Precision QCD measurements at HERA: 

Jet production and $\alpha_s$ determination

Stanislaw Mikocki
Institute of Nuclear Physics PAN, Cracow
on behalf of the H1 and ZEUS collaborations
HERA Experiments

Standard DIS variables:
- $Q^2$: virtuality of the exchanged boson
- $x$: in QPM fraction of proton momentum carried by struck quark
- $y = Q^2 / x s$: inelasticity

Kinematics regimes:
- $Q^2 \approx 0 \text{ GeV}^2$: Photoproduction ($\gamma p$)
- $Q^2 > 1 \text{ GeV}^2$: DIS
Overview

Part I

- jets production in large range of $Q^2$: inclusive jets (PHP) and multijets (DIS)
- measurements of the cross sections and extraction of $\alpha_s(M_Z)$
- comparison with NLO prediction

Photoproduction


DIS Low $Q^2$

DIS High $Q^2$

H1-Prelim-11-032
H1-Prelim-12-031

Part II


Test of QCD evolution mechanisms ($DGLAP / BFKL / CCFM$)
using azimuthal correlation
between the most forward jet and the scattered positron in DIS
Jet Production in DIS

The momentum fraction of the proton carried by the parton entering the hard subprocess:

\[ \xi = x_{Bj} \left( 1 + \frac{M_{12}^2}{Q^2} \right) \]

Only hard QCD process generates significant \( P_T \) in Breit frame
Direct sensitivity to \( \alpha_s \) and gluon PDF
Cross sections are measured as a function of $Q^2$, $p_T(<p_T>)$ and $\xi$.

Main experimental uncertainties:
- Jet energy scale 2% → $\Delta \sigma/\sigma = 4\text{-}10%$
- Uncertainty in acceptance → $\Delta \sigma/\sigma = 2\text{-}15%$

NLO calculation: NLOJET++
- MSbar scheme for 5 massless quark flavors
- PDFs: CTEQ6.5M

Cross sections are measured as a function of $Q^2$, $p_T(<p_T>)$ and $\xi$.

Main experimental uncertainties:
- Jet energy scale 1% → $\Delta \sigma/\sigma = 3\text{-}10%$
- Uncertainty in acceptance → $\Delta \sigma/\sigma = 4\text{-}5%$

NLO calculation: NLOJET++
- MSbar scheme for 5 massless quark flavors
- PDFs: HERAPDF1.5, CT10
Single Differential Cross Sections

**Incl. Jet**

- NLO QCD with $\mu_r = \sqrt{(Q^2 + P_T^2)/2}$ and HERAPDF 1.5 describes well inclusive jet, dijet and trijet single differential cross sections.

**2- Jet**

**3- Jet**

Stanislaw Mikocki

Hadron Structure'13
Benefit:
partial cancellation of experimental and theoretical uncertainties

Comparison with
NLOJet++ and QCDNUM corrected to hadronisation effects

Scale choice:
\[ \mu_f^2 = Q^2, \]
\[ \mu_r^2 = \frac{Q^2 + P_T^2}{2} \]

In all bins (besides the highest \(Q^2\) and highest \(P_T\))
the experimental uncertainties are smaller than the theoretical uncertainties
Normalized Multi-Jet Cross Sections at High $Q^2$

NLO Calculation:
- NLOJet++ and QCDNUM corrected for hadronisation effects

Scale Choice:
- $\mu_f^2 = Q^2$
- $\mu_r^2 = (Q^2 + P_T^2)/2$

- Small experimental uncertainties
- Good NLO description of the data
Largest benefit is from a combined fit
- simultaneous fit to normalised inclusive jet, dijet and trijet cross sections
  (all correlations are included)

Sensitive to higher orders
- Theoretical uncertainties estimated by variation of scale,
  k-factor \( (k = \sigma_{\text{NLO}}/\sigma_{\text{LO}}) \) – an estimator of higher order contributions
  reaches values up to 1.45

Restrict analysis to \( k < 1.3 \)
- faster convergence of perturbative series
- trade-off between number of data points and smaller theoretical uncertainties

Normalised Multijets with \( k < 1.3 \)
\[ \chi^2/\text{ndf}: 53.2/41 = 1.30 \]

\[ \alpha_s(M_Z) = 0.1163 \pm 0.0011 \text{ (exp.)} \pm 0.0008 \text{ (had)} ^{+0.0044}_{-0.0035} \text{ (th.)} \pm 0.0014 \text{ (PDF)} \]

Consistent with other \( \alpha_s(M_Z) \) measurements
Small experimental uncertainties
Theoretical uncertainties are larger than the experimental
Multi-Jet Cross Sections at Low $Q^2$

Inclusive Jet, 2-Jet and 3-Jet Cross Sections

- Measurements are well described by NLO
- Experimental uncertainty 6-11%
- Theory uncertainty dominated by renorm. scale uncertainty: 10% (highest $Q^2$ and $P_T$) to 30% (lowest $Q^2$ and $P_T$)
- PDF uncertainty 2-6%
- Low predictive power of NLO at low $Q^2$ and/or low $P_T$
- Orders beyond NLO are needed to match the precision of data
Multi-Jet Cross Sections at Low $Q^2$

3-Jet to 2-Jet Ratio

- In ratio normalisation errors cancel and other syst. uncertainties reduced by 50%
- Reduced sensitivity to renormalisation scale variation in theory
- Good description of ratio by NLOjet++
Combined Fit Incl.Jet+2-jet+3-jet:

$$\alpha_s(M_Z) = 0.1160 \pm 0.0014 \, (\text{exp.}) \pm 0.0016 \, (PDF)$$

Experimental uncertainties reduced significantly wrt individual $\alpha_s$ extraction

Remarkable agreement between low, high $Q^2\alpha_s$ extraction and QCD expectations

$$\mu_r = \mu_f = \sqrt{(Q^2 + p_{T,\text{jet}}^2)/2}$$
Jet Production in Photoproduction

Direct sensitivity to $\alpha_s$, gluon and photon PDFs
Data: \( \sim 300 \text{pb}^{-1} \) (HERA-2)

Single and double differential inclusive jet cross sections are measured as functions of jet transverse energy \( E_T^{\text{jet}} \) and pseudorapidity \( \eta^{\text{jet}} \) for

- photon virtuality: \( Q^2 < 1 \text{ GeV}^2 \)
- \( \gamma p \) centre-of-mass energies: \( 142 < W_{\gamma p} < 293 \text{ GeV} \)
- Jets in lab frame:
  - \( E_T^{\text{jet}} > 17 \text{ GeV} \)
  - \(-1 < \eta^{\text{jet}} < 2.5 \)

Jets were identified using the \( k_T \), anti-\( k_T \) and SIScone jet algorithms in laboratory frame.
Inclusive Jets in Photoproduction

Data compared to NLO QCD ($O(\alpha_s^2)$):

$$\mu_R = \mu_F = \mu = E_T^{\text{jet}}$$

PDFs: proton PDF - ZEUS-s, photon PDF – GRV-HO, $\alpha_s = 0.118$

The NLO QCD calculation reproduce $d\sigma/dE_T^{\text{jet}}$ well, $d\sigma/d\eta^{\text{jet}}$ is well described for $\eta^{\text{jet}} < 2$
Data comparison to the NLO QCD calculation including an estimation of non-perturbative effects from underlying events (not related to hadronisation)

Possible presence of effects in the data, which are not included in the NLO QCD calculation
Some difference between three predictions, especially at low $E_{\text{jet}}^T$ and high $\eta_{\text{jet}}$

Potential to constrain photon PDFs
Inclusive Jets in Photoproduction

Dependence on proton PDFs

Small difference between three predictions

Low sensitivity to proton PDFs
Inclusive Jets in Photoproduction

Differential cross section based on $k_T$ jet algorithm for inclusive jet photoproduction with $E_{T}^{jet} > 17$ GeV in different $\eta^{jet}$ regions.

Difference between data and NLO at large $\eta^{jet}$ and low $E_{T}^{jet}$ could be from photon PDFs or non-perturbative effects.

The NLO QCD predictions give a good description of the data, except at (low $E_{T}^{jet}$ and high $\eta^{jet}$).
the agreement of the data to the NLO prediction is the same for all three jet algorithms
no sensitivity of the result on the choice of the jet algorithm used
Determination of $\alpha_s(M_Z)$ and Energy scale dependence

The measured single differential cross sections based on the three jet algorithms were used to determine $\alpha_s(M_Z)$ values.

To minimise the effects of non-perturbative contributions and reduce uncertainties coming from proton PDFs only the measurements for $21 < E_{\text{jet}} < 71$ GeV were used in the fit.

$\alpha_s(M_Z)$ obtained from presented data are:

$$\alpha_s(M_Z) |_{k_T} = 0.1206^{+0.0023}_{-0.0022} \text{ (exp.)} +0.0042^{\text{th.}}_{-0.0035},$$

$$\alpha_s(M_Z) |_{\text{anti-}k_T} = 0.1198^{+0.0023}_{-0.0022} \text{ (exp.)} +0.0041^{\text{th.}}_{-0.0034},$$

$$\alpha_s(M_Z) |_{\text{SIScone}} = 0.1196^{+0.0022}_{-0.0021} \text{ (exp.)} +0.0046^{\text{th.}}_{-0.0043}.$$ 

The value of $\alpha_s(M_Z)$ determined from the $k_T$, anti-$k_T$ and SIScone measurements are nicely agreeing.

These determinations are consistent with previous determinations of $\alpha_s(M_Z)$ and have a precision comparable to those obtained from $e^+e^-$ experiments.

Running of $\alpha_s$ in single experiment in good agreement with Renormalisation Group Equations prediction at 2-loops.
Comparison of $\alpha_s(M_Z)$ values

Uncertainties: exp. —— theo. ———

**EW Fit, Z decays, 4NLO**
Gfitter Group, EPJC 72, 2003 (2012)

**H1+ZEUS NC, CC and jet QCD fits**
H1-prelim-11-034, ZEUS-Prel-11-001

**H1 multijets at low $Q^2$**
H1, EPJC 67, 1 (2010)

**H1 norm. multijets at high $Q^2$ (unfold)**
H1-prelim-12-031

**ZEUS inclusive jets in $\gamma^*p$**

**D0 incl. jets, approx. NNLO**
D0, PRD 80, 111107 (2009)

**D0 angular correlations, NLO**

**ATLAS incl. jets, NLO**
B. Malaescu et al., EPJC 72, 2041 (2012)

**CMS R3/2, NLO**
CMS PAS QCD-11-003 (2013)

**World average**
J. Beringer et al. (PDG), PRD 86 010001 (2012)

Experimental precision as good as or better than others measurements

Theory uncertainty dominates and NNLO is needed
Part II
Test of QCD evolution mechanisms (*DGLAP / BFKL / CCFM*)
using azimuthal correlation
between the most forward jet and the scattered positron in DIS
QCD dynamics at low Bjorken-x

HERA: DIS at low Bjorken-x down to $10^{-5}$ → energy in $\gamma^*p$ cms is large ($W_{\gamma^*p} \approx Q^2 / x$)

- long gluon cascades exchanged between the proton and the photon
- pQCD – multiparton emissions described only with approximations:

- **DGLAP** (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution:
  - resums terms $\sim (\alpha_s \ln Q^2)^n$
  - Assumes strong ordering of parton $k_T$

- **BFKL** (Balitsky-Fadin-Kuraev-Lipatov) evolution:
  - resums terms $\sim (\alpha_s \ln(1/x))^n$
  - No ordering in $k_T$, strong ordering in $x_i$
  - Transition from DGLAP to BFKL scheme expected at low $x$

- **CCFM** (Ciafaloni-Catani-Fiorani-Marchesini) evolution:
  - emitted partons are ordered in angles
  - reproduces DGLAP at large $x$ and BFKL at $x \to 0$

Search at HERA for effects of parton dynamics beyond the standard DGLAP approach

- Strong rise of the proton structure function $F_2(x, Q^2)$ with decreasing $x$
  - well described by NLO DGLAP over a large range of $Q^2$
  - $F_2$ measurement too inclusive to discriminate between different QCD evolution schemes

- Look at hadronic final states – reflecting kinematics, structure of gluon emissions
**Forward Jets in DIS (Mueller – Navelet jets):**

- BFKL – more hard partons emitted close to the proton
- Study high transverse momentum and high energy jets produced close to the proton (forward region in LAB)

**Suppress standard DGLAP evolution in** $Q^2$:

$$p^2_{T,fwdjet} \approx Q^2$$

**Enhance BFKL evolution in** $x$:

$$x_{fwdjet} = \frac{E_{fwdjet}}{E_p} \gg x_{Bjorken}$$

**Data:** H1, $L=38.2\text{ pb}^{-1}$

**DIS selection**

- $0.1 < y < 0.7$
- $5 < Q^2 < 85\text{ GeV}^2$
- $0.0001 < x < 0.004$

**Jets reconstructed in the Breit frame and boosted to LAB, all cuts in LAB**

- $p_{T,fwdjet} > 6\text{ GeV}$,
- $1.73 < \eta_{fwdjet} < 2.79$
- $x_{fwdjet} = \frac{E_{fwdjet}}{E_p} > 0.035$
- $0.5 < p_{T,fwdjet}^2 / Q^2 < 6.0$

Measurement of the azimuthal angle difference $\Delta \phi$ between the scattered positron and the forward jet as a function of the rapidity distance $Y$ between them.
Monte Carlo models with different QCD dynamics

**RAPGAP - DGLAP**
LO QCD matrix elements + HO modelled by leading log parton showers

**ARIADNE Colour Dipole Model**
CDM: QCD radiation from the colour dipole formed by the struck quark and the proton remnant. Chain of independently radiating dipoles formed by the emitted gluons.

**CASCADE - CCFM**
Off-shell QCD ME + parton emissions based on the CCFM equation

Single DGLAP ladder with strong ordering in $k_T$

BFKL- like Monte Carlo: random walk in $k_T$

Angular ordering of parton emissions

Stanislaw Mikocki

Hadron Structure'13
Forward jet cross sections – comparison with the predictions of pQCD at NLO ($\alpha_s^2$) accuracy

- Forward jet analysis – reconstruction of jets in the Breit frame $\rightarrow$ at least dijet topology

**NLOJET ++ program (Nagy & Trocsanyi, 2001):**
- dijet production at parton level in DIS at NLO ($\alpha_s^2$)

- PDF: CTEQ6.6, $\alpha_s(M_Z) = 0.118$
- Parton level cross sections corrected for hadronisation effects using the RAPGAP model
Forward Jet Azimuthal Correlations

At higher Y corresponding to lower x, the forward jet is more decorrelated from the scattered positron.

Cross sections best described by BFKL-like model CDM

- DGLAP predictions below the data
- CCFM (set A0) as good description as CDM at large Y

The shape of $\Delta \phi$ distributions are similarly well described by all MC models

$Y = \ln(x_{\text{fwdjet}} / x)$, rapidity distance between the most forward jet and the scattered positron

$$R = \left( \frac{1}{\sigma_{\text{MC}}^{d\sigma}} d\sigma_{\text{MC}}^{d\Delta\phi} \right) / \left( \frac{1}{\sigma_{\text{data}}^{d\sigma}} d\sigma_{\text{data}}^{d\Delta\phi} \right)$$
Forward Jet Azimuthal Correlations

Different splitting functions used in unintegrated gluon density function (uPDF):
set A0 – only singular terms of the gluon splitting function
set 2 – includes also non-singular terms

- Cross sections strongly depend on uPDF
- Shape of $\Delta \phi$ distributions
  - at low Y shows sensitivity to uPDF
  - well described by the set A0

Predictions of the CCFM model depend on the choice of uPDF
Forward Jet Azimuthal Correlations

Comparison to NLO (O($\alpha_s^2$)) predictions

NLO predictions

- shape of $\Delta \phi$ distributions described, but central value too low
- large scale uncertainty (of up to 50%) indicates importance of higher orders

NLOJET++

PDF: CTEQ6.6, $\alpha_s(M_Z)=0.118$

Renormalisation and factorisation scales:

$$\mu_f = \mu_r = \sqrt{\frac{p_{T, fwdjet}^2 + Q^2}{2}}$$

Theoretical uncertainty:

factor 2 or $\frac{1}{2}$ applied to $\mu_r$ and $\mu_f$ scales simultaneously
Forward Jet Azimuthal Correlations (+central jet)

- Subsample of events with forward jet + additional central jet
  
  \[ p_{T,\text{centet}} > 4 \text{ GeV}, \quad -1 < \eta_{\text{centet}} < 1 \]
  
  \[ \Delta \eta = \eta_{\text{fwdjet}} - \eta_{\text{centjet}} > 2 \] (enhance radiation between the forward and central jet)

- \( \Delta \phi \) still between the forward jet and the scattered positron

**NLO \( O(\alpha_s^2) \) predictions**

- at low \( Y \) reasonable description of the data
- at high \( Y \), central value to small but still within theory uncertainty
- large scale uncertainty (of up to 40\%) indicates importance of higher order contributions

**NLOJET++**

PDF: CTEQ6.6, \( \alpha_s(M_Z) = 0.118 \)

\[
\mu_f = \mu_r = \sqrt{\frac{\langle p_T \rangle^2 + Q^2}{2}}, \quad \langle p_T \rangle = \frac{\langle p_{T,\text{fwdjet}} + p_{T,\text{centjet}} \rangle}{2}
\]
**Summary**

**Jets & $\alpha_s$**

HERA jet data among the most precise data for precision test of QCD

Perturbative QCD NLO calculations in general describe the data

**Precision Measurement of Jet Production in DIS**
- inclusive jets, dijets and trijets measurements
- absolute and normalised single and double differential cross sections
- multi-dimensional unfolding of various measurements simultaneously

**Precision Measurement of Inclusive Jet Production in Photoproduction**
- single and double differential cross sections
  - based on the three jet algorithms ($k_T$, anti-$k_T$, SIScone)
- the three jet algorithms give very similar results

**Extracted values of $\alpha_s(M_Z)$** from jet production in different regimes competitive with other measurements, precision dominated by theoretical uncertainties

**Running of $\alpha_s$** determination over a wide range of scale

**Theory**: Missing higher orders calculation (NNLO) often is dominated source of uncertainty

**Azimuthal correlation of forward jets in DIS**

Cross sections as a function of $\Delta\phi$ and rapidity separation between the forward jet and the scattered positron are best described by the BFKL – like model CDM

The shape of $\Delta\phi$ distributions are well described by LO MC models with different QCD evolution schemes

NLO DGLAP predictions are in general below the data, but still in agreement within the large theoretical uncertainties
Adding jet data dramatically decreases the low-x gluon uncertainty, not only the experimental but also the model and parametrization uncertainties.

See Achim Geiser's Wednesday talk