



Measurements of the strong coupling at HERA Extracting the Strong Coupling at the EIC and other Future Colliders

Florian Lorkowski

florian.lorkowski@physik.uzh.ch

University of Zürich

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Motivation Deep inelastic scattering



 $\gamma/Z/W$

 e/ν

α_{s} from HERA

- Florian Lorkowski 2025-05-05
- Motivation DIS Jet production Kinematics Experiments HERAPDF Jets at ZEUS

Summarv

Deep inelastic scattering

- Inclusive deep inelastic scattering (DIS) measurements in lepton-hadron collisions (*ep* → *e'X*) are essential to determine the parton distribution functions (PDFs) of the proton (*xf*)
- Neutral (NC) and charged current (CC) DIS cross sections (at leading order):





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Deep inelastic scattering

- ⇒ Directly sensitive to quark-distributions
- Through higher orders and scaling violations in DGLAP equations, sensitive to product of gluon distribution xg and strong coupling constant α_s
- From higher-order corrections, the two can be disentangled to some extent, but they remain strongly correlated

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

 $\sim xU + x\overline{D}$

 $\sim xU - x\overline{D}$



Motivation Inclusive jet production



α_{s} from HERA

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Motivation DIS Jet production Kinematics Experiments HERAPDF Jets at ZEUS Summary

Jet measurements

- Already at leading order,[†] jet production is directly sensitive to strong coupling independently of gluon distribution
- Jet production also constrains gluon distribution
- \Rightarrow Jet production is sensitive to a different combination of gluon PDF and α_{s}

[†]Leading order in the Breit frame, see slide A1





Motivation Inclusive jet production



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Jet measurements

- Already at leading order,[†] jet production is directly sensitive to strong coupling independently of gluon distribution
- Jet production also constrains gluon distribution
- ⇒ Jet production is sensitive to a different combination of gluon PDF and α_s
- \Rightarrow DIS + jet data allows simultaneous determination of PDFs and $\alpha_{\rm s}$



[†]Leading order in the Breit frame, see slide A1



Motivation Kinematics



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- **Motivation** Jet production Experiments HERAPDE Jets at ZEUS Summarv

Jet production in DIS

- $e(k) + P(P) \rightarrow e/\nu(k') + p'(p') + X$
- Kinematic guantities ►
 - $Q^2 = -q^2$
 - Momentum transfer $x_{\rm Bj} = rac{Q^2}{2P \cdot q}$
 - $y = \frac{P \cdot q}{P \cdot k}$
 - $s = rac{Q^2}{x_{
 m Bi} y}$
- Biorken scaling parameter Inelasticity

Boson virtuality/

- - Centre-of-mass energy squared
- ► In DIS: $Q^2 \gg \lambda_{OCD}$
 - \rightarrow boson acts as point-like probe of hadron

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





Motivation HERA and ZEUS



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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 with protons at up to $\sqrt{s} = 318 \text{ GeV}$
- Two general purpose particle detectors: H1 and ZEUS





HERAPDF HERA data



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- In 2015, released combined dataset of inclusive DIS from H1 and ZEUS[†]
 - Includes NC and CC measurements
 - Electron and positron beams
 - All four different centre-of-mass energies from HERA I and HERA II
- Supersedes all previous combinations of DIS data at HERA
- One of the most important datasets from the HERA collider

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





HERAPDF HERAPDF2.0



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- Based on this dataset, determined the HERAPDF2.0 family of PDF sets using only HERA data at LO, NLO and NNLO
- Most prominent members:
 - HERAPDF2.0 NLO
 - HERAPDF2.0 NNLO
 - HERAPDF2.0Jets NLO $PDF + \alpha_s$ fit

PDF fits

- In 2017, NNLO QCD predictions of inclusive jet and dijet production became available[†]
- This talk: HERAPDF2.0Jets NNLO completes the HERAPDF2.0 family[‡]
- Simultaneous PDF + $\alpha_{s}(M_{Z}^{2})$ fit \rightarrow determine $\alpha_{s}(M_{Z}^{2})$ at NNLO



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



HERAPDF Datasets



NNLO

Used points

NLO

α_{s} from HERA	Dataset	L	
Florian Lorkowski	Dataset	[pb ⁻¹]	
2025-05-05	HERA combined inclusive DIS	_	
Motivation	HERA combined charm data	_	
HERAPDF	H1 HERA I jets at low Q^2	43.5	
HERA data	H1 HERA I jets at high Q^2	65.4	
Datasets	H1 HERA II inclusive jets at high Q^2	351	
Parameterisation	H1 HERA II dijets at high Q ²	351	
Model parameters	H1 HERA II trijets at high Q ²	351	
Impact on PDFs	H1 HERA II inclusive jets at low Q^2	290	
Jets at ZEUS	H1 HERA II dijets at low Q^2	290	
Summary	ZEUS HERA I inclusive jets at high Q ²	38.6	
	ZEUS HERA I+II dijets at high Q^2	374	

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



HERAPDF Parameterisation



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- Parameterise $g, u_v, d_v, \bar{U}, \bar{D}$
- Established HERAPDF functional form of PDFs $xf(x) = A_f x^{B_f} (1-x)^{C_f} (1+D_f x + E_f x^2)$
- Identify relevant parameters; optimal parameterisation is the same as at NLO

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

- A_g , A_{u_v} and A_{d_v} fixed by sum rules
- Fix $C'_g = 25, B_{\bar{U}} = B_{\bar{D}}, A_{\bar{U}} = A_{\bar{D}}(1 f_s)$
- \Rightarrow 14 free PDF parameters + $\alpha_{\rm s}(M_Z^2)$





HERAPDF Model parameters



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	IS
Motivation	$m_{\rm c}$
HERAPDF	$m_{\rm b}$
HERA data	Q^2
HERAPDF2.0	
Datasets	
Parameterisation	μ_{f0}^2
Model parameters	/
Strong coupling	р
Impact on PDFs	
Jets at ZEUS	μ_{t}^{2}
Summary	, ²
	Lur

	ſ	Jets NLO	Jets NNLO			
Model parameters						
f _s		0.4 ± 0.1				
m _c [GeV	/]	1.47 ± 0.06	1.41 ^{+0.04} _symmetrise			
m _b [GeV	/]	4.5 ± 0.25	$\textbf{4.2}\pm\textbf{0.10}$			
Q_{\min}^2 [GeV	²]	$3.5 {}^{+1.5}_{-1.0}$				
Parameterisation						
μ_{f0}^2 [GeV	²]	1.9 ± 0.3	$1.9^{+\text{symmetrise}}_{-0.3}$			
Additional		all missing <i>D</i> and <i>E</i> parameters				
parameters		$(D_g, E_g, D_{u_v}, D_{d_v}, E_{d_v}, E_{\bar{U}}, D_{\bar{D}}, E_{\bar{D}})$				
Scales						
$\mu_{\rm f}^2$ $\mu_{\rm r}^2$		Q^2	$0^{2} + n^{2}$			
		$(Q^2+ ho_{\perp}^2)/2$	$Q^- + P_{\perp}$			
Theory related						
Hadronisation		repeat fit	included in fit			
Statistics		not available	included in fit			

- Model parameters determined similar to previous analysis
- Charm and bottom mass updated using new combined HERA data on heavy quarks
- Perform certain variations one-sided and symmetrise
 avoid double-counting of uncertainty
- Treat hadronisation uncertainty as systematic uncertainty of data
- Include statistical uncertainty of theoretical predictions





α_{s} from HERA

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Motivation HERAPDF HERA data HERAPDF2.0 Datasets Parameterisation Model parameters Strong coupling Impact on PDFs Jets at ZEUS Summary

HERAPDF2.0Jets NLO

 $\alpha_{s}(M_{Z}^{2}) = 0.1183 \pm 0.0009$ (exp./fit) ± 0.0005 (model/param.) $^{+0.0037}_{-0.0030}$ (scale) ± 0.0012 (hadr.)

HERAPDF2.0Jets NNLO

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

- Preferred value at NNLO is smaller that at NLO, as expected from other analyses
- Experimental/fit uncertainty reduced (compared to exp./fit⊗hadr. at NLO), mostly due to improved treatment of hadronisation uncertainty
- Model/parameterisation uncertainty reduced mostly due to symmetrisation of model uncertainties





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Motivation HERAPDF HERA data HERAPDF2.0 Datasets Parameterisation Model parameters Strong coupling Impact on PDFs Jets at ZEUS Summary HERAPDF2.0Jets NLO (scale half correlated)

 $\alpha_{s}(M_{Z}^{2}) = 0.1183 \pm 0.0009$ (exp./fit) ± 0.0005 (model/param.) $\frac{+0.0037}{0.0030}$ (scale) ± 0.0012 (hadr.)

HERAPDF2.0Jets NNLO (scale fully correlated)

 $lpha_{
m s}(M_Z^2) = 0.1156 \pm 0.0011$ (exp./fit) $^{+0.0001}_{-0.0002}$ (model/param.) ± 0.0029 (scale)

HERAPDF2.0Jets NNLO (scale half correlated)

 $\alpha_{\rm s}(M_Z^2) = 0.1156 \pm 0.0011$ (exp./fit) $^{+0.0001}_{-0.0002}$ (model/param.) \pm 0.0022 (scale)

- Preferred value at NNLO is smaller that at NLO, as expected from other analyses
- Experimental/fit uncertainty reduced (compared to exp./fit⊗hadr. at NLO), mostly 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)



HERAPDF Impact on PDFs





H1 and ZEUS



- At fixed α_s, PDF central values do not change significantly[†]
- Most notable effect in α_s-free fit: normalisation of gluon distribution increased

[†]See slide A2



HERAPDF Impact on PDFs



α_{s} from HERA

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- At fixed α_s, PDF central values do not change significantly[†]
- Most notable effect in α_s-free fit: normalisation of gluon distribution increased
- Quark uncertainties similar to the previous fit without jet data
- Gluon uncertainty notably reduced, also due to procedural improvements

[†]See slide A2



Jets at ZEUS Cross-section definition



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- Inclusive jets (count each jet individually, rather than each event)
- ▶ Use entire HERA II dataset (347 pb⁻¹)
- ▶ Jets clustered using k_⊥ algorithm and p_⊥-weighted scheme (massless jets) in Breit frame
- Phase space

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

- Hadron-level jets
- Including electroweak contributions
- QED Born level





Jets at ZEUS

Measured inclusive-jet cross sections







- •ZEUS 347 pb⁻¹ NNLO (grid@scale@PDF@had.) let-energy-scale uncertainty 0.8 0.7 0.6 0.5 P ...Breit (GeV)
- 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)

 (GeV^2)



Jets at ZEUS QED radiation



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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
- $\rightarrow\,$ 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



Jets at ZEUS Fit strategy



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- Simultaneous fit of PDF parameters and $\alpha_s(M_Z^2)$ at NNLO
- Datasets used
 - HERA 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 Q²
- Inclusion of additional jet data is expected to reduce uncertainty of α_s(M²_Z)
- Statistical correlations between ZEUS HERA II jet datasets taken into account via correlation matrix
- Use settings similar to HERAPDF2.0Jets NNLO (parameterisation, scales, cuts, model parameters, treatment of hadronisation and theory grid uncertainty)



arXiv::hep-ex/0208037 §EPJC 70, 965 (2010) arXiv::1010.6167





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For reference, HERAPDF2.0Jets NNLO found

 $\alpha_{\rm s}(M_Z^2) = 0.1156 \pm 0.0011$ (exp./fit) $^{+0.0001}_{-0.0002}$ (model/param.) ± 0.0029 (scale)

ZEUS analysis

 $\alpha_{\rm s}(M_Z^2) = 0.1143 \pm 0.0017 \text{ (exp./fit)} \stackrel{+0.0006}{-0.0007} \text{(model/param.)} \stackrel{+0.0012}{-0.0005} \text{(scale)}$

- 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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 $\alpha_{s}(M_{Z}^{2}) = 0.1143 \pm 0.0017$ (exp./fit) $^{+0.0006}_{-0.0007}$ (model/param.) $^{+0.0012}_{-0.0005}$ (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-Q² 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: assume scale dependence is half correlated between all measurements
- Despite absence of low-Q² jet data in the fit, additional reduction is significant

 $lpha_{s}(M_{Z}^{2}) = 0.1143 \pm \dots + \stackrel{0.0012}{_{-0.0005}}$ (scale) \downarrow $lpha_{s}(M_{Z}^{2}) = 0.1142 \pm \dots + \stackrel{0.0006}{_{-0.0006}}$ (scale)

 Reduced scale uncertainty leads to one of the most precise collider measurements of α_s(M²_Z)[†]









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- ► Upper panel: \(\chi_2^2(\alpha_s(M_Z^2))\)-scan, alongside result from \(\alpha_s(M_Z^2)\)-free fit \(\to \) 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
- Even more relevant when including EIC data, as this further increases the range in phase space



 α_{s} from HERA

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Motivation HERAPDF

Definition

Cross sections

QED radiation

Strong coupling

Summary

Jets at ZEUS Running coupling

Strong coupling depends on the scale at which it is evaluated. At one-loop:

$$\alpha_{s}(\mu^{2}) = \frac{\alpha_{s}(\mu_{0}^{2})}{1 + \alpha_{s}(\mu_{0}^{2})b_{0}\log\left(\frac{\mu^{2}}{\mu_{0}^{2}}\right)}$$

- 'Measure' this curve to test if QCD is the correct theory to describe the 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





Jets at ZEUS Running coupling





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Strong coupling depends on the scale at which it is evaluated. At one-loop:

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

- 'Measure' this curve to test if QCD is the correct theory to describe the 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





Summary



α_{s} from HERA

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Motivation HERAPDF Jets at ZEUS Summary

HERAPDF2.0Jets NNLO[†]

- Completed HERAPDF2.0 family, one of the major legacies of HERA
- Improvements due to additional exp. inputs, procedural changes and transition to NNLO
- A new value of α_s(M²_Z) has been determined with notable reduction of all uncertainties

Inclusive-jet measurement at ZEUS[‡]

- Cross sections are compatible and competitive with corresponding H1 measurement
- Achieved very precise \(\alpha\)s(M²_Z) measurement due to reduced theoretical uncertainty
- Scale dependence of strong coupling found to be consistent with QCD prediction



[†]EPJC 82, 243 (2022). arXiv:2112.01120 [‡]EPJC 83, 1082 (2023). arXiv:2309.02889



Summary Announcement

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- These analyses are only possible due to NNLO QCD corrections to DIS[†]
- Recently: first public release of the NNLOJET code[‡]
- Efficient and easy-to-use tool to compute NNLO cross sections
- Supports single jet and dijet production in neutral-current and charged-current DIS at up to NNLO in QCD



[†]JHEP 2017, 18 (2017). arXiv:1703.05977 [‡]arXiv:2503.22804 https://nnlojet.hepforge.org



Motivation 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



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Motivation Breit frame HERAPDF Jets at ZEUS



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Motivation

Breit frame HERAPDF Jets at ZEUS

Motivation 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



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



HERAPDF Updated PDF fit



- Fit performed at fixed α_s(M_Z²) = 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



HERAPDF Goodness of fit



- Cross sections calculated using fitted PDFs are in very good agreement with the input measurements
- Fit achieved a χ^2 /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



Jets at ZEUS Simulation



- 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



Jets at ZEUS Systematic uncertainties

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Motivation HERAPDF Jets at ZEUS Simulation Systematics Correlation matrix



- Systematic uncertainty mostly dominated by jet-energy scale (uncertainty of MC detector simulation)
- In high-p⊥,Breit or high-Q² region, other uncertainties become relevant/dominant
- Unfolding uncertainty appears large in low-statistics region
- Bins with large unfolding uncertainty usually strongly anti-correlated



Jets at ZEUS Correlation matrix



Inclusive-jet bin