Jets and α_s Measurements at HERA

Jörg Behr
(Hamburg University / DESY)

On Behalf of the H1 and ZEUS Collaborations

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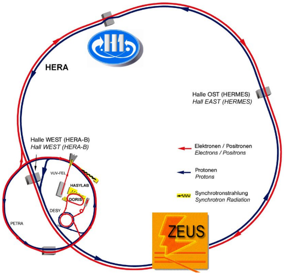
Outline:

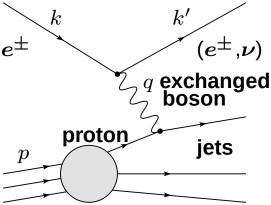
1. DIS and Jet Production at HERA
2. Test General Aspects of pQCD: Low Q^2
3. Firm Grounds: High Q^2
4. What Can We Learn From It?
5. Summary

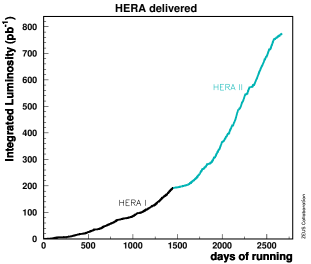
Deep Inelastic Scattering (DIS) at HERA



Electron-Proton Collisions at HERA:

$\sqrt{s} = 318$ 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

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

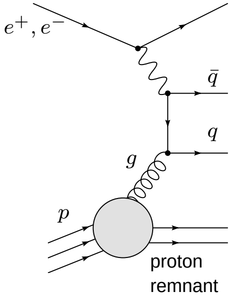
Jet Production in DIS at HERA

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 → extraction of α_s, PDFs
- Access to non-pertubative effects like multiple interactions and underlying event?

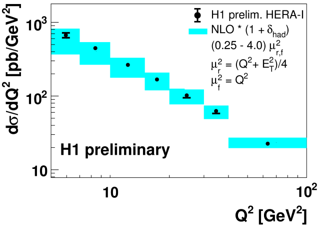
Technicalities:

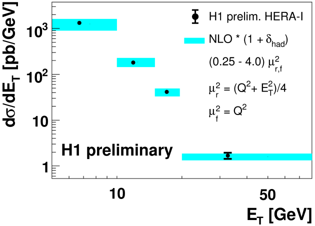
- Breit frame: boson-quark collinear frame. p_T from QCD effects
- Jets are reconstructed using $k_\perp$ cluster algorithm on cells or energy flow objects
  - infrared, collinear safe

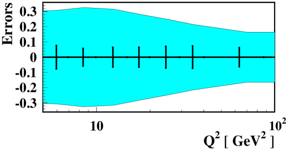
H1: Inclusive Jet Production at Low Q^2

- DIS at low Q^2
  - $\longrightarrow$ lots of statistic
  - $\longrightarrow$ 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: $44\ \mathrm{pb}^{-1}$
- $5 < Q^2/\mathrm{GeV}^2 < 100$
- $E_{T,\mathrm{Breit}}^{\mathrm{jet}} > 5\ \mathrm{GeV}$
- 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!**





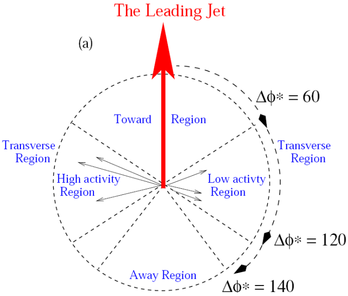


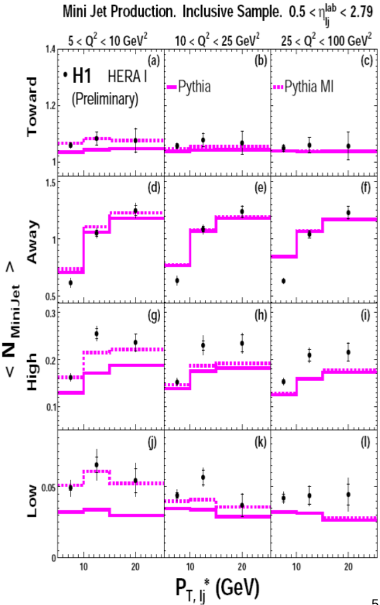
$\longleftarrow$ **μ_R scale uncertainty**

H1: NC DIS Minijet Production

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

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





Conclusion:

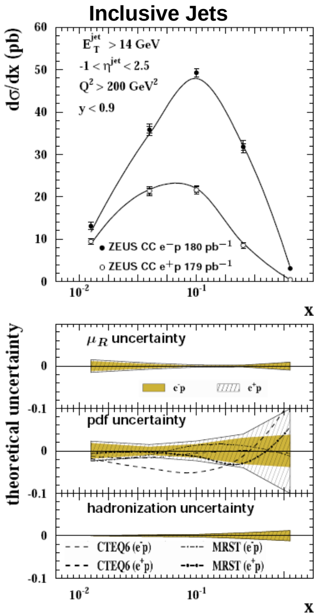
- addition of MI to MC improves data description at low Q^2
- MC behavior: contribution from resolved photon events increases with decreasing Q^2
  - $\hookrightarrow$ higher contributions from MI
- even at high Q^2 not everything understood

ZEUS: Charged Current Multijets

- Measurement uses $359\ \mathrm{pb}^{-1}$ polarized $e^{\pm}p$ data
- $Q^2 > 200\ \mathrm{GeV}^2$
- $E_T^{\mathrm{jet1(2,3)}} > 14(5)\ \mathrm{GeV}$ 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

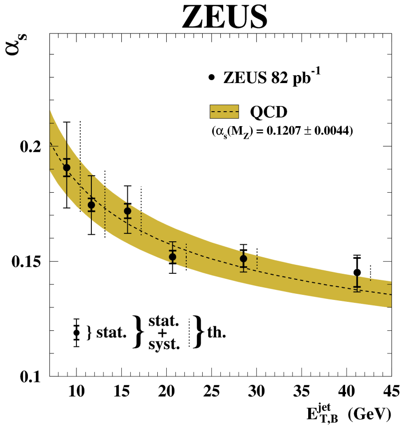
Extraction of α_s:

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

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

Main Sources of Uncertainty

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

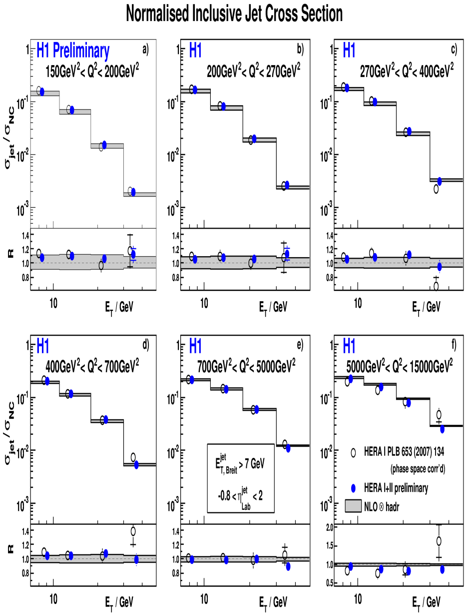


Demonstration of running coupling

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

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

- $150 < Q^2/\mathrm{GeV}^2 < 15000$
- $7 < E_T^{\mathrm{Breit}}/\mathrm{GeV} < 50$
- $M_{12} > 16\ \mathrm{GeV}$ 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
  - $\hookrightarrow$ luminosity uncertainty cancels and scale uncertainty reduces in normalized cross sections
- data are well described by NLO



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

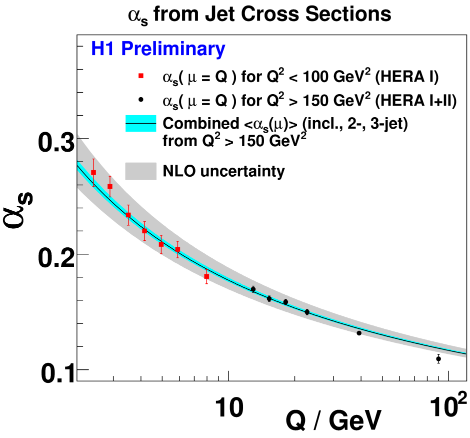
Extraction of α_s

- 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:

$$\alpha_s(M_Z) = 0.1182 \quad \pm 0.0008 \text{ (exp.)} \quad ^{+0.0041}_{-0.0031} \text{ (scale)} \quad \pm 0.0018 \text{ (PDF)}$$

- Fit quality: $\chi^2/\mathrm{ndf} = 55.8/53$
- **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

Experimental Uncertainties:

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

NLO QCD calculations

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

Theoretical Uncertainties:

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

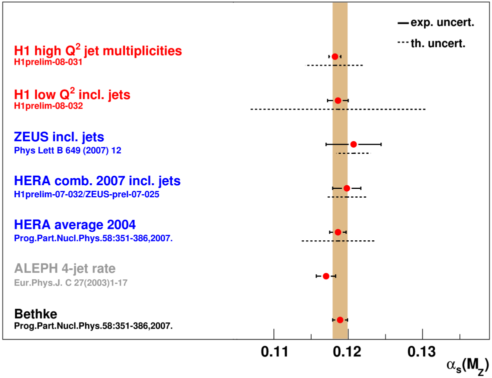
2007 HERA Jets:

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

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

  $\hookrightarrow$ **great success of QCD!!**

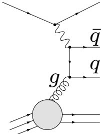


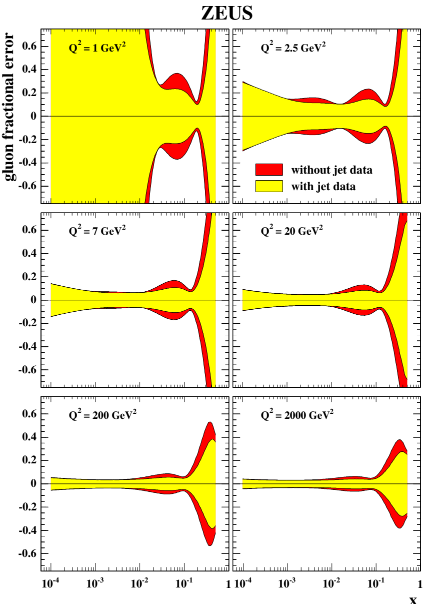
ZEUS: Jet Data and Proton PDF Fits

- 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 particular 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)

  $\hookrightarrow$ **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-pertubative 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

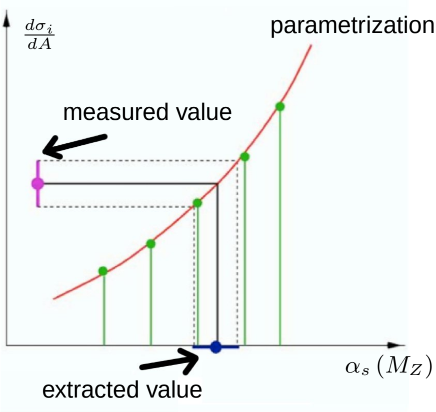
Backup

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