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

International Workshop on Deep Inelastic Scattering 2024

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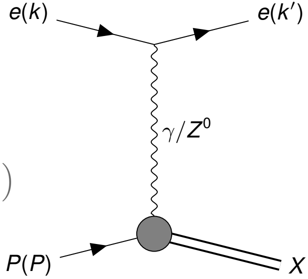
[†] EPJC 83, 1082 (2023). arXiv:2309.02889

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:

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



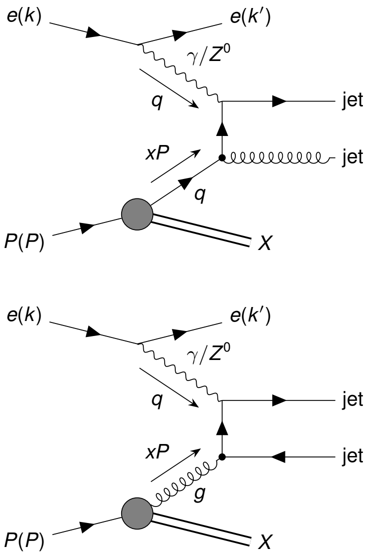
⇒ By measuring F_2 and F_3, the quark- and antiquark-distributions, xq and $x\bar{q}$, can be probed

- 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)

See talk from K.Wichmann on Wednesday 17:45

Jet measurements

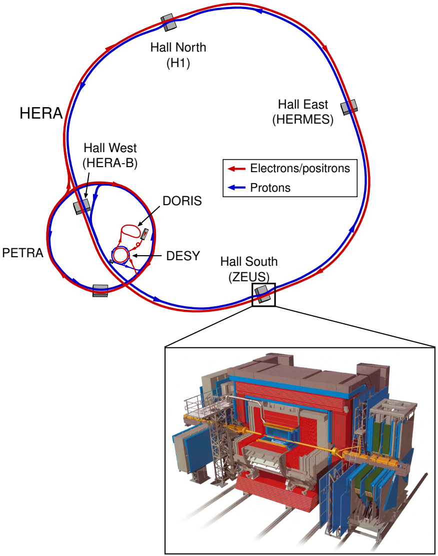
- Already at leading order,† jet production in DIS is sensitive to the strong coupling independently of the gluon distribution (upper graph)
- Additionally, jet production can also be used to further constrain the gluon distribution (lower graph)
- Inclusive jet measurements are especially well suited 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

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



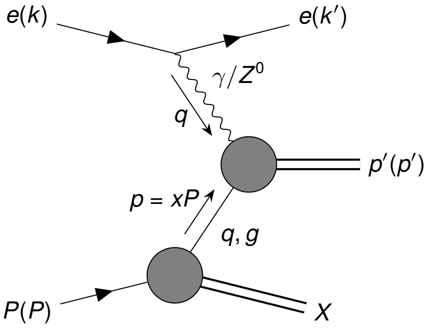
ZEUS detector

- 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 ($347\,\mathrm{pb}^{-1}$)
- Analysis phase space

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



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

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

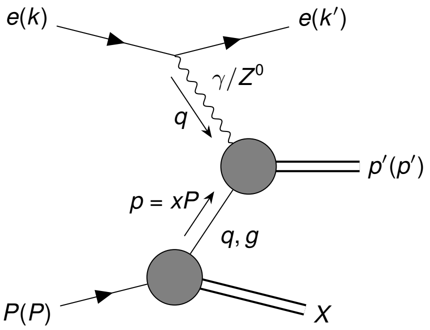
$$y = \frac{P \cdot q}{P \cdot k}$$ Inelasticity

Measurement
Cross section definition

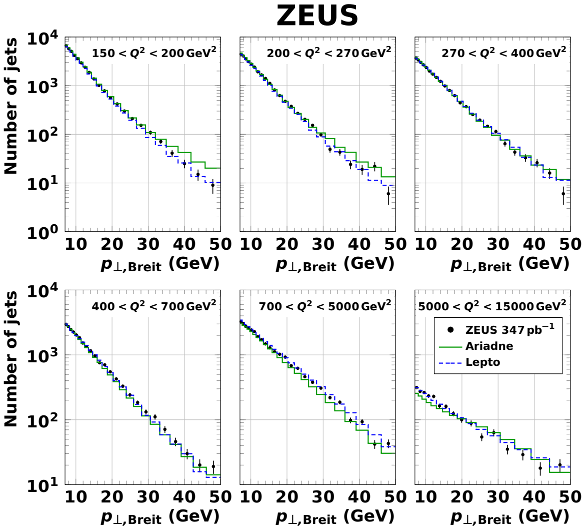
- Inclusive jets, clustered using $k_\perp$ algorithm and $p_\perp$-weighted scheme in Breit frame
- Use entire HERA II dataset ($347\,\text{pb}^{-1}$)
- Analysis phase space

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

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

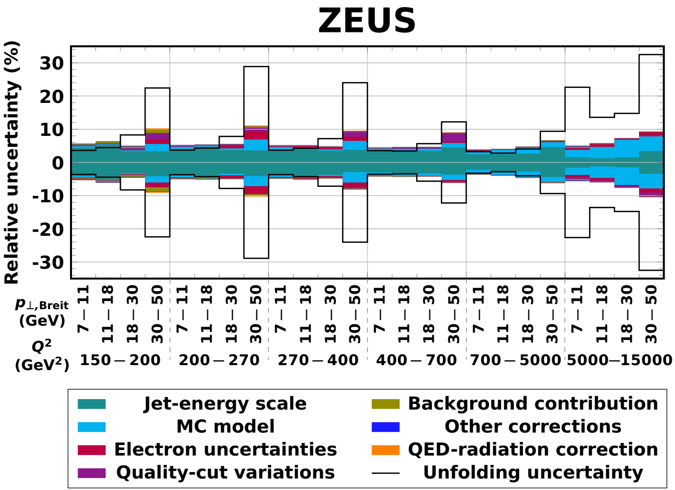


$Q^2 = -q^2 = -(k'-k)^2$	Boson virtuality/ Momentum transfer
$x_\text{Bj} = \dfrac{Q^2}{2P \cdot q}$	Bjorken scaling parameter
$y = \dfrac{P \cdot q}{P \cdot k}$	Inelasticity



- 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

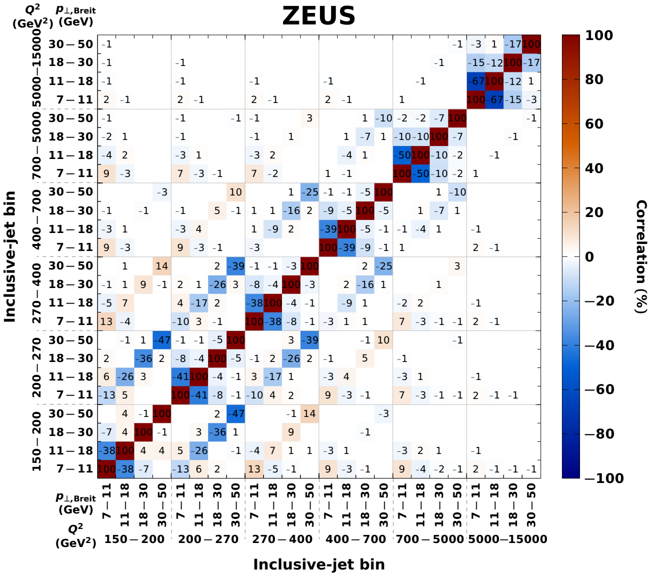
Measurement
Systematic uncertainties



- 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

Measurement

Systematic uncertainties



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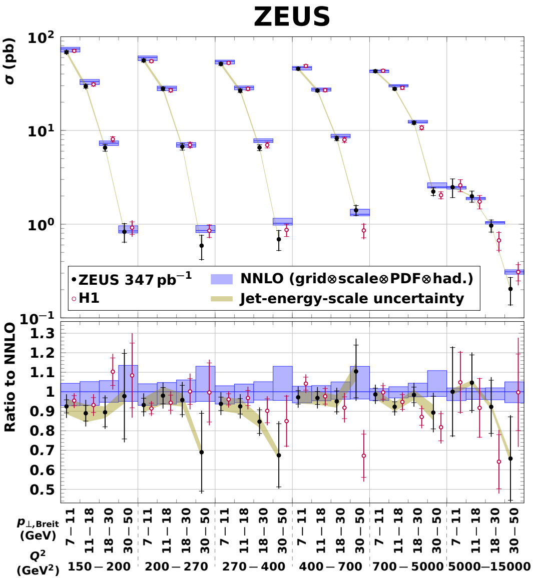
Measurement

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

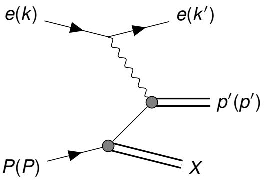
§ Matrix elements from NNLOJET (JHEP 2017, 18 (2017). arXiv:1703.05977), PDFs: HERAPDF2.0Jets NNLO (EPJC 82, 243 (2022). arXiv:2112.01120)

Treatment of QED radiation

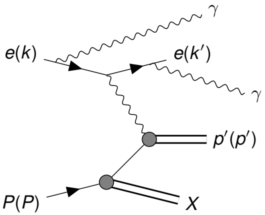
- Predictions for jet production available at QED Born-level (running coupling included, but no radiative corrections)
- In the data, have initial- and final-state QED radiation, especially on the electron line
- Standard procedure: apply ‘correction’ to the data, to convert it to QED Born-level
- Usually, 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



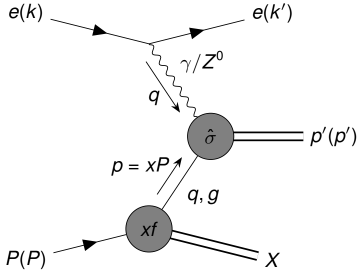
QED radiation



[†] 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

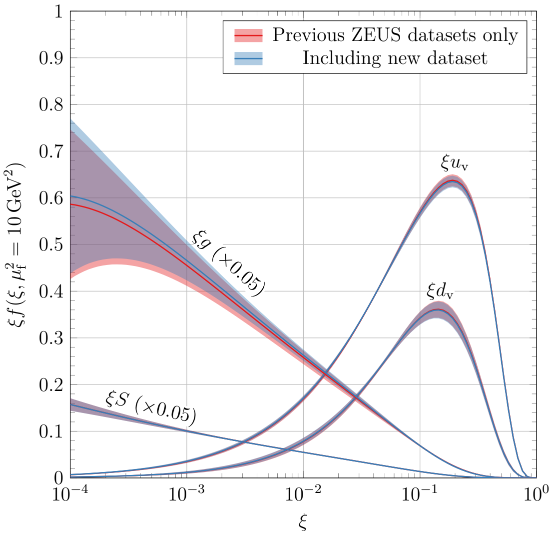


- Use HERAPDF parameterisation of PDFs ($f = g, u_v, d_v, \bar{U}, \bar{D}$)

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

- 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



- 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

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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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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QCD analysis

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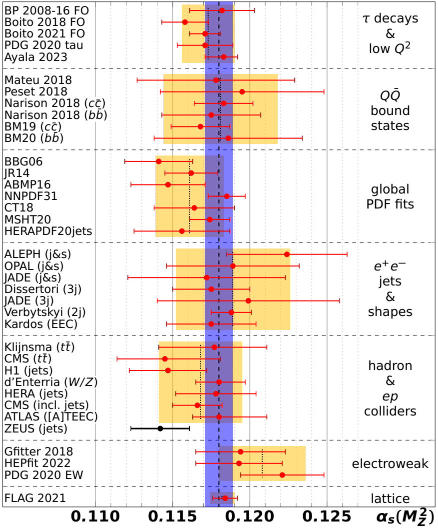
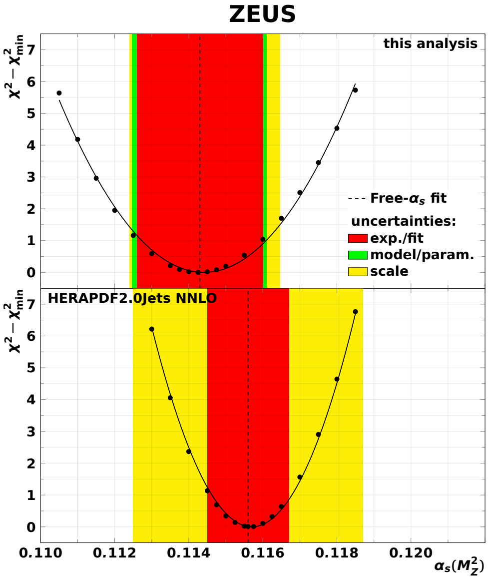
- Reduced scale uncertainty leads to one of the most precise collider measurements of $\alpha_s(M_Z^2)^\dagger$



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



- 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

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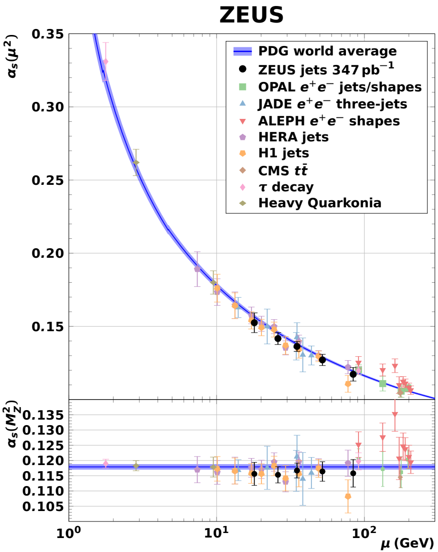
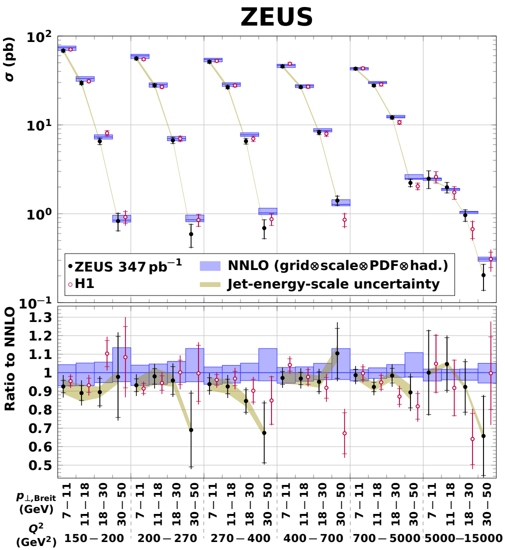
  - Form subsets of jet points with similar scales
  - For each subset, perform a single-parameter α_s fit using fixed PDFs
- Observe no deviation from QCD prediction



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



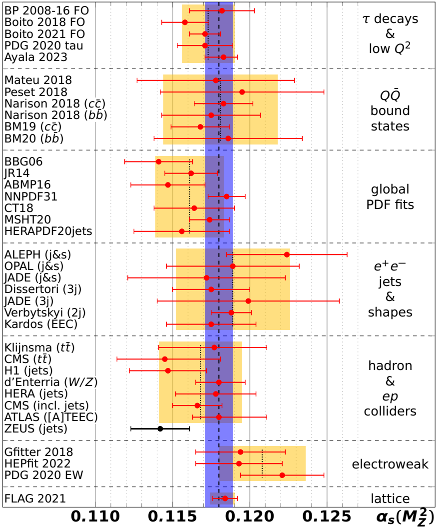
QCD analysis

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

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

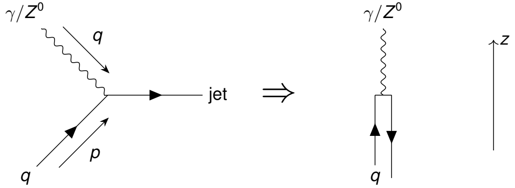
due to

  - 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



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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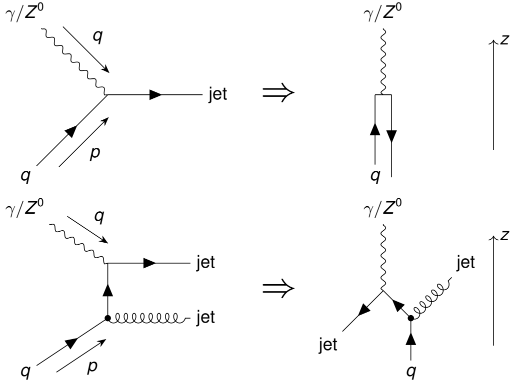

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$$p^\mu = \begin{pmatrix} Q/2 \\ 0 \\ 0 \\ Q/2 \end{pmatrix}$$

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

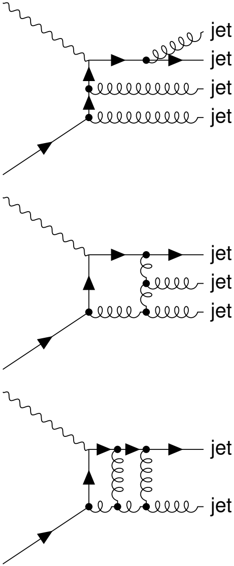
Measurement
Theoretical predictions

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

$C'_g = 25$

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

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

Dataset	Partial χ^2 / Number of points
HERA NC e^+p DIS, $E_P = 920$ GeV	447.65 / 377
HERA NC e^+p DIS, $E_P = 820$ GeV	64.99 / 70
HERA NC e^+p DIS, $E_P = 575$ GeV	219.16 / 254
HERA NC e^+p DIS, $E_P = 460$ GeV	216.58 / 204
HERA NC e^-p DIS, $E_P = 920$ GeV	219.88 / 159
HERA CC e^+p DIS, $E_P = 920$ GeV	47.52 / 39
HERA CC e^-p DIS, $E_P = 920$ 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