Recent Results in High Energy Neutrino Physics

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Abstract

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Recent results on high energy neutrino physics are reviewed in order to demonstrate how the quark concept facilitates our understanding of the structure of the nucleon and neutrino physics.

1. Inelastic scattering

Assuming a current–current coupling via vector boson exchange, then the spin averaged inelastic scattering process is described by

$$\frac{d^2\sigma^{\nu\bar{\nu}}}{dx dy} = G^2 \frac{ME}{\pi} \left[\left(1 - y - \frac{Mxy}{2E}\right) F_2^{\nu,\bar{\nu}}(x, q^2) + \frac{y^2}{2} 2xF_1^{\nu,\bar{\nu}}(x, q^2) \pm y \left(1 - \frac{y}{2}\right) xF_3^{\nu,\bar{\nu}}(x, q^2) \right]$$

The Bjorken variables x, y are defined as

$$x = \frac{q^2}{2M\nu}, \quad \text{where} \quad q^2 = 4EE' \sin^2 \frac{\theta}{2}$$

and

$$y = \frac{\nu}{E}, \quad \text{where } \nu \text{ is the energy transfer}$$

The F_i 's are the structure functions of the nucleon.

A great simplification in this formula comes about if one assumes charge symmetry, i.e., neglecting $\Delta s = 1$ and $\Delta c = 1$ processes. In this case $F_i^{\nu n} = F_i^{\bar{\nu} p}$ and therefore, on an isoscalar target we have only three structure functions as $F_i^{\nu N} = F_i^{\bar{\nu} N}$.

An even greater simplification comes about if one assumes Bjorken scaling

$$F_i(x, q^2) \rightarrow F_i(x)$$

which can be argued on dimensional arguments as $q^2 \rightarrow \infty$. This leads immediately to the prediction that the total neutrino and antineutrino cross-sections rise linearly with energy.

The heavy liquid bubble chamber Gargamelle demonstrated this linearity for energies between 1 and 10 GeV in 1971 [1]. This was a surprising result because of the low q^2 ($q^2 \sim 2 \text{ GeV}^2$), and became known as precocious scaling.

Now in 1978 and many million dollars later we now have reliable data at high energies. The main break-through in cross section measurement has come with the use of dichromatic

neutrino beams coming from fixed momentum parents. The great sacrifice in flux and hence event rate is greatly offset by the accurate knowledge of the absolute neutrino flux when compared to a classical wideband beam used in previous experiments. Figure 1 illustrates well this comparison.

The new results on the cross section comes from a Caltech–Fermilab 100 t iron calorimeter experiment and at the CERN SPS from the CDHS 1000 t iron calorimeter and BEBC with 20 t of Ne/H₂. The most accurate results are those of CDHS [2] and are shown along with BEBC [3] results and the old GGM results in Fig. 2. Both the ν and $\bar{\nu}$ show very good linearity with energy.

From these results, one might conclude that the precocious scaling observed at low energies has indeed become the true scaling at high energies, and that the naive quark–parton model is valid.

Let us just consider some details of this model. If one naively assumes that the nucleon is made up of free (and light) spin $\frac{1}{2}$ constituents then the differential cross-sections are very simple

$$\text{neutrino} \quad \frac{d^2\sigma}{dx dy} = G^2 \frac{ME}{\pi} q(x) + \bar{q}(x)(1-y)^2$$

$$\text{antineutrino} \quad \frac{d^2\sigma}{dx dy} = G^2 \frac{ME}{\pi} q(x)(1-y)^2 + \bar{q}(x)$$

where $q(x)$ and $\bar{q}(x)$ are the parton (quark) momentum density functions, i.e., $q(x) = x n(x)$. The structure functions now have a simple meaning

$$F_2(x) = q(x) + \bar{q}(x)$$

$$xF_3(x) = q(x) - \bar{q}(x)$$

and spin $\frac{1}{2}$ implies $F_2(x) = 2xF_1(x)$. Also charge symmetry is implied in that

$$\frac{d\sigma_\nu}{dy} = \frac{d\sigma_{\bar{\nu}}}{dy} \quad \text{as } y \rightarrow 0$$

Fig. 1. Comparison of narrowband and wideband neutrino fluxes at the CERN SPS.

Fig. 2. Total neutrino and antineutrino cross-sections as a function of energy.

If we identify the constituents as quarks, then

$$F_2^{\nu N}(x) = x(u + d + \bar{u} + \bar{d})$$

$$F_2^{eN}(x) = \frac{5}{18} [x(u + d + \bar{u} + \bar{d}) + \frac{2}{3}(s + \bar{s})]$$

i.e.

$$F_2^{\nu N}(x) \leq \frac{18}{5} F_2^{eN}.$$

Here u , d , s are the up, down and strange quark momentum density functions of the proton.

The present results on charge symmetry are

$$\frac{d\sigma_{\bar{\nu}}}{dy} \frac{d\sigma_{\nu}}{dy} \quad y \rightarrow 0$$

$$\text{BEBC } 1.1 \pm 0.2$$

$$\text{CITF } 0.97 \pm 0.1$$

$$\text{CDHS } 1.05 \pm 0.06$$

Concerning $\int F_2^{\nu} dx$ we have

$$\frac{\int F_2^{\nu} dx}{\text{GGM}} \quad \frac{18}{5} \frac{\int \bar{F}_2^{ed}}{\text{GGM}} \quad 0.49 \pm 0.05$$

$$\text{BEBC } 0.42 \pm 0.04$$

$$\text{CITF } 0.43 \pm 0.04$$

$$\text{CDHS } 0.45 \pm 0.04$$

$$\leq 0.50 \pm 0.03$$

However, the interpretation of the agreement of these results with the naive parton model and hence a test of scaling is incorrect. The reason for this is that scaling really implies $F_2 \rightarrow F_2(x)$, whereas we know $F_2 \rightarrow F_2(x, q^2)$!

This was first pointed out by Perkins, Schreiner and Scott [4] in 1976 who observed that the x distribution of low and high energy (i.e., low and high q^2) experiments were different as shown in Fig. 3.

Fig. 3. Dependence of the shape of F_2 on neutrino energy, CDHS data.

Fig. 4. Comparison of the scaling violations in F_2 found in GGM/BEBC neutrino experiments and electron and muon experiments.

To go to the next step, that is to extract the structure functions as a function of x and q^2 is a very difficult experimental problem for it involves the exact knowledge of the neutrino flux and also the effects smearing due to experimental resolution and Fermi momentum. Also due to the fact that as $q^2 = 2ME_{\nu}xy$, any given experiment (i.e., any given energy) can only cover a limited q^2 and x range. In order to cover a complete range of x and q^2 a low and a high energy experiment must be combined. This has been done using the low energy Gargamelle data and the high energy BEBC data [5]. The results are shown in Fig. 4 along with the electron and muon data. One notices that there are large scaling violations at small x and at large x and that the behaviour is the same in neutrino and electron data.

The explanation of this effect is very simple in terms of quark-quark forces or more colourfully gluons! As we have discussed in the naive quark parton model, the quark was essentially free and hence the structure function was expected to be independent of q^2 . However, if the quarks are interacting with each other, i.e., exchanging gluons, which in turn of giving $q\bar{q}$ pairs, then the type of scaling violations observed are to be expected. QCD [6] has some very simple predictions concerning the moments of $x F_3 = q - \bar{q}$, i.e., the valence quark distributions. The predictions are that the moments have simple logarithmic dependence on q^2 , given by

Fig. 5. Log-log plots of various moments of xF_3 . The straight lines indicate the predicted slopes.

$$M_3(N, q^2) = \text{const}/(\ln q^2/\Lambda^2)^{d^{NS}},$$

where $M_3(N, q^2)$ is the $N-2$ moment of xF_3 and d^{NS} is a constant uniquely predicted by QCD. Hence, if one plots the logarithm of the N_1 moment against the logarithm of the N_2 moment, one should obtain a straight line. The slope of the line is determined by the nature of the gluon, i.e., vector or scalar. Figure 5 shows the experimental results along with the predictions for vector gluons. The agreement is remarkable.

2. Details of the hadronic vertex

What can we hope to learn about the hadronic vertex in neutrino collisions that we cannot learn in normal hadronic physics?

The hope is that, unlike in normal hadronic collisions, in neutrino collisions we are selecting one quark, changing its flavour, and trying to knock it away from its two previous partner quarks.

If this is the case, we can hope to study how the quark sheds hadrons (i.e., $q\bar{q}$ pairs) as it interacts with the confinement forces. Intuitively, also, the way a quark fragments into $q\bar{q}$ pairs must be very much linked to the structure functions. Naively we might think that the way a quark fragments into hadrons depends only on the type of quark and the type of hadron. The fragmentation function for a u quark to fragment into a π^+ is $D^{\pi^+}(z)$, where z is a invariant given by

$$z = \frac{hP}{qP}$$

h is the four-momentum of the π^+ , P is the four-momentum of the proton, and q the four-momentum transfer, all measured in the Breit frame. In the laboratory frame $z \approx Eh/\nu$ (Eh being the hadron energy in the laboratory).

The differential ν cross-sections can now be written

$$\frac{d^2\sigma_{\nu}^+}{dx dz} = cx (d(x)D_u^{\pi^+}(z) + \frac{1}{3}\bar{u}(x)D_d^{\pi^+}(z))$$

$$\frac{d^2\sigma_{\nu}^-}{dx dz} = cx (d(x)D_u^{\pi^-}(z) + \frac{1}{3}\bar{u}(x)D_d^{\pi^-}(z))$$

Isospin invariance and charge-conjugation gives

$$D_u^{\pi^+}(z) = D_d^{\pi^-}(z) = D_u^{\pi^-}(z) = D_d^{\pi^+}(z)$$

$$D_d^{\pi^+}(z) = D_u^{\pi^-}(z) = D_d^{\pi^-}(z) = D_u^{\pi^+}(z)$$

The fragmentation functions obtained in the BEBC neon experiment are shown in Fig. 6.

Fig. 6. Fragmentation functions obtained in the BEBC neon experiment for neutrinos and antineutrinos.

Fig. 7. Comparison of the Feynman predictions on the quark charge distribution as a function of z compared with the BEBC neon data.

Feynman [7] has postulated that on average the hadrons of the quark jet should essentially carry the quantum numbers of the recoiling quark. Figure 7 shows the BEBC neon data for ν and $\bar{\nu}$, compared with the Feynman predictions. The agreement is enticing, but it is hard to really draw concrete conclusions about what one is really measuring.

At first glance the distributions of hadrons in neutrino collisions are very similar to equivalent hadronic collisions and it is up to experimentalists to demonstrate any fundamental differences. It is well known in hadronic collisions that the p_T of the hadrons is limited. However, in neutrino collisions, where one can distinguish the hard quark collisions, one might hope to see some evidence of gluon bremsstrahlung in the form of large p_T . In fact, QCD [8] predictions expect that the q^2 dependence of p_T should have the form

$$\langle p_T^2 \rangle \propto \frac{q^2}{\ln(q^2/\Lambda^2)}$$

Figure 8 shows the BEBC neon data compared to limited p_T phase-space Monte-Carlo calculations. There are indications that the p_T is rising with q^2 in the neutrino case. In $\bar{\nu}$ there is much less high energy flux and hence many less high q^2 events.

The study of quark and gluon properties using the hadronic system is still in its infancy and much work both experimental and theoretical has to be done.

3. New flavours, new leptons

In 1974 the HPWF collaboration presented two events of the type $\nu + N \rightarrow \mu^- \mu^+ + X$. Now, in 1978, about 10^4 events exist and all experiments agree on a production rate of $\sim 0.5\%$ relative to charged-current events. The data fits perfectly the charm GIM mode [9]

Fig. 8. The average of the p_T of the hadrons about the jet axis in the BEBC neon data.

$$\begin{array}{lll}
\nu + d \rightarrow \mu^- + c & \text{rate} & d \sin^2 \theta c \\
\nu + s \rightarrow \mu^- + c & & d \cos^2 \theta c \\
\bar{\nu} + \bar{s} \rightarrow \mu^+ + \bar{c} & & s \cos^2 \theta c
\end{array}$$

It is obvious that dimuon events are a very useful tool to investigate the distribution of strange quarks. On an isoscalar target we have

$$\frac{R^{\bar{\nu}}(2\mu/\mu)}{R^{\nu}(2\mu/\mu)} = \frac{2s \cos^2 \theta c}{2s \cos^2 \theta c + (u + d) \sin^2 \theta c} \times \frac{\sigma_{\nu CC}}{\sigma_{\bar{\nu} CC}}$$

and u, d, s are the *proton* quarks density functions.

The value found by the CDHS experiment is

$$\frac{\langle s \rangle}{\langle u + d \rangle} = 0.026 \pm 0.007$$

Of course, the number of strange particle/dilepton events should also fit the charm model

$$\begin{array}{ll}
\nu + d \rightarrow \mu^- + c & 1 \text{ s.p./event} \\
\quad \quad \quad \downarrow & \\
\quad \quad \quad s l^+ \nu & \\
\nu + s \rightarrow \mu^- + c & 2 \text{ s.p./event} \\
(\bar{s}) \quad (\bar{s}) \downarrow & \\
\quad \quad \quad s l^+ \nu &
\end{array}$$

As $d \sin^2 \theta \approx s \cos^2 \theta$ one expects ~ 1.5 s.p./event. In 1976 a 15' experiment BCHW [10] saw eleven V^0 's in $17 \mu^- e^+$, suggesting ~ 4 strange particles/event! This was suggestive of the production of new higher flavours, however with new experiments all now seems to be in order

$$\left. \begin{array}{ll}
15' \text{ FNAL} & (5 \text{ experiments}) \\
\text{BEBC SPS} & (2 \text{ experiments}) \\
\text{GGM SPS} & (1 \text{ experiment})
\end{array} \right\} \sim 300 \mu^- l^+ \text{ events}$$

These experiments give $0.7 V^0$'s/event yielding 1.5 strange particles/event. However, the τ lepton and the ν exist! Therefore, top and bottom states must be produced in high energy collisions, even though the rates may be extremely small. Like sign dimuons would be a signature for higher flavours. At present the experimental situation here is rather confused because of the high background from $\pi-\mu$ decay. However, HPWF claim a signal of $\mu^- \mu^- / \mu^- \mu^+ = 4 \pm 2 \times 10^{-4}$! CDHS should clarify this problem in the next couple of years.

The difficulty in finding charmed particles decaying hadronically has proved to be quite a disappointment as far as neutrino production is concerned. Though, charmed particles seem to be produced at $\sim 10\%$ level, the large number of decay modes make the detection very improbable. So far, only the D^0 has been seen in a sample of $5 \times 10^4 CC$ events yielding 1800 K^0 events [11]. The rate obtained is

$$\frac{\nu + \text{Ne} \rightarrow \mu^- + D^0 + X, D^0 \rightarrow K^0 \pi^+ \pi^-}{\nu + \text{Ne} \rightarrow \mu^- + X} = (0.7 \pm 0.2)\%$$

Using the SLAC branching ratio this gives

$$\frac{\mu^- + X + D^0}{\mu^- + X} = 17 \pm 7\%$$

which seems rather on the high side.

As far as the charmed baryon production is concerned, no neutrino experiment has yet *clearly* demonstrated their production.

Trimuon events of the type $\nu + N \rightarrow \mu^- \mu^- \mu^+ + X$ are pro-

duced at a rate of $10^{-5} \sim 10^{-4}$ of the normal charged current process. The possible sources of these trimuon events can range from the exotic to the mundane.

(a) Heavy lepton production

$$\begin{array}{l}
\nu N \rightarrow L^- + X \\
\quad \quad \quad \downarrow \\
\quad \quad \quad \mu^- \nu L^0 \\
\quad \quad \quad \quad \quad \downarrow \\
\quad \quad \quad \quad \quad \mu^- \mu^+ \nu
\end{array}$$

(b) Production of bottom states

$$\begin{array}{l}
\nu N \rightarrow \mu^- + \bar{b} + X \\
\quad \quad \quad \downarrow \\
\quad \quad \quad \bar{e} \mu^+ \nu \\
\quad \quad \quad \quad \quad \downarrow \\
\quad \quad \quad \quad \quad \bar{s} \mu^- \nu
\end{array}$$

(c) Inner bremsstrahlung both from the muon and the hadronic system.

(d) Hadronic production of muon pairs.

A beautiful analysis by the CDHS group [12] has demonstrated that all the signal can be explained by processes (c) and (d) and exclude heavy lepton production to the level of 10^{-5} .

4. Neutral currents

If one assumes only V, A couplings, then in terms of the quark parton model the inclusive neutral current cross section is given by

$$\begin{aligned}
\frac{d\sigma}{dy}(\nu \rightarrow \nu) &= (u_L^2 + d_L^2)[Q + \bar{Q}(1-y)^2] + (u_R^2 + d_R^2) \\
&\quad \times [\bar{Q} + Q(1-y)^2] + (s_L^2 + s_R^2)Q_s[1 + (1-y)^2],
\end{aligned}$$

where L and R indicate the left and right handed couplings, $Q = \int x(u + d(dx), \bar{Q} = \int x(\bar{u} + \bar{d}) dx$ and $Q_s = \int x(s + \bar{s}) dx$. For antineutrino left and right are interchanged. By measuring σ_{NC}/σ_{CC} and the hadronic (i.e., y) energy distribution the amount of left and right handed couplings can be determined. The present experimental data on inclusive neutral current reactions [13] is given below

	$g^- = u_L^2 + d_L^2$	$g^+ = u_R^2 + d_R^2$
GGM	0.24 ± 0.05	0.06 ± 0.03
CITF	0.23 ± 0.04	0.08 ± 0.05
HPWF	0.29 ± 0.06	0.02 ± 0.06
BEBC	0.33 ± 0.05	0.02 ± 0.03
CDHS	0.29 ± 0.02	0.03 ± 0.01

We can conclude that the right handed coupling is small and the neutral current is nearly $V-A$. In the Weinberg-Salam model the couplings are

$$\begin{aligned}
g^- &= \frac{1}{2} - \sin^2 \theta \omega + \frac{5}{9} \sin^2 \theta \omega \\
g^+ &= \frac{5}{9} \sin^2 \theta \omega
\end{aligned}$$

The average of the experimental results gives

$$\sin^2 \theta \omega = 0.24 \pm 0.02$$

Experiments on exclusive channels give

$$\begin{array}{ll}
\nu + p \rightarrow \nu + p & \sin^2 \theta \omega \quad 0.22 \pm 0.04 \\
\nu + p \rightarrow \nu + p \pi^0 & \\
\quad \quad \quad \downarrow & \\
\quad \quad \quad \rightarrow \nu + n \pi^+ & \left. \begin{array}{l} \\ \end{array} \right\} \sin^2 \theta \omega \quad 0.22 \pm 0.09
\end{array}$$

Hence, we can conclude that in the case of semi-leptonic neutral currents there is a very consistent agreement with the Weinberg-Salam model.

Of course, if this is the case, then for the purely leptonic reaction, there should also be agreement with this model. This was certainly the case for low energy experiments, however, in April 1978 GGM [14] published a result obtained in the SPS wideband beam, which obtained 10 electrons in 24000 CC events yielding a cross section of $\sigma_{\nu e} = 8 \pm \frac{4}{3} \times 10^{-42} \text{ cm}^2/\text{e}$, i.e., $\sin^2 \theta \omega > 0.74$ (90% CL).

This surprising result (the c.m. energy is only a few hundred MeV) stimulated other experiments to look into the process, and the situation in September 1978 is summarized below.

Experiment	ν GGM	ν 15' C.B.	$\bar{\nu}$ BEBC-TST	$\bar{\nu}$ 15' FIM
Number of events	9	11	1 e [±]	0
Background	0.4	0.7	0.4	0.3
Number of CC events	41 K	106 K	7.5 K	6.3 K
$\sigma \times 10^{-42}/E$	4.5 ± 7	1.8 ± 0.8	< 3.6	< 3
$\sin^2 \theta \omega$	~ 0.7	$0.2 \pm \frac{0.16}{0.18}$	< 0.45	< 0.4

The conclusion would seem that again everything has come back into order and that we witnessed "un grand caprice de la statistique"!

5. Beam dump experiments

The idea of a beam dump experiment is to suppress the "classical" source of neutrinos, i.e., π 's and K 's and leave the neutrinos from very short lived particles, i.e., $< 10^{-11}$ s unaffected. The simplest way to do this is just to dump say 400 GeV protons into a block of copper large enough to completely contain and absorb the hadronic cascade. If the only neutrinos which are produced in such a dump come from π 's and K 's the ratio of $\nu e/\nu \mu \approx 6\%$.

Such an experiment was analyzed at CERN in early 1978 and the result from the two bubble chambers BEBC [15] and GGM [16] was 24 $\nu e(\bar{\nu} e)$ and 48 $\nu \mu(\bar{\nu} \mu)$. It was obvious that some "new" source of neutrino had to be considered. This electron excess allows one to calculate the prompt electron neutrino flux coming from the dump; i.e., $5 \pm 1.5 \times 10^{-8}$ prompt $\nu e, \bar{\nu} e/\text{proton}/\mu\Omega$.

CDHS [17] observed as anomalous neutral current signal of $NC/CC = 0.86$ which they attributed to electron events. This gives a prompt electron neutrino rate of $1.8 \pm 0.4 \times 10^{-8}/\text{proton}/\mu\Omega$, somewhat lower than the bubble chamber rate. One

possible interpretation of the effect is that the neutrinos come from the leptonic decay of charmed particles.

If one assumes:

(a) $D\bar{D}$ production,

(b) $D \rightarrow K^* e \nu$, branching ratio = 10%,

(c) production of the form $e d^3 \sigma/dp^3 \propto (1 - |x|)^n e^{-b p_T}$

(d) $\sigma_{\text{prod}} \propto A^{2/3}$, σ_{pp} inelastic = 33 mb, then the published results are

$$\text{BEBC} \quad 100 \mu\text{b} < \sigma_{\text{prod}} < 200 \mu\text{b} \quad n = 4, \quad b \geq 2$$

$$\text{GGM} \quad 220 < \sigma_{\text{prod}} < 470 \mu\text{b} \quad n = 3$$

$$\text{CDHS} \quad \sigma_{\text{prod}} \sim 40 \mu\text{b} \quad n = 3$$

These cross-sections seem to be high for charm production, especially if one compares them to emulsion experiments [18] and takes the lifetime of charm to be $\sim 5 \times 10^{-13}$ s. Of course, it would be far more interesting if these prompt neutrinos were not due to charm. In this beam dump experiment there was not sufficient data to determine if the prompt neutrino flux was symmetric in νe and $\nu \mu$. An interesting speculation by Salam and Pati [19] that quarks can be liberated, would given an asymmetric $\nu e, \nu \mu$ source.

There are sufficient loose ends around in the interpretation of this beam dump experiment to justify for a much better one to be done in the near future.

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