NAL Proposal No. 98

Correspondent: Luke W. Mo
The University of Chicago
Tel: (312) 667-4700, X-8745/8628
(After December 19, 1970): 753-8745/753-8628

# PROPOSAL
for
Muon-Proton Inelastic Scattering Experiment
at the
National Accelerator Laboratory

Submitted by

H. L. Anderson, N. E. Booth[*], L. W. Mo, L. C. Teng[**] and S. C. Wright
The Enrico Fermi Institute and the Department of Physics
The University of Chicago, Chicago, Illinois 60637

and

T. Kirk, F. M. Pipkin, J. Sanderson, L. Verhey, and Richard Wilson
Department of Physics
Harvard University, Cambridge, Massachusetts 02138

[*] Now at Oxford University, England

[**] NAL

# Table of Contents

Table of Contents (continued)

# MUON-PROTON INELASTIC SCATTERING EXPERIMENT

Muon-proton inelastic scattering in the energy range of 100-300 GeV, attainable only at the National Accelerator Laboratory, is expected to reveal exciting information about the structure of nucleons. After the surprising results given by the SLAC electron-proton scattering experiment,[1] which demonstrated that the form factors in the deep inelastic region decrease very slowly as the momentum transfer $q^2$ increases, great interest has been aroused among theoreticians and much effort directed at attempts to understand these experimental data. This enthusiasm is reflected in the fact that many theoretical papers on the subject are appearing in the literature, and four experimental proposals have been submitted to the National Accelerator Laboratory to do the inelastic muon scattering experiment.[2]

In view of the size of the equipment, manpower, and financial resources required to do this most fundamental experiment in high energy physics, the proponents of the NAL Proposals No. 29 and No. 33 agreed to work together to build a muon facility at the National Accelerator Laboratory, and to do the muon scattering experiment as one collaboration. The University of Chicago has proposed to contribute their 450 MeV Cyclotron as the momentum analyzing magnet for the experiment. This particular proposal immediately makes the muon facility very attractive without invoking any major expenses. Above all, the physicists from the University of Chicago and Harvard

University are experienced in experimental physics and instrumentation development. The majority of them are experienced also in electron- and muon-proton scattering experiments. By joining forces they are confident that in collaboration they can successfully carry out the muon inelastic scattering experiment at NAL. Because of these developments, we submit this new joint proposal on muon inelastic scattering at NAL for new consideration by the Laboratory.

## 1. Description of the Experiment

The experiment we propose to do at the National Accelerator Laboratory with high energy muons is to study the following reaction

$$\mu^- + p \rightarrow \mu^- + \text{Hadrons}.$$

A beam of muons, with an intensity of up to $10^7$/pulse over an area of 4" x 2", as designed by T. Yamanouchi, is scattered by a 1-meter long liquid hydrogen target. The scattered muons will be detected by a magnetic spectrometer, which consists of a large volume bending magnet - the Chicago Cyclotron magnet, a set of proportional wire chambers and wire spark chambers with FET (field-effect transistor) or magnetostrictive readout, and various types of scintillation counters. Since the field of spark and proportional chamber technology is developing very rapidly, we will postpone our decision on chamber types until February 1971. Identification of the scattered muons will be furnished by a 2 - 4 meter thick steel hadron absorber. The momenta of charged hadrons produced in the collision will also be determined in this spectrometer. Gammas from neutral pions produced in the forward direction will be converted by a 6 radiation length thick lead radiator, and their shower multiplicity will be measured in a spark chamber. No other special efforts are made to identify the fast particles.

Initially, the experiment will be performed with muons of energy 100 GeV. Measurements will be made with the momentum transfer squared, $q^2$, in the range of 0.5 to 30 $(GeV/c)^2$; and the energy loss of the muon, $\nu$, in the range of 20 to 90 GeV. The liquid hydrogen target is movable in position. Experiments with the target located outside the magnet will specify the forward going particles with high precision; with the target located inside the magnet a complete measurement of the charged hadrons will be possible. These experiments will be extended to the highest available muon energy, ~ 300 GeV, at NAL. Also, the whole experiment will be repeated with a liquid deuterium target.

From these proposed measurements, the following information over a wide range of kinematical variables can be obtained:

1) The inelastic form factors, $W_1(q^2, \nu)$ and $W_2(q^2, \nu)$, of proton and neutron;
2) The multiplicity and momentum spectra of the charged hadrons in muo-production as a function of the kinematic variables $(q^2, \nu)$;
3) Partial information on the multiplicity of neutral pions in muo-production; and
4) Identification of some specific channels. The most important are the muo-production of vector mesons such as $\rho^0$.

Since we are invited to participate in the design and construction of a <u>facility</u>, we list below further experiments which can be done at a later time.

1) Wide angle $\mu$-bremstrahlung. This tests quantum electrodynamics.
2) $\mu$-p inelastic scattering with a polarized target. Since the $\mu$'s are already polarized this searches for spin dependent effects in the scattering.

3) $\lim_{q^2\to 0} \sigma(W)$ where $W$ is the mass of the final hadron system in μ-p inelastic scattering. From this extrapolation the total absorption cross section of real γ's by protons and neutrons at an energy of $\frac{W^2-M_N^2}{2M_N}$ is determined.
4) The A dependence of the cross section for μ's on high Z targets.
5) Search for Lee-Wick negative metric particles.
6) Search for μ-tridents.
7) Search for W bosons.
8) The A dependence of coherent production of vector mesons in heavy elements.

## 2. Experimental Configuration

The experimental configuration for this proposed inelastic muon scattering experiment at the National Accelerator Laboratory is shown in Figs. 1a and 1b. The precise specification of the equipment is listed in Table 1.

It is to be noted that this design has the following characteristics:

1) It is an expandable system. Both The University of Chicago and Harvard University are contributing the best of their available resources to this joint effort. If financial conditions permit, more equipment can be added easily. For example, it would be ideal if the Chicago Cyclotron magnet could be converted into a large volume window-frame magnet.
2) Requests from NAL have been kept to a minimum.
3) The target is movable in position:
    i) when the target is outside the magnet, we can measure the production angle to a higher precision;
    ii) when the target is moved out far upstream, we can do the

~ $0^0$ experiment with reduced incoming beam intensity. This allows the extrapolation to the limit of $q^2 = 0$ to obtain the total photo-absorption cross sections at energies greater than 100 GeV;

iii)when the target is located inside the magnet, we can have a complete measurement of the final state charged hadron spectra. Not all the chambers necessary for this are shown in Figs. 1a and 1b.

4) Although we have not made a final decision on types of chambers, pending model and cost studies, a workable system is outlined below. The size of the wire chambers are restricted to 1-meter square for proportional chambers; and 2-meter square for wire spark chambers. These sizes conform to the existing winding machines at Chicago and Harvard. The readout system for the wire spark chambers are FET, as they are already fully developed at Chicago where 8000 units exist. They give excellent multiple particle detection efficiency. The price of FET readout is $1/wire. Considerations are also being given to magnetostrictive delay line readout, much of which is available at Harvard. The major worry against it at this moment is that it needs more powerful spark supplies, and the noise they can generate is harmful to the proportional wire chambers.

5) This facility combines the functions of a "single-arm spectrometer" and a "multiple-particle spectrometer".

## 3. Justification of the Experiment

### A. Review of the Current Status of ep Inelastic Scattering

During the past few years, great progress in the study of electromagnetic structure of nucleons has been made because of the advent of big electron accelerators, particularly SLAC. In the SLAC experiment, performed by a SLAC-MIT[1,3] collaboration, only the scattered electrons were detected because of the short duty cycle of the linear accelerator. The interesting features of the results are summarized as follows:

I. The $q^2$ -dependences for the electro-excitation of the 1.238-, 1.512-, 1.688-, and 1.920-GeV nucleon isobars are rather similar. Their electromagnetic form factors decrease slightly faster than that of the elastic peak with increasing values of $q^2$. This behavior agrees with the predictions given by Walecka et al.

II. As $q^2$ increases, the electro-excitation of the nucleon isobars becomes totally unimportant. The cross section is dominated by the non-resonant part. As shown in Figs. 2 and 3, the differential cross section $\frac{d^2\sigma}{d\Omega dE'}$, measured at various fixed incident energies and scattering angles, rises roughly exponentially as a function of the missing mass W. In the deep inelastic region (i.e., when the missing mass W is greater than 2 GeV), the electromagnetic form factor shows a $q^{-2}$, rather than a $q^{-4}$, dependence which is surprising and of considerable current interest.

III. The inelastic neutron cross section is less than that of proton. These results have been compared, in only an approximate way, with the scale invariance model of Bjorken,[4] and the vector dominance model of Sakurai.[5] The situation can be summarized as follows:

Scale Invariance -

Assuming $\sigma_L/\sigma_T = 0$ (where $\sigma_L$ is the longitudinal cross section; and $\sigma_T$ the transverse cross section), the product $\nu W_2$ (where $\nu$ is the energy transfer to the target, $W_2$ is one of the two form factors) exhibits to within ~ 30% a universal feature as a function of the scalar variable $\omega \equiv 2M_p\nu/q^2$. As the value of $\omega$ increases, the product $\nu W_2$ becomes smaller. Also, at the same value of $\omega$, the data still exhibit a weak $q^2$ -dependence.

Vector Dominance -

If the mass of the vector meson in Sakurai's model is made variable, then the differential cross section $\frac{d^2\sigma}{d\Omega dE'}$ can be completely described by his theory. As $q^2$ increases, the value of the vector meson mass varies from the $\rho$ mass to ~ 1.4 GeV. However, the prediction of the ratio $\sigma_L/\sigma_T$ appears to be too large as compared to the few experimental values. The experimental situation is $0 < \sigma_L/\sigma_T \leq 0.5$.

## B. Review of the Current Status of Theory on Inelastic Scatterings:

There has been a tremendous theoretical effort aimed at a basic understanding of these tantalizing phenomena. In addition to Bjorken's scale invariance conjecture and Sakurai's vector dominance model, there have been numerous conjectures mainly along the following lines:

i) Parton Model: Feynman[6] envisaged that the hadrons were composed of particles, "Partons", of unknown properties. The specific prediction of this model is that, in high energy collisions, the momentum distribution of the final state hadrons should follow a dx/x distribution law, where x is the ratio of the longitudinal momentum to the total center-of-mass energy. This prediction can be checked in muo-production at the National Accelerator Laboratory very easily, as no identification of the hadrons is required.

ii) The Limiting Fragmentation Hypothesis: Yang and collaborators[7] suggested, in hadron collisions, the incoming particle and the target particle fragment separately, and the number of fragments approaches a limiting probability distribution as the energy increases. Tests of this idea can be better done in $\mu p$ inelastic scattering experiments than the hadron collision experiments because only the target can fragment.

iii) The Duality Model: Nambu[8] has deduced a closed expression for the inelastic structure functions $W_1$ and $W_2$, from his proposed duality model:

$$W_1 \sim (W^2 - M_p{}^2)\ \exp(-\frac{\lambda_1}{\omega - 1})$$

$$2M_p \nu W_2 \sim (\frac{\omega}{\omega - 1})\ \exp(-\frac{\lambda_2}{\omega - 1})$$

where $\lambda_1 \simeq \lambda_2 \simeq 1.4$ (fitting parameters). Certainly this energy dependence can be easily checked in the proposed $\mu p$ inelastic scattering experiment at NAL.

Of course, there are also many other interesting theoretical suggestions, such as Regge-pole exchange, Pomeranchuk exchange, QED model, etc. We will not try to summarize them here. Proliferation of theories on this subject shows the importance of obtaining good and detailed data on μ-p scattering.

## C. Review of the Current Status of Inelastic Scattering Coincidence Experiments:

There have been coincidence experiments conducted at CEA, Cornell, and DESY on the reactions

$$e^-p \rightarrow e^-p + X^0$$
$$\rightarrow e^-\pi^+ + X^0.$$

The detections were done with $(e^-p)$ or $(e^-\pi^+)$ in coincidence, and $X^0$ is the missing mass of the two detected particles. Some of the preliminary results were already reported at the 1970 Kiev Conference.[3] The interesting feature of the experimental results is that they are very similar to the cases where only the scattered electrons were measured.

With the muon facility proposed at NAL, the final state hadrons will be better measured. A much more clear understanding of the subject of multiple-particle production can be expected.

## D. Kinematics and Counting Rate:

In the standard notation, the differential cross section for μp (same as for ep) inelastic scattering can be written as

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E_0^2 \sin^4\frac{\theta}{2}} \left(W_2 + 2W_1 \tan^2\frac{\theta}{2}\right)$$

where

$E_0, E'$ = incident, scattered muon energy,

$\theta$ = scattering angle

$\alpha$ = fine structure constant = 1/137,

$W_1, W_2$ = two inelastic form factors.

Since we are only interested in small values of $\theta$ ($0.5^\circ$ to $4^\circ$), to first order, the contribution of the $W_1$ term can be neglected. Then the cross section can be written as

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E_0^2 \sin^4 \frac{\theta}{2}} \frac{(\nu W_2)}{\nu}$$

where

$$\nu \equiv E_0 - E'.$$

Further approximations can be made by substituting the actual value of $\nu W_2$, as obtained from the SLAC ep scattering data with the assumption that $\sigma_L/\sigma_T = 0$.

The trigger rate for muons scattered in the angular range $1^\circ$ to $4^\circ$ with energy loss 40 to 80 GeV will be of the order of 1 per burst with $10^7$ muons on a 1-meter liquid hydrogen target. Some of the practical contours of constant rate are shown in Figs. 4 and 5. It is interesting to see that the trigger rate at the high $q^2$ end of our acceptance is always substantial, and it stays essentially unchanged if the primary muon energy is 200, instead of 100 GeV. Of course, much higher rates obtain for small $q^2$ values. This will permit measurements to be made at values of missing mass W = 6 to 13 GeV with a 100 GeV muon beam, and W = 13 to 19 GeV with a 200 GeV muon beam. Values of $q^2$ can be explored in the range up to ~ 40 $(\text{GeV}/c)^2$.

Based on these conservative estimates of the trigger rate, Fig. 6 shows the kinematic regions which the proposed NAL muon scattering experiment could explore with 100 or 200 GeV muons, as compared to those already done at SLAC with 20 GeV electrons. Of course, these studies can be further extended with 300 GeV muons.

From our past experience, when the electron beam energy increased from 6 GeV to 20 GeV, unexpected results suddenly started to show up at SLAC. At the National Accelerator Laboratory, the muon beam energy moves up by a factor of more than ten. New features of physics are certainly expected. It definitely justifies the effort to do this experiment.

## 4. Description of Elements

### A. Muon Beam

The beam planned for the muon area is that designed by T. Yamanouchi. The characteristics important for our experiment are:

1. Intensity - up to $10^7$/pulse in 2" x 4" area.
2. Momentum and angle determination of individual $\mu$'s. We plan to use the NAL hodoscope (presently at BNL) stationed before and after the last bending magnet to determine the vector momentum and position of each muon. Access to the hodoscope sites is essential. Optical lineup will proceed with the beam pipe opened to air.
3. Low $\pi$ (and K) contamination of the beam emerging in the muon area. Strongly interacting particles whose products can decay into $\mu$'s before reaching the hadron absorber of the trigger will constitute false events. Calculations on the allowable contamination are in progress.
4. Low halo. Too many halo $\mu$'s will give false triggers and complicate the track analysis problems. We feel that the halo into our sensitive area of $2^m$ x $4^m$ must be less than 5% of the direct $\mu$ beam.

### B. Site

There are special factors that must be considered in the muon experimental area. First we are planning to use a 2200 ton magnet which extends 12' below the beam line. This clearly requires stable footings for its support. Moreover, since we are examining processes with very small cross sections, we must use those events that occur efficiently. To catch most of the scattered muons the disposition of wire chambers and the hodoscope that make up the trigger require a floor 5' below beam height. A 1' trench at the trigger chambers with a 4' floor elsewhere would be acceptable. Two basic parameters of each event are the momentum transfer and energy loss of the muon. Their accurate measurement requires fractional millimeter accuracy in the spark coordinate determinations of chambers spread over many meters. A good stable floor is essential if we are to be capable of these measurements. Concrete in the working area is very much preferred over asphalt. We feel the much lower coefficient of friction for steel wheels as well as the long term stability of concrete far outweighs the minor economic savings of asphalt.

### C. Magnet

It is proposed that the magnet be that of the Chicago 450 MeV Synchrocyclotron. The iron part of this magnet is made of large forgings. These are bolted together and can be disassembled and assembled with relative ease given adequate crane facilities. The present pole tips will be quite radioactive and it is planned to remove them. The gap will be increased from 36" to 50" by adding iron in both side legs of the yoke. The coils are made of copper 2" x 2" in cross section with a 1-1/8" diameter axial hole for water cooling. Each of the upper and lower coils have 210 turns and are made up of 7 double pancakes. The resistance of the entire coil is 67 m-ohms at $40^{\circ}C$. The total weight of copper is 132 tons. At present the magnet is powered by a 1 M.W. motor-generator set. We have requested that a 3 M.W. 5000 amp solid state supply now unused at P.P.A. be assigned to NAL for powering this magnet. However, recent information about the poor performance of this P.P.A. unit has alarmed us. Field calculations with the TRIM program at ANL show that a central field of 14.6 kg and a field integral of 70 kg-m can be expected at 5000 amp. excitation and 50" gap.

The major components of the magnet are listed below.

Steel

| | | |
|---|---|---|
| 16 top and bottom members | 22-1/2" x 63" x 410" | 81.5 tons each |
| 4 vertical members (notched) | 60" x 63" x 126" | 64 tons each |
| 2 vertical members | 60" x 63" x 126 | 67 tons each |
| 4 pole disks | 22-1/2" thick, 170" diameter | 72 tons each |

Coils

| | |
|---|---|
| 2: I.D.171", O.D. 247", height including support rings 37-1/2" | 65 tons each |

Disassembly and loading on trucks can be handled at the Chicago Cyclotron Laboratory, where a 100 ton crane is available. At the NAL muon area it will be necessary to provide a support for this 2200 ton magnet. Clearance below the beam line must be 12 feet (as the list of major parts shows). The assembly will require substantial crane capacity.

## D. Trigger

Just as in any counter experiment, the triggering system must have a high and measurable efficiency for all events of interest. At the same time the trigger must not accept so many spurious events (even though they can be disentangled later) that the magnetic tape is overfilled.

In order to achieve this we take advantage of one, or all, of the following features of the events in which we are interested, all of which can be studied beforehand with fast electronic logic:

1) $\mu e$ scattering and bremsstrahlung: $\mu e$ scattering at small angles (< 6mr) can give recoil electrons of energy almost up to that of the incident muons.

These electrons will be cut out completely from triggering, as they cannot penetrate the thick hadron absorber at the end of the apparatus

(> 400 radiation lengths).

Muon bremsstrahlung is less important. It cannot go through the hadron absorber either. If we want to study the validity of QED at small distances, this bremsstrahlung can be easily measured by a total absorption counter.

2) Hadron Shower: Most of the events under consideration will give hadron showers, which are more penetrating than electromagnetic showers of the same energy. We could therefore insist on at least 2 separated particles penetrating the front lead absorber.

3) Veto: Without affecting the detection efficiency, we can veto any event on any criterion not dependent on the scattering. Thus we can veto all muons in accidental coincidence, and so forth.

More detail on these trigger strategies is given below:

i) Muon Energy Loss Trigger

A "good beam muon" is defined by the pre-target beam hodoscopes in coincidence with the post hadron-absorber counters outside the direct beam and at the rear end of the apparatus. This trigger is similar to that used in a BNL muon inelastic scattering experiment in 1967. Random coincidences between a beam muon and a beam halo muon will be ~ $5 \times 10^4$/sec, assuming $10^7$ beam muons, $5 \times 10^5$ halo muons per sec, and 10 nsec resolving time. These will be reduced by a down stream veto counter in the beam direction and by veto counters on either side of the beam near the target. Each of these should reduce the rate to near zero. These false events can be discarded later by reconstruction.

ii) Trigger on "Microscopic View" on the Scattering:

This is similar to step i) just described, but it involves more complex fast electronic logic. A charged-particle-free cone of 5 mr minimum half angle about the incoming beam direction and downstream of the target is required for any trigger. What this accomplishes is to require that the muon scatter more than 5 mr before it becomes a trigger candidate. Moreover, the decision is made before the particle leaves the beam area.

We accomplish this trigger by combining incoming hodoscope information (the incident beam direction) with a proportional wire chamber placed inside the magnet. An area of the chamber corresponding to the incoming muon beam plus a cone of half angle 5 mr is required to be off to produce a trigger. Since the chamber elements are very small, the halo veto requirement is much less stringent. This arrangement, in conjunction with the usual requirement that a muon emerge from the hadron absorber, and also use of the anti-coincidence counter at the rear end of the apparatus, should help enormously in case the beam halo is high. Low energy knock-on electrons are swept out by the magnet, thus they cannot cause any problem.

iii) Trigger Requiring Both Muon and Hadrons:

An alternative trigger is to take advantage of the fact that we are interested in events where the target has gained many tens of GeV in excitation energy, and will give many high energy hadrons. Thus we can demand that, in coincidence with the incident beam, there is a muon and a hadron after the magnet. We will distinguish hadrons from electrons and photons (produced by $\mu e$ scattering and bremsstrahlung) by their ability to penetrate high Z absorbers. This is illustrated in Fig. 7.

The only particle which penetrates to counter bank D is the scattered muon. The hadrons penetrate to counter bank C with high efficiency, but only a fraction of one per cent of the electrons or photons so penetrate.

Efficiencies of the counters should not cause any trouble in this scheme, but the granularity of the hodoscopes may be a problem.

It should be remarked that the triggering mode discussed in this section is complex and very likely unnecessary. It just illustrates the way we could possibly proceed in case the trigger should become a problem in the hundred-GeV region.

## E. Muon Identification and Hadron Absorber

In the proposed experiment, high energy muons will be identified by their ability to penetrate a thick steel absorber at the end of the spectrometer. As shown in Fig. 1a and 1b, this absorber is about $2^m \sim 4^m$ meters in thickness. A wire spark chamber will be placed in the middle, and another chamber after it, to follow the muon track. A scintillation hodoscope located at the very end is used to define the trigger. Energy loss of muons in the steel absorber is 2.3 to 4.6 GeV. The collision length of hadrons in iron is 12.8 cm; and the radiation length, 1.8 cm. Therefore, hadrons, knock-on electrons, and photons are not expected to reach the trigger hodoscope.

However, the muons from the pions decaying in flight can cause false triggers; so can beam-halos muons which we will discuss later. The incoming muon beam is estimated to contain a pion contamination of $\sim 3 \times 10^{-6}$. These pions will undergo strong interactions in the target, with cross sections $\sim 10^6$ times bigger than that for inelastic muon scattering. Preliminary calculations have been done using the empirical cross section formula for pion production in strong interaction, as given by Cocconi et al,[9] or that by Trilling.[10] By integrating the differential cross section, $\frac{d^2\sigma}{d\Omega dE'}(E', \theta)$, over the angular and momentum acceptance, and also folding in the pion decay factor (the pion decay length is 55 meters per GeV/c), it was found these false muon triggers should not exceed 4%. It is expected that this spurious contamination can be reduced to a level of less than 1% in the final data analysis. Further calculations are proceeding.

## F. Veto Counters and Total Absorption Counter

### 1) Veto Counters

One plastic scintillation counter, with proper shielding against possible backward pions, will be placed before the target to veto the beam halos. Its size has to be compatible with that of the halo which is under study. Another plastic scintillation counter, with size matching that of the incoming beam, will be placed after the trigger hodoscope to veto the incoming beam. It is clear that the successful operation of these veto counters depends on the amount of beam halo. For $q^2 = 0$ experiment, we have to reduce beam intensity considerably and use proportional wire chambers to decide whether the muon has suffered scattering in the target of not.

### 2) Total Absorption Counter (TA)

A total absorption counter of size ~ 1' x 1' or larger, made of either lead glass or lead-lucite sandwich with a number of wire planes interspersed to determine the number and location of the showers, can be placed before the thick steel hadron absorber to measure the photons. The thickness required is ~ 20 radiation length. Such a device can be assembled from borrowed and existing components. Measurements of the forward and wide angle bremsstrahlung with the total absorption counter will be of interest and may provide a test of quantum electrodynamics. This device is not essential to the main purpose of the experiment.

## G. Wire Chamber, Readout System, and Scanner

### 1) Chambers

In the proposed experiment, both proportional wire chambers and wire spark chambers will be used in the magnetic spectrometer. Choices will be based on the following considerations:

a) Speed:

The proportional wire chamber has a dead time of only ~ 50 nsec, but these signals have to be delayed ~ 200 nsec in order to make coincidence with trigger counters. The spark chamber has a dead time of ~ 1 μsec.

b) Multiple Particle Detection Efficiency:

The proportional chamber has excellent multiple particle detection efficiency; so has the spark chamber with FET (field-effect transistor) or magnetic-core readout. Their multiple spark efficiency depends on the spark disposition and the method of supplying the power. For large size chambers, the spark power supply for a core-readout system is far more demanding than the chambers with FET readout system.

c) Spatial resolution:

Proportional wire chamber: ± 0.5 mm.

Wire chamber with FET or core readout: guaranteed ± 0.5 mm (expect ± 0.3 mm).

Wire chamber with magnetostrictive delay line readout: ± 0.3 mm.

d) Operation in magnetic field:

Proportional wire chambers and FET spark chambers can be operated inside a magnet. Chambers with magnetostrictive delay line or core readout can not.

e) Cost of readout electronics:

| | |
|---|---|
| Proportional wire chamber: | \$5/wire |
| FET readout: | \$1/wire |
| Core readout: | \$0.8/wire |
| Magnetostrictive delay line: | cheap. |

f) Size and construction:

In proportional wire chambers, if the wires are longer than $1^m$ there will be difficulties in supporting them. CERN has built a chamber of size $2^m \times 0.5^m$ with a very big effort and is building one $3^m \times 1^m$. Nevis has a $3^m \times 1^m$ chamber which works well. The construction must be done with care. For wire spark chambers, the size can be bigger. At both Chicago and Harvard, there exist winding machines which can handle chambers of size up to $2^m \times 2^m$ and at Brookhaven successful chambers up to $5^m \times 3^m$ have been wound.

If we put the target inside the magnet, then we have to use proportional wire chambers near the target because of the high rate caused by knock-on electrons. Chambers far away from the target can all be of FET readout type with deadened central region where the primary beam goes through. Extreme care must be exercised to shield the proportional chambers from the noise generated by the spark chambers.

If we put the target outside the magnet, then we can just use wire chambers with FET readout, and with central region deadened. They are competitive in price, yet having excellent multiparticle efficiency.

### 2) Amplifiers and Readout System

The amplifier system for the proportional wire chambers has been very well developed by T. Nunamaker at Chicago. There exist amplifiers of charge-sensitive and voltage sensitive types. The charge-sensitive amplifier is extremely useful when the chamber becomes bigger and its larger wire capacitance reduces the voltage amplitude of the signal. We are in the process of miniaturizing these circuitry to hybrid forms. The schematic diagrams are shown in Figs. 8 and 9.

At Chicago, FET readouts for ~ 8000 wires are already built. The schematic diagram is shown in Fig. 10. These readouts can be built immediately by an outside vendor without further development. At Harvard, there exists a number of large size magnetostrictive delay-line readout chambers which could be converted to FET readout.

### 3) Scanner

A scanner system for reading out information from wire chambers has been built at Chicago. This system can examine the wires and send spark address information to the buffer memory of an on-line computer at a speed of 32 wires/μsec. It is an excellent interfacing system capable of handling information from ADC's and fast scalers, as well as the spark chamber data. The data rate expected in the μp scattering experiment is well below the scanner's capacity. This scanner has been tested at Cornell University during the summer of 1970.

## H. On-line Computer and Program

In the proposed experiment, an on-line computer in the class of PDP-15 or Σ3 is required to do data-logging, equipment monitoring, and on-line evaluation of experimental results. This computer should have a memory size of ~ 16 K words, and be equipped with two 9-track magnetic tape units, card-reader, fast line-printer, display scope, and a drum. As the development of the on-line program in general takes one-year lead time, it has to go in parallel with the hardware construction. We request access to a PDP-15 starting January 1970 for program development and such a computer dedicated to this experiment in July 1972.

## I. Off-line Data Analysis

The off-line data analysis program is in general a translation of the on-line monitoring program with elaborations depending on the complexity of the hadron shower. These programs will be developed at a slightly later stage. Radiative corrections will be a factor of 5 less than for the e-p case. Specific calculations can be easily handled by a modification of the SLAC program.[11]

5. Budget for 18 Months (January 1, 1971 to July 1, 1972)

A. Cost estimate of apparatus including labor and material.*

| | | |
|---|---|---|
| 1) | NAL beam hodoscope (transport from BNL and setup) | $ 4K (NAL) |
| 2) | Beam halo veto counter and shield | 7K |
| 3) | BNL liquid hydrogen target (transport and setup) | 6K (NAL) |
| 4) | Time-of-flight spectrometer (optional) | ( 30K ) |
| 5) | Module No. 1 ($2^m$ x $2^m$, FET) | 12K |
| 6) | Chicago Cyclotron Magnet (disassembly, transport, and assembly) | 150K (NAL) |
| 7) | Module No. 2 ($1^m$ x $1^m$, proportional) | 23K |
| 8) | Module No. 3 ($4^m$ x $2^m$, FET) | 24K |
| 9) | Module No. 4 ($6^m$ x $2^m$, FET) | 36K |
| 10) | Module No. 5 ($1^m$ x $1^m$, proportional) | 23K |
| 11) | Lead radiator ($2^m$ x $4^m$ x $0.036^m$) | 4K |
| 12) | Module No. 6 ($4^m$ x $2^m$, FET) | 24K |
| 13) | Total absorption shower counter (~ $1'$ x $1'$) | 10K |
| 14) | Hadron absorber ($2^m$ x $4^m$ x $4^m$, cutting and transport from University of Chicago) | 8K (NAL) |
| 15) | Module No. 7 ($4^m$ x $2^m$, FET) | 18K |
| 16) | Module No. 8 ($4^m$ x $2^m$, FET) | 18K |
| 17) | Muon hodoscope ($4^m$ x $2^m$, 20 vertical elements) | 25K |
| 18) | Mechanical mounts | 30K |
| 19) | Fast electronics | 50K |
| 20) | Cables, connectors, etc. | 25K |
| 21) | Spark pulsers | 20K |

5. Budget for 18 Months (continued)

| | | |
|---|---|---|
| 22) Computer interfacing | | $ 20K |
| 23) P.P.A. power supply | | |
| (Move and install | $ 7K, | |
| Modification | 10K, | |
| Line transformer | 20K) | |
| | | 37K (NAL) |
| | Total equipment cost | $574K |
| | (Total cost + optional item | $604K) |

*Notes:

1. Cost estimate for $1^m$ x $1^m$ proportional chamber:

| | |
|---|---|
| a) Material and machining | $ 3K |
| b) Winding (salary) | 2K |
| c) Electronics for 3000 wires ($6/wire) | 18K |
| Total | $23K/chamber |

2. Cost estimate for $2^m$ x $2^m$ FET chamber:

| | |
|---|---|
| a) Material and machining | $ 4K |
| b) Winding (salary) | 2K |
| c) FET readout for 6000 wires (~$1/wire) | 6K |
| Total | $12K/chamber |

3. For FET chambers of size bigger than $2^m$ x $2^m$, we plan to overlap $2^m$ x $2^m$ modules. We will also explore the possibility of winding bigger chambers.

## 5. Budget for 18 Months (continued)

B. Scientific personnel (physicists, students, programmer, and secretaries):

| 1. The University of Chicago: | cost/year |
|---|---|
| a) Senior physicists (summer salary only) | $ 15K |
| b) Research Associates (2) | 25K |
| c) Programmer (1) | 10K |
| d) Secretary (1) | 7K |
| e) Graduate students (2) | 10K |
| Sub-total | $ 67,000 |
| Overhead and Retirement (46% and 10.5%) | 37,855 |
| Total | $104,855/year<br>($157,280/18-month |

| 2. Harvard University: | cost/18-month |
|---|---|
| a) Senior physicists (summer salary only) | $ 12K |
| b) Research fellow (1) | 25K |
| c) Assistant professor (1/2) | 18K |
| d) Research assistants (2) | 19K |
| e) Under-graduate students | 15K |
| f) Programmer (part-time) | 10K |
| g) Secretary (1) | 14K |
| Total (this includes overhead ) | $ 113K |

| | | |
|---|---|---|
| C. | Expendable equipment and supplies | $ 150K (18 mos.) |
| D. | Machine shop services | 150K (18 mos.) |
| E. | Travel and Housing | |

## 5. Budget for 18 Months (continued)

| | |
|---|---|
| a) The University of Chicago | $ 15K (18 mos.) |
| b) Harvard University | 35K (18 mos.) |
| F. Computer services | 30K (18 mos.) |
| G. Contingency | 150K |
| Overall 18-month cost: | $1,374,280 |

## 6. Division of Cost and Work, and Time Schedule

A. Division of Cost (January 1, 1971 to July 1, 1972).

We suggest that the National Accelerator Laboratory carry the costs of the beam hodoscope, liquid hydrogen (deuterium) target, moving the Chicago Cyclotron magnet and the steel for the hadron absorber, and installing the P. P. A. power supply [see Budget Items 1), 3), 6), 14), and 23)]. The total cost is $205,000.

The rest of the cost will be divided between Chicago and Harvard. The preliminary division is placed at $690,000 for the University of Chicago, and $479,000 for Harvard University. The respective supporting agencies are NSF and AEC.

B. Division of Work.

1) Proportional wire chambers: University of Chicago
2) Wire spark chambers:
    a) Construction: University of Chicago, Harvard University
    b) FET readout: University of Chicago
3) Magnet: University of Chicago
4) Counters: Harvard University
5) Mechanical supports: University of Chicago, Harvard University

C. Request to NAL.

We request the National Accelerator Laboratory to provide the following items:

1) Cost of disassembly, modification, move, and assembly of the Chicago Cyclotron Magnet.

6. Division of cost and work, and Time Schedule (continued)

2) Cost to move and install the 3 M. W. power supply from P. P. A.

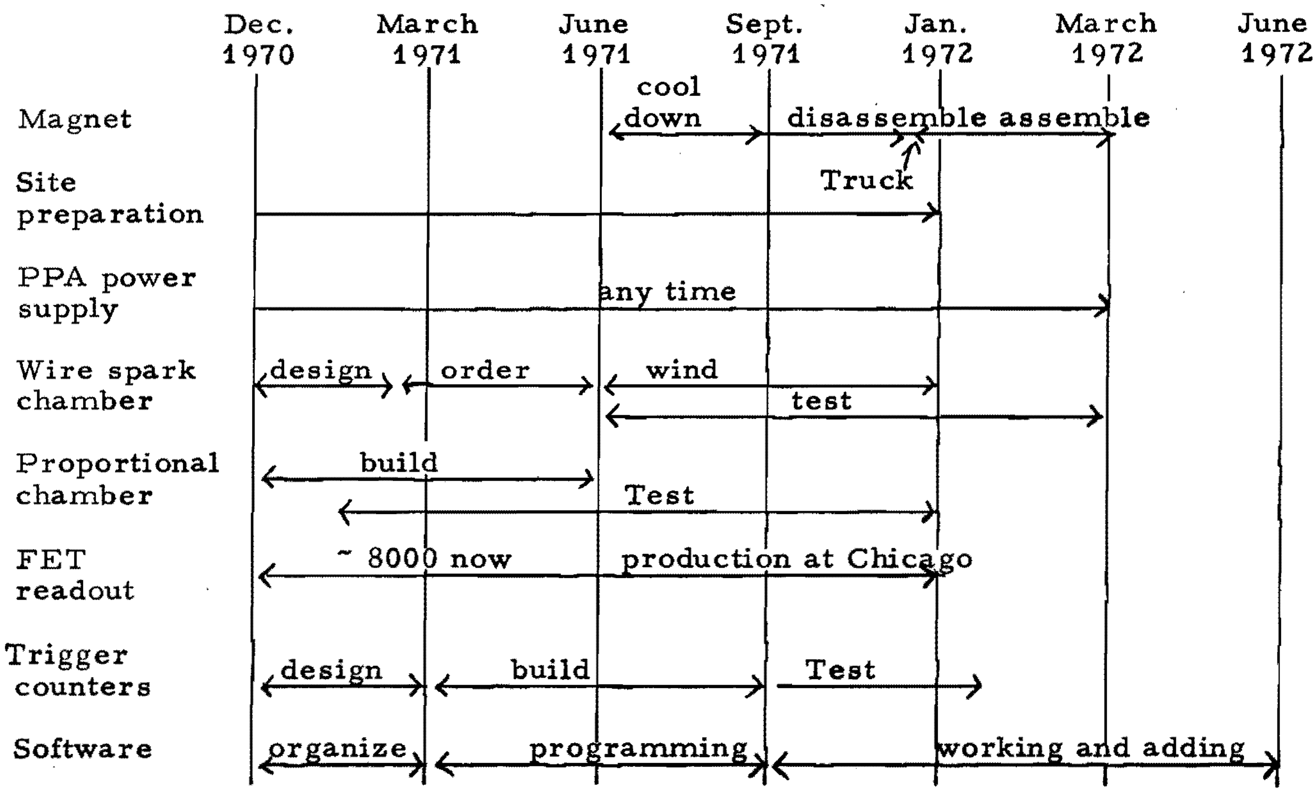
3) Early access to a NAL PDP-15 computer for soft-ware development; and before July 1, 1972, a dedicated PDP-15 computer with line printer, card reader, two tape units, drum and a display scope.

4) A liquid hydrogen target (a BNL target, used at the μp II experiment on the AGS, might be borrowed).

5) The muon beam hodoscope (the NAL beam hodoscope, used at μp II experiment on AGS, is the type we need).

D. Time Schedule.

The time schedule for building the muon facility at the National Accelerator Laboratory, and also the preparation for the muon inelastic scattering experiment is shown in the following table



## 7. Request of Beam Time

We request 1,600 hours of beam time to carry out the proposed experiment: 800 hours each with liquid hydrogen and liquid deuterium target. The muon beam energy will be variable from 50 GeV to the highest possible, ~ 300 GeV. The beam intensity should be variable, up to $10^7$/1-sec long beam spill. We will request extensions of running time at an appropriate stage.

After the initial stage of experimentation with $LH_2$ and $LD_2$ targets, we will consider the possibility of doing experiments with high Z targets and a polarized proton target.

## References

1. E. Bloom, G. Buschorn, R. Cottrell, D. Coward, H. DeStaebler, J. Drees, C. Jordan, G. Miller, L. Mo, H. Piel, and R. Taylor; M. Breidenbach, W. Ditzler, J. Friedman, G. Hartmann, H. Kendall, and J. Poucher, Contributed Paper to the 15th International Conference on High Energy Physics, Kiev, USSR, 1970.
2. (i) NAL Proposal No. 5, B. Dieterle, W. Lakin, F. Martin, M. Perl, E. Pertraske, J. Tenenbaum, W. Toner, and T. Zipf, 1970.
   (ii) NAL Proposal No. 26, K. W. Chen and L. N. Hand, 1970.
   (iii) NAL Proposal No. 29, T. Kirk, F. Pipkin, J. Russell, M. Tannenbaum, R. Wilson, J. Sanderson, L. Verhey, 1970.
   (iv) NAL Proposal No. 33, H. L. Anderson, N. E. Booth, L. W. Mo, L. C. Teng, and S. C. Wright, 1970.
3. Richard Wilson, Rapporteur's Talk, 15th International Conference on High Energy Physics, Kiev, USSR, 1970.
4. J. D. Bjorken, Proceedings of International School of Physics, "Enrico Fermi", Course 41, ed. J. Steinberger (Academic Press, Inc, New York, 1969).
5. J. J. Sakurai, Phys. Rev. Letters 22, 981 (1969).
6. R. P. Feynmann, Phys. Rev. Letters 23, 1415 (1969).
7. J. Benecke, T. T. Chou, C. N. Yang, and E. Yen, Phys. Rev. 188, 2159 (1969),
8. Y. Nambu, Lecture at Copenhagen Summer Symposium, 1970 (unpublished).
9. G. Cocconi, L. Koster, and D. Perkins, UCRL - 10022, 1962 (unpublished).
10. G. Trilling, UCRL - 16830, 1966 (unpublished).
11. L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. 41, 705 (1969).

## Table 1

## Elements of $\mu p$ Inelastic Scattering Apparatus

1. Incoming muon beam hodoscope: We will try to get the NAL hodoscopes currently being used at BNL. (Not shown on Fig. 1a and 1b).

2. Beam halo veto counter: Scintillation counters around the beam, should be shielded against possible backward pions.

3. Liquid hydrogen ($D_2$) target: 1 meter long. Try to borrow from BNL. NAL should provide the cryogenics.

4. Time-of-Flight spectrometer (TOF): optional.

5. Wire spark chamber Module No. 1: $2^m \times 2^m$ (each module has 3 FET readout planes).

6. Chicago Cyclotron Magnet:

| | |
|---|---|
| Gap: | 50" |
| Pole: | 170" diameter |
| Field: | 14.6 KG |
| Power required: | 2 MW |
| Power supply: | PPA 3MW supply |

(The fallback magnet is Jolly Green Giant of CEA.)

7. Proportional wire chamber Module No. 2: $1^m \times 1^m$ (used as part of the trigger when target is outside magnet).

8. Wire spark chamber Module No. 3: $4^m \times 2^m$.

9. Wire spark chamber Module No. 4: Three chambers, $2^m \times 2^m$ each, to be put side by side to cover a $6^m \times 2^m$ area.

10. Proportional wire chamber Module No. 5: $1^m \times 1^m$.

11. Lead radiator: $2^m \times 4^m \times 0.036^m$ (6 radiation length thick).

12. Wire spark chamber Module No. 6: Two chambers, $2^m \times 2^m$ each, to be put side by side to cover a $4^m \times 2^m$ area.

## Table 1 (continued)

## Elements of μ p Inelastic Scattering Apparatus

13. Total absorption shower counters (TA): 2' x 2'

14. Hadron absorber: $2^m$ x $4^m$ x $4^m$ steel, split into two parts to allow an optional wire chamber being put in between. We may use the shielding blocks from The University of Chicago.

15. Wire spark chamber Module No. 7: Two chambers, $2^m$ x $2^m$ each.

16. Wire spark chamber Module No. 8: Two chambers, $2^m$ x $2^m$ each.

17. Muon hodoscope: $2^m$ x $4^m$ plastic scintillation counters.

18. Beam anti-counter: Plastic scintillation counter, size matching the incoming muon beam.

## FIGURE CAPTIONS

| | |
|---|---|
| Fig. 1a | Top view of the proposed muon facility. |
| 1b | Elevation view of the proposed muon facility. |
| Fig. 2 | Inelastic ep scattering results of SLAC. Measurements were done at an electron scattering angle of $26^{\circ}$. |
| Fig. 3 | Inelastic ep scattering results of SLAC. Measurements were done at an electron scattering angle of $34^{\circ}$. |
| Fig. 4 | Kinematics for $\mu p$ inelastic scatterings at NAL with 100 GeV muons. The counting rates indicated in the diagram were calculated for <u>fixed</u> values of missing mass W. We arbitrarily took $\Delta E' = \pm 10$ GeV. The solid angle, $\Delta\Omega$, needed for the estimate was given by the limits defined by $\Delta E' = \pm 10$ GeV and the size of the trigger hodoscope. These numbers indicate the differential counting rates for given values of W and $q^2$. It is to be emphasized that this refers to the deep inelastic region. The total trigger rate of the apparatus is much bigger. |
| Fig. 5 | Kinematics for $\mu p$ inelastic scatterings at NAL with 200 GeV muons. The counting rates indicated in the diagram were calculated for <u>fixed</u> values of missing mass W. We arbitrarily took $\Delta E' = \pm 10$ GeV. The solid angle, $\Delta\Omega$, needed for the estimate was given by the limits defined by $\Delta E' = \pm 10$ GeV and the size of the trigger hodoscope. These numbers indicate |

## FIGURE CAPTIONS

(continued)

Fig. 5 (continued)

the differential counting rates for given values of W and $q^2$. It is to be emphasized that this refers to the deep inelastic region. The total trigger rate of the apparatus is much bigger.

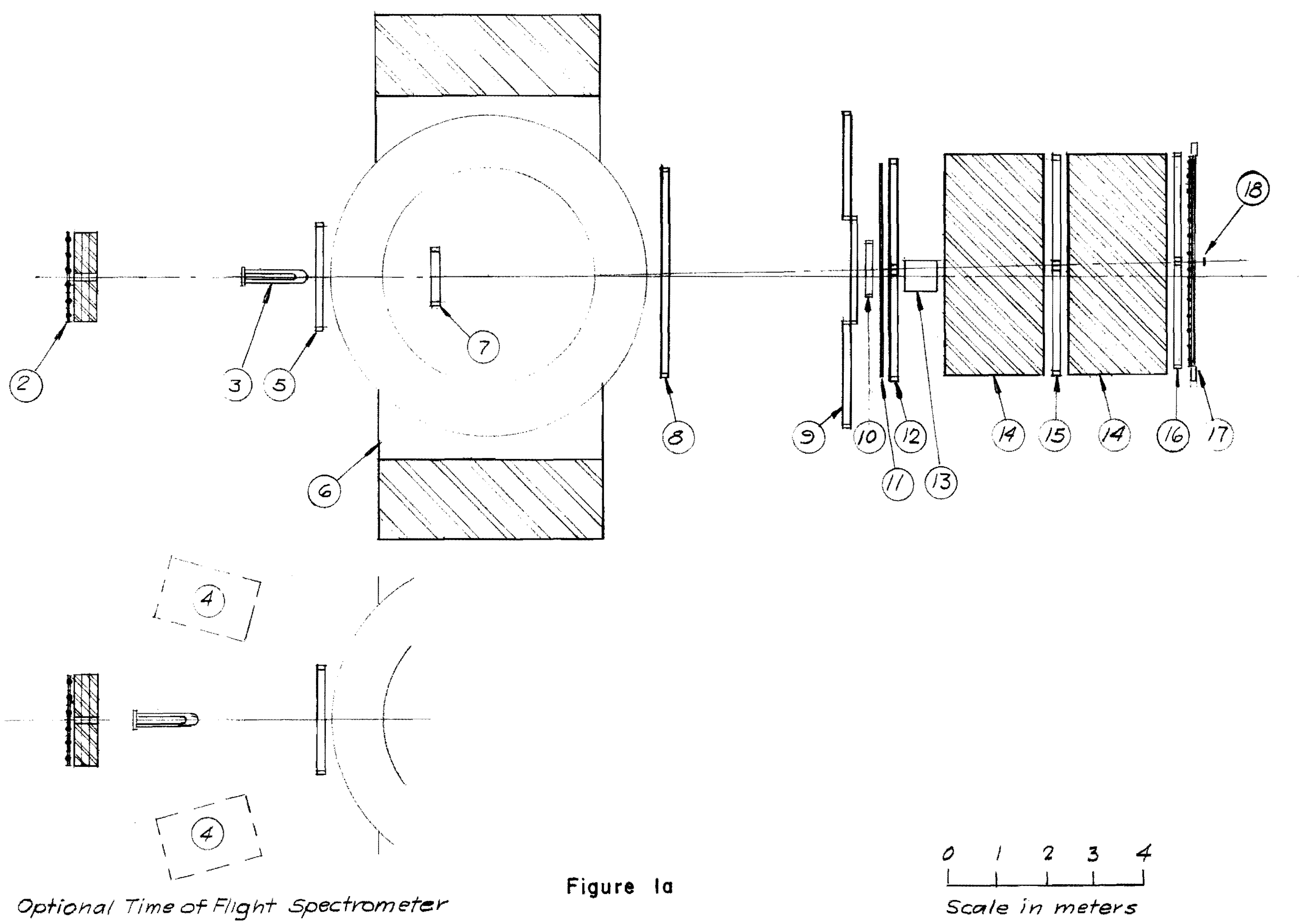
Fig. 6 Kinematical region in which the $\mu p$ inelastic scattering experiment at NAL can explore.

Fig. 7 Illustration of a possible trigger scheme which utilizes the coincidences between a scattered muon and hadrons in muoproduction.

Fig. 8 Schematic diagram for a charge-sensitive amplifier for multiple-wire proportional chambers.

Fig. 9 Schematic diagram for a voltage amplitier for multiple-wire proportional chambers.

Fig. 10 Schematic diagram for the FET readout for wire spark chambers.



Optional Time of Flight Spectrometer

Figure 1a

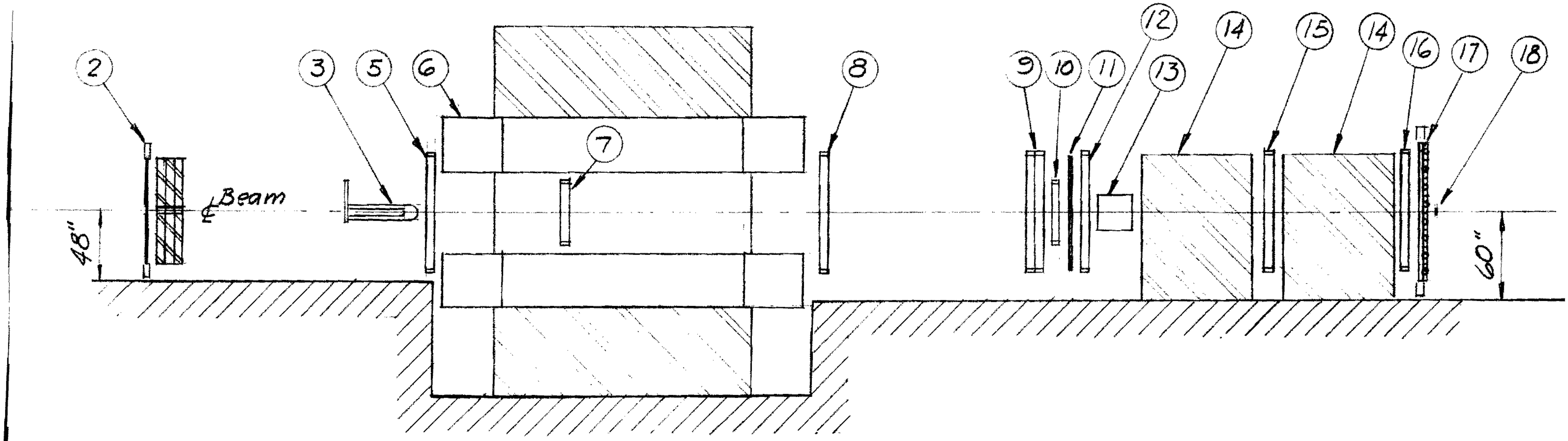
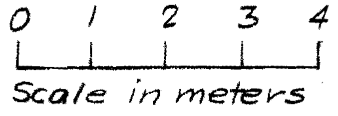

2
3
5
6
7
8
9
10
11
12
13
14
15
14
16
17
18
Beam
℄
48"
60"

Figure 1b


0
1
2
3
4
Scale in meters

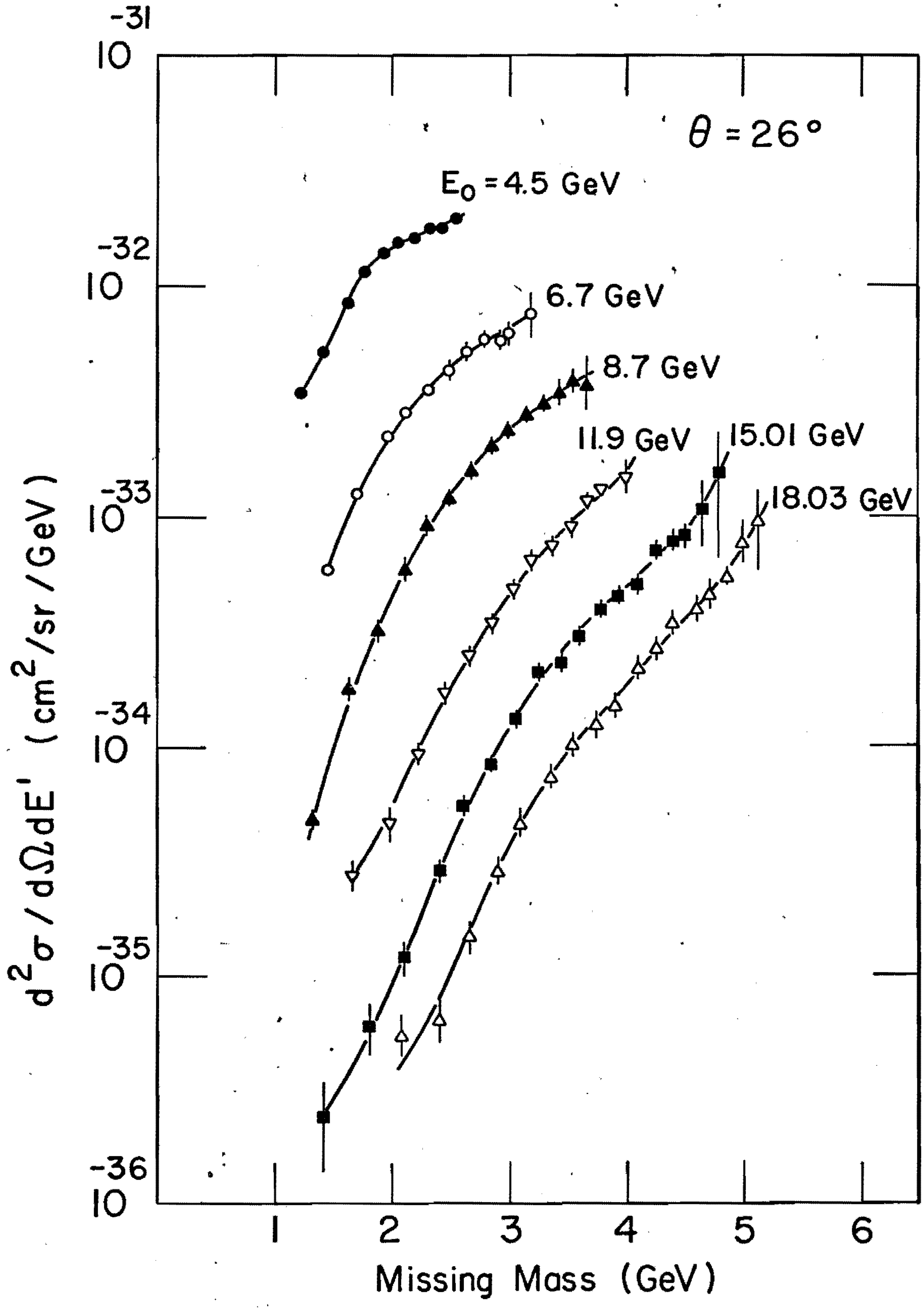
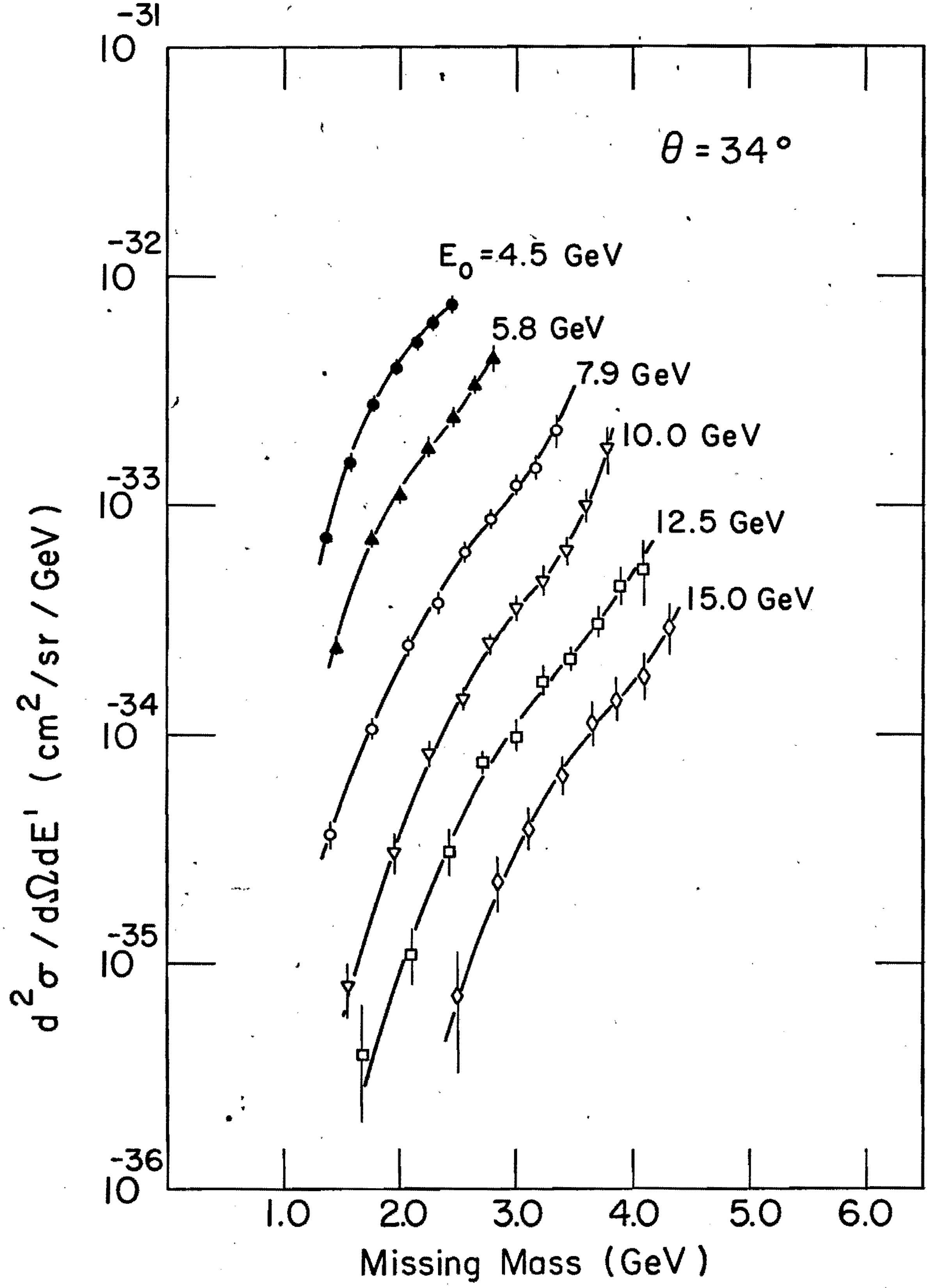
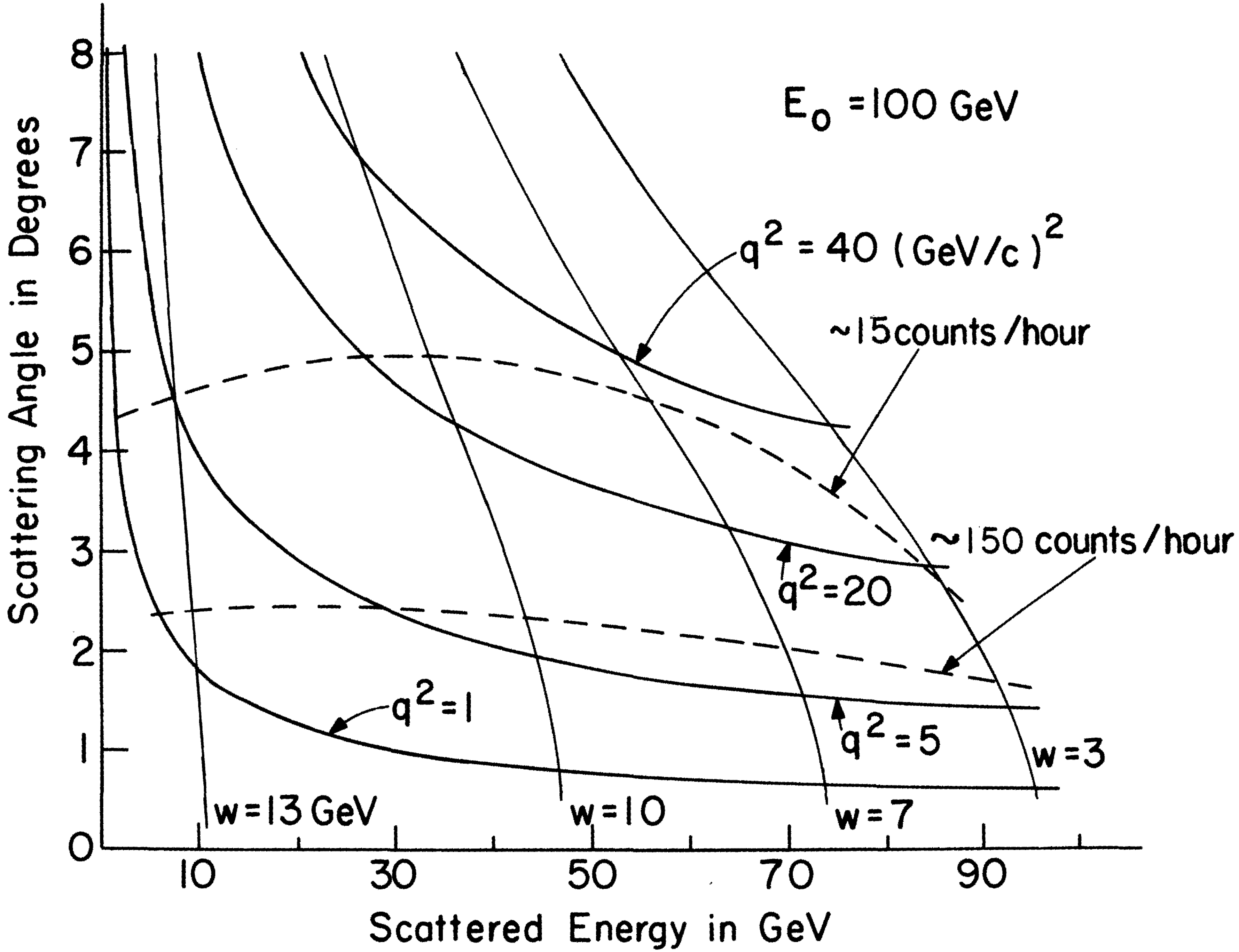

$10^{-31}$
$10^{-32}$
$10^{-33}$
$10^{-34}$
$10^{-35}$
$10^{-36}$
$d^2\sigma/d\Omega dE'$ (cm$^2$/sr/GeV)
$\theta = 26°$
$E_0 = 4.5$ GeV
6.7 GeV
8.7 GeV
11.9 GeV
15.01 GeV
18.03 GeV
1
2
3
4
5
6
Missing Mass (GeV)

Figure 2



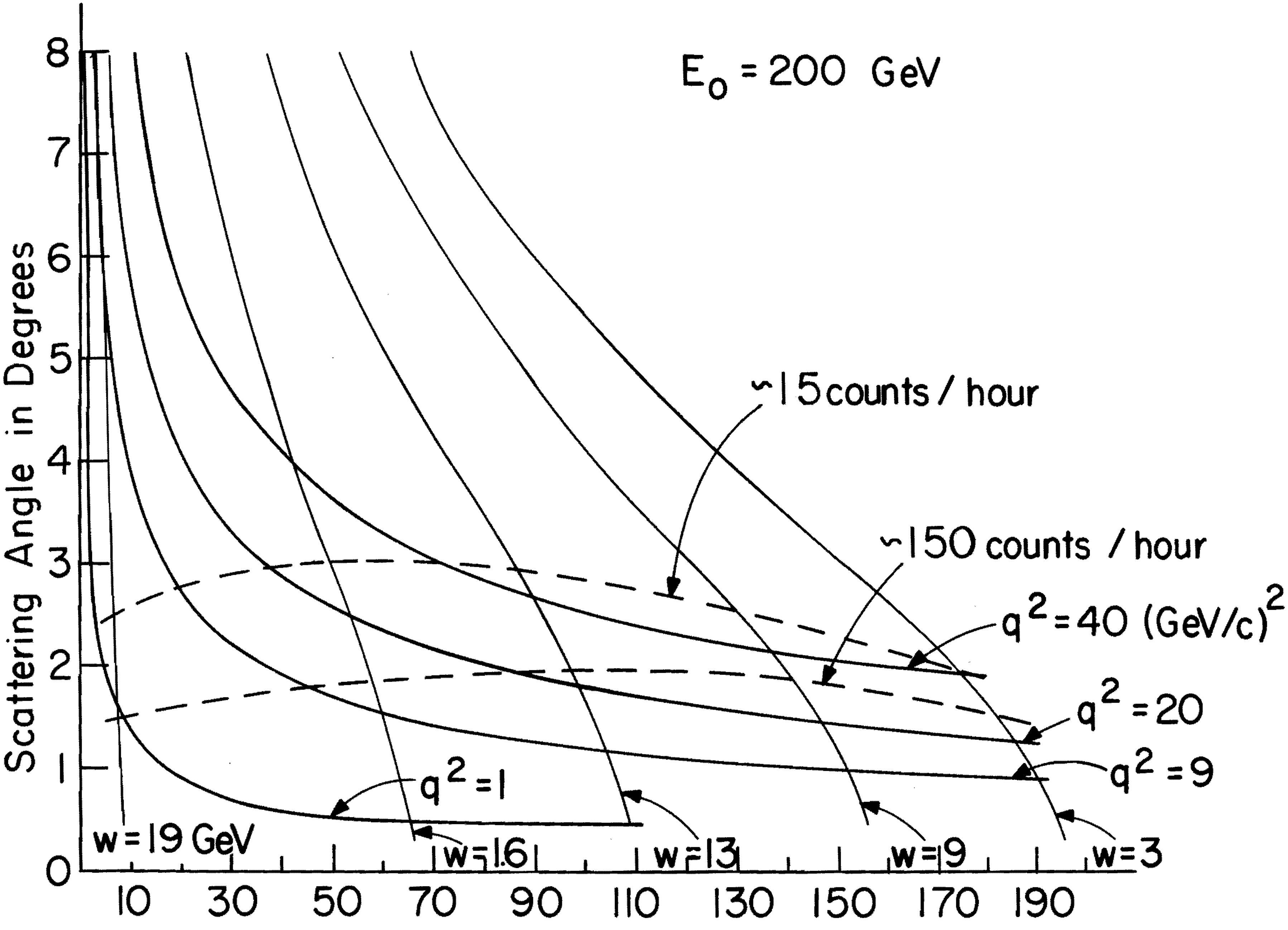
$10^{-31}$
$10^{-32}$
$10^{-33}$
$10^{-34}$
$10^{-35}$
$10^{-36}$
$\theta = 34°$
$E_0 = 4.5$ GeV
5.8 GeV
7.9 GeV
10.0 GeV
12.5 GeV
15.0 GeV
$d^2\sigma / d\Omega dE'$ (cm$^2$/sr / GeV)
1.0
2.0
3.0
4.0
5.0
6.0
Missing Mass (GeV)

Figure 3



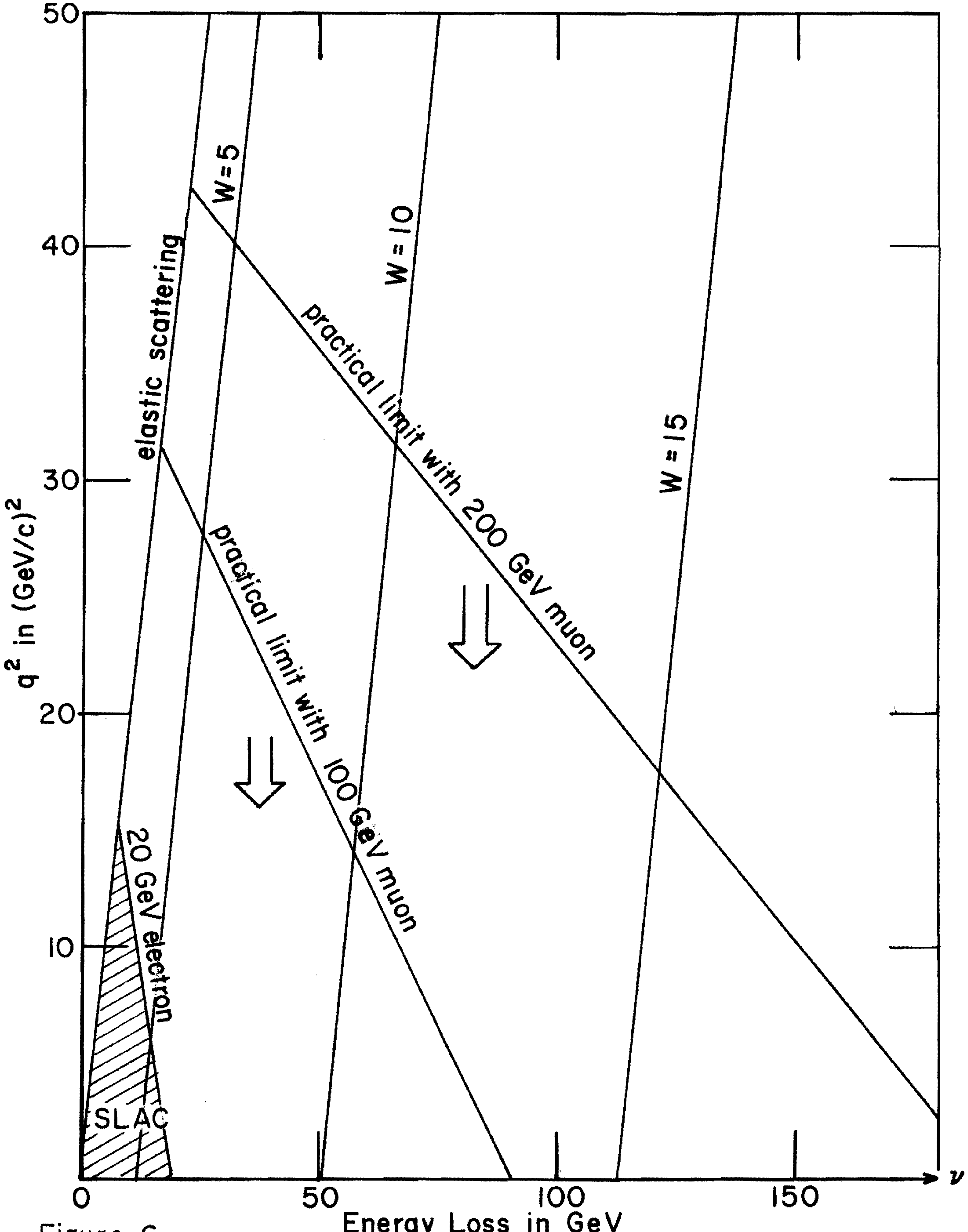
$E_0 = 100$ GeV
$q^2 = 40$ (GeV/c)$^2$
~15counts /hour
~150 counts / hour
$q^2 = 20$
$q^2 = 5$
$q^2 = 1$
w = 13 GeV
w = 10
w = 7
w = 3
Scattering Angle in Degrees
0
1
2
3
4
5
6
7
8
10
30
50
70
90
Scattered Energy in GeV

Figure 4



$E_0 = 200$ GeV
~15 counts / hour
~150 counts / hour
$q^2 = 40$ (GeV/c)$^2$
$q^2 = 20$
$q^2 = 9$
$q^2 = 1$
w = 19 GeV
w = 16
w = 13
w = 9
w = 3
Scattering Angle in Degrees
0
1
2
3
4
5
6
7
8
10
30
50
70
90
110
130
150
170
190
Scattered Energy in GeV

Figure 5



50
40
30
20
10
0
q² in (GeV/c)²
0
50
100
150
ν
Energy Loss in GeV
W=5
W=10
W=15
elastic scattering
practical limit with 200 GeV muon
practical limit with 100 GeV muon
20 GeV electron
SLAC

Figure 6

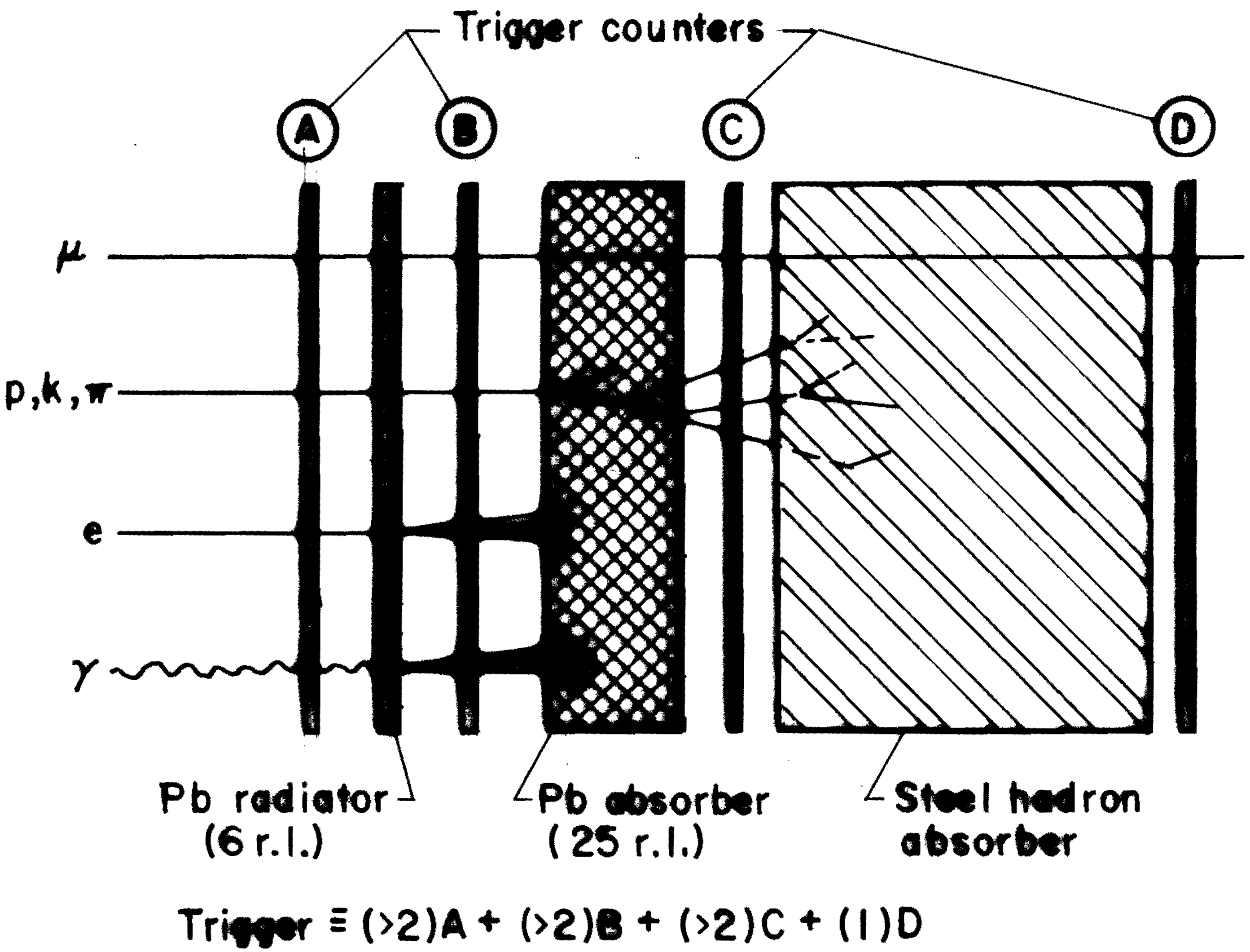
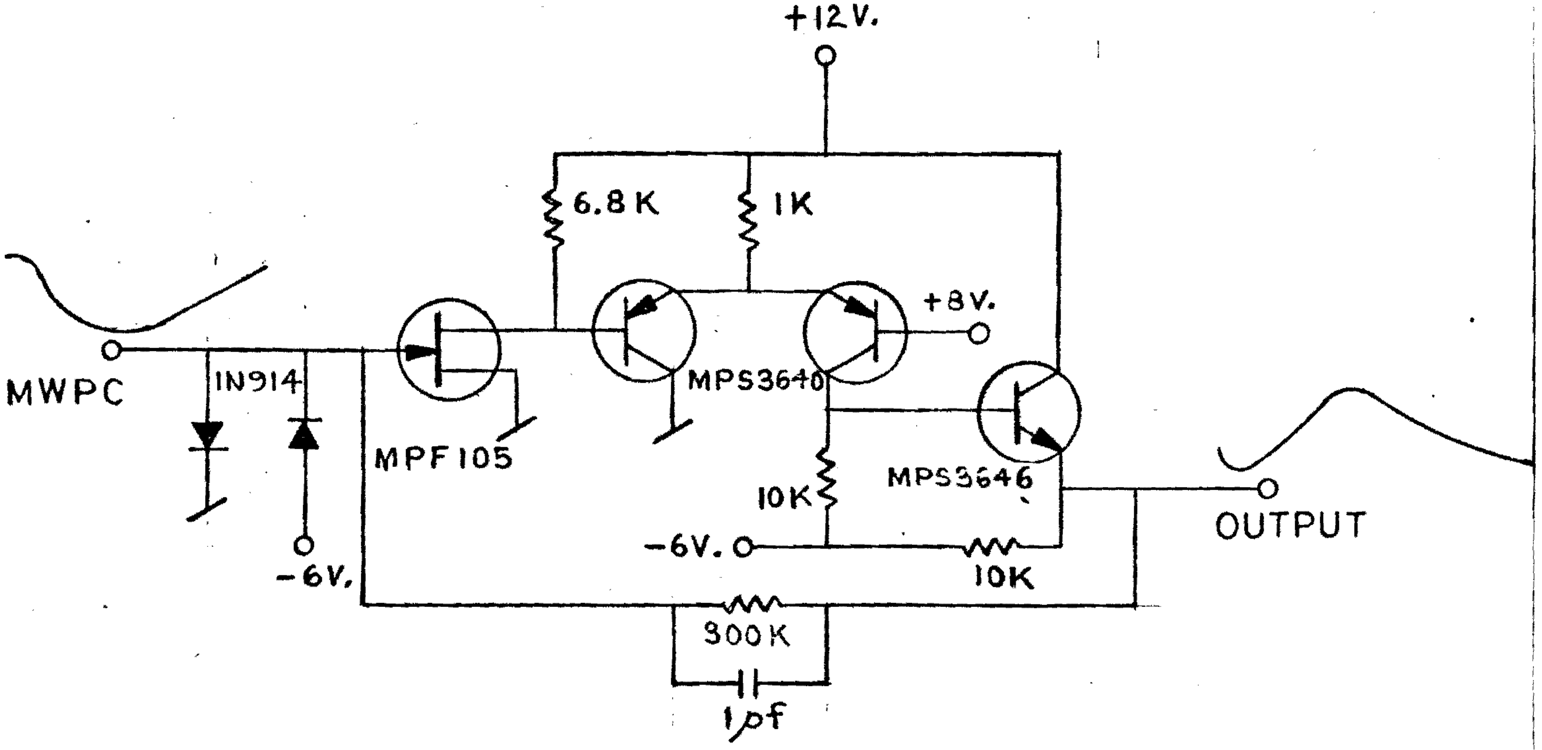
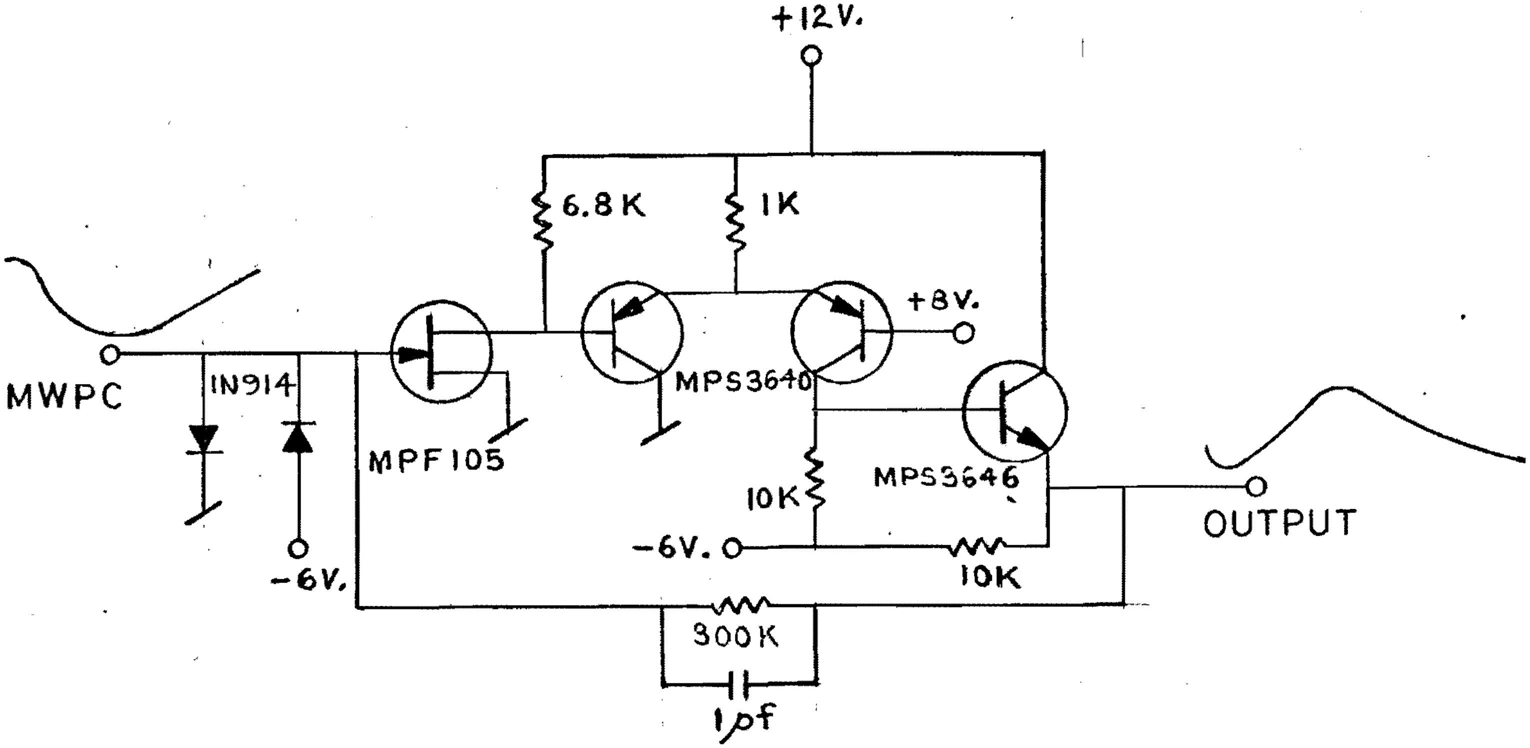


Figure 7 Illustration of possible trigger given by muon and hadrons in coincidence

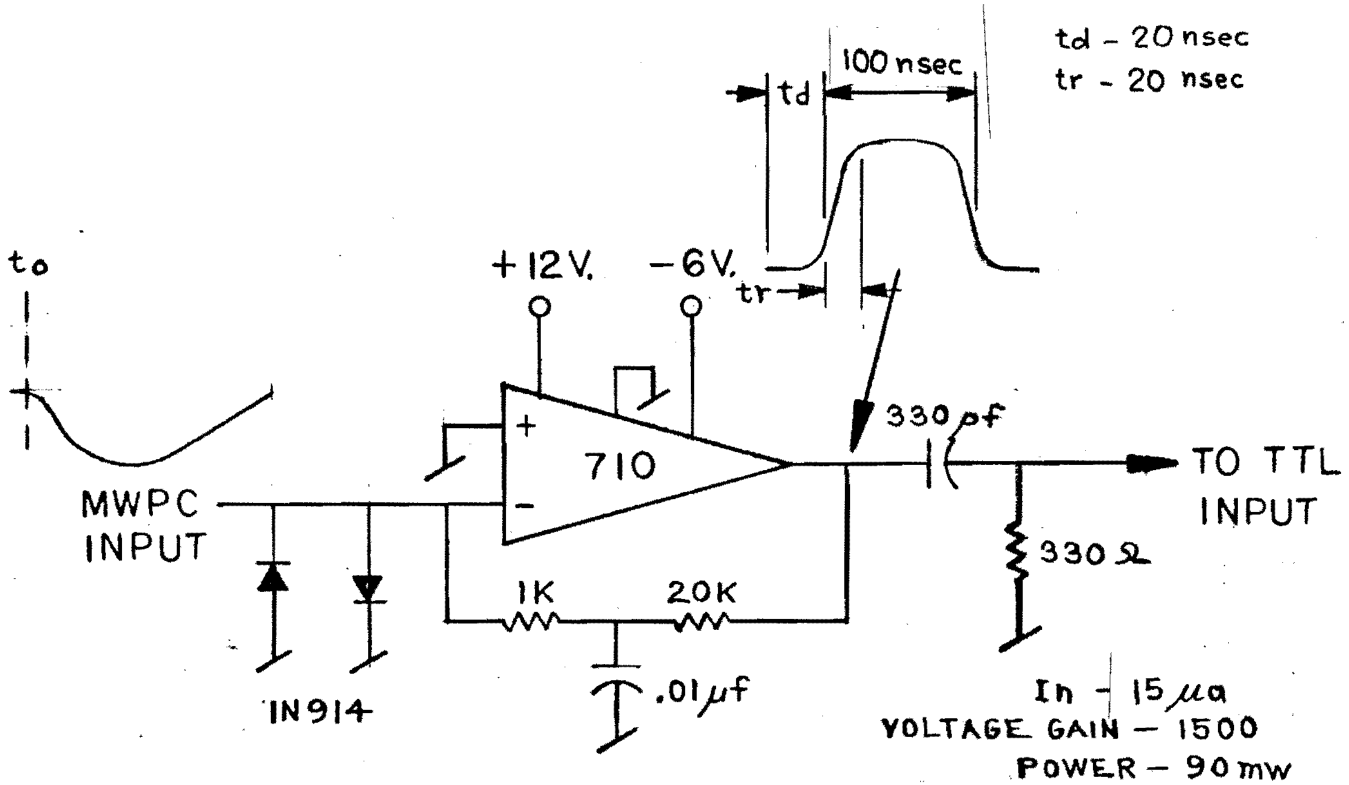


MWPC CHARGE SENSITIVE AMPLIFIER



MWPC CHARGE SENSITIVE AMPLIFIER

FIG. 8



MWPC BASIC VOLTAGE AMPLIFIER

FIG. 9