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OBSERVATION OF SHADOWING OF NEUTRINO AND ANTINEUTRINO - NUCLEUS INTERACTIONS AND COMPARISON WITH PCAC PREDICTIONS

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ABSTRACT

Comparing the kinematical distributions of events obtained on neon and deuterium targets in similar experimental conditions reveals a reduction of the neutrino and antineutrino charged current cross section per nucleon in neon at low Q^2 . The effect, interpreted as due to geometric shadowing of the weak propagator in interactions of neutrinos and antineutrinos with nuclei, agrees well with predictions derived from PCAC.

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1. Introduction

It was predicted by Bell^[1] that in certain kinematical conditions inelastic neutrino and antineutrino interactions on nuclei should show a shadowing effect like the one observed in inelastic pion interactions^[2], i.e. the cross section should depend less than linearly on the mass number A of the nucleus. The prediction was based on Adler's theorems^[3]. These state that the cross section for (anti)neutrino scattering with the muon emerging parallel to the incident (anti)neutrino (i.e. for scattering at zero Q^2) (i) depends on the divergences of the vector and axial vector currents and (ii) – assuming conservation of the vector current (CVC)^[4] and partial conservation of the axial current (PCAC)^[5] – is given by a PCAC-induced term which is proportional to the pion cross-section on the same target.

Tests of the presence of the predicted PCAC term and of its dominance at sufficiently low Q^2 have since been performed successfully for both nuclear^[6,7] and nucleon^[8] targets. However, searches for the shadowing effect in (anti)neutrino interactions^[9] have so far proved inconclusive. The pion-like propagation of the PCAC term in nuclear matter therefore remains undemonstrated.

Following Bell, Stodolsky^[10] predicted that a similar shadowing effect should occur in real and virtual photon interactions. This has meanwhile been confirmed, studied experimentally in some detail^[11], and largely explained in terms of the Glauber formalism and the Vector Meson Dominance model.

In this model, shadowing of the electromagnetic current at low Q^2 is dominated by the lightest vector meson, the ρ meson. If shadowing of the weak axial vector current at zero Q^2 is dominated not by the lightest axial vector meson, the a_1 , but instead by the pion, as predicted by PCAC, then shadowing should set in at lower ν values in neutrino interactions than in electron and muon interactions.

2. The theoretical prediction

For shadowing to occur, the virtual $W^\pm$ must fluctuate into a virtual hadron system (in meson dominance models, a virtual meson) and the fluctuation length must exceed the nucleon dimensions (~ 1 fm) and be at least comparable with the hadron absorption length inside nuclear matter (~ 2.3 fm for $\sigma \sim 25$ mb). Fluctuation into a hadron of mass m requires a change in momentum squared, $\Delta(p^2)$, equal to $m^2 - (-Q^2)$. Hence, since $\Delta(p^2) = 2p\Delta p$ and $\Delta p\Delta d \sim 1$, the fluctuation length Δd must be $\sim \frac{2p}{m^2 + Q^2} \simeq \frac{2\nu}{m^2 + Q^2}$. For the fluctuation length to exceed L fm, $\frac{m^2 + Q^2}{2\nu}$ must be below $0.197 \text{ GeV}/L$. Therefore the value of the scaling variable x must be sufficiently low, below about 0.2, and the energy transfer ν must be sufficiently high, larger than about λm^2 where $\lambda = 2.5 \text{ GeV}^{-1}$.

In fact, a meson dominance model^[12,13] successfully describes not only the cross sections and ν and Q^2 distributions for coherent single pion production^[6] and coherent ρ^- production^[14], but also the total neutrino and antineutrino cross sections at low Q^2 ^[8]. For the total cross section per nucleon in deuterium this model, in simplified form, gives

$$\frac{d^2\sigma_{\nu,\bar{\nu}}^D}{dx dy} = \frac{G^2 M E}{\pi^2} \{T_\pi + T_\rho + T_{a_1}\} \quad (1)$$

where

$$\begin{aligned} T_\pi &= f_\pi^2 \left\{ (1-y) \left(\frac{m_{a_1}^2}{m_{a_1}^2 + Q^2} \right)^2 - y \frac{m_{a_1}^2}{m_{a_1}^2 + Q^2} \frac{m_\mu^2}{m_\pi^2 + Q^2} + \frac{y^2}{4} \frac{m_\mu^2(m_\mu^2 + Q^2)}{(m_\pi^2 + Q^2)^2} \right\} \sigma_\pi \\ T_\rho &= f_{\rho^\pm}^2 Q^2 \left\{ \left(1 - y + \frac{y^2}{2} \right) \left(\frac{1}{m_\rho^2 + Q^2} \right)^2 \right\} (1 + \epsilon R_\rho(Q^2)) \sigma_\rho^T \\ T_{a_1} &= f_{a_1}^2 Q^2 \left\{ \left(1 - y + \frac{y^2}{2} \right) \left(\frac{1}{m_{a_1}^2 + Q^2} \right)^2 \right\} (1 + \epsilon R_{a_1}(Q^2)) \sigma_{a_1}^T \end{aligned}$$

where σ_π , σ_ρ^T and $\sigma_{a_1}^T$ are the virtual hadron-nucleon (transverse) cross sections, $R = \sigma^L/\sigma^T$ is the ratio of longitudinal to transverse cross sections, $\epsilon = \frac{4E(E-\nu)-Q^2}{4E(E-\nu)+Q^2+2\nu^2} \sim \frac{1-y}{1-y+\frac{y^2}{2}}$ is the polarisation parameter, $f_\pi^2 = (0.93m_\pi)^2$ and $f_{a_1}^2 = f_{\rho^\pm}^2 = 2f_{\rho^0}^2 = 0.030 \text{ GeV}^4$.

The T_ρ and T_{a_1} terms correspond to fluctuations of the virtual $W^\pm$ into ρ and a_1 mesons. Assuming CVC, R_ρ vanishes at $Q^2 = 0$. The T_π term is the term whose presence is predicted by PCAC. Only the last of its three parts is the pion pole term itself. Its second part is an interference term. Both of these parts are small for $Q^2 \gg m_\pi^2$. The presence of the a_1 propagator factor in the first part of T_π is not predicted by PCAC, which determines the form of T_π only at Q^2 values much below $m_{a_1}^2$, but it is strongly supported by the data on coherent pion production^[6]. It was originally^[12] motivated by Vector Meson Dominance and by the identification of the first part of T_π with the part of the longitudinal a_1 pole term that does not vanish as Q^2 approaches zero. Alternatively^[15], the first part of the T_π term may be identified with the $\rho\pi$ cut contribution (fluctuations of the virtual $W^\pm$ into non-resonant $\rho\pi$ states).

According to Bell's optical model treatment^[1], in the eikonal approximation the effect of nuclear matter on the amplitude ψ of the virtual hadron wave accompanying an incident lepton can be written as

$$\frac{d\psi}{dz} = \frac{m^2 + Q^2 + V}{2iq} \psi + \frac{m^2 + Q^2}{2iq} \psi_0 \quad (2)$$

where ψ_0 is the corresponding amplitude outside nuclear matter, m and q are the hadron mass and momentum, and V is the potential due to the presence of nuclear matter. The first term represents the attenuation of the virtual hadron wave by the nuclear matter and the off-mass-shell effects; the second represents its re-generation by the lepton. At high energies the potential V is mostly absorptive and given by

$$-Im(V) \simeq \rho \sigma q \quad (3)$$

where ρ is the nucleon density, σ the virtual hadron nucleon cross section, in order to make $d\psi/dz = -\rho\sigma\psi/2$ for real hadrons. From (2) and (3), one can calculate the hadron wave intensity I for any point inside the nucleus, corresponding to a given incident hadron wave intensity I_0 . If both Pauli Exclusion Principle effects and coherent production processes are neglected, averaging I/I_0 appropriately over the nucleon density distribution gives the shadowing factor

$$S = \langle I/I_0 \rangle \quad (4)$$

which is a function of Q^2 , ν and m . The total cross section per nucleon in neon is then given by

$$\frac{d^2\sigma_{\nu,\bar{\nu}}^{Ne}}{dx dy} = \frac{G^2 M E}{\pi^2} \{ S_\pi^{Ne} T_\pi + S_\rho^{Ne} T_\rho + S_{a_1}^{Ne} T_{a_1} \} \quad (5)$$

where S_π^{Ne} , S_ρ^{Ne} and $S_{a_1}^{Ne}$ are the shadowing factors for neon with $m = m_\pi$, m_ρ and m_{a_1} respectively. It is important to note that, at zero Q^2 , PCAC requires^[1] all of T_π to be shadowed by the factor S_π , even though the pion pole contribution itself is small. We assume this is true also for non-zero Q^2 .

Our numerical calculations assumed 2-parameter or 3-parameter Fermi parametrizations^[16] for the nucleon density distributions. The virtual hadron-nucleon cross sections σ_π , σ_ρ and σ_{a_1} were all taken to be the same as the real pion-nucleon cross section at the same ν value. R_ρ and R_{a_1} were assumed to be zero. Using Generalised Vector Dominance^[17], the applicability of the model was extended to higher Q^2 by adding a spectrum of higher mass vector and axial vector mesons equally spaced in mass-squared which, with increasing mass, couple more strongly to the W boson and correspondingly less strongly to the nucleon. Finally, over the whole x range a factor depending linearly on x with an A -dependent slope determined by the data of Arnold et al^[18] in the range $0.3 < x < 0.6$ was included to allow for the EMC effect. It is shown below that, with these extensions, the model agrees sufficiently well for present purposes with data on shadowing in electron and muon scattering.

3. The experimental data

For the data used in this analysis, the Big European Bubble Chamber (BEBC) was filled in turn with a heavy neon-hydrogen mixture (75 mole-% neon) and with deuterium and, with each filling, exposed to both the neutrino and the anti-neutrino wide band beam produced by 400 GeV protons from the CERN SPS. This analysis uses almost 20,000 neutrino and anti-neutrino charged current events in neon (experiment WA59) and about 16,000 in deuterium (experiment WA25).

To reduce systematic effects, the events were required to have a muon of momentum above 5 GeV, to have an estimated neutrino or antineutrino energy $E_{\nu,\bar{\nu}}$ between 15 and 160 GeV, and to lie in the overlap of the fiducial volumes of the WA25 and WA59 experiments. To avoid systematic errors due to the different detection efficiencies of photons and neutrons in neon and deuterium, $E_{\nu,\bar{\nu}}$ was estimated using solely the charged particle tracks from the event vertex and from associated K^0 or Λ^0 decays:

$$E_{\nu,\bar{\nu}} = P_L^\mu + \frac{\langle P_T^\mu \rangle}{\langle P_T^{ch} \rangle} P_L^{ch}, \quad (6)$$

where P_L^μ and P_L^{ch} are respectively the longitudinal momentum of the muon and the sum of the longitudinal momenta of the other charged particles. The values of $\langle P_T^\mu \rangle$ (the average transverse momentum of the muon) and $\langle P_T^{ch} \rangle$ (the average resultant transverse momentum of the other charged particles projected into the lepton plane) are averages, for each combination of beam and target separately, over all events satisfying the energy and muon momentum cuts. Other kinematical variables were then calculated from $E_{\nu,\bar{\nu}}$, P_L^μ and P_T^μ . A more detailed discussion of the experimental conditions and procedure has been presented elsewhere^[19].

The ratio of the cross sections per nucleon between neon and deuterium targets for $x < 0.2$ is shown as a function of Q^2 in figures 1(a) – 1(c). Figures 1(a) and 1(b) show the neutrino and anti-neutrino ratios, $\frac{1}{20}\sigma^{\nu Ne}/\frac{1}{2}\sigma^{\nu D} = (A_{eff}/A)^{\nu Ne}$ and $\frac{1}{20}\sigma^{\bar{\nu} Ne}/\frac{1}{2}\sigma^{\bar{\nu} D} = (A_{eff}/A)^{\bar{\nu} Ne}$, while figure 1(c) shows their weighted average. The relative normalisations of the neon and deuterium data sets used here assume that the total neutrino and antineutrino cross sections per nucleon are equal in neon and deuterium, *ie* that $(A_{eff}/A)^{(\nu,\bar{\nu})Ne} = 1$ on average over the total event sample.

Figure 2 shows the dependence of the combined neutrino and antineutrino data on x in bins of Q^2 . Figure 3 displays the combined data in the bin $Q^2 < 0.2$, $x < 0.2$ as a function of the energy transfer to the hadron system, $\nu = Q^2/2Mx$ where M is the nucleon mass, and as a function of the invariant mass of the final state hadron system, $W = [Q^2(\frac{1}{x} - 1) + M^2]^{\frac{1}{2}}$. In this bin, the mean values of ν and W are 4.7 and 2.9 GeV respectively; 30% (45%) of the events have $\nu < 1(2)$ GeV.

In all three figures, the full curves show our evaluation of the shadowing effect predicted by Bell, taking into account the energy spectra of the neutrino and antineutrino beams, the cuts, the experimental resolution, and our relative normalisation procedure. Note that the prediction does not depend on any free parameters that could be adjusted to fit our data. The total Ne/D cross section ratio per nucleon is predicted by the model to be 0.975, in agreement with the measured value^[19] of 1.00 ± 0.03 .

For the combined neutrino and antineutrino data points with Q^2 below 1 GeV² shown in figure 1(c), the χ^2/N_D values are 21.3/4 for the hypothesis that $(A_{eff}/A) = 1$ and 4.2/4 for the full curve. The difference in χ^2 of 17.1 corresponds to a 4.1 standard deviation signal. Thus the cross section per nucleon in neon is depleted relative to that in deuterium at low Q^2 , as predicted for shadowing.

4. Discussion

Table 1 shows the neon/deuterium ratios of cross sections per nucleon after various selections in order to study systematic effects. Rows 1 and 2 show the ratios obtained when estimating $E_{\nu,\bar{\nu}}$ from (6) by (i) evaluating the ratio $\frac{\langle P_T^\mu \rangle}{\langle P_T^{ch} \rangle}$ averaged over the whole data sample as described

above and by (ii) evaluating the ratio as a function of P_L^{ch} . Within errors, the results are the same. Furthermore, folding the experimental resolution into the curves shown in the figures did not change them perceptibly. Thus the signal is not significantly distorted by the experimental resolution.

The non-isoscalarity of our neon-hydrogen mixture is sufficiently small that its effects can be neglected.

The Pauli exclusion principle and coherent meson production might introduce a non-linear A dependence of the cross section, particularly at low Q^2 , and therefore need more discussion.

The reaction $\nu p \rightarrow \mu \pi p$ observed in hydrogen^[20] shows an enhanced cross section at low $|t|$ which can be described by a diffractive model^[21] (where t is the square of the 4-momentum difference between the incoming and outgoing nucleons[†]). Such reactions will also occur both in neon and in deuterium. But in neon, in particular, the phase space available to the recoil nucleon will be limited^[22] by the Pauli exclusion principle unless its momentum exceeds the maximum Fermi momentum in neon (~ 230 MeV/c^[23]); the cross section will therefore be reduced. The hydrogen data, taken in the same neutrino beam, give insight into the possible magnitude of such Pauli exclusion effects. For Q^2 below 0.2 GeV² and x below 0.2 , $\sim 10\%$ of all νp events, $\sim 15\%$ of those with $\nu < 2$ GeV and $\sim 6\%$ of those with $\nu > 2$ GeV, have a secondary proton of momentum below 300 MeV/c. But if all $\nu p \rightarrow \mu \pi p$ events with $|t| < 0.2$ GeV² are removed, the proportion of νp events having such a proton falls to only $\sim 2\%$ in all cases.

At such low $|t|$ values, not only is scattering off single nucleons suppressed by the Pauli exclusion principle, but constructive interference between the amplitudes for scattering off different nucleons gives rise to coherent meson production^[24]. In general, in the absence of shadowing and reabsorption and threshold ($|t_{min}|$) effects, the cross sections for coherent production would vary as A^2/R^2 , where R is the nuclear radius, rather than varying linearly with A . As has been seen in part of these data^[25], the dominant coherent process is single pion production which occurs mainly at $|t|$ values below ~ 0.1 GeV² (these are the 2-prong events $(\nu, \bar{\nu}) + \text{Nucleus} \rightarrow \mu^\pm \pi^\mp + \text{Nucleus}$).

Removing all 2-prong events with values of $|t|$ below 0.1 or 0.2 GeV² should therefore eliminate most of the effects both of coherent production and of the Pauli exclusion principle. Rows 3 and 4 of table 1 show the effects on our results of making such cuts. They are small. Removing all 2-prong events with values of $|t|$ below 0.2 GeV² from the combined data changes A_{eff}/A from 0.79 ± 0.05 to 0.79 ± 0.06 . Therefore the observed signal cannot be attributed to these effects and, within our statistical errors, is substantially unaltered by them.

Differences in Fermi motion, nuclear reinteractions and measurement errors between neon and deuterium may cause the observed x and Q^2 distributions to be distorted differently. This was evaluated using a Monte Carlo program^[26] that simulated these effects in detail. Row 5 in table 1 shows the cross section ratios expected due to the differences in Fermi motion and reinteractions only. In row 6, the differences in measurement error are also included. All three effects are seen to be negligible.

Our evaluation of the theoretical prediction contains a number of approximations. The best values to use for the virtual hadron-nucleon cross sections are particularly unclear at low ν . However, neither the curves nor the data change substantially if ν is required to exceed 2 GeV, except

[†] Provided the kinetic energy transfer to the target is much less than its mass, $|t|$ is well approximated by

$$|t| = \left(\sum_i [E^i - p_L^i] \right)^2 + \left(\sum_i \vec{p}_T^i \right)^2$$

For consistency, since the recoiling target is not observed in neon, we compute $|t|$ in this way throughout this analysis. The sum is taken over the muon and all charged hadrons except identified protons below 500 MeV/c, which are also not counted as ‘prongs’ (see below). All hadrons with momentum above 500 MeV/c are called pions, in all data sets, to eliminate differences in particle identification efficiency.

that the statistical errors increase for Q^2 below 0.5 GeV^2 (*cf* table 1). The neglected (V, A) interference term is small in the kinematic region of interest here and largely cancels in the combined neutrino and antineutrino data. Giving R_ρ or R_{a_1} large values instead of zero has little effect. Thus the predicted curves and their agreement with the data are not very sensitive to these approximations.

Other aspects of the model can be checked by dropping the non-vector pieces from the cross section and comparing the resulting predictions with data on shadowing in electron or muon scattering. Figure 4 shows such comparisons. The agreement is quite satisfactory. Including the higher mass vector mesons and the EMC effect factor has allowed the high Q^2 data shown in figure 4(a) to be described well, including both the shadowing effect at low x and the ‘anti-shadowing’ effect at intermediate x . While figure 4(b) suggests that the model may overestimate the size of the shadowing effect at low Q^2 , especially for light nuclei, the discrepancy may not be significant if full account is taken of the systematic and normalisation errors in the data.

The model predicts that the shadowing effect depends strongly on x . For fixed x , Q^2 and ν vary together and the predicted Q^2 and ν dependences are rather weak until the Q^2 and ν values become so small that $\nu \leq 2.5m_\rho^2$ where, following the uncertainty principle argument given earlier, the shadowing effect switches off. The possible discrepancy in figure 4(b) suggests that as Q^2 and ν fall, shadowing may switch off faster than the model predicts.

The predictions for our (anti)neutrino data shown in figures 1-3 depend relatively weakly on the details of the shadowing model since, at the rather low ν values ($\nu = Q^2/2Mx$) typical of these data, the shadowing factor S_π has a large effect whereas S_ρ already has a relatively small effect and S_{a_1} and the higher-mass terms a negligible effect. Consequently the form of the full curve shown in figure 1 mainly reflects the changing relative importance, as a function of Q^2 , of the contribution of the strongly shadowed T_π term to the total cross section. At small Q^2 its contribution is approximately independent of Q^2 while the contributions of the weakly shadowed vector and axial vector terms, T_ρ and T_{a_1} , rise linearly with Q^2 to become equal to T_π at $Q^2 \sim 0.2 \text{ GeV}^2$. This produces an explicit Q^2 dependence in addition to the x dependence.

The presence of the a_1 propagator in the first term of T_π might suggest that the shadowing factor S_{a_1} should be applied to it. This would give the dashed curves shown in the figures, which do not fit the data for Q^2 below 0.2 GeV^2 . Our observation of a large shadowing effect at very small Q^2 and small ν in neutrino and antineutrino scattering is therefore a demonstration of the pion-like behaviour of the T_π term in nuclear matter predicted by PCAC.

5. Conclusions

We have compared the kinematical distributions of both neutrino and antineutrino events obtained on neon and deuterium targets in similar experimental conditions. The comparison reveals a depletion of the charged current cross section per nucleon in neon at very low Q^2 . The depletion cannot be interpreted as due to instrumental effects or to Pauli exclusion effects or to coherent interactions. Interpreted as due to geometric shadowing of the weak propagator, however, it agrees well with predictions derived from PCAC. In particular, the data confirm the PCAC prediction that the propagation of the weak current through nuclear matter at low Q^2 (below about 0.2 GeV^2) is dominated by the pion.

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Table 1: Neon/deuterium ratios of cross sections per nucleon, A_{eff}/A , for $Q^2 < 0.2 \text{ GeV}^2$ and $x < 0.2$ under various cuts and conditions to study systematic effects. Rows 5 and 6 show Monte Carlo estimates of some of these effects. The values are given separately for the neutrino data, for the antineutrino data, and for the combined neutrino and antineutrino data. The values obtained when the energy transfer ν is required to exceed 2 GeV are given in brackets.

Cuts and conditions		$(A_{eff}/A)_\nu$	$(A_{eff}/A)_{\bar{\nu}}$	$(A_{eff}/A)_{\nu+\bar{\nu}}$
1	P_L^{ch} -independent correction ($\nu > 2 \text{ GeV}$)	0.70 ± 0.08 (0.78 ± 0.12)	0.85 ± 0.06 (0.86 ± 0.09)	0.79 ± 0.05 (0.84 ± 0.07)
2	P_L^{ch} -dependent correction ($\nu > 2 \text{ GeV}$)	0.73 ± 0.08 (0.77 ± 0.11)	0.88 ± 0.06 (0.86 ± 0.08)	0.84 ± 0.05 (0.83 ± 0.06)
3	No 2-prongs with $ t < 0.1 \text{ GeV}^2$ ($\nu > 2 \text{ GeV}$)	0.73 ± 0.09 (0.76 ± 0.13)	0.76 ± 0.06 (0.78 ± 0.08)	0.75 ± 0.05 (0.77 ± 0.07)
4	No 2-prongs with $ t < 0.2 \text{ GeV}^2$ ($\nu > 2 \text{ GeV}$)	0.86 ± 0.12 (0.82 ± 0.14)	0.77 ± 0.07 (0.79 ± 0.09)	0.79 ± 0.06 (0.80 ± 0.07)
5	MC: Fermi motion + reints. ($\nu > 2 \text{ GeV}$)	0.98 ± 0.03 (0.94 ± 0.04)	1.02 ± 0.02 (1.03 ± 0.03)	1.01 ± 0.02 (1.00 ± 0.03)
6	MC: ditto + meast. errors ($\nu > 2 \text{ GeV}$)	0.99 ± 0.03 (0.97 ± 0.04)	1.01 ± 0.02 (1.05 ± 0.03)	1.00 ± 0.02 (1.02 ± 0.03)

Figure Captions

Fig 1. Neon/deuterium ratios of cross sections per nucleon, A_{eff}/A , as a function of Q^2 for x below 0.2 for the (a) neutrino, (b) antineutrino and (c) combined neutrino and antineutrino data. The full curve is the model prediction derived from PCAC. The dashed curve is obtained by applying the shadowing factor $S_{a_1}^{Ne}$, instead of S_π^{Ne} , to the T_π term in (5). Both curves take into account the neutrino and antineutrino energy spectra, the cuts, the experimental resolution, and the relative normalisation procedure that is applied to the data (see text).

Fig 2. Neon/deuterium ratios of cross sections per nucleon, A_{eff}/A , for the combined neutrino and antineutrino data shown as a function of x in four bins of Q^2 . The curves are as in figure 1.

Fig 3. Neon/deuterium ratios of cross sections per nucleon, A_{eff}/A , for the combined neutrino and antineutrino data with x below 0.2 and Q^2 below 0.2 GeV^2 shown as a function of (a) the energy transfer ν to the hadron system and (b) the invariant mass W of the final-state hadron system. The curves are as in figure 1.

Fig 4. Cross section ratios observed in muon and electron scattering off various nuclei compared with the corresponding model prediction: (a) for data at high Q^2 ($5 - 200 \text{ GeV}^2$) from [27-29], (b) for data at low Q^2 ($0.3 - 3.2 \text{ GeV}^2$) from [30-31]. For the data taken from [30] only the statistical errors are shown, but the point-to-point systematic errors may be of the same order as the vertical spread of the points. For other data the point-to-point systematic errors are included, added in quadrature. Overall normalisation errors – not shown – amount to 1-2% in the high Q^2 data but are larger (4% [30, see 18] to 7% [31]) in the low Q^2 data.

Figure 1

Figure 2

Figure 3

Figure 4(a)

Figure 4(b)