NEUTRINO INTERACTIONS WITH TWO MUONS IN THE FINAL STATE *

B. C. Barish, J. F. Bartlett, A. Bodek, K. W. Brown, D. Buchholz,
F. Jacquet†, F. S. Merritt, F. J. Sciulli, L. Stutte, H. Suter††,
California Institute of Technology, Pasadena, California 91125, U.S.A.

and

H. E. Fisk and G. Krafczyk
Fermilab, Batavia, Illinois 60510, U.S.A.

(April 9, 1975)

Abstract

Neutrino interactions with two muons in the final state have been observed in the Caltech-Fermilab neutrino experiment. At the ~ 1% level neutrino events are observed to have an "extra" muon. Calculations for the decays of π and K mesons in the hadron final state give numbers which make this mechanism for the signal unlikely.

Paper presented at the Colloque International, Physique du Neutrino a Haute Energie, Ecole Polytechnique, Paris, France, ~~March 18 to 20, 1975~~.

---

* Work supported in part by the U.S. Energy Research and Development Administration. Prepared under Contract AT(11-1)-68 for the San Francisco Operations Office.

† On leave of absence from Ecole Polytechnique, Paris, France.

†† Swiss National Fund for Scientific Research Fellow.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT UNLIMITED

For the past few years, considerable emphasis has been placed on studies of neutrino events with no muon in the final state. These, of course, represent the neutral current interaction and understanding the characteristics of this interaction is receiving a great deal of effort.

"Ordinary" neutrino events having a single muon in the final state test many of our ideas about the structure of hadrons. Accurate determination of the behavior of the total cross section and structure functions are essential for our understanding of the charged current interactions.

Besides these two interactions, searches for events having two muons in the final state have been considered as possible signals for new physics. For example, if a W-boson were produced in ν collisions a characteristic signal would be a pair of muons in the final state. Also, production of neutral heavy leptons, four fermion interaction, or new short-lived states produced in the hadron system also could be sources of "extra" muons in neutrino interactions. The characteristics of the events from these different possible sources are different.

We report here on the observations of two-muon events in a recent Caltech-Fermilab experiment, compare the rate and energy spectrum with that expected from the decays of π's and K's in the hadron shower, and present the characteristics of the events that represent an apparent signal (and probably new physics).

Reactions	Relative Rate
No muon-0μ (neutral currents): $\nu + N \rightarrow$ "ν" $+ X$	0.2 - 0.4
Single muon-1μ (charged currents): $\nu + N \rightarrow \mu^- + X$	1.0
Double muons-2μ (new physics ??): $\nu + N \rightarrow \mu^+ + \mu^- + X$	~ .01

Events with two muons in the final state have been observed for some time in the Caltech-Fermilab experiment. A search for W-bosons by looking for events with two muons in the final state has previously been reported.[1] No events characteristic of W-boson production were found, and a mass limit of $M_W \geqslant 8$ GeV (depending on B.R. into leptons) was set. Events from W-boson production and decay are expected to have an energetic μ^+, slow μ^-, and little hadron energy (since the production is electromagnetic). The only observed 2μ events were accompanied by significant hadron energy (E_{had}), and therefore, did not come from W-boson production.

The most plausible simple explanation for the observed events was that they resulted from the decay of π's or K's in the hadron cascade. More information on this source of background was needed before conclusions regarding the source of these events could be drawn.

We report here preliminary results of a run conducted in the narrow band Caltech-Fermilab neutrino beam during September and October of 1974. Much care was taken to calibrate and monitor the calorimeter which measured hadron energies in ν-events. The experiment was primarily conducted to pursue neutral current investigations, and for much of the running, the neutrino beam was "mis-steered" by ~ 1 mr from the center of the apparatus to enchance the relative number of high energy neutrinos (ν_k vs. ν_π) in the beam.

Several features of our apparatus[2] relevant to the investigation of "extra" muon events should be pointed out: the target is a dense material (Fe) minimizing decays from π's or K's in the hadron cascade; muons are identified with good solid angle down to ~ 3 GeV because of the integrated Fe detector; however, the muon spectrometer has small aperture which means the muon momenta and sign are determined only for a fraction of the events.

Figures 5 and 6 show the data along with the predicted curves for neutrinos and antineutrinos respectively. The figures indicate that although the low energy μ's (≤ 10 GeV) might be substantially accounted for by π and K decay the high energy observed muons are highly unlikely to come from this source. From this, we conclude that there are apparently 2μ events that are not easily explainable by π or K decay.

We now discuss the properties of these events. We limit ourselves first to the events with a high energy second muon such that any background events from $\pi \rightarrow \mu$ decay are negligible. For the neutrino running we have 4 events with $E_{\mu}^{+} \geqslant 14$ GeV (the "extra" muon) while only 0.2 events from π and K decay are expected.

The properties of these 4 events are given below:

(1) All have <u>opposite</u> sign μ's

(2) $E_{\mu^-} > E_{\mu^+}$

TABLE

Evt	E_{μ^-}	E_{μ^+}	E_{had}	$E_{had} + E_{\mu^+}$	E_{tot}	y	Q^2	$M_{\mu\mu}$	$P_{\perp}^{\mu^+}$	W
1	84.8	18.8	64.6	83.4	168.2	0.5	39.6	3.4	0.7	10.9
2	29.8	19.0	82.9	101.9	131.7	0.77	5.7	.5	0.8	13.6
3	62.2	14.1	71.2	85.3	148.5	0.58	24.9	2.6	1.0	11.6
4	62.1	44.8	25.1	69.9	132.	0.53	22.1	5.4	2.2	10.4

Averages: 24.2 144.9

Note that the invariant mass W is the mass of the system recoiling against the μ^- (for incident ν s). The main features are that all events are from kaon neutrinos ($E_{\nu} > 90$ GeV), they have Q^2 values typical for deep inelastic scattering events, there is no peak in distribution for the invariant mass of μ-μ system ($M_{\mu\mu}$), and the invariant mass W is very large ($W \geq 10$ GeV). This last feature is not due to experimental biases. The W invariant mass distribution for these events is shown in figure 7 along with the corresponding distributions for all kaon neutrino events. To check whether the events with E^+_μ (extra) < 14 GeV also have high invariant mass, W was calculated for 5 more events having at least one μ through the magnet. In that case it is more probable that some of those events originates from π and K decays. However all but one of those events also have $W > 9$ GeV.

In conclusion, we observe for 2313 events $\nu_\mu + N \rightarrow \mu^- +$ hadrons at least 4 events $\nu_\mu + N \rightarrow \mu^+ + \mu^- +$ hadrons which are not easily explained by π or K decay and estimate the total signal for

$$\langle E_\nu \rangle \sim 150 \text{ GeV} -- 4\text{-}8 \text{ events}/370\ \nu_K \text{ events } (\sim 1\text{-}2\%),$$

and for $\langle E_\nu \rangle \sim 55$ GeV -- ≤ 1 event/490 ν_π events ($\leq 0.2\%$).

During the antineutrino running we observed 446 single μ^+ events and only two events with an extra muon. This rate is compatible with π and K decay calculations. However, the sample is not statistically significant and no conclusions can be drawn about production by antineutrinos.

In summary, new physics seems indicated by the observation of neutrino interactions with two muons in the final state.[(3)] More experimentation will be necessary to isolate and study this new phenomenon. However, since the level is approximately 1% of ν_K events the phenomenon is certainly accessible experimentally.

References

1. B. C. Barish, et.al., Phys. Rev. Letters 31, (1973). Also, XVII Int'l. Conf. on High Energy Physics, London (1974).

2. For detailed description of the apparatus see ref. 1, and also B. C. Barish, et.al., Investigations of the Neutral Current Coupling in Inclusive ν Reactions (this conference).

3. A. Benvenuti, et.al., Phys. Rev. Letters 34, 419 (1975).

Figure Captions

Fig. 1: A type 1 2μ neutrino event.

Fig. 2: A type 4 2μ neutrino event.

Fig. 3: The probability that a muon of energy $E > E_\mu$ will originate from π and K decays in a hadron shower of energy E_{had} cascading in the Caltech-Fermilab iron neutrino target.

Fig. 4: The hadron energy distribution in 1μ charged current neutrino events.

Fig. 5: Neutrino running - Number of 2μ events with a "μ^+" energy $E > E_\mu$. The curve is the expected number from π and K decays.

Fig. 6: Antineutrino running - Number of 2μ events with a "μ^-" energy $E > E_{\mu^-}$. The curve is the expected number from π and K decays.

Fig. 7: The invariant mass distribution for 2μ events compared to the W distribution of kaon neutrinos (the kaon neutrino energy spectrum consists of a band about 150 GeV, the pion neutrino energy spectrum consists of a band about 55 GeV).

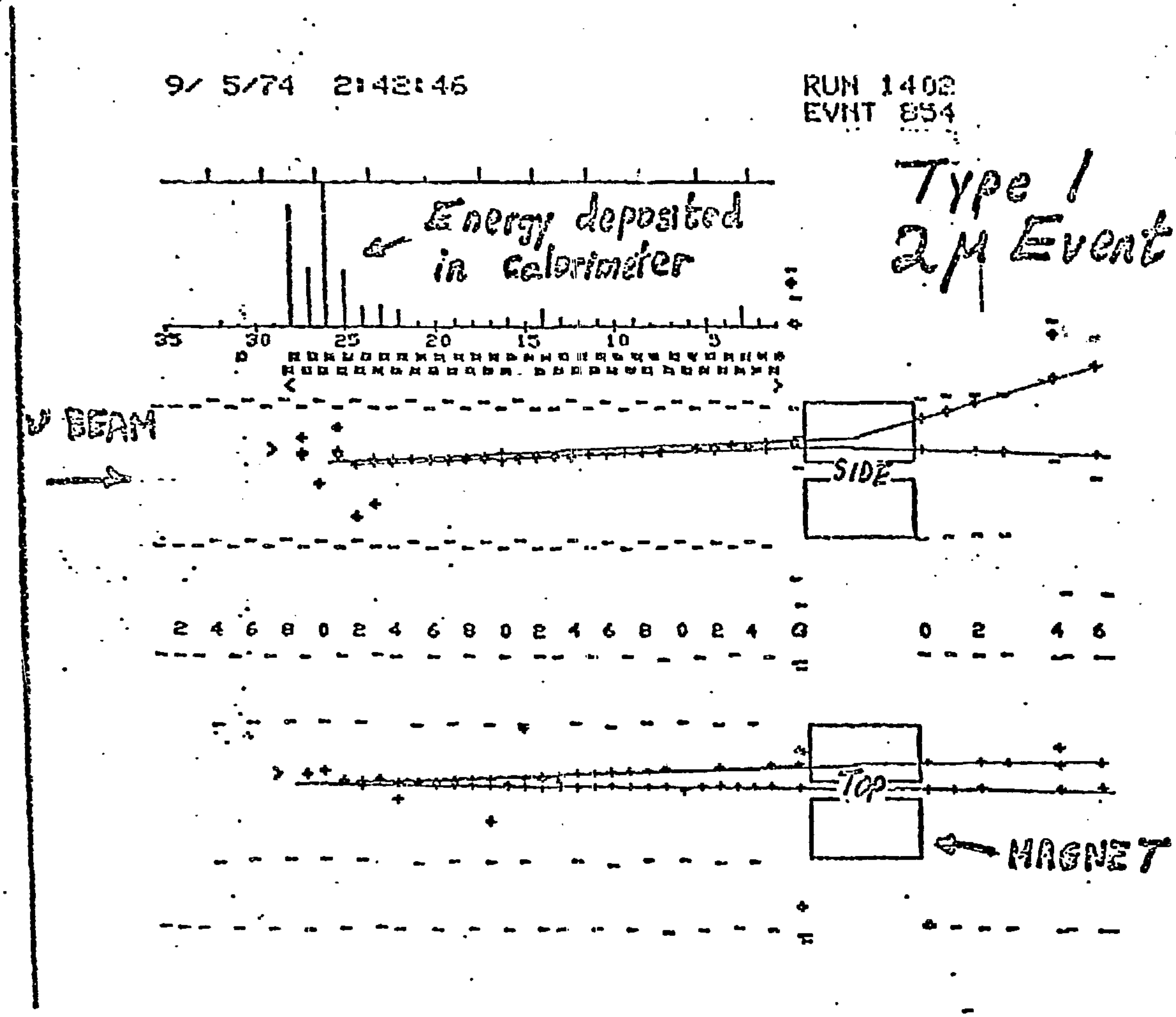

9/ 5/74 2:42:46
RUN 1402
EVNT 854
Energy deposited in calorimeter
Type I 2μ Event
ν BEAM
SIDE
TOP
MAGNET

Fig. 1

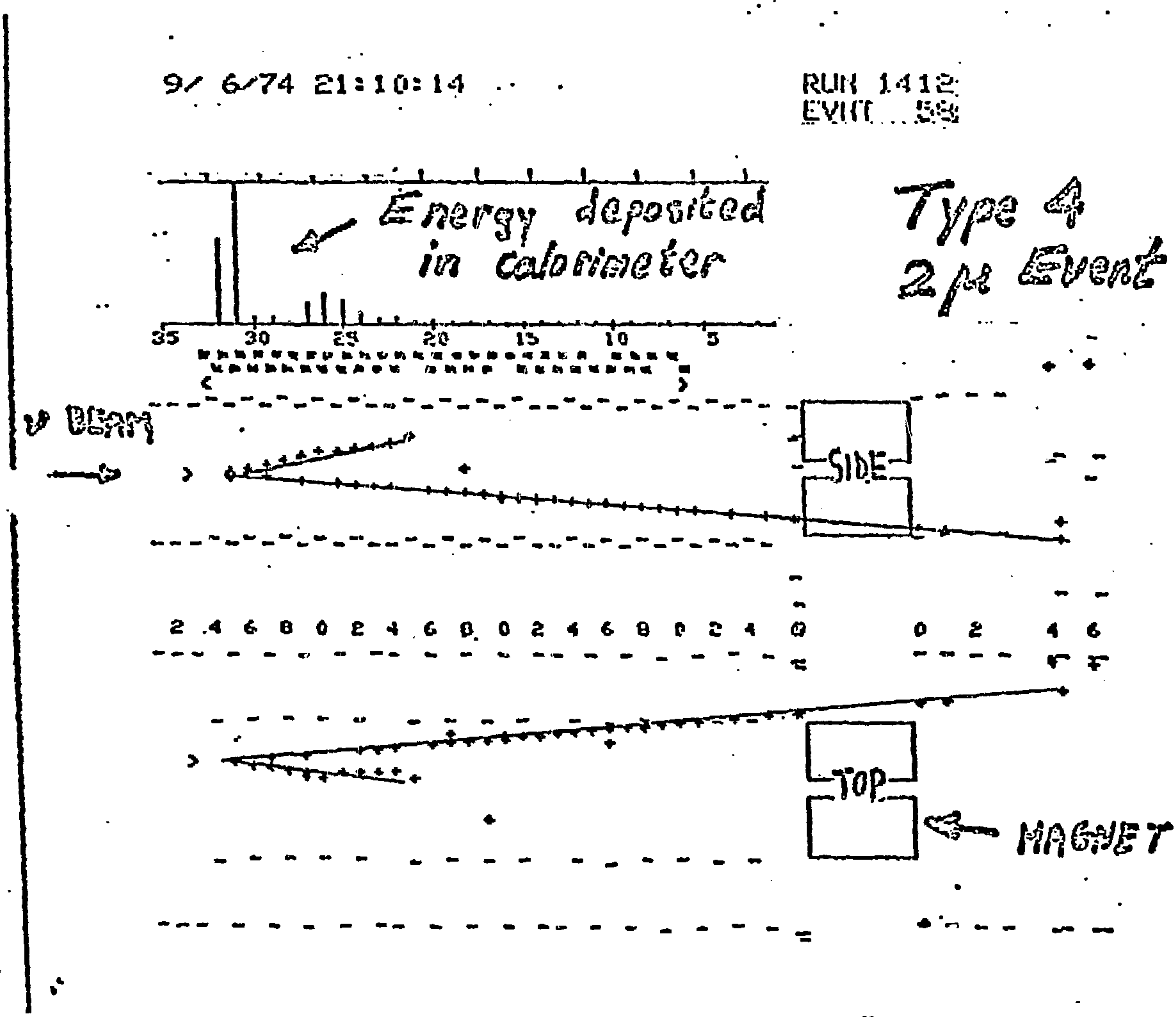

9/ 6/74 21:10:14
RUN 1412
EVNT 58
Energy deposited in calorimeter
Type 4
2μ Event
35 30 25 20 15 10 5
ν BEAM
SIDE
TOP
MAGNET

Fig. 2

Fig. 3

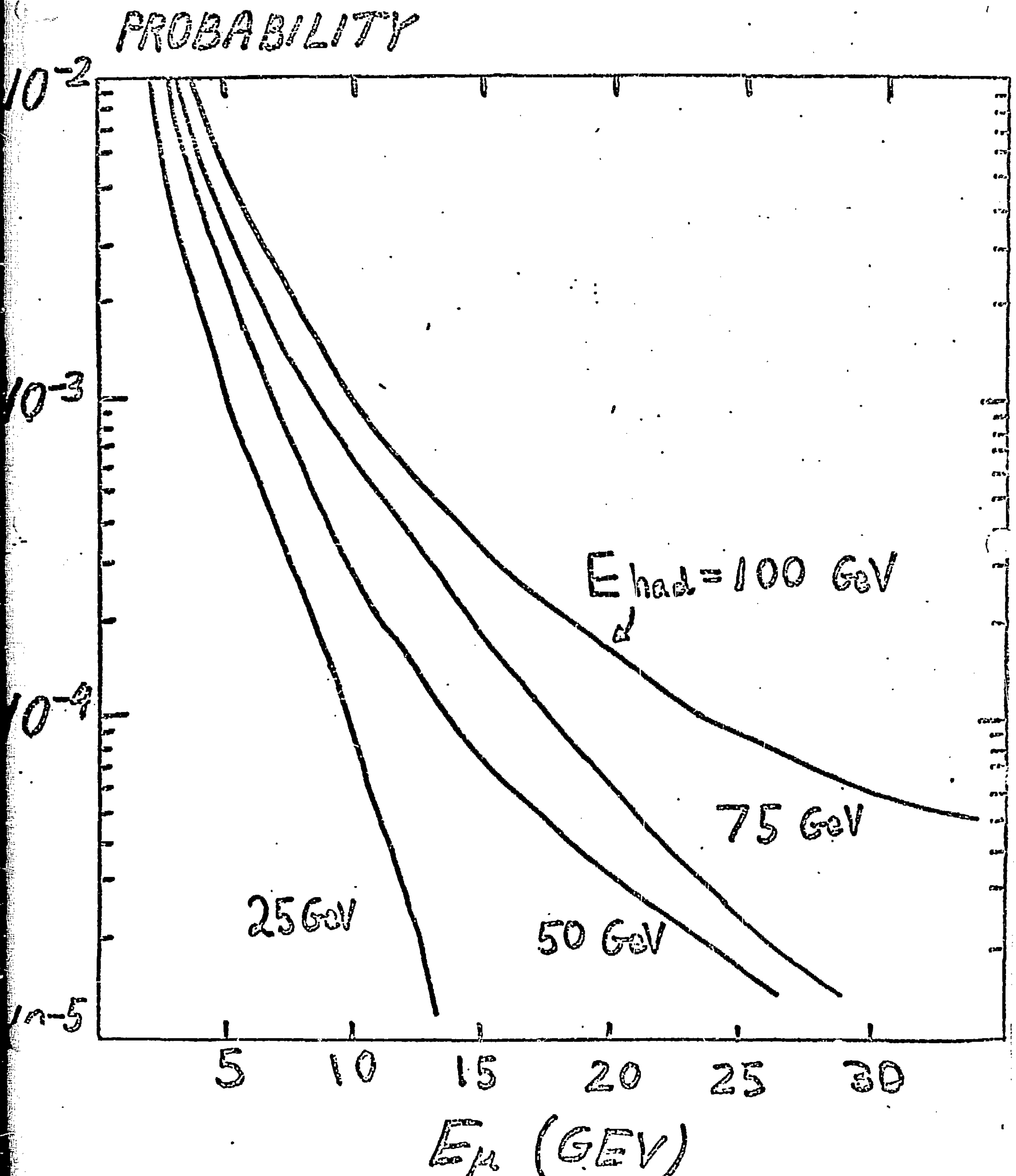
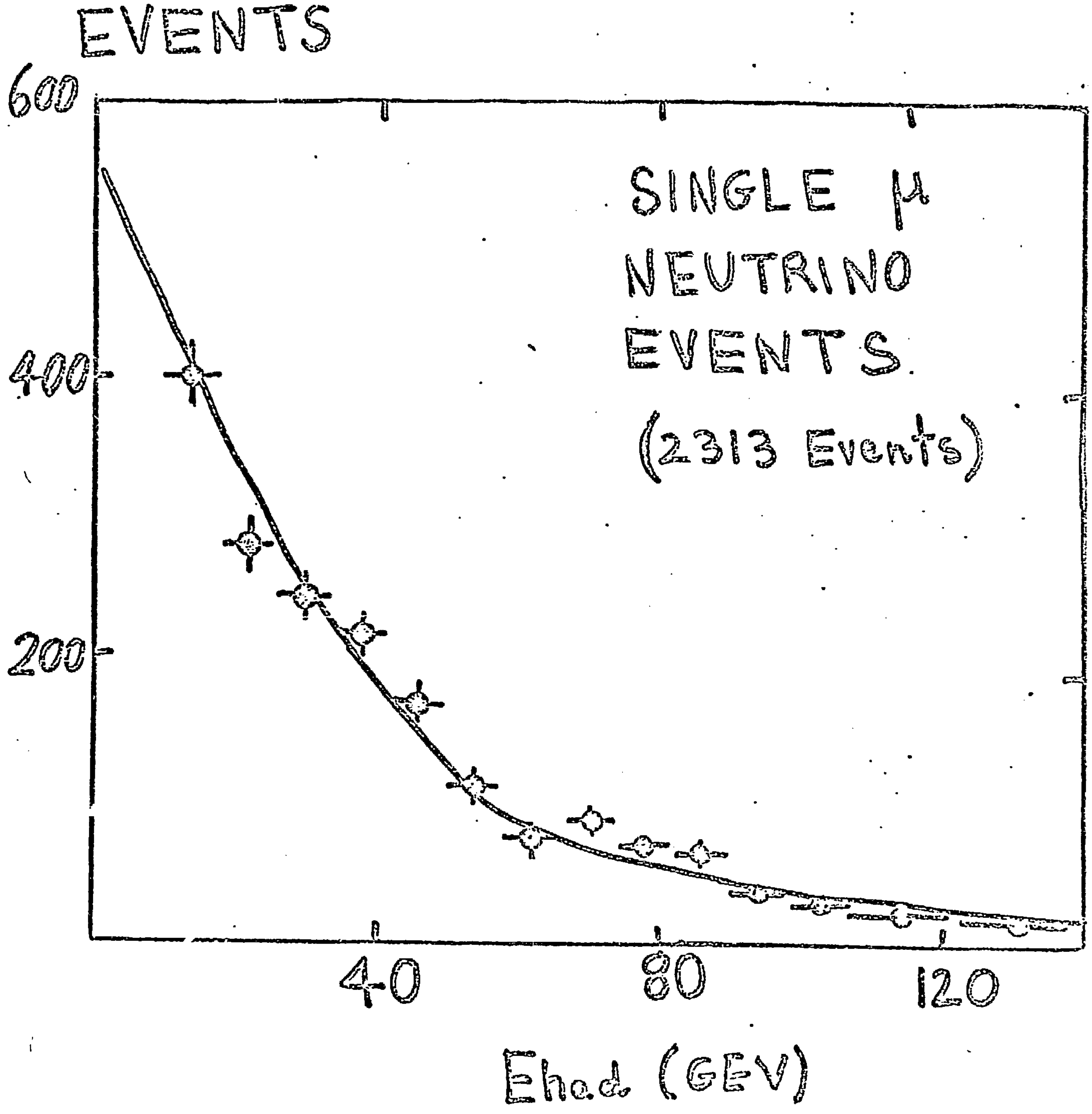
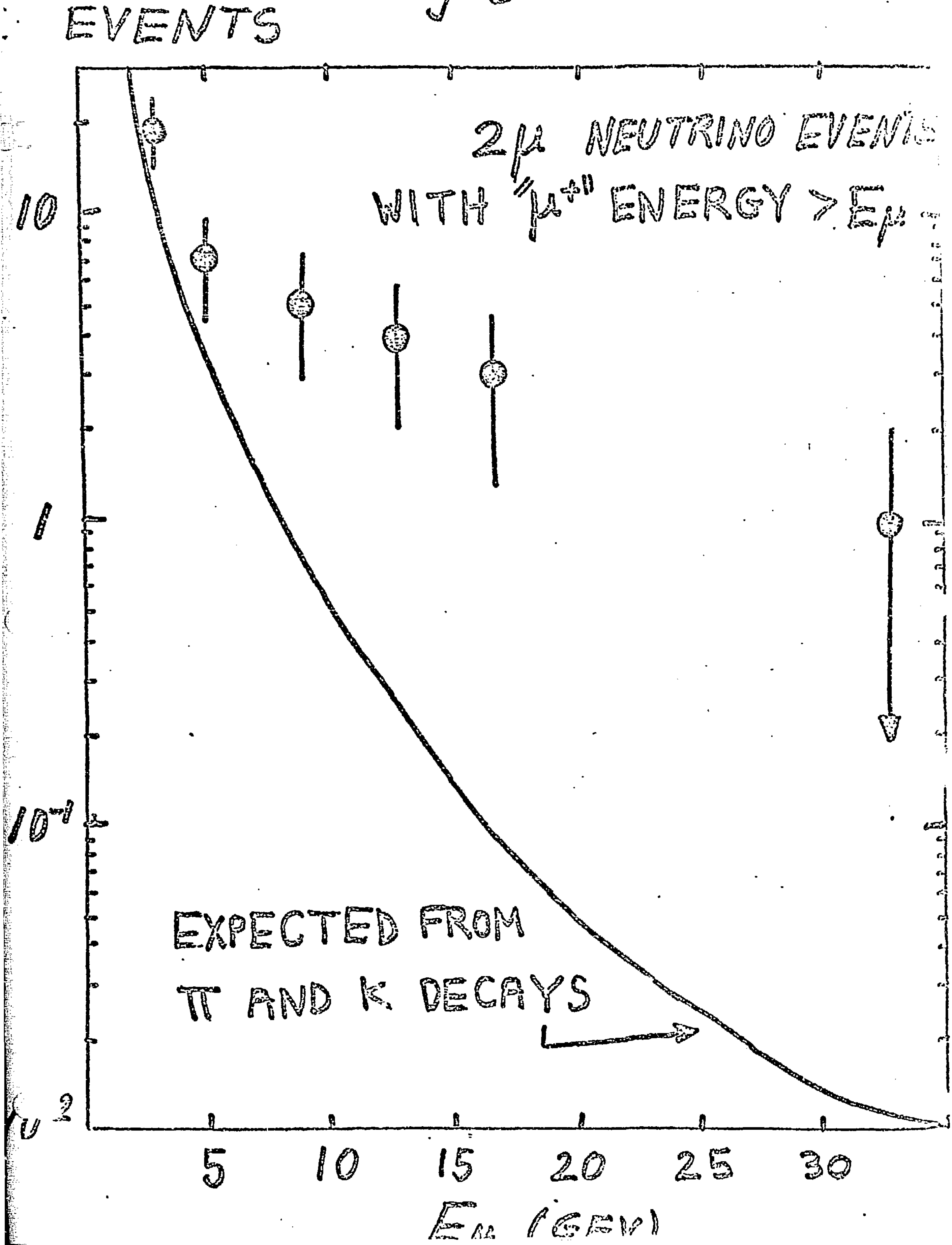

PROBABILITY
10-2
10-3
10-4
10-5
E had = 100 GeV
75 GeV
50 GeV
25 GeV
5
10
15
20
25
30
Eμ (GEV)

Fig. 4

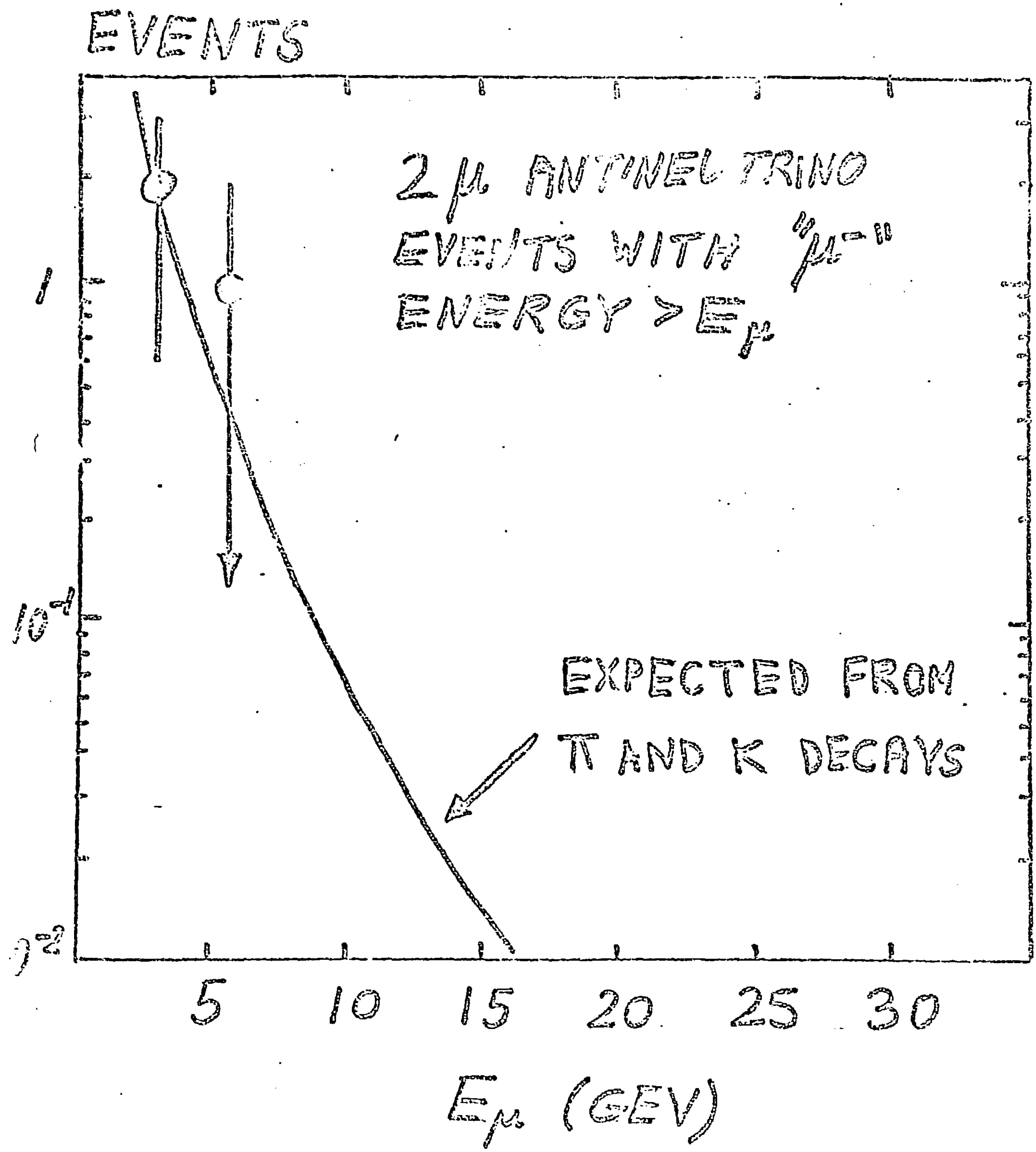

EVENTS
600
400
200
SINGLE μ
NEUTRINO
EVENTS
(2313 Events)
40
80
120
Ehad (GEV)



EVENTS
2μ NEUTRINO EVENTS
WITH "μ+" ENERGY > Eμ
10
1
10^-1
10^-2
EXPECTED FROM
π AND K DECAYS
5
10
15
20
25
30
Eμ (GEV)

Fig. 5

Fig. 6


EVENTS
1
10^{-1}
10^{-2}
2μ ANTINEUTRINO
EVENTS WITH "μ⁻"
ENERGY > E_μ
EXPECTED FROM
π AND K DECAYS
5
10
15
20
25
30
E_μ (GEV)