NAL PROPOSAL #221

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p-p Inelastic Scattering in the Diffractive Region

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June 1, 1973

Addendum to Proposal # 14A

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Abstract

In previous runs at NAL we have taken useable beam for less than one week (approximately 66 hours) with energies of 200, 300 and 400 GeV. Our 200 GeV results have been submitted for publication (copy attached) and indicate that the proton-proton inelastic cross section exhibits unexpected behavior in the region of very low $|t|$ which we study. We have observed that for low M^2 (square of missing mass recoiling against the detected proton) the cross section reaches a maximum at $|t| \approx 0.1\ GeV^2$ and then decreases for smaller $|t|$. These results have aroused significant theoretical interest.

In order to further study this interesting behavior (and especially the dependence on incident energy) we request additional running time in the internal target area. We have proved that we can perform a polyethylene carbon subtraction successfully and hence would run with foil targets. We expect to benefit greatly from the improved duty cycle in the internal beam. We hope that this additional running will be completed by September 1, 1973.

We also request additional time in the external beam. We hope that this additional external running will commence in the fall of 1973 after our run in the internal target area. We propose to use the additional external running to study the multiplicity of and correlations among the reaction products recoiling against the detected proton. This study would be carried out via the addition of a scintillation counter hodoscope downstream of our target.

Results of Previous Runs

Our 200 GeV data were taken during a run of approximately 10 hours duration on October 1, 1972. The results have been submitted for publication and are attached to this request. (Appendix A is a copy of our paper submitted to Physical Review Letters. Appendix B is a copy of the longer but more complete report which we submitted to the Vanderbilt conference.) Our results indicate that the proton-proton inelastic cross section exhibits unexpected behavior in the region of very low $|t|$. We have observed that for low M^2 (square of missing mass recoiling against the detected proton) the cross section reaches a maximum at $|t| \approx 0.1$ GeV^2 and then decreases for smaller $|t|$.

The 200 GeV data were taken at a moment early in the growth of the NAL accelerator. At that time the accelerator was running at low intensity and the present extraction techniques had not yet been developed. Consequently the data have low statistics and poor resolution in kinetic energy due to instantaneous rate problems in the primitive spill. The 300 and 400 GeV data were taken in March, 1973 and May, 1973 respectively. These later data have much better statistics and better resolution in kinetic energy than the 200 GeV data due to improvements in the accelerator and improvements in our sampling technique. However, due to an error of ours, portions of the low M^2 region of these data have been contaminated by elastic events. Efforts to remove the contamination are proceeding along with normal analysis of the data. We expect to publish our results for the uncontaminated portion of the data in the near future. We believe that we can completely remove the source of this contamination in future runs. (The source of the contamination was improper collimation similar to the effect discussed in the report to the Vanderbilt conference under "Dependence on M^2".)

An unexpected bonus result which we have observed in our previous runs is the copious production of deuterons, tritons, He^3 and He^4 in proton-carbon interactions. This result indicates that a carbon nucleus evaporates these particles when heated by a passing proton. Thus, apparently these combinations of nucleons exist in substantial numbers within the carbon nucleus. We expect to publish these nuclear physics results during the first available lull.

At the inception of this experiment the most serious problem which we faced was one of background produced by beam halo. We have performed an experiment with solid state detectors placed 1 m from a beam of 5×10^{11} protons/pulse. The NAL staff has been able to provide us with a beam clean enough that the background due to halo interactions is completely negligible compared with interactions in our target of 13 mg/cm^2. We regard this as a monumental achievement by NAL.

Since our halo background problem has been solved, we are free to point out the advantages of our method:

<u>low $|t|$</u>. Our use of solid state detectors and a stationary target enables us to measure the inelastic cross section in the theoretically interesting region $0.02 < |t| < 0.2$ GeV^2. We are unique in this respect.

<u>good resolution in M^2</u>. Our <u>experimental</u> resolution in M^2 is $\pm$ 0.5 GeV^2 for $|t| \approx 0.03$ GeV^2. This is approximately a factor of 5 better than obtained by other methods either at the ISR or at NAL for $s \approx 400$ GeV^2.

<u>normalization for subtraction</u>. Simultaneous detection of protons, deuterons and tritons provides an essentially perfect normalization for proton-carbon interactions before the polyethylene-carbon subtraction.

<u>solid target</u>. The fact that we have a reliable method for the subtraction means that we can use a solid target (rotating target). Hence

we do not need to concern ourselves with luminosity fluctuations.

detect elastic peak. The fact that we detect elastic and inelastic events simultaneously gives us a reliable absolute normalization to the elastic events. The elastic events also allow us to check the calibration of our energy scale for each detector which sees the elastic peak. In addition the elastic events afford us a chance to check our ability to measure the $|t|$ dependence of the cross section.

carbon events. The carbon cross section is expected to be nearly flat in M^2 due to Fermi motion of the carbon nucleons. Hence by studying this cross section we check that all detector telescopes are working and that analysis procedures do not cause spurious changes in the behavior of the cross section.

lack of corrections. After the subtraction there are essentially no corrections. Specifically, corrections due to interactions in the target and in the detectors are negligible. The deadtime correction at 200 GeV was significant. However, due to improvements in both accelerator performance and in our system, this correction is essentially negligible for all later runs.

Alongside these advantages, however, we must bear in mind the statistical disadvantage of the subtraction method. The statistical error associated with the difference of two numbers is the square root of their sum.

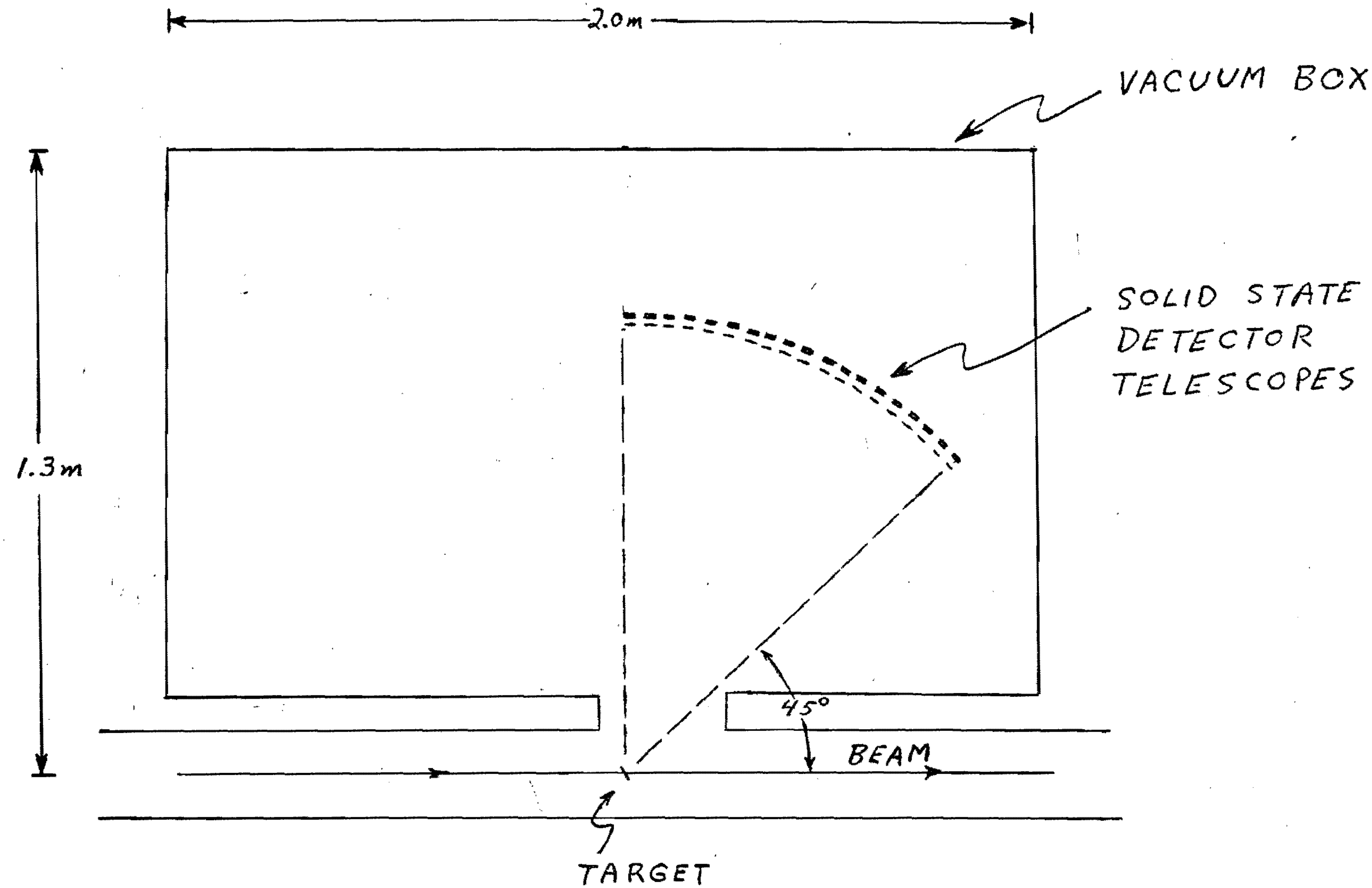
In summary we believe that we now have a working, well understood system. We request extended running time so that we may further study the interesting results we have discovered.

NAL Experiment 14A--Phase II

Under Phase II, to which we give first priority, we request running time in the internal target area. The salient purpose of such running time is to make a systematic study of the s dependence of the inelastic cross section, especially in the region of low $|t|$ and M^2 where we have discovered unexpected behavior. As we have indicated above such a study is of great theoretical interest. This study should be done in the internal target area because of the availability of all energies on the accelerator ramp. In addition we expect to be greatly helped by the improved duty cycle in the internal beam.

The effort required on the part of NAL to grant this request is modest. Our equipment must be moved from its present location in the Neutrino Lab to the CO area. Space must be found in this area to accomodate us. Since we do not require use of the hydrogen gas jet target a rotating foil target could be set up for us at a presently unused portion of the CO area. Our vacuum box must be installed at the appropriate position in the beam line and access must be provided for 100 cables. We also request the assignment of one additional Porta-Kamp to our experiment since we are severely cramped for space in the single Porta-Kamp which we now occupy. In addition we would require a timing signal from NAL to tell us the energy of the beam at a given time on the accelerator ramp. Our only required task would be the interfacing of this signal into the present system.

The total amount of space required for our vacuum box is indicated in Fig. 1. If NAL desires isolation of our vacuum system from the accelerator vacuum system, it is perfectly acceptable to us if the two systems are separated by a thin window (for example 1 mil of kapton).


2.0m
VACUUM BOX
1.3m
SOLID STATE
DETECTOR
TELESCOPES
45°
BEAM
TARGET

We estimate that the time required to install our experiment in the beam line is only one or two days. The accelerator vacuum system may need modification in order to establish a connection with our box and the necessary cables must be strung. The remaining setup time would be spent in retesting our electronics. We thus expect to begin looking at our target signal approximately two weeks after our move.

For the purpose of tuning our system we request 50 hours of beam time spread uniformly over a period of one month. From our past experience we estimate that it would be desirable to obtain 2.5×10^8 triggers which we would accept at 10 discrete energy values within the range of available energies. We expect these triggers to include about 10^7 inelastic scattering events from hydrogen. In order to collect this number of events we request 200 hours of beam time for the purpose of taking data. Thus we are asking for a total of 250 hours of beam.

In order to improve the reliability of the data-taking process we request that our running time be divided at least into three equal intervals. We would prefer smaller intervals. In this manner we could analyse each segment of data before taking the next segment. In this connection it should be pointed out that we now have a complete set of working analysis programs (although we are still, of course, writing improved versions).

Appendix A

Paper submitted to Physical Review Letters

Inelastic P-P Scattering at 200 GeV *

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We have measured the doubly differential cross section $sd^2\sigma/dtdM^2$ for the reaction $p + p \to p + X$ using 200 GeV incident protons in the external beam at the National Accelerator Laboratory. Here t is the square of the four momentum transfer to the target proton, M^2 is the mass squared of X, and s is the total center of mass energy squared. We cover the region of $0.019 < |t| < 0.19$ GeV^2 and $1 < M^2 < 60$ GeV^2. Interesting structure is observed at low $|t|$ and M^2 values.

* Work supported in part by the National Science Foundation.

We have studied the reaction $p + p \rightarrow p + X$ at 200 GeV laboratory incident energy. We select this reaction by detecting the recoil proton in one of 18 telescopes each consisting of two solid state detectors. In this way we can identify each proton and measure its kinetic energy T in the range $10 < T < 100$ MeV. Our accuracy in T is typically better than 10 %. The four momentum transfer squared is given by $t = 2 M_p T$ where M_p is the proton mass. The measured value of T and the telescope angular position θ together determine M^2, the square of the mass of X. Each telescope subtends an angular opening in θ of 0.46° and accepts a solid angle of approximately 6.4×10^{-5} steradians. The 18 telescopes are uniformly spaced in θ between 48° and 89°. Thus our telescopes actually cover only about 20% of the angular range spanned. As a result we have not measured the inelastic cross section continuously in M^2. We might thus be missing interesting structure in the cross section which we would hopefully cover in the future.

In order to obtain the free proton cross section we have used polyethylene $(CH_2)_n$ and carbon targets and performed a subtraction. The normalization of polyethylene and carbon runs before the subtraction was obtained by identifying deuterons and tritons from proton-carbon interactions in the two targets. Such deuterons and tritons were counted simultaneously with the proton recoils. The data which we present were obtained during a run of approximately 10 hours using the extracted proton beam in the Neutrino Laboratory at NAL. For many reasons the data were collected with large deadtimes. However, our interesting conclusions are not affected by the corrections applied for such effects.[1]

The layout of the experiment is shown in Fig. 1. It should be noted that the detectors are located approximately 100cm from the extracted proton beam which, during the run discussed, had an intensity of 3×10^{10} protons/pulse. It was thus very important to obtain an extremely clean beam since interaction of a very small fraction of the beam hundreds of feet upstream of our location would have produced background orders of magnitude larger than our target signal. The fact that such a beam was made available to us is a tribute to the National Accelerator Laboratory, its accelerator, the beam extraction staff, and the staff of the Neutrino Laboratory.

The targets used were $13 mg/cm^2$ foils of polyethylene and carbon approximately 5mm wide and placed at a 45° angle to the beam. Approximately 3×10^{-4} of the beam interacted in our target, the remainder being used by the Neutrino Lab for other experiments. During the run we collected approximately 5×10^6 triggers of which approximately 25% were due to target interactions. The remainder were accidentals due to an extremely lax trigger requirement. Comparison of the energy loss signals in the two detectors of each telescope completely removed such accidentals.

The first (thin) detector of each telescope is a 500 micron totally depleted silicon surface barrier detector. The second (thick) is a 5000 micron lithium drifted silicon detector. A specific ionization measurement is performed in the thin detector and the total energy is measured in the thick detector for T up to approximately 30 MeV. For higher energies the proton does not stop in the second detector but a measurement of the energies E_1 and E_2 lost in the two detectors still allows a good determination of the proton kinetic energy up to approximately 100 MeV. Scatter plots in the E_1-E_2 plane for events collected in a few minutes of running are shown in Fig. 2 for two telescopes and two targets. Protons are clearly identified both when stopping and when traversing the thick detector. The proton-proton elastic scattering peaks are clearly visible with the polyethylene targets. Deuterons and tritons are copiously produced and appear in the plot as bands above the proton band.

We perform the following steps to obtain the free hydrogen event distribution:

(a) Divide the E_1-E_2 plane into a rectangular grid.

(b) Identify protons, deuterons and tritons by their grid positions.

(c) Count the deuterons and tritons.

(d) Determine T of the protons from E_1 and E_2.

(e) Normalize the carbon event density in T from the carbon target to the carbon event density from polyethylene using (c).

(f) Obtain the hydrogen event distribution by subtracting the carbon distribution from the polyethylene distribution.

This procedure is carried out independently for each telescope. Then a deadtime correction (mentioned previously) is applied to each telescope. The final step in the analysis is to compute t, M^2 and the Jacobian $\partial(\theta,T)/\partial(t,M^2)$ from our knowledge of T, θ and the beam momentum. At this point the unnormalized differential cross section $d^2\sigma/dtdM^2$ is obtained in arbitrary units.

The total number of inelastic scattering events on free hydrogen used for the above determination is approximately 35,000. An absolute normalization is obtained from the total number of proton-proton elastic scattering events in each telescope which observes the elastic peak[2]. Some 45,000 elastic scattering events were observed, the elastic peaks being clearly visible in 5 telescopes. Such elastic peaks are also very useful to cross check our energy calibrations[3] and our ability to correctly measure the t dependence of the cross section. To the accuracy of our data we obtain very good agreement with published values[4] for the slope parameter. We find $b = 11.6 \pm 1.4\ GeV^{-2}$.

In Table I and Figs. 3 and 4 we present our measured values of $sd^2\sigma/dtdM^2$ where $s = 377\ GeV^2$ (square of total center of mass energy). The errors quoted are the statistical errors resulting from the subtraction. The limits of the $|t|$ intervals used are shown in Fig. 4. In Fig. 3 we show the M^2 dependence of the cross section in the lowest $|t|$ interval. Table I presents the inelastic data with 6 GeV^2 bins in M^2, coarser binning than used in Fig. 3. The minimum value of $M^2 = 7\ GeV^2$ included in Table I is well outside the region influenced by elastic events even for the data at high $|t|$[5]. In Fig. 4 we plot the data of Table I at the two smallest values of M^2. The most outstanding feature of the data is the peaking of the cross section at $|t| \sim .1\ GeV^2$ and subsequent decrease for lower $|t|$ for $7 < M^2 < 19\ GeV^2$. Around $M^2 = 20\ GeV^2$ there genuinely appears to be a change in the behavior of the cross section dependence versus t.

Previous measurements of the proton-proton inelastic cross section have been performed by Sannes et al.[6] at NAL but at higher values of $|t|$. Measurements have also been performed by Albrow et al.[7] at the ISR but for both higher $|t|$ and s. Both experiments obtain a minimum in the cross section for $x = 1 - M^2/s \simeq 0.9$. Since our minimum for $|t| \simeq 0.03$ GeV^2 occurs at $x \simeq 0.97$, apparently the minimum in the cross section moves with $|t|$. It should be pointed out, however, that Albrow et al. have a poorer resolution in x than we do which may affect the position of their minimum. Sannes et al. do not quote their resolution.

We wish to express our thanks to the NAL accelerator, beam extraction and Neutrino Lab staffs. In particular we wish to thank J. R. Orr, on whom we could always call as a member of our team. E. Blesser and H. Edwards were instrumental in obtaining a clean extracted proton beam. The Nevis machine shop constructed most of our mechanical equipment and some parts of the electronics were built at Nevis. We gratefully acknowledge the help of W. Sippach and Y. Au. We wish to thank our theoretical colleagues, particularly C. Quigg and A. Mueller, for their continuous encouragement and interest in our experiment. We also thank Paula and Catfish.

FIGURE CAPTIONS

Fig. 1. Sketch of the apparatus.

Fig. 2. Scatter plots in the E_1-E_2 plane for (a) polyehtylene data at 83° (b) carbon data at 83° (c) polyethylene data at 80° (d) carbon data at 80°.

Fig. 3. Doubly differential cross section versus M^2 for $|t| \simeq 0.03$ GeV^2.

Fig. 4. Doubly differential cross section versus $|t|$ for indicated M^2.

FOOTNOTES

1. S. Childress et al., Proceedings of the Vanderbilt Internationsl Conference on New Results from Experiments on High Energy Particle Collisions, Nashville, 1973.
2. We take the elastic differential cross section $d\sigma/dt$ to be 26 mb/GeV^2 at $|t| = 0.1$ GeV^2 as given by G. Charlton et al., "Two and Four Prong pp Interactions at 205 GeV", contribution to the XVI International Conference on High Energy Physics, Batavia, 1972. The accuracy of our absolute normalization should be better than 30%.
3. The energy scale for each detector is calibrated with a source producing α particles of 5.477 MeV.
4. G. Barbiellini et al., Phys. Letters <u>39 B</u>, 663 (1972). The slope parameter is given by $b = (d/dt) \ln (d\sigma/dt)$.
5. As can be seen from the elastic peak in Fig. 3 our resolution in M^2 is 1 GeV^2 full width at half maximum for $|t| = 0.03$ GeV^2. However, our resolution deteriorates at higher $|t|$. See reference 1 for details.
6. F. Sannes et al., Phys. Rev. Lett. <u>30</u>, 766 (1973).
7. M.G. Albrow et al., Nuclear Physics <u>B 54</u>, 6 (1973).

Table I. $sd^2\sigma/dtdM^2$ (mb/GeV^2) using 6 GeV^2 bins in M^2

M^2	$\|t\|\simeq.03$	$\|t\|\simeq.08$	$\|t\|\simeq.11$	$\|t\|\simeq.14$	$\|t\|\simeq.17$
10	36± 63	308±33	229±28	132±23	183±19
16	33± 59	128±24	133±24	78±31	45±15
22	228± 63	125±36	70±31	23±23	55±18
28	274± 64	163±35	133±33	117±31	86±23
34	251± 77	101±31	179±39	117±31	93±23
40	303±127	117±31	126±26	81±24	109±23

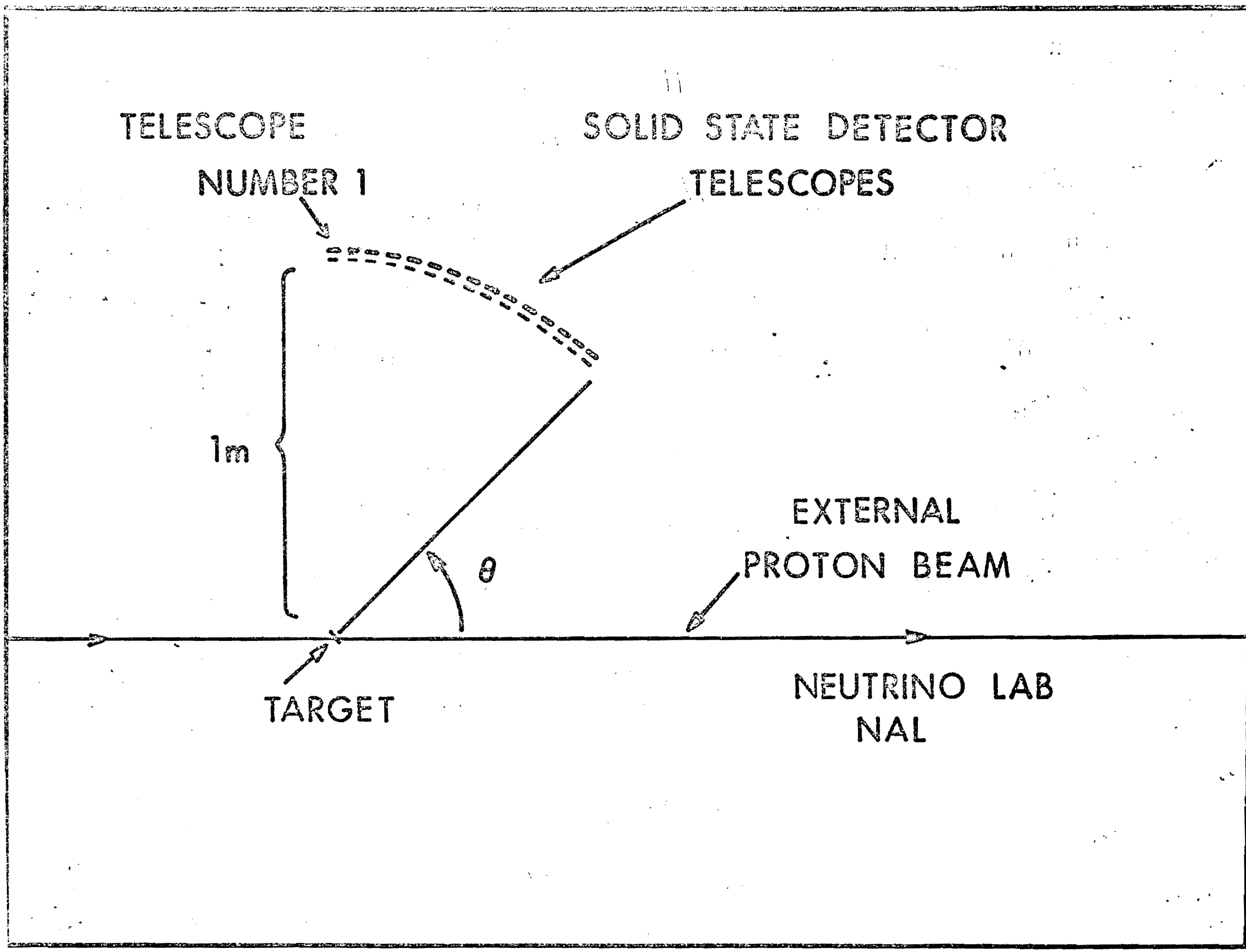

Fig. 1. S. Childress et al. Title: Inelastic P-P Scattering at 200 GeV

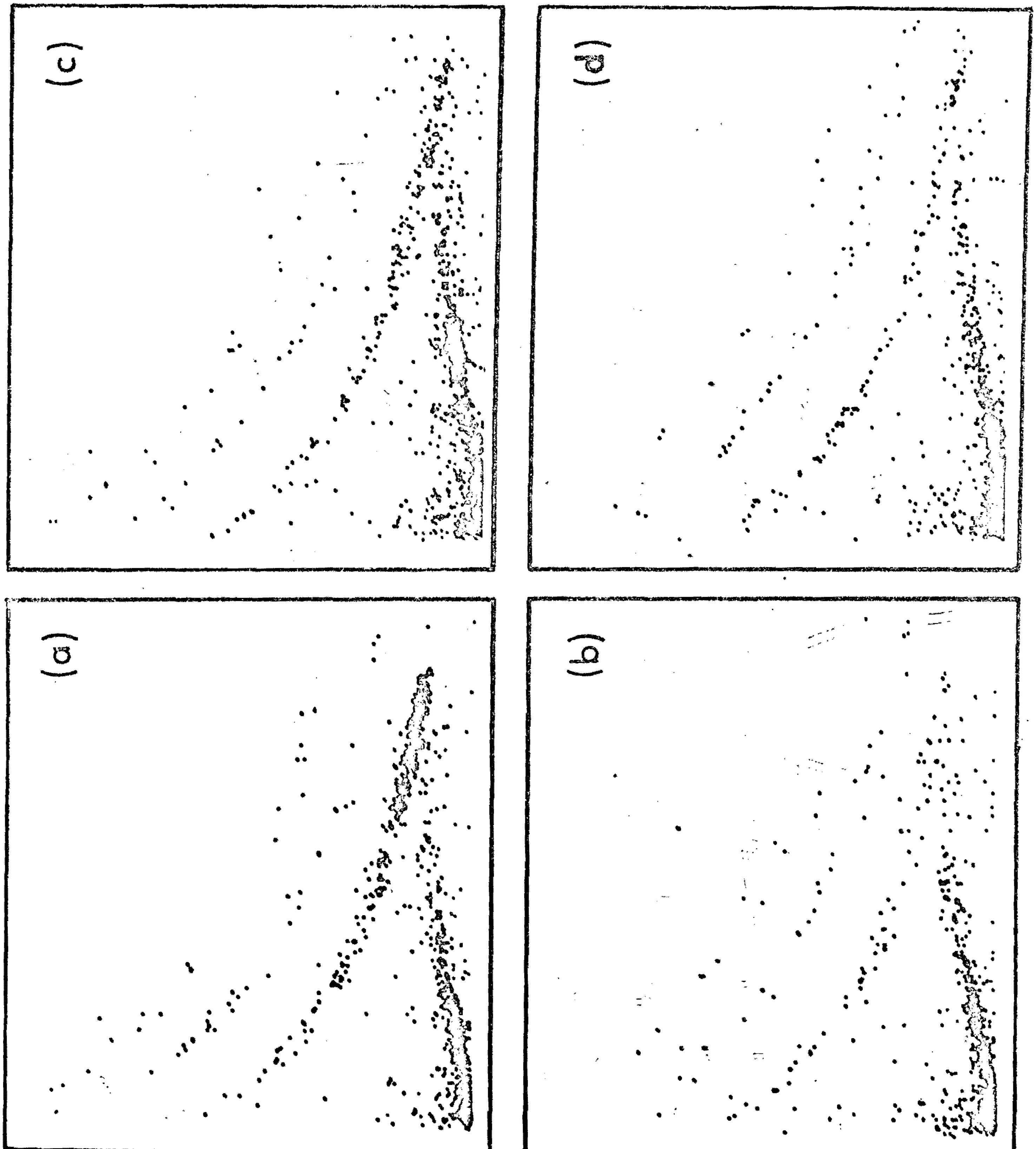

Fig. 2. S. Childress et al. Title: Inelastic P-P̄ Scattering at 200 GeV

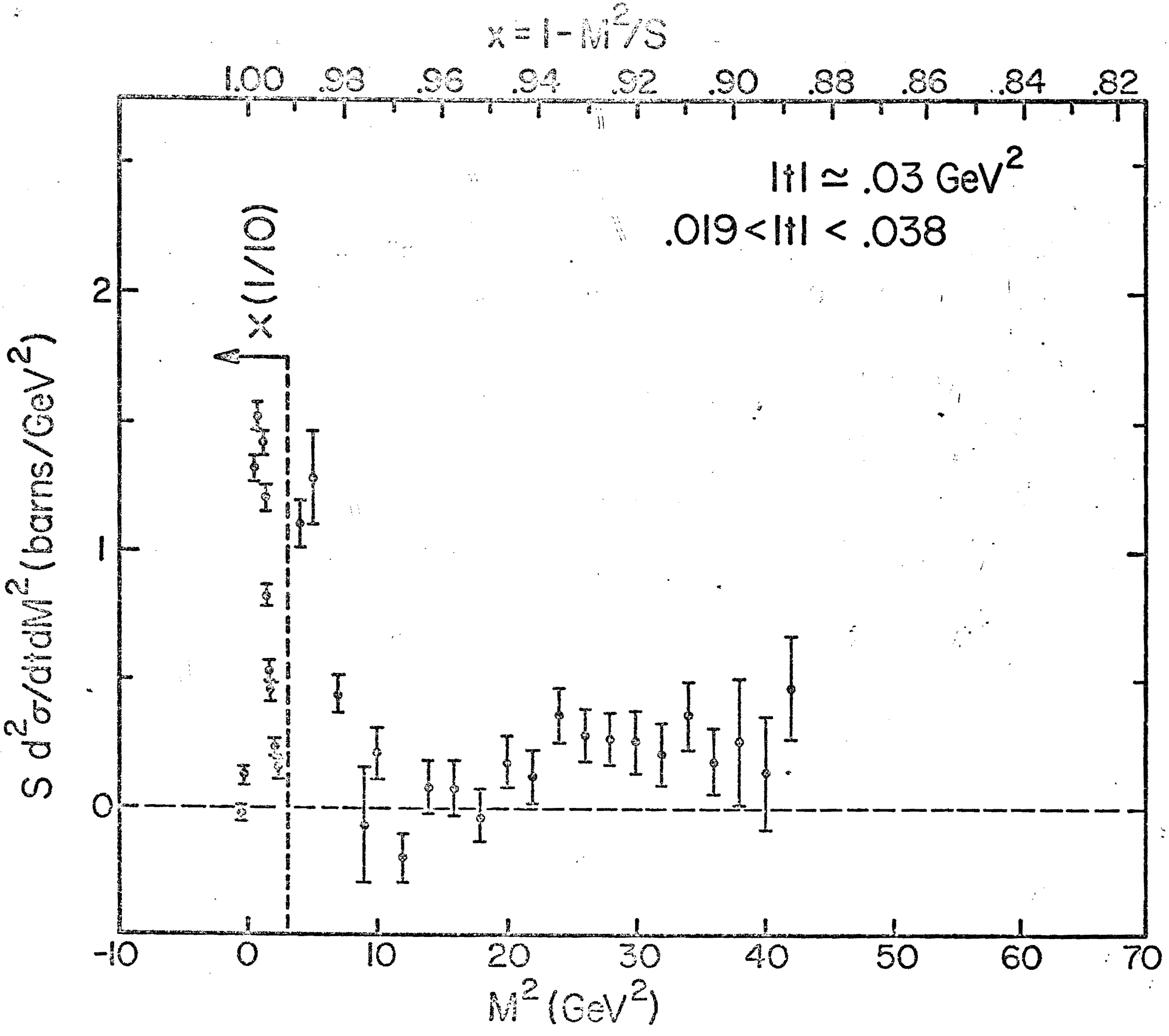

Fig. 3. S. Childress et al. Title: Inelastic P-P Scattering at 200 GeV.

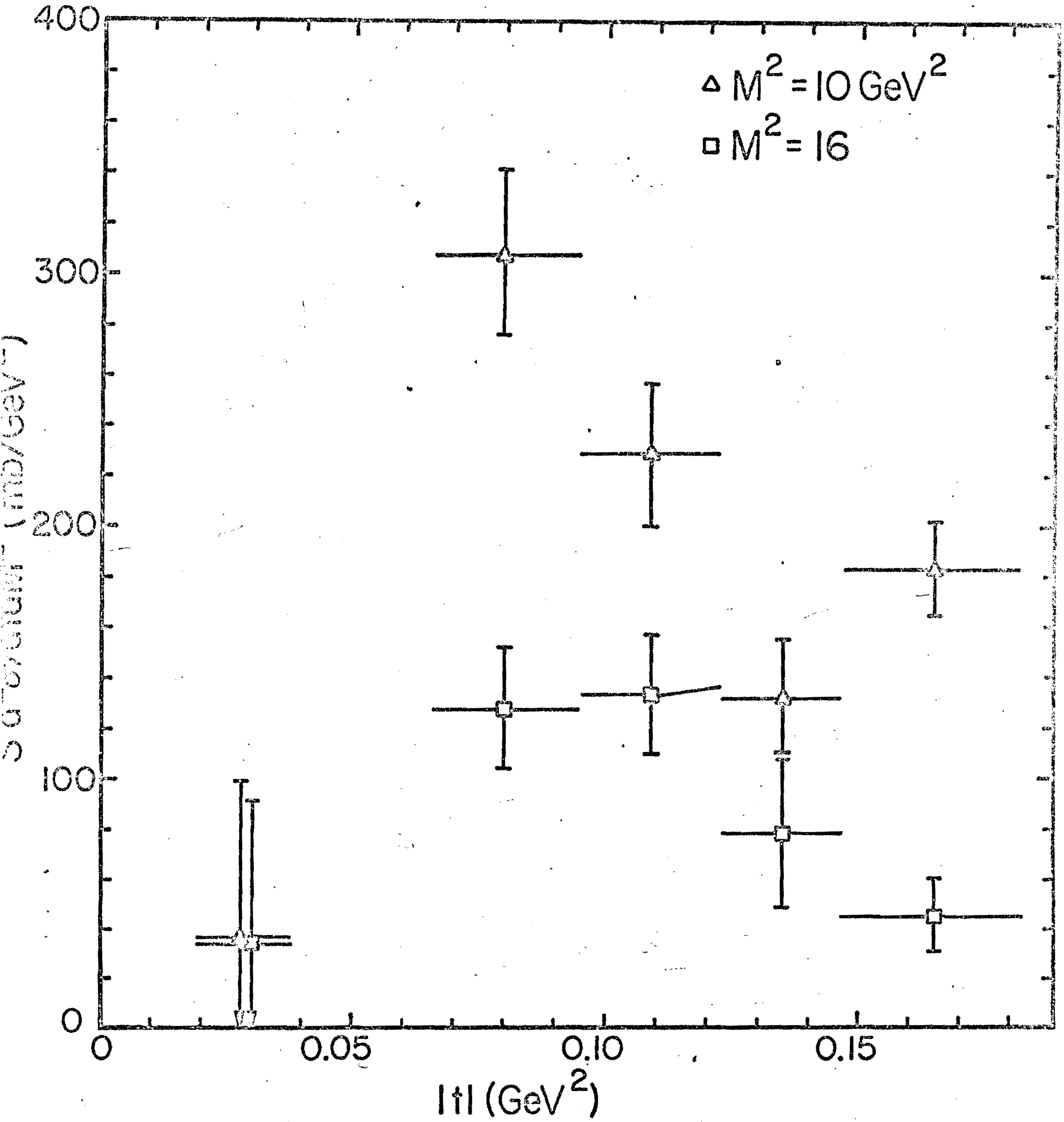

Fig. 4. S. Childress et al. Title: Inelastic P-P Scattering at 200 GeV.

Appendix B

Report to the Vanderbilt Conference

PROTON-PROTON INELASTIC SCATTERING IN THE DIFFRACTIVE REGION AT 200 GeV *

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Presented by R. McCarthy

ABSTRACT

We have measured the doubly differential cross section $sd^2\sigma/dtdM^2$ for the reaction $p + p \to p + X$ using 200 GeV incident protons in the external beam at NAL. The ranges covered in $|t|$ and M^2 are $0.019 < |t| < 0.19$ GeV^2 and $1 < M^2 < 60$ GeV^2 respectively. The hydrogen cross section was obtained by a polyethylene-carbon subtraction and is given with appropriately large statistical uncertainties. However, the cross section does show unexpected structure. In the region $7 < M^2 < 19$ GeV^2 the cross section reaches a maximum near $|t| \sim 0.1$ GeV^2 and then decreases for smaller $|t|$.

INTRODUCTION

We have measured the proton-proton inelastic scattering cross section in the diffractive region using 200 GeV incident protons in the external beam at the National Accelerator Laboratory. Our method (Fig. 1) is to detect the recoil proton in an array of solid state detector telescopes. We have 18 telescopes covering the angular range $48 < \theta < 89$ degrees from the incident proton beam. Each telescope consists of one thin and one thick detector. By studying the correlation between the energies lost in the two detectors, we are able to unambiguously identify each proton and determine its kinetic energy T. This kinetic energy measurement can be performed over the range of $10 < T < 100$ MeV. From the measured values of T, θ and P_B (the beam momentum) we calculate $|t|$ and M^2 via the equations[1]:

$$|t| = 2 M_p T \tag{1}$$

$$M^2 = M_p^2 + 2(P_B P \cos\theta - (E_B + M_p)T) \tag{2}$$

* Work supported in part by the National Science Foundation.

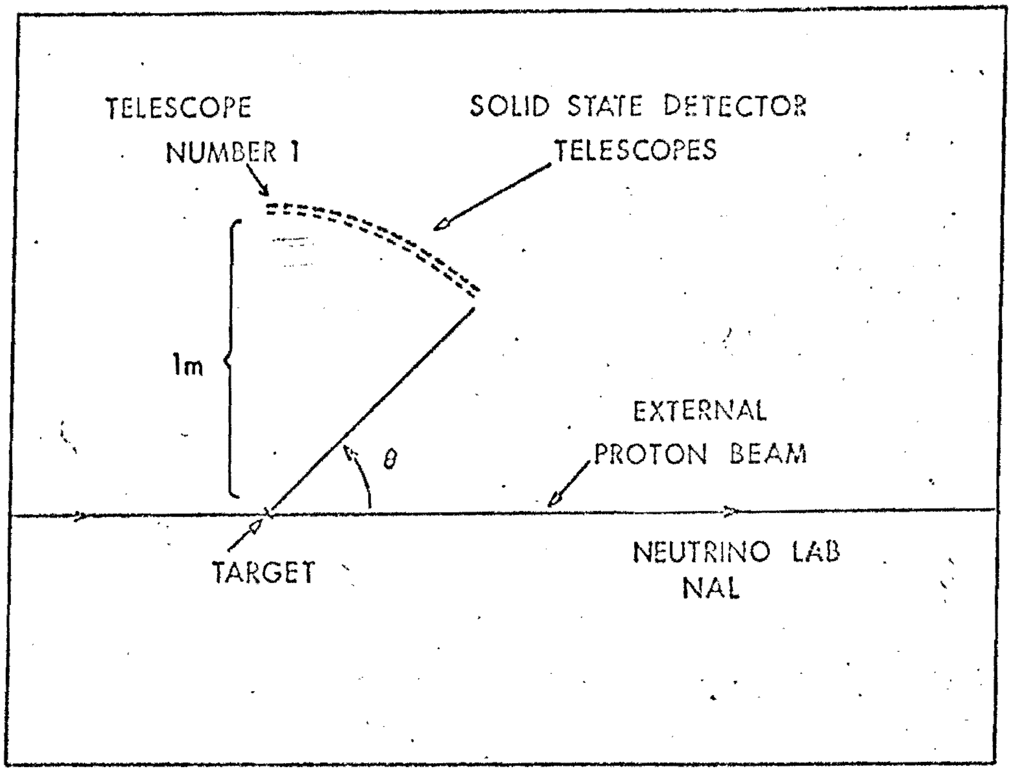


Fig. 1. Sketch of the apparatus.

Here t is the square of the four momentum transfer to the target proton, M is the missing mass of the system against which the target proton recoils, and M_p is the proton mass.

In order to obtain the hydrogen cross section we have used polyethylene $(CH_2)_n$ and carbon (C) targets and performed a subtraction. Each target is a foil 5mm wide and approximately 13 mg/cm^2 thick placed at a 45° angle to the beam. The detector telescopes are at a distance of one meter from the target. Each telescope subtends a solid angle of 6.4×10^{-5} steradians and a range in θ of only 0.46°. Thus our covering efficiency in θ is only 20%. Hence, we have not measured the cross section continuously in M^2 and may be missing interesting structure.

ELECTRONICS

A simplified diagram of the electronics for each telescope is shown in Fig. 2. The charge from each detector is collected by a charge sensitive preamplifier and the resulting signal is sent into a sample and hold system awaiting readout into the analog multiplexer. Concurrently a signal is sent to the discriminator. If the signal exceeds the threshold requirement of the discriminator a pulse is sent to the coincidence circuit at the input to the master trigger. If both detectors in a telescope have signals in coincidence, the master trigger is activated and records in registers which detectors were active at the time of the trigger. At this

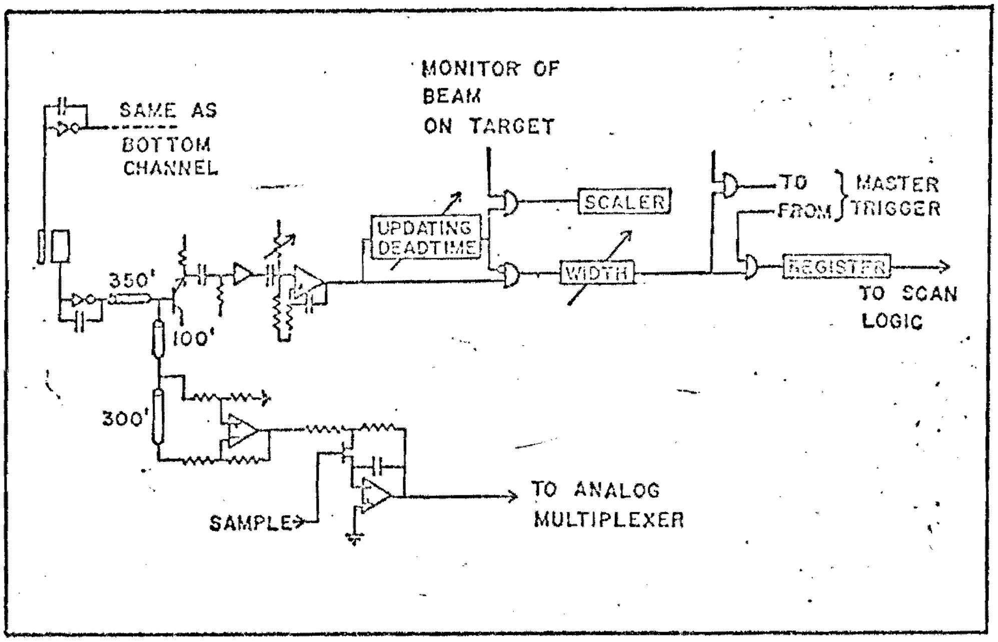


Fig. 2. Simplified diagram of the electronics for each telescope showing discriminator, amplifiers, monitoring and the sample and hold system.

time also the decision is made to hold the analog signals awaiting readout.

In order to avoid pileup of the analog signals each detector generates a deadtime each time its signal exceeds the threshold. The electronics for the detector is then turned off during the deadtime. Since this deadtime necessitates a correction for the inefficiency it causes, the deadtime of each detector is measured by forming a coincidence between the deadtime signal and a signal monitoring beam on target. The resulting number of coincidences is stored in a scaler for each detector. Together with a master scaler which stores the total number of monitor counts these scalers then provide the deadtime correction for each telescope.

ENERGY MEASUREMENT-IDENTIFICATION OF PROTONS

The first (thin) detector of each telescope is a 500 micron totally depleted silicon surface barrier detector. The second (thick) is a 5000 micron lithium drifted silicon detector. The energy measured by the thin detector (E_1) gives essentially dE/dx the energy loss per unit length for the detected particle. The energy deposited in the thick detector (E_2) is nearly the total kinetic energy T up to T $\sim$ 30 MeV. Hence, up to this T value a plot of E_1 versus E_2 (Fig. 3) is essentially a plot of dE/dx versus T

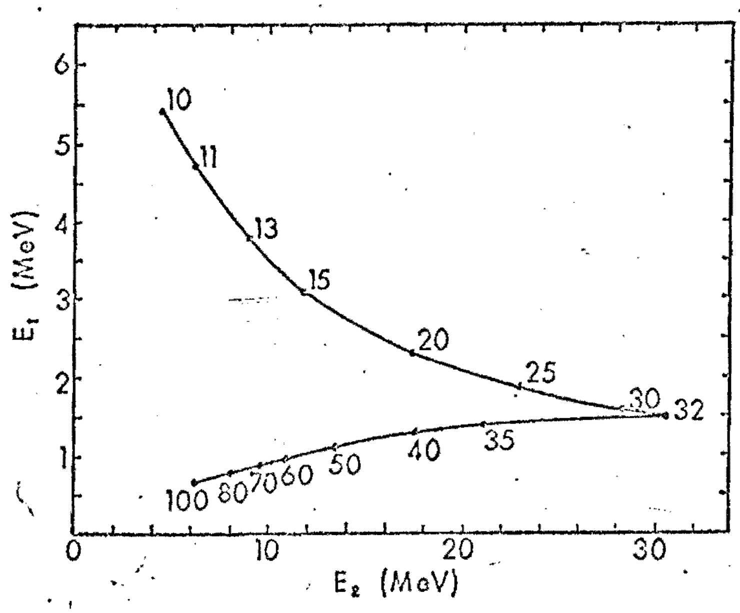


Fig. 3. Energy deposited in the thin (E_1) and thick (E_2) detectors by a proton with a given initial kinetic energy.

and falls as 1/T. For higher T values the proton does not stop in the second detector but a measurement of the energies E_1 and E_2 still allows a good determination of the proton kinetic energy up to T ∿ 100 MeV. As can be seen in Fig. 3, however, our resolution in T gets progressively worse at the higher T values.

Scatter plots in the E_1-E_2 plane of events collected in a few minutes of running are shown in Fig. 4 for two telescopes, each with both polyethylene and carbon targets. The proton bands are clearly separable from background both when the proton stops in the thick detector and when it traverses the thick detector. Proton-proton elastic peaks are prominent in the polyethylene data at the correct T values but are absent in the carbon data.

SUBTRACTION

In order to obtain the hydrogen cross section we subtract the carbon E_1-E_2 plot from the corresponding polyethylene plot for each telescope. The bands in each E_1-E_2 plot (Fig. 4) above the proton band are due to deuterons and tritons produced in proton-carbon interactions. These deuterons and tritons provide an essentially ideal normalization for the carbon data before subtraction since they can not be produced with low laboratory momentum in proton-proton interactions. Hence, we multiply the carbon data for each telescope by the appropriate factor so that the number of deuterons and tritons from carbon equals the corresponding number from polyethylene. There are a sufficient number of deuterons and tritons produced that they do not limit the statistical accuracy of the subtraction. Thus the uncertainty in the number of protons from hydrogen in each kinetic energy bin is essentially given by the

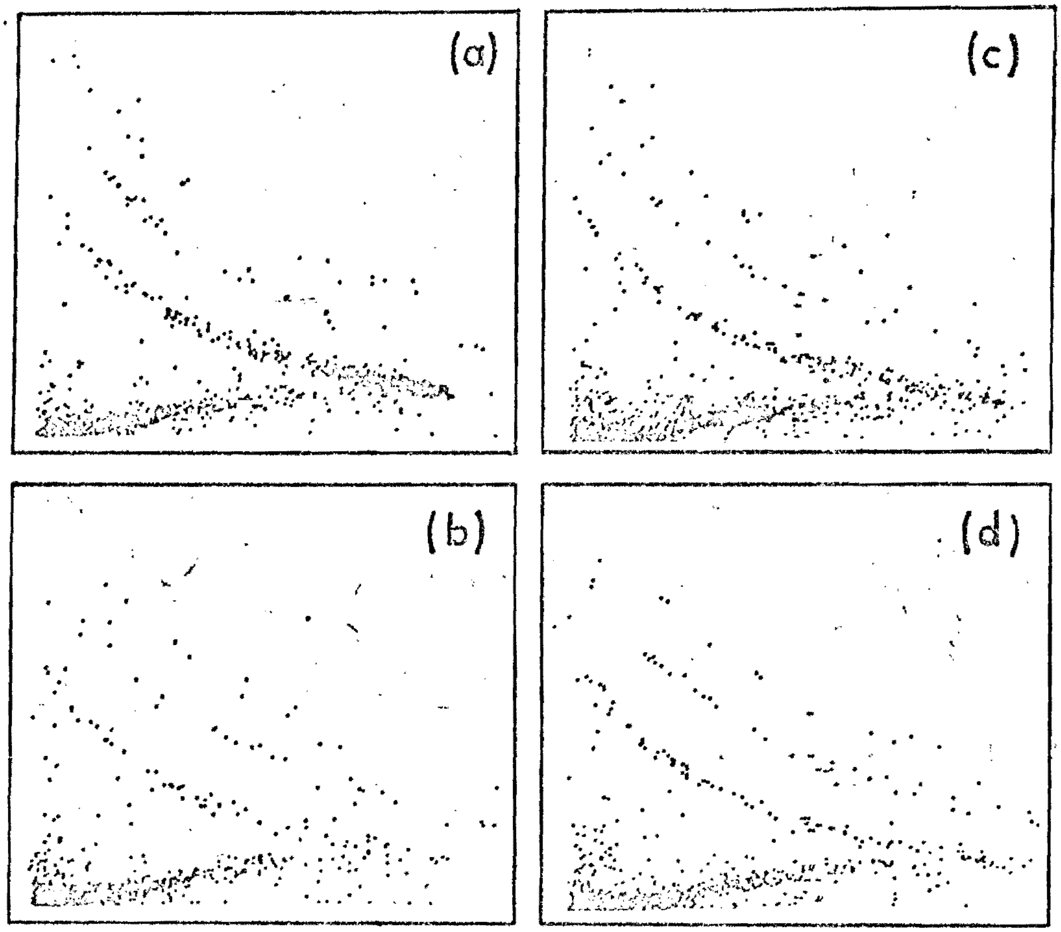


Fig. 4. Scatter plots in the E_1-E_2 plane for (a) polyethylene data at 83° (b) carbon data at 83° (c) polyethylene data at 80° (d) carbon data at 80°.

square root of the sum of the number of protons from polyethylene and carbon in that bin.

In Fig. 5 we plot our polyethylene and carbon data. We plot the unnormalized doubly differential cross section as a function of M^2 for our region of smallest $|t|$, at about 0.03 GeV^2. The statistical errors are smaller than the size of the points. The apparent structure in the carbon cross section is a binning effect due to the rapid fall of the carbon cross section with $|t|$ within a single bin in $|t|$. Consequently the data should be averaged locally in M^2. This effect is not important in the hydrogen cross section. The elastic peak in Fig. 5 is about five times the carbon background. To obtain the hydrogen cross section we subtract the carbon points from the polyethylene points. In the inelastic region we subtract about 90% of the data. As mentioned previously we pay a heavy statistical price for doing the subtraction.

As a check that the subtraction is performed properly we note that the hydrogen cross section should be zero for $M^2 < 0$ GeV^2. This is the case except for telescope number 3. In telescope

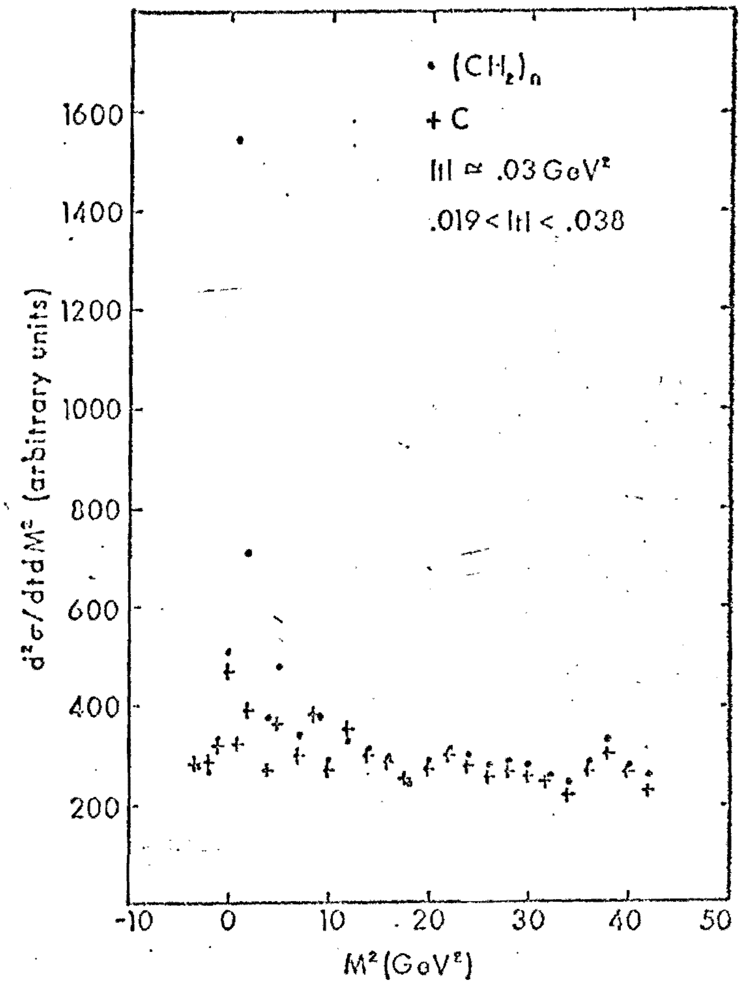


Fig. 5. Unnormalized polyethylene and carbon cross sections near $|t| \sim 0.03\ GeV^2$.

3 the proton-proton elastic peak occurs in the upper branch of the E_1-E_2 plot and some of the events in the tail of this peak contaminate the deuteron sample. A 7% correction has been applied to the data from telescope number 3 in order to eliminate the effects of this contamination. This correction only affects our measurement of the elastic slope and does not influence the inelastic data for $M^2 > 0$ since telescope number 3 does not measure this region. The four other telescopes which measure the hydrogen cross section for $M^2 < 0$ obtain a cross section which is zero within statistics. The effects of telescope number 3 in the inelastic data for $M^2 < 0$ have not been corrected and are displayed in Figs. 9-12 and Table I.

NORMALIZATION TO ELASTIC EVENTS

We measure the unnormalized elastic differential cross section by integrating the elastic peaks in telescopes 3, 4, and 5. We plot our results in Fig. 6. Our measured value of the slope

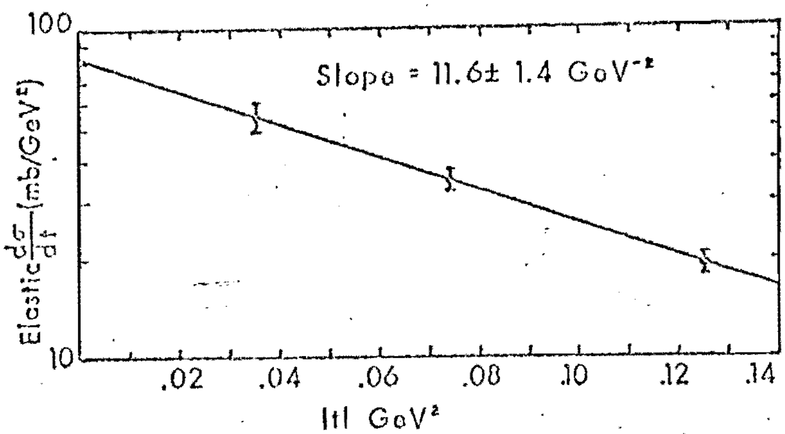


Fig. 6. Measurement of the elastic differential cross section. Normalization determined from reference 3.

11.6 ± 1.4 GeV^{-2} is in good agreement with published values.[2] We have included in our points systematic errors associated with our ability to separate elastic and inelastic events. We cite our measurement of the slope as evidence of our ability to measure the $|t|$ dependence of the proton-proton cross section.

Having demonstrated our ability to measure the unnormalized elastic differential cross section, we use this cross section to establish an absolute normalization. We take the elastic $d\sigma/dt$ to be 26 mb/GeV^2 at $|t| = 0.1$ GeV^2 as obtained by the ANL-NAL bubble chamber experiment at 200 GeV.[3] This absolute normalization is believed to have an accuracy better than 30%.

DEADTIME CORRECTION

The data for this 200 GeV experiment was collected under quite adverse circumstances. It was taken before NAL had really achieved a slow extraction and hence was taken under conditions in which no other counter-type experiment in the external beam could operate. Consequently the deadtimes are quite high, up to 50% for some detectors, and we cannot rely on any results which depend heavily on the deadtime correction. Fortunately most of the interesting aspects of the experiment do not depend upon this correction because we normalize to the elastic cross section after the deadtime correction. Consequently only the differences in deadtime corrections among the various telescopes are important.

In Fig. 7 we plot the doubly differential cross section as a function of M^2 for $|t| \approx 0.03$ GeV^2. The normalization for this plot was obtained without deadtime correction. Consequently we can study the effects of the deadtime correction by comparing Fig. 7 to Fig. 8, the corresponding plot including the deadtime correction. We see that the correction has essentially no effect for small M^2. This is to be expected since the normalization is carried out at $M^2 = 1$ GeV^2. For high M^2, however, the deadtime correction has the effect of raising the cross section by amounts approaching thirty per cent for some of the points. Hence the possible error due to deadtime for high M^2 is less than thirty per cent. Such an error is expected to be a uniform shift in the points at high M^2 and should not affect the point to point errors.

We should point out that we have independent evidence supporting the validity of the deadtime correction. The shape of the carbon cross section versus θ is similar to that observed in a subsequent run at 300 GeV which requires essentially no deadtime correction.

The shape of the cross section versus $|t|$ is essentially unaffected by the deadtime correction. This is due to the fact that a change in $|t|$ for constant M^2 involves a change in θ of only a few telescopes.

DEPENDENCE ON M^2

Our values of $sd^2\sigma/dtdM^2$ are presented in Table I and Figs. 8-12 for fixed $|t|$ intervals. The limits of each interval are given on the appropriate figure. The gaps in the data are due to our covering inefficiency in M^2 discussed earlier. The data near the elastic peaks in the low $|t|$ regions (Figs. 8-10) are displayed via a change in scale and fine binning. From study of the elastic peaks our resolution in M^2 is 1 GeV^2 full width half maximum in the two regions of lowest $|t|$. Due to the deterioration in our T resolution (Fig. 3) our resolution in M^2 increases to 2 GeV^2 for $|t| \approx .11$ GeV^2 and to 4 GeV^2 for $|t| \approx .17$ GeV^2.

Under ideal circumstances our resolution in T would in no case be limiting since our resolution in E_1 and E_2 would be 50 KeV as shown with an α source. However, this experiment was performed one meter from a beam of about 3×10^{10} protons per pulse with an effective spill time of one millisecond. It is a tribute to the National Accelerator Laboratory that the beam was clean enough for the experiment to be performed. However, because of small-signal pileup the high radiation environment did cause deterioration in our T resolution. It also caused a systematic error in our energy measurement ($\sim$ 1 MeV in E_1 and E_2) which has been corrected using knowledge of the T values at the elastic peaks in several telescopes. (Initial calibration was carried out with an α source.)

The uncertainties quoted in Table I and Figs. 8-12 are the statistical errors resulting from the subtraction for all points except one. The exceptional point is at $|t| \approx .08$ GeV^2 and $M^2 = 5$ GeV^2. This point has been reduced by 40% due to contamination resulting from elastic events. In order to define the solid angle of each telescope uniformly, collimators are placed in front of both detectors of each telescope. Protons which pass through the body of the collimators are expected to be excluded because of their improper E_1-E_2 correlation. Because of our poor resolution during this 200 GeV run, however, this exclusion could not be completely carried out. Due to the small size of the active area of the detectors behind the collimators, this failure in most cases did not present a problem. However, for the point in question the elastic peak was at

Table I. $sd^2\sigma/dtdM^2$ (mb/GeV^2)

M^2	$\|t\|\simeq.03$	$\|t\|\simeq.08$	$\|t\|\simeq.11$	$\|t\|\simeq.14$	$\|t\|\simeq.17$
-3	-23± 70	-249± 31	-86±23	-39±16	-23± 8
-2	-249±124	31± 86	0±78	23±54	202±54
-1	93±124	443± 54	---	358±39	---
0	467±233	4030± 93	---	1843±54	---
1	12355±210	6333±101	3010±70	---	1182±54
2	3299±187	---	1859±62	---	1237±54
3	---	---	1961±70	---	824±39
4	1105± 93	---	---	---	622±39
5	1283±179	911±455	---	482±39	---
6	---	---	---	389±39	---
7	444± 78	---	389±39	---	---
8	---	---	365±39	---	124±39
9	-62±226	335± 39	---	---	179±31
10	218± 86	241± 62	---	---	226±31
12	-195±101	---	93±39	132±23	---
14	86±109	101± 31	233±39	---	---
16	78±109	---	---	---	39±16
18	-39± 93	171± 39	70±31	78±31	132±62
20	179±109	---	---	---	---
22	132±109	265± 93	---	---	47±23
24	373±109	101± 39	70±31	23±23	70±31
26	288±109	70± 93	---	---	---
28	272±101	156± 39	194±62	---	---
30	257±124	443±132	109±39	117±31	86±23
32	210±124	62± 54	---	---	---
34	366±140	70± 62	179±39	---	---
36	187±140	148± 47	---	117±31	93±23
38	257±249	117± 47	132±54	---	---
40	148±218	117± 62	124±31	124±39	---
42	467±202	117± 54	132±93	54±31	109±23
44	---	249± 86	171±47	---	---
46	---	233± 54	148±62	179±31	---
48	---	265± 78	233±70	233±70	156±31
50	---	54± 70	101±54	109±93	233±62
52	---	210±117	187±70	163±47	---
54	---	---	195±54	---	124±39
56	---	---	187±62	47±54	0±39
58	---	---	---	86±47	101±78
60	---	---	---	---	171±31
62	---	---	---	---	272±62

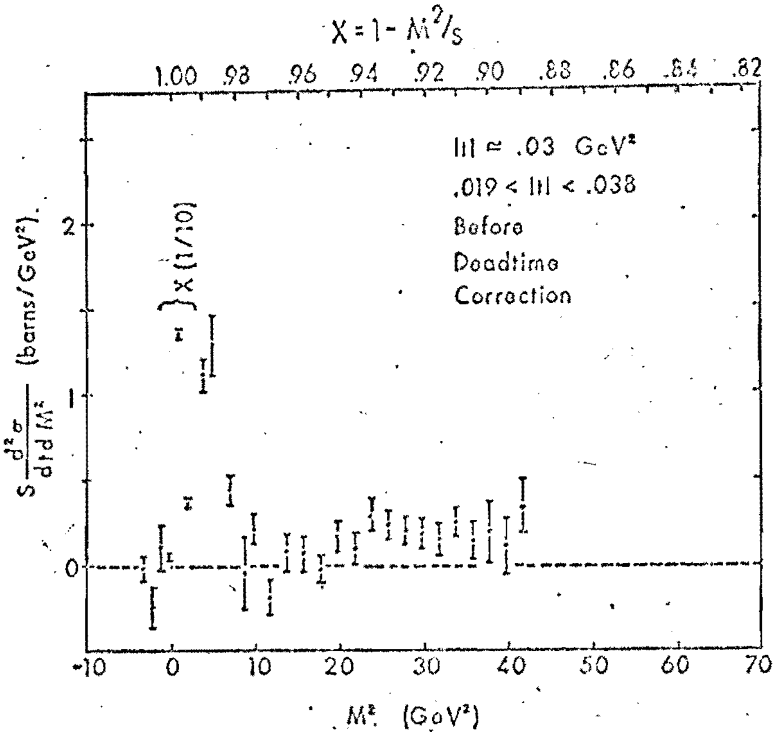


Fig. 7. Doubly differential cross section versus M^2 for $|t| \approx 0.03\text{GeV}^2$ before deadtime correction.

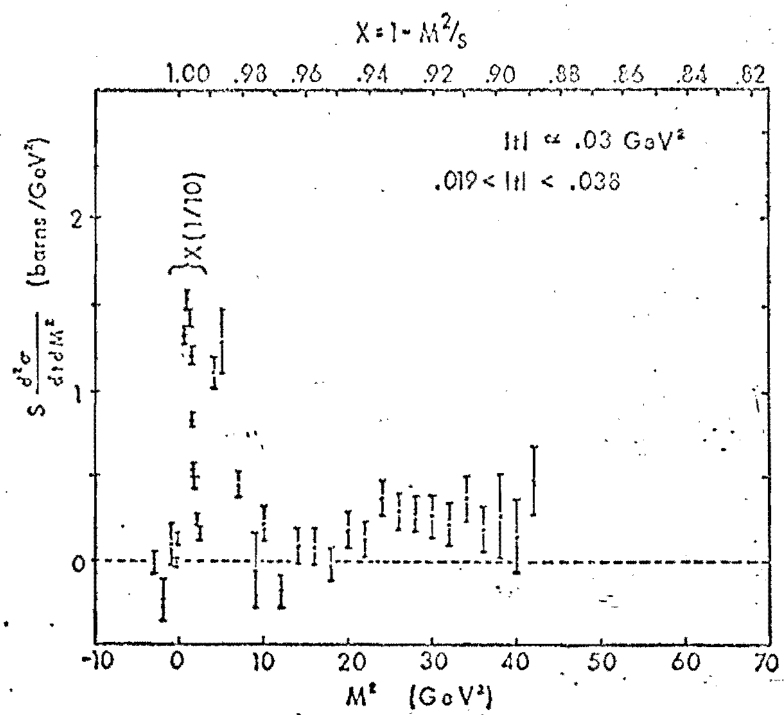


Fig. 8. Doubly differential cross section versus M^2 for $|t| \approx 0.03\text{GeV}^2$.

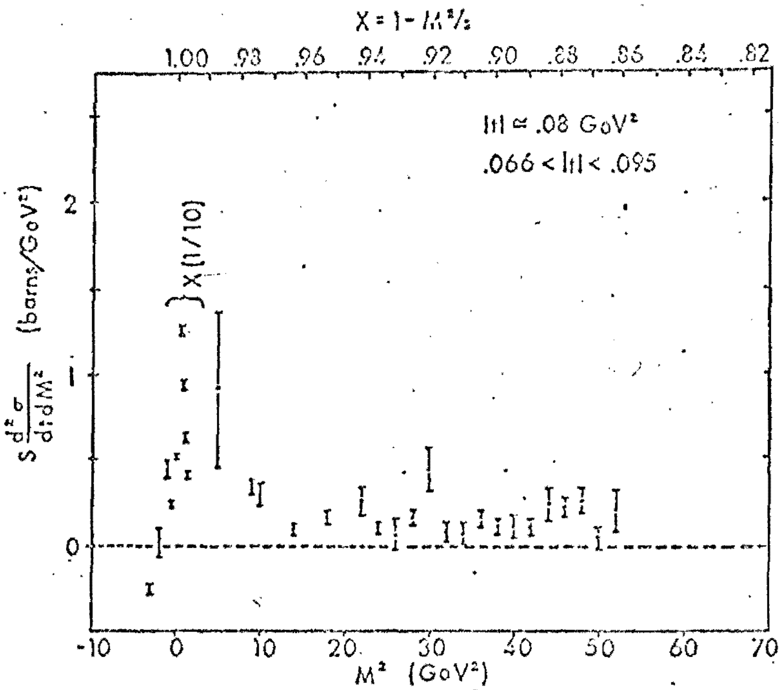


Fig. 9. Doubly differential cross section versus M^2 for $|t| \approx 0.08 GeV^2$.

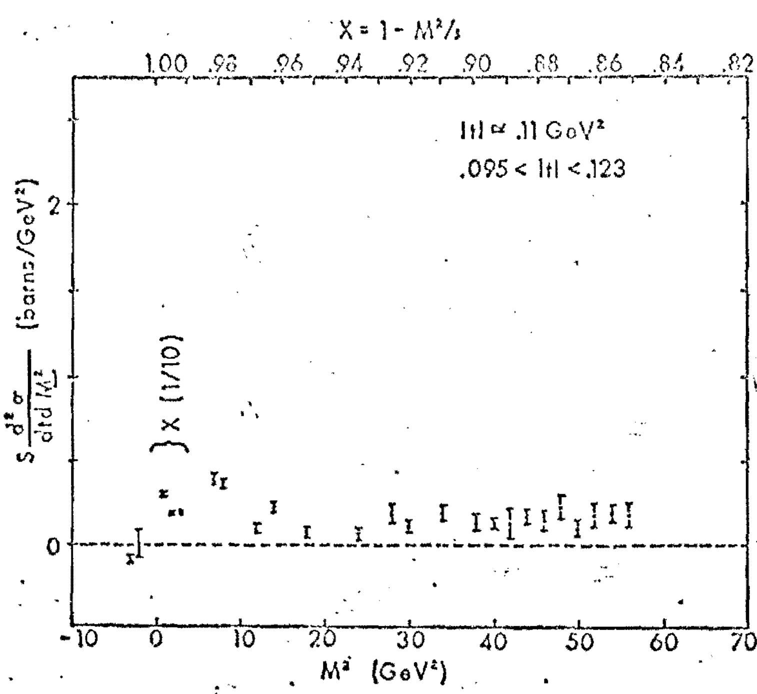


Fig. 10. Doubly differential cross section versus M^2 for $|t| \approx 0.11 GeV^2$.

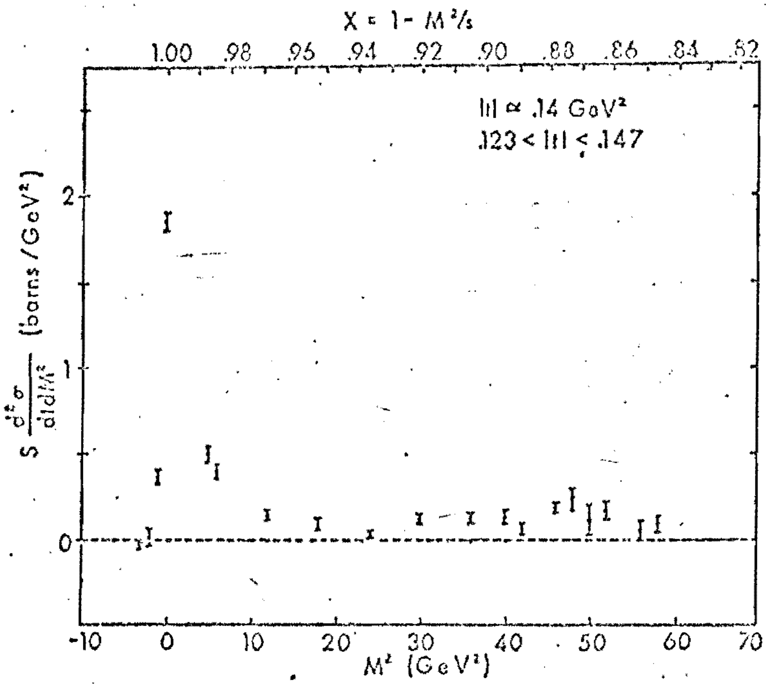


Fig. 11. Doubly differential cross section versus M^2 for $|t| \approx 0.14 GeV^2$.

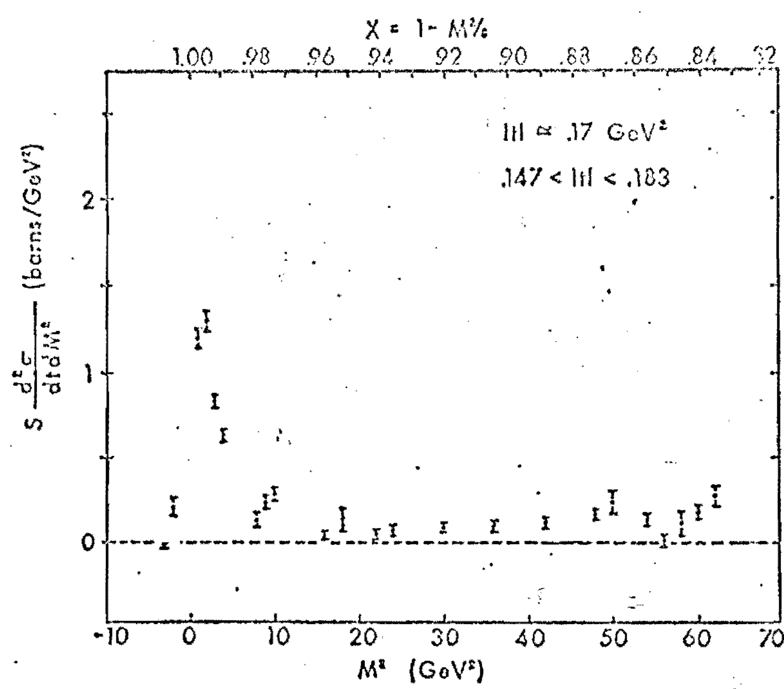


Fig. 12. Doubly differential cross section versus M^2 for $|t| \approx 0.17 GeV^2$.

the proper energy to penetrate the collimators and cause apparently inelastic events. Consequently, the large error attributed to this point is systematic.

Another possible source of background is pion contamination. Such contamination is possible only for low values of E_1 and E_2 corresponding to $|t| > .1$ GeV^2. From study of the E_1- E_2 plots we estimate this contamination to be less than 10% even at our higher $|t|$ values. This estimated upper limit is supported by kinematical considerations.

After the deadtime correction no further corrections have been made. Corrections for the finite thickness of the target would be negligible. A maximum of 0.3 MeV is deposited in the target by a 10 MeV proton which traverses the entire target. The maximum root mean square multiple scattering angle is approximately equal to the angular aperture subtended by one telescope. Thus multiple scattering in the target does not appreciably broaden our resolution. Corrections for loss of protons due to nuclear interactions in the detectors would change the data points by less than 2%.

The most noteworthy feature of the data in Fig. 8 is that the cross section reaches a minimum at $M^2 \approx 12$ GeV^2 or $X \approx .97$. Other experimenters at larger $|t|$ have found the minimum at smaller values of X.[4] If all experiments are to be consistent, this minimum must move toward $X = 1$ for small $|t|$.

DEPENDENCE ON $|t|$

The data from Table I is presented again in Table II using 6 GeV^2 bins in M^2. The central value of M^2 for each bin is listed.

Table II. $sd^2\sigma/dtdM^2$ (mb/GeV^2) using 6 GeV^2 bins in M^2

M^2	$\|t\| \approx .03$	$\|t\| \approx .08$	$\|t\| \approx .11$	$\|t\| \approx .14$	$\|t\| \approx .17$
10	36± 63	308±33	229±28	132±23	183±19
16	33± 59	128±24	133±24	78±31	45±15
22	228± 63	125±36	70±31	23±23	55±18
28	274± 64	163±35	133±33	117±31	86±23
34	251± 77	101±31	179±39	117±31	93±23
40	303±127	117±31	126±26	81±24	109±23

From Table II it seems indeed plausible that the minimum in the cross section moves to larger M^2 values (smaller X) for large $|t|$. Plots of the data from Table II are shown in Figs. 13 and 14 versus $|t|$ for several values of M^2. In the region $7 < M^2 < 19$ GeV^2 $(.98 > X > .95)$ the cross section reaches a maximum near $|t| \approx 0.1$ GeV^2

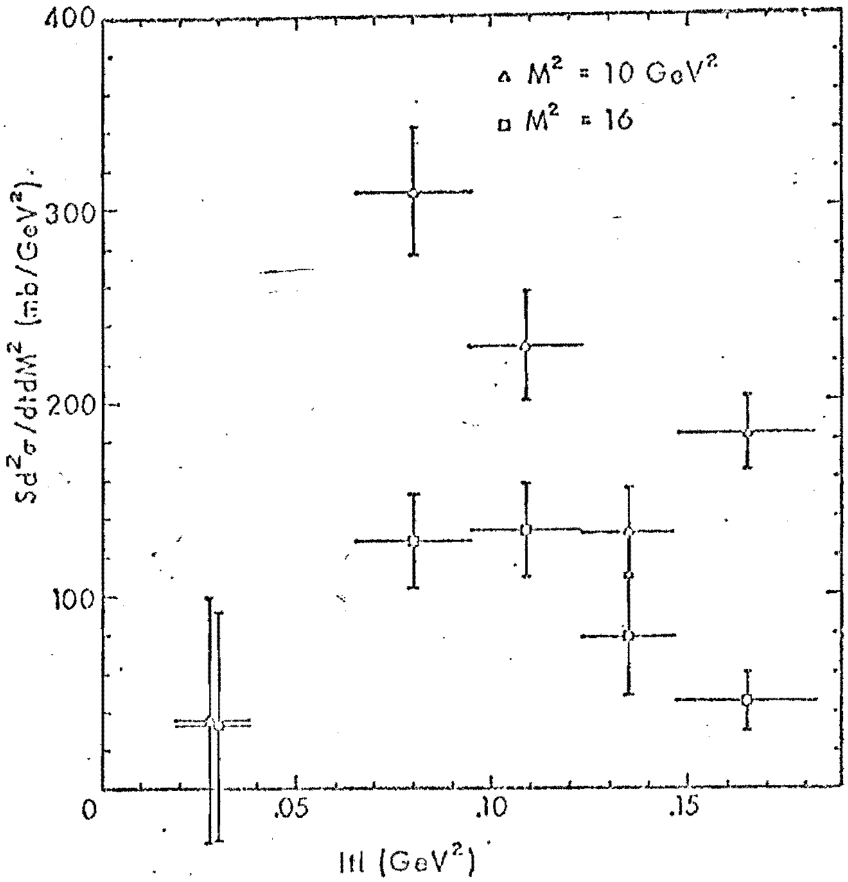


Fig. 13. Doubly differential cross section versus $|t|$ for indicated M^2.

and then decreases for smaller $|t|$. This behavior is unexpected. For larger values of M^2 the cross section exhibits the conventional monotonic decrease versus $|t|$.

In Fig. 14 we present also a few points obtained by Sannes et al.[4] at nearly the same value of s. Their points are consistent with ours and have errors which are approximately the size of the points shown.

ACKNOWLEDGEMENT

We wish to express our thanks to many NAL staff members for their efforts in producing an extremely clean external proton beam. We also thank Professor Panvini for the considerable amount of work which he has done while organizing this conference.

1. In equation (2) P represents the momentum of the recoil proton and E_B represents the total energy of the incident proton. These quantities are determined from T and P_B respectively.

2. G. Barbiellini et al., Phys. Letters 39B, 663 (1972).
3. G. Charlton et al., "Two and Four Prong pp Interactions at 205 GeV", contribution to the XVI International Conference on High

Energy Physics, Batavia, 1972.
4. F. Sannes et al. and M.G. Albrow et al., separate presentations to this conference.

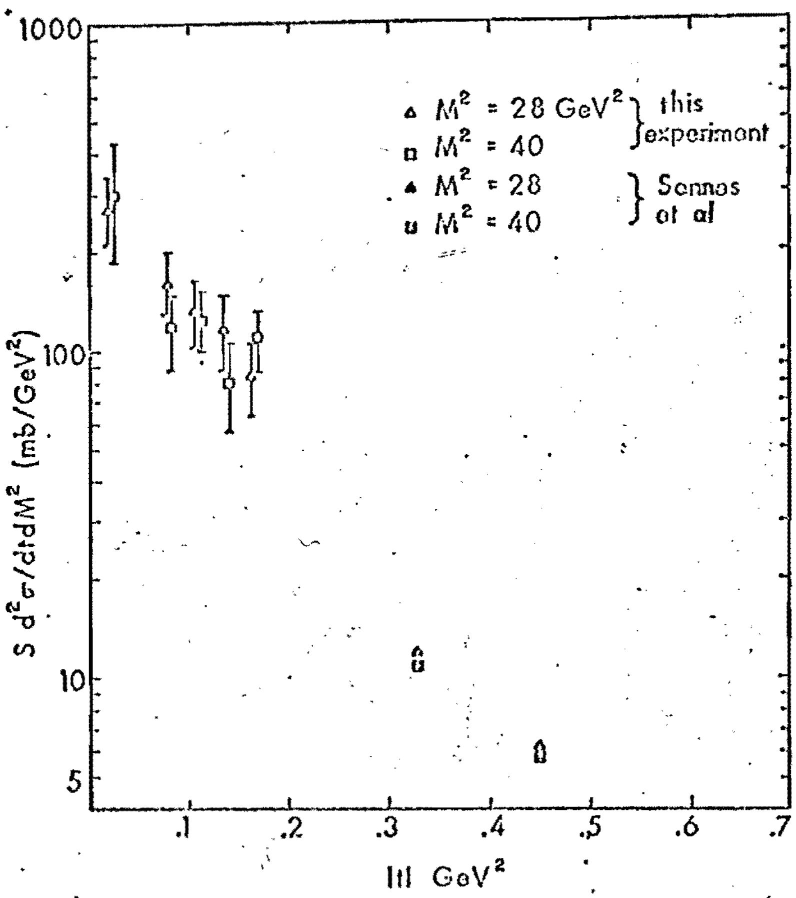


Fig. 14. Doubly differential cross section versus $|t|$ for indicated M^2.

The writeup on Phase III and Appendix C (on theoretical ideas to which our experiment is relevant) will follow.

national accelerator laboratory

June 19, 1973

To: NAL Proposal Distribution

The enclosed letter (R. Feynman to P. Franzini) is an Addendum to Proposal #221 giving theoretical background for the proposal.

Donald R. Getz

Donald R. Getz

CALIFORNIA INSTITUTE OF TECHNOLOGY
CHARLES C. LAURITSEN LABORATORY OF HIGH ENERGY PHYSICS
PASADENA, CALIFORNIA 91109

April 19, 1973

Dr. P. Franzini
Physics Department
National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

Dear Dr. Franzini:

Several times you have asked me what I thought you would get for your experiment, (measuring recoil protons in the lab) according to my ideas. At last I will answer you. One reason is that some recent ISR data (near x = 1) indicates I might have been wrong - and it would be very nice to resolve this. What I will do is first tell you what I thought as if I responded a year ago when you asked me. Then I will say what the new data suggests.

I suppose I do not have to describe the kinematic variables - if p_2 is the beam proton, p_1 the struck proton, p_3 the observed proton (p_3 is your recoil proton, or in the center of mass system where p_1, p_2 each have energy E, momentum P_0, it is the particle moving in the general direction of p_1 with transverse momentum $P_\perp$ and longitudinal momentum $P_0 x$). The unobserved "anything" has momentum $p_1+p_2-p_3$ and square mass $\mathcal{M}^2 = (p_1+p_2-p_3)^2$. We call $s = (p_1+p_2)^2 = 2M(\varepsilon+M)$ where ε is your lab beam energy. Then

$$\frac{\mathcal{M}^2-M^2}{s} = 1 - x = \frac{1}{M}\,[P \cos\alpha - P^2/2M]$$

where P is the momentum of the proton you observe at angle α to the beam direction. (These relations are approximate. x should really be replaced by the energy of p_3 in the center of mass system over E, which is very nearly x; the term $-(P^2/2M)$ should be total energy in lab minus the rest energy M, but your particles are nearly non-relativistic; and $\cos\alpha$ should be $\cos\alpha$ times the momentum of the beam in the lab times 2M/s.) To get near x = 1 we use α near 90°.

I shall give expectations in terms of $\mathcal{M}^2$ and $P_\perp^2$ or in terms of x and $P_\perp^2$; or $t \approx -P^2$. I would divide the processes into four pieces. The total curve is the sum of these pieces.

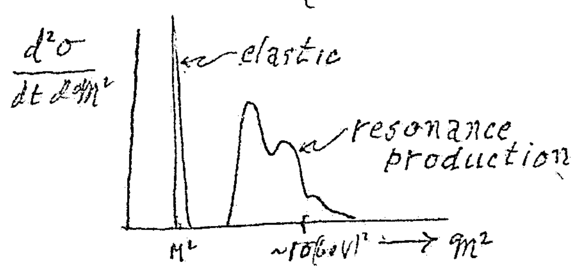
(1) Elastic

(2) Diffraction dissociation of the unobserved particle

(3) Diffraction dissociation of the recoiling particle

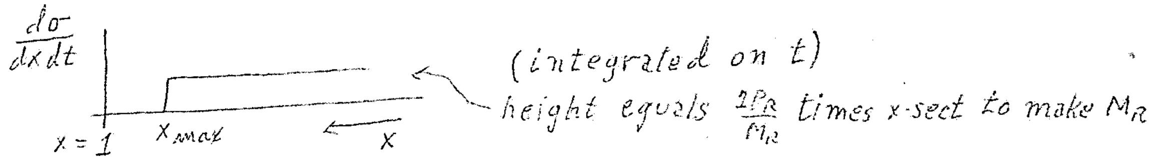
(4) General inelastic scattering.

There is a (5)th category, diffraction dissociation of <u>both</u> protons but it is probably small and you are very insensitive to it and we will leave it out. (1) Elastic is obvious, of course; there is a sharp peak at $\mathcal{M}^2 = M^2$ (near x = 1). (2) Could also be called resonance production. I mean that the unobserved particle gets excited to a resonant state P^* having the isospin of the proton (i.e., Δ^+ is excluded) - such as the 1470 or 1688 resonance - with mass M_R and some width. Thus versus $\mathcal{M}^2$ the cross section $\frac{d\sigma}{dt\,d\mathcal{M}^2}$ would show resonances like



This part of our curve would look about the same for every s. I would guess the cross section to be small compared to the elastic cross section, so perhaps 1 or 2 mb but the size is hard to be sure of. I also guess the curve falls rapidly with $\mathcal{M}^2$ so the entire phenomenon disappears beyond say $\mathcal{M}^2$ or order 10 GeV^2. (As we shall discuss later, it is this latter guess which is subject to question by the new ISR data and other peoples theoretical ideas.)

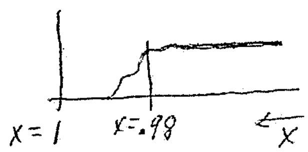
(3) This is the physically symmetric phenomenon to (2), but here it is the recoiling particle which comes out in a resonant state, energy M_R. This state decays into a proton (of energy E_R, momentum P_R in its own rest coordinate system) and let us say one pion. You observe this proton. It makes a small effect in your experiment but we must mention it. If M_R decays into a proton and a pion isotropically in its own rest system what we see in terms of our variables (integrated on $P_\perp^2$) is a uniform distribution in x from $x_{min} = (E_R - P_R)/M_R$ to $x_{max} = (E_R + P_R)/M_R$. We will only see the large x end, near x_{max} which is very close to 1 (approximately $x_{max} = 1 - m_\pi^2/M_R^2 - M^2$) where m_π is the pion mass) where it will look like



$\frac{d\sigma}{dx dt}$

(Please check, I'm not sure I've done this calculation right)

(There is no reason for isotropy - it is only an example - any other decay distribution in cosθ the angle to the beam is reflected by the same shape in x. $x = 1/2\ [x_{min}+x_{max} + (x_{max}-x_{min})\cos\theta]$.) Because of the several resonances it will look like



You can get a good estimate of what this part (3) contribution may be from observation of part (2) contributions to get the curve which determines the probability of making various resonances. (Part (5) contributions (both resonant) will just add a little more on here, looking qualitatively similar and quantitatively perhaps less than 20%).

(4) The general inelastic scattering, the biggest contribution totalling roughly 30 mb including pionization etc., should produce a contribution which scales, I expect that $\frac{d^2\sigma}{dx dt} = f(x,t)$. The question is how f(x,t) varies near x = 1, excluding the effects of (2), (3) above. In my paper I predicted it would go as $(1-x)^{1-2\alpha(t)}$ where α is that of the lowest Regge pole possible, excluding the Pomeron. This is the ω,f trajectory with α(t) near 1/2 + t. For α = 1/2 this gives a flat distribution f(x,t) more or less independent of x for x near 1. How it varies for x distinctly away from 1, say x < .8 I don't know. At any rate ISR has seen the curve over all x and you are familiar with that.

Well, that is what I would have written a year ago. Since then two things have happened. One is theoretical. Using the Mueller approach theorists have found a term called "triple pomeron term" which could give a sharp rise-like 1/(1-x) in f(x,t) near x = 1. A little consideration shows this is the same as saying that in (2) the function $\frac{d\sigma}{d\mathcal{M}^2 dt}$ would not fall fast with $\mathcal{M}^2$ as I guess but would fall slowly - asymptotically for large $\mathcal{M}^2$ as constant/$\mathcal{M}^2$ (because $dx/(1-x) = d\mathcal{M}^2/(\mathcal{M}^2-M^2)$. I have always tried to understand phenomena which go under the name of "pomeron exchange" in a physical way just as total diffraction scattering.

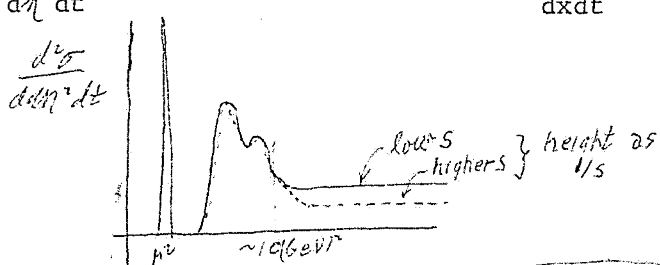
Dr. P. Franzini
April 19, 1973

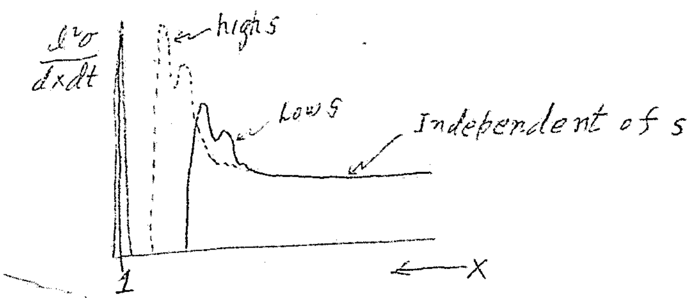
I do not ~~yet~~ see physically from this view where this $1/\mathcal{M}^2$ tail could come from. Therefore I am very interested in your experiment to see whether indeed it is there.

The other thing that has happened is experimental. For example, Albrow et al, of CERN, believe they have seen such an effect. The data looks pretty good but doubt could still be expressed, especially if you are as prejudiced against it theoretically as I am.

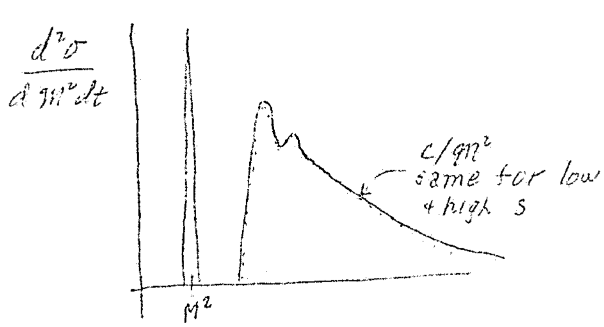
When the idea was first presented (of triple pomeron exchange) there were proofs that the coupling would have to be zero (as I supposed) if α_p were equal 1, for example at t = 0. These were simply based on the assumption that the total cross section was a constant (as I also supposed). Because the total cross section would be $\int f(x,t)\,dxdt$ or near x = 1 if f(x) went as $(1-x)^{-1}$ we have $\int dx/1-x$ logarithmically diverging as $x \to 1$. But x stops scaling at order M^2/s so we have $\ell n\ s/M^2$. Thus total x sections would have to rise logarithmically with s. But there now is some good evidence (but not entirely unequivocal) that they do rise slowly for very large s and so there is the possibility of a 1/1-x term. I wish this would all go away.

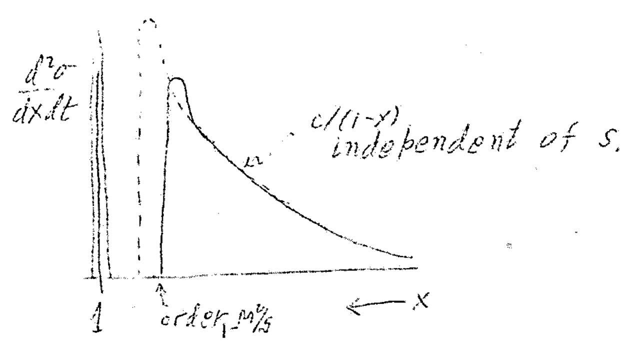
Therefore your experiment has the possibility of resolving this question (as well as telling us many things about how intensely the various resonant states are excited). Disregarding (3), what you should see is this. If you measure $\frac{d^2\sigma}{d\mathcal{M}^2 dt}$ (or s times this which is $\frac{d^2\sigma}{dxdt}$) at two values of s, if I am right you will see





If they are right you will see





Dr. P. Franzini
April 19, 1973

If you have any questions or want more details about one point or another (for example the relative probabilities of exciting various resonances as calculated by Ravndal) please write, including your range of α, P and accuracies $\Delta\alpha$,ΔP which I forget.

I am sorry I took so long to answer. My regards to your wife. Thank you both for taking care of me when I couldn't get breakfast at NAL.

Sincerely,

Dick Feynman

Richard P. Feynman

RPF;ht

To NAL Proposal Distribution
(R. Feynman to P. Franzini)

The enclosed letter is an Addendum to Proposal #221 giving ~~—~~ theoretical background ~~to~~ for the proposal.

DRG

(WITH explanatory note)

Dear Ned,

Since we did not consider our addendum to be a new proposal, we did not include a theoretical introduction. However, since we hear it is going to be a new proposal, may we attach the following letter as part of the theoretical background?

Juliet Lee-F.

X3784

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NAL Directors Office

Ned For Don G. — To be distributed to previous and future recipients of 186 ~~with~~