ESTIMATE OF THE OPE CONTRIBUTION TO THE SINGLE PION NEUTRINO PRODUCTION OFF NUCLEONS

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It is shown that the One Pion Exchange (OPE) between the nucleon and the weak leptonic current accounts only for about 10% of the total cross section of the peripheral single pion neutrino production off nucleons. This means that the pion coupling to the vector part of the weak leptonic current is very weak contrary to the expectations. A comparison is made with a recent CERN bubble chamber experiment.

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1. *Introduction*

Single pion neutrino production off nucleons in the reaction $\nu N \rightarrow \mu\pi N'$ has been studied for various reasons both experimentally [1–11] and theoretically [12–32]. While for the low πN invariant mass W ($W < 2$ GeV) the process goes via quasielastic resonance production according to the graph of Fig. 1 for high W ($W > 2$ GeV) the cross section is dominated by nonresonant single pion production mechanisms.

Recently Rein has shown [33] that beyond the resonance region one is able to ascribe nearly the whole single pion production to the coupling of the longitudinally polarized

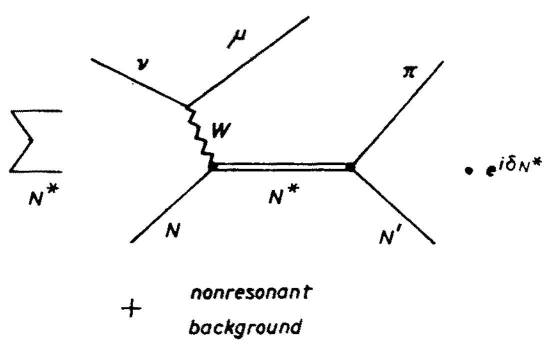

Fig. 1. Resonant pion production for low πN invariant mass ($W < 2$ GeV)

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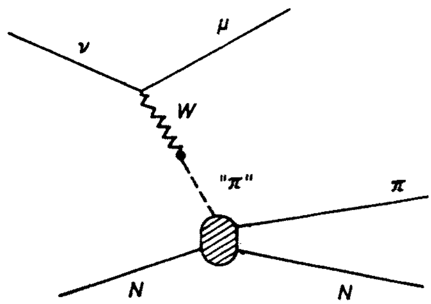

Fig. 2. Peripheral pion production according to the PCAC hypothesis

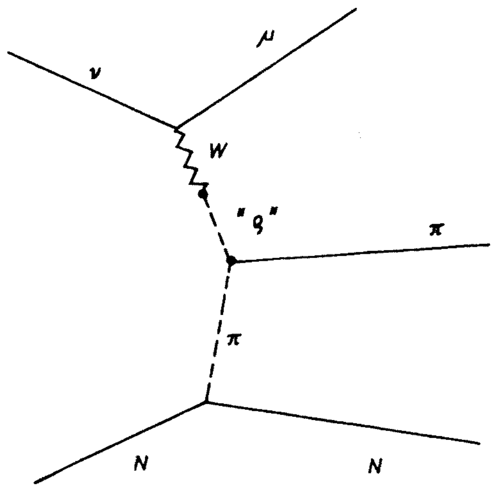

Fig. 3. One Pion Exchange contribution to the peripheral single pion production

W-boson to the virtual pion according to Adler's PCAC hypothesis [34]. The process is then determined by the πN elastic amplitude (Fig. 2). Such an assumption requires that the external pion should be entirely coupled to the axial-vector part of the leptonic weak current.

The aim of this paper is to estimate the pion coupling to the vector part of the leptonic current through the pion exchange between the nucleon and the weak leptonic current (Fig. 3). A comparison with the recent CERN neutrino experiment [10] is also done.

2. *Kinematics*

The reactions considered in the paper are:

$$\nu_\mu p \rightarrow \mu^- \pi^+ p, \qquad \{1\}$$

and

$$\bar{\nu}_\mu p \rightarrow \mu^+ \pi^- p. \qquad \{2\}$$

Both reactions have been studied experimentally [10].

Let k, k', p, p', q' denote the four-momenta of ν, μ, incoming p, outcoming p and π, respectively. Then $q = k - k'$ is the W-boson four-momentum. To describe the process the following kinematical variables will be used: $Q^2 = -q^2$, $t = (p-p')^2$, z_π, $W^2 = (p+q)^2$ being πp invariant mass squared, ϕ and ϑ^*. With the definition $\nu' = p \cdot q/m$, m being the proton mass we get: $W^2 = m^2 + 2m\nu' - Q^2$. The authors of the experimental paper [10] defined a data sample with a nonresonant pion production requiring each event to have $W^2 > 4$ GeV^2. This condition will be followed in further calculations in order to compare a model with the experiment.

The variable z_π is defined as the ratio of the pion energy to the current energy in the laboratory frame. The following relation holds: $z_\pi = 1 + t/2m\nu'$. The angle ϕ is determined in the laboratory frame as an azimuthal angle in the xy plane. This frame is in turn constructed as follows (Fig. 4): the z-axis is parallel to the vector $\vec{q}$, the x-axis is parallel to the projection of the ν and μ momenta onto the plane perpendicular to the vector $\vec{q}$, the y-axis is chosen so as this frame be right-handed. The angle ϕ is invariant under a Lorentz boost to the πp center of mass frame where hadronic helicity amplitudes are evaluated.

The angle ϑ^* is defined as the polar angle with respect to the z-axis in the pπ center of mass frame.

The suitable cross section formulae for single hadron neutrino production off nucleons have already been published [35–38], so we shall only write down those which will be used later. The differential cross section formula reads:

$$\frac{d\sigma}{dQ^2 dW^2 dt d\phi} = \frac{1}{2\pi} \cdot \left(\frac{G_F \cos\vartheta_c}{2\pi}\right)^2 \cdot \frac{Q^2|\vec{q}|}{4E^2 m} \cdot \frac{1}{64\pi m^2 |\vec{q}|^2} \cdot \overline{|\mathcal{M}|^2}, \tag{2.1}$$

where G_F denotes the Fermi weak coupling constant, $\cos\vartheta_C$ is the cosine of the Cabibbo angle, E denotes incoming neutrino energy in the laboratory system while

$$\overline{|\mathcal{M}|^2} = \tfrac{1}{2} \cdot \sum_{\{\lambda\}} |\mathcal{M}_{\{\lambda\}}|^2 \tag{2.2}$$

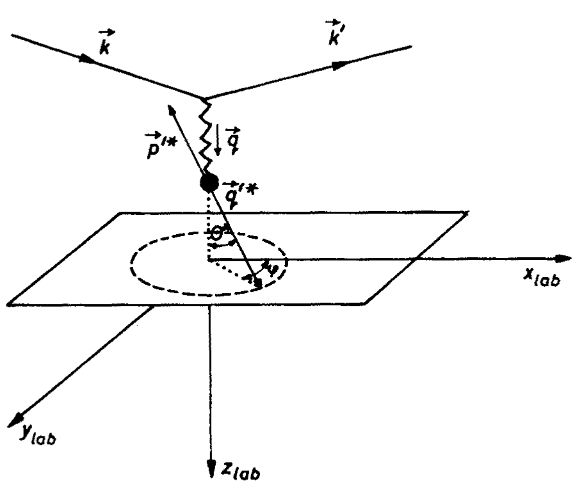

Fig. 4. Definition of the laboratory frame and the angles ϕ and ϑ^*

is the invariant matrix element squared. The latter is expressed in terms of the helicity amplitudes $\mathscr{M}_{\{\lambda\}}$, $\{\lambda\}$ denoting the set of incoming proton, intermediate boson and outgoing proton helicities. For $\overline{|\mathscr{M}|^2}$ we have the formula:

$$\begin{aligned}\tfrac{1}{2}\cdot\overline{|\mathscr{M}|^2} &= \sigma_U+\varepsilon\sigma_L+\varepsilon\sigma_T\cos 2\phi+\varepsilon\sigma_T'\sin 2\phi\\ &+[2\varepsilon(1+\varepsilon)]^{1/2}\sigma_I\cos\phi+[2\varepsilon(1-\varepsilon)]^{1/2}\sigma_I'\sin\phi\\ &+\eta(1-\varepsilon^2)^{1/2}\sigma_C+\eta[2\varepsilon(1-\varepsilon)]^{1/2}\sigma_{CL}\cos\phi\\ &+\eta[2\varepsilon(1-\varepsilon)]^{1/2}\sigma_{CL}'\sin\phi,\end{aligned} \tag{2.3}$$

where $\eta = +1$ for neutrinos, $\eta = -1$ for antineutrinos, E' is the muon energy in the LAB frame and

$$\varepsilon = \left(1+\frac{2|\vec{q}|^2}{4EE'-Q^2}\right)^{-1}. \tag{2.4}$$

Partial cross sections σ_i, i = U, L, T, T′, I, I′, Cl, CL′ are expressed in terms of various W-boson helicity amplitudes both vector and axial-vector ones with respect to Lorentz transformations:

$$\begin{aligned}\sigma_U &= \tfrac{1}{2}\cdot\sum_{[\lambda]}(|V^+_{[\lambda]}|^2+|A^+_{[\lambda]}|^2),\\ \sigma_L &= \tfrac{1}{2}\cdot\sum_{[\lambda]}(|V^0_{[\lambda]}|^2+|A^0_{[\lambda]}|^2),\\ \sigma_T &= -\tfrac{1}{2}\cdot\sum_{[\lambda]}\mathrm{Re}\,(V^+_{[\lambda]}V^{-*}_{[\lambda]}+A^+_{[\lambda]}A^{-*}_{[\lambda]}),\\ \sigma_I &= \frac{1}{\sqrt{2}}\cdot\sum_{[\lambda]}\mathrm{Re}\,(V^+_{[\lambda]}V^{0*}_{[\lambda]}+A^+_{[\lambda]}A^{0*}_{[\lambda]}),\\ \sigma_{CL}' &= -\frac{1}{\sqrt{2}}\cdot\sum_{[\lambda]}\mathrm{Im}\,(V^+_{[\lambda]}V^{0*}_{[\lambda]}+A^+_{[\lambda]}A^{0*}_{[\lambda]}),\\ \sigma_T' &= -\sum_{[\lambda]}\mathrm{Im}\,(V^+_{[\lambda]}A^{-*}_{[\lambda]}),\\ \sigma_I' &= \frac{1}{\sqrt{2}}\cdot\sum_{[\lambda]}\mathrm{Im}\,(V^+_{[\lambda]}A^{0*}_{[\lambda]}+A^+_{[\lambda]}V^{0*}_{[\lambda]}),\\ \sigma_C &= -\sum_{[\lambda]}\mathrm{Re}\,(V^+_{[\lambda]}A^{+*}_{[\lambda]}),\\ \sigma_{CL} &= -\frac{1}{\sqrt{2}}\cdot\sum_{[\lambda]}\mathrm{Re}\,(V^+_{[\lambda]}A^{0*}_{[\lambda]}+A^+_{[\lambda]}V^{0*}_{[\lambda]}),\end{aligned} \tag{2.5}$$

where +, 0, −, denote the W-boson helicities; $[\lambda] \equiv [\lambda_1, \lambda_2]$ is the set of incoming proton and outgoing proton helicities, respectively, V and A denote the vector and axial-vector hadronic helicity amplitudes. The notation in Eqs (2.3)–(2.5) is the same as in Ref. [38].

3. A model for pion production by vector current

Assuming that an external pion couples to the vector part of the leptonic current we are led to a straightforward conjecture for the peripheral pion production that is to the one pion exchange between a nucleon and the leptonic current. This follows from the fact that the vector part of the current carries the ϱ quantum numbers. G-parity conservation then requires that in the picture of single t-channel exchange between the nucleon and the leptonic current an exchanged particle (Regge trajectory) should have $G = G_\pi = -1$. In the simplest case it is the pion.

The One Pion Exchange model (OPE) [39–41] need not be explained here as it is a well known concept. Usual corrections to the pure OPE model known as the absorptive corrections have to be taken into account. Due to the limited computer time, the required precision with regard to the experimental statistics and for the sake of simplicity we shall follow Williams' prescription [42] for the modification of the helicity amplitudes.

The matrix element can be written down in the form:

$$\mathcal{M} = j^{\mathrm{w}}_\mu \cdot j^{\mathrm{h}}_\mu, \tag{3.1}$$

where $j^{\mathrm{w}}_\mu = \bar{u}(k')\gamma_\mu(1-\gamma_5)u(k)$ denotes the leptonic weak current while j^{h}_μ is the hadronic current. According to the OPE model the hadronic current reads:

$$j^{\mathrm{h}}_\mu \equiv j^{\mathrm{OPE}}_\mu = -\sqrt{2}\, g_{\mathrm{NN}\pi}\bar{u}(p')\gamma_5 u(p)\frac{1}{t-m_\pi^2}(2q'_\mu - q_\mu)F_\pi^{\mathrm{EM}}(Q^2), \tag{3.2}$$

where m_π is the pion mass, $g_{\mathrm{NN}\pi}$ is the πN coupling constant with $g^2_{\mathrm{NN}\pi}/4\pi = 14.8$, $F_\pi^{\mathrm{EM}}(Q^2)$ denotes the pion electromagnetic form factor. It reads [43]:

$$F_\pi^{\mathrm{EM}}(Q^2) = \frac{1}{1+\dfrac{Q^2}{m_{\mathrm{ff}}^2}}, \qquad m_{\mathrm{ff}}^2 = 0.47\ \mathrm{GeV}^2. \tag{3.3}$$

The absorption affects the hadronic current through the proper modification of its value at the pion pole and through the damping factor $\Phi_{\mathrm{abs}}(t)$ which is equal to unity at the pion pole. This factor is an exponential function of t [42]:

$$\Phi_{\mathrm{abs}}(t) = \exp\left[\tfrac{1}{2} A\cdot(t-m_\pi^2)\right], \tag{3.4}$$

where the constant A is adjusted from experiments and in purely hadronic reactions it is known to be about 3 GeV^{-2}. To our knowledge it has been never fitted in semileptonic reactions so in the present paper it has been taken directly from the data [10]. Fig. 5 shows two plots of $\ln(d\sigma/dt)$ versus t for various W^2 intervals with the straight lines fitted to the data. Their slopes are: 1.7 ± 0.2 GeV^{-2} and 3.5 ± 0.5 GeV^{-2} for the lower and higher W^2

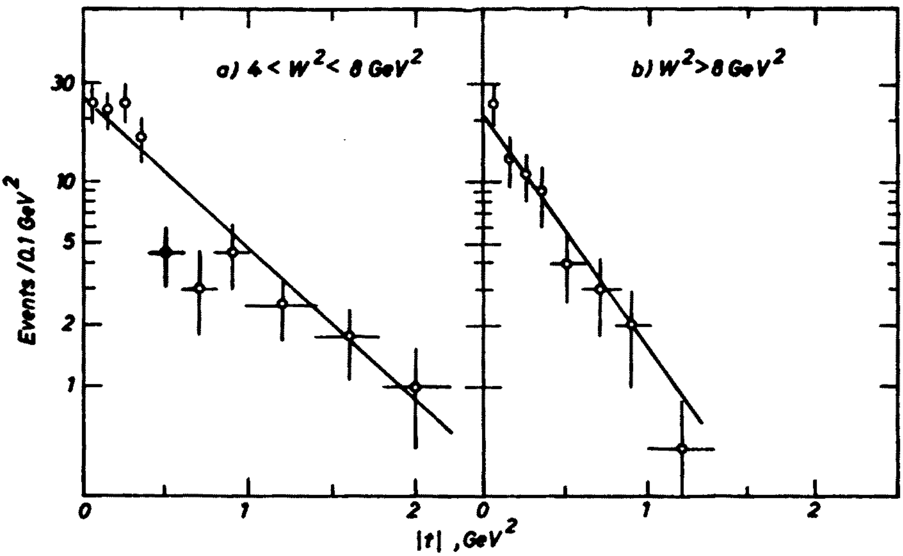

Fig. 5. Experimental t-distribution for the combined $\nu/\bar{\nu}$ data sample for the two W^2 intervals: $4\ \mathrm{GeV}^2 < W^2 < 8\ \mathrm{GeV}^2$ and $W^2 > 8\ \mathrm{GeV}^2$; plots a) and b), respectively [10]

intervals, respectively [10]. The fits are quite good within the experimental errors thus the simplest idea is to take their slopes as the values of the constant A, i.e. for our purpose:

$$A = \begin{cases} 1.7\ \mathrm{GeV}^{-2} & \text{for } 4\ \mathrm{GeV}^2 \leqslant W^2 \leqslant 8\ \mathrm{GeV}^2, \\ 3.5\ \mathrm{GeV}^{-2} & \text{for } W^2 > 8\ \mathrm{GeV}^2. \end{cases} \tag{3.5}$$

The next step is to obtain the helicity amplitudes $V^{\lambda}_{[\lambda]}$. They will be purely vector ones. This is done in the following way.

Interpreting j^{W}_{μ} as the W-boson polarization vector [27] one can decompose it into a linear combination of the standard polarization vectors corresponding to the right-handed, left-handed and scalar polarization. The usual definitions are [44]:

$$\varepsilon^{L}_{\mu}(-1) = \frac{1}{\sqrt{2}}(0, 1, -i, 0),$$

$$\varepsilon^{R}_{\mu}(+1) = \frac{1}{\sqrt{2}}(0, -1, -i, 0),$$

$$\varepsilon^{S}_{\mu}(0) = \frac{1}{\sqrt{Q^2}}(|\vec{q}^{\,*}|, 0, 0, \nu'^{*}), \tag{3.6}$$

where the numbers in brackets at the LHS of the above equations denote the W-boson helicities in the πp center of mass frame and starred quantities refer to that frame. They are connected to the coreesponding quantities in the laboratory frame through:

$$|\vec{q}^*| = \frac{m|\vec{q}|}{W}, \quad \nu'^* = \sqrt{\nu'^2 |-\vec{q}|^2 + |\vec{q}^*|^2}. \tag{3.7}$$

For j_μ^w we then get the following decomposition in the πp center of mass frame [27]:

$$j_\mu^{w\pm} = -2\sqrt{2}\, E \frac{\sqrt{Q^2}}{|\vec{q}|} [u\varepsilon_\mu^{\overset{L}{R}}(\mp 1) - v\varepsilon_\mu^{\overset{R}{L}}(\pm 1) + \sqrt{2uv}\, \varepsilon_\mu^s(0)],$$

$$u = \frac{E+E'+|\vec{q}|}{2E}, \quad v = \frac{E+E'-|\vec{q}|}{2E}. \tag{3.8}$$

By definition:

$$V_{\lambda_1\lambda_2}^{\lambda} \equiv \varepsilon_\mu(\lambda) \cdot j_\mu^h(\lambda_1, \lambda_2). \tag{3.9}$$

Then all the single kinematical variable distributions can be computed by inserting (3.9) into (2.1)–(2.5) and integrating over the remaining variables within their kinematical bounds allowed for the reaction. A comparison with the experiment may be done provided that these distributions have been averaged over the neutrino (antineutrino) energy spectrum.

4. *Results*

4.1. Total cross section

The results are displayed in Figs 6–10 (solid lines) together with the experimental data points (histograms). For comparison the Rein model predictions [33] are also shown (dashed-dotted lines). Though the experimental statistics is poor (≃ 100 events for ν/ν̄) some interesting conclusions can be derived from its analysis.

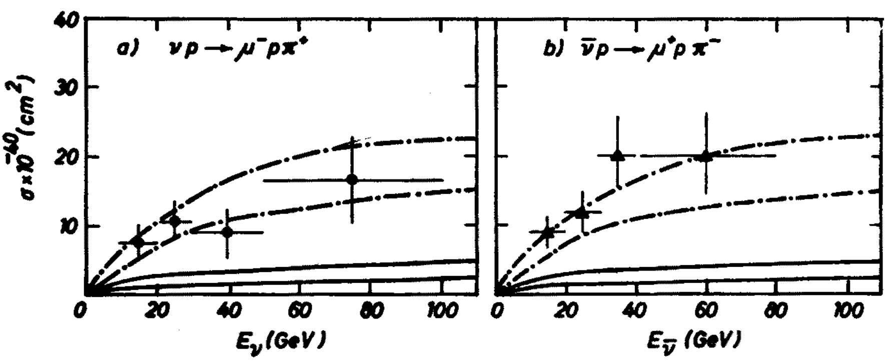

Fig. 6. Total cross section for the reactions {1} and {2}; plots a) and b), respectively (data quoted from Ref. [10]); the two dashed-dotted curves of the Rein model at each plot correspond to the two values of the constant b: $b = 5\ \mathrm{GeV}^{-2}$ (the upper curve) and $b = 7\ \mathrm{GeV}^{-2}$ (the lower curve) [33]; the two solid curves of the OPE model correspond to the two values of the constant A for the entire W^2 interval: $A = 1.5\ \mathrm{GeV}^{-2}$ (the upper curve) and $A = 4\ \mathrm{GeV}^{-2}$ (the lower curve)

There is strong disagreement between the data and the OPE model for the total cross section prediction (see Fig. 6). The two curves from Fig. 6 are constructed so as to give the upper and the lower bound on the total OPE cross section within the uncertainty of the model parameters. It seems to be a correct assumption that the largest error comes from the formula (3.4) which accounts for the absorptive corrections. Not only the Williams model is itself an approximation but as the data suggest (see Fig. 5) the coefficient A is not a constant but rather a function of W^2. The data also indicate that A is probably a growing function of W^2. So one can estimate the lower (upper) bound of the total cross section by iserting into (3.4) a single value of A from (3.5) for the entire W^2 interval, namely the higher (lower) one increased (decreased) by its experimental error.

The experimental value of the neutrino (antineutrino) total cross section for the considered reaction averaged over the (ν, $\bar{\nu}$) energy range $5 \div 120$ GeV is $(9.4 \pm 1.4,\ 12 \pm 2) \times 10^{-40}$ cm^2. The same quantities for the OPE model are $(0.9^{+0.5}_{-0.3},\ 1.2^{+0.5}_{-0.9}) \cdot 10^{-40}$ cm^2 where the errors here are simply the differences between the mean value and the averaged upper and lower bound of the total cross section. Then the ratio $\zeta = \langle\sigma_{\mathrm{OPE}}\rangle / \langle\sigma_{\exp}\rangle$ can play a role of a quantitative measure of the weak vector current contribution to the single π production: $\zeta_\nu = (10^{+7}_{-5})\%$, $\zeta_{\bar{\nu}} = (10^{+6}_{-9})\%$. This contribution is indeed very small contrary to the preliminary simplified data analysis [10].

In contrast Rein's model seems to match the data points very well. This fact and also some other experimental facts indicate, that the hadronic axial-vector amplitudes might be much larger than the vector ones. If this is the case then any vector-axial-vector interference is very small compared to the absolute value of the axial-vector longitudinal amplitude as suggested by the PCAC-hypothesis model prediction. The equality $\sigma_\nu(E) \simeq \sigma_{\bar{\nu}}(E)$ holding within the experimental errors confirms this provided that there is one dominant single particle exchange in the t-channel between the nucleon and the leptonic current. In such a case phases of all hadronic amplitudes are equal and all partial cross sections defined in (2.3) depend only on absolute values of the amplitudes.

4.2. Differential cross sections

The Q^2, t, W^2, z_π and $\cos\vartheta^*$ distributions are rather inconclusive. As the model predictions have to be averaged over the ν ($\bar{\nu}$) energy spectrum the normalization is lost because:

$$\frac{1}{N} \cdot \frac{dN}{dx} = \left\langle \frac{1}{\sigma} \cdot \frac{d\sigma}{dx} \right\rangle, \tag{4.1}$$

where x denotes a kinematical variable. Both models cross section formulae are dominated by the factors of the same shape for t and for Q^2 that is $\exp(b \cdot t)$ and $1/(1+Q^2/m_{\mathrm{ff}}^2)$ with the constants b and m_{ff}^2 of the same order of magnitude. All that makes it difficult significant differences between them in Q^2, t and related kinematical variables distributions to be seen.

The experimental t, z_π, and $\cos\vartheta^*$ distributions (Figs 7, 8) confirm that the pion is produced peripherally taking nearly all the current energy. The process goes with a very low four-momentum transfer t and at very small angles. Both models are in agreement with the data. Rein's curves are steeper than the corresponding OPE ones (they tend faster to zero from the maximal values) because of the exp $(b \cdot t)$ damping factor which dominates with b being about $2 \div 3$ times larger [33] than the corresponding b value in the OPE model. (Remark: Rein's plots in the Fig. 7a, d seem to be not correctly normalized.)

The experimental Q^2 distribution (Fig. 8) shows that a considerable fraction of events has $Q^2 \simeq 0$. Though looking at the data one cannot exclude that the Q^2 distribution has a richer structure near $Q^2 = 0$ (a maximum for a small $Q^2 > 0$ for example) which is lost due to the bin size of the histogram and/or smearing this seems not to be the case at the first sight. If so Rein's model would again be better showing that the axial-vector longitudinal amplitude dominates. Referring to the Vector Dominance Model [45] this means that neither W coupling to ϱ nor W coupling to A_1 (both have spin 1) and hence transverse hadronic amplitudes can contribute significantly for the total cross section. The OPE model which is in fact a vector dominance model for the reaction considered predicts a very steep fall off to zero (as VDM does) of the Q^2 distribution as Q^2 tends to zero.

The W^2 distribution (Fig. 9) is plotted for the neutrino and antineutrino data samples combined together. There are no significant differences between both models so as to draw

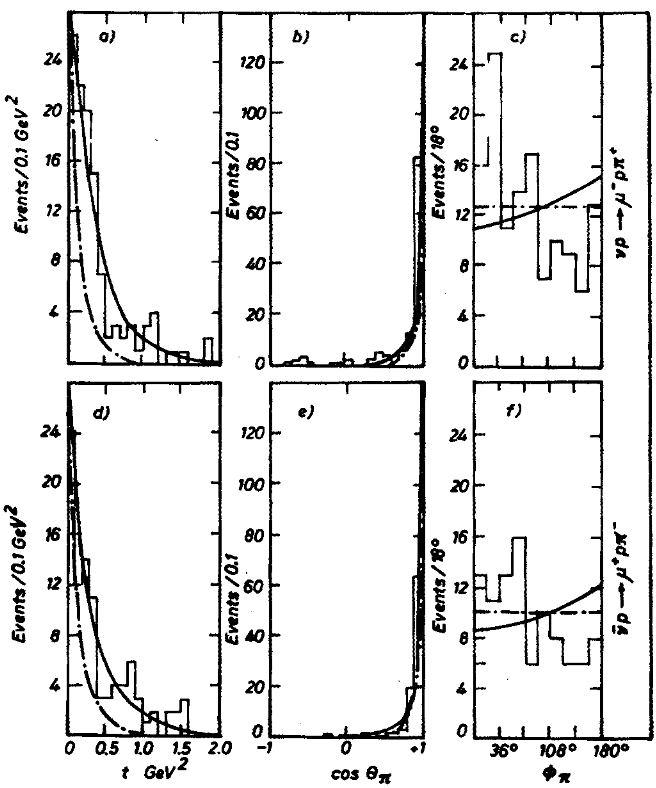

Fig. 7. Distributions of t, $\cos \vartheta^*$ and ϕ for the reactions {1} and {3}; plots a), b), c) and d), e), f), respectively (data quoted from Ref. [10]); dashed-dotted lines are the Rein model predictions [33] while the solid lines represent the OPE model predictions

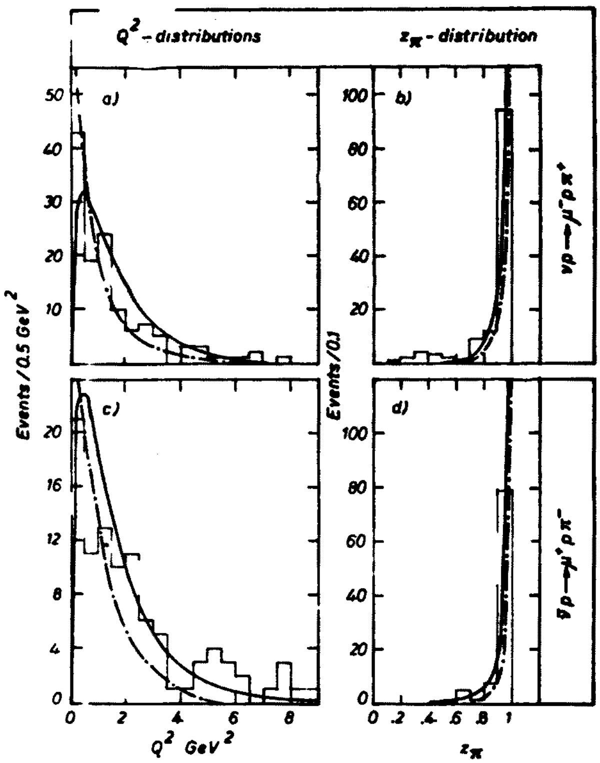

Fig. 8. Distributions of Q^2 and z_π for the reactions {1} and {2}; plots a), b) 'and c), d), respectively (data quoted from Ref. [10]); dashed-dotted lines are the Rein model predictions [33] while the solid lines represent the OPE model predictions

interesting information. The first data point which is somewhat higher than the both models predict reflects perhaps the fact that near $W^2 = 4$ GeV^2 there might be still a small contamination from resonances [33].

Very interesting physics may be obtained by inspecting the ϕ angle distributions. According to (2.3) and (2.5) one can isolate various partial cross sections and hence various amplitude interferences both vector-axial-vector and longitudinal-transverse ones. This is possible with a larger experimental statistics but even with the present some physically interesting information can be extracted. According to (2.3) the most general expression for the ϕ distribution is:

$$\frac{1}{N} \cdot \frac{dN}{d\phi} = \frac{1}{2\pi} + a \sin\phi + b \cos\phi + c \sin 2\phi + d \cos 2\phi, \tag{4.2}$$

where the coefficients a, b, c, d are proportional to the partial cross sections defined by the equations (2.5). Experimentally $\langle \sin\phi \rangle \simeq \langle \sin 2\phi \rangle \simeq \langle \cos 2\phi \rangle \simeq 0$ within errors both for ν and $\bar{\nu}$. Only $\langle \cos\phi \rangle_\nu^{\exp} \simeq \langle \cos\phi \rangle_{\bar{\nu}}^{\exp} \simeq 0.19 \pm 0.06$ [10]. Terms proportional to

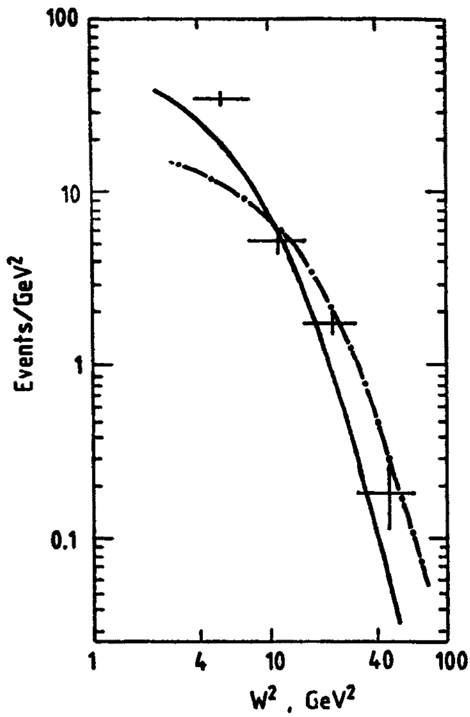

Fig. 9. Distribution of W^2 for the combined $\nu/\bar{\nu}$ data sample [10] along with the models predictions: the Rein curves (dashed-dotted) [33] and the OPE model curves (solid)

$\langle \sin \phi \rangle$ and $\langle \sin 2\phi \rangle$ are P-odd so the process is effectively parity conserving. This is possible only if there is no vector-axial-vector interference or if it is very small. This conclusion is consistent with that obtained previously. The nonzero value of $\langle \cos \phi \rangle$ originates from the interference of a W-boson amplitude of longitudinal polarization w iththose of transverse polarization.

According to (2.3) and (2.5) we have:

$$\langle \cos \phi \rangle = \left\langle \frac{2[\varepsilon(1+\varepsilon)]^{1/2}\sigma_I + \eta[2\varepsilon(1-\varepsilon)]^{1/2}\sigma_{CL}}{\sigma} \right\rangle, \tag{4.3}$$

where $\langle \; \rangle$ denotes integrating over W^2, Q^2, t with proper kinematical coefficients and averaging over the neutrino (antineutrino) energy spectrum. Since $\langle \cos \phi \rangle_\nu \simeq \langle \cos \phi \rangle_{\bar{\nu}}$ and $\eta = +1$ for ν and $\eta = -1$ for $\bar{\nu}$ we have $\sigma_{CL} \simeq 0$. It means that there is no vector--axial-vector interference contributing to the value of $\langle \cos \phi \rangle$, or this interference is negligible.

The quantity σ_{CL} may also be estimated if one evaluates the interference of the A^0 amplitude from the Rein model with the vector amplitudes from the OPE model neglecting the term proportional to A^+V^{0*} as it is very small compared to the term V^+A^{0*} (see (2.5)). The upper limit for σ_{CL} estimated in such a way is close to zero as expected.

This means that:

$$\langle \cos \phi \rangle \simeq \left\langle \frac{[2\varepsilon(1+\varepsilon)]^{1/2}\sigma_{\mathrm{I}}}{\sigma} \right\rangle. \tag{4.4}$$

On the other hand, according to (2.5),

$$\sigma_{\mathrm{I}} = \frac{1}{\sqrt{2}} \cdot \sum_{[\lambda]} \mathrm{Re}\,(V^{+}_{[\lambda]}V^{0*}_{[\lambda]} + A^{+}_{[\lambda]}A^{0*}_{[\lambda]}). \tag{4.5}$$

The quantity $\mathrm{Re}\,(V^{+}V^{0*})$ can be obtained directly from the OPE model and it is about -0.02 both for ν and $\bar{\nu}$, very small compared to the experimental value and again in very good agreement with the conjecture that $|V|^2 \ll |A^0|^2$. Thus:

$$\sigma_{\mathrm{I}} \simeq \frac{1}{\sqrt{2}} \cdot \sum_{[\lambda]} \mathrm{Re}\,(A^{+}_{[\lambda]}A^{0*}_{[\lambda]}) \tag{4.6}$$

which implies the necessity to incorporate in Rein's model a mechanism generating transverse axial-vector amplitudes to account for this nonzero interference.

It is easy to see from the above analysis that the models fail to explain the ϕ distribution. The model based on the PCAC hypothesis predicts a flat ϕ distribution as it takes into account only longitudinal axial-vector hadronic amplitude as dominant thus not being able to describe the interference between amplitudes of various polarizations. The OPE model which gives $\langle \cos 2\phi \rangle \simeq 0$ and $\langle \cos \phi \rangle \simeq 0$ both for ν and $\bar{\nu}$ also fails because the absolute values of the amplitudes are too small.

5. *Conclusions*

The analysis has shown that the single pion neutrino production off nucleons becomes a peripheral process for high (>2 GeV) πN invariant mass. An external pion couples predominately to the axial part of the leptonic current while the pion coupling to the vector part of the leptonic current gives only about 10% contribution to the total cross section. A longitudinal axial-vector amplitude dominates thus allowing the process to be described with the πN elastic amplitude according to Adler's PCAC hypothesis. However one has to take into account also the axial-vector amplitudes for the W-boson with transverse polarization so as to explain a nonzero value of the interference terms between the axial-vector, longitudinal and transverse hadronic amplitudes according to the experimental observation.

The above conclusions together with the prediction of the semiqualitative Regge analysis [46] which states that in the high energy limit ($W^2 \to \infty$) the pion production will become purely diffractive show that we are very near this limit already for W^2 not much greater than 4 GeV^2.

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