Fermi National Accelerator Laboratory

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SEARCH FOR NEUTRAL, PENETRATING, METASTABLE PARTICLES PRODUCED IN THE SLAC BEAM DUMP*.

SLAC Experiment E-137†
Presented by J. Bjorken

Abstract

A search was made for neutral objects which might be produced by 20 GeV electrons incident on the SLAC beam dump, penetrate the downstream natural shielding, and decay upstream of an electromagnetic shower calorimeter. With about 30 coulombs of electrons dumped, no candidate events were found above an energy of ~2 GeV. Preliminary analysis implies the 95% confidence level limit on the product of mass and lifetime of light axion-like bosons decaying primarily into two photons to be greater than 0.8 keV-sec. Preliminary limits on photino parameters are also given.

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I. INTRODUCTION

In this note we report preliminary results of SLAC Experiment E-137. It was a search for neutral objects which might be produced by 20 GeV electrons incident on the SLAC beam dump, penetrate the downstream natural shielding, and decay upstream of an electromagnetic shower calorimeter. A primary motivation for this experiment was to search in a general way for axion-like, pseudo-Nambu-Goldstone-bosons. It turns out that the experiment sets useful bounds on the production of photinos, particles slightly more related to the subject matter of this workshop (They at least have the right spin). While the experiment is not a very sensitive probe of "conventional" massive neutrinos, there does exist a proposed follow-up search at Fermilab which is relevant to the topic of this workshop. That proposal, which has a "stage one" approval pending cost review and addition of more personnel, will make a similar search downstream of the Fermilab beam dump.

II. THE EXPERIMENT

We shall not enter here into a detailed discussion of the underlying phenomenology and motivation for experiment E-137, since it deals mainly with properties of conjectured axion-like entities. Suffice it to say that a search experiment as speculative as this one most probably will, in the unlikely case of a positive result, find something unanticipated and not what was proposed. For example, the first SLAC beam dump experiment[1] was motivated by possible existence of sequential heavy neutrinos, but became most relevant to axion searches[2]. Our experiment E-137, primarily motivated by axions, turns out to be relevant to photino searches.

We should mention features of this beam-dump experiment quite unique to SLAC. There is of course the high intensity of the primary beam, with a yield of approximately one coulomb of 20 GeV electrons delivered per (very good) day. The 1.6 μsec pulse length (180 pulses/sec) allows good cosmic-ray rejection. But most importantly the electrons, positrons, and photons which are produced in the dump (a large tank of water) have traverse momenta $\lesssim$ 20 MeV, much lower than in hadronic showers. This collimation, together with production mechanisms even more collimated, implies that beams of the sundry hypothetical X-particles will be well collimated. This in turn allows a long decay region without significant loss of acceptance. The E-137 apparatus is located about 380 m downstream of the dump, with 200 m of available decay path in front of the detector. This geometry is typical of hadron dump experiments with more than an order of magnitude higher energy.

Typical collimated production mechanisms are shown in Fig. 1. They include coherent photoproduction of bosons which could then decay into $\gamma\gamma$ or e^+e^-, bremstrahlung of bosons from electrons followed by decay into e^+e^-, or annihilation of positrons upon atomic electrons, either resonantly (again followed by e^+e^- decay) or nonresonantly into a pair of particles such as photinos. (The photinos purportedly decay into γ + goldstino).

A sketch of the experimental layout is shown in Fig. 2. The SLAC primary beam was transported through end-station A, site of the classic deep-inelastic electron-scattering experiments. At that point a remotely controllable target could be inserted into the beam to generate beam-associated "sky shine" background. Charged pions photoproduced in this target emerged into the airspace viewed by the detector, where they interacted, producing at the detector mainly muons (along with a few photons) coming from decaying pion secondaries. These were useful for timing purposes as well as for checking out and monitoring detector performance. During dump running, the target was of course removed, and the primary electron beam was transported, without steering, to the primary beam dump located in the berm at the downstream end of the SLAC research area.

The detector itself was an 8-layer, 8 radiation-length shower calorimeter. Each layer consisted of a hodoscope of 0.5 m x 1.5 m x 1cm scintillation counters, one radiation length of iron or aluminum converter, and a plane of multiwire proportional chambers. For the first phase of the experiment (~10 Coulombs dumped), each plane was a 2 x 3 mosaic of the 1m x 1m chambers used in the Fermilab experiment of Heisterberg et. al[3]. which measured ν_μ e elastic scattering; aluminum radiator was used. For the final phase of the experiment (~20 Coulombs dumped) new 3m x 3m chambers of similar design were installed, and the radiator was replaced by steel.

Clearly good angular resolution (<<50 mrad) was essential, and this capability was obtained from the multiwire proportional chambers. As shown in Fig. 3, the two cathode planes of the chambers consist of delay lines milled from copper-clad G10, one for horizontal readout, the other for vertical. Each delay line was tapped at several points (5 for the 1m x 1m chambers and 24 for the 3m x 3m chambers), and the cathode signals were fed into CCD's operating at 50 MHz. The CCD, acting as a fast shift register, subdivided an incoming pulse into 20 nsec segments, and stored the charge of each segment into consecutive CCD "buckets". When a trigger from the scintillator hodoscope occurred, the CCD clock rate was reduced to 20 MHz until the charges in the 36 CCD "buckets" could be read out and digitized in sequence by one ADC. This provided essentially analogue information on the cathode pulse size and shape, with a spatial resolution of ~3 mm for the 3m x 3m chambers and ~8 mm for the original 1m x 1m chambers.

Two triggering schemes were used in parallel. The first emphasized energy and required that the total pulse height (per plane) in three out of any four adjacent planes be above a preassigned threshold. The threshold shower energy for this trigger was 400 MeV. The second trigger, which emphasized directionality, was highly efficient even for horizontal muons, and required at least four out of eight 0.5m x 1.5m x 1cm scintillators in a given row (i. e. having the same transverse location in the apparatus) to fire. Here the discriminator thresholds were set well below minimum ionizing.

The experiment was proposed and approved in 1980. The first run, with 9.5 coulombs of electrons dumped, occurred in January of 1982. The final run, with 20.4 coulombs of electrons dumped, occurred in November and December of 1982. In February 1984 the scintillator hodoscope was calibrated in the SLAC test beam.

The running conditions turned out to be quite clean. With the 1/4" aluminum target inserted into the beam, the trigger rate was ~3 x 10^6/coulomb, dominated by low energy muons. The energy spectrum of these beam-associated triggers is shown in Fig. 4a. Essentially nothing is found above an energy of 3 GeV. With the target removed, the triggers were dominated by cosmic rays with a rate ~10^3/coulomb. The energy spectrum is considerably harder, as shown in Fig. 4b. Of course the angular distribution is much broader, leading to easy rejection of almost all these triggers. Examination of the time distribution of the low energy component of the spectrum does reveal a beam-associated signal. If the energy spectrum of that beam-associated signal is the same as for "target-in" data, there should be in the data sample less than (0.2) beam-associated triggers per coulomb with energy above 3 GeV.

A typical event as seen by the multiwire proportional chambers is shown in Fig. 5. The angular resolution for showers is difficult to estimate directly from the data because the incident direction is not known. Fits to the tracks give an estimated angular resolution of $\lesssim$10-20 mrad(FWHM), which, as will be seen in the next section, is very comfortable.

III. ANALYSIS and RESULTS

After the final run in late 1982, the data was scanned via computer-generated visual displays. Candidates of interest would be single or double showers which pointed in the general direction of the beam dump. It will come as no surprise that no signal was found. However, the limits we quote should still be regarded as preliminary pending completion of more work on estimating production cross-sections and efficiencies. Here we report on results from the final 20 Coulomb run. During that run ~23,000 triggers were written on tape. After cuts for energy (>1 GeV) and timing, ~6000 triggers survived. The overwhelming majority of these candidates were readily categorized as muons and cosmic ray showers. After the scan, where events which were observed to be grossly nondirectional were rejected, 189 events remained. These were measured, and after cuts requiring vertical and horizontal angles less than 300 mrad, only 24 events remained. These are shown in Fig. 6. One sees that only one event lies within a reasonable fiducial region of horizontal angle less than ±100 mrad and vertical angle less than 30 mrad (the approximate horizon of the shielding berm as seen by the detector). Just from the multiwire proportional chamber data this surviving event may be regarded as pointing toward the dump. But it has too low an energy; 2 GeV was the optimistic threshold cut already suggested in the proposal. The scintillator data implies that this event is caused by a muon which radiated a photon in the front portion of the detector and penetrated the entire eight planes. We thus end up with no convincing candidate events.

A second line of analysis was also used which avoids possible subjectivity associated with the visual scanning. (However, in a search experiment such as this, and with the complex topology of the typical cosmic ray triggers, we believe there is no substitute for making the full scan.) In this alternative analysis, we required that the observed energy exceed 3 GeV, that the signal be in time with the beam, and that at least 2/3 of the energy be within a single scintillator row, as would be expected for almost all horizontal showers. Only 36 events passed these criteria, and the event sample overlapped the preceding sample of 189 obtained from the visual scan, again leading to no candidate events.

As already mentioned, we have not completed the full analysis, especially with regard to questions of resolution and efficiency, and to calculations of yields for a variety of conjectured particles. We here restrict ourselves to two reasonably topical candidate phenomena: light axions and photinos.

A) Axions

We assume the axion is photoproduced via the Primakoff effect, decays predominantly into two photons, and is of low mass (<30 MeV). Under these circumstances the experimental yield depends only upon lifetime and mass, and our preliminary estimate is

$$M_X \tau_X > 0.8 \text{ keV-sec.} \qquad \text{(preliminary; } M_X < 30 \text{ MeV; 95\%CL)}$$

In this estimate we have conservatively assumed the threshold energy for detection to be 3 GeV. The expected energy spectrum is proportional to the track-length distribution of photons in the water beam dump. This was computed via the EGS shower simulation program[4] (Fig. 7), and one sees that ~30% of the expected axion flux above 1 GeV actually lies above 3 GeV. Thus our quoted limit (which scales with the square root of the flux) is not inordinately sensitive to the cut in energy.

For a given mass, the axion lifetime must of course be long enough for the particle to penetrate the shielding berm before decaying. However, in that edge of the parameter domain, previous beam dump experiments are at least as sensitive as this experiment.

The classical Peccei-Quinn-Weinberg-Wilczek (PQWW) axion[5] has by now been convincingly ruled out experimentally[6]. The sensitivity of this experiment to a PQWW axion[7] is marginal, and is shown in Fig. 8. Were the PQWW axion to exist, experiment E-137 might have seen it. But E-137 never could have ruled out the whole mass range of 200-400 keV which was of interest two or three years ago[8]. However, it still remains important to search for generic axion-like entities (i. e. pseudo-Nambu-Goldstone-bosons) associated with perhaps some totally unanticipated spontaneous symmetry-breaking scheme remote from present experience. The present result most improves previous bounds on parameters if the axion-like entity is not coupled to currents containing known lepton or quark degrees of freedom.

B) Photinos

Some phenomenological supersymmetry schemes[9] have posited a light photino decaying into photon and goldstino. In this experiment, photino pairs may be produced in e^+e^- annihilation (on atomic electrons) via scalar-electron (selectron) exchange. The yield thus depends not only on photino mass and lifetime but also - quite sensitively - to the selectron mass[10]. The photino lifetime in turn depends[11] upon the scale $\Lambda=\sqrt{d}$ of supersymmetry breaking, conjectured to perhaps be in the range of 100 GeV to 10 TeV.

The positron spectrum was again computed via EGS. When convoluted with production cross-section and decay lifetime our estimated limit from this experiment is

$$\frac{\mu^3}{M^2\Lambda^2} < 6 \text{ mm. } (95\% \text{ CL})$$

where
μ = photino mass <<30 MeV
M = selectron mass
Λ = supersymmetry breaking scale

The condition that the photino survives a journey through the shielding berm must also be met. This is, roughly

$$\frac{\mu^3}{\Lambda^2} \geq 60 \text{ eV}$$

The opacity of these results must be even greater to the reader than to this author; a more transparent way of viewing them is shown in Fig. 9. To our knowledge the region excluded by this experiment has not been covered by previous measurements.

IV. FUTURE PLANS

The running of SLAC experiment E-137 is complete. Final analysis should be finished within a few months, with the remaining work consisting of refining the estimates of production cross-sections and detection efficiencies.

Meanwhile a new proposal for a similar experiment at Fermilab has been submitted and in principle approved in November 1983, pending an increase in group size and an acceptably small cost estimate. This experiment, E-635, is similar in concept to the SLAC experiment as well as to previous dump experiments such as carried out by the CHARM collaboration[12]. In brief, the E-137 apparatus, supplemented by a solid iron toroid magnet and some extra radiation lengths of electromagnetic calorimetry, will be placed 300 m downstream from Lab C, where resides the large neutral-current experiment of F. Taylor et. al. This locale is about 560 m from the new Fermilab beam dump. The purpose of the experiment is again to search for low mass (<1-3 GeV) neutral particles which might be produced in the hadronic shower and which might decay in the 300 m region upstream of the detector. The signature for the trigger will be either electromagnetic energy deposition or a dimuon with vertex in the decay volume. A candidate particle might be an axion-like pseudo-Nambu-Goldstone-boson X of mass $M_X \sim 200$ MeV - 2 GeV decaying into dimuons, with decay constant $F_X \sim 10^4$ TeV. For such a particle we estimate that the sensitivity (per proton dumped) is a factor >30 better than previous experiments such as the CHARM or (thus far unpublished) CDHS experiments. The experiment will be sensitive to other decay modes such as $\gamma\gamma, e^+e^-, \mu^{\pm}e^{\mp}$, etc. It will of course also be a sensitive search for heavy neutrinos, and will hopefully be ready well before the beam dump (ca. 1986-1987).

V. ACKNOWLEDGMENT

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FIGURE CAPTIONS

Fig. 1. Collimated production mechanisms for neutral bosons: (a) Primakoff photoproduction, (b) bremsstrahlung from electrons, (c) resonant annihilation of positrons on atomic electrons, and (d) nonresonant production (by positrons on atomic electrons) of photino pairs via selectron exchange.

Fig. 2 Layout of SLAC experiment E-137.

Fig. 3. Schematic of the delay-line multiwire proportional chambers and the CCD electronics.

Fig. 4. Energy spectrum of experimental triggers as determined from total scintillator pulse height: (a) beam-associated skyshine with removable Al target in beam, and (b) beam dump running with target removed.

Fig. 5. Typical event as seen by the 3m x 3m multiwire proportional chambers. On the left is the top view of the chambers. The ticks locate the taps on the delay line. The bold-faced region is that portion of the chamber read by the CCD's which is shown expanded on the right, where the observed pulse shape is exhibited. The peak values have been plotted on the layout at the left.

Fig. 6. Scatter plot of the angular distribution of candidate events. Only the bold-faced point has energy >3 GeV; the triangular point has energy >2 GeV, but unambiguously does not point toward the dump. The three points apparently emergent from below the horizon are actually cosmic rays entering the detector from the rear.

Fig. 7. Track length distribution of photons in the dump whose emission angle subtends the E-137 detector. This distribution is directly proportional to the flux of low mass hypothetical axions into the detector.

Fig. 8. Preliminary limits on hypothetical axion properties from experiment E-137. It is assumed the axion decays predominantly into $\gamma\gamma$.

Fig. 9. Preliminary limits on photino properties from experiment E-137. The dotted region of the boundaries are as yet only roughly estimated and will soon be refined.

Fig. 10. Layout of Fermilab beam dump experiment E-635: (a) general plan, and (b) detailed layout. The two portions of the experiment are separated by about 20 m.

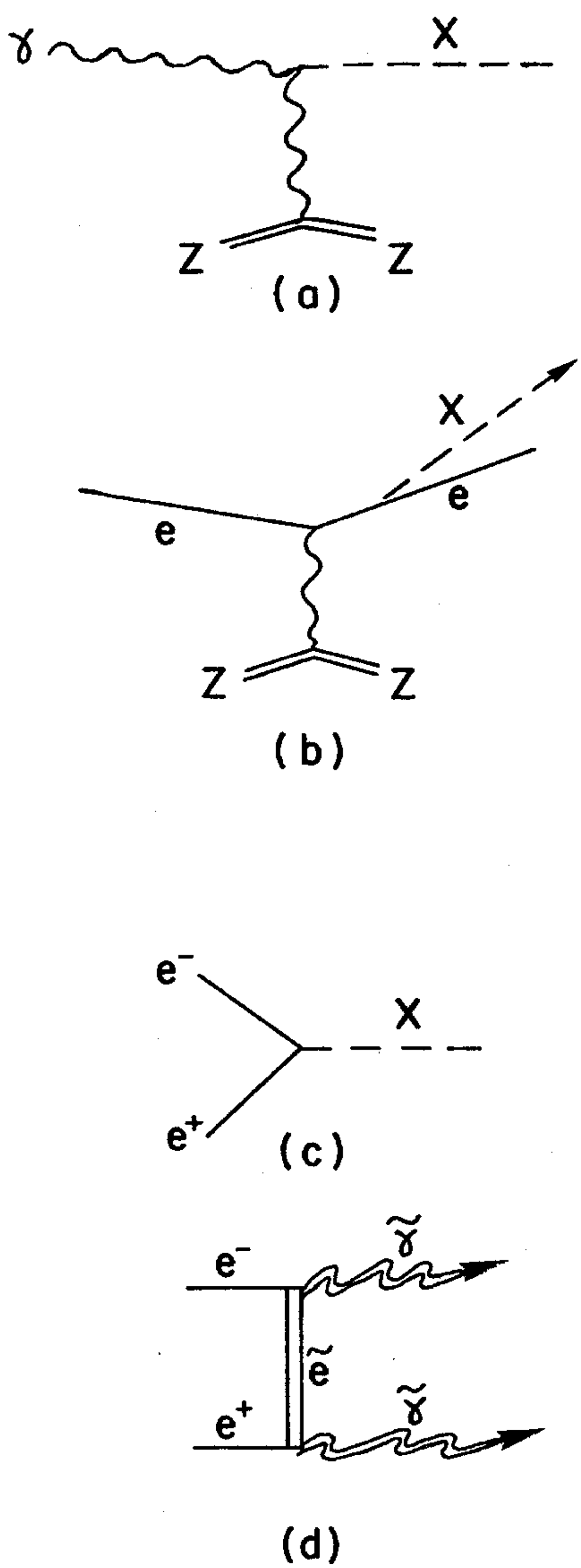
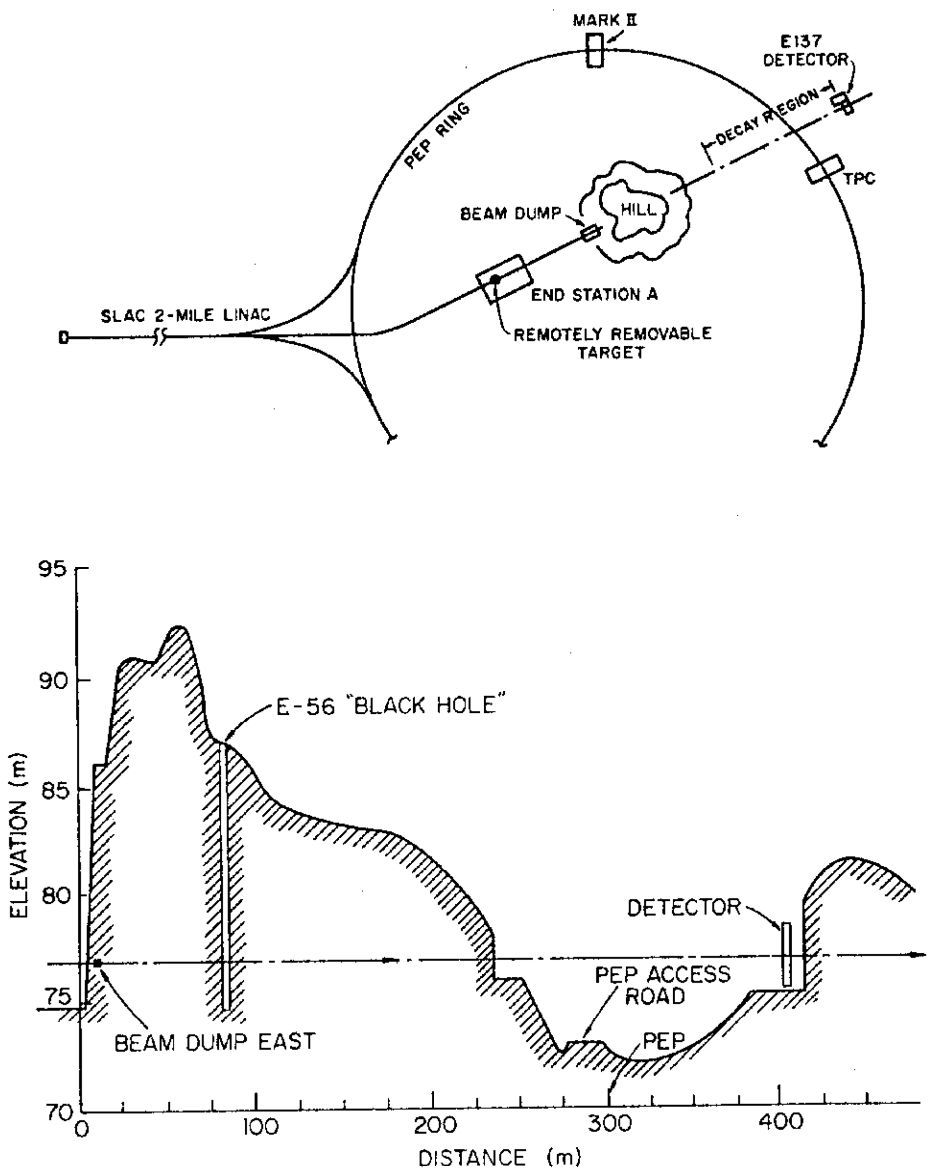


Figure 1



MARK II
E137
DETECTOR
PEP RING
DECAY REGION
TPC
HILL
BEAM DUMP
END STATION A
SLAC 2-MILE LINAC
REMOTELY REMOVABLE
TARGET
95
90
85
80
75
70
ELEVATION (m)
E-56 "BLACK HOLE"
DETECTOR
PEP ACCESS
ROAD
PEP
BEAM DUMP EAST
0
100
200
300
400
DISTANCE (m)

Figure 2

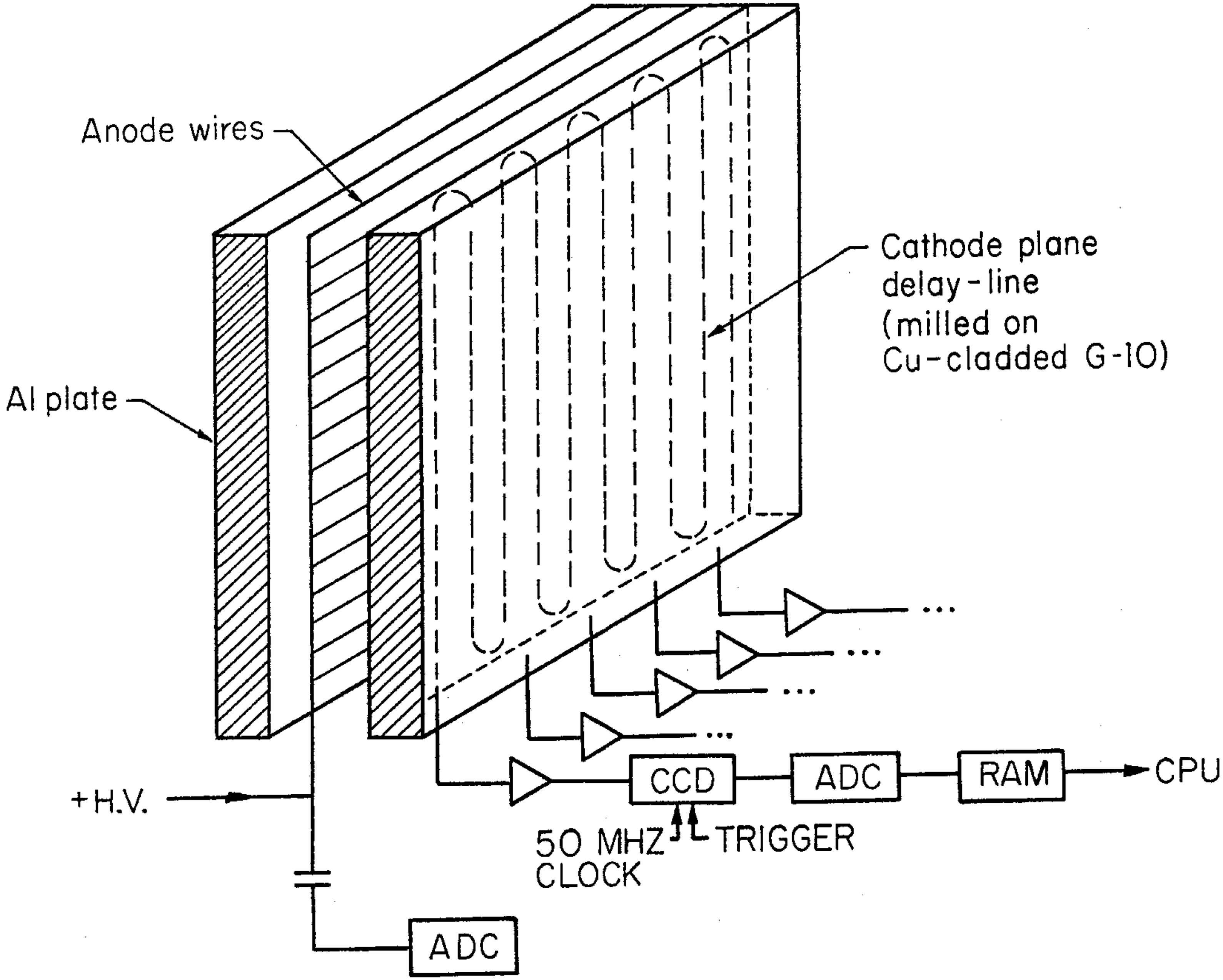
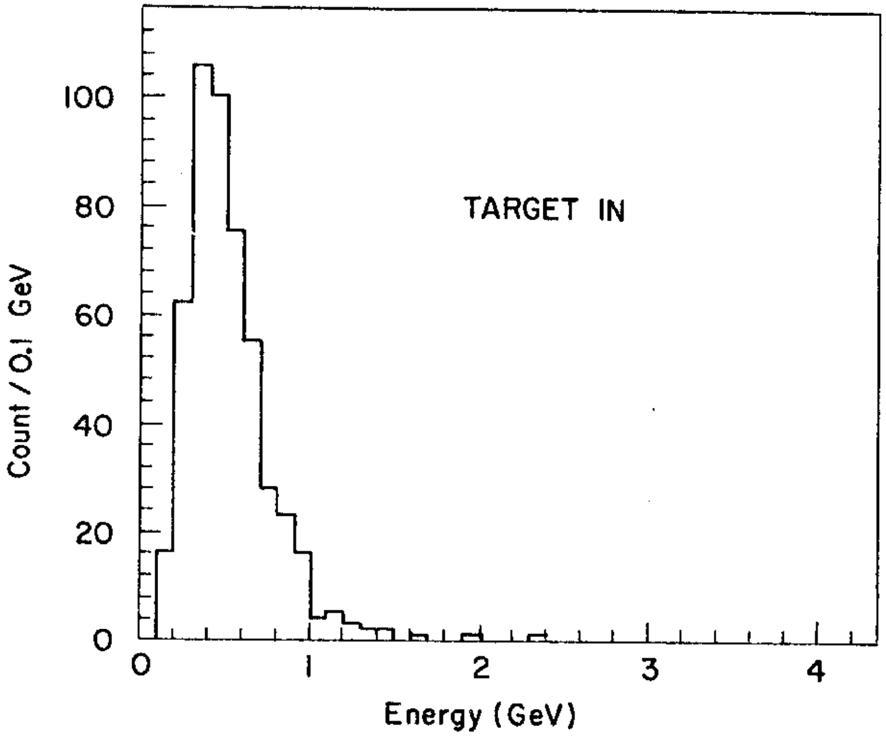

Anode wires
Cathode plane
delay-line
(milled on
Cu-cladded G-10)
Al plate
+H.V.
CCD
ADC
RAM
CPU
50 MHZ
CLOCK
TRIGGER
ADC

Figure 3


TARGET IN
Count / 0.1 GeV
Energy (GeV)
0
20
40
60
80
100
0
1
2
3
4

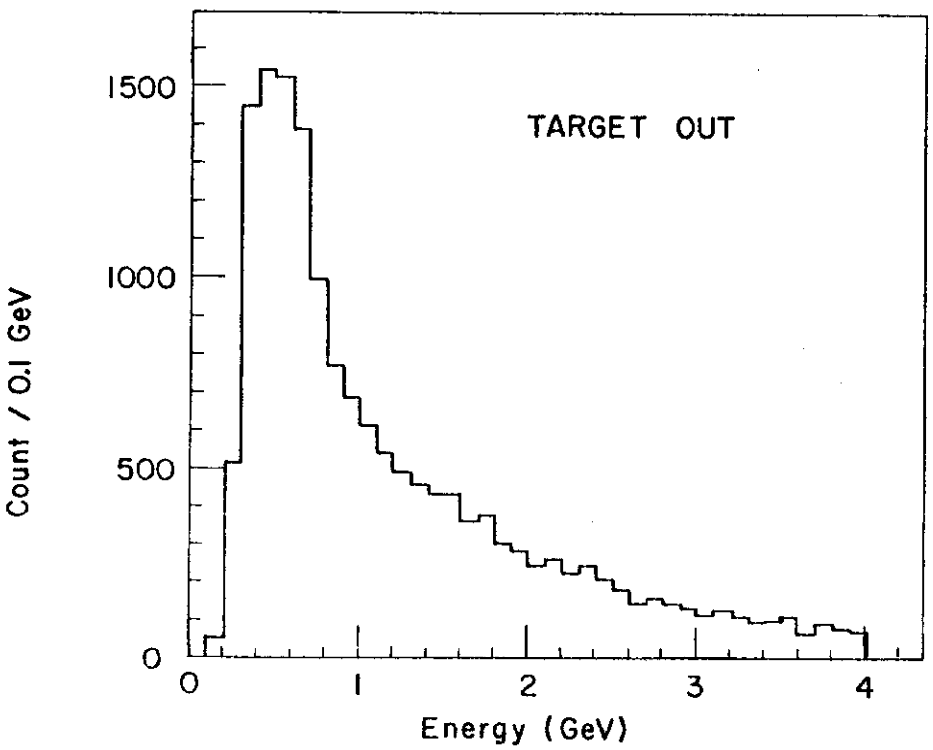

TARGET OUT
Count / 0.1 GeV
Energy (GeV)
0
500
1000
1500
0
1
2
3
4

Figure 4

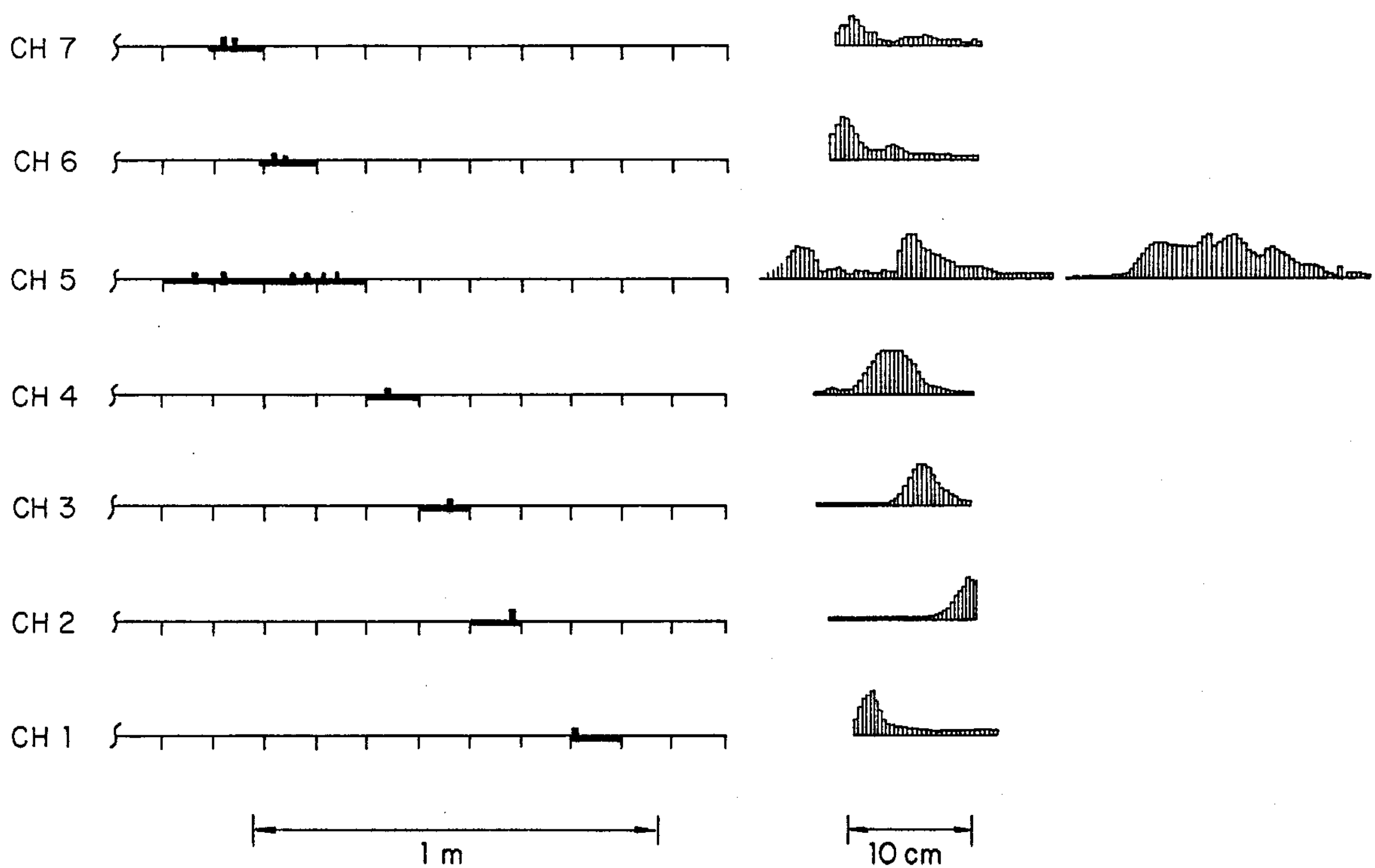
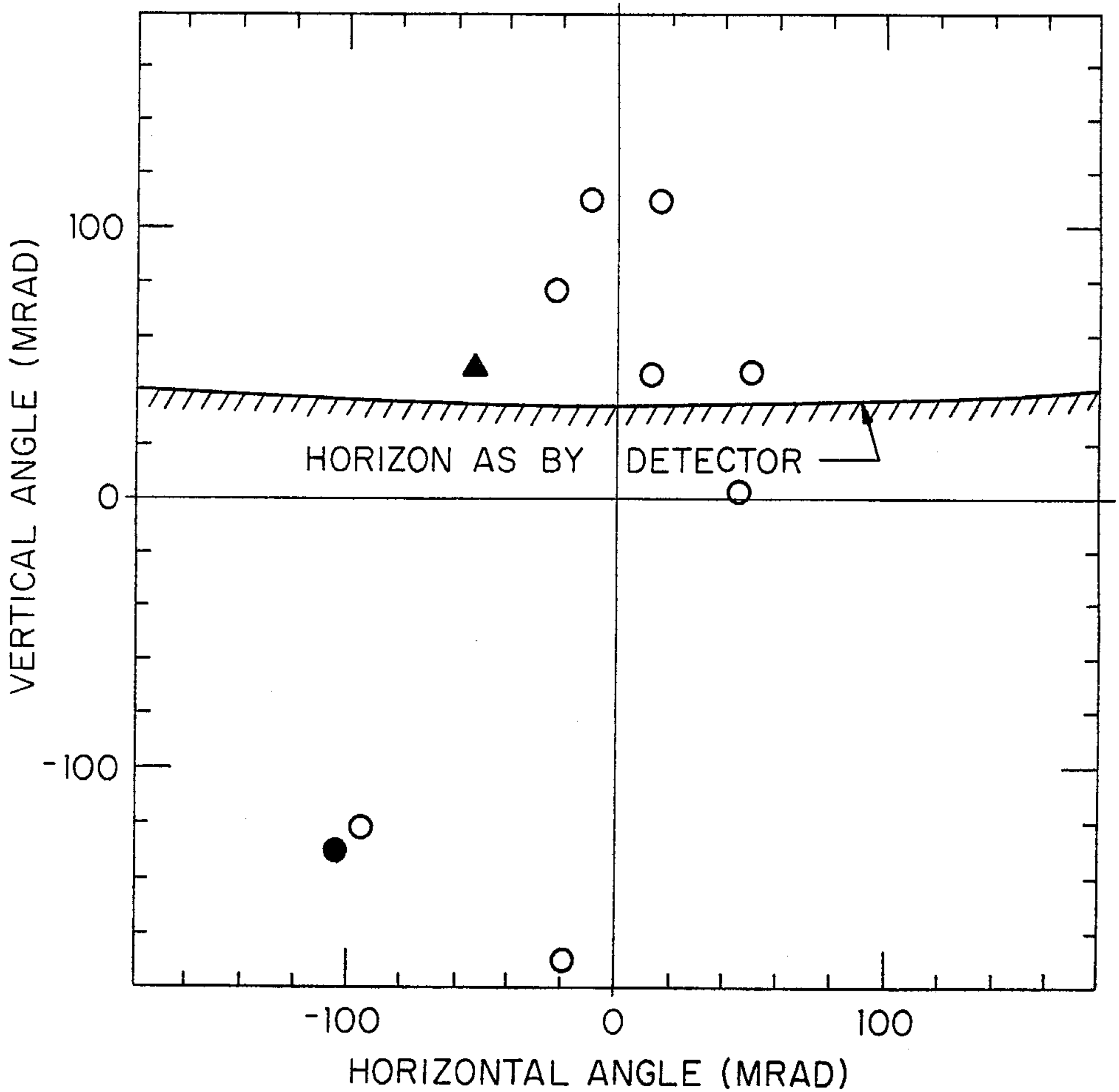
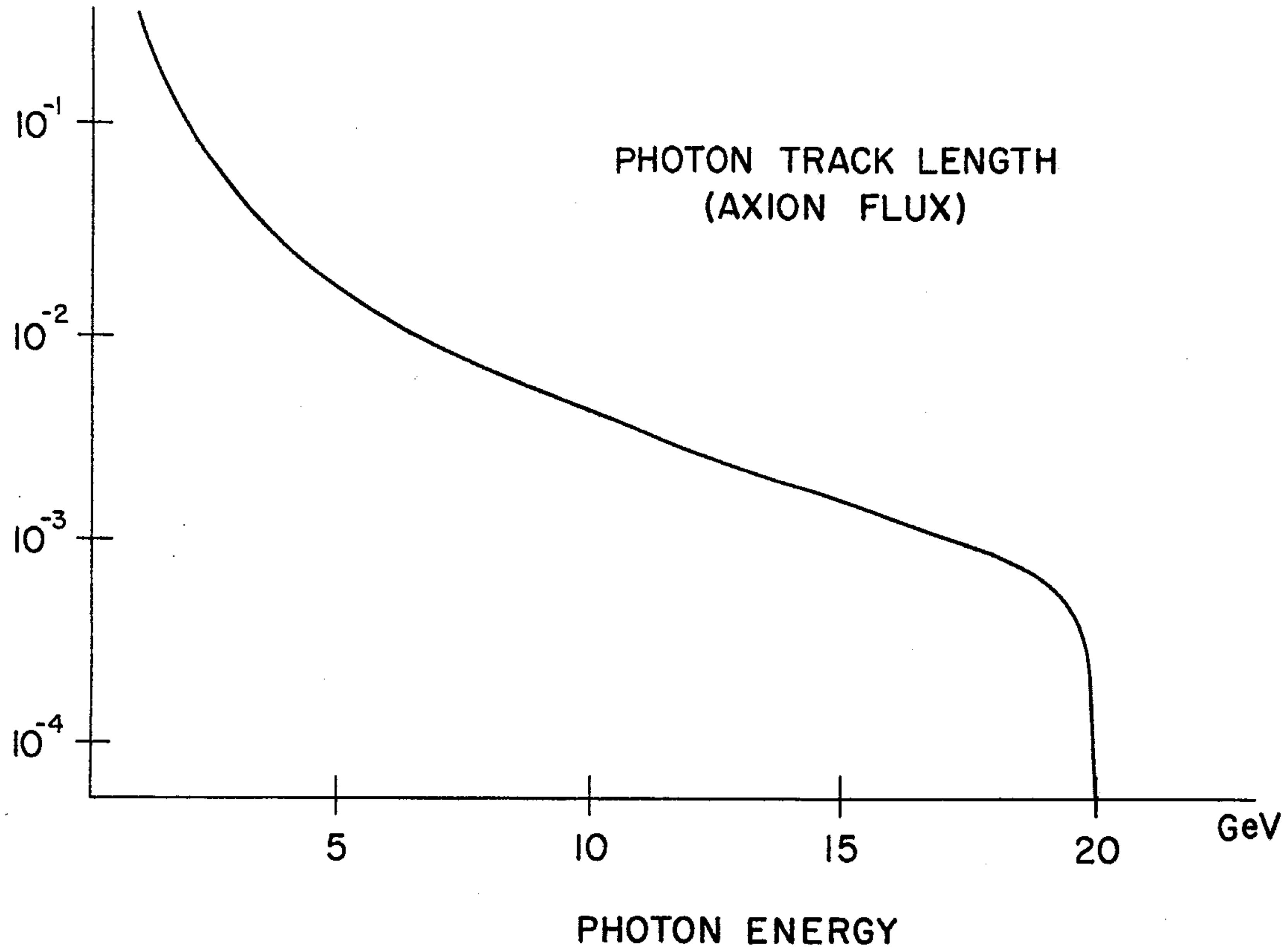


Figure 5



100
0
-100
VERTICAL ANGLE (MRAD)
HORIZON AS BY DETECTOR
-100
0
100
HORIZONTAL ANGLE (MRAD)

Figure 6



PHOTON TRACK LENGTH
(AXION FLUX)
10-1
10-2
10-3
10-4
5
10
15
20
GeV
PHOTON ENERGY

Figure 7

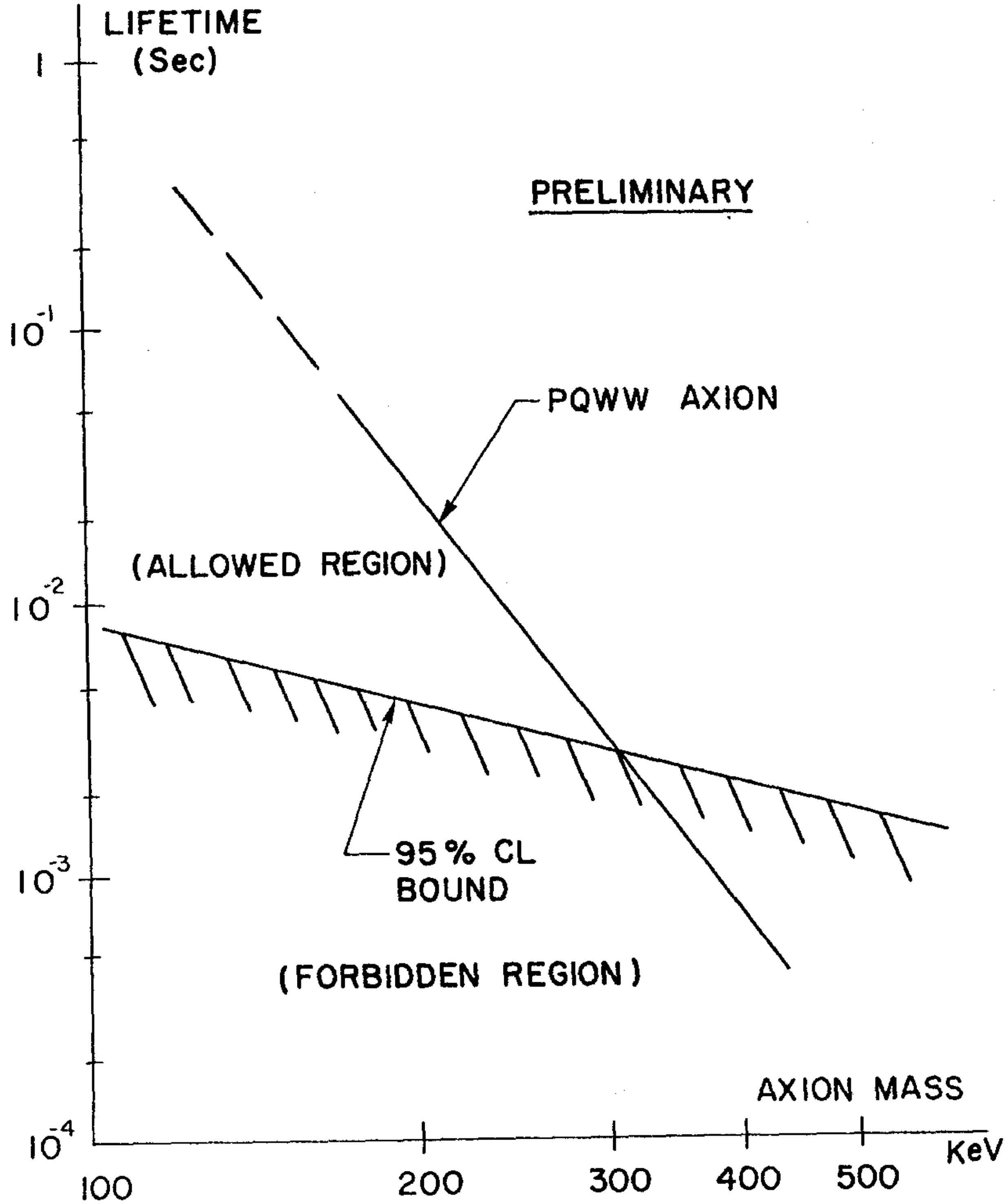
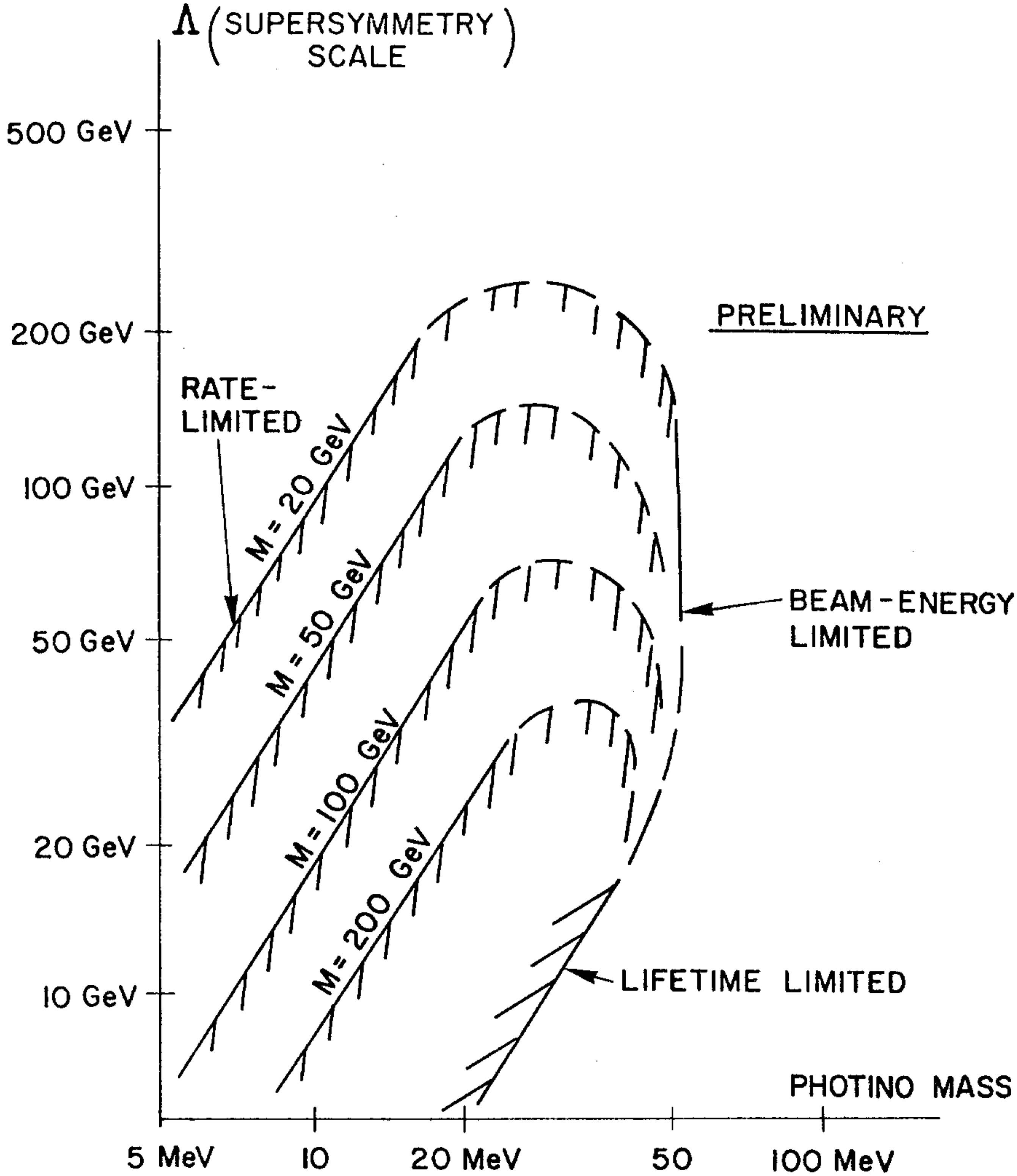

LIFETIME
(Sec)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PRELIMINARY
PQWW AXION
(ALLOWED REGION)
95% CL
BOUND
(FORBIDDEN REGION)
AXION MASS
KeV
100
200
300
400
500

Figure 8



Λ (SUPERSYMMETRY SCALE)
500 GeV
200 GeV
100 GeV
50 GeV
20 GeV
10 GeV
PRELIMINARY
RATE-LIMITED
M = 20 GeV
M = 50 GeV
M = 100 GeV
M = 200 GeV
BEAM-ENERGY LIMITED
LIFETIME LIMITED
PHOTINO MASS
5 MeV
10
20 MeV
50
100 MeV

Figure 9

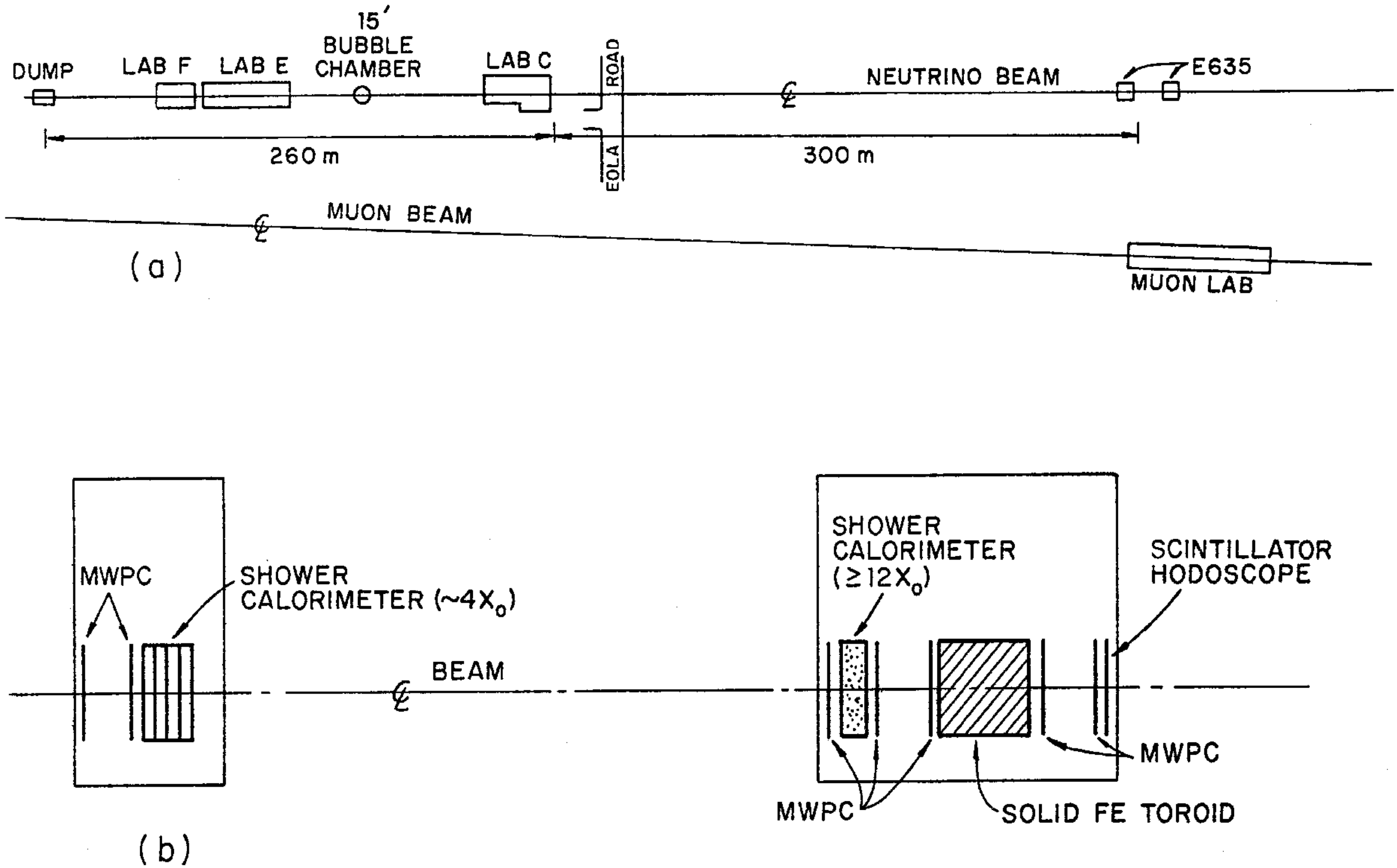

15′
BUBBLE
CHAMBER
DUMP
LAB F
LAB E
LAB C
ROAD
EOLA
NEUTRINO BEAM
E635
260 m
300 m
MUON BEAM
MUON LAB
(a)
MWPC
SHOWER
CALORIMETER (~4X₀)
BEAM
SHOWER
CALORIMETER
(≥12X₀)
SCINTILLATOR
HODOSCOPE
MWPC
MWPC
SOLID FE TOROID
(b)

Figure 10