Figure 19.8: The proton structure function $F_p^2$ measured in electromagnetic scattering of electrons and positrons on protons (collider experiments H1 and ZEUS for $Q^2 \geq 2 \text{ GeV}^2$), in the kinematic domain of the HERA data (see Fig. 19.10 for data at smaller $x$ and $Q^2$), and for electrons (SLAC) and muons (BCDMS, E665, NMC) on a fixed target. Statistical and systematic errors added in quadrature are shown. The H1+ZEUS combined values are obtained from the measured reduced cross section and converted to $F_p^2$ with a HERAPDF NLO fit, for all measured points where the predicted ratio of $F_p^2$ to reduced cross-section was within 10% of unity. The data are plotted as a function of $Q^2$ in bins of fixed $x$. Some points have been slightly offset in $Q^2$ for clarity. The H1+ZEUS combined binning in $x$ is used in this plot; all other data are rebinned to the $x$ values of these data. For the purpose of plotting, $F_p^2$ has been multiplied by $2^i_x$, where $i_x$ is the number of the $x$ bin, ranging from $i_x = 1$ ($x = 0.85$) to $i_x = 24$ ($x = 0.00005$). References: H1 and ZEUS—H. Abramowicz et al., Eur. Phys. J. C75, 580 (2015) (for both data and HERAPDF parameterization); BCDMS—A.C. Benvenuti et al., Phys. Lett. B223, 485 (1989) (as given in [86]); E665—M.R. Adams et al., Phys. Rev. D54, 3006 (1996); NMC—M. Arneodo et al., Nucl. Phys. B483, 3 (1997); SLAC—L.W. Whitlow et al., Phys. Lett. B282, 475 (1992).
Figure 19.9: The deuteron structure function $F_2^d$ measured in electromagnetic scattering of electrons (SLAC) and muons (BCDMS, E665, NMC) on a fixed target, shown as a function of $Q^2$ for bins of fixed $x$. Statistical and systematic errors added in quadrature are shown. For the purpose of plotting, $F_2^d$ has been multiplied by $2^{i_x}$, where $i_x$ is the number of the $x$ bin, ranging from 1 ($x = 0.85$) to 29 ($x = 0.0009$).

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Figure 19.10: a) The deuteron structure function $F_2$ measured in deep inelastic scattering of muons on a fixed target (NMC) is compared to the structure function $F_2$ from neutrino-iron scattering (CCFR and NuTeV) using $F_2^D = (5/18)F_2^\mu - x(s + \bar{s})/6$, where heavy-target effects have been taken into account. The data are shown versus $Q^2$, for bins of fixed $x$. The NMC data have been rebinned to CCFR and NuTeV $x$ values. For the purpose of plotting, a constant $c(x) = 0.05i_x$ is added to $F_2$, where $i_x$ is the number of the $x$ bin, ranging from 0 ($x = 0.75$) to 7 ($x = 0.175$). For $i_x = 8$ ($x = 0.125$) to 11 ($x = 0.015$), $2c(x)$ has been added. References: NMC—M. Arneodo et al., Nucl. Phys. B483, 3 (1997); CCFR/NuTeV—U.K. Yang et al., Phys. Rev. Lett. 86, 2741 (2001); NuTeV—M. Tzanov et al., Phys. Rev. D74, 012008 (2006).

b) The proton structure function $F_2^p$ mostly at small $x$ and $Q^2$, measured in electromagnetic scattering of electrons and positrons (H1, ZEUS), electrons (SLAC), and muons (BCDMS, NMC) on protons. Lines are ZEUS Regge and HERAPDF parameterizations for lower and higher $Q^2$, respectively. The width of the bins can be up to 10% of the stated $Q^2$. Some points have been slightly offset in $x$ for clarity. The H1+ZEUS combined values for $Q^2 \geq 3.5$ GeV$^2$ are obtained from the measured reduced cross section and converted to $F_2^p$ with a HERAPDF NLO fit, for all measured points where the predicted ratio of $F_2^p$ to reduced cross-section was within 10% of unity. A turn-over is visible in the low-$x$ points at medium $Q^2$ (3.5 GeV$^2$ and 6 GeV$^2$) for the H1+ZEUS combined values. In order to obtain $F_2^p$ from the measured reduced cross-section, $F_L$ must be estimated; for the points shown, this estimate is obtained from HERAPDF2.0. No $F_L$ value consistent with the HERA data can eliminate the turn-over. This may indicate that at low $x$ and $Q^2$ there are contributions to the structure functions that cannot be described in standard DGLAP evolution.


Statistical and systematic errors added in quadrature are shown for both plots.
Figure 19.11: a) The charm-quark structure function $F_2^{cc}(x)$, i.e. that part of the inclusive structure function $F_2^p$ arising from the production of charm quarks, measured in electromagnetic scattering of positrons on protons (H1, ZEUS) and muons on iron (EMC). For the purpose of plotting, a constant $c(Q) = 0.07iQ^{1.7}$ is added to $F_2^{cc}$ where $iQ$ is the number of the $Q^2$ bin, ranging from 1 ($Q^2 = 2.5$ GeV$^2$) to 12 ($Q^2 = 2000$ GeV$^2$). References: H1 and ZEUS run I combination—H. Abramowicz et al., Eur. Phys. J. C73, 2311 (2013); ZEUS run II—H. Abramowicz et al., JHEP 05, 023 (2013); H. Abramowicz et al., JHEP 05, 097 (2013); H. Abramowicz et al., JHEP 09, 127 (2014); EMC—J.J. Aubert et al., Nucl. Phys. B213, 31 (1983).

b) The bottom-quark structure function $F_2^{bb}(x)$. For the purpose of plotting, a constant $c(Q) = 0.01iQ^{1.6}$ is added to $F_2^{bb}$ where $iQ$ is the number of the $Q^2$ bin, ranging from 1 ($Q^2 = 5$ GeV$^2$) to 12 ($Q^2 = 2000$ GeV$^2$). References: ZEUS—S. Chekanov et al., Eur. Phys. J. C65, 65 (2010); H. Abramowicz et al., Eur. Phys. J. C69, 347 (2010); H. Abramowicz et al., Eur. Phys. J. C71, 1573 (2011); H. Abramowicz et al., JHEP 09, 127 (2014); H1—F.D. Aaron et al., Eur. Phys. J. C65, 89 (2010).

For both plots, statistical and systematic errors added in quadrature are shown. The data are given as a function of $x$ in bins of $Q^2$. Points may have been slightly offset in $x$ for clarity. Some data have been rebinned to common $Q^2$ values. Also shown is the MMHT2014 parameterization given at several $Q^2$ values (L. A. Harland-Lang et al., Eur. Phys. J. C75, 204 (2015)).
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Figure 19.12: The structure function $x F_3^{\gamma Z}$ measured in electroweak scattering of a) electrons on protons (H1 and ZEUS) and b) muons on carbon (BCDMS). The line in a) is the HERAPDF parameterization. References: H1 and ZEUS—H. Abramowicz et al., Eur. Phys. J. C75, 580 (2015) (for both data and HERAPDF parameterization); BCDMS—A. Argento et al., Phys. Lett. B140, 142 (1984).

c) The structure function $x F_3$ of the nucleon measured in $\nu$-Fe scattering. The data are plotted as a function of $Q^2$ in bins of fixed $x$. For the purpose of plotting, a constant $c(x) = 0.5(i_x - 1)$ is added to $x F_3$, where $i_x$ is the number of the $x$ bin as shown in the plot. The NuTeV and CHORUS points have been shifted to the nearest corresponding $x$ bin as given in the plot and slightly offset in $Q^2$ for clarity. References: CCFR—W.G. Seligman et al., Phys. Rev. Lett. 79, 1213 (1997); NuTeV—M. Tzanov et al., Phys. Rev. D74, 012008 (2006); CHORUS—G. ¨Oneng¨ut et al., Phys. Lett. B632, 65 (2006).

Statistical and systematic errors added in quadrature are shown for all plots.
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Figure 19.13: Top panels: The longitudinal structure function $F_L$ as a function of $x$ in bins of fixed $Q^2$ measured on the proton (except for the SLAC data which also contain deuterium data). BCDMS, NMC, and SLAC results are from measurements of $R$ (the ratio of longitudinal to transverse photon absorption cross sections) which are converted to $F_L$ by using the BDCMS parameterization of $F_2$ (A.C. Benvenuti et al., Phys. Lett. B223, 485 (1989)). It is assumed that the $Q^2$ dependence of the fixed-target data is small within a given $Q^2$ bin. Some of the other data may have been rebinned to common $Q^2$ values. Some points have been slightly offset in $x$ for clarity. Also shown is the MSTW2008 parameterization given at three $Q^2$ values (A.D. Martin et al., Eur. Phys. J. C63, 189 (2009)). References: H1—V. Andreev et al., Eur. Phys. J. C74, 2814 (2014); ZEUS—S. Chekanov et al., Phys. Lett. B682, 8 (2009); H. Abramowicz et al., Phys. Rev. D90, 072002 (2014); BCDMS—A. Benvenuti et al., Phys. Lett. B223, 485 (1989); NMC—M. Arneodo et al., Nucl. Phys. B483, 3 (1997); SLAC—L.W. Whitlow et al., Phys. Lett. B250, 193 (1990) and numerical values from the thesis of L.W. Whitlow (SLAC-357).


The results shown in the bottom plot require the assumption of the validity of the QCD form for the $F_2$ structure function in order to extract $F_L$. Statistical and systematic errors added in quadrature are shown for both plots.
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Figure 19.15: The hadronic structure function of the photon $F_2^\gamma$ divided by the fine structure constant $\alpha$ measured in $e^+e^-$ scattering, shown as a function of $Q^2$ for bins of $x$. Data points have been shifted to the nearest corresponding $x$ bin as given in the plot. Some points have been offset in $Q^2$ for clarity. Statistical and systematic errors added in quadrature are shown. For the purpose of plotting, a constant $c(x) = 1.5i_x$ is added to $F_2^\gamma/\alpha$ where $i_x$ is the number of the $x$ bin, ranging from 1 ($x = 0.0055$) to 8 ($x = 0.9$).