Longitudinal structure function measurements from HERA

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on behalf of H1 and ZEUS

- Deep Inelastic Scattering / Structure functions
- Longitudinal structure function $F_L(x,Q^2)$
- HERA / H1 and ZEUS
- Measurement strategy for $F_L$
- Experimental details of the $F_L$ analyses
- $F_L$ results
- Summary
Deep Inelastic Scattering

**Neutral Current (NC):** \( e^\pm p \rightarrow e^\pm X \)

\[ Q^2 = -q^2 = -(k-k')^2 \] virtuality of \( \gamma^*,Z \)

\[ x = \frac{Q^2}{2(Pq)} \] Bjorken x

\[ y = \frac{(Pq)}{(Pk)} \] inelasticity

\[ Q^2 = sxy \]

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

**Factorisation**

\[ \sigma_{DIS} \sim \hat{\sigma} \otimes pdf(x) \]

\( \hat{\sigma} \) – perturbative QCD cross section

pdf – universal parton distribution functions
The Proton Structure Functions

\[ \frac{d^2\sigma^{\pm}}{dx_dQ^2} = \frac{2\pi\alpha^2Y}{xQ^4} \sigma^{\pm} = \frac{2\pi\alpha^2Y}{xQ^4} \left[ F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \mp \frac{Y_-}{Y_+} xF_3(x,Q^2) \right] \]

helicity factors: \[ Y_\pm = 1 \pm (1 - y)^2 \]

dominant contribution:

\[ F_2(x,Q^2) = \sum e_{q_i}^2 x(q_i \pm \bar{q}_i) \]

contributes only at high \( Q^2 \) (\( > M_Z^2 \))

\[ xF_3(x,Q^2) = x \sum B_i (q_i - \bar{q}_i) \]

\[ F_2 \sim \sigma_L \gamma p + \sigma_T \gamma p, \quad F_L \sim \sigma_L \gamma p \]

\[ 0 \leq F_L \leq F_2 \]
The longitudinal structure function $F_L(x,Q^2)$

- $F_L$ is an independent structure function to be measured at HERA to complete the DIS program
- $F_L$ is a pure QCD effect which allows to make critical tests of the perturbative QCD framework used for pdf determinations
- $F_L$ is directly sensitive to gluon density

Breit frame:

\[
\frac{1}{2} \left[ \alpha_s \pi \int^1_x \frac{dz}{z^3} \left[ \frac{16}{3} F_2 + 8 \sum_q e_q^2 \left( \frac{1-x}{z} \right) \cdot x_g \right] \right]
\]

in QPM due to helicity and angular momentum conservation for spin $\frac{1}{2}$ quarks

$F_L \sim \sigma_L \gamma p = 0$

$F_L = F_2 - 2x F_1 = 0$

Callan-Gross relation

in QCD:
Gluon and $F_L$ in LO–NLO–NNLO (MSTW)

$\rightarrow$ poor stability for gluon at small $x$  $\rightarrow$ similarly for $F_L$ but less prominent
Theory predictions for $F_L$ in the HERA domain

- firm NLO/NNLO QCD predictions for $Q^2 > 10 \text{ GeV}^2$
- spread of predictions at $Q^2$ below 10 $\text{ GeV}^2$
HERA (1992–2007)

- peak luminosity $5 \times 10^{31}$ cm$^{-2}$ sec$^{-1}$
- $Q^2_{\text{max}} = 10^5$ GeV$^2$
- $\lambda_{\text{max}} \sim 1/1000 r_{\text{proton}}$
- longitudinal e-beam polarisation

- HERA-1 (1992–2000)
- HERA-2 (2003–2007)

- electrons
- positrons
- low $E_p$

- V.Chekelian, 28.06.2008
- FL measurements from HERA

- $e (E_e = 27.5$ GeV$)\rightarrow E_p = 920 \ (575, 460$ GeV$)$

- H1+ZEUS in total $\sim 1$ fb$^{-1}$
  - about equally shared between experiments (H1, ZEUS)
  - $e^+$ and $e^-$,
  - positive and negative $P_e$

- low proton energy run for direct $F_L$ measurements
  - 13 pb$^{-1}$ $E_p = 460$ GeV
  - 7 pb$^{-1}$ $E_p = 575$ GeV
Measurement strategy for $F_L$

$$\tilde{\sigma}_{NC} = \frac{d^2\sigma_{NC}^{ep}}{dxdQ^2} \left( \frac{2\pi\alpha^2}{xQ^4} Y_+ \right) = F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

→ one possible way:
measure $\sigma$ at high $y$
and assume $F_2$

→ free from theoretical assumption:
measure $\sigma$ at the same $x$ & $Q^2$ and different $y$
by changing the proton beam energy ($y = Q^2/sx$)

sensitivity to $F_L$
only at high $y$
H1 and ZEUS

\[ E'_e > 3 \text{ GeV} \ (y \approx 0.90) \quad y = 1 - \left( \frac{E'_e}{E_e} \right) \sin^2 \left( \frac{\theta_e}{2} \right) \quad E'_e > 6 \text{ GeV} \ (y \approx 0.76) \]

**FL measurements in H1**

| \( Q^2 \) range (GeV\(^2\)) | Spacal+CT | LAr+CT | DESY-08-053 |
|-------------------------------|-----------|--------|-------------|
| medium \( Q^2 \)              | 12-90     |        |             |
| high \( Q^2 \)                | 35-800    |        |             |
| low \( Q^2 \)                 | 5-15      | Spac+BST | to come    |

**FL measurements in ZEUS**

- \( \theta_e < 168^\circ \)
- \( 24 \leq Q^2 \leq 110 \text{ GeV}^2 \)
- more to come
Hardware & software improvements

**H1:** new trigger hardware since fall 2006:
- **Jet Trigger** (real time clustering in LAr)
- **Fast Track Trigger** (FTT)

**ZEUS:** new tool is developed to extend the tracking region:
- acceptance of the track reconstruction is limited to $\theta < 154^\circ$
- use single hits in the tracking detector along a road from primary vertex to el. candidate in CAL taking into account the charge of the scattered electron
  - reject neutral particles up to $\theta \approx 168^\circ$

$\rightarrow$ combined trigger eff. $\approx 100\%$ for $E_e > 3$ GeV
Photoproduction background estimation using 6m electron tagger (ZEUS)

- In photoproduction ($Q^2 \approx 0$) quasi-real photon interacts with the proton
- Electron with reduced energy goes along the e beam direction, bends in the dipole magnet and hits the electron tagger located at 6 m

$\rightarrow$ Fraction of $\gamma p$ events is measured in 6m tagger and used to normalize PYTHIA $\gamma p$ MC for each $E_p$ period

$\rightarrow$ H1 uses similar technique for $E_p$=920 GeV at $y < 0.56$
\( \gamma p \) bkg identification up to \( y=0.90 \) (H1)

Electric charge of the scattered electron using track from the primary interaction, pointing to the electron cluster:
- good charge measurement resolution
- wrong assignment of the charge < 1%

1. identify and exclude half of \( \gamma p \) bkg require the "right" charge for el.
2. estimate and subtract remaining \( \gamma p \) bkg using "wrong" charge el.

taken into account in statistical subtraction:
- charge asymmetry in \( \gamma p \) data due to antiprotons determined using "wrong charge" el. candidates in the \( e^\pm p \) HERA II data and in \( \gamma p \) events identified by the 6 m electron tagger

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FL measurements from H1
PIC 2008
High y region at medium $Q^2$ (H1)

$E_p = 460$ GeV

before "wrong" charge subtraction

$E'_e < 10$ GeV

$\gamma p$ background (green) concentrates at low $E_e$

the data are well understood in terms of MC

after "wrong" charge subtraction

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PIC 2008

FL measurements from HERA 2008
High \( y \) region \((0.70 < y < 0.90)\) at high \( Q^2 \) (H1)

\[
\text{E}_p = 460 \text{ GeV}
\]


data

\[
\text{NC MC + BG}
\]

\[
\text{BG (data)}
\]

\[
\text{E-P}_z > 35 \text{ GeV}:
\]

- rejects \( \gamma p \) background
- rejects initial state radiation (ISR)

\( \rightarrow \) step at \( E_e = 6 \text{ GeV} \) is due to selection requirements

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FL measurements from HERA
PIC 2008
Full $y$ range at high $Q^2$ after $\gamma p$ background subtraction (H1)

for $E_p = 920$ GeV ($y < 0.56$) $\gamma p$ bkg is taken from PYTHIA MC checked using 6m electron tagger
ZEUS: control plots ($E_p = 460, 920$ GeV)

MC is shown without $F_L$ contribution

- **$E_p = 460$ GeV**
  - $E'_e > 6$ GeV
  - $42 < E-Pz < 65$ GeV

- **$E_p = 920$ GeV**
  - $E'_e > 6$ GeV
  - $42 < E-Pz < 65$ GeV

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PIC 2008

FL measurements from HERA
NC cross sections for $E_p = 460, 920$ GeV

ZEUS

$Q^2 = 24$ GeV$^2$  
$Q^2 = 32$ GeV$^2$  
$Q^2 = 45$ GeV$^2$

$Q^2 = 60$ GeV$^2$  
$Q^2 = 80$ GeV$^2$  
$Q^2 = 110$ GeV$^2$

ZEUS (prel.)

$\sqrt{s} = 225$ GeV (14.0 pb$^{-1}$)
$\sqrt{s} = 318$ GeV (32.8 pb$^{-1}$)

ZEUS-JETS
ZEUS-JETS (F_L=0)
\( F_L (x, Q^2) \) from ZEUS

\( F_L \) measurements are consistent within errors with QCD calculations and with \( F_L = 0 \)
NC cross sections at medium $Q^2$ (H1)

$$E_p = 460, 575, 920 \text{ GeV}$$

$$\tilde{\sigma}_{NC} = F_2 - \frac{y^2}{1 + (1 - y)^2} F_L$$

→ determine $F_L$ and $F_2$ from linear fits at each $x$ and $Q^2$

$Q^2 = 25 \text{ GeV}^2$

→ use relative normalisation (the same for LAr and Spacal) of $E_p = 460, 575, 920 \text{ GeV}$ from the low $y$ data for the $F_L$ measurement
The published $F_L(x, Q^2)$ and averaged $F_L(Q^2)$ at medium $Q^2$ (H1)

$\rightarrow$ measured $F_L$ are above zero and consistent with QCD calculations

DESY-08-053
NC cross section in the full $Q^2$ range (H1)

The full range of medium and high $Q^2$ obtained using Spacal and LAr data

$E_p = 460, 575, 920$ GeV

use relative normalisation (the same for LAr and Spacal) of $E_p = 460, 575, 920$ GeV from the low $y$ data for the $F_L$ measurement
NC cross sections at the same x & Q² which involve both the LAr and Spacal data (H1)

\[ \tilde{\sigma}_{NC} = F_2 - \frac{y^2}{1+(1-y)^2} F_L \]

From linear fits at each x and Q² one determines \( F_L \) and \( F_2 \)

\( \rightarrow \) nice interplay of the two fully independent analyses using different detectors: Lar and Spacal
$F_L (x, Q^2)$ in the full $Q^2$ range using the LAr and Spacal data (H1)

H1 Preliminary $F_L$

| $Q^2$ (GeV$^2$) | $F_L (x, Q^2)$ |
|-----------------|----------------|
| 12              |                |
| 15              |                |
| 20              |                |
| 25              |                |
| 35              |                |
| 45              |                |
| 60              |                |
| 90              |                |
| 120             |                |
| 150             |                |
| 200             |                |
| 250             |                |
| 300             |                |
| 400             |                |
| 500             |                |
| 650             |                |
| 800             |                |

$E_p = 460, 575, 920$ GeV

H1 PDF 2000

medium $Q^2$ measurements are taken in the preliminary form
Averaged $F_L(Q^2)$ in the full $Q^2$ range (H1)

Spacal and LAR provide a cross check of the $F_L$ measurements

→ overall correlated systematics between $F_L$ points is $\delta F_L \approx 0.05-0.10$

medium $Q^2$ measurements are taken in the preliminary form

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FL measurements from HERA
Comparison of $F_L$ from H1 with recent theory predictions

$F_L = 0.27 \times F_2$ is motivated by Schildknecht et al. arXiv:0806.0202

$F_L$ measurements are in a good agreement with the NLO/NNLO QCD calculations

→ extension to $Q^2 < 10$ GeV$^2$ will provide an important constraint
Summary

The longitudinal structure function $F_L(x,Q^2)$ is measured at HERA in a model independent way using low $E_p$ data

H1:
- measured at medium and high $Q^2$: $12 \leq Q^2 \leq 800$ GeV$^2$
  using the $e^+p$ 2007 data collected with $E_p = 460, 575$ and $920$ GeV
- nice interplay of the two fully independent analyses which use two different detectors: LAr and Spacal
- measured $F_L(x,Q^2)$ is in agreement with the recent theoretical calculations in the QCD framework

ZEUS:
- measured in the range $24 \leq Q^2 \leq 110$ GeV$^2$
  using the $e^+p$ 2007 data collected with $E_p = 460$ and $920$ GeV
- measured $F_L(x,Q^2)$ consistent within errors with QCD calculations but also with $F_L=0$

→ more to come: $F_L$ at $Q^2<10$ GeV$^2$ (H1), analysis of $E_p=575$ GeV data (ZEUS), $F_L^D$, ...
Experimental challenge: $\gamma p$ bkg at high $y$

**ZEUSS:**
- $\gamma p$ background contribution in the $Q^2$-$y$ bins used for FL
  - $<2\%$ for $E_p = 920$ GeV ($y < 0.40$)
  - $10$-$15\%$ for $E_p = 460$ GeV ($y \approx 0.76$)

**H1:**
- the same binning in $x$ and $Q^2$ for all $E_p$ and LAr/Spacal
- measurements up to $y = 0.90$
- where $\gamma p$ bkg is up to $50\%$ and more
Electron identification & background suppression at high y

Electron is identified by compactness of the cluster in calorimeter and track pointing to the cluster.

Further reduction of γp background keeping high eff. for electron:

*Spacal sample*
- distance between extrapolated track and the electron cluster \( D < 6 \text{ cm} \)
- energy fraction behind the electron cluster \( E_h/E_e < 0.15 \)

*LAR sample at \( E_e < 6 \text{ GeV} \)*
- small transverse size of the electron cluster in LAR: \( E_{\text{cr}} < 4 \text{ cm} \)
- matching between track momentum and cluster energy: \( 0.7 < E_t^{\text{cluster}}/P_t^{\text{track}} < 1.5 \)