PROPOSAL FOR THE

INVESTIGATION OF VIRTUAL PHOTOABSORPTION BY NUCLEAR MATTER

FROM

THE CHICAGO-HARVARD-ILLINOIS-OXFORD MUON COLLABORATION

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Abstract

The behavior of muon nucleus scattering presents an apparent paradox which can possibly be resolved by various forms of Generalized Vector Dominance. The experimental investigation of the paradox requires that data be taken at very large values of the scaling parameter

$$\omega = \frac{2\ M\nu}{q^2}$$

The Muon Scattering Facility is ideally and uniquely equipped for these studies and we propose to carry out the investigation.

Introduction

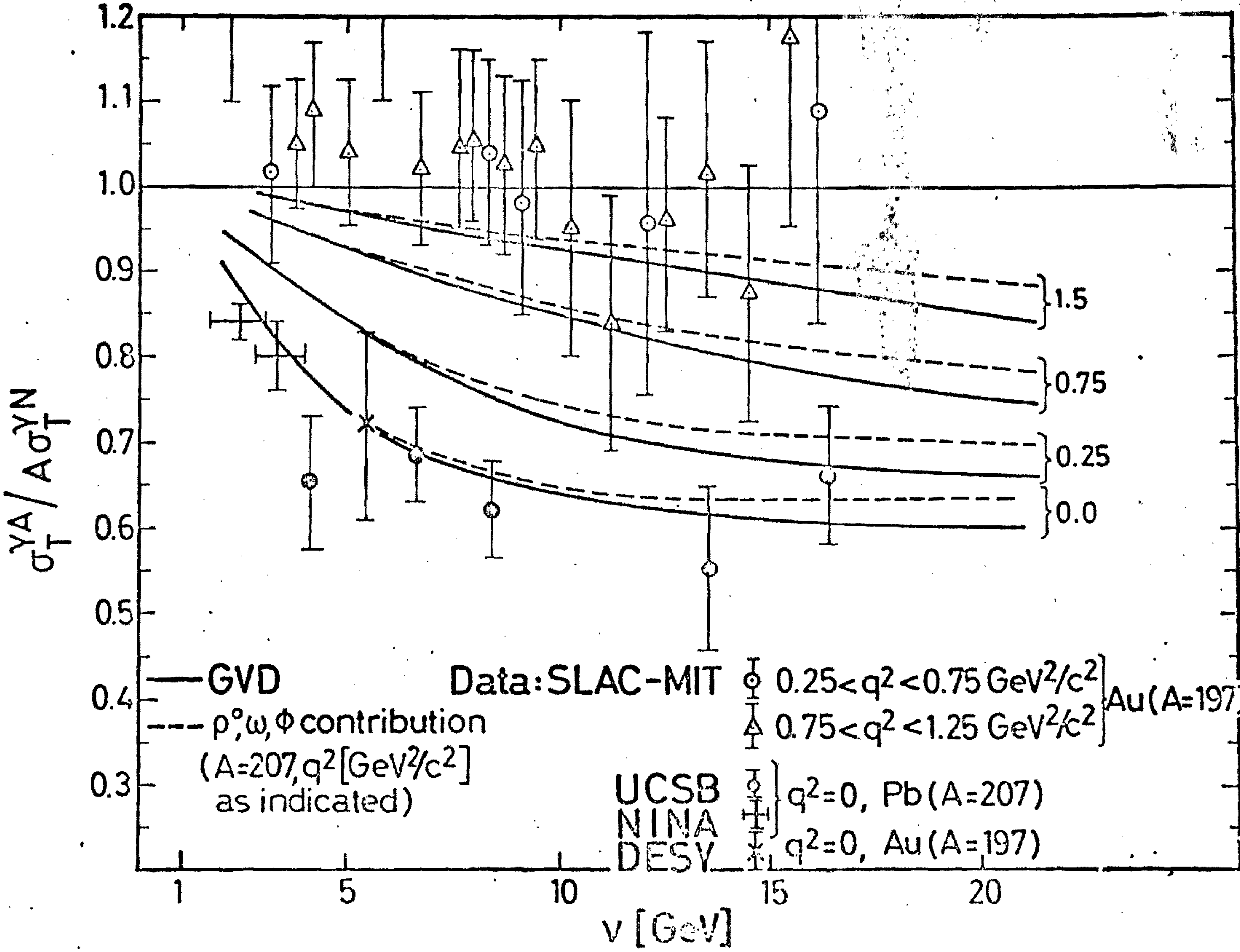
It long seemed obvious that nuclei should be transparent to γ rays of any energy, since the total cross section for γ rays on protons -- 125 μb -- is much less than the "geometric" cross section of a proton -- 40 mb. Yet measurements[1] made with real photons with energies greater than a few GeV shown in Figure 1, shows that $\sigma_T(\gamma A)/A\ \sigma_T(\gamma N)$ is much less than 1 indicating opacity.

Several calculations[2] have been made to describe this phenomenon. The opacity is assumed to arise from the existence of the vector mesons ρ^o ω^o ϕ^o, (and now presumably ρ', ψ, ψ' also) which have the same quantum numbers as the photon, and strong interactions. At a high enough energy, the mass difference is negligible in the sense that the photon and a rho meson will stay in phase over a distance the size of a nucleus, then the photon can appear to have the strong interactions of the rho meson in spite of the low total cross section.

The critical parameter which separates the two variables -- transparency and opacity -- is the ratio $k/m_V^2\lambda$ where k is the γ ray energy, λ is the absorption length of the vector meson in nuclear matter and m_V is the mass of the vector meson. When this parameter is large compared with unity, nuclei will show shadowing; when small, transparency. The lines in figure 1 are calculations by Schildnecht[2] according to the theory of Generalized Vector Dominance (GVD) where many vector mesons are included.

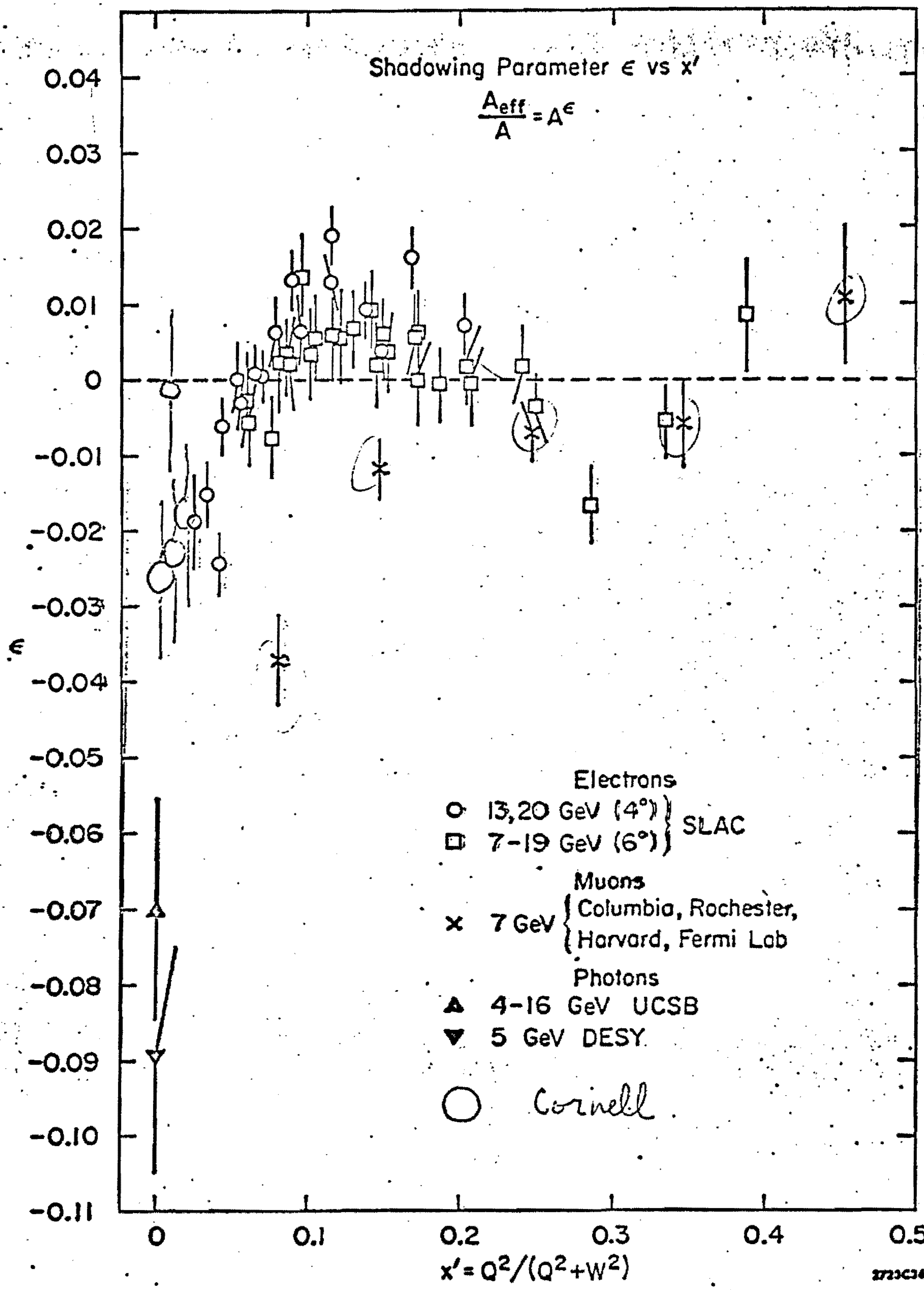
The calculations should also apply to virtual photons. The dimensionless parameter then becomes $\nu/[\lambda(m_V^2 + q^2)]$. This is closely related to the scaling variable $\omega = 2M\nu/q^2 \approx (2M\lambda)$ $\nu/[\lambda(m_V^2 + q^2)]$. The experiments that have been performed so far have not shown so much shadowing a shown in figures 1, 2 and 3. This distinction is not understood and, indeed, it is hard to conceive of a reason.

It is the prupose of this proposed experiment to search systematically for this effect with virtual photons.



1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1.5
0.75
0.25
0.0
GVD
ρ°,ω,Φ contribution
(A=207, q²[GeV²/c²] as indicated)
Data: SLAC-MIT
0.25 < q² < 0.75 GeV²/c²
0.75 < q² < 1.25 GeV²/c²
Au(A=197)
UCSB
NINA
DESY
q²=0, Pb(A=207)
q²=0, Au(A=197)
1
5
10
15
20
ν [GeV]

Fig. 1



Shadowing Parameter ε vs x′
$\frac{A_{eff}}{A} = A^{\epsilon}$
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.10
-0.11
ε
Electrons
13,20 GeV (4°)
7-19 GeV (6°)
SLAC
Muons
7 GeV
Columbia, Rochester,
Harvard, Fermi Lab
Photons
4-16 GeV UCSB
5 GeV DESY
Cornell
0
0.1
0.2
0.3
0.4
0.5
x′ = Q²/(Q²+W²)

Figure 2

Advantages of Fermilab muon spectrometer

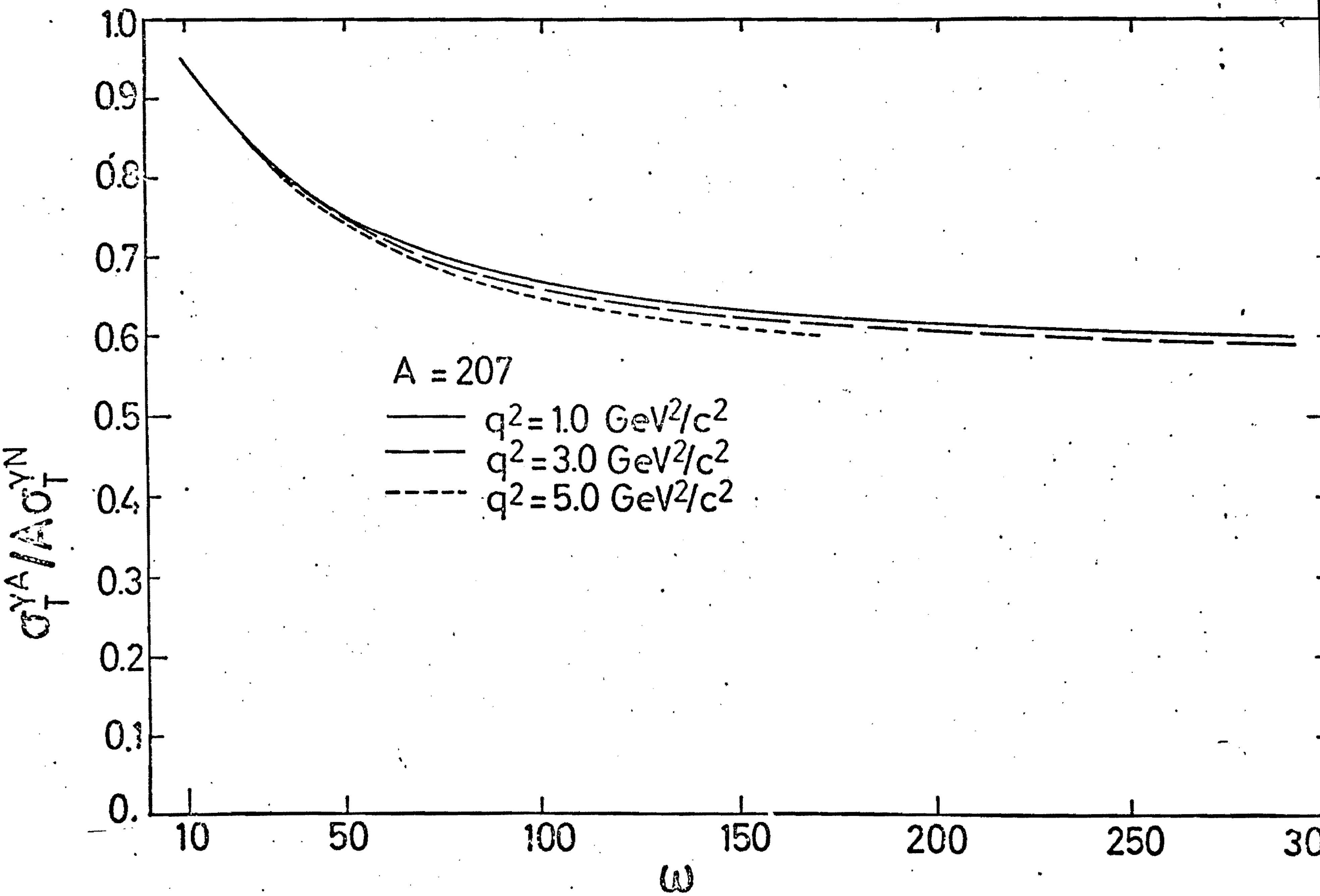
All but one of the pervious experiments with virtual photons used inelastic electron scattering as the source of virtual photons. For small values of q^2, the radiative correction can be very large (up to 90% of the measured cross section) and it has therefore been speculated that the radiative correction has been incorrectly calculated (particularly at high Z where Born's approximation fails) and the effect has been masked.

A recent experiment at Cornell (figure 3) considers only the scattering when a hadron has been emitted and therefore the radiative correction is reduced -- nonetheless the full shadowing effect was not observed. Some shadowing was observed with 7 GeV muon scattering as shown in figure 1.

The radiative correction for muons is less than that for electrons by the factor

$$\log\,(q^2/m_\mu^2)\;/\;\log\,(q^2/m_e^2)$$

Moreover the large solid angle muon scattering spectrometer used for E98 and E398 allows the detection of the radiative γ ray when it has a large energy, or a single hadron, like the Cornell experiment, or rho and rho prime mesons. The energies available at Fermilab allow much higher values of ω than available at other accelerators. According to the calculations of Generalized Vector Dominance, the shadowing should become more complete at high ω (figure 4). It is conceivable that the theory is basically correct, but that the full shadowing appears at higher values of ω.



A = 207
q² = 1.0 GeV²/c²
q² = 3.0 GeV²/c²
q² = 5.0 GeV²/c²
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.
10
50
100
150
200
250
300
ω

Fig. 4

The full shadowing effect (high ω) expected does not seem to depend much on which calculation (Brodsky-Pumplin; Gottfried Yennie; Schildknecht) is used. As shown in Table I.

TABLE I

$\frac{\sigma(\gamma A)}{A\,\sigma(\gamma\ \text{nucleon})}$	Nucleus	A
1	½(H) + ½(N)	1
0.93	D	2
0.77	Be	9
0.69	Al	27
0.61	Cu	64
0.51	Pb	207

This could be appreciably watered down for some reason, but the A dependence is a function of nuclear radius and is likely to have the same form no matter which vector mesons are involved and what the photon-vector meson couplings are.

The theory suggests that the shadowing effect should disappear as ω' decreases, as $1/(q^2 + m^2) \approx 1/(q^2 + 0.5)$. As $q^2 \to 0$, we should find the same effect as found for real photons. It is therefore important to make measurements at low values of q^2 -- down to $q^2 = 0.1\ (\text{GeV/c})^2$, where the virtual photon-proton cross section is close to the real photon proton cross section.

The Cornell measurements of figure 3 are at $q^2 = 0.1\ (\text{GeV/c})^2$ and are therefore particularly puzzling.

According to the parton model $\int \nu W_2 dx$ $(x = q^2/2M\nu)$ defines the charges of the partons, and therefore should be strictly proportional to A; at low x (high ω) there should be shadowing, so that this must be compensated by an antishadowing or increase at moderate x. This illustrates the importance of measuring over a wide range of ω.

Measurement of ρ and ρ'

There should be a shadowing in the production of ρ and ρ' mesons; and it is possible that there is shadowing for ρ production but not for the total virtual photon cross section -- we note that rho production varies roughly as $1/q^2 + m_\rho^2)^2 \approx 1/(q^2 + 0.5)^2$ (figure 5) whereas the total virtual photon-proton cross section varies more slowly, as $1/(q^2 + 0.7)$.

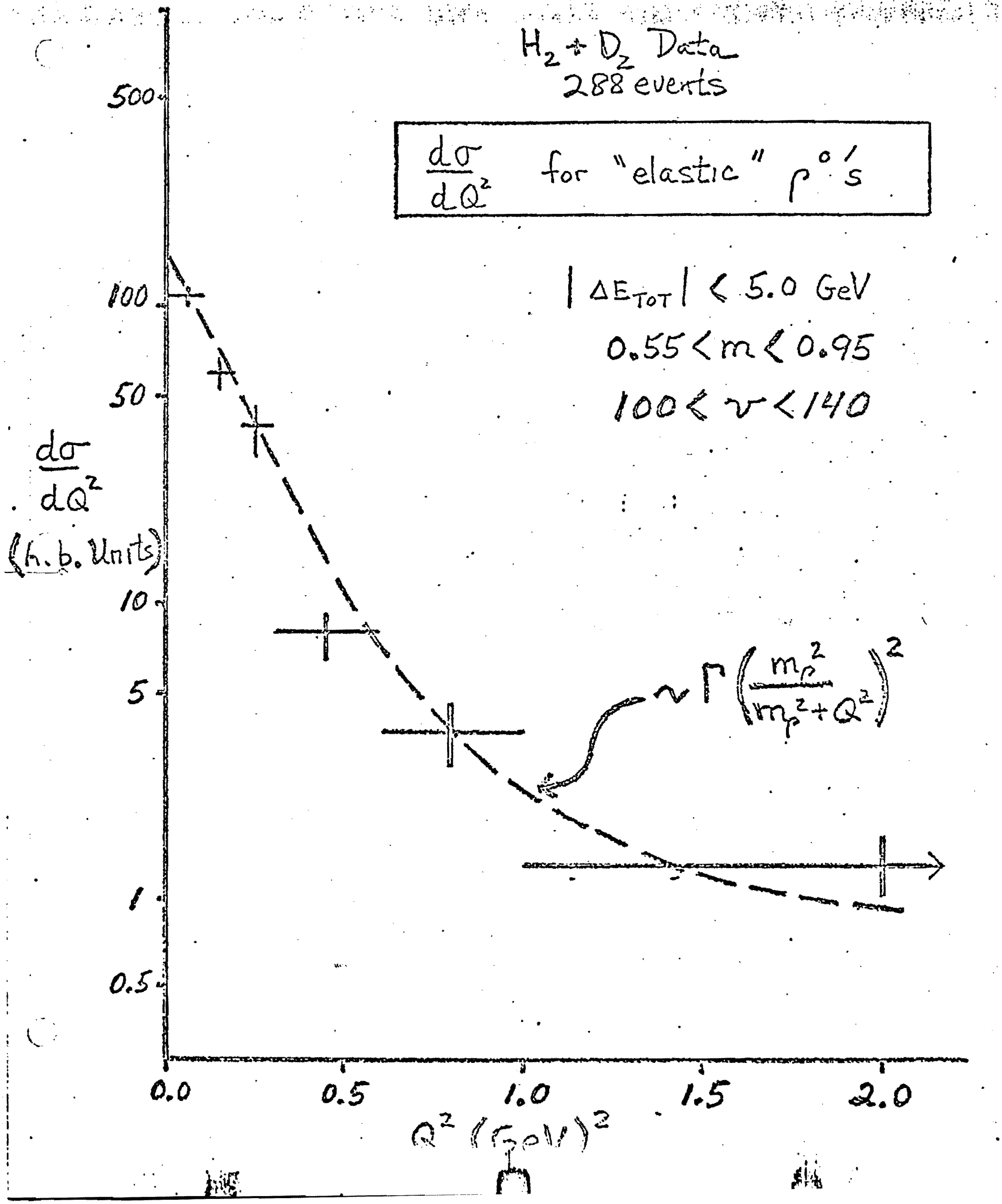
For this reason we place some emphasis on measuring the shadowing for ρ and ρ' production, which is possible with the muon scattering spectrometer.

In addition to studying the shadowing in the ρ and ρ' production we expect to measure the coherence by examining the distribution in momentum transfereed to the recoil nucleus; the limit in this will be the resolution in the opening angle of the $\pi^+\pi^-$ pair; we expect to improve this over the E98 apparatus by adding more proportional chambers, including some in the middle of the magnet at some distance from the target. Also, the position

Figure 5

PRELIMINARY

E 98



of the target is well defined and does not have to be defined by these same proportional chambers.

We propose to run with targets of nucleons 17 gm/cm^2 which is the same thickness as the E98, and future E398, running on deuterium. With this thickness, 25% of the ρ mesons will have one pion absorbed in the target.

For the heavier elements, we will have electromagnetic showers produced in the target from radiative processes, and these will tend to confuse track recognitions. However, we have a target well defined in z and Figure 6 shows that we can identify, that events come from the target region using information from downstream of the magnet only, at least at high q^2. Moreover we will have many more proportional chambers including some in the magnet. Therefore we feel that this is a manageable problem.

Experimental Plan

The proposal has been revised from one presented in 1974 in order to include the results of some data obtained in E98 and to use this experience to help formulate improved running plans for the future.

We note that this is an experiment where the emphasis is on low q^2. Thus we can usefully operate with a muon beam with less than the full intensity and may be compatible with neutrino operation.

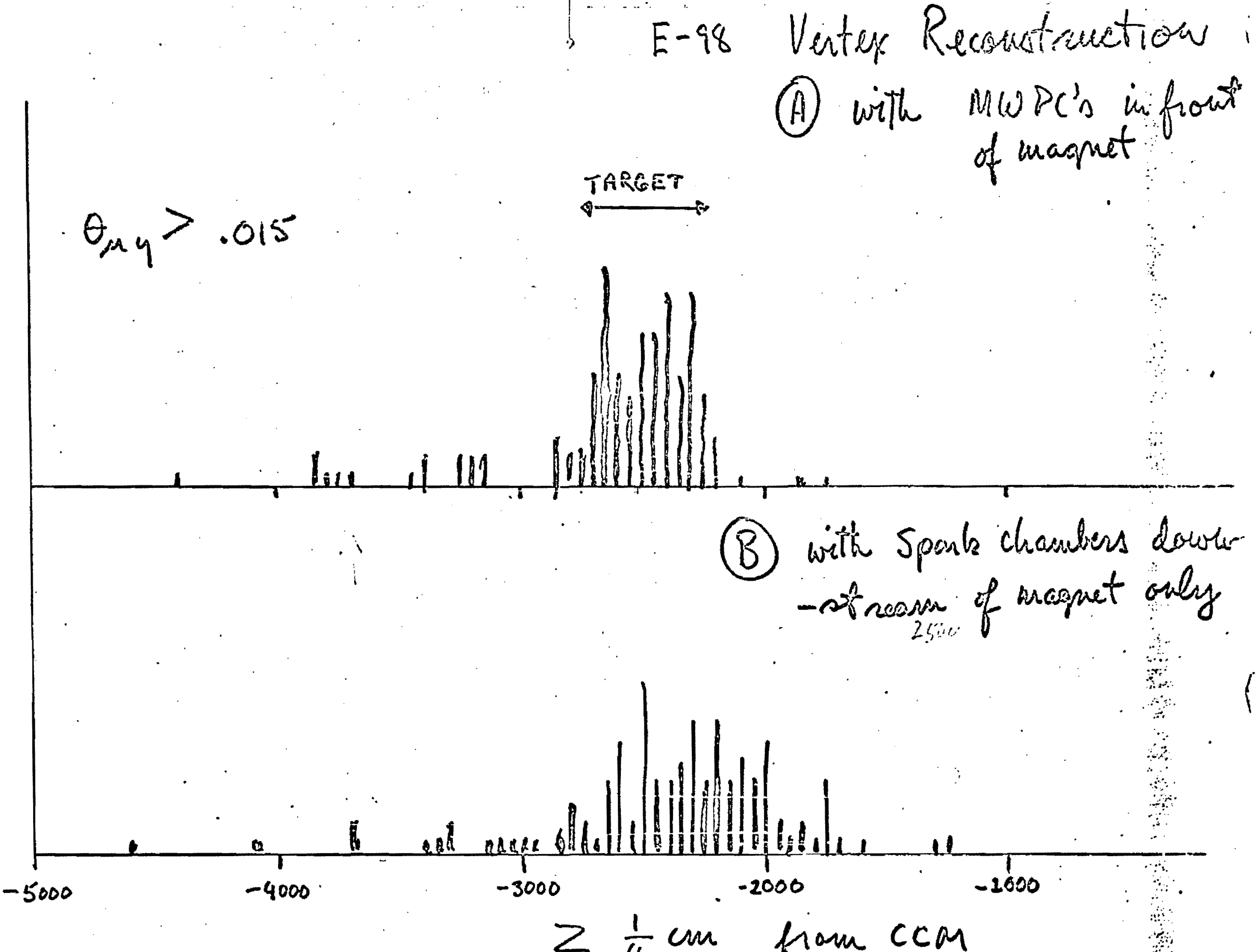

E-98 Vertex Reconstruction
(A) with MWPC's in front of magnet
TARGET
$\theta_{\mu y} > .015$
(B) with Spark chambers down-stream of magnet only
-5000
-4000
-3000
-2000
-1000
Z $\frac{1}{4}$ cm from CCM

Figure 6

Rates and Yields

We propose to run this experiment with three nuclear targets, beryllium, copper and lead. These data will be combined with the deuterium results from E-98 to cover the entire range of nuclear radii with an appropriate number of sample nuclei. We have enough data from our E98 runs to estimate both the trigger rates and event yields. Since there are a number of relevant considerations involving beam intensities, target thicknesses, acceptances, and q^2-ν weighting, we will quote the rate and yield information in more than one format. The final number of beam hours needed will be stated in terms of our estimate of the most probable beam conditions, plus our constraints on target thickness and trigger conditions. If these beam conditions do not obtain at the point of actual running, it will be possible to scale the running time in a realistic manner from the data below.

Basic to the calculation of rates is the need to obtain data over a very large range of q^2 with emphasis on reaching values of q^2 as low as possible. The trigger condition (beam veto size and position) controls this rate. We display in Fig. 5 a calculation of the target associated nuclear rates for our two "standard" beam veto configurations. The lower graph is appropriate for high intensity running on liquid targets (where a strong emphasis on high q^2 is desirable). The smaller veto gives a high acceptance for very low q^2 and is appropriate for the present experiment. The total number of events are those which we would obtain under the requested program. This trigger has a high deadtime fraction and therefore does not optimize accumulation of high q^2 events. We base our event yields on the use of this veto.

The trigger rate for a given target and veto has several important contributions. The target empty rate is appreciable and must be included in the rate estimates. The trigger rates shown in Table I assume the small veto described above and targets 17 gm/cm^2. It is seen that muon Bremsstrahlung and target empty rate dominate the trigger in all cases. This is the price we pay to reach the lowest q^2 values.

Table II. Trigger Rates* for Nuclear Targets
(per beam muon)

	17 gm/cm^2 Cu	17 gm/cm^2 Be	17 gm/cm^{2}Pb
μN	6	6	6
μe	6	6	6
γμ	46	10	100
MT tgt	18	18	18
Total	76	40	120

*Assumes a small standard beam veto

From the trigger rates shown in Table II we can calculate event yields. In order to get a realistic picture, we must calculate with appropriate beam intensities and apparatus deadtime. We know that a yield of 1 to 2 x 10^{-7} μ/p can be achieved for positive muons by the quadrupole trainload. If we have perhaps 5 x 10^{12} protons targeted, this means a beam of 5 x 10^{5} muons per pulse at our nominal energy of 150 GeV/c. We take this as a likely running condition, or less for lead running. Our apparatus operates at high trigger rates with a 50 ms/event deadtime. Combining these factors, we calculate event yield rates as shown in Table III.

Table III. Event Rate Yields for Nuclear Targets (per hour)

Target	Livetime fraction	no nuclear rescattering	"good" event rate
Cu	0.5	0.8	500
Be	0.6	0.8	600
Pb	0.2	0.8	200

The basic nuclear rates are eroded by corrections for livetime fraction and nuclear rescattering in the target (calculated for real rhos). Since we can change targets easily, the lead will be run during periods of low beam intensity, or else a thinner target can be used, thereby reducing the confusion from radiative processes producing a shower.

In order to see the shadowing effect clearly, and in particular to see many rho muons, we would like to have about 20,000 events on each target (3% statistics in each of 10 ω bins). This requires the following amounts of "perfect" beam times:

Cu	40 hours
Be	30 hours
Pb	90 hours
Total	160 hours

With thin targets we must add to this about 25% additional empty target running. Since the beam phase space has been observed to vary with time (probably due to many small effects acting collectively), we will take an event trigger off the beam only every sixteenth trigger. This requires an additional 5% of beam time. Finally, our experience over the period of recent good running is that all other problems and conditions which prevent running (CCM crashes, run terminations, beam tuning, etc.) lose us another 50% of potential beam time. Adding all these effects together, we come out with a total "realistic" beam requirement of 285 hours. This amount of running should provide a clear and unequivocal answer to the nuclear shadowing question and a 15% type measurement of the behavior of real rho production in an equivalent binning. We therefore, request 285 hours of beam at 5×10^5 per pulse, or 8×10^{10} muons at 150 GeV/c with the best possible duty cycle. The distribution of the sum total of these events in q^2 is shown as the solid line in Figure 5.

Timing

We hope that this experiment can be performed at any time after the end of E398.

Radiative Corrections

We noted in the main narrative that electron scattering at low q^2 has a large radiative correction which might have masked the shadowing effect. For muon scattering, not only is the effect smaller by a factor of 5, but we can, with our spectrometer identify the radiation; we propose to do this by placing a lead glass counter in the beam; this and in some cases, showers after the target, will enable us to subtract out these events in the analysis.

It is possible, and this depends upon further tests, that we will be able to use this information in the trigger to reduce the deadtime for the lead target.

References

1. V. Heynen, *et al.*, Physics Letters 34B, p. 651 (1971).
D. O. Caldwell, *et al.*, UCSB preprint (1972) unpublished.
G. R. Brookes, *et al.*, Daresbury Report DNPL/P136 (1972).

2. J. S. Bell, PRL 13, p. 57 (1964).
L. Stodolsky, PRL 18, p. 135 (1967).
S. J. Brodsky and J. Pumplin, PR 182, 5, p. 1794 (1969).
K. Gottfried and D. R. Yennie, PR 182, 5, p. 1794 (1969).
D. Schildknecht, SLAC-PUB-1238 (1973).
J. J. Sakurai and D. Schildknecht, Phys. Letts. 40B, p. 121 (1972); Phys. Letts. 41B, p. 489 (1972); Phys. Letts. 42B, p. 216 (1972).

3. C. Driver, *et al.*, Nucl. Physics B38 (1972) and Erratum (to be published).
V. Eckardt, *et al.*, DESY 72/67 (1972).
J. T. Dakin, *et al.*, SLAC-PUB-1154 (1972).
J. Ballam, et al., Contribution to the XVI International Conference on High Energy Physics, Chicago and Batavia, Ill. (1972).

ADDENDUM TO

INVESTIGATION OF VIRTUAL PHOTOABSORPTION BY NUCLEAR MATTER

FROM

THE CHICAGO-HARVARD-ILLINOIS-OXFORD MUON COLLABORATION

P448

April 27, 1976

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Coherent Production of ρ^o Mesons

Data on production of ρ^o mesons from H, D and C is now available from E98. A draft paper is included as an appendix.

We note that ρ^o production in the forward direction follows the vector dominance prediction

$$\sigma(\gamma P \to P\rho^o) \propto \left(\frac{4\pi}{\gamma_\rho}\right)^2 \tfrac{1}{2}(\sigma_{\pi+\rho} + \sigma_{\pi-\rho}) \text{ [Appendix Figure 21]}$$

We also note that coherent production of ρ^o mesons from D and C is observed. The coherent production has not yet been compared in detail with theory. The absence of any strong shadowing effects seems in direct conflict with the presence of coherence. By measuring both in the same experiment, we believe we can either resolve the problem, or establish a definite contradiction.

Uniqueness of P448

Scattering by muons involves a smaller radiative correction than scattering by electrons by the ratio

$$[\log (q^2/m_\mu^2)/(q^2/m_e^2) \approx 5]$$

It is widely conjectured that the existing electron scattering experiments are wrong because of an incorrectly applied radiative correction. Another conjecture is that the electron scattering experiments are at too low an energy to see shadowing. The reason for this is at present unclear.

Neither of these conjectured effects are present for muon scattering at 150 GeV. Therefore our experiment is unique. If we do not see shadowing, there will be no way out for the theorists, and this will be an experiment of major importance. If we do see shadowing, we will have resolved an outstanding discrepancy which has involved several competent experimenters.

Changes from E257

Some early runs were made on heavy elements under the number E257. It was the hope that 20,000 muons per pulse could be achieved parasitically and that, with a thick heavy target, some data on shadowing could be obtained.

In fact the beam varied between 1000 and 7000 muons per pulse, and the experiment was not possible.

P448 proposes up to 500,000 muons per pulse. This enables a thinner target to be used than in E257. There are several favorable consequences of the thinner target; we have improved energy and angular resolution (by avoiding multiple scattering). We can also allow the pions to escape the target and study coherent ρ^o production in the same targets. This latter was not contemplated in E257, but is important. If we find coherent ρ^o production and no shadowing, there would be a major theoretical problem.

With targets of heavy elements, particularly if they are thick, we get electromagnetic showers produced in the target. This can confuse any detectors immediately downstream of the target. We will be better off than in our E257 trials because we have installed, for E398, more proportional chambers and have generally improved operation. Moreover, we have established (Figure 6 of the original proposal) that we can identify scatters even without measurement of a scattered muon upstream of the magnet. Only for $q^2 < 0.3$ GeV^2 will the extra precision be necessary.

Experimental Plan

The plan of this experiment is to use about 500,000 muons per pulse at 150 GeV. The present beam line, if all magnets are adjusted, is capable of an intensity $\mu/p = 2 \times 10^{-7}$ at $E_p = 300$ GeV, $E_\mu = 150$ GeV (although 1×10^{-7} was obtained during previous runs due to component failures).

With $E_p = 400$ GeV, $E_\mu = 150$ GeV we expect $\mu/p \gtrsim 4 \times 10^{-7}$. Thus the planned beam intensity may be achievable with 10^{12} protons/pulse or with a less optimal beam (e.g., a narrow band train). An appreciable fraction of the running (on lead) can be at a lower intensity still.

Therefore we suggest that this experiment can be run at one of the many times when a full intensity muon beam is not available.

The apparatus configuration for P448 is not as critical as E398, or E369. It can, for example, be performed at the end of either, without moving any apparatus, solely by emptying the liquid target and adding the thin solid target.

Since the personnel for P448 overlaps the personnel for E398, there should be no problem in arranging the dovetailing of these experiments. E398 is planned to run with high intensity, E369 when the muons are not available, and P448 when muons of moderate intensity can be obtained.