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Pion Diffraction Dissociation

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University of Illinois and Northeastern University

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PION DIFFRACTION DISSOCIATION

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Abstract

We propose to use the Chicago Cyclotron Spectrometer to study:

(a) $\pi^{\pm}p \rightarrow X^{\pm}p$ $\qquad |t_{pp}| = 0.05\text{-}0.45\ \text{GeV}^2$

$\quad \hookrightarrow \pi^{\pm}\pi^{+}\pi^{-}$ or $\pi^{\pm}\pi^{+}\pi^{-}\pi^{+}\pi^{-}$ $\qquad M_X \leq 4$ GeV

(b) Inclusive distributions in $\pi^{\pm}p$ reactions.

(c) Coherent production of 3π and 5π by π^{-} on nuclei

The measurements will cover $p_{LAB} = 50\text{-}150$ GeV

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Index

APPENDICES

Figures After Page

I. Introduction

Early in the discussion leading to the construction of the Muon Scattering Facility, it was recognized that the spectrometer would be powerful and flexible enough to be useful for experiments with hadrons as well as muons. It was further recognized that the large demands on proton flux and the use of pre-emptive focussing facilities implied that there would be large blocks of time during which muon running would be very inefficient. It was recognized then that such periods of time could be exploited to carry out a modest physics program using the same equipment. We wish to propose such a program.

The general design and the geometry of the CCM (Chicago Cyclotron Magnet) spectrometer are such that one has nearly complete acceptance in the forward hemisphere in the c.m. system (see section on Acceptance) at laboratory incident momenta above about 150 GeV. Our proposal makes use of this large acceptance to study multiparticle correlations among final state particles in $\pi^{\pm}p$ collisions. With slight changes in the target region, we will also be able to study particular final states in the reactions:

$$\begin{aligned} \pi^{\pm}p &\rightarrow \pi^{\pm}\pi^{+}\pi^{-}p \\ &\rightarrow \pi^{\pm}\pi^{+}\pi^{-}\pi^{+}\pi^{-}p \end{aligned}$$

and in the corresponding reactions with nuclear targets.

We have written the proposal to use the existing CCM-spectrometer with essentially no changes. If the future of the CCM-spectrometer as a facility should make it necessary to replace parts of the present hardware, we are of course willing to participate in the required work.

The general plan of the proposal (by section) is:

II: We list data we will obtain.

IIA: We estimate beam times required to obtain the data.

III: We outline the physics to be extracted from the data.

IV: We summarize the things which we are asking the laboratory to provide. Some essential details are given in a series of Appendices.

II. What

The broad aim of the proposal is to study pion diffraction dissociation at the highest available energy. A secondary aim is to obtain data on pion initiated reactions for a comparison to the "deep inelastic" processes initiated by virtual photons in Exp. 98.

Before getting into details we list what data we plan to acquire:

(a) We will run the spectrometer for a relatively short time in a "bubble chamber" mode, in which the spectrometer is triggered by any inelastic interaction in the hydrogen target. Every charged track within the acceptance of the spectrometer will be recorded and measured. We plan 3 runs (50 GeV π^-, 150 GeV π^- and 150 GeV π^+). At the higher momentum about 50% of the charged secondaries (in the forward hemisphere in the c.m. system) will be completely measured, an additional 25% will have their laboratory direction measured. We expect to record 750K events in this mode.

(b) We will record about 2500K proton triggers:

$$\pi^\pm p \rightarrow X^\pm p. \qquad |t_{pp}| = 0.05 - 0.45 \text{ GeV}^2$$

$$M_X \lesssim 4 \text{ GeV}$$

The focus of interest is on fully measured, fitted events:

$$\pi^\pm p \rightarrow \pi^\pm \pi^+ \pi^- p$$
$$\pi^\pm p \rightarrow \pi^\pm \pi^+ \pi^- \pi^+ \pi^- p.$$

We expect to obtain a total of about 200K 3-π events ($M_{3\pi} \lesssim 2$ GeV) and comparable numbers of 3π events at higher masses and 5π events. We plan to cover the energy range from $p_{LAB} = 50$ to 150 (or 200) GeV with π^- and to have at least one π^+ run.

(c) We will study the coherent production of 3π and 5π final states from nuclei. We expect to run with four different nuclei (C to Ag) with 100 GeV π^- incident and to have additional runs with one nucleus (e.g. Al) at 50 and 150 GeV momentum. We propose to obtain a total of 120K 3π events (20K in each run).

IIA. An Estimate of Required Beam Time

We list first the "ideal" data taking time required, based on 500 bursts = 1 hr.

Run	Required beam/burst	"Events" Required	"Events" (triggers) per burst	"Ideal" Beam Hours
Inclusive				
$\pi^{\pm}p$	$\lesssim 10^4\ \pi^+$ or π^-	750K	20 (20)	75 hrs.
Exclusive				
$\pi^{\pm}p \rightarrow X^{\pm}p$	$10^5\ \pi^+$ or π^-	200K†	$\gtrsim$ 1 (15)	400 hrs.
π^- + Nuclei	$\frac{1}{2} \times 10^5\ \pi^-$	120K†	∿ 2 (20)	120 hrs.
			Total	595 hrs.

† "Events" means fitted $\pi^+\pi^-\pi^-$ events.

We estimate that time required for test runs, tuning and equipment malfunction will increase the data taking time by 60 to 80% to <u>∿1000 hrs.</u>

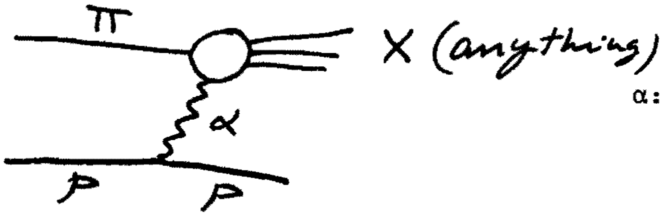
We also estimate that initial set up and testing will require <u>∿ 300 hrs.</u>

III. Why

In this section we give a very sketchy review of current ideas on "diffraction", and explain why - in our view - one should obtain exclusive as well as inclusive data.

Experimental information on inelastic diffraction phenomena is fragmentary and so is the interpretation of the data. For our purposes diffraction refers to $a + p \to X + p$ (in particular to $\pi^{\pm}p \to X^{\pm}p$) at modest values of momentum transfer to the proton and of M_X^2. It seems worthwhile to review briefly current attempts to interpret such diffraction data as exist, in part because - for better or for worse - these theoretical prejudices tend to determine what data are acquired.

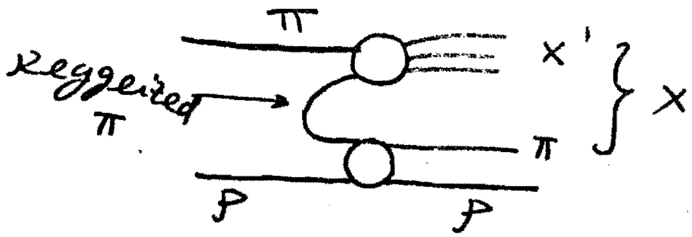
One currently favored approach is based on considerations of diagrams of the type



α: some Regge pole, possibly a Pomeron

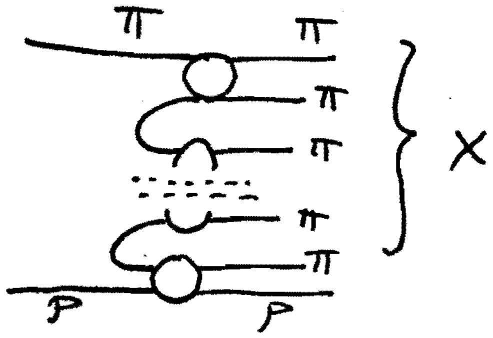
Following Chew and Low one relates the contribution of such diagrams to the total cross section for $\pi + \alpha$. Use of unitarity and of a Regge pole expansion of the $\pi + \alpha \to \pi + \alpha'$ amplitudes then leads to the so-called triple Regge formula. This scheme (or rather an artifically truncated version) has been applied to ISR and FNAL data on $d^2\sigma/dtdM_X^2$ for $p + p \to p + X$.[1] Theoretical motivation aside, the scheme boils down to a double expansion (in inverse powers of s and M_X^2) of $d^2\sigma/dtdM_X^2$.

Another approach is an obvious extension of the Deck model. In this model the main contributions are given by diagrams of the type:



In this model the diffractive cross section is related to π-p elastic scattering and to the total π-π cross section (with one pion off-the-mass-shell).

Continuing in the same vein leads to (a particular, explicit version of) the multiperipheral model:



In this model the diffractive amplitudes are related to the π-p elastic amplitude and to the (low-energy) π-π elastic scattering amplitudes.

In the sequence of approaches outlined, one moved from rather general considerations to specific models and - hopefully - toward a closer look at the underlying physics. One is also led from a consideration of the gross features of the data ($d^2\sigma/dtdM_X^2$ vs. s and t) toward a study of more detailed features (single π distribution, π-π correlations both in rapidity and sub-energies) and eventually to a study of exclusive processes such as

$$\pi^{\pm} + p \rightarrow \pi^{\pm} + n(\pi^+\pi^-) + p \qquad n = 1, 2, \ldots$$

We believe there are at least two compelling reasons to obtain and analyze data on particular final states - in spite of the current popularity of the inclusive approach.

The first reason is that exclusive reaction studies will provide additional - and stronger - tests of current (and future) models. The second reason is that one should take care not to overlook - in the rash of inclusive enthusiasm - unexpected contributions to diffraction. The most surprising result from the spectrometer studies at Serpukhov[2/] was to find that the A_2 contribution to the 3π final state continued to be as important at $p_{LAB} = 25$ and 40 GeV as at lower momenta (quantitatively the ratio of A_2 production to A_1 (A_3) production is nearly independent of the incident momentum from $p_{LAB} = 5(10)$ GeV to 40 GeV).[3/] The data on $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ and $\pi^- p \rightarrow \eta^\circ \pi^- p$ lead to the conclusion that the A_2 resonance is produced diffractively (the s-dependence implies dominance of Pomeron exchange at high energies). This result was - as far as we know - totally unexpected and lies outside the scope of current models of diffraction.

We believe it would be presumptuous and foolish to suppose that no further surprises are in store. We believe instead that progress in understanding of diffraction should include an extension of studies of particular final states to higher incident momenta, to higher masses and to higher multiplicities. We believe it is essential to confirm the diffractive nature of A_2 production, to look for the possible production of higher-mass, $I^G = 1^-$, resonances, and to see whether non-resonant contributions to 3π, 5π, ... final states can be understood in terms of Deck, multiperipheral (or other) models.[4/]

We now proceed to a somewhat more detailed discussion of what is known in the three areas to be studied in our proposal and what we expect to add to our knowledge in the proposed experiment.

IIIA. Exclusive Pion Interactions

The reaction $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ has been studied intensively in bubble chamber experiments from 5 to 25 GeV[5] and in the CIBS spectrometer experiment at Serpukhov at 25 and 40 GeV.[2] A partial wave analysis of the 3π system has been used to decompose the contributions to the final state from states of definite spin-parity, J^P, definite J_z,decaying by definite decay modes, e.g. $\rho\pi$, $f\pi$, ... The analysis includes also interference terms between different states thus allowing a determination of interference phases. The data show that of the three prominent low mass enhancements, only the A_2 (2^+) has the phase variation expected for a resonance. For the A_1 (1^+) and A_3 (2^-) enhancements the phase varies only slowly with $M_{3\pi}$.

It should be made clear that the firmness of these conclusions rests essentially on the spectrometer results (a total of 70,000 3π events were obtained at 25 and 40 GeV). The conclusions from the bubble chamber - which were fortunately confirmed at Serpukhov - are by themselves not quite as convincing (in the A_3 paper[5] a compilation of 6 bubble chamber exposures at various energies from 10 to 25 GeV was used with some 15,000 3π events). If such studies are to be pursued at all they will require the high statistics available only in spectrometer experiments.

As already mentioned in the previous section, the 25 - 40 GeV data contained at least one surprise, namely that as far as one can tell from the s-dependence, the A_2 is produced diffractively in contradiction to previously well entrenched prejudices[6] (see the Morrison-Gribov rule). We intend to continue pion diffractive studies to higher energies to find out experimentally what <u>is</u> produced diffractively at high energies, rather than relying on "theory" to tell us what <u>should</u> be produced.

We want to extend measurements also to higher masses (in the Serpukhov experiment the spectrometer acceptance prevented going beyond about $M_{3\pi} = 2$ GeV). It seems reasonable to expect that higher mass states (whether resonances or not) will lead quite often to states of higher multiplicities. We intend therefore to study at least 3π and 5π states to masses up to about 4 GeV. The geometrical acceptance of the CCM spectrometer (see Appendix E2) is adequate for this purpose.

From the experience with previous studies we conclude that at least 20-30,000 3π events are required to do a reasonably accurate analysis. Since we intend to look for possible new effects at higher masses (where the cross section is lower) we propose to obtain some 50,000 3π events (with $M_{3\pi} \leq 2$ GeV) at the highest available π^- incident energy (150 GeV with the present beam line) and the same number of events at the highest available π^+ energy (probably 120 GeV if the accelerator is running at 300 GeV, or about 150 GeV if the accelerator is running at 400 GeV). We propose also to obtain 25,000 events at each of two lower energies (e.g. 50 and 100 GeV) with both π^+ and π^- incident. The total number of 3π events will therefore be about 200,000 ($M_{3\pi} \leq 2$ GeV, with somewhat smaller numbers of higher mass 3π events, and of 5π events). The details of the setup and our estimates of required number of triggers and of required beam time are given in later sections.

Up to now we have discussed only the data on diffractively produced 3π and 5π states. We plan however to run with a very loose trigger, requiring only a recoil proton, so that we will, in fact, record all events of the type

$$\pi^{\pm}p \rightarrow X^{\pm}p \qquad 0.05 \leq |t_{pp}| \leq 0.45$$

$$M_X \leq 4 \text{ GeV.}$$

For each event every charged track (within the acceptance of the spectrometer) will be measured. We will also have some γ-ray detection capability (the spectrometer includes a 2" steel plate for γ-ray conversion and a set of 2x4 meter spark chambers at about 16 meters from the target).

This means that events will be available also for inclusive distribution studies (discussed in the next section) and for a wide variety of non-diffractive as well as diffractive exclusive final states. One could at this point make a long list of such possibilities. We prefer to mention only three, by way of examples:

(1) We will be able to detect the alternate decay mode of the A_2: $A_2 \to \eta\pi$ with both $\eta \to \pi^+\pi^-\pi^\circ$ and $\eta \to \gamma\gamma$.

(2) As suggested in the original NAL51 proposal, one can do a systematic search for the production of neutral resonance (with G = +1) by looking at the process:

$$\pi^\pm p \to X^\pm + p$$
$$\hookrightarrow X^\circ\pi^\pm$$

both treating X° as a missing-mass object (double missing mass technique) and (more restrictively) by looking for $X^\circ \to \pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$...., decays.

(3) It will be possible to look at such typical non-diffractive reactions as

$$\pi^\pm p \to \rho^\pm p$$
$$\hookrightarrow \pi^+\pi^\circ$$

to find out whether the rapid drop with energy observed up to 40 GeV[7] continues to higher energies.

If past experience is any guide, one should add the comment that in experiments of this type the amount of useful physics that can be extracted from the data, beyond that promised in the proposal, is limited only by the enthusiasm, imagination and endurance of the physicists who analyze the data.

IIIB. Inclusive Pion Interactions

The point that one can learn a great deal about hadron interactions by studying inclusive cross-sections (1-, 2-, n- particle distributions) needs no elaboration. As far as studies with incident pions at high energy are concerned, the number of published theoretical papers, review, suggestions, ..., probably exceeds the number of events studied.

From bubble chamber experiments one has adequate information on single particle distribution, and future bubble chamber experiments[8/] will probably give adequate information about 2-particle correlations in the central region. The CCM spectrometer can add significantly by obtaining more detailed information in the π-diffractive region and in the transition region between the diffractive region and the central plateau, where bubble chamber measurements suffer both from inadequate statistics and from a lack of momentum resolution.

The acceptance in the CCM spectrometer (at 100 GeV or higher) is not as good as in bubble chambers, but covers nevertheless most of the forward hemisphere (with momentum measurement) and somewhat more (direction only).

The momentum resolution is very good ($\sim$ 2% at 100 GeV) and so is the resolution on effective masses ($\pm$ 20 MeV for a ρ).

We expect to add useful data on the following points:

(1) The single particle x (or y) distribution, (as a function of $p_\perp$) will be measured accurately up to the kinematic limit.

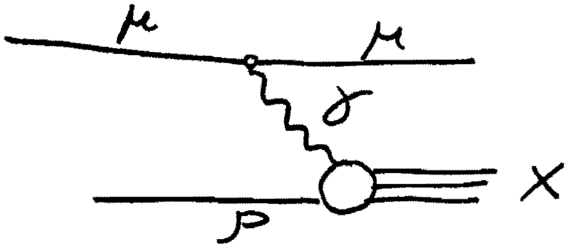
(2) We will obtain sufficient statistics for 2-particle correlations[9/] (+ -, - - and + +) for binning in $\Delta y = 0.25 - 0.5$ and $\Delta p_\perp = 0.1 - 0.2$ GeV even in the more sparsely populated forward region.

(3) With increased statistics and resolution, it seems reasonable to expect that we can begin to ask questions about the nature of the clusters out of which the multiperipheral model is supposed to be built (e.g. is it dominated by low-energy π-π scattering?).

By trying to answer such more detailed questions one can reasonably expect to begin to explore the physics underneath the statistical superstructure.

As discussed in the previous section we will also obtain substantial samples of events with a measured proton recoil, and will obtain also inclusive distributions from this subsample, where the target proton does not dissociate.

Last but not least we are interested in comparing (in whatever detail is reasonable - given the available muon data) the hadronic stuff produced by virtual photons in the muon scattering experiment:



with the hadronic stuff produced in π-p collisions.

We tentatively propose 2 or 3 runs (p_{LAB} = 50-150 GeV) with incident π^- and one run (p_{LAB} = 150 GeV) with incident π^+, for a total of 750,000 events[10/] (equivalent to ∿ 5,000,000 30" HBC pictures).

IIIC. Coherent Pion-Nucleus Interactions

We propose to measure the cross sections for coherent production of low-mass 3π and 5π systems in π^--nucleus interactions:

$$\pi^- + A \rightarrow \pi^-\pi^+\pi^- A$$

$$\pi^- + A \rightarrow \pi^-\pi^+\pi^-\pi^+\pi^- A.$$

There are at least two reasons for such a study:

(a) Only isoscalar, nucleon non-flip amplitudes contribute to coherent production. The same is assumed to be true in the corresponding π-p interactions at high energy, on the basis of somewhat indirect evidence and of theoretical bias.

In the coherent production processes at high energy only f° and Pomeron exchanges will contribute, and a study of the energy dependence should be subject to a particularly clean interpretation.

(b) From the A-dependence of the coherent cross section, one can infer the total cross section for the collision of fast 3π and 5π quasiparticles with nucleons. The pioneer work of Beusch et al.,[11-15] at CERN gave puzzling results:

$$\sigma(3\pi+N) = 20 \pm 2 \text{ mb}$$

$$\sigma(5\pi+N) = 10 \pm 7 \text{ mb}.$$

These results are unexplained.[16-18] We comment below on the possibility that the results could be wrong.

More recently a Carnegie-Mellon, Northwestern, Rochester group at BNL studied coherent 3π production from nuclei at $p_\pi = 23$ GeV. The data have been analyzed,[19] at the University of Illinois, to obtain a spin-parity decomposition. The significant new result is that there is clear evidence for A_2 (as well as A_1) production. This leads to the intriguing possibility of measuring the cross section for the collision of a bona fide, genuine 3π resonance with nucleons.

We hinted above that something could be wrong with the coherent production measurements (and consequently with the 3π-N and 5π-N cross sections). In both the CERN and the BNL experiment a veto box around the target suppressed triggers from incoherent events. Unfortunately the veto box also suppressed incoherent events of the type $\pi + p$ (in nucleus) $\rightarrow 3\pi + p$, with only a recoil proton detected in the veto box. The efficiency for vetoing such events drops very rapidly just in the region of small $\Delta^2(\pi \rightarrow 3\pi)$ where the coherent events occur. There may therefore be an error in the subtraction of incoherent events in the above experiments.

In this experiment we will use a veto box which will not suppress events where only a proton recoil leaves the target (with KE < 110 MeV, $\Delta^2 < 0.2$ GeV^2). We intend furthermore to devote considerable attention to the study of trigger biases.

The details of the proposed target, target veto and estimates of trigger event rates are given in Appendix G.

Here we mention briefly our plans:

(1) We intend to run with 100 GeV π^- incident on four different targets (from C to Ag) to determine the A dependence. The choice of energy and nuclei is dictated by the fact that at higher energies or for nuclei heavier than Ag, we begin to suffer by the finite resolution on $p_\perp$ ($\Delta^2 \cong p_\perp^2$).

(2) For one nucleus (Al or Si) we intend to run also at 50 and 150 GeV to determine the s-dependence of the cross section.

For each of the six runs we would like to obtain at least 20K 3π events, in order to do an adequate spin-parity decomposition (to pick out the $2^+ = A_2$ component).

The trigger efficiency is somewhat uncertain at this time. A reasonable estimate is 0.1 coherent events per trigger. For reasonable target thickness the beam intensities required to saturate the trigger (20 triggers - 30 msec deadtime) are about $4\text{x}10^4$ π's/burst.

IV. Things Needed From FNAL

We summarize in one place items on which a major laboratory contribution is expected (we will supply as much help as the laboratory is willing to accept).

1) Beam: We require π^+ and π^- beams with 10^5 $\pi^\pm$/1 sec burst.

2) Target: We require a 30-cm x 4 cm LH_2 target. This can be designed and built by us, if allowed.

3) On-line computer: It seems reasonable that the laboratory should supply a PDP-11. Alternatively a Northeastern PDP-9 could be used.

4) Off-line computer: We would like to have ∿50 hrs of CDC 6600 time to do data reduction on samples of data while running.

APPENDIX A

Beam

We have explored several possibilities of a hadron beam for the CCM-spectrometer.

The present μ-beam, after removing the hadron absorber and retuning the existing magnetic elements, provides an excellent hadron beam. We estimate a pion yield of $2\cdot10^6$ at 100 GeV/c for 10^{12} protons on the target. At this time we have not yet explored the detailed beam optics. This beam has the obvious disadvantage that it cannot run simultaneously with the neutrino horns.

We are also investigating the possibility of a hadron beam, that can run simultaneously with the neutrino horns. By using a target in the vicinity of the present targets for the μ- and ν-beams, and retuning the existing magnets of the μ-beam in enclosures 100 through 104, we estimate a yield of about 10^5 π^- at 100 GeV/c per 10^{12} protons on the target. At this time we are investigating the feasibility of such a beam with F. Huson and other members of the neutrino laboratory.

APPENDIX B

Cherenkov

We plan to use the beam pipe between enclosure 104 and the muon laboratory as an 80' threshold Cherenkov counter. The beam pipe may have to be lined with glass tubing or Alzac aluminum to reflect the Cherenkov light. The required air pressure, the expected number of photoelectrons and the Cherenkov angle are given in the table below:

Table

p(GeV)	Air Pressure (atm. abs.)	N_{pe}	θ(mr)
50	0.61	84	18.6
75	0.27	37	12.4
100	0.15	21	9.3
150	0.067	9.3	6.2
200	0.037	5.2	4.6

There should be no problem to distinguish protons from pions up to 150 GeV/c, and it may be possible to work up to 200 GeV/c.

Layout of the proton telescope (birds eye view)

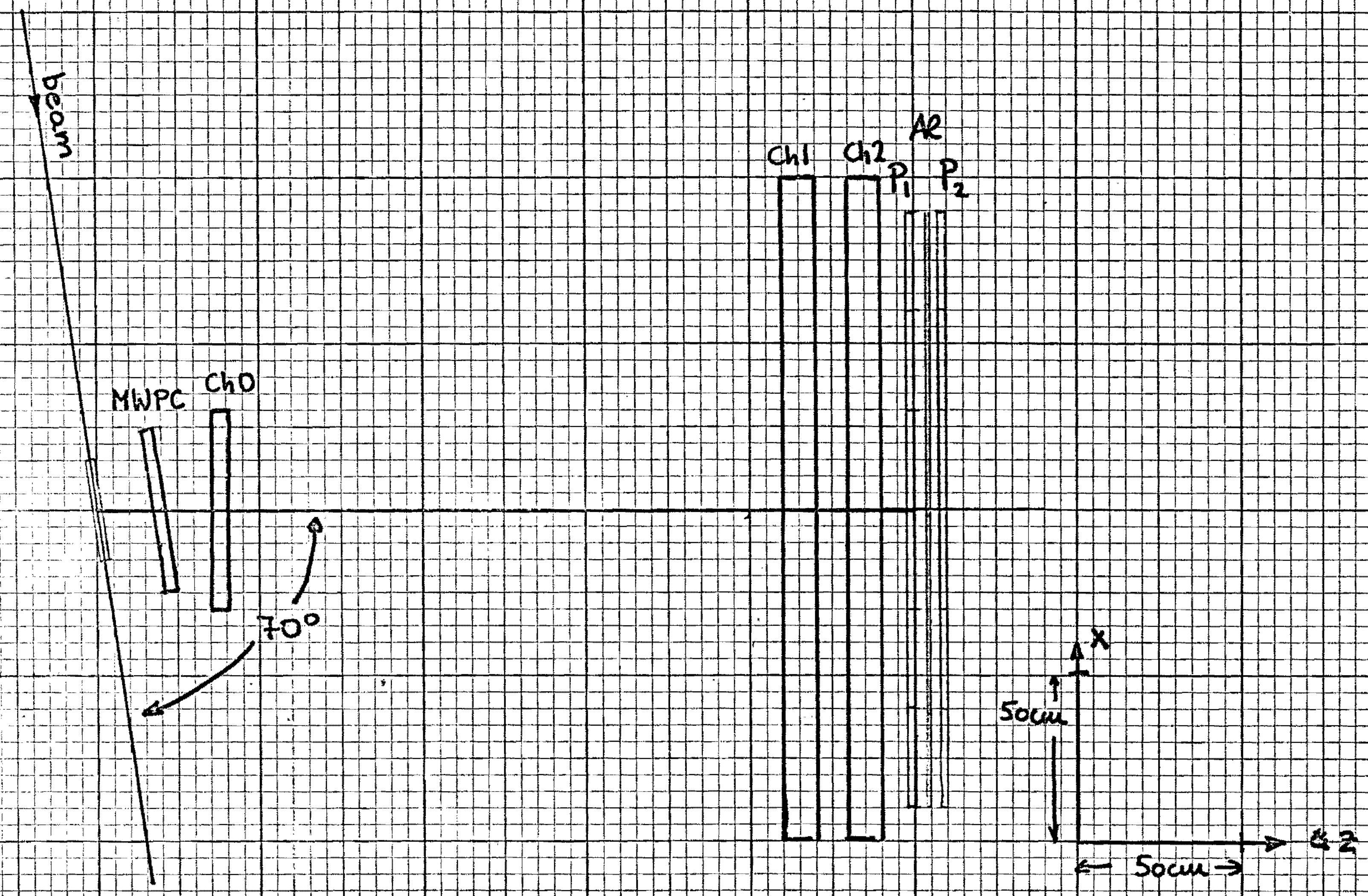


FIG. 1

APPENDIX C

Liquid Hydrogen Target

We propose to use a 30-cm long, 4-cm diameter liquid hydrogen target. We expect that such a target box can be engineered to use the same plumbing used currently by Exp. 98. Targets of the above dimensions have been used at BNL, FNAL and elsewhere with a total wall thickness (target wall + super-insulation + vacuum window) of about 0.03 cm of mylar.

The target now in use in Exp. 98 is unsuitable for our experiment because it is too long (120 cm) resulting in too many secondary interactions and the proton window is too thick (0.25 cm of Al) resulting in excessive proton energy loss and multiple scattering.

APPENDIX D

Proton Recoil Detector

The proton hodoscope identifies and measures slow recoil protons produced by the incident particle in the liquid hydrogen target, and measures their momenta and scattering angles. As shown in Fig. 1 it consists of the following parts:

- 1 multiwire proportional chamber (MWPC) - 50 cm x 20 cm, 20 cm from the target.
- 1 magnetostrictive wire spark chamber (CHO) - 60 cm x 60 cm, measuring x- and y-coordinates, 40 cm from the target.
- 2 magnetostrictive wire spark chambers (CH1, CH2) - 200 cm x 200 cm, measuring 2 x- and 2 y-coordinates, ∿ 230 cm from the target.
- 1 array of six scintillation counters (P1), 30 cm x 180 cm x 2.5 cm each, 250 cm from the target for time-of-flight and pulse-height measurement. The counters are arranged vertically with phototubes at both ends. By adding and time-averaging the signals from both phototubes, pulse height response and timing of the counter, become fairly independent of the position of impact point of the proton along the counter.
- 1 Al absorber (180 cm x 180 cm x 1.2 cm)
- 1 array of six 30 cm x 180 cm x 2.5 cm scintillation counters (total surface

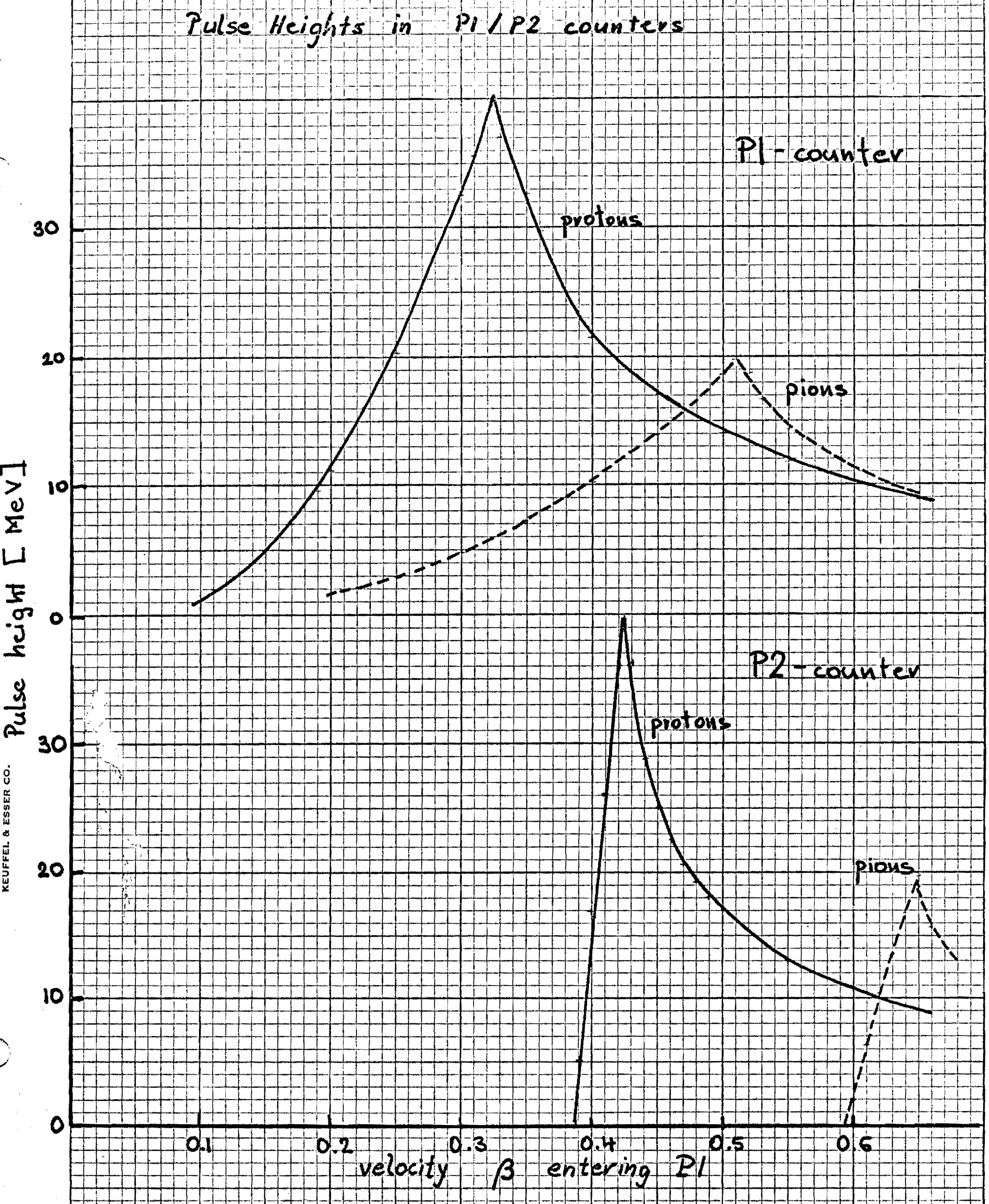

Pulse Heights in P1 / P2 counters
P1-counter
protons
pions
P2-counter
protons
pions
30
20
10
0
30
20
10
0
Pulse height [MeV]
0.1
0.2
0.3
0.4
0.5
0.6
velocity β entering P1

FIGURE 2.

180 cm x 180 cm) for pulse height measurement. (P2) All parts are mounted at an angle of 70° with respect to the direction of the incident beam.

The magnetostrictive wire chambers measure the angle of the recoil proton. The angular resolution is limited by the multiple scattering in the target and the chambers and amounts to about $\pm$ 4.2 mrad at 500 MeV/c (helium bags between target and proportional chamber, and between the wire spark chambers are used to minimize the multiple scattering).

The proportional chamber is used as a practically massless trigger counter of $\sim$ 30 nsec time resolution, to ensure that the recoil particle originates from the liquid hydrogen target. For a clean proton trigger we require, in addition, a signal in one of the P1 counters, with a pulse height exceeding an energy loss of $\gtrsim$ 10 MeV, in a time interval 14 to 45 nsec (i.e., a velocity interval $\beta = 0.6 - 0.2$) after the interaction has taken place in the target. From Fig. 2 which shows the pulse height in the P1 and P2 counters for pions and protons as a function of their velocity β, one finds that this trigger is sensitive to recoil protons with momenta between 200 MeV/c and 700 MeV/c and pions in the range from 60 to 100 MeV/c. We thus expect only a very small contamination from pions in the trigger. In the off-line analysis these remaining pions can be easily removed by the pulse height information from the P2 counter, as pions in the 60 - 100 MeV/c range stop in the Al-absorber.

The lower limit of the accepted proton momentum range is given by the energy loss of the protons in the liquid hydrogen, target walls and spark chambers ($\sim$ 0.5 g/cm^2) and is about 230 MeV/c; the upper limit of 700 MeV/c (apart from the exponentially decreasing cross sections) by the capability of distinguishing π's from protons.

The losses of recoil protons due to nuclear interactions is $\lesssim$ 5%.

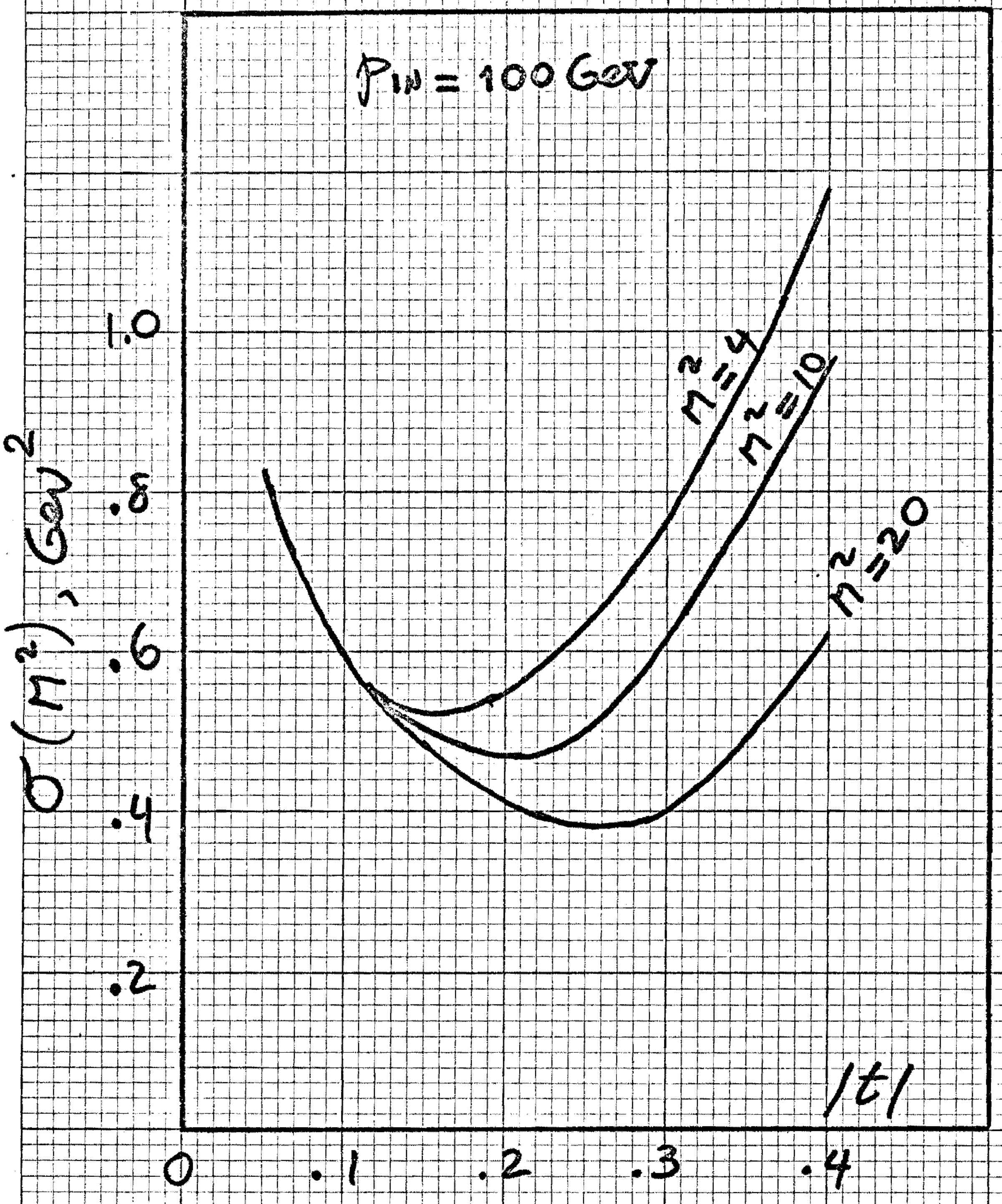


FIG. 3

For the identified recoil protons, the time-of-flight information is used to determine their momenta. From our experience with a similar setup at an experiment at Serpukhov, we know that a time-of-flight resolution of ± .4 nsec can be easily obtained.

Fig 3 shows the missing mass resolution ΔM^2 versus momentum transfer to the proton for the reaction $\pi p \rightarrow Xp$ at E_{inc} = 100 GeV/c obtained from above measurement errors. Missing mass errors for different incident momenta and masses can be obtained from these curves by noting the "scaling law"

$$\Delta M^2 = E_{inc} \times f(M^2/E_{inc})$$

The vertical acceptance of the proton spectrometer is about 10% of 2π. The horizontal angular acceptance (for a point target) is about 40° if all of the 6 counters of the P1-counter array are used. It can be reduced by using a smaller number of counters. In this way the same missing mass range in the reaction $\pi p \rightarrow Xp$ can be accepted at different incident energies. As examples we show the missing-mass versus momentum transfer acceptance for 5 (4) counters at 50 (200) GeV incident energy and a target length of 30 cm in Figs. 4a and 4b.

p_{inc} = 50 GeV/c

Acceptance of recoil spectrometer
[30 cm target - 5 counters]

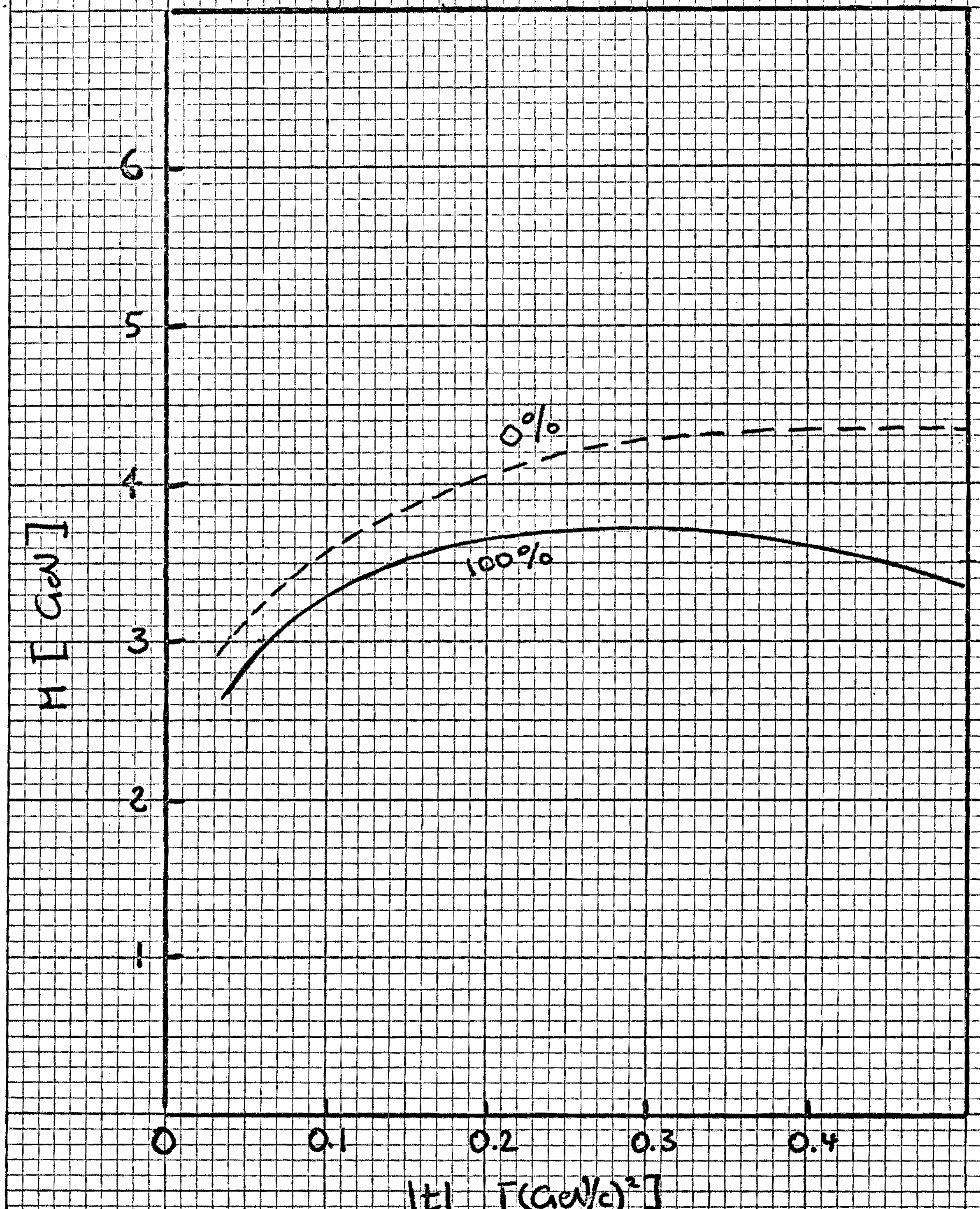


FIG. 4a

$P_{inc}=200$ GeV/c: Acceptance of recoil spectrometer
[30 cm target - 4 counters]

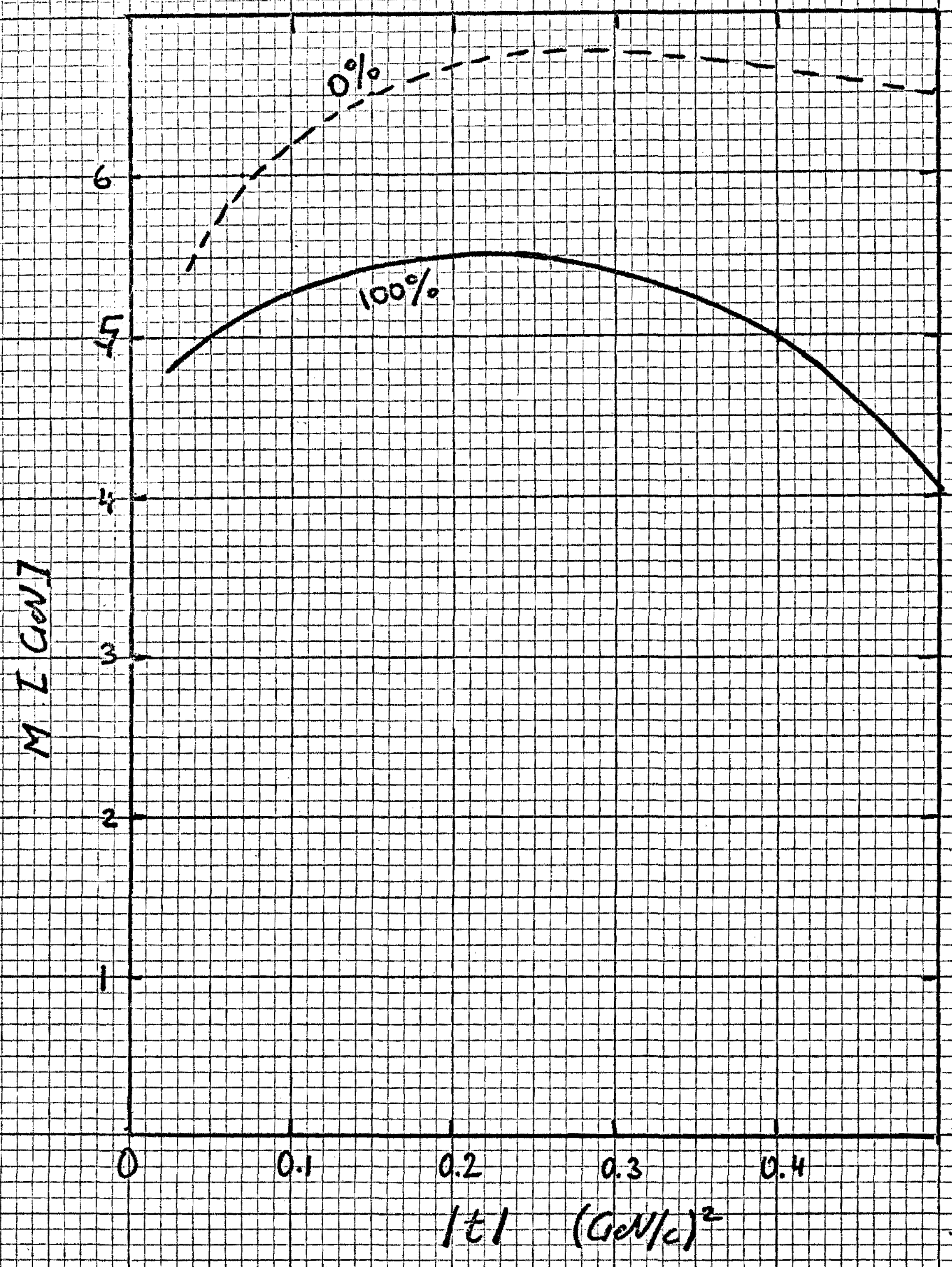
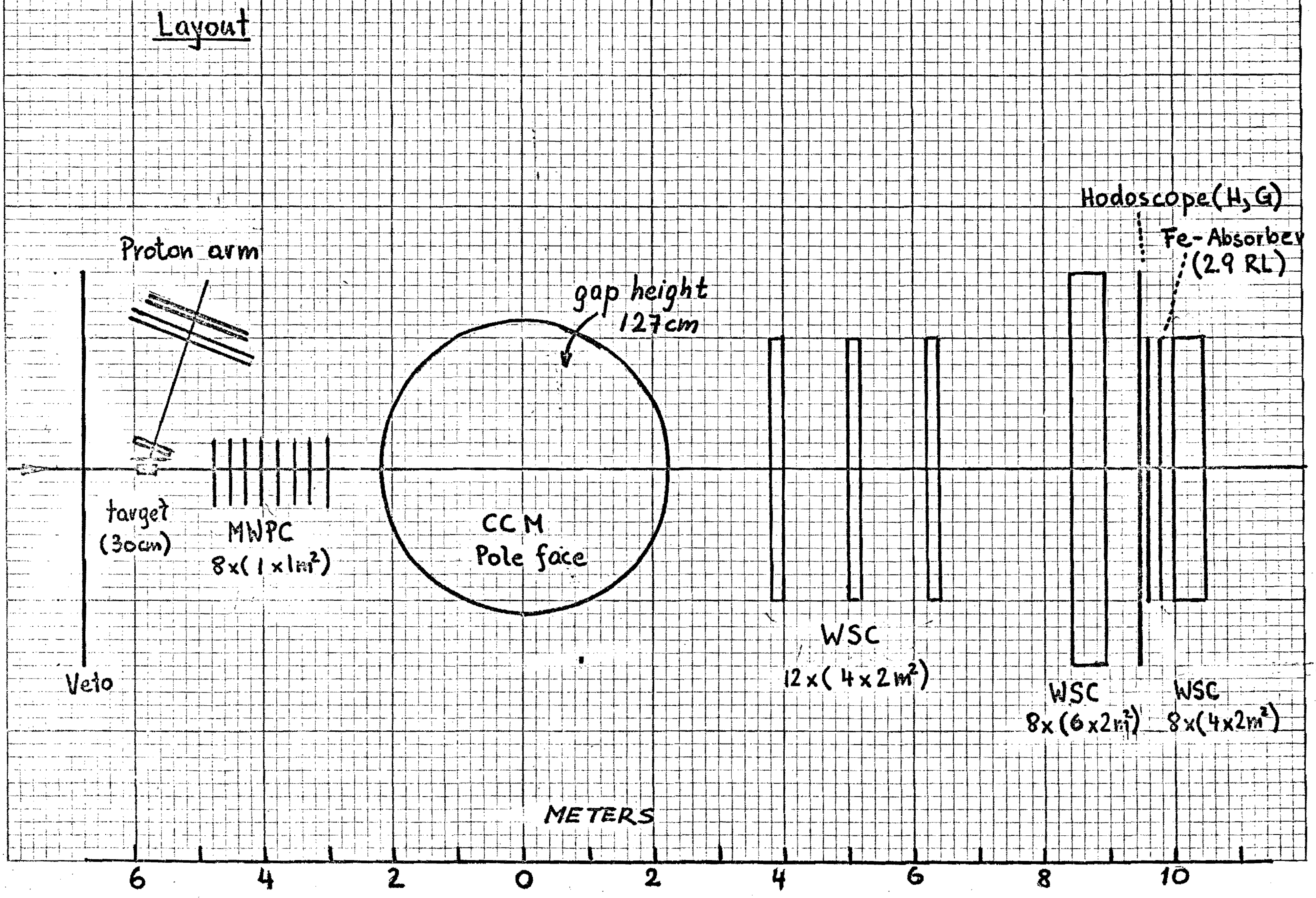


Fig. 4b

FIG 5

Layout


Proton arm
Veto
target (30cm)
MWPC 8x(1x1m²)
gap height 127cm
CCM Pole face
Hodoscope(H, G)
Fe-Absorbe
(2.9 RL)
WSC 12x(4x2m²)
WSC 8x(6x2m²)
WSC 8x(4x2m²)
METERS
6
4
2
0
2
4
6
8
10

APPENDIX E

Downstream Spectrometer

E1. Layout

We propose to employ the equipment now in use by Exp. 98 without changes. The geometry of the spectrometer is shown in Fig. 5 . A set of 8 multiwire proportional chambers (1m x 1m, 1.6mm wire spacing) records the tracks between the target and the magnet. Two sets of wire spark chambers (a set of 12 2m x 4 m planes and a set of 8 2m x 6m planes) record the tracks after the spectrometer. The two 2m x 4m counter hodoscopes G and H provide a rough counting of the number of forward particles. Downstream of these there is a 2m x 4m x 5 cm steel γ-converter and a set of WSC (8 2x4 meter planes) to detect electron showers. At the present time we are not planning to use the additional equipment (hadron converter, muon filter and related spark chambers) downstream of the shower chambers. We expect to use the CCM magnet at reduced field (12 kG) at least for $p_{LAB} \lesssim 150$ GeV. ($\int B d\ell = 1.8$ radians-GeV).

While geographically upstream of the target, we mention at this point the logically related beam tagging equipment. In the present layout of Exp. 98 various hodoscopes are used to measure the momentum (to about $\pm$ 0.1%) and the direction (to about $\pm$ 0.1 mrad) of individual beam tracks. We propose to use this equipment in our experiment. We intend also to measure the lateral coordinates of each beam track just upstream of the target with two small MWPC's. In conjunction with the measurement of the proton recoil, this will be used to obtain a precise measurement of the vertex position. With a precise location of the vertex the accuracy of measurement of the angles of outgoing tracks will be improved by nearly a factor of two.

E2. Acceptance

We have looked at the acceptance of the spectrometer by tracing particles through the magnet and into the post-magnet chambers. The results are shown on Figs. 6 and 7 for p_{LAB} = 50 and 200 GeV. The figures show the $p_\perp - p_{\parallel}{}^*$

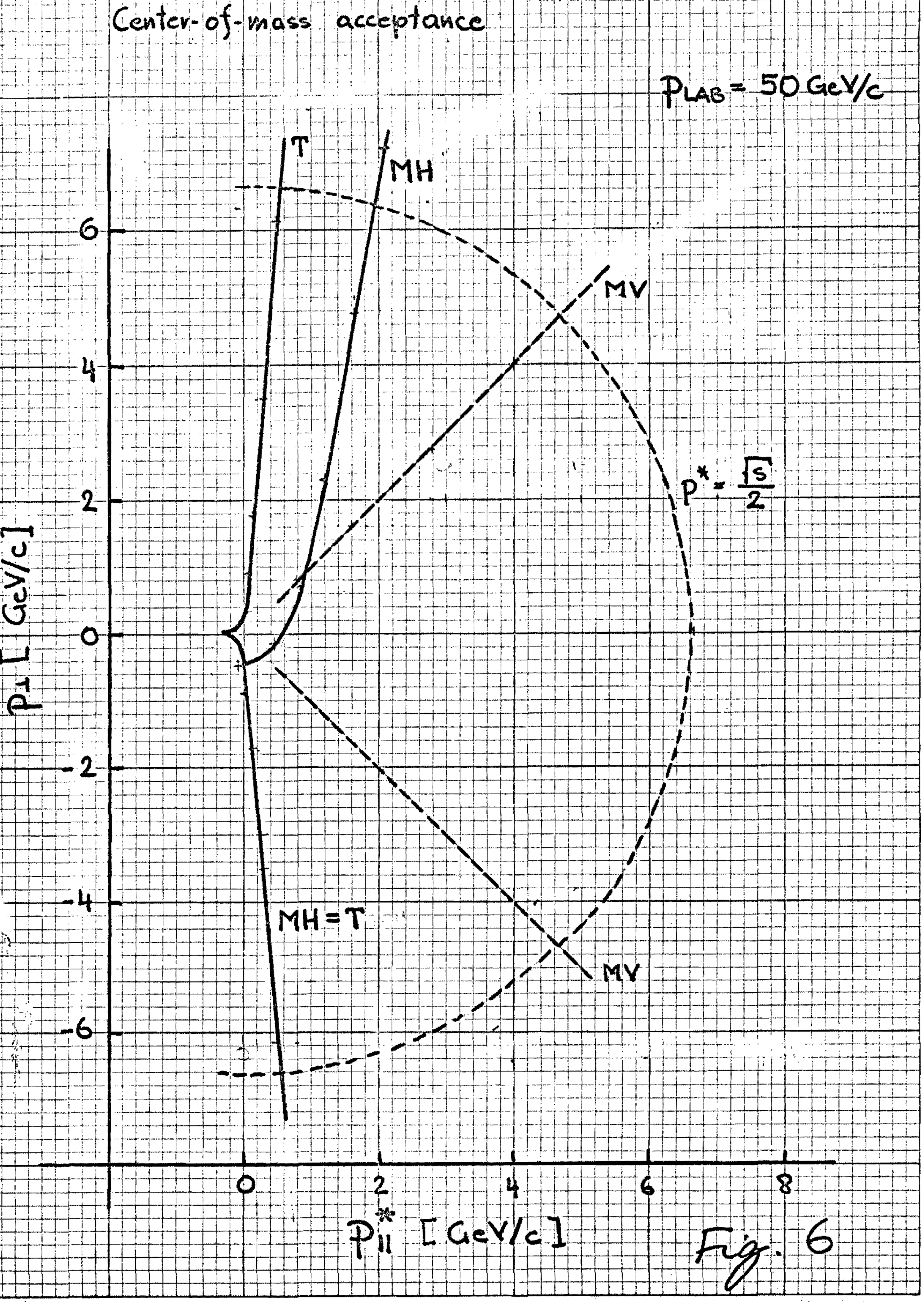

Center-of-mass acceptance
p_{LAB} = 50 GeV/c
T
MH
MV
$p^* = \frac{\sqrt{s}}{2}$
MH = T
MV
6
4
2
0
-2
-4
-6
$p_\perp$ [GeV/c]
0
2
4
6
8
$p^*_{\parallel}$ [GeV/c]

Fig. 6

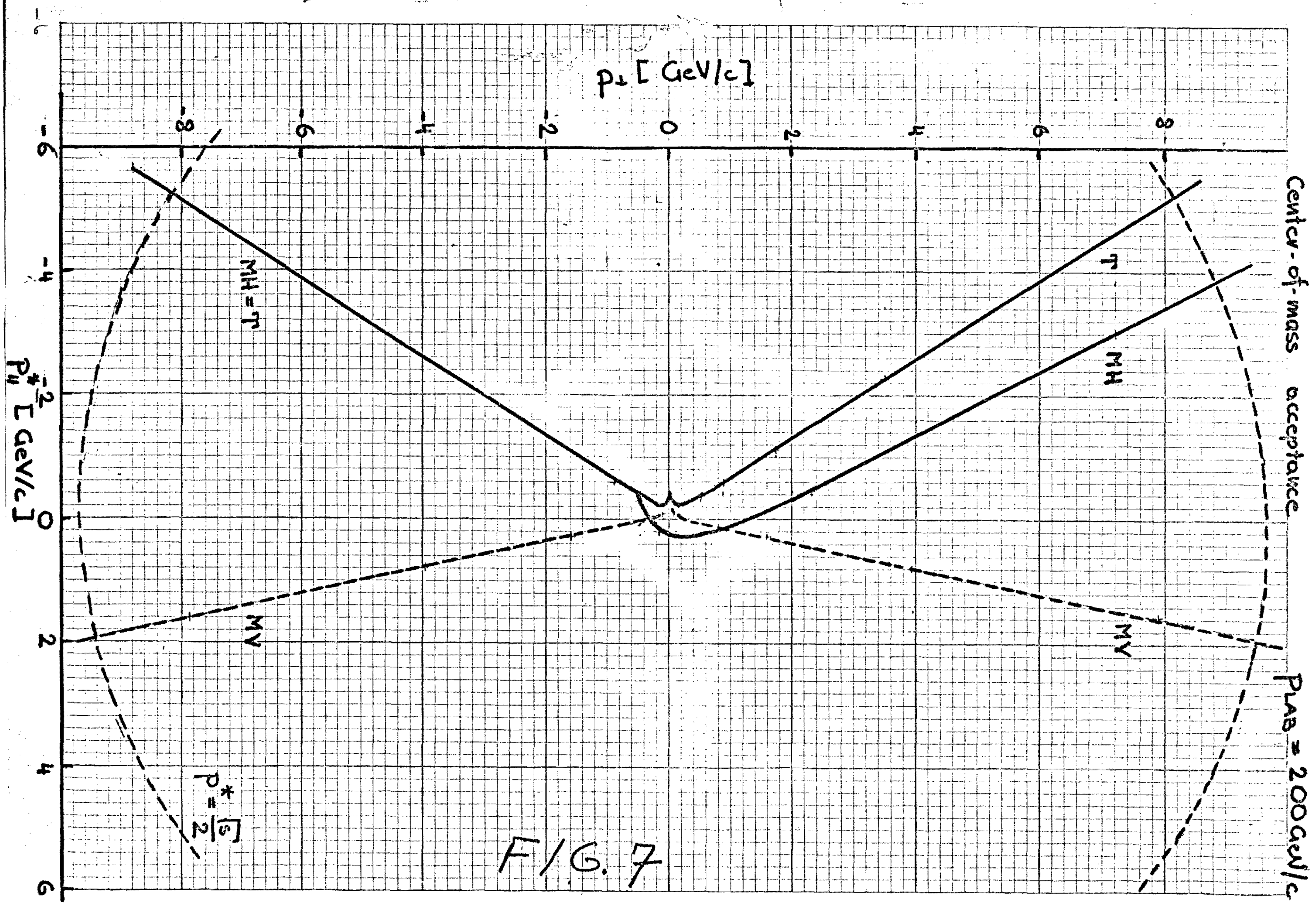

p⊥ [GeV/c]
-8
-6
-4
-2
0
2
4
6
8
-6
-4
-2
0
2
4
6
P*∥ [GeV/c]
MH=T
T
MH
MY
MY
Center-of-mass acceptance
PLAB = 200 GeV/c
P* = √s/2

FIG. 7

(transverse - longitudinal c.m. momenta) acceptance boundaries. The lines MH-MV are the acceptance boundaries for tracks to be fully measured (i.e. to be recorded before and after the magnet). The MH(MV) are the boundaries for tracks with $\vec{p}_1$ in the horizontal (vertical) plane. The lines T are the boundaries for tracks seen before the magnet (but not necessarily after the magnet). For exclusive studies (with a measured proton recoil), events with one track with unmeasured momentum (but known direction) are nearly as useful as events where all tracks are fully measured. Such events were used in the CIBS Serpukhov experiment. The inclusion of such events greatly increases the effective acceptance of the spectrometer.

From inspection of the figures, it is clear that the acceptance of the spectrometer is exceptionally good, particularly at the higher energies. We have - up to now - made no detailed Monte-Carlo studies. We note however that the acceptance of the CCM spectrometer at 50 GeV is far greater than the CIBS spectrometer acceptance at 40 GeV. In the CIBS spectrometer the acceptance was adequate for 3-π events with $M_3 \lesssim 2$ GeV.[†] The CCM spectrometer will be adequate to study 3π and 5π events at least up to $M_{3\pi} = 3$ GeV at 50 GeV and up to $M_{3\pi} = 4$ GeV at $p_{LAB} = 100$ GeV and higher.

E3. Precision

We have estimated the precision of angle and momentum measurements for the CCM:

	Standard Error
$\Delta\theta_x$, $\Delta\theta_y$	± 0.25 mrad
$\Delta p/p^2$	$\pm 1.6 \times 10^{-4}$ GeV^{-1}
$\Delta\theta_y$ (for fast tracks)	± 0.1 mrad

[†] Geometrical acceptance 90% for $M_{3\pi} = 1.3$ GeV, 75% at $M_{3\pi} = 2$ GeV.

Using these estimates we find typical errors on momentum balance for $p_{LAB} = 150$ GeV:

$$\Delta p_x = 33 \text{ MeV (horizontal)}$$
$$\Delta p_y = 23 \text{ MeV (vertical)}$$
$$\Delta p_z = 1.6 \text{ GeV (along beam)}$$

These errors include contributions from the beam track, proton recoil and forward tracks. Comparison with the results of the CIBS experiment at 40 GeV (where contamination due to π^o events was $\lesssim 2\%$) indicates that the contamination of $\pi^\pm p \rightarrow \pi^\pm\pi^-\pi^+ p$ and $\pi^\pm p \rightarrow \pi^\pm\pi^+\pi^-\pi^+\pi^- p$ events by events with additional π°'s will be $\lesssim 4\%$ (at $p_{LAB} = 150$ GeV). In addition we expect to confirm our ability to discriminate against π° events by looking at showers in the shower chambers, which cover quite adequately photons emitted by low $|\vec{p}_\perp|$ π_o's. At higher momenta the shower chambers may have to be used (and clearly could be used) to keep the background of events with π°'s to a few percent. The other sources of background are events with a $\pi^+\pi^-$ pair replaced by a K^+K^- or $p\bar{p}$ pair. The resolution on the energy balance[†] is adequate to remove $p\bar{p}$ events cleanly, but most of the $K\bar{K}$ events will be unresolved (the energy balance is changed by about 4 MeV at $p_{LAB} = 150$ GeV when $m_\pi \rightarrow m_K$). We therefore expect a background of about 3-4% $\pi^\pm K^+K^-$ events in our $\pi^\pm\pi^-\pi^-$ events.

We have estimated errors on effective masses (2 and 3-body) by scaling the CIBS results (the errors on masses are proportional to $p_{LAB}\,\Delta\theta$). We estimate

$$\Delta m_\rho = \pm 10 \text{ MeV}$$
$$\Delta m_{A2} = \pm 15 \text{ MeV.}$$

These refer to fitted events with proton-recoil and all outgoing tracks fully measured at $p_{LAB} = 150$ GeV. For 3-C events (one track momentum unmeasured) the corresponding errors are about 50% higher. For unfitted events the corresponding errors are roughly a factor of two higher.

[†] We expect $\Delta E = \pm$ 2-3 MeV (after balancing 3-momenta). Most of this error is due to the multiple scattering of the recoil protons.

We conclude that - with our assumptions about measuring errors - the precision of the spectrometer is more than adequate up to p_{LAB} = 150 GeV, and will still be adequate even if the errors should turn out to be a factor of two worse than our estimates.

APPENDIX F

Trigger and Event Rates for Exclusive πp Interactions

For exclusive πp interactions we intend to use the following trigger condition.

(beam) x (interaction) x (recoil proton)

beam - is defined by the four beam hodoscopes and an anti-counter with a hole for the beam in front of the target.

interaction - is defined by two counters in the beam behind the magnet, which give a veto signal, if the incident beam particle does not interact. These counters also veto low momentum transfer elastic events.

recoil proton - is defined by a signal in the proportional chamber of the proton telescope, and a signal in one of the P1-counters of the recoil telescope. To avoid triggering on pions we require a pulse height exceeding a 10 MeV energy loss, and an arrival-time of the signal corresponding to particle velocities between 0.2 and 0.6c.

To further clean up our trigger we could require two or more hits in one of the counter hodoscopes G and H downstream from the magnet. This trigger condition however, rejects events of the type $\pi^{\pm}p \rightarrow \pi^{\pm}\pi^{\circ}p$, which are of considerable interest; we would use it only if we cannot obtain a sufficiently clean trigger otherwise.

The following estimation of trigger and event rates is based on cross-sections of the reaction $\pi^-p \rightarrow X^-p$ and $\pi^-p \rightarrow \pi^-\pi^-\pi^+$ measured at 25 and 40 GeV/c at Serpukhov, and first bubble chamber results on π^-p interactions at 205 GeV/c at FNAL 10,20/ Table F-1 lists the estimated trigger cross-sections, and expected number of $\pi p \rightarrow \pi\pi\pi p$ events at 50 and 200 GeV/c per 10^5 incident pions. In estimating the rates we assumed an efficiency of the recoil proton-trigger of 75%[†], a factor of 0.7 for "fiducial volume" cuts (vertex cuts, size of the counters, nuclear interactions...) to obtain a clean data sample, and a 30msec deadtime of the apparatus.

To meet our requirements of 25,000 events in $\pi^{\pm}p \rightarrow \pi^{\pm}\pi^-\pi^+p$ with $M_{3\pi}$<2GeV at 50 and 100 GeV/c and 50,000 events at the highest energy available (i.e. 150 or

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[†] In the Serpukhov experiment this number was typically 75%.

200 GeV/c) thus requires a total of 2 x 10^5 accelerator pulses of 1 sec and 10^5 incident particles.

The following table F-2 lists how many events of the types $\pi^{\pm} p \rightarrow A_2^{\pm}(\rightarrow \eta^{\circ}\pi^{-})p$ $\hookrightarrow \pi^{+}\pi^{-}\pi^{\circ}$ and $\pi^{\pm} p \rightarrow \rho^{\pm}(\rightarrow \pi^{\pm}\pi^{\circ})p$ are expected simultaneously with the 3π events.

Table F-1

Estimation of Event Rates

	50 GeV/c	200 GeV/c
$\sigma(\pi^\pm p \to \pi^\pm \pi^- \pi^+ p) M_{3\pi} < 2$ GeV	400 μb	400 μb
$\sigma(\pi^\pm p \to \pi^\pm \pi^- \pi^+ p)$ * acceptance(1)	30 μb	30 μb
$\sigma\ \pi^\pm p \to X^\pm p)$ * acceptance(1)	185 μb	150 μb
electronic triggers/$10^5\ \pi_{inc}$ (2)	31	25
triggers/$10^5\ \pi_{inc}$ (3)	16	14
good ($\pi p \to Xp$) events/$10^5\ \pi_{inc}$ (4)	8	7
good ($\pi p \to \pi\pi\pi p$) events/$10^5 \pi_{inc}$ (4)	1.2	1.3

(1) momentum and solid angle acceptance of recoil spectrometer

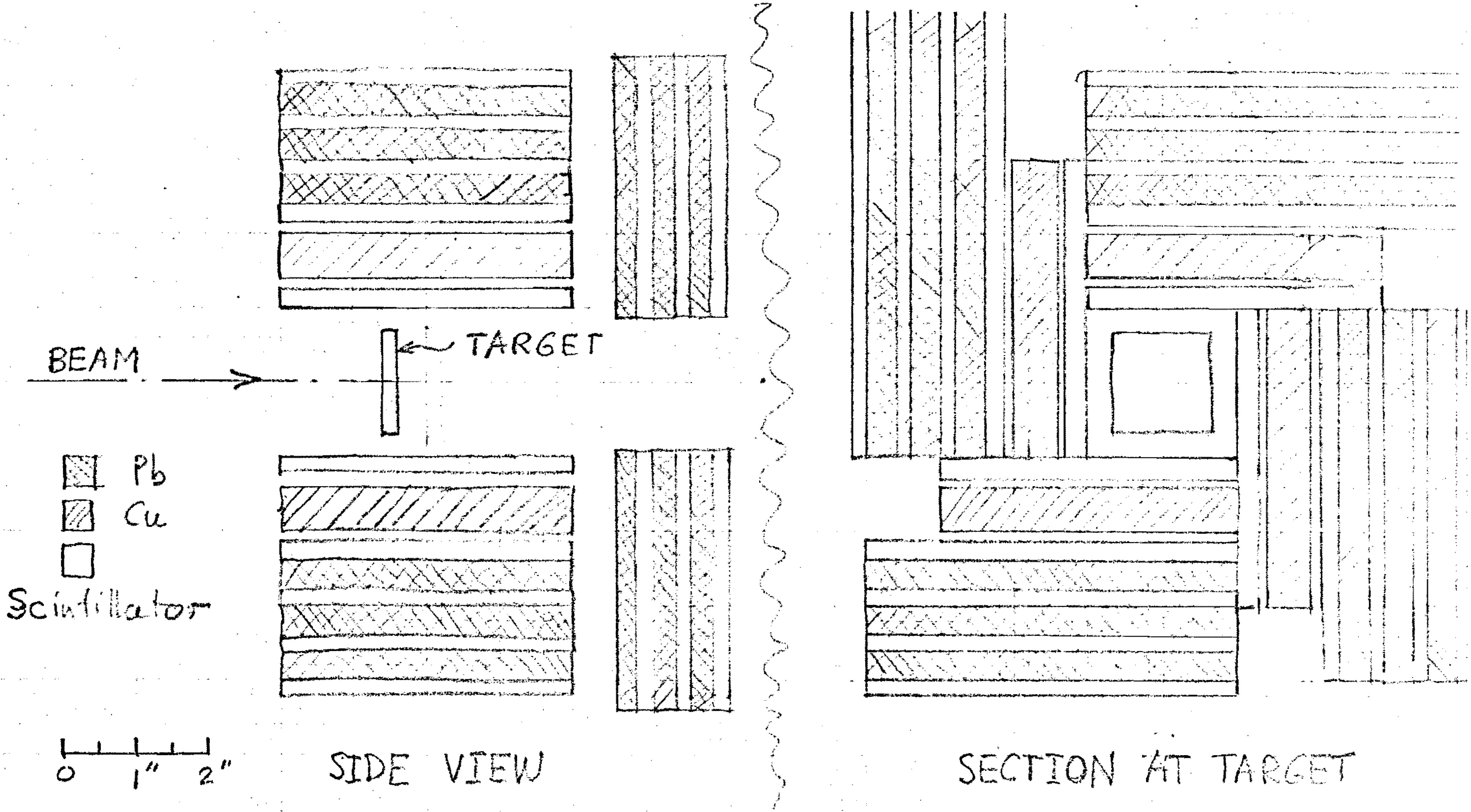
(2) for 30 cm liquid hydrogen target and an efficiency of the proton trigger of 0.75

(3) for 30 msec deadtime of the apparatus and 1 sec spill

(4) for an efficiency of the proton trigger of 0.75 and a factor of 0.7 for fiducial volume cuts (target cuts...)

Table F-2

P_{inc} [GeV/c]	N(3π) $M_{3\pi} < 2$ GeV	$N(A_2^\pm \to \eta^\circ\pi^\pm)$ $\hookrightarrow \pi^+\pi^-\pi^\pm$	$N(\rho^\pm \to \pi^\pm\pi^\circ)$
50	50,000	250	600
100	50,000	180	150
200	100,000	250	75



SIDE VIEW

SECTION AT TARGET

FIG. 8

APPENDIX G

π-Nucleus Interactions

G1. Detector-Trigger

In this part of the experiment a nuclear target surrounded on four sides by a veto box replaces the hydrogen target. The apparatus is otherwise the same as in Exp. 98 or the remaining runs of this proposal.

The veto box, shown schematically in Fig. 8 , is meant to suppress incoherent events by vetoing events with charged particles or π°'s emitted outside the forward cone. In order to produce a veto a charged particle will have to traverse a 0.6" layer of copper. In this way we prevent vetoes by proton recoils with kinetic energies below 110 MeV ($\Delta^2 < .2$ GeV^2). This will remove the difficulty due to the strong $\Delta^2(\pi \rightarrow n\pi)$ dependence of this veto. π°'s emitted outside the forward cone will be detected in the Pb-scintillator sandwich outside the charged particle detector. The remaining part of the trigger (apart from the beam defining counters and the veto box) will require 2-5 particles in the forward cone to be detected in hodoscope G-H behind the magnet. A further γ-ray veto behind the magnet is under consideration.

G2. Rates

We have tried to estimate trigger rates by using the trigger rates obtained in the CERN experiments by Beusch *et al.*,[11-15] at 15 GeV, and by using $\pi^- p$ topological cross-sections at 200 GeV.[10] The trigger efficiency (number of $3\pi + 5\pi$ coherent events/trigger) in the CERN experiment was 0.25. Our trigger efficiency will be lower because low energy proton recoils will not cause a veto. Using the topological cross-sections in $\pi^- p$ - and disregarding completely our π° veto capability - we obtain a lower limit on the efficiency of 0.05. We have based our rate estimates on an assumed trigger efficiency of 0.1.

APPENDIX H

On-Line Computer Requirements

The present use of the CCM spectrometer by Exp. 98 employs a $\Sigma 3$ computer for on-line data handling. We assume that a different computer will have to be used in our proposed experiment. We have considered two possibilities:

(a) The Northeastern University high-energy group has a PDP-9 computer, now used in Exp. 51A. This computer has a 24 K-word (18-bit word length) core memory, 250 K-word disk, 2 9/7 track Kennedy magnetic tape drives, line printer, plus the usual accessories.

If this computer is used we expect that we will have to acquire additional core memory (we estimate that a total of 32K should be enough), and possibly a second disk.

(b) If the CCM-spectrometer is to become - in some sense at least - a laboratory facility, it may be more reasonable to use a laboratory computer (presumably a PDP-11).

We are aware that a well developed on-line computer program, is an essential ingredient to the success of our proposed experiment. In addition to data logging, we expect to do equipment checking and - on a sample basis - some partial on-line data reduction, including track reconstruction.

We expect that - relying in part on existing programs used by some of us at BNL, FNAL and at IHEP (Serpukhov) - we should be able to put together the required system in a few months.[†]

The data logging load is not severe, since we will record a maximum of 20 events/burst, each event requiring approximately 600 (16 bit) words.

The interface to the $\Sigma 3$ uses standard Camac, we therefore anticipate no difficulty in switching to a different computer.

[†] All technical and physics programs for the CIBS experiment exist in Fortran versions.

APPENDIX I

Off-Line Computer Requirements

We propose to record ∿ 4×10^6 events (triggers). The information from the counter hodoscopes behind the magnet will provide a fast selection of events with different topologies. We thus expect to analyze specific channels (e.g. $\pi p \rightarrow 3\pi p$) fairly fast, and postpone the analysis of more complex and computer-time consuming events. Based on our experience in track-reconstruction and kinematic fitting of the CIBS data, we estimate that about 100-150 hours of CDC-6600 time will be required for this phase of the analysis. We will be able to handle this on our own computers (the University of Illinois high-energy group has a PDP-10 computer for its exclusive use, the Northeastern University group has access to a CDC Cyber 70 University computer). It would nevertheless make life very much easier if one could have access to a laboratory computer to process some fraction of the data during the data-taking period. Depending on the availability of computer time at FNAL we would tentatively suggest that ∿ 50 hours of CDC 6600 time would be very welcome.

A comparable amount of computer time will be used to extract physics from the data. We expect to do all of this on our own computers.

We expect to check out most of the programs required for track reconstruction and geometric reconstruction before taking any data, by using data samples obtained in the muon Exp. 98. In fact, we expect to lean heavily on the experience gained by University of Illinois (and other) participants in Exp. 98 to develop our geometry programs.

APPENDIX J

Personnel

The following physicists are committed to carry out the work outlined in this proposal:

Northeastern University	University of Illinois (Urbana)
D. Garelick	G. Ascoli
M. Glaubman	R. Klanner (R. Assoc.)
E. von Goeler	L. J. Koester, Jr.
D. Potter (R. Assoc.)	U. E. Kruse
H. Johnstad (R. Assoc.)	R. D. Sard

We expect that about four graduate students from the two universities will also participate in the work. Engineers, technicians and computer programmers will also be available.

We further expect, when the time table becomes clearer, to obtain the participation of other faculty members not listed above. We would clearly welcome being joined by physicists from FNAL and from the current muon experiments.

APPENDIX K

Time Table

We cannot make reasonable estimates at this point of the time required to achieve the required work on the beam, since this task has to be scheduled by the laboratory.

We estimate that six months (possibly less) will be required to fabricate and test the required hardware (mainly counters) and to write and debug the required on-line programs. We expect to get busy with the required work immediately, so that we should be ready to run in late fall of 1974.

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