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NAL PROPOSAL
Spokesman: T.B.W. Kirk
Univ. Illinois
Dept. Physics
Urbana, Ill. 61801

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Proposal For A Program of Muon Scattering at High Intensity

W. Francis, G. Gladding, T. Kirk
University of Illinois
Urbana, Illinois 61801

and

A. Loomis, F. Pipkin, A. Sessoms,
L. Verhey, R. Wilson
Harvard University
Cambridge, Massachusetts 02138

I. Introduction

The great current interest in short distance photon phenomena in both the spacelike[1] and timelike[2] regions of four momentum transfer grew out of the phenomenon of scaling as observed in the inclusive ep scattering through a program of experiments at SLAC.[3] Now, the first results of muon-nucleus inclusive scattering at FNAL[4] and preliminary measurements of muon-nucleon scattering (both inclusive and exclusive),[5] combined with recent measurements of e^+e^- annihilation into hadrons at CEA[6] and SLAC[7] give indications that a new level of structure may be appearing at q^2 values of about 25 $(\text{GeV}/c)^2$. Since anomalies appear in both the spacelike and timelike regions, it seems that far from being completely told, the story of virtual photons is about to enter a rich new phase at distances of order 0.04 fermis or smaller. This would imply masses in the range 5-10 GeV acting as scale breaking structure constants. Whether these masses can be connected with specific constituent models (partons or quarks) is far from clear, but it is reasonable to hope that data describing the behavior of hadron systems excited to these levels by both spacelike and timelike photons will help in our understanding of the new structure. It will be the primary purpose of the experiment presently proposed to make significant advances in obtaining this information for spacelike photons. The means of accomplishing this goal is an upgraded muon-nucleon experimental program in the FNAL muon facility. Other experiments which relate to this program are being discussed and are mentioned at appropriate points below.

There are three basic approaches which can be pursued in a muon-nucleon scattering experiment. The first is the inclusive scattering measurement in which the total virtual photon-nucleon cross-section is determined as a function of the C energy (ν) and the violence of the collision (q^2). This measurement is interesting principally in testing the range of scaling and should be pursued to the highest possible kinematic values. It is of particular interest to perform the high q^2 measurements on hydrogen and deuterium, since nuclear effects in heavy elements could produce anomalous scattering behavior (similar to that observed in proton-nucleus collisions at high transverse momentum).[8]

Once the new scale is found and the cross-section ceases to be pointlike, the principal interest shifts to the second and third types of experiments (understanding the character of the breakdown). Here, information about the final state hadrons or polarization of the muon is required to make further progress. The study of final state hadrons is a natural preserve of the FNAL Muon Scattering Facility. Using this facility, the E-98 collaboration has already made measurements on the final states in a moderate intensity beam. The upgrading necessary to accommodate muon beams up to 10^8 per pulse which then permits us to carry out the proposed program of final state hadron analysis will be outlined below. (The value of this general approach has been well appreciated by the European Muon Collaboration who have very nearly replicated the facility in their proposal of July 1974.)[9]

The study of polarization phenomena deserves separate mention at this point. When the original muon scattering proposal was submitted, it was noted that the natural polarization of the muon beam could be exploited to tell us more about the nucleon structure, provided the target protons were also polarized. Particular emphasis was placed on the applications to the spin of quarks. This interest remains, but the discovery of neutral currents in weak interactions[10] has opened another potentially exciting class of experiments to investigation, namely the interference of the neutral weak current with the (neutral) electromagnetic current. If there is a parity violating term in the weak current, it will produce measurable asymmetries in the scattering of longitudinally polarized muons from <u>unpolarized</u> targets. If the effect is maximal, it will have a magnitude of approximately $10^{-4} \times q^2$. It could well be much reduced from this.[11]

Until the situation becomes clearer, we will not emphasize the neutral current aspects of the proposal (but see Appendix A). We do, however, wish to mention them because of their great potential importance and to assure that the improved muon beam include in its design a provision for forming beams of either muon helicity.

Finally, no muon scattering proposal is complete without a mention of other experiments and embellishments which might be pursued in parallel or subsequently. In this category we might mention the muon trident production which could reignite interest in QED tests, particularly as muon energies climb to 500 GeV and intensities exceed 5×10^7 per pulse. This experiment would be run simultaneously with the inelastic scattering experiment if preliminary calculations show yields appropriate to a QED test. (We plan to scan our present data for trident triggers when pressure eases off on the μp analysis effort.)

There have been suggestions, for a long time, for detailed examination of the particles of low momentum, and/or large angle from the target. A convenient arrangement would be a vertex spectrometer. The LASS detector at SLAC uses a solenoidal magnet preceding just such a forward particle spectrometer as ours. The target might be located inside the cyclotron magnet, but at some sacrifice in measurement of the forward particles. A further alternative is a special vertex magnet surrounding the target, as is proposed, for example, by CERN.

Another possibility is to place the target inside a streamer chamber.

We do not, at present, propose these alternatives, but another group may choose to do so, and we would help or collaborate with them.

Another possibility, which makes good sense once there is a high rate available, is to use a large polarized target to study the helicity dependent form factor. Although eventually we will also want to measure with the polarization <u>transverse</u> to the beam, in the first instance the longitudinal polarization is interesting. This was envisaged in the E-28 proposal and is included in the CERN proposal. We defer it to a later stage of experimenting, and possibly other experimenters.

At the present time, the FNAL muon facility is limited mainly by the beam quality. The very modest muon beam was, in turn, a deliberate choice of the laboratory for a first stage experiment. Now, the success of the first set of experiments seems assured, so the beam and apparatus should be upgraded to explore the exciting region where scaling fails, new structure appears and changes in the behavior of hadron multiplicities, longitudinal and transverse momentum distributions, and electric charge correlations can reasonably be expected. (Certainly, if <u>none</u> of the final state properties change in the new structure regime this would be of remarkable interest by itself!) Our principal goal, therefore, will be to extend the q^2 range of present hydrogen behavior of the final states up to and into the regime of scaling breakdown. The specific way in which we propose to accomplish this is contained in the following sections. Details on how the other experiments mentioned can be carried out require further work and will appear as addenda to this proposal.

III. Beam

The key element in realizing the goals of the proposed experiment is to upgrade the FNAL muon beam. The improvement most urgently needed is an increase in intensity by a factor of 20 to 100 accompanied by a drastic reduction of halo. Increasing the beam energy to 500 GeV* would also be very useful, particularly for the trident experiment. A useful and sensible goal for an improved muon beam might be 10^8 muons with half the machine energy per 10^{13} incident protons. The halo should be less than 10^6 muons per pulse over a 4 meter square cross section at the experiment, and the beam transport should permit selection of either muon charge sign and both muon helicities.

There is by now a large literature on the subject of muon beam design

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* We anticipate that FNAL will be able to deliver beams of 1000 GeV protons in the fairly near future.

beginning with the proposal of Toohig[12] in the 200 GeV Design Study and continuing up to the elaborate study presented to CERN II by the European Muon Collaboration.[9] Most relevant to the present proposal, is the 1973 NAL Summer Study in which attention was devoted to the specific conditions at FNAL. Beams appropriate to these conditions were discussed and a consensus of recommendations was made.[13] We will not attempt to replicate the arguments used to advocate specific approaches, but emphasize the unanimity reached on desirability and feasibility of the general goal. We therefore assume a set of numbers within the limits set forth by that study and use these as a basis for developing the remainder of the proposal. Detailed calculations by the CERN group have borne out the feasibility of the values chosen, and at an appropriate time, a subset of the proposers will be happy to offer their services to the laboratory to decide on a final practical beam and help design it. Our assumed beam parameters are given in Table I below.

Table I

Assumed Parameters of an Improved
Muon Beam at FNAL

Parameter	Assumed Value	Present Value*
Proton Energy	300, 400, 500 GeV	300, 400 GeV
Proton Intensity (on target)	1.0×10^{13} ppp	5.0×10^{12} ppp
Muon Yield at		
150 GeV	1.0×10^{-5} μ/p(300)	1.0×10^{-7} μ/p(300)
150 GeV (opposite helicity)	1.0×10^{-6} μ/p(400)	
225 GeV	1.0×10^{-5} μ/p(400)	1.0×10^{-7} μ/p(400)
500 GeV	1.0×10^{-5} μ/p(1000)	
Beam/Halo	100.0	1.0
Duty Factor (beam on)	0.8	0.5
Efficiency of Use	4×10^{4} pulses/week	3×10^{4} pulses/week
Practical Muon Flux (including = 1 beam req.)	1.5×10^{12} muons/week	1.5×10^{10} muons/week

* Based on an average of E-98 runs in 1974

IV. Apparatus

The Muon Scattering Facility constructed and tested through the joint efforts of E-98 and FNAL physicists has been shown to perform within the design specifications. With rather small upgrading, it can be made useful for accomplishing the increased intensity experiment outlined in the introduction. The most critical parameter is the muon halo which must be kept below about 10^6/pulse if the apparatus is to continue to be useful for studies of final state hadrons. We believe an appropriate beam is possible and proceed under the assumptions given in Table I.

With the halo under control, the only elements which see high instantaneous rates will be the beam telescope, beam veto, target hodoscope, and probably the close-in target veto counters. There will also be a region of the spark chambers in the immediate vicinity of the beam which will have to be deadened (this is done at present, as well). Single muons outside the beam will be no more difficult than in the present beam where they are removed by counter timing and vertex fitting criteria. The once feared problem of multi-track efficiency in the magnetostrictive spark chambers has proved to be absent for more than 5 tracks per chamber, consequently, we no longer worry about a few out-of-time halo muons.

The modifications of the apparatus that are necessary to raise the intensity by a factor of 20 are four-fold. First, we must replace the beam MWPC's with a set of small scintillation counter hodoscopes. Second, we will need to place another small scintillation counter array downstream of the target to replace the present 1m x 1m MWPC's. (The fact that we lose a significant amount of sensitivity in vertex resolution is compensated by the larger scattering angles which will obtain for the new range of q^2.) Third, we will extend the scattered muon hodoscopes (M + M') obtain better acceptance at high q^2. Fourth, we will need a few more veto counters to intercept halo which presently bends into the trigger counters as it passes through the yoke field of the CCM. All four modifications are straightforward and moderate in cost. The halo veto counters will be added before our next run if we can prepare them in time. The new beam scintillation hodoscopes could be the set currently on loan to BNL from FNAL which were used in a previous muon experiment. They would probably need overhauling and reconditioning. The scattered particle hodoscope downstream of the target would be new and furnished by the proposers. The extended $(M + M')$ hodoscopes will increase the acceptance for high q^2 events and exploit the large hadron absorber already in place. The increase is evident in Figure 2 where the original acceptance is shown with dashed lines and the new acceptance with solid lines. The additional hodoscope area is not presently planned to be covered by spark chambers as we feel a counter coincidence is sufficient in regions this far from the beam.

There will also be some modifications of the electronics, but these changes are better described as they relate to the trigger system. All the other apparatus remains essentially as is. A simple drawing of the proposed new experiment is shown in Figure 1; a representative set of E', q^2 locii are shown in Figure 2 for a qualitative visualization of how acceptance relates to geometry.

V. Trigger

The trigger for the present muon scattering experiment E-98, is essentially an energy loss trigger. This requires that the muon comes in through the momentum tagging system, loses energy before entering the CCM and is bent out of the beam by virtue of this energy loss. No. q^2 requirement is imposed. Symbolically:

$$T = B \cdot \bar{V}_B \cdot (M+M') \cdot G = \text{trigger}$$

where

$B = T1 \cdot T2 \cdot T3 \cdot T4 \cdot \bar{V}$ = beam

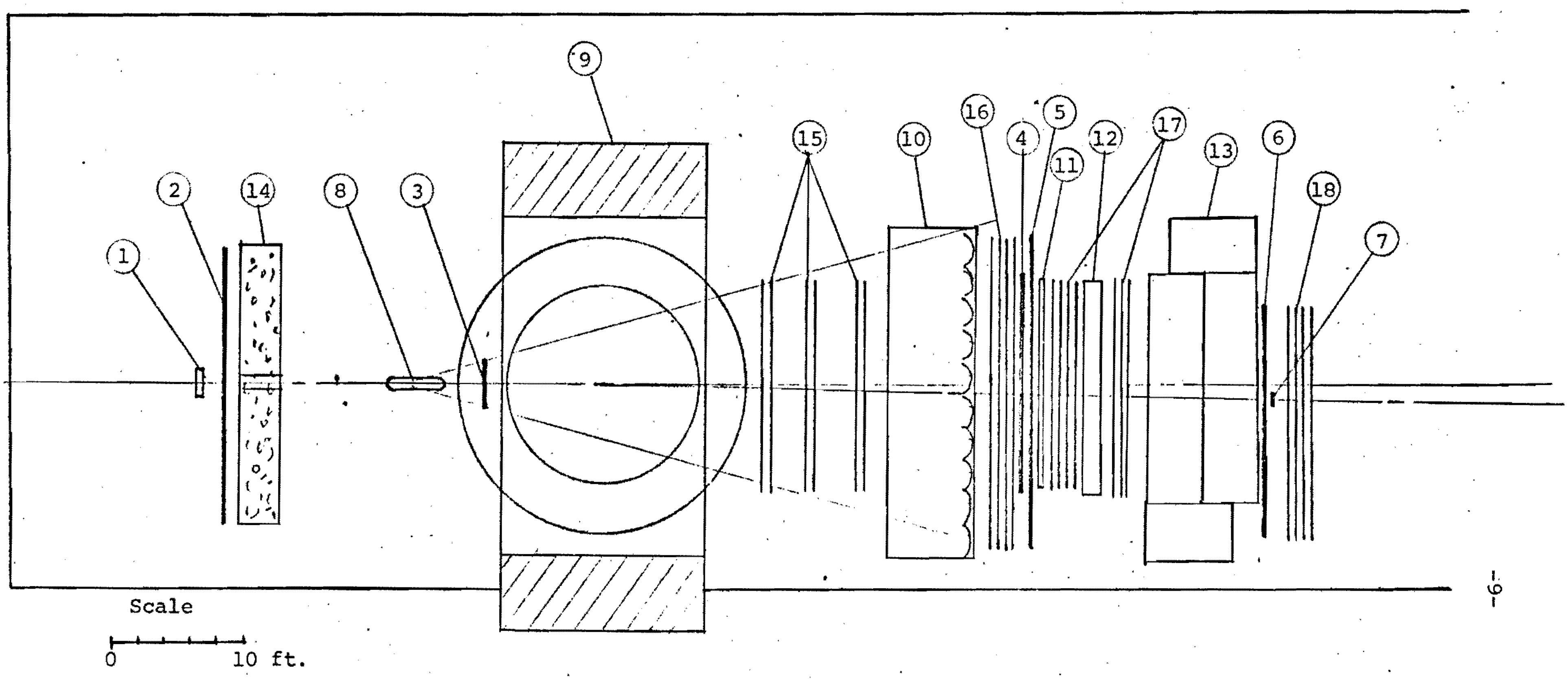
V_B = small beam veto behind apparatus

M = scattered muon hodoscope y elements

M' = scattered muon hodoscope, x elements

G = large bank of hadron tagging counters

V = large halo veto in front of target; various beam vetos



1. BEAM XY HODOSCOPE
2. VETO COUNTER ARRAY "V"
3. SCATTERED PARTICLE Y HODOSCOPE "S"
4. HADRON X HODOSCOPE "H"
5. HADRON Y HODOSCOPE "G"
6. MYON XY HODOSCOPE "M,M'"
7. BEAM VETO "VB"
8. 1.2M LH_2, LD_2 TARGET
9. CHICAGO CYCLOTRON MAGNET
10. SEGMENTED GAS CERENKOV COUNTER "Č"
11. 2" FE PHOTON CONVERTER
12. 16" PB PHOTON ABSORBER
13. 120" FE HADRON ABSORBER
14. 60" CONCRETE BACKSCATTER SHIELD
15. 2Mx4M SPARK CHAMBERS
16. 2Mx6M SPARK CHAMBERS
17. 2Mx4M SPARK CHAMBERS
18. 2Mx4M SPARK CHAMBERS

FIG. 1.

EXPERIMENTAL LAYOUT IN MUON LAB.

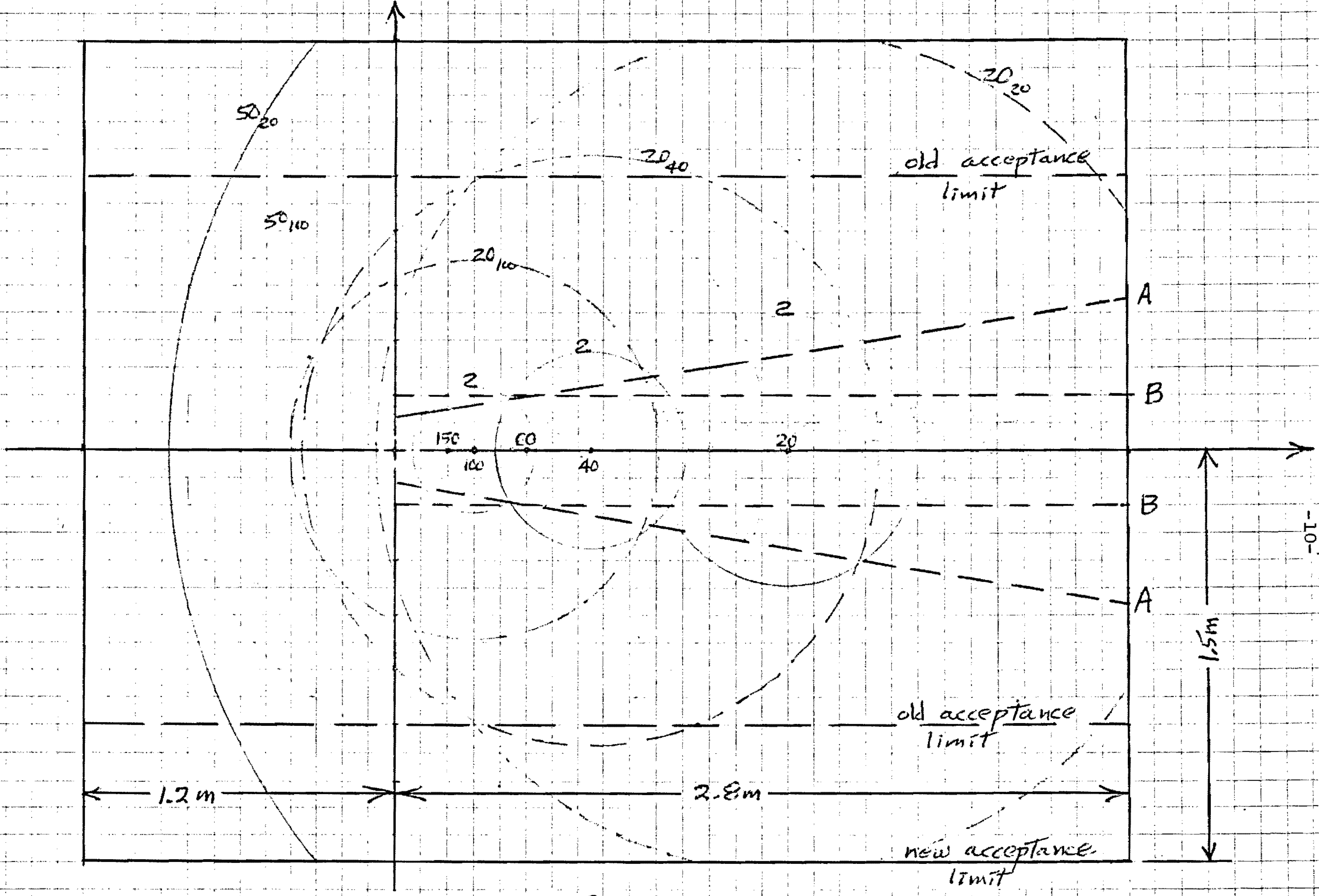


FIG 2.

CIRCLES OF CONSTANT q^2 ARE SHOWN FOR VARIOUS VALUES
OF E'. E IS TAKEN AS 150 GEV. ACCEPTANCE IS
DETERMINED AT THE M, M' HODOSCOPES

Two banks of scattered muon hodoscopes are used in logical OR to compensate small inefficiencies in either. No redundancy is needed in the beam counters since the beam inefficiency cancels out identically in the cross-section. The G counter bank inefficiencies are effectively compensated by the fact that several counters are hit in each event so that an effective OR is achieved by the $(G \geq 1)$ logical requirement. This "simple" trigger is shown in Fig. 3.

The result of using energy loss as a trigger is to enable us to reach very low q^2 values. At the same time, the other low q^2 muon scattering processes, μe and $\mu\gamma$ contribute heavily to the rate. The μe process, in fact, currently dominates the trigger. We now have enough data on the low q^2 μN scattering to drop the restriction on simple energy loss. When this is done, we impose a minimum q^2 on the trigger and drop the real trigger rate by the appropriate factor of 50. The proposed new trigger is described next.

It can be shown that for high energy processes (where P, E >> m), $q^2 \sim \left(\frac{E}{E'}\right) p_\perp^2$ where $p_\perp$ is the component of the final muon momentum perpendicular to the beam. The vertical component of the final muon momentum is therefore connected to q^2 through the relationship:

$$p_y = p \ \sin\phi = \sqrt{\frac{E'q^2}{E}} \ \sin\phi \qquad .$$

Thus, any trigger which seeks to isolate events with $q^2 > q^2_{min}$, needs only to restrict the vertical scattering angle to values larger than some minimum, and the q^2 will, of necessity, be larger than q^2_{min}. We choose a <u>vertical</u> requirement for the obvious reason that the cyclotron magnet does not bend in that direction. If we wanted to make a sharp cut in q^2_{min}, we would make θ a function of E' (line A in Fig. 2). It is probably more practical to use a <u>constant vertical angle</u> requirement and impose a fuzzy q^2_{min} in terms of the overall rate. The acceptance must needs be computed on an event to event basis in either case. Consequently, we will probably choose the line E in Fig. 2 as our definition of minimum scattering angle.

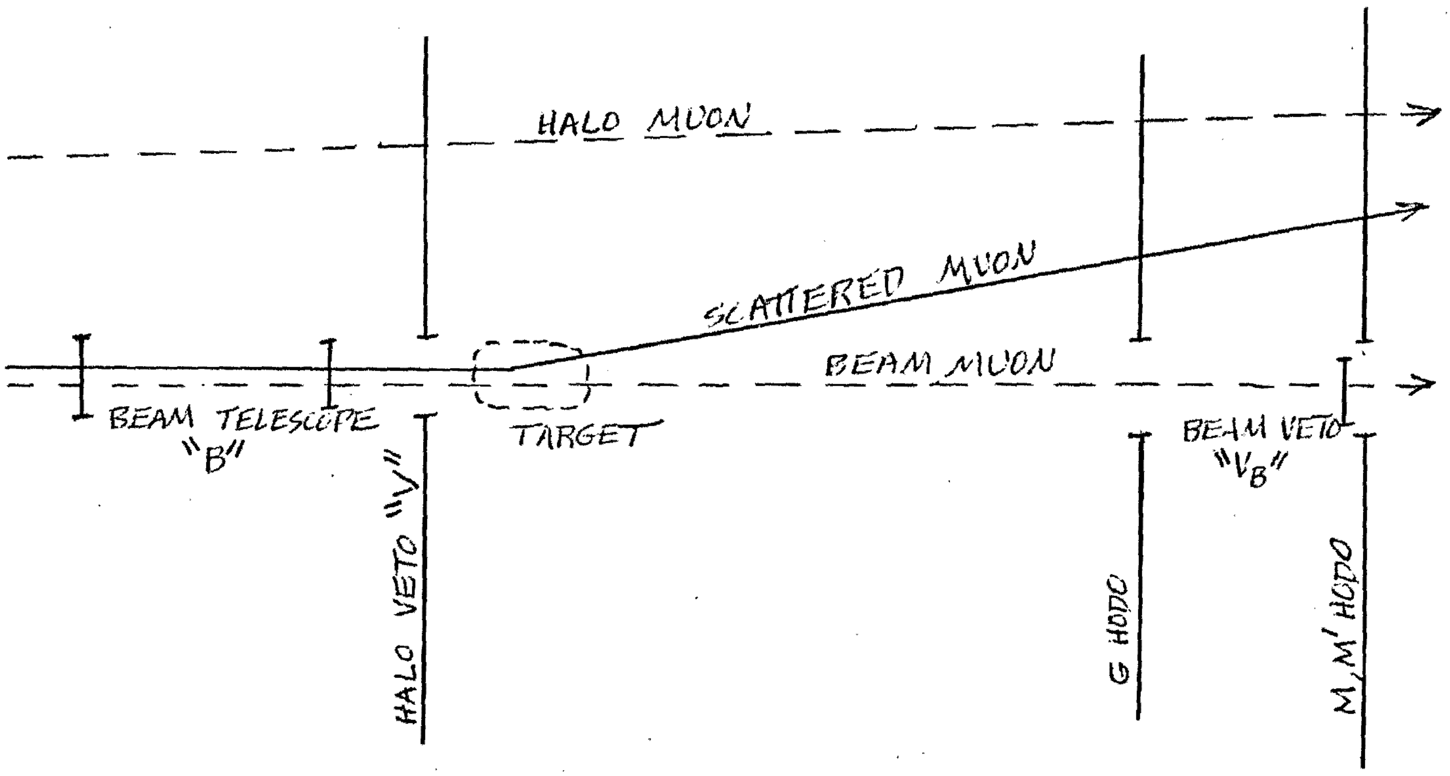


FIG. 3.
SCHEMATIC OF "SIMPLE" TRIGGER SCHEME

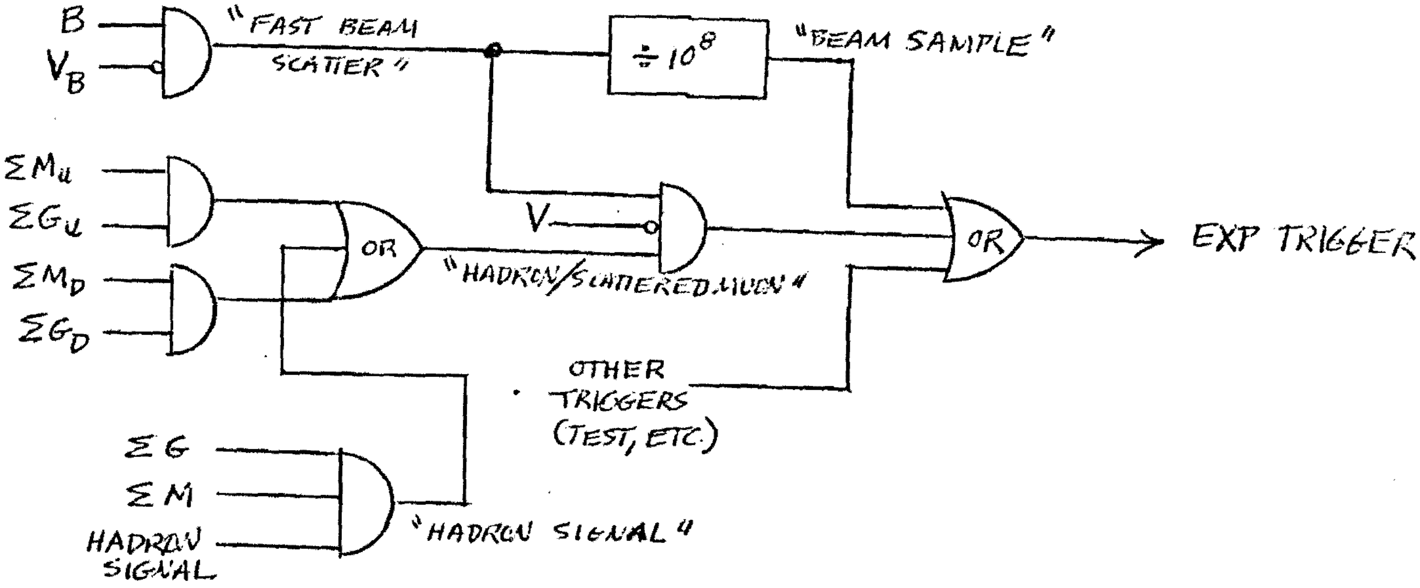


FIG. 4.
SCHEMATIC TRIGGER SCHEME
(TRIGGERS LATCHED AND INCLUDED
IN RECORDED DATA)

In addition to the vertical scattering requirement in the muon and hadron hodoscopes, we will continue to use the requirement that the muon has disappeared from the beam, by using a "beam veto". Such a counter vetoes any event where a muon stays in the beam behind the hadron absorber; for good measure we will also veto events with more than one muon in the beam hodoscope counters during the 6 ns coincidence resolving time. This will reduce random triggers and insure a clean signal from the beam defining hodoscopes. At a beam rate of 10^8 per pulse there will be an overage of 2 particles in each 20 nanosecond machine bucket, so that most events will be vetoed if the present machine RF structure is retained.

Accordingly, we ask for a beam with the RF structure removed, and will operate in this beam with a 6 nanosec resolution time. To do this successfully we will change the beam veto counter to a Cherenkov counter, and use fast photomultiplier tubes producing narrow pulses. Conversations with members of the Accelerator division convince us that this RF structure could be smoothed to a duty factor of 0.8.

We have considered eliminating the beam veto element entirely. It is possible we could subdivide the counters and demand a track coming from the target, and we will be prepared to do this. But the trigger we propose is a simple extension of the present trigger, already well developed at BNL and NAL and is therefore well understood.

Our main trigger then becomes, with the above notation:

$$T = (B=1) \cdot \bar{V}_B \cdot (M_U+D_D+M'_U+M'_U) \cdot (G_U+G_D)$$

where the U,D subscripts mean up and down respectively. The counters in the midplane would be latched but not included in the trigger.

The trigger scheme we propose is a "high q^2" trigger and will eliminate events with $q^2 < q^2_{min}$. Already in our first look at the E-98 data, it is clear that there will probably be some specific channels for which statistics will be inadequate. Accordingly, we will be prepared with alternate triggers which will allow low q^2 events to trigger the apparatus, provided that an event of interest - a ρ' meson for example - has been produced at the same time. These will be put in logical OR as shown in Fig. 4 which permits simultaneous data acquisition.

By this means, we will be able to study specific processes at low q^2 in addition to the main high q^2 experiment discussed. We will decide which processes are actually of interest as analysis of our current experiment proceeds, reporting results in the form of addenda to this proposal.

We have not explicitly mentioned accidentals yet, but experience has already shown us the principal source of these triggers. They come from halo muons in accidental coincidence with beam particles either missing the beam veto or not counting in it. This rate for present intensities is about 1 per pulse. We expect to tighten this up by a factor 10 through the use of CCM yoke veto counters and a more restrictive beam telescope. We can tolerate the ensuing random trigger rate of 5 per pulse since our deadtime will be reduced to 20 ms by improvements to the "read in" electronics already underway. If the halo flux missing the planned vetoes is still too large, we could impose a horizontal angle logic in the trigger using the H and M' hodoscopes, but we do not expect this to be a serious problem. It is probably better to use our current method of seeking out "halo hot spots" and placing veto counters there. If the halo flux is 10^6/pulse, we should lose only 6% of our live time to the halo veto. This is acceptable, but it points out the crucial role of halo suppression in the beam design.

VI. Rates

Under the conditions described in the sections on Beam, Apparatus and Trigger we can calculate the event rates for muons scattered by the present 1.2 meter liquid hydrogen target. In order to separate the yield of the experiment from the assumptions about the beam and accelerator performance, the rates are quoted per 10^{12} beam muons. According to the assumed parameters, this number of muons should take about one week. Two considerations should be borne in mind before beginning to think of the experiment as a "one week run". The first is the usual one that between the first presentation of a proposal and the final publication of data, a cumulative net loss factor of between two and ten seems to creep in. This is particularly true when new facilities or beams are proposed. The present proposal is conservative in this respect.

Secondly, the desire to study the hadron properties and exclusive channels with acceptable statistics amplifies the need for many events. Accordingly, we would anticipate a need for about 6×10^{12} muons total, observing that this should take about six weeks on the nominal schedule adopted and still provide statistics at each of three beam energies.

With these circumstances in mind, we request the following fluxes:

Energy	Target	Total Muon Flux
150	LH_2	1.0×10^{12}
150	LD_2	1.0×10^{12}
225	LH_2	1.0×10^{12}
225	LD_2	1.0×10^{12}
500*	LH_2	1.0×10^{12}
500	LD_2	1.0×10^{12}

The yield corresponding to this target illumination is shown in Figures 5, 6 and 7 for hydrogen with the stated assumptions about the cross section behavior. The yields for deuterium will be greater than for hydrogen by about 30% corresponding to the smaller total virtual photon cross-section for the neutron. All of the rates were calculated using the acceptance program currently used for the E-98 data analysis.

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* The last assumes that Fermilab will reach 1000 GeV in the near future.

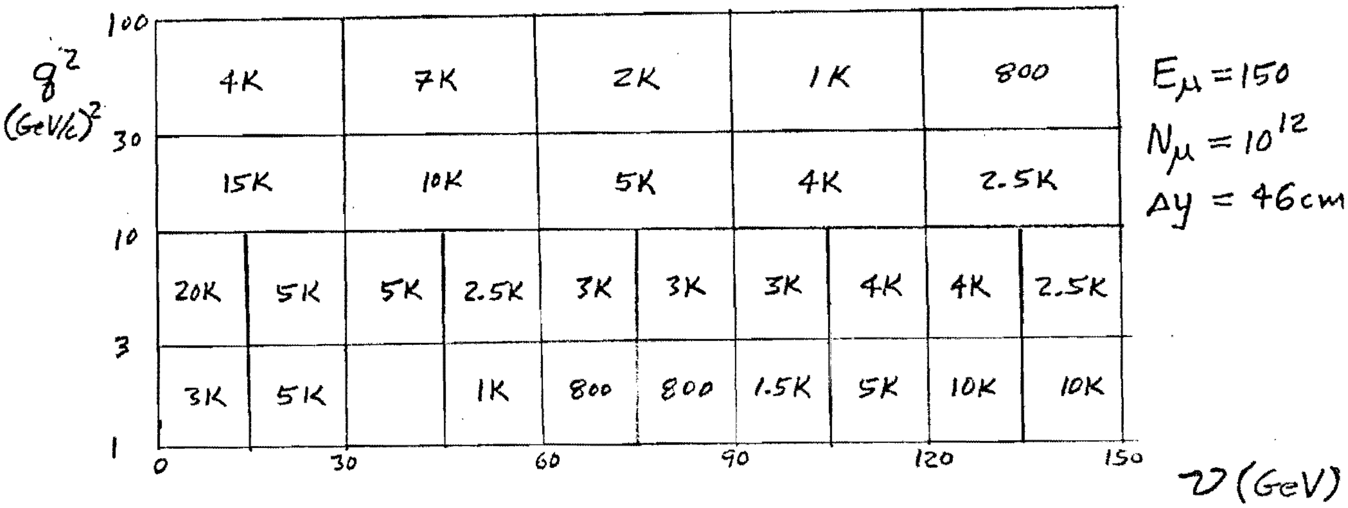

FIG. 5.

RATES FOR 150 GeV BEAM

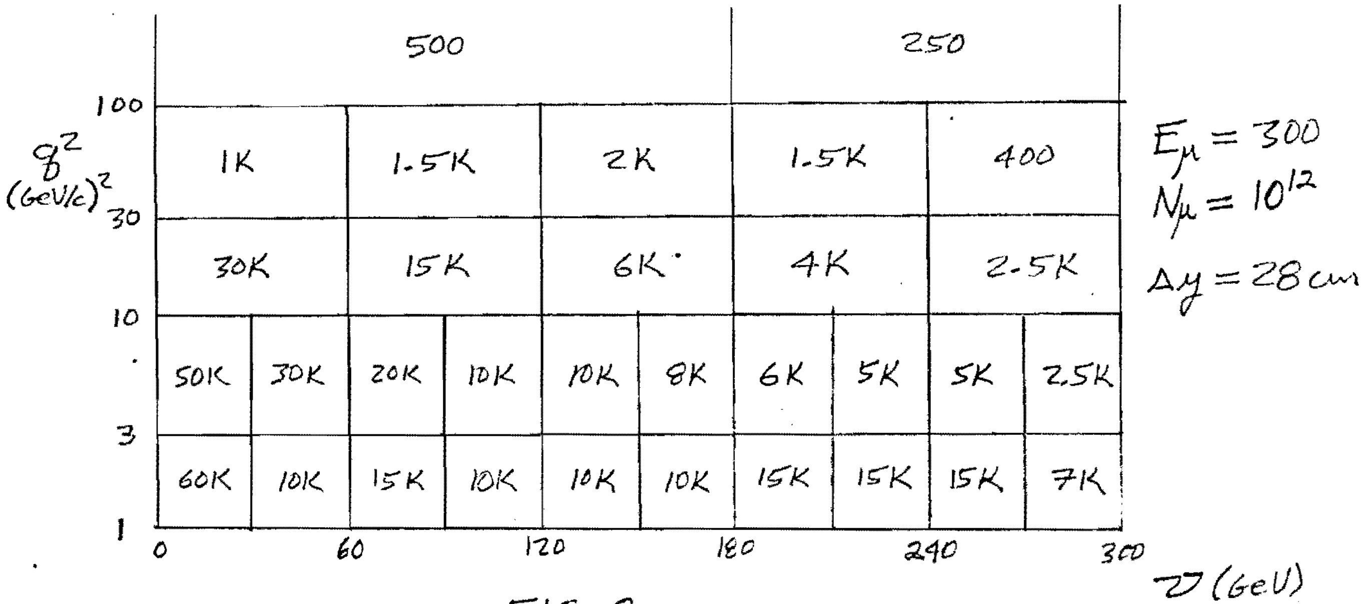

FIG. 6

RATES FOR 300 GeV BEAM

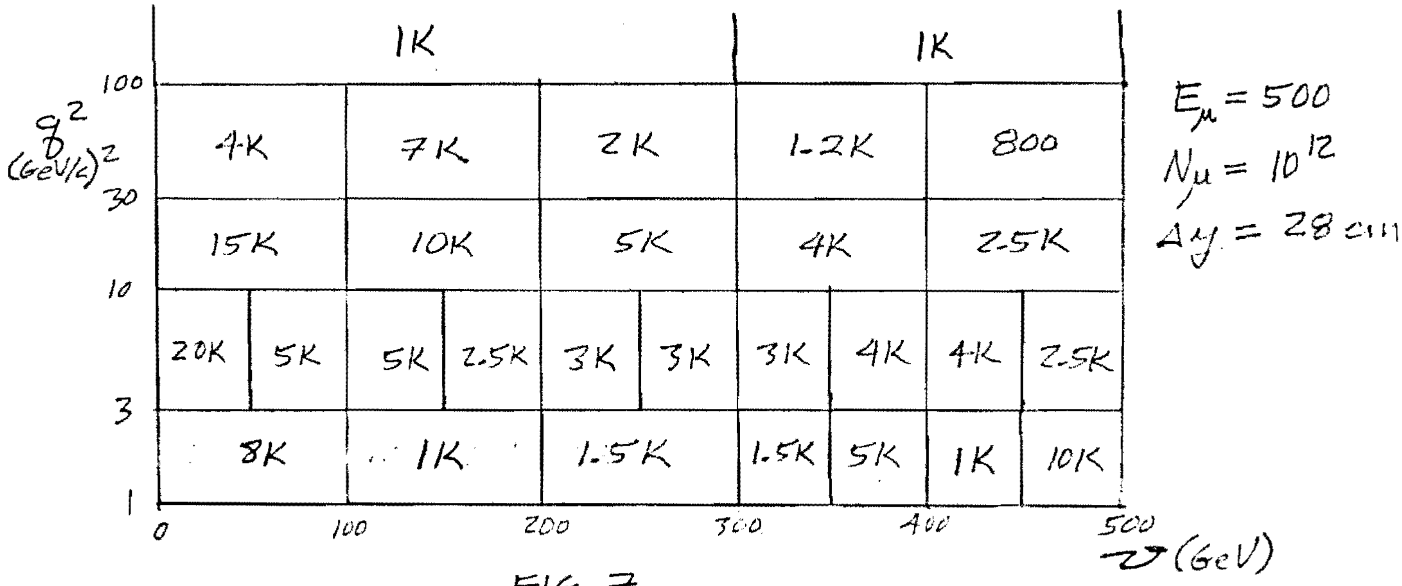

FIG. 7

RATES FOR 500 GeV BEAM

VII. Logistics and Timing

By virtue of the new beam required, this proposal is clearly not of an "add-on" character. Just the same, we feel that a second generation of muon nucleon scattering experiments with a first class muon beam is an important step for FNAL to take and that it will yield physics rich enough to justify an appreciable investment. We certainly feel that the present muon scattering program is fulfilling its purpose and yielding interesting and unique data. This is clearly the feeling in Europe, where a very elaborate muon beam and spectrometer are being designed to carry the work done at FNAL to higher q^2 values. We would like to have a chance to extend our own work as well.

If the laboratory agrees with the notion of constructing a high intensity, high quality muon beam, there are still the questions of when and where to be answered. We, of course, would like to argue that "when" be as soon as a beam can be designed and constructed. The question of "where" has already been discussed by people interested in using a new beam. Various locations have been proposed, some leading to the present muon scattering facility and some to a relocated or newly built facility. The question has been raised, is the present facility, with modifications, the best facility for a program of high intensity muon scattering? We believe the answer is "yes", and the CERN proposal shows that they do also. Therefore, we feel that replicating the present muon scattering facility elsewhere is likely to make sense only if it were technically impossible to construct a new beam along the current neutrino beam line. We would strongly prefer the beam be directed to the present highly developed facility. Advantages in preparation time as well as construction money favor using the current equipment in its present location.

The people listed as proposers represent an initial complement, and will probably be joined by others interested in this type of work. All of the new capital items mentioned can be provided by the present proposers.

APPENDIX A

Neutral Current Asymmetry Measurements

Several calculations of the asymmetry for opposite charges, normal helicity give

$$A^{+-} = \frac{\sigma_{\mu^+L} - \sigma_{\mu^-R}}{\sigma_{\mu^+L} + \sigma_{\mu^-R}} \sim 10^{-4}\, q^2 \qquad (q^2 \text{ in } (\text{GeV}/c)^2)$$

where L, R correspond to left- or right-handed helicity. This result is model-dependent, but not a function of the V, A coupling of the neutral weak current. The presence of two-photon effects which can also cause asymmetries of this type, can be confusing. Fortunately, the two-photon effects will have a ln q^2 dependence and so a measurement at several values of q^2 can establish the cause of an observed effect.

The opposite helicity, fixed charge asymmetries, A^{++} and A^{--} are not modified by two-photon exchange, but they are very sensitive to the coupling of the weak vector meson and to the chosen model.

If continuing work indicates a favorable outlook for this experiment, we will propose to measure A^{+-} and A^{++} and we present here a preliminary estimate of the errors on the asymmetry based on the following assumptions:

E_μ = 300 GeV
Tgt = 200 g/cm^2 Fe (∿ 12)
300 GeV π, μ^{+L} Intensity = 6×10^7 μ/pulse
520 GeV π, μ^{-R} Intensity = 2×10^7 μ/pulse
300 GeV π, μ^{+r} Intensity = 6×10^6 μ/pulse
Repetition rate = 10 pulses/min
Polarization = 0.7
Running Time = 500 hours (200 hours μ^{+1}, 300 hours μ^{-R})

For $\Delta\Delta_\mu^{+-} = \frac{1}{2p} \quad \frac{1}{N^+} + \frac{1}{N^-}$ where p = polarization,

$N^{\pm}$ = the number of events accepted for positive (negative) muons, we get

APPENDIX A

q^2	ΔA_μ^{+-}	expected
30	10^{-4}	3×10^{-3}
100	3×10^{-3}	10^{-2}

This corresponds to $\sim 10^{13}$ muons total (about 5×10^{12} muons of each sign)

For A_μ^{++}, we need to run additional 500 hours of abnormal helicity μ^{-R}, this then yields the same accuracy as for A_μ^{+-}.

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