Recent results from HERA

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Abstract After the end of data taking in 2007, the experiments H1 and ZEUS have entered into an intense phase of data analysis. Recent results of this effort on neutral (NC) and charged current (CC) cross sections at high Q^2, the longitudinal structure function $F_{\rm L}$, inclusive diffraction, heavy flavour production and on searches for glueballs are presented. Also shown are results of a combined analysis on inclusive NC and CC cross sections performed by H1 and ZEUS using HERA-I data.

Key words lepton-proton scattering, structure functions, QCD, glueballs

PACS 12.38.Aw, 13.85.Hd, 14.40.Rt

1 Introduction

HERA is the only lepton-proton collider ever built. It collided electrons or positrons of 27.6 GeV with protons of energy between 460 and 920 GeV for a maximum centre-of-mass energy of $\sqrt{s} = 318$ GeV. HERA operated at DESY in Hamburg, Germany from 1992 – 2007. During this period HERA delivered a total integrated luminosity of approximately 800 pb^{-1} to the colliding beam experiments H1 and ZEUS. During the HERA-II period from 2003 – 2007, the lepton beam was longitudinally polarized. The average polarization was between 30% and 40% and the polarity of the lepton beam was flipped a number of times. Running was also split approximately evenly between electrons and positrons.

The H1 and ZEUS detectors were large general purpose magnetic instruments. They were designed, built and operated by international collaborations comprising more than 800 physicists during the peak of HERA activity. Currently these collaborations together still have more than 500 authors. The detectors were built with a common physics programme in mind but employed quite different individual technical solutions, in particular in the areas of calorimetry and tracking. This diversity provides an effective cross calibration of the results as will be demonstrated in this paper.

The physics programmes of H1 and ZEUS comprise precision measurements of the proton structure functions including the contributions from charm and beauty quarks, investigations of the gluon dynamics inside the proton, tests of perturbative QCD, searches for new baryonic and mesonic states and searches for new physics at the energy frontier.

After the close of data taking at HERA, the experiments entered a period of intense analysis which will continue until 2013. The goal is to fully exploit the rich data set collected at HERA. These efforts involve final and optimal calibrations and alignments of the detectors, but also combining the different experiments' data sets for much improved precision. The first outcome of these efforts is presented in the following.

2 Neutral and charged current cross sections at high Q^2

At the core of the physics programme at HERA-II is the measurement of the inclusive neutral and charged-current cross sections at high Q^2. This measurement fully exploits the unique combinations of beam conditions, namely the availability of both lepton species and both polarities. This measurement exhaustively probes the electroweak sector of the standard model up to the kinematic limit of HERA. It reaches scales of the masses of the heavy vector bosons where electromagnetic and weak interactions are of equal strengths.

Received 19 January 2010

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This is demonstrated in Fig. 1, where the neutral- and charged current cross sections as functions of the virtuality Q^2 of the exchanged boson are shown for both lepton species. More details can be found in the respective published papers[1, 2].

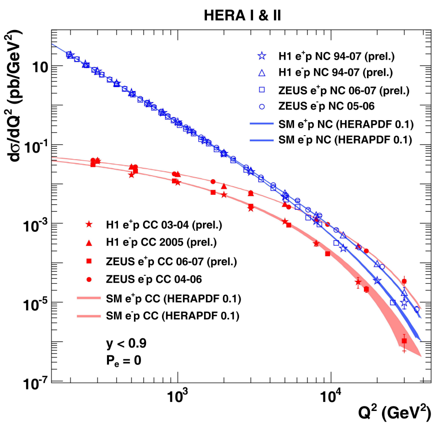

Fig. 1. Cross section $\frac{d\sigma}{dQ^2}$ for deep inelastic $e^{\pm}p$ neutral and charged current scattering with positively and negatively polarized lepton beams.

As Q^2 increases, the NC cross section falls much more steeply than the CC cross section. Around $Q^2 \approx 10000$ GeV^2 the two cross sections become roughly equal. This is a very direct and visual demonstration of electro-weak unification. Another effect is very prominent in this figure: the CC cross section is about two times larger for e^-p than for e^+p scattering, since the W^-, exchanged in e^-p scattering, dominantly couples to u-valence quarks which are about two times more abundant in the proton than d-quarks. A similar but much smaller effect is seen for the neutral current process where it arises from the interference of photon and Z^0 exchange.

These measurements can be further exploited in at least two different ways. On the one hand, they serve to extract parton distribution functions. In the electro-weak regime the structure function xF_3 provides the crucial handle on the valence quark distributions. On the other hand, the level of compatibility with the Standard Model provides limits on the existence of new physics. Examples for the latter are given in the next section.

3 Searches for new physics beyond the standard model

New physics can be searched for in a number of different ways. Most commonly, one searches for very prominent effects such as resonances in regions of phase space where very little background from the standard model is expected. Alternatively, measured cross sections can be tested for global small deviations from Standard Model expectation. The level of agreement can be translated into limits on new physics. A very comprehensive programme of studies was carried out by H1 and ZEUS looking for things such as excited fermions, leptoquarks, R-parity violating SUSY, Supergravity, lepton-flavour violation or anomalous single top production. Only one example will be given here, namely the extraction of a limit on a possible finite quark radius.

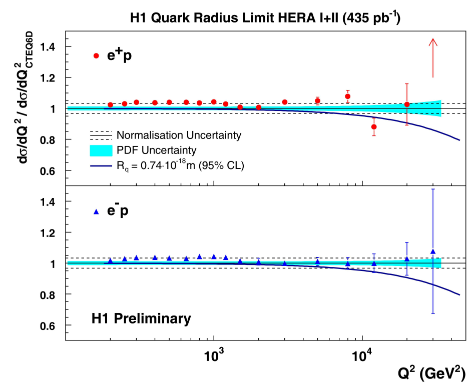

Fig. 2. Ratio of the measured neutral current cross section $\frac{d\sigma}{dQ^2}$ to the expectation in the standard model. The lines indicate the hypothetical behaviour if there were a finite quark radius of 0.74×10^{-18} m excluded at 95% confidence limit.

It is demonstrated in Fig. 2 which shows the ratio of the measured neutral current e^+p scattering cross section as a function of Q^2, over the the corresponding standard model prediction. The solid lines show the hypothetical behaviour of this ratio if there were a finite quark radius of 0.74×10^{-18} m, which is excluded at 95% confidence limit. This result is in nice agreement with a very simple argument that uses the Heisenberg uncertainty principle to extract that the smallest structures resolved by HERA should indeed have a size of 10^{-18} m.

4 High precision combined inclusive DIS cross sections and extraction of parton densities

The H1 and ZEUS collaborations achieve a significant reduction of their systematic uncertainties by combining 14 independent cross section measurements performed with the HERA-I data both for the neutral current and charged current processes [3]. A significant part of the reduction in the uncertainties stems from a cross-calibration of the two detectors. In total 1402 individual data points are combined into 741 cross section values on a common grid in the x, Q^2-plane. The uncertainties are extracted taking 102 correlated sources into account.

In the so-called bulk region of the measurement, $10 \lesssim Q^2 \lesssim 100$ GeV^2, the level of the total uncertainty reaches $\approx 1\%$. An example is given in Fig. 3 which shows the structure function $xF_2(x_{\rm Bj}, Q^2)$ in three different bins of Q^2 from $Q^2 = 3.5$ GeV^2 to $Q^2 = 650$ GeV^2. At small Q^2, F_2 rises moderately. This rise becomes more and more pronounced as Q^2 increases. This rise is an effect of gluon-splitting. It is well described by the QCD fit which is also shown in the figure. These HERA data are the only precise source of information on the structure of the proton at values of $x_{\rm Bj}$ smaller than 10^{-3} which is of particular interest at the LHC.

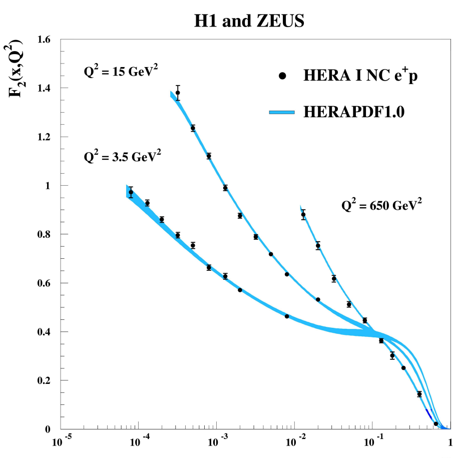

Fig. 3. Structure function xF_2 of the proton measured by the H1 and ZEUS collaborations at HERA in 3 bins of Q^2 as a function of $x_{\rm Bj}$.

5 Measurement of the longitudinal structure function

The differential cross section for neutral current deep inelastic scattering can be written in the following form

$$\sigma^{\pm}_{\rm r,NC} = \frac{{\rm d}^2\sigma^{\rm e^\pm p}_{\rm NC}}{{\rm d}x{\rm d}Q^2}\cdot\frac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2 \mp \frac{Y_-}{Y_+}xF_3 - \frac{y^2}{Y_+}F_{\rm L}\ ,\quad(1)$$

where the propagator and a helicity factor are absorbed in the definition of the reduced cross section $\sigma^{\pm}_{\rm r,NC}$, and $Y_\pm = 1\pm(1-y)^2$. In addition to the structure functions F_2 and F_3 discussed previously, there is a third function, $F_{\rm L}$ which arises entirely from the interaction of the probe with the gluon field in the proton. The quantity $F_{\rm L}$ is an independent structure function. It plays an important role at low Q^2 and at values of the inelasticity y close to one. In fact, the structure function F_2 cannot be extracted without making assumptions about $F_{\rm L}$. Until recently, only rudimentary information about $F_{\rm L}$ existed, in particular at small values of $x_{\rm Bj}$.

At HERA F_2 and $F_{\rm L}$ can be extracted completely independently, without any assumptions on one versus the other, using data taken at different centre-of-mass energies. For this purpose, data were taken with proton beam energy lowered to $E_{\rm P} = 460$ GeV and $E_{\rm P} = 575$ GeV for centre-of mass energies of 225 and 252 GeV respectively. This allows measuring the relevant cross sections for the same values of $x_{\rm Bj}$ and Q^2 but at different values of the inelasticity y. Taking these data together with the results obtained at $\sqrt{s} = 318$ GeV, the function $F_{\rm L}$ can be extracted with a linear fit from Eq. (1). The results from ZEUS [4] are shown as a function of Q^2 in Fig. 4.

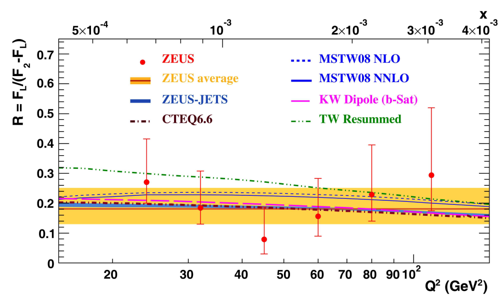

Fig. 4. Structure function $xF_{\rm L}$ of the proton measured by the ZEUS collaboration at HERA as a function of Q^2 together with different phenomenological predictions.

The errors of the measurement are sizeable, but this is the only information available in this kinematical regime. Hence the data are very valuable. Their value lies mostly in confirming that the phenomenological expectations from QCD are correct thus justifying previous extractions of F_2.

6 Diffraction

The process of diffractive scattering has been known for a long time and has been extensively studied in hadron-hadron collisions. It was phenomenologically described in terms of Regge theory and seen as a soft phenomenon which would not be present in hard interactions. Hence, it came as a surprise when in 1993 a sizable diffractive contribution amounting to as much as 15% of the total photoproduction ($\gamma^\star$p) scattering cross section was found in deep inelastic scattering at HERA through the observation of rapidity gap events. In these processes the proton escapes intact even though the point-like photon interacts with a small configuration inside the proton.

In the naive picture of deep-inelastic interactions, such processes do not occur with any sizeable rate since the proton is described as a gas of uncorrelated quarks and gluons. The photon knocks out one of these partons leaving behind a colored state and hadronization occurs between the struck parton and the proton remnant. The existence of a large diffractive component at high Q^2 shows that the structure of the proton is indeed not gas-like. There exist strong correlations between partons which make the proton grainy, so that the interactions take place between the photon and a color-less correlated state made of more than one parton inside the proton. In QCD this state is comprised of at least two gluons and is sometimes called the Pomeron.

A very important observation in diffractive scattering is demonstrated in Fig. 5 which shows the total γP cross section together with the production cross section for different vector mesons as a function of the γP centre-of-mass energy W. The total γP cross section rises slowly with W. For the vector mesons this rise is much faster and is well described by a power-like behaviour with increasing power as the mass of the vector meson increases. This indicates that as the mass of the vector meson becomes large enough to provide a hard scale, these diffractive processes are indeed hard and described by perturbative QCD. The power of the rise with energy is close to two times that of totally inclusive DIS, indicating that it is roughly governed by the square of the gluon density.

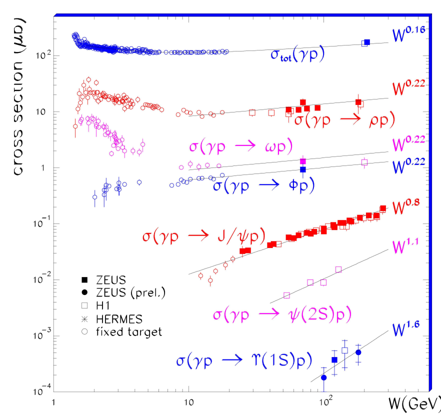

Fig. 5. The total γP cross section and the cross sections for diffractive production of ρ, ω, ϕ, J/ψ, ψ(2s) and Υ(1s) mesons as a function of the γP center-of-mass energy, W.

These results pave the way for further studies at the LHC or at a future electron-ion collider where diffractive scattering will provide a very clean laboratory to test many aspects of the standard model and also to search for new physics.

7 Heavy quark production in DIS

Heavy quarks are produced abundantly at HERA with charm constituting roughly 20% and beauty about 5% of the total deep inelastic scattering cross section. Perturbative QCD should describe these cross sections adequately considering the fact that the mass of the heavy quark provides a hard scale. Hence, these cross sections are an excellent testing ground of perturbative QCD and in addition provide a handle on the gluon density inside the proton.

However, it remains to be shown whether the dynamic generation from gluon radiation is indeed the only source of heavy quarks or whether there might be an "intrinsic", non-perturbative source of heavy quarks in the proton. In order to answer this question, one needs to overcome significant experimental and theoretical challenges. Heavy quarks can be tagged exclusively by identifying the respective mesons or inclusively, by looking for displaced secondary vertices.

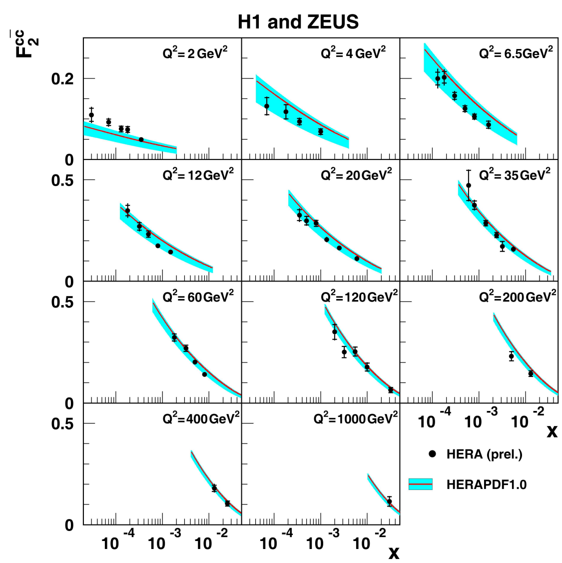

Fig. 6. Combined H1 and ZEUS results on the structure function $F_2^{c\bar{c}}$ as a function of $x_{\rm Bj}$ in bins of Q^2. The data are compared to the predictions based on the HERAPDF1.0 parton density functions.

Significant progress has been made on both of these fronts recently: the HERA-II data sample provides larger numbers of identified mesons and the improved vertexing capabilities of both experiments yield yet another quantitative step in statistical precision. This fact is nicely demonstrated in Fig. 6 which presents the first combination of H1 and ZEUS results on the charm fraction of the structure function, $xF_2^{c\overline{c}}(x_{\rm Bj},Q^2)$. The data are shown as a function of $x_{\rm Bj}$ in bins of Q^2. The data are compared to NLO QCD predictions using the recent HERAPDF1.0 parton density function. The data and the predictions are compatible at the level of both the experimental and theoretical uncertainties indicating that there is no sizeable non-perturbative source of charm production. However, it needs to be noted that the uncertainties are sizeable. The experimental uncertainties currently amount to approximately 10%. The major part of the theoretical uncertainties are from the detailed treatment of the NLO calculation at the charm threshold. Significant improvements can be expected from ongoing experimental studies and from better theoretical treatment and from NNLO calculations.

8 Exotic hadrons

All observed hadrons are either classified as mesons with a two or as baryons with a three quark content. QCD allows for a much richer particle spectrum including states with more than three quarks, for hybrids with both quarks and gluons and for glueballs. However, no such states have convincingly been established so far. In 2004 there was considerable excitement over the so called Θ^+, which is a pentaquark candidate. This state was observed by several different experiments including ZEUS which had a 5σ signal in deep inelastic scattering in the HERA-I data. No signal was seen by H1. On the other hand H1 observed yet another state around 3.1 GeV decaying to a charmed meson and a proton.

In the meantime both H1 and ZEUS looked without success for these states in the HERA-II data. Other experiments at JLAB and the B factories have also failed to strengthen the evidence for these states. Nevertheless, this topic remains of considerable interest. In fact, one should either find these states, or alternatively understand why they are not observed.

However, a very interesting result was obtained on the $\rm f_0(1710)$ [5], a state decaying to two neutral kaons, which is observed with a significance of five standard deviations, as shown in Fig. 7. It is consistent with a $J^{PC}=0^{++}$ glueball state. It needs to be stated though that, should it be the same state as that seen in $\gamma\gamma\rightarrow {\rm K_S^0K_S^0}$, it can obviously not be a pure glueball state, as photons do not couple to gluons directly.

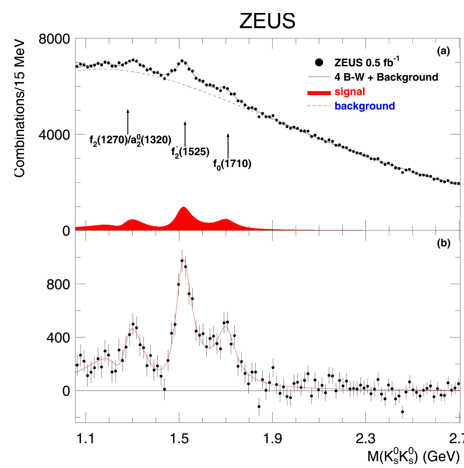

Fig. 7. Invariant mass of the $\rm K_S^0K_S^0$ final state. The solid line shown corresponds to a $SU(3)$ fit, the dashed line is a background function.

9 Summary and outlook

After fifteen years of data taking, the HERA eP-collider ended operation in 2007. The H1 and ZEUS collaborations continue to analyze a wealth of unique data and are currently in their most productive publication phase. A number of recent results on inclusive cross sections both at high and at low Q^2 with the extraction of both electro-weak parameters and parton distribution functions, on searches for new physics, on inclusive diffraction, on heavy flavor production and on hadron spectroscopy were presented in this paper. This effort will continue for at least three more years and will focus increasingly on combined analyses and precision results.

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