Measurement of jet production in deep inelastic scattering and NNLO determination of the strong coupling at ZEUS[†]

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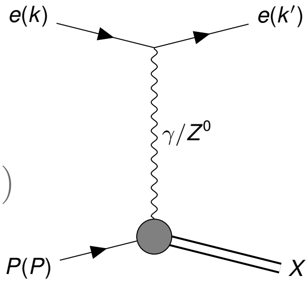
[†] EPJC 83, 1082 (2023). arXiv:2309.02889

Deep inelastic scattering

- Inclusive deep inelastic scattering (DIS) measurements in lepton-hadron collisions ($ep \to eX$) are essential to determine the parton distribution functions (PDFs) of the proton (xf). At leading order:



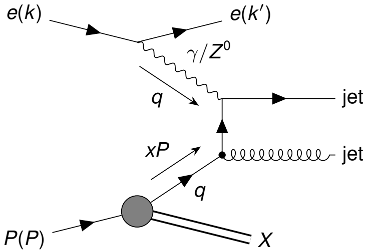
$$\frac{\mathrm{d}^2\boldsymbol{\sigma}^{\pm}_{\text{NC DIS}}}{\mathrm{d}x_{\text{Bj}}\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{x_{\text{Bj}}Q^4}\left(\underbrace{Y_+ F_2(x_{\text{Bj}},Q^2)}_{\sim\, \boldsymbol{xq+x\bar{q}}} \mp \underbrace{Y_- x_{\text{Bj}} F_3(x_{\text{Bj}},Q^2)}_{\sim\, \boldsymbol{xq-x\bar{q}}}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

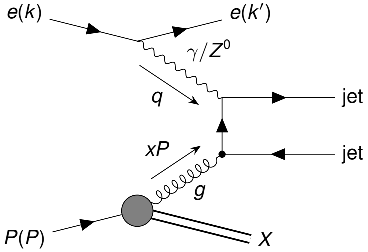
$\Rightarrow$ By measuring F_2 and F_3, the quark- and antiquark-distributions, xq and $x\bar{q}$, can be probed

- By measuring F_{L} or using scaling violations in DGLAP equations the product of the gluon distribution xg and the strong coupling constant α_{s} can be determined
- Using higher-order terms, the two can be disentangled to some extent, but a strong correlation remains (when using only HERA data)

Jet measurements

- Already at leading order,† jet production in DIS is sensitive to the strong coupling independently of the gluon distribution (upper graph)
- Additionally, jet production can also be used to further constrain the gluon distribution (lower graph)
- Inclusive jet measurements are especially well suited for precision determinations of the strong coupling constant due to their small uncertainties on both the experimental and theoretical side



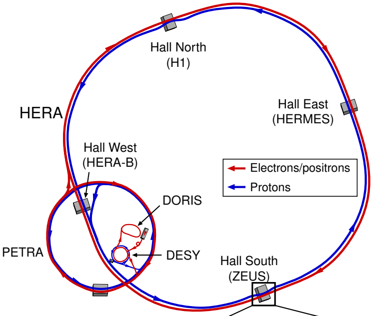


†Leading order in the Breit frame; see slide A1

Experiment
HERA and ZEUS

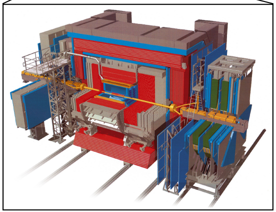
HERA accelerator

- World's only lepton-hadron collider so far
- Located at DESY in Hamburg, Germany
- Two run periods:
  - HERA I: 1992 – 2000
  - HERA II: 2003 – 2007
- Circular collider of length 6336 m
- Collide electrons/positrons at 27.5 GeV with protons at 920 GeV $\rightarrow \sqrt{s} = 318$ GeV



ZEUS detector

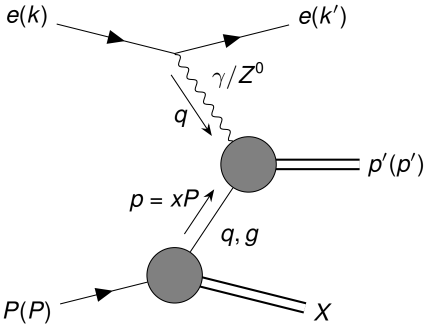
- General purpose particle detector
- Integrated luminosity during HERA II: 347 pb^{-1}
- High-resolution uranium-scintillator calorimeter allows precise measurement of jet energies



Measurement
Cross section definition

- Inclusive jets, clustered using $k_\perp$ algorithm and $p_\perp$-weighted scheme in Breit frame
- Use entire HERA II dataset ($347\,\text{pb}^{-1}$)
- Analysis phase space

$$150\,\text{GeV}^2 < Q^2 < 15\,000\,\text{GeV}^2$$
$$0.2 < y < 0.7$$



$$Q^2 = -q^2 = -(k' - k)^2$$ Boson virtuality/ Momentum transfer

$$x_{\text{Bj}} = \frac{Q^2}{2P \cdot q}$$ Bjorken scaling parameter

$$y = \frac{P \cdot q}{P \cdot k}$$ Inelasticity

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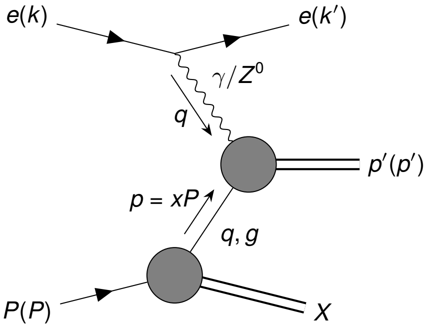
- Use entire HERA II dataset (347 pb^{-1})
- Analysis phase space

$$150\,\mathrm{GeV}^2 < Q^2 < 15\,000\,\mathrm{GeV}^2$$
$$0.2 < y < 0.7$$
$$7\,\mathrm{GeV} < p_{\perp,\mathrm{Breit}} < 50\,\mathrm{GeV}$$
$$-1 < \eta_{\mathrm{lab}} < 2.5$$

- Hadron-level jets
- Weak-boson exchange included
- QED Born-level (higher-order radiative effects removed)



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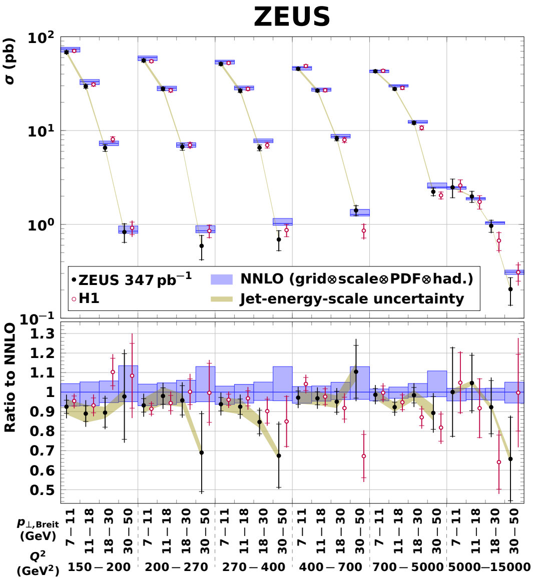
Measurement

Measured inclusive jet cross sections



- Measured cross sections are compatible with previous measurement from H1 collaboration† and uncertainties are comparable‡
- Measurements are compatible with NNLO QCD predictions§
- Inner error bars: unfolding uncertainty; outer error bars: total uncertainty

† EPJC 75, 65 (2015). arXiv:1406.4709

‡ For both measurements, uncertainties appear larger due to negative correlations

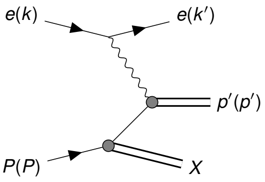
§ Matrix elements from NNLOJET (JHEP 2017, 18 (2017). arXiv:1703.05977), PDFs: HERAPDF2.0Jets NNLO (EPJC 82, 243 (2022). arXiv:2112.01120)

Treatment of QED radiation

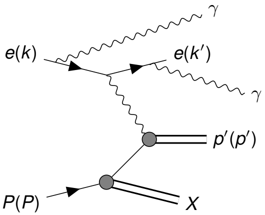
- Predictions for jet production available at QED Born-level (running coupling included, but no radiative corrections)
- In the data, have initial- and final-state QED radiation, especially on the electron line
- Standard procedure: apply 'correction' to the data, to convert it to QED Born-level
- Usually, this cannot be undone, such that data can only ever be compared to QED Born-level predictions
- This analysis: apply correction in a reversible way and provide additional, alternative correction that facilitates more comprehensive comparisons

→ Data can be compared to NNLO QCD+NLO EW predictions, when they become available in the future†

QED Born-level



QED radiation



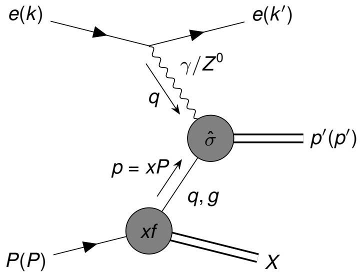
† DIS at NLO EW already available: CPC 94, 2 p.128 (1996). arXiv:hep-ph/9511434

QCD analysis
Strategy

- Simultaneous fit of PDF parameters and $\alpha_s(M_Z^2)$ at NNLO
- Datasets used
  - H1+ZEUS combined inclusive DIS[†]
  - ZEUS HERA I inclusive jets at high Q^2[‡]
  - ZEUS HERA I+II dijets at high Q^2[§]
  - **ZEUS HERA II inclusive jets at high Q^2**
- Inclusion of additional jet data is expected to reduce uncertainty of $\alpha_s(M_Z^2)$
- Statistical correlations between ZEUS HERA II jet datasets taken into account via correlation matrix
- Use HERAPDF parameterisation of PDFs ($f = g, u_v, d_v, \bar{U}, \bar{D}$)

$$xf(x) = A_f x^{B_f}(1-x)^{C_f}(1 + D_f x + E_f x^2)$$

- Use settings similar to HERAPDF2.0Jets NNLO (central scales, cuts, model parameters, treatment of hadronisation and theory grid uncertainty)



† EPJC 75, 580 (2015) arXiv::1506.06042
‡ PLB 547, 164 (2002) arXiv::hep-ex/0208037
§ EPJC 70, 965 (2010) arXiv::1010.6167

For reference, HERAPDF2.0Jets NNLO found

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

This analysis

$$\boxed{\alpha_s(M_Z^2) = \mathbf{0.1143} \pm 0.0017 \text{ (exp./fit) } {}^{+0.0006}_{-0.0007} \text{ (model/param.) } {}^{+0.0012}_{-0.0005} \text{ (scale)}}$$

- Central value is compatible with HERAPDF and with PDG world average
- Increased experimental uncertainty, due to fewer jet datasets used
- Significantly decreased scale uncertainty, due to absence of low-Q^2 jet data
  - Cross-section scale-dependence assumed as fully correlated between all jet measurements
  - When fitting points far away from each other in phase space, the cross-section scale-dependence can be much less correlated or even anti-correlated

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QCD analysis
Alternative treatment of scale uncertainty

- Alternative treatment: assume scale dependence is half correlated between all measurements
- Despite absence of low-Q^2 jet data in the fit, additional reduction is significant

$$\alpha_s(M_Z^2) = 0.1143 \pm \ldots {}^{+0.0012}_{-0.0005} \text{ (scale)}$$
$$\downarrow$$
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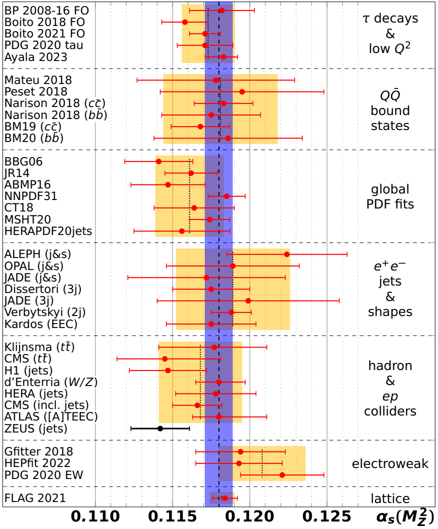
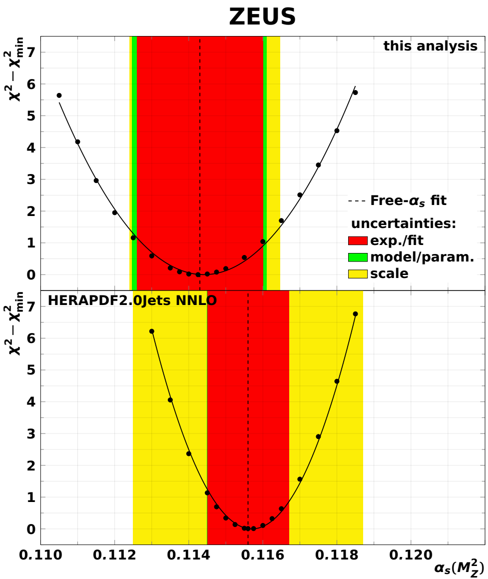
- Reduced scale uncertainty leads to one of the most precise collider measurements of $\alpha_s(M_Z^2)^\dagger$



† PTEP 2022, 8, 083C01 (2022) + 2023 update

QCD analysis

α_s-scan



- Upper panel: $\chi^2(\alpha_s(M_Z^2))$-scan, alongside result from $\alpha_s(M_Z^2)$-free fit
  $\rightarrow$ excellent agreement
- Lower panel: analogous figure from HERAPDF2.0Jet NNLO
- Need better treatment of scale uncertainty, so that we can combine small scale uncertainty from ZEUS with small experimental uncertainty from HERAPDF

- Strong coupling depends on the scale at which it is evaluated. At leading order

$$\alpha_s(\mu^2) = \frac{\alpha_s(\mu_0^2)}{1 + \alpha_s(\mu_0^2) b_0 \log\left(\frac{\mu^2}{\mu_0^2}\right)}$$

- ‘Measure’ this curve to test if QCD is the correct theory to describe strong interaction
  - Assign each jet point a scale
  - Form subsets of jet points with similar scales
  - For each subset, perform a single-parameter α_s fit using fixed PDFs

QCD analysis
Running of the strong coupling

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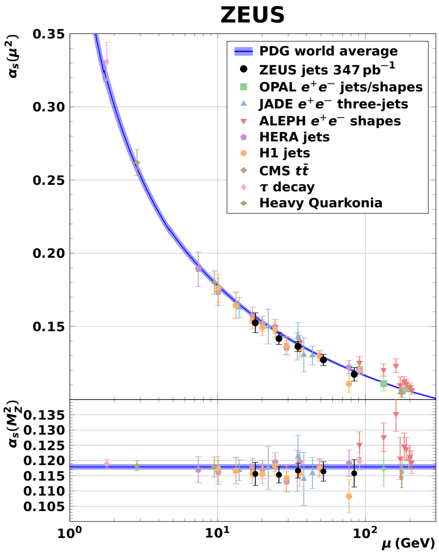
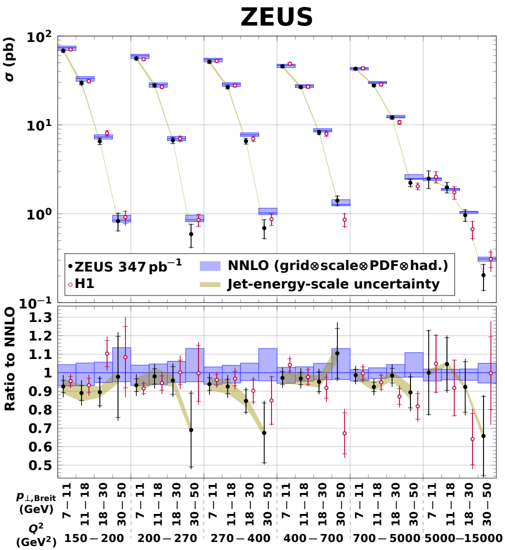
- 'Measure' this curve to test if QCD is the correct theory to describe strong interaction
  - Assign each jet point a scale
  - Form subsets of jet points with similar scales
  - For each subset, perform a single-parameter α_s fit using fixed PDFs
- Observe no deviation from QCD prediction



Cross section measurement

- Performed precision measurement of inclusive jet cross sections in deep inelastic scattering at ZEUS
- Used more than 70% of the entire available luminosity at ZEUS
- Cross sections are compatible with the corresponding H1 measurement and NNLO QCD theory
- New dataset is an ideal ingredient for precision determinations of $\alpha_s(M_Z^2)$ in QCD fits



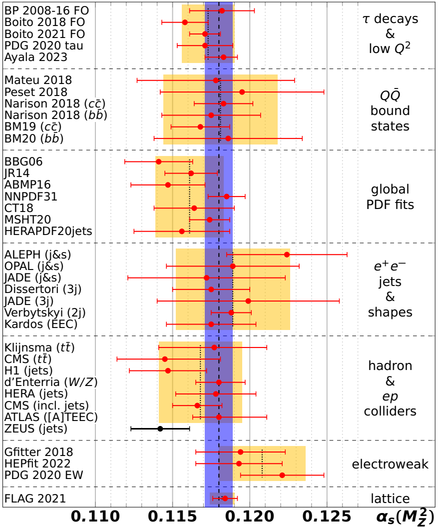
QCD analysis

- Dataset used in $\alpha_s(M_Z^2)$ determination at NNLO
- Achieved very precise measurement of $\alpha_s(M_Z^2)$

$$\alpha_s(M_Z^2) = 0.1142 \pm 0.0019$$

due to

  - Newly measured inclusive jet dataset
  - Restriction to high-Q^2 jet data in the fit
  - Improved treatment of theoretical uncertainty
- Investigated scale-dependence of strong coupling and found results consistent with NNLO QCD prediction



Electron-ion collider

- EIC is expected to start operation in 2030 at Brookhaven National Laboratory in New York
- Will deliver *ep*-collisions at $\sqrt{s} = 29, 45, 63, 105, 141$ GeV

Strong coupling from inclusive DIS

- Inclusive DIS data at different energies has very good sensitivity to $\alpha_s(M_Z^2)$, even without jet data
- Projection of PDF + $\alpha_s(M_Z^2)$ fit using HERA and EIC inclusive DIS[†]
- Assuming one year of data at each of the five centre-of-mass energies of EIC

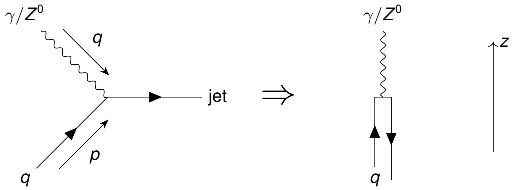
$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004 \text{ (exp./fit) } {}^{+0.0002}_{-0.0001} \text{ (model/param.)}$$

- So far no consensus how to treat scale uncertainty of inclusive DIS data

[†] EPJC 83, 1011 (2023). arXiv:2307.01183

Measurement
Breit frame

- Single jets may arise purely from QED, which is less interesting for the study of QCD
- To suppress these events: require minimum transverse momentum in Breit frame



In the **Breit frame**, the parton and boson collide head-on

$$q^\mu = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -Q \end{pmatrix}$$

$$p^\mu = \begin{pmatrix} Q/2 \\ 0 \\ 0 \\ Q/2 \end{pmatrix}$$

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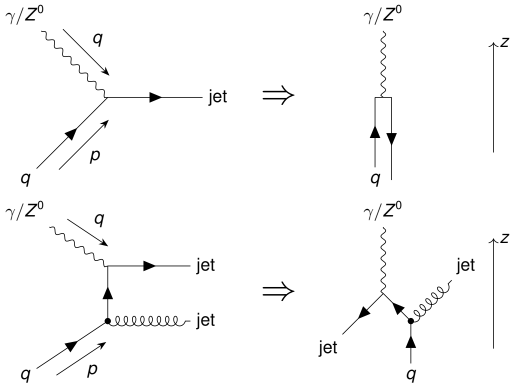

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$$q^\mu = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -Q \end{pmatrix}$$

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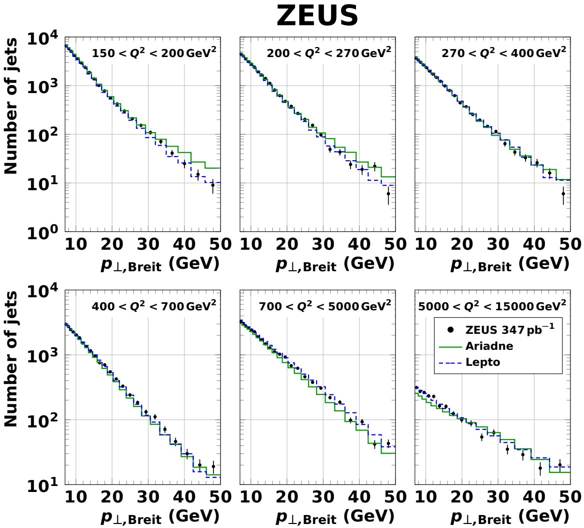
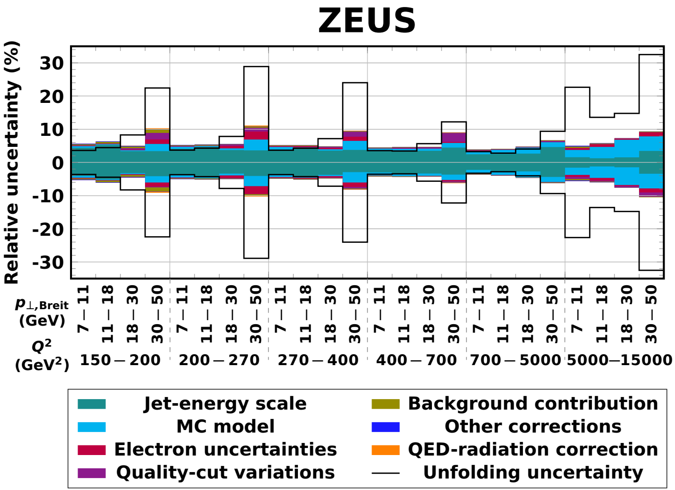
- Lowest order process: produce two jets of equal transverse momentum (“dijet”)
- Inclusive jets: count each jet individually; events can contribute multiple times



- Reconstructed jets corrected to hadron level via two-dimensional matrix unfolding procedure using response matrices obtained from Monte Carlo samples
  - ARIADNE: colour-dipole model
  - LEPTO: leading-log parton cascade
- After reweighting, the models give a good description of the data across the entire phase space
- Performed cross-check using bin-by-bin correction; results are very consistent



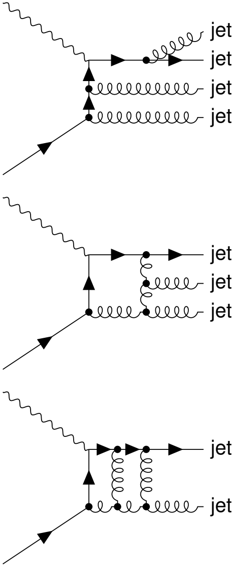
- Systematic uncertainty mostly dominated by jet-energy scale (uncertainty of MC detector simulation)
- In high-$p_{\perp,\mathrm{Breit}}$ or high-Q^2 region, other uncertainties become relevant/dominant
- Unfolding uncertainty appears large in low-statistics region
- Bins with large unfolding uncertainty usually strongly anti-correlated

Theoretical predictions

- Cross section predictions are calculated at NNLO
- Matrix elements calculated using NNLOJET[†]
- PDFs taken from HERAPDF2.0Jets NNLO[‡]
- $\alpha_s(M_Z^2) = 0.1155$, $\mu_r^2 = \mu_f^2 = Q^2 + p_\perp^2$
- Predictions corrected for hadronisation and Z^0-exchange

Theoretical uncertainties

- Six point scale variation by factor 2
- PDF uncertainty (fit, model, parameterisation)
- Statistical uncertainty of matrix element generation
- Hadronisation correction uncertainty



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

Fit settings

	NLO	NNLO
Model parameters		
f_s	0.4 ± 0.1	
m_c [GeV]	$1.46\,^{+0.04}_{-\text{symmetrise}}$	$1.41\,^{+0.04}_{-\text{symmetrise}}$
m_b [GeV]	4.3 ± 0.10	4.2 ± 0.10
Q^2_{min} [GeV^2]	$3.5\,^{+1.5}_{-1.0}$	
Parameterisation		
μ^2_{f0} [GeV^2]	$1.9\,^{-0.3}_{+\text{symmetrise}}$	
Additional parameters	all missing D and E parameters (D_g, E_g, D_{u_v}, D_{d_v}, E_{d_v}, $E_{\bar{U}}$, $D_{\bar{D}}$, $E_{\bar{D}}$)	
Scales		
μ^2_{f}	Q^2	$Q^2 + p^2_\perp$
μ^2_{r}	$(Q^2 + p^2_\perp)/2$	$Q^2 + p^2_\perp$

Parameterisation

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

Constraints

A_g determined by sum rules

A_{u_v} determined by sum rules

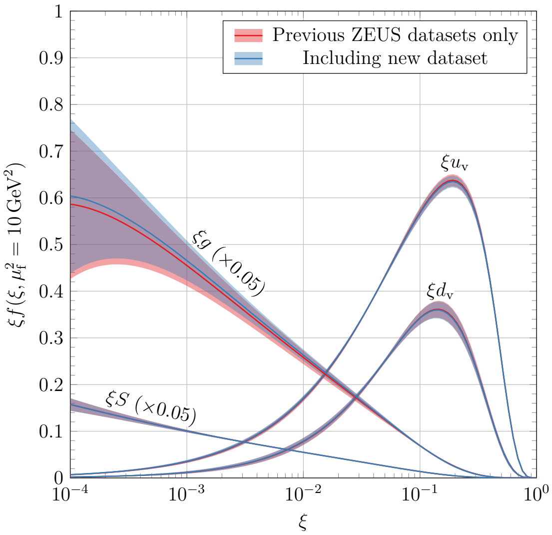
A_{d_v} determined by sum rules

$C'_g = 25$

$B_{\bar{U}} = B_{\bar{D}}$

$A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$

QCD analysis
Parton distribution functions



- Perform two fits and compare PDFs:
  1. HERA inclusive DIS dataset + previous ZEUS jet datasets
  2. Also include newly measured ZEUS HERA II inclusive jet datasets
- Shown is exp./fit uncertainty
- Gluon distribution is slightly constrained†
- As expected, quark distributions are not significantly affected/constrained

†Uncertainties, especially of gluon distribution, appear larger than in HERAPDF, because $\alpha_s(M_Z^2)$ is left free in the fit, compare e.g. fig. 4 in arXiv:2112.01120

Dataset	Partial χ^2 / Number of points
HERA NC e^+p DIS, $E_P = 920\,\text{GeV}$	447.65 / 377
HERA NC e^+p DIS, $E_P = 820\,\text{GeV}$	64.99 / 70
HERA NC e^+p DIS, $E_P = 575\,\text{GeV}$	219.16 / 254
HERA NC e^+p DIS, $E_P = 460\,\text{GeV}$	216.58 / 204
HERA NC e^-p DIS, $E_P = 920\,\text{GeV}$	219.88 / 159
HERA CC e^+p DIS, $E_P = 920\,\text{GeV}$	47.52 / 39
HERA CC e^-p DIS, $E_P = 920\,\text{GeV}$	51.73 / 42
HERA I inclusive jets	26.38 / 30
HERA I/II dijets	14.65 / 16
HERA II inclusive jets	14.98 / 24

Shifts of correlated systematics	96.24
Global χ^2 per degree of freedom	1418.93 / 1200 = 1.182

HERAPDF2.0 NNLO	1363 / 1131 = 1.205
HERAPDF2.0Jets NNLO	1614 / 1348 = 1.197