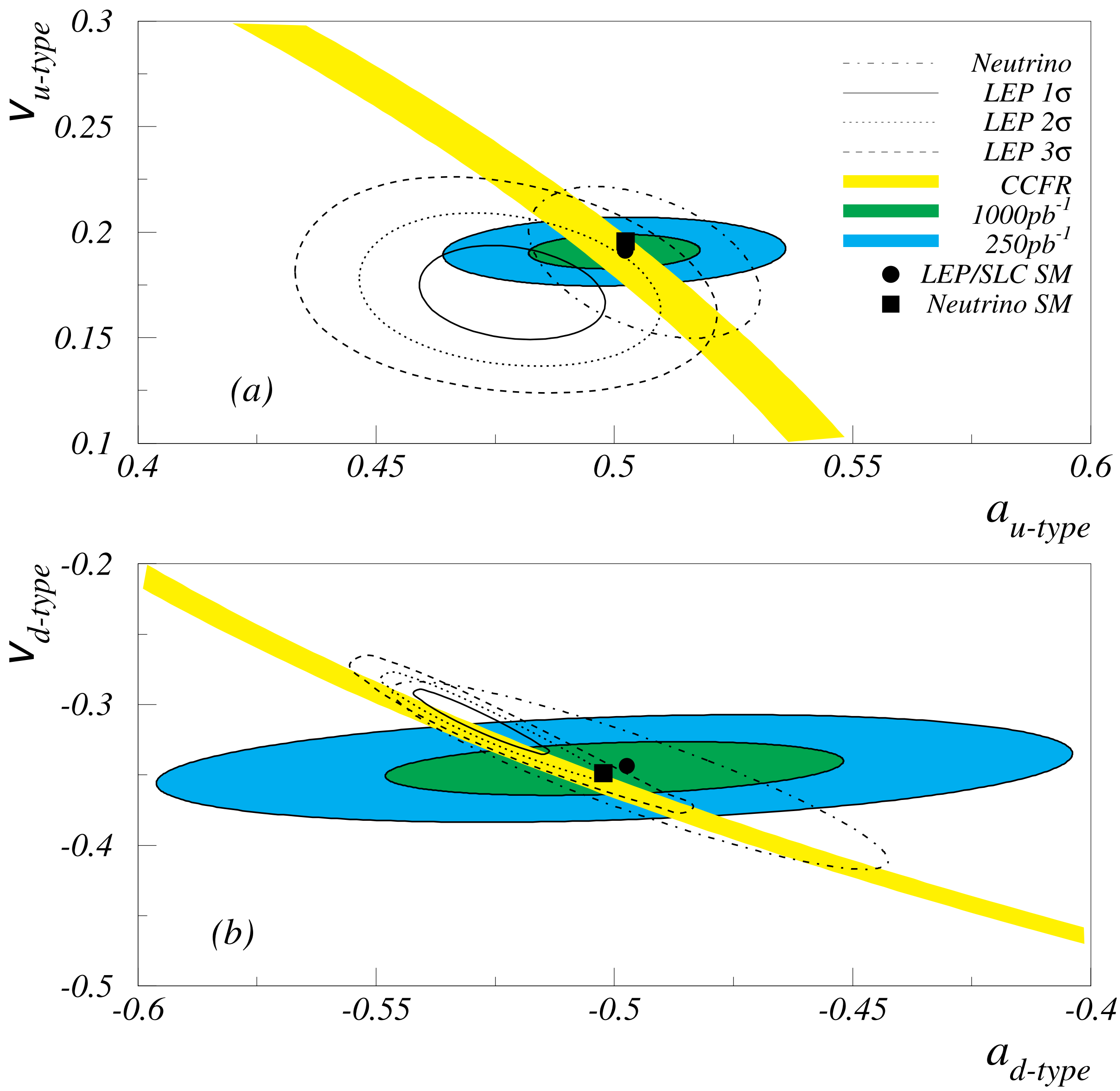


Figure 2: *Summary of measurements of u-type (a) and d-type (b) quark couplings to the $Z^0$. The results of a measurement at HERA are shown as the shaded ellipses. The outer ellipse shows the result which would be obtained with 250 pb$^{-1}$ divided equally between the four lepton beam charge/polarization combinations, the inner ellipse shows the result which would be obtained with 1000 pb$^{-1}$ equally divided. Fits for the couplings of the u (d) quarks were performed with the d (u) quark couplings fixed at their SM values. The open ellipse drawn with a dash-dotted line shows the one standard deviation ($1\sigma$) contour obtained in a fit of the four chiral couplings of the u and d quarks to a compilation of neutrino DIS data. The solid, dotted and dashed ellipses show the 1, 2 and 3 $\sigma$ limits of the combined LEP/SLD results for the c and b quark couplings. The shaded band shows the result obtained by the CCFR collaboration from the ratio of NC and CC cross sections projected onto the quark coupling plane. In the case of the CCFR the couplings of the u (d) quarks are obtained with the d (u) quark couplings fixed at their SM values. SM coupling values including radiative corrections appropriate for comparison with* $e^+e^-$ *(circle) and neutrino (square) measurements are also shown.*

charge and polarization asymmetries of NC cross sections are particularly suited for the search and the identification of a heavy $Z'$ boson and exclusion limits for its mass have been given there. A model independent analysis, considering the 6-dimensional space of $Z'f\bar{f}$ couplings was performed in Ref. [15].

Similar discovery limits for a heavy charged boson $W'$ can be derived by considering a possible deviation of the measured CC cross section from its standard model prediction assuming the existence of a heavy $W'$. A possible signal could show up in a comparison of the CC cross section at HERA with data at zero-momentum transfer, e.g. the $\mu$-decay constant. The enhancement of the CC cross section with respect to the SM prediction in the presence of two charged $W$ bosons is approximately given by

$$\frac{d\sigma(W+W')}{d\sigma_{SM}} = 1 + \frac{2x^2}{1+x^2\frac{m_W^2}{m_2^2}}\left(1-\frac{m_W^2}{m_2^2}\right)\frac{Q^2}{Q^2+m_2^2}, \tag{1}$$

where $x = g_2/g_1$ is the ratio of the coupling constants of the two charged bosons. The mass of the lighter one has been identified with that of the standard model $W$, while the heavier one is denoted by $m_2$. The exclusion limits in the $(x,\, m_2)$ plane derived from the condition that the enhancement be larger than the statistical precision of the measurement of the CC cross section are shown in Fig. 3. Assuming equal coupling strengths, $g_2/g_1 = 1$, the resulting limits are $m_2 \lesssim 400$ GeV for positron scattering and $m_2 \lesssim 630$ GeV [16]. These mass limits do not supersede corresponding limits from the Tevatron and we have not considered them in further detail.

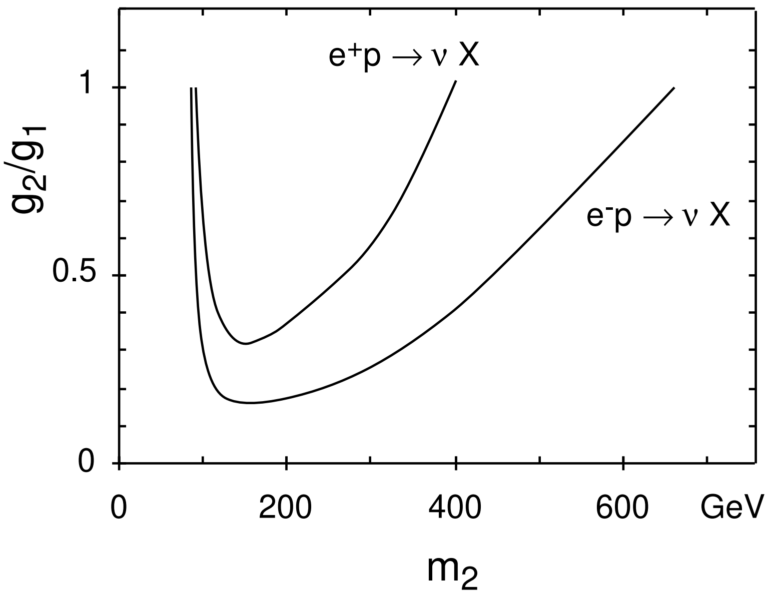


Figure 3: *95 % exclusion limits for a heavy $W'$ in the $(g_2/g_1,\, m_2)$ plane.*

## 2.4 $W$ production

The study of single $W$ production offers the challenging opportunity to test the nonabelian structure of the standard model at HERA, in particular to search for deviations of the $WW\gamma$ couplings from its standard model values [17, 18]. In a new study of this process during the present workshop [19], a discussion of the event topology and kinematical cuts to optimize the event selection is presented. It is shown that HERA offers greater sensitivity to anomalous values of $\Delta\kappa_\gamma$ than $\lambda_\gamma$ and therefore complements measurements made at the Tevatron and LEP 2 where the sensitivity to $\lambda_V$ is greater. Since single $W$ production at HERA is quite insensitive to anomalous $WWZ$ couplings, unlike $WW$ production at the Tevatron or LEP 2, measurements at HERA will be important to identify the nature of possible deviations, if they would be observed.

The sensitivity to anomalous $WW\gamma$ couplings has been studied for various integrated luminosities and at two center-of-mass energies. The resulting 95 % confidence level limits at $\sqrt{s} = 300$ GeV are given in Table 1. At $\sqrt{s} = 346$ GeV, the limits for $\int \mathcal{L}dt = 1000\,\mathrm{pb}^{-1}$ are $-0.27 < \Delta\kappa_\gamma < 0.26$ and $-1.26 < \lambda_\gamma < 1.28$. They are limited by statistical rather than systematic errors. For $\int \mathcal{L}dt = 1000$ pb$^{-1}$ the future sensitivity on anomalous values of $\Delta\kappa_\gamma$ which can be obtained at HERA is competitive with projected limits from $W\gamma$ production at the Tevatron (see Fig. 4). The bounds from LEP 2 shown in this figure are based on the auxiliary assumption that the $WWZ$ and $WW\gamma$ couplings are not independent from each other (HISZ scenario) and can thus not be compared with the HERA results on equal footing.

| $\int \mathcal{L}dt$ | $\Delta\kappa_\gamma$ | $\lambda_\gamma$ |
|---|---|---|
| 100 pb$^{-1}$ | $-1.43 < \Delta\kappa_\gamma < 0.95$ | $-2.93 < \lambda_\gamma < 2.94$ |
| 200 pb$^{-1}$ | $-0.87 < \Delta\kappa_\gamma < 0.72$ | $-2.46 < \lambda_\gamma < 2.47$ |
| 1000 pb$^{-1}$ | $-0.38 < \Delta\kappa_\gamma < 0.38$ | $-1.65 < \lambda_\gamma < 1.66$ |

Table 1: *95% CL limits derived for $WW\gamma$ couplings from the measurement of $\sigma(ep \to eWX)$ at HERA for the nominal center-of-mass energy of 300 GeV.*

## 2.5 Radiative NC scattering

Radiative deep inelastic scattering offers another possibility to study trilinear gauge boson couplings. Radiative CC scattering and its potential to probe the $WW\gamma$ couplings has been studied in Ref. [20]. As a new contribution to this workshop, Ref. [21] investigated whether $Z\gamma\gamma$ couplings can be tested in radiative NC scattering. Contributions due to $ZZ\gamma$ couplings are suppressed by two $Z$ propagators. Since the rates are too small to exploit differential cross sections, estimates for bounds are obtained from total cross sections taking into account realistic cuts to improve the sensitivity to this source of new physics. HERA will explore these couplings in a different kinematic regime than at LEP 2, NLC or hadron colliders. However, it turns out that competitive bounds on these anomalous couplings cannot be achieved, even with the future luminosity upgrades.

## 2.6 SM Higgs-boson production

The prospects of producing light SM Higgs bosons at HERA under nominal conditions were discussed in the 1987 proceedings [22]. In the meantime, LEP has ruled out the mass range $M_H < 65.2$ GeV at the 95% confidence level [23]. An update of the 1987 analysis assessing the benefits from luminosity and proton energy upgrades may be found in Ref. [24]. $W^+W^-$

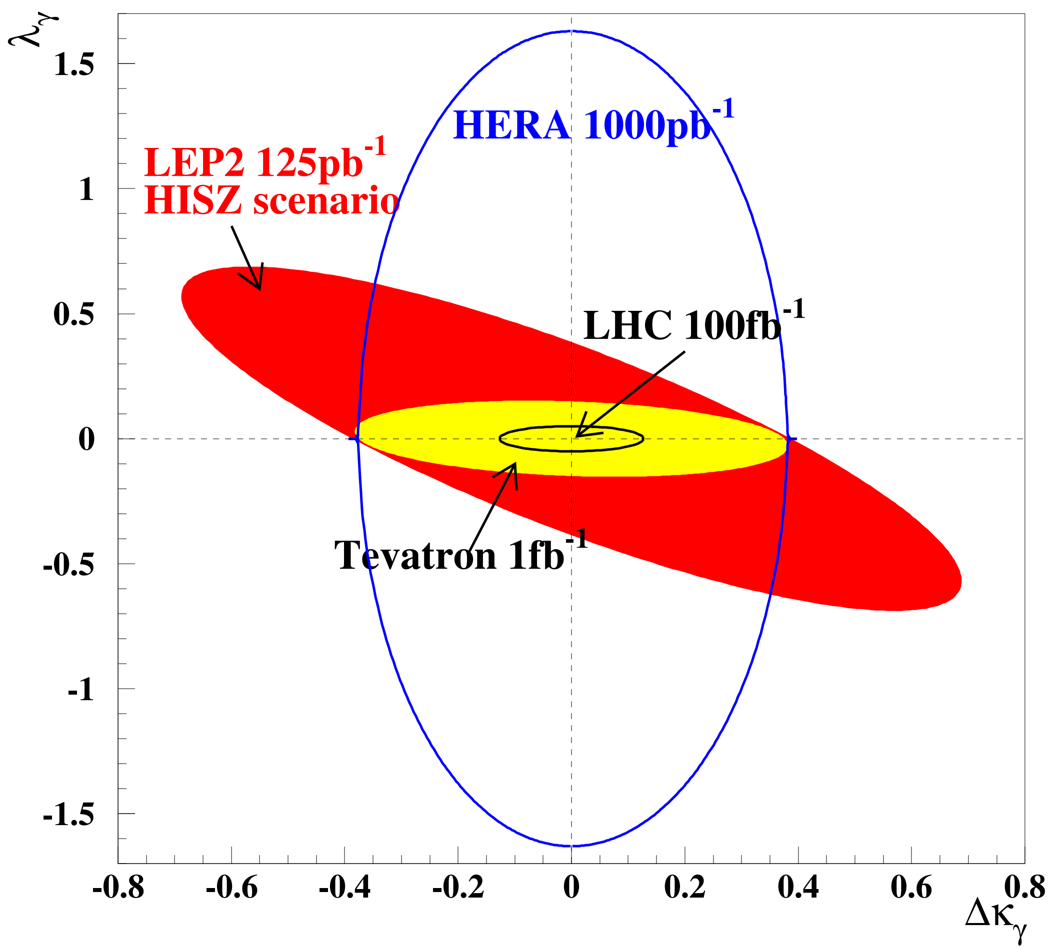


Figure 4: *Projected 95% confidence level sensitivity limits for $WW\gamma$ couplings determined from the single $W$ production cross section at HERA and from $W\gamma$ production at the Tevatron and the LHC. The solid shading indicates the limits for the $WWV, V = \gamma, Z$ couplings from $WW$ production at LEP 2 assuming the HISZ scenario.*

and $ZZ$ fusion are by far the most copious sources of SM Higgs bosons at HERA. In the mass range 65 GeV $< M_H <$ 100 GeV, the Higgs boson decays with about 90% branching fraction to $b\bar{b}$ pairs, so that its visibility at HERA will suffer from severe intrinsic backgrounds due to continuum $b\bar{b}$ production. If such a Higgs boson exists, its production cross section at HERA will be below 6 (9) fb for $E_p = 820$ GeV (1 TeV). It is therefore unlikely that a signal can be established in the $b\bar{b}$ channel, even if the luminosity and/or proton energy are upgraded leaving this terrain to LEP 2.

# 3 Conclusions

The observation of the propagator effect due to $W$ exchange was one of the first results from HERA at high $Q^2$ after decades of searching for deviations of the linearly rising cross section of the CC process. In the meantime, the finite mass of the $W$ boson responsible for this effect, the propagator mass, has been measured with an accuracy of a few GeV at HERA. First candidate events for the direct production of the $W$ boson have also been observed at HERA. In order to turn these observations into measurements of parameters and conclusive tests of the standard model electroweak sector the luminosity has to be increased tremendously. Luminosities of $1\,\mathrm{fb}^{-1}$ and polarized beams will make these measurements possible.

The cross section for the production of $W$ bosons is the order of 1 pb so that it is an experimental challenge to establish the experimental signal and it is essential to consider all available decay channels. The study performed in this report shows that already with an integrated luminosity of $250\,\mathrm{pb}^{-1}$ deviations from the standard model couplings parametrized in terms of $\Delta\kappa_\gamma$ and $\lambda_\gamma$ can be tested at a level which is comparable to present collider results.

While for $W$ production neither lepton charge nor polarization is a prerequisite, the precision measurement with the charged current process profits especially from $e^-p$ scattering due to the roughly threefold larger cross section as compared to $e^+p$ scattering. For an analysis in terms of NC quark couplings it is indispensable to have available both charge states, while not necessarily with equal luminosity. To disentangle up- and down-type quark vector and axial-vector couplings beams have to be polarized. A proper choice of polarization would also render the NC data useful, and evidently enhance the significance of the CC data, for the precise determination of e.g. $m_W$ or $m_t$.

The result of these measurements constitutes an important test of the standard model by comparing precision measurements of SM parameters obtained at HERA with those at other experiments. Differences appearing in such tests have always stimulated extensive research. The separation of the light up- and down-type quark couplings at HERA would complement the achievements of LEP in the heavy quark sector.

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