Inclusive measurements at HERA from low to high x

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New inclusive Deep Inelastic Scattering (DIS) measurements are presented, obtained with the H1 and ZEUS detectors at HERA. The results comprise (flavour) inclusive DIS cross sections as well as inclusive charm production. In the area of inclusive DIS, both H1 and ZEUS completed last year their high Q^2 Neutral and Charged current measurements exploiting the large statistics from the HERA II running period. For inclusive charm production, H1 and ZEUS published a combination of numerous existing measurements based on various tagging methods. Among other things a precise determination of the running charm quark mass $m_c(m_c)$ was obtained from the combined data.

1. Introduction

Since more than 40 years one studies in Deep Inelastic Scattering (DIS) simultaneously the nucleon structure and the strong interactions as represented by the theory of Quantum Chromo Dynamics (QCD). HERA, the worldwide only *ep* collider, plays a crucial role in this field. Figure 1 (left) shows a typical DIS process at HERA. A highly virtual gauge boson, either a photon or a Z in Neutral Current (NC) reactions or a W boson in Charged Current (CC) interactions, is emitted from the lepton and knocks out a quark of the proton which is destroyed. One of the many possible higher order reactions of the strong interaction takes places: a hard gluon is emitted from the struck quark. The basic kinematics of the DIS scattering is described by the following observables:

- $Q^2 = -q^2$, the negative of the squared four-momentum vector q of the exchanged gauge boson.
- the inelasticity $y = qp/kp$, with k and p denoting the four-momentum vectors of the incident lepton and proton, respectively.
- the *Bjorken* x, defined as $x = Q^2/2pq$. In the quark parton model x specifies the longitudinal momentum fraction of the proton carried by the quark that is struck by the gauge boson.

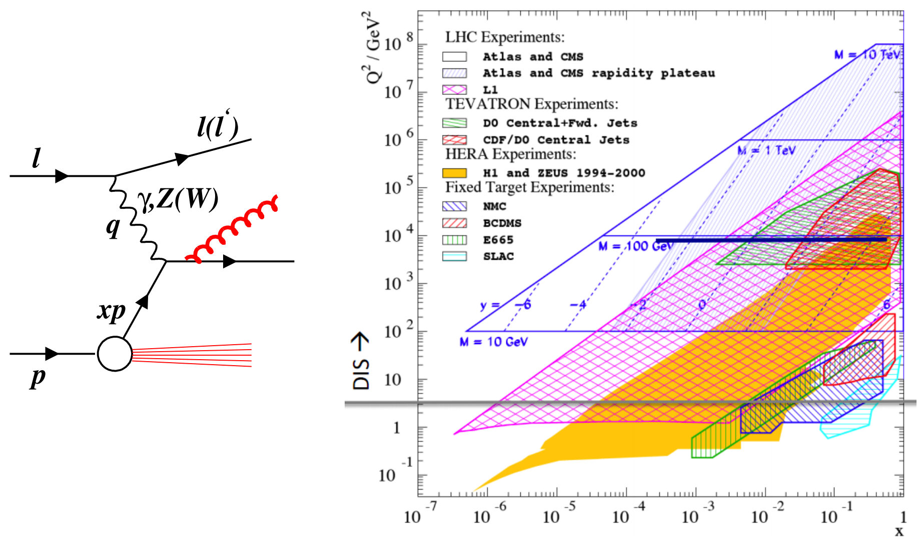

Fig. 1. Left: Sketch of an exemplary higher order DIS process. Right:DIS kinematic plane of Q^2 and x and coverage of various experiments.

The three variables are constrained by the relation $Q^2 = xys$, where s denotes the fixed squared centre-of-mass energy of the lepton-proton system.

Figure 1 (right) shows the kinematic plane in Q^2 and x, covered by various experiments in the past, present and future. The DIS region is defined by $Q^2 \geq$ few GeV^2, while the photoproduction region (exchange of quasi-real photons) is defined by $Q^2 < 1$ GeV^2. Decades ago fixed target experiments started the exploration of the nucleon structure from the region of large x and small Q^2. The H1 and ZEUS experiments at the HERA collider extended the phase space to the region of smallest $x \sim 0.000001$ and highest $Q^2 \sim 40000$ GeV^2. The coverage of the central detector experiments at the $p\bar{p}$ collider TEVATRON and the pp collider LHC is also indicated in Figure 1. It overlaps with HERA; this makes the proton structure information from HERA so crucial for obtaining predictions for many important reactions at the two hadron colliders (e.g. Higgs production at the LHC).

In the following we will discuss some selected highlights of new inclusive measurements from H1 and ZEUS, starting with inclusive DIS and moving to charm production. As a reminder, H1 and ZEUS collected each about 0.5 fb^{-1} of ep collisions; the first quarter was taken in the HERA I period and the other three in the HERA II period, where the lepton beams were polarised. About half of the data were taken with e^+p collisions and the other with e^-p collisions.

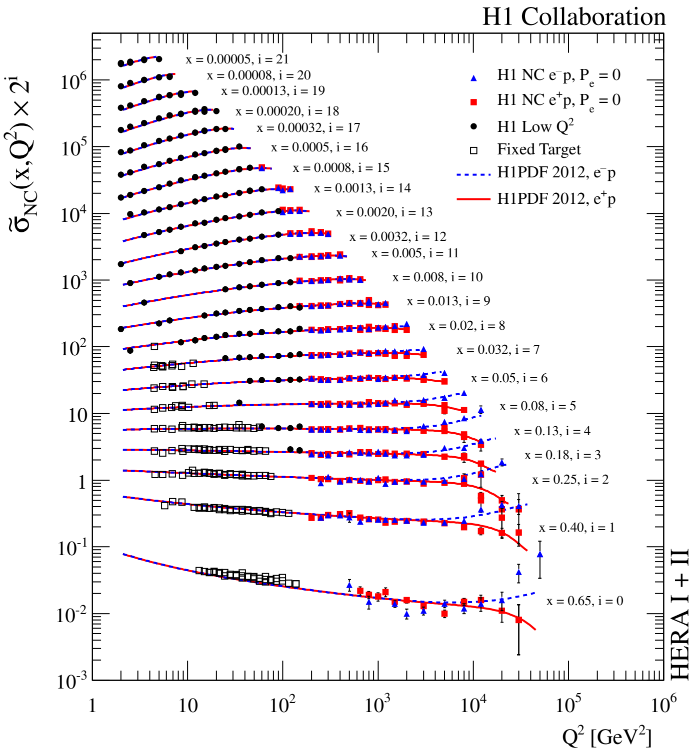

Fig. 2. Recent Neutral Current reduced cross section measurements from H1.

2. Inclusive DIS

Inclusive DIS means to count every DIS event in a given region of Q^2 and x. Recently the H1 and ZEUS experiments completed their inclusive DIS analyses by releasing the full high Q^2 data sets taken in the HERA II period. The H1 publication [1] contains the finalised inclusive $e^{\pm}p$ NC and CC data. The ZEUS paper [2] covers the last missing high Q^2 data set from ZEUS, the e^+p NC data.

Figure 2 shows the $e^{\pm}p$ NC reduced cross section[1] measurements by H1 [1] as a function of Q^2 for various values of x. The data were obtained from a weighted averaging of the HERA II high Q^2 inclusive DIS data, their HERA I counterparts and also the HERA I low Q^2 data. An excellent experimental precision of about 1.5% has been reached for a large region $Q^2 < 500$ GeV^2. In an Next-To-Leading Order (NLO) QCD analysis based

[1] The NC reduced cross section is in a large part of the HERA kinematic phase space approximately equal to the structure function F_2. In specific phase phase parts the structure functions F_L and F_3 also contribute significantly.

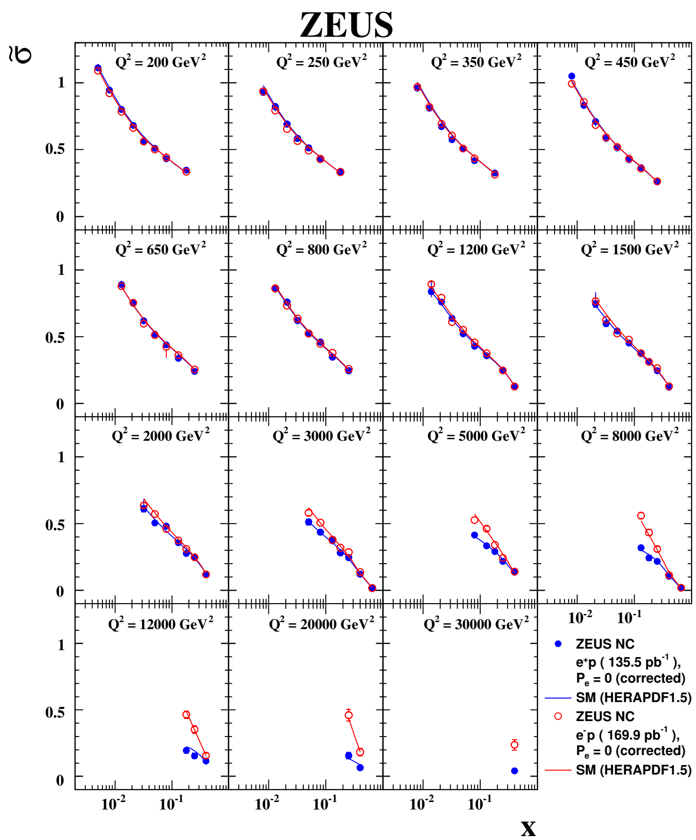

Fig. 3. Recent Neutral Current reduced cross section measurements from ZEUS.

on the DGLAP evolution equations, PDFs were fitted to the data. The fit function from the resulting PDF set "H1PDF2012," is also depicted in Figure 2. It provides a reasonable description of the data in the whole kinematic range. It was often hypothesised that one might find a prominent breakdown of the NLO DGLAP fit description at low Q^2 and low x due to uncontrollable higher order QCD effects, but there is at least no blatant evidence from this plot.

Figure 3 shows the $e^{\pm}p$ NC reduced cross sections by ZEUS [2], using the HERA II high Q^2 data sets. Here the data are plotted as a function of x for various fixed values of Q^2. A very good experimental precision is reached of about 1.5% in some lower Q^2 regions. Also shown is the prediction using the PDF set "HERAPDF1.5", which was obtained from an NLO DGLAP fit to specific subsets of the H1 and ZEUS inclusive data. As in the H1 case, the data are described well by the fit.

In the future it is planned to combine the finalised/new high Q^2 HERA II

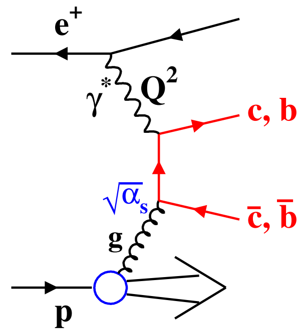

Fig. 4. Leading order BGF process for charm and beauty quark production at HERA.

inclusive DIS data from H1 and ZEUS together with the HERA I combined inclusive data in order to obtain the best available HERA data set to be used for QCD analyses and PDF determinations.

3. Charm production in DIS

The heavy charm and beauty quarks are produced at HERA mainly by boson gluon fusion (BGF) processes. The leading order diagram is shown in Figure 4. Due to the large gluon density in the proton, the BGF processes gives large contributions to DIS; charm production alone accounts at low x and high Q^2 for up to $\sim 35\%$ of the inclusive DIS cross section. Furthermore, the process provides direct sensitivity to the gluon density in the proton. There are different schemes to treat the heavy flavour production (for references consult [3]). At low Q^2, that is $Q^2 \sim m_c^2$, with m_c denoting the charm quark mass, there is no doubt that the *massive scheme* is correct. The scheme is rigorous quantum field theory in which the masses of the heavy quarks are fully taken into account in every part of the calculation. In this scheme, charm and beauty quarks can only be dynamically produced in the hard interaction. The proton PDFs contain only light quarks and gluons and hence the scheme is also called *Fixed-Flavour-Number Scheme* (FFNS). However, at very high virtualities $Q^2 \gg m_c^2$, it might be favourable to treat the charm quark (and similarly the beauty quark for $Q^2 \gg m_b^2$) as massless which is done in the *Zero-Mass-Variable-Flavour-Number Scheme (ZMVNFS)*. In this scheme, the charm and beauty quarks appear above some kinematic thresholds also as massless sea quarks in the proton. The nice feature of this scheme is that it allows to resum to all orders certain logarithmic terms appearing in the perturbative calculation related to collinear gluon radiation from the heavy quark lines. The

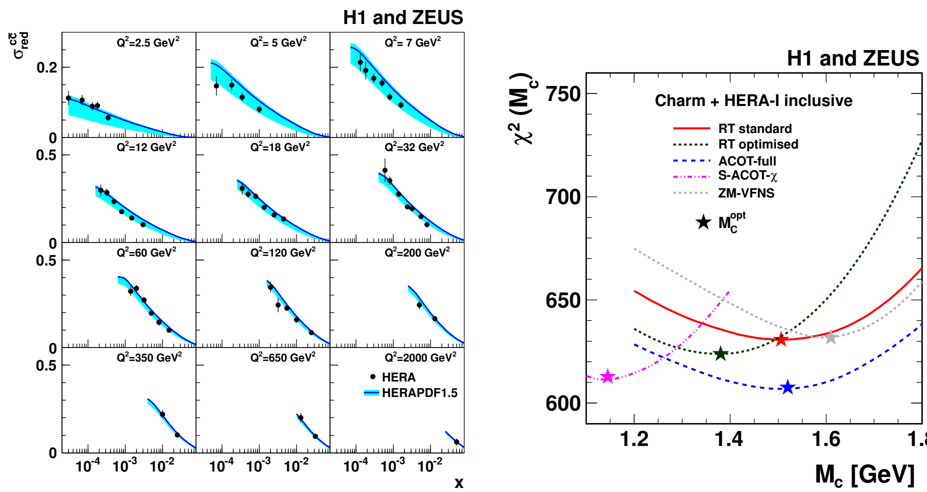

Fig. 5. Left: Reduced cross sections for charm production in DIS. The HERA combined data are compared to a GMVFNS prediction. Right: χ^2 of the PDF plus charm mass fit as a function of the charm mass parameter M_c — for further details see the main text.

General-Mass-Variable-Flavour-Number Schemes (GMVFNS) make use of the best of “both worlds”: at low Q^2 the massive scheme is used and at high Q^2 the massless scheme, with a suitable interpolation in the intermediate region. However, what is a suitable interpolation is debated for a long time as well as many other details of the treatment of mass dependent terms in pQCD; in fact there are numerous GMVFNS variants on the market and used by the various PDF fitter groups in the world.

3.1. Charm combination and determination of the running charm mass

Recently, H1 and ZEUS published the combination of charm production data in DIS [3]. The data, based on various tagging methods such as full reconstruction of D^* mesons, D^+ mesons, semileptonic decays, or inclusive secondary vertex tagging, have been combined at the level of the so called reduced cross sections. This cross section is related to the total charm production cross section in a region of Q^2 and x. In the combination the correlated systematics is fully taken into account. The combined data reach a for charm production at HERA unprecedented best precision of about 5% in certain phase space regions. Figure 5 (left) shows the obtained combined reduced cross sections as a function of x for various values of Q^2. Also shown is the prediction based on the “HERAPDF1.5” PDF, using the GMVFNS in the “Robert Thorne standard” scheme variant (for proper references consult [3]). These PDFs were obtained from fitting only inclusive DIS data, without any knowledge of charm production data. The prediction describes the charm data reasonably well which is a triumph for the QCD collinear factorisation approach used in the calculations: the gluon density in HERAPDF1.5, obtained from the scaling violations observed in inclusive DIS, is in agreement with the gluon density that is needed to describe the charm production data. The not so nice thing is the large theory uncertainty, as indicated by the error band, which is dominated by variations of the charm quark mass. Turning the tables, a simultaneous fit of PDFs plus the charm quark pole mass was performed in [3]. Both the HERA combined charm data and combined HERA I inclusive DIS data were used as input and various GMVFNS variants were tried out. Figure 5 (right) shows a χ^2 scan of this fit as a function of the charm mass parameter M_C. It can be seen that the fitted M_c values (called optimal mass "M_c^{opt}" in the plot) differ considerably between the various GMVFNS variants (e.g. "RT standard","S-ACOT-χ"). In fact, when using a fixed value $M_c = 1.4$ GeV, some of the schemes fail to describe (not shown here) the combined charm data in the lower Q^2 regions, while when using the optimal masses most of the schemes give a good description. What can we learn from this? The various GMVFNS interpolate differently between the massive and massless schemes and this leads to a different quality of the charm data description for a fixed charm mass; these deficiencies can be compensated by using the M_c^{opt} values. This has even broader ramifications as discussed in [3]. Using the specific M_c^{opt} value for each scheme stabilises the PDF mixture of the various quark flavours and of the gluon; in turn this stabilises predictions for W and Z production at the LHC which depend crucially on the flavour mixture.

The massive scheme predictions (not shown here) which are available at NLO plus partial NNLO, provide the best description of the HERA charm combined data. A simultaneous fit of PDFs and of the running charm quark mass has been performed with this scheme, yielding a value $m_c(m_c) = 1.26 \pm 0.06$; GeV, which is consistent with the world average value $m_c(m_c) = 1.275 \pm 0.025$ GeV [4].

At this conference two further brand new publications on charm production in DIS have been presented by ZEUS, based on the full reconstruction of D^* mesons [5] or D^+ mesons [6]. The data have good precision and are consistent with the HERA combined charm data; in the future they can be used to improve the combination.

Finally a general remark: the existing measurements of open charm and beauty quarks at HERA in DIS and also in photoproduction are described over the whole kinematic phase space, from smallest to largest transverse momenta or Q^2, by the NLO massive scheme calculations, so one could say that *the massive scheme prevails at HERA.*

4. Conclusions

Six years after the end of the HERA data taking there is still a continuous flow of new inclusive DIS precision results from the H1 and ZEUS experiments. Recently both experiments completed (and published) the analysis of the full high Q^2 data sets taken in the HERA II period. As a result, DIS data sets are now available spanning a huge phase space from smallest to highest Q^2 and x, with high precision up to Q^2 of a few 1000 GeV^2. Over the whole perturbative phasespace $Q^2 > 3.5$ GeV^2, the data are reasonably well described from smallest to largest x values by NLO DGLAP calculations.

The combination of H1 and ZEUS charm data in DIS provides a data set with (for charm production at HERA) unprecedented precisions of $\sim 5\%$. These data are a unique testing ground for the treatment of heavy quark mass dependent terms in pQCD. Among other things, a precise measurement of the running charm quark mass $m_c(m_c)$ was obtained, compatible with the world average value.

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