(Submitted to the London Conference, June 1974)

Paper # 693

CONF-74-120-E
E-0001

EXPERIMENTAL OBSERVATION OF $\mu^+\mu^-$ PAIRS PRODUCED BY VERY HIGH ENERGY NEUTRINOS*

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ABSTRACT

We have observed two events induced by high energy (>150 GeV) neutrinos in which two highly penetrating particles (muons)of opposite sign are produced . Both events have a large inelasticity and a massive μ-hadron system.

June 15, 1974

We report the observation of two events of the type:

$$\nu_\mu + \text{nucleons} \rightarrow \mu^+ + \mu^- + \text{anything}.$$

Neutrinos are produced by the decays of the secondary products of the 300 and 400 GeV external proton beam colliding with an aluminum target. Some focussing of the positive parent particles is achieved with a pulsed lens (horn). The experimental apparatus[1] (Fig. 1) consists of a large segmented container of liquid scintillator (calorimeter) followed by a magnetized iron spectrometer (muon detector). Wide gap spark chambers between calorimeter modules and the four independent sections of the muon spectrometer determine the topology of the events. Large scintillation counters signify incoming charged particles (A) and penetration at different depths of the muon detector (B, C, D). Counters A, B, D are further subdivided into three equal horizontal sections which are recorded separately. Sensitive times are $\sim$ 3 μs for the spark chambers and $\sim$150 ns for the scintillation counters. In addition we record the precise timing of each of the counters with respect to the trigger pulse. The pulse heights and timing information are recorded on magnetic tape. An event is triggered by at least one penetrating particle (muon) through the entire muon spectrometer or an energy deposition of at least 3 GeV in the calorimeter. The equipment is active during a $\sim$2ms interval centered around the burst of the ejected protons ($\sim$200 μs).

The film has been examined twice (by physicists and by scanners). In the present search we retain events provided:

(a) They originate in the liquid of the calorimeter and

(b) Two or more charged particles penetrate at least the first 1.25m thick iron block of the muon detector.

Fifteen events satisfy these criteria in the 400 GeV sample. Thirteen are immediately discarded since (a) they do not form a vertex (i.e., separation >2 meters (6) or vertex extrapolates outside the calorimeter volume (2)) or (b) one of the muons enters from the front (1) or from the side (e.g., cosmic rays) (4).

The two remaining events (Figs. 1a and 1b) need to be examined in more detail. Both events have no count in the anti-coincidence A. A cascade initiated inside the calorimeter is accompanied by two highly penetrating tracks of opposite sign which traverse the rest of the calorimeter and the muon detector without visible interaction. The main kinematical parameters are listed in Table 1.

The events have been examined against a number of possible hypotheses (N is the number of events expected within the sample):

(a) <u>An accidental time and space superposition of independent neutrino and antineutrino interactions</u>. The vertex reconstructed from the two muon tracks is within 10 cm of the observed apex of the hadronic cascade. The timing of the two muon tracks must be within 150 ns, since they hit separate sections of the counters B and D. The probability for an accidental time coincidence is $\lesssim 10^{-3}$ and for an accidental spatial coincidence is $\leq 10^{-3}$. The fraction of antineutrino events (μ^+) in the neutrino beam is ~200/800. Therefore the resultant probability for an accidental superposition is $<2 \times 10^{-7}$. Since we have observed ~800 events, $N<2\times10^{-4}$.

(b) <u>An accidental time and space superposition of a neutrino or antineutrino interaction and of a muon track entering from outside the detector</u>. Both muon tracks extrapolate through

the anticoincidence counter A, which in both events did not count over a time window of 512 ns starting 80ns before the event while separate B and C sections are triggered by each muon with the correct timing . The composite probability of a space and time superposition and of counter A to fail ($\leq 10^{-1}$) give $N \leq 10^{-4}$, since the number of μ^+ from upstream is ~ 5 times the number of $\bar{\nu}$ interacting in the detector.

(c) <u>A neutrino induced event, $\nu + N \rightarrow \mu +$ hadrons, followed by a straight forward decay into a muon of a hadronic constituent of the shower.</u> The incident neutrino energy must be larger than the total visible energy of the event because a decay neutrino is undetected. We have observed 15 ν induced events and no $\bar{\nu}_\mu$ of $E_\nu > 130$ GeV. The most likely alternative is a ν_μ induced event associated with a secondary positive muon track. A Monte Carlo calculation[2] taking into account the complete development of the cascade inside the calorimeter gives a probability $\leq 10^{-3}$, or $N \leq 1.5 \times 10^{-2}$. We have verified this important result by direct measurements in which a pion beam of variable energy (15, 25, 35, 50, 75, 100, 125, and 150 GeV) is incident on the calorimeter. Out of 3000 pions we did not observe any candidate with the proper topology to simulate the two events. This is to be expected since these calculations are in good agreement with many specific experiments on the muonic component inside shielding[3]. We have verified that the result $N \leq 1.5 \times 10^{-2}$ remains valid for any possible combination of hadrons with total energy equal to the sum of the hadron and μ^+ energies, i.e., <u>the result is valid for any possible hadron jet configuration that is compatible with over-all energy conservation</u>. Finally

amongst the bulk of 800 events with visible energy < 130 GeV we have detected one pion decay whilst the Monte Carlo calculation predicts a relatively modest variation of the muon yield as a function of total hadronic energy.

(d) Neutron or neutral current neutrino initiated hadronic cascade with simultaneous muon decay of two hadrons. A muonless rate of ~ 0.20 of the total neutrino rate has been observed[4]. The probability of a double decay is $\sim 10^{-6}$. Therefore $N_4 = 10^{-6} \times 0.2 \times 15 = 3 \times 10^{-5}$.

The expectation for events of conventional origin is therefore $N \simeq 1.5 \times 10^{-2}$, mainly due to process (c).

Further evidence of the unusual nature of these events is displayed in Figure 3, a scatter plot of E_v, the total visible energy, and M_X, the invariant mass of X in ν_μ + nucleon $\rightarrow \mu^- + X$. For the dimuon events, $X \equiv$ hadrons + $\mu^+ + \nu$ (lepton conservation!) and hence the calculated values of M_X and E_v are only lower bounds. This choice is the most natural one since there are essentially no antineutrinos of energy > 130 GeV. (See Fig. 2). We remark that dimuon events distinguish themselves kinematically from single muon production (see Fig. 3). For $M_X > 7.5$ GeV/c^2 and $E_v > 130$ GeV, we retain an essentially pure dimuon sample. With these cuts the background (c) is reduced, substantially increasing the statistical significance of the events.

The amount of information available is insufficient to define uniquely the physical origin of the two events. The direct production of a conven-

tional intermediate boson[5] W, is very probably excluded since coherent production is expected to be several times greater. Likewise we can rule out standard processes of type[6]: $\nu_\mu + Z \rightarrow Z + \mu^+ + \mu^- + \nu$, because of the inelasticity of the process and the appreciable transverse momenta of the observed leptons. One possibility is that the particle jet produced by very high energy neutrinos has an anomalously large probability to decay into a (positive) muon. Models generating this type of effect due to the presence of novel hadronic quantum numbers (charm) have been recently suggested by Glashow, Iliopoulos and Maiani[7]. The production of heavy leptons cannot be excluded.

Finally we would like to stress the preliminary nature of the result based only on two events. Investigations are being pursued to increase considerably the size of our sample.

Footnotes and References

*Supported in part by the U.S. Atomic Energy Commission under Contract AT(11-1)-881-428.

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Figure Captions

Fig. 1 Schematic view of apparatus. For each of the dimuon events, photographs of spark chambers SC1 to SC8 have been superimposed on the diagram (one of three stereo-views). The trigger counters or sections which fired are cross-hatched. The energy deposition in each of the 16 calorimeter modules is also labeled (0.1 GeV is the energy deposited by one single ionizing particle transversing one module). Dark lines trace the best fit trajectory of each muon.

Fig. 2 Total visible energy distribution of neutrino events.

Fig. 3 Scatter plot of the invariant mass of X vs. the total visible energy for all events of the form $\nu_\mu N \rightarrow \mu^- X$ The two dimuon events are labeled. The open circle denotes the one possible pion decay in flight candidate.

TABLE I

KINEMATICS OF THE $\mu^+\mu^-$ EVENTS

		Event 1	Event 2	
Run Number		412	415	
Frame Number		253659	254784	
Negative Muon Track				
(a) Momentum	P_{μ^-}	107	36	GeV/c
(b) Angle respect ν-beam	θ_{μ^-}	29	33	mrad
(c) Total number of nuclear collision lengths traversed		58	61	
Positive Muon Track				
(a) Momentum	P_{μ^+}	16.7	13.9	GeV/c
(b) Angle respect to ν-beam	θ_{μ^+}	55	45	mrad
(c) Total number of nuclear collision lengths traversed		58	61	
Hadronic Cascade				
(a) Total energy E_h	E_h	23.7	104.7	GeV
(b) Energy fraction continued inside calorimeter		0.93	0.89	
Total Visible Energy	$P_{\mu^+} + P_{\mu^-} + E_h$	147	155	GeV
Dimuon Invariant Mass	$M_{\mu\mu}$	3.1	1.0	GeV/c^2
Invariant Mass of μ^+-hadron system	M_X	> 7.9	> 14.7	GeV/c^2

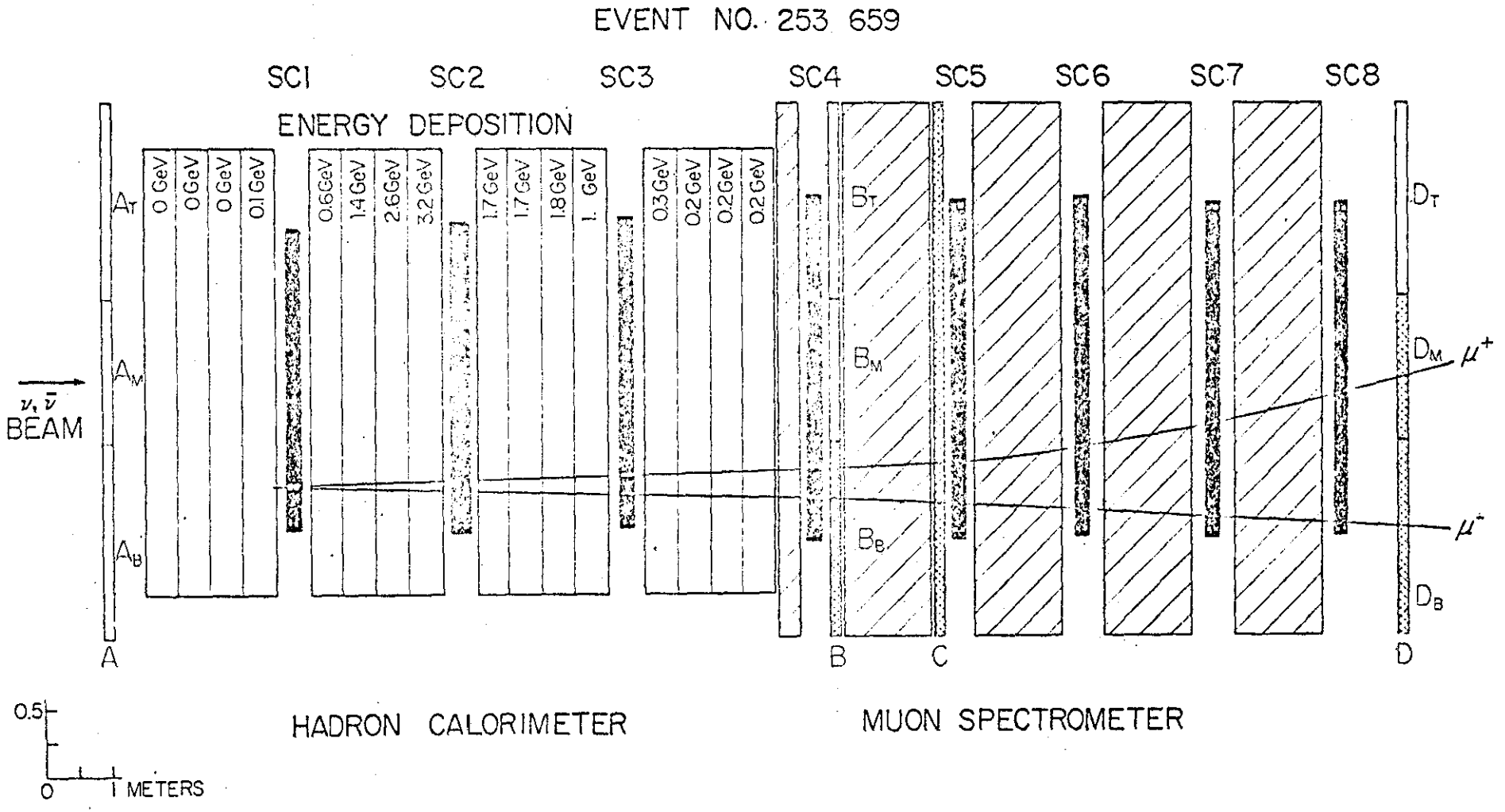
EVENT NO. 253 659
SC1
SC2
SC3
SC4
SC5
SC6
SC7
SC8
ENERGY DEPOSITION
0 GeV
0 GeV
0 GeV
0.1 GeV
0.6 GeV
1.4 GeV
2.6 GeV
3.2 GeV
1.7 GeV
1.7 GeV
1.8 GeV
1. GeV
0.3 GeV
0.2 GeV
0.2 GeV
0.2 GeV
A_T
A_M
A_B
B_T
B_M
B_B
D_T
D_M
D_B
μ^+
μ^-
$\nu, \bar{\nu}$
BEAM
A
B
C
D
0.5
0
1 METERS
HADRON CALORIMETER
MUON SPECTROMETER

Fig 1a

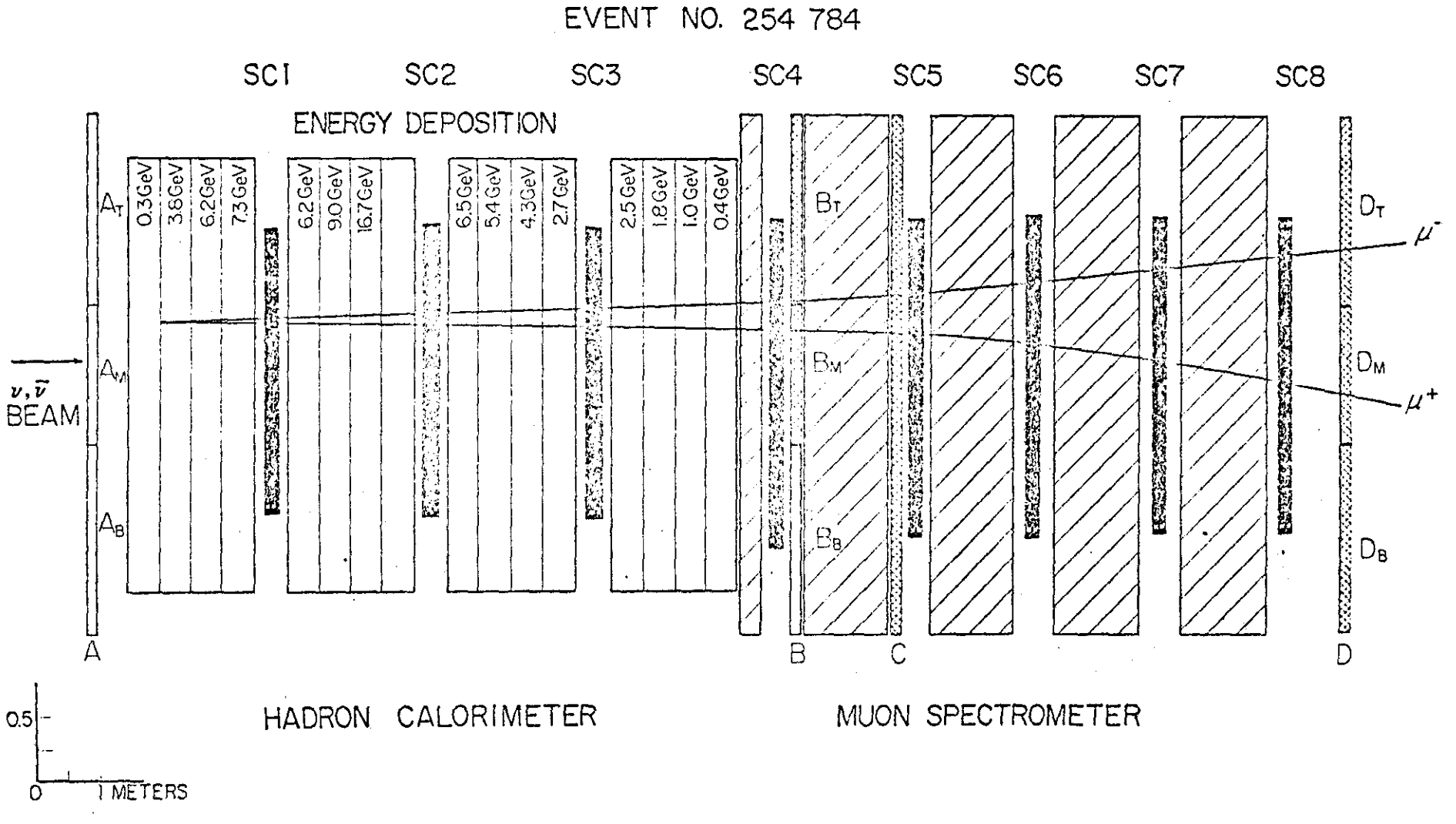
EVENT NO. 254 784
SC1
SC2
SC3
SC4
SC5
SC6
SC7
SC8
ENERGY DEPOSITION
0.3GeV
3.8GeV
6.2GeV
7.3GeV
6.2GeV
9.0GeV
16.7GeV
6.5GeV
5.4GeV
4.3GeV
2.7GeV
2.5GeV
1.8GeV
1.0GeV
0.4GeV
A_T
A_M
A_B
B_T
B_M
B_B
D_T
D_M
D_B
μ^-
μ^+
$\nu, \bar{\nu}$
BEAM
A
B
C
D
HADRON CALORIMETER
MUON SPECTROMETER
0.5
0
1 METERS

Fig. 1b

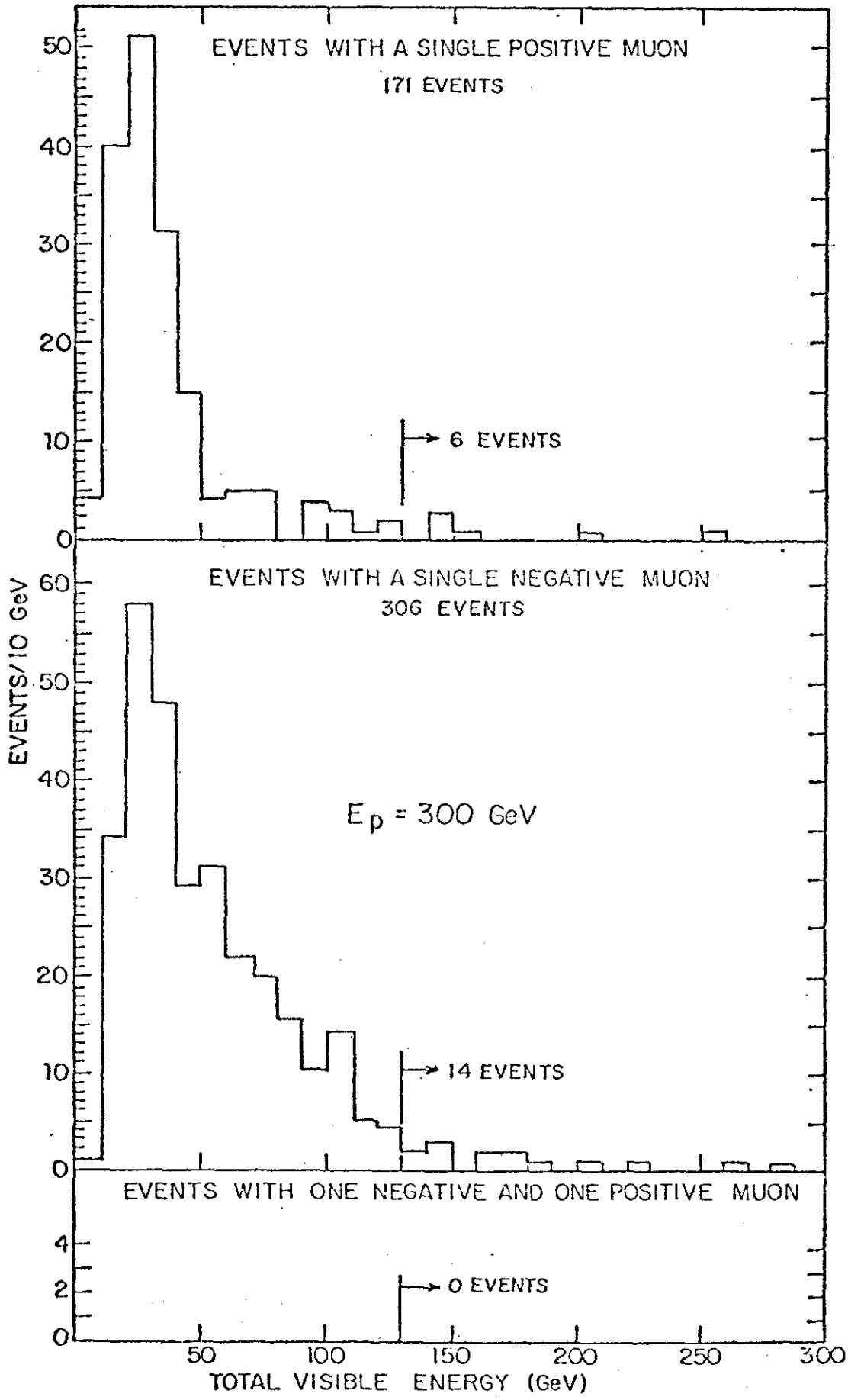
EVENTS WITH A SINGLE POSITIVE MUON
171 EVENTS
6 EVENTS
EVENTS WITH A SINGLE NEGATIVE MUON
306 EVENTS
E_p = 300 GeV
14 EVENTS
EVENTS WITH ONE NEGATIVE AND ONE POSITIVE MUON
0 EVENTS
EVENTS/10 GeV
TOTAL VISIBLE ENERGY (GeV)
0
10
20
30
40
50
60
2
4
50
100
150
200
250
300

Fig. 2a

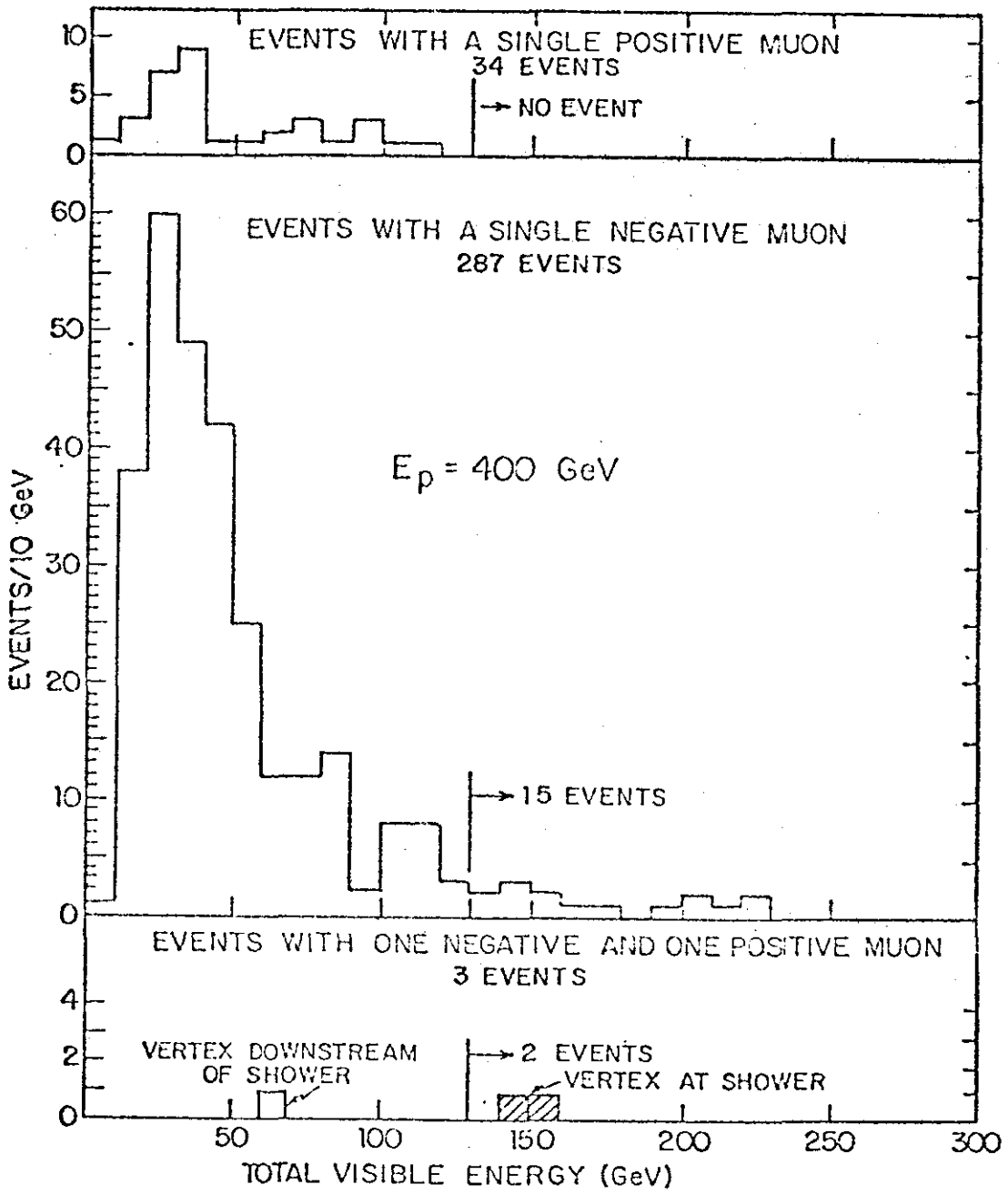
EVENTS WITH A SINGLE POSITIVE MUON
34 EVENTS
NO EVENT
EVENTS WITH A SINGLE NEGATIVE MUON
287 EVENTS
E_p = 400 GeV
15 EVENTS
EVENTS WITH ONE NEGATIVE AND ONE POSITIVE MUON
3 EVENTS
VERTEX DOWNSTREAM OF SHOWER
2 EVENTS
VERTEX AT SHOWER
EVENTS/10 GeV
TOTAL VISIBLE ENERGY (GeV)

Fig. 2b

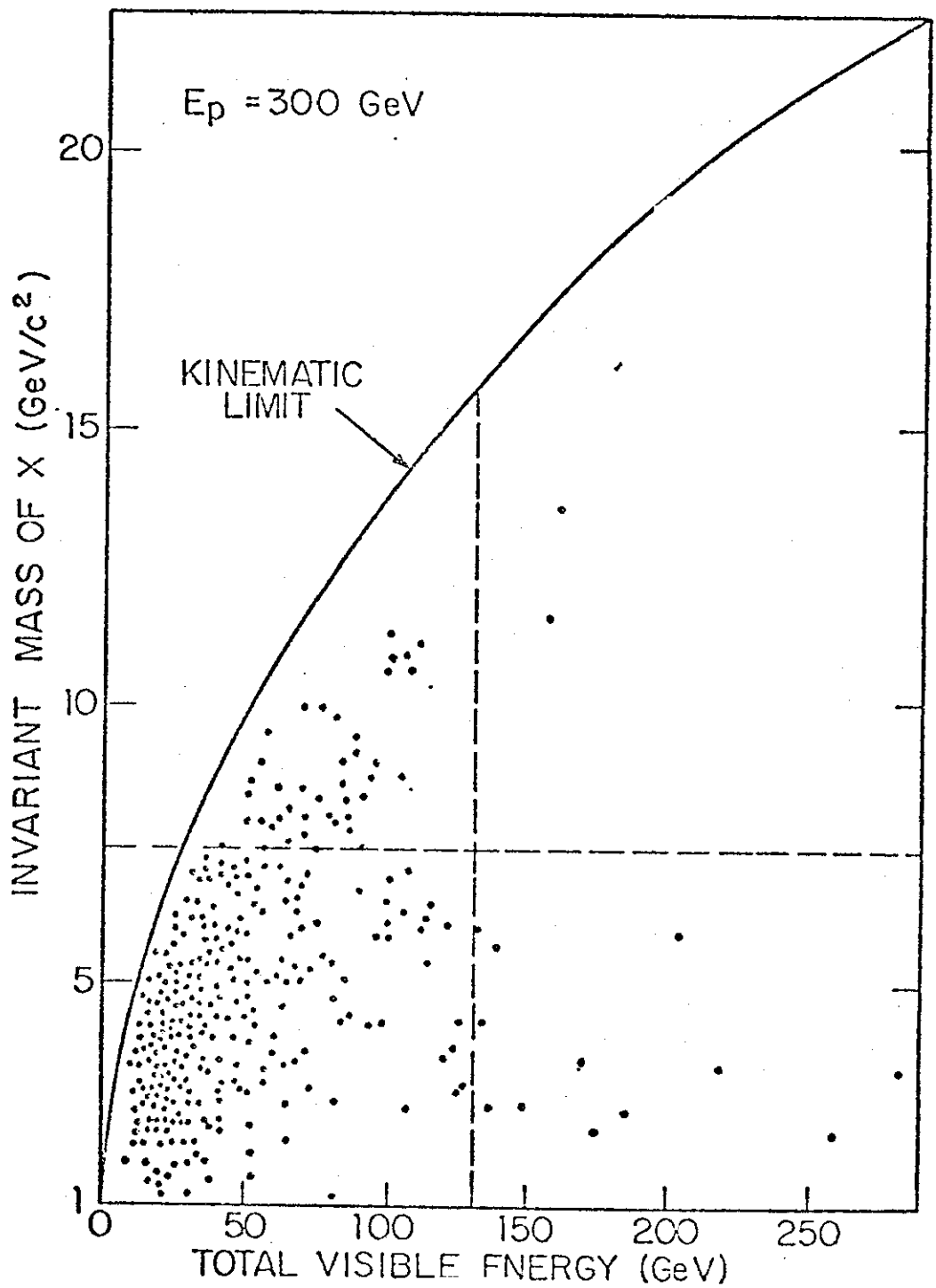
Ep = 300 GeV
KINEMATIC LIMIT
INVARIANT MASS OF X (GeV/c²)
20
15
10
5
1
0
50
100
150
200
250
TOTAL VISIBLE ENERGY (GeV)

Fig. 3a

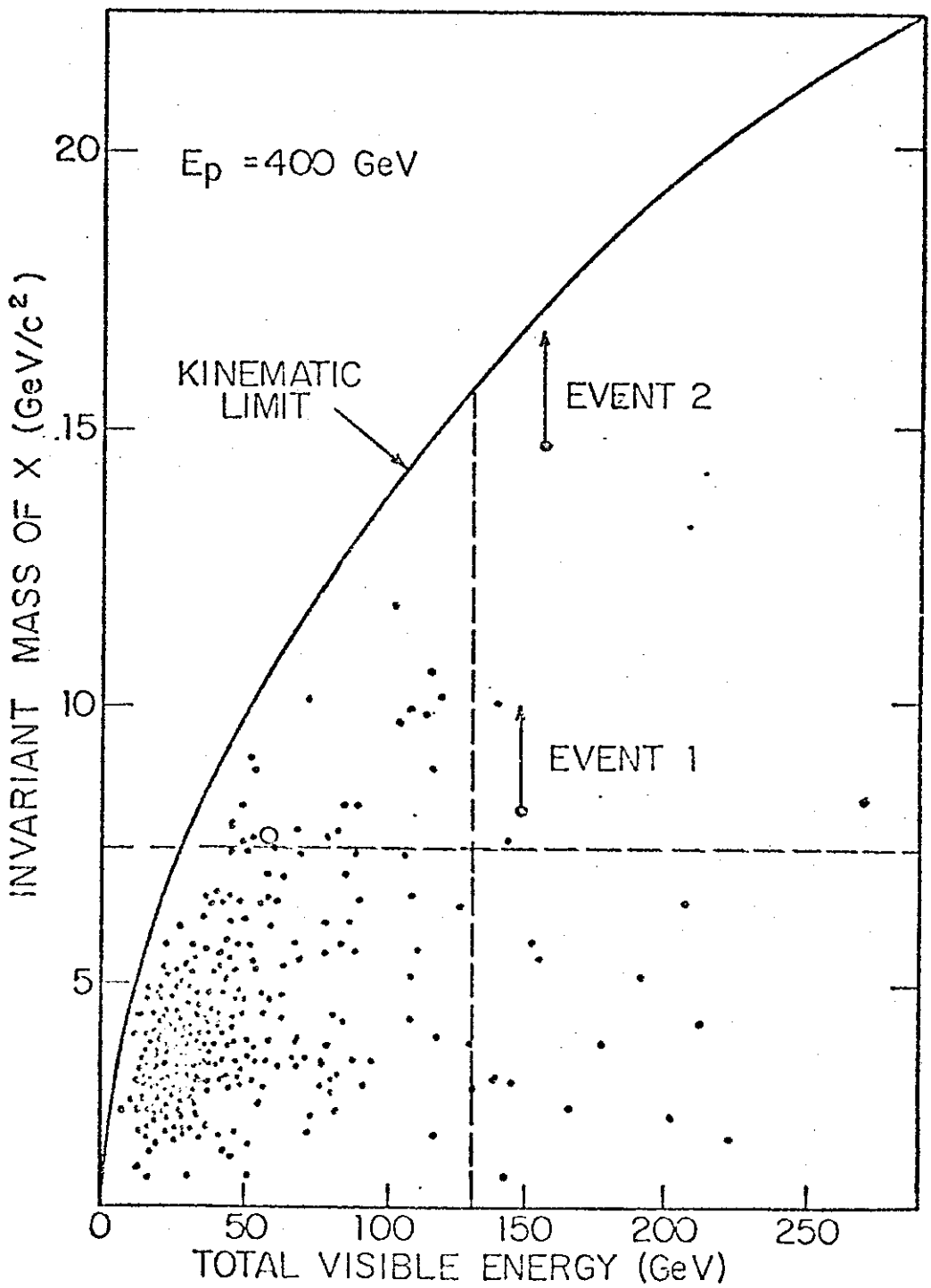
Ep =400 GeV
KINEMATIC LIMIT
EVENT 2
EVENT 1
INVARIANT MASS OF X (GeV/c²)
20
15
10
5
0
50
100
150
200
250
TOTAL VISIBLE ENERGY (GeV)

Fig. 3b