Jets and $\alpha_s$ Measurements at HERA

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Outline:

1. Jet Production at HERA and Technicalities
2. Inclusive Jets in Photoproduction
3. Inclusive Jets at Low $Q^2$
4. Inclusive- and Multi-Jets at High $Q^2$
5. Summary
Electron-Proton Collisions at HERA:
\[ \sqrt{s} = 318 \text{ GeV} \leftarrow \text{center of mass energy} \]

Kinematic Variables:

- \[ Q^2 = - (k - k')^2 \leftarrow \text{virtuality of exchanged boson} \]
- \[ x = \frac{Q^2}{p \cdot q} \leftarrow \text{Bjorken scaling variable} \]
- \[ y = \frac{Q^2}{s \cdot x} \leftarrow \text{inelasticity parameter} \]

\[ Q^2 = s \cdot x \cdot y \]
Jet Production at HERA

Kinematic Regimes:
1. photoproduction ($\gamma p$): $Q^2 \approx 0$ GeV$^2$
2. deep inelastic scattering (DIS): $Q^2 > 1$ GeV$^2$

Jet cross section in pQCD: Series expansion in powers of $\alpha_s$

$$\sigma_{\text{jet}} = \sum_m \alpha_s^m (\mu_R) \sum_{a=q, \bar{q}, g} f_{a/p} (x, \mu_F) \otimes \hat{\sigma}_{a,m} (x, \mu_R, \mu_F) (1 + \delta_{\text{had}}) \ldots$$

Coefficients are convolutions of:
- parton distribution functions (PDFs) $f_{a/p}$ (and of $\gamma$-PDF in case of $\gamma p$)
- hard scattering matrix element $\hat{\sigma}$

Measurement:
- test concept of pQCD, factorization, universality of strong coupling and PDFs
- using factorization, pQCD $\rightarrow$ extraction of $\alpha_s$, PDFs
The Breit Frame in DIS

the Breit frame is suitable for studying QCD with high $E_T$ jets

- exchanged boson space-like
- **struck quark in Born level has zero** $E_T$ (no QCD involved)
- directly sensitive to hard QCD processes → $E_T$ can be used for identification
- suppression of beam remnant jet

- **jets are reconstructed in the Breit frame** using the $k_\perp$ cluster algorithm
  → infrared and collinear safe
- data are corrected for detector, QED, electro-weak effects with MC models
- NLO predictions are corrected for parton shower and hadronisation effects


### ZEUS: Inclusive Jets in Photoproduction (1/2)

#### Previous Publication:
- data (98-00) with $82 \text{ pb}^{-1}$ luminosity
- $\alpha_s$ extracted from $\frac{d\sigma}{dE_T}$
  
  $$\alpha_s (M_Z) = 0.1224 \pm 0.0001 \text{ (stat.)}$$
  $$\pm 0.0022 \text{ (exp)}$$
  $$\pm 0.0054 \text{ (th)}$$

- theory error dominates (4.2%) over experimental error ($\approx 1.7\%$)

#### $\alpha_s$ from re-analysis (same data):
- theory:
  - $O(\alpha_s^2)$: Klasen, Kleinwort, Kramer
  - MRST2001 (previously: MRST99)
  - photon PDFs: GRV-HO
  - $\mu_R = \mu_F = E_T^{\text{jet}}$ for each jet
- new method for $\mu_R$ variation (Jones et al.)

- good data description by NLO prediction!
**ZEUS: Inclusive Jets in Photoproduction (2/2)**

**$\alpha_s$ Extraction:**

- pQCD calculations depend on $\alpha_s$ via the partonic cross section and the PDFs.
- NLO calculations using various sets of PDFs with different assumed $\alpha_s$ were performed.
- Parametrize $\alpha_s(M_Z)$ dependence of observable $d\sigma/dA$ in bin $i$ according to

$$\frac{d\sigma_i}{dA} = C_1 \cdot \alpha_s(M_Z) + C_2 \cdot \alpha_s^2(M_Z)$$

- Map measured $d\sigma/dA$ to x-axis and extract $\alpha_s(M_Z)$

\[\Rightarrow \text{complete $\alpha_s$ dependence of the calculations and the PDFs is preserved! (matrix elements and PDF evolution)}\]

- $\alpha_s(M_Z) = 0.1223 \pm 0.0001(\text{stat.})^{+0.0023}_{-0.0021}(\text{sys.}) \pm 0.0030(\text{th.})$

\[\Rightarrow \text{very precise $\alpha_s$ determination with 3.1% total error!}\]
**H1: Inclusive Jet Production at Low $Q^2$ (1/3)**

- **DIS at low $Q^2$:**
  - lots of statistic
  - electron in backward region
  - natural place to look first
- **but:** reliability of pQCD at NLO with decreasing $Q^2$ or $E_T$?

- used integrated luminosity: $44 \text{ pb}^{-1}$
- $5 < Q^2/\text{GeV}^2 < 100$
- $E_{T,\text{Breit}} > 5 \text{ GeV}$
- inclusive jet and dijet measurement

**Main Sources of Experimental Systematical Uncertainties:**

1. hadronic energy scale uncertainty
   - $\Delta \sigma / \sigma \approx 4 - 10\%$
2. acceptance correction uncertainty
   - $\Delta \sigma / \sigma \approx 2 - 15\%$
H1: Inclusive Jet Production at Low $Q^2$ (2/3)

- larger NLO errors compared to data uncertainties
- good data description by NLO predictions within errors!

\[ \frac{d^2 \sigma}{dQ^2 dE_T} \]

5 < $Q^2$ < 7 GeV$^2$

7 < $Q^2$ < 10 GeV$^2$

10 < $Q^2$ < 15 GeV$^2$

15 < $Q^2$ < 20 GeV$^2$

20 < $Q^2$ < 30 GeV$^2$

30 < $Q^2$ < 40 GeV$^2$

40 < $Q^2$ < 100 GeV$^2$

- H1 preliminary HERA-I

- NLO*$(1 + \delta_{\text{had}})$

\[ \mu_r^2 = (Q^2 + E_T^2)/4, \quad \mu_f^2 = Q^2 \]
Jets and $\alpha_s$ Measurements at HERA

H1: Inclusive Jet Production at Low $Q^2$ (3/3)

- NLO not very predictive at low $Q^2$ or $E_T$ because of low scales
- Renormalization scale uncertainty dominates and increases with decreasing $Q^2$ and at low $E_{T,\text{Breit}}$

→ Orders beyond NLO are needed in theoretical predictions!

$\alpha_s$ Extraction:
- Double differential inclusive jet cross sections
  $$\alpha_s(M_Z) = 0.1186 \pm 0.0014 \text{ (exp.)}$$
  $$+0.0132$$
  $$-0.0101 \text{ (theory)}$$
  $$\pm 0.0021 \text{ (PDF)}$$
- ≈ 1% exp. uncertainty, ≈ 10% theoretical error
ZEUS: Inclusive NC Jets at High $Q^2$ (1/4)

- Stringent tests of pQCD calculations at high $E_T$
- Data taken between 2004 - 2006 were used
- Integrated luminosity: $188 \text{ pb}^{-1}$

→ Shown is the single-differential inclusive jet NC cross section as a function of $Q^2 > 125 \text{ GeV}^2$

- Dijet cross sections: see Juan Terron's talk

- Good description of data by NLO QCD over many orders of magnitude (for both $\mu_R = E_{T,B}$ and $Q$)
- Smaller theoretical uncertainty than dijets, but still dominates over experimental except at high $Q^2$

Main Sources of Exp. Sys. Uncertainties:

1. Hadronic energy scale uncertainty
   \[ \frac{\Delta \sigma}{\sigma} \approx 5\% \]

2. Model dependence of acceptance correction
   \[ \frac{\Delta \sigma}{\sigma} \approx 3\% \]
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Jets and $\alpha_s$ Measurements at HERA

ZEUS: Inclusive NC Jets at High $Q^2$ (2/4)

- $\mu_R$ uncertainty dominates except at high $E_{T,B}$ where the PDF uncertainty is dominant ⇒ potential to further constrain the gluon density in the proton
ZEUS: Inclusive NC Jets at High $Q^2$ (3/4)

- inclusive jet cross section as a function of $\eta_{\text{Breit}}$
- $\frac{d\sigma}{d\eta}$ shape is dictated by kinematic constraints
- good agreement between data and NLO for $\frac{d\sigma}{d\eta}$

**Diagram:**
- ZEUS (prel.) 188.3 pb$^{-1}$
- $E_{T,B} > 8$ GeV
- $Q^2 > 125$ GeV$^2$
- $|\cos \gamma_h| < 0.65$
- jet energy scale uncertainty
- theoretical uncertainty

**Graph:**
- $d\sigma/d\eta_{\text{B}}$ (pb)
- rel. diff. to NLO
- $\eta_{\text{B}}$
- $\sigma_{\text{jet}}$
- ZEUS (prel.) 188.3 pb$^{-1}$
- $E_{T,B} > 8$ GeV
- $Q^2 > 125$ GeV$^2$
- $|\cos \gamma_h| < 0.65$
\( \alpha_s \) Extraction:

- extracted from \( \frac{d\sigma}{dQ^2} \) for \( Q^2 > 500 \text{ GeV}^2 \) ⇒ yields smaller total \( \alpha_s \) error
- experimental uncertainties:
  → largest contribution due to jet energy scale uncertainty (±1.9%)
- theoretical uncertainties:
  → dominated by terms beyond NLO (±1.8%)
  → PDF (±0.8%)
  → hadronisation corrections (±0.8%)

\[ \alpha_s (M_Z) = 0.1192 \pm 0.0009 \text{(stat.)}^{+0.0035}_{-0.0032} \text{(exp.)}^{+0.0020}_{-0.0021} \text{(th.)} \]

⇒ precise measurement with a total error of about 3.5%!
data sample with $395 \text{ pb}^{-1}$ luminosity

- $150 < Q^2 / \text{GeV}^2 < 15000$
- single inclusive, 2- and 3-jet cross sections were measured
- normalization to the inclusive neutral current DIS scattering cross section
  - luminosity uncertainty cancels and energy scale uncertainty reduces in normalized cross sections
- data are well described by NLO predictions!
Dijet Production:

- momentum fraction carried by the interacting parton:
  \[ \xi = x_{Bj} \cdot \left(1 + \frac{M_{12}^2}{Q^2}\right) \]

- normalised dijet cross sections as a function of \( \xi \) in several regions of \( Q^2 \)

- NLO predictions provide a good description of the data over the whole used phase space

- theory error is significantly larger than experimental errors in almost all bins
  \[ \mu_R \] uncertainty is largest theory error
  \[ \text{jet energy scale uncertainty dominates experimental uncertainty} \]
Extraction of $\alpha_s$

- QCD predictions were fitted using a $\chi^2$ method
  - parameters representing systematic shifts of detector observables are left free in the fit (Hessian method)
- values of $\alpha_s$ were extracted by fitting the individual normalized inclusive, 2-jet, 3-jet cross sections and their combination

Combined value:

$$\alpha_s (M_Z) = 0.1168 \pm 0.0007 \text{ (exp.)}$$
$$+0.0046 \text{ (th.)}$$
$$-0.0030 \pm 0.0016 \text{ (PDF)}$$

Fit quality: $\chi^2/\text{ndf} = 65/53$

Observed running agrees with QCD expectation!
Summary of $\alpha_s$ Extractions

- extracted $\alpha_s$ values are consistent with the world average!
- precision is comparable to the values obtained from $e^+e^-$ interactions
- HERA competitive!
- different measurements and environments and processes are consistent

$\leftrightarrow$ great success of QCD!!

- experimental
- theoretical uncertainty

$\alpha_s(M_Z)$

- ZEUS: Jets in $\gamma p$ (2008)
- ZEUS: Jets in $\gamma p$ (2003)
- H1: Jets at low $Q^2$ (2008)
- H1: Multi-Jets at high $Q^2$ (2009)
- ZEUS: Jets at high $Q^2$ (2009)
- $e^+e^-$ four-jet rates
- world average (S. Bethke 2006)
Summary

Measurements of jet production at HERA allow detailed tests of QCD dynamics.

- the strong coupling $\alpha_s$ was extracted using ...
  - inclusive jets in photoproduction
  - inclusive jets at low $Q^2$
  - inclusive and multi-jets cross sections at high $Q^2$.

Conclusion:

- pQCD calculations describe the data over a wide range of phase space
- theoretical errors are often much larger than experimental uncertainties
- $\alpha_s$ extractions at HERA are competitive!