Neutrino Lepton Physics with the CHARM2 Detector

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1. Introduction

The CHARM2 detector has been designed to obtain a precision determination of the electro-weak mixing parameter $sin\ 2\theta_W$ via a mesurement of the ratio of the cross section of the purely leptonic neutral current processes

$$\nu_\mu + e \rightarrow \nu_\mu + e$$

and

$$\overline{\nu}_\mu + e \rightarrow \overline{\nu}_\mu + e \quad .$$

Preliminary results of this experiment on the determination of $sin\ 2\theta_w$ have been published in [1].

The main difficulties for the study of these processes come from the very small value of the cross section ($\sigma/E = 1.5 \times 10\ -42cm\ 2/GeV$) and from the high level of background. The single electron events produced in the $\nu_\mu - e$ scattering must be extracted from the deep inelastic neutrino nucleon scattering ones that have a three order of magnitude higher rate.

To match these requirements CHARM2 [2] has been built as a high mass,low Z, high granularity, sampling calorimeter (total mass 692 tons). The calorimeter is made of 420 modules, each module consisting of a 3.7 m × 3.7 m, 4.8 cm thick, glass plate and of a plane of 352 plastic limited streamer tubes with digital readout of the wires and analog readout of pickup strips orthogonal to the wires. The calorimeter is followed by a muon spectrometer (magnetized iron plates and drift chambers) for a measurement of the momentum of muons produced in charge current interactions.

The discrimination of e.m. against hadronic showers is essentially based on their different lateral profile. The widths are about 8 cm and 80 cm respectively for e.m. and hadronic showers. The detector allows also to reconstruct with high precision the direction of e.m. showers. We shall see that this is a very important feature of the apparatus, in fact the $\nu_\mu e$ events are kinematically constrained in a very small forward cone, while the background has a much wider angular distribution. We have used calibration data taken in 1989 to improve the algorithms used to determine the direction so that the angular resolution is now $\frac{16mrad}{\sqrt{E}}$, compared with the value $\frac{22mrad}{\sqrt{E}}$ given in [2].

The detector has been exposed to the CERN WB neutrino beam starting from 1987. Neutrino and antineutrino runs have been alternated every few days to ensure uniform detector behaviour and a total of 2×10 19 protons on target have been collected in 87,88,89,90 runs. The analyses that will be presented here refer to 87,88,89 data (75% of the total statistics).

The low Z of the target material allows a precise measurement of muon direction, while the high granularity of the detector makes possible a detailed study of vertex activity. These characteristics of the CHARM2 calorimeter together with the muon momentum information have allowed us to study two leptonic processes in which the neutrino electron interaction gives rise to final states containing only muons and precisely

1. Inverse muon decay. [3]

$$\nu_\mu + e - \rightarrow \mu \; - + \nu_e$$

2. Muon pair production in the electromagnetic field of a nucleus.[4]

$$\nu + A \rightarrow \nu + \mu \; + + \mu \; - + A$$

This process, usually called neutrino trident production, can be seen from the point of weak interactions as $\nu_\mu \mu$ elastic scattering.

We shall present in the following sections the result obtained until now from the CHARM2 Collaboration in the study of these purely leptonic neutrino processes.

2. $sin\ 2\theta_W$ determination from $\nu_\mu - e$ scattering

The determination of the value of $sin\ 2\theta_W$ can be performed with high sensitivity, by measuring

$$R = \sigma(\nu_\mu e)/\sigma(\overline{\nu}_\mu e) =$$

$$= 3(1 - 4\sin\ 2\theta_w + 16/3 \sin\ 4\theta_w)/(1 - 4\sin\ 2\theta_w + 16\sin\ 4\theta_w).$$

High sensitivity can be obtained because, in the region of $\sin\ 2\theta_w = 0.25$, $\Delta(\sin\ 2\theta_w) = 1/8(\Delta R/R)$. The use of R reduces the systematic error, in fact the efficiency of selections cancel out in the ratio and only the relative neutrino fluxes are needed.

What we can measure in a real experiment is $N\ \nu$, the number of ν-e scattering events in the neutrino beam and the equivalent quantity $N\ \overline{\nu}$ for the antineutrino beam. $N\ \nu$ will count events due to scattering of neutrino of any type contained in the beam. We can also measure

$$F = \frac{\int \phi(\overline{\nu}_\mu) E dE}{\int \phi(\nu_\mu) E dE}$$

i.e., the energy weighted flux ratio of the main components of the two beams. We define

$$R_{vis} = \frac{N\ \nu}{N\ \overline{\nu}} \times F \quad .$$

R_{vis} will reduce to R in the case of an ideal experiment with pure, monochromatic, equal energy neutrino and antinuetrino beams and its dependence on $\sin\ 2\theta_w$ is similar to the one of R with some loss in the sensitivity factor due to beam contaminations, kinematical cuts, etc.

The $\nu_\mu e$ scattering events are characterized by a single electron emitted at a small angle with respect to the beam direction. In fact for these events

$$E_e\theta_e\ 2 = 2m_e(1-y) \leq 2m_e = 1Mev \quad , \quad y = \frac{E_e}{E_\nu} \quad .$$

We have classified our events in terms of $E\theta\ 2$. In fact the spread of signal events in the $E\theta\ 2$ variable is almost energy independent since the angular resolution, that is the dominant smearing factor, goes as $\frac{1}{\sqrt{E}}$.

The single electron showers have been selected asking for

1. a narrow width high density shower and

2. no vertex activity, i.e., hit in the first plane of the shower.

The efficiency for selecting pure electrons events has been measured, using calibration data taken with an electron test beam, to be 0.76 (energy independent). Events have been selected in the energy range of 3-24 GeV. The low energy cut has been fixed by the trigger efficiency, the high energy one has been choosen taking into account the fact that at high energies the signal/background ratio deteriorates.

The $E\theta\ 2$ distribution of the selected events is shown in figure 1. The neutrino electron peak is clearly visible at small values of $E\theta\ 2$ over a smooth background.

We have described the background in terms of ν_e quasi elastic interactions (the ν_e contamination is of the order of 1%) and of single $\pi\ 0$ production. Both these processes produce an electromagnetic shower in the final state but their kinematics do not give any peaking at low values of $E\theta\ 2$.

We have succesfully represented our data using these assumptions, a two dimensional fit to E and $E\theta\ 2$ has been made and we have obtained the following result for the number of signal events: 1481± 56 (ν_μ beam) and 1621±62 ($\overline{\nu}_\mu$) beam.

To get from the number of events the ratio R_{vis} one has to compute the relative flux ratio F. Four different methods have been used:

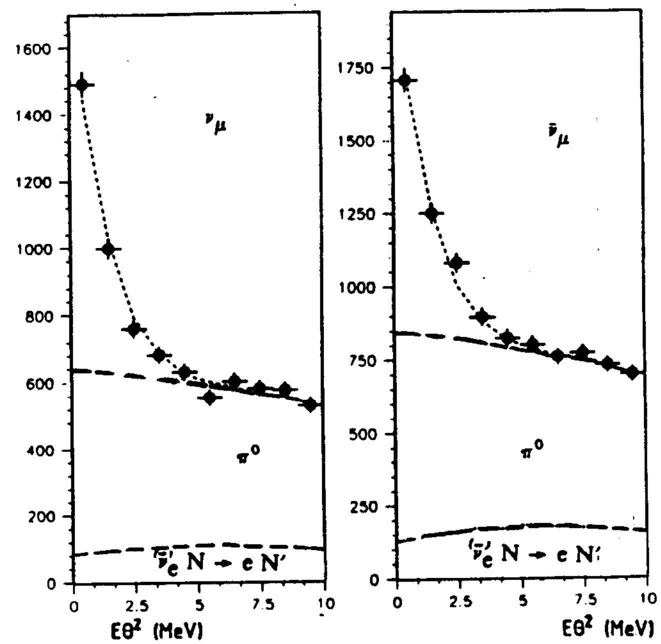

Figure 1 Distribution of selected events as a function of $E\Theta^2$. (a) in the neutrino. (b) in the antineutrino beam. The background reactions $\nu_e N \to eN'$ and $\nu N \to \nu\pi^0 N$ are shown separately.

1. measurement of the flux of muons accompanying the neutrino beam;
2. measurement of the rate of quasi elastic ν_μ and $\overline{\nu}_\mu$ events at low Q^2;
3. measurement of the rate of single π^0;
4. measurement of the total number of neutrino interactions in both beams.

The cross sections for neutrino and antineutrino in cases 2) and 3) are equal, and for case 4) is well known. The four methods give well consistent results and the F results to be

$$F = 1.011 \pm 0.024 \quad .$$

We finally obtain

$$\sin^2\theta_W = 0.240 \pm 0.009(stat) \pm 0.008(syst) \quad .$$

There are various contributions to the quoted systematic error but the dominant one (0.007) is due to the background subtraction.

Applying radiative corrections [5] we obtain, using the Sirlin definition, $sin^2\theta_w = 1 - M_W^2/M_z^2$,

$$\sin^2\theta_W = 0.239 \pm 0.009 \pm 0.008 \quad .$$

This value can be compared directly to the value obtained from the neutrino deep inelastic data [6]

$$\sin^2\theta_W = 0.230 \pm 0.004 \pm 0.005$$

and from the collider data [7]

$$\sin^2\theta_W = 0.220 \pm 0.009 \quad .$$

A comparison with the mass of the Z, as measured by LEP, allows a test of radiative corrections at a level of two standard deviations.[1] I shall stress that this is still a preliminary result; the data collected in the 1990 run are not included in the analysis, more work on the systematics will go on and we hope to reach a final precision of 0.007.

3. Inverse muon decay

The inverse muon decay process (IMD)

$$\nu_\mu + e^- \longrightarrow \mu^- + \nu_e$$

is a purely leptonic charged current process. Experimentally these events can be extracted from single muon events with small hadronic activity. Figure 2 shows the p_t^2 distribution for events with $E_\mu \geq 10.9$ GeV and $E_{had} \leq 1.5$GeV for ν_μ (solid line) and for $\overline{\nu}_\mu$ (dots). The antineutrino spectrum has been normalized in the range $0.05 \leq p_t^2 \leq 0{,}1\ GeV^2$. The insertion in the figure shows the small p_t^2 region where the peak due to the inverse muon decay in the neutrino case is more clearly visible. The background is given by quasi elastic ν N events. Since at small p_t^2 the differential cross sections of ν_μ and $\overline{\nu}_\mu$ are equal, we have used the antineutrino spectrum to obtain the background under the IMD peak. The Standard Model (SM) cross section is predicted to be

$$\sigma = \sigma_{as} E_\nu \left(1 - \frac{M_\mu^2}{2 m_e E_\nu}\right)^2 \quad .$$

$\sigma_{as} = \frac{G_F^2}{\pi} = 17.23 \times 10^{-42} cm^2 GeV^{-1}$ is usually called the asymptotic cross section. Our experimental result is

$$\sigma_{as} = (17.62 \pm 1.32) 10^{-42} cm^2 GeV^{-1} \quad .$$

Applying radiative corrections we obtain

$$\sigma_{as} = (18.16 \pm 1.36) 10^{-42} cm^2 GeV^{-1}$$

in good agreement with the SM predictions. Defining S as

$$S = \frac{\sigma_{as}(exp)}{\sigma_{as}(SM)} = 1.054 \pm 0.079 = |G_{LL}^V|^2$$

and comparing it with the result on the muon decay, $\frac{1}{4}|G_{LL}^S|^2 + |G_{ll}^V|^2 \leq 1$, we can constrain the scalar coupling of leptons to their neutrinos to be $|G_{LL}^S|^2 \leq 0.40$ at 90% CL.

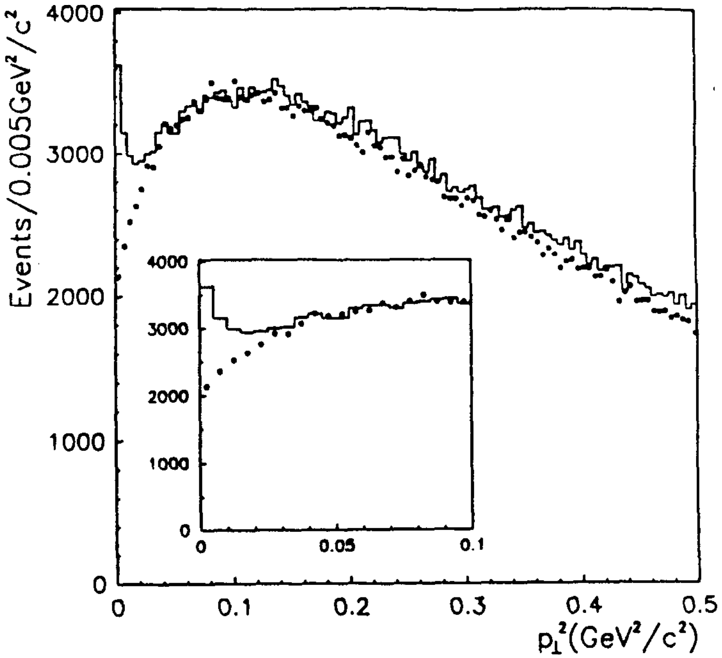

Figure 2

$p_\perp^2$ distribution for events with $E_\mu > 10.9$ GeV and $E_{had} < 1.5$ GeV for incident ν_μ (solid line) and $\bar{\nu}_\mu$ (marked with dots). The $\bar{\nu}_\mu$-distribution was normalized to the ν_μ-distribution in the range $0.05 < p_\perp^2 < 0.1$ GeV^2/c^2. The insertion shows the small $p_\perp^2$ region with the peak due to the inverse muon decay reaction.

4. Neutrino trident production

The diagrams for production of muon pairs in the electromagnetic field of a nucleus

$$\nu + A \rightarrow \nu + \mu^+ + \mu^- + A$$

are shown in fig 3. Both W and Z exchange contribute and the measurement of the total cross section of this process will provide a direct test of the interference between the two amplitudes as predicted by the Standard Model. The total cross sections for neutrino and antineutrino are equal and can be exactly computed if the nuclear elctromagnetic form factor is known. Using a phenomenological form factor integrating over the energy distribution of our neutrino and antineutrino beams we expect

$$\sigma_{theor} = [1.9 \pm 0.4] 10^{-41} \text{ cm}^2 \text{ per nucleus} \quad .$$

The theoretical error is mainly due to the uncertainty on form factors and to the uncertainty on the contribution of non-coherent production. The kinematics of this process predict a small invariant mass of the dimuon system (≤ 2.5 GeV). The experimental signature of these events is a dimuon pair with no hadronic activity. Figure 4 shows the distribution of the vertex activity determined by the number of additional hits in the first ten planes following the vertex. The histogram shows a peak at low vertex activity for events having a dimuon mass smaller than 2.5 GeV. We attribute this peak to the effect of trident production. The crosses are the distribution for events with dimuon mass bigger than 2.5 GeV; in this case no peak is seen.

The two distributions have been normalized in the interval 20-180 hits and assuming the same behaviour of the two distributions in the low activity region, we obtain an excess of 63 ± 15 events due to trident production. After a small correction for contamination of coherent single pion production in which the pion

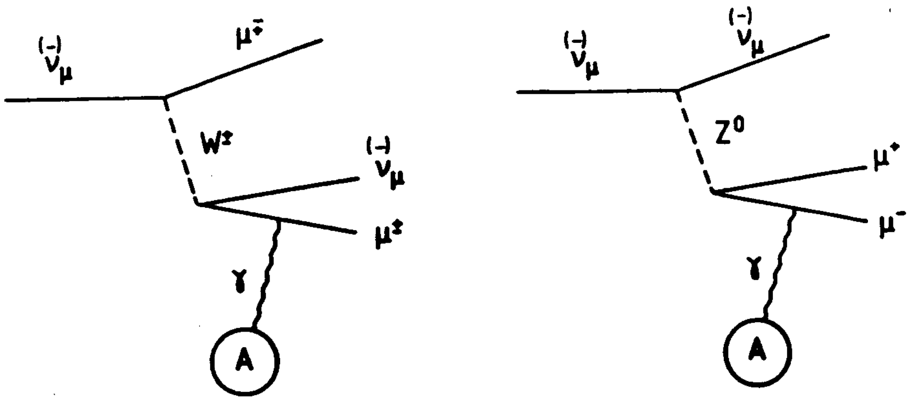

Figure 3 Feynman diagrams for trident production by neutrinos and antineutrinos.

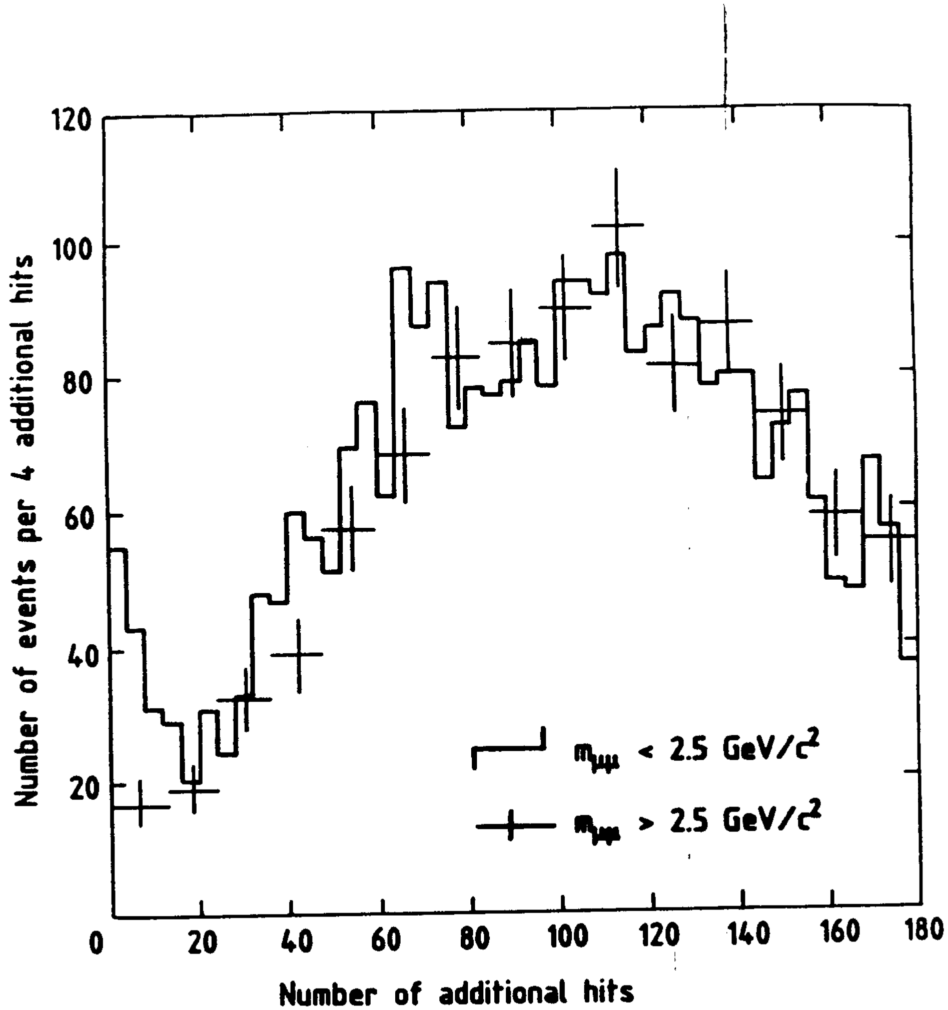

Figure 4 Vertex activity determined by the number of additional hits in 10 planes following the vertex for dimuon events of opposite charge.

decays before interacting with no visible decay kink, taking into account detection efficiencies and neutrino fluxes we obtain the following result for the cross section:

$$\sigma_{exp} = [3.0 + -0.9(stat) + -0.5(syst)]10\ -41\ \text{cm}\ 2\ \text{per nucleus}\quad .$$

We can summarize our result in the following way: neutrino trident production has been experimentally observed for the first time with high statistical significance, the cross section is in agreement with the SM predictions; however the reached precision is not yet sufficient to demonstrate interference effects.

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