Measurement of the Proton Structure Function $F_2$ in DIS at low $x$ and low $Q^2$

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Abstract

A measurement of the proton structure function $F_2(x, Q^2)$ in the kinematic range $2 < Q^2 < 15 \text{ GeV}^2$, $5 \times 10^{-5} < x < 2 \times 10^{-3}$ with the ZEUS detector at HERA is presented. The rise of $F_2$ with decreasing $x$ observed in the previous HERA measurements persists in this previously unmeasured $x$ and $Q^2$ region. The $Q^2$ evolution of $F_2$, even at the lowest $Q^2$ measured, is well described by perturbative QCD.

Résumé

Dans cet article, nous présentons une mesure de la fonction de structure du proton $F_2(x, Q^2)$ dans le domaine cinétique $2 < Q^2 < 15 \text{ GeV}^2$, $5 \times 10^{-5} < x < 2 \times 10^{-3}$ avec le détecteur ZEUS à HERA.

1. Introduction

In previous measurements [1] of the proton structure function, $F_2$, at the HERA $ep$ collider, $F_2$ was found to rise rapidly with decreasing $x$. The importance of this increase has been discussed extensively in the literature [2]. The rise of $F_2$ at low $x$ is equivalent to a strong rise in the virtual photon-proton cross section as a function of the $\gamma p$ centre-of-mass energy, $W$. This rise contrasts with the rather slow rise shown by the real photon photoproduction cross section as a function of $W$ [3]. In this paper a measurement of $F_2$ at large $W$ in a $Q^2$ region between the photoproduction data and previous $F_2$ measurements at HERA is presented. This has been made possible by a dedicated run in which the interaction point was shifted in the proton beam direction in order to increase the acceptance of low $Q^2$ deep inelastic scattering (DIS) events. In addition the acceptance of the ZEUS detector was improved at low $Q^2$ for the 1994 data taking period through the addition of a new detector component: the small angle rear tracking detector (SRTD). The shifted interaction point together with the SRTD has allowed ZEUS to measure $F_2$ at $Q^2$ as low as $2 \text{ GeV}^2$ and $x$ as low as $5 \times 10^{-5}$. This shifted vertex measurement is based on an integrated luminosity of $58 \pm 1.4 \text{ nb}^{-1}$ taken by ZEUS in October 1994. During this running period HERA collided $27.6 \text{ GeV}$ positrons with $820 \text{ GeV}$ protons.

2. The ZEUS Detector

ZEUS is a multipurpose detector that has been described elsewhere [4]. The components pertinent to
this analysis are the high resolution uranium scintillator calorimeter (CAL) [5], the SRTD, the luminosity monitor [6] and the inner tracking detectors [7]. The inner tracking detectors operating in a magnetic field of 1.43T provide a vertex resolution of 4 mm in Z and 1 mm in X and Y. The CAL is divided into three parts: forward, barrel and rear (FCAL, BCAL and RCAL) with each part subdivided into towers which in turn are subdivided longitudinally into electromagnetic (EMC) and hadronic (HAC) sections. The sections are subdivided into cells which in the RCAL have sizes of: 10 x 20 cm$^2$ (EMC) and 20 x 20 cm$^2$ (HAC). Under test beam conditions the CAL has an energy resolution of $\sigma/E = 18%/\sqrt{E(\text{GeV})}$ for electrons and $\sigma/E = 35%/\sqrt{E(\text{GeV})}$ for hadrons. The CAL also provides a time resolution of better than 1 ns for energy deposits greater than 4.5 GeV, which is used to reject non-$ep$ background. Luminosity information is obtained through the detection of quasi-elastic $ep \rightarrow ep\gamma$ events in the two lead scintillator calorimeters placed 35 m(e) and 107 m(γ) downstream of the main detector [6]. The SRTD consists of two planes of 1 cm wide scintillator strips arranged orthogonally and covering the region 68 x 68 cm$^2$ in X and Y on the face of the RCAL. The energy resolution is better than one minimum ionising particle (mip) while the time resolution is better than 2 ns. A cutout of 20 x 20 cm$^2$ at the face of the calorimeter accommodates the beampipe.

3. Deep Inelastic Kinematics

The kinematic variables relevant to the $F_2$ analyses are $x$, $Q^2$ and $\delta$ where $x$ and $Q^2$ are determined from the scattered positron's energy($E_\gamma$) and angle(\theta_{\gamma}) and $\delta$ is defined as: $\delta = \delta_h + \delta_e$; $\delta_h = \Sigma_i E_h(1 - \cos \theta_h)$; $\delta_e = E_\gamma(1 - \cos \theta_e)$. $E_h$ is the energy deposited in the calorimeter cell $h$ and the angle, $\theta_h$, is determined from the cell centre and event vertex. The sum $\delta_h$ excludes cells belonging to the scattered positron. For fully contained DIS events in the absence of QED initial state radiation and detector resolution effects: $\delta = 2E_e$, whereas for photoproduction events, where the scattered positron escapes down the beampipe, $\delta = 2(E_e - E_\gamma)$. A cut on $\delta$ thus rejects background from photoproduction and significantly reduces the radiative correction.

4. Event Selection and Backgrounds

Events are filtered online by a three level trigger system. At the first level, DIS events are selected based on energy deposits in the calorimeter consistent with an electromagnetic shower. The beam related background is rejected using the time measurement of the energy deposits from downstream veto counters and the SRTD. At the second level, backgrounds are further reduced using the times and summed energy quantities from the calorimeter. At the third level, the full detector information is available. Tighter timing and calorimeter cuts are applied. Events are selected for which a scattered positron, with a loose criteria, is identified. For this analysis, a total of $5.6 \times 10^4$ events were recorded and reconstructed offline.

For the final event selection the energy of the scattered positron measured in the calorimeter is corrected for the energy loss in inactive material in front of the calorimeter using a relation between the energy loss and the energy deposited in the SRTD. The SRTD energy correction is tuned using two separate data samples. Firstly, a "Kinematic-Peak" sample, where the scattered positron energy is closely peaked at the incident positron energy, as selected with the cut : $\delta_h < 0.06E_e$. Secondly, a sample of elastic QED Compton events where the photon and positron energies can be precisely determined from angle measurements of the photon and positron alone. The energy correction was cross checked with DIS elastic $\gamma p$ events where the scattered positron energy can be determined from tracking information alone. The positron energy scale is determined to be correct to $\sim 1\%$ after the corrections are applied.

The following requirements are set to select the final event sample: scattered positron energy (corrected) $> 8$ GeV - this ensures the probability of finding the scattered positron is high and reduces the photoproduction background where energy deposits in the calorimeter are falsely identified as positrons; impact point of the scattered positron on the face of the SRTD to be at least 3 cm from the inner edge of the SRTD and 1 cm away from the outer edge of the SRTD - this ensures full containment of the positron within the SRTD; $\delta$ for the event must be in the range 35 to 65 GeV - this reduces the photoproduction background and the size of the radiative corrections. Additionally a tracking vertex is required to be in the range 25 < $Z$ < 200 cm. For the events without a tracking vertex ($\sim 25\%$ of the data sample) the vertex is set to the nominal interaction point of $Z = 67$ cm. For all events the $X,Y$ of the vertex is taken from the nominal beam position of 1.2 mm($X$), -1.3 mm ($Y$). The distribution in the $x - Q^2$ plane of the 13800 events passing the above selection cuts is shown in Figure 1 along with the bins used for the $F_2$ analysis. For the bins shown the resolution in $x$ is 10% for the low $x$ bins increasing to 40% for the highest $x$ bins while the $Q^2$ resolution is $\sim 10\%$ for all bins. Non $ep$ backgrounds are negligible after the final selection cuts. The dominant background

† The ZEUS coordinate system is defined as right handed with the Z axis pointing in the proton beam direction and the X axis horizontal, pointing towards the centre of HERA.
is from photoproduction events. This background is estimated in two ways. The first method is based on a photoproduction Monte-Carlo (MC) [8] and the second uses a fit to the $\delta$ distribution within the bin. The two estimates agree within errors. The photoproduction background is significant only in the lowest $x$ bins where it is up to 10%.

5. $F_2$ Extraction

For the bins used in this analysis the $Z^0$, $F_L$, and radiative corrections are small such that the measured cross section can be expressed as:

$$\frac{d^3\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} F_2(1 + (1 - y)^2)(1 + \Delta),$$

where $\Delta$ incorporates the corrections due to $F_L$, $Z^0$ exchange and QED radiative effects. The $F_2$ extracted contains contributions from $\gamma^*$ exchange only. The size of $\Delta$ and the acceptance and event migration are corrected with an event sample generated using the HERACLES [9] Monte-Carlo. The hadronic final state is simulated using the colour-dipole model [10] incorporating boson-gluon fusion as implemented in ARIADNE [11] for the QCD cascade, and JETSET [12] for the hadronisation. The detector simulation is based on the GEANT [13] program. The MC distributions show good agreement with the data in both shape and normalisation as is shown in Figure 2. The systematic errors were calculated by varying selection cuts and the analysis procedure. The systematics are typically large at the lowest-$x$ points due to the uncertainty in the positron identification and at the highest-$x$ points due to the uncertainty in the positron energy scale. The systematics of the positron angle determination are found to be small. A variety of other consistency checks and systematic variations not listed here were also performed to obtain the final systematic error. The total systematic error for this preliminary analysis is typically 10–20% to be compared with the statistical error of $\sim 5\%$. The preliminary $F_2$ values are shown in Figure 3 as a function of $x$ in the $Q^2$ range $2 < Q^2 < 15 GeV^2$.

6. Discussion

In Figure 3 the $F_2$ values are compared to parameterisations derived from fits to data and evolved using perturbative QCD. In the low $x$ region the MRSA' [14] and CTEQ3 [15] parameterisations are based on fits to previous higher $Q^2$ HERA $F_2$ data. The GRV [16] parameterisation is only fitted to high $x$ data and derives the rise in $F_2$ at low $x$ from an evolution in $Q^2$ from valence-like partons at a low starting scale of $Q_0^2 = 0.4 GeV^2$. The
Figure 3. The $F_2$ values obtained from the shifted vertex run as a function of $x$ at various $Q^2$ values (in GeV$^2$). Also shown are the latest parameterisations from MRS, CTEQ and GRV as well as the Regge inspired prediction of Donnachie and Landshoff (for $Q^2 < 6$ GeV$^2$).

$F_2$ values are well described by these parameterisations. In contrast, the Regge inspired model of Donnachie and Landshoff [17] is found not to describe the data even at the lowest $Q^2$ values covered by this analysis. The strong rise of $F_2$ with decreasing $x$ is equivalent to a strong rise in the virtual-photon proton total cross section which is in contrast to the comparatively slow rise exhibited by the total photoproduction cross section. This is illustrated in Figure 4. This fast rise is seen to persist down to $Q^2 = 2$ GeV$^2$, indicating that the transition to the energy behaviour of the photoproduction cross section occurs at yet smaller $Q^2$.

References
