



**Measurement and QCD analysis of inclusive jet production in
deep inelastic scattering at HERA**
Resummation, Evolution, Factorization 2022

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ZEUS

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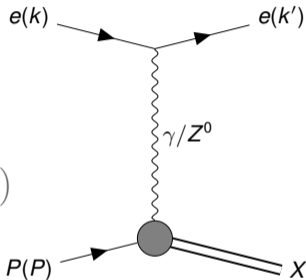
Deep inelastic scattering

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

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

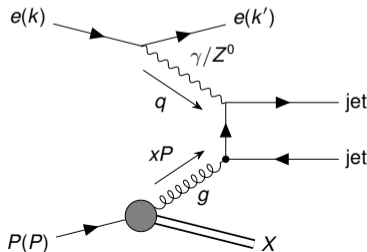
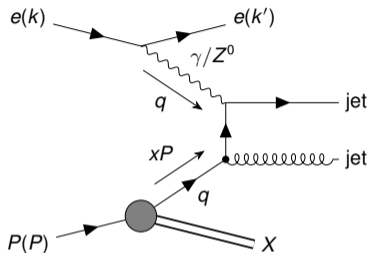
⇒ By measuring F_2 and F_3 , the quark- and antiquark-distributions, xq and $x\bar{q}$, can be probed

- ▶ 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



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

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

- ▶ Boson acts as point-like probe of the hadron

Kinematic quantities

$$Q^2 = -q^2 = -(k' - k)^2$$

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

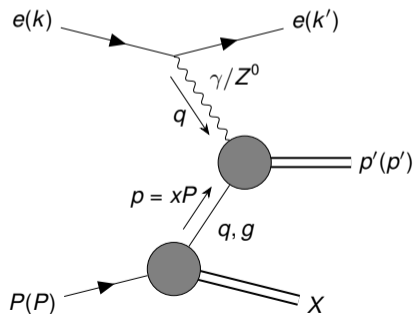
$$y = \frac{P \cdot q}{P \cdot k}$$

Boson virtuality/
Momentum transfer

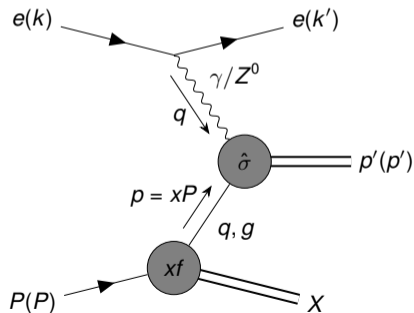
Bjorken scaling
parameter

Inelasticity

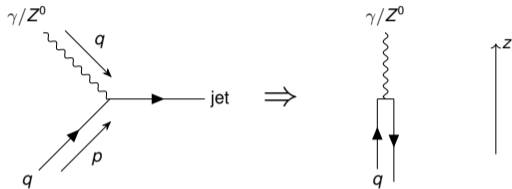
p' ... Scattered hadronic system
 X ... Proton remnant



- ▶ 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



- ▶ 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

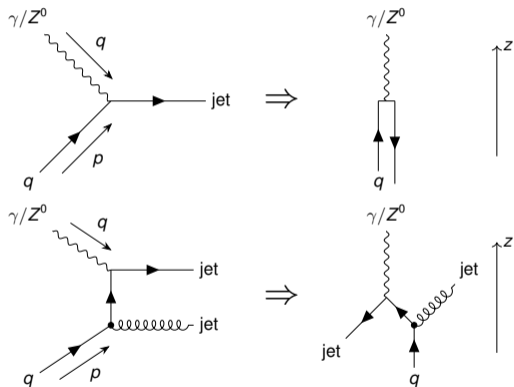


In the **Breit frame**, the
parton and photon
collide head-on

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

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

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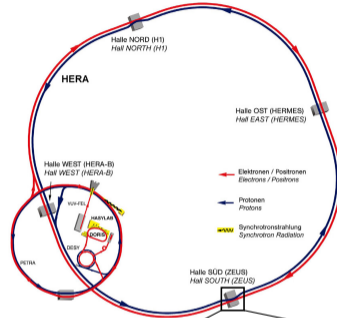
$$q^\mu = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -Q \end{pmatrix}$$

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

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

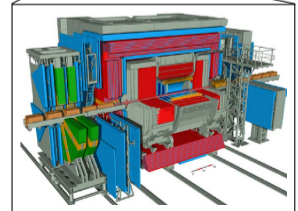
HERA accelerator

- ▶ 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



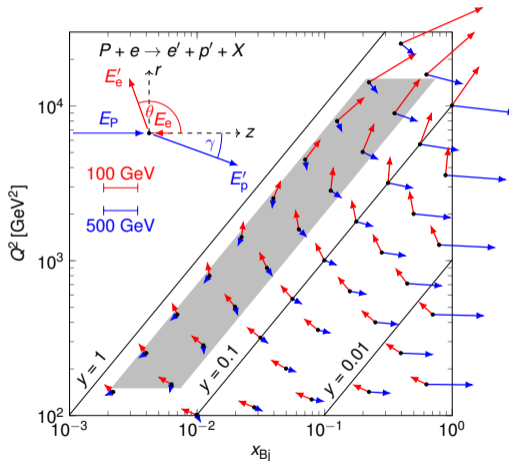
Inclusive jet
production in
DIS at HERA

Florian Lorkowski
2022-11-02

Motivation
Theory of DIS
Experiment
Analysis
Definitions
Simulation
NNLO predictions
Cross sections
QCD analysis
Summary

- ▶ 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

$150 \text{ GeV}^2 <$	$Q^2 <$	$15\,000 \text{ GeV}^2$
$0.2 <$	$y <$	0.7
$7 \text{ GeV} <$	$p_{\perp, \text{Breit}} <$	50 GeV
$-1 <$	$\eta_{\text{lab}} <$	2.5
- ▶ Hadron level jets
- ▶ Exchange of Z^0 boson included
- ▶ QED Born level (higher order effects removed)

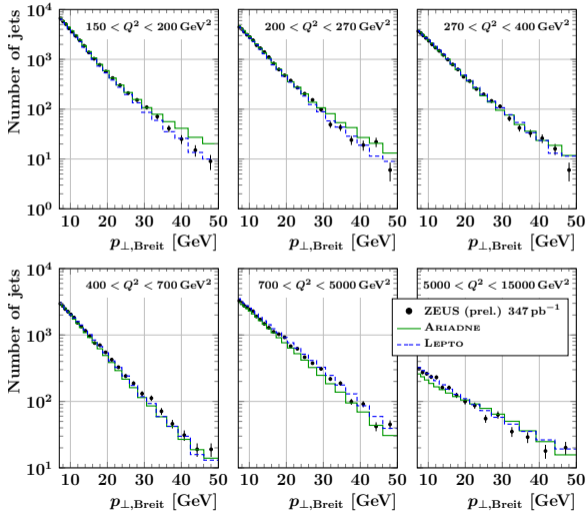


Inclusive jet production in DIS at HERA

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- Motivation
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- Definitions
- Simulation**
- NNLO predictions
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- QCD analysis
- Summary

ZEUS preliminary



- ▶ 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

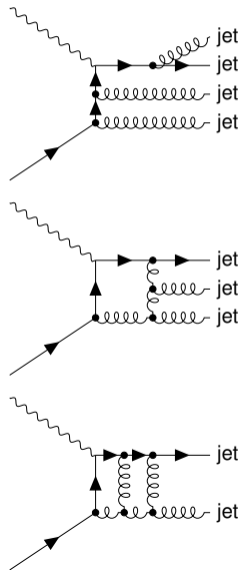
- ▶ Cross section predictions are calculated at NNLO accuracy
- ▶ Matrix elements calculated using NNLOJET[†]
- ▶ PDFs taken from HERAPDF2.0Jets NNLO[‡]
- ▶ $\alpha_s(M_Z^2) = 0.1155$, $\mu_r^2 = \mu_f^2 = Q^2 + p_{\perp}^2$
- ▶ Predictions corrected for hadronisation and Z^0 -exchange

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

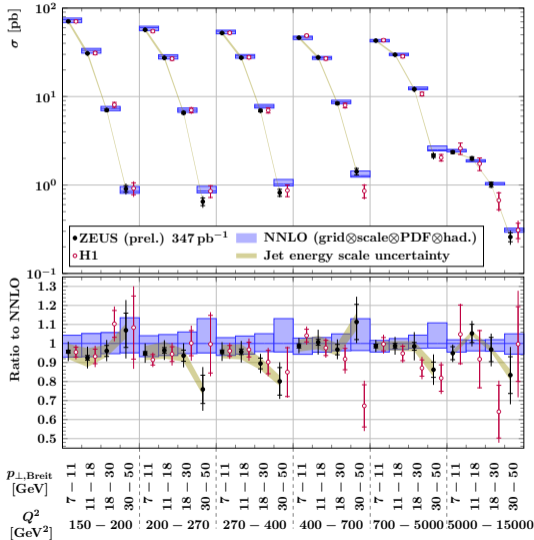


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- ▶ Measured cross sections[†] are compatible with previous measurement from H1 collaboration[‡] and uncertainties are comparable[§]
- ▶ Measurements are compatible with NNLO QCD predictions and show similar trends relative to the theory
- ▶ Uncertainty 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

- ▶ Simultaneous fit of PDF parameters and $\alpha_s(M_Z^2)$ at NNLO accuracy

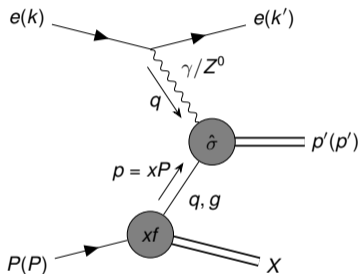
- ▶ Datasets used

- ▶ 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

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

This analysis

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

- ▶ 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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- ▶ 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

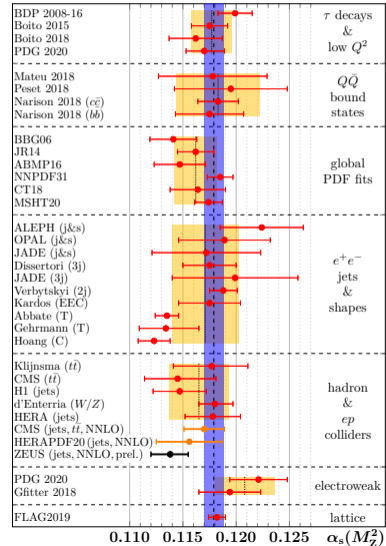
$$\begin{array}{ccc} +0.0012 & \rightarrow & +0.0008 \\ -0.0005 & & -0.0007 \end{array}$$

- ▶ 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)

ZEUS preliminary

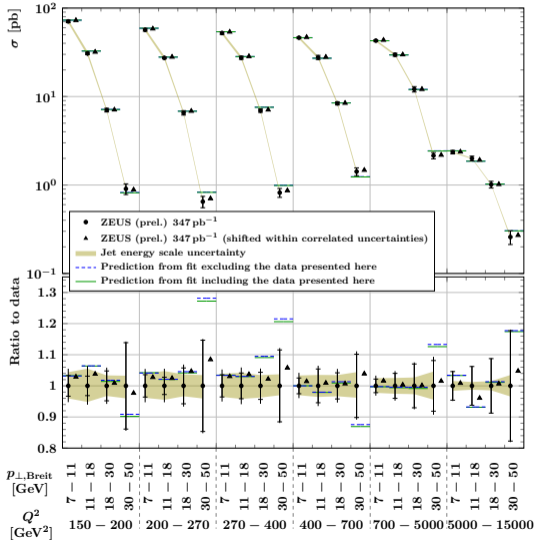


Inclusive jet production in DIS at HERA

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ZEUS preliminary



- ▶ 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

Inclusive jet production in DIS at HERA

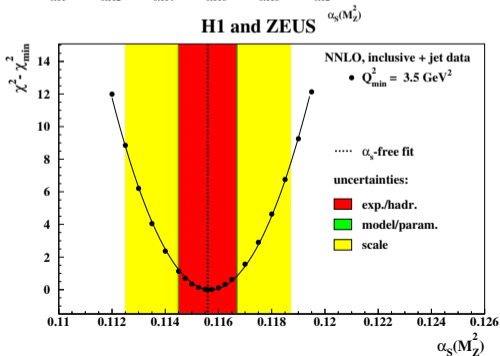
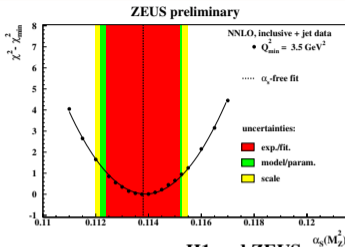
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QCD analysis

α_s -scan

Fit settings

Results at NLO



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

Inclusive jet
production in
DIS at HERA

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QCD analysis
 α_s -scan
Fit settings
Results at NLO

Fit settings

	NLO	NNLO
--	-----	------

Model parameters

f_s	0.4 ± 0.1	
m_c [GeV]	$1.46^{+0.04}_{-symmetrise}$	$1.41^{+0.04}_{-symmetrise}$
m_b [GeV]	4.3 ± 0.10	4.2 ± 0.10
Q_{min}^2 [GeV ²]	$3.5^{+1.5}_{-1.0}$	

Parameterisation

μ_{f0}^2 [GeV ²]	$1.9^{-0.3}_{+symmetrise}$	
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_f^2	Q^2	$Q^2 + p_{\perp}^2$
μ_r^2	$(Q^2 + p_{\perp}^2)/2$	

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

$$C'_g = 25$$

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

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



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QCD analysis
 α_s -scan

Fit settings

Results at NLO

HERAPDF2.0Jets NLO

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

This analysis (fully correlated scale uncertainty)

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

This analysis (half correlated scale uncertainty)

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

- ▶ 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