Diffractive DIS Cross Sections and Parton Distributions from Rapidity Gap and Leading Proton Data

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Outline:
• hep-ex/0606003
• hep-ex/0606004
Final Results from two Publications

DESY 06-049, hep-ex/0606004

Measurement and QCD Analysis of the Diffractive Deep-Inelastic Scattering Cross Section at HERA

H1 Collaboration

Abstract

A detailed analysis is presented of the diffractive deep-inelastic scattering process $ep \rightarrow eXp$, where $X$ is a proton at a low mass proton excitation carrying fraction $1-x_p > 0.95$ of the incident proton longitudinal momentum and the squared four-momentum transfer at the proton vertex satisfies $|t| < 1 \text{ GeV}^2$. Using data taken by the H1 experiment, the cross section is measured for photon virtualities in the range $3.5 < Q^2 < 1600 \text{ GeV}^2$, triple differentially in $p_T$, $Q^2$ and $\beta = \tau/\tau_p$, where $\tau$ is the Bjorken scaling variable.

At low $p_T$, the data are consistent with a factorisable $p_T$ dependence, which can be described by the exchange of an effective pomeron trajectory with intercept $\alpha_p(0) = 1.118 \pm 0.006 \text{ (exp.)} \pm 0.009 \text{ (model)}$. Diffractive parton distribution functions and their uncertainties are determined from a next-to-leading order DGLAP QCD analysis of the $Q^2$ and $\beta$ dependences of the cross section. The resulting gluon distribution carries an integrated fraction of around 70% of the exchanged momentum in the $Q^2$ range studied. Total and differential cross sections are also measured for the diffractive charged current process $e^+p \rightarrow eXp$ and are found to be well described by predictions based on the diffractive parton distributions. The ratio of the diffractive to the inclusive neutral current $ep$ cross sections is studied. Over most of the kinematic range, this ratio shows no significant dependence on $Q^2$ at fixed $\tau_p$ and $\tau$ as on $\tau$ at fixed $Q^2$ and $\beta$.

Submitted to Eur. Phys. J. C

DESY 06-048, hep-ex/0606003

Diffractive Deep-Inelastic Scattering with a Leading Proton at HERA

H1 Collaboration

Abstract

The cross section for the diffractive deep-inelastic scattering process $ep \rightarrow eXp$ is measured, with the leading final state proton detected in the H1 Forward Proton Spectrometer. The data analysed cover the range $x_p < 0.1$ in fractional proton longitudinal momentum loss, $0.08 < |t| < 0.5 \text{ GeV}^2$ in squared four-momentum transfer at the proton vertex, $2 < Q^2 < 50 \text{ GeV}^2$ in photon virtuality and $0.04 < \beta = \tau/\tau_p < 1$, where $\tau$ is the Bjorken scaling variable. For $x_p \lesssim 10^{-3}$, the differential cross section has a dependence of approximately $d\sigma/d\beta \propto 1/x_p^2$, independently of $x_p$, $\beta$ and $Q^2$ within uncertainties. The cross section is also measured triple differentially in $x_p$, $\beta$ and $Q^2$. The $x_p$ dependence is interpreted in terms of an effective pomeron trajectory with intercept $\alpha_p(0) = 1.114 \pm 0.018 \text{ (stat.)} \pm 0.013 \text{ (syst.)} \pm 0.008 \text{ (model)}$ and a sub-leading exchange. The data are in good agreement with an H1 measurement for which the event selection is based on a large gap in the rapidity distribution of the final state hadrons, after accounting for proton dissociation contributions in the latter. Within uncertainties, the dependence of the cross section on $x$ and $Q^2$ can thus be factorised from the dependences on all studied variables which characterise the proton vertex, for both the pomeron and the sub-leading exchange.

Submitted to Eur. Phys. J. C
Contents

• Comparison between leading proton and rapidity gap data

• Dependences on $t$

• $Q^2$ and $\beta$ dependences and NLO DGLAP QCD fits

• $x_{IP}$ dependences and $\alpha_{IP}(0)$

• First measurement of charged current diffraction

• Comparisons between diffractive and inclusive DIS cross sections
Event Selection Methods

1. Tag and measure final state proton in Forward Proton Spectrometer (FPS method)
   - No proton dissociation
   - Can measure $t$
   - Acceptance at high $x_{IP}$
   - ... but low Pot acceptance

2. Require Large Rapidity Gap spanning at least $3.3 < \eta < 7.5$ and measure hadrons in central detector (LRG method)
   - Some proton dissociation
   - Correct to $M_y < 1.6$ GeV
   - Near-perfect acceptance at low $x_{IP}$
Data Sets and Observables

- **FPS data sample**
  - 1999-2000 data (28 pb\(^{-1}\))
  - Study of \(t\) dependence:
    \[
    x_{IP} \frac{d^2 \sigma^{ep \to eXp}}{dx_{IP} dt}
    \]

- **LRG data sample**
  - 1997 data (2 pb\(^{-1}\), \(Q^2<13.5\) GeV\(^2\))
  - 1997 data (11 pb\(^{-1}\), 13.5<\(Q^2<105\) GeV\(^2\))
  - 99-00 data (62 pb\(^{-1}\), \(Q^2>133\) GeV\(^2\))

- The Diffractive reduced cross section:
  \[
  \frac{d^4 \sigma^{ep \to eXp}}{dxdQ^2dx_{IP}dt} = \frac{4\pi\alpha^2}{xQ^4} Y_+ \sigma_r^{D(4)}(x, Q^2, x_{IP}, t)
  \]

- Relates to the structure functions \(F_2^D\) and \(F_L^D\) as:
  \[
  \sigma_r^{D(4)}(x, Q^2, x_{IP}, t) = F_2^{D(4)} - \frac{y^2}{Y_+} F_L^{D(4)} \approx F_2^{D(4)}
  \]

- Integrated over \(t\):
  \[
  \sigma_r^{D(3)}(x, Q^2, x_{IP}) = \int_{-1}^{t_{min}} \sigma_r^{D(4)}(x, Q^2, x_{IP}, t) dt
  \]
Two Levels of Factorization

- QCD hard scattering collinear factorization (Collins) at fixed $x_{IP}$ and $t$
  - After integration over measured $M_\gamma, t$ ranges
- “Proton vertex” factorization of $x, Q^2$ from $x_{IP}, t$ (and $M_\gamma$) dependences
  - Separately for leading IP and sub-leading IR exchanges

\[
\frac{d\sigma_i}{dt}(ep \rightarrow eXY) = \int f_i^D(x, Q^2, x_{IP}, t) \otimes d\sigma^{ei}(x, Q^2) = f_{IP/p}(x_{IP}, t) \times f_i^{IP}(\beta = x/x_{IP}, Q^2)
\]
Data Overview

- **LRG**: $M_\gamma < 1.6$ GeV
  - $3.5 < Q^2 < 1600$ GeV$^2$

- **FPS**: $Y=p$
  - $2.7 < Q^2 < 24$ GeV$^2$

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![Graphs showing data distribution](image_url)

- H1 FPS ($|t|=0.25$ GeV$^2$)
- Regge fit IP+IR
- IP only

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Comparison LRG vs FPS Data

- Form ratio LRG/FPS of measurements as function of $x_{IP}$, $\beta$ or $Q^2$ after integration over others.

- Independent of kinematics within errors

$$\frac{\sigma(M_\gamma<1.6 \text{ GeV})}{\sigma(Y=p)} = 1.23\pm0.03(\text{stat.})\pm0.16(\text{syst.})$$

- Agreement in detail between methods

- $M_\gamma$ dependence factorizes within (10% non-normalization) errors!
Comparison of H1-LRG with H1-FPS and ZEUS-LPS data

- **LRG vs FPS data:**
  - FPS and ZEUS-LPS data scaled by global factor of 1.23
  - ZEUS-LPS and H1-FPS normalizations agree to 8%
  - Very good agreement between proton tagging and LRG methods if p dissociation is accounted for!

- **LRG vs ZEUS LPS data:**

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• **Fit to exp(Bt) in bins of $x_{IP}$**

\[
f_{P/P}(x_{IP}, t) = \frac{e^{B_{IP}t}}{2\alpha_{IP}(t) - 1}
\]

- **B($x_{IP}$) data constrain IP,IR flux factors in p vertex fact. Model**
- **Regge motivated form:**

\[
\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}t
\]

- **E.g. fitting low $x_{IP}$ data to yields**

\[
B_{IP} = 5.5^{+2.0}_{-1.7} \text{ GeV}^{-2} \quad \alpha'_{IP} = 0.06^{+0.19}_{-0.06} \text{ GeV}^{-2}
\]
t-slope dependence on $\beta$ or $Q^2$?

- $B$ measured double differentially in $(\beta$ or $Q^2)$ and $x_{IP}$

- No change of $t$ dependence with $\beta$ or $Q^2$ at fixed $x_{IP}$

- Proton vertex factorization for $t$ dependence working within errors
\[ \sigma_r^{D(3)}(\beta, Q^2, x_{IP}) \] at \( x_{IP} = 0.0003 \)

- Principal binning scheme for LRG data
- Study \( Q^2 \) and \( x (= \beta^* x_{IP}) \) dependences in detail at small number of fixed \( x_{IP} \) values

- Good precision – in best regions 5% (stat.), 5% (syst.), 6% (norm.)

- Directly measures diffractive quark density at fixed \( x_{IP} \)
- Data compared with “H1 2006 DPDF fit” and its error band (assumes p vtx factorization, see later)
\[ \sigma_r^{D(3)}(\beta, Q^2, x_{IP}) \text{ at } x_{IP}=0.001 \]

- Like an inclusive \( F_2 \) measurement at each value of \( x_{IP} \).
\[ \sigma_r^{D(3)}(\beta, Q^2, x_{IP}) \] at \( x_{IP} = 0.003 \)
$\sigma_r^{D(3)}(\beta,Q^2,x_{IP})$ at $x_{IP}=0.01$
\[ \sigma_r^{D(3)}(\beta, Q^2, x_{IP}) \text{ at } x_{IP} = 0.03 \]
Q$^2$ dependence in more detail

- $\sigma_{rD}^{(3)}$ measures diffractive quark density
- Its dependence on Q$^2$ is sensitive to diffractive gluon density
- Fit data at fixed $(x, x_{IP})$ to $\sigma_{rD}=A+B \ln Q^2$, so that $B=d\sigma_{rD}/d \ln Q^2$
- Divide results by $f_{IP/p}(x_{IP})$ to compare different $x_{IP}$ values

- Derivatives large and positive at low $\beta$
- Suggests large gluon density (independent of $x_{IP}$ within errors)
H1 2006 DPDF fit: Overview

- **Fit LRG data from fixed** $x_{IP}$ **binning,** using NLO DGLAP evolution of DPDFs (massive scheme) to describe $x,Q^2$ dependences

- **Proton vtx factorisation framework** (supported by data)
  - relate data from different $x_{IP}$ values with complementary $x,Q^2$ coverage

- **For IP exchange,** free parameters are
  - $\alpha_{IP}(0)$ (describes $x_{IP}$ dependence)
  - DPDF parameters at evolution starting scale $Q_0^2$

- **For sub-leading IR**
  - all flux parameters taken from previous data
  - PDFs taken from Owens-$\pi$; single free param for normalization
Kinematic range and DPDF parameterization

- To ensure data fitted are compatible with chosen framework, test sensitivity of fit results to variations of kinematic boundaries
  - Results stable for most variations ($\beta_{\text{max}}, \beta_{\text{min}}, M_{x,\text{min}}, x_{\text{IP, max}}$)
  - Systematic variation of gluon density with minimum $Q^2$ of data included in fit for $Q^2<8.5$ GeV$^2$; stable for larger $Q^2$-min
- Fit all LRG data with $Q^2 \geq 8.5$ GeV$^2$, $M_x>2$ GeV, $\beta \leq 0.8$
- Parameterize
  - Quark singlet $z\Sigma(z, Q_0^2)$
  - Gluon $zg(z, Q_0^2)$ density

\[
z\Sigma(z, Q_0^2) = A_q z^{B_q} (1 - z)^{C_q} \quad zg(z, Q_0^2) = A_g (1 - z)^{C_g}
\]

- Gluon insensitive to $B_g$
- Small number of parameters
  - Need to optimize $Q_0^2$ wrt $\chi^2$
- Using world average value for $\alpha_s(M_z) = 0.118$
- Results reproducible with Chebychev polynomials
H1 2006 DPDF fit results (log z scale)

- $Q_0^2 = 1.75 \text{ GeV}^2$
- $\chi^2 \sim 158 / 183$ dof

- Experimental uncertainty obtained by propagating errors on data (c.f. incl. fits, $\Delta\chi^2 = 1$)

- Theoretical uncertainty from varying fixed parameters of fit (flux params, $\alpha_s$, $m_c$, $m_b$ etc.) and $Q_0^2$ ($\Delta\chi^2 = 1$)

- Singlet constrained to $\sim 5\%$, gluon to $\sim 15\%$ at low z; error blowing up at highest z
A closer look at high z region

- As there are only singlet quarks, the evolution eq. for $F_2^D$ is
  \[ \frac{dF_2^D}{d \ln Q^2} \sim \frac{\alpha_s}{2\pi} \left[ P_{qg} \otimes g + P_{qq} \otimes \Sigma \right] \]

- At low $\beta$, evolution driven by $g \to qq$:
  - strong sensitivity to gluon
- At high $\beta$, relative error on derivative grows, $q \to qg$ contribution becomes important:
  - sensitivity to gluon is lost
H1 2006 DPDF fit results (lin. z scale)

- Lack of sensitivity to high z gluon confirmed by dropping $C_g$ parameter, so gluon is simple constant at $Q_0^2$:

- Fit B, $\chi^2 \sim 164/184$ dof
  - Singlet very stable
  - Gluon similar at low z
  - Substantial change to gluon at high z
Effective Pomeron Intercept

- From QCD fit to LRG data

\[ \alpha_{IP}(0) = 1.118 \pm 0.008 \text{(exp.)}^{+0.029}_{-0.010} \text{(th.)} \]

- Dominant uncertainty from strong correlation with \( \alpha'_{IP} \): taking \( \alpha'_{IP} = 0.25 \) instead of 0.06 GeV\(^{-2} \) yields \( \alpha_{IP}(0) \approx 1.15 \)

- Stable w.r.t adding extra parameters for \( \alpha_{IP}(0) \) in different \( Q^2 \) or \( \beta \) regions (consistent with p vtx factorization)

- Consistent result from fits to FPS data:

\[ \alpha_{IP}(0) = 1.114 \pm 0.018 \text{(stat.)} \pm 0.012 \text{(syst.)}^{+0.040}_{-0.020} \text{(th.)} \]
Diffractive Charged Current

- Sensitive to flavour decomposition of singlet (completely unconstrained by NC data)
- Good agreement with 2006 DPDF fit (assumes $u=d=s=\bar{u}=\bar{d}=\bar{s}$, $c$ from BGF), though statistics very limited so far
Ratio diffractive/inclusive: $Q^2$ dependence

- Make ratio at fixed $x_{IP}$ and $x$ and fit it to $A+B \ln Q^2$

- Ratio remarkably flat (derivative~0) except at high $\beta$
Q^2 derivative and gluon/quark ratios

- If \( \frac{d(\sigma^D_r/\sigma_r)}{d \ln Q^2} \sim 0 \) then

\[
\frac{1}{\sigma^D_r} \frac{d\sigma^D_r}{d \ln Q^2} \sim \frac{1}{\sigma_r} \frac{d\sigma_r}{d \ln Q^2} \rightarrow \frac{g^D}{q^D} \sim \frac{g}{q}
\]

At low x, quark:gluon ratio \( \sim 70\%/30\% \), common to diffractive and inclusive.
Ratio diffractive/inclusive: x dependence

- **Plot** $\sigma_r^D/\sigma_r$ at fixed $\beta, Q^2$ (hence fixed $M_X$) vs $x$ ($\sim 1/W^2$)
- **Corresponds to**
  $$M_X^2 \cdot \frac{d\sigma_r^D}{dM_X^2}/\sigma_{tot}$$

- Remarkably flat vs $x$ over most of kinematic range (bins with large $F_L$ or IR contrib not shown)

- Diffractive and inclusive cross sections cannot be described with the same $\alpha_{ip}(0)$, even if it is $Q^2$ dependent
Summary

- **H1 diffractive measurements using FPS and LRG methods published last week:**
  - FPS method: DESY 06-048, hep-ex/0606003, subm. to EPJC
  - LRG method+QCD fits: DESY 06-049, hep-ex/0606004, subm. to EPJC
- Data from two methods agree in detail

- **Slope parameter** $B \sim 6 \text{ GeV}^{-2}$ at low $x_{IP}$, indep. of $x_{IP}, \beta, Q^2$
- **Proton vtx factorization with reggeon exchanges at high $x_{IP}$ continues to provide good model for $x_{IP}$ dependence:** $\alpha_{IP}(t) \sim 0.118 + 0.06 t$

- **Diffractive PDFs extracted from fits to $\beta, Q^2$ dependences for $Q^2 \geq 8.5 \text{ GeV}^2$ (H1 2006 DPDF Fits A+B)**
  - Quark singlet very well constrained ($\sim 5\%$)
  - Gluon constrained to $\sim 15\%$, but poorly known at high $z$
- **DPDFs predict charged current cross sections OK**
  - More comparisons with jets, charm etc. to follow
- **Ratio diffractive/inclusive DIS measured**
  - $\sim$flat with $Q^2$ at fixed $x, x_{IP}$
  - $\sim$flat with $W$ at fixed $Q^2, M_X$
Extra Figures
Comparison H1-LRG and ZEUS-Mx data
Ratio diffractive/inclusive vs Q^2 extra plots
t dependence in bins of $\beta$ or $Q^2$
Q² and \( \beta \) dependences of FPS data
$x_{IP}$ dependence of FPS data

- **H1 FPS**
- **H1 2006 DPDF Fit A, IP+IR**
- **IP only**

For each $Q^2$ value:

- $Q^2 = 2.7 \text{ GeV}^2$
- $Q^2 = 5.3 \text{ GeV}^2$
- $Q^2 = 10.7 \text{ GeV}^2$
- $Q^2 = 24 \text{ GeV}^2$

Parameters:

- $\beta = 0.02$
- $\beta = 0.06$
- $\beta = 0.15$
- $\beta = 0.35$
- $\beta = 0.7$

Graphs show the dependence of $x_{IP}$ on $Q^2$ for different values of $\beta$.