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EVIDENCE FOR THE LEPTONIC NEUTRAL CURRENT REACTION

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$

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ABSTRACT

In the Gargamelle neutrino experiment, three unambiguous candidates for the reaction $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$ have been observed corresponding to a cross section for a recoil electron energy within the range $0.3 < E_{e^-} < 2.0$ GeV of $0.06 \times 10^{-41} E_{\bar{\nu}}$ (cm^2/electron). The calculated background is 0.44 ± 0.13 events and the probability that all three candidates could be due to this background is 1 %.

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1. INTRODUCTION

A direct test of neutral current models may be performed by studying the purely leptonic weak neutral current interaction

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^- \qquad (1)$$

where the cross section is exactly calculable for a given model. The study of this reaction is important because it provides information about the neutral current which is free from the assumptions made in the analysis of the semileptonic neutral current interactions.

The heavy liquid bubble chamber Gargamelle, filled with freon (CF_3Br, X_o = 11 cm), has been used to study reaction (1). Since our original letter[1)] concerning reaction (1), an additional million pictures have been analysed to search for this process. Ninety per cent of the new sample was obtained with the aid of the PS booster which increased the primary proton intensity by an average factor of 4. Thus, the total number of pictures now examined, including the original sample, corresponds to a total of 4.7×10^{18} protons on target and represents a ninefold increase in statistics compared to the first report. The $\bar{\nu}_\mu$ and ν_e spectra are shown in fig. 1.

2. EVENT SELECTION

The 6.3 m^3 visible volume of the chamber has been double scanned for two main categories of events. A category I event : any isolated track which, through bremsstrahlung or spiralization, is clearly identified as that of an e^-, e^+ or $e^{\pm}$ (ambiguous charge). Due to the short radiation length of the liquid, there is no confusion between electron and non-electron tracks in this experiment. A category II event : any e^+e^- pair without visible source. Due to shower development or delta rays close to the vertex, some events remain ambiguous between categories I and II.

To be accepted as a candidate for reaction (1), a category I track had to show negative curvature before any bremsstrahlung conversion occurs and satisfy the following criteria. To ensure a reasonable scan efficiency and reduce the low energy electromagnetic background, it was required that a candidate should have at least 0.3 GeV energy. Similarly, to reduce any possible ν_e induced background and to keep corrections for ambiguous events small, an upper energy cut of 2.0 GeV was also applied. From the kinematics of reaction (1), any signal event with $E > 0.3$ GeV must have an electron recoil angle (θ) less than 3^o with respect to the incoming $\bar{\nu}$ direction. It was therefore required that a candidate should have an electron recoil angle less than 5^o which includes the estimated angle error of about 1.5^o.

Table I lists all events satisfying the angle cut. After the energy cuts, there remain three unambiguous candidates for reaction (1), six clear e^+e^- pairs, and one ambiguous event.

3. BACKGROUND

The major background arises from the possibility that the observed single electrons are electromagnetically produced. This could occur via the production of a Compton electron or an extremely asymmetric e^+e^- pair in which the electron takes all the energy. By examining over 700 electromagnetically induced showers associated with ν events, it was determined that $(3.4 \pm 0.7)\%$ of all gamma conversions with energy greater than 0.3 GeV were classified as single electrons. As mentioned above, six e^+e^- pairs were found satisfying the cuts. These events are consistent with being due to neutral current 1 π^o production where only one e^+e^- pair is detected. Adding the e^-/e^+e^- ambiguous event to these six, the background from this source is found to be 0.26 ± 0.11 events. Since there are no e^+e^- pairs with energy greater than 2.0 GeV, the upper energy cut has no effect on this contribution.

Another possible background is the ν_e quasi-elastic interaction

$$\nu_e + n \rightarrow e^- + p \qquad (2)$$

in which the proton is not observed and the electron satisfies the energy and angle cuts. This background can be estimated using the reaction

$$\nu_\mu + n \rightarrow \mu^- + p \qquad (3)$$

which is kinematically quite similar to (2) at these energies. In a sample of 890 events with topology

$$\mu^- + m \text{ protons } (m \geq 0)$$

ten were of the type : $\theta_{\mu^-} < 5^o$ and no visible proton. The scanning efficiency for an isolated μ^- is 80 % so that we obtain

$$\frac{\mu^- (\theta_\mu < 5^\circ) + 0p}{\mu^- + mp} = (1.4 \pm 0.5)\ \%$$

None of the ten isolated μ^- with $\theta < 5^\circ$ had energy less than 2.0 GeV, in agreement with differential cross section predictions. Therefore, the effect of the upper energy cut on the e^- background has been estimated using the predicted e^- energy and angle distributions. These predictions are based on the differential cross section at low q^2 with Pauli exclusion principle effects taken into account. Using the ν_e spectrum in the $\bar{\nu}$ beam, the (1.4 ± 0.5) % background quoted above for all energies is reduced by a further factor of 15 yielding

$$\frac{e^- (\theta < 5^\circ, E_{e^-} < 2.0 \text{ GeV}) + 0p}{e^- + mp} = (0.1 \pm 0.04)\ \%$$

In a subsample of film, equivalent to 60 % of the total, 26 e^- + m proton events were found in $3.1\ m^3$ fiducial volume. After normalization, and taking the radial distribution of the neutrino flux into account, the background due to this source is 0.07 ± 0.04 events(*).

The third background to be considered is the reaction

$$\nu_e\ (\bar{\nu}_e) + e^- \rightarrow \nu_e\ (\bar{\nu}_e) + e^- \tag{4}$$

which goes via the charged current as well as the neutral current. With the predicted cross-sections and the ν_e $(\bar{\nu}_e)$ spectra, the expected background within the energy region considered $(0.3 < E_{e^-} < 2.0 \text{ GeV})$ is 0.11 events.

(*) Without the 2.0 GeV upper energy cut, the background from this source is 0.9 ± 0.4 events.

Since the background from the reaction

$$n + e^- \to n + e^-$$

is negligible(2), the total background to the three single electron candidates is 0.44 ± 0.13. The probability that these events are due to non-neutral current background is 1 %.

It is possible to confirm the calculations of the background from the electromagnetic and ν_e quasi-elastic sources : if the energy cuts (0.3 GeV < E < 2.0 GeV) are maintained, but the angular cut is now made between 5° and 30°, then, inasmuch as the electrons from reaction (1) and (4) are kinematically bound to $\theta < 3^\circ$, any isolated e^- remaining should be due to these two background sources. Figure 2 is a scatter plot of θ^2 vs E for all isolated electrons and e^+e^- pairs found with E > 0.2 GeV and $\theta < 30^\circ$. Between 5° and 30°, 69 e^+e^- pairs with 0.3 GeV < $E_{e^+e^-}$ < 2.0 GeV have been found. Following the procedure described above, 2.34 ± 0.54 isolated e^- would be expected from the electromagnetic source. Similarly 0.38 ± 0.06 ν_e induced isolated electrons should be seen in this angular interval. A total of 2.72 ± 0.55 events are thus predicted for $5^\circ < \theta < 30^\circ$ and, referring to figure 2, two events have been found.

4. SIGNAL LOSSES AND OBSERVED CROSS SECTION

The scanning efficiency for the isolated electron topology, assumed to be the same as that of isolated e^+e^- pairs, was found to be 92 % . Correcting only for the scan loss, the observed (0.3 GeV < E_{e^-} < 2.0 GeV) cross-section based on three events is

$$\sigma_{obs} = 0.06 \quad \times 10^{-41} \; E_{\bar{\nu}} \text{ (GeV) } (\text{cm}^2/\text{electron})$$

Since only unambiguous electrons have been accepted, candidates for reaction (1) are lost if the e^- is interpreted as an e^+e^- pair (e^-/γ ambiguity) because of shower development close to the vertex. Two methods have been employed to study the e^-/γ ambiguity over the energy region considered. Using electrons from e^+e^- pairs it was found that (8 ± 2) % of all electron with an energy between 0.3 and 1.0 GeV could be confused with γ's. Secondly, with the aid of ν_e induced events, it was determined that (20 ± 12) % of electrons over 1.0 GeV could be e^-/γ ambiguous.

It should be noted that 5 unambiguously identified e^+e^- pairs lie below the kinematical bound as shown in fig. 2b, demonstrating that the high e^-/γ distinguishability is an essential feature of this type of experiment.

Events are also rejected if the charge of the isolated electron is ambiguous. Using ν_e interactions [3] the probability of an e^+/e^- ambiguity was found to vary between 5 and 13 % within the energy range considered.

5. INTERPRETATION

The results may be compared with theoretical predictions after correction for signal losses.

Assuming that the neutral leptonic current is a linear combination of V and A [4]

$$l_\mu = \bar{\nu}\,\gamma_\mu\,(1 + \gamma_5)\,\nu + \bar{e}\,\gamma_\mu\,(G_V + G_A\,\gamma_5)e$$

then the differential cross-section for reaction (1) can be expressed as :

$$\frac{d\sigma}{dy} = \frac{G^2 m}{2\pi} E_{\bar{\nu}} \left[(G_V + G_A)^2\,(1 - y)^2 + (G_V - G_A)^2 \right] \qquad (5)$$

with $y = E_{e^-}/E_{\bar{\nu}}$. The notation is such that a pure V - A current would have $G_V/G_A = +1$. The contribution from the neutral current part of reaction (4) is negligible because the ν_e contamination in the $\bar{\nu}_\mu$ flux is less than 1 %.

Expression (5) has to be integrated over the electron energy range 0.3 to 2 GeV, taking into account the probability of identifying the electron. Integrating over the antineutrino spectrum and correcting for scanning efficiency leads to a predicted number of events and allows the computation of a likelihood function for the 3 observed events :

$$L = \frac{n^3 e^{-n}}{6}$$

where n is the sum of the number of expected events for given G_A and G_V, and of the background.

The results of this calculation are shown in fig. 3, where the ellipses are curves of equal probability. The middle ellipse corresponds to the maximum of likelihood, the two others being the 90 % confidence limits. Since the detection efficiency is about constant in the whole G_V, G_A domain (the relative variation being less than 5 %), the ellipses shown are also close to curves of equal cross-sections. Hence it is possible to express our result as a total corrected cross-section in the framework of the V,A theory :

$$\sigma_{tot} = (0.10\ {}^{+\,0.21}_{-\,0.09}) \times 10^{-41}\ E_{\bar{\nu}}\ (\text{GeV})\ \text{cm}^2/\text{electron}$$

where the errors correspond to a 90 % confidence level.

Fig. 3 also shows the 90 % confidence ellipse deduced from our previous analysis of the reaction $\nu_\mu e^- \rightarrow \nu_\mu e^-$ (1). The shaded area corresponds to the 90 % confidence domain deduced from both reactions.

Some theoretical models predict that neutral currents should be purely vector or purely axial vector. For this case we can give limits for G_V (or G_A) from a one parameter likelihood function :

$$G_V \text{ (or } G_A) = .42 \begin{matrix} + .26 \\ - .22 \end{matrix}$$

with 90 % confidence.

In the Weinberg-Salam model, the only parameter is θ_w, related to G_V and G_A as follows :

$$G_V = -\frac{1}{2} + 2 \sin^2 \theta_w$$

$$G_A = -\frac{1}{2}$$

The one parameter likelihood function (fig. 4) leads to $\sin^2 \theta_w < 0.4$ with 90 % confidence. Combining this result with our previous analysis for neutrinos, we get :

$$0.1 < \sin^2 \theta_w < 0.4$$

ACKNOWLEDGEMENTS

This experiment depended completely on high proton intensity, a high quality neutrino beam, good bubble chamber operation, and reliable film scanning. The collaboration gratefully acknowledges the excellent co-operation of the CERN PS staff, the beam and Gargamelle crews, and the patient and efficient work of the scanning staff of all participating laboratories.

REFERENCES

(1) F. J. Hasert et al., Phys. Lett. 46B (1973) 121.

(2) The Dirac cross-section for producing a recoil electron of mass m and energy E, by a neutron of mass M, magnetic dipole moment μ and energy E_o is

$$d\,\sigma/dE = \pi\alpha^2\mu^2 \;/\; (M^2 E_{max})\ \text{cm}^2/\text{GeV/electron}$$

where

$$E < E_{max} = 2mE_o^2\ /M^2 .$$

For E_{max} = 0.3 GeV, the electron cut-off energy in this experiment, E_o > 16 GeV. Hence with $\pi\alpha^2\mu^2/M^2 = 2.10^{-31}\ \text{cm}^2$, at least two neutrons of ~ 20 GeV energy must traverse the chamber per pulse to account for the observed signal of 3 events. The maximum possible high energy neutron flux, calculated on the extreme assumption that <u>all</u> hadronic neutral current events are due to neutrons, is at least a factor 10^4 smaller than this.

(3) T. Eichten et al., Phys. Lett. 46B (1973) 281.

(4) L.M. Seghal, Nucl. Phys. B70 (1974) 61; Phys. Letters 48B (1974) 60.

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TABLE I

Isolated e^-, e^+, $e^{\pm}$ and e^+e^- Pairs with $\theta < 5^0$ and $E > 0.3$ GeV

Type	Depth within visible volume along $\bar{\nu}$ direction (radiation Lengths)	Angle (Degrees)	E (GeV)
e^-	5.1	$1.4^{+1.6}_{-1.4}$	0.39±0.13
e^-	23.4	2.0±2.0	0.50±0.12
e^-	34.3	1.5±1.0	0.80±0.25
e^-/γ	10.1	2.0	1.9
γ(e^+e^- pair)	9.6	3.1	0.9
γ	13.7	2.3	0.4
γ	22.9	4.7	0.35
γ	28.0	2.4	0.4
γ	33.4	1.7	0.7
γ	35.7	4.9	1.8
e^+	14.7	4.1	5.4
e^+	14.8	1.2	3.2
e^+	28.5	4.2	4.5
$e^{\pm}$	2.8	2.7	4.7
$e^{\pm}$	4.0	3.9	2.0
$e^{\pm}$	8.8	4.3	4.5

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FIGURE CAPTIONS

Fig. 1 $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$ energy spectra.

Fig. 2 a) θ^2 versus E for isolated e^-, e^+ and e^+e^- pairs.
b) shows detail for $\theta^2 < (5^\circ)^2$ and the kinematical bound for reaction (1) : $\theta^2 = 2\ m_e/E$, one standard deviation error included.
X e^-, ▲ e^+, O e^+e^- pair, ● e/e^+e^- ambiguous.

Fig. 3 Allowed regions of G_V and G_A from measured cross-sections (shaded area corresponds to 90 % confidence domain).

Fig. 4 One-parameter likelihood function for $\sin^2\theta_W$.

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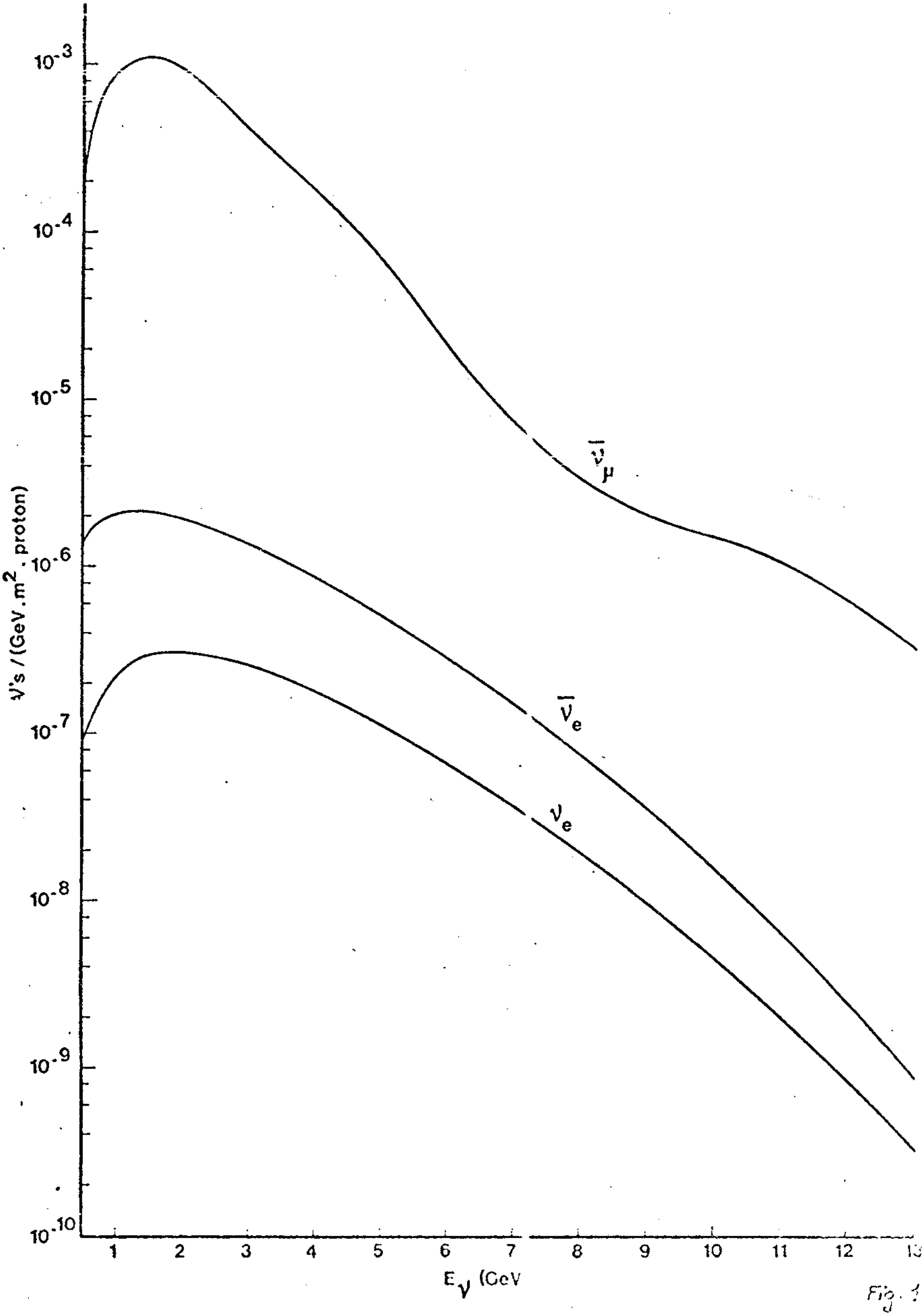
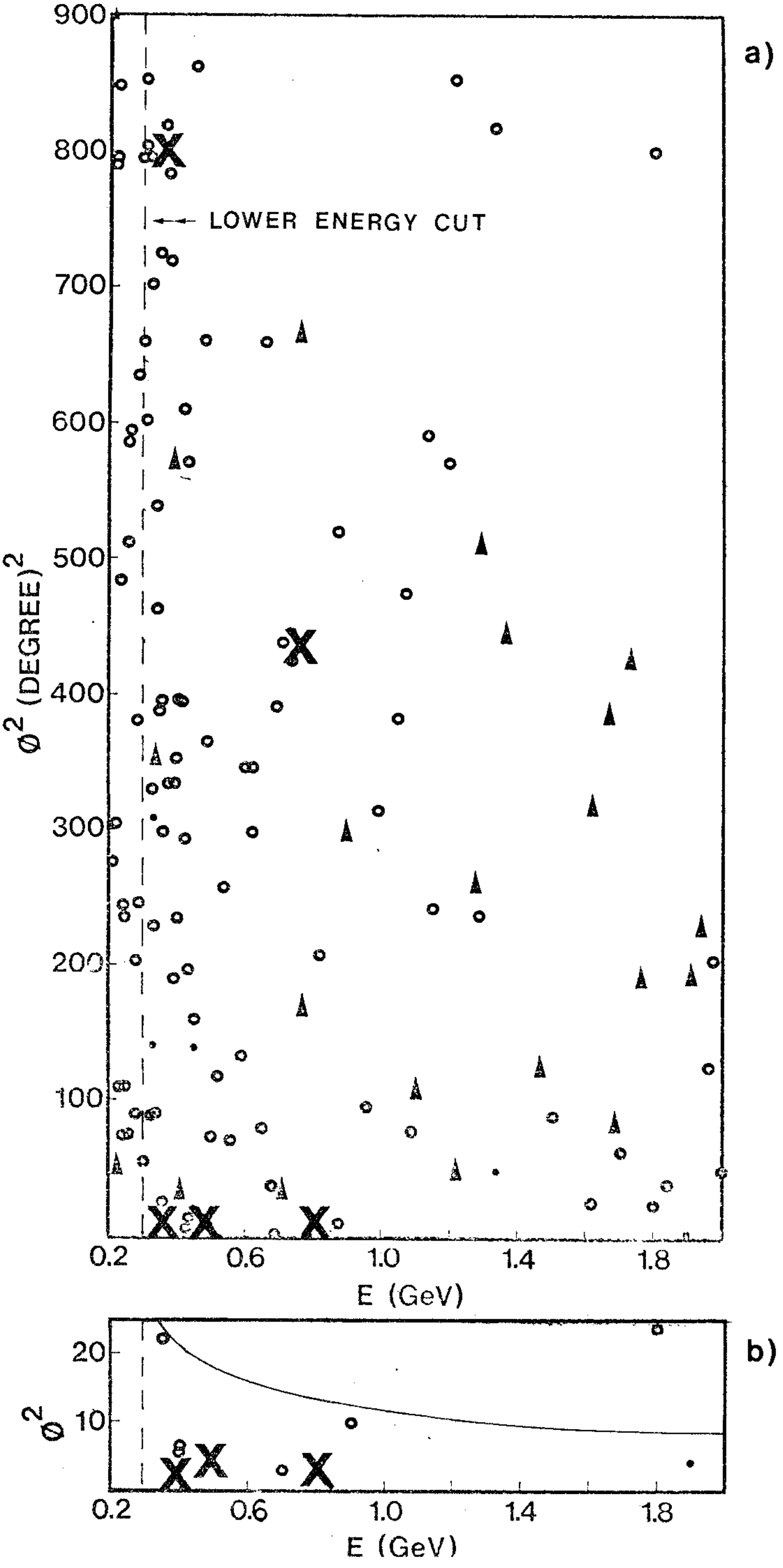


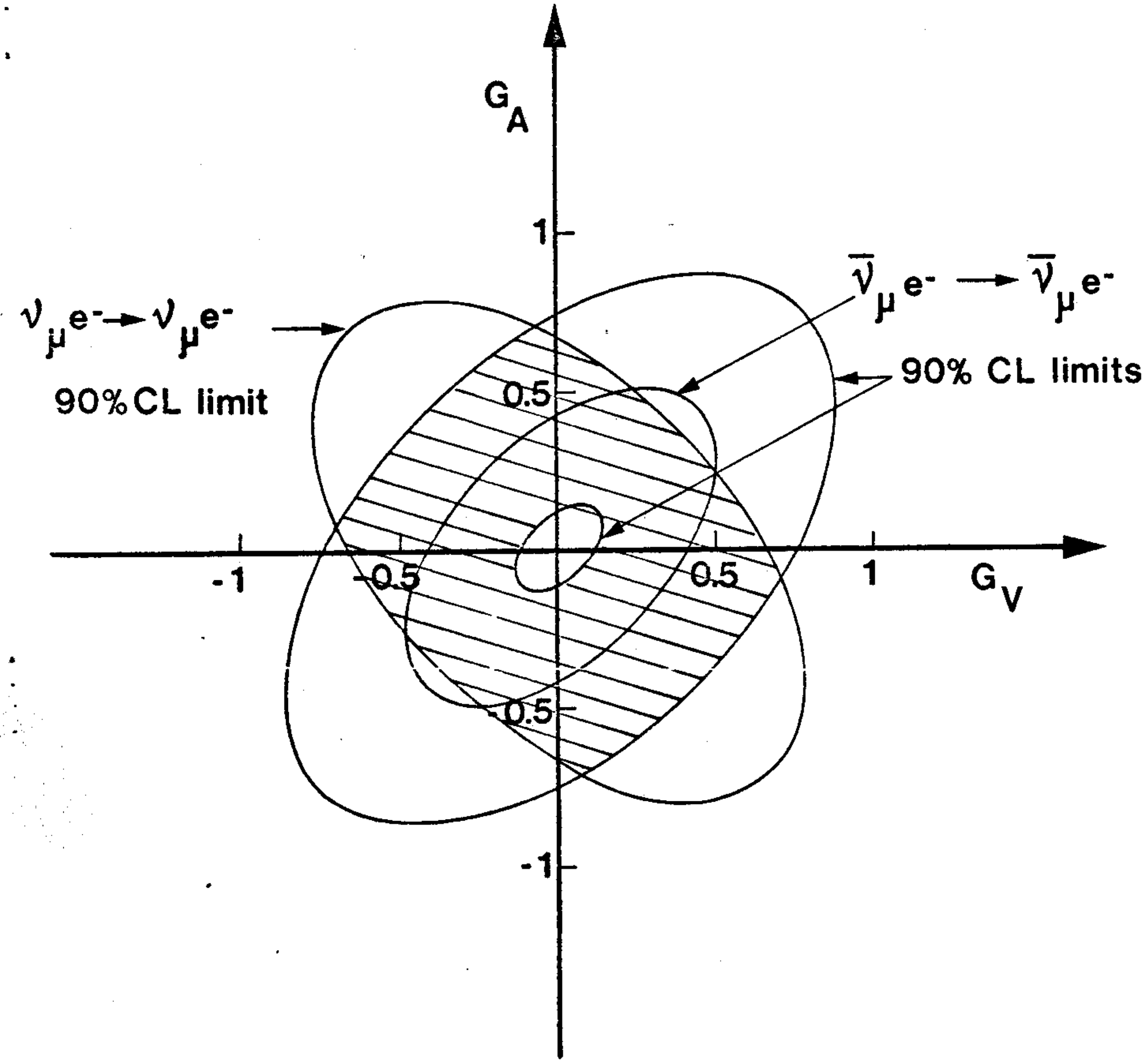
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
ν's / (GeV . m^2 . proton)
$\bar{\nu}_\mu$
$\bar{\nu}_e$
ν_e
1 2 3 4 5 6 7 8 9 10 11 12 13
E_ν (GeV

Fig. 1



900
800
700
600
500
400
300
200
100
a)
LOWER ENERGY CUT
ϕ^2 (DEGREE)^2
0.2
0.6
1.0
1.4
1.8
E (GeV)
b)
20
10
ϕ^2
0.2
0.6
1.0
1.4
1.8
E (GeV)

Fig. 2.



G_A
1
0.5
-0.5
-1
G_V
-1
-0.5
0.5
1
$\nu_\mu e^- \rightarrow \nu_\mu e^-$
90% CL limit
$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$
90% CL limits

Fig.3

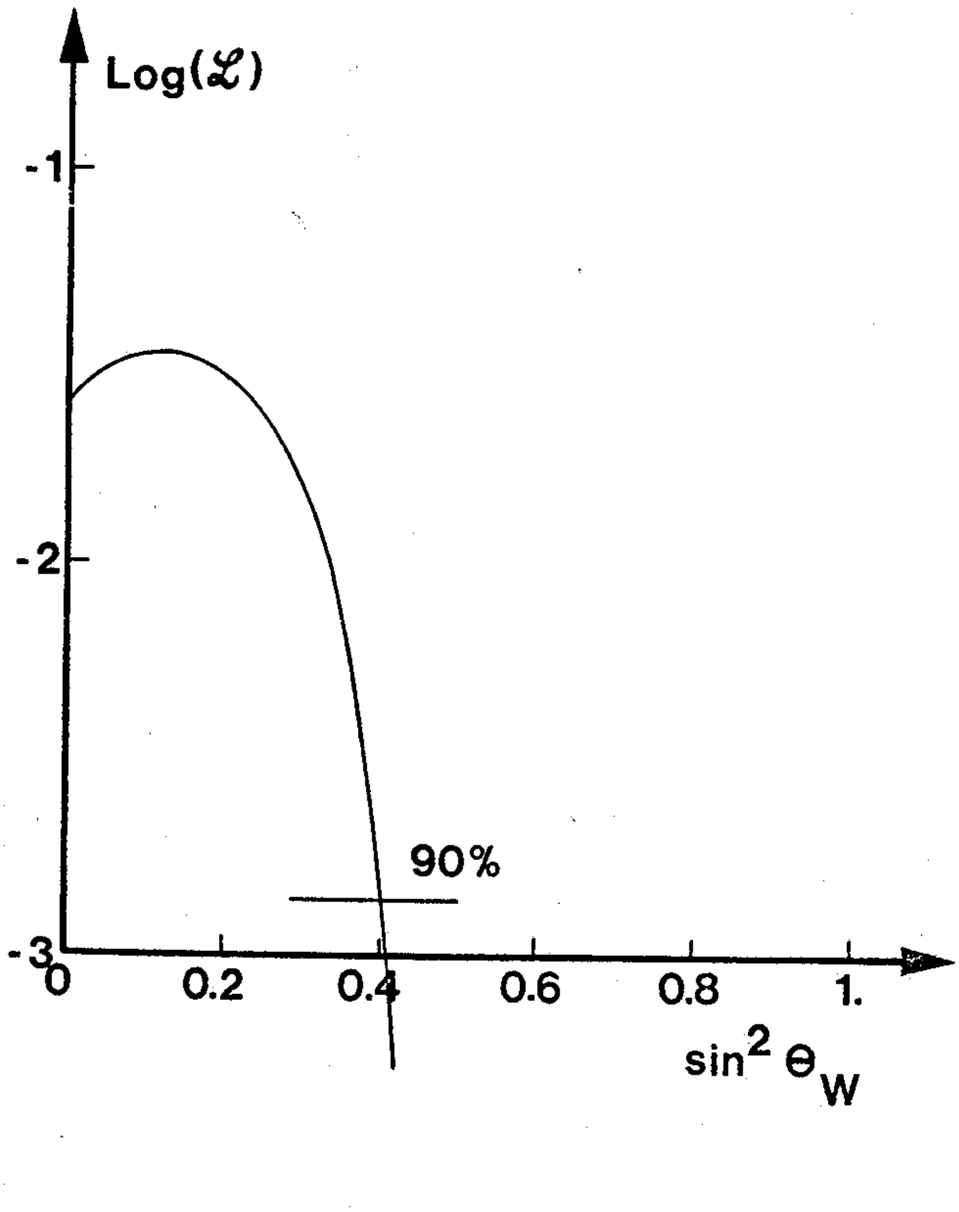


Fig.4