EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

LOWER LIMIT FOR THE MASS OF THE INTERMEDIATE BOSON

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SUMMARY

The search for the muonic and the non-leptonic decays of the hypothetical intermediate boson among the neutrino events produced in the CERN neutrino experiment has been continued and concluded. The data do not give any clear evidence for such decays. Comparing the rate of possible boson reactions, observed in the spark chamber and the bubble chamber, with the calculated production rate, we arrive at a lower limit for the boson mass, ranging from 1.7 to 2.2 GeV/c² for various assumptions about the relative abundance B of leptonic decays (Table VI).

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CERN, Geneva, Switzerland.

1. INTRODUCTION

The hypothetical heavy boson W^+ mediating the Fermi interaction[1], could be produced by high-energy neutrinos[2-4]. Preliminary results of the CERN neutrino groups[5,6] have already set a lower limit to the boson mass of 1.5 nucleon masses. Therefore the production by the μ neutrinos available at present would predominantly occur through the incoherent reaction[2-4] :

$$\nu_\mu + p \rightarrow W^+ + \mu^- + p \ . \tag{1}$$

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Here p is the proton providing the electromagnetic field in which the (W^+, μ^-) pair is created. The boson would then decay within $\sim 10^{-18}$ seconds through various channels:

$$W^+ \rightarrow \mu^+ + \nu \tag{1.2}$$

$$W^+ \rightarrow e^+ + \nu \tag{1.3}$$

$$W^+ \rightarrow \text{mesons, etc.} \tag{1.4}$$

Because of μ-e universality the rates for (1.2) and (1.3) are practically equal. The relative abundance of leptonic decays

$$B = \frac{(W^+ \rightarrow \mu^+ + \nu) + (W^+ \rightarrow e^+ + \nu)}{W^+ \rightarrow \text{anything}}$$

is not well known. Theoretical estimates, involving only two-body decays into known mesons[7], indicated values of $B \lesssim \frac{1}{2}$ for boson masses around 1.5 GeV/c^2. The probability for mesonic decay increases with increasing boson mass. It can be further enhanced by other decay modes, in particular through suitable resonances.

The present work extends and concludes our previous search for boson production and its subsequent decays[5,6]. The data of the spark chamber and of the bubble chamber are combined to give a lower limit for the boson mass, with the branching ratio B as a free parameter. The analysis is based on a systematic search for the muonic and mesonic decay modes.

For the muonic mode spark chamber data have been used. Because of the large amount of matter transversed, this set-up allows a good discrimination between strongly interacting particles and muons. The region with magnetized iron plates yields the sign of the charge. The mesonic mode has been studied in a bubble chamber where the nature of the particles produced can be better determined, in most of the cases, and the kinematics of the events can be reconstructed to a good degree of accuracy. The data on the electronic decay mode have already been presented[5,6].

2. NEUTRINO FLUX AND BOSON PRODUCTION

The neutrino spectrum has been computed[8], both at the spark chamber and at the bubble chamber positions. Both spectra are shown in Fig. 1 for the energy interval of interest. The spectrum at the spark chamber refers to the 1964 run. The spectrum at the bubble chamber is a weighted average over the 1963 and 1964 runs, since data from both have been used.

Since the elastic cross-section for low 4-momentum transfer $[q^2 < 0.2\ (\mathrm{GeV}/c)^2]$ does not depend appreciably on nucleon form factors, one can in principle deduce the neutrino spectrum from the observed rate of low q^2 elastic events[9]. The spark chamber data indicate that the rate of "elastic" events for neutrino energies above 4 GeV is 2.7 times higher than that expected from calculation[8]. However, among these events classified as "elastic"[6,10] there are many inelastic events in which a single low-energy pion was produced and was either reabsorbed in the nucleus or not recognized in the spark chamber. At low q^2 low-energy pions are produced predominantly from the decay of the $(3/2, 3/2)$ resonance. The cross-section for N* production, computed by Berman and Veltman[11] has been used. For low q^2 it is practically independent of the form factors involved, and is twice the cross-section for the elastic reaction. If all the low q^2 isobar events are mistaken for elastic events, the experimental spectrum is approximately reduced to the calculated spectrum. Bubble chamber observations have been found consistent with the calculated flux for neutrino energies between 1 and 4 GeV[5]. In the same energy range the low q^2 method applied to the spark chamber data gives a rate of "elastic" events twice as large as that predicted. Above 1 GeV the background of inelastic events in this kind of spectrum determination should not depend much on the energy. Therefore, the comparison between the bubble chamber and the spark chamber data indicates that the inelastic background in the low q^2

measurement is about 50% for energies about 1 GeV. This inelastic background can also be estimated from the spark chamber event distribution for all q^2's. Taking for M_A and M_V the values found by the bubble chamber group[5] and assuming the background to be small for high q^2, we find that 45% ± 20% of the "elastic" events are due to background at low q^2. This leads us to estimate that the neutrino flux above 4 GeV is 1.5 ± 0.6 times that computed. In what follows the spectra of figure 1 [see reference[8]] will be used.

For the computation of the expected rates, only the "elastic" production of W^+'s is considered, i.e. those reactions in which no other particle is produced apart from a W^+ and a negative lepton. Cross-sections for this process have been recently computed by Wu et al.[4] for boson masses up to 2.5 GeV/c^2. They include the W production on neutrons due to the neutron magnetic moment, which amounts to 20% of the total cross-section and was not taken into account in the previous computations. From the spectrum[8] and the cross-sections of Wu et al., the rates of boson production have been calculated as a function of neutrino energy and are shown in figures 2a, b. Since the production cross-sections have been computed[4] only up to 10 GeV, they have been extrapolated to 15 GeV.

3. MUONIC DECAY (SPARK CHAMBER RESULTS)

The production of a boson and its subsequent muonic decay would be observed as a pair of muons: a negative muon associated with the production (1.1) and a positive muon resulting from its decay (1.2). These events would appear in the spark chamber as a pair of non-interacting particles of opposite charge. Figure 3 shows the detailed structure of the magnetized iron region. The magnetic field inside the 5 cm iron plates was 18 kilogauss. Three pictures were taken of each event, two from the side and one from the top, providing 90° stereo. Most of the spark chamber events considered in the present analysis originated in the fiducial volume drawn in figure 3 (15 tons of iron). This magnetized iron region was followed by a non-magnetized region of similar structure. Two stereo views only are available in that section. The set-up ended with a thick-plate region (5 - 15 cm of lead) followed by two 15 cm magnetized iron slabs. Events originating in that region have been used for part of the analysis.

3.1 Selection of events

Only events which occurred in the first 15 tons of the magnetized iron section were accepted for inspection. For this fiducial region it is possible to determine the sign of muons in 95% of the cases, provided they do not escape before having traversed 6 iron plates. To be selected, an event had to fulfil the following conditions:

a) It contains at least two tracks, both of which have a visible range larger than 30 cm of iron, when projected along the neutrino direction. This corresponds to a minimum momentum of 470 MeV/c for a muon.

b) The two tracks do not interact. An interaction is defined as: a single scattering with an angle ≥ 12° in any stereo view, after which the track continues through at least three chambers (≥ 15 cm of iron); or as a star with two or more prongs, where a prong is defined by aligned sparks over at least three chambers.

c) The sign combination of the two particles is: (+,-), (+,?), (-,?) or (?,?). Tracks for which the sign cannot be determined, because the sagitta is too small, are mostly due to protons which stop or to very energetic particles which escape from the chamber.

Table I gives a list of the 52 events which fulfilled the selection criteria. In addition, we have found 2 (+,+) events and 8 (-,-) events which have been rejected in view of criterion (c). One expects to observe a few cases with the "wrong" sign combination from the (μ^-,π^-) and (μ^+, p or π^+) events. Furthermore, in some cases a single scattering of a strongly interacting particle, while not falling into the definition of an interaction, can modify the magnitude and even the sign of the curvature. This apparent change of sign could also happen for a muon through multiple scattering. For the 10 events which have a "wrong" sign combination this last effect has an average probability smaller than 2% and is therefore negligible.

Figure 4 shows the sagitta versus range distribution for the 60 stopping particles in the sample. The sagitta distribution of stopping μ^- has been determined experimentally. According to this calibration, 95% of the stopping muons will fall in the region above the solid line in figure 4. If all stopping particles in our sample were muons, not more than two should lie below the solid line; instead there are 19. These are mainly stopping protons, which have a sagitta about four times smaller than a muon of the same range. The 19 events which fall below the solid line of figure 4 have been eliminated from the sample. Taking into account the number of events without a stopping particle, this should eliminate at most 3% of the boson events which could be contained in the sample.

When these various criteria have been applied, 33 events are left from about 5000 neutrino events produced in the same volume. Figure 5 shows one of the events.

3.2 Range distribution of pairs

A two-dimensional plot of the 33 events which constitute the final sample is presented in figure 6. Each point corresponds to one event. The ranges of the negative and of the positive tracks are given as abscissa and ordinate, respectively. In all 33 events the sign of at least one of the two tracks is known. When the second track has a null sagitta, it is assumed that the two tracks have opposite signs.

In muon pairs due to an intermediate boson the positive muon should have on the average a range about 1.5 times longer than the negative one. This property is practically independent of the neutrino spectrum. Figure 6 shows a completely different behaviour for the events, indicating that most of them cannot be due to boson production.

3.3 Range distribution of the positive tracks

In order to investigate further this problem, the integral range distribution of the positive tracks has been plotted in figure 7. The theoretical curves shown give the range distributions of the positive muons from boson decays for various values of the boson mass. The boson production and decay kinematics calculated by Bell and Veltman[2,3], have been used here and are corrected for losses due to escaping tracks. The branching ratio B is assumed to be 50%. This plot also shows clearly, from the difference in shape between the experimental and theoretical distributions, that the majority of the events are not due to boson production.

The μ^+ angular distribution and momentum spectrum have been evaluated under the assumption that in the production process the boson is almost completely polarized backwards. Therefore, the positive muon is predominantly emitted backwards in the boson rest system. This property emerges from a detailed theoretical study of the production process. However if the boson were not so strongly polarized, the angular distribution of the positive muons would be more peaked forward and its momentum would be higher. This would lead to an even more pronounced difference between the theoretical and experimental range distributions of the positive tracks.

3.4 Expected and observed number of events

The number of events which should be observed for various range-cuts on the positive track has been computed from the bubble chamber data on (μ,π) and (μ,p) production. This estimate of the background has been made under the assumption that the spectra and angular distributions of μ, π, p are identical in the bubble chamber and in the spark chamber. We have used the measured attenuation lengths and the escape probabilities to compute the number of predicted events. Table II gives the results of these computations, together with the observed number of events.

To give a limit on the boson mass, we will compare the expected and observed number of muon pairs for a cut of 80 cm on the positive track.

The events originating in the thick-plate region have also been studied in a similar way. As the magnetized iron slabs are at the end of the set-up there is no possibility of making a saggita versus range study; furthermore, no 90° stereo being available the interactions are harder to detect. For a uniform cut of 60 cm in both tracks, the computed background is 0.5 ± 0.25.

In Table III the number of expected and observed events in the two regions are given for different values of the boson mass with B = 50%.

4. NON-LEPTONIC DECAYS (BUBBLE CHAMBER RESULTS)

Due to its comparatively long lifetime, a W particle created inside a nucleus would, in general, emerge from it before decaying. Thus, its mass could be determined from the momenta and energy of its decay products. Such an analysis is possible with a bubble chamber, where momenta and energies of individual particles can be determined quite accurately. The bubble chamber had a total volume of 500 litres, the fiducial volume being 220 litres. It was filled with heavy freon (CF_3Br) and was equipped with a magnetic field of 27 kG. A preliminary search[5] for non-leptonic modes gave a lower limit

$$M_W \gtrsim 1.5 \ \text{GeV}/c^2 .$$

This analysis has been repeated considering only events which satisfied the following criteria:

a) They could be interpreted as neutrino events, each producing a number of mesons with a total charge equal to + 1 and any number of nucleons. Events containing tracks which could be interpreted either as due to mesons or nucleons were considered separately for each possible interpretation.

In doing so we restricted ourselves to the "elastic" production of W's, i.e. we assume that all the mesons produced in the event have emerged from the decay of the W.

b) The measured meson invariant mass "M", thus obtained from the dynamical analysis of the produced mesons was larger than 1 GeV/c^2 and smaller than 2.5 GeV/c^2.

In fact, (see Fig. 3b), we expected that in the present experiment the yield of W's be negligible for $M_W > 2.5$ GeV/c^2. The lower limit of 1 GeV/c^2 was fixed on the basis of our previous determination (1.5 GeV/c^2) relaxed to allow for experimental errors in the mass determination.

c) The measured visible energy (E_{vis}) of the event was equal or larger than 4 GeV. As shown in figure 3b, for $M_W > 1.5$ GeV/c^2 the production of W's can take place practically only for energies above this limit.

d) The momentum of the negative muon (P_{μ^-}) did not exceed 2 GeV/c*). In boson production the average momenta of the μ^- and W^+ are expected to be in the ratio of their masses, therefore P_{μ^-} is in general low. This property is practically independent of the shape of the neutrino spectrum. For a $M_W > 1.5$ GeV/c^2 the fraction of events with P_{μ^-} exceeding 2 GeV/c^2 is expected to be smaller than 24%.

Five "candidates" have been found satisfying these criteria, out of the 456 observed in the fiducial volume. The relevant parameters are given in Table IV.

In Table V the integral distribution in E_{vis} is compared with that expected for several values of M_W. These have been computed assuming B = 0, a total neutrino flux corresponding to 7.3×10^{17} ejected protons and E_{vis} to be equal to the neutrino energy.

5. NON-LEPTONIC DECAYS (SPARK CHAMBER RESULTS)

A search for events which might be considered as possible non-leptonic decays of the intermediate boson has also been made in the thin-plate region of the spark chamber set-up. The events have been selected within a reduced fiducial volume, and must contain at least four tracks, two tracks + n showers, or two tracks + $1V^0$, which are the minimum

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*) This criteria was suggested by J-M. Gaillard and B. Hahn[12].

configurations for a boson event. The total estimated energy of the visible tracks and showers must be greater than 3.5 GeV; of course the energy measurements are less precise than in the bubble chamber case.

From about 500 neutrino events originating inside the fiducial volume, 51 events constitute the final sample. This relative rate is in good agreement with the bubble chamber observation (25 multipion events with $E_{vis} > 3.5$ GeV for 245 neutrino events in the 1964 experiment). Figure 8 shows the μ^- momentum distribution for these 51 events. The muon momenta below 800 MeV/c are due mainly to events for which the muon was not recognized; the shortest non-interacting stopping track in the event has been chosen as the muon.

The expected μ^- momentum distributions[3)] for the boson events have been plotted in figure 8 for $M_W = 1.5$, 1.7 and 1.9 GeV with $B = 0$. These curves are computed for 2.9×10^{17} ejected protons and the fiducial mass of 2.3 tons. In spite of the enlarged acceptance for the low momentum muons, the number of observed events with a total energy above threshold and a μ^- momentum smaller than 1.2 GeV/c is less than the number of events expected for $M_W = 1.7$ GeV/c^2.

6. CONCLUSION

From the combined results of the spark chamber and of the bubble chamber, lower limits for the boson mass with a level of confidence of 99% can be computed. They are given in Table VI as a function of

$$B = \frac{(W^+ \to \mu^+ + \nu) + (W^+ \to e^+ + \nu)}{W^+ \to \text{anything}} .$$

These estimates have been made under the following assumptions:

a) The production of W's is only elastic; the cross-section for the "inelastic" channels has not been computed. With the selection criteria which we have adopted for muonic decay (Section 3.1), events corresponding to inelastic production of W's would have been included. Therefore, this additional production will, in any case, increase the lower limit on the boson mass derived from leptonic decays. The inelastic production of W's does not modify the results of the analysis of the bubble chamber data.

b) The high-energy part of the neutrino spectrum follows the computations[8] and the boson production cross-sections are those given by Wu et al.[4].

As outlined above there are experimental indications that the true spectrum is in fact (1.5 ± 0.6) times that computed. A change by a factor of two either way in the product (production cross-section × neutrino flux) would modify the limit on M_W by ± 0.2 GeV.

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Table I

Classification of muon pair candidates
(spark chamber results)

Type	Number of Events
(-, ? stop)	19
(+, ? stop)	1
(?, ? stop)	2
(?, + stop)	5
(+, -)	23
(+, ?) or (-, ?)	2

Table II

Calculated background and observed number of events

R_+ (cm of Fe)	Calculated background	Observed events
30	36 ± 10	33
40	12 ± 4	9
50	4.7 ± 1.6	5
60	2.3 ± 1	3
70	1.1 ± 0.6	0
80	0.4 ± 0.25	0
90	0.1 ± 0.1	0

R_+ is the cut on the positive track; the cut R_- on the negative track is 30 cm of iron in all cases.

Table III

Expected and observed number of muon pairs with B = 0.5, and imposing different cutt-offs on the ranges of positive and negative particle, R_+ and R_-. The two last columns refer to the thick-wall chamber at the end of the spark chamber set-up; the other data were obtained in the magnetized iron chamber (Fig. 3).

Boson mass GeV/c ^{2}	$R_+ > 80$ cm Fe $R_- > 30$ cm Fe		R_+, $R_- > 60$ cm Fe	
	cal.	obs.	cal.	obs.
1.5	12		9	
1.7	7.2		5.7	
1.9	3.6		2.7	
2.1	1.8	0	1.5	0
2.3	0.95		0.75	
2.5	0.5		0.35	

Table IV

Details on boson candidates (bubble chamber results)

Event No.	E_{vis} GeV	P_{μ^-} (GeV/c^2)	Analysis of the decay products: Observation (*)	Analysis of the decay products: Tentative interpretation of the decay mode	M_W (GeV/c^2)
106	6.2 ± 0.6	1.6 ± 0.4	(+) (+)K^o $\bar{K}^o$ p	$W^+ \rightarrow \pi^+ K^o \bar{K}^o$	1.9
160	4.3 ± 0.4	1.75 ± 0.3	π^+ (+)γ π^-	$\pi^+ \pi^+ \pi^- \pi^o$	1.4
475	5.5 ± 0.8	1.62 ± 0.34	(+) (+) π^- n	$\pi^+ \pi^+ \pi^-$	1.6
788	5.8 ± 0.5	0.32 ± 0.06	π^+ (+)(+) p $\gamma\gamma\gamma\gamma$	$\pi^+ \pi^o \pi^o \pi^o$	1.8
791	5.5 ± 0.8	0.7 ± 0.07	(+) (+) $\gamma\gamma\gamma$ (-)	$\pi^+ \pi^+ \pi^o \pi^o \pi^-$	2.0

(*) The symbol (+) or (-) indicates a positive or negative particle, whose nature could not be determined.

Table V

Expected number of events and numbers of observed candidates for non-leptonic decay of elastically produced W's (B = 0) for different masses M_W and different energy ranges.

	Expected number of events				Observed No. of candidates
E_ν (GeV) \ M_W (GeV/c²)	1.5	1.7	1.9	2.1	
> 4	13.8	7	3	1.3	5
> 5	11.2	6.2	2.9	1.3	4
> 6	8.6	5.4	2.7	1.3	1
> 7	5.9	4	2.3	1.1	0

Table VI

Lower limits for M_W with 99% confidence limit for different values of B. (Combined bubble chamber and spark chamber results)

B =	1	3/4	1/2	1/4	0
M_W > (GeV/c²)	2.2	2.2	2.1	1.9	1.7

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FIGURE CAPTIONS

Fig. 1 Spectra of the high-energy neutrinos at the spark chamber position (1964 experiment) and at the bubble chamber position (weighted average between 1963 and 1964 experiments).

Fig. 2 Rates of boson production:

a) in the spark chamber apparatus (the dashed portions of the curves correspond to an extrapolation of the production cross-sections);

b) in the bubble chamber.

Fig. 3 Spark chamber set-up. Top view of the magnetized iron region.

Fig. 4 Sagitta distribution for the stopping particles of the sample. A stopping μ^- has a 95% probability to give a point either below the top curve or above the bottom one.

Fig. 5 Example of an event. The positive and negative tracks traverse 65 cm and 105 cm of iron, respectively.

Fig. 6 Correlation between the ranges of the positive and negative tracks for the events of the sample.

Fig. 7 Experimental and theoretical range distributions of positive particles.

Fig. 8 Experimental and theoretical momentum distributions of negative muons.

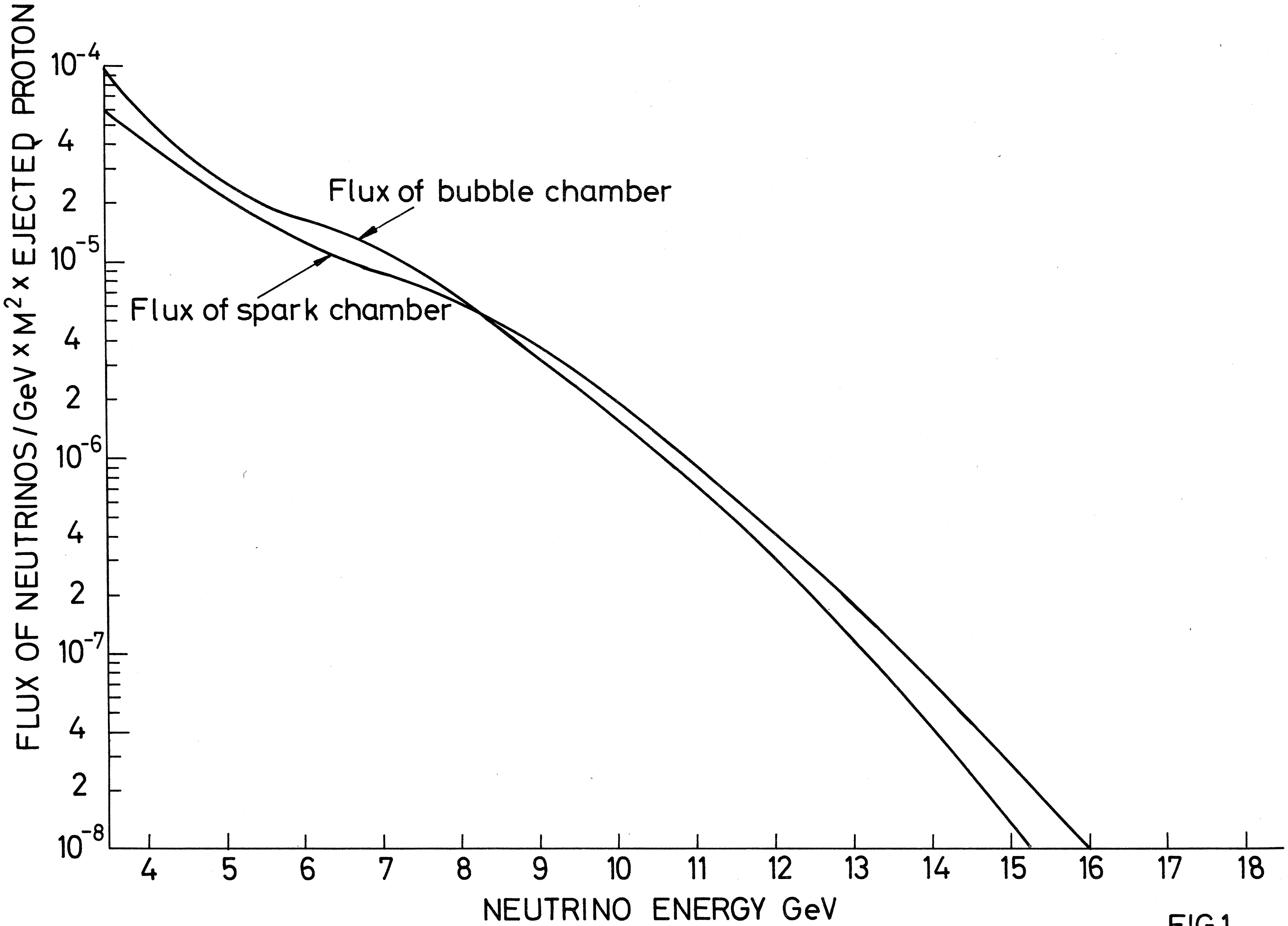
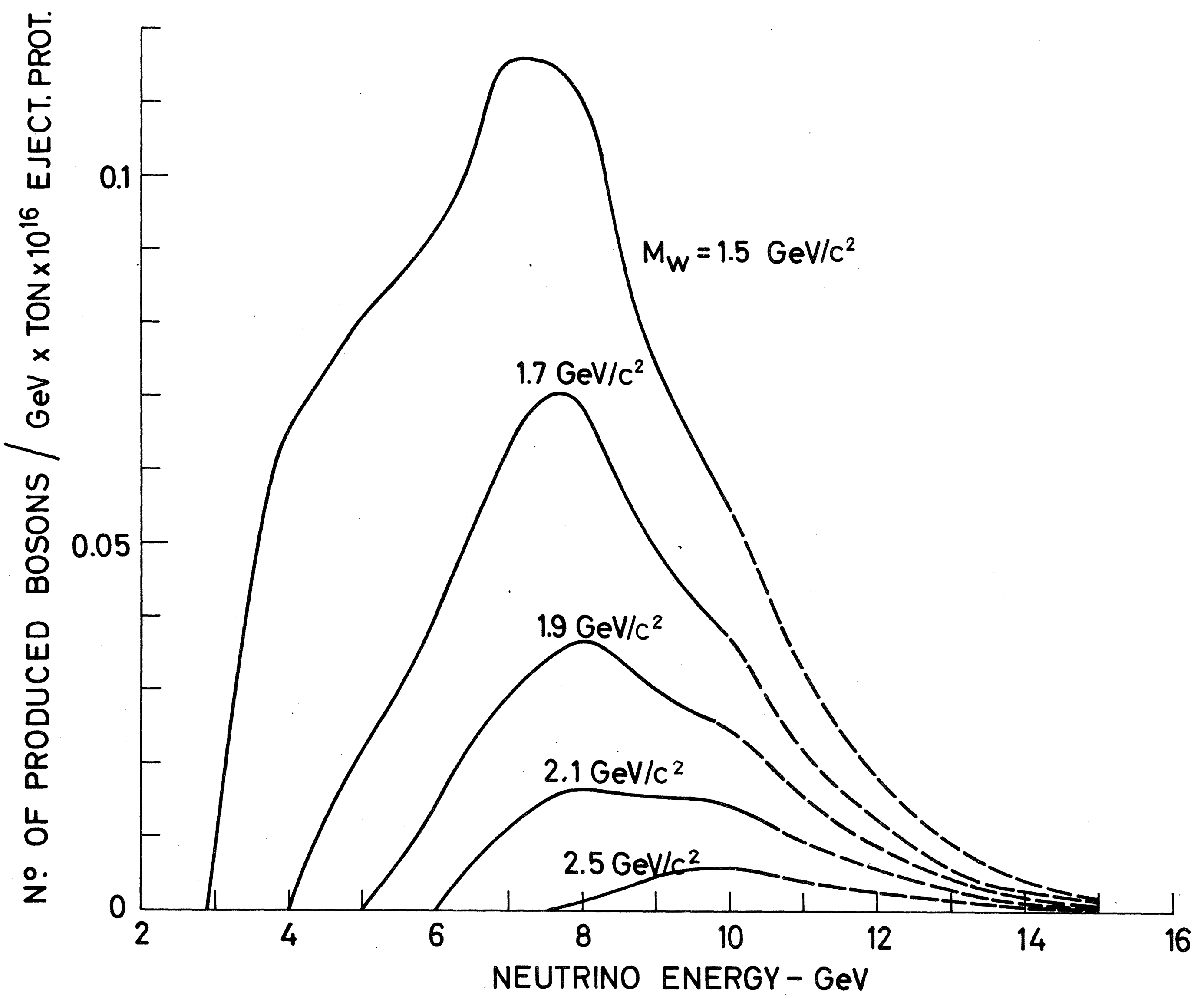

FLUX OF NEUTRINOS / GeV x M2 x EJECTED PROTON
10-4
4
2
10-5
4
2
10-6
4
2
10-7
4
2
10-8
Flux of bubble chamber
Flux of spark chamber
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
NEUTRINO ENERGY GeV

FIG.1



N° OF PRODUCED BOSONS / GeV x TON x 10^16 EJECT. PROT.
0.1
0.05
0
2
4
6
8
10
12
14
16
NEUTRINO ENERGY - GeV
M_W = 1.5 GeV/c²
1.7 GeV/c²
1.9 GeV/c²
2.1 GeV/c²
2.5 GeV/c²

FIG. 2a

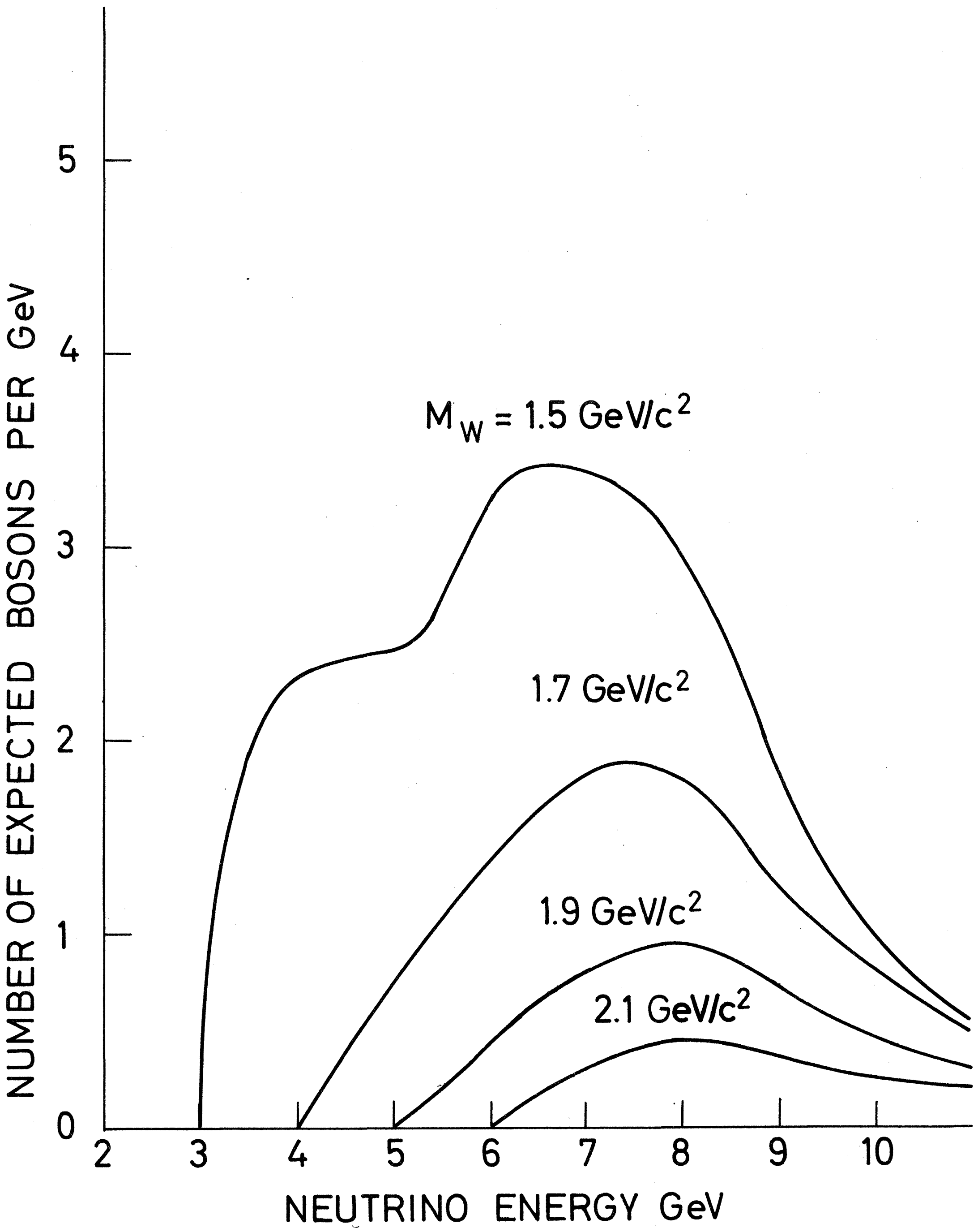
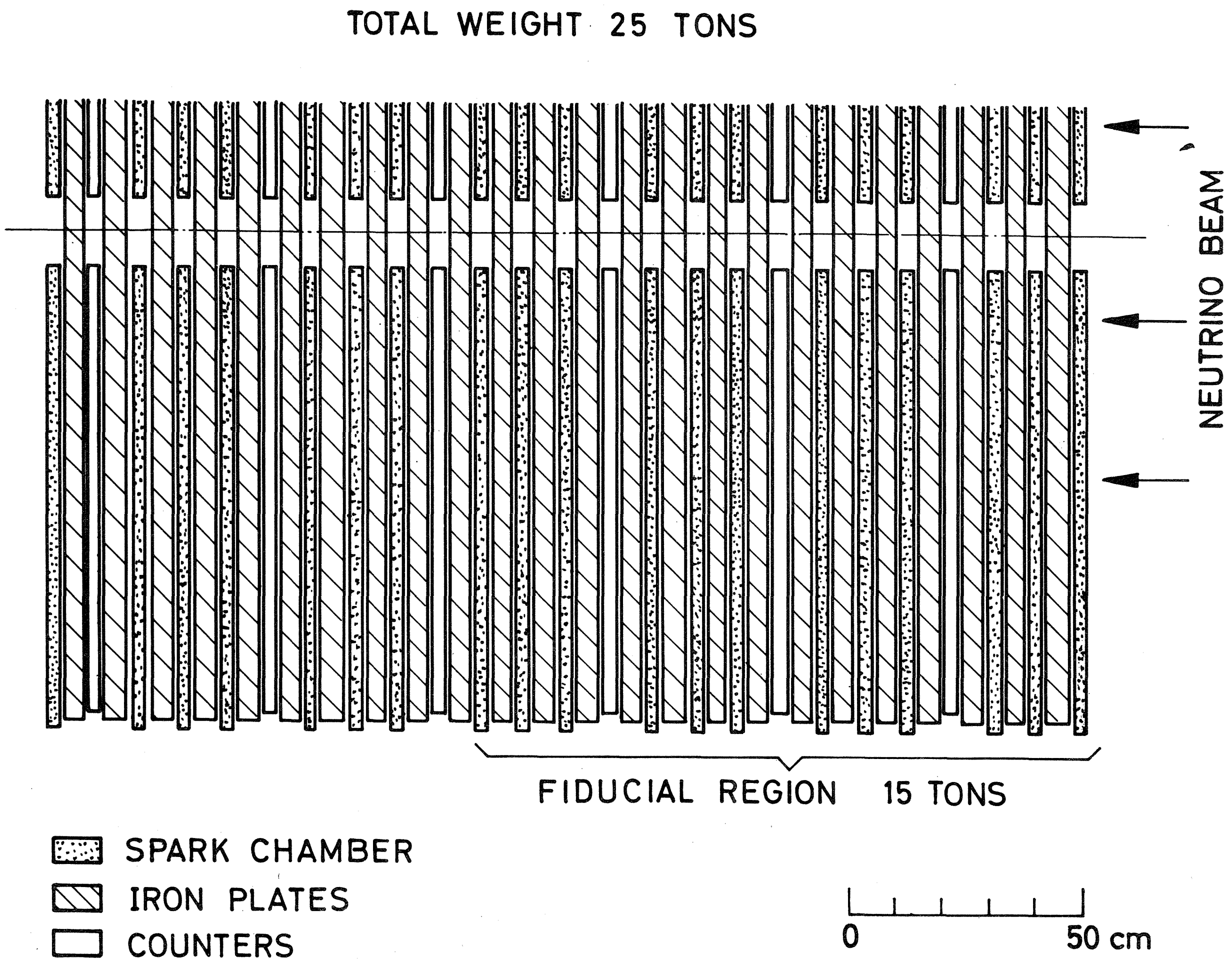


FIG. 2b

SIS/R/10716



MAGNETIZED IRON REGION

FIG. 3

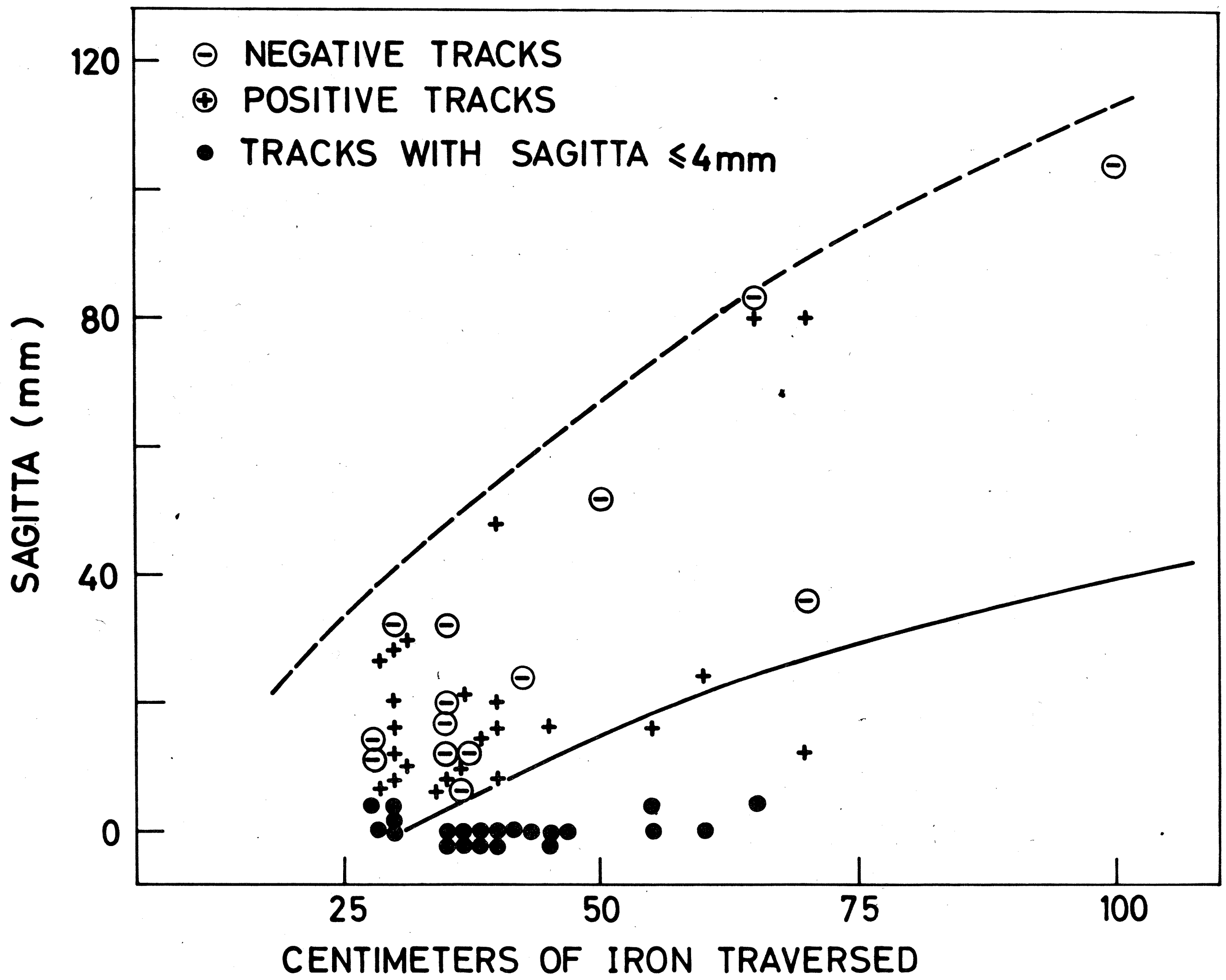

NEGATIVE TRACKS
POSITIVE TRACKS
TRACKS WITH SAGITTA ≤4mm
120
80
40
0
SAGITTA (mm)
25
50
75
100
CENTIMETERS OF IRON TRAVERSED

FIG.4

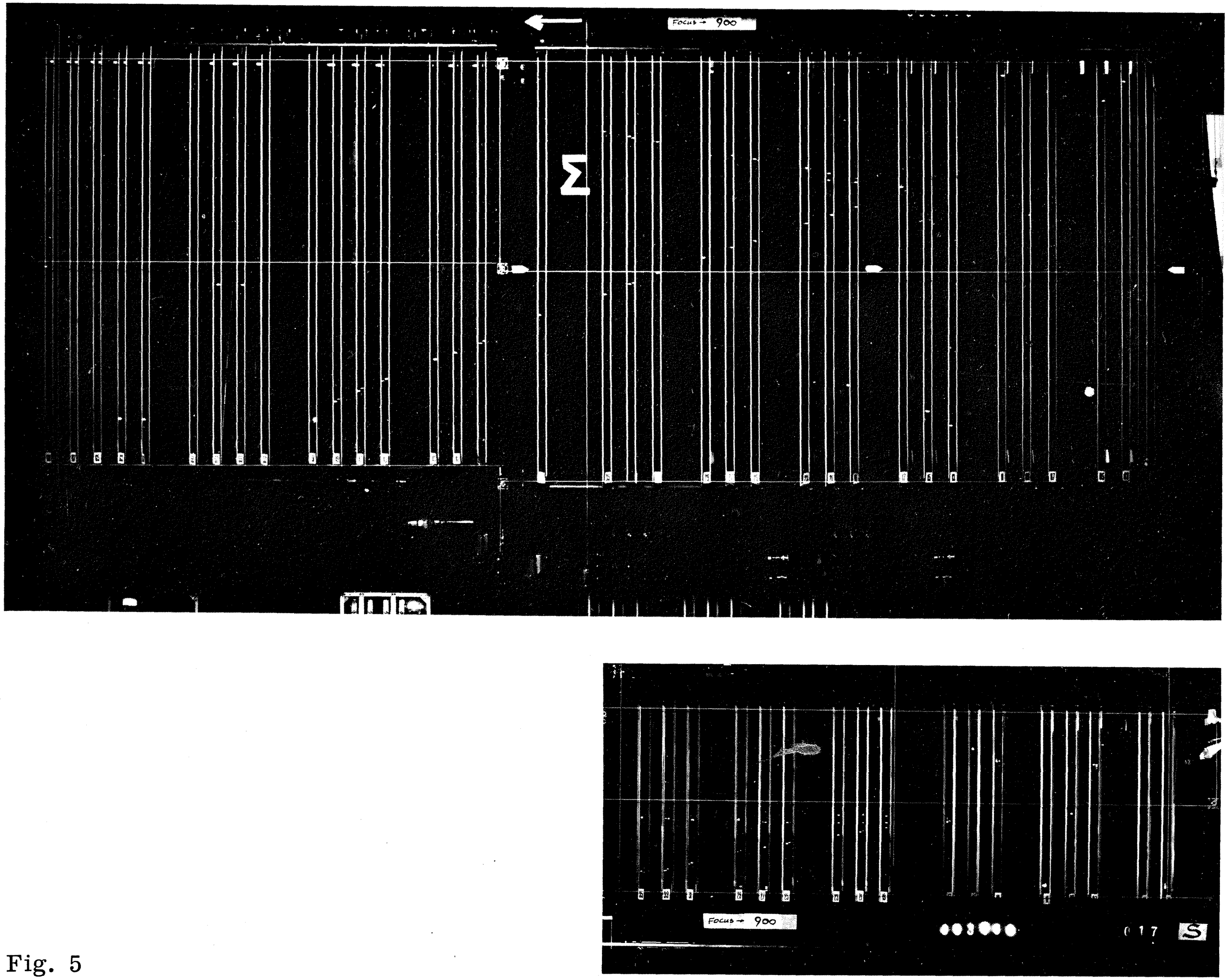


Fig. 5

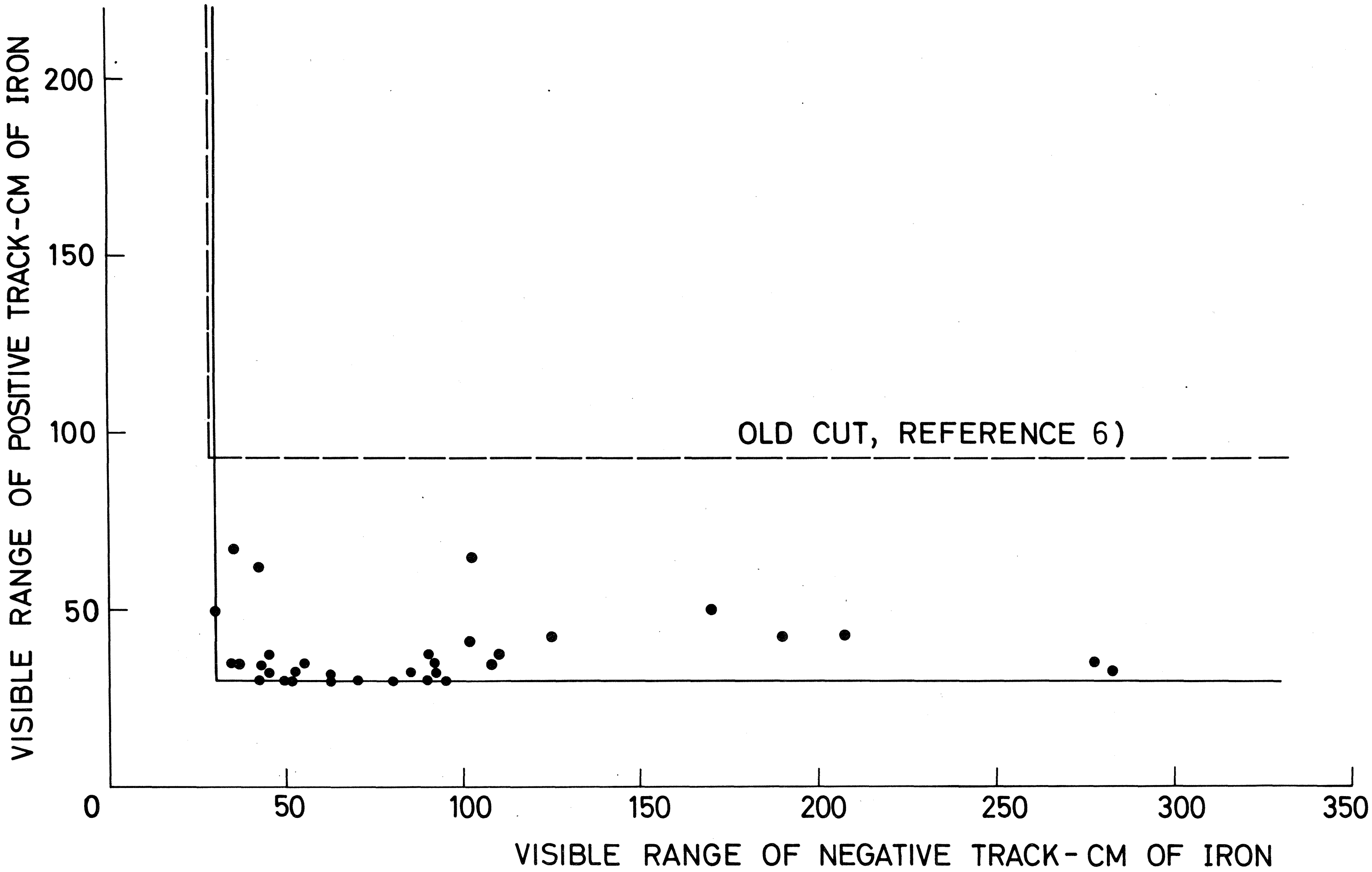
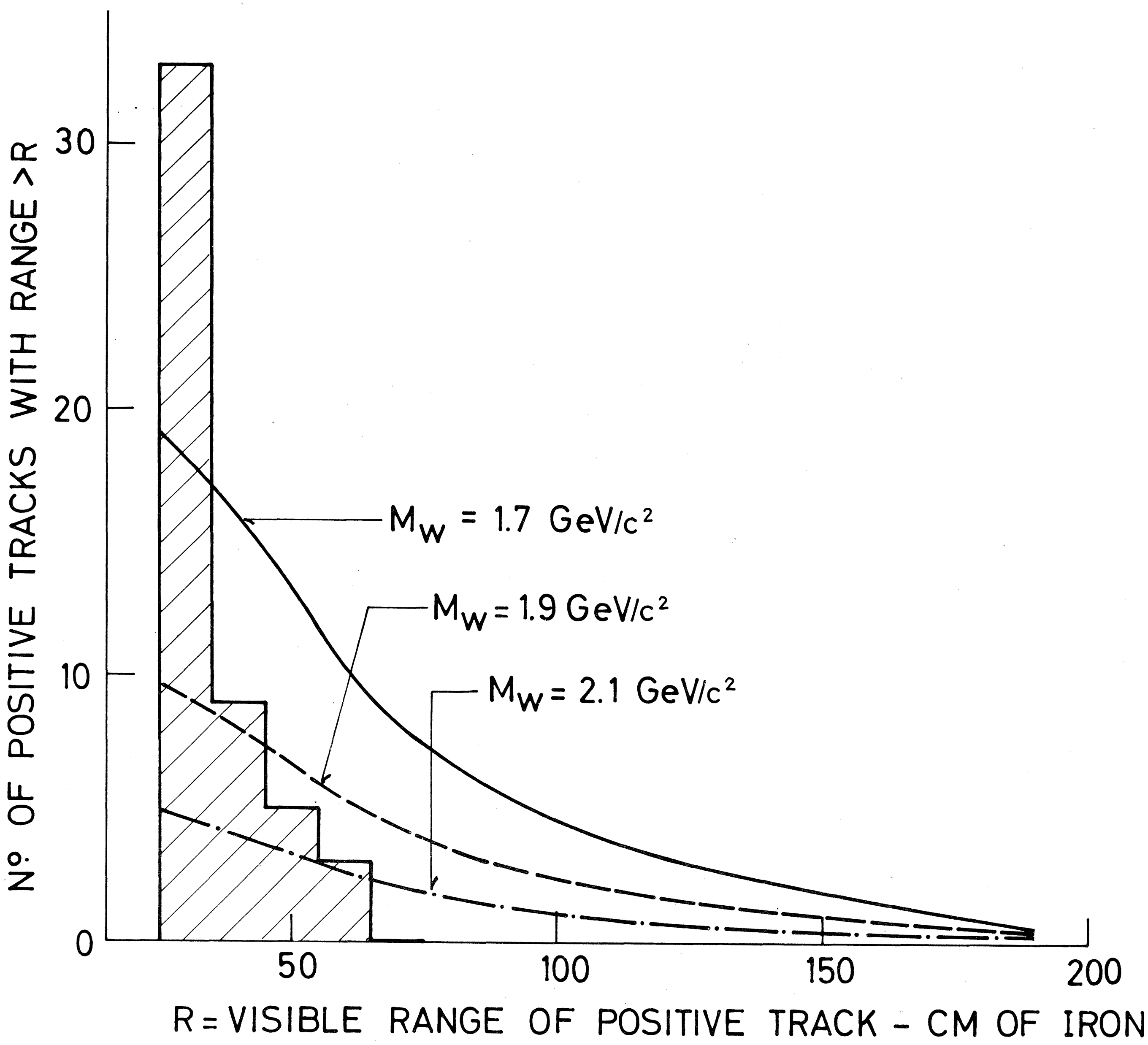

OLD CUT, REFERENCE 6)
VISIBLE RANGE OF POSITIVE TRACK-CM OF IRON
VISIBLE RANGE OF NEGATIVE TRACK-CM OF IRON
0
50
100
150
200
250
300
350

FIG. 6



N° OF POSITIVE TRACKS WITH RANGE >R
30
20
10
0
50
100
150
200
R = VISIBLE RANGE OF POSITIVE TRACK - CM OF IRON
M_W = 1.7 GeV/c²
M_W = 1.9 GeV/c²
M_W = 2.1 GeV/c²

FIG. 7

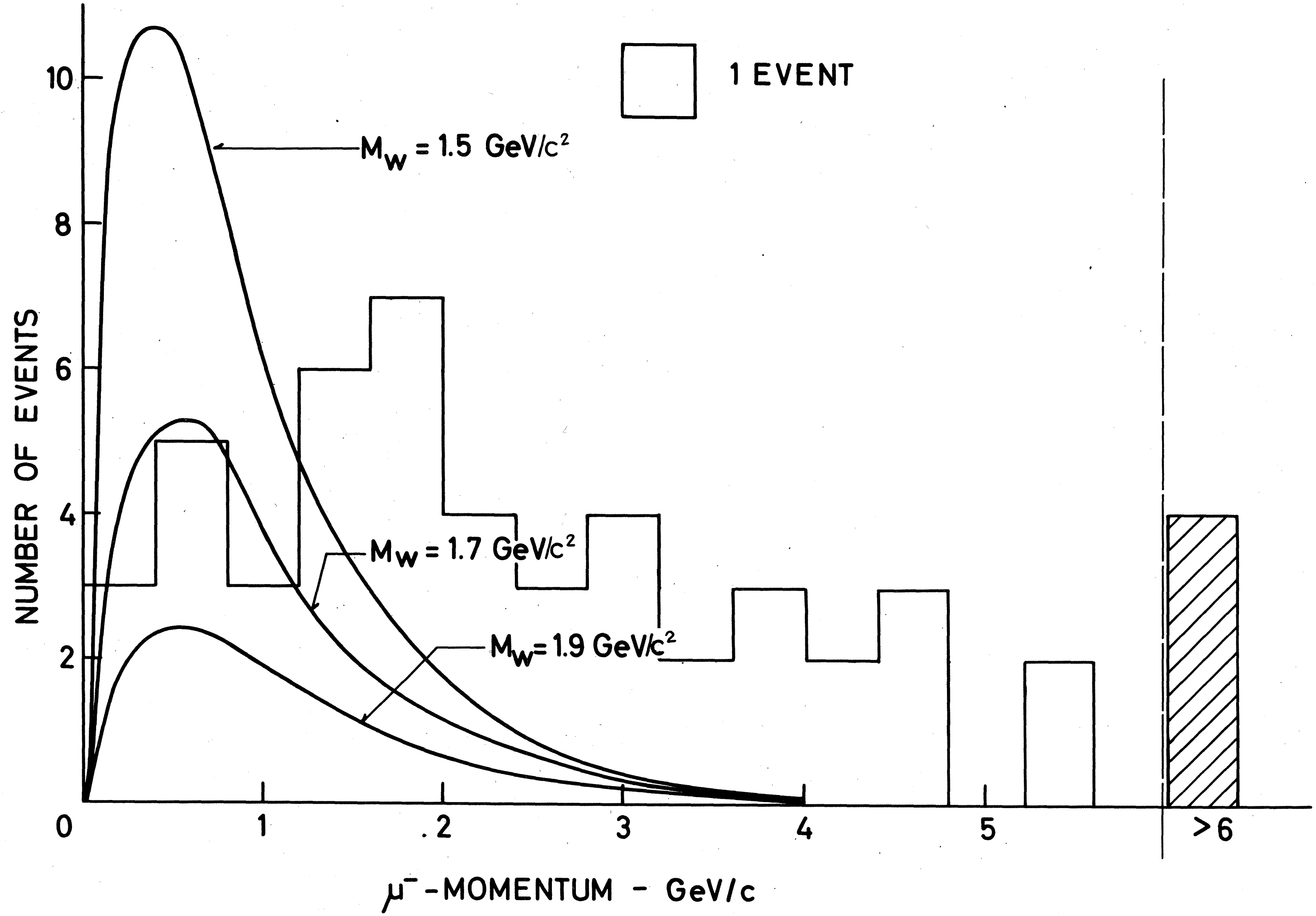

1 EVENT
M_W = 1.5 GeV/c²
M_W = 1.7 GeV/c²
M_W= 1.9 GeV/c²
NUMBER OF EVENTS
10
8
6
4
2
0
1
2
3
4
5
>6
μ^- -MOMENTUM - GeV/c

FIG. 8