Jet physics at HERA

from ZEUS Collab.

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at HERA

p (Ep = 920 GeV)

e (Ee = 27.5 GeV)

\( \sqrt{s} = 318 \text{ GeV} \)
Jet physics at HERA

- *ep* collider HERA: very suitable environment to do precision studies of QCD
  - tests of QCD in hadronic-induced reactions (as opposed to *e*⁺*e*⁻ at LEP)
  - but cleaner than *p*¯*p* at TeVatron or *pp* at LHC

- Jet physics at HERA
  - tests of pQCD and precision measurements of QCD parameters
  - constraints on PDFs
  - input to understand QCD background and make cross-section predictions at LHC

- Jet production at HERA in different kinematic regimes:

  \[ Q^2 \gg \Lambda_{QCD}^2 \]

  NC deep inelastic scattering (DIS)

  \[ ep \rightarrow e + \text{Jet (+Jets)} + X \]

  Photoproduction (PHP)

  \[ Q^2 \approx 0 \text{ GeV}^2 \]

  \[ ep \rightarrow e + \text{Jet (+Jets)} + X \]
Jets in NC DIS at HERA

- Jet production in neutral current deep inelastic $ep$ scattering at $\mathcal{O}(\alpha_s)$ in the Breit frame:

- Jet production cross section in NC DIS is given in pQCD by:

$$d\sigma_{\text{jet}} = \sum_{a=q,\bar{q},g} \int dx \ f_a(x, \mu_F) \ d\hat{\sigma}_a(x, \alpha_s(\mu_R), \mu_R, \mu_F)$$

- $f_a$: parton $a$ density, determined from experiment
  → long-distance structure of the target

- $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD
  → short-distance structure of the interaction

Kinematics:
- momentum transfer:
  $$Q^2 = -q^2 = -(k - k')^2$$
- Bjorken $x$:
  $$x = \frac{Q^2}{2P \cdot q}$$
- inelasticity:
  $$y = \frac{P \cdot q}{P \cdot k} = 1 - \frac{E_e'(1 - \cos \theta_e)}{2E_e}$$
Jets in PHP at HERA

Jet production in photoproduction at $O(\alpha_s)$:

- Direct photoproduction
- Resolved photoproduction

Jet production cross section in photoproduction is given in pQCD by:

$$d\sigma_{\text{jet}} = \sum_{i,j} \int dy \ f_{\gamma/e}(y) \ \int dx_p \ f_{j/p}(x_p, \mu_{Fp}) \ \int dx_\gamma \ f_{i/\gamma}(x_\gamma, \mu_{F\gamma}) \ d\hat{\sigma}_{i(\gamma)j}$$

Measurements of jet cross sections in photoproduction allow tests of:
- Structure of the photon
- pQCD, $\alpha_s$
- Structure of the proton
Jets and PDFs at HERA
Very precise jet cross sections in NC DIS and photoproduction (directly sensitive to the gluon content of proton): constraints on gluon density

The measurements were incorporated in a QCD fit (together with structure function data from ZEUS) to determine the PDFs:

**Jets and PDFs at HERA**

**NC DIS**

**photoproduction**

**proton parton densities**

**ZUS**
• Very precise jet cross sections in NC DIS and photoproduction (directly sensitive to the gluon content of proton): constraints on gluon density

• The measurements were incorporated in a QCD fit (using function data from ZEUS) to determine the PDFs:

NC DIS

photoproduction

The result was an improvement of the determination of the gluon density

→ the uncertainty in the gluon density decreased up to a factor of two for mid- to high-$x$

→ relevant for new physics searches at LHC
Constraints on the proton PDFs

- Gluon fraction and theoretical uncertainties for dijet cross sections for $125 < Q^2 < 20000 \text{ GeV}^2$:

  **Predicted gluon fraction:**
  - $> 75\%$ at low $Q^2$
  - $> 50\%$ at $Q^2 \sim 500 \text{ GeV}^2$

  → PDF uncertainty large and uncertainty from higher orders small in regions of phase space where the gluon fraction is still sizeable

  → potential to constrain PDFs with jet data

ZEUS Collab, ZEUS-pub-10-005

C Glasman (Universidad Autónoma de Madrid)
Constraints on pPDFs: dijet cross sections in NC DIS

\[ \text{ep} \to e + \text{jet} + \text{jet} + X: \text{dijets at low } Q^2 \]

- Jets searched using the \( k_T \) cluster algorithm in BF
- Kinematic region: \( 5 < Q^2 < 100 \text{ GeV}^2 \) and \( 0.2 < y < 0.7 \)
- Two jets with \( P_T > 5 \text{ GeV} \) and \( -1 < \eta^{\text{jet}} < 2.5 \)
- \( M^{\text{jj}} > 18 \text{ GeV} \)

- Small experimental uncertainties
  - uncorrelated: \( \sim \pm 5 \) (15)% at low (high) \( \langle P_T \rangle \)
  - correlated (energy scale \( \pm 2\% \) (!)): \( \sim \pm 5 \) (15)% at low (high) \( \langle P_T \rangle \)

- Comparison to NLO predictions (NLOJET++)
  - \( \mu_R^2 = \mu_F^2 = (Q^2 + \langle P_T \rangle^2)/2; \text{pPDFs: CTEQ6.5M; } \alpha_s(M_Z) = 0.118 \); corrected for hadronisation
  - The measured dijet cross sections are well described by the NLO predictions in the whole measured range

\[ \mathcal{L} = 43.5 \text{ pb}^{-1} \]
Constraints on pPDFs: dijet cross sections in NC DIS

\( ep \rightarrow e + \text{jet} + \text{jet} + X: \) dijets at low \( Q^2 \)

- Jets searched using the \( k_T \) cluster algorithm in BF
- Kinematic region: \( 5 < Q^2 < 100 \text{ GeV}^2 \) and \( 0.2 < y < 0.7 \)
- Two jets with \( P_T > 5 \text{ GeV} \) and \( -1 < \eta_{LAB} < 2.5 \)
- \( M_{jj} > 18 \text{ GeV} \)
- \( \xi = x_{Bj} (1 + (M_{jj}^2/Q^2)) \) estimator of the fractional momentum carried by the struck parton
- Small experimental uncertainties
  - uncorrelated: \( \sim \pm 6\% \)
  - correlated: \( \sim \pm 5\% \)
  - The measured dijet cross sections are well described by the NLO predictions in the whole measured range

- Large gluon fraction at low \( Q^2 \)
- Theoretical uncertainty dominated by terms beyond NLO: NNLO predictions needed to take full advantage of high-precision data

\[ L = 43.5 \text{ pb}^{-1} \]
**Constraints on pPDFs: dijet cross sections in NC DIS**

\[ \text{dijets at high } Q^2 \]

- Jets searched using the \( k_T \) cluster algorithm in Breit frame
- Kinematic region: \( 125 < Q^2 < 20000 \text{ GeV}^2 \) and \( 0.2 < y < 0.6 \)
- Two jets with \( E_{T,B}^{\text{jet}} > 8 \text{ GeV} \) and \(-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5 \)
- \( M_{jj} > 20 \text{ GeV} \)

**Small experimental uncertainties:**
- Uncorrelated: \( \sim \pm 2 \) (10)\% at low (high) \( Q^2 \)
- Correlated (energy scale \( \pm 1\% \)) for \( E_T^{\text{jet}} > 10 \text{ GeV} \):
  \( \sim \pm 5 \) (2)\% at low (high) \( Q^2 \)

**Comparison to NLO predictions (NLOJET++):**
- \( \mu_R^2 = Q^2 + \left( \overline{E}_{T,B}^{\text{jet}} \right)^2 \); \( \mu_F = Q \); pPDFs: CTEQ6.6;
  \( \alpha_s (M_Z) = 0.118 \); corrected for hadronisation and \( Z^0 \)

-> The measured dijet cross sections are well described by the NLO predictions in the whole measured range

- Gluon fraction still sizeable at \( Q^2 \sim 500 \text{ GeV}^2 \)
- Theoretical uncertainty from higher orders: \( \pm 6\% \)

-> more sensitivity to PDFs

**ZEUS**

\[ \mathcal{L} = 374 \text{ pb}^{-1} \]

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ZEUS Collab, ZEUS-pub-10-005

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Constraints on pPDFs: inclusive-jet cross sections in NC DIS

$$ep \rightarrow e + \text{jet} + X: \text{inclusive jets at low } Q^2$$

- Jets searched using the $k_T$ cluster algorithm in BF
- Kinematic region: $5 < Q^2 < 100 \text{ GeV}^2$ and $0.2 < y < 0.7$
- Jets with $P_T > 5 \text{ GeV}$ and $-1 < \eta_{LAB}^{\text{jet}} < 2.5$
- Small experimental uncertainties
  - uncorrelated: $\sim \pm 5 \ (10)\%$ at low (high) $P_T$
  - correlated: $\sim \pm 5 \ (10)\%$ at low (high) $P_T$
- Comparison to NLO predictions (NLOJET++)
  - $\mu^2_R = \mu^2_F = (Q^2 + (P_T)^2)/2$; pPDFs: CTEQ6.5M;
  - $\alpha_s(M_Z) = 0.118$; corrected for hadronisation
  - The measured jet cross sections are well described by the NLO predictions in the whole measured range
- Large gluon fraction at low $Q^2$
- Theoretical uncertainty dominated by terms beyond NLO: $\pm 30\%$ (PDF uncertainty: $\pm 6\%$)
  - NNLO predictions needed to take full advantage of high-precision data

Inclusive Jet Cross Section

$\mathcal{L} = 43.5 \text{ pb}^{-1}$
Constraints on pPDFs: inclusive-jet cross sections in NC DIS

\[ ep \to e + \text{jet} + X: \text{inclusive jets at high } Q^2 \]

- Jets searched using the \( k_T \) cluster algorithm in Breit frame
- Kinematic region: \( Q^2 > 125 \text{ GeV}^2 \) and \( |\cos \gamma_h| < 0.65 \)
- At least one jet with \( E_{\text{jet}}^{T,B} > 8 \text{ GeV} \) and \(-2 < \eta_{\text{B}}^{\text{jet}} < 1.5\)

- Small experimental uncertainties:
  \( \rightarrow \) uncorrelated: \( \sim \pm 3 \) (10)\% at low (high) \( Q^2/E_{\text{jet}}^{T,B} \)
  \( \rightarrow \) correlated: \( \sim \pm 5 \) (2)\% at low (high) \( Q^2/E_{\text{jet}}^{T,B} \)

- Comparison to NLO predictions (DISENT):
  \( \rightarrow \) \( \mu_R = E_{\text{jet}}^{T,B}; \mu_F = Q; \) pPDFs: ZEUS-S; \( \alpha_s(M_Z) = 0.118; \)
  corrected for hadronisation and \( Z^0 \) effects
  \( \rightarrow \) The measured inclusive-jet cross sections are well described by the NLO predictions in the whole measured range
**Constraints on pPDFs: inclusive-jet cross sections in NC DIS**

\( ep \rightarrow e + \text{jet} + X: \text{inclusive jets at high } Q^2 \)

- Jets searched using the \( k_T \) cluster algorithm in Breit frame
- Kinematic region: \( Q^2 > 125 \text{ GeV}^2 \) and \( |\cos \gamma_h| < 0.65 \)
- At least one jet with \( \eta^\text{jet} < 1.5 \)

- Small experimental uncertainties:
  - uncorrelated: \( \sim \pm 3 \) (10)\% at low (high) \( Q^2/E^\text{jet}_{T,B} \)
  - correlated: \( \sim \pm 5 \) (2)\% at low (high) \( Q^2/E^\text{jet}_{T,B} \)

- Comparison to NLO predictions (DISENT):
  - \( \mu_R = E^\text{jet}_{T,B}; \mu_F = Q; \) pPDFs: ZEUS-S; \( \alpha_s(M_Z) = 0.118 \); corrected for hadronisation and \( Z^0 \) effects
  - The measured inclusive-jet cross sections are well described by the NLO predictions in the whole measured range
  - High precision NC DIS inclusive-jet and dijet data at low and high \( Q^2 \) have the potential to constrain further the proton PDFs in regions of phase space relevant for new physics searches at LHC

\( \mathcal{L} = 300 \text{ pb}^{-1} \)

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**ZEUS**

- ZEUS (prel.) 300 pb\(^{-1}\)
- Jet energy scale uncertainty
- Theoretical uncertainty
- \( 10 < Q^2 < 500 \text{ GeV}^2 \)
- \( 1000 < Q^2 < 2000 \text{ GeV}^2 \)
- \( 500 < Q^2 < 1000 \text{ GeV}^2 \)
- \( 250 < Q^2 < 500 \text{ GeV}^2 \)
- \( 125 < Q^2 < 250 \text{ GeV}^2 \)

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Constraints on p/γ PDFs: inclusive-jet cross sections in PHP

**ep → e + jet + X:** inclusive jets at high $E_T^{\text{jet}}$

- Jets searched using the $k_T$ cluster algorithm in Laboratory frame
- Kinematic region: $Q^2 < 1 \text{ GeV}^2$ and $0.2 < y < 0.85$ and $-1 < \eta^{\text{jet}} < 2.5$
- Comparison to NLO predictions (Klasen et al.):
  - $\mu_R = \mu_F = E_T^{\text{jet}}$

**At least one jet with $E_T^{\text{jet}} > 17 \text{ GeV}**

\[ \mathcal{L} = 189 \text{ pb}^{-1} \]

Good description of data by NLO QCD, except for low $E_T^{\text{jet}}$, high $\eta^{\text{jet}}$ (see page 21)

Sensitivity to proton (high $E_T^{\text{jet}}$, low $\eta^{\text{jet}}$) and photon (low $E_T^{\text{jet}}$, high $\eta^{\text{jet}}$) PDFs
Constraints on $p/\gamma$ PDFs: dijet cross sections in PHP

$ep \rightarrow e + \text{jet} + \text{jet} + X$: dijets at high $E_T^{\text{jet}}$

- Jets searched using the $k_T$ cluster algorithm in Laboratory frame
- Kinematic region: $Q^2 < 1$ GeV$^2$ and $0.2 < y < 0.85$
- Two jets with $E_T^{\text{jet}1} > 21$ GeV, $E_T^{\text{jet}2} > 17$ GeV and $-1 < \eta^{\text{jet}} < 2.5$

$\mathcal{L} = 189$ pb$^{-1}$

→ Good description of data by NLO QCD in the whole measured range
→ Sensitivity to proton (high $E_T^{\text{jet}}$) and photon (high $\eta^{\text{jet}}$, low $x_{\gamma^{\text{obs}}}$) PDFs
Tests of pQCD at HERA and determination of $\alpha_s$
Tests of pQCD: jet cross sections in NC DIS

$ep \rightarrow e + \text{jet(s) + } X$: jets at low $Q^2$

- Jets searched using the $k_T$ cluster algorithm in Breit frame
- Kinematic region: $5 < Q^2 < 100 \text{ GeV}^2$ and $0.2 < y < 0.7$
- Jets with $P_T > 5 \text{ GeV}$ and $-1 < \eta_{\text{LAB}} < 2.5$
- $(M_{jj} > 18 \text{ GeV})$

- Small experimental uncertainties
  - uncorrelated: $< \pm 5$, $\sim \pm 5$, $\sim \pm 8\%$
  - correlated: $\sim \pm 5$, $\sim \pm 5$, $< \pm 8\%$

- Theoretical uncertainties:
  - higher orders ($\pm 30 (10)\%$ at low (high) $Q^2$)
  - proton PDFs ($\pm 6 (2)\%$ at low (high) $Q^2$)
  - parton-to-hadron corrections ($\pm 1 - 2.5, \pm 1 - 2, \pm 5\%$)

$\rightarrow$ Good description of data by NLO predictions
  $\rightarrow$ validity of the description of the dynamics of jet production at $\mathcal{O}(\alpha_s^2)$

$\rightarrow$ Measurements provide direct sensitivity to $\alpha_s(M_Z)$ with small experimental uncertainties

$\mathcal{L} = 43.5 \text{ pb}^{-1}$
Tests of pQCD: determination of $\alpha_s$

- The energy-scale dependence of the coupling was determined by extracting $\alpha_s$ from the measured jet cross sections at low $Q^2$:

  $\rightarrow$ Results in good agreement with the predicted running of $\alpha_s$ within the measured range with small experimental uncertainties

- A value of $\alpha_s(M_Z)$ was determined from a simultaneous fit to the inclusive-jet, dijet and trijet measurements:

  $\alpha_s(M_Z) = 0.1160 \pm 0.0014 \text{ (exp.)}^{+0.0094}_{-0.0079} \text{ (th.)}$

  experimental uncertainty: $\pm 1.2\%$
  theoretical uncertainty: $^{+8.1\%}_{-6.8\%}$

\* Reduction of theoretical uncertainties can be achieved by determining $\alpha_s$ from the measured trijet to dijet ratio:
**Tests of pQCD: normalised jet cross sections in NC DIS**

*ep → e + jet(s) + X: jets at high $Q^2$*

- Jets searched using the $k_T$ cluster algorithm in Breit frame
- Kinematic region: $150 < Q^2 < 15000$ GeV$^2$ and $0.2 < y < 0.7$
- Jets with $P_{T,1} > 7$ GeV, $(P_{T,2}, P_{T,3} > 5$ GeV) and $-0.8 < \eta_{LAB} < 2$
- $(M_{jj} > 16$ GeV)

\[ \mathcal{L} = 395 \text{ pb}^{-1} \]

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**Normalised Inclusive Jet Cross Section**

**Normalised 2-Jet Cross Section**

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Tests of pQCD: normalised jet cross sections in NC DIS

\( ep \rightarrow e + \text{jet(s)} + X: \) jets at high \( Q^2 \)

- Jets searched using the \( k_T \) cluster algorithm in Breit frame
- Kinematic region: \( 150 < Q^2 < 15000 \text{ GeV}^2 \) and \( 0.2 < y < 0.7 \)
- Jets with \( P_{T,1} > 7 \text{ GeV}, (P_{T,2}, P_{T,3} > 5 \text{ GeV}) \) and \( -0.8 < \eta_{\text{LAB}} < 2 \)
- \( (M_{jj} > 16 \text{ GeV}) \)

\( L = 395 \text{ pb}^{-1} \)

\begin{align*}
\text{Normalised 3-Jet Cross Section} & \quad \text{Normalised 3-Jet to 2-Jet Cross Section} \\
\sigma_{3\text{-jet}}/\sigma_{\text{NC}} & \quad \sigma_{3\text{-jet}}/\sigma_{2\text{-jet}} \\
R & \quad R \\
1 \quad 10^3 \quad 10^4 & \quad 0.2 \quad 0.1 \quad 0.0 \quad 0.2 \quad 0.1 \quad 0.0 \\
0.8 \quad 1.0 \quad 1.2 & \quad 1.0 \quad 1.2 \quad 1.2 \\
Q^2 [\text{ GeV}^2] & \quad Q^2 [\text{ GeV}^2]
\end{align*}

\( \rightarrow \) Good description of data by NLO predictions
\( \rightarrow \) validity of the description of the dynamics of jet production at \( \mathcal{O}(\alpha_s^2) \)
\( \rightarrow \) Measurements provide direct sensitivity to \( \alpha_s(M_Z) \) with small experimental and theoretical uncertainties

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C Glasman (Universidad Autónoma de Madrid)
Tests of pQCD: normalised jet cross sections in NC DIS

$ep \rightarrow e + \text{jet} + X$: inclusive jets at high $Q^2$

- Jets searched using the $k_T$ cluster algorithm in BF
- Kinematic region: $150 < Q^2 < 15000$ GeV$^2$ and $0.2 < y < 0.7$
- At least one jet with $P_T > 7$ GeV and $-0.8 < \eta_{LAB} < 2$
- Small experimental uncertainties
  - uncorrelated: $\sim \pm 3 (10)\%$ at low (high) $Q^2/P_T$
  - correlated: $\sim \pm 2 (4)\%$ at low (high) $Q^2/P_T$
- Theoretical uncertainties:
  - higher orders
  - proton PDFs
  - parton-to-hadron corrections

- Good description of data by NLO predictions
- Validity of the description of the dynamics of jet production at $\mathcal{O}(\alpha_s^2)$
- Measurements provide direct sensitivity to $\alpha_s(M_Z)$ with small experimental and theoretical uncertainties

$\mathcal{L} = 395$ pb$^{-1}$

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Tests of pQCD: determination of $\alpha_s$

- The energy-scale dependence of the coupling was determined by extracting $\alpha_s$ from the measured normalised jet cross sections at high $Q^2$:

\[ \text{Normalised Jet Cross Sections} \]

- Results are in good agreement with the predicted running of $\alpha_s$ with small experimental and theoretical uncertainties in a wide range of the scale

* Reduction of experimental (extraction from normalised cross sections) and theoretical (extraction at higher $Q^2$) uncertainties

- A value of $\alpha_s(M_Z)$ was determined from a simultaneous fit to the normalised inclusive-jet, dijet and trijet cross-section measurements:

\[ \alpha_s(M_Z) = 0.1168 \pm 0.0007 \text{ (exp.)}^{+0.0049}_{-0.0034} \text{ (th.)} \]

\[ \text{experimental uncertainty: } \pm 0.6\% \]

\[ \text{theoretical uncertainty: } \pm 4.2\% \]

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C Glasman (Universidad Autónoma de Madrid)
Tests of pQCD: inclusive-jet cross sections in NC DIS

$ep \rightarrow e + \text{jet} + X$: inclusive jets at high $Q^2$

- Jets searched using the $k_T$ cluster algorithm in Breit frame
- Kinematic region: $Q^2 > 125$ GeV$^2$ and $|\cos \gamma_h| < 0.65$
- At least one jet with $E_{T,B}^{\text{jet}} > 8$ GeV and $-2 < \eta_{B}^{\text{jet}} < 1.5$

- Small experimental uncertainties
  → uncorrelated: $\sim \pm 3 (7)\%$ at low (high) $Q^2/E_{T,B}^{\text{jet}}$
  → correlated: $\sim \pm 5 (2)\%$ at low (high) $Q^2/E_{T,B}^{\text{jet}}$

- Small theoretical uncertainties
  → higher orders (below $\pm 5\%$ for $Q^2 > 250$ GeV$^2$)
  → proton PDFs (below $\pm 3\%$)
  → $\alpha_s(M_Z)$ (below $\pm 1 (2)\%$ at low (high) $Q^2/E_{T,B}^{\text{jet}}$)
  → parton-to-hadron corrections (below $\pm 2\%$)

→ Good description of data by NLO prediction
  → validity of the description of the dynamics of jet production at $\mathcal{O}(\alpha_s^2)$

→ Measurements provide direct sensitivity to $\alpha_s(M_Z)$ with small experimental and theoretical uncertainties
Tests of pQCD: determination of $\alpha_s$

- The energy-scale dependence of the coupling was determined by extracting $\alpha_s$ from the measured $d\sigma/dE_{T,B}^{jet}$ at different $E_{T,B}^{jet}$ values:

Results in good agreement with the predicted running of $\alpha_s$ over a large range in $E_{T,B}^{jet}$

- A value of $\alpha_s(M_Z)$ was determined from $Q^2 > 500$ GeV$^2$:

$$\alpha_s(M_Z) = 0.1208^{+0.0037}_{-0.0032} \text{ (exp.)} +0.0022_{-0.0022} \text{ (th.)}$$
Tests of pQCD: inclusive-jet cross sections in PHP

\[ ep \rightarrow e + \text{jet} + X: \text{inclusive jets at high } E_T^{\text{jet}} \]

* Jets searched using the \( k_T \) cluster algorithm in Laboratory frame
* Kinematic region: \( Q^2 < 1 \text{ GeV}^2 \) and \( 0.2 < y < 0.85 \)
* At least one jet with \( E_T^{\text{jet}} > 17 \text{ GeV} \) and \( -1 < \eta^{\text{jet}} < 2.5 \)

* Small experimental uncertainties
  → uncorrelated: typically < ±4%
  → correlated: \( \sim \pm 5\% \)

* Small theoretical uncertainties
  → higher orders (±10 (7)\% at low (high) \( E_T^{\text{jet}} \))
  → proton PDFs (±1 (5)\% at low (high) \( E_T^{\text{jet}} \))
  → photon PDFs (−10 (−2)\% at low (high) \( E_T^{\text{jet}} \))
  → \( \alpha_s(M_Z) \) (below ±3%)
  → parton-to-hadron corrections (below ±3%)

→ Good description of data by NLO prediction
  → validity of the description of the dynamics of jet production at \( \mathcal{O}(\alpha_s^2) \)

→ Measurements provide direct sensitivity to \( \alpha_s(M_Z) \) with small experimental and theoretical uncertainties

\[ \mathcal{L} = 189 \text{ pb}^{-1} \]

ZEUS

\[
\frac{d\sigma}{dE_T^{\text{jet}}} \text{ (pb/GeV)}
\]

-1 < \( \eta^{\text{jet}} < 2.5 \)
\( Q^2 < 1 \text{ GeV}^2 \)
0.2 < \( y < 0.85 \)

\[
\text{rel. diff. to NLO}
\]

\[
\text{jet energy scale uncertainty}
\]

\[
\text{theoretical uncertainty}
\]

ZEUS Collab, ZEUS-prel-10-003

C Glasman (Universidad Autónoma de Madrid)
Tests of pQCD: inclusive-jet cross sections in PHP

$e p \rightarrow e + \text{jet} + X$: inclusive jets at high $E_T^{\text{jet}}$

$\mathcal{L} = 189 \text{ pb}^{-1}$

**ZEUS**

- ZEUS (prel.) 189 pb$^{-1}$
- $E_T^{\text{jet}} > 17 \text{ GeV}$
- $0.2 < y < 0.85$
- $Q^2 < 1 \text{ GeV}^2$

- NLO: $p/\gamma$ PDFs
- ZEUS-S/GRV-HO
- ZEUS-S/AFG04
- MSTW08/GRV-HO
- ZEUS-S/CJK

Jet energy scale uncertainty

- theoretical uncertainty

**Discrepancies at high $\eta^{\text{jet}}$ might be due to $\gamma$PDFs or non-perturbative effects**

- $\gamma$PDFs: AFG04 (CJK) gives lower (higher) prediction than GRV-HO

- Non-perturbative contribution increases jet rate at high $\eta^{\text{jet}}$

- Disagreement between data and NLO disappears when increasing $E_T^{\text{jet}}$

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Tests of pQCD: dijet cross sections in PHP

\[ ep \rightarrow e + \text{jet} + \text{jet} + X: \text{dijets at high } E_T^{\text{jet}} \]

- Jets searched using the \( k_T \) cluster algorithm in Laboratory frame
- Kinematic region: \( Q^2 < 1 \text{ GeV}^2 \) and \( 0.2 < y < 0.85 \)
- Two jets with \( E_T^{\text{jet}} > 17 \text{ GeV}, -1 < \eta^{\text{jet}} < 2.5, M^{\text{jj}} > 60 \text{ GeV} \) and \( |\cos \theta^*| < 0.8 \)

- \( M^{\text{jj}} \) and \( |\cos \theta^*| \):
  - well suited to test underlying dynamics
  - \( M^{\text{jj}} \) sensitive to form of matrix elements
  - \( \theta^* \) sensitive to spin of exchanged particle

\[ \mathcal{L} = 189 \text{ pb}^{-1} \]

- Good description of data by NLO prediction
- Validity of the description of the dynamics of jet production at \( \mathcal{O}(\alpha_s^2) \)

ZEUS Collab, ZEUS-prel-10-014

C Glasman (Universidad Autónoma de Madrid)
Tests of pQCD: determination of $\alpha_s$

- The energy-scale dependence of the coupling was determined by extracting $\alpha_s$ from the measured $d\sigma/dE_T^{\text{jet}}$ at different $E_T^{\text{jet}}$ values:

\[ \alpha_s \] (exp.) $= 0.1208^{+0.0024}_{-0.0023}$
\[ \alpha_s \] (th.) $= 0.1304^{+0.0044}_{-0.0033}$

$\rightarrow$ Results in good agreement with the predicted running of $\alpha_s$ over a large range in $E_T^{\text{jet}}$.
Tests of pQCD: jet algorithms

- Tests of pQCD with jets require infrared- and collinear-safe jet algorithms:
  - $k_T$ cluster algorithm in the longitudinally invariant inclusive mode (S Catani, S Ellis & D Soper)
- Performance of $k_T$ algorithm tested extensively
  - stringent tests of pQCD: good description of data for all jet radii with similar precision
  - good performance of $k_T$ algorithm: small theoretical uncertainties and small hadronisation corrections
- New jet algorithms being used at LHC
  - need test of performance
- NEW STUDIES in NC DIS and PHP:
  - test of performance of anti-$k_T$ and SIScone in a hadron-induced but well-understood reaction:
    * comparison to measurements based on $k_T$
    * comparison of measurements and NLO QCD calculations
    * study of theoretical uncertainties and hadronisation corrections


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Tests of pQCD: $k_T$ vs anti-$k_T$ vs SIScone

- New infrared- and collinear-safe jet algorithms:
  - anti-$k_T$ (M Cacciari, G Salam & G Soyez)
  - and SIScone (G Salam & G Soyez)

- Cluster algorithms:
  - $d_{ij} = \min[(E_T^i)^{2p}, (E_T^j)^{2p}] \cdot \Delta R^2/R^2$
  - with $p = 1$ ($-1$) for $k_T$ (anti-$k_T$)
  - anti-$k_T$ keeps infrared and collinear safety and provides $\approx$ circular jets
    (experimentally desirable)

- Cone algorithms:
  - seedless cone algorithm produces
    also jets with well-defined area and
    is infrared and collinear safe
    (theoretically desirable)
Tests of pQCD: $k_T$ vs anti-$k_T$ vs SIScone

- Theoretical uncertainties:
  - PDFs and value of $\alpha_s(M_Z)$:
    - very similar for all three jet algorithms
  - terms beyond NLO and QCD cascade/hadronisation modelling:
    - very similar for $k_T$ and anti-$k_T$; somewhat larger for SIScone

![Graph showing theoretical uncertainties for $E_{T,B}$ vs $E_{T,B}$, $E_{T}$ vs $E_{T}$]
Tests of pQCD: inclusive-jet cross sections

- Inclusive-jet cross sections in NC DIS and PHP for $k_T$, anti-$k_T$ and SIScone:

\[ \frac{d\sigma}{dE_{T,B}} (\text{pb/GeV}) \]

\[ k_T (\times 100) \quad \text{anti-}k_T (\times 10) \quad \text{SIScone} \]

\[ Q^2 > 125 \text{ GeV}^2 \]
\[ -2 < \eta_{h} < 1.5 \]
\[ |\cos\gamma_h| < 0.65 \]

\[ \text{jet energy scale uncertainty} \]
\[ \text{hadronisation uncertainty} \]

\[ \eta < 2.5 \]
\[ 0.2 < y < 0.85 \]

\[ \text{ratio to NLO} \]

\[ E_{T,B} (\text{GeV}) \]

\[ E_T (\text{GeV}) \]

\[ \text{ZEUS (prel.) 189 pb}^{-1} \]
\[ \text{NLO hadr (Klasen et al.)} \]

→ Good description of data in shape and normalisation by NLO QCD

→ Bigger hadronisation corrections for SIScone than anti-$k_T$ (similar to $k_T$)

→ Similar shape and normalisation in data and theory for the three jet algorithms


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Tests of pQCD: inclusive-jet cross sections

- Ratio of cross sections based on different jet algorithms:
  - NC DIS: differences < 3.6% at low $E_{T,B}$ and increase to 10% at high $E_{T,B}$
  - PHP: anti-$k_T$ same shape and $\approx 6\%$ smaller than $k_T$
  - SIScone slightly different shape than $k_T$ and anti-$k_T$
  - the uncertainty due to higher orders in the $\mathcal{O}(\alpha_s^3)$ calculation is reduced
  - theoretical uncertainty dominated by QCD-cascade modelling

$\Rightarrow$ Demonstration of ability of pQCD calculations with up to four (three) partons in final state to account adequately for the differences between jet algorithms
Tests of pQCD: determination of $\alpha_s(M_Z)$

- Values of $\alpha_s(M_Z)$ were determined from the measured cross sections to quantify the performance of the jet algorithms:

  \[ \alpha_s(M_Z) = 0.1207^{+0.0038}_{-0.0036} \text{ (exp.)} +0.0022_{-0.0023} \text{ (th.)} (k_T) \]

  \[ \alpha_s(M_Z) = 0.1188^{+0.0036}_{-0.0035} \text{ (exp.)} +0.0022_{-0.0022} \text{ (th.)} (\text{anti-}k_T) \]

  \[ \alpha_s(M_Z) = 0.1186^{+0.0037}_{-0.0035} \text{ (exp.)} +0.0026_{-0.0026} \text{ (th.)} (\text{SIScone}) \]

  \[ \alpha_s(M_Z) = 0.1208^{+0.0024}_{-0.0023} \text{ (exp.)} +0.0044_{-0.0033} \text{ (th.)} (k_T) \]

  \[ \alpha_s(M_Z) = 0.1200^{+0.0024}_{-0.0023} \text{ (exp.)} +0.0043_{-0.0032} \text{ (th.)} (\text{anti-}k_T) \]

  \[ \alpha_s(M_Z) = 0.1199^{+0.0022}_{-0.0022} \text{ (exp.)} +0.0047_{-0.0042} \text{ (th.)} (\text{SIScone}) \]

→ $\alpha_s(M_Z)$ from inclusive-jet cross sections in NC DIS and PHP with different jet algorithms are consistent with each other and have similar precision
Jet physics at HERA continues providing precision measurements towards understanding QCD and improving the determination of the $p/\gamma$ PDFs

→ Precise new jet measurements will help to constrain further the proton and photon PDFs
→ Precise tests of the performance of new jet algorithms
→ Precise values of $\alpha_S(M_Z)$ extracted from jet production in different regimes
→ Precise determination of the running of $\alpha_s$ over a wide range of the scale
Back-up slides
Tests of pQCD: $k_T$ vs anti-$k_T$ vs SIScone

- Inclusive-jet cross sections in NC DIS can be calculated only up to $O(\alpha_s^2)$ using the programs DISENT or NLOJET++

- Differences of cross sections using different algorithms can be calculated up to $O(\alpha_s^3)$ with NLOJET++

- Ratios of cross sections for different algorithms can be calculated using the differences up to $O(\alpha_s^3)$ as:

\[
\frac{d\sigma_{\text{SIScone}}}{d\sigma_{k_T}} = 1 + \frac{d\sigma_{\text{SIScone}} - d\sigma_{k_T}}{d\sigma_{k_T}} \approx 1 + \frac{D\alpha_s^2 + E\alpha_s^3}{A\alpha_s^2 + B\alpha_s^2}
\]

\[
\frac{d\sigma_{\text{anti}-k_T}}{d\sigma_{k_T}} = 1 + \frac{d\sigma_{\text{anti}-k_T} - d\sigma_{k_T}}{d\sigma_{k_T}} \approx 1 + \frac{C\alpha_s^3}{A\alpha_s^2 + B\alpha_s^2}
\]
The method to determine $\alpha_s$ from jet observables

- The procedure to determine $\alpha_s$ from jet observables used by ZEUS is based on the $\alpha_s$ dependence of the pQCD calculations, taking into account the correlation with the PDFs:
  - perform NLO calculations using different sets of proton PDFs
  - use as input in each calculation the value of $\alpha_s(M_Z)$ assumed in each PDF set
  - parametrise the $\alpha_s$ dependence of the observable:
    \[ A^i(\alpha_s(M_Z)) = A^i_1 \alpha_s(M_Z) + A^i_2 \alpha_s(M_Z)^2 \]
  - determine $\alpha_s(M_Z)$ from the measured value using the NLO parametrisation

![](image)

- This procedure handles correctly the complete $\alpha_s$-dependence of the NLO calculations (explicit dependence in the partonic cross section and implicit dependence from the PDFs) in the fit, while preserving the correlation between $\alpha_s$ and the PDFs