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

Diffraction and Low-x 2022

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Introduction
Deep inelastic scattering

- Inclusive deep inelastic scattering (DIS) measurements at lepton-hadron colliders are an essential tool to determine the parton distribution functions (PDFs) of the proton (xf)
- Neutral (NC) and charged current (CC) DIS cross sections (at leading order):

$$\left(\frac{2\pi\alpha^2}{x_{Bj}Q^4}\right)^{-1}\frac{d^2\sigma^{\pm}_{NC}}{dx_{Bj}dQ^2} = \underbrace{Y_+F_2^{NC}(x_{Bj},Q^2)}_{\sim xq+x\bar{q}} \mp \underbrace{Y_-x_{Bj}F_3^{NC}(x_{Bj},Q^2)}_{\sim xq-x\bar{q}} - \underbrace{y^2F_L^{NC}(x_{Bj},Q^2)}_{\sim xg\times\alpha_s}$$

$$\left(\frac{G_F^2}{4\pi x_{Bj}}\frac{M_W^4}{(Q^2+M_W^2)^2}\right)^{-1}\frac{d^2\sigma^{\pm}_{CC}}{dx_{Bj}dQ^2} = \underbrace{Y_+F_2^{CC}(x_{Bj},Q^2)}_{\substack{\sim xD+x\bar{U} \quad + \\ \sim xU+x\bar{D} \quad -}} \mp \underbrace{Y_-x_{Bj}F_3^{CC}(x_{Bj},Q^2)}_{\substack{\sim xD-x\bar{U} \quad + \\ \sim xU-x\bar{D} \quad -}} - \underbrace{y^2F_L^{CC}(x_{Bj},Q^2)}_{\sim xg\times\alpha_s}$$

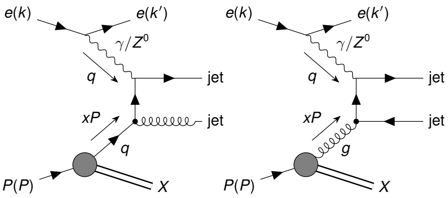
- Measurements of inclusive DIS cross sections allow determination quark- and antiquark densities, xU, xD and $x\bar{U}$, $x\bar{D}$

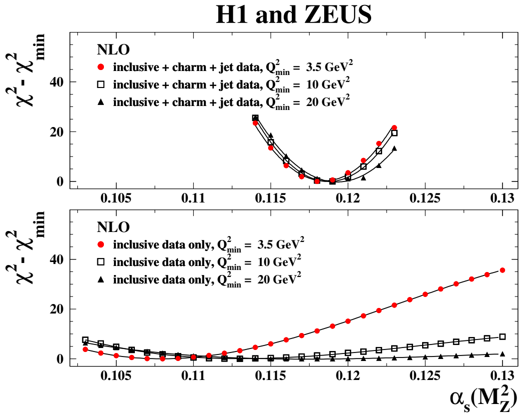
⇒ Inclusive DIS data from HERA is the basis of every recent PDF determination

- Including higher order terms or scaling violations in the DGLAP equations, the gluon density xg and the strong coupling constant α_s can be measured, though they remain highly correlated

Introduction
Jet production

- Already at leading order,† jet production in DIS is sensitive to the strong coupling independently of the gluon distribution (left graph)
- Additionally, jet production can also be used to further constrain the gluon distribution (right graph)





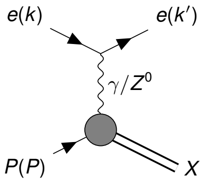
⇒ Adding jet data to the analysis allows a simultaneous determination of PDFs and the strong coupling constant

† Leading order in the Breit frame

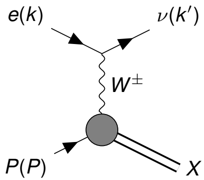
Introduction
HERA data

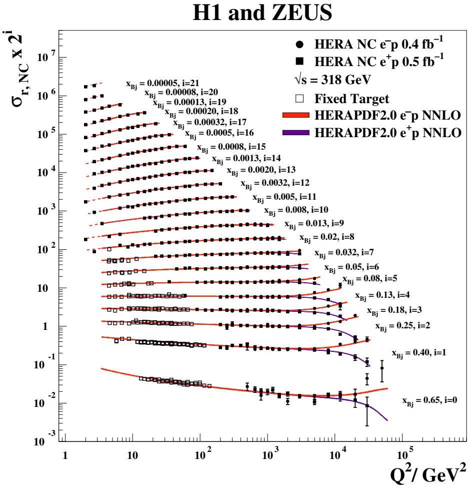
- In 2015, a combined dataset of inclusive DIS from H1 and ZEUS was released†
- Based on measurements of neutral and charged current processes at four different centre-of-mass energies
- Supersedes all previous combinations of DIS data at HERA

NC



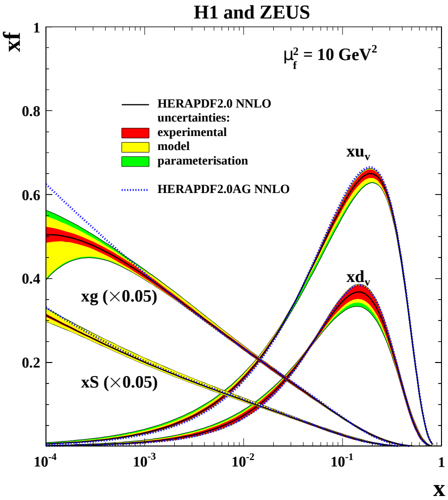
CC





† EPJC 75, 580 (2015). arXiv:1506.06042

- Based on this combined dataset, the HERAPDF2.0 family has been determined using only HERA data at LO, NLO and NNLO
- Most prominent members:
  - HERAPDF2.0 NLO } PDF fits
  - HERAPDF2.0 NNLO } PDF fits
  - HERAPDF2.0Jets NLO } PDF + α_s fit
- In 2017, NNLO QCD predictions of inclusive jet and dijet production became available†
- Now: HERAPDF2.0Jets NNLO completes the HERAPDF2.0 family‡
- Present two new QCD fits at NNLO accuracy
  1. PDF fit with fixed $\alpha_s(M_Z^2)$ → judge impact of jet data on PDF fit
  2. Simultaneous PDF + $\alpha_s(M_Z^2)$ fit → determine $\alpha_s(M_Z^2)$ at NNLO



† JHEP 2017, 18 (2017). arXiv:1703.05977
‡ EPJC 82, 243 (2022). arXiv:2112.01120

Fit strategy
Datasets

Dataset	$\mathcal{L}$ [pb^{-1}]	Used points	
		NLO	NNLO
H1+ZEUS combined inclusive DIS	–	1145	1145
H1+ZEUS combined charm data	–	47	–
H1 HERA I jets at low Q^2	43.5	22	20
H1 HERA I jets at high Q^2	65.4	24	24
H1 HERA II inclusive jets at high Q^2	351	24	30
H1 HERA II dijets at high Q^2	351	24	24
H1 HERA II trijets at high Q^2	351	16	–
H1 HERA II inclusive jets at low Q^2	290	–	37
H1 HERA II dijets at low Q^2	290	–	37
ZEUS HERA I inclusive jets at high Q^2	38.6	30	30
ZEUS HERA I+II dijets at high Q^2	374	22	16

- Some newly published data points could be added since previous NLO analysis
- Some data points had to be excluded since NNLO predictions are unavailable/unreliable

Fit strategy
Parameterisation

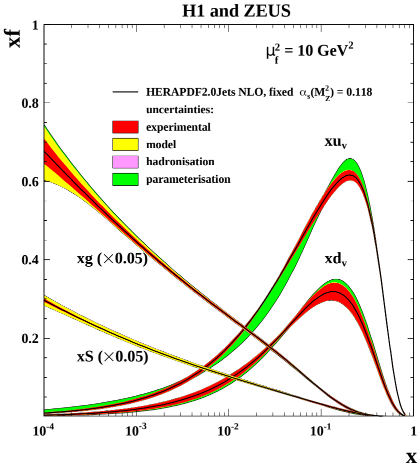
- Use standard HERAPDF functional form of PDFs
- Use χ^2 saturation method to determine relevant parameters

→ Optimal parameterisation is the same as at NLO

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

- A_g, A_{u_v} and A_{d_v} determined by sum rules
- Fix $C'_g = 25$, $B_{\bar{U}} = B_{\bar{D}}$, $A_{\bar{U}} = A_{\bar{D}}(1-f_s)$

⇒ 14 free PDF parameters + $\alpha_s(M_Z^2)$



Fit strategy
Settings

	Jets NLO	Jets NNLO
Model parameters		
f_s	0.4 ± 0.1	0.4 ± 0.1
m_c [GeV]	1.47 ± 0.06	$1.41\,^{+0.04}_{-\text{symmetrise}}$
m_b [GeV]	4.5 ± 0.25	4.2 ± 0.10
Q^2_{min} [GeV^2]	$3.5\,^{+1.5}_{-1.0}$	$3.5\,^{+1.5}_{-1.0}$
Parameterisation		
μ^2_{f0} [GeV^2]	1.9 ± 0.3	$1.9\,^{+\text{symmetrise}}_{-0.3}$
Additional parameters	all missing D and E parameters (D_g, E_g, D_{u_v}, D_{d_v}, E_{d_v}, $E_{\bar{U}}$, $D_{\bar{D}}$, $E_{\bar{D}}$)	all missing D and E parameters (D_g, E_g, D_{u_v}, D_{d_v}, E_{d_v}, $E_{\bar{U}}$, $D_{\bar{D}}$, $E_{\bar{D}}$)
Scales		
μ^2_f	Q^2	$Q^2 + p^2_\perp$
μ^2_r	$(Q^2 + p^2_\perp)/2$	$Q^2 + p^2_\perp$

Parameter choice

- Model parameters determined similar to previous analysis
- Charm and beauty mass updated using new combined HERA data on heavy quarks
- Changed choice of central scales improves description of data at NNLO (lower χ^2), especially for low Q^2 jets

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Scales		
μ^2_{f}	Q^2	$Q^2 + p^2_\perp$
μ^2_{r}	$(Q^2 + p^2_\perp)/2$	$Q^2 + p^2_\perp$

Uncertainties

- Model: Repeat fit with each parameter in turn modified by its uncertainty
- Parameterisation: Perform fits with one additional parameter
- Variation of m_c and μ_{f0} performed one sided and symmetrised, to ensure $m_c > \mu_{\text{f0}}$
- Scale: Perform additional fits, corresponding to a nine-point scale variation by a factor 2, assuming fully correlated cross section scale uncertainty

Theory related uncertainties

- In previous analysis: change hadronisation correction within its uncertainty and repeat fit
- Now: treat hadronisation uncertainty as systematic uncertainty of data points half correlated/half uncorrelated across all jet points and datasets

$\rightarrow$ Hadronisation uncertainty becomes part of fit uncertainty

$\rightarrow$ Significantly reduced influence of hadronisation uncertainty

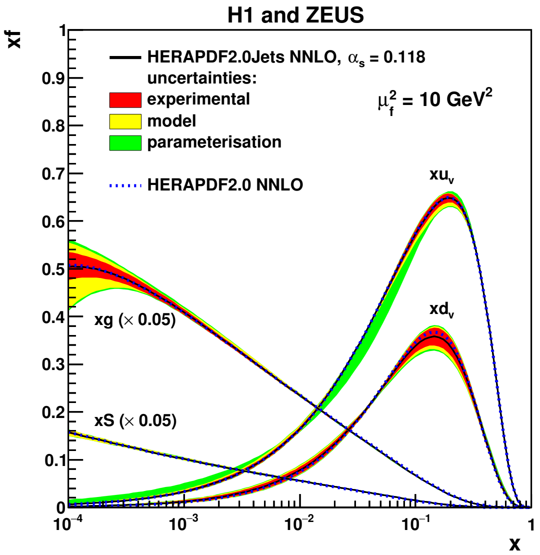
- Similar treatment for statistical uncertainty of theory grids (in previous analysis, uncertainty of NLO grids was not available)

Experimental/fit uncertainty

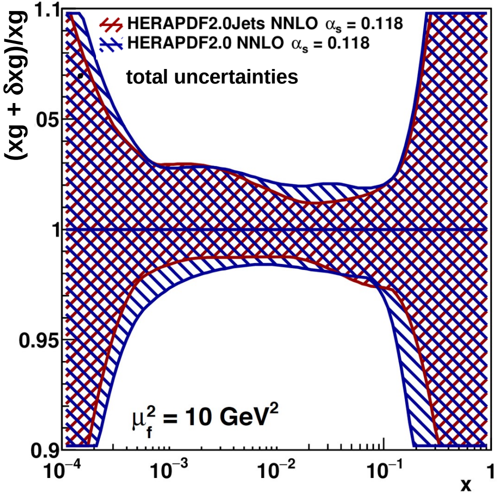
- Vary each parameter according to its uncertainty ($\Delta\chi^2 = 1$)†
- Determine 14 eigenvector pairs (hessian uncertainties)
- Exp/fit uncertainty is given by sum of variations of eigenvectors from central value

† After diagonalising the Hesse matrix, to obtain uncorrelated parameters

Results: PDFs
Central values



- Fit performed at fixed $\alpha_s(M_Z^2) = 0.118$, as was used for HERAPDF2.0 NNLO
- As expected, PDF central values do not change significantly when including jet data
- The same effect was already observed at NLO



- Uncertainty of gluon distribution reduced significantly
- Improvements at small x ($x \lesssim 10^{-3}$) mostly due to improved procedures
- Improvements at larger x mostly due to inclusion of jet data

Results: α_s
Strong coupling

HERAPDF2.0Jets NLO

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009 \text{ (exp/fit) } \pm 0.0005 \text{ (model/param.) } {}^{+0.0037}_{-0.0030} \text{ (scale) } \pm 0.0012 \text{ (hadr.)}$$

HERAPDF2.0Jets NNLO

$$\boxed{\alpha_s(M_Z^2) = 0.1156 \pm 0.0011 \text{ (exp/fit) } {}^{+0.0001}_{-0.0002} \text{ (model/parameterisation) } \pm 0.0029 \text{ (scale)}}$$

- Preferred value is smaller that at NLO, as expected from other analyses
- NNLO value is compatible with PDG world average (0.1179 ± 0.0009)
- Exp/fit uncertainty reduced (compared to exp/fit$\otimes$hadr. at NLO), due to improved treatment of hadronisation uncertainty
- Model/parameterisation uncertainty reduced mostly due to symmetrisation of model uncertainties

HERAPDF2.0Jets NLO

$$\alpha_s(M_Z^2) = 0.1183 \pm \mathbf{0.0009}\ \textbf{(exp/fit)} \pm 0.0005\ \text{(model/param.)}\ ^{+0.0037}_{-0.0030}\ \text{(scale)} \pm \mathbf{0.0012}\ \textbf{(hadr.)}$$

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Results: α_s
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- NNLO value is compatible with PDG world average (0.1179 ± 0.0009)
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- Model/parameterisation uncertainty reduced mostly due to symmetrisation of model uncertainties

HERAPDF2.0Jets NLO (half correlated cross section scale uncertainty)

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009 \text{ (exp/fit)} \pm 0.0005 \text{ (model/param.)} {}^{+0.0037}_{-0.0030} \textbf{ (scale)} \pm 0.0012 \text{ (hadr.)}$$

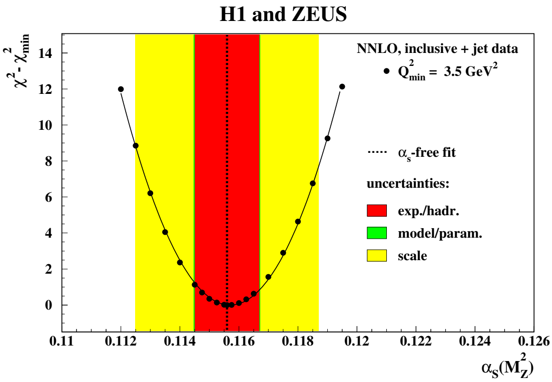
HERAPDF2.0Jets NNLO (fully correlated cross section scale uncertainty)

$$\boxed{\alpha_s(M_Z^2) = 0.1156 \pm 0.0011 \text{ (exp/fit)} {}^{+0.0001}_{-0.0002} \text{ (model/parameterisation)} \pm 0.0029 \text{ (scale)}}$$

HERAPDF2.0Jets NNLO (half correlated cross section scale uncertainty)

$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011 \text{ (exp/fit)} {}^{+0.0001}_{-0.0002} \text{ (model/parameterisation)} \pm \mathbf{0.0022} \textbf{ (scale)}$$

- Preferred value is smaller that at NLO, as expected from other analyses
- NNLO value is compatible with PDG world average (0.1179 ± 0.0009)
- Exp/fit uncertainty reduced (compared to exp/fit$\otimes$hadr. at NLO), due to improved treatment of hadronisation uncertainty
- Model/parameterisation uncertainty reduced mostly due to symmetrisation of model uncertainties
- Scale uncertainty significantly reduced (when evaluated similar to NLO)



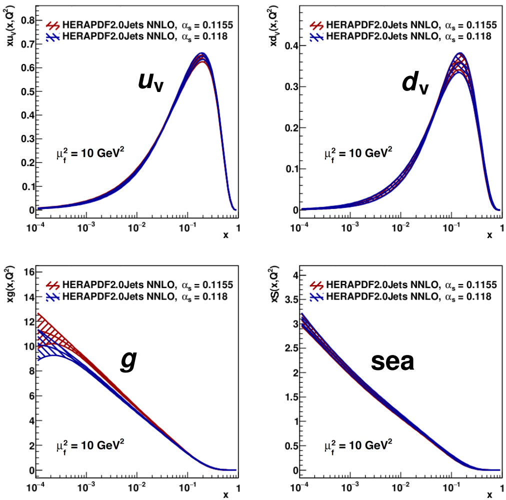
α_s-scan

- Result from α_s-free fit confirmed by α_s-scan
- Series of α_s-fixed fits performed
- Location and width of minimum of $\chi^2(\alpha_s)$ curve correspond very well to central value and fit uncertainty obtained of α_s-free fit

Uncertainties

- Total uncertainty dominated by scale uncertainty
- Model/parameterisation uncertainty negligible

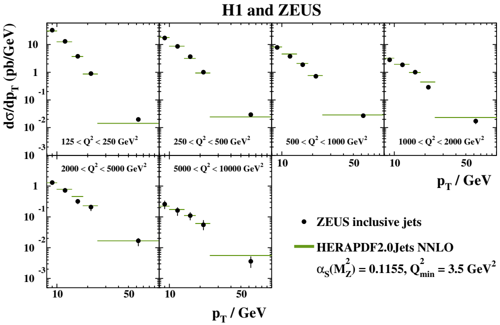
H1 and ZEUS

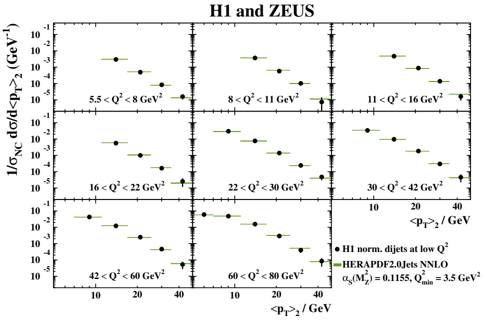


- PDF central values are affected by the change in α_s
- Most notable effect: normalisation of gluon distribution increased
- PDF uncertainties similar to the previous fit at fixed α_s

Results: α_s

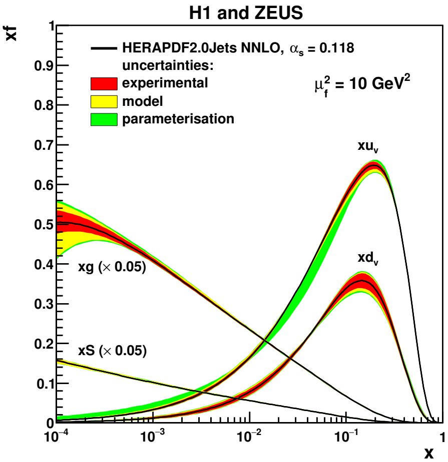
Comparison to data

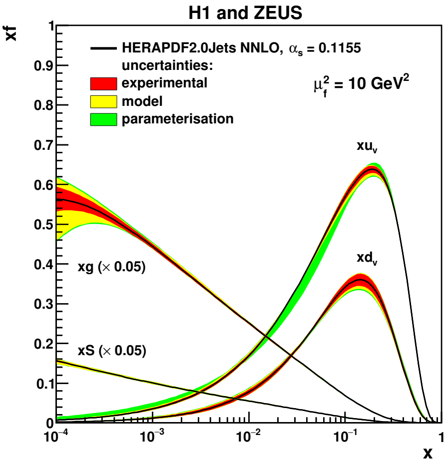




- Cross sections calculated using fitted PDFs are in very good agreement with the input measurements
- Fit achieved a $\chi^2/\text{d.o.f.} = 1614/1348 = 1.197$ (cf. without jets: $1363/1131 = 1.205$), indicating that the jets do not introduce additional tension compared to fit with inclusive data only

Summary
Published PDF sets





- Two PDF sets are provided including full uncertainties at fixed $\alpha_s(M_Z^2) = 0.118$ and $\alpha_s(M_Z^2) = 0.1155$

Summary

- HERAPDF2.0 family has been completed, which is one of the major legacies of HERA
- Settings from previous analysis have been kept, except when improvements were possible due to new data or when transition to NNLO required change in strategy
- At fixed $\alpha_s(M_Z^2)$, the PDF central values do not change significantly, but the uncertainty of the gluon PDF is reduced
- A new value of $\alpha_s(M_Z^2)$ has been determined at NNLO

$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011 \text{ (exp/fit)} \, ^{+0.0001}_{-0.0002} \text{ (model/param.)} \pm 0.0029 \text{ (scale)}$$

- Exp/fit and model/parameterisation uncertainties reduced due to improved procedures
- Scale uncertainty of $\alpha_s(M_Z^2)$ reduced due to NNLO corrections