Jet Production at HERA with ZEUS

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Outline:
1. Jet Production at HERA
2. Inclusive Jets and Dijets in Photoproduction
3. Inclusive Jets and Dijets in Deep-Inelastic Scattering
4. Extraction of the Strong Coupling $\alpha_s$
5. Summary
Jets at HERA: Deep-Inelastic Scattering

\[ \text{deep inelastic scattering (DIS)} \rightarrow Q^2 > \Lambda_{\text{QCD}}^2 \]

**Kinematics:**
- centre-of-mass energy: \( \sqrt{s} = 318 \ \text{GeV} \)
- momentum transfer: \( Q^2 = -q^2 = -(k - k')^2 \)
- Bjorken \( x \): \( x = \frac{Q^2}{2p \cdot q} \)
- inelasticity: \( y = \frac{Q^2}{s \cdot x} \)

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

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

**Coefficients are convolutions of:**
- parton distribution functions (PDFs): \( f_{a/p} \leftarrow \) long-distance structure (proton)
- lepton-parton cross section: \( \hat{\sigma} \leftarrow \) short-distance structure of the interaction
Photoproduction \((\gamma p) \rightarrow Q^2 \approx 0 \text{ GeV}^2\)

In lowest order two types of processes:

1. Direct process: photon interacts directly with parton
2. Resolved process: photon acts as source of partons

- Final state closer to that encountered in hadron-hadron collisions

Jet cross section in pQCD incorporates photon structure function

Observables (used in this talk):

- Momentum fraction carried by gluon: \(\xi = x_{Bj} \left( 1 + \frac{M_{jj}^2}{Q^2} \right)\)
- CMS scattering angle: \(\theta^*\)
- Transverse energy and invariant mass: \(E^\text{jet}_T, M_{jj}\)
- Pseudorapidity: \(\eta^\text{jet}_{\text{lab}}\)
• at least one jet with in the range 
  \(-1 < \eta^{\text{jet}} < 2.5\) with \(E_T^{\text{jet}} > 17\) GeV

**Experimental Uncertainties:**

• uncorrelated: mostly \(< 4\%\)

• correlated (jet energy scale):
  • uncertainty \(\pm 1\%\)
  • \(\approx \pm 5 - 10\%\) effect on cross section

**Theoretical Uncertainties:**

• higher orders: \(< \pm 10 (\pm 7)\%\) at low (high) \(E_T^{\text{jet}}\)

• \(\gamma\) PDFs: \(-10 (\pm 2)\%\) at low (high) \(E_T^{\text{jet}}\)

• proton PDFs: \(\pm 1 (5)\%\) at low (high) \(E_T^{\text{jet}}\)

• hadronisation: mostly \(< 2.5\%\)

• \(\alpha_s (M_Z)\): typically \(< \pm 3.7\%\)

⇒ Good description of data by NLO calculations

Measurement suited for \(\alpha_s (M_Z)\) extraction with small uncertainties
proton PDFs ZEUS-S and MSTW08 provide roughly similar predictions

- non-perturbative effects or the $\gamma$ PDFs at high $\eta^{\text{jet}}$ could cause observed discrepancy between data and the theory
  - $\gamma$ PDFs: predictions for AFG04 and CJK significantly differ from GRV-HO
  - contributions from non-perturbative effects significantly depend on $\eta^{\text{jet}}$
  - after increasing the $E_T^{\text{jet}}$ cut the theory agrees with the data
CMS Scattering Angle:

- $\theta^* \rightarrow \cos \theta^* = \tanh \frac{\eta_1 - \eta_2}{2}$

QCD Dynamics:

- study underlying dynamics by measuring differentially in $M^{jj}$ and $\theta^*$
- expectation from QCD: different shape of $d\sigma/d|\cos \theta^*|$ for resolved and direct processes due to different nature of propagator

→ good description of data by NLO predictions at $O(\alpha_s^2)$
→ concept of resolved photons holds
Dijets in DIS at High $Q^2$ (1/2)

- jets produced in the boson-gluon-fusion process are sensitive to the gluon density
- gluon fractional contribution:
  - $125 < Q^2 < 500$ GeV$^2$: $> 60\%$
  - $500 < Q^2 < 2000$ GeV$^2$: $> 40\%$
- PDFs depend on $\xi$ and $\mu_F^2 = Q^2$
- possibility to constrain gluon PDF with dijet measurement:
  - at least two jets with $E_{T,B}^{\text{jet}} > 8$ GeV and $-1 < \eta_{\text{lab}} < 2.5$
  - $M_{jj} > 20$ GeV

![Graph showing dijet production at HERA with ZEUS]
Dijets in DIS at High $Q^2$ (2/2)

Experimental Uncertainties:
- uncorrelated: $\pm 2 \pm 6\%$ at low (high) $Q^2$
- correlated: $\approx 5 \pm 3\%$ at low (high) $Q^2$

Theoretical Uncertainties:
- missing higher orders: $\approx 3 - 6\%$
- PDF: $\approx 4\%$
  $\rightarrow$ in some regions larger than $\mu_R$ uncertainty
- $\alpha_s(M_Z)$: $< 3\%$
- hadronisation: $\approx 2\%$
- choice of $\mu_F$: negligible

Dijet cross sections have potential to constrain PDFs in global QCD fits!
Inclusive Jets at High $Q^2$

- at least one jet with $E_{T,B}^{\text{jet}} > 8$ GeV and $-2 < \eta_B < 1.5$

Experimental Uncertainties:
- uncorrelated: $\pm 3\,(7)\%$ at low (high) $Q^2$
- correlated: $\approx 5\,(2)\%$ at low (high) $Q^2$

Theory Uncertainties:
- dominated by choice of $\mu_R$ ($\approx \pm 5\%$) and PDF (typically < 3%)}

• NLO pQCD describes the data very well in the whole measured range

→ Due to small uncertainties $\alpha_s$ can be extracted with high precision
Extraction of $\alpha_s(M_Z)$

Inclusive Jets in NC DIS phase space:

- $Q^2 > 500$ GeV yields 21 $< E_T < 71$ GeV smaller $\alpha_s$ uncertainty
- Theoretical uncertainty dominated by terms beyond NLO: $\pm 1.5\%$
- Experimental uncertainty ruled by jet energy scale: $\pm 1.9\%$

NC DIS:

$$\alpha_s(M_Z) = 0.1208^{+0.0037}_{-0.0032} \text{(exp.)} \pm 0.0022 \text{(th.)}$$

$\rightarrow$ total uncertainty: $\pm 3.5\%$

PHP:

$$\alpha_s(M_Z) = 0.1206^{+0.0023}_{-0.0022} \text{(exp.)}^{+0.0042}_{-0.0033} \text{(th.)}$$

$\rightarrow$ total uncertainty: $\pm 4.0\%$

- World average (2009):
  $$\alpha_s(M_Z) = 0.1184 \pm 0.0007$$

- Predicted running of $\alpha_s$ agrees very well with the data
Jet Algorithms

- Study of pQCD with jets require infrared- and collinear safe jet algorithms
- Cross check of the influence of the choice of jet algorithms ($k_T$, anti-$k_T$ and SIScone)
- Differences of jet cross sections between these jet algorithms can be calculated with NLOJet++ up to $O(\alpha_s^3)$

⇒ QCD calculations with up to four final state partons agree very well with the data
⇒ Algorithms can be used in hadron-hadron collisions (e.g. LHC) with theoretically reliable performance
Summary

Measurement of jet production allow detailed tests of QCD dynamics!

- Recently, at ZEUS stringent tests of pQCD were performed using...
  - inclusive jets and dijets in photoproduction
  - inclusive jets and dijets in deep-inelastic scattering

- The strong coupling constant $\alpha_s$ was extracted from
  - inclusive jets in photoproduction and deep-inelastic scattering

Conclusion:

- pQCD calculations describe the data over a wide range of phase space!
- theoretical uncertainties are often larger than experimental uncertainties.
- $\alpha_s$ extractions are competitive!
Backup
Technicalities:

• jet search performed with the $k_T$ cluster algorithm in . . .
  1 DIS: . . . in boson-quark collinear frame (Breit frame).
    ↝ directly sensitive to hard QCD processes, $E_T$ can be used for identification
  2 Photoproduction: . . . laboratory frame.

• data are corrected for detector and higher-order QED effects
• theory is corrected with LO MC $\otimes$ parton shower $\otimes$ hadronisation model $\otimes$
  electro-weak effects
Extraction of $\alpha_s(M_Z)$

**$\alpha_s$ 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 $\alpha_s(M_Z)$

$\Rightarrow$ complete $\alpha_s$ dependence of the calculations and the PDFs is preserved! (matrix elements and PDF evolution)
Jet Algorithms

\[ \frac{d\sigma_{\text{SIScone}}}{d\sigma_{kT}} = 1 + \frac{d\sigma_{\text{anti-}k_T}}{d\sigma_{kT}} \]

\[ = \frac{d\sigma_{\text{SIScone}}/dX - d\sigma_{kT}/dX}{d\sigma_{kT}/dX} = 1 + \frac{E_2 \cdot \alpha_s^2 + E_3 \cdot \alpha_s^3}{A_1 \cdot \alpha_s + A_2 \cdot \alpha_s^2} \]

\[ \frac{d\sigma_{\text{anti-}k_T}}{d\sigma_{kT}} = 1 + \frac{d\sigma_{\text{anti-}k_T}/dX - d\sigma_{kT}/dX}{d\sigma_{kT}/dX} = 1 + \frac{F_3 \cdot \alpha_s^3}{A_1 \cdot \alpha_s + A_2 \cdot \alpha_s^2} \]