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EXPERIMENTAL STUDY OF THE REACTION $\nu_\mu e^- \to \mu^- \nu_e$

CHARM Collaboration

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ABSTRACT

We present data of the reaction $\nu_\mu e^- \to \mu^- \nu_e$, the inverse of muon decay, collected in a long exposure of the CHARM neutrino detector to the CERN SPS horn-focussed wide band neutrino beam.

After correction for efficiencies, a sample of 594 ± 56(stat.) ± 22(syst.) events has been found. The ratio of the measured and expected cross sections is 0.98 ± 0.12 assuming pure V-A interaction. In an $SU(2)_L \times SU(2)_R \times U(1)$ model containing two charged intermediate vector bosons, one can relate this ratio to the ratio of the masses of the two vector bosons and to their mixing angle ω. From the result of this experiment, the limits $M(W_2)/M(W_1) \geq 1.9$ and $\omega \leq 15°$ at 90 % c.l. can be derived.

A search for the reaction $\bar{\nu}_\mu e^- \to \mu^- \bar{\nu}_e$, allowed by multiplicative lepton number conservation, gave a limit of $\sigma(\bar{\nu}_\mu e^- \to \mu^- \bar{\nu}_e) / \sigma(\nu_\mu e^- \to \mu^- \nu_e) < 0.05$, at 90 % confidence level.

1.

A study of the reaction

$$\nu_\mu e^- \rightarrow \mu^- \nu_e \qquad (1)$$

usually called inverse muon decay, provides information about the chiral structure of the leptonic charged current interaction [1] and the two-component nature of neutrinos [2].

Assuming completely left-handed charged leptons and making no assumptions on the helicity of the neutral leptons, the differential cross section for reaction (1) can be written as [3]

$$d\sigma/d(\cos\theta^*) = G^2\,(s-m_\mu^{\,2})^2\,/16\pi s \qquad (2a)$$
$$\times\ [(1+P)(1-\lambda)(1-\cos\theta^*)(a-b\cos\theta^*)+4(1-P)(1+\lambda)] \quad ,$$

where θ^* is the angle in the c.m. system between the incoming ν_μ and the outgoing μ^-, $a = 1+m_\mu^{\,2}/s$, $b = 1-m_\mu^{\,2}/s$, $\lambda = -\,2(g_V g_A)\,/\,(|g_V\,|^2 + |g_A\,|^2)$, and $P = [N(\nu_R) - N(\nu_L)]/[N(\nu_R) + N(\nu_L)]$ is the neutrino polarization.

In the limit $s >> m_\mu^{\,2}$ the cross section (2a) can be expressed in terms of the inelasticity $y = (1-E_\mu/E_\nu)$

$$d\sigma/dy = G^2\,s/4\pi\ [\ (1+P)(1-\lambda)y^2 + (1-P)(1+\lambda)\ ]. \qquad (2b)$$

The y^2 term in (2b) describes the scattering of possible right-handed ν_μ by left-handed e^-, coupled by S,P terms in the effective Lagrangian.

A pure V-A structure of the interaction implies $\lambda = 1$, and left-handed two component neutrinos imply $P = -1$.

In a different approach reaction (1) can be described in terms of a left-right symmetric electroweak model based on the gauge group $SU(2)_L\times SU(2)_R\times U(1)$

[4]. In this model two charged gauge bosons exist, W_L and W_R , whose exchange in reaction (1) produces respectively the constant part and the y^2 part in cross-section (2b).

A symmetry-breaking mechanism causes the W_L and W_R to mix with an angle ω forming two mass eigenstates W_1 and W_2 . When $\omega = 0$ and $M(W_2) = \infty$, $W_1 = W_L$ is the ordinary W-boson of the standard model.

In this model the rate of reaction (1), normalized to the integrated V-A cross-section, is a function of the mass ratio $r = M(W_1)/M(W_2)$ and of the mixing angle ω [5]. A measurement of the rate of reaction (1) then tests directly the V-A coupling dominance of all the leptons involved, and in the left-right symmetric model it limits the mass ratio of the two charged bosons and their mixing angle.

Theories of multiplicative conservation of the lepton number [6] allow the final state of reaction (1) to be induced also by "wrong" neutrinos :

$$\bar{\nu}_\mu e^- \rightarrow \mu^- \bar{\nu}_e \quad . \qquad (3)$$

Up to now only few results have been presented on reaction (1), because of the high energy threshold and the small cross section [7,8].

We have studied reaction (1) and searched for reaction (3) using the CHARM neutrino detector, exposed to horn-focussed wide band neutrino and antineutrino beams produced by 400 GeV protons from the CERN SPS, with a mean energy of 31 GeV for the neutrino and 24 GeV for the antineutrino beam.

The data presented here have been taken from 1979 to 1981 ; the previously published data [8] concern only 1979 wide band runs and are part of the sample we present here.

A detailed description of the CHARM detector may be found elsewhere [9]. Briefly,it consists of a segmented ionization calorimeter surrounded by a magnetized iron frame,and a muon spectrometer.

The calorimeter is made of 78 modules, each one consisting of a marble plate of 3×3 m^2 surface area and 8 cm thickness followed by a plane of 128 proportional drift tubes and a plane of 20 plastic scintillators oriented at 90° with respect to the tubes.

The muon spectrometer is composed of four toroidal iron magnets providing information for the identification and the momentum analysis of forward going muons. Each magnet is segmented in iron disks, 5 cm thick in the first module (the "end calorimeter"), and 15 cm thick in the next three modules (the "end magnet"), for a total iron length of 3 m, with an external diameter of 3.7 m, and a central hole of 16.7 cm diameter. Eighteen planes of proportional drift tubes, interspersed between the disks, are used to measure the muon momentum with a resolution of 16% on average. Six planes of scintillation counters have been inserted in the gaps of the last three magnets to detect and to measure muon "bremsstrahlung" energy loss.

The detector was triggered requiring that at least four scintillator planes were hit, that the detected ionization loss was larger than 50 MeV, and that a track had penetrated through at least four planes of the muon spectrometer end magnets, equivalent to 1.35 m of iron. In later runs it was further requested that at least nine consecutive planes in the calorimeter were hit. The two samples have been compared in all the relevant variables, and found compatible with each other.

The particular characteristics of reaction (1) are the energy threshold $E_\nu > 10.8$ GeV, the small muon emission angle $\theta_\mu < 10$ mrad, and the absence of a visible recoil. Consequently, the analysis aims at selecting recoil-less single muon events above threshold.

A fiducial volume was defined to ensure good track measurement. Tracks starting between plane 3 and 69 (59 for later data), with $| y,z | < 150$ cm, were accepted. Tracks were required to have a distance from the beam axis of $25 < R \leq 180$ cm, to ensure full detection efficiency in the muon spectrometer.

Events were selected which satisfied the following conditions :

1. less than 92 MeV deposited energy in the first six planes of scintillators following the vertex, less than 18 MeV in each of the first three scintillator planes, and the sum of the deposited energy in the first two planes less than 20 MeV (the peak value of the Landau distribution of the energy deposited by a minimum ionizing particle in one plane of the calorimeter is 6 MeV). In addition, less than 10 MeV in each of the first three scintillator planes was required if more than one proportional drift tube was hit in one of the first three planes.

2. negative (positive) muon charge for neutrino (antineutrino) runs ;

3. the time-of-flight measured between the scintillators in the last plane of the calorimeter and the scintillation counters in the last magnet of the muon spectrometer was compatible with a track following the direction of the neutrino beam.

Out of 43478 neutrino and 99596 antineutrino quasi-elastic candidates, the final sample selected in this way contains 16843 neutrino and 44703 antineutrino events.

Above E_ν = 10 GeV the q^2 dependence of quasi-elastic scattering

$$\nu_\mu\, n \to \mu^-\, p \qquad (4a)$$

and of one pion production

$$\nu_\mu\, N \to \mu^-\, \pi\, N \qquad (4b)$$

is expected to be energy independent and equal for ν and for $\bar{\nu}$ on an isoscalar target . On the other hand the reaction (1) is expected to occur at very low values of q^2 .

Our selection criteria imposed a limit of $q^2 < 0.1\ \mathrm{GeV}^2$ on the detection of quasi-elastic ν and $\bar{\nu}$ scattering, because of the rejection of proton recoils at larger q^2 and excluded at the same time events belonging to reaction (4b). This fact allowed us to separate the background from the signal in the ν sample, in the region $0 < q^2 < 0.02\ \mathrm{GeV}^2$, by subtracting the q^2 distribution of the $\bar{\nu}$ sample normalized to the equivalent ν sample in the range $0.02 \leq q^2 < 0.1\ \mathrm{GeV}^2$. We approximate q^2 by $p_t^{\ 2}$, the muon transverse momentum squared, because θ_μ is very small. For $q^2 < 0.02\ \mathrm{GeV}^2$ we observe an excess of μ^- events (fig. 1),

$$N_\nu(\mu^-) - \varepsilon N_{\bar{\nu}}(\mu^+) = 937 - (0.407\times 1355) = 386 \pm 36, \qquad (5)$$

where $\varepsilon = N_\nu(\mu^-;0.02 \leq q^2 < 0.1\ \mathrm{GeV}^2)/\ N_\nu(\mu^+;0.02 \leq q^2 < 0.1\ \mathrm{GeV}^2)$, which we attribute to reaction (1). The binning in fig. 1 is of the same order of our q^2 resolution .

The efficiency of the selection criteria has been determined experimentally by applying them to later parts of the same tracks, starting at least 18 planes after the vertex, with the result :

$$\varepsilon_{sel} = 0.882 \pm 0.003 \quad . \qquad (6)$$

Two other corrections must be applied to the number of events obtained :

i) for the efficiency ε_{cut} of the cuts ($q^2 < 0.02\ \mathrm{GeV}^2$ and $p_\mu > 10$ GeV/c), which is estimated using the observed E_ν spectrum and the simulated detector resolution

$$\varepsilon_{cut} = 0.789 \pm 0.030 \quad , \qquad (7)$$

ii) for the muon track fitting efficiency ε_{fit}

$$\varepsilon_{fit} = 0.934 \pm 0.002 \quad . \qquad (8)$$

The quoted errors of the efficiencies are mainly of systematic origin . Correcting the result for the efficiencies (6-8) we find

$$N(\nu_\mu e^- \rightarrow \mu^-\ \nu_e) = 594 \pm 56(\mathrm{stat.}) \pm 22(\mathrm{syst.}) \quad (9)$$

for a total number of acceptance-corrected inclusive one-muon events with E_{vis} > 10 GeV of $(1.046 \pm 0.063) \times 10^6$, or a relative rate of

$$R = \left. \frac{N(\nu_\mu e^- \to \mu^- \nu_e)}{N(\nu_\mu N \to \mu^- X)} \right|_{E_{vis} > 10\ \mathrm{GeV}} = [5.68 \pm 0.53(\mathrm{stat.}) \pm 0.40(\mathrm{syst.})] \times 10^{-4} .$$

Integrating eq. (2) over the observed E_ν spectrum, we obtain the predicted number of inverse muon decays

$$N = \frac{N_0}{32} [(1+P)(1-\lambda)C + 8(1-P)(1+\lambda)], \qquad (10)$$

where C = 2.98 is given by the integrated neutrino spectrum and N_0 is the expected number of events for pure V-A interaction.

Assuming respectively left-handed or right-handed neutrinos, we predict the following rates for reaction (1) :

$$N_1 = 607 \pm 35,$$
$$N_2 = 226 \pm 13.$$

Comparing these predictions with the observed signal (9) we obtain :

$$R_1 = 0.98 \pm 0.12,$$
$$R_2 = 2.63 \pm 0.33.$$

R_1 expresses the ratio between the observed rate and the rate expected from V-A coupling among all the leptons in reaction (1), while R_2 excludes at the level of 6 standard deviations the dominance of S,P couplings in the interaction.

Fig. 2a shows the q^2 distribution of the inverse muon decay candidates and fig. 2b shows their μ^- momentum distribution. We note that fig. 2b does show the expected threshold behaviour of reaction (1).

In fig. 3 we compare our result in terms of V-A interaction and left-handed neutrinos to the previous experiments [7,8], and show the statistical significance and correlation with which the parameters λ and P of equation (2) are determined.

Evaluating now R_1 in the $SU(2)_L \times SU(2)_R \times U(1)$ model [5], as a function of the ratio of the masses $r = M(W_1)/M(W_2)$ and of the mixing angle ω we find the 90% confidence limits $\omega \leq 15°$ and $M(W_2) \geq 1.9\ M(W_1)$.

We conclude that the V-A structure of the leptonic charged current interaction and the two component theory with left-handed neutrinos is confirmed again, on the basis of four times larger statistics than in the previous result [8].

Candidates of reaction (3) have been searched for in the antineutrino exposure. We observed 9406 recoil-less single μ^- events in antineutrino runs, and found an excess of 120 ± 20 μ^- events with $p_\mu > 10$ GeV/c and $q^2 < 0.02\ GeV^2$.

We expect a contribution from reaction (1), due to neutrino contamination of the antineutrino beam. This can be computed by scaling the observed excess in neutrino runs, taking into account the fitting efficiencies for focussed and defocussed muons :

$$386 \times 9406 / 43478 = 84 \text{ events.}$$

Another contribution to the μ^- sample in antineutrino runs may be due to the reaction

$$\bar{\nu}_e\ e^- \rightarrow \mu^-\ \bar{\nu}_\mu \qquad (11)$$

induced by the $\bar{\nu}_e$ contamination of the antineutrino beam. This can be computed from the knowledge of the beam composition to be :

$$84 \times \frac{N(\bar{\nu}_e)}{N(\nu_\mu)} \times \frac{\langle E(\bar{\nu}_e)\rangle}{\langle E(\nu_\mu)\rangle} \times \frac{\sigma(\bar{\nu}_e e)}{\sigma(\nu_\mu e)} = 7 \text{ events,}$$

with $N(\bar{\nu}_e) / N(\nu_\mu) = 0.11$ and $\langle E(\bar{\nu}_e)\rangle / \langle E(\nu_\mu)\rangle = 1.89$ derived from the calculated neutrino flux spectra [10], and $\sigma(\bar{\nu}_e e) / \sigma(\nu_\mu e) = 3/8$ for V-A interaction [3].

The candidates of reaction (3) are thus

$$120 - 84 - 7 = 29 \pm 22$$

If we assume a multiplicative lepton number conservation [6] which allows reaction (3) to occur, we can evaluate the ratio between cross-sections of reaction (1) and (3), with the result

$$\frac{\sigma(\bar{\nu}_\mu e \to \mu^- \bar{\nu}_e)}{\sigma(\nu_\mu e \to \mu^- \nu_e)} = \frac{N(3)/N_{\bar{\nu}}(\mu^+)}{N(1)/N_\nu(\mu^-)} < 0.05 \qquad (12)$$

at the 90 % confidence level, where $N_{\bar{\nu}}(\mu^+)$ and $N_\nu(\mu^-)$ are respectively the number of quasi-elastic antineutrino and neutrino events. Our result seems to exclude multiplicative lepton number conservation [11].

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give a 90 % confidence upper limit of R < 0.098.

Figure captions

Fig. 1: q^2 distribution of single recoil-less μ^- and μ^+ events, normalized to equal numbers for $0.02 \leq q^2 < 0.1$ GeV^2 . The excess at $q^2 < 0.02$ GeV^2 is attributed to the reaction $\nu_\mu e^- \rightarrow \mu^- \nu_e$.

Fig. 2: a) Observed q^2 distribution of the difference $N_\nu(\mu^-) - \varepsilon N_{\bar{\nu}}(\mu^+)$, normalized to equal rate for $0.02 \leq q^2 < 0.1$ GeV^2, compared to the prediction for inverse muon decay assuming V-A coupling and left-handed neutrinos (solid line).

b) Observed μ^- momentum distribution of the difference $N_\nu(\mu^-;q^2 < 0.02 \text{ GeV}^2) - N_\nu(\mu^-;q^2 > 0.02 \text{ GeV}^2)$ normalized to 386 events, and V-A prediction for inverse muon decay.

Fig. 3: 90 % confidence contour of the V-A parameter λ and left-handed neutrino polarization P deduced from the observed rate of the inverse muon decay reaction. Previous limits from the Gargamelle Collaboration [7] and from the CHARM Collaboration [8] are shown as well.

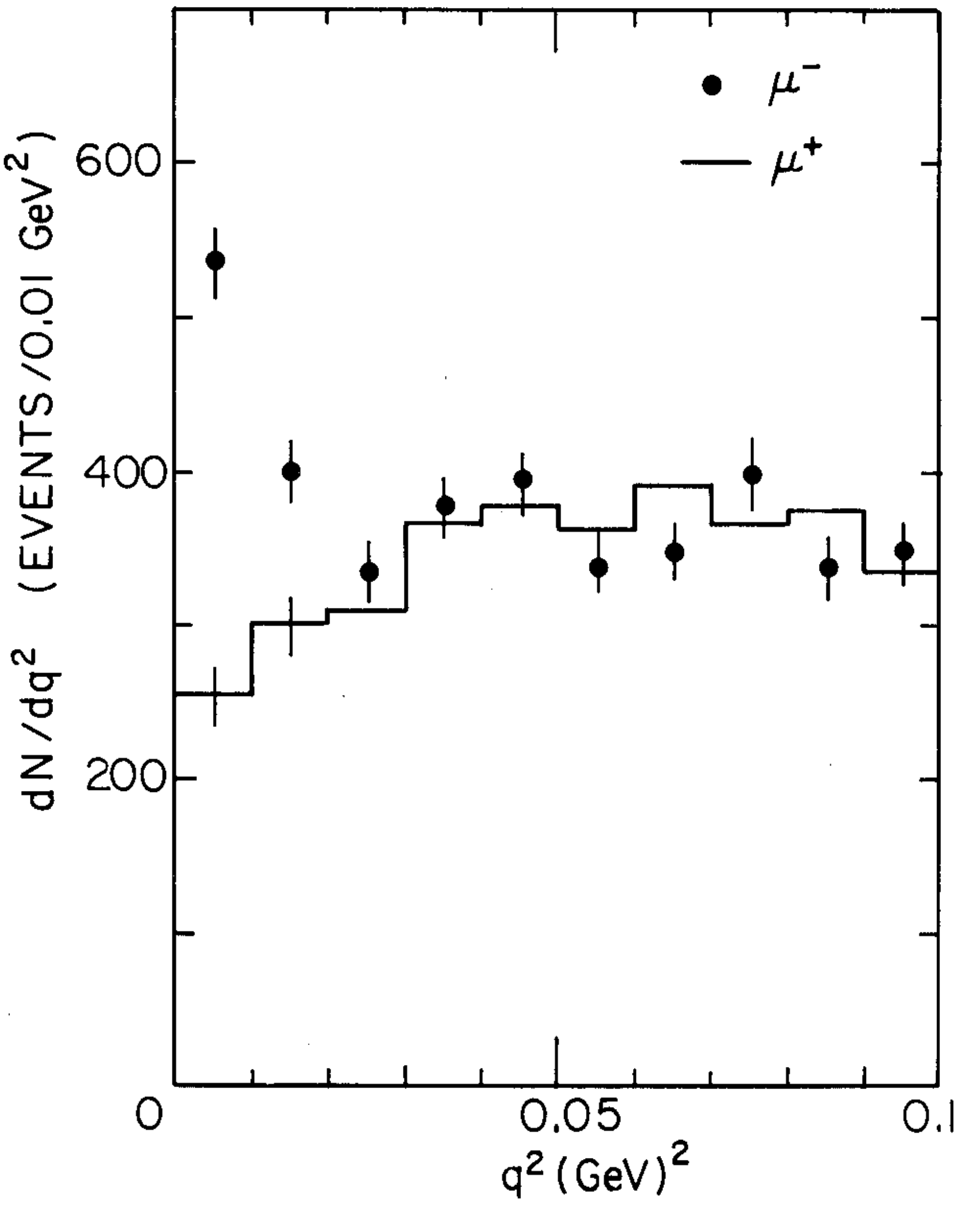

Fig. 1

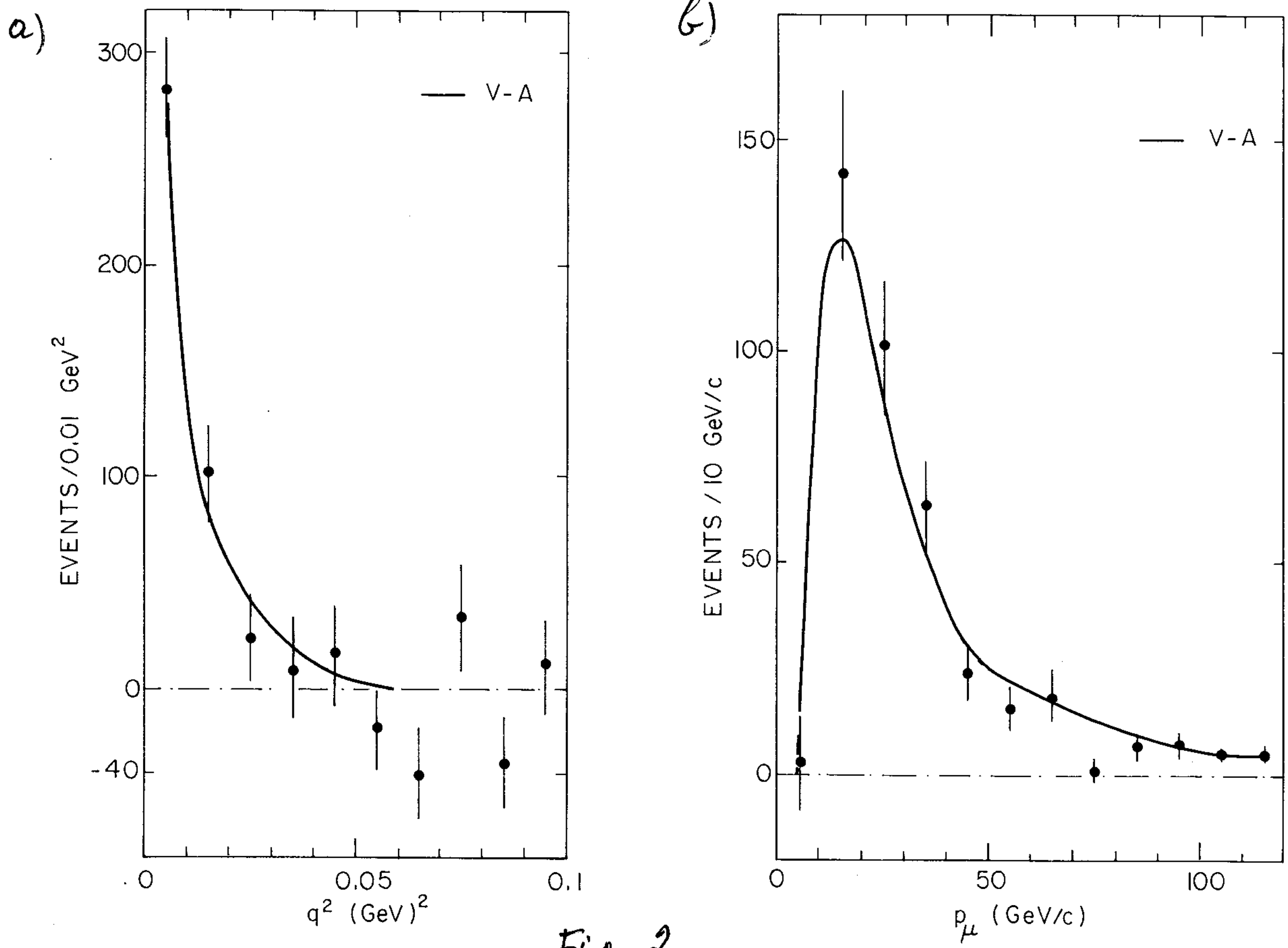
a)
V-A
300
200
100
0
-40
EVENTS/0.01 GeV^2
0
0.05
0.1
q^2 (GeV)^2
b)
V-A
150
100
50
0
EVENTS / 10 GeV/c
0
50
100
p_μ (GeV/c)

Fig. 2

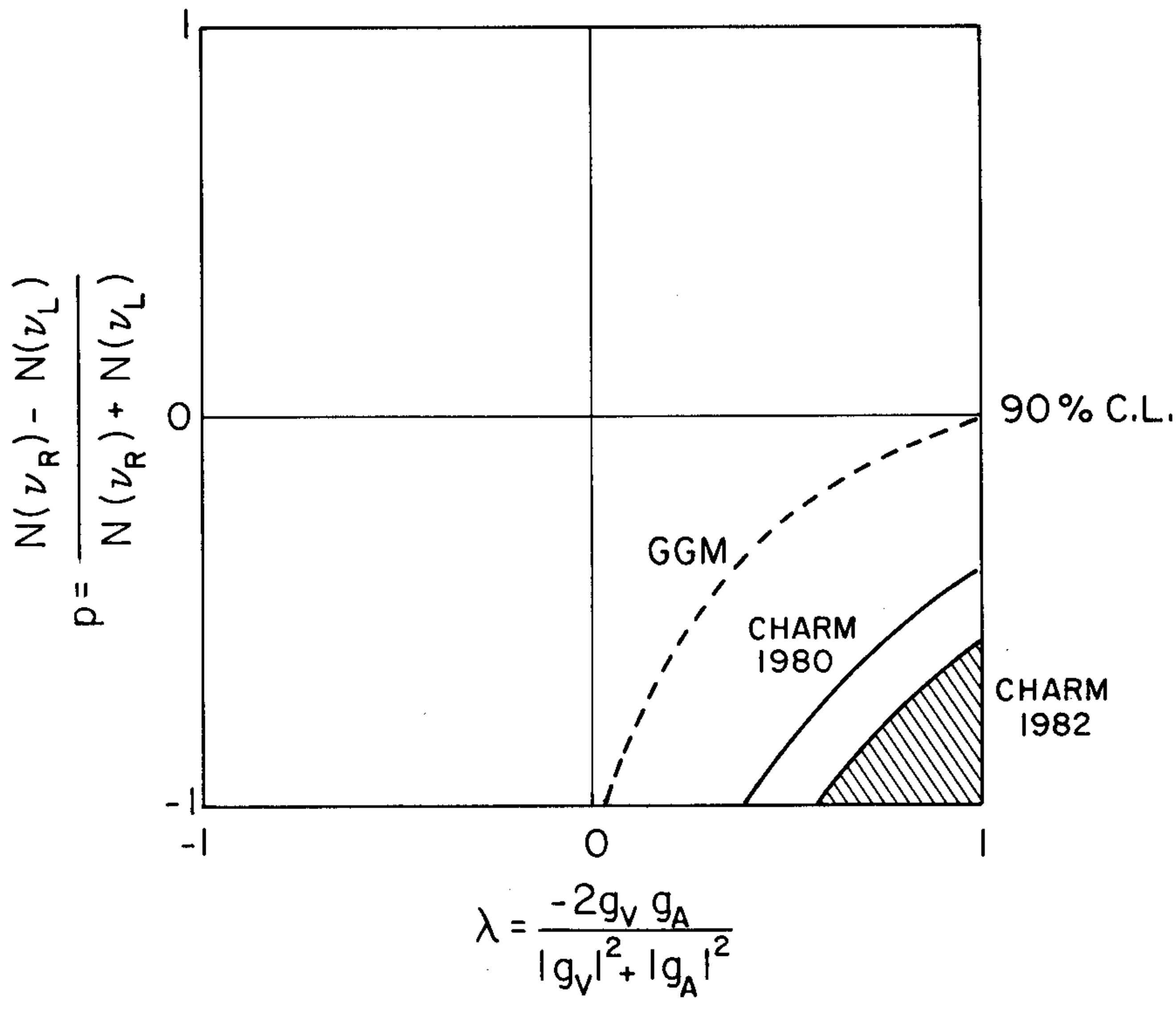
1
0
-1
-1
0
1
90% C.L.
GGM
CHARM
1980
CHARM
1982
ρ = (N(ν_R) − N(ν_L)) / (N(ν_R) + N(ν_L))
λ = −2g_V g_A / (|g_V|² + |g_A|²)

Fig. 3