

Jets and α_s Measurements at HERA

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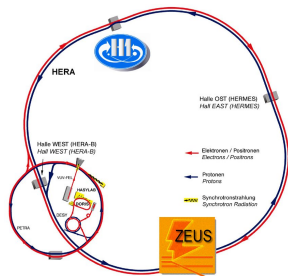
On Behalf of the H1 and ZEUS Collaborations
QCD '08 Conference
Montpellier, July 2008



Outline:

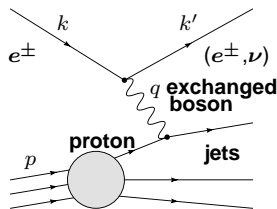
- 1 DIS and Jet Production at HERA
- 2 Test General Aspects of pQCD: Low Q^2
- 3 Firm Grounds: High Q^2
- 4 What Can We Learn From It?
- 5 Summary

Deep Inelastic Scattering (DIS) at HERA



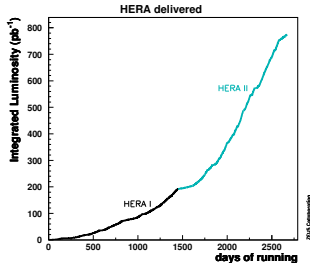
Electron-Proton Collisions at HERA:

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



Kinematic Variables:

- $Q^2 = -(k - k')^2 \leftarrow$ Virtuality of exchanged boson
- $x = \frac{Q^2}{p \cdot q} \leftarrow$ in lowest order: fraction of proton momentum carried by struck parton
- $y = \frac{Q^2}{s \cdot x} \leftarrow$ In-elasticity parameter



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

Jet Production in DIS at HERA

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

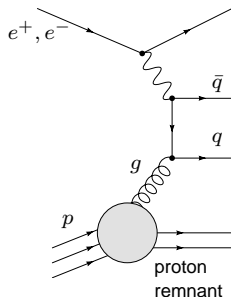
$$\sigma_{\text{jet}} = \sum_m \alpha_s^m(\mu_R) \sum_{a=q, \bar{q}, g} f_{a/p}(x, \mu_F) \otimes \hat{\sigma}_{a,m}(x, \mu_R, \mu_F) (1 + \delta_{\text{had}}) \dots$$

Coefficients are **convolutions** of:

- Parton-Distribution-Functions (PDFs)
 $f_{a/p}$
- hard scattering matrix element $\hat{\sigma}$

Measurement:

- Test concept of pQCD, factorization, universality of strong coupling and PDFs
- Assume factorization, pQCD \rightarrow extraction of α_s , PDFs
- Access to non-perturbative effects like multiple interactions and underlying event?

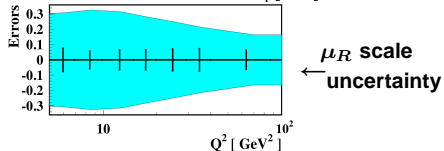
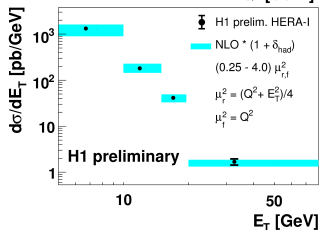
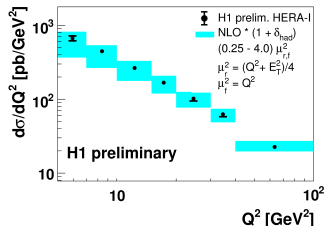


Technicalities:

- Breit frame: boson-quark collinear frame. p_T from QCD effects
- Jets are reconstructed using k_{\perp} cluster algorithm on cells or energy flow objects
 - infrared, collinear safe

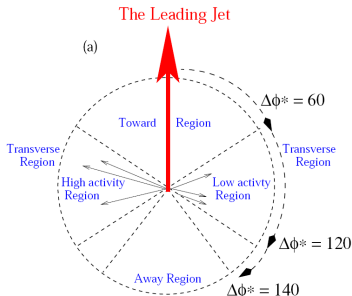
H1: Inclusive Jet Production at Low Q^2

- 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 pb^{-1}
- $5 < Q^2/\text{GeV}^2 < 100$
- $E_{T,\text{Breit}}^{\text{jet}} > 5 \text{ GeV}$
- 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 $E_{T,\text{Breit}}^{\text{jet}}$
- **orders beyond NLO are needed in theoretical predictions!**



H1: NC DIS Minijet Production

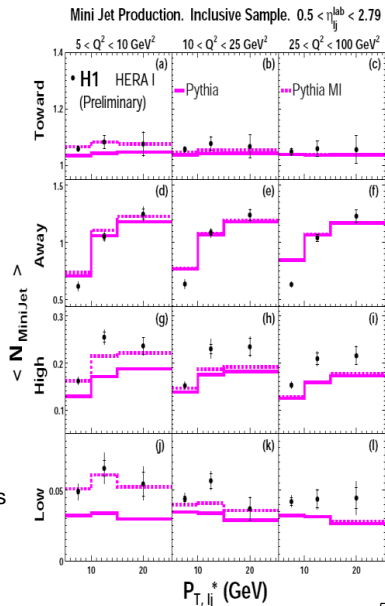
- **multiple interactions** in DIS?
- investigation of hadronic activity in regions transverse to leading jet in HCM frame



- **leading jet:**
 $P_T^{jet} > 5 \text{ GeV}$
- **Minijet:**
 $P_T^{jet} > 3 \text{ GeV}$

Conclusion:

- addition of MI to MC improves data description at low Q^2
- MC behavior: contribution from resolved photon events increases with decreasing Q^2
 - higher contributions from MI
- even at high Q^2 not everything understood

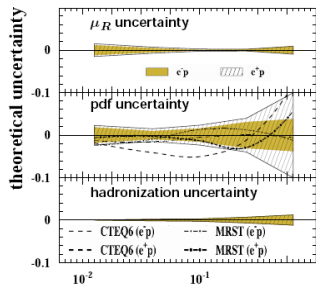
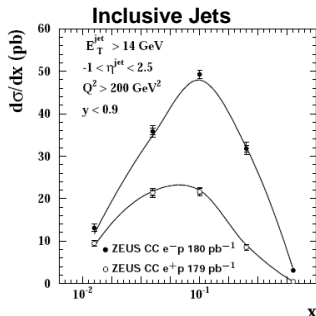


ZEUS: Charged Current Multijets

- Measurement uses 359 pb^{-1} polarized $e^\pm p$ data
- $Q^2 > 200 \text{ GeV}^2$
- $E_T^{\text{jet}1(2,3)} > 14(5) \text{ GeV}$ in lab frame

Conclusion:

- good agreement between theory (*MEPJET*) and measurement over a wide range of phase space (problems for dijet cross sections)
- uncertainty coming from the PDFs is dominant
- e^- and e^+ beams probe different flavor content of the proton, because $W^{-(+)}$ boson couples primarily to $u(d)$ quarks
- uncertainty in d parton density is larger than that for u quarks
- measurement has the potential to constrain the flavor content of the proton at high x



ZEUS: Inclusive-Jet Cross Sections in DIS at High Q^2

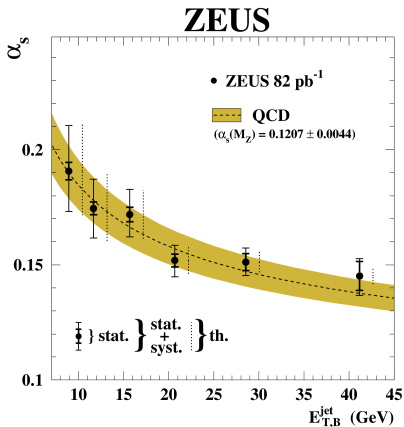
Extraction of α_s :

- minimized theoretical and experimental systematic uncertainties: $Q^2 > 500 \text{ GeV}^2$

$$\alpha_s(M_Z) = 0.1207 \quad \begin{array}{l} \pm 0.0014 \text{ (stat.)} \\ +0.0035 \text{ (exp.)} \\ -0.0033 \text{ (exp.)} \\ +0.0022 \text{ (th.)} \\ -0.0023 \text{ (th.)} \end{array}$$

Main Sources of Uncertainty

- jet energy scale: 2%
- hadronisation: 0.8%
- terms beyond NLO: 1.5%
- uncertainty due to choice of PDF: 1%



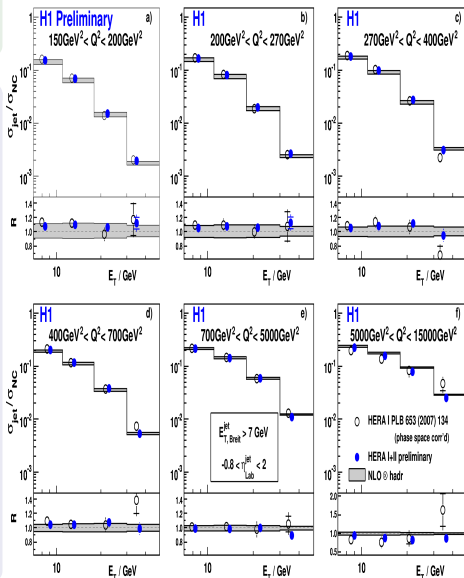
Demonstration of running coupling

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

combined data sample of HERA I and
HERA II $\rightarrow 395 \text{ pb}^{-1}$ luminosity

- $150 < Q^2 / \text{GeV}^2 < 15000$
- $7 < E_T^{\text{Breit}} / \text{GeV} < 50$
- $M_{12} > 16 \text{ GeV}$ for 2- and 3-jet events
- single inclusive, 2- and 3-jet cross sections were measured
- normalization to the inclusive neutral current deep-inelastic scattering cross section
 - \rightarrow luminosity uncertainty cancels and scale uncertainty reduces in normalized cross sections
- data are well described by NLO

Normalised Inclusive Jet Cross Section



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

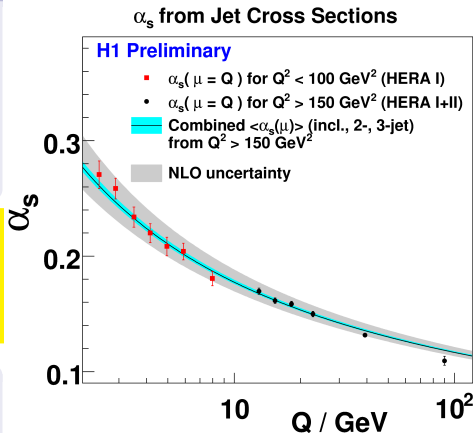
Extraction of α_s

- QCD predictions were fitted using a χ^2 method
- values of α_s were extracted by fitting the individual normalized inclusive, 2-jet, 3-jet cross sections and their combination

Combined value:

$$\alpha_s(M_Z) = 0.1182 \quad \begin{array}{l} \pm 0.0008 \text{ (exp.)} \\ +0.0041 \\ -0.0031 \text{ (scale)} \\ \pm 0.0018 \text{ (PDF)} \end{array}$$

- Fit quality: $\chi^2/\text{ndf} = 55.8/53$
- Observed running agrees with QCD expectation!



2007 HERA $\alpha_S(M_Z)$ from Inclusive Jets

- **Combined fit to 30 data points of inclusive jet cross sections in NC DIS using ZEUS and H1 data**
- only those jet measurements which gave most precise values of α_S were considered to minimise total error

NLO QCD calculations

- MRST2001 PDFs were used
- factorisation scale: $\mu_f = Q$
- renormalization scale:
 $\mu_R = E_T^{\text{jet}}$

Experimental Uncertainties:

- “Hessian Method”
- correlation between systematic uncertainties are treated within one experiment

Theoretical Uncertainties:

- terms beyond NLO (as per Jones et. al. JHEP 12 (2003) p007)
- factorization scale uncertainty
- PDF uncertainty
- hadronisation uncertainty

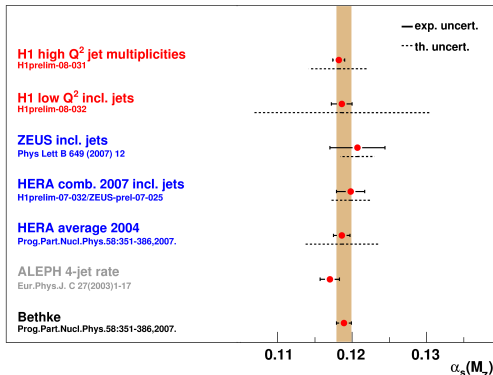
2007 HERA Jets:

$$\alpha_S(M_Z) = 0.1198 \pm 0.0019(\text{exp.}) \pm 0.0026(\text{th.})$$

Summary of α_s Extractions

- HERA 2007 jets: theoretical uncertainty cut in half compared to 2004 HERA
- compatible with world average
- HERA competitive!
- different measurements and environments and processes are consistent

↪ **great success of QCD!!**



ZEUS: Jet Data and Proton PDF Fits

- Including jet data in global QCD fits reduces proton PDF uncertainty

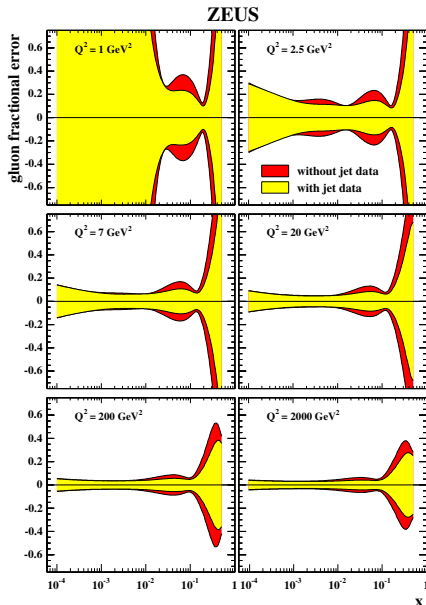
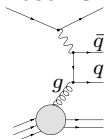
- 1 high Q^2 neutral current inclusive jet measurement
- 2 measurement of dijets in photoproduction

- via **boson-gluon-fusion process** jets are particularly sensitive to gluon PDF

- jet data have large effect on gluon PDF in the *mid-to-high* x region (up to 30% to 35% reduced errors)

→ **high Q^2 region relevant for LHC physics!**

Boson-Gluon Fusion



Summary

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

- possibility to reduce errors on PDFs in global QCD fits
- study of non-perturbative effects in minijet analysis shows the need of multiple interactions at low Q^2 in theoretical predictions
- the strong coupling α_s was extracted using ...
 - inclusive and multi-jets cross sections at high Q^2 .
 - combined fit to H1 and ZEUS inclusive jet cross sections.

Conclusion:

- NLO works very well for HERA at high Q^2
- theoretical errors are often much larger than experimental uncertainties
- potential of HERA data for PDFs

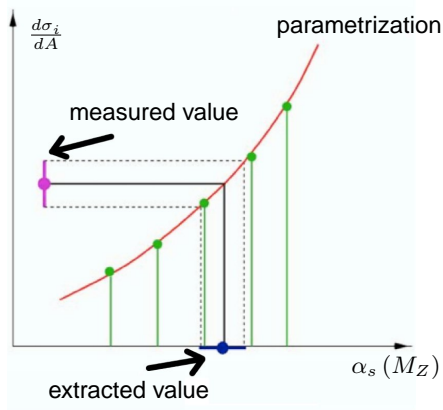
Backup

Extraction of α_s :

- Perform NLO calculation with different values of $\alpha_s(M_Z)$
- The values of α_s used correspond to those used in different PDFs sets available
- 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 $\alpha_s(M_Z)$



Backup

The Breit Frame

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
- Suppression of beam remnant jet
- directly sensitive to QCD hard processes (α_s)

- Jets are reconstructed in the Breit frame using k_\perp cluster algorithm on cells or energy flow objects
 - infrared and collinear safe
- Data corrected for detector and QED, Z^0 effects with LO MC models
- NLO is corrected with LO MC + parton

