Jet Production at Low Momentum Transfer at HERA

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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
\[
y = \frac{p \cdot q}{p \cdot k}
\]

**Factorisation in \( ep \) collisions**
Hard scattering coefficients and parton distribution functions (PDFs)
\[
\sigma_{ep \rightarrow eX} = \int_{p \rightarrow i} \hat{\sigma}_{ei \rightarrow eX}
\]

**Predictions in perturbative QCD**
Hard scattering is calculated perturbatively
PDFs have to be determined from experimental data (usage of DGLAP)
Jet production in $ep$ scattering

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

Jet measurement sensitive to $\alpha_s$ already at leading-order
- Boson-gluon fusion
- QCD compton

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
- 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$^{-1}$
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 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
- Matrix based unfolding method
- Consider an 'extended phase space' for accurate description of migrations into and out of 'measurement phase space'

Extended phase space for unfolding

<table>
<thead>
<tr>
<th>NC DIS</th>
<th>$Q^2 &gt; 3$ GeV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$y &gt; 0.08$</td>
</tr>
<tr>
<td>(inclusive) Jets</td>
<td>$P_T^{jet} &gt; 3$ GeV</td>
</tr>
<tr>
<td></td>
<td>$-1.5 &lt; \eta^{lab} &lt; 2.75$</td>
</tr>
<tr>
<td>Dijet and Trijet</td>
<td>$&lt;P_T^{jet}&gt; &gt; 3$ GeV</td>
</tr>
</tbody>
</table>

Phase space of cross sections

<table>
<thead>
<tr>
<th>NC DIS</th>
<th>$5 &lt; Q^2 &lt; 100$ GeV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.2 &lt; y &lt; 0.65$</td>
</tr>
<tr>
<td>(inclusive) Jets</td>
<td>$P_T^{jet} &gt; 5$ GeV</td>
</tr>
<tr>
<td></td>
<td>$-1.0 &lt; \eta^{lab} &lt; 2.5$</td>
</tr>
<tr>
<td>Dijet and Trijet</td>
<td>$M_{jj} &gt; 18$ GeV</td>
</tr>
<tr>
<td></td>
<td>$&lt;P_T^{jet}&gt; &gt; 5$ GeV</td>
</tr>
</tbody>
</table>
Control distributions

Acceptance of NC DIS events
- Scattered lepton is found in SpaCal
- Lepton energy $E_e > 11$ 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 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

**Monte Carlo predictions**
- MC simulations used for unfolding procedure
- Jet multiplicities and spectra not well modelled
  - Djangoh: $p_T^{\text{jet}}$ spectra too hard
  - Rapgap: Jet multiplicity underestimated
  - Both generators tend to have too few jets in forward direction
- -> MC generators are weighted to describe data
- Weighted MC predictions

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

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

Simultaneous unfolding of Inclusive jet, Dijet, Trijet, NC DIS
- Similar to EPJ C75 (2015) 2
  -> One measurement of multiple observables
- Matrix constituted from $O(10^6)$ entries
- Migrations in up to 6 variables considered for a single measurement
- 'detector-level-only' jets/events are constrained with NC DIS data
- System of linear equation becomes overconstrained when using more bins on detector than on generator level

\[
\chi^2(x, \tau) = (y - Ax)^T V_y^{-1} (y - Ax) + \tau L^2
\]
Data to theory comparisons

Data is compared to predictions based on next-to-leading order QCD calculations

NLO calculations
nlojet++ (Z. Nagy et al.) with NNPDF 3.0
- $ep \rightarrow 2 \text{jets}$ for inclusive jet and dijet
- $ep \rightarrow 3 \text{jets}$ for trijets
Scale choices
$$\mu_r^2 = \mu_f^2 = \frac{1}{2} \left(P_T^2 + Q^2\right)$$

Estimated uncertainty
- 6-point asymmetric scale variations
k-factors: $0.9 < \text{NLO/LO} < 3.8$

Hadronisation corrections to NLO predictions
Lund string model
- Average of correction factors from the two MC models
Multiplicative factors
- typically $0.88 - 0.95$
- up to 0.75 for trijets at low $<P_T>$

Corrections to data
Bin-wise correction factors for QED radiative effects
Dijet cross sections

Double-differential Dijet cross sections

\[ \langle P_T \rangle = \frac{P_{T,1} + P_{T,2}}{2} \]

High precision
- Exp. uncertainty dominated by jet energy scale and model uncertainty

Compared with NLO
- NLO gives reasonable description over full kinematic range
- Large k-factors may indicate relevant contributions beyond NLO
- Large uncertainties from scale variation

Data precision overshoots significantly theory precision
Inclusive jet cross sections

**Double-differential inclusive jet cross sections**

**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 jet**
- $H1$ HERA-II (prel.)
- Systematic uncertainty
- NLO ⊗ hadr. corr.
- $H1$ HERA-I
Double-differential Trijet cross sections

- Precision limited by systematic uncertainties over whole kinematic range
- dominated by: Jet energy scale and model uncertainty
- At low values of $Q^2$:
  Data precision significantly overshoots NLO precision

$$\langle P_T \rangle = \frac{P_{T,1} + P_{T,2}}{2}$$
Correlation matrix of multijets

**Covariance matrix**
- Correlations between all data points are measured
- Obtained through linear error propagation of statistical uncertainties

**Correlations**
- Resulting from unfolding
- Physical correlations
  - Between measurements
  - Within inclusive jet

**Useful for**
- Cross section ratios
- Combined fits
- Normalised cross sections
**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</td>
<td>This analysis</td>
</tr>
<tr>
<td></td>
<td>Dijet</td>
<td>H1prelim 16-061</td>
</tr>
<tr>
<td></td>
<td>Trijet</td>
<td></td>
</tr>
<tr>
<td>High $Q^2$</td>
<td>Inclusive jet</td>
<td>EPJ C 75</td>
</tr>
<tr>
<td></td>
<td>Dijet</td>
<td>(2015) 2</td>
</tr>
<tr>
<td></td>
<td>Trijet</td>
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**Probing running of $\alpha_s$ over one order of magnitude with all H1 jet data**

- Very high experimental precision on $\alpha_s(M_Z)$
  Expect experimental precision of ~5.5%
- Looking forward for theory developments
  - aNNLO for low-$Q^2$ regime
  - full NNLO predictions
    (Currie, Niehues, Gehrmann et al., see plenary on monday)
Summary

**New double-differential inclusive jet, dijet and trijet cross sections**
- New measurements of multijet cross sections at low $Q^2$ presented
- Large HERA-II dataset analysed
- High statistical and experimental precision
- Analysis uses final H1 data re-processing and precise calibration of the H1 detector
- Sophisticated unfolding allows simultaneous usage of all data in future fits
- Data well described by NLO predictions within large theoretical uncertainties

**Outlook**
- Data will be valuable input for $\alpha_s$ extractions
  - Use HERA-I and HERA-II, low- and high-$Q^2$ jet data
- Looking forward for confrontation with aNNLO and NNLO predictions