Jets and α_s Measurements at HERA

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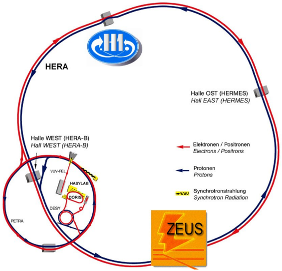
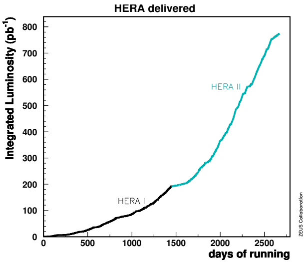
Outline:

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

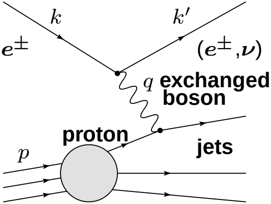
HERA





Electron-Proton Collisions at HERA:

$\sqrt{s} = 318$ GeV $\leftarrow$ center of mass energy



Kinematic Variables:

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

$$Q^2 = s \cdot x \cdot y$$

Jet Production at HERA

Kinematic Regimes:

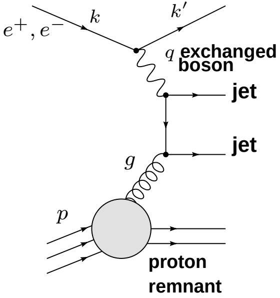
1. photoproduction (γ**p**): $Q^2 \approx 0\ \mathrm{GeV}^2$
2. deep inelastic scattering (**DIS**): $Q^2 > 1\ \mathrm{GeV}^2$

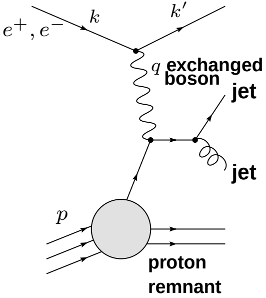
Jet cross section in pQCD: Series expansion in powers of α_s

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

Coefficients are convolutions of:

- parton distribution functions (PDFs) $f_{a/p}$ (and of γ-PDF in case of γp)
- hard scattering matrix element $\hat{\sigma}$





Measurement:

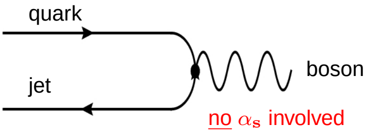
- test concept of pQCD, factorization, universality of strong coupling and PDFs
- using factorization, pQCD $\rightarrow$ extraction of α_s, PDFs

Technicalities

The Breit Frame in DIS

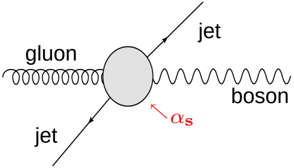
the Breit frame is suitable for studying QCD with high E_T jets

- exchanged boson space-like
- **struck quark in Born level has zero $\mathbf{E_T}$** (no QCD involved)
- directly sensitive to hard QCD processes $\rightarrow$ 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

  $\rightarrow$ 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:

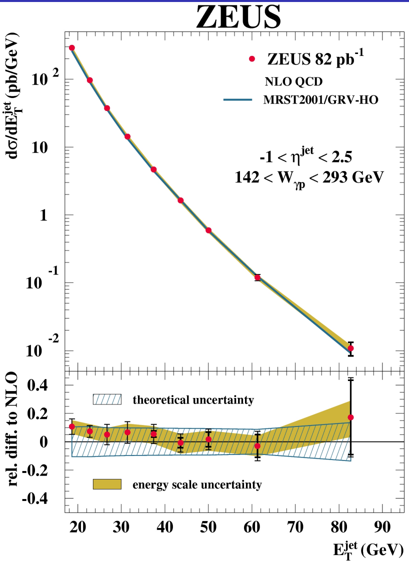
- data (98-00) with $82\ \mathrm{pb}^{-1}$ luminosity
- α_s extracted from $\frac{d\sigma}{dE_T}$

$$\rightarrow \quad \alpha_s(M_Z) = 0.1224 \quad \pm 0.0001\ \text{(stat.)} \quad {}^{+0.0022}_{-0.0019}\ \text{(exp)} \quad {}^{+0.0054}_{-0.0043}\ \text{(th)}$$

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

α_s from re-analysis (same data):

- **theory:**
  - $\rightarrow$ $O(\alpha_s^2)$: Klasen, Kleinwort, Kramer
  - $\rightarrow$ MRST2001 (previously: MRST99)
  - $\rightarrow$ photon PDFs: GRV-HO
  - $\rightarrow$ $\mu_R = \mu_F = E_T^{\mathrm{jet}}$ for each jet
- **new method for μ_R variation** (Jones et al.)



- **good data description by NLO prediction!**

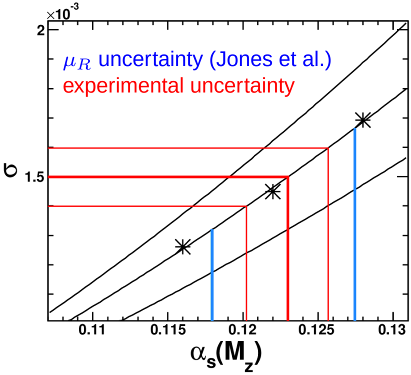
ZEUS: Inclusive Jets in Photoproduction (2/2)

α_s Extraction:

- pQCD calculations depend on α_s via the partonic cross section and the PDFs
- NLO calculations using various sets of PDFs with different assumed α_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 $\alpha_s(M_Z)$



⇒ complete α_s dependence of the calculations and the PDFs is preserved! (matrix elements and PDF evolution)

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

⇒ **very precise α_s determination with 3.1% total error!**

H1: Inclusive Jet Production at Low Q^2 (1/3)

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

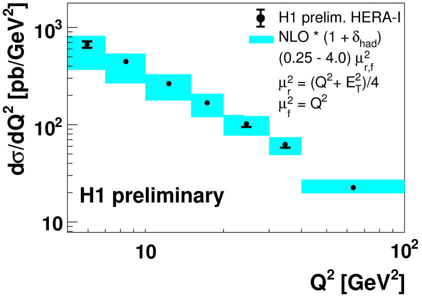
- used integrated luminosity: $44\ \mathrm{pb}^{-1}$
- $5 < Q^2/\mathrm{GeV}^2 < 100$
- $E_{T,\mathrm{Breit}}^{\mathrm{jet}} > 5\ \mathrm{GeV}$
- inclusive jet and dijet measurement

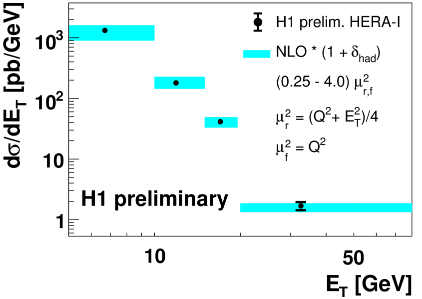
Main Sources of Experimental Systematical Uncertainties:

1. hadronic energy scale uncertainty

   $\rightarrow \frac{\Delta\sigma}{\sigma} \approx 4 - 10\%$
2. acceptance correction uncertainty

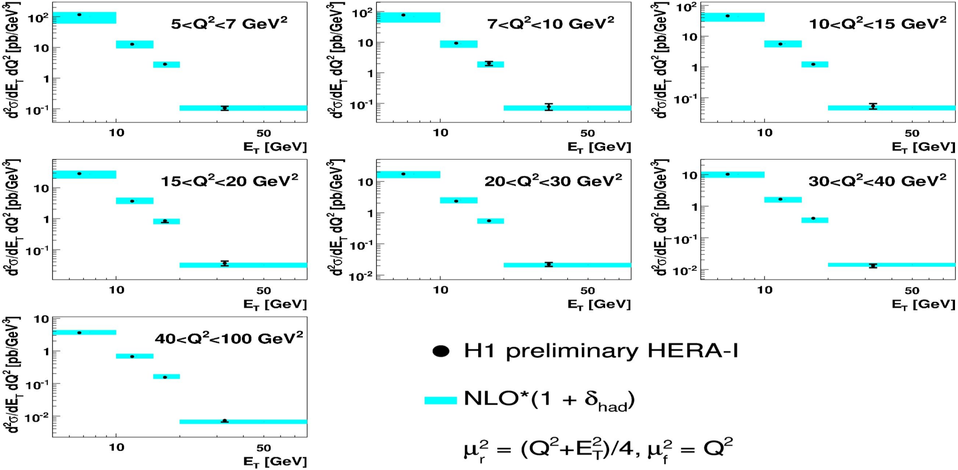
   $\rightarrow \frac{\Delta\sigma}{\sigma} \approx 2 - 15\%$





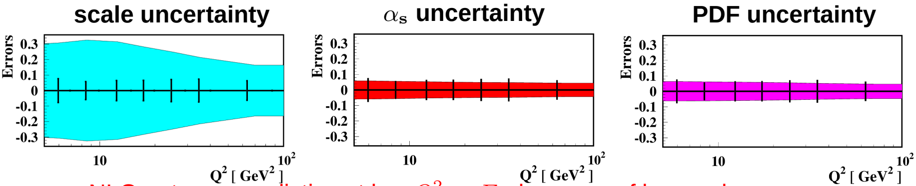
H1: Inclusive Jet Production at Low Q^2 (2/3)

$$\frac{d^2\sigma}{dQ^2 dE_T}$$



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

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 $E_{T,\mathrm{Breit}}^{\mathrm{jet}}$

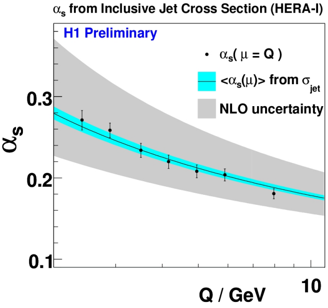
$\longrightarrow$ **orders beyond NLO are needed in theoretical predictions!**

α_s Extraction:

- double differential inclusive jet cross sections

$$\Rightarrow \quad \alpha_s(M_Z) = 0.1186 \quad \pm 0.0014 \text{ (exp.)} \quad {}^{+0.0132}_{-0.0101} \text{ (theory)} \quad \pm 0.0021 \text{ (PDF)}$$

- **$\approx 1\%$ exp. uncertainty, $\approx 10\%$ theoretical error**

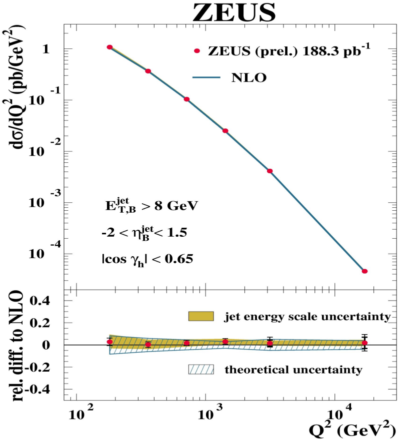


ZEUS: Inclusive NC Jets at High Q^2 (1/4)

- **stringent tests of pQCD calculations at high E_T**
- data taken between 2004 - 2006 were used
- integrated luminosity: $188\ \mathrm{pb}^{-1}$

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

- *dijet cross sections: see Juan Terron's talk*

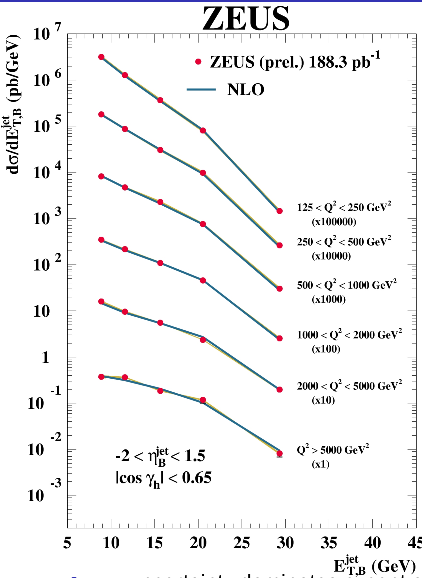


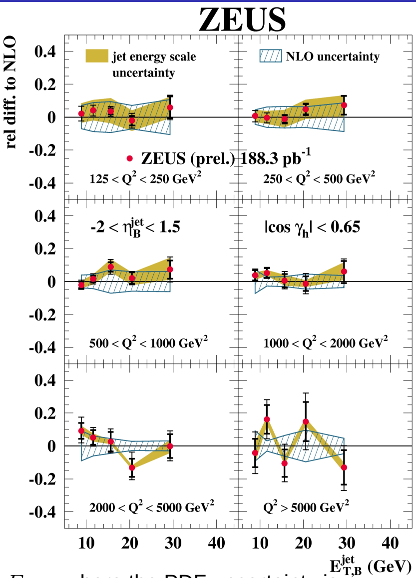
- **good description** of data by NLO QCD over many orders of magnitude (for both $\mu_R = E_{T,B}$ and Q)
- smaller **theoretical uncertainty** than dijets, but still **dominates** over experimental except at high Q^2

Main Sources of Exp. Sys. Uncertainties:

1. hadronic energy scale uncertainty
   → $\frac{\Delta\sigma}{\sigma} \approx 5\%$
2. model dependence of acceptance correction
   → $\frac{\Delta\sigma}{\sigma} \approx 3\%$

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

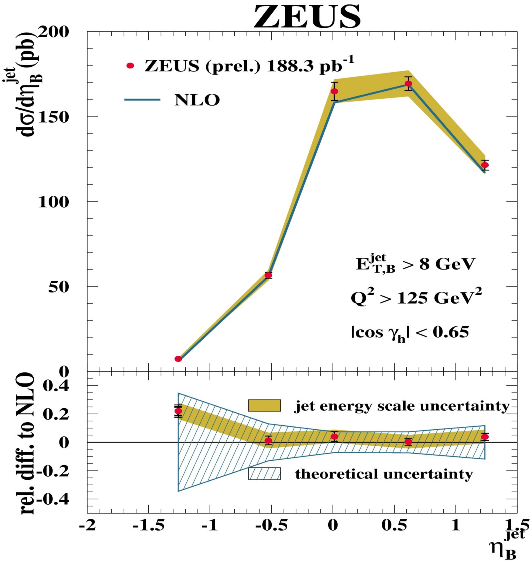




- μ_R uncertainty dominates except at high $E_{T,B}$ where the PDF uncertainty is dominant $\Rightarrow$ **potential to further constrain the gluon density in the proton**

ZEUS: Inclusive NC Jets at High Q^2 (3/4)

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



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

α_s Extraction:

- extracted from $\frac{d\sigma}{dQ^2}$ for $Q^2 > 500\ \mathrm{GeV}^2$ $\Rightarrow$ yields smaller total α_s error
- **experimental uncertainties:**

  $\longrightarrow$ largest contribution due to jet energy scale uncertainty ($\pm\mathbf{1.9}\%$)
- **theoretical uncertainties:**

  $\longrightarrow$ dominated by terms beyond NLO ($\pm\mathbf{1.8}\%$)
  $\longrightarrow$ PDF ($\pm\mathbf{0.8}\%$)
  $\longrightarrow$ hadronisation corrections ($\pm\mathbf{0.8}\%$)

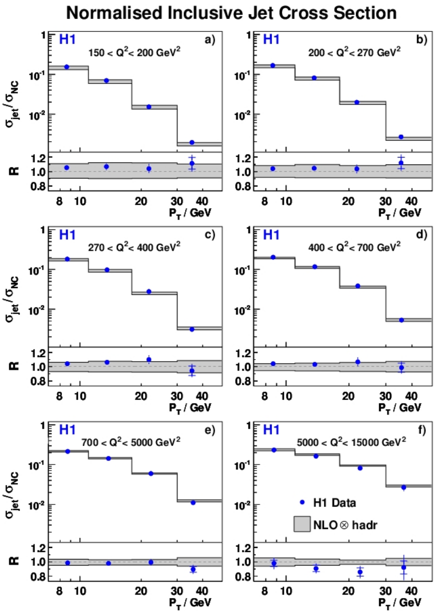
$$\alpha_s(M_Z) = 0.1192 \pm 0.0009(\mathrm{stat.})^{+0.0035}_{-0.0032}(\mathrm{exp.})^{+0.0020}_{-0.0021}(\mathrm{th.})$$

$\Rightarrow$ **precise measurement with a total error of about $\mathbf{3.5}\%$!**

H1: Inclusive and Multi-Jet Production at High Q^2 (1/2)

data sample with 395 pb^{-1} luminosity

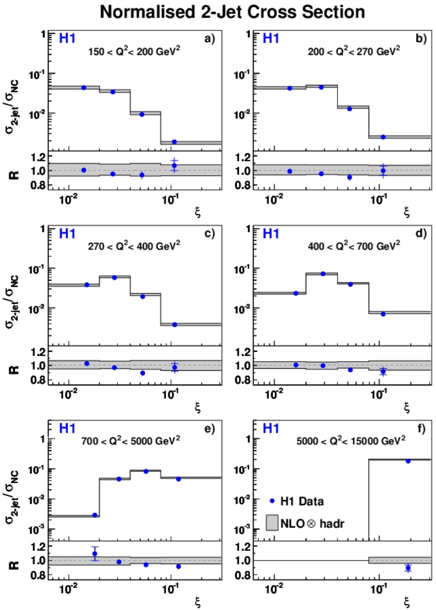
- $150 < Q^2/\text{GeV}^2 < 15000$
- single inclusive, 2- and 3-jet cross sections were measured
- normalization to the inclusive neutral current DIS scattering cross section
  - ↪ luminosity uncertainty cancels and energy scale uncertainty reduces in normalized cross sections
- **data are well described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



H1: Inclusive and Multi-Jet Production at High Q^2 (2/3)

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 ξ 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
  - $\rightarrow$ μ_R uncertainty is largest theory error
  - $\rightarrow$ jet energy scale uncertainty dominates experimental uncertainty



H1: Inclusive and Multi-Jet Production at High Q^2 (3/3)

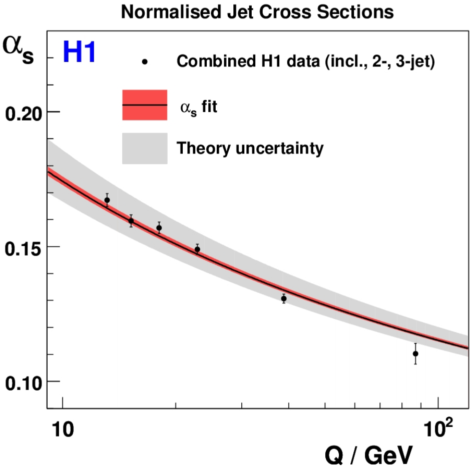
Extraction of α_s

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

Combined value:

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

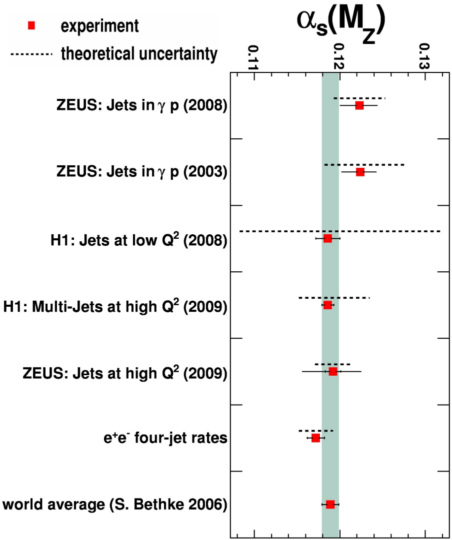
Fit quality: $\chi^2/\mathrm{ndf} = 65/53$



Observed running agrees with QCD expectation!

Summary of α_s Extractions

- **extracted α_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
  - $\hookrightarrow$ **great success of QCD!!**



Summary

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

- the strong coupling α_s was extracted using ...
  - $\longrightarrow$ inclusive jets in photoproduction
  - $\longrightarrow$ inclusive jets at low Q^2
  - $\longrightarrow$ 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
- α_s extractions at HERA are competitive!