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DILEPTON AND TRILEPTON PRODUCTION BY NEUTRINOS
IN GARGAMELLE AT CERN SPS ENERGIES

Bergen-CERN-Strasbourg Collaboration

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ABSTRACT

We report on a search for $\nu_\mu N \rightarrow \mu^- e^- X$ and $\nu_\mu N \rightarrow \mu^- e^+ e^- X$ events in Gargamelle at CERN Super Proton Synchrotron (SPS) energies. Ten $\mu^- e^-$ events were found with $p_{e^-} > 0.5$ GeV/c and $p_{\mu^-} > 4.5$ GeV/c (seven of these events have $p_{e^-} > 0.8$ GeV/c). The rate relative to the charged-current events is $(6.7 \pm 3.9) \times 10^{-4}$, and to the opposite-sign dileptons 0.20 ± 0.11 . Some characteristics of the $\mu^- e^-$ events are compared with $\mu^- e^+$ and charged-current events. Three $\nu_\mu N \rightarrow \mu^- e^+ e^- X$ events were observed with $p_{e^\pm} > 0.3$ GeV/c, $p_{\mu^-} > 4.5$ GeV/c, and $m_{e^+e^-} > m_{\pi^0}$. The rate of these events relative to the charged-current events is $(3.1 \pm 1.9) \times 10^{-4}$.

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1. THE AIM OF THE EXPERIMENT

The production of multimuons $\nu_\mu N \rightarrow \mu^- \mu^+ X$, $\nu_\mu N \rightarrow \mu^- \mu^- X$, and $\nu_\mu N \rightarrow \mu^- \mu^+ \mu^- X$, is well established in counter experiments where a large number of events have been observed. Owing to severe cuts imposed on the muon momenta (4-10 GeV/c), the rates are low, from 10^{-5} - 10^{-4} for trimuons [1], 10^{-5} - 10^{-3} for same-sign dimuons [2], and up to 10^{-2} for the opposite-sign dimuons [3].

Although heavy-liquid bubble chamber experiments have poorer statistics when compared with counter experiments, they favour the study of the similar reactions $\nu_\mu N \rightarrow \mu^- e^+ X$, $\nu_\mu N \rightarrow \mu^- e^- X$, and $\nu_\mu N \rightarrow \mu^- e^+ e^- X$, where the lower momentum cuts for the electrons make it possible to reach different kinematical regions, thus getting supplementary information.

The aim of this experiment is to study the little-known reactions $\nu_\mu N \rightarrow \mu^- e^- X$ and $\nu_\mu N \rightarrow \mu^- e^+ e^- X$.

Indeed only two experiments have reported results for the production of $\mu^- e^-$ events: the BNL-Columbia Collaboration (see Murtagh [2] and [4]) found 20 events with a background of 9 events, giving a rate of $\sim 3 \times 10^{-4}$; whereas the Berkeley-Fermilab-Honolulu-Seattle-Madison (BFHSM) Collaboration [5] found 3 events with a background of 3.6 events, concluding that no signal is present. An anti-neutrino experiment [6] has found evidence for $\mu^+ e^+$ production, getting 4 events, a background of 1.1 event, and the rate $\left(4.8 \pm 5.3\right) \times 10^{-4}$.

Concerning the reaction $\nu_\mu N \rightarrow \mu^- e^+ e^- X$, there is no evidence of its existence in bubble chambers [4,5].

In order to study the reaction $\nu_\mu N \rightarrow \mu^- e^- X$, we used the well-studied reaction $\nu_\mu N \rightarrow \mu^- e^+ X$ [7] for comparison and control of possible biases.

Preliminary results of this experiment have already been presented [8].

2. DETECTOR AND BEAM

The experiment was carried out using the heavy-liquid bubble chamber Gargamelle, filled with a 90.5/9.5 (in moles) propane + freon mixture. The radiation length

was 61 cm, the interaction length for pions of the order of 200 cm, and the density 0.51 g/cm³. The fiducial volume used was 3 m³.

Muons were identified by using the two-plane External Muon Identifier (EMI) information. In order to have a very high EMI efficiency [9], only muons with momenta greater than 4.5 GeV/c were considered. According to these criteria, a total of 24,354 charge current (CC) events with neutrino energy larger than 10 GeV were used in the present analysis; 3055 events were measured completely [10].

The experiment was done in the CERN Super Proton Synchrotron (SPS) wide-band neutrino beam, which peaks at about 25 GeV and extends up to 200 GeV. There were 2.3×10^{18} protons of 350 GeV on target. The mean energy of the CC events is about 40 GeV.

3. SELECTION OF EVENTS

At the scanning level, events were recorded with at least one electron (e^+ or e^-) and at least one negative particle leaving the chamber.

The electrons were identified by the following signatures: spiralization, bremsstrahlung, significant δ -rays taking at least 25% of the track energy, significant tridents taking at least 10% of the track energy, shower, and annihilation (for the e^+).

At least one signature was required at the scanning level and at least two at the checking level. This latter control was carried out by physicists on an event-by-event basis on the scanning/measuring tables.

The events were divided into two categories according to the confusion length L_c of the e^+ or e^- . The confusion length is defined as the minimum distance from the vertex after which the electron track is clearly seen as a single track. Events with $L_c \leq 3$ mm on the scanning table (~ 1.2 cm in space) are classified as "clear events", in contrast to the "confused events" with $L_c > 3$ mm. Our analysis was based on clear events only, and the confused events were used to check whether biases are thereby introduced.

In order to eliminate Dalitz pairs and close-in $\gamma \rightarrow e^+e^-$ pairs in which one of the electrons is not signed, no event was accepted when the observed e^+ or e^- gave an effective mass less than $0.140 \text{ GeV}/c^2$ when combined with an opposite-sign leaving particle without electron signature ("partner").

The scanning efficiency was 0.78 ± 0.03 for one scan and 0.95 ± 0.02 for two scans. Only 30% of the films were scanned twice.

4. ELECTRON DETECTION PROBABILITY

In order to estimate the electron detection probability, related to the requirement of two signatures, we made a special experimental study of a sample of externally converted $\gamma \rightarrow e^+e^-$ pairs. We have looked at the number of signatures of each electron of the pair as a function of its momentum and of the position in the chamber. Also, we determined the frequency of each type of signature. The resulting average detection probability for electrons with momenta $p_{e^\pm} > 0.3 \text{ GeV}/c$ and at least two signatures is 0.60. For electrons showing at least one signature, this probability is 0.90.

The energy of the electrons belonging to the externally converted $\gamma \rightarrow e^+e^-$ is on the average lower than the $e^\pm$ momenta from $\nu_\mu N \rightarrow \mu^-e^+X$ and $\nu_\mu N \rightarrow \mu^-e^+e^-X$ events (as will be seen later). This means that we have a good estimate of the detection probability for electrons with lower momenta; but at higher momenta, where the number of $\gamma \rightarrow e^+e^-$ is smaller, this detection probability is affected by the poorer statistics.

As the detection probability is a function of the electron energy, we have made in addition a Monte Carlo program in order to get a better estimate of the energy dependence of the detection probability at higher electron energies*). In

*) In order to take into account the energy angle correlation (the angle between the electron and the ν_μ beam direction) and possible differences in this correlation for background and signal, we used respectively: a) the experimental distribution from externally converted γ -rays; b) the distribution of e^+ in $\nu_\mu N \rightarrow \mu^-e^+X$ production, calculated by Monte Carlo; c) the distribution of $e^+(e^-)$ in $\nu_\mu N \rightarrow \mu^-e^+e^-X$ production, calculated by Monte Carlo using the Smith model [11].

Note that the Monte Carlo program used to calculate point (b) was based on the GIM scheme, assuming production and subsequent semileptonic decay of charmed hadrons. The fragmentation function for charmed quarks was taken as a constant. No rescaling was used.

this program we generated electron tracks in the chamber and took into account bremsstrahlung, δ -rays, and trident production. Following each track through the chamber, we could estimate the detection probability as a function of energy and position in the chamber. The Monte Carlo calculation and the experimental data agreed very well.

5. DILEPTONS

5.1 The reaction $\nu_{\mu} N \rightarrow \mu^{-} e^{+} X$

The reaction $\nu_{\mu} N \rightarrow \mu^{-} e^{+} X$, which has been studied well in bubble chambers [7], was used in this experiment as the monitor reaction to control possible electron losses. Also, a comparison was made between the kinematical quantities for this reaction and for the reaction $\nu_{\mu} N \rightarrow \mu^{-} e^{-} X$.

Inside the cuts, $p_{\mu^{-}} > 4.5$ GeV/c and $p_{e^{+}} > 0.3$ GeV/c, 40 clear events and 16 confused events were found, satisfying our selection criteria.

The main backgrounds for this reaction are the following:

- i) the e^{+} background coming mainly from
 - a) asymmetric Dalitz pairs and asymmetric close-in $\gamma \rightarrow e^{+} e^{-}$ pairs^{*)},
 - b) the K_{e3}^{+} decay ($K^{+} \rightarrow e^{+} \pi^0 \nu$); and
- ii) the μ^{-} background coming from punch-through and decay of pions in the reactions $\bar{\nu}_e N \rightarrow e^{+} \pi^{-} (\rightarrow \mu^{-}) X$ and $\nu_{\mu} N \rightarrow \nu_{\mu} \pi^{-} (\rightarrow \mu^{-}) e^{+} X$, which is negligible.

The e^{+} background is given in Table 1a. This background was estimated for the produced (corrected) number of events and is based partly on a study of externally converted $\gamma \rightarrow e^{+} e^{-}$ pairs, on Dalitz pairs, and on QED calculations.

In addition there exists also the background due to Dalitz and close-in $e^{+} e^{-}$ pairs in which the e^{-} gives no electron signature. However, this background is eliminated in the criteria that no e^{+} together with an opposite-sign leaving particle without electron signature should give an effective mass larger than

*) The lowest momentum limit for the electron visibility is 5 MeV/c.

0.140 GeV/c² (see Section 3). Using the externally converted $\gamma \rightarrow e^+e^-$ pairs mentioned in Section 4, we estimated that there should be 33 events of this kind attached to the vertex, and we found 29 on a sample of our films. We can therefore conclude that this "partner effect" is small. The same conclusion is also valid for μ^-e^- events.

Losses are due to μ^-e^+ events with δ -rays near the vertex, faking a close-in e^+e^- pair (this kind of event is then considered as a $\mu^-e^+e^-$ candidate). We estimated by QED calculations that this loss due to δ -rays with momenta larger than 5 MeV/c is $\sim 3\%$.

There are also losses in the confused μ^-e^+ events, and we have to estimate this fraction for the corresponding correction. In order to do this we assume that the behaviour of the electron is similar to that of a hadron in CC events. Therefore a special scan on CC events was performed, from which we estimated a fraction of $(75 \pm 3)\%$ of clear μ^-e^+ events.

Also, losses due to the scanning efficiency and to the electron detection probability (by the requirement of at least two signatures) were taken into account.

Using only clear events, we obtained the rate

$$R_1 = \frac{\sigma(\nu_\mu N \rightarrow \mu^- e^+ X)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} = (4.0 \pm 0.9) \times 10^{-3}$$

corrected for all losses and background.

As a check we used both clear and confused events, and we obtained

$$R_1 = (4.1 \pm 0.8) \times 10^{-3} ,$$

in agreement with the rate based on clear events only.

In Fig. 1 we show the rate R_1 for clear events as a function of the neutrino energy E_ν . A correction in E_ν for unseen neutral particles was made event-by-event

according to the Heilman method [12]^{*)}. In the same figure our results are compared with data from the following Collaborations: BNL-Columbia [4], BFHSM [5], and CDHS (Abramowicz [3]). The comparison with the CDHS counter experiment was possible since they corrected their data for acceptance and cuts.

In the sample of clear μ^-e^+ events we found 13 V^0 , 2 of which were unmeasurable; the 11 others (8 K^0 and 3 Λ^0) gave a good 3C kinematical fit, leading to the corrected rate

$$\frac{\sigma[\nu_\mu N \rightarrow \mu^- e^+ K^0(\Lambda^0) X]}{\sigma(\nu_\mu N \rightarrow \mu^- e^+ X)} = 1.1 \pm 0.4 .$$

Comparing all our μ^-e^+ data with the published data, we conclude that the agreement is good and that no important electron losses are present in this experiment.

5.2 The reaction $\nu_\mu N \rightarrow \mu^- e^- X$

The study of $\nu_\mu N \rightarrow \mu^- e^- X$ events is much more delicate than that of opposite-sign dileptons for the following reasons:

- i) the background is much higher for low-momentum electrons, so we did not use events with $0.3 < p_{e^-} < 0.5$ GeV/c; ii) the rate of μ^-e^- events is lower.

In this study we used only clear events; the confused ones were examined merely to check that no biases were introduced.

According to this procedure we finally got 13 events with $p_{e^-} > 0.3$ GeV/c, 10 events with $p_{e^-} > 0.5$ GeV/c, and 7 events with $p_{e^-} > 0.8$ GeV/c. The cut on the muon momenta was (as for the opposite-sign μ^-e^+ events) $p_{\mu^-} > 4.5$ GeV/c. No V^0 was found among these events.

*)

$$E_V = p_{x\mu} + p_{xH} \left[1 + \left(\left| \sum_{i=1}^n \vec{p}_{Ti} \right| / \sum_{i=1}^{n_H} \left| \vec{p}_{Ti} \right| \right) \right],$$

where $p_{x\mu}$ and p_{xH} are respectively the components of the muon momentum and of the visible hadronic system in the neutrino direction. The sum over n runs over all visible final-state particles, including the muon, and the sum over n_H refers to hadrons only.

The main backgrounds in this reaction are:

- i) the e^- background due to the following effects:
 - a) Compton electrons near the vertex;
 - b) δ -rays on muons and pions near the vertex;
 - c) asymmetric Dalitz and asymmetric close-in e^+e^- pairs;
 - d) K_{e3} decay ($K^- \rightarrow e^-\pi^0\nu$); and
- ii) the μ^- background coming from punch-through and decay of pions in the reaction $\nu_e N \rightarrow e^-\pi^-(\rightarrow \mu^-)X$, which is negligible.

The e^- background estimate is given in Table 1b for the produced (corrected) number of events. As for μ^-e^+ events, this was based on externally converted $\gamma \rightarrow e^+e^-$, on Dalitz pairs, and QED calculations.

The losses (as in the reaction $\nu_\mu N \rightarrow \mu^-e^+X$) are due to confused events (we used the same correction as for $\nu_\mu N \rightarrow \mu^-e^-X$ events), scanning efficiency, and the electron detection probability.

Using only the clear events, we obtained the following rates:

$$R_2 = \frac{\sigma(\nu_\mu N \rightarrow \mu^-e^-X)}{\sigma(\nu_\mu N \rightarrow \mu^-X)} = \begin{cases} (6.7 \pm 3.9) \times 10^{-4} & \text{for } p_{e^-} > 0.5 \text{ GeV/c} , \\ (5.3 \pm 2.9) \times 10^{-4} & \text{for } p_{e^-} > 0.8 \text{ GeV/c} , \end{cases}$$

both corrected for all losses and background.

If we normalize to the μ^-e^+ events, the rates become:

$$R = \frac{\sigma(\nu_\mu N \rightarrow \mu^-e^-X)}{\sigma(\nu_\mu N \rightarrow \mu^-e^+X)} = \begin{cases} 0.20 \pm 0.11 & \text{for } p_{e^+}, p_{e^-} > 0.5 \text{ GeV/c} , \\ 0.22 \pm 0.12 & \text{for } p_{e^+}, p_{e^-} > 0.8 \text{ GeV/c} . \end{cases}$$

These results are shown in Table 2 together with those of other experiments.

Several models have been introduced for the like-sign dileptons [13], but so far none of them is able to explain the experimental rates [14,15].

5.3 Comparison between the reactions $\nu_\mu N \rightarrow \mu^-e^+X$ and $\nu_\mu N \rightarrow \mu^-e^-X$

All clear $\nu_\mu N \rightarrow \mu^-e^-X$ and $\nu_\mu N \rightarrow \mu^-e^+X$ (as well as confused $\nu_\mu N \rightarrow \mu^-e^+X$ events) were measured completely. We found no systematic differences between kinematical distributions for clear and confused $\nu_\mu N \rightarrow \mu^-e^+X$ events within our statistics.

The variables used in the present analysis are defined in the following way:

E_ν is the energy of the incident neutrino, corrected for unseen particles;

E_μ is the energy of the leading muon;

$E_{e^\pm}$ is the energy of the e^+ or the e^- ;

$$\nu = E_\nu - E_\mu;$$

$\theta_{\nu\mu}$ is the angle between the neutrino direction and the muon direction;

$$Q^2 = 2E_\nu E_\mu (1 - \cos \theta_{\nu\mu});$$

m_N is the mass of the nucleon;

$$W^2 = m_N^2 + 2m_N \nu - Q^2;$$

$$x = Q^2 / (2 m_N \nu);$$

$$y = \nu / E_\nu;$$

$$z = E_{e^\pm} / (\nu + m_N);$$

$\phi_{\mu e}$ is the angle between the projections of the muon and the electron directions on a plane perpendicular to the neutrino direction.

The distributions of the kinematical quantities for the two above-mentioned reactions as well as for ordinary CC events have been compared. Only clear events were used, and the number of events was corrected for electron detection probability. Tables 3a and 3b show the average of various kinematical quantities for both reactions.

There are no significant differences between the kinematical quantities for the above-mentioned reactions within our statistics, with three exceptions:

- i) $\mu^- e^-$ events are produced with higher y -values than the $\mu^- e^+$ events and the CC events;
- ii) the average electron momentum is lower in $\mu^- e^-$ events than in $\mu^- e^+$ events, which is reflected also in the z values.
- iii) the $\phi_{\mu e}$ distribution for $\mu^- e^-$ events is flat, whereas the $\mu^- e^+$ distribution peaks at 180° .

These differences are shown in Figs. 2-5. The hatched areas correspond to events with $0.3 < p_{e^+} < 0.5$. The histograms for the CC events were normalized to

the produced (corrected) number of μ^+e^- events. Monte Carlo results^{*)} are also shown for the $\nu_\mu N \rightarrow \mu^- e^+ X$ reaction for a cut of $p_{e^+} > 0.3$ GeV/c.

6. TRILEPTONS

The reaction $\nu_\mu N \rightarrow \mu^- e^+ e^- X$

The study of this reaction was one of the aims of our experiment; no evidence of its existence in bubble chambers has been found so far [4,5].

The existence of the equivalent reaction $\nu_\mu N \rightarrow \mu^- \mu^+ \mu^- X$ is well established in counter experiments with rates of the order of 10^{-5} - 10^{-4} [1]; it is explained to about 25% by electromagnetic $\mu^+ \mu^-$ pairs, and the rest of hadronic origin by the decay of ρ , ω , $\phi \rightarrow \mu^+ \mu^-$, plus a low-mass continuum. The relation

$$\frac{\sigma(\nu_\mu N \rightarrow \mu^- \mu^+ \mu^- X)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} \approx 2.5 \frac{\sigma(\pi^- N \rightarrow \mu^- \mu^+ X)}{\sigma_{\text{tot}}(\pi^- N)},$$

where 2.5 is an empirical factor which was used in the theory for the hadronic component [14].

We have searched for prompt $\mu^- e^+ e^-$ events produced in the reaction $\nu_\mu N \rightarrow \mu^- e^+ e^- X$, where the $e^+ e^-$ do not come from the π^0 decay.

At the scanning level, events with at least one negative track leaving the chamber and one e^+ and one e^- at the vertex were recorded.

At the checking level, done by physicists, the cuts $p_{\mu^-} > 4.5$ GeV/c, $p_{e^+} > 0.3$ GeV/c, $p_{e^-} > 0.3$ GeV/c, and at least one signature for each electron were required. No distinction between clear and confused events was made.

Applying these criteria, we obtained 360 events. The $m_{e^+e^-}$ distribution of these events is presented in Fig. 6. In order to eliminate the large amount of background coming from π^0 decay (close-in $\gamma \rightarrow e^+ e^-$ and Dalitz pairs), we have to look for events with $m_{e^+e^-} > m_{\pi^0}$. In this region only three events with two signatures for each electron are present. For each of these three events it was impossible to fit the hypothesis $\gamma \rightarrow e^+ e^-$. The effective mass distribution $m_{e^+e^-}$

^{*)} See footnote point (b) in Section 4.

has been calculated according to Kroll-Wada [16]. The calculation of a distorted distribution of $m_{e^+e^-}$ for Dalitz pairs, based on a momentum error of 40% for the e^+, e^- , indicates that $\lesssim 0.1$ event with $m_{e^+e^-} > 160$ MeV should be seen in our experiment. Thus we conclude that background coming from π^0 Dalitz pairs is small.

The remaining background for this trilepton reaction is negligible and comes mainly from the following sources:

- i) μ^-e^+ events with a δ -ray ($p_\delta > 0.3$ GeV/c) near the vertex;
- ii) μ^-e^+ events with a Compton electron ($p_{\text{Compton}} > 0.3$ GeV/c) near the vertex;
- iii) μ^-e^+ events with an asymmetric Dalitz pair or an asymmetric close-in e^+e^- pair (only e^- visible).

Losses are due to scanning efficiency, to electron detection probability, and to δ -rays near the vertex (estimated to be 5%) with momenta larger than 5 MeV/c.

We have tried to investigate in more detail the eventual losses in events where a black cone, consisting of a superposition of several tracks emerging from the vertex, make the analysis impossible.

In order to try to evaluate these losses we studied a set of such events, measuring their opening angle (and their confusion length). The result shows that these events have opening angles of less than 4° - 5° .

Using the Smith model, with our experimental conditions [17] for the opening angle between e^+ and e^- in the $\nu_\mu N \rightarrow \mu^- e^+ e^- X$ reaction indicates that only 10-15% of the events have opening angles less than 5° , which shows that this kind of loss is not important.

The features of the three trilepton events are given in Tables 4 and 5.

Correcting our events for all losses we got a signal of 7.6 ± 4.5 events. This corresponds to the rate

$$\frac{\sigma(\nu_\mu N \rightarrow \mu^- e^+ e^- X)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} = (3.1 \pm 1.9) \times 10^{-4} ,$$

corrected for scanning efficiency and electron detection efficiency. (The upper limit is $\sim 6.8 \times 10^{-4}$ with 90% confidence level.)

The Smith theory for the reaction $\nu_\mu N \rightarrow \mu^- e^+ e^- X$ and our experimental conditions, based on the same ideas as for the $\nu_\mu N \rightarrow \mu^- \mu^+ \mu^- X$ reaction, give a rate

$$\frac{\sigma(\nu_\mu N \rightarrow \mu^- e^+ e^- X)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} = 4.5 \times 10^{-4} \quad (\text{without the empirical factor of 2.5}).$$

According to this rate, we expect a number of 11 events, which is compatible with our data within statistics. From Table 4 it can be seen that one event which has $\phi_{\mu^-(e^+e^-)} = 25^\circ$ could be of electromagnetic origin. According to Smith, the electromagnetic component is 10% of the total number of $\nu_\mu N \rightarrow \mu^- e^+ e^- X$ events.

7. CONCLUSIONS

Within our statistics, the main results concerning dilepton and trilepton events are the following:

- 1) A prompt $\mu^- e^-$ signal has been seen. The rates are:

$$\frac{\sigma(\nu_\mu N \rightarrow \mu^- e^- X)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} = \begin{cases} (6.7 \pm 3.9) \times 10^{-4} & \text{for } p_{e^-} > 0.5 \text{ GeV/c} , \\ (5.3 \pm 2.9) \times 10^{-4} & \text{for } p_{e^-} > 0.8 \text{ GeV/c} , \end{cases}$$

and

$$\frac{\sigma(\nu_\mu N \rightarrow \mu^- e^- X)}{\sigma(\nu_\mu N \rightarrow \mu^- e^+ X)} = \begin{cases} 0.20 \pm 0.11 & \text{for } p_{e^+}, p_{e^-} > 0.5 \text{ GeV/c} , \\ 0.22 \pm 0.12 & \text{for } p_{e^+}, p_{e^-} > 0.8 \text{ GeV/c} . \end{cases}$$

- 2) No V^0 's were found in the $\nu_\mu N \rightarrow \mu^- e^- X$ events, whereas 13 V^0 's are present in the $\nu_\mu N \rightarrow \mu^- e^+ X$ sample. Assuming $c\bar{c}$ production as a possible source of these events, we expect to observe three to four V^0 in the events with $p_{e^-} > 0.5 \text{ GeV/c}$.
- 3) $\nu_\mu N \rightarrow \mu^- e^- X$ events have higher y -values and smaller electron momenta than $\nu_\mu N \rightarrow \mu^- e^+ X$ events; also they have a flat $\phi_{\mu e}$ distribution.
- 4) The existing theoretical models do not explain the $\nu_\mu N \rightarrow \mu^- e^- X$ rates in a satisfactory way [14,15].
- 5) We found direct evidence for the production of trilepton events $\nu_\mu N \rightarrow \mu^- e^+ e^- X$, (three events) giving a rate

$$\frac{\sigma(\nu_\mu N \rightarrow \mu^- e^+ e^- X)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} = (3.1 \pm 1.9) \times 10^{-4} .$$

Within our statistics our results are compatible with the model of Smith [17] without the empirical factor of 2.5.

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Table 1a

Background for e^+ in $\mu^- e^+$ events (corrected)
(per CC event)

Energy cut (GeV)	No. of asym. close-in e^+e^- and Dalitz pairs (10^{-3})	No. of K^+ (10^{-5})	Total background (10^{-3})
0.3	0.27	≈ 1	0.28
0.5	0.12	≈ 1	0.13
0.8	0.058	≈ 1	0.068

Table 1b

Background for e^- in $\mu^- e^-$ events (corrected)
(per CC event)

Energy cut (GeV)	No. of asym. close-in e^+e^- and Dalitz pairs (10^{-3})	No. of Compton electrons (10^{-3})	No. of δ -rays (10^{-3})	No. of K^- (10^{-5})	Total background (10^{-3})
0.3	0.27	0.30	0.18	≈ 1	0.76
0.5	0.12	0.13	0.08	≈ 1	0.34
0.8	0.058	0.053	0.04	≈ 1	0.16

Table 2
Experimental world results for like-sign μe events

Neutrino	$\langle E_\nu \rangle$ (GeV)	No. of CC events	Cuts		No. of observed events	No. of background events	Rates	
			P_{μ^-} (GeV/c)	P_{e^-} (GeV/c)			$\mu^- e^- / \mu^-$	$\mu^- e^- / \mu^- e^+$
Berkeley-FNAL-Honolulu-Seattle Wisconsin Collab. 15' BC, Ne-H ₂	90	8,900	> 4.0	> 0.8	3	3.6	-	Upper limit = 0.07 (90% CL)
Brookhaven-Columbia Collab. 15' BC, Ne-H ₂	Flux peaks at 25 GeV	$\sim 100,000$	> 10.0	2-20	20	9	$\sim 3 \times 10^{-4}$	0.16 ± 0.08
Bergen-CERN-Strasbourg Collab. (this experiment) GGM BC, propane-freon	40	24,354	> 4.5	$\begin{cases} > 0.5 \\ > 0.8 \end{cases}$	10 7	4.1 2.1	$(6.7 \pm 3.9) \times 10^{-4}$ $(5.3 \pm 2.9) \times 10^{-4}$	0.20 ± 11 0.22 ± 12
Antineutrino	$\langle E_\nu \rangle$ (GeV)	No. of CC events	Cuts		No. of observed events	No. of background events	Rates	
			P_{μ^+} (GeV/c)	P_{e^+} (GeV/c)			$\mu^+ e^+ / \mu^+$	$\mu^+ e^+ / \mu^+ e^-$
FNAL-IHEP-ITEP-Michigan Collab. 15' BC, Ne-H ₂	32	6,780	> 4.0	> 0.4	4	1.1	$\left(4.8^{+5.3}_{-3.2} \right) \times 10^{-4}$	$0.13^{+0.15}_{-0.09}$

Table 3a

Comparison of kinematical quantities of μ^-e^+ events (Monte Carlo predictions, clear events, combined clear and confused events). All values are corrected for electron detection efficiencies. Errors are statistical only.

Variable	$\mu^-e^+ (p_{e^+} > 0.3 \text{ GeV/c})$		
	Monte Carlo	Clear events	Clear + confused events
$\langle E_\nu \rangle$	49.7	50.0 ± 6.0	49.5 ± 5.0
$\langle E_\mu \rangle$	23.2	30.2 ± 4.6	28.6 ± 3.7
$\langle E_{e^+} \rangle$	4.2	3.0 ± 0.8	3.5 ± 0.7
$\langle \nu \rangle$	25.3	19.8 ± 2.3	21.4 ± 2.2
$\langle Q^2 \rangle$	8.7	8.0 ± 1.6	7.6 ± 1.2
$\langle W \rangle$	5.7	5.2 ± 0.3	5.5 ± 0.3
$\langle x \rangle$	0.21	0.21 ± 0.03	0.20 ± 0.02
$\langle y \rangle$	0.52	0.43 ± 0.03	0.46 ± 0.03
$\langle z_{e^+} \rangle$	0.17	0.15 ± 0.02	0.15 ± 0.02
$\langle \phi_{\mu e} \rangle$	113.9	119.4 ± 7.0	124.2 ± 5.6

Table 3b

Comparison of kinematical quantities between μ^-e^+ and μ^-e^- events for $p_{e^\pm} > 0.5$ GeV/c and $p_{e^\pm} > 0.8$ GeV/c

Variable	CC events	$p_{e^\pm} > 0.5$ GeV/c		$p_{e^\pm} > 0.8$ GeV/c	
		μ^-e^+	μ^-e^-	μ^-e^+	μ^-e^-
$\langle E_\nu \rangle$	39.5 ± 0.5	46.5 ± 5.9	38.1 ± 6.2	49.1 ± 7.9	41.8 ± 8.2
$\langle E_\mu \rangle$	22.6 ± 0.4	27.2 ± 4.8	17.1 ± 4.0	28.4 ± 6.2	20.3 ± 5.6
$\langle E_e \rangle$	* $\begin{cases} 2.3 \pm 0.05 \\ 2.8 \pm 0.06 \end{cases}$	3.6 ± 1.0	1.0 ± 0.1	5.0 ± 1.2	1.2 ± 0.1
$\langle \nu \rangle$	15.92 ± 0.3	19.3 ± 2.3	20.1 ± 3.1	20.8 ± 2.9	21.0 ± 3.6
$\langle Q^2 \rangle$	6.96 ± 0.2	8.3 ± 1.8	8.6 ± 1.8	8.2 ± 2.2	7.7 ± 1.5
$\langle W \rangle$	4.50 ± 0.04	5.1 ± 0.3	5.4 ± 0.6	5.4 ± 0.3	5.6 ± 0.06
$\langle x \rangle$	0.24 ± 0.003	0.22 ± 0.03	0.26 ± 0.06	0.19 ± 0.03	0.23 ± 0.06
$\langle y \rangle$	0.41 ± 0.008	0.45 ± 0.03	0.56 ± 0.06	0.47 ± 0.04	0.55 ± 0.06
$\langle z_{e^\pm} \rangle$	* $\begin{cases} 0.11 \pm 0.002 \\ 0.13 \pm 0.002 \end{cases}$	0.18 ± 0.02	0.06 ± 0.01	0.24 ± 0.02	0.06 ± 0.01
$\langle \phi_{\mu e} \rangle$	* $\begin{cases} 111.2 \pm 0.8 \\ 113.6 \pm 0.9 \end{cases}$	120.0 ± 7.5	104.3 ± 20	132.7 ± 8.1	95.8 ± 24

*) In this case, the variable is $\langle z_\gamma \rangle$, $\langle E_\gamma \rangle$, and $\langle \phi_{\mu\gamma} \rangle$ (first line for $E_\gamma > 0.5$ GeV/c; second line for $E_\gamma > 0.8$ GeV/c).

Table 4

Main characteristics of the trileptons. Here $\phi_{\mu^-(e^+e^-)}$ is the angle between the μ^- and the e^+e^- pair in the plane perpendicular to the ν_{μ} direction.

Event number	p_{μ^-}	p_{e^+}	p_{e^-}	$\phi_{\mu^-(e^+e^-)}$ (degrees)	$m_{e^+e^-}$
6077-145	24.3	3.45	2.07	178	0.270
6018-678	15.2	6.29	0.58	176	0.244
6414-461	23.6	0.65	9.83	25	0.195

Table 5

Kinematical quantities for trileptons

Event number	E_{ν}	ν	Q^2	W	x	y
6077-145	38.3	15.7	10.2	4.5	0.35	0.41
6018-678	42.61	27.89	15.85	6.12	0.30	0.65
6414-461	46.7	21.8	4.15	6.34	0.10	0.50

Figure captions

- Fig. 1 : Rates of μ^-e^+ and $\mu^-\mu^+$ relative to CC events as a function of ν_μ energy, for various experiments.
- Fig. 2 : The y distribution for a) μ^-e^+ , with Monte Carlo prediction; b) μ^-e^- ; c) CC events.
- Fig. 3 : The $E_{e^\pm}$ distribution for a) μ^-e^+ , with Monte Carlo prediction; b) μ^-e^- events.
- Fig. 4 : The $z_{e^\pm}$ distribution for a) μ^-e^+ , with Monte Carlo prediction; b) μ^-e^- ; c) CC events.
- Fig. 5 : The $\phi_{\mu e^\pm}$ distribution for a) μ^-e^+ , with Monte Carlo prediction; b) μ^-e^- events.
- Fig. 6 : The e^+e^- mass distribution for $\mu^-e^+e^-$ events.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6