Measurement of Jet Production Cross Sections in Deep-inelastic ep Scattering at HERA

Daniel Britzger
for the H1 Collaboration

DIS 17
25th International Workshop on Deep Inelastic Scattering and Related Topics
Birmingham, UK
05.04.2017
Deep-inelastic scattering

**Neutral current deep-inelastic scattering**
- Process: \( ep \rightarrow e'X \)
- Electron or positron

**Kinematic variables**
- Virtuality of exchanged boson \( Q^2 \)
  \[ Q^2 = -q^2 = -(k - k')^2 \]
- Inelasticity
  \[ y = \frac{p \cdot q}{p \cdot k} \]

**NC and CC DIS cross sections (HERA-II) are mandatory ingredients for PDF fits**
- Only one proton involved
  - \( \rightarrow \) lepton directly probes (charged) constituents of proton

**Gluon is mainly indirectly constrained by DGLAP and sum-rules**
- \( \rightarrow \) Measurement of \( ep \rightarrow 2j+X \) will allow direct access of gluon content
Jet production in $ep$ scattering

Jet measurements are performed in Breit reference frame
- Exchanged virtual boson collides 'head-on' with parton from proton ('brick-wall' frame)

Jet measurements directly sensitive
- to $\alpha_s$ already at leading-order
- to gluon content of proton

Trijet measurement
- More than three jets with significant transverse momenta
- Leading-order already at $O(\alpha_s^2)$
The HERA ep collider

**HERA ep collider in Hamburg**
- Data taking periods
  - HERA I: 1994 – 2000
  - HERA II: 2003 – 2007
- Delivered integrated luminosity ~ 0.5 fb⁻¹

**HERA-II period**
- Electron and positron runs
- $\sqrt{s} = 319$ GeV
  - $E_e = 27.6$ GeV
  - $E_p = 920$ GeV
- Analysed int. Luminosity: $L = 290$ pb⁻¹
H1 Experiment at HERA

**H1 multi-purpose detector**
- Asymmetric design
- Trackers:
  - silicon tracker, jet chambers, proportional chambers, ...
- Calorimeters
  - Liquid Argon sampling calorimeter
  - SpaCal: scintillating fiber calorimeter
- Superconducting magnet: 1.15T
- Muon detectors

**Excellent experimental precision**
- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
- Luminosity: 2.5%
Analysis strategy and kinematic range

Data must be corrected for detector effects
- Kinematic migrations
- Acceptance and efficiency effects

Regularised unfolding
- For accurate description of migrations consider an 'extended phase space'

<table>
<thead>
<tr>
<th></th>
<th>Extended phase space for unfolding</th>
<th>Cross section phase space</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC DIS</td>
<td>$Q^2 &gt; 3 \text{ GeV}^2$</td>
<td>$5.5 &lt; Q^2 &lt; 80 \text{ GeV}^2$</td>
</tr>
<tr>
<td></td>
<td>$y &gt; 0.08$</td>
<td>$0.2 &lt; y &lt; 0.6$</td>
</tr>
<tr>
<td>(inclusive) jets</td>
<td>$P_T^{\text{jet}} &gt; 3 \text{ GeV}$</td>
<td>$P_T^{\text{jet}} &gt; 4.5 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>$-1.5 &lt; \eta^{\text{lab}} &lt; 2.75$</td>
<td>$-1.0 &lt; \eta^{\text{lab}} &lt; 2.5$</td>
</tr>
<tr>
<td>Dijet and trijet</td>
<td>$&lt;P_T^{\text{jet}} &gt; 3 \text{ GeV}$</td>
<td>$P_T^{\text{jet}} &gt; 4 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>$&lt;P_T^{\text{jet}} &gt; 5 \text{ [5.5] GeV}$</td>
<td>$&lt;P_T^{\text{jet}} &gt; 5 \text{ [5.5] GeV}$</td>
</tr>
</tbody>
</table>

- Dijets/trijets: asymmetric cuts on $p_T^{\text{jet1}}$ & $p_T^{\text{jet2}}$ avoid IR sensitive regions in NNLO
Regularised unfolding

Regularised unfolding using TUnfold
- Calculate unfolded distribution $x$ by minimising
  \[ \chi^2(x, \tau) = (y - Ax)^T V_y^{-1} (y - Ax) + \tau L^T L \]
  - Linear analytic solution
  - Linear error propagation
  - Statistical correlations are considered in $V_y$

Simultaneous unfolding of
Inclusive jet, Dijet, Trijet, NC DIS
- Statistical correlations are considered
- Matrix constituted from $O(10^6)$ entries
  - Two generators used
  - Difference between the two -> model uncertainty
- Up to 6 variables considered for migrations
- 'detector-level fake jets' (or events) are constrained with NC DIS data
Control distributions

Acceptance of NC DIS events
- Scattered lepton is found in SpaCal
- Lepton energy $E_e > 10.5$ GeV
- Selection based on un-prescaled SpaCal electron trigger

Monte Carlo generators
- Rapgap: LO matrix elements + PS
- Djangoh: Color-dipole model
- String fragmentation for hadronisation

Background
- Photoproduction simulation using Pythia
- Normalised to data using dedicated event event selection
- Background for jet quantities almost negligible
Detector-level distributions for jets

Jet reconstruction
- $k_T$ jet algorithm with $R=1$
- Jets built from tracks and clusters
- Jet energy calibration using neural networks
  Approx. 1% Jet energy scale uncertainty

Monte Carlo used for unfolding
- Jet multiplicities and spectra not well modelled
- Django: $p_T^{\text{jet}}$ spectra too hard
- Rappgap: Jet multiplicity underestimated
- Both generators tend to have too few jets in forward direction
- $\rightarrow$ MC generators are weighted to describe data

Dijet and Trijet
- Distributions raise steeply due to $p_T^{\text{jet}} > 5$ GeV requirement
- $\rightarrow$ Extended phase space important for migrations
Comparisons to Predictions

**Recently improved prediction became available for DIS jets**

- NNLO (Rev. Lett. 117 (2016) 042001) and [arXiv:1703.05977]
- Both theory groups have extended their calculations for our data

<table>
<thead>
<tr>
<th>Predictions</th>
<th>NLO</th>
<th>aNNLO</th>
<th>NNLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program for jet cross sections</td>
<td>nlojet++</td>
<td>JetViP</td>
<td>NNLOJET</td>
</tr>
<tr>
<td>pQCD order</td>
<td>NLO</td>
<td>approximate NNLO</td>
<td>NNLO</td>
</tr>
<tr>
<td>Calculation detail</td>
<td>Dipole subtraction</td>
<td>Phase space slicing</td>
<td>Antenna subtraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Program for NC DIS</td>
<td>QCDNUM</td>
<td>APFEL</td>
<td>APFEL</td>
</tr>
<tr>
<td>Heavy quark scheme</td>
<td>ZM-VFNS</td>
<td>FONLL-C</td>
<td>FONLL-C</td>
</tr>
<tr>
<td>Order</td>
<td>NLO</td>
<td>NNLO</td>
<td>NNLO</td>
</tr>
<tr>
<td>PDF set</td>
<td>NNPDF3.0_NLO</td>
<td>NNPDF3.0_NNLO</td>
<td>NNPDF3.0_NNLO</td>
</tr>
<tr>
<td>$\alpha_s(M_Z)$</td>
<td>0.118</td>
<td>0.118</td>
<td>0.118</td>
</tr>
<tr>
<td>Hadronisation corrections</td>
<td></td>
<td>Django and Rapgap</td>
<td></td>
</tr>
<tr>
<td>Available for</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Normalised) Inclusive jet</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(Normalised) Dijet</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(Normalised) Trijet</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Dijet cross sections

Dijet cross sections in NC DIS as a function of $Q^2$ and $<p_T>_2$

- $<p_T>_2 = (p_{T_{jet}} + p_{T_{jet}^2})/2$
  with: $p_{T_{jet}} > 4$ GeV

Comparison to Predictions

- NLO (nlojet++, NNPDF30_nlo)
- approximate NNLO (JetVip, NNPDF30_nnlo)
- NNLO (NNLOJET, NNPDF30_nnlo)

- Overall: predictions give reasonable description of data
Ratio of dijet cross sections to NLO

Scale uncertainty
- So-called '7-point scale variation': Vary $\mu_R$ and $\mu_F$ independently by factors of 2 and 0.5, but exclude variations in 'opposite' directions

Ratio to NLO prediction
- NLO give reasonable descriptions within large scale uncertainties
- aNNLO improves shape
  - aNNLO expected to improve description at high $<p_T>$
- NNLO improves shape dependence
  - NNLO predictions have smaller scale uncertainties than NLO at high-$<p_T>$
Normalised jet cross sections

Normalised jet cross sections
• Normalised to: 'inclusive neutral-current DIS cross section' in respective $Q^2$ bin

Advantages
• Reduced experimental uncertainties
• Cancellation of normalisation uncertainty (in our case: only partial cancellation, because NC DIS cross sections are measured only with a subset of the jet data because of trigger reasons)

NC DIS cross sections
• NLO (ZM-VFNS) and NNLO (FONLL-C) predictions provide a good description of the data
• PDFs are fitted to NC DIS cross sections

Inclusive neutral-current DIS cross sections

DIS17, April 2017
Daniel Britzger – H1 Jets
Normalised dijet cross sections

\[ \sigma_{i}^{\text{norm}} = \frac{\sigma_{i}}{\sigma_{NC}^{i_q}} \]

Predictions
- Predictions obtained as ratio of jet to NC DIS calculations
- Scale uncertainties by varying jet cross sections only (because NC DIS are fitted to data)

Data to theory agreement
- Overall good description by NLO, aNNLO and NNLO predictions
- (only) somewhat reduced experimental uncertainties
- NNLO slightly overshoots data -> partially caused by normalisation w.r.t. NC DIS

H1 Normalised dijets

- H1 HERA-II
- Systematic uncertainty
- NLO @ hadr. corr.
- aNNLO @ hadr. corr.
- NNLO @ hadr. corr.
**Reminder: inclusive jets @ high-$Q^2$**


- H1 HERA-II jet cross sections at high-$Q^2$
- Inclusive jet, dijet and trijet cross sections
- $150 < Q^2 < 15\ 000\text{GeV}^2$

**Inclusive jets in range**

- $7 < p_T < 50\ \text{GeV}$

**Recent studies showed**

- Inclusive jets are well measurable down to $p_T \sim 4\ \text{GeV}$
- The original 'high-$Q^2$ '-analysis contained a cross section bin for inclusive jets for $5 < p_T < 7\ \text{GeV}$

**Extension to low-$p_T$ : $5 < p_T < 7\ \text{GeV}$**

- for each $Q^2$ range
- Absolute and normalised cross sections
**Inclusive jet cross sections**

- **Inclusive jet cross sections**
  - low $Q^2$: $4.5 < P_T < 50$ GeV
  - high $Q^2$: $5 < P_T < 50$ GeV

**Predictions**

- NLO, aNNLO & NNLO

**NLO**

- Data well described within uncertainties

**aNNLO**

- Somewhat improved shape description

**NNLO**

- Improved shape and normalisation
- Reduced scale uncertainties for larger values of $\mu_r$

**Also measured**

- Normalised inclusive jet cross sections
Normalised inclusive jet cross sections

**Normalised inclusive jets**
- Normalisation w.r.t. inclusive NC DIS cross section in respective $Q^2$ bin
- Significant reduction of uncertainties at higher values of $Q^2$

**Normalised jet cross sections**
- Increase as a function of $Q^2$ for a given $P_T$ interval
- $Q^2$ and $P_T$ are both important scales for inclusive jet production
**Trijet cross sections**

- ep -> 3jets
- Leading order $O(\alpha_s^2)$

Exemple for LO matrix element

- No NNLO predictions available yet

**Description by NLO**

- Data well described by NLO (nlojet++)
- Data precision mainly higher than scale uncertainties
- Similar trends than observed for dijets low scales: NLO undershoots data
  high $<P_T>$: NLO overshoots data

**Normalised trijets also measured**
Phenomenological application

PDF dependence of inclusive jet cross sections
- Cross sections as a function of $x_{PDF}$
- $P_T$-bins probe different $x$-regions
  - Lowest $x$-values: $x \sim 10^{-3}$
  - High-$P_T$ cross sections: $x > 10^{-1}$
- $x$-dependence shows little dependence on $Q^2$

H1 jets may become important for PDFs
- high-$x$ gluon
- only a single hadron involved (decorrelate high-$x$ $\rightarrow$ low-$x$)

Cross sections for $16 < Q^2 < 22 \text{ GeV}^2$
Determination of the strong coupling $\alpha_s(M_Z)$

**Determination of $\alpha_s(M_Z)$ in a fit to H1 HERA-II jets**
- Use low- and high-Q2 data
  - Low-Q2 jets [arxiv:1611.03421]
- Use all normalised jet cross sections
  - All correlations of uncertainties are known
- Fit $\alpha_s(M_Z)$ in $\chi^2$-minimization procedure

**Two results (NLO)**
- Probe running of $\alpha_s(\mu_r)$
- One fit to all data points together: $\alpha_s(M_Z)$

$$\alpha_s(M_Z) = 0.1173 \times (4)_{exp} \times (3)_{PDF} \times (7)_{PDF(\alpha_s)} \times (11)_{PDFset} \times (6)_{had} \times (^{+5}_{-4})_{scale}$$
- Very high experimental precision
- Future improvements on dominating theory uncertainties in NNLO

**World average (PDG2016)**
$$\alpha_s(M_Z) = 0.1181 \pm 0.0011$$
Strong coupling $\alpha_s(M_Z)$ in NNLO

**H1-prelim-17-031**
- See talk on tuesday morning

**NNLO predictions available for**
- Inclusive jets
- Dijets

**First extractions of strong coupling constant in NNLO precision**
- Excellent agreement of theory and data
- Data at lower values of $\mu_R$ have an increased sensitivity to $\alpha_s(M_Z)$

**Scale uncertainty in NNLO**
- reduction by approx. factor 2-3 compared to NLO
- Scale uncertainty remains dominant uncertainty
Conclusion

Last missing piece of H1 jet legacy

<table>
<thead>
<tr>
<th>Process</th>
<th>HERA-I</th>
<th>HERA-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low $Q^2$</td>
<td>Inclusive jet Dijet Trijet</td>
<td>EPJ C 67 (2010) 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>arXiv:1611.03421 acc. by EPJ C</td>
</tr>
<tr>
<td>High $Q^2$</td>
<td>Inclusive jet Dijet Trijet</td>
<td>EPJ C 65 (2010) 363</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EPJ C 75 (2015) 2</td>
</tr>
</tbody>
</table>

Probe running of $\alpha_s$ over one order of magnitude with H1 jet data
- Very high experimental precision on $\alpha_s(M_Z)$

Constrain PDFs with H1 jet data
- Very high sensitivity to gluon density

Outlook
- First extractions of $\alpha_s(M_Z)$ in NNLO on the way.

Finally we arrived: High-precision jet data together with NNLO predictions
PDF dependence

Study different (NNLO) PDF sets

- NNPDF3.0
- CT14
- MMHT
- HERAPDF2.0
- ABMP

- Technical remark: convolution with NLO matrix elements because NNLO matrix elements are too time-consuming to recalculate

Different PDFs

- Mosy studied NNLO PDF sets are quite consistent
- Different PDFs mainly covered by NNPDF30 PDF uncertainty
- only ABMP with difference (due to $\alpha_s(m_Z)$ ?)
Figure 6: Comparison of NLO predictions obtained with scale choices of $\mu_0^2 = \mu_R^2 = \frac{1}{2}(Q^2 + P_{T}^2)$, $\mu_0^2 = \mu_R^2 = P_{T}^2$, $\mu_0^2 = \mu_R^2 = Q^2$, and $\mu_0^2 = \mu_R^2 = \frac{1}{2}(Q^2 + P_{T}^2)$ with $\mu_0^2 = Q^2$ for selected $Q^2$ bins of the inclusive jet, dijet and trijet cross sections. The shaded area around the theory predictions indicates the scale uncertainty on the nominal scale choice of $\mu_0^2 = \mu_R^2 = \frac{1}{2}(Q^2 + P_{T}^2)$ as described in the text.
Figure 7: Matrix of statistical correlation coefficients of the unfolded cross sections. The bin labels are specified in table 5.
Normalised dijet cross sections in NC DIS as a function of $Q^2$ and $<p_T>^2$

- $<p_T>^2 = (P_{T_{\text{jet}1}} + P_{T_{\text{jet}2}})/2$
  - with: $P_{T_{\text{jet}}} > 4$ GeV

Comparison to NLO and NNLO predictions

- NLO give reasonable descriptions within large scale uncertainties (‘6-point’ variation)
- NNLO improves shape dependence
- NNLO slightly overshoots data
  - partially caused by normalisation w.r.t. NC DIS
- high-pT region difficult to describe
Inclusive jet cross sections

Double-differential inclusive jet cross sections as function of $Q^2$ and $p_T^{\text{jet}}$

Inclusive jets
• Count each jet in an NC DIS event
• Stat. uncertainty and correlations are measured
• Well described by NLO

Compared to H1 HERA-I
• Largely independent measurement
• HERA-II data with comparable precision
• Benefit from refined experimental methods
• Statistical uncertainty reduced for high $P_T$ and high $Q^2$
Inclusive jets production in NC DIS

'Normalised' jet cross sections
• H1prelim-16-062
• Normalise jet cross sections w.r.t. inclusive NC DIS cross section
  • Full/partial cancellation of uncertainties

New Data
HERA-II low-\(Q^2\)
HERA-II high-\(Q^2\), 5\(<\ p_T\ <7\)GeV
Inclusive jets for major part of HERA NC DIS phase space

New predictions
aNNLO from JetViP
• Approximate NNLO using threshold resummation
  \textit{PR D 92 (2015) 074037} \& work in progress
NNLO
• Full NNLO
  \textit{PRL 117 (2016) 042001} \& work in progress
See talk by J. Currie @ QCD@LHC2016
• Improved description of data by NNLO

DIS17, April 2017
Daniel Britzger – H1 Jets
Normalised Inclusive Jets

**Detailed ratio to NLO prediction**
- Data reasonably described by NLO theory, but NLO scale uncertainty large

**Normalisation w.r.t. NC DIS for predictions**
- NNLO & aNNLO predictions normalised with NC DIS predictions from APFEL using FONLL-C [V. Bertone et al.]
- NLO predictions normalised with ZM-VFNS using QCDNUM

**PDF:** NNPDF30 \( (n)nlo \_0118 \\
**Scale:** \( \mu_r = \mu_r = (Q^2 + P_{T}^2)/2 \)

**aNNLO**
- Improved data description at high-pT
- At low-pT aNNLO similar to NLO

**NNLO**
- Improved description of data by NNLO
- Significantly reduced scale uncertainty (particularly for higher scales)
Double-differential (normalised) Trijet cross sections as a function of $Q^2$ and $<p_T>_3$

- Precision limited by systematic uncertainties over whole kinematic range
- 4 x 8 data points
  - Excellent measurement of shape and dependence
- Dominated by: Jet energy scale and model uncertainty
- Data precision overshoots NLO precision
- NLO has similar problems in describing the shape at low-$Q^2$ as for dijet cross sections

No NNLO calculations available yet
History and Outlook

Last missing piece of H1 jet legacy

<table>
<thead>
<tr>
<th>Process</th>
<th>HERA-I</th>
<th>HERA-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low $Q^2$</td>
<td>Inclusive jet Dijet Trijet</td>
<td>EPJ C 67 (2010) 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Probe running of $\alpha_s$ over one order of magnitude with all H1 jet data
- Very high experimental precision on $\alpha_s(M_Z)$

Contrain PDFs with H1 jet data
- Very high sensitivity to gluon density
  Particularly at low $\mu_f$

HERA-I and HERA-II data can be used together for PDF fits

Finally we arrived: High-precision jet data and NNLO calculations
<table>
<thead>
<tr>
<th>Predictions</th>
<th>NLO</th>
<th>aNNLO</th>
<th>NNLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet cross sections</td>
<td>nlojet++</td>
<td>JetViP</td>
<td>NNLOJET</td>
</tr>
<tr>
<td>pQCD order</td>
<td>Dipole subtraction</td>
<td>NLO plus NNLO contributions from unified threshold resummation formalism</td>
<td></td>
</tr>
<tr>
<td>Calculation detail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC DIS cross sections</td>
<td>QCDNUM</td>
<td>APFEL</td>
<td>APFEL</td>
</tr>
<tr>
<td>Program</td>
<td>ZM-VFNS</td>
<td>FONLL-C</td>
<td>FONLL-C</td>
</tr>
<tr>
<td>Heavy quark scheme</td>
<td>NLO</td>
<td>NNLO</td>
<td>NNLO</td>
</tr>
<tr>
<td>Order</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDF</td>
<td>NNPDF3.0.NLO</td>
<td>NNPDF3.0.NNLO</td>
<td>NNPDF3.0.NNLO</td>
</tr>
<tr>
<td>$\alpha_s(M_Z)$</td>
<td>0.118</td>
<td>0.118</td>
<td>0.118</td>
</tr>
<tr>
<td>Hadronisation corrections</td>
<td>Django and Rapgap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Available for</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalised inclusive jet</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Normalised dijet</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Normalised trijet</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Summary of the theory predictions for the normalised jet cross sections. All predictions are corrected for hadronisation effects with multiplicative corrections factors obtained from Django and Rapgap.
The H1 experiment

**H1 multi-purpose detector**
- Asymmetric design
- Trackers
  - Silicon tracker
  - Jet chambers
  - Proportional chambers
- Calorimeters
  - Liquid Argon sampling calorimeter
  - SpaCal: scintillating fiber calorimeter
- Superconducting solenoid
  - 1.15T magnetic field
- Muon detectors

**Excellent control over experimental uncertainties**
- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet-calibration with neural networks as functions of $\eta$ and $p_T$
  - Jet energy scale: 1%
  - Luminosity: 2.5%
**The HERA ep collider**

**HERA ep collider in Hamburg**
- Data taking periods
  - HERA I: 1994 – 2000
  - HERA II: 2003 – 2007
- Special runs with reduced $E_p$ in 2007
- Delivered integrated luminosity $\sim 0.5$ fb$^{-1}$

**HERA-II period**
- Electron and positron runs
- $\sqrt{s} = 319$ GeV
- $E_e = 27.6$ GeV
- $E_p = 920$ GeV
- Analysed int. Luminosity: $L = 184$ pb$^{-1}$