Measurement and QCD analysis of inclusive jet production in deep inelastic scattering at HERA

Diffraction and Low-x 2022

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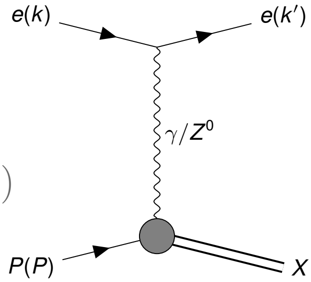
Deep inelastic scattering

- 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:

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

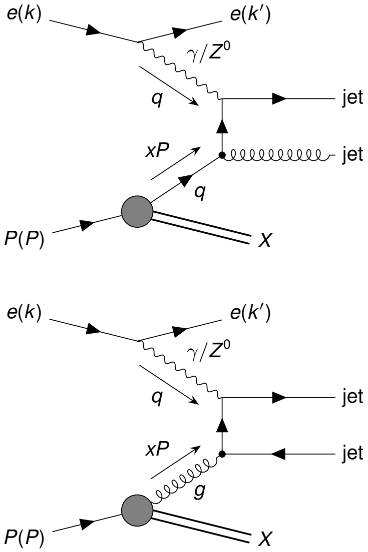


$\Rightarrow$ By measuring F_2 and F_3, the quark- and antiquark-distributions, xq and $x\bar{q}$, can be probed

- 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

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 5

Deep inelastic scattering

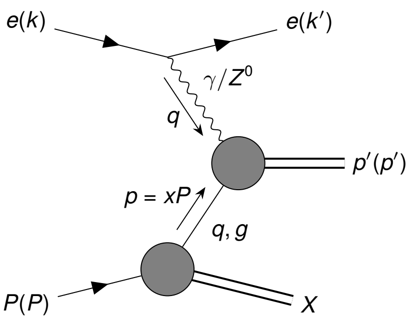
- Scattering of leptons off hadrons at high momentum transfer Q^2

$$e(k) + P(P) \to e(k') + p'(p') + X$$

- Boson acts as point-like probe of the hadron

p' . . . Scattered hadronic system

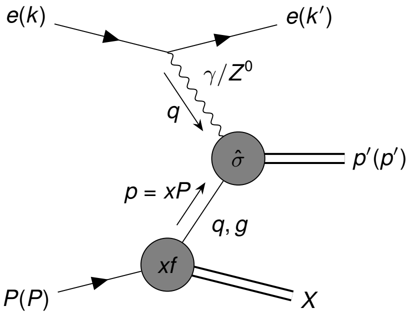
X . . . Proton remnant



Kinematic quantities

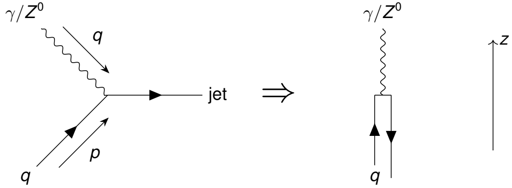
$Q^2 = -q^2 = -(k' - k)^2$	Boson virtuality/ Momentum transfer
$x_{\mathrm{Bj}} = \dfrac{Q^2}{2P \cdot q}$	Bjorken scaling parameter
$y = \dfrac{P \cdot q}{P \cdot k}$	Inelasticity

- To predict cross sections of lepton-hadron collisions, one needs
  - The boson-parton cross sections $\hat{\sigma}$ (calculable using perturbative QCD)
  - The parton content of the hadron (unknown but assumed to be universal for each hadron); parameterised using PDFs *xf*
- PDFs can only be determined from fits to measurements
- Adding jet data to the fit allows a simultaneous determination of α_s and the PDFs



Theory of deep inelastic scattering
Breit frame

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



In the **Breit frame**, the parton and photon 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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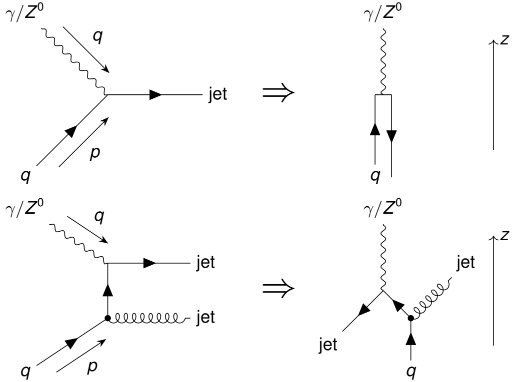

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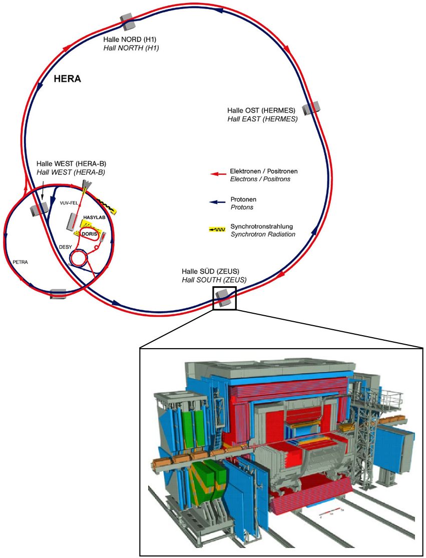
$$q^\mu = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -Q \end{pmatrix}$$

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

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

HERA accelerator

- Only lepton-hadron collider so far
- Located at DESY in Hamburg, Germany
- Two run periods:
  - HERA 1: 1992 – 2000
  - HERA 2: 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



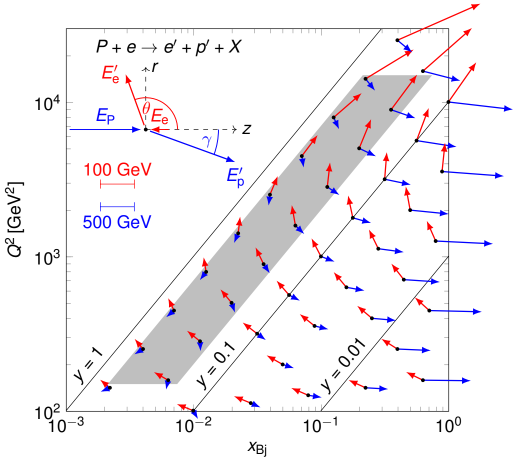
ZEUS detector

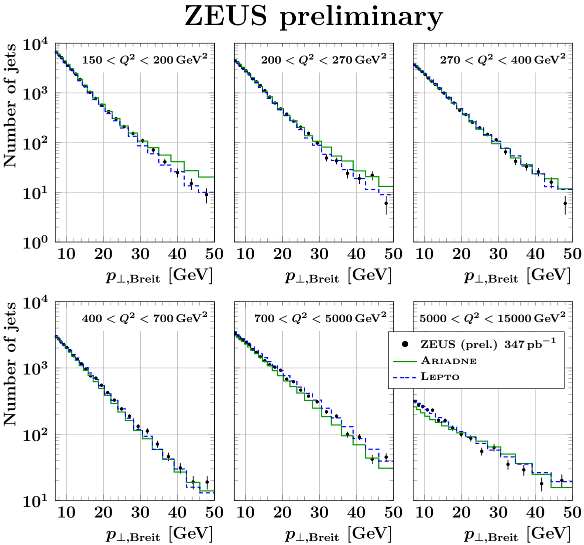
- General purpose particle detector
- Integrated luminosity during HERA 2: 347 pb^{-1}
- High-resolution uranium-scintillator calorimeter allows precise measurement of jet energies

- Inclusive jets (count each jet individually, rather than each event)
- Jets clustered using $k_\perp$ algorithm and $p_\perp$-weighted scheme (massless jets) in Breit frame
- Phase space

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

- Hadron level jets
- Exchange of Z^0 boson included
- QED Born level (higher order effects removed)





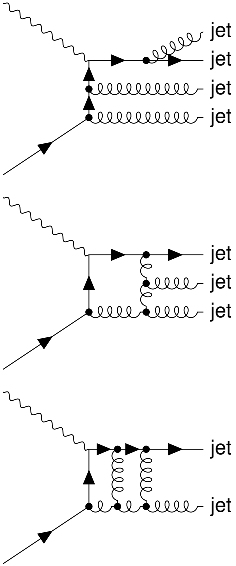
- Reconstructed jets corrected to hadron level using bin-by-bin correction factors obtained from Monte Carlo samples
  - ARIADNE: colour dipole model
  - LEPTO: leading $\log(Q^2)$ parton cascade
- After reweighting, the models give a good description of the data across the entire phase space

Theoretical predictions

- Cross section predictions are calculated at NNLO accuracy
- 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

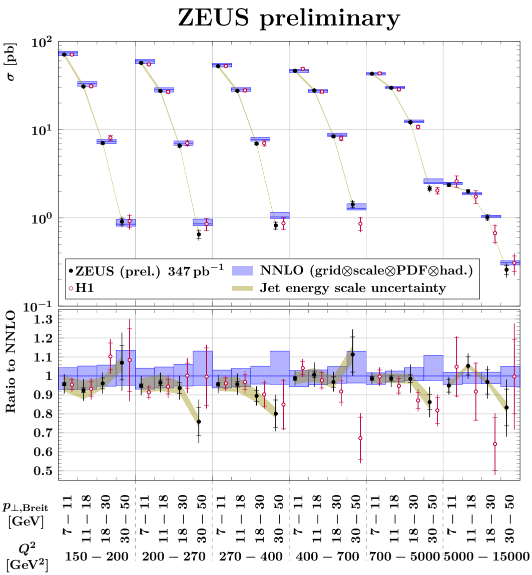
- Six point scale variation by factor 2
- Statistical uncertainty of matrix element generation
- Hadronisation correction uncertainty
- PDF uncertainty (fit, model, parameterisation)



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

Cross sections

Measured inclusive jet cross sections

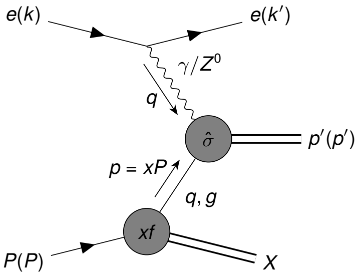


- Measured cross sections† are compatible with previous measurement from H1 collaboration‡ and uncertainties are comparable§
- Measurements are compatible with NNLO QCD predictions and show similar trends relative to the theory
- Uncertainty mostly dominated by jet energy scale; at high Q^2 or high $p_{\perp,\text{Breit}}$ statistical uncertainty becomes dominant

† ZEUS-prel-22-001 (2022)
‡ EPJC 75, 65 (2015). arXiv:1406.4709
§ Statistical uncertainties of the H1 measurement appear large, due to negative correlations between the data points, which are not shown

QCD analysis
Strategy

- Simultaneous fit of PDF parameters and $\alpha_s(M_Z^2)$ at NNLO accuracy
- Datasets used
  - H1+ZEUS combined inclusive DIS
  - ZEUS HERA 1 inclusive jets at high Q^2
  - ZEUS HERA 1+2 dijets at high Q^2
  - **ZEUS HERA 2 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 2 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)

For reference, HERAPDF2.0Jets NNLO found

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

This analysis

$$\boxed{\alpha_s(M_Z^2) = 0.1138 \pm 0.0014 \text{ (exp/fit) } {}^{+0.0004}_{-0.0008} \text{ (model/parameterisation) } {}^{+0.0012}_{-0.0005} \text{ (scale)}}$$

- 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
  - Scale uncertainty of the cross sections is assumed as fully correlated between all jet points and datasets, which is reasonable for neighbouring points in phase space
  - When fitting points far away from each other in phase space or in different final states, the scale uncertainty might be much less correlated or even anti-correlated
  - Fully correlated treatment across entire phase space might give a larger uncertainty

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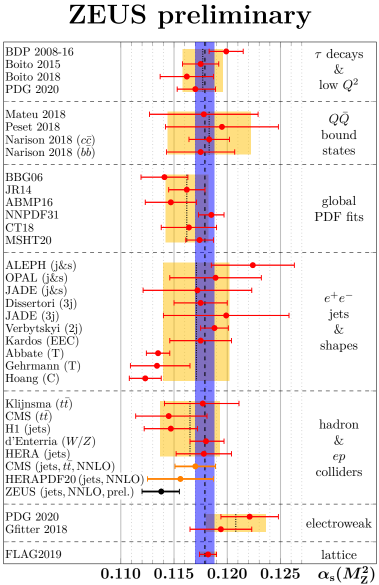
QCD analysis

Results

- To further mitigate this problem, an alternative treatment of the scale uncertainty as half correlated/half uncorrelated between all points and datasets was investigated
- Due to absence of low Q^2 jet data in fit, additional reduction is moderate

$$^{+0.0012}_{-0.0005} \rightarrow ^{+0.0008}_{-0.0007}$$

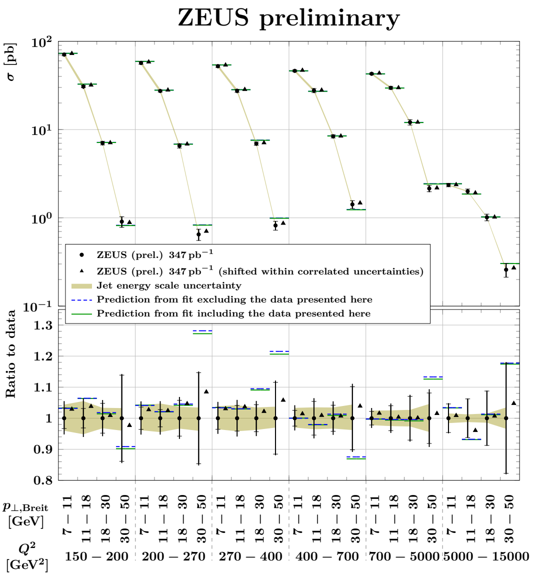
- When fitting data across a wider range in phase space, the alternative approach is expected to make a more significant impact
- Reduced scale uncertainty means that the present analysis is one of the most precise measurements of $\alpha_s(M_Z^2)$ at hadron colliders so far†



† PTEP 2020, 8, 083C01 (2020)

QCD analysis

Results



- Compare measurement to two sets of calculated cross sections:
  1. Using on PDFs and α_s from fit presented on previous slides (green line)
  2. Using similar fit, but excluding the new jet dataset (dashed blue line)
- Including the new dataset improves the agreement between calculation and data very slightly, indicating that the new cross sections are consistent with previous jet datasets from ZEUS
- Changes are due to updated value of α_s and the gluon PDF; quark distributions are not significantly affected by additional jet dataset

Cross section measurement

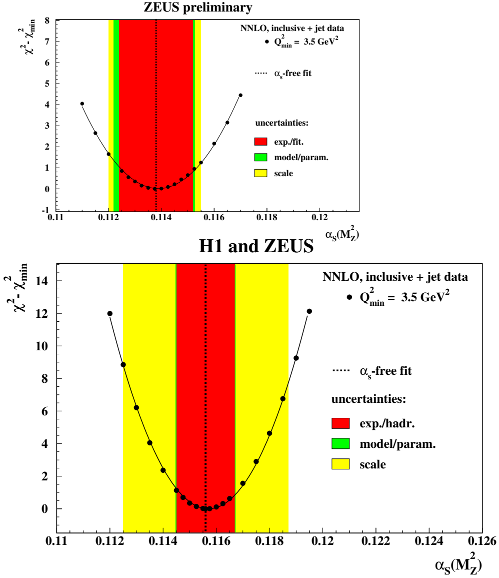
- Inclusive jet cross sections have been measured using ZEUS data during HERA 2
- Cross sections are compatible with the corresponding H1 measurement and NNLO theory
- Uncertainties comparable with the corresponding H1 measurement

QCD analysis

- New dataset is ideal ingredient for precision determinations of $\alpha_s(M_Z^2)$ in future QCD fits
- A very competitive measurement of $\alpha_s(M_Z^2)$ has been achieved due to
  - Restriction to high Q^2 jet data in the fit
  - To a lesser extent: alternative treatment of scale uncertainty

QCD analysis

α_S-scan



- Upper plot: this analysis
- Lower plot: HERAPDF2.0Jets NNLO
- Increased experimental uncertainty but decreased overall uncertainty

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
$C'_g = 25$
$B_{\bar{U}} = B_{\bar{D}}$
$A_{\bar{U}} = A_{\bar{D}}(1-f_s)$

HERAPDF2.0Jets NLO

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

This analysis (fully correlated scale uncertainty)

$$\alpha_s(M_Z^2) = 0.1170 \pm 0.0015 \text{ (exp/fit) } ^{+0.0005}_{-0.0007} \text{ (model/parameterisation) } ^{+0.0028}_{-0.0014} \text{ (scale)}$$

This analysis (half correlated scale uncertainty)

$$\alpha_s(M_Z^2) = 0.1170 \pm 0.0015 \text{ (exp/fit) } ^{+0.0005}_{-0.0007} \text{ (model/parameterisation) } ^{+0.0015}_{-0.0012} \text{ (scale)}$$

- In HERAPDF2.0Jets NLO, the scale uncertainty was already treated as half correlated/half uncorrelated
- Improved scale uncertainty due to absence of low Q^2 jets