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SMALL ANGLE HADRON-NUCLEUS SCATTERING AT FERMILAB

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INTRODUCTION

The study of small angle high energy hadron-nucleus scattering can provide an important laboratory for understanding the gross features of nuclear shapes and for studying aspects of the small time or short distance behavior of the strong interactions.

We propose to measure leading particle cross sections and coherent elastic scattering of $\pi^{\pm}$, $k^{\pm}$, $p^{\pm}$ on several nuclei (Be, C, Cu, Al, Sn, Pb,) at beam energies of 50, 100, 150 and 200 GeV. The experiment can be done with the existing E69 apparatus in its current configuration with nuclear targets substituted for the liquid hydrogen target.

PHYSICS

Just as small angle electron scattering has been an important tool in determining the charge distribution in nuclei, small angle hadron scattering probes the distribution of hadronic matter in nuclei. Thus information from small angle hadron scattering would complement electron scattering data. Such measurements have been done by Bellettini et. al.,[1] and by Bleiden et. al.,[2] at energies below 30 GeV/c.

These data are interpreted in terms of the eikonal approximation by adding the phase shifts due to scattering from individual nucleons which are distributed in the nucleus with an assumed nuclear density profile. Short range correlations between nucleons can also be included in the model even though their effects are quite small. In these descriptions the differential cross section is written as

$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2 + \frac{d\sigma}{d\Omega}\Big|_{inel}$$

where $f(\theta)$ is the coherent elastic scattering amplitude and $\frac{d\sigma}{d\Omega}\Big|_{inel}$ is the part of the incoherent cross section (either to excite or break up the nucleus) which is included in the data sample due to the finite momentum resolution of the apparatus.

The elastic nuclear scattering amplitude gives a sharp forward peak, with an angular width $\Delta\theta$ characteristic of the nuclear radius R ($\Delta\theta \sim \hbar/RP$ where P is the projectile momentum).

The quasielastic term, $\frac{d\sigma}{d\Omega}\Big|_{inel}$, is expected to be dominated by scattering from individual nucleons in the nucleus. At small angles single scattering dominates this term and the angular distribution is of the shape familiar from elastic hadron-hadron scattering. At larger scattering angles multiple nucleon scattering dominates. These multiple effects have been evaluated by Glauber and Matthiae.[3] Figure 1 illustrates this angular distribution as seen by Bleiden et. al.,[2] for P-Pb, $\pi^{\pm}$-Pb, P-Cu and $\pi^{\pm}$-Cu at 9.92 GeV/c. The dotted curve shows the expected contribution from quasielastic scattering.

The detailed theoretical analyses of high energy hadron-nucleus scattering assume that the nucleus may be treated as a dilute gas of nucleons whose interactions with hadronic projectiles are not affected by nuclear binding forces. These analyses also assume that hadronic projectiles scatter as waves on nucleons in their path and that these waves interfere with each other to give the total nuclear scattering amplitude. A study of high

energy hadron-nucleus scattering would best test this picture and thus verify at the highest available energies a basic assumption underlying more complex models of nuclear processes. For example, models which propose tests of the short time behavior of hadronic matter by the study of hadronic cascades in nuclear targets[4] depend on the correctness of the assumption of the quasi independent interaction with the constituent nucleons. In addition to such tests, coherent hadron-nucleus scattering would result in beautiful Frauenhofer diffraction patterns characteristic of the wave nature of quantum processes.

By considering the nucleus as an extended hadronic medium one can also study the effects of multiple interactions of the beam particle in order to learn something about the short time or short distance behavior of the strong interactions. One such effect is the predicted increase in the transparency of nuclei due to the production of coherent intermediate states by beam projectile interactions.[5] At high energies it is possible for such a hadron to be excited to a resonant state on one nucleon and then to reconvert to its original state on a second nucleon in the same nucleus. Such processes are true elastic scattering and (since they provide a mechanism for "inelastically scattered" projectiles to appear as elastic scatters), they should result in a decrease of the measured nuclear cross section. Because of the difference in mass between the excited intermediate state and the beam particles there is a non zero momentum transfer to the nucleon which has propagated as a diffractive resonance for part of its path in the nucleus. There is a corresponding phase difference between amplitudes due to this process and those for which the projectile

has propagated without excitation. For an incident proton at 200 GeV/c, for example, the momentum transfer in producing an N^* (1470) is only 3.5×10^{-3} GeV/c so that it is reasonable to expect that the target nucleus will recoil as a whole. At this energy the phase difference due to several fermis of propagation as an N^*(1470) is of the order of a tenth of a radian. The intermediate resonance amplitude can thus be very nearly coherent with the usual amplitude. In such an example using Pb^{208} with a Woods-Saxon potential, it is found that the ratio of forward amplitudes for direct proton propagation through the nucleus and for the production of an N^* (1470) intermediate state is 17%. Figure 2 depicts the expected decrease in p-Nucleus cross sections at 200 GeV/c. Such coherent processes are expected to contribute to high energy hadron nucleus scattering for all hadrons which can couple diffractively to excited states. Thus, effects are expected for incident pions, kaons and protons and their magnitude depends on the total cross section for the production of the excited state on a nucleon. A measurement of this effect could give some idea of resonance-nucleon cross sections. In addition, if such effects are, in fact, observed at Fermilab energies, it would then be interesting to use hyperons as projectiles to search for evidence, albeit indirect, that strange analogues of the N^* (1470) exist.

A second aspect of the short space-time behavior of hadronic physics that can be studied in nuclei is the question of whether the evolution time of a hadronic state is short or long compared with its propagation time through nuclei. The energy flux picture of Gottfried[4] has been remarkably successful in explaining the low multiplicities observed[6] in high energy interactions in

nuclei. Leading particle effects may also be sensitive to the question of hadronic evolution time. If the leading particle is instantaneously produced, it should be degraded in propagating through the nucleus due to secondary, tertiary, and higher order interactions. Thus one expects the leading particle cross section in nuclei to be considerably less than that for hydrogen and the momenta of leading particles to be degraded as compared to hydrogen. In the energy flux picture the leading particle is part of an energy pulse which propagates through the nucleus. If the evolution time of this pulse is long then successive interactions in the same nucleus should not degrade its leading particle characteristics. The leading particle then materializes as seen in scattering from hydrogen. In the instantaneous evolution time picture the leading particle cross section is expected to depend on the area of the annulus at the edge of the nucleus where its thickness is small ($A^{1/3}$) while if the evolution time is long the leading particle cross section should go as the nuclear surface ($A^{2/3}$). Of course, one must make detailed calculations to account for nuclear shapes. The energy dependence of the leading particle cross section should also be measured as a method for varying the evolution time per nuclear length by varying the time dilation of the produced hadronic state.

We propose to measure the small angle (.2 - 3.5 mr) elastic, and quasielastic scattering cross sections and the leading particle cross sections for $\pi^{\pm}$, $K^{\pm}$ and $P^{\pm}$ on Be, C, Al, Cu, Sn, and Pb, at several beam energies between 50 GeV/c and 200 GeV/c. Such measurements can be made in the high resolution beam (M6W)

of the Meson Laboratory using the apparatus of E69 by substituting nuclear targets for the existing hydrogen target. The apparatus, which is completely debugged and currently taking data on small angle elastic scattering on hydrogen, is ideally suited to the purposes outlined here.

THE APPARATUS

The E69 detection apparatus and the high resolution M6W beam form a system which is capable of triggering on and analyzing elastic scatters with momentum transfers as small as 10^{-3} $(GeV/c)^2$ with beam rates of several x 10^5 particles per machine pulse. The beam has a dispersive focus which is used to determine the incident particle momentum to 0.03%. Three Cerenkov counters (threshold, differential and DISC) in the beam simultaneously tag π, K and P. The detection apparatus is shown in Fig. 3.

A pair of high resolution proportional wire chamber clusters (70 μm resolution) separated by 3.5 meters determines the direction of beam particles incident on a 52 cm long liquid hydrogen target. A second pair of high resolution PWC's separated by 4.6 meters determine the direction of the scattered particle. The scattering angle is measured by this system with an accuracy of 35 μr. These PWC's are mounted on a concrete block to insure stability of the system.

The second pair of high resolution PWC's are followed by two Main Ring Bending Magnets and conventional PWC's to form a high resolution spectrometer ($\Delta P/P \sim 0.1\%$ at 100 GeV/c).

The spectrometer and the high resolution beam provide an

elastic constraint. The target excitation is determined to better than a pion mass. The detection apparatus has been configured to minimize multiple scattering with vacuum pipes installed inside magnets and between detectors. The PWC's downstream of the spectrometer magnets are separated by a low pressure helium filled threshold Cerenkov counter to provide some redundancy in tagging pions. The spectrometer is followed by an electron shower counter and by an iron-scintillator calorimeter whose function is to discriminate muons from hadrons.

In summary, the E69 detector and beam tag π, K, p, μ, e and determine their scattering angle to 35 μr. The target excitation is measured to better than a pion mass. The system is capable of operating up to 200 GeV/c beam momentum with fluxes of 5×10^5 per pulse. The data acquisition system can record up to 800 triggers/sec.

Aside from its high resolution, the power of the apparatus comes from its triggering capability. It is designed to trigger on the ~ 0.2% of beam particles which are deflected by only a few millimeters at a plane 20 meters from the scattering target. This is accomplished amid fluxes of up to 5×10^5 particles/sec.

The scattering trigger is accomplished in two stages. There is a small veto counter placed at the beam focus at the end of the spectrometer magnet. This counter is small enough to intercept no scattered particles with $t > .001$ $(\mathrm{GeV/c})^2$. In principle, if the full beam were focused to a sufficiently small spot on the veto, it would provide an adequate trigger. In fact, it succeeds in rejecting only 50% - 90% of the incident beam (recall that

only ~ 0.2% of the beam scatters elastically with $t > .001\ (GeV/c)^2$). The second stage of the scattered trigger then must carry most of the burden. This stage is accomplished by rapidly encoding the output of the high resolution proportional wire chambers and performing several rapid calculations with analogue circuitry to define a scattered event. Two such calculations are performed in each view and the results used in the trigger. The PWC's upstream of the target are used to choose only those beam particles which would strike the veto counter if not scattered, and the trajectories of these particles are extrapolated to the most downstream high resolution PWC. If the particle has scattered the wire hit in this PWC is not that determined by the extrapolation. Such an event is then a good scatter and triggers the data acquisition system. These calculations are performed independently in X and Y. The system, including the chamber encoding time, reaches a trigger decision within 5 μs of the passage of the particle. All information is stored in latches and ADC's until the trigger decision is made.

Several features of the system can be best illustrated with preliminary results from E69 data (Elastic Scattering on Hydrogen). Figure 4 depicts the scattering angle for all scattered triggers. This shows the complete efficiency of the two stage trigger in defining scatters. The cutoff is at a value of $t \sim .001\ (GeV/c)^2$. Figure 5 and 6 show the reconstructed scattering vertex along the beam line for target full and target empty respectively. Scattering from the hydrogen and from the chambers on either side of the target are clearly separable. Figure 7

illustrates the momentum resolution of the system at 70 GeV/c for unscattered particles. Figure 8 depicts the target excitation spectrum. The elastic peak is clearly evident. These data represent several hours of beam time and have no kinematic or fiducial cuts.

TARGETS AND RATES

Nuclear target lengths for this experiment are chosen to match the multiple scattering in the E69 hydrogen target. This choice results in all properties of the apparatus remaining unchanged when nuclear targets are substituted for hydrogen. The detailed understanding of the system gained during E69 is then directly relevant for this experiment. Table I shows the target lengths proposed (.045 radiation lengths) and the number of coherent elastic scatters per 10^5 beam particles. The cross sections used in calculating these rates are those obtained by Bellettini et. al., at lower energies.
These target lengths will help to minimize coulomb corrections to the data and the resulting rates are well matched to the capabilities of the data acquisition system.

Typical particle mixtures in the beam at 100 GeV are, for positive polarity, ~ 4% K^+, the remainder approximately equally divided between π^+ and protons. For negative polarity ~ 4% K^-, 4% $\bar{P}$ and 92% π^+. A typical running mode is to prescale the predominant particles to the level where the live time is < 50%.

With, for example, 500 K beam particles this gives 10 K of each rare particle in the system's live time and after prescaling, roughly 50,000 π^+, and p or π^-. These numbers are applicable to the Sn and Pb targets. For the other targets the event rate per beam particle is higher but in order to achieve 50% live time the predominant particles must be prescaled to a correspondingly lower rate so that the number of triggers due to predominant particles is independent of the target but rather due to the live time requirement. Thus, a typical good event rate per pulse is ~ 20 for $\bar{p}$, K^+ or K^- and 100 for π^+, p or π^-. These rates, of course, are very crude and represent an attempt to average over all targets. A factor of 1/3 should also be included for the fraction of events with clean chamber topologies and for target empty runs. With a 6 sec. repetition rate and a factor of 1/2 for safety this gives approximately 2000 good $\bar{p}$ and K^- or K^+ per hour and 10,000 p and π^+ or π^- events per hour. We emphasize that these numbers are quite crude and are included only to illustrate the good event rates possible with the system. At 200 GeV/c, for example, the beam flux of rare particles depends critically on whether the accelerator runs at 400 GeV or 300 GeV. We hope to obtain 20 K good events for K^+, K^-, $\bar{p}$ and 100 K good events for p, π^+ and π^- for each target at 50 GeV, 100 GeV, 150 GeV and 200 GeV. This would then require ~ 20 hours of beam per target per energy or a total of 480 hours. An additional 120 hours for beam tuning and careful apparatus checkout is also required. We note that these rates would allow a determination of the real parts of the forward hadron-nucleus cross section to several percent for the

predominant particles. The nuclear and coulomb interference for the targets to be used is maximal at values of t between 1.5 x 10^{-3} and 5 x 10^{-3} $(GeV/c)^2$. This momentum transfer is inside the region of uniform acceptance for the apparatus.

BEAM AND EQUIPMENT REQUIREMENTS

All of the equipment to be used in this experiment is identical to that used for E69. We thus request continued use of all PREP equipment assigned to E69. We also request 100 CPU hours of online computing time on the Fermilab 6600 computer. The experiment requires 600 hours of beam time in the M6W beam as prime user. It would be of some advantage at the highest energy if this time were available during 400 GeV operation of the accelerator. The experimenters will provide the nuclear targets.

TABLE I

Material	A	$\sigma_{elastic}$ (barns)*	Target Length (mm)	# elastic events/10^5 beam
Be	9	.051	21.0	1350
C	12	.081	16.5	1050
Al	27	.215	6.6	880
Cu	64	.51	0.85	350
Sn	119	.77	0.72	200
Pb	107	1.54	0.33	165

*From measurements with incident protons at 20 GeV by Belletini, et. al.[1]

REFERENCES

†Rutherford Laboratory, Chilton, Didcot, Berkshire, England.

[1]G. Bellettini et. al., Nucl. Phys. 79, 609 (1966).

[2]H. R. Bleiden et. al., Phys. Rev. D 11, 14 (1975).

[3]R. J. Glauber and G. Matthiae, Nucl. Phys. B21, 135 (1970).

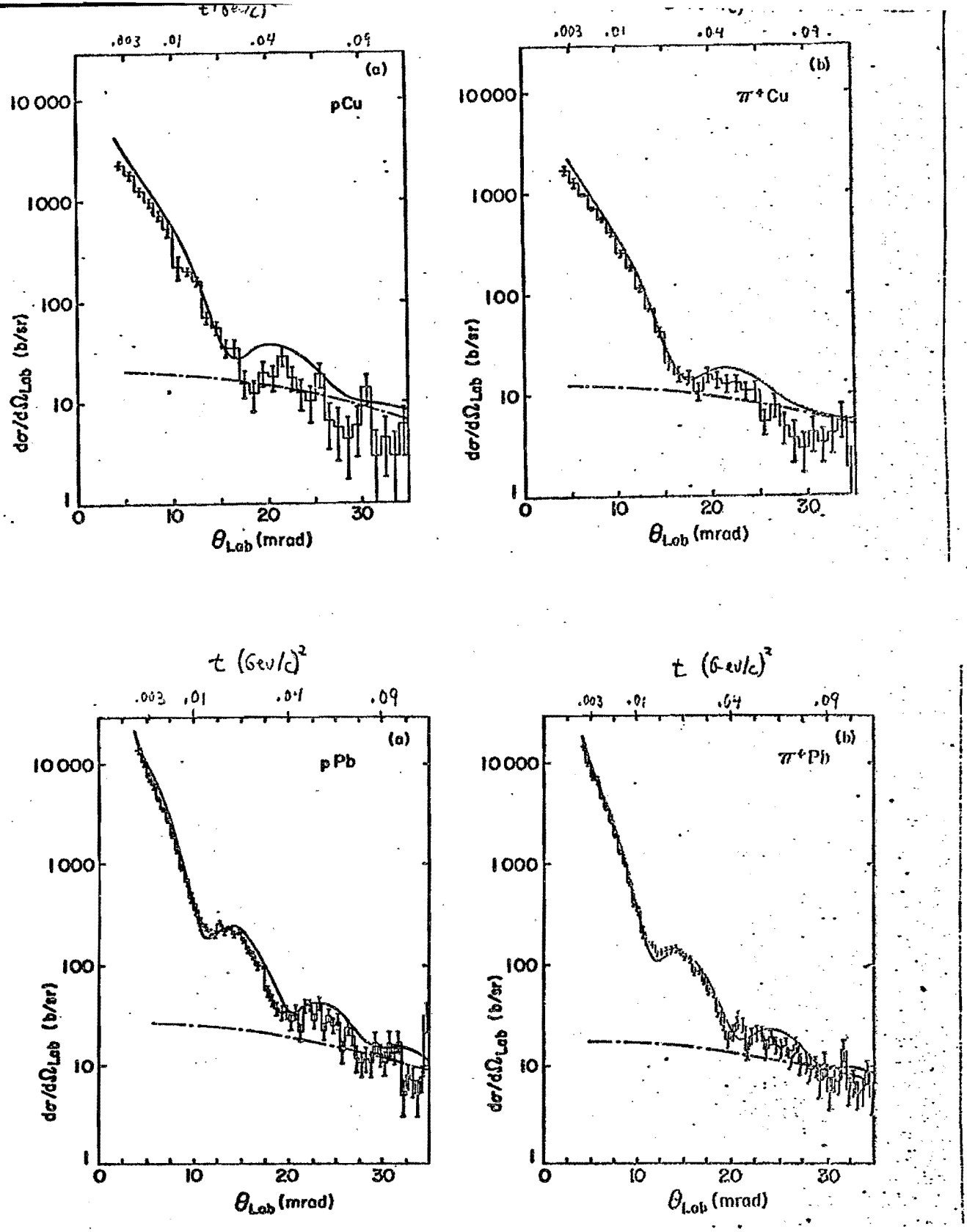
[4]K. Gottfried, Phys. Rev. Lett. 32, 957 (1974); J. Marx and R. Slanksy, unpublished.

[5]J. Hoffnagle, Senior Thesis - Yale University (unpublished) 1975; J. S. Trefil, Phys. Rev. D 3, 1615 (1971).

[6]W. Busza et. al., Phys. Rev. Lett. 34, 836 (1975).

[7]J. Sandweiss et. al., to be submitted to Nucl. Instr. and Meth.

[8]S. Dhawan and R. Majka, IEEE Trans. on Nucl. Sc. NS-22 (1975).



Differential Cross Sections at 9.92 Gev/c
(Dashed line indicates level of elastic scattering on single nucleon)

Fig 1.

Relative Cross Section For P + Nucleus vs. Nuclear Mass to Illustrate Effect of Coherent $N^*(1400)$ Intermediate State. (Calculated at 200 Bev with Wood-Saxon Potential (assuming 2 mb cross section for $P+N \to N^* + N$)

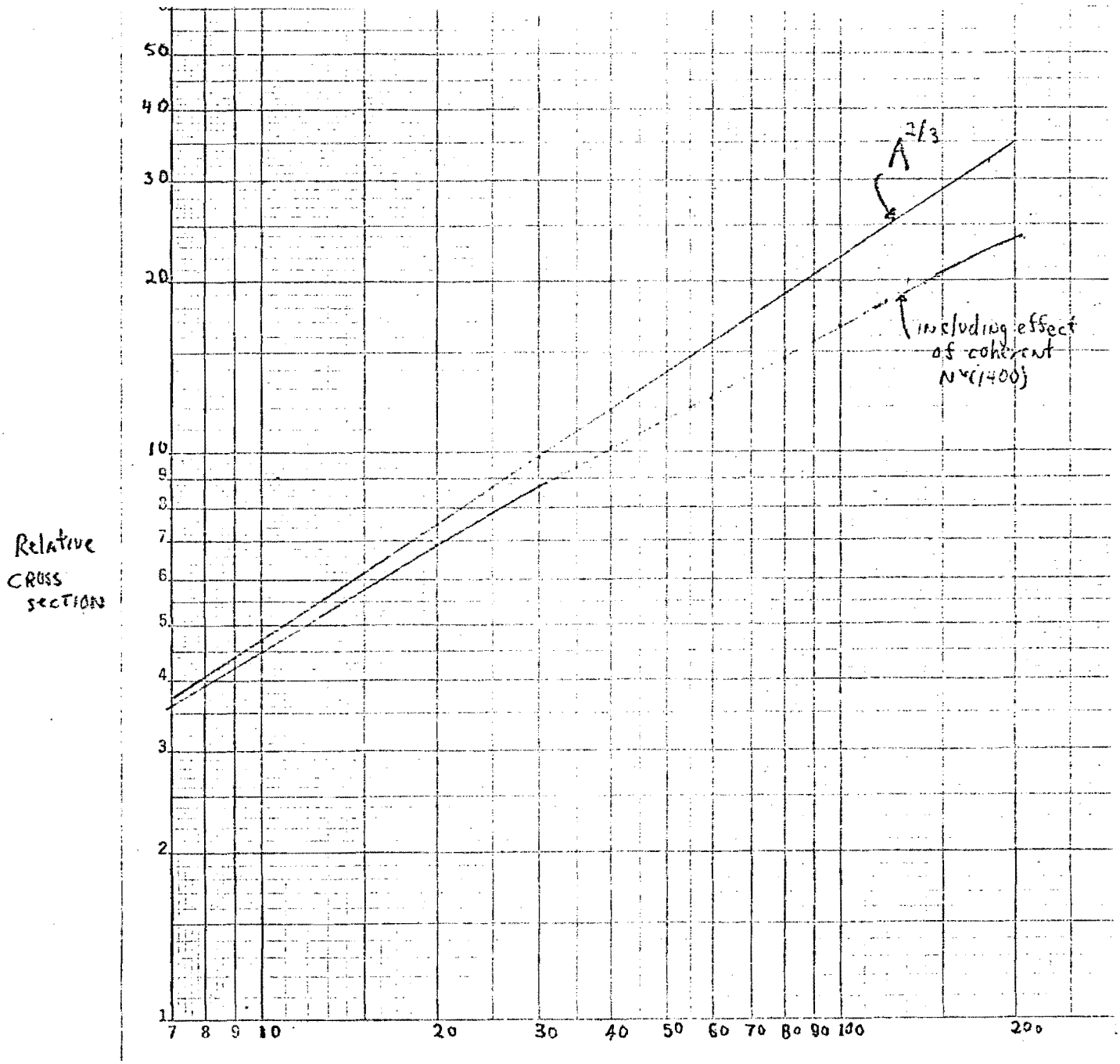


Fig 2.

E 69 Simplified Schematic Layout
(NOT To Scale)

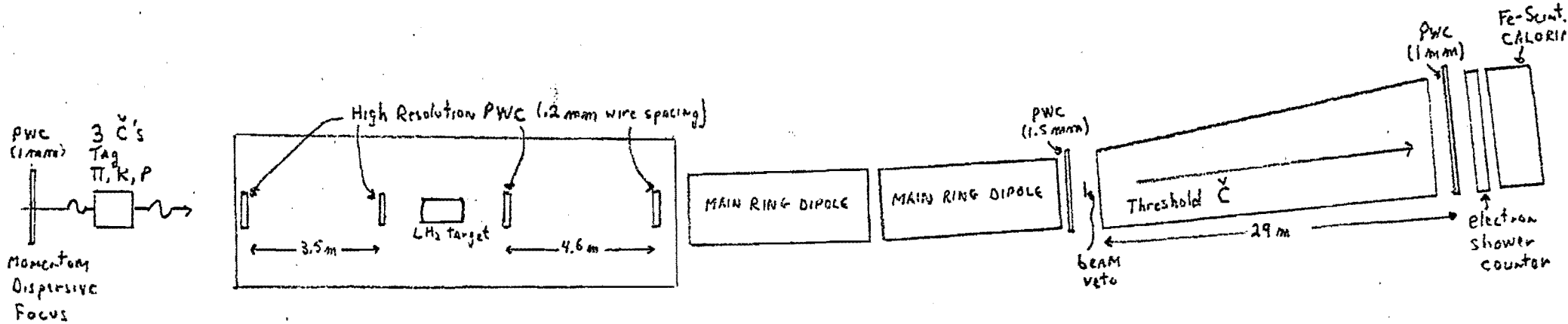


Fig 3.

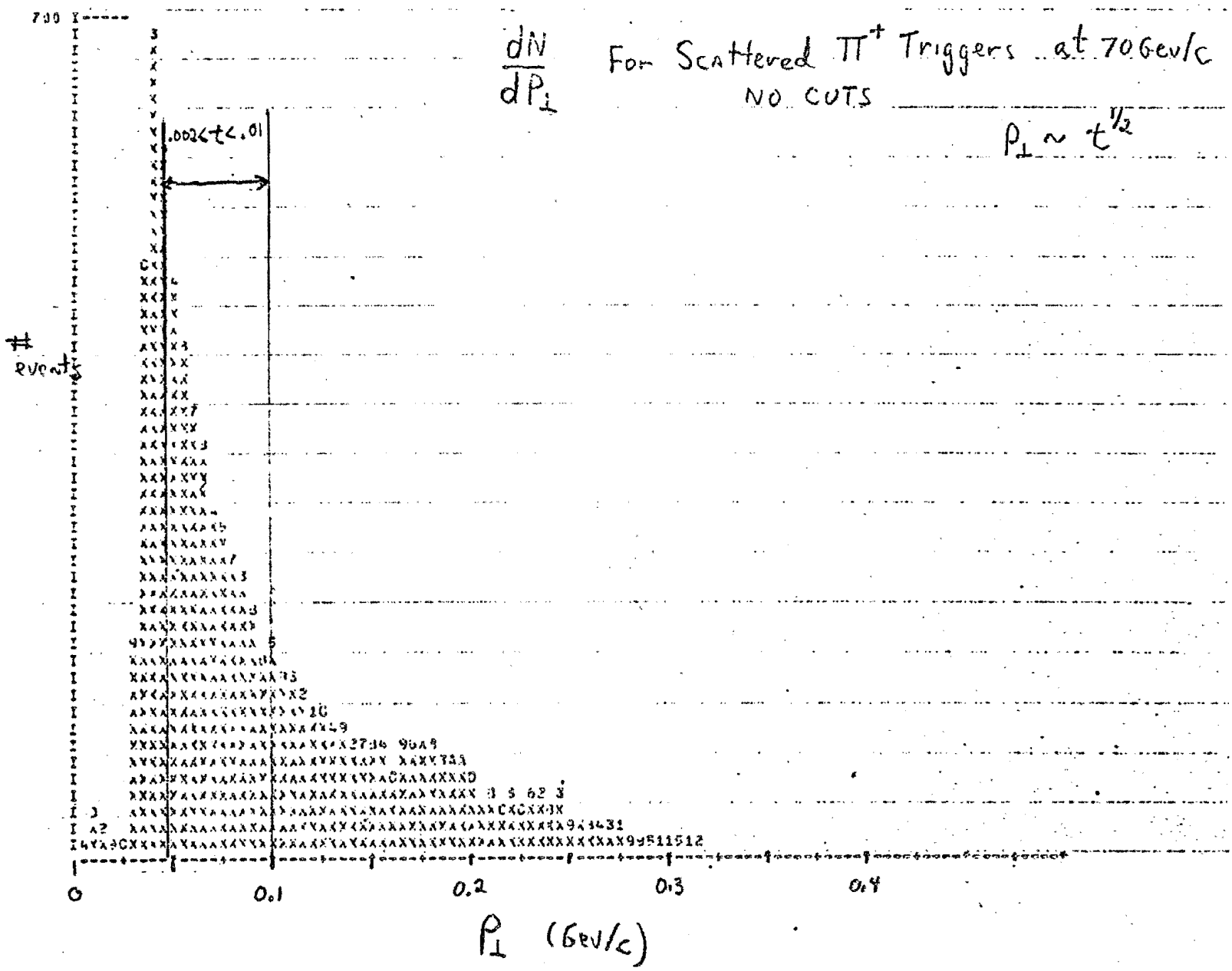

$\frac{dN}{dP_\perp}$ For Scattered π^+ Triggers at 7.0 Gev/c
NO CUTS
$P_\perp \sim t^{1/2}$
.002<t<.01
Events
0
0.1
0.2
0.3
0.4
$P_\perp$ (Gev/c)

Fig 4.

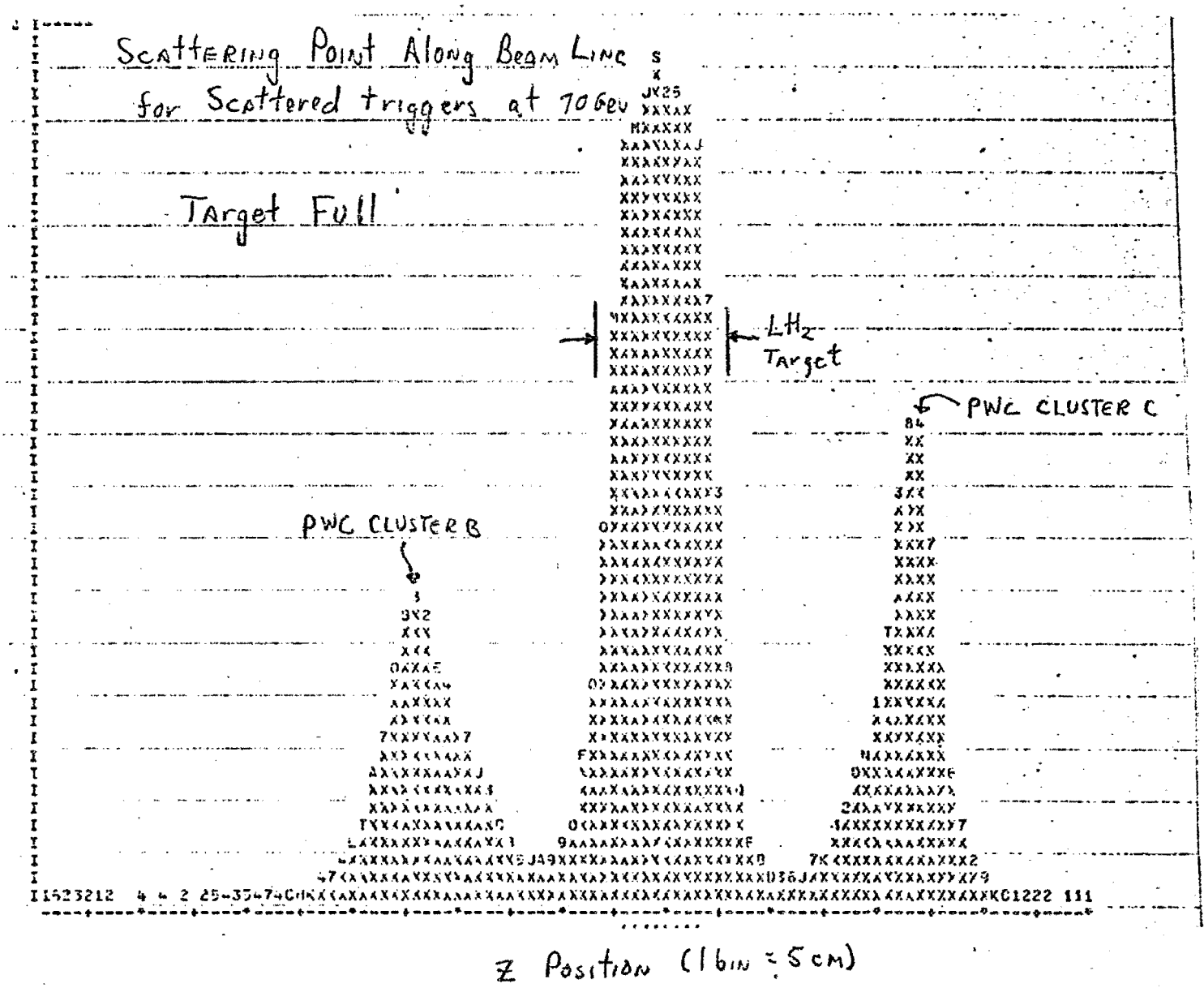

Scattering Point Along Beam Line
for Scattered triggers at 70 GeV
Target Full
LH2 Target
PWC CLUSTER C
PWC CLUSTER B
Z Position (1 bin ≈ 5 cm)

Fig 5

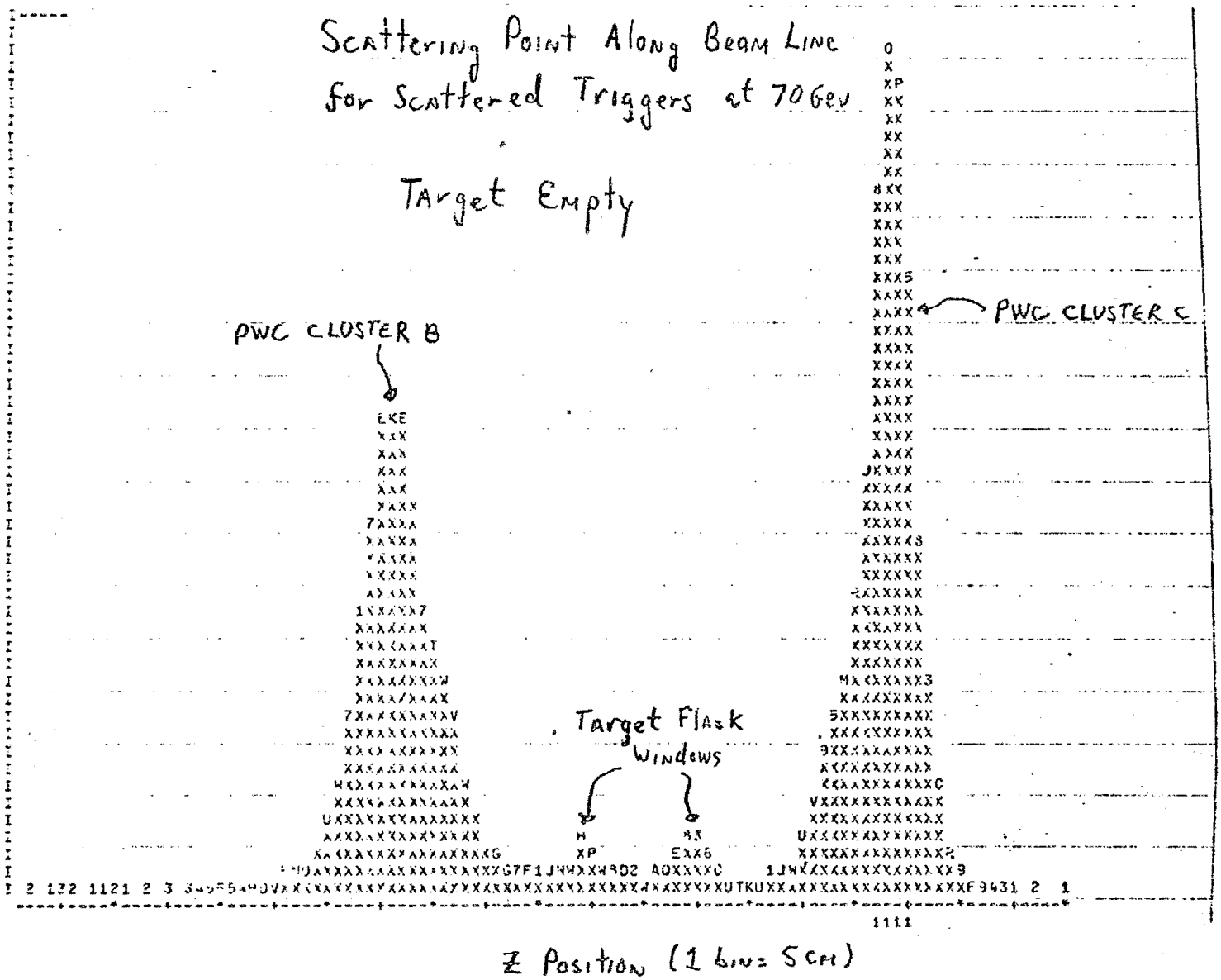

Scattering Point Along Beam Line
for Scattered Triggers at 70 Gev
Target Empty
PWC CLUSTER B
PWC CLUSTER C
Target Flask
Windows
Z Position (1 bin = 5 cm)

Fig. 6

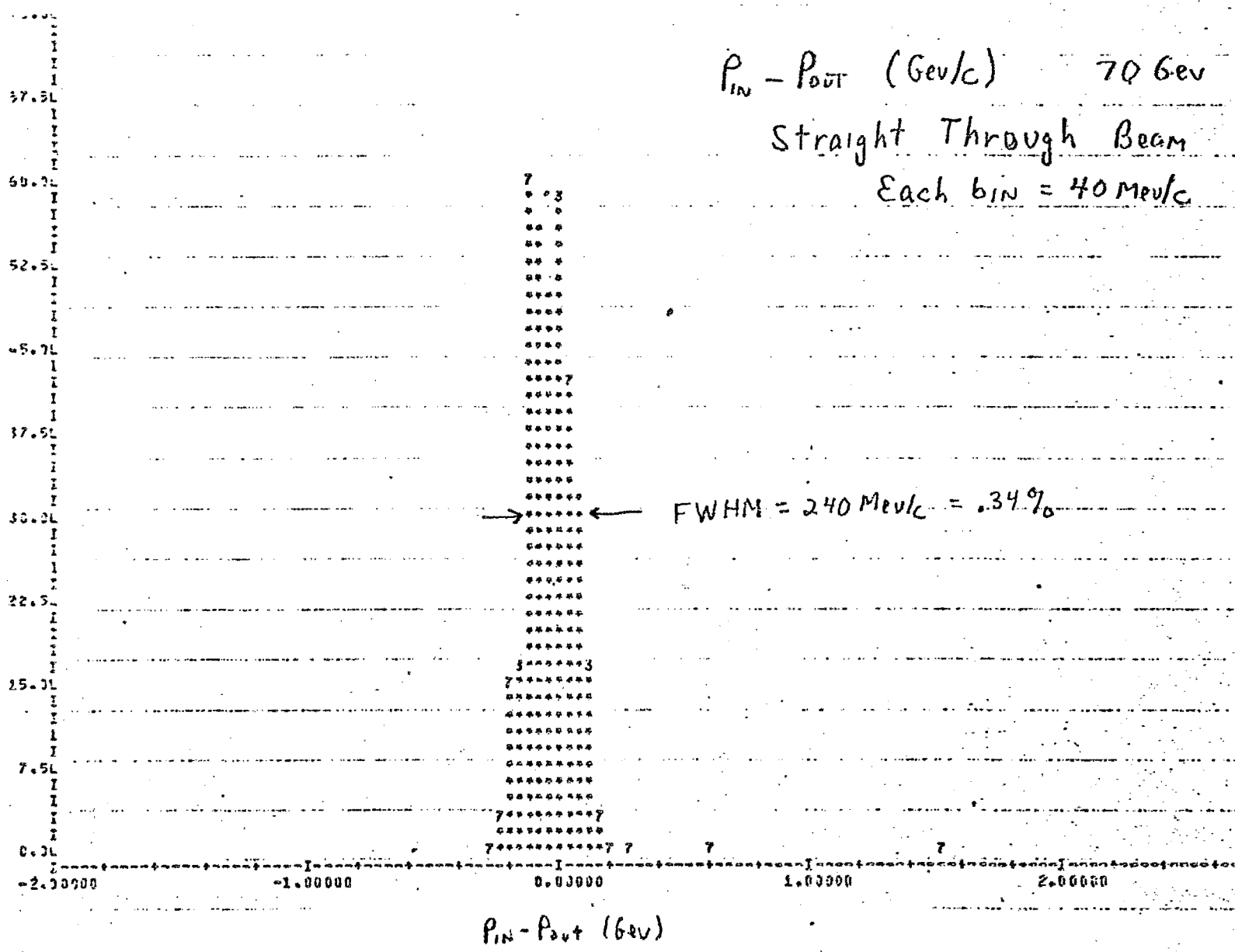

$P_{IN} - P_{OUT}$ (Gev/c)
70 Gev
Straight Through Beam
Each b_{IN} = 40 Mev/c
FWHM = 240 Mev/c = .34%
37.5
60.0
52.5
45.0
37.5
30.0
22.5
15.0
7.5
0.0
-2.00000
-1.00000
0.00000
1.00000
2.00000
$P_{IN} - P_{out}$ (Gev)

Fig 7.

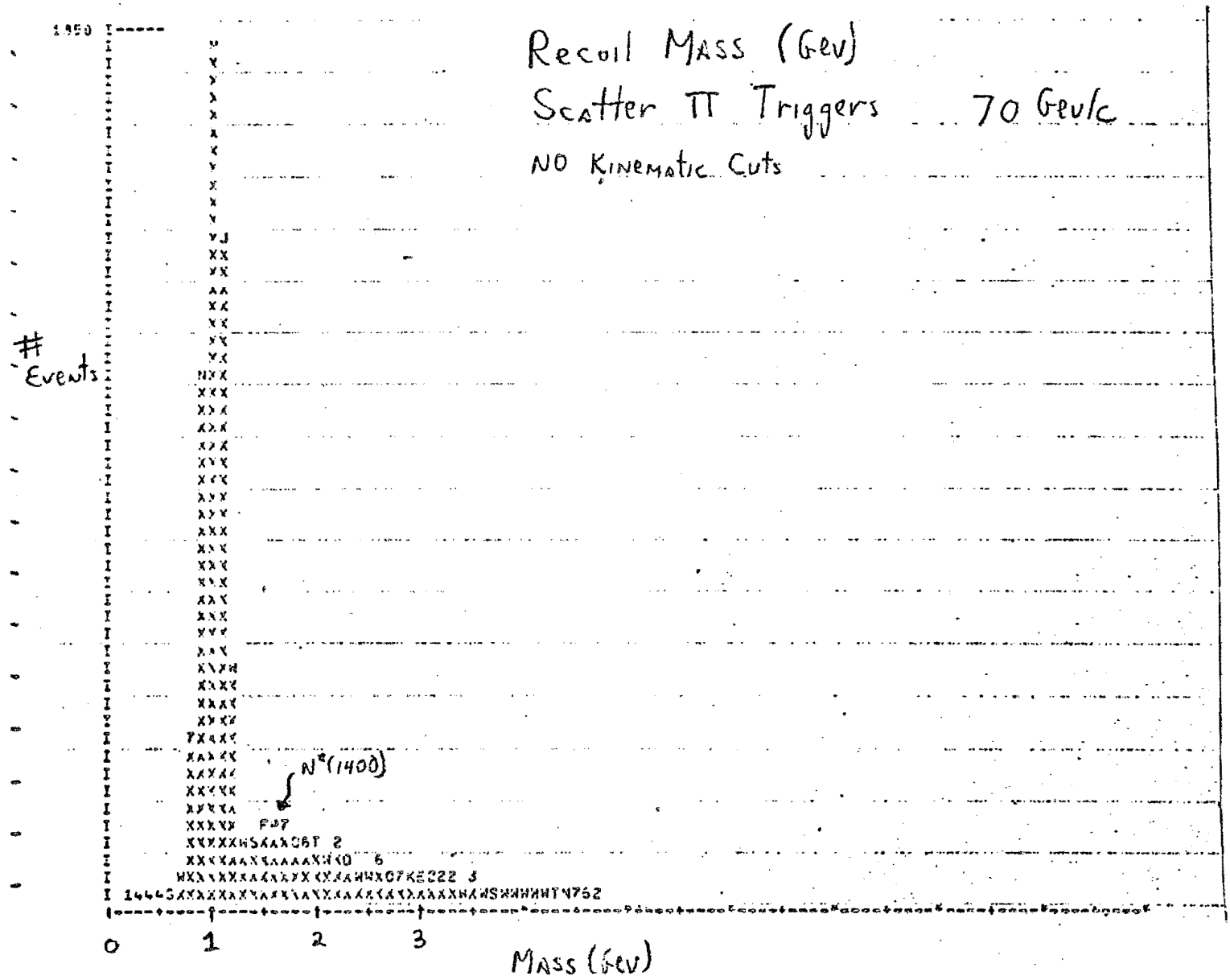

Recoil Mass (Gev)
Scatter π Triggers 70 Gev/c
NO Kinematic Cuts
Events
N*(1400)
0
1
2
3
Mass (Gev)

Fig 8.