Perturbative QCD at HERA

L. K. Gladilin* on behalf of the H1 and ZEUS Collaborations

Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (SINP MSU), Moscow, 1(2), Leninskie gory, GSP-1, 119991, Russian Federation

* E-mail: gladilin@sinp.msu.ru

Recent measurements of proton structure, jet production cross sections, the strong coupling constant value, prompt photon production cross sections, charmed hadron production cross sections and the charm and beauty quark mass values, performed by the H1 and ZEUS collaborations at the $e^\pm p$ collider HERA, are presented.

Keywords: QCD; proton structure; jets; prompt photons; heavy quarks.

1. Introduction

The unique $e^+p$ and $e^-p$ collider HERA operated in 1992-2007 in DESY, Hamburg, with collision centre-of-mass energy of $300-320$ GeV. Two collider experiments, H1 and ZEUS, accumulated data samples corresponding to an integrated luminosity of $\sim 0.5$ fb$^{-1}$ each. Both experiments continue the data analysis. Their new results in the area of perturbative QCD are briefly summarised in this note.

2. Proton structure

The H1 and ZEUS combined data set on Neutral Current (NC) and Charged Current (CC) $e^+p$ and $e^-p$ inclusive cross sections is used as the input for next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) QCD parton density function (PDF) fits resulting in a new preliminary PDF set called HERAPDF2.0 (prel.).

The analysis yields small experimental uncertainties and includes estimates for model and parametrisation uncertainties.

Figure 1 shows the parton distribution functions $xu_v$, $xd_v$, $xS = 2x(\bar{U} + \bar{D})$ and $xg$ from HERAPDF2.0 (prel.) at the factorisation scale $\mu_f^2 = 10$ GeV$^2$ for the $Q^2_{\text{min}} = 3.5$ GeV$^2$ fit at NLO and NNLO.

3. Jets and $\alpha_s$

Measurements of inclusive jet, dijet and trijet cross sections in the Breit frame in deep-inelastic scattering (DIS) in the kinematical range $150 < Q^2 < 15000$ GeV$^2$ and $0.2 < y < 0.7$ are performed, using H1 data corresponding to an integrated luminosity of 351 pb$^{-1}$. Jets are determined using the $k_T$ and the anti-$k_T$ jet algorithm. The measurements consist of absolute jet cross sections as well as jet cross sections normalised to the neutral current DIS cross sections.
hadronisation and electroweak effects, provide a good description of the measured uncertainties and the statistical and systematic uncertainties added in quadrature. The NLO QCD predictions, corrected for hadronisation and electroweak effects, together with their uncertainties are shown by the shaded band. The cross sections for individual $Q^2$ bins of the jet measurements. The inner and outer error bars indicate the statistical uncertainties and the statistical and systematic uncertainties added in quadrature. The NLO QCD predictions, corrected for hadronisation and electroweak effects, together with their uncertainties are shown separately.

Figure 2 shows the double-differential jet cross sections as a function of $Q^2$ and $P_T$ before (a) and after (b) normalisation to the inclusive neutral current cross sections in the respective $Q^2$ bins of the jet measurements. The inner and outer error bars indicate the statistical uncertainties and the statistical and systematic uncertainties added in quadrature. The NLO QCD predictions, corrected for hadronisation and electroweak effects, together with their uncertainties are shown by the shaded band. The cross sections for individual $Q^2$ bins are multiplied by a factor of $10^4$ for better readability.

Figure 2 shows the double-differential jet cross sections as a function of $Q^2$ and $P_T$ before and after the normalisation. The variable $P_T$ is the jet transverse momentum $P_T^{jet}$ or, in case of dijets and trijets, the mean transverse momentum $<P_T>$ and $<P_T>_2$. Theoretical QCD calculations at NLO, corrected for hadronisation and electroweak effects, provide a good description of the measured
double-differential jet cross sections.

The jet cross sections are used to determine the value of the strong coupling constant $\alpha_s$ at the scale of the mass of the Z-boson, $M_Z$, in the framework of perturbative QCD. The value of the strong coupling constant $\alpha_s$, determined in an iterative $\chi^2$-minimisation procedure using NLO calculations, is

$$\alpha_s(M_Z) = 0.1165 \pm 0.0008_{\text{exp}} \pm 0.0038_{\text{pdf}}.$$
4. Prompt photons

Measurements of isolated-photon production at high transverse energy with and without an explicit accompanying-jet requirement are performed\textsuperscript{3,4} in photoproduction ($Q^2 < 1\text{ GeV}^2$). Photon candidates are identified as calorimeter clusters with no associated track, and with at least 90\% of the reconstructed energy measured in the electromagnetic calorimeter. Jet reconstruction is performed by means of the $k_T$ clustering algorithm.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure4.png}
\caption{Differential cross sections as functions of (a) $E_T^\gamma$ and (b) $\eta^\gamma$ for events containing an isolated photon, compared to predictions from FGH and LMZ. The inner and outer error bars respectively denote statistical uncertainties and statistical uncertainties combined with systematic uncertainties in quadrature. The theoretical uncertainties are shown as hatched and dotted bands.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure5.png}
\caption{Differential cross sections as functions of (a) $\eta^\text{jet}$ and (b) $x_{\gamma^\text{meas}}$ for events containing an isolated photon accompanied by a jet, compared to predictions from FGH and LMZ. The inner and outer error bars respectively denote statistical uncertainties and statistical uncertainties combined with systematic uncertainties in quadrature. The theoretical uncertainties are shown as hatched and dotted bands.}
\end{figure}

Figure 4 shows differential cross sections as functions of $E_T^\gamma$ and $\eta^\gamma$ for events containing an isolated photon, compared to predictions from Fontannaz, Guillet and Heinrich (FGH)\textsuperscript{5} and Lipatov, Malyshev and Zotov (LMZ)\textsuperscript{6}. Figure 5 compares differential cross sections as functions of $\eta^\text{jet}$ and $x_{\gamma^\text{meas}}$ for events containing an
isolated photon accompanied by a jet, with the FGH and LMZ predictions. The quantity

$$x_{\gamma}^{\text{meas}} = \frac{E_{\gamma} + E_{\text{jet}} - p_{Z} - p_{Z}^{\text{jet}}}{E_{\text{all}} - p_{Z}^{\text{all}}}$$

is a measure of the fraction of the incoming photon energy given to the final-state photon and jet, at a lowest-order approximation. The energies and longitudinal momentum components of the photon, the jet and all of the energy deposits in the event are combined as indicated. The NLO-based predictions from FGH describe the distributions well. The predictions of LMZ, within their uncertainties, also describe the photon distributions well, but give a less good description at low $\eta^{\text{jet}}$ and low $x_{\gamma}^{\text{meas}}$.

5. Heavy quark production and masses

Differential cross sections for the production of $D^{*\pm}$ mesons in DIS have been measured\(^7\) in the kinematic range $5 < Q^2 < 1000 \text{ GeV}^2$, $0.02 < y < 0.7$, $1.5 < p_{T}^{D^*} < 20 \text{ GeV}$, $|\eta^{D^*}| < 1.5$, using data from an integrated luminosity of $363 \text{ pb}^{-1}$.

![Figure 6](image-url)

Fig. 6. Differential $D^{*\pm}$ cross sections as a function of (a) $Q^2$, $y$, $x$ and (b) $p_{T}^{D^*}$, $\eta^{D^*}$, $z^{D^*}$. The error bars show the statistical and systematic uncertainties added in quadrature, the inner bars show the statistical uncertainties alone. Also shown are NLO QCD predictions calculated using HVQDIS (dashed line and shaded area for the uncertainties) and RAPGAP MC prediction for charm creation via boson-gluon fusion (long-dashed line). The contribution from b-quark decays, calculated with the RAPGAP MC (continuous line), is included in the predictions. The MC cross sections for charm (beauty) are scaled by 1.1 (1.6).

Figure 6 shows differential $D^{*\pm}$ cross sections as a function of $Q^2$, $y$, $x$, $p_{T}^{D^*}$, $\eta^{D^*}$ and $z^{D^*}$. The variable $z^{D^*}$ is defined as $z^{D^*} = (E^{D^*} - p_{Z}^{D^*})/(2E_{e}y)$. The data are reasonably well described by NLO QCD calculations.

Measurements of open charm production in deep-inelastic $ep$ scattering by the H1 and ZEUS experiments using different charm tagging methods are com-
combined, accounting for the systematic correlations. The measurements are extrapolated to the full phase space using an NLO QCD calculation to obtain the reduced charm quark-pair cross sections, \( \sigma_{c\bar{c}}^{\text{red}} \), in the region of photon virtualities \( 2.5 < Q^2 < 2000 \text{ GeV}^2 \). In total, 155 measurements are combined to 52 cross section measurements.

Figure 7(a) shows the combined reduced cross sections as a function of \( x \), in bins of \( Q^2 \), and compares them to the input H1 and ZEUS data. The combined data are significantly more precise than any of the individual input data sets. In Fig. 7(b), the data are compared to the NLO predictions based on HERAPDF1.5 extracted in the Robert Thorne (RT) standard scheme using as inputs the HERA inclusive DIS data. For the central PDF set, a charm quark mass parameter \( m_c = 1.4 \text{ GeV} \) is used. The uncertainty bands of the predictions reflect the full uncertainties on the HERAPDF1.5 set. They are dominated by the uncertainty on \( m_c \) which is varied between 1.35 GeV and 1.65 GeV. A combined NLO QCD analysis is performed using the reduced charm cross sections together with the combined inclusive DIS cross sections. For each heavy flavour scheme, a number of PDF fits is performed with varying \( m_c \) from 1.2 GeV to 1.8 GeV. For each fit, the \( \chi^2(m_c) \) value is calculated and the optimal value, \( m_c^{\text{opt}} \), of the charm quark mass parameter in a given scheme is subsequently determined from a parabolic fit.

Figure 8(a) shows the values of \( \chi^2 \) for the PDF fit to the combined HERA DIS data including charm measurements as a function of the running charm quark mass.
Fig. 8. (a) The values of $\chi^2$ for the PDF fit to the combined HERA DIS data including charm measurements as a function of the running charm quark mass $m_c(m_c)$. The FFNS ABM scheme is used, where the charm quark mass is defined in the MS-bar scheme. (b) Measured charm mass $m_c(\mu)$ in the MS running mass scheme as a function of the scale $\mu$. The red point at scale $m_c$ is the PDG world average and the band is its expected running.

$m_c(m_c)$ in the ABM version of the massive fixed-flavour-number scheme (FFNS), where the charm quark mass is defined in the MS scheme. The fit of the parabolic function results in a value of

$$m_c(m_c) = 1.26 \pm 0.05_{\text{exp}} \pm 0.03_{\text{mod}} \pm 0.02_{\text{param}} \pm 0.02_{\alpha_s} \text{GeV}$$

for the running charm mass in NLO. The errors correspond to the experimental, the model, parameterisation and $\alpha_s$ dependent uncertainties.

Figure 8(b) shows the measured charm mass $m_c(\mu)$ in the MS running mass scheme as a function of the scale $\mu = \sqrt{Q^2 + 4m_c(m_c)^2}$. The data are consistent with this running.

Inclusive jet production cross sections in events containing beauty or charm quarks have been measured, exploiting the long lifetimes and large masses of $b$ and $c$ hadrons. The heavy-quark contributions to the proton structure function $F_2$ as well as beauty and charm reduced cross sections were extracted from the double-differential cross sections as a function of $x$ and $Q^2$.

Figure 9(a) shows the reduced beauty cross section, $\sigma_{b\bar{b}}$, as a function of $x$ for seven different values of $Q^2$. Also shown are the results of the QCD fit. The fit for the running beauty-quark mass was performed using the ABM implementation of the FFNS at NLO.

Figure 9(b) shows the values of $\chi^2$ for the PDF fit to the combined HERA DIS data including the beauty measurements, as a function of the running beauty quark mass $m_b(m_b)$. The beauty-quark mass and its uncertainty are determined from a parabolic parameterisation. The best fit yields

$$m_b(m_b) = 4.07 \pm 0.14 \text{ (fit)}^{+0.01}_{-0.07} \text{ (mod.)}^{+0.05}_{-0.06} \text{ (param.)}^{+0.08}_{-0.05} \text{ (theo.) GeV}$$
Fig. 9. (a) Reduced beauty cross section, $\sigma_b^{br}$, (filled symbols) as a function of $x$ for seven different values of $Q^2$. The inner error bars are the statistical uncertainty while the outer error bars represent the statistical, systematic and extrapolation uncertainties added in quadrature. Also shown are the results of the QCD fit. The central line indicates the best fit, the lower and upper line give the fit for a higher and lower beauty mass, respectively. (b) The values of $\chi^2$ for the PDF fit to the combined HERA DIS data including the beauty measurements, as a function of the running beauty quark mass $m_b$. The FFNS ABM scheme is used, where the beauty quark mass is defined in the $\overline{\text{MS}}$ scheme. The solid line is a second order polynomial parameterisation of the points.

for the $\overline{\text{MS}}$ running beauty-quark mass at NLO. The errors correspond to the fit (fit), the model parameters (mod.), PDF parameterisation (param.) and QCD parameters (theo.) uncertainties. This value agrees well with the world average.

References

1. H. Abramowicz et al., the H1 and ZEUS Collaborations, ZEUS-prel-14-007, H1prelim-14-042, https://www.desy.de/h1zeus/combined_results/herapdftable/.
4. H. Abramowicz et al., the ZEUS Collaboration, JHEP 08, 023 (2014).