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² following H1prelim-19-041, ZEUS-prel-19-001

Impact of jet production data on the next-to-next-to-leading order determination of HERAPDF2.0 parton distributions

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Author list

Abstract

The HERAPDF2.0 ensemble of parton distribution functions (PDFs) was introduced in 9 2015. Presented is the final stage, a next-to-next-to-leading order analysis of the HERA 10 data on inclusive deep inelastic *ep* scattering together with jet data as published by H1 and ZEUS. A pQCD fit to the data with free $\alpha_s(M2)$ and free PDFs was used to determine $_{+0.0001}^{2}$ 11 12 $\alpha_s(M_Z)$ with the result $\alpha_s(M_Z) = 0.1156 \pm 0.0011 \text{ (exp)} - _{0.0002} \text{ (model + parameterisation)}$ 0.0029 (scale). The HERAPDF2.0 Jets NNLO sets of parton density functions from fits with fixed $\alpha_s(M_Z) = 0.1155$ and $\alpha_s(M_Z) = 0.118$, the value used for the published HERA-13 14 15 PDF2.0 NNLO analysis based on inclusive data only, are presented and compared. The 16 PDFs of HERAPDF2.0Jets NNLO for fixed $\alpha_s(M_z^2) = 0.118$ are also compared to the PDFs 17 of HERAPDF2.0 NNLO. The similarity of the PDFs demonstrates the consistency of inclu-18 sive and jet-production cross-section data. Predictions based on HERAPDF2.0Jets NNLO 19 agree very well with the jet-production data used in the fits. 20

To be submitted to EPJC

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22 1 Introduction

²³ Data from deep inelastic scattering (DIS) of electrons¹ on protons, *ep*, at centre-of-mass energies ²⁴ of up to $s \approx 320$ GeV at HERA have been central to the exploration of proton structure and ²⁵ quark-gluon dynamics as described by perturbative Quantum Chromo Dynamics (pQCD) [1].

The combination of H1 and ZEUS data on inclusive *ep* scattering and the subsequent pQCD analysis, introducing the ensemble of parton density functions (PDFs) known as HERAPDF2.0, were milestones for the exploitation [2] of the HERA data. The HERAPDF analyses are based on pQCD fits to the HERA DIS data in the DGLAP [3–7] formalism in the MS scheme [8].

The sets of PDFs presented in this work complete the HERAPDF2.0 ensemble [2] of PDFs. They were determined with an NNLO analysis of HERA inclusive and selected jet-production

³² data as published separately by the H1 and ZEUS collaborations [9–14]. An analysis of jet data

at NNLO was not possible at the time of the introduction of the HERAPDF2.0 ensemble. It became possible when predictions of jet cross-section at NNLO [15–23] for *ep* became available. The strategy of the analysis follows the strategy of the of the original and worked to a first of the original

The strategy of the analysis follows the strategy of the original and verified pQCD [2] analysis at NLO. As the value of the strong coupling constant, $\alpha_s(M^2)$, cannot be separated from the PDFs resulting from any pQCD fit, a suitable value of $\alpha_s(M^2_Z)$ has to be determined first by fitting the PDFs and $\alpha_s(M^2_Z)$ simultaneously. This avoids biases on $\alpha_s(M^2_Z)$ as would be introduced by fitting $\alpha_s(M^2_Z)$ with fixed PDFs [24]. In a second step brianfoster

fit with $\alpha_s(\mathcal{M})$ fixed to the optimised value.

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masses, M_c and M_b , as input. These parameters were optimised us is based on

³⁹ and bottom production, which were published as combined data by

tions together with a pQCD analysis [28]. An inclusion of the heav brianfoster

41 including jets is considered inappropriate due to the different treat42 for the predictions on inclusive and jet data.

⁴³ The results presented here are based entirely on HERA data, i.e But this sounds like we exclude heavy ⁴⁴ data. The HERA inclusive data represent a single, highly consister quarks

- ⁴⁵ jet data have been found to be very consistent with the inclusive d ⁴⁵ presented here also tests consistency at NNLO. In addition, DIS is simply aren't tagged. Can't we somehow
- the factorisation theorem is fully established. It is only a standard assumption that it is also valid
- 48 for hadron-hadron interaction processes. However, even if this assumption is valid, PDF fits
- to LHC data would be biased by any physics Beyond the Standard Model (BSM) whose effects
- ⁵⁰ have so far escaped detection, thereby reducing the sensitivity of searches for BSM due to biased
- ⁵¹ background predictions. Thus, the HERAPDF2.0 ensemble of PDFs provides a benchmark to

⁵² which PDFs including data from LHC colliders may be compared. This could reveal BSM

⁵³ effects or the need for an extension of the QCD analyses for some processes.

¹From here on, the word "electron" refers to both electrons and positrons, unless otherwise stated.

2 Data 54

Data taken by the H1 and ZEUS collaborations from 1993 to 2007 were combined to form 55 a coherent set of inclusive HERA ep DIS cross sections [2], which was used as input to the 56 determinations of all previous members of the HERAPDF2.0 ensemble. The HERAPDF2.0Jets 57 analysis at NLO, in addition, used selected data [9-12,14] on inclusive jet and dijet production 58 from H1 and ZEUS, which were again used for the present analysis at NNLO. In addition, new 59 data [13], published by the H1 collaboration on jet production in lower Q^2 events, where Q^2 60 is the four-momentum-transfer squared, together with six new high- Q^2 points at low p_T , where 61 p_T is the transverse energy of the jet, which were published by H1 in the same publication to 62 complete the previously published high- Q^2 data set [14], were added as input to the NNLO 63 analysis. A summary on the data of jet production used is provided in Table 1. For all data sets, 64 the jets were identified with the k_T algorithm with the R parameter set to one. 65

The new treatment of inclusive jet and dijet production at NNLO was, however, only applicable to a slightly reduced phase space compared to HERAPDF2.0Jets NLO. All data points 66 67

with $\mu = qhp_{\tau}^2 i + Q^2 \leq 10.0$ GeV had to be excluded in order to ensure the convergence of 68

- the perturbative series and to limit the NNLO scale uncertainties of brianfoster 69
- to below 10 % compared to below 24 % at NLO. This requirement 70 2021-08-24 11:42:00
- larger than the b-quark mass, which is necessary because the jets a 71
- massless partons in the calculation of the NNLO predictions. In adding understand 72
- six data points with the lowest hp_T had to be excluded from the 73
- the available NNLO predictions for these points were judged to be 74
- brianfoster kinematic cuts². The resulting reduction of data points is detailed 75 2021-08-24 11:42:12
- trijet data [14] which were used as input to HERAPDF2.0Jets NL 76 NNLO treatment was available. 77

don't understand

The inclusive charm data [29], which were included in the an Ach 78 explicitly used in the PDF fits of the analysis presented here, since 79 were not available. Heavy quark data [28] were only used to optim. 80 for charm, M_c , and beauty, M_b , which are needed as input to the atopted 81 J just write this shiff and was told it makes sense. approach to the fitting of the inclusive data. 82

QCD Analysis 3 83

The analysis presented here was done along the same lines as all previous HERAPDF2.0 anal-84 yses [2]. Only cross sections for Q^2 starting at $Q_{mi}^2 = 3.5 \text{ GeV}^2$ were used in the analysis. The 85 χ^2 definition was taken from equation 32 of the previous paper [2]. The value of the starting 86 scale for the evolution was taken as $\mu_f^2 = 1.9 \text{ GeV}^2$. The parameterisation and choice of free 87 parameters also followed the prescription for the HERAPDF2.0Jets NLO fit, see Section 3.1 88 below. 89

All fits were performed using the programme QCDNUM [30] within the xFitter, formerly 90 HERAFitter, framework [31] and were cross-checked with an independent programme, which 91

²Due to the kinematic cuts used in selecting the dijet data, the LO prediction for the cross sections is zero. Thus, the NNLO term is only the second non-zero term.

was already used as a second programme in the HERAPDF2.0 analysis. The results obtained
 using the two programmes, as previously for all HERAPDF2.0 fits [2], were in excellent agree ment, i.e. well within fit uncertainties. All numbers presented here were obtained using xFitter.

The light-quark coefficient functions were calculated in QCDNUM. The heavy-quark coefficient functions were calculated in the general-mass variable-flavour-number scheme RTOPT [25],

with recent modifications [26,27].

The analysis presented here became possible due to the newly available treatment of jet 98 production at NNLO, using the zero-mass scheme. This is expected to be a reasonable ap-99 proximation when the relevant OCD scales are significantly above the charm- and beauty-quark 100 masses. The jet data were included in the fits at full NNLO using predictions for the jet cross 101 sections calculated using NNLOJET [15-17], which was interfaced to the fast interpolation grid 102 codes, fastNLO [18-20] and APPLgrid [21,22] using the APPLfast framework [23], in order to 103 achieve the required speed for the convolutions needed in an iterative PDF fit. The NNLO jet 104 predictions were provided in the massless scheme and were corrected for hadronisation and Z^0 105 exchange before they were used in the fits. A running electro magnetic α as implemented in the 106 2012 version of the programme EPRC [32] was used in the treatment of the jet cross sections. 107 The predictions were provided with fully correlated uncertainties, w brianfoster 108 got new information 2021-08-24 11:46:41 included in all fits. 109

The choice of scales for the jet data had to be adjusted for the N sounds wrong - "associated with"? factorisation scale was chosen as for the inclusive data, i.e. $\mu r = Q$ scale was linked to the transverse momenta, p_T , of the jets as $\mu_r = |by|$? analysis, $\mu_f^2 = \mu_r^2 = Q^2 + p^2$ was used. This resulted in an impression of the second data in the second data is the second data in the second data in the second data is the second data in the second data in the second data is the second data in the second data

115 3.1 Choice of parameterisation and model parameters

The PDFs were parameterised as a function of x at the input scale by the generic form

117

$$xf(x) = Ax^{B}(1 - x^{S})(1 + Dx + Ex^{2}).$$
(1)

The PDF of the gluon was an exception, for which an additional term of the form $A_g^{0} x^B 0^{\circ} (1-x)^{C_0} 0$ was subtracted ³. This choice of parameterisation follows the original concept of HERAPDF2.0, for which all details were previously published [2]. The parameterisation is an effective way to store the information derived from many data points in a limited se brianfoster

The parameterised PDFs are the gluon distribution xg, the value xd_{v} , and the *u*-type and *d*-type anti-quark distributions xU, xl_{q} ? Is this philosophy? xd + xs at the chosen starting scale. The parameterisation for the by initially fixing the *D*, *E* and A^{0}_{g} parameters to zero. This restricted in further The extra parameters were introduced one at a time until the χ^{2} of the fit courd proto be further improved [2,33]. This is also called the χ^{2} saturation method. This resulted in a 14 parameter fit which satisfied the criteria that all PDFs and all predicted cross sections were positive throughout

³The parameter $C_g^0 = 25$ was fixed since the fit is not sensitive to this value, provided it is high enough ($C_g^0 > 15$) ensuring that the term does not contribute at large x. This was acheed for .

the kinematic region probed by the data entering the fit. The suitability of the parameterisation
 was, thus, also verified for the selection of jet data.

¹³¹ The final parameterisation was

 $x\mathbf{g}(x) = A_{g} x^{B_{g}} (1-x)^{C_{g}} - A_{g}^{0} x^{B_{g}} 0 (1-x)^{C_{g}} 0, \qquad (2)$

133 $xu_{v}(x) = A_{u}^{v} x^{B_{uv}} (1-x)^{C_{uv}} 1 + E_{u}^{v} x^{2} , \qquad (3)$

134
$$xd_{v}(x) = A_{d_{v}}x^{B_{d_{v}}}(1-x)^{C_{d_{v}}}, \qquad (4)$$

135
$$xU_{-}(x) = AU^{-}xB^{U}(1-x)C^{U}(1+DU^{-}x),$$
 (5)

132

 $xD^{-}(x) = AD^{-}xB^{D^{-}}(1-x)C^{D^{-}}.$ (6)

¹³⁷ The normalisation parameters, A_g , A_{u_v} , A_{d_v} , were constrained by the quark-number and momen-¹³⁸ tum sum rules. The *B* parameters, BU^- and BD^- , were set equal, $BU^- = BD^-$, such that there was a ¹³⁹ single *B* parameter for the sea distributions.

The strange-quark distribution was expressed as an x-independent fraction, f_s , of the d-type sea, $xs^- = f_s xD$ at $_0Q^2$. The central value $f_s = 0.4$ was chosen to be a compromise between the determination of a suppressed strange sea from neutrino-induced di-muon production [34,35] and the determination of an unsuppressed strange sea from the ATLAS collaboration [36]. The further constraint $AU^- = AD^-(1 - fs)$, together with the requirement $BU^- = BD^-$, ensured that $xu^- \rightarrow xd$ as $x \rightarrow 0$.

¹⁴⁶ 3.2 Model and parameterisation uncertainties

¹⁴⁷ Model and parameterisation uncertainties on the PDFs determined by a central fit were evaluated with modified input assumptions. The central values of the model parameter

149	The value of α (M2)	is eithe
150	free for the simultaneous fit of α s(M2) and the PDFs.	2021-08-24 11:48:22

The uncertainties on the PDFs obtained from variations of M_c , don't understand quadrature, separately for positive and negative uncertainties, and tainty. The uncertainty obtained from the variation of μ_f^2 was added to the parameterisation uncer-

The uncertainty obtained from the variation of μ_f^2 was added to the parameterisation uncertainty. A variation of the number of terms in the polynomial $(1 + Dx + Ex^2)$ was considered for each of the parton distributions listed in Eqs. 2–6. For this, all 15-parameter fits which have one more non-zero free *D* or *E* parameter were considered as possible variants and the resulting PDFs compared to the PDF from the 14-parameter central fit. The only significant change in the PDFs was observed for the addition of a D_{u_v} parameter. The uncertainties on the central fits from the parameterisation variations were stored as an envelope representing the maximal deviation at each *x* value.

The total uncertainties on the PDFs were obtained by adding experimental, i.e. fit, model and parameterisation uncertainties in quadrature.

164 3.3 Optimisation of M_c and

The RTOPT scheme used to calculate predictions for the inclusive data requires the charm- and

beauty-mass parameters, M_c and M_b , as input. The optimal values of these parameter were reevaluated using new combined HERA data, which became available [28], superseding the

¹⁶⁸ previously published combination of charm data [29] and the data published separately by H1

169 and ZEUS on beauty production. The optimisation was done using the standard procedure [?]

through fits to the inclusive HERA data together with the new combined heavy-flavour data with

varying choices of the mass parameter values. The values resulting in the lowest χ^2 values of the

fit were chosen for the jet analysis. This was done both at NLO to **f** *brianfoster* NLO published previously [28] and at NNLO for the analysis press²⁰²¹⁻⁰⁸⁻²⁴ 13:59:04

¹⁷³ NLO published previously [28] and at NNLO for the analysis presq²⁰²¹⁻⁰⁸⁻ deviation uncertainties of the mass parameters were determined by

quadratic function and finding the mass-parameter values corresport How can you facilitate a previous analysis?

well, they forgot to At NNLO, the fits for the optimisation were performed using the 176 publish this and want at NLO, $\alpha_s = 0.118$ was used. As a first iteration at NNLO (NLO 177 3 (it used GeV). i.e. the $M_b = 4.5 \text{ GeV}$ (4.5 GeV) and M_b was varied with fixed $M_c = 1.4$ 178 mass-parameter values used for HERAPDF2.0 NNLO (NLO) were 179 brianfoster iteration, the mass-parameter values as obtained in the previous ite 180 brianfoster points. The iteration was ended once values stable to 0.1 % for M_c 181 2021-08-24 11:49:43 final χ^2 scans at NNLO are shown in Figs. 1 a) and c) and at NLO₁Fi 182 brianfoster values at NNLO are $M_c = 1.41 \pm 0.04$ GeV and $M_b = 4.20$ 0.10 G 183 2021-08-24 11:49:58 determined for HERAPDF2.0 NNLO, with slightly reduced uncer 184 are $M_c = 1.46 \pm 0.04$ GeV and $M_b = 4.30 \pm 0.10$ GeV. The min 185 in the power of the method. The minimum in χ^2 for the parameter M_d 186 to the technical limit of the fitting procedure. 187

The part of the model uncertainty concerning the heavy-flavour mass parameters would nom-188 inally have involved varying the value of M_c to the minimum and maximum of its one standard 189 deviation uncertainty. However, for M_c , the downward variation created a conflict with $\mu_{f,0}$, 190 which has to be less than M_c in the RTOPT scheme, such that charm can be generated perturba-191 tively. Thus, only an upward variation of M_c was considered and the resulting uncertainty on the 192 PDFs was symmetrised. In addition, the condition $\mu_{f0} < M_c$ created a conflict with the variation 193 of μ_f^2 . The normal procedure would have included an upward variation of μ_f^2 to 2.2 GeV² but 194 μ_{f0} would have become larger than the upper end of the uncertainty interval of M_c^{5} . Thus, μ_f^2 195 was only varied downwards to 1.6 GeV², and the resulting uncertainty on the PDFs was again 196 symmetrised. The suitability of the chosen central parameterisation was re-verified for the new 197 settings for M_c and M_b using the χ^2 saturation method as described in Section 3.1. 198

Since predictions at NNLO for the jet data were only available in the zero-mass scheme, and results for the treatment of the inclusive data in different VFNS and FFNS schemes were consistent [2], no other heavy-flavour schemes were investigated.

& I rewrote this without saying what was done Then -

⁴A cross-check was performed with the fixed value of $\alpha_s = 0.118$ and no significant difference in the resulting M_c and M_b values were observed.

⁵In previous HERAPDF analyses, the uncertainty on M_c was large enough to accommodate the upward μ_f^2 variation.

3.4 Hadronisation uncertainties 202

For the jet-data analysis, it was also necessary to consider hadronisation and the effect of the 203 uncertainties on hadronisation corrections. The uncertainties on the hadronisation corrections, 204 which were supplied in the original publications, were reviewed for this analysis. The H1 un-205 certainties were used as published, while for technical reasons, those for the ZEUS data were 206 increased to the maximum value quoted in the publications, 2 %. It was checked that this change 207 made no significant difference to any of the results presented below. 208

In the HERAPDF2.0Jets NLO analysis, hadronisation uncertainties were applied using the 209 offset method, i.e. performing separate fits with the hadronisation corrections set to their maxi-210 mal and minimal values. This resulted in a hadronisation uncertainty on $\alpha_s(M_7^2)$ of ± 0.0012 [2]. 211

The current procedure is different from this previously used propadure. The uncertain 212 brianfoster the hadronisation corrections were included as input to the HERAP 213 2021-08-24 11:51:25

were treated as systematic uncertainties correlated between all data 214

became part of the overall experimental, i.e. fit, uncertainties. For 215 used previously contribution was negligible. For fits with free $\alpha_s(M_Z^2)$, their contribution 216 uncertainty on $\alpha_s(M_z)$ was ± 0.0006 . This represents a significant 217 the hadronisation uncertainties. 218



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compared to previous analyses

HERAPDF2.0Jets NNLO – results 219

Simultaneous determination of $\alpha_s(M_z^2)$ and PD 4.1 220

Jet-production data are essential for the determination of the strong coupling constant, $\alpha_s(M_z^2)$. 221 In pQCD fits to inclusive DIS data alone, the gluon PDF is determined via the DGLAP equations, 222 using the observed scaling violations. This results in a strong correlation between the shape of 223 the gluon distribution and the value of $\alpha_s(M_{\pi}^2)$. Data on jet and dijet production cross-sections 224 provide an independent constraint on the gluon distribution and are also directly sensitive to $\alpha_s(M^2)$. Thus, such data are essential for an accurate simultaneous determination of $\alpha_s(M^2)$ and 225 226 the gluon distribution. 227

When determining $\alpha_s(M^2)$, it is necessary to consider so-called "scale uncertainties". They 228 approximate the uncertainty due to the influence of higher orders in the perturbation extension. 229 This uncertainty was evaluated by varying the renormalisation and factorisation scales by a 230 factor of two, both separately and simultaneously⁶, and selecting the maximal positive and 231 negative deviations of the result as the "de facto" scale uncertainty. These were observed for 232 $(2.0\mu_r, 1.0\mu_f)$ and $(0.5\mu_r, 1.0\mu_f)$, respectively. 233

The HERAPDF2.0Jets NNLO fit with free
$$\alpha_s(M_Z^2)$$
 results in
 $\alpha_s(M_Z) = 0.1156 \pm 0.0011$ (exp) $_{-0.0002}$ (model + parameterisation) ± 0.0029 (scale), (7)

⁶This procedure is often called 9-point variation, where the nine variations are $(0.5\mu_{\rm f}, 0.5\mu_{\rm f}), (0.5\mu_{\rm f}, 1.0\mu_{\rm f}),$ $(0.5\mu_r, 2.0\mu_f), (1.0\mu_r, 0.5\mu_f), (1.0\mu_r, 1.0\mu_f), (1.0\mu_r, 2.0\mu_f), (2.0\mu_r, 0.5\mu_f), (2.0\mu_r, 1.0\mu_f), (2.0\mu_r, 2.0\mu_f).$

where "exp" denotes the experimental uncertainty, which was taken as the fit uncertainty, in-236 cluding the contribution from hadronisation uncertainties. The value of $\alpha_s(M_7^2)$ and the size of 237 the experimental uncertainty were confirmed by the the result of a so-called χ^2 scan in $\alpha_s(M_Z^2)$, 238 which is shown in Fig. 2 a). Numerous fits with varying $\alpha_s(M_2^2)$ were performed and the clear 239 minimum observed in χ^2 coincides with the value of $\alpha_s(M_z)$ determined with the fit. The width 240 of the minimum in χ^2 confirms the fit uncertainty. The combined model and parameterisation 241 uncertainty shown in Fig. 2 a) was determined by performing similar scans, for which the values 242 of the model parameters and the parameterisation were varied as described in Section 3.1. 243

Figure 2 a) also shows the scale uncertainty, which dominates the uncertainties. The scale uncertainty as listed in Eq. 7 was evaluated under the assumption of 1000 -1000

ties between bins and data sets. The previously published result a 2021-08-24 14:08:28

tainties calculated under the assumption of 50 % correlated and 50

between bins and data sets. A strong motivation to determine $\alpha_s(M_1 \text{ still feel that we need to say something})$ substantially reduce scale uncertainties. Therefore, the analysis was tions in order to be able to compare the NNL O to the NL O scale un

tions in order to be able to compare the NNLO to the NLO scale ur
 NNLO scale uncertainty of (±0.0022) is indeed significantly lower
 previously observed in the HERAPDF2.0Jets NLO analysis.

The HERAPDF2.0Jets NNLO fit with free $\alpha_s(M_Z^2)$ was based on 1363 data points and had a $\chi^2/d.o.f. = 1614/1348 = 1.197$. This can be compared to the $\chi^2/d.o.f. = 1363/1131 = 1.205$ for HERAPDF2.0 NNLO based on inclusive data only [2]. The similarity of the $\chi^2/d.o.f.$ values indicates that the data on jet production do not introduce any additional tension to the fit. The jet data are fully consistent with the inclusive data.

The question whether data with relatively low Q^2 bias the determination of $\alpha_s(M_Z^2)$ arose within the context of the HERAPDF2.0 analysis [2]. Figure 2 b) shows the result of $\alpha_s(M_Z^2)$ scans with Q_{mi}^2 for the inclusive data set to 3.5 GeV², 10 GeV² and 20 GeV². Clear minima are visible which coincide within uncertainties. Figure 2 c) shows the result of similar scans with only the inclusive data used as input [2]. The inclusive data alone cannot sufficiently constrain $\alpha_s(M_Z^2)$.

It has also been suggested that the use of the A_g^0 term, in the g **brianfoster** bias the determination of $\alpha_s(M_2^2)$. Thus cross-checks were made w 2021-08-24 14:12:16 rameterisations, $A_g^0 = 0$ and $xg(x) = A_g x^{B_g}(1 - x)^{C_g}$ as well at meterisation, AG [2], for which $A_g^0 = 0$ and $xg(x) = A_g x^{B_g}(1 - ref?)$ If there isn't a specific reference to suc $\alpha_s(M_2^2) = 0.1151 \pm 0.0010(\exp)$ was obtained for both modification which is in agreement with the result for the standard parameteric suggestion, we should say something like the AG parameterisation was consistent with zero. These results a To check whether the use of the A_g term $\alpha_s(M_2^2)$ determination is not sensitive to the details of the gluon parameterisation biases the

The result presented here cannot be directly compared to an H1 result [37] and a result published by the NNLOJET authors and their collaborators [38] because a previous version of the theoretical predictions were used for these analyses. The groups have to tell me what to compare to. I could write something about the same version, but as I expect errata, I would prefer to compare to what will come or has come. Decisions and info during EB meeting, please. The following text is tentative.

Other determinations of $\alpha_s(M_Z^2)$ at NNLO using jet data as published by H1 [37] and NNLO-JET authors and their collaborators [38] used fixed PDFs for their fits to determine $\alpha_s(M_Z^2)$.

Please. It was age EB decision and we did what Thomas wanted. What should I write? The last time we had triget data, so it was sort of orkay bill. This time we had triget data, so it was sort of orkay bill. This time Lel and Thomas arread

Therefore, the values of $\alpha_s(M^2)$ should not be directly compared. However, both analyses were 280 performed with a cut on μ of $\mu > 2M_b$, which is quite similar to the $\mu > 10.0$ GeV cut used for 28 this analysis. Thus, the scale uncertainties can be compared. The H1 result is based on H1 data 282 only and the quoted scale uncertainty of ± 0.0042 can be compared to the 0.0029 obtained for 283 the analysis presented here based on H1 and ZEUS data. The scale uncertainty published by 284 NNLOjet is ± 0.0036 . 285

The H1 collaboration provided one simultanous fit of $\alpha_s(M_7^2)$ and PDFs, based on H1 inclu-286 sive and jet data only, and with $Q_{min}^2 = 10 \text{ GeV}^2$. For comparison, the analysis presented here was modified by also setting $Q_{min}^2 = 10 \text{ GeV}^2$. The value of $\alpha_s(M^2)$ published by H1 is $\alpha_s(M^2) = \frac{10 \text{ GeV}^2}{2}$ 287 288 $0.1142 \pm 0.0011(\exp) \pm 0.0003(\text{model/parameterisation}) \pm 0.0026(\text{scale})$ while the current mod-289 ified analysis resulted in $\alpha_s(M_7^2) = 0.1156 \pm 0.0011(\exp) \pm 0.0002(\text{model/parameterisation}) \pm$ 290 0.0021(scale). 291

The PDFs of HERAPDF2.0Jets NNLO obtained for fixed $\alpha_s(M_z^2)$ 4.2202

The value of $\alpha_s(M_z) = 0.1155$ was used for the determination of the PDFs in the HERA-293 PDF2.0Jets NNLO analysis. The value listed in PDG12 [39], 0.118, which was also the value 294 determined in the HERAPDF2.0Jets NLO analysis, was used for the original HERAPDF2.0 295 analyses at NNLO based on inclusive data only. Therefore, the PDFs of HERAPDF2.0Jets NNLO are shown in Fig. 3 a) and b) for both, fixed $\alpha_s(M^2) = 0.1155$ and fixed $\alpha_s(M^2) = 0.118$, 296 297 respectively, together with their uncertainties, at the scale $\mu_f^2 = 10 \text{ GeV}^2$. The uncertainties 298 shown are the experimental, i.e. fit, uncertainties as well as the model and parameterisation 299 uncertainties as defined in Section 3.2. The parameterisation uncertainty dominates the uncer-300 tainties and is itself dominated by the introduction of the parameter $D_{\mu_{y}}$ as a variation. Details 301 on the two sets of PDFs as released are listed in Appendix A. 302

As the PDFs were derived with a fixed $\alpha_s(M_Z^2)$ value scale uncertainties 303 brianfoster not considered, because, in this case, a quantification of theory unc 304

2021-08-24 11:59:14 of the renormalisation and factorisation scales in the fit becomes 305

compensation of explicit scale-dependent terms in the NLO and N 306

of the renormalisation scale effectively amounts, in its numerical effectively of $\alpha_s(M^2)$. Fixing the value of $\alpha_s(M^2)$ externally amounts to 307 Torying

308

a local minimum, where a variation of the scales could map out the putative uncertainty from 309 missing higher orders. Therefore, scale variations cannot be used as a proxy for uncertainties 310 on the PDF extraction due to missing higher orders. Nevertheless, a cross-check with scale 311 variations as described in Section 4.1 for the fit with free $\alpha_s(M_r^2)$ was made. The impact on 312 the resulting PDFs was found to be negligible compared to the other uncertainties presented in 313 Fig. 3. 314

A comparison between the PDFs obtained for $\alpha_s(M_{\gamma}^2) = 0.1155$ and $\alpha_s(M_{\gamma}^2) = 0.118$ is 315 provided in Figs. 4 and 5 for the scales $\mu_f = 10 \text{ GeV}^2$ and $\mu_f = M_Z^2$, respectively. Here, only total 316 uncertainties are shown. At the lower scale, a significant difference is observed between the gluon distributions; the distribution for $\alpha_s(M) = 0.1155$ is above the distribution for $\alpha_s(M) = 0.1155$ 317 318

0.118 for x less than $\approx 10^{-2}$. This correlation between the value of $\alpha_s(M_z^2)$ and the shape of 319 the gluon PDF is as expected from QCD evolution. At the scale of M_{Z}^2 the differences become 320 negligible in the visible range of x due to QCD evolution. 321

A comparison of the PDFs obtained for $\alpha_s(M_Z^2) = 0.118$ by HERAPDF2.0Jets NNLO to the PDFs of HERAPDF2.0 NNLO, based on inclusive data only, is provided in Fig. 6. These two sets of PDFs do not show any significant difference in the central values. However, there is a significant reduction of the uncertainties on the gluon PDFs as shown in Fig. 7 at the scale of $\mu_f = 10 \text{ GeV}^2$ and in Fig. 8 at the scale of $\mu_f = M^2$. The reductions in the uncertainties for HERAPDF2.0Jets NNLO for $\alpha_s(M_Z^2) = 0.1155$ compared to $\alpha_s(M_Z^2) = 0.118$ are shown in Fig. 9 and Fig. 10. At high x and $\mu_f = M^2$, the parameterisaton uncertainties become important as can be seen by comparing Fig. 10 b) and 10 c).

The reduction in model and parameterisation uncertainty for $x < 10^{-3}$ compared to HERA-330 PDF2.0 NNLO is mostly due to the improved procedure to estimate this uncertainty. The ranges, 331 in which M_c and M_b were varied were reduced, but but this had basically no effect on the uncer-332 tainties but for the following effect. As discussed Section 3.3, it was necessary to symmetrise 333 the downward variation of μ_{ℓ}^2 rather than allowing both upward and downward variations. This 334 had the positive effect of removing a slight double-counting of sources of uncertainty that could 335 not be avoided in the original HERAPDF2.0 NNLO procedure. The reduction in the model and 336 parameterisation uncertainties for $x < 10^{-3}$ is mostly due to this effect, whereas the reduction 337 in experimental as well as model and parameterisation uncertainties for $x > 10^{-3}$ is due to the 338 influence of the jet data. This is also demonstrated in Fig. 11, which shows ratios of uncer-339 tainties with respect to the total uncertainties of HERAPDF2.0 NNLO based on inclusive data 340 only. Shown are the contributions of the experimental, the experimental plus model and the 341 experimental plus parameterisation uncertainties to the the total uncertainties of HERAPDF2.0 342 NNLO and the respective reductions for HERAPDF2.0Jets NNLO. Further such ratio plots are 343 provided in Appendix B. 344

4.3 Comparisons of HERAPDF2.0Jets NNLO predictions to jet data

³⁴⁶ Comparisons of the predictions based on HERAPDF2.0Jets NNLO with fixed $\alpha_s(M_Z^2) = 0.1155$ ³⁴⁷ to the data on jet production used as input to the fit are shown in Figs. 12 to 19. Each figure ³⁴⁸ presents in a) a direct comparison of the cross sections and in b) the respective ratios.

The uncertainties on the NNLO predictions as provided by appl brianfoster

in all HERAPDF2.0Jets NNLO fits. The predictions based on the 2021-08-24 12:03:44

³⁵¹ PDFs were computed using the assumption of massless jets, i.e. the assumption of massless jets, i.e. the

the transverse momentum of a jet, p_T , were assumed to be equivided and we make this not look like it is a proper analyses, each jet p_T was entered separately. For dijet analyses, the word entry of the main entry momenta, h_{p_T} i was used. In these cases, h_{p_T} i was also used to reprint talics? risation and

renormalisation scales to $\mu_{f}^{2} = \mu_{r}^{2} = Q^{2} + hp_{T}i^{2}$ for calculating predictions State uncertainstices

were not considered [16] for the comparisons to data. The predictions based **Thattle PDE 445** HERAPDF2.0Jets NNLO clearly fit the data on jet production used as input very well, showing that the inclusive data and jet production data both used as input to the NNLO QCD fit are fully consistent.

360 5 Summary

The HERA data set on inclusive *ep* scattering as published by the H1 and ZEUS collaborations [2], together with selected data on jet production, published separately by the two collab³⁶³ orations, were used as input to a pQCD analysis at NNLO.

An analysis was performed where $\alpha_s(M^2)$ and the PDFs were fitted simultaneously. This resulted in a value of $\alpha_s(M_Z^2) = 0.1156 \pm 0.0011 (\exp)_{0.0002}^{+0.0001}$ (model//parameterisation) \pm 0.0029 (scale). This result on $\alpha_s(M_Z^2)$ is compatible with the world average [40] and it is competitive in comparison with other determinations at NNLO. The scale uncertainties were calculated under the assumption of fully correlated uncertainties between bins and data sets. They would decrease to ± 0.0021 under the assumption of 50 % correlated and 50 % uncorrelated uncertainties which is the value that can be directly compared to the previously published [2] scale uncertainties of (+0.0037,-0.0030) observed in the HERAPDF2.0Jets NLO analysis.

Two sets of PDFs were determined for HERAPDF2.0Jets NNLO for fixed $\alpha_s(M_z^2) = 0.1155$ 372 and $\alpha_s(M^2) = 0.118$. They are available to the community. Comparisons between the PDFs of 373 HERAPDF2.0Jets NNLO obtained for the two values of $\alpha_s(M^2)$ were shown, as well as com-374 parisons to HERAPDF2.0 NNLO, for which jet data were not used as input to the fit. All these 375 PDFs are very similar, showing the consistency of the inclusive and the jet production data. 376 On balance, the inclusion of the jet data had two consequences: i) a lower value of $\alpha_s(M_z^2)$ is 377 favoured; ii) the uncertainty on the gluon PDF was reduced. Predictions based on the PDFs of 378 HERAPDF2.0Jets NNLO were compared to the jet production data used as input. The predic-379 tions describe the data very well. 380

The PDFs of HERAPDF2.0Jets NNLO complete the HERAPDF2.0 ensemble of parton distribution functions. This ensemble of PDFs, extracted from HERA data alone, presents a consistent picture in the framework of pQCD. It is on of the legacies of LEPA

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