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QCD analysis and determination of α_s using the combined H1 and ZEUS inclusive cross sections together with the jet production cross section measured by the H1 and the ZEUS experiments.

H1 and ZEUS Collaborations

Abstract

An NLO QCD PDF fit analysis with simultaneous determination of the strong coupling constant $\alpha_s(M_Z)$ is presented. The analysis is based on the same combined H1 and ZEUS inclusive DIS measurements as the HERAPDF1.5 fit, together with jet measurements provided by both the H1 and ZEUS collaborations. The inclusion of jet data in the analysis significantly reduces the correlation between the gluon parton density function and the strong coupling constant, improving the precision of the gluon PDF and providing an accurate unbiased determination of $\alpha_s(M_Z)$.

1 Introduction

The analysis presents an NLO QCD fit to determine Parton Density Functions (PDFs) simultaneously with the strong coupling constant $\alpha_s(M_Z)$. The strong correlation between the gluon density function and the strong coupling constant, leading to a high experimental uncertainty on both the gluon PDF and α_s, has been significantly reduced by the inclusion of the H1 and ZEUS jet data to the fit.

1.1 Data used in the PDF fit

The cross sections of jet production in DIS as measured by the H1 [4, 5] and ZEUS [6, 7] experiments are used in the analysis together with the combined NC and CC e^+ and e^- cross sections from the HERA I [1] and HERA II running periods [2].

To study the impact of the jet measurements on the simultaneous determination of the gluon density function and the strong coupling constant, the following jet data sets are used:

- H1 HERA I+II high Q^2 DIS normalised inclusive jet data [4]
  Measurements in the kinematic range $150 < Q^2 < 15000$ GeV^2 are based on the data collected in the HERA I and HERA II running periods and correspond to an integrated luminosity of 395 pb^{-1}. In this study only the normalised inclusive jet cross section measurement as a function of P_T and Q^2 is used (see table 4 in [4]).
- H1 HERA I low Q^2 DIS inclusive jet data [5]
  Measurements were performed in the kinematic range $5 < Q^2 < 100$ GeV^2 and are based on the data collected in the HERA I running period, corresponding to an integrated luminosity of 43.5 pb^{-1}. This measurement has particularly large theoretical uncertainties due to missing orders of the pQCD calculation. In this study only the inclusive cross section points as a function of Q^2 and P_T were used. The data points with very large k-factors (NLO to LO ratio) of > 2.5 have been excluded.
- ZEUS HERA I 96/97 high Q^2 DIS inclusive jet data [6]
  Measurement were performed in the kinematic range $Q^2 > 125$ GeV^2 and are based on the data collected in the 1996-1997 HERA running period, corresponding to an integrated luminosity of 38.6 pb^{-1}.
- ZEUS HERA I 98-00 high Q^2 DIS inclusive jet data [7]
  Measurement were performed in the same kinematic range as [6] bur are based on the data collected in 1998-2000, corresponding to an integrated luminosity of 82 pb^{-1}.

  In the following the fit using only inclusive DIS data is referred to as HERAPDF1.5(f). If the four above mentioned jet data sets are used simultaneously with the inclusive DIS data the fit is called the HERAPDF1.6 fit.

1.2 Parametrisation

The PDF fit is performed using NLO DGLAP equations, for which the evolution code QCDNUM 17 [10] is used. Heavy quarks are treated as massive using the Thorne-Roberts variable flavour number scheme [11, 12].

Two parametrisations are studied: a 10-parameter fit which corresponds to the preliminary PDF fit of the NC and CC combined HERA I and HERA II data, HERAPDF1.5 [3], and a 14-parameter fit, HERAPDF1.5f, which allows more flexibility, in particular for the low-x gluon distribution. At the starting scale $Q_0^2 = 1.9$ GeV^2 the PDFs are parametrised as follows:

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g} && (1)\\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + D_{u_v} x + E_{u_v} x^2) && (2)\\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}} && (3)\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} \cdot (1-x)^{C_{\bar{U}}} && (4)\\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} \cdot (1-x)^{C_{\bar{D}}} && (5)
\end{aligned}
$$

The parameters A_g, A_{u_v}, A_{d_v} are constrained by the sum rules. It is assumed that $B_{\bar{U}} = B_{\bar{D}}$, $C'_g = 25$, $A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$, where f_s is the strangeness fraction.

In the 10-parameter fit four additional constraints are enforced: $A'_g = B'_g = 0$, $B_{d_v} = B_{u_v}$ and $D_{u_v} = 0$. In both, the 10- and 14-parameter fits these choices define the central fit, while further parameters are considered when evaluating the parametrisation uncertainty, as described in section 2.3.

Greater flexibility in the gluon density helps to avoid a parametrisation bias when adding more data that is sensitive to the gluon density, like charm or jet production. Therefore, the 14-parameter fit is preferred and used for HERAPDF1.6.

1.3 Theoretical predictions

The NLO cross sections of jet production were calculated using the NLOJET++ program [13]. These calculations are slow and thus to include jet data in a PDF fit the FASTNLO interface was used to efficiently convolute the matrix elements from NLOJET++ with the fitted PDFs.

In the prediction for the normalised jet cross sections [4] QCDNUM has been used to calculate the corresponding inclusive cross sections. The factorisation and renormalisation for the inclusive cross sections is $\mu_f = \mu_r = \sqrt{Q^2}$.

For the jet data the factorisation and renormalisation scales follow those used in the relevant publications, the combination of Q^2 and transverse jet energy measured in the Breit frame E_T ($\mu_f = \mu_r = \sqrt{(Q^2 + E_T^2)/2}$) for the H1 measurements and transverse jet energy measured in the Breit frame ($\mu_f = \mu_r = \sqrt{E_T^2}$) for the ZEUS measurements.

2 Determination of uncertainties

The total uncertainty of the PDFs and α_s includes the experimental uncertainties of the measurements and the variations of model and parametrisation assumptions, as described in the following.

2.1 Experimental uncertainty

The experimental uncertainties of the H1 and ZEUS combined NC and CC cross sections are accounted for following the description in [1]. The details on the determination of the experimental uncertainties of the jet cross sections are described in [4, 5, 6, 7]. Twelve systematic error sources are treated as correlated between data points of a given measurement and as uncorrelated between different measurements. In addition a theoretical uncertainty on the luminosity measurement of 0.5% has been considered as correlated between all H1 and ZEUS jet measurements. The correlated error sources considered are summarised in Table 1.

Source of correlated uncertainty	**Correlation fraction**	**Data set**
H1 LAr electron energy scale (99-07)	25%	[4]
H1 LAr electron angle (99-07)	100%	[4]
H1 Jet energy scale (99-07)	50%	[4]
H1 Luminosity (99-00)	100%	[5]
H1 Spacal electron energy scale (99-00)	50%	[5]
H1 Spacal electron angle (99-00)	50%	[5]
H1 Jet energy scale (99-00)	50%	[5]
H1 low Q^2 jet measurement model dependence	50%	[5]
ZEUS luminosity measurement (96-97)	100%	[6]
ZEUS jet energy scale (96-97)	100%	[6]
ZEUS luminosity measurement (98-00)	100%	[7]
ZEUS jet energy scale (98-00)	100%	[7]
Theoretical luminosity measurement uncertainty	100%	[4], [5], [6], [7]

Table 1: Experimental uncertainties and the correlation fraction for the particular jet data set.

2.2 Model uncertainty

The model assumption variations are the same to those performed for HERAPDF1.0 [1]. They are summarised in table 2.

Model parameter	**Standard value**	**Lower Limit**	**Upper Limit**
Strange fraction f_s	0.31	0.23	0.38
Charm mass m_c [GeV]	1.4	1.35	1.65
Beauty mass m_b [GeV]	4.75	4.3	5.0
Minimum Q^2 [GeV^2]	3.5	2.5	5.0

Table 2: Assumed parameters of the model and their variations.

In addition the hadronization uncertainty for each of the jet data samples is taken into account. All the model uncertainties are added in quadrature.

The renormalisation and factorisation scales are varied separately for the jet NLO cross section predictions but simultaneously for all the data sets. This variation corresponds to $1/2\mu < \mu_{f,r} < 2\mu$. The simultaneous variation of the scales for all jet data sets yields larger uncertainties than variation of the individual data sets and thus has been preferred as the more conservative approach. The variation of the renormalisation and factorisation scales for the inclusive DIS measurements ware found to be negligible compared to the influence of jet scales. In the end the renormalisation scale is the dominant source of the model error.

2.3 Parametrisation uncertainty

For the parametrisation uncertainty estimation the generalised parametrisation is studied:

$$xg(x,Q_0^2) = Ax^B \cdot (1-x)^C \cdot (1 - Dx + Ex^2 + \epsilon\sqrt{x}) - A'x^{B'} \cdot (1-x)^{C'} \quad (6)$$

$$xf(x,Q_0^2) = Ax^B \cdot (1-x)^C \cdot (1 - Dx + Ex^2 + \epsilon\sqrt{x}) \quad (7)$$

where f refers to $u_v, d_v, \bar{U}, \bar{D}$.

For the HERAPDF1.5 parametrisation the negative gluon term is neglected ($A' = B' = C' = 0$). All the other additional parameters are added one at a time resulting in a set of 11 free parameter fits. An additional parametrisation with the $B_{d_v} = B_{u_v}$ constraints released is also considered. Finally, the starting scale at which distributions assume their analytic form is varied between $Q_0^2 = 1.5$ GeV^2 and $Q_0^2 = 2.5$ GeV^2. For the variation down to $Q_0^2 = 1.5$ GeV^2 the negative gluon term is enabled.

For HERAPDF1.5f and HERAPDF1.6 adding parameters one at a time results in a set of 15 free parameter fits. The starting scale has been varied in the same range as for HERAPDF1.5.

The most significant parametrisation variation for all the fits is the variation of the starting scale. The difference between all these parametrisation variations and the central fit is used to construct an envelope representing the maximal deviation at each x value which represents the parametrisation uncertainty.

3 Results

The PDF fits using the jet data are performed for the case when α_S is fixed or is a free parameter of the fit. The values of α_s, number of data points and the χ^2 for the 10 and 14-parameter fits including or not the jet data are summarised in table 3.

Fit	Nparam	DIS χ^2	jets χ^2	α_S	DIS Ndp	jets Ndp
HERAPDF1.5	10	735.9	-	fixed, 0.1176	674	-
HERAPDF1.5f	14	729.8	-	fixed, 0.1176	674	-
HERAPDF1.5 + α_s	$10 + \alpha_s$	734.7	-	free, 0.1198 ± 0.0024	674	-
HERAPDF1.5f + α_s	$14 + \alpha_s$	729.5	-	free, 0.1186 ± 0.0037	674	-
HERAPDF1.6	14	730.2	81.3	fixed, 0.1176	674	106
HERAPDF1.6 + α_s	$14 + \alpha_s$	730.0	77.6	free, 0.1202 ± 0.0013	674	106

Table 3: The χ^2 for the fits using 10 or 14 parameters. If the jet data are used, the partial χ^2 for the jet data is also indicated. The strong coupling α_s is fixed or treated as a parameter of the fit. The values of α_s obtained in the fit are given together with their experimental uncertainty.

3.1 Fits using fixed strong coupling $\alpha_s = 0.1176$

In Fig. 1 and Fig. 2 the HERAPDF1.5 and HERAPDF1.5f are shown as functions of x at photon virtuality $Q^2 = 10$ GeV^2. In both cases the strong coupling constant is fixed $\alpha_s = 0.1176$. The total uncertainty for HERAPDF1.5 and HERAPDF1.5f is similar, but the dominant part of the parametrisation uncertainty on HERAPDF1.5 is absorbed into the experimental uncertainty for HERAPDF1.5f. This is due to larger parametrisation flexibility used for HERAPDF1.5f fit. The HERAPDF1.5f yields a softer sea density at high x and a suppressed d-valence at low x as compared to HERAPDF1.5.

In Fig. 3 summary plots of the PDFs are shown for the HERAPDF1.5 and HERAPDF1.5f.

In Fig. 4 the HERAPDF1.6 PDFs obtained by including the H1 and ZEUS jet measurements in the fit are shown. There is little difference in the size of PDF uncertainties when the jet data are included in the fit, however the high-x gluon uncertainty is somewhat reduced.

The blue lines indicate the shape of the HERAPDF1.5f fit using only inclusive data so that the shape of the PDF with and without jet data may be easily compared. The sea density gets softer at high-x when jet data are included.

In Fig. 5 the summary plot of HERAPDF1.6 is shown.

3.2 Determination of α_s

The HERAPDF1.6 fit and the HERAPDF1.5f fit were also performed with the strong coupling constant $\alpha_s(M_Z)$ as a free parameter. The HERAPDF1.6 fit determines the value of $\alpha_s(M_Z)$ as

$$\alpha_S(M_Z) = 0.1202 \pm 0.0013(\text{exp}) \pm 0.0007(\text{model/param}) \pm 0.0012(\text{hadronisation})^{+0.0045}_{-0.0036}(\text{scale}).$$

with a χ^2 of 807.6 for 780 data points.

The HERAPDF1.5f fit does not give a good determination of $\alpha_s(M_Z)$ because the correlation between the gluon PDF and $\alpha_s(M_Z)$ is too strong when inclusive data alone are used. The jet data introduces a strong sensitivity to $\alpha_s(M_Z)$. This is illustrated in in Fig. 6, where the χ^2 for both the HERAPDF1.5f and the HERAPDF1.6 fits with free α_s are shown as a function of $\alpha_s(M_Z)$. The HERAPDF1.5f fit shows a shallow minimum, while the HERAPDF1.6 fit with the addition of jet data provides a strong constraint on the α_s value.

In addition to the sensitivity to α_s the jet data provides an additional constrain on the gluon density. The data reduces significantly the strong correlation between α_s and the gluon density observed when fitting the inclusive data alone. In Fig. 7 the HERAPDF1.5f and HERAPDF1.6 fits obtained using $\alpha_s(M_Z)$ as a free parameter are shown for $Q^2 = 10\,\text{GeV}^2$. The gluon density has a very large uncertainty for the HERAPDF1.5f fit with free $\alpha_s(M_Z)$, but this uncertainty is dramatically reduced for the HERAPDF1.6 fit with free $\alpha_s(M_Z)$, because of the inclusion of the jet data. The PDF uncertainty introduced by freeing α_s affects only the gluon PDF as can be seen by comparing HERAPDF1.6 with free α_s (Fig. 7 right hand side) and HERAPDF1.6 with fixed α_s (Fig. 5). Once jet data are included the extra uncertainty in the gluon PDF due to the use of a free α_s is not large.

Figure 8 presents the comparison of the value of $\alpha_s(M_Z)$ obtained in this analysis to the world average value [9] and different H1 ([4], [5]) and ZEUS ([6], [8]). measurements. One should note that the error on the fitted α_s value due to the PDF uncertainty for the jet publications is usually included in the theoretical uncertainty, while for HERAPDF1.6 it is part of the experimental error.

In Fig. 9-Fig. 12 the measured jet cross sections used for the PDF fit HERAPDF1.6 are shown in comparison to the NLO prediction using the parton densities HERAPDF1.6 with free α_s. The ratio of data to theory is presented. The NLO prediction describes the data very well within the uncertainties. The dominant error on the prediction originates from the variation of factorisation and renormalisation scales.

3.3 Summary

The impact of jet measurements on the determination of PDFs and the strong coupling constant α_s has been studied. For this purpose the jet cross section measurements from the H1 and ZEUS experiments are included in the PDF fit to the combined H1 and ZEUS NC and CC cross section measurements based on the HERA I and HERA II data samples.

Two parametrisations of the PDFs are studied using the combined H1 and ZEUS NC and CC cross sections. Greater flexibility in the gluon distribution helps to avoid parametrisation bias, especially when adding more data which is sensitive to the gluon distribution, like charm or jet production. This flexible parametrisation, HERAPDF1.5f, is consistent with the more rigid parametrisation of HERAPDF1.5, but results in a softer sea distribution at high x.

The PDF fit of the combined H1 and ZEUS NC and CC cross section measurements based on HERA I and HERA II data samples together with the jet cross section measurements from H1 and ZEUS is performed using the flexible parametrisation. This fit, called HERAPDF1.6 is made with fixed and free α_s. Parton density functions resulting from the fixed α_s version of the fit are consistent with those from HERAPDF1.5f, which is based on inclusive data only, but have a softer sea distribution at high-x.

The impact of the jet data on the PDF fit using the strong coupling constant α_s as a free parameter of the fit was studied. HERAPDF1.5f, based on inclusive data, and HERAPDF1.6, in which jet data are used in addition, are compared. While HERAPDF1.5f with free α_s is not very sensitive to the α_s value, the HERAPDF1.6 fit has strong sensitivity to the value of α_s. In the HERAPDF1.6 + α_s fit the value of $\alpha_s(M_Z)$ was determined together with the parton density functions. The addition of the jet cross sections into the PDF fit reduces significantly the strong correlation between the gluon distribution and the strong coupling constant and the resulting uncertainty on the gluon PDF at low x.

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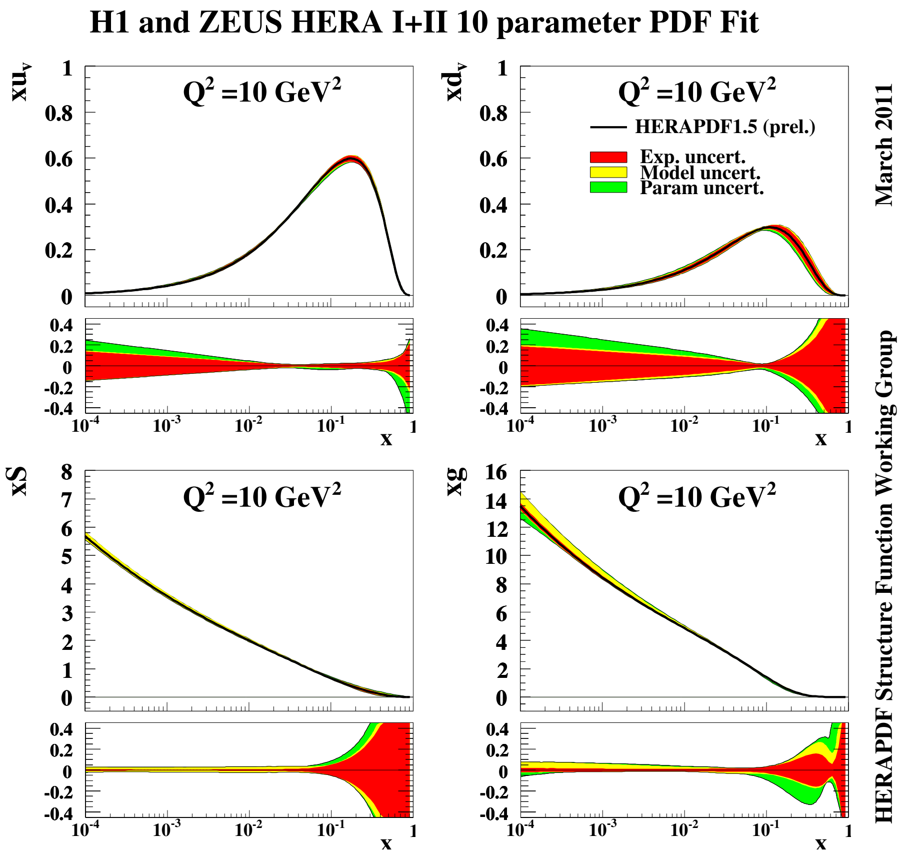

Figure 1: Valence, sea and gluon distributions for HERAPDF1.5 as a function of x for $Q^2 = 10$ GeV^2. The central value (solid line) is shown together with the experimental, model and parametrisation uncertainties represented by the red, yellow and green shaded bands, respectively. The fractional uncertainties are represented separately below each of the parton densities.

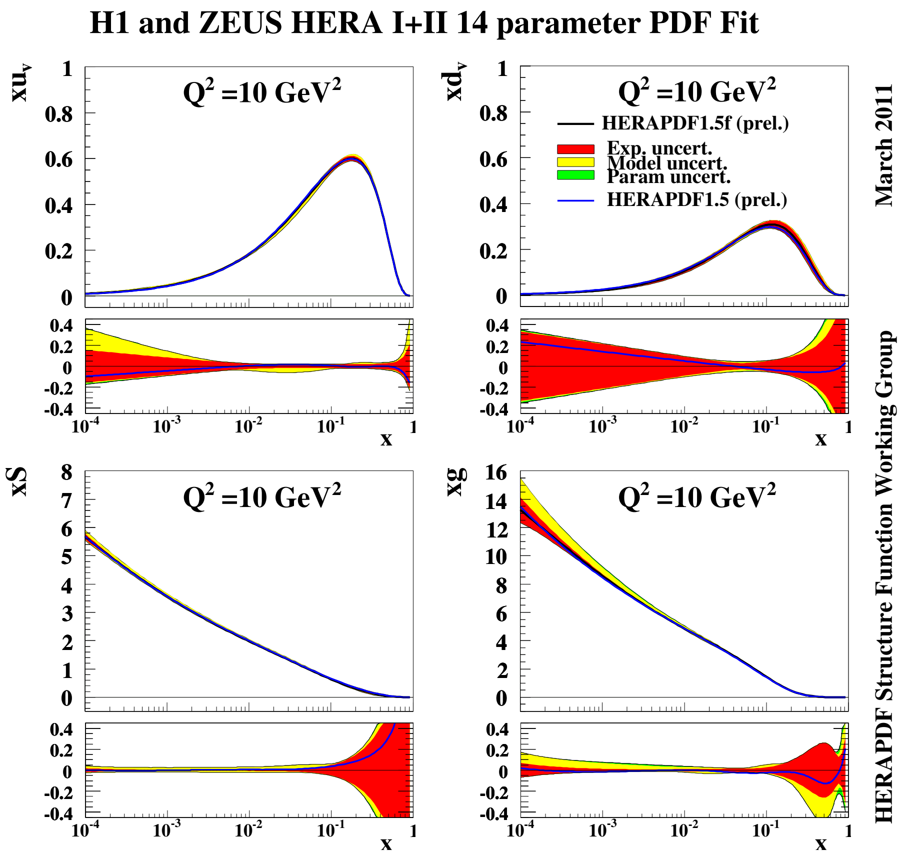

Figure 2: Valence, sea and gluon distributions for HERAPDF1.5f as a function of x for $Q^2 = 10$ GeV^2. The central value (solid line) is shown together with the experimental, model and parametrisation uncertainties represented by the red, yellow and green shaded bands, respectively. The central values for HERAPDF1.5 are represented by the blue line. The fractional uncertainties are represented separately below each of the parton densities together with the ratio of the central values of HERAPDF1.5 and HERAPDF1.5f (blue line).

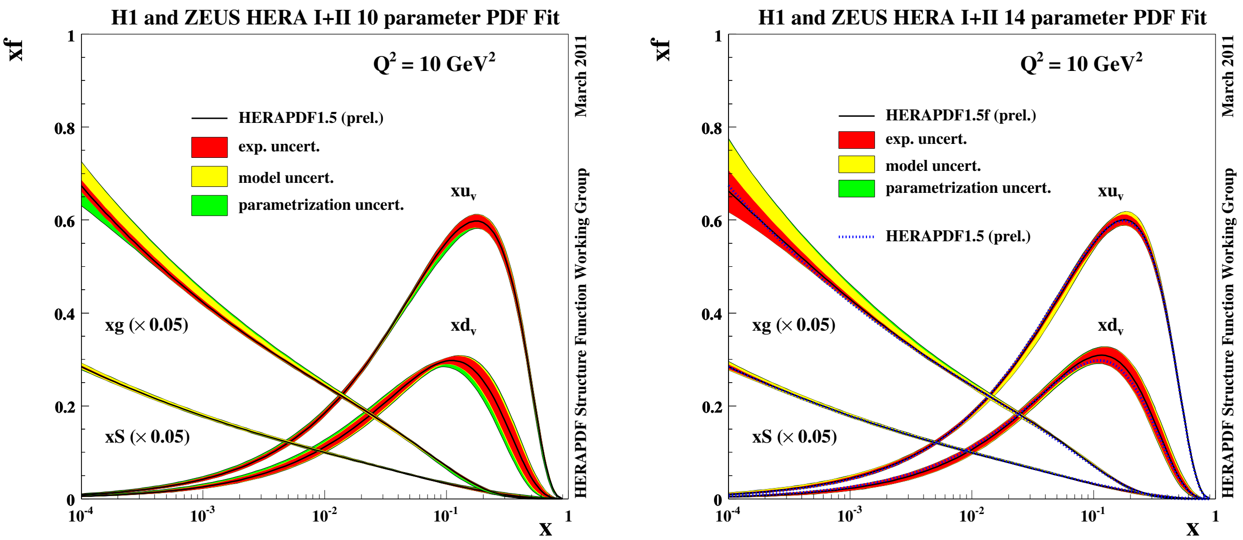

Figure 3: Parton density functions for HERAPDF1.5(left) and HERAPDF1.5f (right) as a function of x for $Q^2 = 10$ GeV^2. The central value (solid line) is shown together with the experimental, model and parametrisation uncertainties represented by the red, yellow and green shaded bands, respectively. The central value for HERAPDF1.5 is also indicated on the right hand side plot with a dotted line.

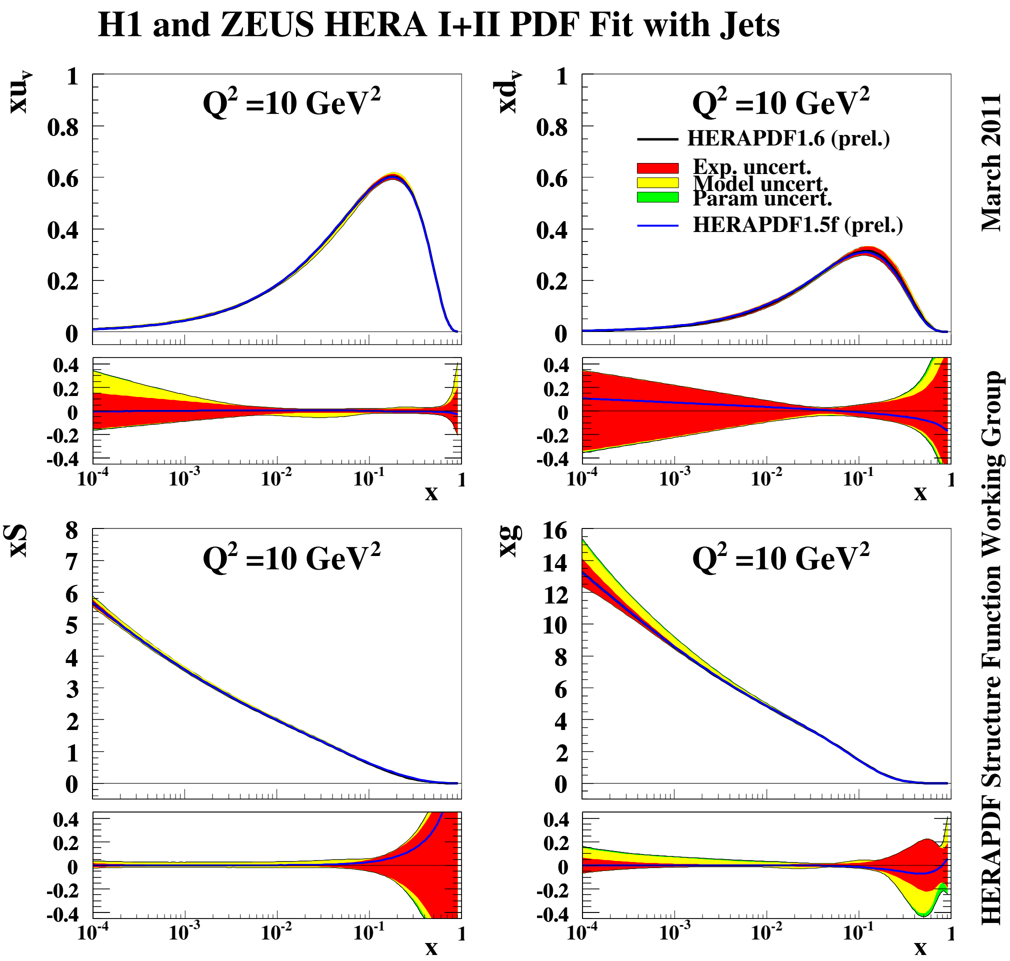

Figure 4: Valence, sea and gluon distributions for HERAPDF1.6 shown as a function of x for $Q^2 = 10$ GeV^2. The central value (solid line) is shown together with the experimental, model and parametrisation uncertainties represented by the red, yellow and green shaded bands, respectively. The central values for HERAPDF1.5f are represented by the blue line. The fractional uncertainties are represented separately below each of the parton densities together with the ratio of the central values of HERAPDF1.6 and HERAPDF1.5f (blue line).

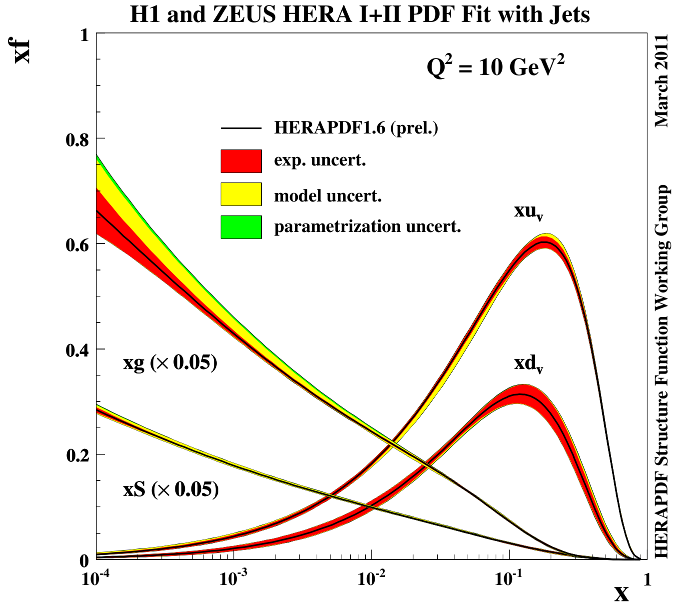

Figure 5: Parton distribution functions for HERAPDF1.6 as a function of x for $Q^2 = 10$ GeV^2. The central value (solid line) is shown together with the experimental, model and parametrisation uncertainties represented by the red, yellow and green shaded bands, respectively.

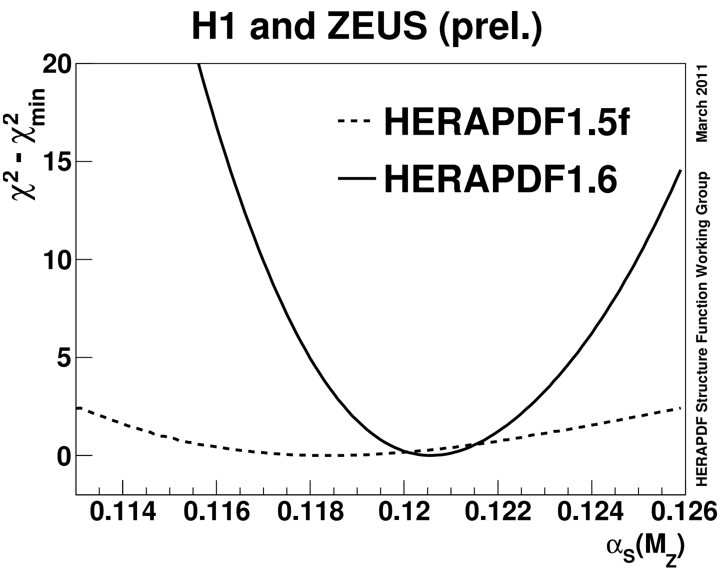

Figure 6: $\Delta\chi^2$ distribution as a function of the value of $\alpha_s(M_Z)$ value in the PDF fits for HERAPDF1.5f (dashed line) and HERAPDF1.6 (solid line).

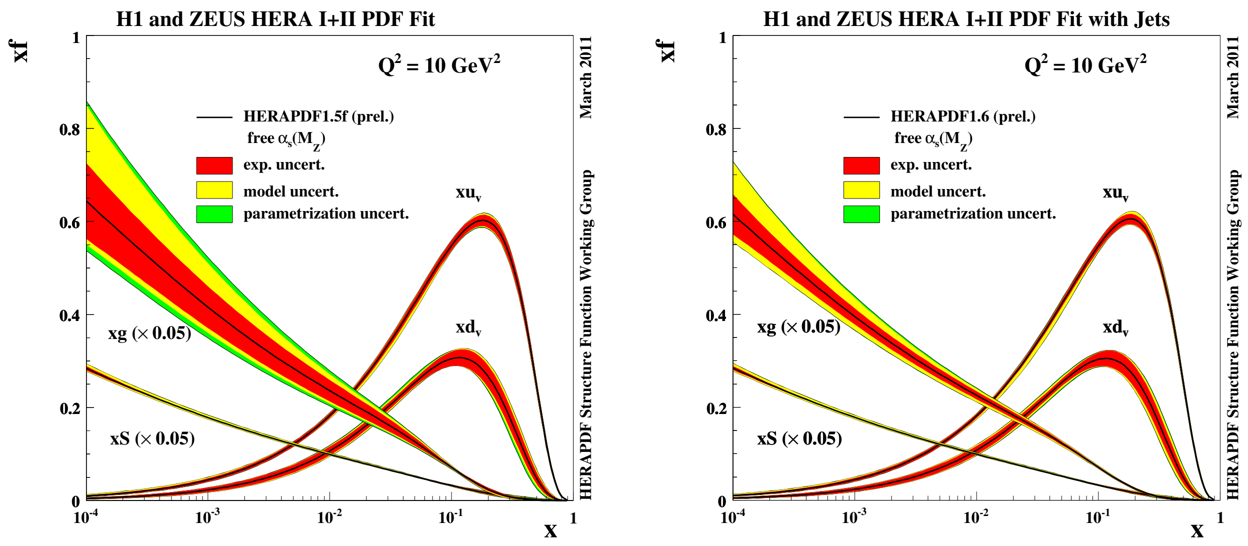

Figure 7: Parton distribution functions for HERAPDF1.5f (left) and HERAPDF1.6 (right) as a function of x for $Q^2 = 10$ GeV^2. The strong coupling constant $\alpha_s(M_Z)$ is a free parameter in both fits. The central values of the PDFs (solid lines) are shown together with the experimental, model and parametrisation uncertainties represented by the red, yellow and green shaded bands, respectively.

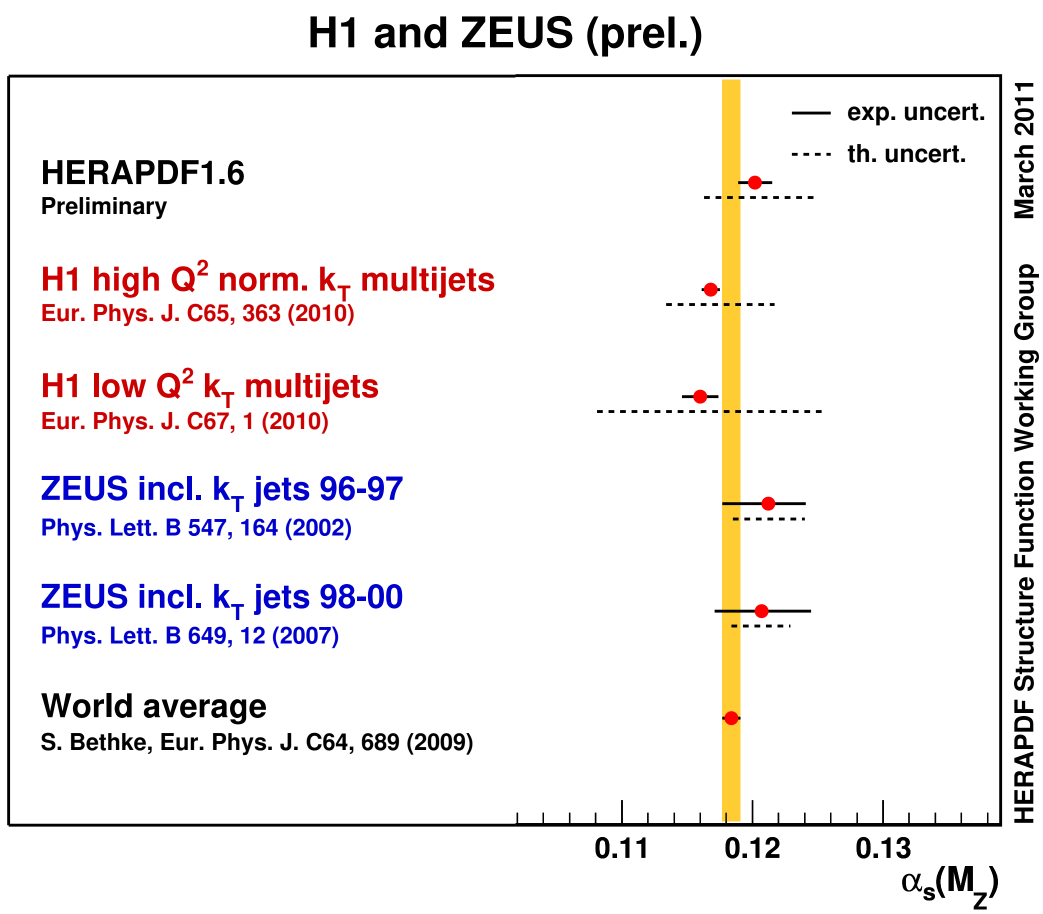

Figure 8: The fitted α_s value compared to different H1 and ZEUS α_s measurements and the world average.

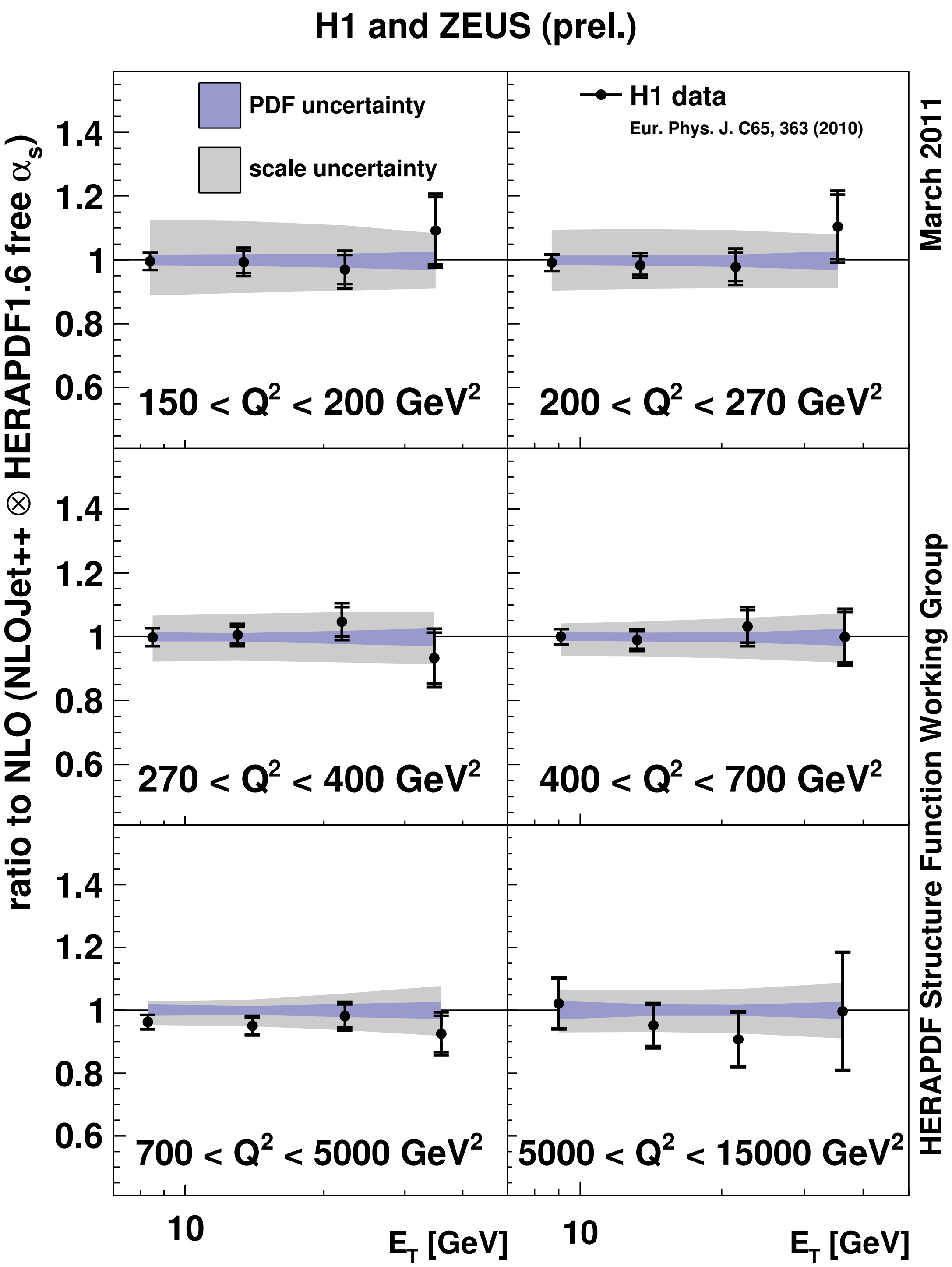

Figure 9: The ratio of the high Q^2 normalised inclusive jet data [4] used in the fit to the NLO prediction using the fitted HERAPDF1.6 PDF set and fitted $\alpha_s(M_Z) = 0.1202$. The inner error bars represent the uncorrelated errors, while the outer indicate the total error. The theoretical error band is separated into PDF error (including experimental, parametrisation and model uncertainties added in quadrature) and the scale error which depicts the uncertainty coming from the missing orders in the calculations.

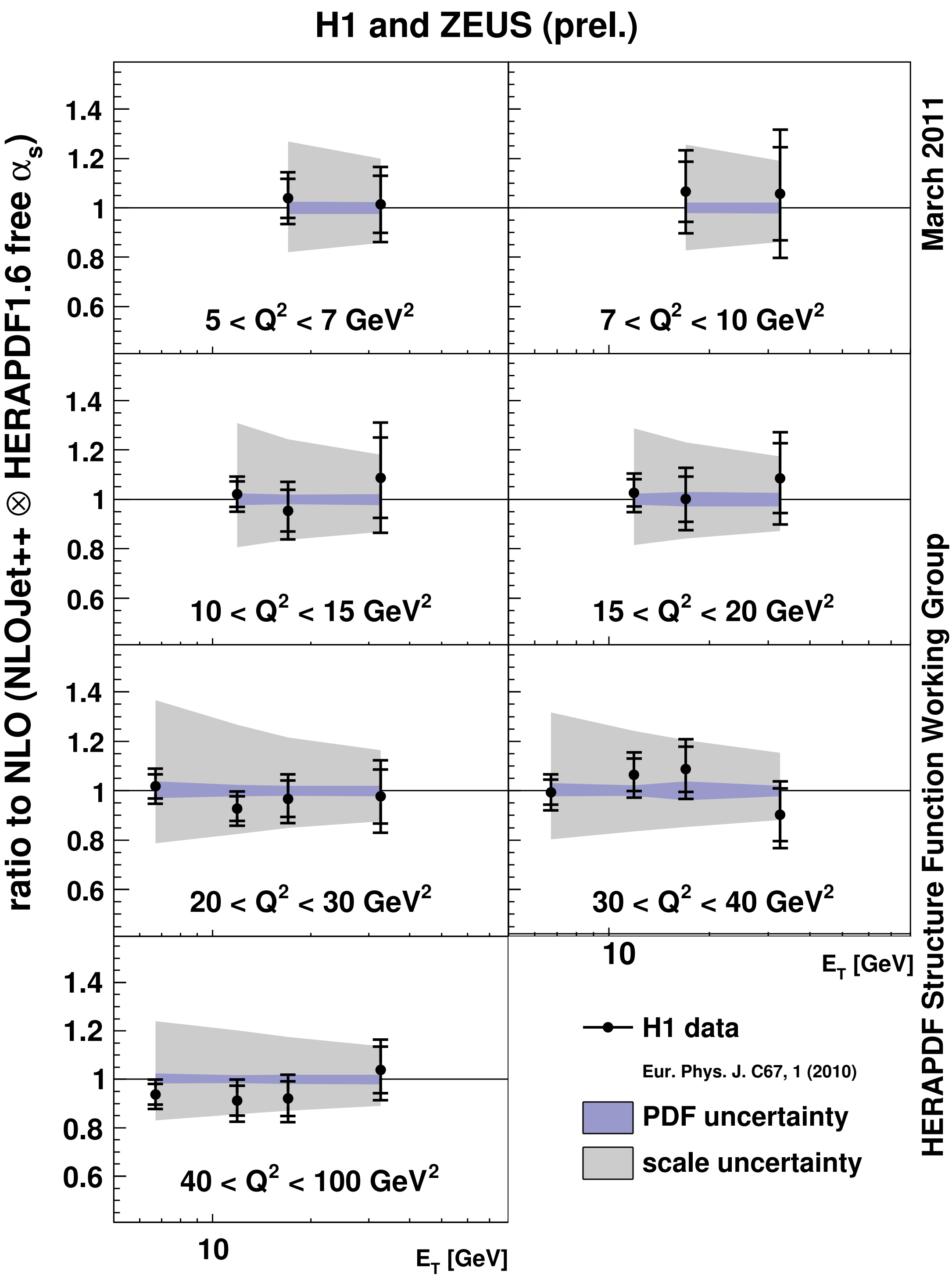

Figure 10: The ratio of the low Q^2 inclusive jet data [5] used in the fit to the NLO prediction using the fitted HERAPDF1.6 PDF set and fitted $\alpha_s(M_Z) = 0.1202$. Other details are explained in the caption of figure 9.

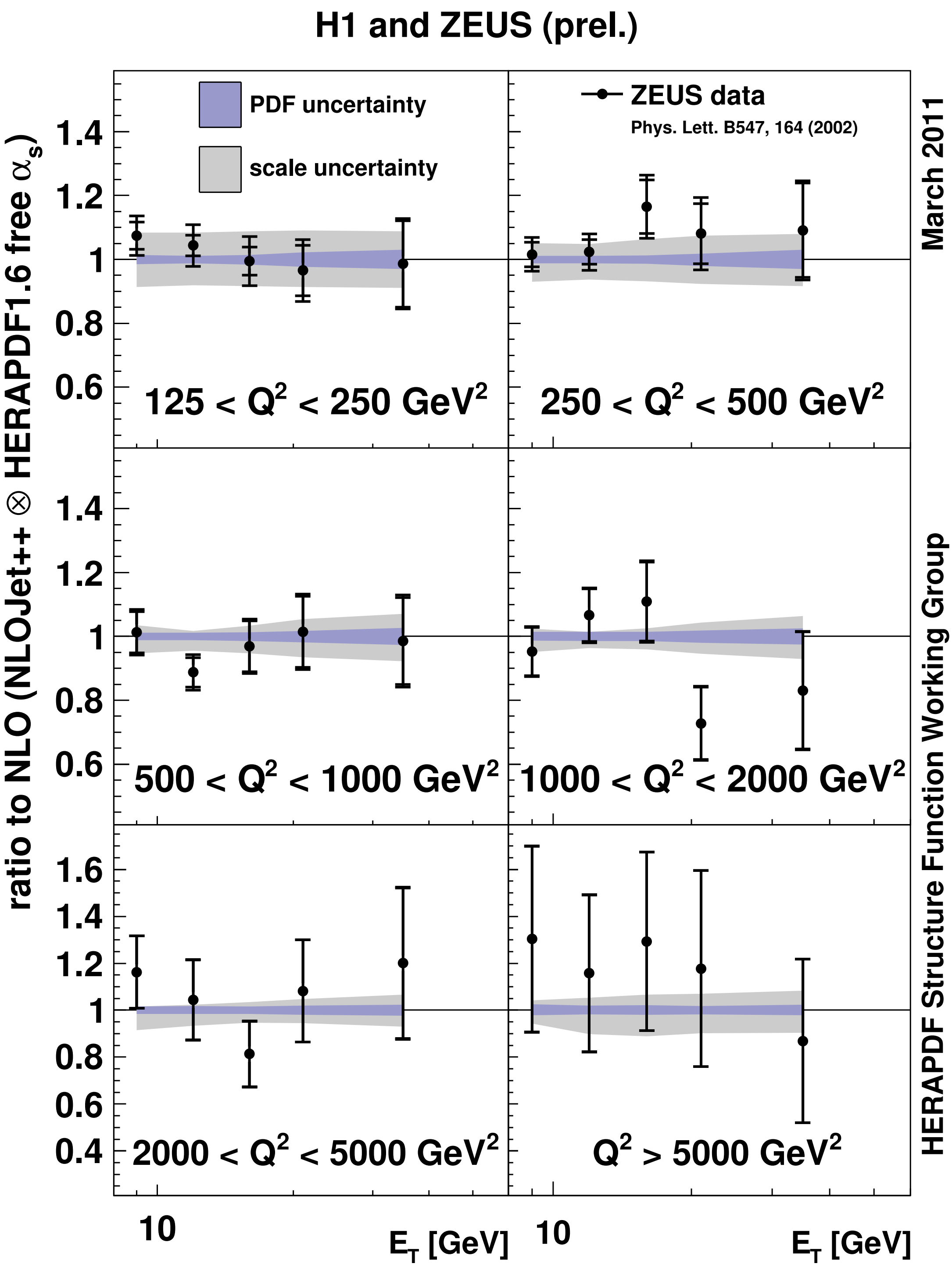

Figure 11: The ratio of the high Q^2 inclusive jet data [6] used in the fit to the NLO prediction using the fitted HERAPDF1.6 PDF set and fitted $\alpha_s(M_Z) = 0.1202$. Other details are explained in the caption of figure 9.

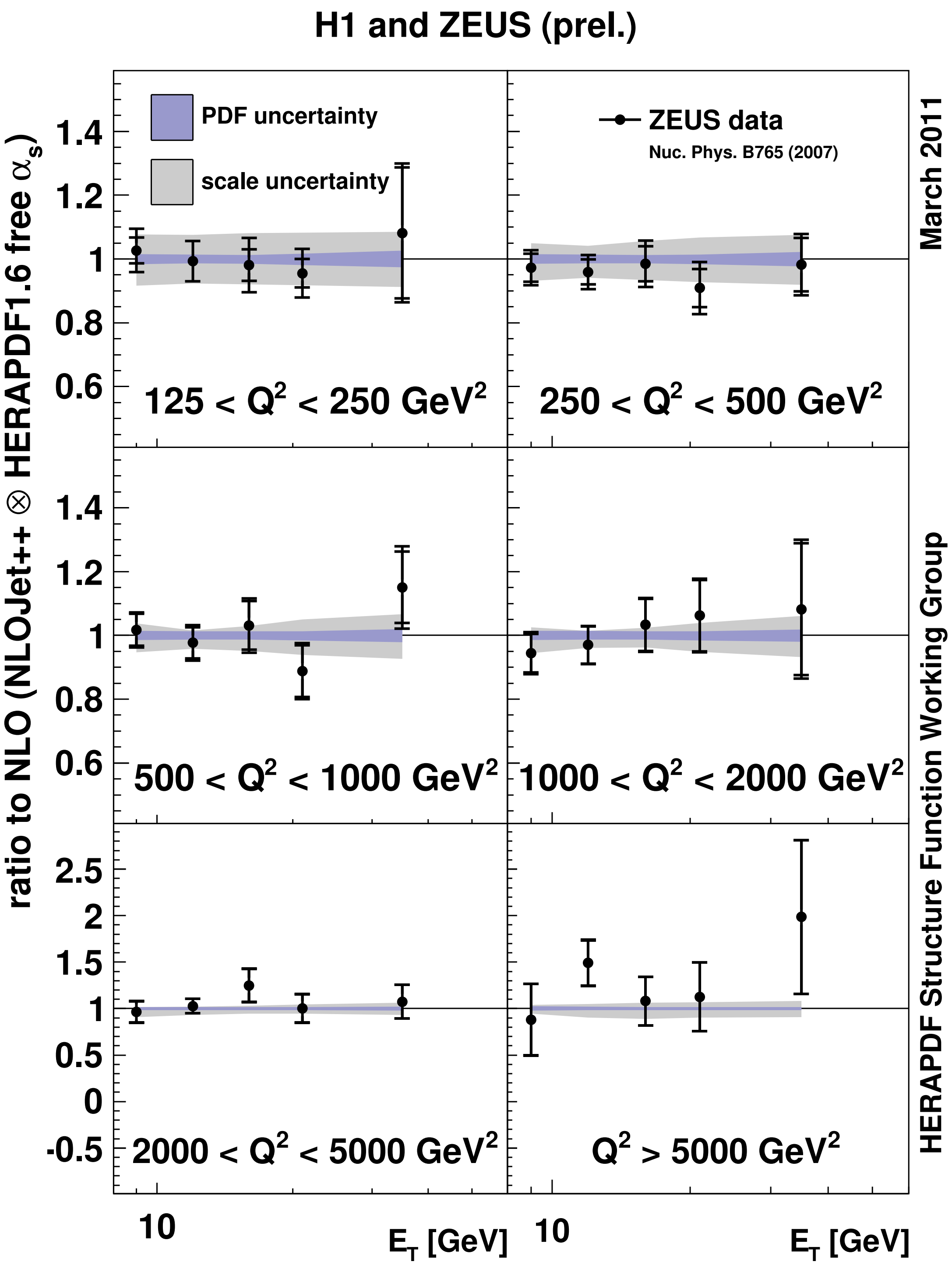

Figure 12: The ratio of the high Q^2 inclusive jet data [7] used in the fit to the NLO prediction using the fitted HERAPDF1.6 PDF set and fitted $\alpha_s(M_Z) = 0.1202$. Other details are explained in the caption of figure 9.