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LOW Q^2 NEUTRINO INTERACTIONS AND HADRONIC COMPONENT

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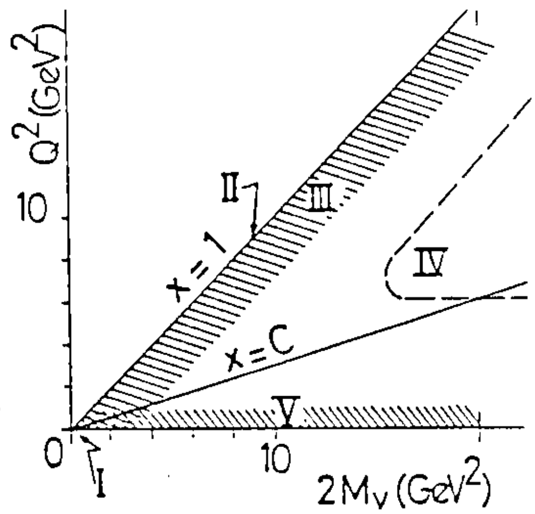
ABSTRACT

A review is presented of experimental data on neutrino scattering at low Q^2- and large ν-values : shadowing; total cross section and pion production on nucleons; coherent π, ρ and a_1 production on nuclei. The data are interpreted in the framework of the PCAC hypothesis and the hadron dominance model.

1. Introduction

The kinematics of neutrino interactions is described by the two invariants $Q^2 = - q^2$ and ν, respectively (minus) the square of the 4-momentum transfer and (in the lab system) the energy transfer from the leptons to the hadrons. The Bjorken variables are $y = \nu / E_\nu$ and $x = Q^2 / 2M\nu$ (M is the nucleon mass).

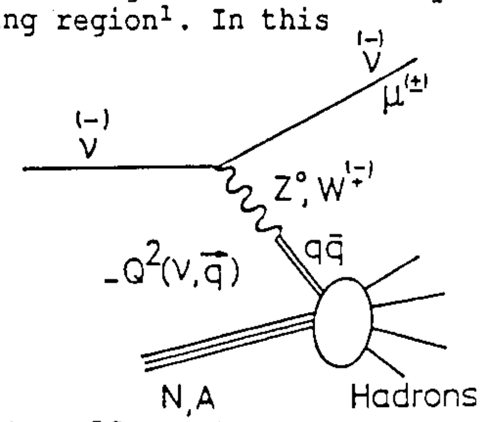
The (Q^2,ν) plane can be divided in several physical domains, as sketched here. Region I, where q is time-like and Q^2 is negative, is the domain of semi-leptonic β decays. Neutrino scattering happens in the upper-half plane, below the diagonal line II, which corresponds to elastic scattering (x=1). Along this line is region III, the low W region of resonance production (W is the invariant mass of the hadronic system: $W^2 = 2M\nu - Q^2 + M^2$). Region IV is the deep inelastic domain, with large Q^2- and large ν-values, which made neutrino scattering studies glorious in the '70's : discovery of (hadronic) neutral current interactions, dilepton events due to charm production, tests of the parton model and QCD tests of scaling violation.



In this paper, we are interested in region V, with low Q^2-values, but extending up to high ν-values. Only in the last years was a detailed study of this domain possible, mainly thanks to the large samples of high energy data obtained in bubble chamber experiments.

Perturbative QCD calculations are of poor utility in this low Q^2

and large distance region, also known as the "higher twist" region. A convenient approach is thus provided along an alternative picture, the hadron dominance model. For electromagnetic interactions, the vector meson dominance model ("VMD") is indeed known to give a satisfactory description of the data in the corresponding region[1]. In this framework, one considers the possible fluctuations of the current into quark-antiquark pairs, dominated by the lightest meson states with relevant quantum numbers, which interact strongly with the target. For neutrino interactions -either of neutral or charged current type-, the vector current is thus believed to be dominated by the ρ meson, whereas the axial current is dominated by the gradient of the pion field and by the chiral partner of the ρ with $J^{PC} = 1^{++}$, the a_1 meson.



This hadronic behaviour of the current only shows up if the hadronic fluctuation of mass m has a sufficient "life-time", i.e. if its coherence length l_c is large compared to the relevant dimension R :

$$l_c \approx \frac{2\,\nu}{Q^2 + m^2} > R \qquad (1)$$

2. PCAC and meson dominance

The PCAC hypothesis (partial conservation of the axial current) states that

$$\partial_\mu A^\mu = f_\pi \; m_\pi^2 \; \Phi_\pi \;, \qquad (2)$$

where A^μ is the weak axial current, and f_π, m_π and Φ_π are the pion-current coupling constant, the pion mass and the pion field.

Adler[2] has shown, on basis of the CVC (conservation of the vector current) and PCAC hypotheses, that for $Q^2 = 0$ the inelastic neutrino cross section is proportional to the corresponding pion cross section. Bell[3] stressed the fact that this pionic behaviour of the weak axial current is due to the non-pionic (a_1 dominated) part of the current : the pion pole itself gives negligeable contributions to the cross section (they are proportional to the final state lepton mass squared). Adler's prediction thus reads :

$$\frac{d^2\sigma(\nu N \to \mu X)}{dQ^2\; d\nu} = \frac{G^2}{4\pi^2}\, f_\pi^2\, \frac{|\vec{q}|}{E^2} \left(\frac{m_a^2}{Q^2 + m_a^2}\right)^2 \sigma(\pi N \to X) \quad + \quad O\,(m_\mu^2), \qquad (3)$$

where G is the weak coupling constant, and m_a is the a_1 mass or the mass of other systems (e.g. non resonant $(\rho\pi)$ systems) dominating the axial current. For $Q^2 = 0$, the neutrino cross section as given by Eq. 3 is thus purely longitudinal.

For $Q^2 \neq 0$, the contribution of the vector current, of the transverse axial current, and possibly of an additional part of the longitudinal axial current (which would vanish for $Q^2 = 0$ in contrast with Eq. 3) has been computed by Piketty and Stodolsky[4] :

$$\frac{d^2\sigma(\nu N \to \mu X)}{dQ^2\, d\nu} = \frac{G^2}{4\pi^2} f_\rho^2 \frac{|\vec{q}|}{E^2} \left(\frac{1}{Q^2 + m_\rho^2}\right)^2 \frac{Q^2}{1-\varepsilon} (\sigma_T + \varepsilon\, \sigma_L)(\rho N \to X)$$
$$+ \frac{G^2}{4\pi^2} f_a^2 \frac{|\vec{q}|}{E^2} \left(\frac{1}{Q^2 + m_a^2}\right)^2 \frac{Q^2}{1-\varepsilon} (\sigma_T + \varepsilon' \sigma_L)(a_1 N \to X)$$
$$+ (\rho\ a_1) \text{ interference }, \qquad (4)$$

where f_ρ (f_a) is the coupling constant of the ρ (a_1) meson to the weak current, ε is the polarisation parameter, σ_T and σ_L are the transverse and longitudinal cross sections. The interference term is small.

3. Shadowing

Already in 1964, Bell[5] predicted the existence of shadowing for low Q^2 neutrino interactions on nuclei : the incident wave, -behaving like a pion according to Adler's theorem-, should be strongly absorbed on the outer face of the nucleus, yielding a reduced averaged cross section per nucleon.

Shadowing has been abundantly studied in electromagnetic interactions[6a-b], including at large Q^2-values[6c]. In agreement with Eq. 1, it is observed to fully develop only for sufficient values of ν (ν > 4-5 GeV^2; here R is the hadronic mean free path in the nuclear matter).

Only in 1989, however, was Bell's prediction confirmed for neutrino interactions[7], by the comparison of 16000 ν and $\bar{\nu}$ interactions on deuterium (exp. WA25) with 20000 interactions on neon (exp. WA59), obtained in the bubble chamber BEBC at the CERN SPS -see Fig. 1. The observation of shadowing already for small ν-values (see Fig. 1b) confirms that, for $Q^2 \approx 0$, the weak current behaves like a pion and is thus completely shadowed, as predicted from PCAC.

Using Glauber's model, Kopeliovich[8] showed that the shadowing is really due to the second order inelastic correction to the elastic

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        σ(1)                          σ(2)
  -------x-------           ------x-----------x------
   jA        jA              jA         π          jA
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cross section, which exactly cancels the first order (non shadowed) contribution, leaving the (shadowed) pion-nucleus cross section. This explains why, although the a_1 dominates the axial current j_A, full shadowing is attained as soon as the condition of Eq. 1 is fulfilled for the pion mass, i.e. at very low ν.

4. Cross sections on nucleons

4.1 Total cross section

The total neutrino-proton cross section, for low Q^2-values, was studied by the WA21 collaboration[9] at the CERN SPS, which collected 15000 ν and 9000 $\bar{\nu}$ charged current interactions in BEBC filled with H_2. One observes on Fig. 2 a good agreement with the predictions of Eq. 3-4. In particular, the PCAC contribution of Eq. 3 (curve "PCAC") is

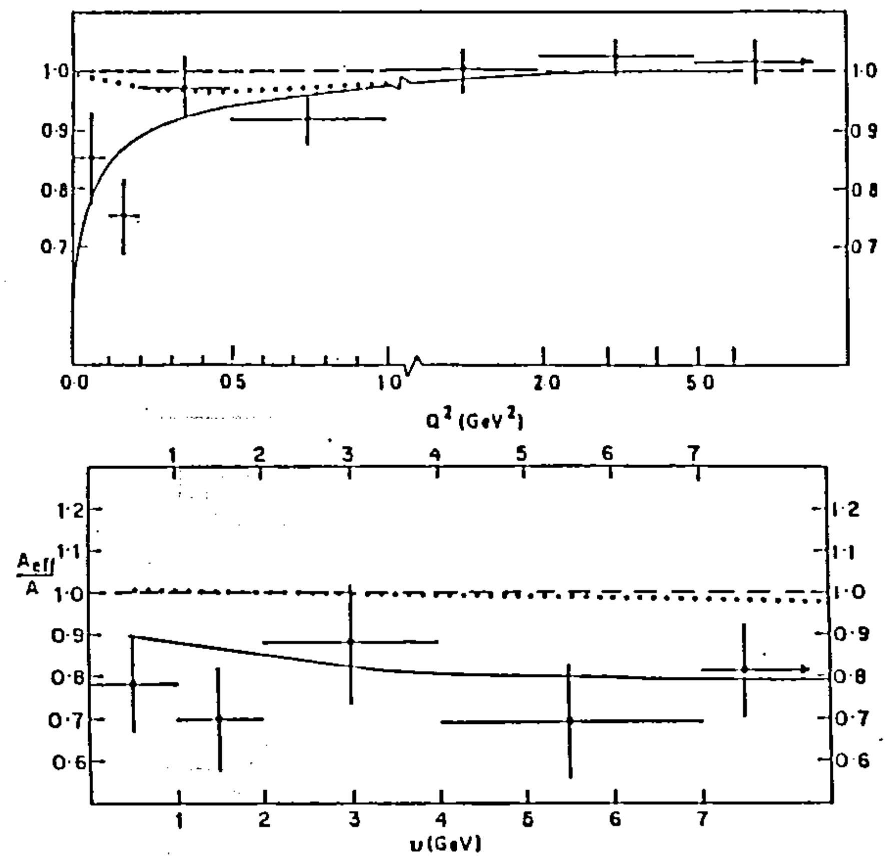


Fig. 1 Ratios of the neon and deuterium cross sections, per nucleon, a. (top) as a function of Q^2 for $x < 0.2$; b. (bottom) as a function of ν for $x < 0.2$ and $Q^2 < 0.2$ GeV^2. The full curve is the PCAC prediction; the dotted curve is obtained if the condition of Eq. 1 has to apply on the a_1 mass instead of the pion mass

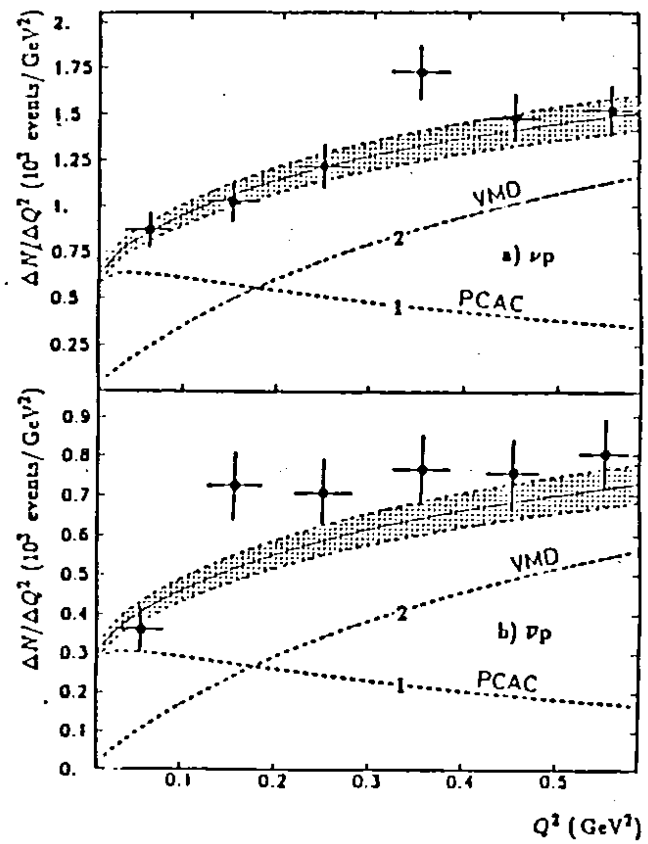


Fig. 2 Q^2-distribution for the total neutrino- and antineutrino-proton cross sections. The solid line is the prediction of Eq. 3 ("PCAC") and 4 ("VMD"); the shaded area corresponds to a one σ error on the prediction.

required to describe the data for $Q^2 \approx 0$, whereas the meson dominance contributions of Eq. 4 (curve "VMD") dominate for higher Q^2-values.

4.2 Δ resonance production

Abundant data[10] have been collected at small Q^2- and small ν-values on Δ resonance production. The 837 neutrino-induced $\mu^-\pi^+p$ and 130 antineutrino-induced $\mu^+\pi^-p$ events with $Q^2 < 1$ GeV^2 collected by the the WA21 collaboration[10a] are well described by Adler's model[11] for Δ production; the data for $Q^2 \approx 0$ provide a test of PCAC (see Fig. 3).

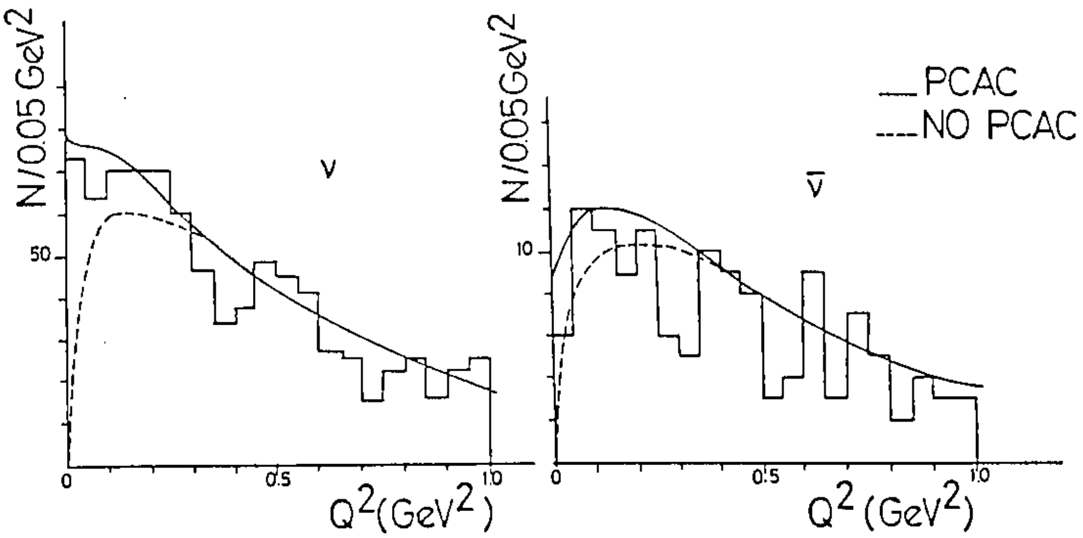


Fig. 3 Q^2-distribution of the $\mu\pi p$ events with $1.1 < m(p\pi) < 1.4$ GeV; the curve is a prediction based on[11], including the PCAC contribution

4.3 Diffractive pion production

An analysis by D. Rein[12] of WA21 data[13] consisting of $\mu^-\pi^+p$ and $\mu^+\pi^-p$ events with $W > 2$ GeV, outside the resonance region, support the idea of a diffractive process, arising mainly from the longitudinal component of the axial current, as expected from PCAC.

5. Coherent interactions on nuclei

Coherent interactions on nuclei[14] constitute a spectacular illustration of quantum mechanics : the wave associated to the incident particle is coherently scattered by the different nucleons, which develop maximum constructive interferences, such that :

$$T(A) = A\,T(N) \;; \quad \sigma(A) = A^2\,\sigma(N) \;. \qquad (5)$$

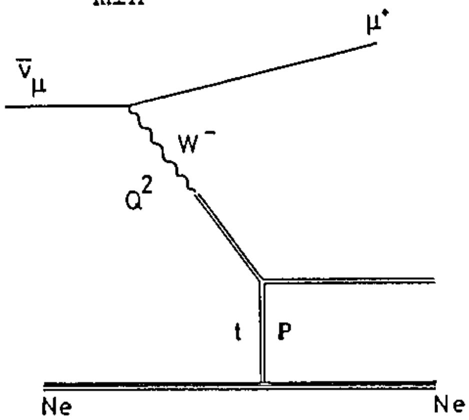
The condition for such a cooperative behaviour is that the wave be essentially constant on the entire nucleus of radius R :

$$|\vec{k}|\,R < 1, \qquad (6)$$

where k is the 4-momentum transfer to the nucleus; k_L and k_T are the component of k longitudinal and transverse to the current direction; $k^2 = t$ is negative, and the energy transfer to the nucleus is very small. Coherent interactions are thus characterised by a rapidly falling $|t|$-distribution. It has been shown[15] using Glauber's model (see also[16]) that this dependence can be parametrised as :

$$\frac{d\sigma}{dt} \sim e^{-B_L k_L^2}\; e^{-B_T k_T^2} \;, \text{ where} \qquad (7)$$

$$k_L^2 \approx t_{min} \approx \left(\frac{2\,\nu}{Q^2+m^2}\right)^2 \quad , \quad k_T^2 \approx t' = t - t_{min} \; ; \qquad (8)$$



t_{min} is the minimum value of $|t|$ kinematically necessary to create a real particle of mass m. As stressed in [15], B_L is related to the depth of the backward slice from which the produced hadrons can escape the nucleus without reinteraction, and on which the coherence condition (6) must hold. B_T is related to the transverse dimensions of the nucleus. Both parameters are thus of quite different physical origins, but in practice, for light nuclei, $B_L \approx B_T$, as used in the model[17].

Using the optical theorem, the coherent neutrino-nucleus cross section deriving from Eq. 3 or 4 can thus be parametrised as

$$\frac{d\sigma\ (\nu A \rightarrow hA)}{dt} \sim \frac{A^2}{16\pi}\ \sigma_{tot}(hN)\ e^{-B_L\, t_{min}}\ e^{-B_T\, t'}\ F_{abs} \ , \qquad (9)$$

where A is the atomic number and F_{abs} accounts for the possible reinteraction of the coherently produced hadron inside the nucleus.

Experimental data on coherent meson production were mainly obtained from charged current interactions in bubble chambers, which allow the full reconstruction of the reaction kinematics. The nucleus recoils as a whole, acquiring very low kinetic energy, and remains undetected, without emission of nucleons, evaporation protons or nuclear fragments ("stubs").

5.1 Coherent pion production

Since 1983, coherent pion production[17] has been extensively studied, as well in neutral as in charged current interactions[18-26]. It is due to the scattering of the longitudinal component of the axial current along Eq. 3 and 9.

The measured cross sections give a consistent picture over two orders of magnitude in the neutrino energy, as shown in Fig. 4 (except possibly for 2 data points of[22], but the average cross section over their full energy domain is compatible with the data from the other experiments). In agreement with the Standard Model predictions, taking account of PCAC, one has indeed (see also[22]) :

$$\sigma(\pi^+) \approx \sigma(\pi^-) \approx 2\,\sigma(\pi^0) \ . \qquad (10)$$

The kinematical distributions have been compared[21,25,26] with the model predictions, thus providing a detailed test of PCAC (see Fig. 5). The agreement is good. In particular, the Q^2-distribution has a maximum for $Q^2 = 0$, and extends up to $Q^2 \approx 1$ GeV^2, in agreement with Bell's statement on the role of the non-pionic component of the axial current.

5.2 Coherent ρ meson production

Two experiments[27,28] have reported the observation of coherent ρ^+ and ρ^- production, the π^o meson from the ρ decay being reconstructed from the observation of the gammas converting in the bubble chamber.

The kinematical distributions and total cross sections are in

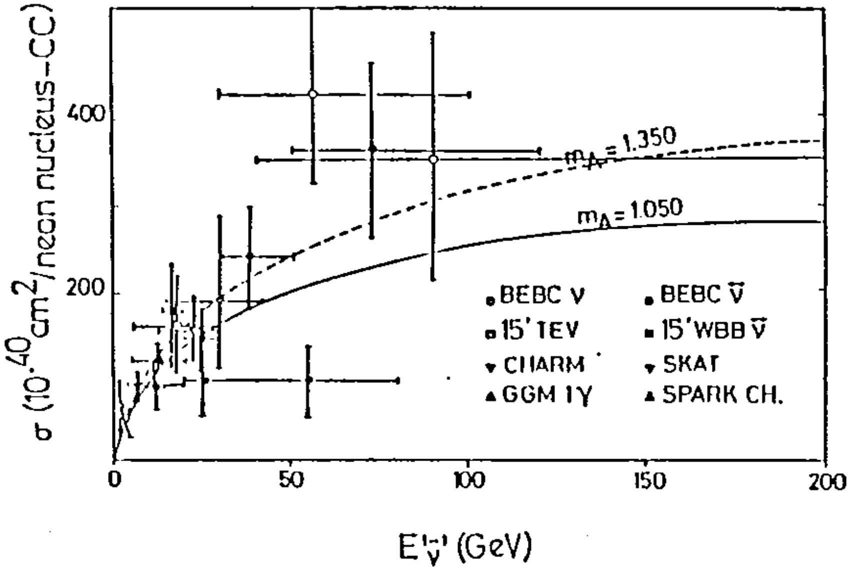


Fig. 4 Cross section for coherent pion production by charged current interactions on neon, as a function of the (anti-)neutrino energy. The curves are the prediction of Eq. 3 and 9, for two choices of the axial mass m_a. The data for pion production in several experiments have been scaled to correspond to charged current interactions on neon

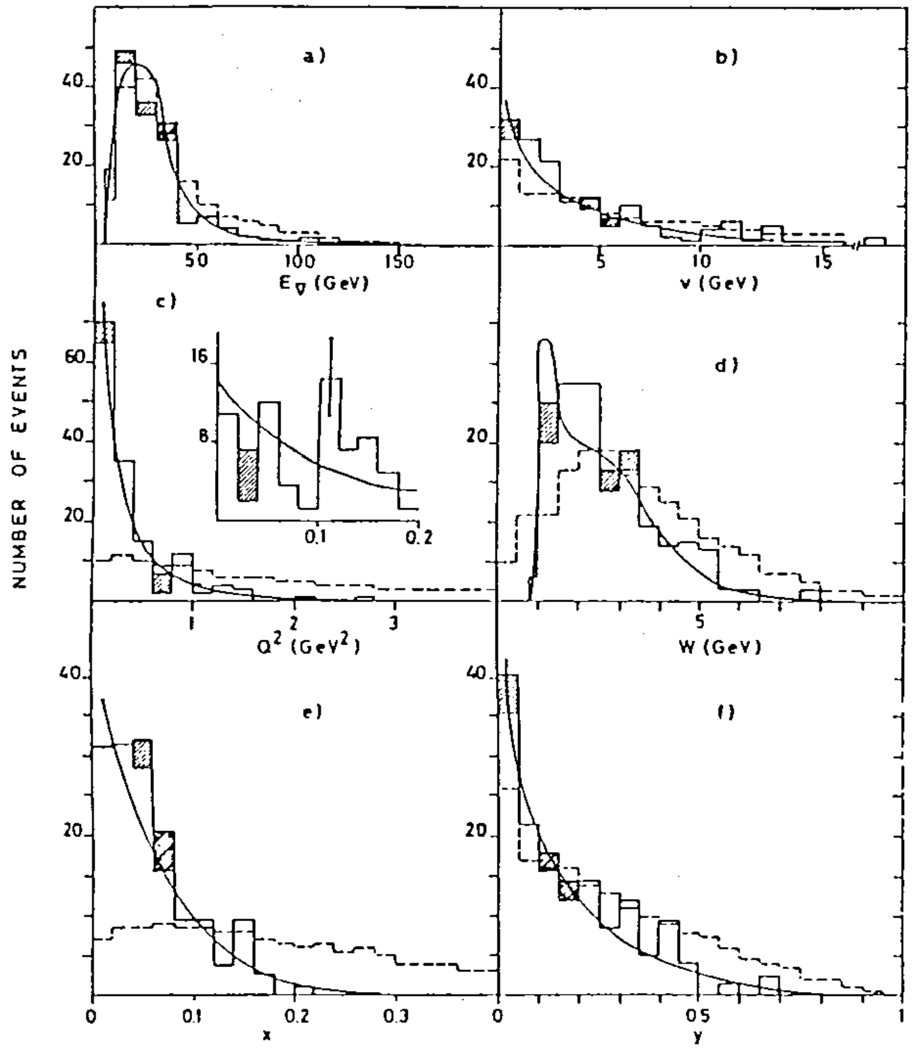


Fig. 5 Distribution of kinematical variables for the coherent $\mu^+\pi^-$ events with $|t| < 0.05$ GeV; the incoherent background, estimated from the events with stubs, is shown hatched. The curves, normalised to the signal, are the predictions of Eq. 3 and 9, with m_a being the a_1 mass. The dashed histogram represents the distributions of the full sample of charged current events, divided by a factor 100

agreement with the predictions deduced from Eqs. 4 and 9[29]. In contrast with single pion production, the Q^2-distribution supports the prediction of a vanishing cross section for $Q^2 = 0$, as required by CVC. The energy distribution might however be softer than expected from the model. On basis of the angular distributions, both experiments report the presence of a sizeable longitudinal component.

5.3 Coherent a_1 and $(\rho\pi)$ production

The coherent production of 3 pions by antineutrino scattering was studied[30] in the channels $(\pi^-\pi^+\pi^-)$ and $(\pi^-\pi^0\pi^0)$; the observation of $(\pi^-\pi^+\pi^-)$ systems has also been reported in[31].

This process[32] is due to the scattering of the transverse axial current, with a possible longitudinal contribution,similar to that in the ρ case, along Eq. 4 (the contribution of the PCAC term of Eq. 3 is of a few %). As stressed in[15], the axial current is not necessarily dominated by the a_1 meson, but non-resonant $(\rho\pi)$ systems could also give an important contribution : in the case of diffractive (3π) production by real pion scattering, the interference between those two contributions -known as the "Deck mechanism"[33]- have made a_1 productions studies very delicate for many years[34].

The mass distributions (Fig. 7) indeed suggest $(\rho\pi)$ production, either non-resonant or from a_1 decay, but favour an axial mass lower than the a_1 mass. The qualitative features of the kinematical distributions are reproduced by the model, but the $|t|$-, t_{min}- and x-distributions are flatter than expected, and the E_ν-, ν-, y- and W-distributions softer; the total cross section also seems higher than expected,- in spite of the numerous uncertainties on the model. All these features might indicate a sizeable contribution of non-resonant $\rho\pi$ systems, with an effective mass lower than the a_1 mass, and -possibly- a cross section higher than expected for the a_1 meson.

6. Conclusions

The observation of shadowing and of coherent interactions on nuclei, as well as the total cross section, Δ production and pion diffractive production on nucleons form an array of consistent evidences, in low-Q^2 neutrino and antineutrino interactions, in favour of the PCAC hypothesis and the hadron dominance model.

The hadronic component thus contributes to the higher-twist effects at low Q^2-values, and in particular to the longitudinal cross section[35],- through the PCAC hypothesis and Adler's theorem.

Besides its own interest, the study of these effects is of practical importance, especially for the study of elastic neutrino-electron scattering[20] and for the extraction of $\sin^2\theta_W$, from the ratio of neutral to charged current cross sections[36].

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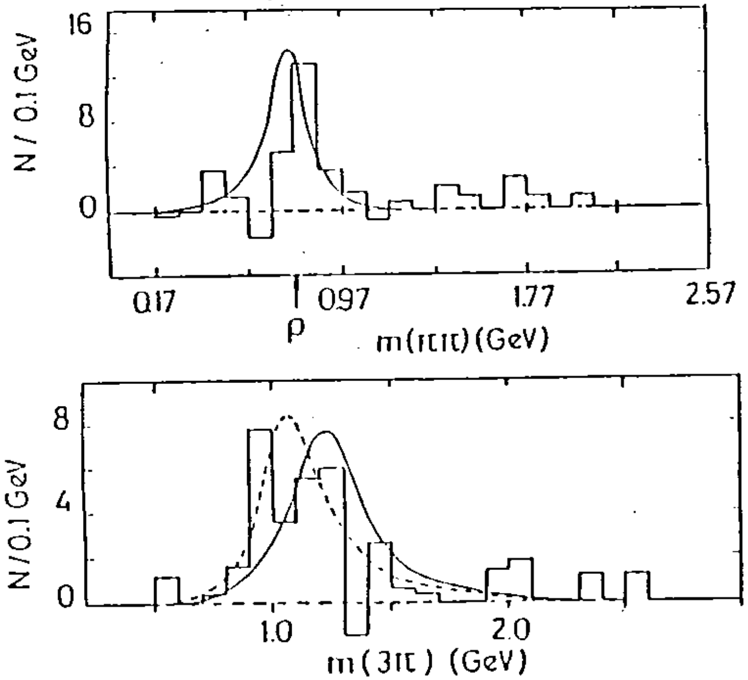

Fig. 6 Distribution for a. (top) the (2π) mass after subtraction of the like-sign (ππ) contribution; b. (bottom) the (3π) mass, for the coherent $\mu^+\pi^-\pi^+\pi^-$ and $\mu^+\pi^-\pi^0\pi^0$ events with $|t| < 0.10$ GeV^2. The curves are for m_a = 1.260 GeV (solid) and m_a = 1.050 GeV (dashed)

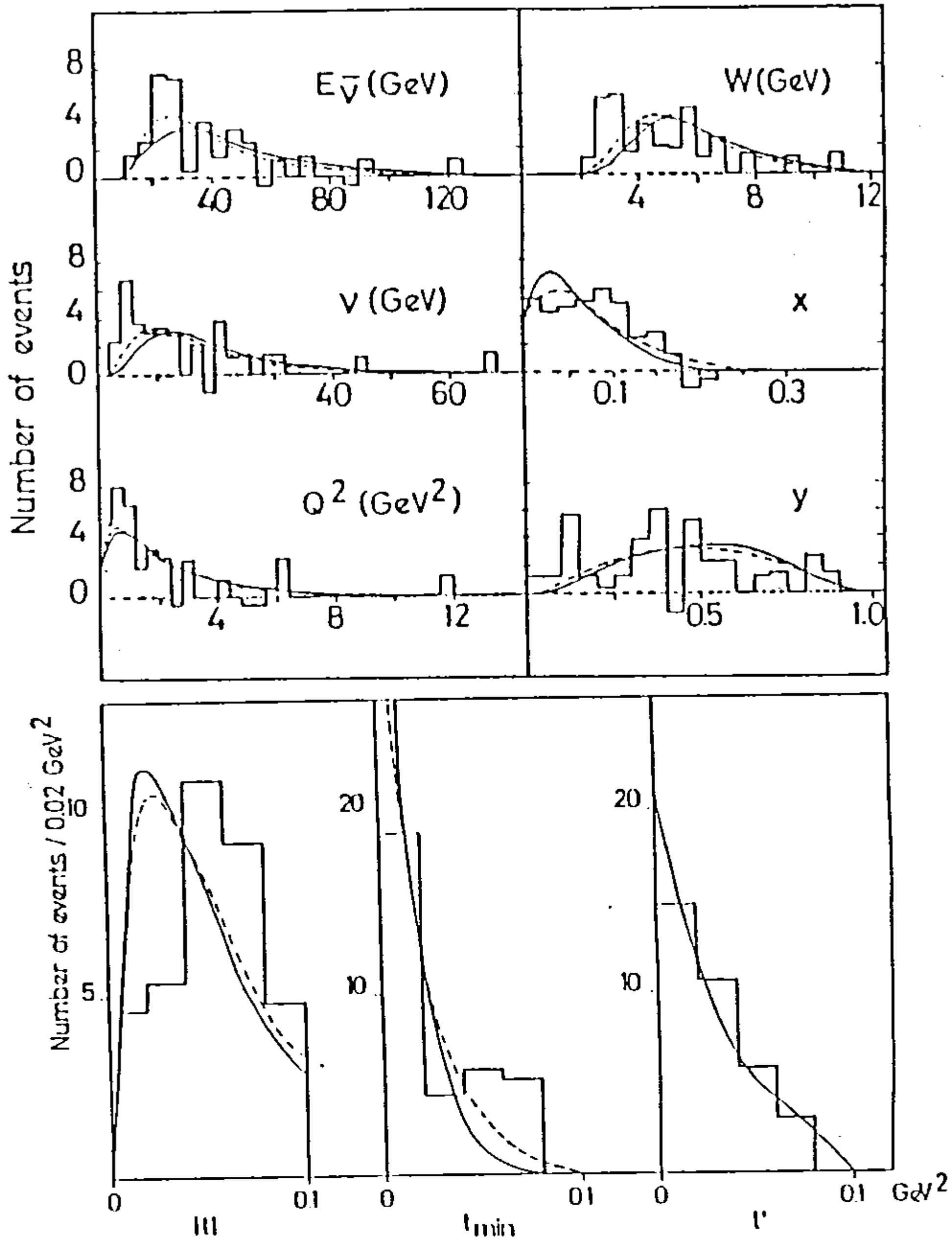

Fig. 7 Distribution of kinematical variables for the $\mu^+\pi^-\pi^+\pi^-$ and $\mu^+\pi^-\pi^0\pi^0$ coherent events with $|t| < 0.10$ GeV^2. The curves, normalised to the signal, are the predictions of Eq. 3 and 9, with m_a = 1.260 GeV (solid) and m_a = 1.050 GeV (dashed)

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