Physics Results on the Tagged Structure Functions at HERA

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DESY
on behalf of H1 and ZEUS

HERA, the H1 and the ZEUS Detector

Three periods of data taking:

**HERA I:** \( \sim 120 \, pb^{-1} \)

**HERA II:** \( \sim 380 \, pb^{-1} \)

**Low proton energy:** \( \sim 65 \, pb^{-1} \)

\( E_p = 920 \, GeV \quad E_e = 27.5 \, GeV \quad \sqrt{s} = 4E_pE_e = 318 \, GeV \)

- **ZEUS Detector**
  - Inner tracking system
  - Superconducting solenoid
  - Calorimeter
  - Iron yoke
  - Muon chambers inside/outside yoke
  - Forward muon detector
  - Plus
    - Forward proton and neutron spectrometers
    - About 100m downstream

- **H1 Detector**

Bernd Loehr

Exploring Hadron Structure with Tagged Structure Functions, JLAB January 16-18, 2014
The Proton Taggers at HERA I

Proton

FNC

S6 S5

FPS

B77 B72 B67 Q51,55,58 B47 Q42 Q30,34,38 B26 B18,22 Q6-15

ZEUS

H1

HERA magnets

P-beam direction

Silicon strip detectors

Z=26 m

Z=96 m

H1 FPS module

Scintillating fibers

Position resolution 2-3 mm

$\sigma_E/E = 0.63/\sqrt{E} + 2\%$
Kinematics of DIS Events

Inclusive non-diffractive deep inelastic scattering (DIS) events

\[ s = (k+p)^2 \]

\[ W^2 = (q+p)^2 \]

\[ Q^2 = -q^2 = -(k-k')^2 \]

\[ x = \frac{Q^2}{2p\cdot q} \]

\[ y = \frac{p\cdot q}{p\cdot k} \]

\( s \): center of mass energy squared
\( W^2 \): photon-proton center of mass squared
\( Q^2 \): virtuality, size of the probe
\( x \): fraction of the proton momentum carried by the struck parton
\( y \): inelasticity, fraction of the electron momentum carried by the virtual photon

Diffraction DIS events

Proton or dissociative system, measured in FPS/LPS

For diffractive events in addition:

\[ M_x \]

\[ t = (p-p')^2 \]

\[ x_{IP} = \frac{(p-p')\cdot q}{p\cdot q} = \frac{M_x^2 + Q^2}{W^2 + Q^2} \]

\[ \beta = \frac{Q^2}{2(p-p')\cdot q} = \frac{x}{x_{IP}} = \frac{Q^2}{M_x^2 + Q^2} \]

\( M_x \): mass of the diffractive system \( x \)
\( t \): four-momentum transfer squared at the proton vertex
\( x_{IP} \): momentum fraction of the proton carried by the Pomeron
\( \beta \): fraction of the Pomeron momentum which enters the hard scattering
The tagged Proton Signal

\[ x_L = \frac{p'}{p} \approx 1 - x_{ip} \quad x_L \approx 1 \quad \text{\(\rightarrow\) elastically (diffractively) scattered proton} \]

\[ t = -\frac{p_T^2}{x_L} - \frac{(1 - x_L)^2}{x_L} M_p^2 \]

Detecting the elastically scattered Proton is the only method to measure the four-momentum transfer, \(|t|\), at the proton vertex.

Events with \( x_L < 1 \) originate from mainly from proton dissociative processes.

The resolution in \( X_L \) determines the background under the elastic peak.

Identification of Diffractive Events

Three methods have been used at HERA to select diffractive events:

- large rapidity gap selection \( \rightarrow \) p-dissociation background and Regge-contributions
  - large acceptance;

- \( M_X \) method \( \rightarrow \) no Regge-contributions but p-dissociation background,
  - large acceptance;

- detecting proton at \( x_L \approx 1 \) \( \rightarrow \) almost no background from p-dissociation but Regge-contributions,
  - very small acceptance.
Inclusive DIS Proton Structure Functions

\[
\frac{d^2 \sigma_{\gamma^* p}}{dx dQ^2} = \frac{2\pi\alpha_{em}}{x \cdot Q^4} \left[ 1 - (1 - y)^2 \right] \cdot \sigma_r (x, Q^2)
\]

\[
\sigma_r (x, Q^2) = F_2(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L (x, Q^2)
\]

xF₃ can safely be neglected at not too high \(Q^2\) for HERA data

For HERA data typically:

\[
y = \frac{Q^2}{x \cdot s} \approx 0.1
\]

Inclusive Diffractive Proton Structure Functions

Analogous to inclusive DIS:

\[
\frac{d^4 \sigma}{dQ^2 dt dx_{IP} d\beta} = \frac{2\pi\alpha_{em}}{\beta Q^2} \left[ 1 - (1 - y)^2 \right] \cdot \sigma_r^{D(4)} (Q^2, t, x_{IP}, \beta)
\]

\[
\sigma_r^{D(4)} (Q^2, t, x_{IP}, \beta) = F_2^{D(4)} (Q^2, t, x_{IP}, \beta) - \frac{y^2}{1 + (1 - y)^2} F_L^{D(4)} (Q^2, t, x_{IP}, \beta)
\]

If \( t \) is not measured and integrated over:

\[
\sigma_r^{D(3)} (Q^2, x_{IP}, \beta) = F_2^{D(3)} (Q^2, x_{IP}, \beta) - \frac{y^2}{1 + (1 - y)^2} F_L^{D(3)} (Q^2, x_{IP}, \beta)
\]
Proton tagged DIS Cross-sections from H1

**Regge fit**

\[ F_2^{D(4)} = f_{IP}(x_{IP}, t) F_P(\beta, Q^2) + n_{IR} \cdot f_{IR}(x_{IP}, t) F_{IR}(\beta, Q^2) \]

Assumption: Regge/vertex factorization

*Pomeron contribution*  *Reggeon contribution*

\[ f_{IP}(x_{IP}, t) = A_{IP} \cdot \frac{e^{B_{IP} t}}{x_{IP}^2} \]

\[ f_{IR}(x_{IP}, t) = A_{IR} \cdot \frac{e^{B_{IR} t}}{x_{IR}^2} \]

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

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

\[ F_{IR}(\beta, Q^2) \]

from the parametrization of the pion trajectory

Input from other Measurements:

\[ \alpha_{IP}(0) = 0.50 \]

\[ \alpha'_{IR} = 0.3 \text{ GeV}^{-2} \]

**Fit Results**

\[ B_{IR} = 1.6 \text{ GeV}^{-2} \]

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_{IP}(0) )</td>
<td>1.10 ± 0.02 (exp.) ± 0.03 (model)</td>
</tr>
<tr>
<td>( \alpha'_{IP} )</td>
<td>0.04 ± 0.02 (exp.) +0.08 (-0.06) (model) GeV(^{-2})</td>
</tr>
<tr>
<td>( B_{IP} )</td>
<td>5.73 ± 0.25 (exp.) +0.80 (-0.90) (model) GeV(^{-2})</td>
</tr>
<tr>
<td>( n_{IR} )</td>
<td>[0.87 ± 0.10 (exp.) +0.60 (-0.40) (model)] \cdot 10^{-3}</td>
</tr>
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$d\sigma_{pp}/dp_T^2 = A \cdot e^{-Bp_T^2}$

$B(x_P, \beta, Q^2) = [1 - w_R(x_P, \beta, Q^2)][B_P - 2\alpha'_P \ln x_P] + w_R(x_P, \beta, Q^2)[B_R - 2\alpha'_R \ln x_P]$
Proton tagged DIS Cross-sections from H1

H1 FPS data from HERA II; comparison with fit from LRG data

DPDF fit:
pQCD fit to earlier LRG dataset,

Dashed line shows the diffractive (Pomeron) contribution.

For $x_{IP} > 10^{-2}$ considerable contributions from Regge exchanges are present.
Ratio of Proton tagged Events at Low $x_L$ to Inclusive DIS Events

**ZEUS**

$$r^{LP(3)}(x, Q^2, x_L) = \frac{N^{DIS}(x, Q^2, x_L)}{N^{DIS}(x, Q^2)} \frac{A_{DIS}}{A_{LPS}} \frac{L^{DIS}}{L^{LPS}} \frac{1}{\Delta x_L}$$

- **ZEUS 12.8 pb$^{-1}$**
- $0.32 < x_L < 0.92$
- $p_T^2 < 0.5 \text{ GeV}^2$

**ZEUS**

$$r^{LP(2)}(x, Q^2) = \frac{F_2^{LP(2)}(x, Q^2)}{F_2(x, Q^2)}$$

- $Q^2 = 237 \text{ GeV}^2$
- $Q^2 = 88 \text{ GeV}^2$
- $Q^2 = 44 \text{ GeV}^2$
- $Q^2 = 22 \text{ GeV}^2$
- $Q^2 = 11 \text{ GeV}^2$
- $Q^2 = 7.3 \text{ GeV}^2$
- $Q^2 = 4.2 \text{ GeV}^2$
pQCD Analysis of Diffractive Data

The concept of diffractive parton distribution functions (DPDF)

\[ \sigma_r^{D(3)}(Q^2, x_{IP}, \beta) = F_2^{D(3)}(Q^2, x_{IP}, \beta) - \frac{y^2}{1 + (1 - y)^2} F_L^{D(3)}(Q^2, x_{IP}, \beta) \]

QCD-factorization theorem for diffractive DIS:

\[ F_{2/L}^{D(3)}(\beta, Q^2, x_{IP}) = \sum_i \int \frac{dz}{z} C_{2/L,i} \left( \frac{\beta}{z} \right) f_i^D(z, x_{IP}; Q^2) \]

Regge-factorization assumption:

\[ f_i^D(z, x_{IP}; Q^2) = f_P(x_{IP}) f_i(z, Q^2) + f_R(x_{IP}) f_i^{IR}(z, Q^2) \]

DPDFs obey DGLAP evolution

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

Parametrisation of DPDFs at \( Q_0^2 = 1.8 \text{ GeV}^2 \)

\[ z f_d, u, s(z, Q_0^2) = A_q z^{B_q} (1 - z)^{C_q} \]
\[ z f_g(z, Q_0^2) = A_g z^{B_g} (1 - z)^{C_g} \]

Additional factor \( e^{\frac{0.001}{1-z}} \) included to ensure that distributions vanish for \( z \rightarrow 1 \).

Fit the DGLAP evolution with these parameterizations to inclusive diffractive data

9 parameters left free in fit:

\[ A_{q,g}, B_{q,g}, C_{q,g}, \alpha_{IR}(0), \alpha_{IP}(0), A_{IR}. \]
Data used in fit:

ZEUS Coll.

Nucl. Phys.

B 816, 1 (2009)

’S’ Standard Fit: \( A_g, B_g, C_g \) as free parameters

\[ 2 < Q^2 < 305 \text{ GeV}^2, \quad \text{40} < W < \text{240 GeV}, \quad 2 < M_X < 25 \text{ GeV}, \quad 0.0001 < x_{IP} < 0.02 \]

LPS sample: \( 2 < Q^2 < 120 \text{ GeV}^2, \quad 40 < W < 240 \text{ GeV}, \quad 2 < M_X < 40 \text{ GeV}, \quad 0.002 < x_{IP} < 0.1 \)

Samples are corrected for proton dissociation where necessary.

‘Standard’ Fit: \( A_g, B_g, C_g \) as free parameters

\[ ZEUS \; DPDF \; S \]

\[ ZEUS \; LPS \]

Data: DESY 08-175


pQCD analysis: DESY 09-191

Nucl. Phys B 831 (2010)
Diffractive Parton Density Functions (DPDF) from ZEUS

Diffractive quark density functions from the ZEUS DPDF S and DPDF C fits.

Diffractive gluon density functions from the ZEUS DPDF S and DPDF C fits.
Choose a common \((x, Q^2)\)-grid, if necessary swim data using fit of diffractive structure functions. Then combine data, taking into account correlations of systematic errors.
Results from Events with a Leading Neutron

Final state neutron in the proton fragmentation system

Leading neutron production via an exchange process.

One pion exchange (OPE) is the dominating mechanism for the production of neutron tagged events.

There is no elastic (diffractive) peak present.

ZEUS

X_L Distributions

DESY 07-011

DESY 09-185
Comparison of Leading Proton and Leading Neutron Cross-sections

The leading neutron rate is roughly a factor of two lower than the leading proton rate for $x_L < 1$.

No diffractive processes, including dissociative events, contribute to leading neutron production.
The semi-inclusive leading neutron cross-section can be written as, neglecting the longitudinal structure function.

\[
\frac{d^4\sigma(ep \rightarrow enX)}{dx \, dQ^2 \, dx_L \, dt} = \frac{4\pi\alpha^2}{x \, Q^4} \left( 1 - y + \frac{y^2}{2} \right) F_2^{LN(4)}(Q^2, x, x_L, t)
\]

\[
\frac{d^3\sigma(ep \rightarrow enX)}{dx \, dQ^2 \, dx_L} = \frac{4\pi\alpha^2}{x \, Q^4} \left( 1 - y + \frac{y^2}{2} \right) F_2^{LN(3)}(Q^2, x, x_L)
\]

The neutron tagged structure function has the same Q² dependence as the inclusive structure function.
The Pion Structure Function

Assuming the validity of the vertex factorisation:

\[
\frac{f_{\pi^+}/p}{2\pi} \frac{g_{\pi n n}^2}{4\pi} \frac{1-x_L}{(1-x_L)^2} \cdot \exp\left(-\frac{m_{\pi^-}^2 - t}{m_n^2 - t}\right)
\]

with, e.g.

\[
F_2^{LN(3)}(x_L=0.73)/\Gamma_\pi, \quad \Gamma_\pi = 0.13
\]

\[
d\sigma(ep \to e' n X) = f_{\pi^+}/p(x_L, t) \cdot d\sigma(e\pi^+ \to e' X)
\]

(Various parametrisations exist)

Then one can write:

\[
F_2^{LN(3)}(\beta, Q^2, x_L) = \Gamma_\pi(x_L) \cdot F_2^\pi(\beta, Q^2)
\]

with

\[
\Gamma_\pi(x_L) = \int_{t_0}^{t_{\text{min}}} f_{\pi/p}(x_L, t) \, dt
\]

\[
F_2^\pi(\beta, Q^2)
\]

might be interpreted as the pion structure function.

The data are compared to two different parametrisations of the pion structure function: \(Eur.Phys.J.C10\) (1999), \(Phys.Lett. B\) 233 (1989), and the \(H1\) parametrisation of the proton structure function scaled by a factor 2/3.
Despite very low acceptance of the proton taggers a large amount of proton tagged data has been collected.

The proton tagged data are mainly diffractive events for $X_{IP} < 10^{-2}$. For $X_{IP} > 10^{-2}$ Regge-exchange process contribute considerably.

Proton tagged data can be described well by Regge theory inspired fits assuming vertex factorization.

pQCD fits including Regge contributions deliver the Pomeron structure function assuming vertex factorization.

From inclusive diffractive data measured with the LRG method and leading proton tagged events diffractive parton distribution functions can be extracted.

Neutron tagged data are dominated by pion exchange processes. They are not diffractive.

Assuming vertex factorization and taking the pion flux factor from hadronic scattering data the pion structure function can be extracted.
Backup Slides
Results from the VFPS of H1

VFPS results are compared to Data from the FPS, LRG selected data, and DPDF fit.

The LRG data and the DPDF fit are scaled by a factor of 0.81 for the proton-dissociative contributions.
Measurements of $\sigma_r^D$ done so far in kinematical regions where $F_L^D$ can be neglected or it is corrected for by taking $F_L^D$ from pQCD predictions.

$F_L^D$ is strongly correlated to the diffractive gluon density \( \Rightarrow \) necessary to measure $F_L^D$ directly

Need measurements of $\sigma_r^D$ for different values of $y$ at fixed $(x,Q^2)$

\[
y = \frac{Q^2}{x_ip} \cdot \frac{1}{s}
\]

\( \Rightarrow \) vary center of mass energy squared \( s = 4 \cdot E_e E_p \)

\[
F_L^D = \frac{\partial \sigma_r^D}{\partial (y^2/Y_+)}
\]

with

\[
Y_+ = \frac{1}{1+(1-y)^2}
\]

Keep electron energy $E_e$, vary proton energy $E_p$

\[
E_p = 920 \text{ GeV}, \ 575 \text{ GeV}, \ 460 \text{ GeV}
\]
Measurement of the Diffractive Longitudinal Structure Function $F_L^D$ by H1

DESY 11-084
The ratio is independent of $x_{\text{IP}}$, $Q^2$, and $\beta$.

$$r = 0.76 \pm 0.01\,(\text{stat.})^{+0.03}_{-0.02}\,(\text{syst.})$$

The difference of $r$ to one is due to the proton-dissociative contributions included in the LRG data.
The $M_X$ Method to extract Diffractive DIS Events

ZEUS

Fit($c \exp(b \ln M_X^2)$)
Fit($D + c \exp(b \ln M_X^2)$)

DJANGOH, SATRAP + ZEUSVM, SANG($M_X < 2.3 \text{ GeV}$), SANG($M_X > 2.3 \text{ GeV}$)

$W = 37 - 55 \text{ GeV}$
$W = 200 - 245 \text{ GeV}$

$M_X$ in GeV
$Q^2 = 10 - 20$
$2.2 - 3 \text{ GeV}^2$

$\ln M_X^2$

DESY 05-011
Results from the $M_X$ method

**Vertex factorization assumption:**

$$ F_2(x_{IP}, \beta, Q^2) = f_{IP}(x_{IP}) \cdot F_{IP}(\beta, Q^2) $$

**Consequence:**

For fixed $\beta$, the $Q^2$ dependence should be independent of $x_{IP}$.

Within a column of fixed $\beta$, $x_{IP}$ dependence results only in scale factors.

Visible are scaling violations:

At high $x_{IP}$ the structure function falls with $Q^2$ whereas at low $x_{IP}$ it rises with $Q^2$. 
In the OPE model, the cross-section for leading neutron production factorises:

$$d\sigma(ep \rightarrow e'nX) = f_{\pi^+/p}(x_L, t) \cdot d\sigma(e\pi^+ \rightarrow e'X)$$

The pion flux factor can be derived from hadron scattering data. Various parametrisations exist, e.g.:

$$f_{\pi^+/p} = \frac{1}{2\pi} \frac{g_{\pi n}^2}{4\pi} (1-x_L) \frac{-t}{(m_n^2-t)^2} \cdot \exp \left( -\frac{\pi^2}{m_n^2} \frac{m_n^2-t}{1-x_L} \right)$$

In the OPE model, $\beta$ can be interpreted as the momentum fraction of the pion which takes part in the hard interaction with the virtual photon.

$$\beta = \frac{x}{1-x_L} = \frac{x}{x_{\pi}}$$

**Fit:**

$$F_2^{\text{LN}(3)}(Q^2, \beta, x_L) = c(x_L) \cdot \beta^{-\lambda(Q^2)} \quad \text{with} \quad \lambda = a \cdot \ln(Q^2/\Lambda^2)$$
Inclusive DIS PDFs from H1-ZEUS combined data

Parton distribution functions from HERAPDF1.0 at $Q^2 = 1.9 \text{ GeV}^2$ and $Q^2 = 10 \text{ GeV}^2$
For $xu_\nu$, $xd_\nu$, $xS(\text{sea})$ and $xg$. 