Proton Structure and QCD tests at HERA

Part 2
The proton structure function $F_2$

NLO QCD describes data over >4 orders of magnitude in $Q^2$ and $x$!
Fit works well even for very low $Q^2$ and $x$! ($\sim 1$ GeV$^2$, $\sim 0.00005$)
Including Jet data: The ZEUS-JETS NLO-QCD fit

Reasonable agreement:
With H1 PDF2000, MRST2001, CTEQ6
The global fits and their data

MRST
Martin, Roberts, Stirling, Thorne

CTEQ
Pumplin et al.

GRV
Glueck, Reya, Vogt

H1 and ZEUS,
using mainly HERA data
A great triumph and success for NLO QCD!

Such a big diversity of data,
all very well described,
with a common set of parameters,
and with a fit based only on pQCD and DGLAP!
ZEUSS: NC events at high x

Aim: Access data at x values higher than ever reached before
Previous HERA measurements reach 0.65
Fixed Target DIS data extend to 0.75 (BCDMS)
ZEUS: NC events at high $x$

Cross section in the highest $x$ bin “0-jet” events

MC simulation: High purity!

Lower edge, $x_{max}$ of highest bin
ZEUS: NC events at high $x$

Integral, divided by bin width

$e^+ p$  $e^- p$

Curves from Standard Model (CTEQ6D), describe data well (?)

$\Rightarrow$ look at ratio
ZEUS: NC events at high $x$

Ratio of measured cross sections to the Standard Model expectations, CTEQ6D

Deviations from SM seen at highest $x$

$e^+ p$  $e^- p$

$\Rightarrow$ Expect impact from these data on future PDF fits!
The larger $Q^2$ is, the more gluons are seen at low $x$.

Gluons split into $q\bar{q}$.

But $F_2 \propto x(q + \bar{q})$.

Thus the gluon “drives” the rise of $F_2$ at low $x$.

The dotted lines represent the Scaling Violations, given by the increasing gluon density.

LO DGLAP, low $x$:

$$\frac{dF_2}{d\ln Q^2} \sim \alpha_s x g(x)$$
The proton longitudinal structure function $F_L$

\[
\frac{d^2\sigma_{NC}^\pm}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ Y_F^2 + Y_F^3 \right] - y^2 \tilde{F}_L
\]

Neglect the small electroweak contributions in this region of the kinematic plane \( \Rightarrow \) Extract $F_L$ from data
Extraction of $F_L$ at high $Q^2$

$F_L$ is non-zero and falls between the extreme values of 0 and $F_2$ (low $y$ fit)

$e^+$ and $e^-$ results compatible

The $x$-dependence cannot be extracted, data cover too small a region
Extraction of $F_L$ at low $Q^2$

2 Methods are used for the extraction of $F_L$:

Extrapolation method

Derivative method

Consistent results in overlap region
Extraction of $F_L$ at low $Q^2$, Derivative method

\[
\left( \frac{\partial \sigma_r}{\partial \ln y} \right)_{Q^2} = \left( \frac{\partial F_2}{\partial \ln y} \right)_{Q^2} - F_L \cdot 2y^2 \cdot \frac{2-y}{Y_+^2} - \frac{\partial F_L}{\partial \ln y} \cdot \frac{y^2}{Y_+^2}
\]

Note: It is assumed that $dF_2/d\ln y$ is linear also at high $y$

Extraction, but not a measurement!
To obtain data at very high $y$ values, one must detect low energy electrons $\Rightarrow$ Photoproduction background! Estimate this background with opposite sign electrons.

### Data at very high $y$

$y = 0.89 \iff E_e = 3 \text{ GeV}$. 

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### Graphs

- **Data $+$**
- **Data $-$**
- **MC $+$**

- **3–6 GeV**
- **5–10 GeV**
Summary I: $F_L$ extractions

Minimum Bias low $Q^2$ data from 1996/97 and 1999/2000

Results extend to lower $x$, since proton energy increased to 920 GeV

Results extracted, using “Subtraction method” “Derivative method”

Results agree with the QCD fit of H1
By shifting the interaction point by +70 cm (in the proton direction) lower electron scattering angles can be detected, giving access to still lower $Q^2$ and $x$ values.

Also with this data sample, $F_L$ was extracted, using the derivative method.

However, one can do better!

The “shape method” gives smaller errors than the “derivative method”
Extraction of $F_L$, using the “Shape method”

Criticism of the “derivative method”:

- assumes a linear behaviour of $dF_2/d\ln y$
  with lny and extrapolates the information about $F_2$ from the low y region to the high y region.
- It does not make full use of the information provided by the cross section measurement in the intermediate y region
- Thus, for the linear fit the lowest points in y are used, and $F_L$ extracted only for the highest points in y.
- The result on $F_L$ consists in a few points very close in y, and with sizeable errors.
- The x-dependence of $F_L$ is not resolved

Better:

The “Shape Method”, so called since it utilizes the shape of the reduced cross section in a given $Q^2$ bin. The shape is driven by the kinematic factor $y^2/Y_+$

2 Assumptions:

- $F_L$ is constant in each $Q^2$ bin in high y range of sensitivity to $F_L$ via the $y^2$ term.
- $F_2$ behaves like a power of x at fixed $Q^2$

$$\sigma_{FIT} = c \cdot x^{-\lambda} - \frac{y^2}{1 + (1 - y)^2} F_L$$

Fit to data, extract c, lambda and $F_L$
Extraction of $F_L$ at low $Q^2$, using the “Shape method”

Shifted Vertex and MB99 data
Summary II: Extraction of $F_L$ in H1 data

3 orders of magnitude in $Q^2$

Reasonable agreement with NLO and NNLO pQCD

But, the $x$-dependence cannot be determined!

These are extractions! Need a direct measurement!
Measurement of $F_L$

Reduce the beam energies (e.g. $E_p$ to 500 GeV)

--> new value of CM energy

Measure the cross section at same values of $Q^2$ and $x$, for both beam energies

Since $Q^2 = x \, y \, s$

==> different value of $y$, for same values of $Q^2$ and $x$

$\sigma_1 - \sigma_2 = [(y^2/Y_+)_1 - (y^2/Y_+)_2] \cdot F_L$

Better still: measure at several different beam energies, and fit the cross sections!

Will this happen before the end of HERA operations, i.e. before July 2007?
Changing electron beam energy via ISR

Identifying ISR Events with the ZEUS Detector

- Standard DIS event selection:
  - identify scattered positron in main detector
- Identify ISR photon in luminosity monitor

![Diagram]

Normally used to identify photon in $ep \rightarrow ep\gamma$

Structure Function measurements using ISR events
It is a measurement!

BUT:

Need in fact very large statistics (200 \(\text{pb}^{-1}\))

Overlap at the same \(x\) and \(Q^2\) is in fact not very big

Pile-up of Bethe-Heitler events in photon detector is a problem

\[\Rightarrow\] huge errors!
Measurement of $F_2$ at low $Q^2$ and low $x$
H1: QED Compton events and $F_2$ at low $Q^2$

**Modified kinematics**

Access lower $Q^2$ and higher $x$

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

\[ x = \frac{Q^2}{2P \cdot (l - l' - k)} \]
$F_2$ measurement with QEDC events

Low $Q^2$ but higher $x$

Good agreement with the fixed target experiment results
Low $Q^2$ but higher x, with SVTX00 ISR events

Equivalent to inclusive DIS at reduced $s$

$$Q^2 = xys$$

**Access higher x**
Measurement of $F_2$ with SVTX00 ISR events

Very low $Q^2$

Small overlap with Fixed Target data
Measurements of $F_2$ at lowest $Q^2$

Extrapolation of H1 QCD Fit into the low $Q^2$ region

Fit uses data with $Q^2 > 3.5$ GeV$^2$

Undershoots data

NLO QCD not expected to work at these low $Q^2$ values
Measurements of $F_2$ at lowest $Q^2$

Virtual photon cross section,

$$\sigma_{\gamma^* p} \propto \frac{F_2}{Q^2}$$

as function of $Q^2$ at fixed

$$W^2 \approx s_y$$
Measurements of $F_2$ at lowest $Q^2$

Take the derivative

$$(d \ln F_2(x, Q^2)/d \ln x)_{Q^2} = -\lambda(x, Q^2)$$

Constant in $x$, at any given $Q^2$

$\lambda(x, Q^2) \implies$ Function of $Q^2$ only
F_2 at low Q^2

Rise of F_2 at low x can be parameterised as

\[ F_2(x, Q^2) = c(Q^2) x^{-\lambda(Q^2)} \]

\[ \lambda(Q^2) \] is \( \sim \) ln Q^2 above 3 GeV^2

\[ \lambda(Q^2) \] approaches the value 0.08 at lowest Q^2 -- Transition to “soft physics”
Theoretical description complicated by the presence of several “hard scales”, $Q^2$, $m^2_Q$ and $p_T^2$

Variable Flavour number schemes

Sensitivity to gluon distribution in proton (at high $Q^2$ up to 35% charm content!)
$F_2$ for heavy quarks, c and b

Vertex tracking to determine impact parameters of tracks

Determine signed impact parameter $\delta$
(Distance of Closest Approach)
and its Significance $S_i = \delta / \sigma(\delta)$
$F_2$ for heavy quarks, c and b

Define $S_1$, $S_2$, $S_3$ for the most significant track, 2$^{nd}$ most significant, etc.

In principle, heavy quark fractions can be fitted from these distributions.

From the fitted fractions of events, the $c\bar{c}$ and $b\bar{b}$ cross sections can be determined, as functions of $x$ and $Q^2$.

From these cross section measurements, $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ can be evaluated.

(The $F_L$ contribution is estimated from the NLO QCD expectation.)
$F_2$ for heavy quarks, $c$ and $b$

Consistent with the NLO QCD fit predictions

Shows the same features as $F_2$ for the light quarks
$F_2$ for heavy quarks, c and b
$F_2$ for heavy quarks, c and b

Summary of charm structure from HERA

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{hera_f2_summary}
\end{figure}
Events with isolated lepton and missing $p_T$
Events with isolated lepton and missing $p_T$

\[ e^+ p \rightarrow \mu^+ X \]

Event \text{MUON-2}

\[ P_T^{\mu} = 28 \text{ GeV}, P_T^X = 67 \text{ GeV}, P_T^{\text{miss}} = 43 \text{ GeV} \]
Events with isolated lepton and missing $p_T$
Events with isolated lepton and missing $p_T$

Some events agree with the SM process of $W$-production.

Others do not agree with the expected kinematics of this process.

(simulation data correspond to 500 times greater luminosity than the real data have)

Exotic, non-SM process: Anomalous top-quark production?
Why is Proton Structure important?
HERA and LHC: The importance of proton PDF's

Production of Higgs boson, top-antitop quark pairs...
To see the Higgs boson, you must know the background!

Proton structure, as explored at HERA, is absolutely vital for the discovery of the Higgs boson!
We wish the National Centre for Physics at Islamabad all the best for a bright future and a great success in their taking part in the LHC adventure at CERN.