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~~We have observed~~ 11 events of the reaction $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ in a sample of 106,000 charged current neutrino interactions in a heavy neon-hydrogen mixture in the 15 ft. bubble chamber at Fermilab. ~~We obtain~~ a cross section for this process of $(1.8 \pm 0.8) \times 10^{-42} E_\nu$ cm^2, where E_ν is the incident neutrino energy in units of GeV. This result is in good agreement with the prediction of the Weinberg-Salam model with $\sin^2\theta_W = 0.2$.

The observation of neutral current induced neutrino interactions gave strong support to the gauge theories unifying weak and electromagnetic interactions. Presently all neutrino-hadron neutral current interactions are consistent with the SU(2) x U(1) gauge model proposed by Weinberg[(1)] and Salam[(2)] with a Weinberg angle $\sin^2\theta_W \approx 1/4$. One of the theoretically most stringent tests of this theory is provided by the purely leptonic process, $\nu_\mu e^- \rightarrow \nu_\mu e^-$ which can proceed only via the weak neutral current interaction, and the theory can be compared to experimental measurement without uncertainties introduced by using hadronic targets. Early experimental results on this reaction at neutrino energies of a few GeV[(3,4,5)] are consistent with the Weinberg-Salam model. A recent result at higher energies[(6)] indicates a significantly higher cross section for this paper process than that expected from the Weinberg-Salam model. In this we report a four times more sensitive measurement of this cross section which is in good agreement with the Weinberg-Salam model.

The experiment was carried out at the Fermi National Accelerator Laboratory using the two-horn focused wideband neutrino beam with an average of 10^{13} 400 GeV protons per pulse hitting the neutrino target. The neutrino spectrum extends from a few GeV to beyond 100 GeV, peaking near 30 GeV. The neutrino detector was the 15 ft. bubble chamber filled with a 64 atomic percent neon-hydrogen mixture, a radiation length of 40 cm and a hadronic interaction length of 125 cm. The chamber magnetic field was 30 kG.

The entire data sample of 134,000 photographs containing 106,000 charged current ν_μ interactions has been subjected to a dedicated scan for isolated electromagnetic showers; 93,000 of the pictures have been double scanned. All forward energetic single e^-, single e^+, or $\gamma \rightarrow e^+e^-$ pairs with no other tracks originating at the interaction vertex were recorded. Electrons of either sign were identified by at least two of the following signatures: bremmstrahlung conversion or spiral at the end of the track. All such events were examined by a physicist, measured, and geometrically reconstructed using the program, TVGP. By using the 93,000 double-scanned pictures the scanning efficiency was determined[7] to be (61 ± 15)% for a single scan, giving an overall scan efficiency of (78 ± 15)%.

Events which had energy $E \geq 2$ GeV and angle $\theta \leq 3^\circ$ and which were not associated with other events were retained for further consideration. The subsequent procedures adopted were guided by the philosophy of retaining single electron events and rejecting γ-ray conversions. An event was defined to be a single e^- if there was no visible radiation on a negative track before there was observable curvature so that the event clearly had a single track at the origin. If there was early radiation within a short distance of the origin such that it was not possible to determine whether the event began as a single or double track (in all ambiguous cases this distance was less than 10 cm), then the event was still classified as a single e^- if, a) the fastest track was negative, b) the fastest positron coming from the confused region was less than 25% of the electron energy ($E^+/E^- < 1/4$), and c) the energy of the second fastest electron was greater than 10% of the positron energy. Condition (b) removes fast symmetric pairs while condition (c) obviates the problem of low energy δ rays on asymmetric pairs. In most instances the identification was clear cut; the spatial resolution and lack of confusion being sufficient to clearly distinguish among the noted categories. In three cases it was not possible to distinguish between a single e^- with early conversion and the production of a delta ray from a converted γ pair before clear separation of the lepton tracks. Adoption of the above rules relegated these three events to the γ category (two of the three are consistent with $\nu_\mu e^- \to \nu_\mu e^-$ kinematics). Corrections are made for real e^- events being classified as γ's by these procedures. The probability of an e^- radiating more than 1/4 of its energy in a single radiation within the first 10 cm sufficiently asymmetrical to be classified as a γ by our criteria, has been calculated to be 3%.

The final sample contains 11 unambiguous e^- events, 5 unambiguous e^+ events, and 22 γ pairs. The number of single e^+ events is quite consistent with what we expect from the reaction $\bar{\nu}_e p \to e^+ n$ induced by the small $\bar{\nu}_e$ contamination in the beam.(8) The energies and angles of the 11 single e^- events, listed in Table I, are compared to the kinematics of $\nu_\mu e^- \to \nu_\mu e^-$ scattering on Fig. 1. The curves show the expected correlation between E and θ of the electrons in the lab frame for $E_\nu = 30$ GeV, the peak of our spectrum, and $E_\nu = 10$ and 100 GeV, which are the approximate limits of our spectrum. All 11 e^- events are consistent with the kinematics of this reaction. The single e^+ and the γ events are not sharply peaked like the e^- events but are spread out up to the 52 mrad angle cut. An appropriate variable to illustrate this difference is $E\theta^2$, since the kinematic limit in $\nu_\mu e^- \to \nu_\mu e^-$ scattering, $E\theta^2 \leq 2\, m_e$ (electron mass) is independent of the incident neutrino or outgoing electron energies. The distributions in $E\theta^2$ for the e^-, e^+ and γ events are shown in Fig. 2. The e^- events are peaked below the $2m_e$ ($\sim$1 MeV) kinematic limit, while the e^+ and γ events are much more spread out.

We have considered three sources of background that could produce single electrons in this experiment:

a) Photons which Compton scatter or convert to e^+e^- pairs so asymmetrically that the e^+ is not seen are a negligible background. Another background comes from photons which convert into asymmetric e^+e^- pairs and have an early energetic δ so as to be classified as an e^- and not as a γ by the criteria noted above. The probability for this is calculated to be $\sim$1%. When multiplied by the total number of unassociated γ's that are consistent with the kinematics of $\nu_\mu e^- \to \nu_\mu e^-$ (8 events with $E\theta^2 < 3$ MeV) this yields .08 events which is neglibible.

b) The process $\nu_e n \to e^- p$ and $\nu_e n \to e^- p\pi^o$, where the proton is too low in energy to be seen, and the γ's from the π^o are mixed in with the shower of the e^-. In this experiment, we have also scanned for and measured events with an e^- and hadrons,[8] and find 22 events with an e^- and a proton (with additional stubs which could be nuclear fragments) and possibly γ's from a π^o. From the expected q^2 distributions for these events, we calculate[9] that 3% of these events would have an invisible proton and an e^- at a small enough angle to be consistent with the kinematics of $\nu_\mu e^- \to \nu_\mu e^-$. We calculate this background to be 0.7 events or (6 ± 6)% of the $\nu_\mu e^- \to \nu_\mu e^-$ signal.

c) The reactions $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$, $\nu_e e^-$, and $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$ are indistinguishable from the $\nu_\mu e^- \to \nu_\mu e^-$ reaction. However, since the relative fluxes in our beam are $\nu_\mu/\bar{\nu}_\mu/\nu_e/\bar{\nu}_e$ = 100/3/1/0.1, the contribution of these reactions in any reasonable model is expected to be small in this experiment.

The 11 $\nu_\mu e^- \to \nu_\mu e^-$ events and the corresponding 106,000 charged current ν_μ interactions are in a volume visible to all three cameras. To calculate the cross section for this process, we impose a more restricted fiducial volume to insure a uniform (and essentially 100%) detection efficiency for high energy electrons.[10] We find 8 of the 11 $\nu_\mu e^- \to \nu_\mu e^-$ events and 79% of the charged current ν_μ interactions in this fiducial volume. We subtract (6 ± 6)% for the $\nu_e n \to e^- p$ background, correct for the (78 ± 15)% scan efficiency, and correct for the following losses of single electrons: 10% for the 2 GeV cut[11] on E_e, 3% for loss of e^- classified as γ, and 3% miscellenous losses such as a false association with another ν event etc. to obtain the ratio

$$\frac{\nu_\mu + e^- \to \nu_\mu + e^-}{\nu_\mu + Ne \to \mu^- + \ldots} = (1.36 \pm 0.54) \times 10^{-4}.$$

We can calculate the total cross section for this process by using the total charged current cross section $\sigma_{tot} = (0.67 \pm 0.06) \times 10^{-38} E_\nu \text{ cm}^2$/nucleon measured in the energy range of 20 to 60 GeV in a BEBC experiment[12] and by noting that the electron to total nucleon ratio in neon is 1/2. Our result is

$$\sigma(\nu_\mu + e^- \rightarrow \nu_\mu + e^-) = (1.8 \pm 0.8) \times 10^{-42} E_\nu \text{ cm}^2$$

where E_ν is the incident neutrino energy in units of GeV.

This result is in disagreement with a recent measurement in the Gargamelle experiment[6] at the CERN SPS. On the other hand, our result is in good agreement with the Weinberg-Salam model. Figure 3a shows a comparison of our results with the prediction of the model as a function of the mixing angle $\sin^2\theta_W$. Our data restrict the value of $\sin^2\theta_W$ to be $0.20^{+.16}_{-.08}$ or $0.57^{+.07}_{-.17}$, the former value being in excellent agreement with several previous neutral current measurements.[13] Figure 3b shows the energy distribution of our 11 $\nu_\mu e^- \rightarrow \nu_\mu e^-$ events. The curve on the figure is the prediction of the Weinberg-Salam model with $\sin^2\theta_W = .25$ integrated over our incident neutrino energy spectrum. The agreement is quite good.

We are grateful to all the people at Fermilab as well as the scanning and measuring groups at Columbia University and Brookhaven National Laboratory whose hard work made this experiment possible. This research was supported by the U.S. Department of Energy and the National Science Foundation.

TABLE I

List of $\nu_\mu + e^- \to \nu_\mu + e^-$ Events

Event	E_{e^-} (GeV)	θ_{e^-} (mrad)	$E\theta^2$ (MeV)
1	3.7 ± 1.6	10 ± 5	0.4
2	4.7 ± 0.3	5 ± 8	0.1
3*	5.6 ± 2.6	5 ± 7	0.1
4	6.5 ± 1.6	8 ± 4	0.4
5*	8.8 ± 1.7	4 ± 3	0.1
6	9.0 ± 1.0	8 ± 5	0.6
7	14.0 ± 3.0	14 ± 10	2.7
8*	15.8 ± 2.6	8 ± 5	1.0
9	20.8 ± 5.6	2 ± 3	0.1
10	27.5 ± 9.0	8 ± 4	1.8
11	34.6 ± 4.0	4 ± 4	0.6

*Event out of fiducial volume used for the cross section calculation.

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7. To determine the scan efficiency a sample of 134 high energy forward e^+, e^-, and γ's was used. The result is consistent with an (86±20)% efficiency obtained from the 11 single e^- events alone.

8. In a sample of 27,600 total $\nu_\mu \to \mu^-$ interactions, we found 187±14 and 28±6 total $\nu_e \to e^-$ and $\bar{\nu}_e \to e^+$ interactions, respectively (A. Cnops et al., Phys. Rev. Lett. 40, 144). We scale these numbers by 106,000/27,600 to obtain 723±54 and 108±23 total ν_e and $\bar{\nu}_e$ interactions, respectively, in the present sample. From these numbers we estimate that we should have 15 $\nu_e n \to e^- p$ and 6 $\bar{\nu}_e p \to e^+ n$ events, consistent with the actual numbers we see.

9. This estimate is in good agreement with the measurement in the Gargamelle experiment of R_μ = (μ^- within 3^o) (proton unseen)/(μ^- + p) = (5 ± 3)%, assuming $\nu_e - \nu_\mu$ universality. ibid Reference 6.

10. The fiducial volume is defined by $R \leq 170$ cm, $|z| \leq 125$ cm, and $D \geq 78$ cm, where R is the distance from the center of the chamber, z is the vertical distance from the median plane, and D is the distance from the back wall of the chamber along the beam direction.

11. The 10% loss due to the $E_e \geq 2$ GeV cut was calculated using the Weinberg-Salam model with a $\sin^2\theta_W = 1/4$. However, this loss is only weakly dependent on the model used.

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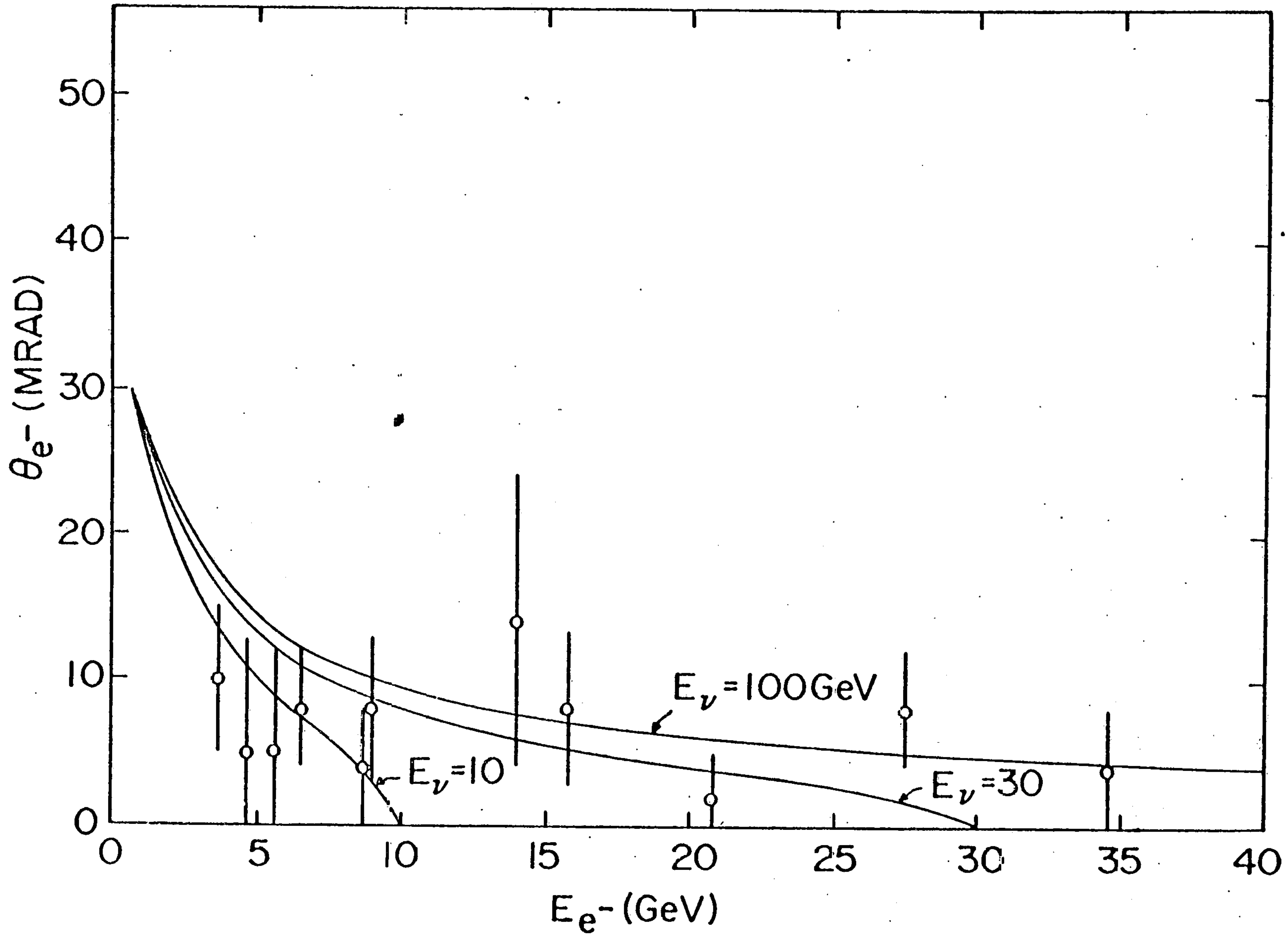
FIGURE CAPTIONS

Fig. 1 Electron angle vs. energy of the 11 observed single electron events compared to the kinematics of the reaction $\nu_\mu e^- \rightarrow \nu_\mu e^-$ for various neutrino energies E.

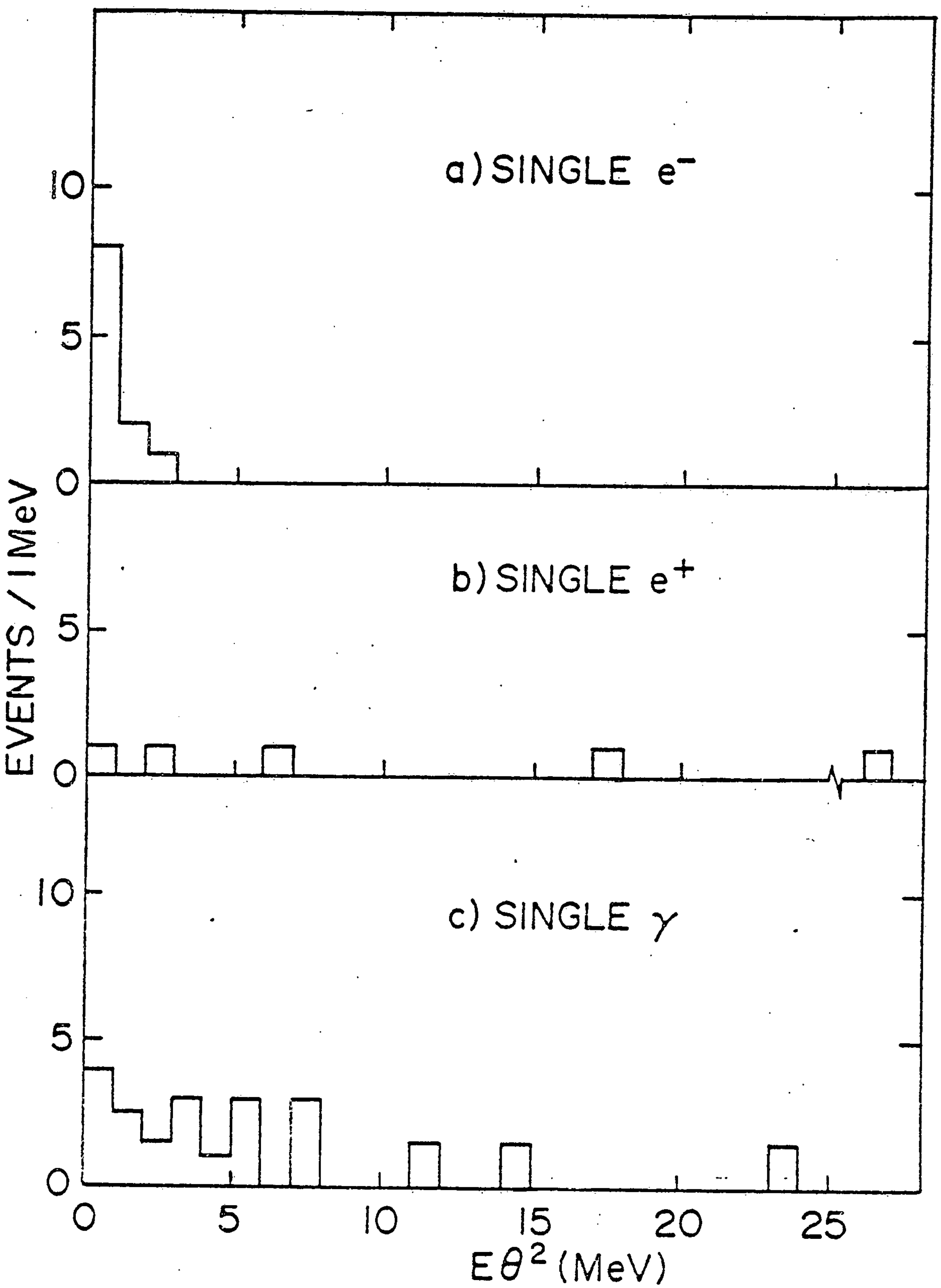
Fig. 2 Distribution in the variable $E\theta^2$ for a) the single e^- events, b) the single e^+ events, and c) the single $\gamma \rightarrow e^+e^-$ pairs.

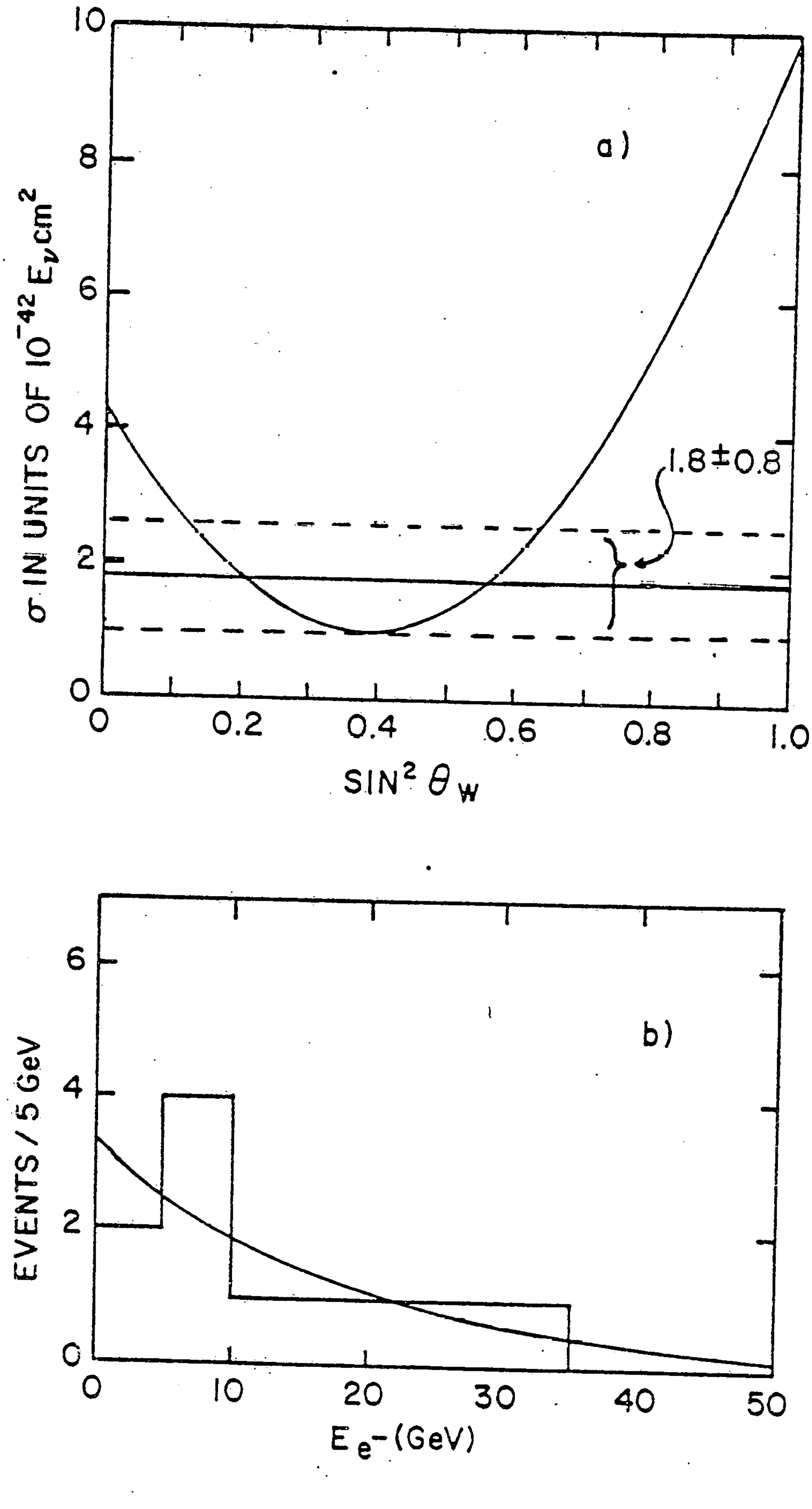
Fig. 3a Comparison of the prediction of the Weinberg-Salam model with the measured cross section for $\nu_\mu e^- \rightarrow \nu_\mu e^-$.

Fig. 3b Distribution in the electron energy of the 11 $\nu_\mu e^- \rightarrow \nu_\mu e^-$ events. The curve is the prediction of the Weinberg-Salam model with $\sin^2\theta_W = 1/4$ integrated over the incident neutrino energy spectrum of the experiment.



50
40
30
20
10
0
θ_{e^-} (MRAD)
0
5
10
15
20
25
30
35
40
E_{e^-} (GeV)
E_ν=100GeV
E_ν=10
E_ν=30


a) SINGLE e⁻
b) SINGLE e⁺
c) SINGLE γ
EVENTS / 1 MeV
Eθ² (MeV)
0
5
10
15
20
25


a)
σ IN UNITS OF 10^-42 E_ν cm^2
SIN^2 θ_W
1.8±0.8
b)
EVENTS / 5 GeV
E_e- (GeV)