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Nuclear Physics B Proceedings Supplement 00 (2012) 1–6

Nuclear Physics B Proceedings Supplement

Precision Tests of QCD at HERA

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Abstract

The study of inclusive deep inelastic scattering (DIS) and jet production processes in ep scattering at HERA allows precision tests of QCD and constraining the parton density functions (PDF) of the proton which are of particular importance for the measurements at the LHC. A selection of new measurements of structure functions and hadronic final state observables by the H1 and ZEUS collaborations is presented. Recent results on PDF fits (HERAPDF) using the inclusive DIS and jet data from both experiments are shown.

Keywords: HERA, structure functions, DIS, jets

1. Introduction

The HERA accelerator at DESY in Hamburg was operated with 27.5 GeV electrons and 920 GeV protons colliding at a centre of mass energy of $\sqrt{s} = 318$ GeV. Around the two collision points the multipurpose 4π detectors H1 and ZEUS detector were build. There were two running periods: the HERAI period from 1992-2000 delivering an integrated luminosity L of $L \sim 120\,\text{pb}^{-1}$ and after a luminosity upgrade the HERAII period from 2003-2007 with $L \sim 380\,\text{pb}^{-1}$. At the end of the HERAII running period low energy runs were performed ($L \sim 20\,\text{pb}^{-1}$) with proton beam energies of 460 GeV and 575 GeV, respectively.

The electron proton scattering can be described in lowest order via the exchange of a electro weak gauge boson between the electron and a parton from the proton. The most important kinematic variables are the boson virtuality Q^2 and the Bjorken variable x which denotes in the quark parton model the fraction of the proton momentum carried by the parton scattered off. The measurements at HERA are made in two kinematic regions. In the photoproduction regime (γp) the photon virtuality is small, $Q^2 \approx 0\,\text{GeV}^2$, whereas deep inelastic scattering (DIS) is characterized by $Q^2 > 1\,\text{GeV}^2$.

For the description of the measurements presented here the QCD factorisation theorem holds which allows the production cross section to be written as the convolution of the parton distribution functions (PDFs) and the hard scattering matrix element. The hard scattering part can be treated with perturbative QCD (pQCD) in the presence of a hard scale. Important processes at leading order of the strong coupling constant α_s are boson gluon fusion (BGF) in which a quark-antiquark pair is created and QCD compton scattering where a quark from the proton is scattered off and radiates a gluon. These processes are enriched in jet samples compared to inclusive DIS. Therefore jet measurements provides direct sensitivity to the gluon density in the proton (BGF) and to α_s.

Inclusive and jet measurements provide a good testing ground for perturbative QCD and constraints on the PDFs. The PDFs measured at HERA can also be used to predict pp collisions at the LHC where instead of the electron a parton from the other proton enters the hard process. HERA covers the x range of the LHC. The evolution of the PDFs to higher Q^2 is done via the DGLAP equations.

2. Inclusive DIS

Inclusive neutral current (NC) DIS ep cross sections have been measured by H1 [1] covering a kinematic region of photon virtuality $Q^2 = 120 - 30000\,\mathrm{GeV}^2$. This brand-new measurement covers the full HERA data set. In Fig. 1 the reduced cross section is shown in bins of Q^2 for different values of x separately for e^+ and e^- data. A very high precision is achieved with a statistical accuracy of $1-3\%$ and a systematic uncertainty of about 1.5% for $Q^2 < 1000\,\mathrm{GeV}^2$. The cross sections are compared to predictions from the H1 NLO QCD fit (H1PDF2012) which describes the data well over this wide range of x, Q^2. ZEUS also provides a similar measurement [2]. The cross sections measured with a similar precision are well described by predictions from a HERA NLO QCD fit.

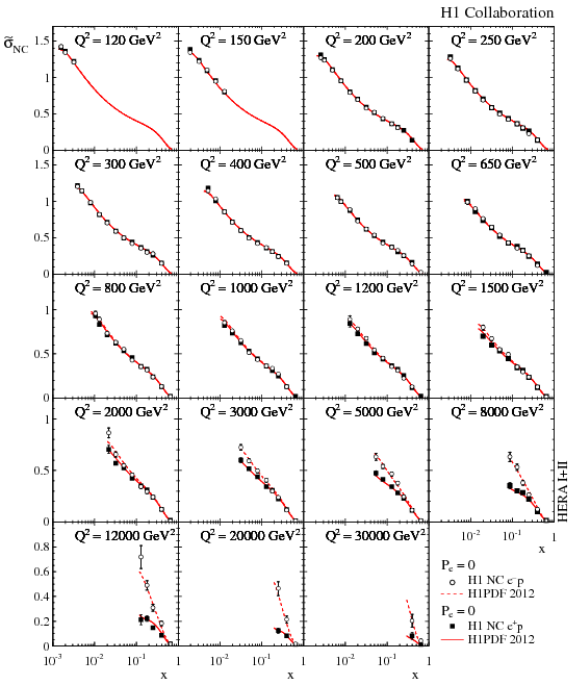

Figure 1: Reduced cross section in bins of Q^2 for different values of x for e^+ and e^- data measured by H1. The data are compared with NLO pQCD fit (H1PDF2012).

ZEUS performed an extension of the NC DIS measurement to higher values of x up to 1 [3] using a new reconstruction method for the kinematical variables. The data are in good agreement with standard model NLO predictions using different PDF sets. This analysis is expected to provide an important constraint on PDF at largest x.

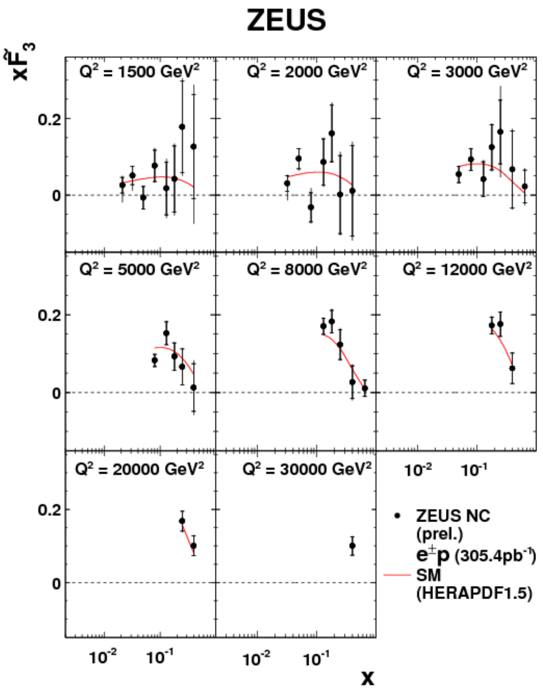

Figure 2: Measured xF_3 from NC DIS in bins of Q^2 for different values of x. The measured values (points) are compared to the standard model prediction from the HERAPDF1.5 fit.

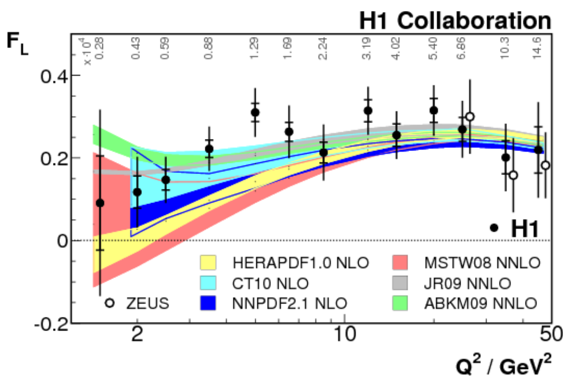

Figure 3: Measured F_L as a function of Q^2. Shown are the measurements from H1 (massive dots) and ZEUS (open points) and NLO (NNLO) pQCD predictions from different PDF groups.

From the ZEUS measurement in Ref. [2] mentioned above the structure function xF_3, is extracted from the difference of the cross sections for e^+ and e^- data for $Q^2 > 1500\,\mathrm{GeV}^2$. The result is shown in Fig. 2. The data agree well with expectations from the HERA-PDF1.5 NLO QCD fit. The good description of the data by the prediction means that the weak interaction contribution to the NC DIS cross section is understood and therefore the results can be used for PDF fits to constrain valence quark distributions.

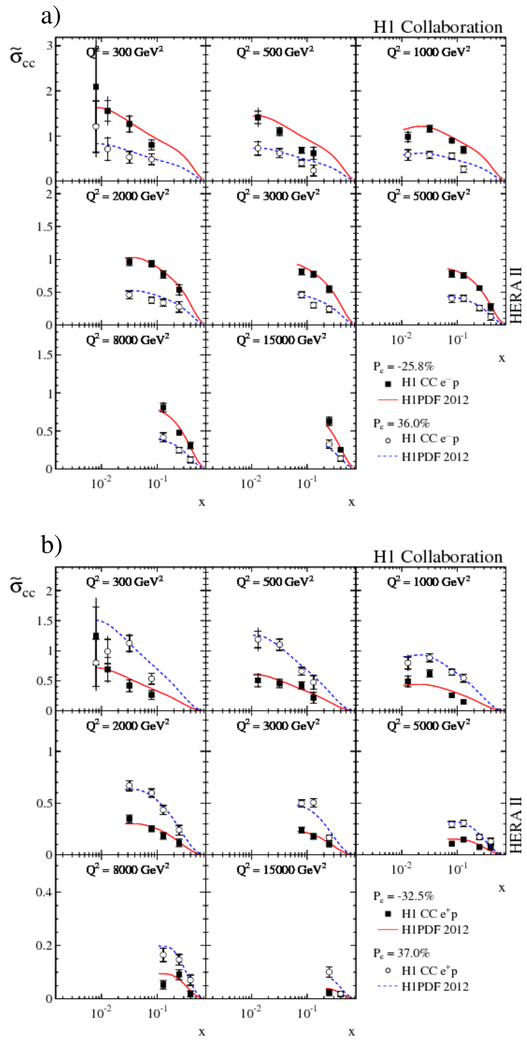

Figure 4: Reduced charged current cross section in for (a) e^- data and (b) e^+ data. The results are shown for left and right handed polarisation of the incoming lepton beam each. The measured cross sections are compared to expectations from NLO QCD fit H1PDF2012.

Based on HERA H1 data taken with different proton beam energies at the end of the HERAII run period the longitudinal structure function F_L has been extracted [4]. The result is shown in Fig. 3. The direct F_L measurement is in agreement with NLO (NNLO) QCD calculations using different PDF sets. The result provides a direct constraint of the gluon density in the proton.

Within the new H1 high Q^2 inclusive analysis [1] mentioned above charged current (CC) cross sections have been measured in x, Q^2 bins. The results are shown in Fig. 4 separated into charge and polarisation states of the incoming lepton beam. The measured cross sections agree well with the predictions from the NLO QCD fit H1PDF2012. The cross sections measured dependent on charge for left and right handed incoming lepton beam are an important input for PDF fits for the high x behavior of the valence quarks.

3. HERAPDF

The inclusive DIS NC and CC cross section results from H1 and ZEUS using data from all run periods are used to extract the PDFs [5, 6]. For this fit only HERA data are used since the data sets are consistent with well understood correlations. Furthermore, no nuclear cor-

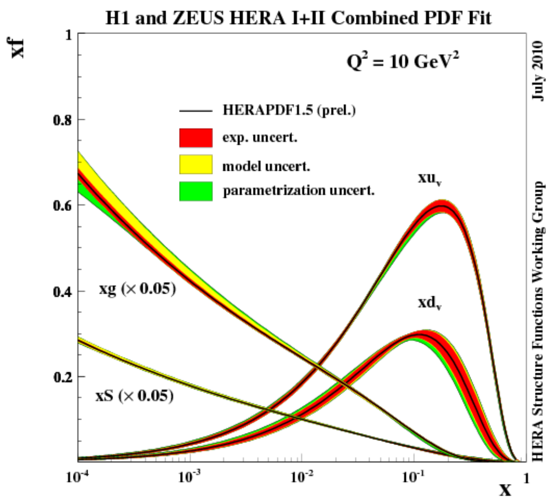

Figure 5: PDFs for valence quarks, gluons and sea quarks from HERAPDF1.5 fit at $Q^2 = 10\,\mathrm{GeV}^2$ as a function of x. For each PDF the central value (line) is shown together with the experimental, model and parametrisation uncertainty. The gluon and sea quark distributions are scaled by a factor of 0.05 for better visibility.

rections have to be applied as in the case of including fixed target data. For the fit NLO and NNLO pQCD predictions are used. The PDFs are parametrized at a starting scale $Q_0^2 = 1.9\,\mathrm{GeV}^2$ by $xf(x, Q_0^2) = Ax^B(1 -$

$x)^C(1 + Dx + Ex^2)$. The parameter A describes the overall normalisation, and B and C the small and the large x behavior, respectively. The parameters (D, E) reflect further information on the shape especially in the intermediate x region. The following PDFs are fitted: 1. gluon: xg, 2. valence quarks: xu_v and xd_v and 3. the sea quark distributions $x\bar{U} = x\bar{u}$ and $x\bar{D} = x\bar{d} + x\bar{s}$. The PDFs are evolved from the starting scale Q_0^2 to higher Q^2 using the DGLAP evolution equations. The QCD calculations are performed with a strong coupling constant $\alpha_S(M_Z) = 0.1176$.

The resulting PDFs from the HERAPDF1.5 fit are shown in Fig. 5 for $Q^2 = 10\,\text{GeV}^2$ together with the different unceretainties: The experimental uncertainty of the PDF fit arises from the errors on the measured cross sections. The model uncertainty is calculated from variations of parameters used in the QCD calculations like the masses of charm and beauty quarks or the strangeness fraction in the proton. The parametrisation uncertainty is calculated from varying the parametrisation of the PDFs used for fit.

4. Jets and α_s

Inclusive jet cross sections in γp with ($Q^2 < 1\,\text{GeV}^2$) have been measured by ZEUS[7]. Jets are reconstructed using the k_T clustering algorithm. For this analysis at least one jet is required with transverse energy E_T^{jet} and pseudorapidity η^{jet} of the jet of $E_T^{jet} > 21\,\text{GeV}^2$ and $-1 < \eta^{jet} < 2.5$, respectively. The measured cross sections as a function of E_T^{jet} and η^{jet} are shown in Fig. 6 and are described reasonably well by NLO pQCD calculations. The strong coupling constant α_s is extracted via NLO QCD fit to the measured cross section as a function of E_T^{jet}. A value of $\alpha_s(M_Z) = 0.1206 + 0.0023 - 0.0022\,(exp.) + 0.0042 - 0.0035\,(theo)$ is obtained. The strong coupling constant α_s is shown in Fig. 7 as a function of E_T^{jet} together with its bin to bin uncorrelated and correlated errors. The dominating theory error arises mainly from the variation of the renormalisation scale in the pQCD calculations used for fit. The accuracy of this measurement is therefore limited by theory due to missing NNLO pQCD calculations. An impressive property of the measured result is that the running af α_s is clearly visible in one experiment. The measured values are compared to QCD predictions of α_s at two loops which describe the data well.

New results from H1 concerning normalized multi jet cross sections in DIS are existing[8]. Inclusive jet, dijet and trijet cross sections have been measured as a function of the (mean) jet transverse momentum in different

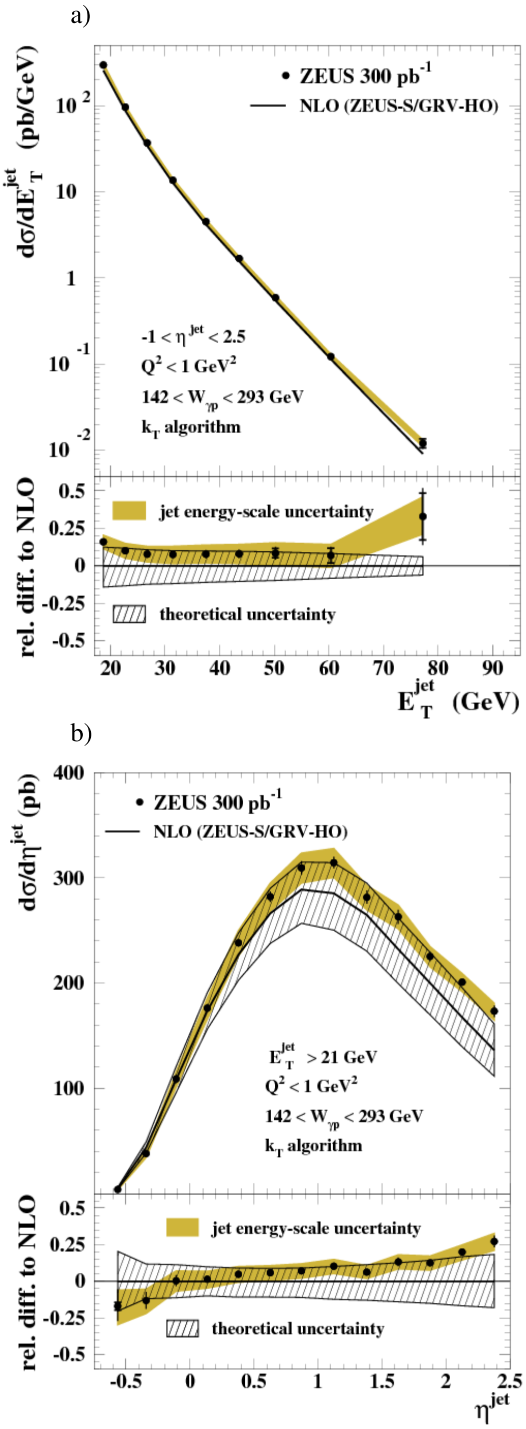

Figure 6: Measured inclusive jet cross sections in bins of (a) the transverse energy and (b) pseudorapidity of the leading jet together with the jet energy scale uncertainty. The predictions from NLO QCD are also shown. Below each panel the relative difference of the data to the NLO calculation is shown.

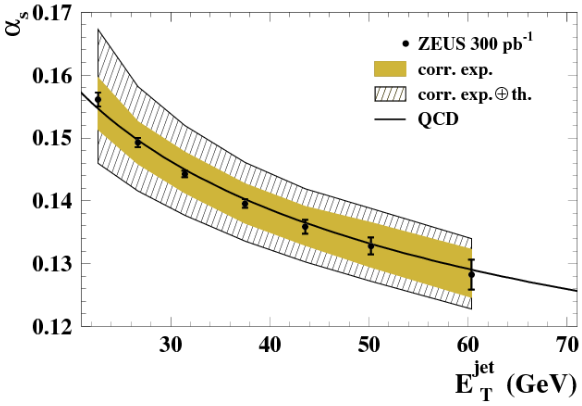

Figure 7: Strong coupling constant α_s as a function of the transverse jet energy E_T^{jet}. The points with error bars show the measured values together with the uncorrelated experimental uncertainties. The inner band show the correlated experimental uncertainty and the outer band the total correlated error consisting of the correlated experimental and theoretical uncertainty. The line shows the predicted value of α_s

Q^2 ranges from $Q^2 = 150\,\text{GeV}^2$ to $Q^2 = 15000\,\text{GeV}^2$. The measured values are normalized to the inclusive NC DIS cross section in each Q^2 region.

The results are shown in Fig. 8. The measured cross sections are compared to NLO pQCD calculation which describe the data well. The different orders in α_s for processes with different jet multiplicities motivates a combined NLO fit to the normalized inclusive, dijet and trijet cross sections to extract α_s. A value of $\alpha_s(M_Z) = 0.1163 \pm 0.0011\,(exp.) \pm 0.0014\,(PDF) \pm 0.0008\,(hadr) \pm 0.0039\,(ho)$ is obtained. The errors are the experimental error, the error due to the PDF uncertainty, error due to hadronisation correction uncertainties and the error from the variation of the renormalisation scale in pQCD. The latter is clearly dominanting because of missing higher orders in pQCD.

Since jet production processes provide direct sensitivity to the gluon density in the proton and α_s QCD fits with jet data allow to constrain simultanously α_s and the gluon PDF. Within the PDF fit HERAPDF1.6 [9, 10] the HERA inclusive NC,CC data from HERAPDF1.5 is used together with the inclusive jet measurements from H1 and ZEUS. The fit is performed with free α_s as additional fit parameter. To illustrate the effect of including jet data for fit Fig. 9 shows $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ as a function of $\alpha_s(M_Z)$. The local minimum is much more distinct

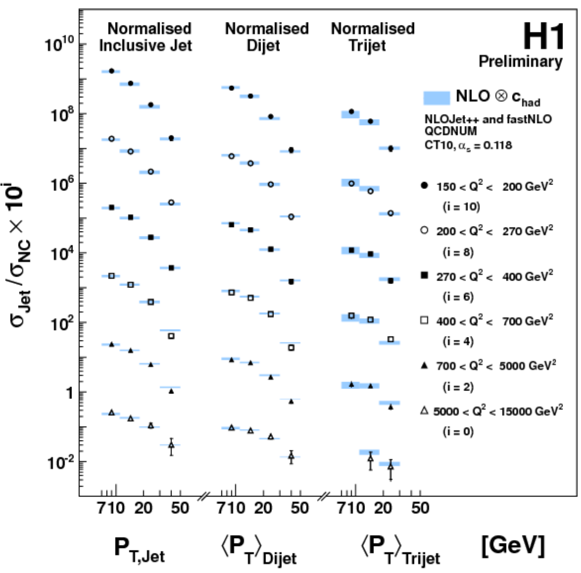

Figure 8: Normalized inclusive jet, dijet and trijet cross sections as a function of the (mean) jet transverse momentum. The results are plotted for diffeent Q^2 ranges indicated by the different markers. The band shows the results from a NLO pQCD calculation.

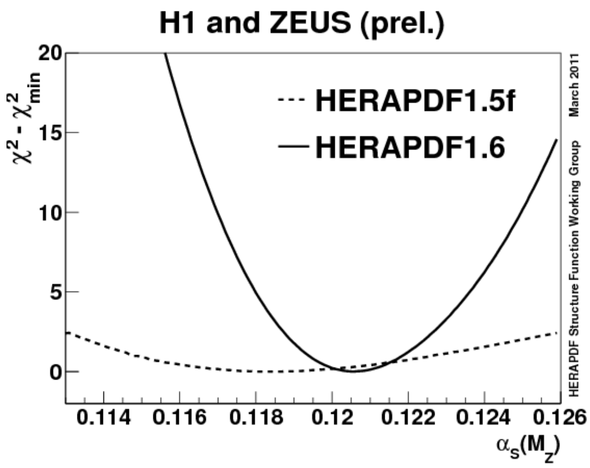

Figure 9: $\Delta\chi^2(\alpha_s(M_Z)) = \chi^2(\alpha_s(M_Z)) - \chi^2_{min}$ from the fit for free α_s fit. The solid line shows the case of the HERAPDF1.6 fit including jet data and the dashed line corresponds to the fit without jet data.

when including jet data. In addition the uncertainty on the gluon density for free α_s fit is reduced by a factor up to 2 when including jets.

As final result the value of $\alpha_s(M_Z)$ is $\alpha_s(M_Z) = 0.1202 \pm 0.0013\,(exp.) \pm 0.0007\,(PDF) \pm 0.0012\,(hadr) + 0.0045 - 0.0036\,(ho)$. Also here the dominant error on

α_s is due to missing higher orders in pQCD. All results on α_s presented here are consistent with the world average of $\alpha_s(M_Z) = 0.1184 \pm 0.0007$ taken from Ref. [11].

5. Summary

New inclusive and jet measurements from the H1 and ZEUS experiments at HERA with high experimental precision in an extended range of x and Q^2 are performed. The measured cross sections and structure functions allow precise tests of pQCD. All measurements are well described by predictions from NLO pQCD. The good understanding of the measurements allows the data to be used to determine the proton PDFs. The inclusive HERA data provide the backbone for all modern PDFs. For the HERAPDF1.5 set only the inclusive HERA data with well understood correlations are used. The extracted proton PDFs from HERA are of particular importance for understanding measurements at the LHC. A new PDF fit (HERAPDF1.6) has been performed which uses in addition to the inclusive also the jet HERA data. This allows to constain simultanously the gluon PDF and α_s. The precision on α_s is limited by the theoretical uncertainty due to missing higher orders in pQCD. The extracted value of α_s is consistent with the world average with a experimental precision comparable to the error on the world average.

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