ZEUS NLOQCD fits

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ABSTRACT: NLO QCD fits using the DGLAP formalism have been made to the high precision ZEUS e^+p reduced cross-section data and to fixed target structure function data, in order to determine parton distribution functions and the value of $\alpha_s(M_Z^2)$, taking full account of correlated systematic errors.

The new high precision ZEUS data on the neutral current e^+p reduced cross section [1] are fit to the predictions of NLO QCD using the DGLAP equations, in order to determine parton distribution functions and the value of $\alpha_s(M_Z^2)$. The increased range ($6.3 \times 10^{-5} < x < 0.65$, $2.7 < Q^2 < 30000 GeV^2$) and precision (systematic errors $\sim 3\%$, statistical errors $\lesssim 1\%$, for $2 < Q^2 < 800 GeV^2$) of the ZEUS data allow a much improved determination of the gluon and sea distributions compared to our previous work [2]. In recent years more emphasis has been placed on estimating errors on extracted parton distributions. We present parton distributions including full accounting for uncertainties from experimental correlated systematic errors. We are also able to measure the value of $\alpha_s(M_Z^2)$ taking full account of the correlations between the shape of the parton distribution functions and α_S. Full details of the analysis are given in [3].

This analysis is performed within the conventional paradigm of leading twist, NLO QCD, with the renormalisation and factorization scales chosen to be Q^2. The heavy quark production scheme is the general mass variable flavour number scheme of Roberts and Thorne [4]

The kinematics of lepton hadron scattering is described in terms of the variables Q^2, the invariant mass of the exchanged vector boson, Bjorken x, the fraction of the momentum of the incoming nucleon taken by the struck quark (in the quark-parton model), and y which measures the energy transfer between the lepton and hadron systems. The differential cross-section for the process is given in terms of the structure functions by

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left[Y_+\, F_2(x,Q^2) - y^2\, F_L(x,Q^2) - Y_-\, xF_3(x,Q^2)\right],$$

where $Y_\pm = 1 \pm (1-y)^2$. The structure functions F_2 and xF_3 are directly related to non-singlet and singlet quark distributions, and their Q^2 dependence, or scaling violation, is predicted by pQCD. At $Q^2 \lesssim 1000\text{GeV}^2$ F_2 dominates the charged lepton-hadron cross-section and for $x \lesssim 10^{-2}$ the gluon contribution dominates the Q^2 evolution of F_2, such that ZEUS data provide crucial information on quark and gluon distributions. (Schematically, $F_2 \sim xq$, $dF_2/dlnQ^2 \sim \alpha_s P_{qg} xg$).

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We have performed a global fit of ZEUS and fixed target DIS data. The fixed target data sets used are those with precision data for which full information on the correlated systematic errors is available (NMC, E665, BCDMS muon induced F_2 data on proton and deuterium targets and CCFR $\nu, \bar{\nu}$ xF_3 data on an Fe target [5]). These data are used to gain information on the valence quark distributions and the flavour composition of the sea, and to constrain the fits at high x. However, our focus is on the additional information to be gained from the new precision ZEUS data, particularly on the gluon and quark densities at low x and on the value of $\alpha_s(M_Z^2)$.
In the standard fit the following cuts are made on the ZEUS and the fixed target data: (i) $W^2 > 20$ GeV^2 to reduce the sensitivity to target mass and higher twist contributions which become important at high x and low Q^2; (ii) $Q^2 > 2.5$ GeV^2 to remain in the kinematic region where perturbative QCD should be applicable.
The QCD predictions for the structure functions needed to construct the reduced cross-section are obtained by solving the DGLAP evolution equations at NLO in the $\overline{\mathrm{MS}}$ scheme. These equations yield the quark and gluon momentum distributions (and thus the structure functions) at all values of Q^2 provided they are input as functions of x at some input scale Q_0^2. The parton distribution functions (PDFs) for u valence, d valence, total sea, gluon and the difference between the d and u contributions to the sea, are each parametrized by the form

$$p_1 x^{p_2}(1-x)^{p_3}(1+p_5 x)$$

at $Q_0^2 = 7\mathrm{GeV}^2$. Thus the flavour structure of the light quark sea allows for the violation of the Gottfried sum rule. We also impose a suppression of the strange sea of a factor of 2 at Q_0^2, consistent with neutrino induced dimuon data from CCFR.
The parameters $p_1 - p_5$ are constrained to impose the momentum sum-rule and the number sum-rules on the valence distributions. The gluon distribution has $p_5 = 0$, because non zero values have minimal effect on the χ^2 of the fit, and because this choice constrains the high x gluon to be positive without the need for penalty χ^2 terms. There are 11 free parameters in the standard fit when the strong coupling constant is fixed to $\alpha_s(M_Z^2) = 0.118$ [6], and 12 free parameters when $\alpha_s(M_Z^2)$ is determined by the fit. Full account has been taken of correlated experimental systematic errors as follows. The definition of the χ^2 is

$$\chi^2 = \sum_i \frac{[F_i(p,s) - F_i(meas))]^2}{(\sigma_{stat}^2 + \sigma_{unc}^2)} + \sum_\lambda s_\lambda^2$$

where

$$F_i(p,s) = \frac{F_i(NLOQCD)(p)}{[1 + \sum_\lambda s_\lambda \Delta_{i\lambda}^{sys}]}$$

The latter equation modifies the NLOQCD prediction for the measured quantity F (structure function or reduced cross-section), which is a function of the PDF parameters p, to include the effect of the correlated systematic errors. $\Delta_{i\lambda}^{sys}$ is the fractional systematic error on data point i due to source λ and s_λ are systematic error parameters. These systematic errors are assumed to represent a one standard deviation error. The systematic error parameters are fixed to zero for the fit, but allowed to vary for error analysis, such that both the error matrices

$$M_{jk} = \frac{1}{2}\frac{\delta^2\chi^2}{\delta p_j \delta p_k}, C_{j\lambda} = \frac{1}{2}\frac{\delta^2\chi^2}{\delta p_j \delta s_\lambda}$$

are evaluated, and the systematic covariance matrix is given by $V^{ps} = M^{-1}CC^TM^{-1}$, so that the total covariance matrix is given by $V^{tot} = V^p + V^{ps}$, where $V^p = M^{-1}$. This method is equivalent to offsetting each systematic parameter by ± 1, reminimizing and adding the resulting deviations, Δp, from the parameters determined in the standard fit in quadrature [7]. Thus it produces a conservative estimate of the effect of systematic errors. Normalization errors are included as correlated systematic errors. In total 71 independent sources of systematic error are included.

A good description of the structure function and reduced cross-section data over the whole range of Q^2 from 2.5 to 30000 GeV^2 is obtained. The quality of the fit to the new ZEUS NC reduced cross-section and F_2 data is shown in [1]. The quality of the fit to all the data sets may be judged from the χ^2. Adding the statistical and systematic errors in quadrature gives a total χ^2 per data point of 0.95 for 1263 data points and 11 free parameters.

The parton distributions extracted from the fit are shown in Fig. 1. The ZEUS data are crucial in determining the gluon and the sea distributions so we consider these in more detail. In Fig 2 we show the extracted gluon distribution in several Q^2 bins. The uncertainty in these distributions is further illustrated in Fig 3 where the ratio of the error bands to the central value is shown. In these figures the innermost error bands show the statistical and uncorrelated systematic error, the middle error bands show the total experimental error including correlated systematic errors and the outer error bands show the additional uncertainty coming from variation of the strong coupling constant $\alpha_s(M_Z^2)$, which is taken into account with full correlations by allowing $\alpha_s(M_Z^2)$ to be a parameter of the fit.

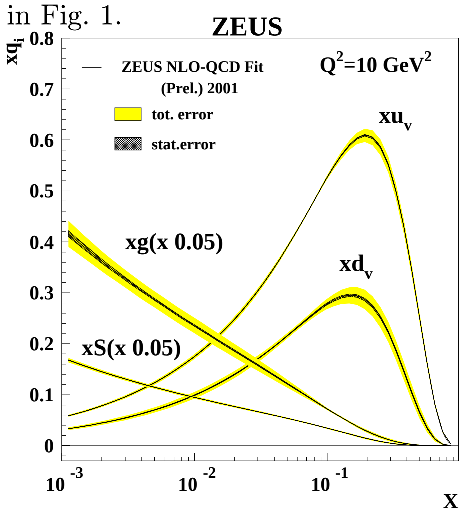

Figure 1: The gluon, sea, u and d valence distributions extracted from the standard ZEUS fit, at $Q^2 = 10\text{GeV}^2$, with the error bands resulting from statistical, uncorrelated and correlated systematic errors.

For $Q^2 \gtrsim 5$ GeV^2, the gluon distribution rises steeply at low x . It is well determined to within $\sim 10\%$ for $Q^2 > 20$ GeV^2, $10^{-4} < x < 10^{-1}$, and its uncertainty decreases as Q^2 evolves upwards. Considerable uncertainty remains for $x > 0.1$, where one needs information from Tevatron jet studies or prompt photon

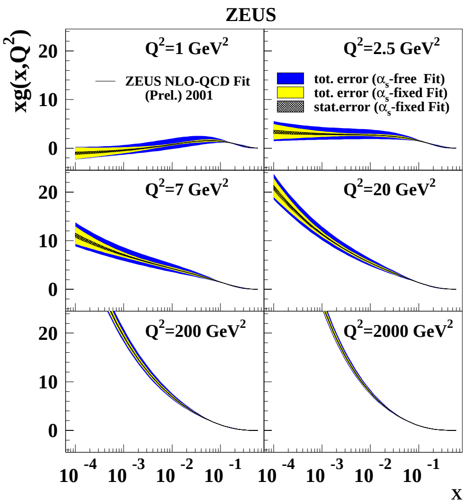

Figure 2: The gluon distribution from the standard ZEUS NLOQCD fit.

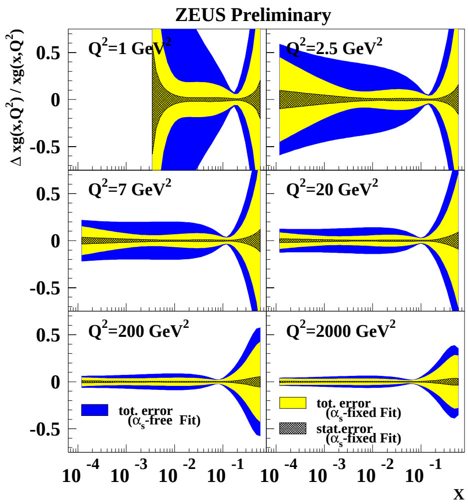

Figure 3: The uncertainties on the gluon distribution from the standard ZEUS NLOQCD fit, shown as the ratio of the error bands to the central value.

data. At low Q^2 the gluon shape is flatter at low x, and if the fit is extrapolated back to $Q^2 = 1$ GeV^2 the gluon shape becomes valence like, with low x values that are negative within errors. (This is also true of the structure function F_L which is closely related to the gluon.) The new precision ZEUS data collected in 96/97 shows this tendency even more strongly than the previous 94/5 data [2].

In Fig 4 we show the extracted sea distributions in several Q^2 bins. The uncertainty in these distributions is is less than $\sim 5\%$ for $Q^2 \gtrsim 2.5$ GeV^2 and $10^{-4} < x < 10^{-1}$. It can be seen that even at the smallest $Q^2 \sim 1$ GeV^2 the sea distribution is still rising slightly at small x. In the same Q^2, x region the gluon distribution is falling and is consistent with zero. Thus the rise in the sea distribution cannot be driven by the gluon $g \to q\bar{q}$ splitting in this region.

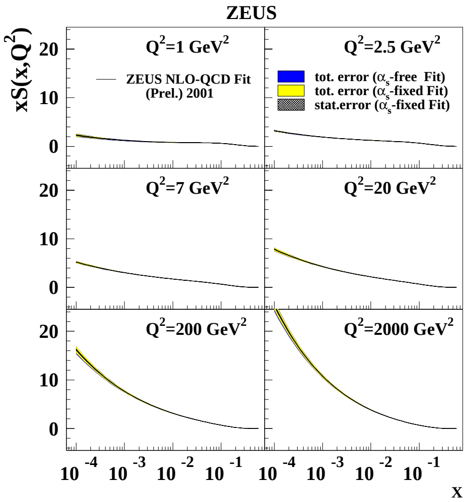

Figure 4: The sea distribution from the standard ZEUS NLOQCD fit

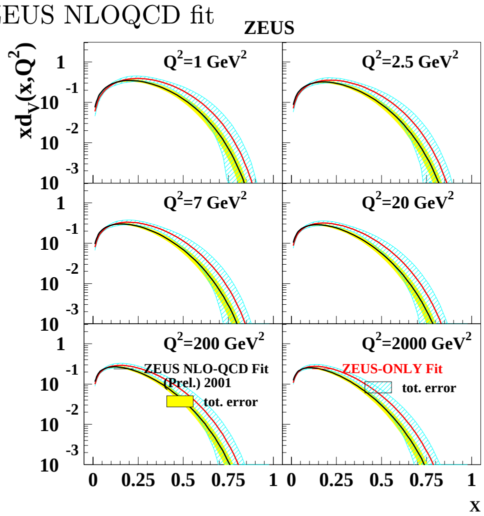

Figure 5: The xd_v distribution from the NLOQCD fit to ZEUS data alone.

We also make a fit using only ZEUS data, including the charged current e^+p reduced cross-section data [8] and the neutral and charged current e^-p data [9], [10]. This high Q^2 data is very well described by the standard fit. However now we use this data to constrain the valence distributions. The d_v valence distribution for this fit is shown in Fig 5 where the d_v distribution for the standard fit, including fixed target data, is shown for comparison. Clearly the standard fit gives a more precise determination, but the high Q^2 ZEUS reduced cross-section data is able to provide some constraint on the valence distributions. We can see that ZEUS data prefer a larger d valence distribution at high x than the standard fit.

NLO DGLAP QCD fits give good descriptions of F_2 data down to Q^2 values in the range $1 - 2$ GeV^2 but such fits assume the validity of the NLO DGLAP QCD formalism even for low Q^2 (where α_S is becoming larger such that NNLO corrections are increasingly important) and very low x (where $ln(1/x)$ resummation terms could be important). The fits also ignore high density and non-perturbative effects (see Refs. [11] for a discussion of these effects). To investigate if there is a technical low Q^2 limit to the NLO QCD fit (in the sense that the fit fails to converge or gives a very bad χ^2), we extrapolate our standard fit into the region covered by the very low Q^2 ZEUS BPT [12] data. In Fig 6 the main ZEUS data sample and the ZEUS BPT data are shown in very low Q^2 bins compared to the fit predictions.

We see that NLO DGLAP fit is unable to describe the very precise BPT data for $Q^2 \lesssim 0.65$ GeV^2, even when the full error bands on the fit due to the correlated systematic errors are included. This remains true even if these data are included in the fit: they produce very poor fits, with χ^2 per data point of 3.9 or more. The predictions for F_L for these low Q^2 values are also significantly negative for $Q^2 \lesssim 0.8$ GeV^2 indicating that the NLO DGLAP formlism cannot be valid in this region.

The value of $\alpha_s(M_Z^2)$ is measured by allowing it to be a parameter of the fit. We obtain,

$$\alpha_s(M_Z^2) = 0.1172 \pm 0.0008(stat+uncorr) \pm 0.0054(corr),$$

where the first error represents statistical and uncorrelated systematic errors and the second error represents the correlated systematic errors from all the contributing experiments, including their normalization errors. The contribution of normalization errors is as large as half the correlated systematic error.
The renormalization and factorization scales used in the fit may be varied from $Q^2/2 \to 2Q^2$, as a way of estimating the importance of NNLO and $ln(1/x)$ terms. This produces variations in $\alpha_s(M_Z^2)$ of ~ 0.004. Within the paradigm of NLO DGLAP the contribution of the correlated systematic errors is the most significant source of uncertainty. Variation of analysis choices, such as the form of the parametrization at Q_0^2, the value of Q_0^2, the minimum Q^2 of data entering the fit, do not produce a significant model error. A more significant choice is that of the heavy quark production scheme. Repeating the standard fit using the FFN scheme or the ZMVFN scheme produces a variation in $\alpha_s(M_Z^2)$ of ± 0.001.

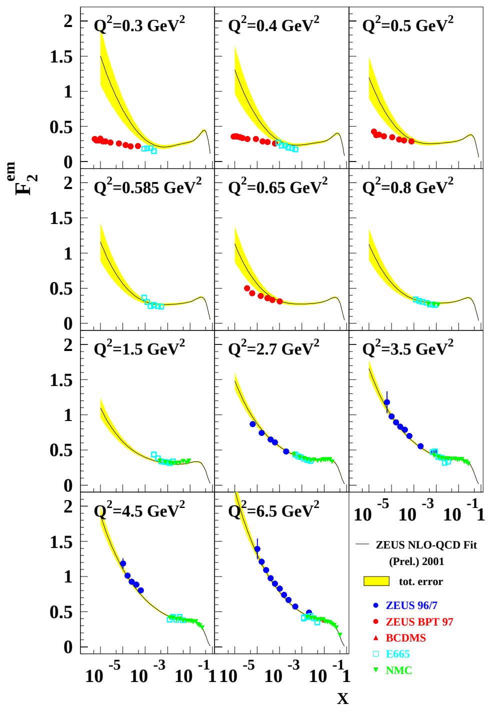

Figure 6: F_2 data down to the very low Q^2 (including BPT data) compared to the standard NLOQCD fit backward extrapolated.

The well known correlation of the value of $\alpha_s(M_Z^2)$ to the gluon shape is accounted for by performing a simultaneous fit for $\alpha_s(M_Z^2)$ and the PDF parameters. The largest uncertainty in the gluon shape is now at large x. Tevatron jet data suggests a larger gluon at high x than that found in our standard fit, and if we use such data to constrain our fit we obtain $\alpha_s(M_Z^2) \sim 0.121$, a variation within the quoted error.
Thus, when a full accounting of correlated systematic errors is included, there is no contradiction between the lower values of $\alpha_s(M_Z^2)$ originally determined from fixed target DIS data, e.g. $\alpha_s(M_Z^2) = 0.113$ from BCDMS [13], and the higher values favoured by LEP data $\alpha_s(M_Z^2) \sim 0.120$ [6].

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