

STUDY OF HADRONIC JETS
PRODUCED BY
CHARGED PION AND PROTON BEAMS
INCIDENT ON
HYDROGEN AND ALUMINUM TARGETS

Thesis by

A handwritten signature in black ink, consisting of three stylized Chinese characters: '翁', '素', and '永'.

Kar Woo Yung

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♥To Kathy

麗麗

.....♥

ABSTRACT

High transverse momentum ($p_{\perp}$) particles are thought to reflect the underlying parton (quark or gluon) mechanisms of hadron interactions. A particularly simple model by Feynman, Field and Fox (or FFF), involves hard scattering of a pair of partons via gluon exchange (Quantum Chromodynamics or QCD) with subsequent fragmentation of the partons into hadrons.

We present results from an experiment (E260 at Fermilab) on the production of jets (groups of particles) and single charged particles, at both low and high $p_{\perp}$, in 200 GeV interactions. The experiment used a calorimeter triggered multiparticle spectrometer. Results are presented on the comparisons of cross sections and associated charged particle distributions for pion and proton beams and aluminium and hydrogen targets.

Our high $p_{\perp}$ proton data agree with the FFF

predictions in most cases. However, there are signs of discrepancies.

We define α by the equation :

$A_{AL}^{\alpha} = \sigma_{AL} / \sigma_{HY}$ where A_{AL} is the atomic weight of aluminium and σ_{AL} and σ_{HY} are cross sections for the aluminium and hydrogen targets. The proton beam data show larger nuclear anomalies (in particular, $\alpha > 1$) than the pion beam data. There is essentially no difference between π^+ and π^- beams.

We compare the associated charged particle distributions for the two targets. The observed difference between these two targets could be related to the propagation and secondary scattering of partons in the nuclear matter; interpreting our data in this framework, we find that any secondary scattering must be coherent with the main interaction.

E260 is the first experiment to study both high and low $p_{\perp}$ interactions off nuclear targets with detailed measurements of the event structure. This is essential for understanding both nuclear effects and QCD in high energy interactions.

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CHAPTER I

INTRODUCTION

1.1 OVERVIEW

During recent years, deep inelastic lepton-nucleon scattering has been most successfully interpreted by parton models [1.1] (see Fig. 1.1a), where it is assumed that the underlying process is the scattering of the incident leptons on constituents of the nucleon. It is supposed, in such models, that these elementary point-like constituents or "partons" are very strongly bound inside the nucleon. Nevertheless, for high energy-momentum transfers, large compared with the nucleon mass, an individual parton can be regarded as effectively independent of the rest.

This physical picture has led to the prediction [1.2], verified by experiment [1.3], that in hadron-hadron interactions (see Fig. 1.2), particles with high transverse momentum ($p_{\perp}$) should be produced with much higher cross section than

expected from extrapolation of the low $p_{\perp}$ behaviour.

Further support for this picture has been provided by the observation [1.4] of jet-structure in hadronic events from e^+e^- annihilation (Fig. 1.1b), which can be interpreted as the manifestation of the production of parton pairs and their subsequent decay into hadrons (fragmentation). A similar structure is expected to be present in events in which a high $p_{\perp}$ particle is produced in hadron-hadron interactions. However, in contrast with the lepton initiated reactions, it is only in the latter type of process that the effect of direct parton-parton scattering can be observed. Ultimately, this opens the possibility of inferring the properties of parton-parton interactions from the study of hadron collisions producing high $p_{\perp}$ particles or jets.

Experimentally, jets appear as clusters of particles going approximately in the direction of the original partons. The mean transverse momentum of particles in the jet with respect to the parton momentum vector is expected to be around 350 Mev/c.

Attempts have been made to analyse all the experimental results on the production of high $p_{\perp}$ particles or jets in terms of the presently existing Quantum Chromodynamic Field Theory [1.5]. In such a theoretical framework, partons are quarks and gluons. Hard scattering among these partons is believed to be dominated by gluon exchange processes. The gluon, which is the field carrier of the strong interaction (also called the color field), is very analogous to the photon in the electromagnetic interaction (see Fig. 1.2b), except it can also interact with itself. Of course the gluon quark coupling is much larger than that of the photon to quarks.

In a particular QCD model discussed by Feynman, Field and Fox (or FFF) [1.6], it is supposed that the high $p_{\perp}$ jet production in hadron-hadron collision is due to hard scattering between partons, one from the beam and the other from the target, via gluon exchange. The resulting scattered partons and the unaffected parts of the colliding particles are assumed to fragment into jets of hadrons. This gives rise to a four-jet structure in high $p_{\perp}$ hadron-hadron collision (Figure 1.2c).

The purpose of our experiment is to investigate these phenomena in hadron-hadron collision at an incident momentum of 200 GeV/c. Hopefully, our experimental results may lead to a better understanding of quarks, gluons and QCD.

1.2 THE EXPERIMENT

The experiment described by this thesis is the Fermilab Multiparticle Spectrometer experiment E260. It is a Caltech-UCLA-FNAL-UICC-Indiana collaboration. The experiment was triggered by two calorimeters which allowed us to select events containing either a single particle at high $p_{\perp}$ or a group of particles (jet) which together sum up to give large $p_{\perp}$. In both triggers, we were able to study the properties of the associated charged particles over a wide kinematic range as the spectrometer had essentially full azimuthal acceptance for the range $0^{\circ} < \theta_{c.m.} < 90^{\circ}$.

The experiment was performed in the M6W beamline at Fermilab with a beam energy of 200 GeV and different species (π, K, p) of beam particle

tagged by four beam Cerenkov counters.

Some initial data were taken with a beryllium target in December 1975 and January 1976. The main run was in June through September 1976. Results of the test run and part of the main run have been published [1.7]. This thesis concentrates on the discussion of the data from the main run, sketching some results from the test run whenever it is necessary. The methods and procedures described here are those used on the main run unless specified otherwise. Some of the results presented here will be published [1.8]. Further discussion of our experiment can be found in other theses [1.9].

1.3 MOTIVATION FOR OUR MEASUREMENTS

There are two major classes of measurements in our experiment:

A. The production cross sections for ;

$$bA \longrightarrow h^{\pm} X \quad (1.1)$$

$$bA \longrightarrow \text{Jet } X \quad (1.2)$$

where we observe either a single charged hadron

$h^\pm$ or a group of particles (jet) at high $p_\perp$. Here the beam $b = p, \pi^+$ or π^- has a momentum of 200 or 190 Gev/c and the target $A =$ hydrogen or aluminium.

B. Correlations and characteristics of the associated charged particles in regions of phase space allowed by the experiment.

Interest in the measurement of high $p_\perp$ production cross sections stemmed from early ISR results [1.10]. These experiments showed a much larger yield of hadrons at high $p_\perp$ than expected from a naive $\exp(-6p_\perp)$ extrapolation of the low $p_\perp$ data. This yield also increased with energy at fixed $p_\perp$. These single high $p_\perp$ particle cross sections can be parametrized by the scaling law:

$$E \, d^3\sigma/d^3p = f(x_\perp) \, p_\perp^{-N} \quad (1.3)$$

where $(E \, d^3\sigma/d^3p)$ is the invariant cross section and $x_\perp = 2p_\perp/\sqrt{s}$.

For a proton beam and a pion final state, the observed $p_\perp^{-1}$ power N is approximately 8. This was in fact predicted by the CIM model (Constituent Interchange Model) where the typical scattering is $\pi q \rightarrow \pi q$ and the π is a "constituent" of the proton. However the simple CIM model, without

substantial modifications, also predicts jet production at about the same cross section as for single particles. Our earlier analysis (mainly by Fox) clearly indicates [1.7] that the jet cross section is at least five hundred times that for a single hadron. This suggests that our jet trigger is probably directly observing the quarks and gluons predicted naturally by QCD. Although the Born scattering graphs of QCD give the incorrect prediction of a $p_{\perp}^{-4}$ behavior for the cross section, there are many corrections to this in a realistic calculation. An analysis of QCD by Field [1.5], which includes all the effects which are currently known, suggests QCD is capable of describing all presently existing high $p_{\perp}$ single hadron and jet measurements. Our new results on the jet cross section can be used for further comparison with the QCD predictions.

The event structure is an important extra constraint for theoretical models of high $p_{\perp}$ processes. For instance, the original Constituent Interchange Model [1.11] which fitted the single particle cross section data well, failed completely for both the event structure and cross

section for the jet events [1.7]. Studies of associated multiplicity and correlations are hence essential for understanding such rare (the high $p_{\perp}$ cross section is very small) processes. Our experiment enables us to study the associated charged particles in the following three regions which correspond approximately to those populated by three out of the four jets shown in Fig. 1.2c :

A. The Trigger Side

This mainly includes those particles associated directly with the trigger jet. If QCD is correct, the distribution of momenta for charged particles making up the jet cluster in hadron scattering should be similar to the analogous distribution in lepton process. This momentum distribution for particles in the jet is usually called the fragmentation function. The quantum number distributions of particles on the trigger side should also reflect the flavour of the original triggered parton.

B. The Away Side

This includes particles opposite to the trigger jet. Theoretically we expect a jet here which is

directly opposite to the trigger jet in the center of mass frame of the colliding partons after the deep elastic scattering. In practice, it is hard experimentally to determine this parton center of mass frame on the event by event basis as it does not coincide with the beam target center-of-mass frame. It is more convenient to understand the away side "jet" in a statistical sense. There is evidence for clustering of particles (or a "fan" structure) on the away side for the case of single high $p_{\perp}$ triggers [1.10]. Our experiment enables us to make similar studies for the jet trigger, and compare results with different incoming beam types. Our earlier analysis [1.7] has already shown that the jet away side is very similar to the single particle away side, indicating that comparable dynamics were probably behind both triggers. Please refer to our previous publications for more details.

C. The Forward Region

In this region, we expect to see fragments of whatever remains of the beam after the parton collision [1.12]. Particles here are also expected to balance some of the transverse momenta of the triggered partons. The quantum number correlations

between the trigger jet and the forward region should be stronger than those between the away side and the trigger jet (this is only true in QCD, and is not predicted in the CIM model).

For both cross section and correlation studies, the comparison between beam types is especially interesting. Theoretically, the pion is made of a valence quark-antiquark pair embedded in a sea of soft quarks and gluons; on the other hand the proton has 3 valence quarks. Significant differences between these two beam types are thus predicted. Experimentally, there is little known about the pion beam high $p_{\perp}$ events. Most of the published results [1.3, 1.10 and 1.12] in this field are from proton beam measurements. Our group is one of the first to report results on high $p_{\perp}$ pion beam interactions; some of the publications by other groups on pion beams are listed in [1.13].

So far, I have been summarizing some of the general physics involved in jet productions mainly in the framework of a popular model (QCD model by FFF). Other models do exist, they are either

similar to the FFF implementation of QCD or they are much less promising. In this thesis, I shall present some new data in jet physics, emphasizing the differences between proton and pion beams. Qualitative comparisons with FFF will be given throughout this thesis as a motivation for some of our analyses. The detailed comparison of the FFF model with our data will be given in Jim Rohlfs's thesis.

1.4 ATOMIC WEIGHT DEPENDENCE OF THE HIGH $P_{\perp}$ CROSS SECTION

An unexpected piece of physics that was discovered when we were analysing our E260 jet data concerns the effect of a nuclear target on jet production. This was not mentioned in our original E260 proposal. Our aluminium target is really the vacuum jacket for our main liquid hydrogen target. It was only after the discovery that our aluminium target jet cross section is much larger than expected that we realized that we had enough statistics to study the effect of a nuclear target on the jet production. This in fact is the main

topic in this thesis.

During the past three years, several groups [1.14, 1.15] have studied the production of single high $p_{\perp}$ charged hadrons in proton-nucleus collisions. These experiments cover the ranges $2 \leq A \leq 184$, $1 \leq p_{\perp} \leq 7$ GeV/c, $28.5 \leq p_{\text{INCIDENT}} \leq 400$ GeV/c, all six outgoing charged particle types, and different interaction length targets. Although, of course, not all combinations of these parameters have been explored, it is found in all cases that the A-dependence of the cross section with all other parameters fixed is well described by a power law: σ (target of atomic weight A) is proportional to A^{α} . α however depends on the kinematic variables. At low $p_{\perp}$, α becomes .7 as expected from Glauber theory [1.16] and found from total cross section measurements. As $p_{\perp}$ increases, α increases rapidly until at the highest $p_{\perp}$ measured so far it is significantly larger than 1. This phenomenon has been called [1.17] the anomalous nucleus enhancement (ANE). In this thesis I shall discuss $\alpha(p_{\perp})$ for various triggers. The ANE is seen in our data for both the single high $p_{\perp}$ trigger and the jet trigger.

1.5 ATOMIC WEIGHT DEPENDENCE OF PARTICLE DISTRIBUTIONS

The distribution of particles in hadron-nucleus collisions can be very interesting. This may give us a clue to the underlying dynamics of the ANE mentioned above. It is commonly believed that this physics is related to topics such as the space-time development of particle production, the interaction of resonances with nucleons, and perhaps even to the interactions of almost free quarks and gluons with nuclear matter. A qualitative discussion of hadron nucleus scattering in QCD has been given in Ref. [1.18]. Although the theoretical predictions are not firm, it seems clear that the hadrons nucleus scattering amplitude is fundamental. Namely it cannot be predicted, independent of the particular strong interaction theory, from a knowledge of the hadron hadron scattering amplitude and the make up of the nucleus in terms of hadrons.

There have been many attempts to understand the various qualitative features of hadron-nucleus collisions, at both low and high $p_{\perp}$, in terms of models of hadron-hadron interactions. However, as

far as we know there is still no quantitative description that can explain all the nuclear effects observed in high energy hadron collisions [1.19].

Experimentally, the data on low p nuclear interactions have 3 characteristic features:

(A) In the central rapidity region ($Y_{C.M.}$ roughly between 0 and 1) the particle production ($\frac{1}{\sigma} \frac{d\sigma}{dY}$) is independent of nuclear number. Here rapidity, which is denoted by $Y_{C.M.}$ in the c.m. frame, is defined by the equation: $Y = .5 \ln((E-p_z)/(E-p_z'))$ where E = particle energy and p_z = z component of the particle momentum.

(B) In the forward region, the number of produced particles decreases with the nuclear number. In some heavy nuclei, this reduction can be factor of two compared with the hydrogen measurements. The data in this region are still very ambiguous. The reduction at the very forward rapidity values is most plausibly interpreted as the the attenuation of the "beam jet" as it transverses the nucleus.

(C) In the target fragmentation ($Y_{C.M.} < 0$) region, there is a general increase with A (the nuclear number) of the number of particles in collisions off nuclear targets. This could be due to nucleons

knocked out from the target nucleus; central region fragments of a second scattering of the beam jet can also populate the region $Y_{C.M.} < 0$.

The general experimental observation is that the multiplicity of particles produced in low $p_{\perp}$ collision with a nucleus of nuclear number "A" is significantly less than the multiplicity expected off a cluster of "A" independent quasi free nucleons. These observations indicate that there is very little (if any) intra-nuclear cascading by the "intermediate" state produced in the hadron-nucleus collisions. Some people have suggested that the large α observed in high $p_{\perp}$ scattering could be due to additional hard scattering of the "intermediate" state (quasi free parton state?) before it was transformed into the observed hadronic state. In a recent paper [1.20] it has been pointed out that the larger gluon hadron than quark hadron cross section expected in QCD could enhance gluon production in nuclear target experiments. Other possibilities have also been suggested. For reviews of existing data on nuclear effects and further discussions on various models please refer to Reference [1.19].

Above we have described previous data on the particle distributions in low $p_{\perp}$ interactions off nuclear targets. We have also discussed some of their implications which may be useful in interpreting the high $p_{\perp}$ data. Our experiment also has a low $p_{\perp}$ minimum bias trigger which will be defined precisely in Chapter II. Our minimum bias data off aluminium show a event structure similar to that seen in the earlier experiments. However we have been able to observe the two particle correlations with a nuclear target for the first time.

In our high $p_{\perp}$ events, we observe not only the ANE, or large α , in the jet cross section but also some interesting features of the distributions of the associated charged particles both inside and outside the jet. We compare these distributions for the two targets. Observed difference between these targets could be related to the behaviour of partons as they propagate through the nuclear matter.

CHAPTER II

APPARATUS AND TRIGGERS

2.1 APPARATUS

The data described here come from the main run of the Fermilab Multiparticle Spectrometer (E260) in the summer of 1976. The apparatus is shown schematically in figures 2.1 and 2.2. Details of the hardware are discussed in Ref. [2.1]. I shall only give an overview of the apparatus here.

We define our coordinate system by taking the z -axis as the incoming beam direction, and the y -axis as the direction pointing up. The positive x -axis side is called the left side (looking in the increasing z direction).

The experiment used the M6W secondary beam in the Meson Area which can be run at momenta up to 200 GeV/c. The intensity was around 2×10^6 /sec, during a 1.75-second spill while the cycle time was approximately four times per minute. Most of the

analyzed data in this thesis were taken at 200 Gev/c, with about 20% at 190 Gev/c. A list of beam polarities and energies for all the data in the main run (including the 130 Gev data which have not been analyzed yet) is presented in [2.2]. The beam composition has been determined to be [2.3a] :

	<u>-200 Gev</u>	<u>-190 Gev</u>
π^-	.949	.946
K^-	.043 $\pm$.004	.044 $\pm$.004
$\bar{p}$	.008 $\pm$.001	.010 $\pm$.001

	<u>200 Gev</u>	<u>190 Gev</u>
π^+	.180 $\pm$.020	.206 $\pm$.020
K^+	.023 $\pm$.002	.026 $\pm$.003
p	.797 $\pm$.020	.768 $\pm$.020

We shall now describe the various parts of the apparatus in the order that they are transversed by the beam as it passes through our spectrometer.

A. Beam Cerenkov Counters

These counters which are used for pion-kaon-proton separation are not shown in figures 2.1 and 2.2.

Further discussion of the beam particle identification is presented in Ref. [2.3b].

B. Beam PWC's (BA and BB)

These are proportional wire chambers (PWC) used to define the beam direction (only the station BB, nearer to the target, is shown in Fig. 2.1).

The BA chambers have two x-y modules and are located about 20 meters upstream from the target. Each module consists of an x-y pair with each view having 56 wires which are spaced 13/inch.

There are 5 BB chambers just upstream of the target; BBV and BBW are similar to BA, with 56 wires, which are spaced 13/inch and they are rotated at angles of 30° and 120° relative to the horizontal respectively. BBX, BBY and BBU are 64 wire planes with spacing at 26/inch and they have similar construction to the A chambers discussed below.

C. Target

This a 12-in long, 1-in radius liquid hydrogen target enclosed by an aluminium jacket which is about .03-in thick.

D. ABC-station

These are PWC's used to find tracks before the magnet.

The A station consists of two modules: an x-y module and a 45° rotated u-v module. The x-y module consists of two x-planes staggered for higher resolution, while the two y-planes were also intended to be staggered but due to assembly errors they were not. The u-v module is a separate module, assembled like the x-y module but containing only 2 planes (one x and one y), and rotated 45° . Each of the six measuring planes in the A station consists of 256 wires spaced at 26/inch.

The B and C station PWC's are a total of 5 planes of similar construction, divided into B' (vertical wires only), B (x and y in one module) and C (x and y, configured so as to fit into the magnet as shown). The apertures of all these modules are 40 inches horizontally by 26 inches vertically. Each vertical (x coordinate) set has 512 wires at 13 wires per inch and each horizontal (y coordinate) set has 320 wires at 13 wires per inch.

E. Magnet

This is a superconducting magnet for momentum analysis of our tracks. For the measurements

reported here, the field was run at about half the maximum value which corresponds to a transverse momentum kick of .379 Gev/c imparted by the magnet. The field was deliberately set low even though this led to poorer momentum resolution. A higher field would lead to a greater bias in our calorimeter $p_{\perp}$ trigger.

F. D-station

This station consists of 4 planes: Dx, Dy, Du and Dv where Du and Dv are at angles of 15° and 105° respectively relative to the vertical. Each plane has 320 wires at 5.5 wires/inch. These PWC's are used for track finding after the magnet. Although their resolution is poor compared to the spark chambers they do have much better time resolution and are not sensitive to interactions other than the trigger one that occur within the memory time of the spark chambers.

G. E-station

These are magnetostrictive read out spark chambers with better spatial accuracy than the PWC's. There are 4 modules in the E station. Each module consists of a y-y gap and x-u gap. The chamber size

is 8' (horizontal) by 4' (vertical). The chambers use .005" thick aluminium wires spaced at 32/inch. The signal is read out with magnetostrictive wands which have pickups at both ends. The complete system has 6 signals (2 each for x,y,u) per module or a total of 24. The wires in the u-plane are at an angle θ given by $\tan\theta = .1$ with respect to the x wires. The signals are amplified, discriminated and fed into MTD's (Multi-Time Digitizer. Reference: B. Bertolucci, SLAC-PUB-1177).

The spatial resolution, which depends on the accuracy of determining the centroid of the signal, is found to be around .7 mm.

The pair resolution which indicates how well we can separate two distinct tracks was determined to be around 5.5 mm in a detailed analysis which I have described in a memo [2.4]. Obviously the poor pair resolution reflects the intrinsic width of the magnetostrictive pulse; the resolution of .7 mm shows that one can find the mean of a pulse to a much better accuracy than its width. No correction has been made for tracks which have been lost because they were so close to another track as to be within the pair resolution. The problem is most serious in the y view where 5% of the tracks are

affected. However we do correctly identify particles as distinct those which although together in the y view are separate in the x view. As the magnet bends oppositely charged particles apart. We see that the pair resolution only affects particles, or matched tracks, that have the same charge, comparable momenta and are close in both x and y views. Less than 0.1% of particles fall into this category.

H. C1

Gas Cerenkov counter C1, with 22 cells, can be used for final state particle identification. The data reported here do not use information from this counter. Analyses using C1 and C2 will be reported in other theses [1.9].

I. F-station

These are spark chambers which are of similar construction to the E-station spark chambers, but larger in size (12'X6').

J. F'-station

These are two x-plane PWC's covering the faces of the calorimeters. They are constructed similarly to

the D chambers but with 4 wires/inch and only 130 vertical wires per module. Their use is as for the D station to provide good time resolution information on tracks entering the calorimeters.

K. Calorimeters

Two large calorimeters, placed at approximately 90° in the center-of-mass frame, are used for triggering on high $p_\perp$ events. Each calorimeter is divided into 4 modules which are each divided longitudinally into two sections. The front section is a lead-scintillator sandwich shower counter containing 15 radiation lengths of lead. The back section is a iron-scintillator sandwich designed to measure hadronic energy. This back section contains 30" or 4.5 absorption lengths of steel. By using the ratio of the top and bottom phototube pulse heights, the mean vertical position of particles entering the module can be determined with a resolution of 10cm at $E = 25$ Gev. This resolution scales like $1/\sqrt{E}$ with energy. It is $.33/\sqrt{E}$ for the front section, and $1.03/\sqrt{E}$ for the hadronic section. Further descriptions of the hardware and the response of the calorimeter are discussed elsewhere ([2.5] to [2.8]).

L. F''

This x-plane PWC is also called the F'-center. It is placed in the center of the xy-plane perpendicular to the beam line, covering the central regions that are missed by the F'-station mentioned above in section J. Its construction is the same as the D chamber. This chamber is particularly important because of the large density of fake tracks in the sparks chambers near the beam region.

M. C2

This is our second gas Cerenkov counter for identification of the final particle. It has 16 cells and it is also not used for the data reported in this thesis.

The time required to read in an event is dominated by the time it takes to read in data from the spark chamber which is approximately 20 msec for reading in the 48 channels with 16 words/channel. Thus the data collection system is limited to around 50 events per 1-sec spill with 1200 to 1500 words read in per event. In the actual E260 run, due to high event multiplicity and beam intensity, we ran the spark chamber with 50 msec dead time and we take

in around 10 to 15 events per 1.75-sec spill. The data are read into the computer and buffered to the disk during the beam spill. After the beam spill, the data on the disk is written onto the tape and also made available to our on-line software program (MULTI) for histogramming event attributes and making event displays.

2.2 TRIGGERS

Our experiment has 3 major triggers:

A. Minimum Bias or Interacting Beam Trigger

If an incident beam particle is observed before the target and no count is recorded by a 2"x 2" scintillator counter placed along the beam line just downstream of the F-station (see Fig. 2.1), then a pretrigger was generated. This was the prerequisite for firing the spark chambers, manipulating the calorimeter pulses, recording all the information onto the magnetic tape and so on; therefore every E260 trigger is associated with a pretrigger. For every 9 calorimeter triggers a pretrigger was also recorded as a trigger. This selected pretrigger,

also called the interacting beam trigger, gives an essentially unbiased sample of high multiplicity low $p_{\perp}$ events but is inefficient for elastic and diffractive scatterings.

B. Single Particle Trigger

The pulse heights in the 4 modules of the calorimeters are attenuated relative to each other by amounts proportional to the mean laboratory angles of the modules to give signals proportional to $p_{\perp}$. If this $p_{\perp}$ (as defined by the attenuated pulse) in any one of the 4 modules (in either calorimeter) is greater than the trigger bias (set at nominal values of 2 and 3 Gev/c), then a high $p_{\perp}$ single particle trigger is generated.

C. Jet Trigger

This trigger requires the summed calorimeter $p_{\perp}$ of the 4 modules (in either calorimeter) to exceed the preset trigger bias (set at nominal values of 3 and 4 Gev/c).

For both single particle and jet triggers, the exact hardware trigger bias setting varies slightly from run to run. These settings are listed in

Ref. [2.2].

Although we have 3 types of triggers, there are really 5 triggers (2 thresholds for both single particle and jet triggers) in our hardware triggering system. They have been called in our experiment as the INTBM, MEDPT, HIPT, LOJET, and HIJET triggers. All these triggers could be generated simultaneously during the data taking. The lower threshold triggers (MEDPT and LOJET triggers) were "divided" before the online hardware logic decided whether to fire the spark chambers. When I say "divided", I mean that only one out of a certain number of triggers (this number is also called the hardware division factor) could be accepted as a real trigger. In cases when we were taking in more than one type of divided trigger, the real division factor used for computing cross section is smaller than the hardware division factor due to a nonzero probability for satisfying both triggers simultaneously (see [2.9] for more detail). All these hardware division factors are again listed in Ref. [2.2].

CHAPTER III

PROCEDURE

3.1 Track Finding and Clean Up

Track reconstruction in front of the magnet was done entirely with PWC's; behind the magnet it was done with a combination of large PWC's and spark chambers. There were four stages to the procedure (see References [3.1] and [3.2]) :

(1) Tracks were fitted in the x view before the magnet and in the y view all the way through the spectrometer. The best of these x and y tracks were selected to determine the vertex position in three dimensions. In the case that the above algorithm failed (about 5% of the finally analyzed events), a second attempt was then made to find the vertex with the beam chamber information. An event with a successful vertex was then passed through the following three stages. These stages only used the vertex information from the first stage; this vertex point was used for all the y tracks (stage 2)

and the x tracks before the magnet (stage 3). The vertex constraint made the track finding much easier and allowed us to disentangle tracks that were impossible without this constraint.

(2) We found all the y view tracks and the x view tracks after the magnet. These x and y tracks were then matched together using the stereo-angle spark chambers.

(3) These matched sets of tracks were linked to tracks in front of the magnet, requiring that tracks in front of the magnet must go through the vertex. A set of matched tracks was called a "particle". The difference in the slope of the x view tracks before and after the magnet defined the momentum of the "particle".

(4) We deleted some spurious particles that shared tracks, in either the x or y view, with other good particles. This selection was based on the chi-squared probability of matching and the number of sparks used in the matching. Note that each stage was run with rather loose constraints so as to be very efficient. As described later, we cleaned

up the sample by using cuts based on information from all the stages of track finding.

Our vertex distribution is shown in Fig. 3.1a and it will be discussed further in Chapter V. The target is clearly seen with very little background. The measurement resolution for the z coordinate of the vertex, which can be estimated from the width of the aluminium peak, is around 2 mm.

The momentum resolution of a particle is related to the spatial resolution of our chambers: the quantity $\Delta p/p^2$, which is proportional to the angular resolution in the x view in front of the magnet, should be a constant in the laboratory frame. By running beams of known energy through the spectrometer, we determined the momentum resolution for the charged particle to be around $\Delta p/p = .0007p$ (p in GeV/c) [3.3].

Due to the high event multiplicity and sparks that were not associated with the triggered event, we were concerned about spurious particles generated by our track finding method. These bad particles contain both incorrect tracks and real tracks that

were incorrectly matched. We removed some particles whose track momentum is significantly larger than the calorimeter signal. For particles that do not hit the calorimeter, we cannot apply such cuts. Fake particles in the forward region are therefore much harder to handle. In order to handle these and other spurious particles, we devise the procedure described below.

We construct a quality factor Q for each particle from the number of PWC hits on all its tracks and the chi-squared for its tracks in front of the magnet. We remove those candidate particles with very low quality Q . However the density of fake tracks in the forward region is so high that special treatment is needed here. First we remove all particle with $P_{LAB} > 200$ Gev/c and those that hit the 2X2 counter. We also remove some of the poor quality particles, with low values for Q (but above the previous cut), that are either very close to the 2X2 counter or have at least one track that hits the 2X2 counter. We remove about 10% of all particles with these cuts. The majority of the particles removed have large momenta and are in the forward region where the track finding is most ambiguous.

After all these cuts, we make further physics plots with yet more stringent cuts and find no significant differences. We conclude that our quality cuts have given us a clean data sample. A detailed description of the quality factor studies and these clean particle cuts are presented in Ref. [3.4].

Two approaches have been used to estimate our overall track finding efficiency. They are described in the following:

(1) We histogram the number of PWC hits (N_p) used by each track. We observe results typified in Fig. 3.2a. The sharp edge at the lower end of the curve is mainly due to the minimum hit requirement for accepting a track in our chi squared fit. By extrapolating (as indicated by the dotted line) from this edge to the zero point, we can estimate the track finding efficiency by calculating the ratio of the area underneath the dotted curve to the total. This fraction usually turns out to be around 95%. The problem with this scheme is that we still do not understand the various smearings of the edge due to our complicated software cuts used in our track reconstruction scheme and we also do not know exactly how to extrapolate (we do not know the

slope) ; although we do expect that the hit distribution should be very similar to a binomial distribution.

(2) D_X and D_Y are probably the best two chambers after the magnet. The fact that I was involved in building these chambers is probably irrelevant. We found that there is almost no noise in these chambers during most of our data taking. I define the fraction f_D by the equation

$$f_D = \frac{\text{No. of particles that have hits in the D chamber}}{\text{Total no. of D hits}}$$

A plot of f_D (for the average of D_X and D_Y chambers) vs. the mean event multiplicity (N_p) is shown in Fig. 3.2b. If each D hit can be used only once in the track reconstruction, then f_D essentially gives the fraction of the total D hits that are used. Events with large values of f_D are events that are very efficient in finding all the tracks. In real situation, f_D can be greater than 1 due to sharing of sparks between tracks. The dip at the lower f_D end is due to tracks missed because of the inefficiency of other chambers. The plateau above $f_D \approx .75$ seems to indicate that our $f_D > 1$ values are

not due to extra spurious particles that share D hits with some real particles, but rather due to the sharing of D hits by real particles. This happens quite often due to the crude spatial resolution of the D chambers. We propose that the true mean event multiplicity is that given by the plateau value $\langle N_p \rangle \sim 10$ for $f_D > 0.75$. Then the overall track finding efficiency can be estimated by dividing the observed mean event multiplicity for all events by the true mean estimated as above. This efficiency turns out to be 93% for that particular run shown in Fig.

3.2b.

From these studies, we believe our track finding efficiency is between 90 TO 95%. Most of these estimates are based on results for a group of few selected runs. Although it would be better to use all runs, our current analysis is sufficient for the physics discussed in this thesis.

3.2 CALORIMETER ANALYSIS

A good understanding of the calorimeter is essential for any calorimeter-triggered jet

experiment. Since we are measuring a steep $p_{\perp}$ spectrum, the jet $p_{\perp}$ will be most likely to be overestimated due to bad calorimeter resolutions. Some experiments assume that the real jet $p_{\perp}$ is just the calorimeter $p_{\perp}$ (calculated from the pulses) minus some constant number that represents fluctuations. This, we believe, is not a very satisfactory approach. In our experiment, we can measure the charged tracks very accurately within a large kinematic acceptance (Fig. 3.1b). Our calorimeter is used mainly, in the final analysis, for checking the charged energies and estimating neutrals. In this thesis, we avoid the study of mainly neutral jets for which one has to rely heavily on the calorimeter. Our jet $p_{\perp}$ used here is almost independent of the calorimeter fluctuations.

The analysis of our calorimeter consists of following steps [a] :

1. We first calibrate our calorimeter by running the beam directly into the calorimeter. Beam energies from 10 to 40 Gev were used. This process determined all the pulse height to energy proportionality constants, the attenuation lengths

and any calorimeter constants used in our neutral analysis (e.g. the average fraction of energy deposited by a charged hadron in the electromagnetic calorimeter).

2. We then take the real data, using only tracks opposite to the trigger side (called away side in this thesis). We only select events that we believe have very little or no neutral energy entering the calorimeter (see Ref. [2.8] for a detailed description of these neutral cuts). We confirm our beam calibration in step 1 by comparing the total detected calorimeter energy with the track energy. By plotting the calorimeter energy in the hit module over p_{LAB} versus distance of the track from the center of the hit module (this distance is named as " $D_{HIT} - D_{MOD}$ " in Figure 3.3), we generate an energy distribution shape [2.8b] which tells us the mean energy deposited by a single charged particle in the hit module as a function of " $D_{HIT} - D_{MOD}$ ".

3. Now, we shall describe how we analyse the calorimeter signals on our jet and single particle data. The basic idea is to use the energy distribution shape derived above to predict the

energy deposited by all the charged particles entering the calorimeter. We compare our predicted energies with the actual calorimeter pulse heights. If the calorimeter signals do not agree with the predictions, we shall then try to find neutral particles that correspond to the energy discrepancy. To illustrate our neutral extraction scheme, we shall go over the whole procedure in detail for the following simplified case.

Let us assume we have only one module. A charged particle of energy E_q entering the calorimeter will deposit

$$f_h * E_q \quad \text{in the hadronic section,}$$

$$(1 - f_h) * E_q \quad \text{in the electromagnetic section;}$$

Where:

f_h is the fraction of energy deposited in the hadronic section,

E_q is the amount of energy that it will deposit in the hadronic section, according to the known pulse shape, if it loses all its energy in the hadronic section,

E_q is the similar response prediction for the electromagnetic section.

We also define the neutral energy

$$E_n = E_h + E_e - f_h E_{qh} - E_{qe}(1-f_h)$$

We fit with the chi squared sum:

$$\chi^2 = \frac{(E_h - f_h E_{qh})^2}{\sigma_h^2} + \frac{(E_e - E_{qe}(1-f_h))^2}{\sigma_e^2}$$

where E_h , E_e are the energies detected in the hadron and electron sections of the calorimeter. If $\chi^2 < 5$, we say the event fits with the pure charged energy only. For $\chi^2 > 5$, we fit again with neutrals plus the charged energies; first with additional pure hadronic neutrals only (FIT2 in Fig. 3.4 on the next page), then with additional pure electromagnetic neutrals only (FIT3 in Fig. 3.4). We pick the best fit (among FIT2 and FIT3). If all fits mentioned fail, we assume that both electromagnetic and hadronic neutrals are present. We find their energies by a simple subtraction that assumes $f_h = .8$ which is the mean value of f_h seen in our beam calibration. The whole procedure is summarized by the following chart (Figure 3.4):

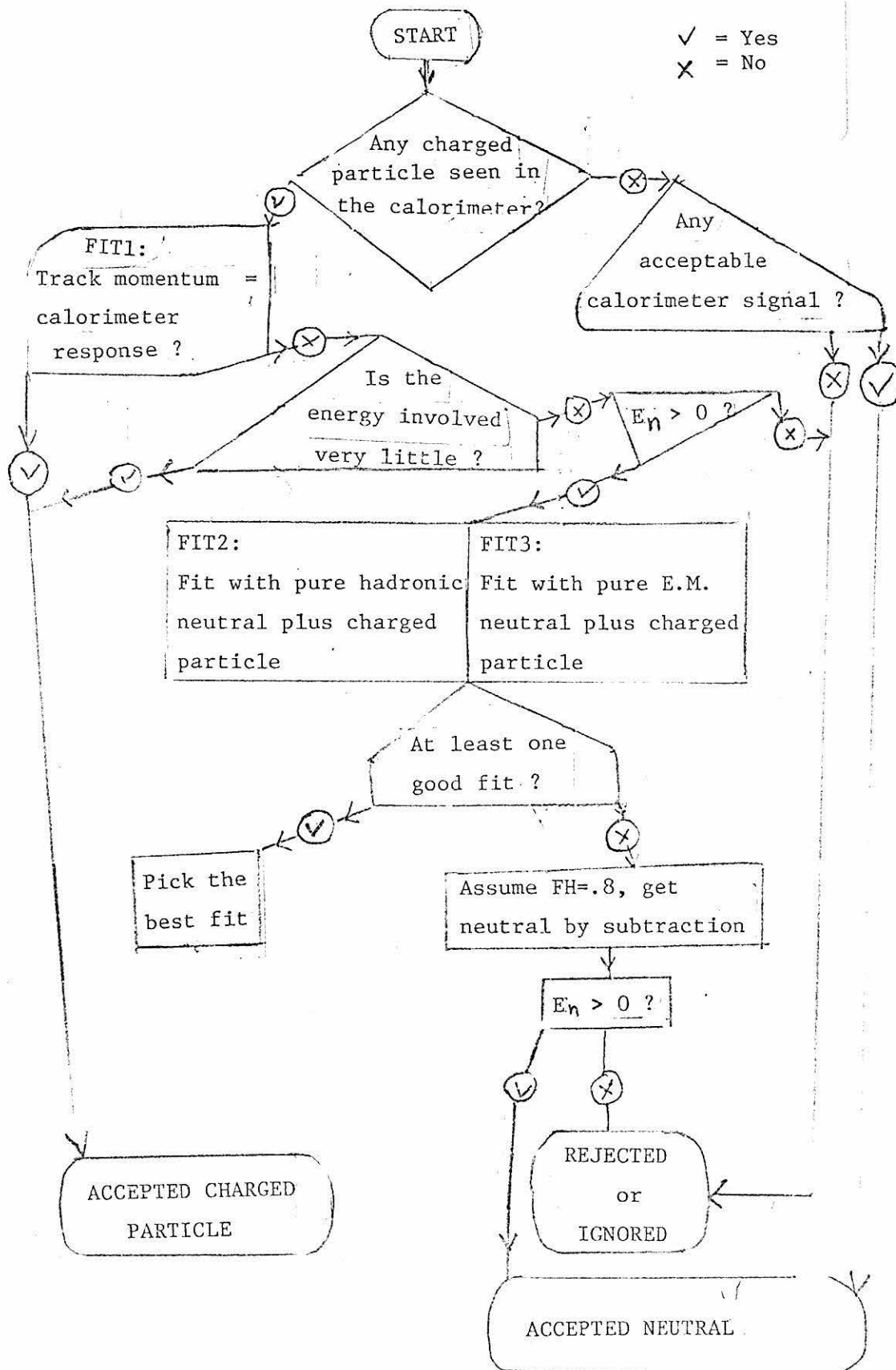


Fig. 3.4

In the real analysis, we have more information than mentioned. Each calorimeter module has 2 TOP and 2 BOTTOM pulses, which means we have 4 inputs for both the hadronic and the electromagnetic sections, and we have 3 free parameters: E_q , Y_q (Y_q is the y coordinate of the charged particle) and f_h in step FIT1 (see Fig.3.4). The real formula of the chi squared sum used is also more complicated, it includes correlation coefficients (between TOP and BOTTOM pulses) obtained in our beam calibration studies. Also in our fitting, f_h is forced to lie between 0 and 1. Our fitted f_h in FIT1, which is a free parameter, is found to be around .8 and has a very similar shape to that in our beam calibration run.

Cases where χ^2 is large and E_h is large and negative are rare. If this does happen, large momentum tracks that contribute to E_{qh} and E_{qe} are removed. This calorimeter comparison cut has already been mentioned (in section 3.1) previously in our track quality discussions.

For events accepted by our FIT1, i.e., ones for which no neutral was generated; we found $\langle E_n \rangle = 0$ on

the away side, and $\langle E_n \rangle$ greater than 0 on the trigger side. The trigger side $\langle E_n \rangle > 0$ can be understood as the high $p_{\perp}$ trigger favours the upward fluctuation of the calorimeter signal. These also indicate our chi squared fitting procedure takes into account the calorimeter trigger bias automatically on the trigger side, and our cut for the chi squared sum is reasonable as indicated by the $\langle E_n \rangle = 0$ on the away side. We justify further our neutral scheme by applying the scheme on some Monte Carlo data. The derived neutrals agree very well with the theoretical neutrals used in the Monte Carlo generation program.

FOOTNOTE [a] Steps 1 and 2 are discussed in more detail in references [2.7] and [2.8] (see also [2.5] and [2.6]).

FOOTNOTE [b] There are differences in responses between hadrons and electrons entering our electromagnetic calorimeter section. Such a difference is included in our response predictions.

CHAPTER IV

JETS

4.1 JET DEFINITION

Our calorimeters trigger on the part of a jet contained within a particular solid angle. Study of both Monte Carlo and real data showed that it was possible to improve the jet definition by including particles that missed the calorimeter. We now describe the technique developed. Details may be found in Jim Rohlf's long paper [4.1].

A jet is defined here as a cluster of particles going together in a certain direction. We add up all particles (charged particles from tracks and neutrals extracted from the calorimeter signals) within a 45 degree cone of the calorimeter vector

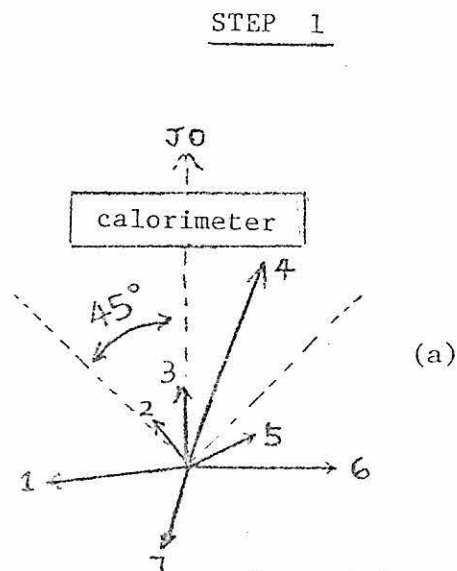
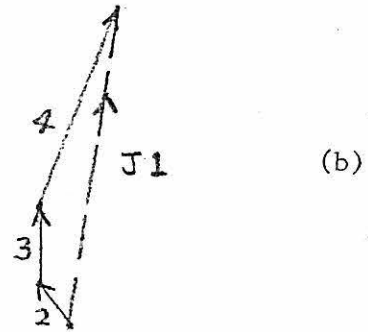


Figure 4.1

(vector J_0 in Figure 4.1a).

The latter is defined to be the vector that points to the center of the calorimeter in the center of mass frame. The vector sum (vector J_1 in Figure 4.1b) of all the particles in the cone defines a direction which we use as the axis of a new cone of 40 degrees. All particles within this new cone are considered to be parts of the final jet (see Figure 4.1c). The 4-vector of the jet is the vector sum (vector J_2 in Figure 4.1d) of all particles in the jet. The second step in our jet definition can be considered as an iteration of the first. It is intended mainly to reduce the bias by the initial



STEP 2

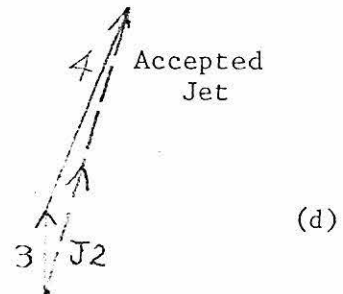
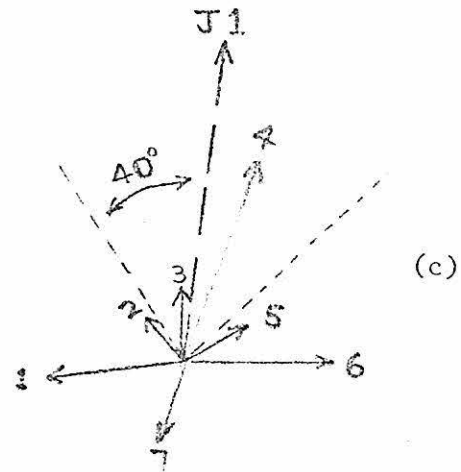


Figure 4.1

condition in our jet definition.

We only study jets that satisfy the following fiducial cuts (on J2) :

$$|\text{C.M. rapidity}| < .2$$

$$|\phi| < 20^\circ \quad \text{or} \quad |180^\circ - \phi| < 20^\circ$$

$$\text{where } \tan\phi = (p_Y/p_X)$$

The cone angles used in our jet definition are defined essentially by the calorimeter size. They are picked after a Monte Carlo study using a quark-gluon jet model developed by FFF [1.6]. In this model, a jet going at $X_{||}=0$ ($x_{||}=2p_Z/\sqrt{s}$) in the C.M. frame fragments into a cluster of particles of various energies E . Our Monte Carlo study with this model shows that high energy jet fragments ($E > 1.0$ Gev) will almost always be included in our empirically defined jet discussed above. For lower energy fragments, the number of particles in the real jet that are missed by our empirical jet is almost equal to the number of outside particles (i.e. members of beam, target and away side jets) that are included in our empirical jet. Low energy particles are hard to handle both in theoretical

models and experimental analyses. Fortunately, such particles can always be shown to be unimportant in most jet physics. Despite this low energy fragment uncertainty, the mean derived $p_{\perp}$ of our empirical jet agrees very well with the real jet $p_{\perp}$ input into our Monte Carlo program. This study convinces us that we have a reasonable jet definition. It can be used to test many theoretical ideas.

4.2 JET SELECTION

Our jet consists of 3 components: charged, electromagnetic neutral, and hadronic neutral. The hadronic neutral component includes track finding inefficiencies and non-vertex associated charged tracks (e.g., K_S^0 , Λ^0 decays) as well as real neutral hadrons (K_L^0 and neutrons). This component has the biggest uncertainty and unless handled carefully would be dominated by the background of fake hadronic neutrals produced by the upward fluctuations in the calorimeter energies deposited by charged particles in the hadronic section. This is enhanced by the trigger bias due to the sharply falling high $p_{\perp}$ spectrum. A study of hadronic

neutral fraction versus jet $p_{\perp}$ indicates that most of our $p_{\perp} > 7$ Gev/c jets have large hadronic neutral components. This indicates that especially at high $p_{\perp}$ most of our hadronic neutrals are fake neutrals. This is, in fact, the main headache of all presently existing calorimeter triggered jet experiments. In this thesis, we avoid this headache by selecting jets with a hadronic neutral fraction less than .4. This is suggested by our study that if we make a hadronic neutral fraction cut of .5 or less on both sides, the away side neutral fraction agrees with the trigger side. A cut of .4 is in fact reasonably conservative. We will justify this cut further in chapter V.

Another background, that had worried us, is caused by events with a beam halo particle going into the calorimeter simultaneously with an ordinary interaction in our target. Such events should be rare, because we do have shieldings against halo particles (the magnet and some other shielding near the beam). Unfortunately the cross section for high $p_{\perp}$ events is also very small. Such a background could be serious at high $p_{\perp}$. Scanning through some data, we found such a halo background could be as

high as 10% for $p_{\perp} > 6$ events before any hadronic fraction cut. For $p_{\perp} > 7$, it could be occurring 50% of the time in some runs. All these halo events typically consists of one beam halo going parallel to the z-axis with its track clearly seen in our spectrometer going together with a low $p_{\perp}$

interaction in our target. Such a halo track is usually missed by our track finding as we only look for tracks coming from the vertex. Therefore, this background will almost always be defined as a pure neutral jet event by our jet definition. Our hadronic neutral fraction cut removed almost all of this background. We make a further cut by requiring the total neutral fraction to be less than .9. We also ignore jets with $p_{\perp} > 6.5$.

We cut away about 23% of our jet triggers (becoming as high as 50% at high $p_{\perp}$) with these neutral fraction cuts. Most of these events which are removed are probably junk; in any reasonable model our neutral cuts should remove very few real high $p_{\perp}$ jets. We are studying here a particular class of jets, but we believe our specially selected jets are clean and their $p_{\perp}$ value is very well determined. Our results presented here are

therefore quite independent of the poor calorimeter resolution.

4.3 JET CROSS SECTION

Although I try to discuss here only the results of certain selected jets, one can try to correct for the cuts made in getting a clean sample. The total Jet cross section is computed by using a Monte Carlo correction for losses from neutral cuts (10% to 15% loss in models like FFF) and apparatus acceptances (around 50%) . Jim Rohlf has written such a Monte Carlo program using the FFF quark-gluon jet model mentioned above. All his work is discussed in his thesis [1.9] but some of his preliminary results are presented here (Figures 4.2 and 4.3) without further detailed discussion. Most of the other results presented in this thesis do not involve his Monte Carlo corrections. Therefore my results are not sensitive to the theoretical assumptions used in our Monte Carlo program which may affect the cross section results slightly.

CHAPTER V
COMPARISON OF HYDROGEN AND ALUMINIUM
CROSS SECTIONS

5.1 DEFINITION OF α

In a conventional way, we define α by

$$A_{AL}^{\alpha} = \frac{\sigma_{AL}}{\sigma_{HY}} \quad (5.1)$$

where σ are cross sections per nucleus and A_{AL} is the atomic weight of aluminium.

In fact, we use the formula

$$\alpha = C_2 \ln \left(C_1 \frac{N_{AL}}{N_{HY}} \right) \quad (5.2)$$

$$\text{where } C_1 = \frac{A_{AL}}{A_{HY}} \frac{\Delta Z_{HY}}{\Delta Z_{AL}} \frac{D_{HY}}{D_{AL}} \frac{R_{HY}}{R_{AL}} \quad (5.3)$$

A = atomic weight

ΔZ = target length used

R = beam attenuation in the target

D = density of the target

N = number of events

$$C_2 = 1/\ln(A_{AL}) = .303$$

Our hydrogen target is about 30 cm long. In order to reduce nuclear contaminations due to caps at both tips (see Figures 2.2 and 3.1), we make a fiducial cut by removing 1-cm off each ends in our analysis (Fig. 3.1a). This makes $\Delta Z_{HY} = 28$ cm. Our aluminium target is measured to be: $\Delta Z_{AL} = .031'' \pm .005''$. The uncertainty in ΔZ_{AL} is the main systematic error in our α computation. Other uncertainties, such as the acceptance difference between the two targets, can be estimated by looking at the slope of vertex distribution (see next section 5.2) or using a Monte Carlo simulation of the data. Another possible systematic shift is the difference in the trigger efficiency caused by the different $p_{\perp}$ kicks from the magnet for the different target z positions. This effect is only important for $p_{\perp}$'s near the trigger threshold. This and any other threshold related bias can be checked by computing α 's for different trigger thresholds. We shall always ignore data far below the thresholds.

Our total systematic error in α is estimated to be around $\sigma_{\alpha} = .05$. It is included (in addition to the statistical error) in our α versus $p_{\perp}$ plots, while it is not included in most of the other plots.

R_{HY}/R_{AL} is calculated with the known absorption cross section. It is around 1.024 for proton beam and 1.016 for pion beams. This is a very small effect compared to other uncertainties in α . We include such corrections just for completeness. Our final values of C_1 used are:

255.1 for proton beam

252.8 for pion beam

5.2 ACCEPTANCE STUDY

The Aluminum and proton target data come from two slightly different target positions. Any dependence of the acceptance on the target position will affect our results. We do not need the absolute acceptances for both targets in our present study. What we want to show here is that there is essentially no difference in the value of the acceptances between our hydrogen and aluminium targets.

Our Monte Carlo study shows there is no such difference. We pursue this problem further using our real data. As shown in Figure 3.1a, we have a

long hydrogen target and our very thin aluminium target is very close to the lower tip of the hydrogen target. Any serious acceptance bias as a function of position will appear when we look at the slope of our hydrogen vertex distribution (Figures 5.1a to 5.1c). We do not have enough statistics for jets above threshold to determine the slope very accurately. It agrees with the zero slope, but it agrees even better with the expected beam attenuation (Figure 5.1d). We have more statistics for lower $p_{\perp}$ (2 to 3 GeV/c) jets which are however just below the threshold. The vertex distribution for this biased sample has about the same slope as the high $p_{\perp}$ unbiased jets'. A more careful fit indicates there could be a maximum acceptance difference of about 2%, for lower $p_{\perp}$ jets, which corresponds to $\sigma_{\alpha} = .006$ which is small compared to other uncertainties in our computation of α . One possible source for this tiny difference is the trigger bias caused by the magnet which we shall discuss further in section 5.5.

The vertex distribution for minimum bias data is flat for all beam types. This means we also have an acceptance difference of about 2% (the value of

the estimated beam attenuation) for our interacting beam triggers. However this difference has the opposite sign to the corresponding difference for the jets discussed above. This can be explained by the difference in the geometric efficiency of the 2X2 veto counter which is again sensitive to the different effective magnet kick. This will be discussed in section 5.5 .

This study of the hydrogen target vertex distribution confirms that we do not have any serious acceptance problem within the expected accuracy of our target comparison results. The uncertainty in the slope determination is used to estimate the systematic error in α due to acceptance uncertainties. This was added in quadrature to the total systematic error in α .

5.3 RESULTS

In figures 5.2a to 5.2c, we plot α versus $p_{\perp}$ for jets, single charged particles and double-jets for different trigger biases. The definition of a jet has been discussed in Chapter

IV. I shall describe the other trigger types in the following:

A. Single Charged Particle

This sample comes from the calorimeter single particle trigger. This trigger was in fact not very clean--being contaminated by calorimeter fluctuations and multiparticle triggers. However we were able to select true single particles very cleanly in the offline software. We impose the same fiducial window cut (described in section 4.1) as for the jets on these particles. We use both the calorimeter energy comparison and track quality factor to clean up the tracks entering the calorimeter. Particles included in this data set are very clean.

B. Double-jets

A double-jet event is defined as an event in which 2 back to back jets (one in each calorimeter) are found by our jet definition (see section 4.1) and the absolute $p_{\perp}$ difference between these 2 jets is less than 1 GeV/c. This happens about 10% of the time for all our single jet events.

C. Minimum Bias

The minimum bias trigger has already been described in section 2.2. We in fact distinguish two different selections of this data sample which are denoted "jet" and "single particle". In the "jet" minimum bias plots, we include the whole minimum bias data sample. The $p_{\perp}=0$ bin includes events in which no jet is found, i.e. in which there is no calorimeter signal. On the other hand, for the single charged particle plots, we require at least one charged particle incident on the calorimeter within our $x_{\parallel}=0$ fiducial window defined above in Chapter IV.

The data shown in figures 5.2a to 5.2c show that our α values are quite independent of the trigger thresholds. This is another indication that our results are not affected by the crude resolution of the calorimeter or any other threshold dependent trigger biases. We do not have enough statistics to say anything very conclusively about double-jets. There is no strong indication of decreasing α at large $p_{\perp}$ for these events. This is in contrast with the results for double single particle events [5.1]

which show an α that lies lower than that for single particles. This does not contradict our jet data because we show in chapters 6 and 7 that the make up (in terms of charged particles) of both the trigger and the away side jets are different for Aluminum and proton targets.

In Figure 5.3, we combine all the interesting results for α . Some general observations are:

- (1) α seems to be larger for the jet trigger than the single charged particle trigger. For both triggers α is greater than 1 for $p_{\perp} > 1$ GeV/c.
- (2) For both minimum bias and single particle data sets, α is independent of the beam types. For the jet trigger, the value of α for a proton beam is significantly larger than that for a pion beam, especially when $p_{\perp} > 3.5$. There is no difference seen between π^+ and π^- beams.
- (3) α does not approach the expected value of .7 as $p_{\perp}$ approaches 0.

The significance of these observations will be discussed further in later sections.

We try to compare our data with the published single particle results from the Chicago-Princeton collaboration [1.15]. We take their proton and Aluminum (interpolated from their Ti and Be data) cross sections at 200 GeV, and using equation 5.1, we derived α for the $p_{\perp}$ values of: .77, 3.08 and 4.61 GeV/c. These points are included in Figure 5.3a and they agree with our data within the estimated errors. A relative shift of .04 between the experiments leads to better agreement. This is a small shift compared to the large α values shown in these plots. The Chicago-Princeton measurement has an overall normalization uncertainty of order 20%, which corresponds to a possible σ_{α} of around .07. The small shift of order .04 between the two experiments can be due to systematic uncertainties in either experiments.

5.4 EFFECT OF MULTIPLICITY ON α

The observation, that our α does not approach .7 at low $p_{\perp}$, was annoying. This could be an indication that our overall normalization is very wrong. We believe, as indicated by our vertex study

(section 5.2), that this is unlikely. We are now convinced that this can be due to the way we define our minimum bias sample. The anti-beam counter, defining this sample, has removed most of the low multiplicity diffractive type of interactions. Further, when we analyse our data, we require at least 2 charged particles detected before the magnet to form a good vertex. All these conditions mean we have very poor efficiency for low multiplicity events. This will not affect our high $p_{\perp}$ data at all since the mean charged multiplicity seen in our experiment for such events is around 10, but it does affect our very low $p_{\perp}$ interacting beam events. In Figure 5.4, we plot the mean charged multiplicity seen after the magnet (denoted by $\langle N \rangle$) versus α . It clearly indicates that α depends strongly on multiplicity and α approaches .7 for low $p_{\perp}$ as $\langle N \rangle$ approaches 1. This confirms our idea that the reason α does not approach .7 as $p_{\perp}$ approaches 0 in Fig. 5.3 is probably due to a loss of low multiplicity events.

It has been observed by other experimenters [1.18] and by us (see figures in Chapter VI and VII) that in general there are increases in

multiplicities in the central (C.M. rapidity around 0) and target fragmentation (C.M. rapidity < 0) regions for low $p_{\perp}$ interactions off a heavy nucleus. It is interesting to ask the question whether this observed α dependence on the overall multiplicity can be attributed to either the particles in the jet or those outside the jet.

We divide the total charged multiplicity into two parts: the charged multiplicity in the jet and the charged multiplicity outside the jet. We plot separately α against both of these multiplicities in figures 5.5 and 5.6. The trigger jet is defined to be the jet with the larger calorimeter signal in case of double-jet events. These plots show that the ANE ($\alpha > 1$) is enhanced by an increase in either multiplicity. The general increase in α with increasing jet multiplicity, as shown in Figure 5.5, is also consistent with the α increase as we switch from the single particle trigger (which has a jet multiplicity of 1) to the jet trigger.

In Figure 5.7, we plot α vs. the charge of the trigger jet. We do not see any significant difference between the positively charged and the

negatively charged jets. The larger α value for jets of larger absolute charges is probably just a reflection of the multiplicity effects shown above (i.e. large net charge implies large multiplicity).

The multiplicity is a rather crude average characteristic of the event. We shall discuss in more detail the event structure of interactions off the aluminium target in the later chapters.

5.5 TESTS FOR THE RELIABILITY OF OUR DETERMINATION OF α

A charged particle with laboratory momentum (p_x, p_z) , coming from the center of our hydrogen target ($z=1.7$), will hit the calorimeter roughly at the x-coordinate:

$$x_{int} = \frac{10.8 (p_x \pm .28)}{p_z} \quad (5.4)$$

The apparent p_x change (Δp_x) of order .28 comes from the momentum kick (.379 GeV/c) imparted by the magnetic field roughly at $z=4.5$. This is illustrated in the following figure (see trajectory H1) :

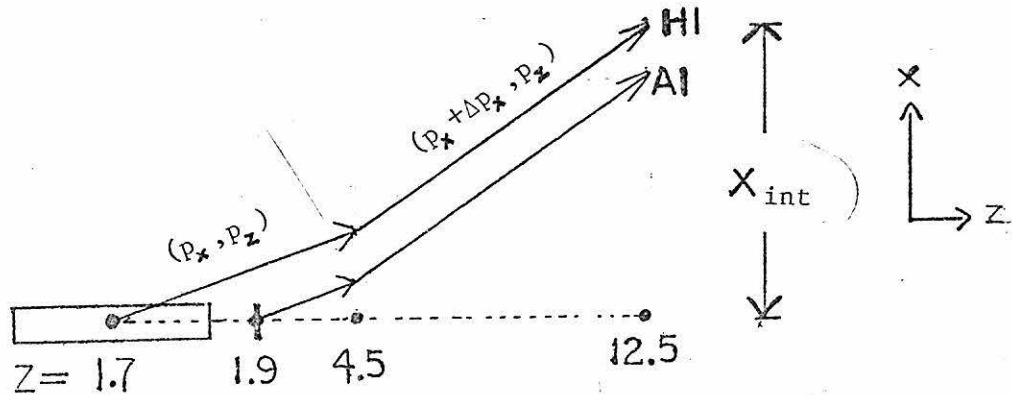


Fig. 5.8a Trajectories of charged particles in MPS

A charged particle, with the same kinematic parameters but coming from the aluminium target, takes the trajectory A1 which is parallel to H1 (see the above figure). When we trigger our experiment, we calculate our triggering $p_{\perp}$ at the calorimeter ($z=12.5$) using the detected X_{int} , assuming that the particle comes from the middle of the hydrogen target ($z=1.7$). This means for interactions off aluminium, the value of Δp_x mentioned above will be different by a tiny amount $.02p_x$ from $.28$. If we assume the p_x spectrum is $\exp(-3p_x)$, and let us take mean $p_x = 500$ Mev/c, this tiny change in

Δp_x can easily contribute a 2% acceptance difference between the 2 targets for jets triggered below the threshold. of course this is only a trigger bias and will not affect data above threshold which is analyzed offline with the correct vertex.

In the real situation, the sign of this apparent change Δp_x can be either positive or negative. Since we are studying here a sharply falling spectrum, the configuration shown in Figure 5.8a is more dominant.

In order to show that there are no serious magnet biases, we plot, in Figure 5.9, α as a function of the following variable:

$$f_{mk} = \frac{.379 \text{ (JET CHARGE)}}{\text{JET } p_{\perp}} \quad (5.5)$$

The sign of f_{mk} indicates whether the magnet kick favours or acts against the jet trigger. Its magnitude is a measure of the fractional change in p_x due to the magnet kick (The actual change in p_x is given in (5.4)). We see no significant difference in α between the positive and negative values of f_{mk} . This shows that our results are not

affected by the magnet kick.

For the minimum bias data, the magnet kick has a slightly different effect on the triggering efficiency. This is illustrated in the following figure:

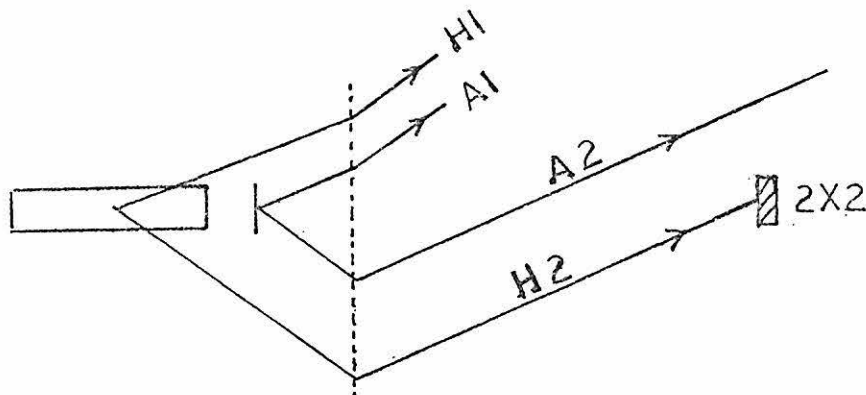


Figure 5.8b Effect of magnet bend for Interacting Beam triggers

The amount of bending in the magnet for 200 Gev beam particle is negligible in comparison with the bend for other lower momentum particles and so we can assume, for simplicity, that the 2"X2" counter is centered on the beam line. Most of the particles in our interacting beam sample have momenta much less than 100 Gev/c. Therefore, the only way, that lower

momentum particles can hit the 2X2 counter is by bending in the opposite direction to the x-component of their momenta (trajectories H2 and A2 in Figure 5.8b). In this bend-in configuration, a charged particle coming from the hydrogen target can be vetoed more easily by the 2X2 counter. The order of magnitude of this effect is related to the difference in X_{int} mentioned above. A similar rough estimate (like the high $p_{\perp}$ trigger) can easily explain the 2% effect (for the interacting beam trigger) observed in section 5.3. We shall talk about the 2X2 problem again when we discuss the forward region later in Chapter VI.

As illustrated in Figure 5.3, α increases with $p_{\perp}$ for our high $p_{\perp}$ jet trigger. Any random background, like that due to halo particles, should have a smaller value for α . This means the magnitude of α within a fixed $p_{\perp}$ range can be used to indicate the cleanliness of our data. From a study of the trigger side versus the away side, we believe our neutral fraction cuts have already cleaned up our data sufficiently (section 4.2). We justify this cut further by plotting the hadronic neutral fraction versus α before any other cut in

Figure 5.10 . These plots clearly show our hadronic fraction cut of .4 was a sensible choice for removing most of the backgrounds. Thus α is flat for neutral fraction less than 0.5 (indicating no significant background) but dips above this. Presumably most of the high neutral fraction data, really come from lower $p_{\perp}$, where α is smaller and is promoted by either the calorimeter fluctuations or halo particles.

5.6 INTERPRETATION OF THE ANOMALOUS VALUES FOR α

After all these checks and justifications, we are convinced that there is indeed a huge ANE for high $p_{\perp}$ productions off aluminium. This effect is also more prominent for the proton beam than for the pion beam. We are not aware of any detailed theoretical models with which we can compare our results and use to make reliable estimates. Instead, we shall discuss some of the qualitative features of these theoretical attempts :

A. Scatterings before the Main Interaction

One possible explanation for this anomalously

high α is multiple scatterings inside the nucleus. If it is due to scattering of the beam before the main interaction, it has the same effect as if the target nucleon has some kinetic motion (Fermi motion) during the interaction. This can either raise the effective c.m. energy ($\sqrt{s}$) or give a net $p_{\perp}$ kick to the interacting system. The possibility that effective s is increased is very unlikely, since it has been observed (Figure 5.11 taken from Ref. [1.15]) that the p/π production ratio increases with A but decreases with s , at least in the case of the single particle trigger. How about the possibility that this is due to some additional $p_{\perp}$ added for the nuclear target? As the high $p_{\perp}$ cross section behaves like $\exp(-3p_{\perp})$, the contribution to α for any nuclear target will be around $0.9k_F^2/\ln(A)$ where k_F is the maximum $p_{\perp}$, due to the Fermi motions, that can be added to the nucleon. If we take $k_F=200$ Mev/c, then we shall have $\alpha=1.01$ for the aluminium target which is obviously too small to agree with our results. The p/π production ratio for the single particle trigger also does not agree with such an explanation (see Fig. 5.11). Let us assume that we do not know how to estimate such effect and this large α is still

caused by some effective $p_{\perp}$ kick. This implies that a jet with transverse momentum $p_{\perp}$ produced off the aluminium target should behave like a jet with transverse momentum $(p_{\perp} - .2)$ produced off the hydrogen target. In Figure 5.12, we plot the charged multiplicity in the jet as a function of $p_{\perp}$ for both targets. We observe a large difference in $\langle N \rangle$ (mean charged multiplicity in the jet) between these 2 targets, and such a difference can not be explained by a general $p_{\perp}$ shift of .2 Gev/c (at least $\Delta p_{\perp} = 2$ is needed). There is essentially no observed difference in jet multiplicity between proton and pion interactions, while there is a significant difference in α between these 2 beams. Thus fermi motion can be ruled out as an important contribution to the anomalous value of α .

B. Nuclear Effects During the Main Interaction

Since we are dealing with a high density of nucleons in collisions off nuclear targets, some people have suggested that many nucleons may act coherently in such interactions (see discussion of the "Coherent tube model" in Ref. [1.18a]). This means the interaction time must be of order of the size of the nucleus, and it may contradict the

general belief that the high $p_{\perp}$ interactions are related to the deep underlying hard (short distance) scatterings of the asymptotically free partons.

C. Additional Interactions of the Final State

Some theorists believe that this $\alpha > 1$ phenomenon is due to additional hard scatterings after the main one. They suggest formalisms [1.18b] like :

$$\frac{\sigma_A}{\sigma_{HY}} = A(c_0 + c_1 A^{\frac{1}{3}} + c_2 A^{\frac{2}{3}} + \dots) \quad (5.6)$$

where $c_0, c_1, \dots$ are some free parameters and A is the atomic weight. Additional soft scatterings, or multiple scatterings, of the final state after the main interaction can also give rise to such effects. If such secondary scatterings can enhance an increase in $p_{\perp}$ without changes in jet multiplicity, then the large α differences seen between jets and single charged particles will be very hard to understand. In a recent publication [1.20], it is shown that multiple scattering may enhance the high $p_{\perp}$ gluon production in nuclei. Such mechanism can be used to explain the strong dependence of α on the multiplicities and many other observations. Unfortunately, some of the assumptions used in Ref. [1.20] are not fully

justified [1.18] and therefore their quantitative results are probably not credible. No matter how the final forms of such models may look, we believe it is probably still very hard to explain the large difference in α between proton and pion beams while still predicting that their jet multiplicities are almost the same.

D. Background Smearing

It is possible that the difference in α between the proton and pion beams is related to the sharper slope of the proton beam high $p_{\perp}$ spectrum. It has been observed ([1.7d], [1.13] and Fig. 4.3a) that the relative jet production off hydrogen by the proton beam compared to the π beam decreases from 1.5 to .5 (a factor of 3) between $p_{\perp} = 2$ and 6 GeV/c. The difference $\Delta\alpha = .2$ between proton and pion in Fig. 5.3 corresponds to the proton/pion ratio changing not by 3 but rather by 1.5 off an aluminium target. If one imagines that the nuclear jet cross section is obtained by smearing (of whatever kind) of the hydrogen data, one will always smear the sharper cross section more and so find a larger value of α for it.

One smearing effect in any jet experiment is due to additional low $p_{\perp}$ particles that happen to be in the cone defining jet although, in fact, they may come from the beam or target fragmentations. This smearing is more pronounced for the aluminium compared to the hydrogen target as the former has a substantially higher multiplicity at zero rapidity (see Figures 6.12 to 6.14). We investigated this effect by generating random particles in the C.M. rapidity range $-.5$ to $.5$ with equal probability to be plus, minus or zero charges. The $p_{\perp}$ distribution used for the random particles was a Gaussian with a mean $p_{\perp}$ equal to 330 Mev. We added these extra particles to our hydrogen data and analyzed these modified data just like our original hydrogen data. We repeated this "particle adding" process until the mean charged multiplicity in the jet from our modified hydrogen data agreed with the aluminium data. The addition of 2 to 3 particles gave the best fit, and the away side rapidity distribution also seemed to agree for this choice. We found that this smearing contributes about .15 to the anomalous α value reported in Figure 5.3, but it did not appear that it can explain the difference of about .5 between the jet and single particle

α values. There is some difference between proton and pion beams in our "particle added" results, but it is much too small.

The single particle result published by the Chicago-Princeton group [1.15] shows that the α value for the proton final state is usually larger than that for pions; our data seem to indicate that the proton beam can enhance nuclear anomalies more easily than the pion beam (see also later chapters on target comparisons of the event structure and the jet composition). These observations could be related to the larger total cross section for protons, or the sharper proton beam high $p_{\perp}$ spectrum, while the single particle results may be sensitive to protons knocked out of the nucleus. However the current estimates of the effects mentioned above are all too small to explain the observations quantitatively. We believe that the current theoretical models can not predict the large enhancement of jet production off nuclei seen in our data.

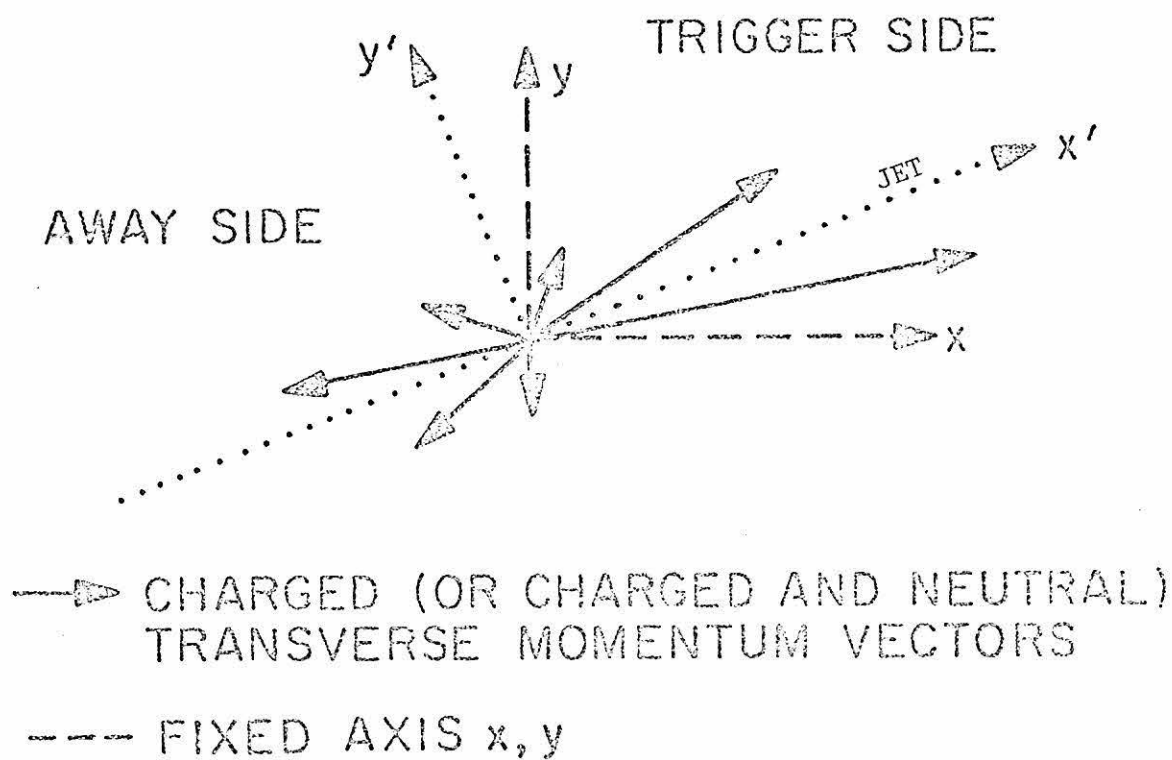
CHAPTER VI

CORRELATIONS

6.1 GENERAL FEATURES

It is generally believed that jet production interactions are related to the underlying scattering of partons in the colliding hadrons. If such underlying hard collision is truly elementary and the transverse momenta of the jet fragments are limited, then the event structure of such interactions should be very coplanar. It has been shown in our previous publications [1.7] that the structure of particle distributions in jet events is much more coplanar than that of some isotropically produced particle distributions. Without further discussion of this coplanarity problem, we define the C.M. Jet Frame to be the center-of-mass frame with its x-axis pointing along the transverse projection of the jet momentum.

TRANSVERSE COMPONENTS



..... THE AXES x', y' FOUND FOR EACH EVENT

THESE AXES ARE USED TO DEFINE THE C.M. JET FRAME

We shall always present our results on the associated charged particle distributions in this frame unless it is specified otherwise.

The multiplicity density function $D(X)$ used in this thesis is defined by :

$$D(X) = (dN_Q/dX)/(\text{number of events}) \quad (6.1)$$

where X can be any kinematic variable, like $p_{\perp}$ or Y (rapidity) in the C.M. Jet Frame, and dN_Q is the number of charged particles within the kinematic region dX . $D(X)$ is also called as $\rho(X)$ in some references.

The first kinematic variable we would like to discuss is θ_{xz} , where $\tan(\theta_{xz}) = p_x/p_z$ in the "C.M. Jet Frame". Ideally, θ_{xz} is independent of the measured energy of the particle. In reality, if we assign a wrong mass to a particle (we assume a pion mass for all particles) in the laboratory frame, our θ_{xz} which is calculated in the center of mass frame will be slightly distorted by an incorrect Lorentz transformation. We believe that this is a small effect, since most of the particles are believed to

be pions (see the Cerenkov counter studies in other theses [1.9]).

One nice thing about the θ_{xz} distribution is that it gives us an overview of particle distributions in all 3 regions: the away side region ($\theta_{xz} < 0^\circ$), the forward region (θ_{xz} near 0°), and the same side region ($\theta_{xz} > 0^\circ$). The particles in the jet are in the region $50^\circ < \theta_{xz} < 130^\circ$, centered at 90° .

These θ_{xz} plots are presented in Figures 6.1a to 6.1f for all charged particles with C.M. energies (E) greater than .5 Gev.

In Figure 6.2, we make a similar plot for particles with $E < .5$ Gev. It does not show any significant structure. Most of the interesting features of the jet events are probably due to higher momentum associated particles. Our $E > .5$ Gev cut seems to be very reasonable.

None of these θ_{xz} plots are corrected for acceptance. We shall present our results in terms of ratios when we compare our results for different beams and targets so that the acceptance will be cancelled out.

Our track finding efficiency is around 95%, and from our Monte Carlo study, the 2X2 problem (which will be discussed more later) only affects particle around the region $|\theta_{xz}| < 15^\circ$ for $E > .5$ and is about a 4% loss in this region. Within the uncertainty of these effects, we can still discuss some of the general features of these plots:

A. There is a peak at 90° . It increases with $p_\perp$. This was also indicated by the jet multiplicity plot which was presented in Figure 5.12. The width of this peak is about 20° which is smaller than the size of our calorimeter (about 30°) and the cone angle (40°) used in our jet definition. This is an indication that our jets are not biased strongly on the size of our calorimeter. We shall talk more about particles in the jet in Chapter VII.

B. The peak in the forward region is not centered at 0° . It is roughly at -10° . It tends to shift to more negative values at higher jet $p_\perp$ (see Fig. 6.1e). This phenomenon of a bias to the away side is more pronounced for the π^- beam than the proton beam (compare Fig. 6.1e with Fig. 6.1a). The height of the forward peak also decreases with the

increasing jet $p_{\perp}$. The theoretical interpretation of these observations will be discussed later in section 6.2.

C. There is no clear separation between the forward peak and the "away side jet" region. For $-60^{\circ} < \theta_{xz} < 0^{\circ}$, the multiplicity is higher than the corresponding toward side $0^{\circ} < \theta_{xz} < 60^{\circ}$. Further, the total multiplicity in the region $-120^{\circ} < \theta_{xz} < -45^{\circ}$ increases with the increasing jet $p_{\perp}$; this can be considered as an indication that the dynamics of the "away side jet" dominate within this θ_{xz} (-120° to -45°) range. The general structure of the away side is dependent on the beam and target types as we shall discuss in the later sections.

In Figure 6.3, we also present a θ_{xz} plot for data simulated by our Monte Carlo program. These Monte Carlo data are analyzed identically to the real data. Our Monte Carlo program uses the gluon and quark scattering model developed by FFF; the quarks and gluons are fragmented into hadrons using a model developed by Field and Feynman [1.6]. Unfortunately, FFF does not have any detailed prediction about the forward region. The assumption

we made in our Monte Carlo program is that the remaining parts of the hadrons fragment like single quarks (after the main hard collision). The flavours of these quarks are picked, in such way, that on the average, the total flavour of the final 4 jets equals the flavour sum of the incoming hadrons. The program does not require the conservation of quantum numbers on an event by event basis.

A detailed comparison of the FFF with our data, and a more thorough discussion about the Monte Carlo program, will be presented in another thesis [1.9]. I shall only discuss some of the general features of Fig. 6.3. The Monte Carlo calculation shows a very similar structure to our real proton data (Figure 6.1a). It also exhibits about the same shift in the peak (to about -10°) of the forward region shown in the real data. However, the Monte Carlo data have a larger enhancement around -90° (on the away side) at lower $p_\perp$ (2 to 3), and the forward peak also decreases slower with increasing $p_\perp$. These indicate that we are probably observing more smearings between the forward region and the away side than expected in the FFF model.

6.2 FORWARD REGION

Before we discuss other correlations, we would like to give more details on the forward region. As we have described in Chapter II, all our triggers have the pretrigger requirement which is defined by the absence of charged particles in the 2X2 counter. This creates a hole in our acceptance function in the forward region. This hole is also shifted and distorted by the magnet bend. The real situation is even more messy. It is known that our spark chambers have long memory times such that we have "ghost" particles in the beam region left over from the previous events. There are also "ghost" tracks from beam particles that did not interact (remember only 5% of the beam interact). These "ghost" tracks can be matched easily to other good tracks around the 2X2 region. This is mainly due to the high density of tracks (ghost or real) in the forward region. As we have discussed in section 3.1, the algorithm for our track finding is to find all tracks in the x and y views separately, then use hits in the skew chambers (most of these are spark chambers after the magnet) to match these tracks to form particles. Whenever, there is a high density

of tracks, it is very likely to have tracks mismatched (good with bad, bad with bad) to form "fake" particles. The problem is accentuated by the small angle stereo ($\tan \theta = 0.1$) in the spark chambers. Most of these "fake" particles have already been removed by our preliminary pattern recognition clean ups (see section 3.1 and [3.2]). However, in the very forward region, we have so many "ghost" tracks that it is necessary to make stricter cuts for particles in the forward region. The number of left over bad tracks can be significantly reduced by making cuts on PWC (the PWC's have a smaller memory time [2.1] than the spark chambers) quality factors that are based on PWC hits only, and by removing tracks that go into the 2X2 or close to it. In fact, we made all these cuts [3.4] before our final analysis. The problem is that the net track finding efficiency in the forward region is clearly reduced by these cuts.

In order to show that our forward region cuts are efficient in removing these "ghosts", we plot the particle distribution in the spatial x-y space before and after cuts. We saw a cross shape (Fig. 6.4a) centered at the 2X2 before any cut. These are

a combination of truly "ghost" particles and real tracks mismatched to "ghost" tracks. After some PWC quality cuts, this cross structure vanishes and the 2X2 hole starts to appear (Fig. 6.4b). We then just remove the remaining ghost particles that "hit" the 2X2 and some particles very close to it.

The main problem for the forward region is in fact how to estimate the efficiency after all these cuts. We can, of course, avoid the problem by just computing ratios. However, it is still very important to know roughly the size of such losses and which kinematic regions are affected by these losses. Our Monte Carlo program allows all particles in the forward region—including particles that go into the 2X2 counter. By imposing our cuts in the forward region on the Monte Carlo data, we can thus estimate the fractional losses due to our software cuts and the anti-2X2 triggering system. In Figures 6.4c and 6.4d, we plot the fraction of particles lost in our Monte Carlo data as a function of θ_{XZ} for all particles with $E > .5$ Gev. We find a maximum fractional loss of around 4% in the forward region. Our Monte Carlo program is not sophisticated enough to be able to estimate

correctly some of the losses due to all the quality cuts, the real loss is probably slightly higher.

We can also estimate the 2X2 losses using the real data. This is illustrated in the following:

consider a particle with a definite value for p_x (x-component of its momentum) in the C.M. Jet Frame. Its acceptance as a function of p_x has a hole roughly in the region:

$$p_{xL} < p_x < p_{xH} \quad (6.2)$$

$$\text{where } p_{xL} = -.25(2x + Z_1(1-Z_2x)) \quad (6.3)$$

$$p_{xH} = .25(2x - Z_1(1-Z_2x)) \quad (6.4)$$

x = (laboratory momentum)/(200 Gev/c)

Z_1 = (charge of the particle)X(sign of
the magnet kick in the C.M. Jet
Frame)

Z_2 = (charge of the particle)X(charge
of the beam)

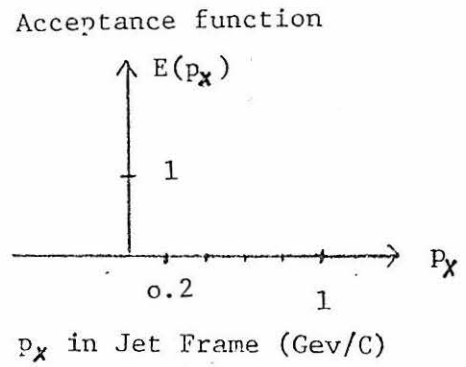
where the quantity Z_1 indicates whether the charged particle is bent towards the trigger side or away

from it, while Z_2 indicates whether the charge of the particle is the same as the incoming beam particle or not. The values of p_{xL} and p_{xH} also depend slightly on the vertex position as mentioned in Chapter V. A vertex z position = 1.7 is assumed in this simple illustration.

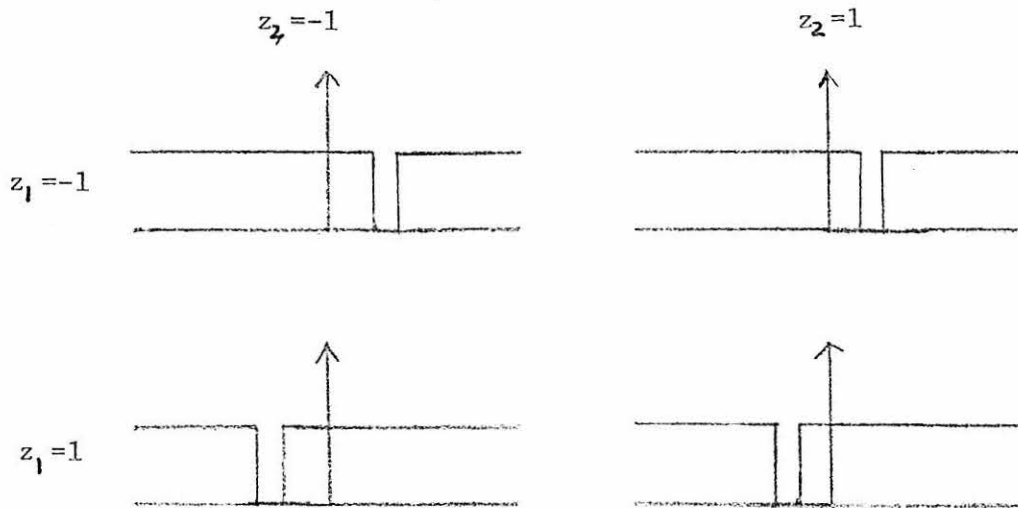
A plot of x (defined above) indicates that we have very few particles for $x > .35$. This is expected from the conservation of the total momentum as the maximum possible total energy in the C.M. frame, in the forward region, is around $(10 - (\text{jet } p_{\perp}))$ which corresponds to $x = .5$ for jet $p_{\perp} = 5 \text{ GeV}/c$.

The acceptance function (due to 2×2 losses) as a function of p_x in the C.M. Jet Frame is sketched in the following figure for two values of x :

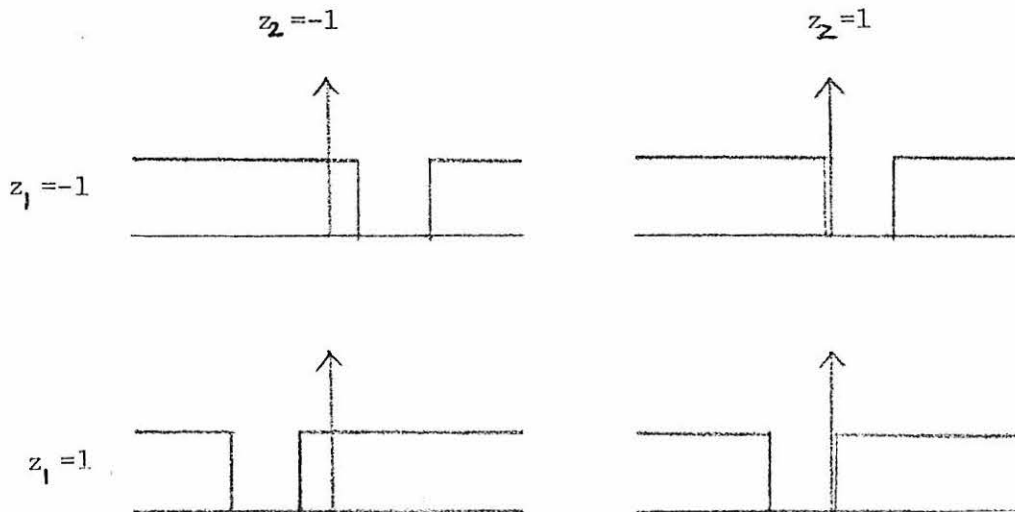
Figure 6.5 Acceptance (2×2 loss only) as a function of p_x . x is defined in section 6.2.



a) $x=0.1$



b) $x=0.35$



The interesting feature about the 2X2 loss is that these holes (in the acceptance function) do not overlap (see Figures 6.4c and 6.4d) for different magnet kicks (different Z_1) if x is small enough and if the charge is fixed (fixed Z_2). This means we can also estimate our efficiency by comparing the distributions for different magnet polarities for the region $x < 0.33$ which in fact includes most of our data. A preliminary estimate using this algorithm indicates that the 2X2 loss is around 5% for $E > 0.5$ particles. The final analysis of the 2X2 efficiency is not completed at the time of this report.

The forward region contains a lot of interesting physics connected with the beam jet. We have already shown that the forward peak tends to move away from the trigger side as $p_{\perp}$ increases. Theoretically, such a tilt is related to the transverse momentum of a quark or gluon inside the hadron. A more thorough analysis will be attempted on our data (in the forward region) in the near future. So far, most of our results on the forward region studies are preliminary. The current data are however sufficient for a comparison of hydrogen

and aluminium targets. The main purpose of this section is to discuss problems associated with the 2X2 counter and possible ways of solving it.

6.3 CHARGE CORRELATIONS

As we have shown above, the loss due to the 2X2 veto is probably around 4% level in the forward region, and for lower x values such losses are almost independent of the particle charge (see Fig. 6.5a above and also $|\theta_{xz}| > 10^\circ$ in figures 6.4c and 6.4d). We can therefore study the ratio of positive to negative charged particle production with a maximum uncertainty of order 4%. This $\pm$ ratio is plotted as a function of θ_{xz} in Figure 6.6 for various values of the jet charge (Q_{JET}), where Q_{JET} is the sum of the charges of particles in the jet, requiring that these particles must have p_x 's greater than .1 of the jet p_L . The mean p_L of the jets for all these plots are listed in Table 6.1. I have also plotted these ratios for various p_L bands (within 2 to 6.5) but I do not show them here as the different p_L cuts all looked very similar.

In Figure 6.7, I make a similar plot using our Monte Carlo data. Although the quantum number correlation in the forward region is handled incorrectly in our Monte Carlo program, the correlation on the away side still represents what is expected from the FFF model. It is believed that there should be very little correlation between the $\pm$ ratio on the away side and the various values of Q_{JET} . This comes naturally from the assumption that the underlying scattering is elementary and the scattered partons fragment independently. Such assumptions also lead to large quantum number correlations between the forward region (the beam jet) and the triggered jet. Of course, there are always smearings between these 3 regions due to uncertainties in the dynamics of the low momentum particles. Our $E > .5$ Gev cut should have removed most of this smearing.

When we try to compare our proton beam data (Figure 6.6a) with what is expected (Figure 6.7) on the away side, we observed significant difference (between the two plots). The theory predicts a smaller correlation than seen in our data. For the pion beam data, we expect some correlations on the

away side due to asymmetry of the beam target system, while we observe about the same amount of correlations as in the proton data. It is possible that all these observed discrepancies between the data and the theory are due to the approximate handling in the model of the transverse momenta for quarks in the hadron or the omission of other processes. Naturally it is important to study the origin of this correlation of the (average) quark charges both theoretically and experimentally.

Although we believe that our data (used for the final analysis) are very clean, we would still like to make some more checks on our $\pm$ ratios. As I have discussed above, most of the ghost tracks should have fewer hits in the PWC's. This means their PWC quality factors should have lower values than for the real tracks. We divided our data into two samples based on a cut of the total PWC quality and we plot the $\pm$ ratios for these two samples in Figure 6.8. We see no difference between the two even in the forward region (Notice this is not completely precise as the PWC quality factor can be slightly momentum dependent and so a momentum dependence of the $\pm$ ratio could show up in

Fig. 6.8). It is important to note that the ghost particles usually have the same charge sign as the beam particle (they "were" beam particles). Any excess of ghost tracks should show up as larger $\pm$ ratio, in the forward region, for the lower quality particle sample in Fig. 6.8. (Note that we only use the positive beam polarity in this plot). The fact that there is no difference in the $\pm$ ratio between these 2 samples (of different qualities) for all values of θ_{xz} indicates that our final data (after all cleanliness cuts) are probably very clean.

6.4 BEAM COMPARISON

In order to study the effect of incoming beam types on the structure of a jet event, relative $D(\theta_{xz})$ plots for different beams are presented in Figures 6.9 and 6.10. We observe no difference between the π^+ and π^- beams (Figure 6.9b has very low statistics). All these plots in Figure 6.9 are consistent with 1 for all values of θ_{xz} . Figure 6.10 is much more interesting. These plots indicate that the away side θ_{xz} distribution for the pion beam interaction tends to shift more towards the

forward region than the proton beam interaction. This is expected in the theory as the pion has one less valence quark than proton, and therefore the scattered parton from the pion is more likely to have a higher p_z in the C.M. frame (see discussion in Chapter I). This forward shift, for particles in the pion beam interaction, seems to increase with the jet $p_{\perp}$. This observed variation with increasing $p_{\perp}$ would be obviously statistically significant if we combine some of the bins (like those from -80° to -20°) to show more clearly the difference between the lower $p_{\perp}$ (2 to 3) jets and the rest. One of the amazing results from our experiment is that we see no obvious difference between Figures 6.10a and 6.10b. If we believe this forward shift of the pion beam relative to the proton beam is a manifestation of the underlying QCD dynamics, then it seems that the nuclear effects (which could a priori easily smear such dynamics) are all cancelled neatly in Figure 6.10b.

In Figure 6.11, we plot the relative $D(z)$ distribution (proton over π^+ beam) for all charged particles on the away side ($p_x < 0$). z is defined as the absolute value of p_x in the C.M. Jet Frame

divided by the jet $p_{\perp}$ (or $p_{\perp}$ of the triggered particle in single high $p_{\perp}$ trigger). We find that the pion interaction has slightly more higher z particles on the away side for the hydrogen target and this effect seems to be larger for the aluminium target. This large z enhancement for pion beams is not completely unexpected as the scattered parton on the away side, in pion interaction, can be detected more easily by our spectrometer due to the forward shift effect discussed above.

6.5 COMPARISON OF ALUMINIUM AND HYDROGEN TARGETS

For the comparison of different targets, we will use the kinematic variable Y (rapidity) instead of θ_{xz} , as Y is the variable used more often in previous publications. Figure 6.12 shows some published results taken from Ref. [1.18a]. We make similar plots of the relative $D(Y)$ (aluminium over hydrogen) distributions for all charged particles (except that in the single high $p_{\perp}$ trigger, the trigger particle is excluded) for 3 different triggers (Figure 6.13). They all seem to have very similar structures. In Figure 6.14, we

repeat these relative $D(Y)$ distribution plots for all charged particles on the away side only. Figures 6.13 and 6.14 are almost identical to each other, except maybe, for regions near $Y=0$. We make no energy cut for particles included in these plots. The shape of these relative $D(Y)$ distributions in the lower Y regions could be mainly due to low momentum particles ($E < .5$ GeV). The effect of energy cuts like $E > .5$ GeV is still to be studied.

We now make some checks on our relative $D(Y)$ plots. In Figure 6.15, we present the $D(Y)$ distributions for the aluminium target and 3 different vertex regions of the hydrogen target. We do not see any vertex (spatial) dependence of $D(Y)$ for interactions off hydrogen. They are all well separated from the aluminium target $D(Y)$ distribution in regions $Y < .6$, indicating that we do not have any serious acceptance difference problem in this rapidity region.

For the very forward region, the 2X2 problem may affect $D(Y)$ slightly. In order to justify our results for all regions presented, we plot the relative $D(Y)$ distributions on the away side for the

following two classes of particles:

- (1) not affected by the 2X2
- (2) affected by the 2X2

when I say "not affected by the 2X2" , I mean a particle, on the away side, that is bent (by the magnetic field) away from the 2X2 (see previous figures and discussion on the 2X2 problems). If the energy of this particle is low enough, then it will never hit the 2X2 counter and its acceptance will not be affected by the 2X2. The other class of particles are those that are bent towards the 2X2, their acceptance will always be affected by the 2X2. These two classes of particles are labelled as "outside 2X2" and "affected by 2X2" in Figure 6.16. We cannot find any noticeable difference for the relative $D(Y)$ distributions between these two samples. Our results on the relative $D(Y)$ distributions are thus probably quite independent of any possible acceptance problems.

It is generally believed that the shape of the relative $D(Y)$ distributions is related to the propagation of the beam jet through the nuclear matter (see discussion in Chapter I) both before and after the main interaction. Unfortunately, there

exists no theory with which we can compare our results quantitatively. I shall point out some of the general features of our plots without referring to any model:

(1) The shape of the relative $D(Y)$ (also called $R(Y)$) distributions is almost independent of trigger $p_{\perp}$ for events of a given trigger.

(2) There seems to be differences between the relative $D(Y)$ distributions for different triggers. $R(Y)$ in the $Y > 0$ region decreases, for different trigger types, in the following order:

(all I.B.) $>$ (single particle I.B.) $>$ (single high $p_{\perp}$) $>$ (jet)

where $(A) > (B)$ means trigger A has the higher value of $R(Y)$ in regions $Y > 0$ than trigger B.

These observations indicate that, maybe, $R(Y)$ is sensitive to the overall event multiplicity. If this is true, then we shall be wary of the multiplicity effects (like whether diffractive interactions are included) for such $R(Y)$ plots from any experiment.

In Figure 6.17, we plot the relative $D(z)$ (also called $R(z)$) on the away side for the 2 targets. We observe, in general for all $p_{\perp}$'s, more lower z particles on the away side for interactions off aluminium. At higher $p_{\perp}$'s (4 to 6.5 for jets and 3 to 5 for single high $p_{\perp}$ particles), interaction off aluminium seems to have less high z particles on the away side. We do not see any significant difference between the 4 plots in Figure 6.17, except may be, that $R(z)$ for the proton beam has a slightly sharper slope than the pion data at high $p_{\perp}$. $R(z)$, in general, decreases with increasing z . This decrease at large z is also observed for charged particles in the trigger jet as we shall discuss in the next chapter.

The observation that there is no significant difference in $R(z)$ distributions between the jet and the single high $p_{\perp}$ particle triggers is very interesting. Theoretically, the single high $p_{\perp}$ trigger is a subset of the jet trigger. We expect "similar" away side z distributions for these 2 triggers. When we say "similar", we mean they should be almost the same if the z of the single high $p_{\perp}$ trigger is multiplied by approximately 0.8.

This .8 factor is the mean z of the triggered single high $p_{\perp}$ particle in the jet whose fragmentation led to the the single high $p_{\perp}$ trigger particle. The similarity of $R(z)$ for these two triggers indicates that this relation between the single high $p_{\perp}$ trigger and the jet trigger is not altered by the nuclear effects.

As indicated by plots presented in both this and the next chapter, interactions off aluminium have in general more low momentum particles than those off hydrogen. This leads naturally to the general expectation that there are probably additional nuclear scatterings of the final state (either hadron or parton) produced in the main high $p_{\perp}$ interaction. Figures 6.10 and 6.17 seem to indicate that such additional nuclear scatterings (if they exists) are probably very coherent with the main interaction, so the dynamics of the main interactions can still be seen. In our minimum bias interacting beam data, we also observe some correlations that seem to be unaffected by the nuclear scatterings. This is shown in Figure 6.18 which is a two body correlation plot from work done with the help of T. Tse [6.1] where the correlation

function R is defined as follows :

$$R = \frac{\sigma \frac{d\sigma}{dY_1 dY_2}}{\frac{d\sigma}{dY_1} \frac{d\sigma}{dY_2}} \quad \text{for} \quad |Y_1| < .25 \quad (6.5)$$

where Y_1, Y_2 are rapidities of charged particles.

Figure 6.18b is for all events, while Figure 6.18a is only for events with the total charged multiplicity greater than 6. In all cases, we observe no difference between the hydrogen and the aluminium targets. This indicates that the coherence indicated by the positive correlation (R positive) for Y approximately equals to 0 is not affected by the nucleus. It can be understood theoretically if we believe that the final hadrons are always produced outside the nucleus.

Our experiment is the first to study both high and low $p_{\perp}$ interactions off a nuclear target with a large kinematic acceptance. We have observed many interesting nuclear effects that were not predicted theoretically. This could be the starting point of a deeper understanding of nuclear effects in high energy collisions.

CHAPTER VII

JET COMPOSITION

7.1 RELATIVE Z DISTRIBUTIONS

As we have already shown in Figure 5.12, jets produced off aluminium are composed of more charged particles than jets off hydrogen. In this chapter we are going to make a further comparison of the jet structure between hydrogen and aluminium targets, and also between different beam types. The distribution function that we are going to discuss here is:

$$D(z) = (dN/dz)/N_{JET} \quad (7.1)$$

where $z = (p_x \text{ of charged particle in the jet in the C.M. Jet Frame}) / (\text{jet } p_L)$.

This $D(z)$ function has already been defined previously. z is also called as x_e in some publications.

For particles in the jet, $D(z)$ is usually interpreted as the parton (mainly quarks, with some gluons) fragmentation function in models (like that

due to FFF) where jets are produced by constituent scattering. $D(z)$ is expected to approximately scale, that is, be independent of $p_{\perp}$, although QCD does predict a small $p_{\perp}$ dependence that has not yet been seen experimentally.

In our previous analysis [1.7], $D(z)$ is found to scale as a function of $p_{\perp}$ within the experimental uncertainty. This scaling, especially at high $p_{\perp}$, however, can be sensitive to the scheme of neutral extractions. If we use the old neutral analysis scheme as developed for our early data in [1.7], such scaling is observed [7.11]. However, with the present neutral scheme and "neutral cuts" described in this thesis, scaling is no longer observed. This indicates that details of neutral analysis (especially the neutral cuts) may affect this $D(z)$ scaling in a non-trivial way. Whether this scale breaking is really due to QCD corrections (or some other theoretical effect), or is mainly an artifact of the neutral cuts, is still to be studied.

Our Monte Carlo data, in general, have higher $\langle z \rangle$ values than the real data, indicating that the real data have probably more low z particles than

predicted by the FFF model.

With all these ambiguities about the absolute magnitude of $D(z)$, we can still make a meaningful study of the relative $D(z)$ for different beams and targets.

We show the ratio of $D(z)$ for the π^+ beam over that for the π^- beam in Figure 7.1 and $D(z)$ for the proton beam over the π^- beam in Figure 7.2. The ratios presented in all these plots are consistent with 1. Due to limitations in statistics, we cannot say anything very quantitative about Figure 7.1. However, Figure 7.2 seems to indicate that the proton data have slightly less high z particles than the π^- data. This can be statistically significant, for the aluminium target, if we combine the $p_{\perp}$ ranges (3 to 4) with (4 to 6.5). We shall discuss one possible explanation for this different $D(z)$ phenomenon later in the next section.

In Figure 7.3, we have the relative $D(z)$ (called $R(z)$ from now on) of the aluminium target over the hydrogen target. We observe here a similar effect at large z (i.e., aluminium is lower than

hydrogen) as shown in the away side $R(z)$ distribution discussed in the last chapter. Such effects seem to occur at even lower $p_{\perp}$ values for particles in the trigger jet than for the away side.

7.2 CONTAMINATIONS FROM LOW $p_{\perp}$ PARTICLES

One possible explanation for this $R(z) \neq 1$ effect (in both target and beam comparisons) is that this is due to additional low $p_{\perp}$ particles that happen to be in the cone defining the jet, although in fact, they come, for instance, from the beam or target fragmentations.

In order to understand this contamination effect, we define for all charged particle in the jet:

$$z_Q = \frac{z}{\sum_{z_i > z_{\text{cut}}} z_i} \quad (7.2)$$

where i sums over all the charged particles in the jet. We ignore cases where the denominator becomes 0. This parameter z_Q is really defined in such a

way that it behaves like the variable z for different triggers as we switch smoothly (by increasing ZCUT) from the jet trigger (no ZCUT) to the single charged particle trigger (ZCUT greater than or around .8). When we say there is "no ZCUT", we mean $z_Q = z$. The case for ZCUT=0 corresponds to the charged component of the jet.

In Figures 7.4 and 7.5, we combine the higher $p_{\perp}$ bands and plot $D(z_Q)$ distributions for various values of ZCUT's. The mean jet $p_{\perp}$ of these plots are listed in Table 6.1.

The proton over π^- $D(z)$ plot (Figure 7.4a) was consistent with 1 originally (see Fig. 7.1a). The operation of using finite ZCUT has only a small effect on the ratio, although it does tend to make the ratio closer to 1. For the aluminium target (Figure 7.4b), the relative $D(z_Q)$ is definitely affected by the ZCUT. For ZCUT=.2, our relative $D(z_Q)$

has already become consistent with 1, while our old relative $D(z)$ is about 20% below 1 at high z . Both of these plots seem to indicate that any slight difference in $D(z)$ between proton and π^- beams can be due to low z particles.

On the other hand, this explanation seems to fail in cases of target comparisons. For both proton and π^- beams, $Z_{\text{CUT}}=.4$ is still insufficient to make $R(z_Q)=1$ for all values of z_Q (Figure 7.5), indicating that things are probably more subtle here. However, these plots may still support possibilities like multiple scatterings of the jet fragments in the nuclear matter for interactions off aluminium. Comparisons of these plots with predictions of a reasonable theoretical model (let us hope there will be one) will be very intriguing.

CHAPTER VIII

SUMMARY AND CONCLUSION

8.1 SUMMARY

The Fermilab experiment E260 has three major triggers: jet, single high $p_{\perp}$ and interacting beam. This thesis reports on some of the recent studies on our data and emphasizes comparisons of two targets (hydrogen and aluminium) and three beams (π^- , π^+ and proton). Here is a summary of our results:

(1) A jet is defined here as a group of particles going into either of the two calorimeters. Both our jet cross section and the associated particle distributions agree pretty well with the QCD predictions (FFF model).

(2) We understand the problems associated with the 2X2 counter. Results on the forward region study is still very preliminary.

(3) We observe a larger charge correlation than predicted by FFF between the $+/-$ ratio on the away side and the charge of the jet.

(4) Target comparison:

a) $\alpha > 1$ at high $p_{\perp}$ for both jet and single particle triggers. The value of α for our proton beam single high $p_{\perp}$ data agrees with the Chicago-Princeton result. α depends strongly on multiplicity.

b) Interactions off the aluminium target have higher associated charged multiplicities in all regions except in the very forward region. This could be due to the enhancement of gluon production in the hadron nucleus scattering.

c) If this higher multiplicity is caused by additional nuclear scatterings, then such additional nuclear scatterings are probably very coherent with the main interaction. The two body correlation for all the associated charged particles, in our interacting beam trigger, is the same for both the hydrogen and aluminium targets. This seems to indicate that the final hadrons are produced outside the nucleus.

(5) Beam comparison:

- a) The results on π^+ and π^- beams are essentially the same.
- b) Our proton data look different from the pion beam; they have a slightly higher charged multiplicity and the proton almost always enhances nuclear effects (like larger α) more than the pion.

8.2 CONCLUSION

(1) Qualitatively, our data agree well with the QCD predictions by FFF. However, there are indications of discrepancies especially when we try to make some quantitative comparisons. Both theoretical and experimental studies are needed to understand such discrepancies.

(2) We are the first experimental group to study nuclear anomalies with the detailed measurement of the event structure. Some of the qualitative predictions suggested by the QCD theory for the hadron nucleus scattering, such as, enhancement of the gluon production and that the final

hadronization process is well separated from the main interaction, are all in good agreement with the data. However, it is still not clear that results like $\alpha > 1$ can be explained by the theory. We believe that the study of the hadron nucleus scattering is important in the investigation of many fundamental processes. Hopefully our results will stimulate further researches in this fascinating field.

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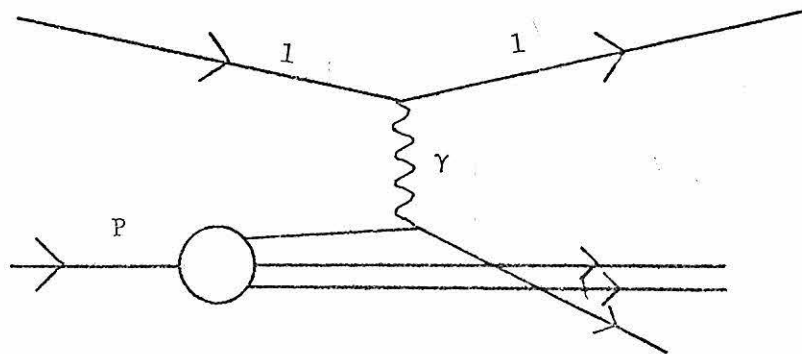
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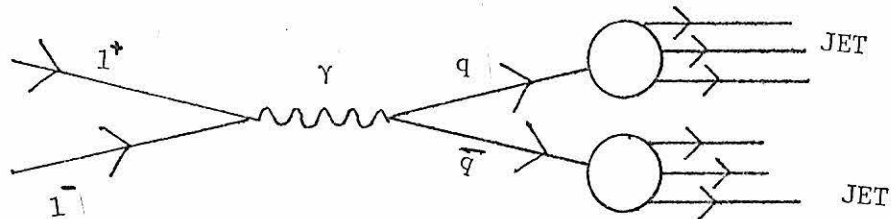
TABLE 6.1: Mean jet $p_{\perp}$ for the following plots.Cut used to define the $p_{\perp}$ range is $2 < p_{\perp} < 6.5$.

BEAM	TARGET	$\langle \text{JET } p_{\perp} \rangle$ in GeV/c	FIGURE NUMBER	COMMENTS
Proton	Hydrogen	$2.94 \pm .006$	6.6a 6.16b	HIJET
Proton	Aluminum	$3.14 \pm .010$	6.6b 6.16b	HIJET
π^+	Hydrogen	$3.10 \pm .020$	6.6c	HIJET
π^+	Aluminum	$3.24 \pm .032$	6.6d	HIJET
π^-	Hydrogen	$2.96 \pm .005$	6.6e	HIJET
π^-	Aluminum	$3.11 \pm .009$	6.6f	HIJET
Proton	Proton	$2.90 \pm .004$	6.7	Monte Carlo
Proton	Hydrogen	$2.64 \pm .006$	6.16a	LOJET
Proton	Aluminum	$2.80 \pm .013$	6.16a	LOJET

a) Deep Inelastic Lepton-Nucleon Scattering



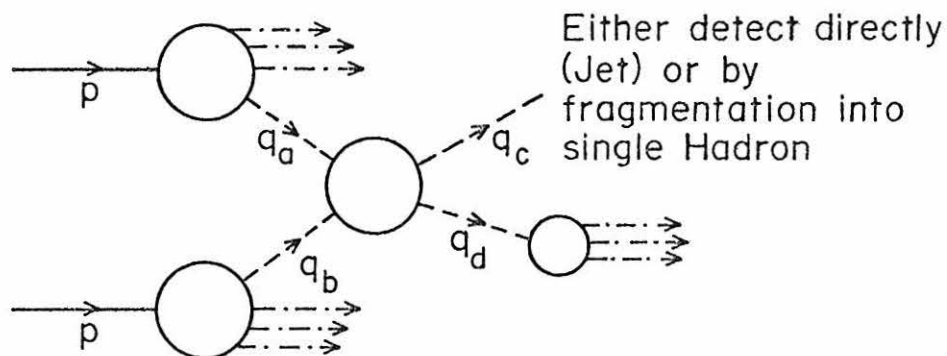
b) Lepton Pair Annihilation



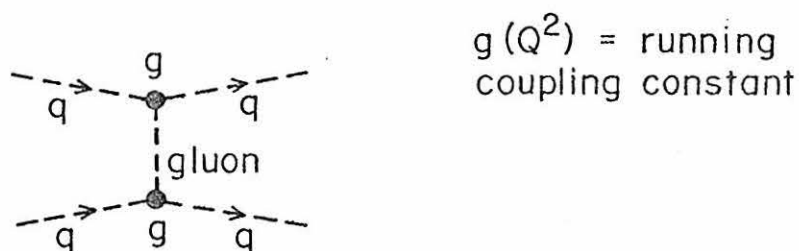
l leptons
 P nucleons
 q quarks
 γ photons

Figure 1.1

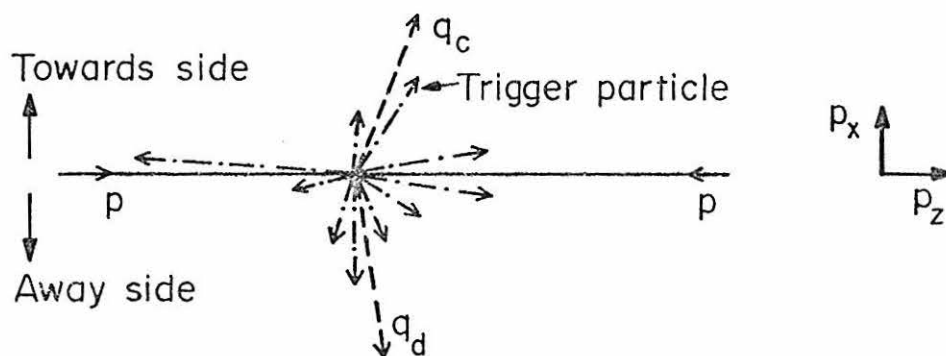
(a) Constituent Scattering



(b) Typical "QCD" Quark Quark Scattering

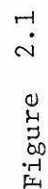


(c) 4-jet Structure of Events



- Initial state Hadron
- · - · - · → Final state Hadron
- - - - - → Constituent (Quark or Gluon)

Figure 1.2



ELEVATION: FRONT PORTION OF MULTIPARTICLE SPECTROMETER

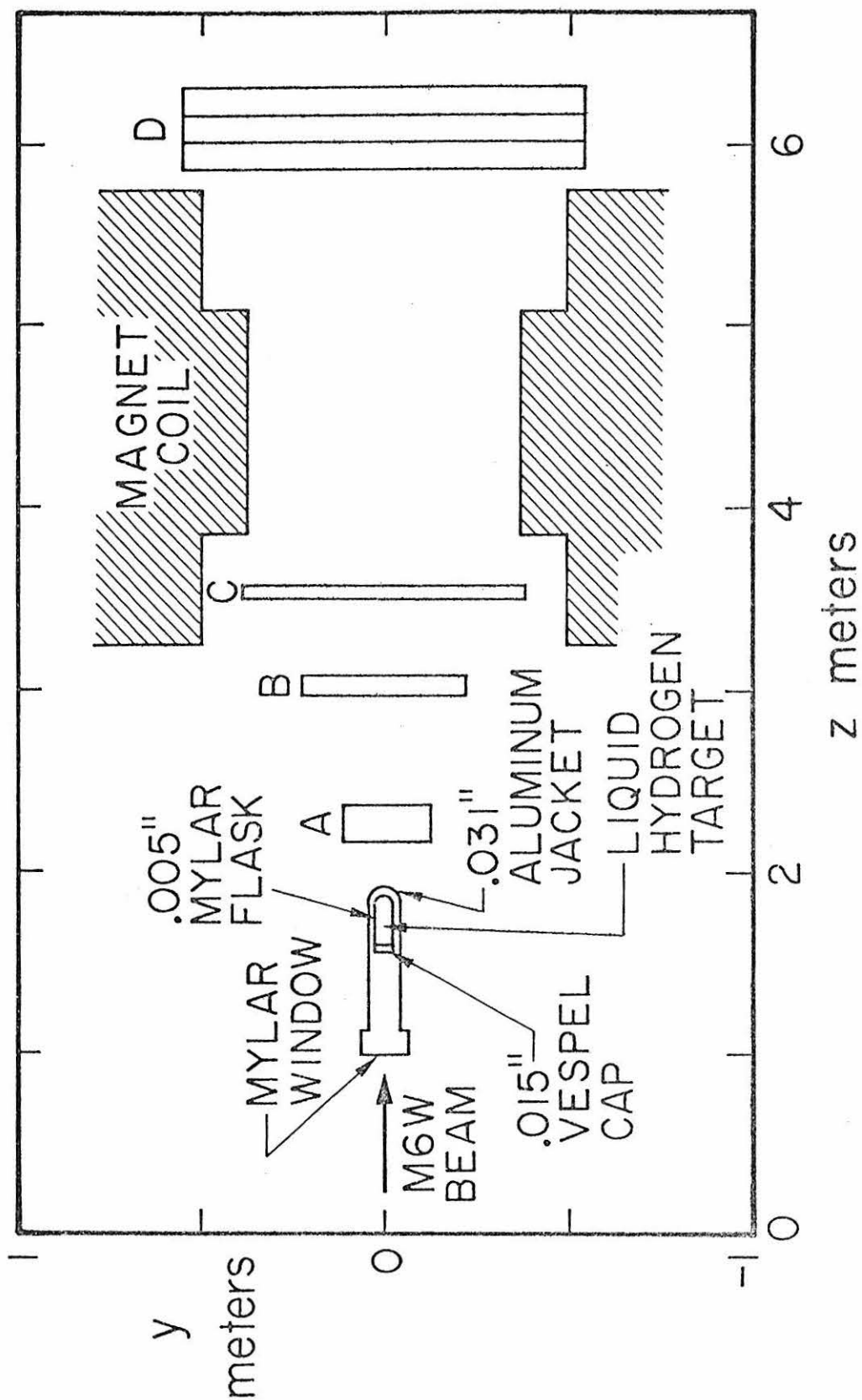
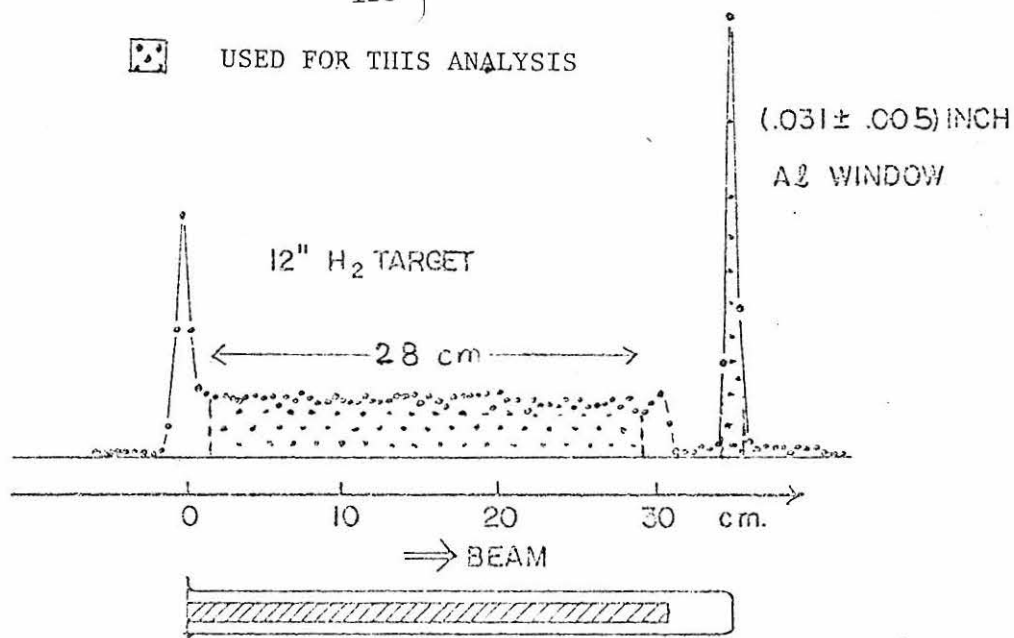


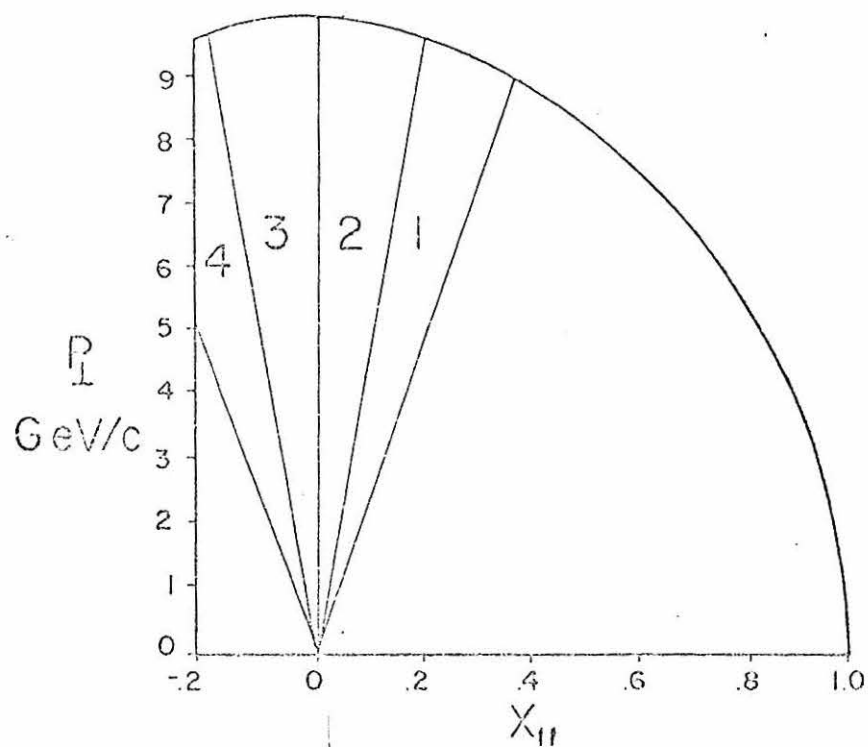
Figure 2.2



USED FOR THIS ANALYSIS



a) The vertex distribution of all triggers.



b) Acceptance of our apparatus for the charged particles (no magnet bending)

Figure 3.1

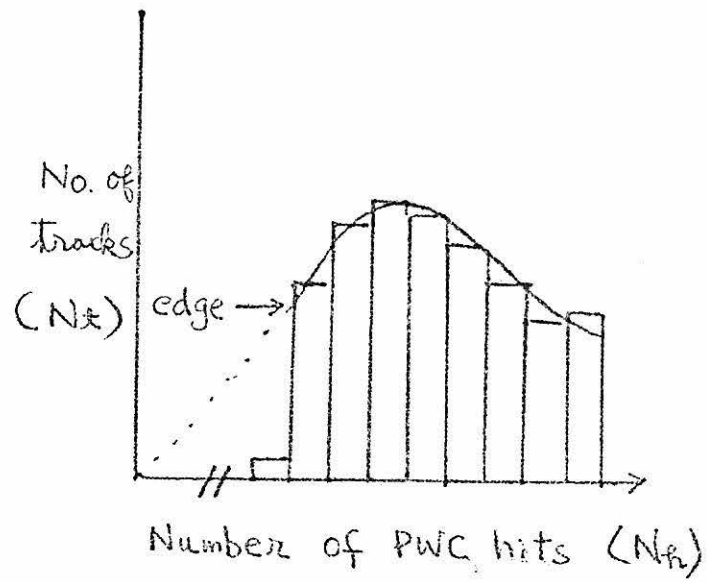


Figure 3.2a

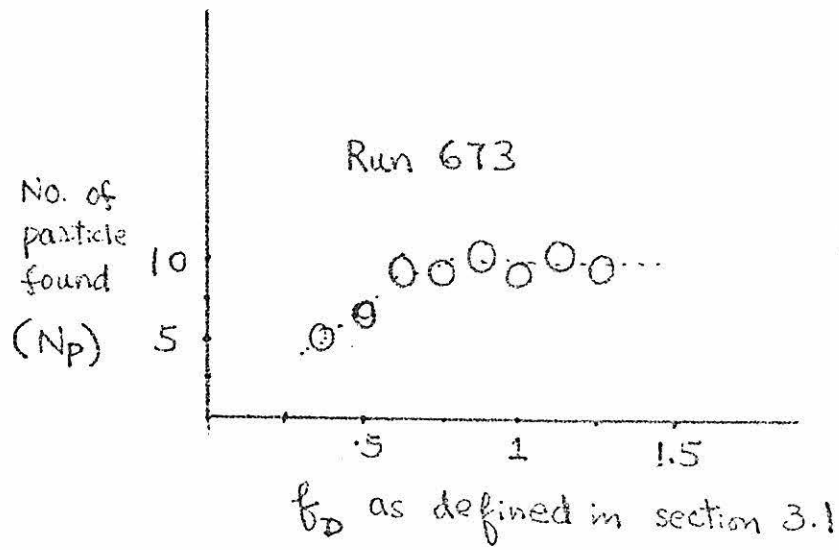


Figure 3.2b

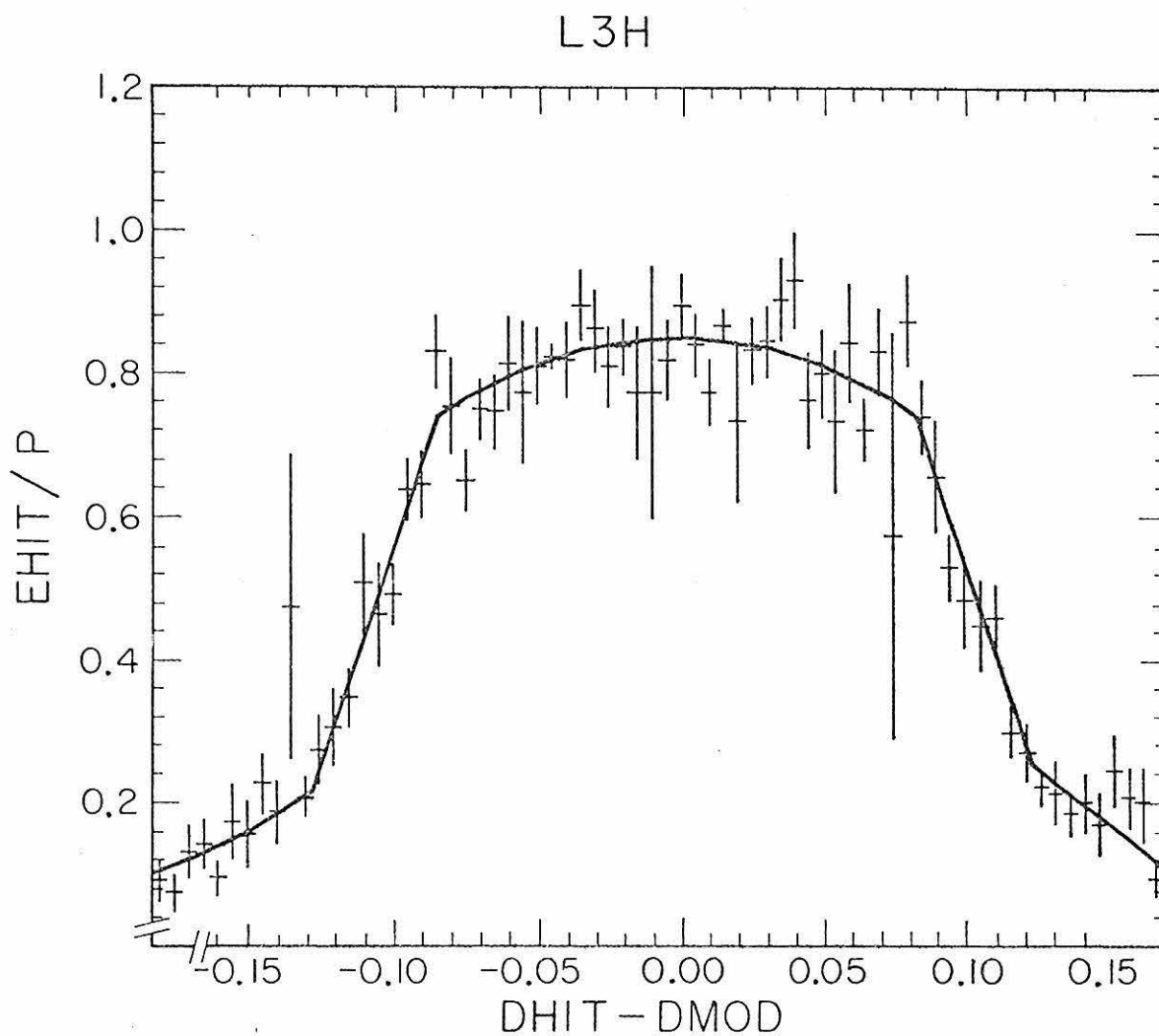


Figure 3.3 Fraction of energy deposited in the module versus distance with respect to the center of the module. Derivation of this curve is described in [2.8b].

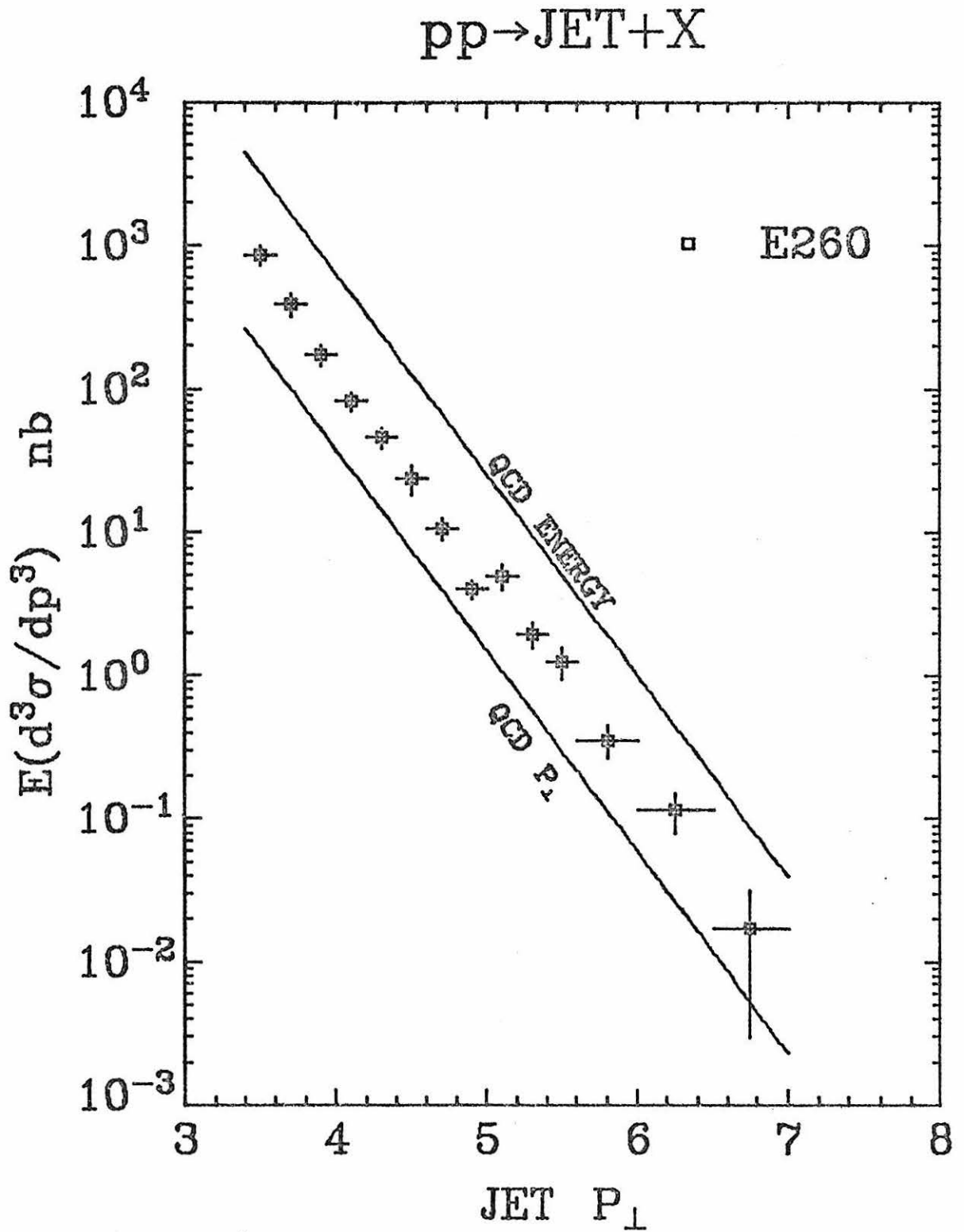


Figure 4.2a E260 jet cross section and comparison with QCD predictions (using FFF model).

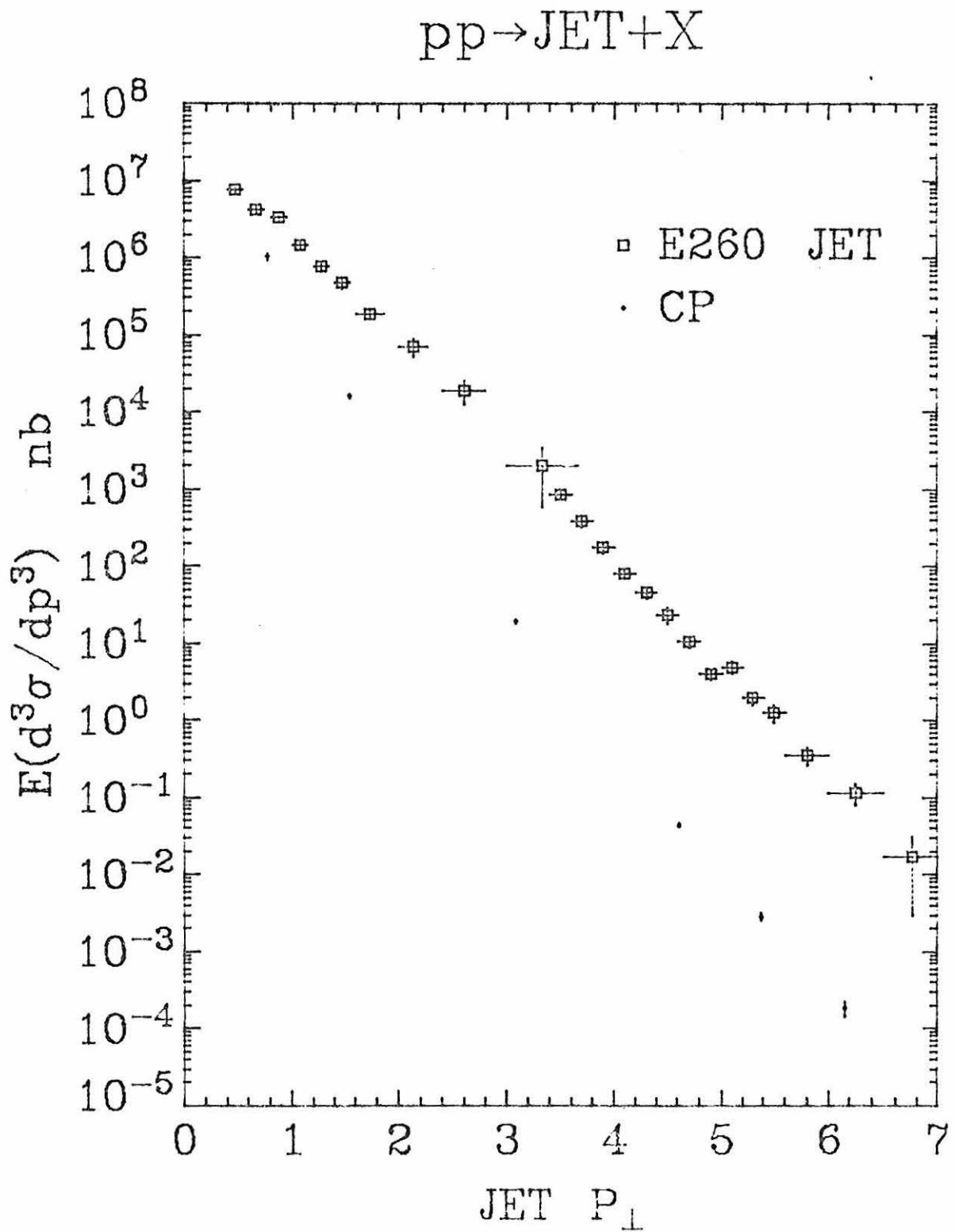


Figure 4.2b E260 jet cross section and Chicago-Princeton single particle cross section.

Figure 4.3 Ratios of jet cross sections
(vs. jet $P_{\perp}$) for different beam types.

EXPT. 260

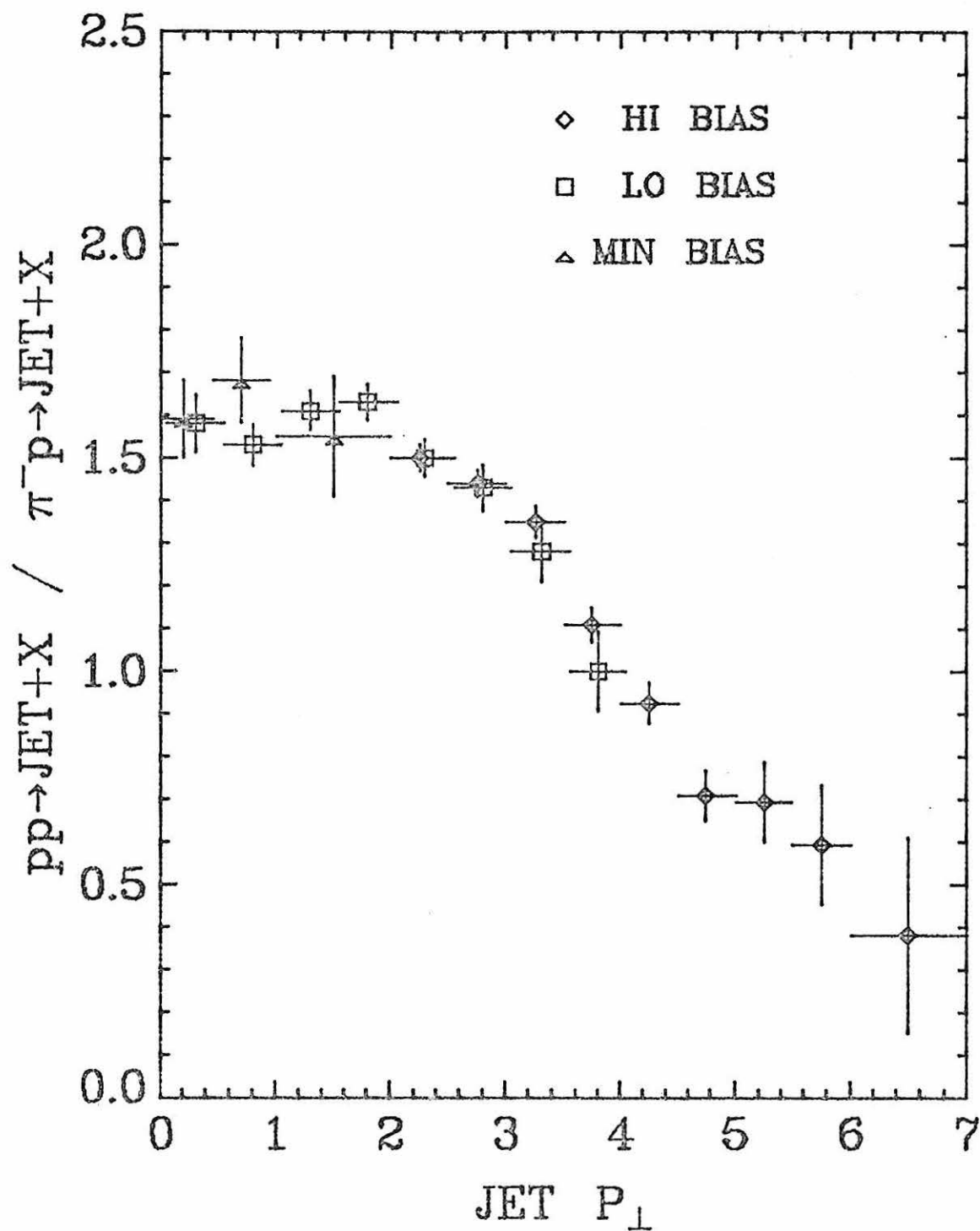


Figure 4.3a

EXPT. 260

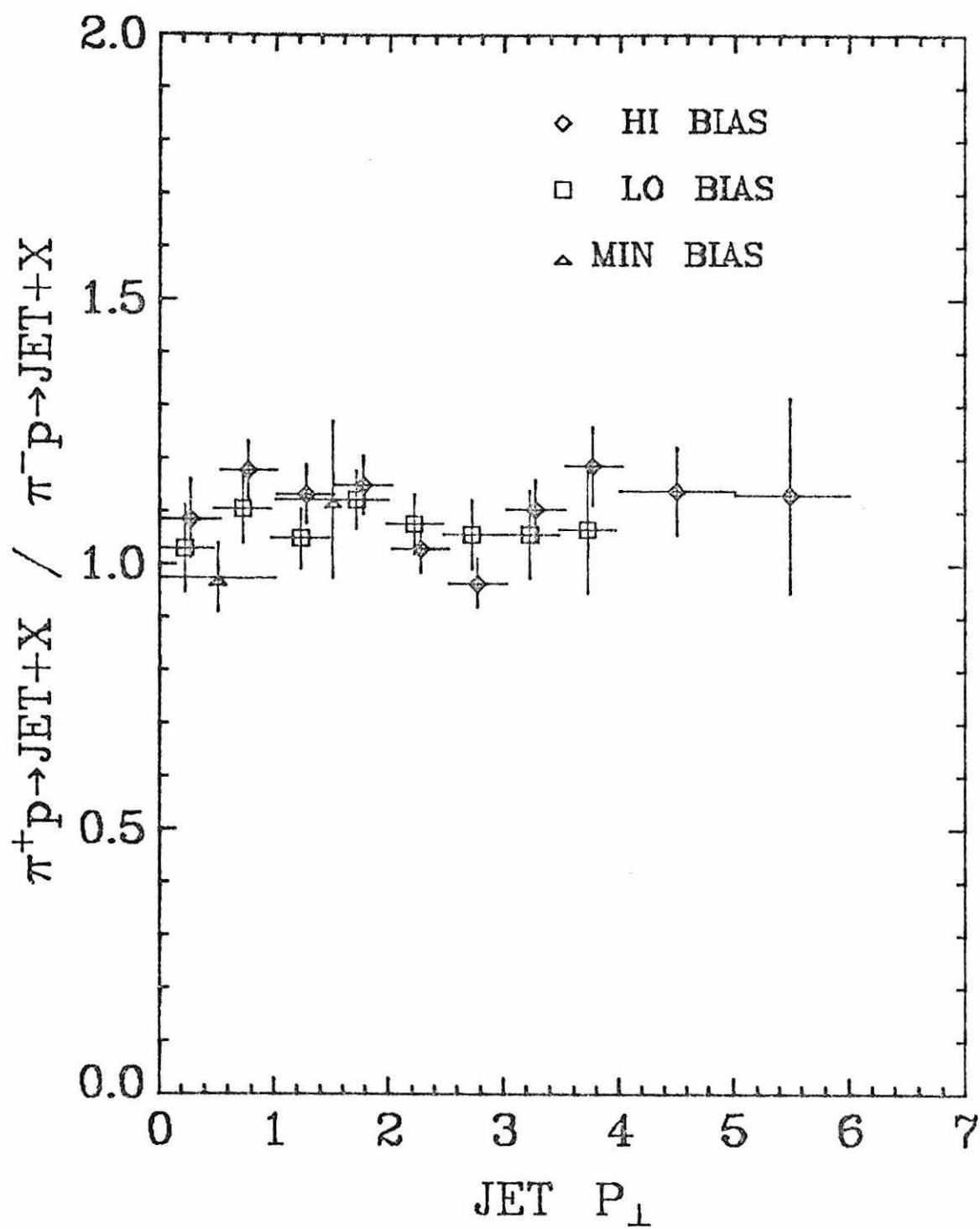


Figure 4.3b

EXPT. 260

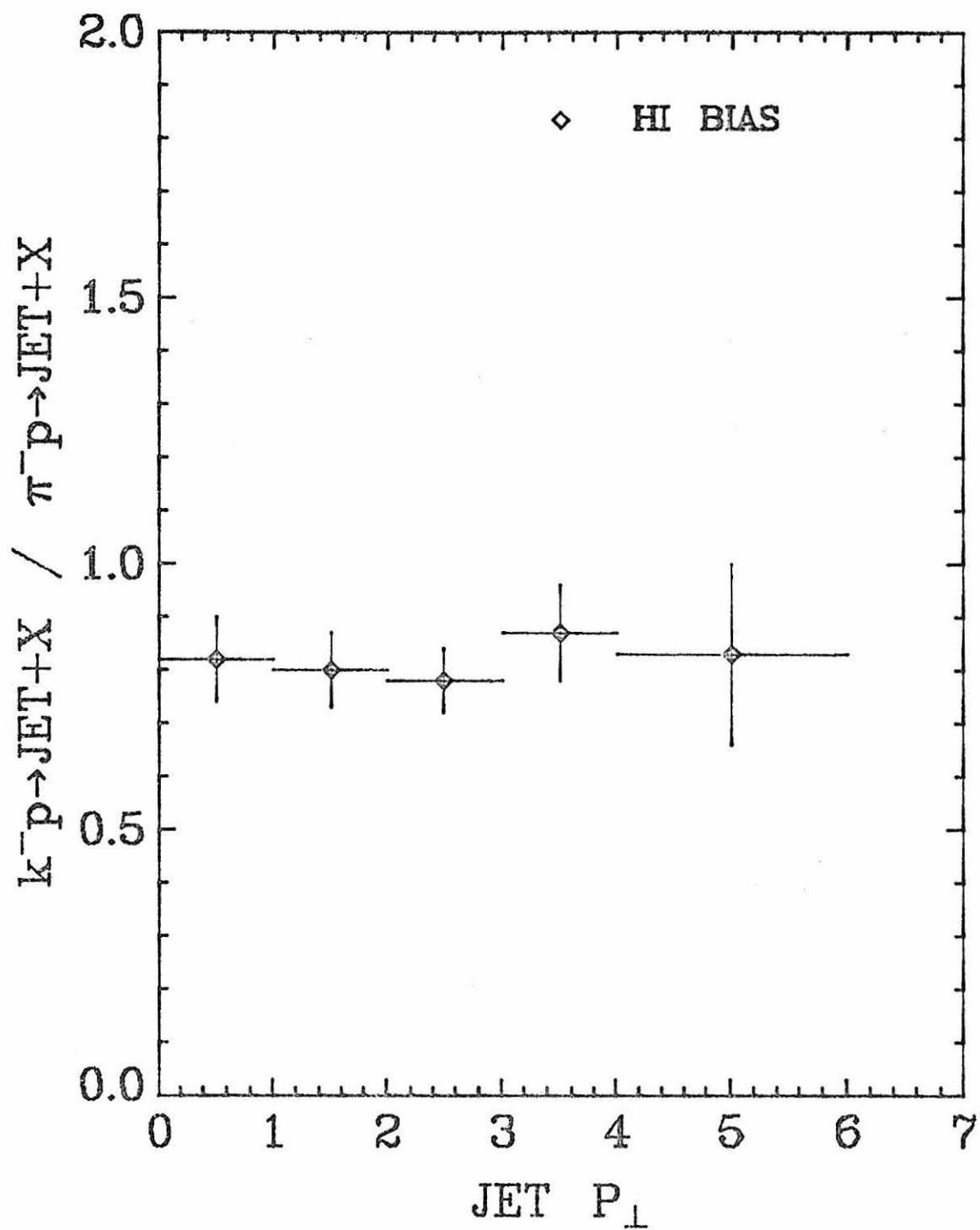


Figure 4.3c

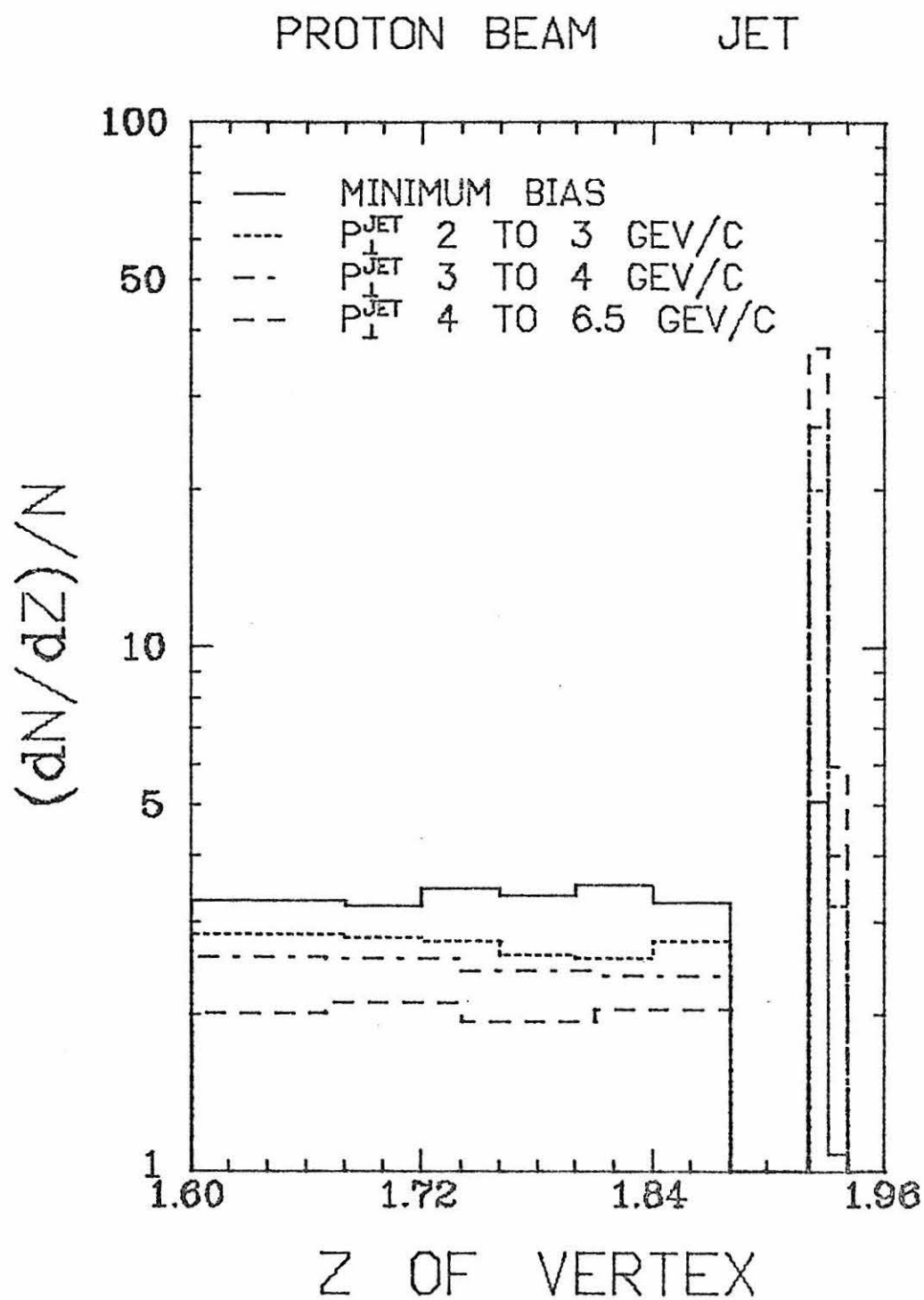


Figure 5.1a Vertex distribution for jet trigger.

π^- BEAM JET

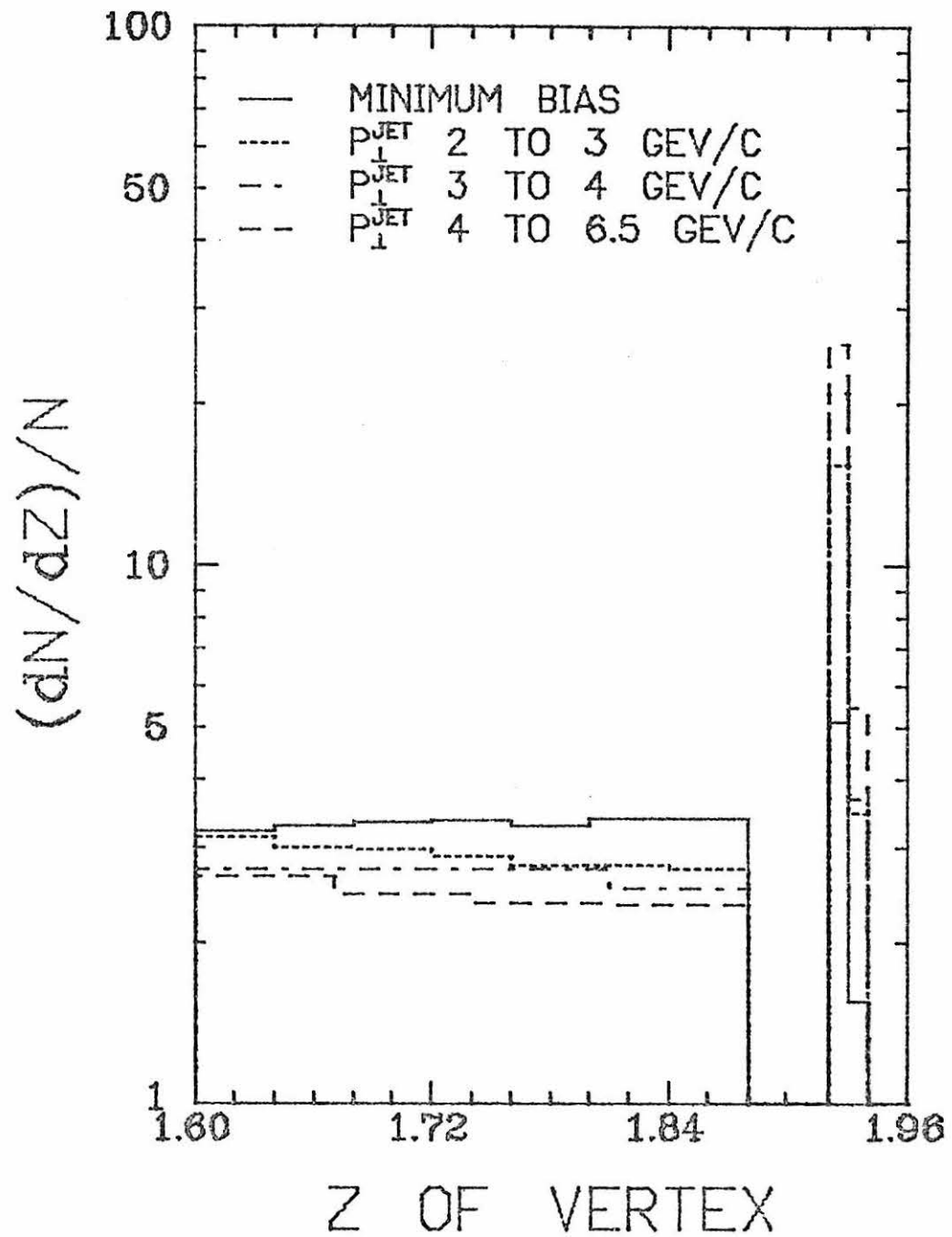


Figure 5.1b Vertex distribution for jet trigger.

π^+ BEAM JET

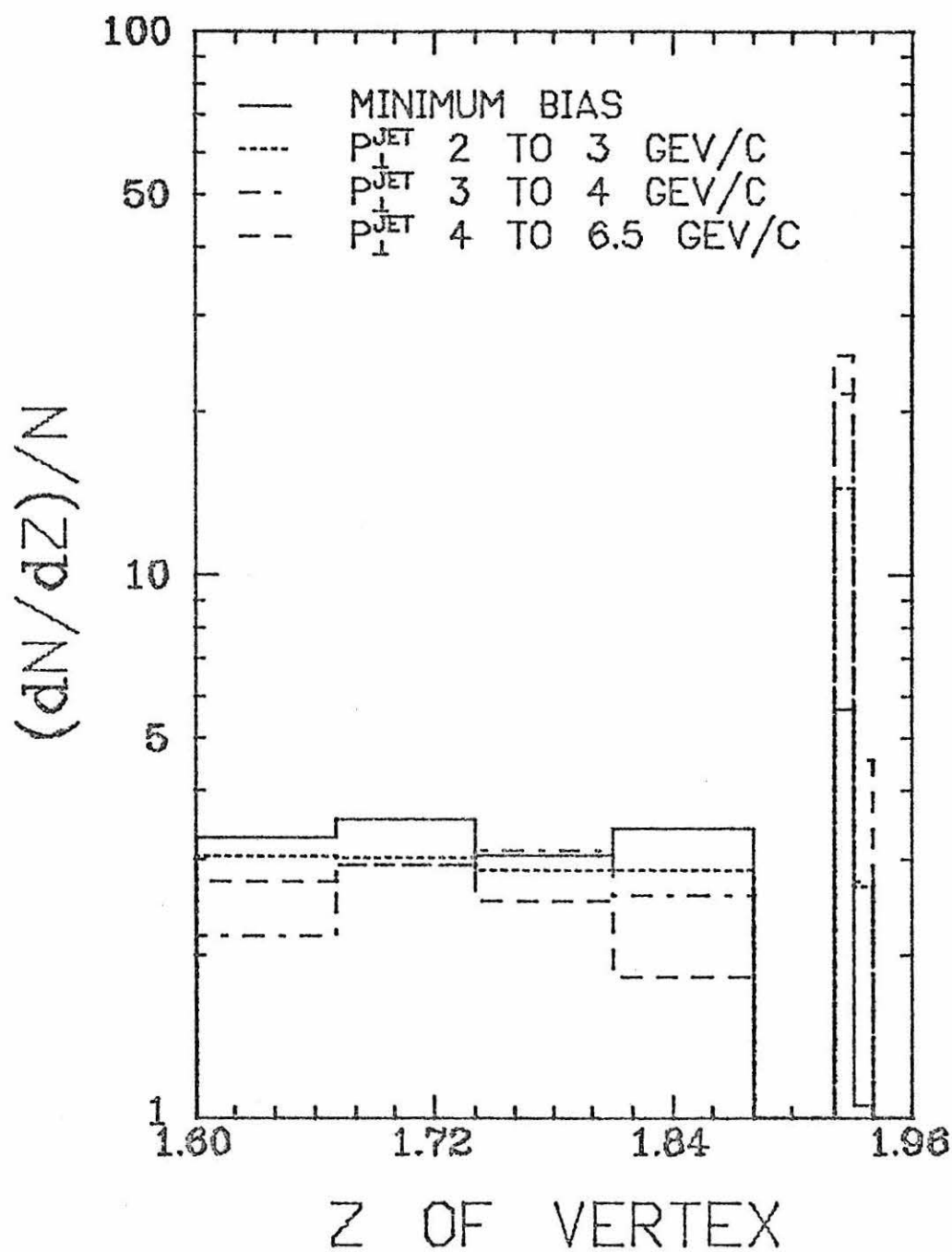


Figure 5.1c Vertex distribution for jet trigger.

π^- BEAM
 $6.5 \geq PT_{TRG} \geq 4$

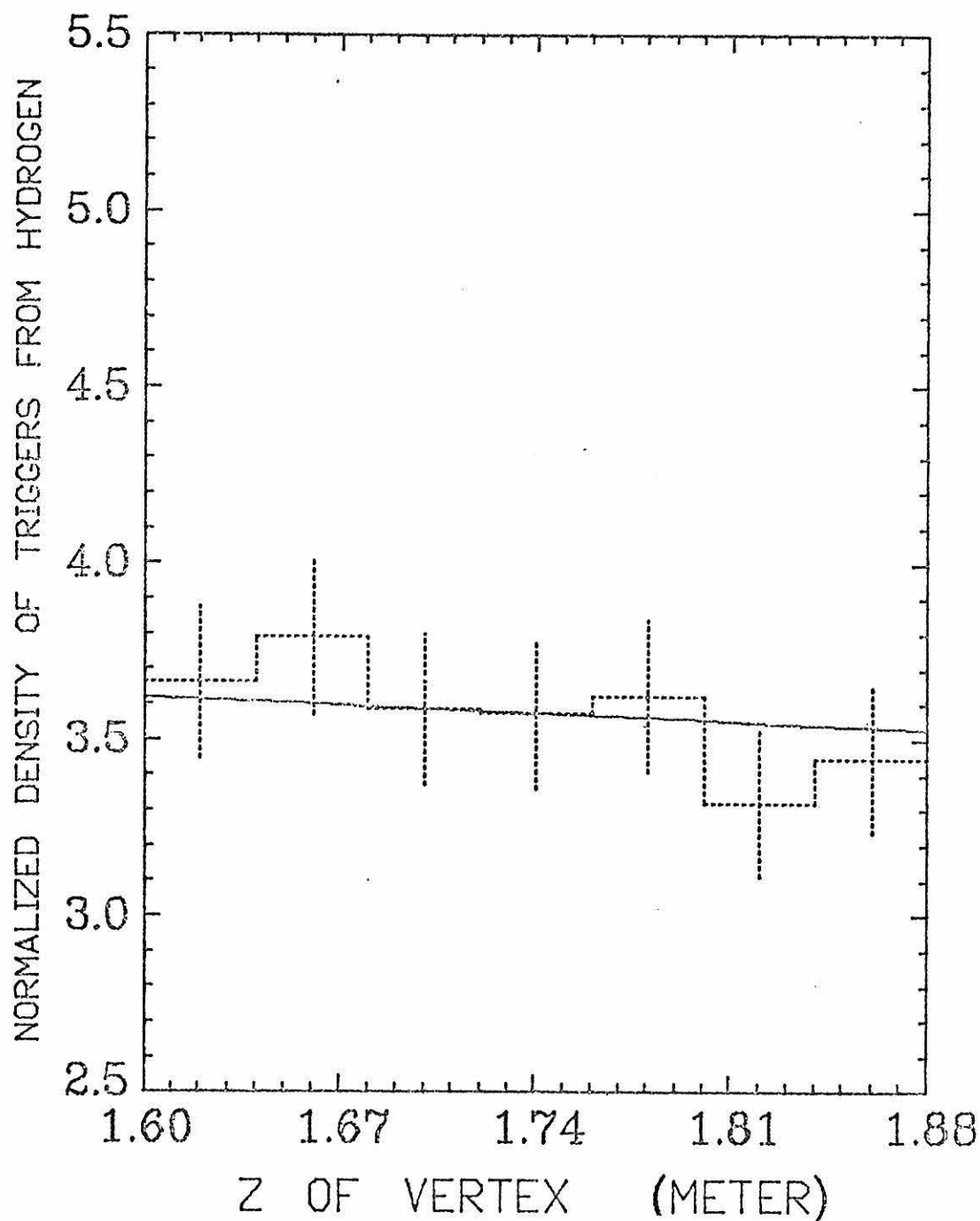
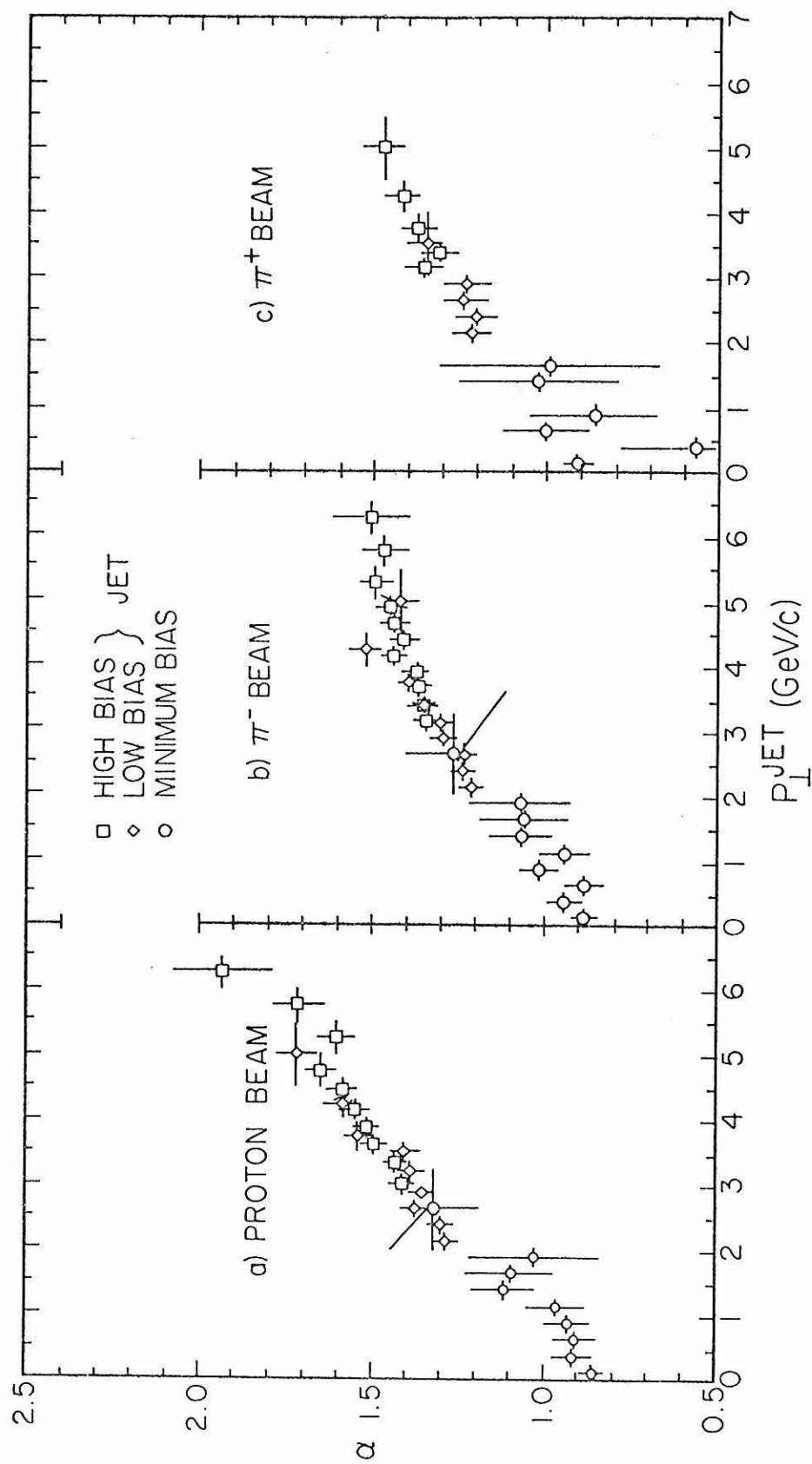
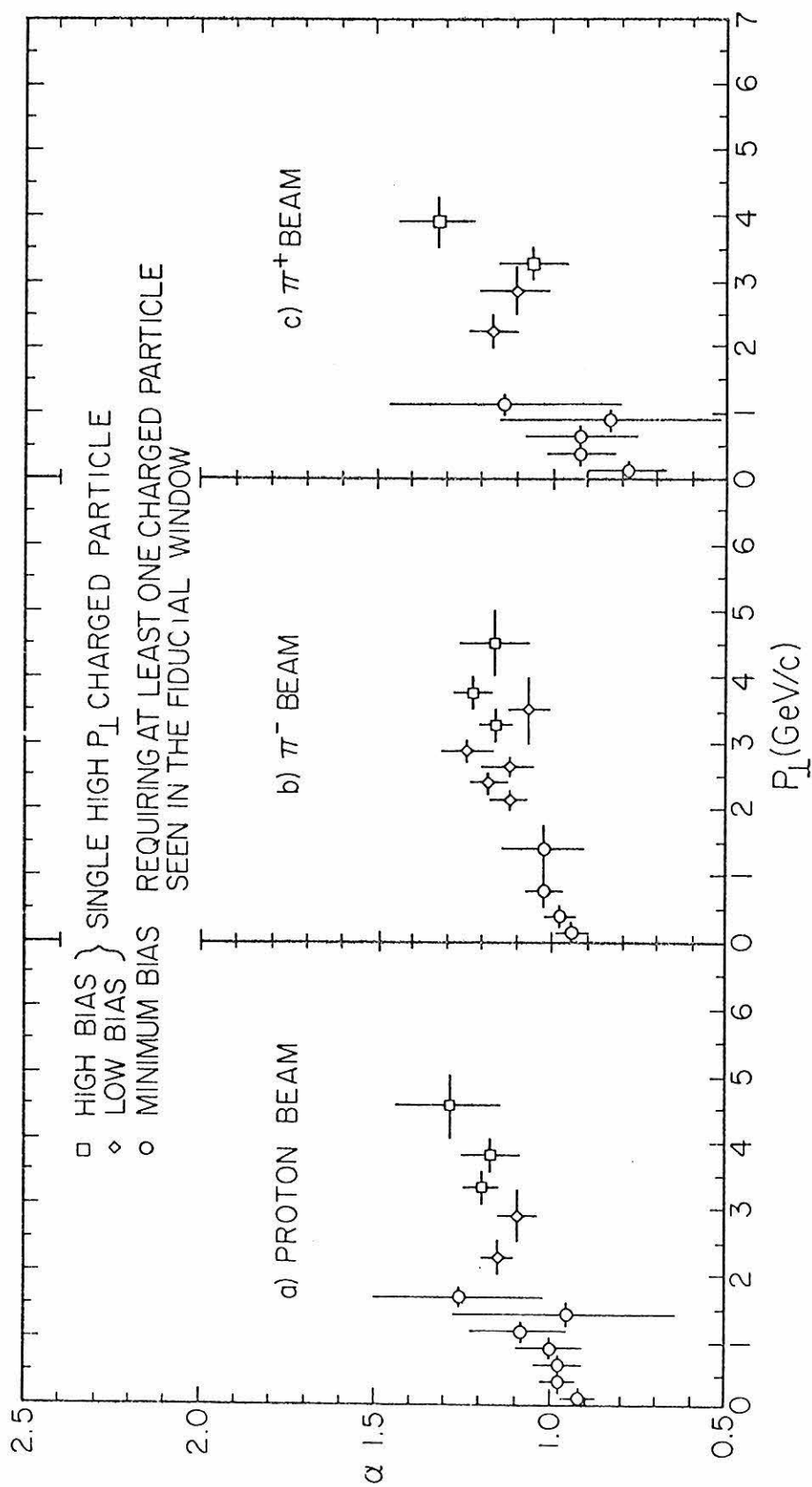
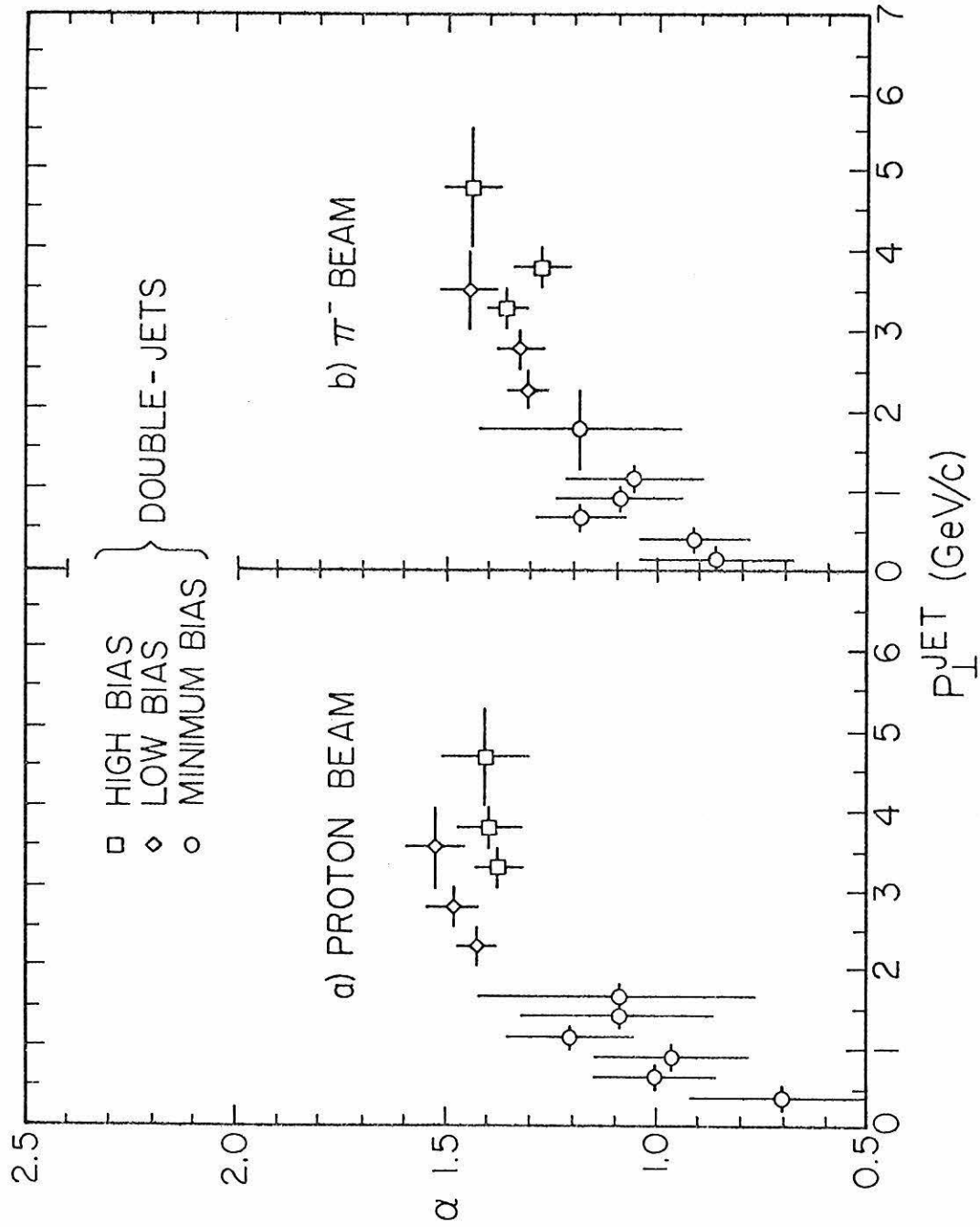


Figure 5.1d Vertex distribution for jets produced off Hydrogen by π^- . The curve is the expected beam attenuation calculated from π^- absorption cross section.

Figure 5.2a α vs. jet p_T for jets.

Figure 5.2b α vs. p_L for single charged particles.

Figure 5.2c α vs. jet p_T for double-jets.

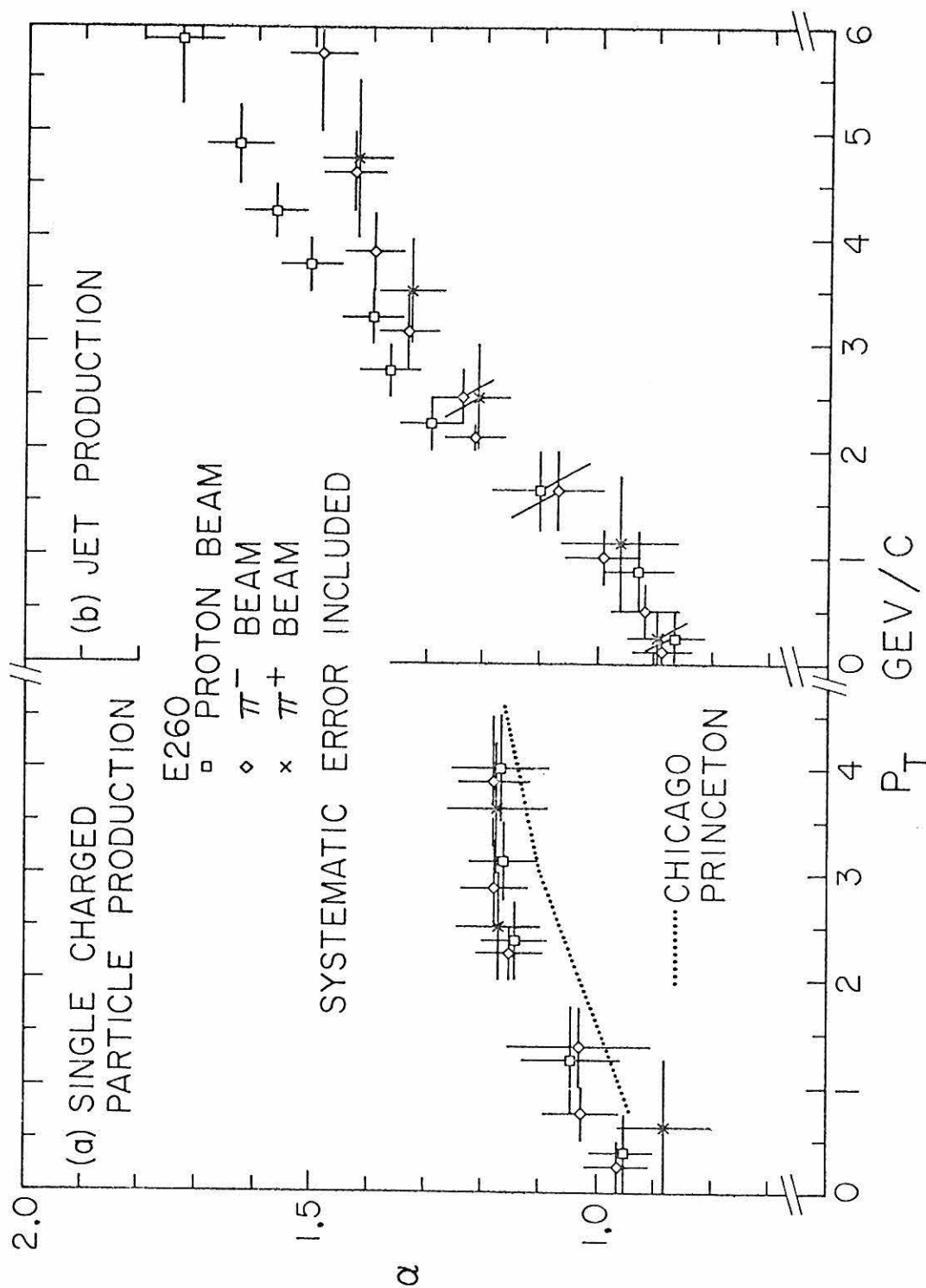


Figure 5.3 α vs. p_T for jet, single particle and minimum bias triggers. The curve marked CHICAGO PRINCETON comes from [1.15].

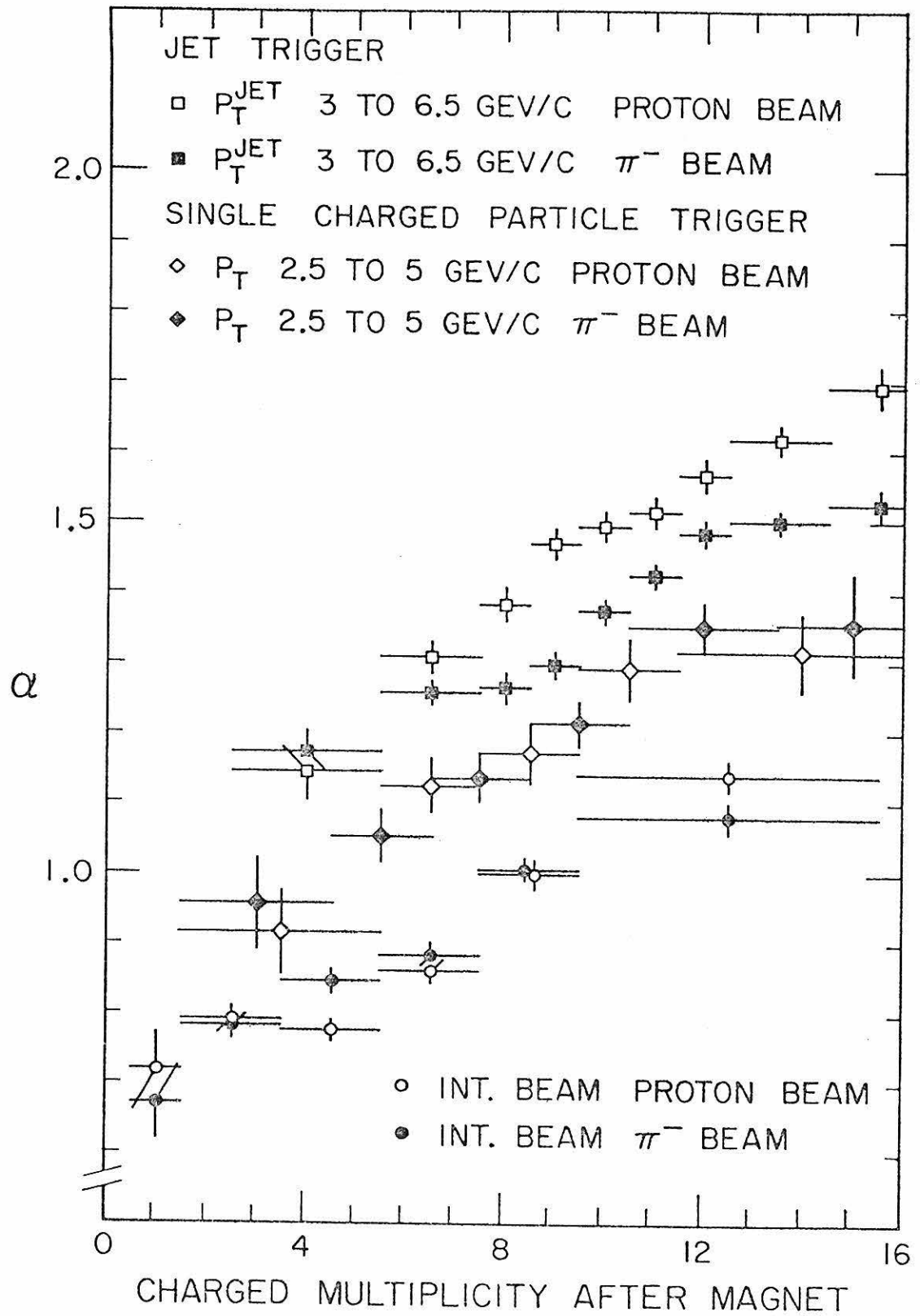


Figure 5.4 α vs. the total charged multiplicity seen after the magnet.

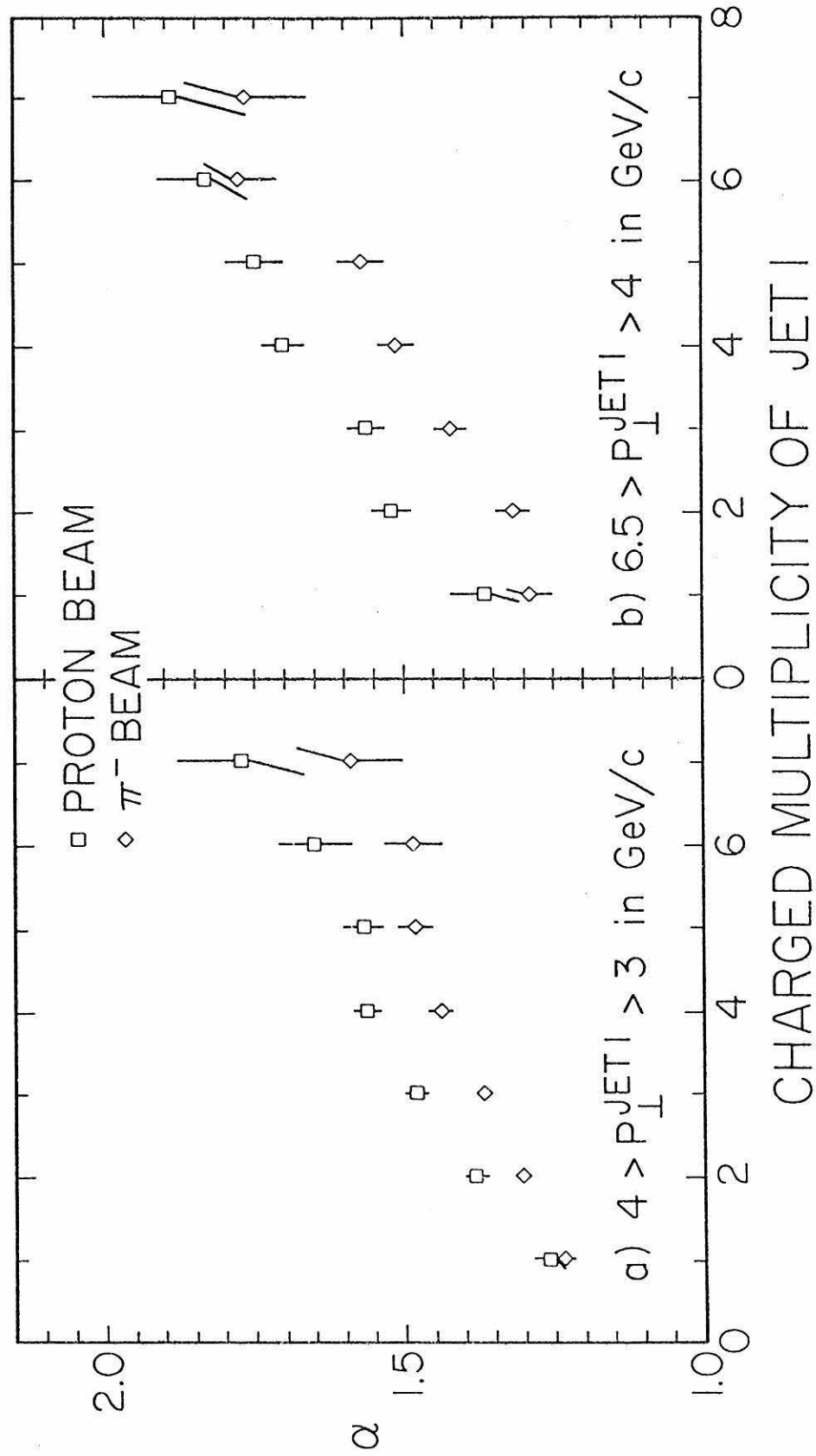


Figure 5.5 α versus multiplicity of charged particle in the jet.

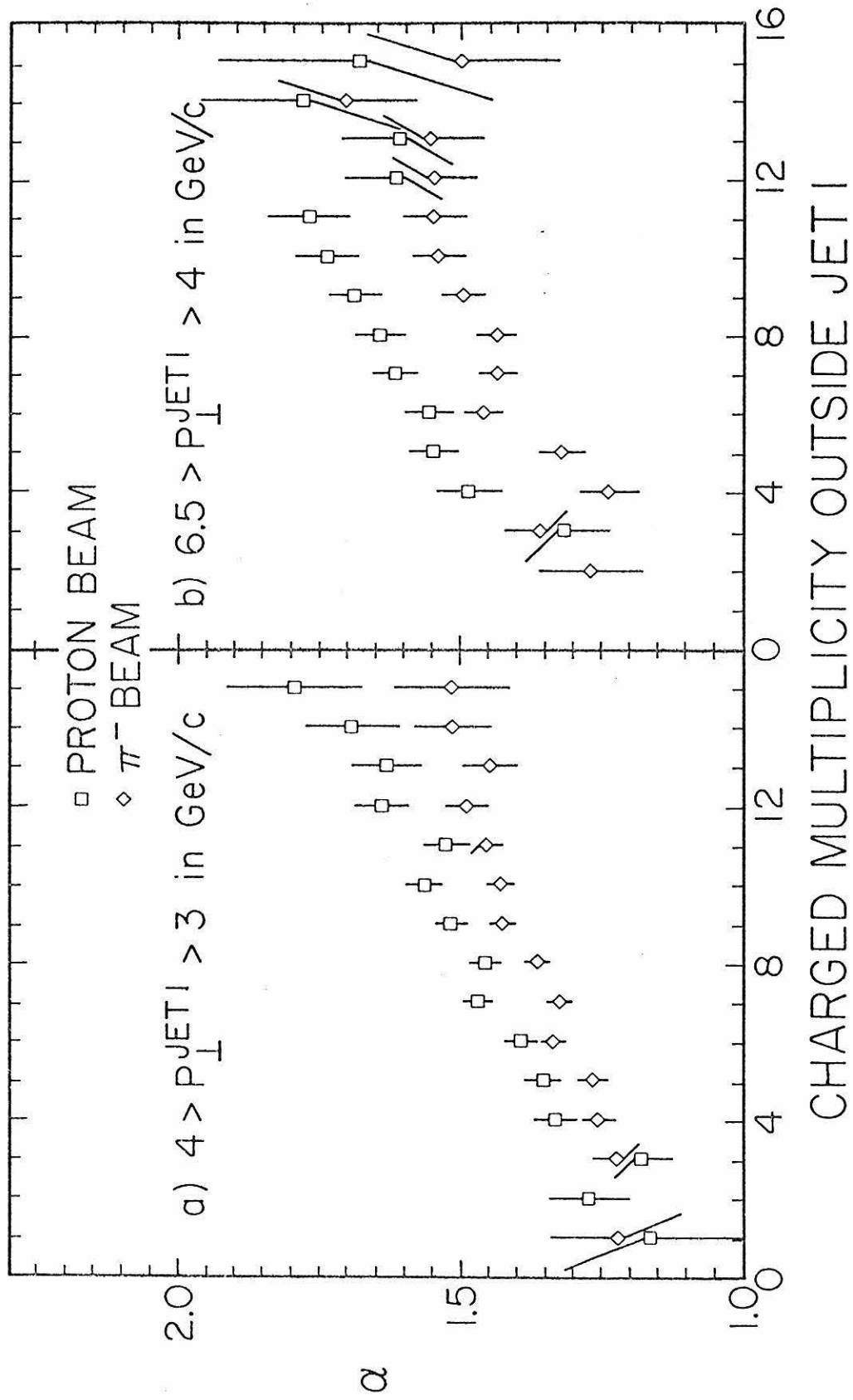
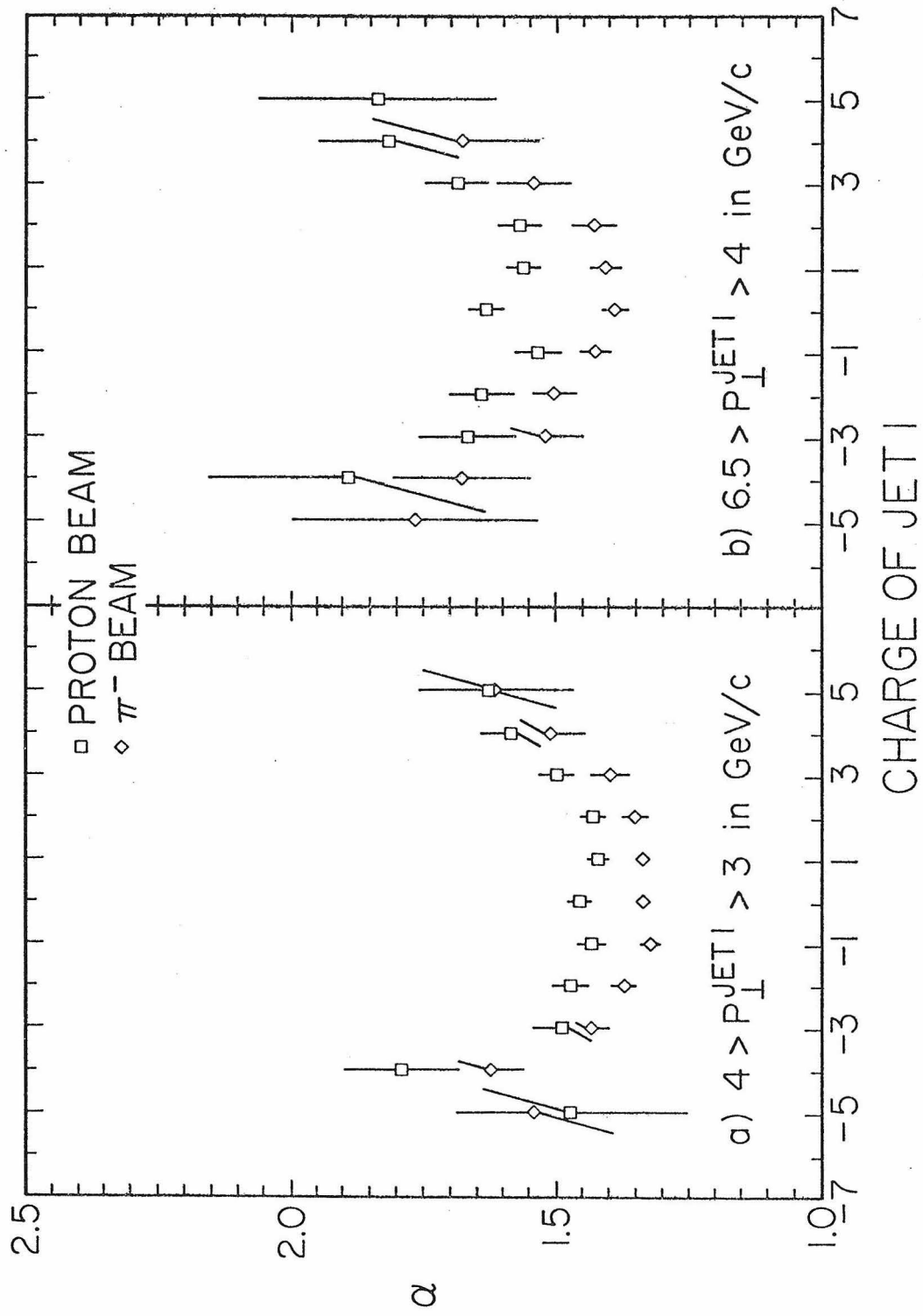


Figure 5.6 α versus charged multiplicity outside the jet.

Figure 5.7 α vs. charge of the jet

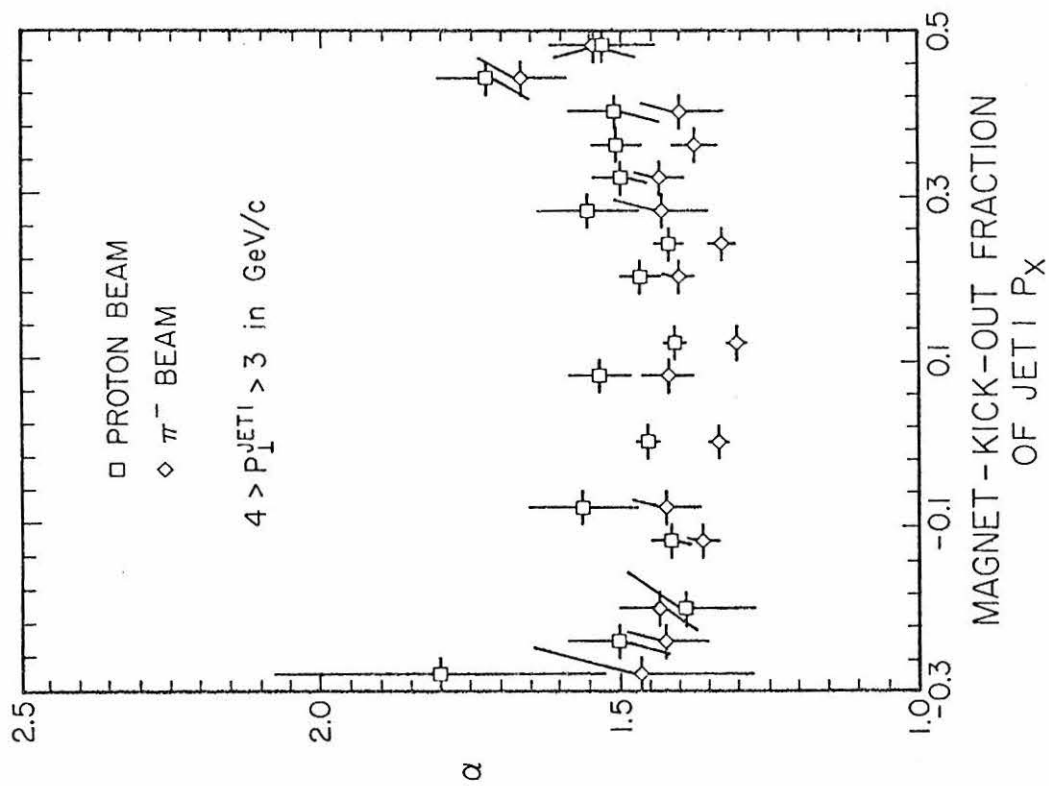


Figure 5.9 α versus f_{mk} , where f_{mk} is defined in the text.

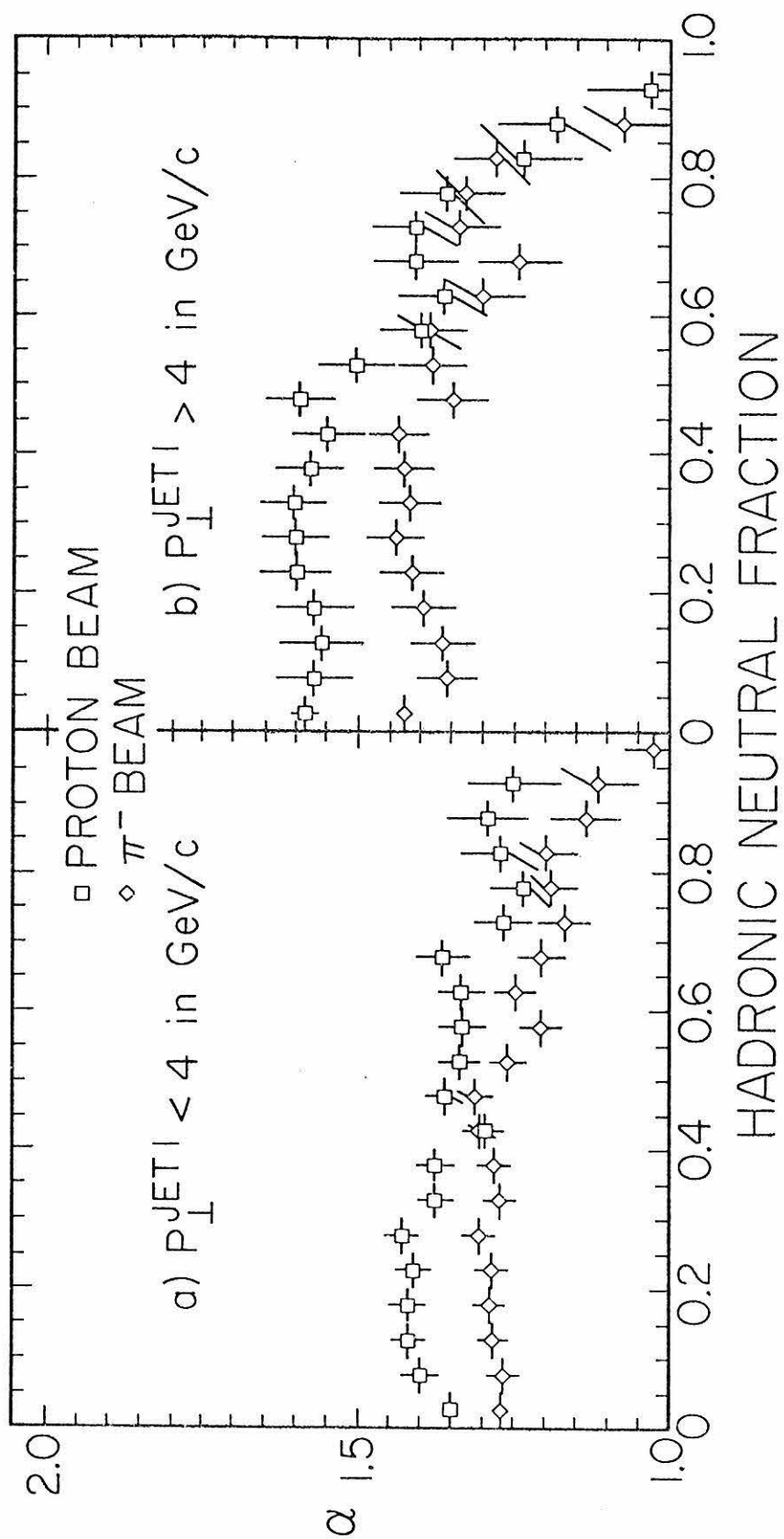


Figure 5.10 α vs. hadronic neutral fraction before any other cut.

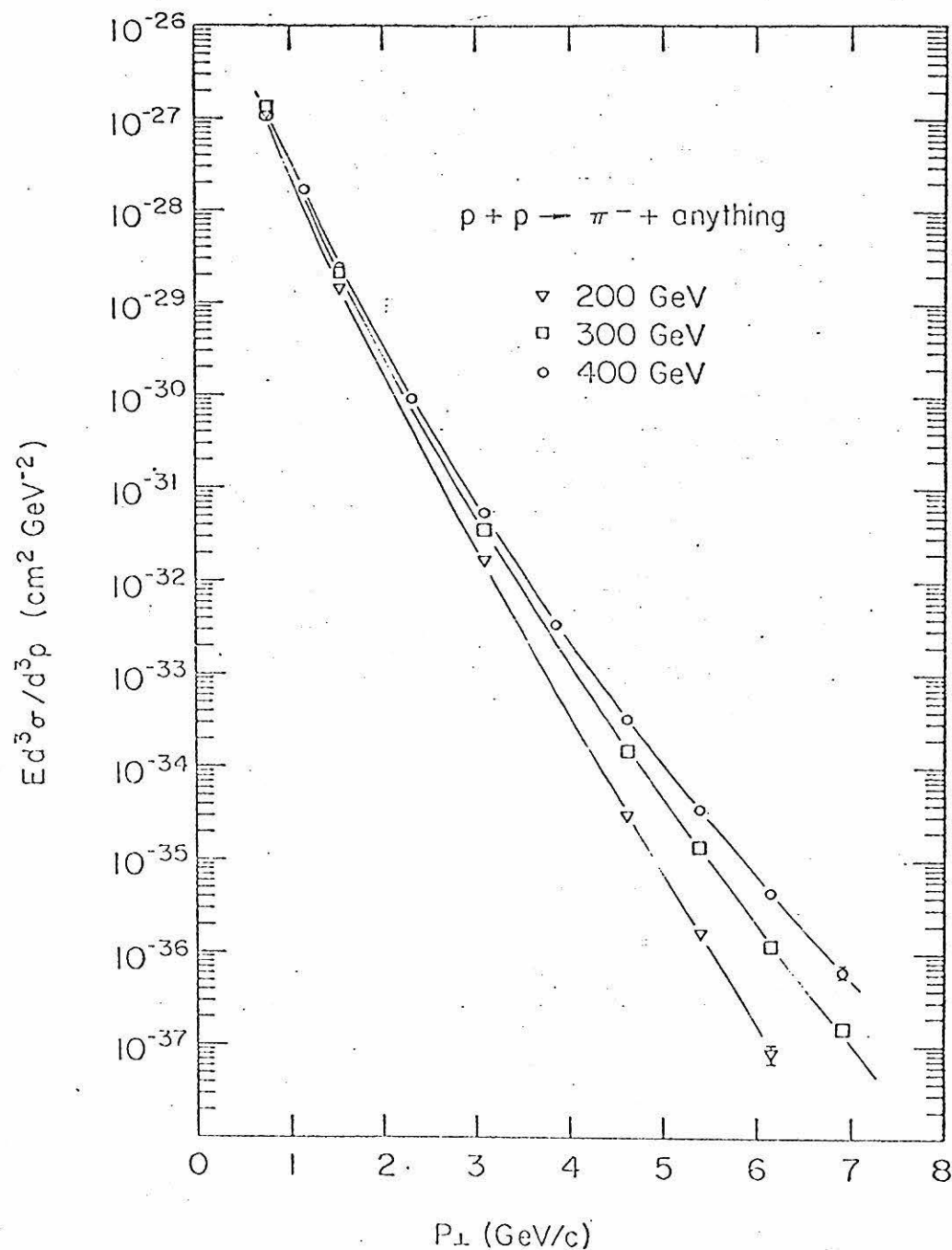


Figure 5.11a Data showing that the invariant cross section for π^- production increases with s at fixed $p_{\perp}$.

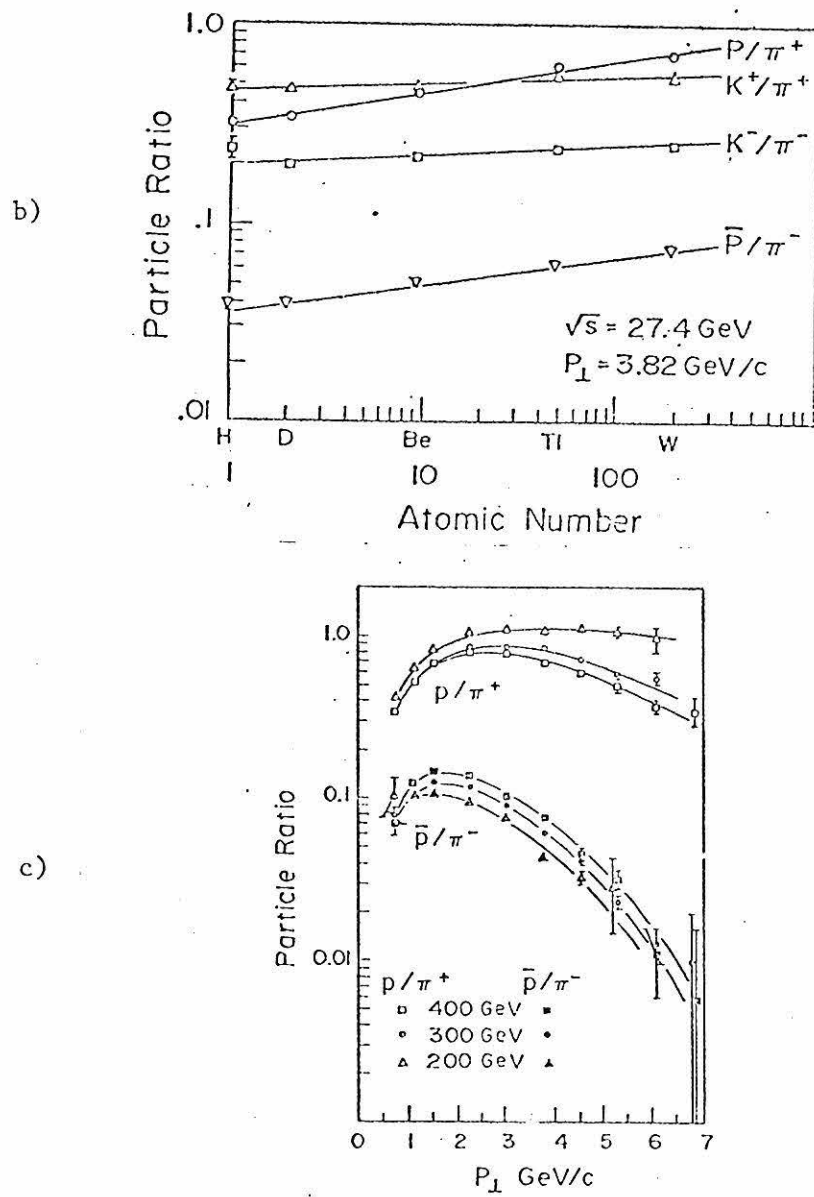


Figure 5.11

b) Data showing that p/π^+ ratio increases with A .

c) Data showing that p/π^+ ratio decreases with s .

All data (a to c) come from Ref. [1.15].

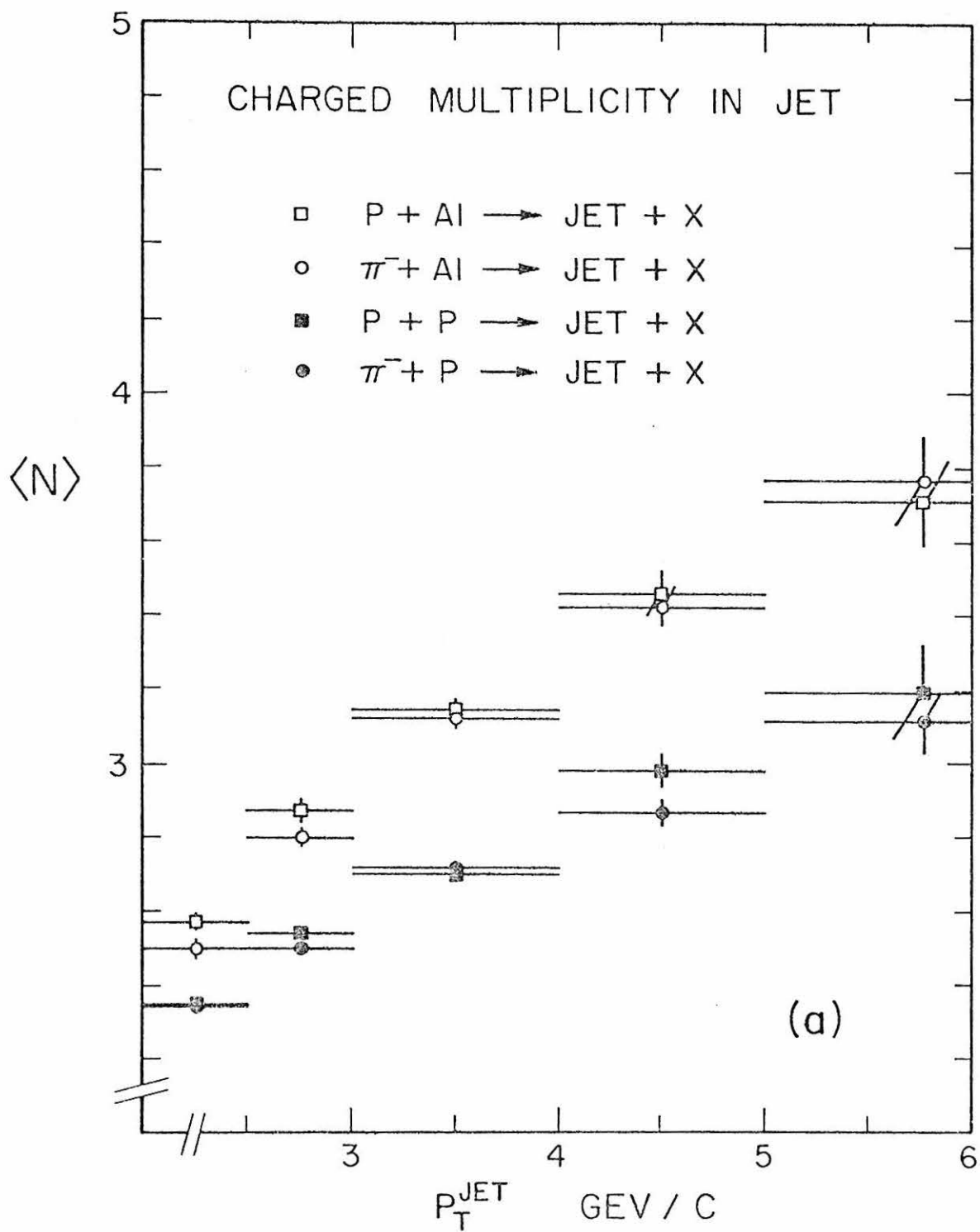


Figure 5.12 Charged multiplicity in the jet vs. jet $p_{\perp}$ for aluminium and hydrogen targets; p and π^- beams.

Figure 6.1 Multiplicity density function $D(\theta_{xz})$ of the associated charged particles with energy greater than 0.5 Gev in the C. M. Jet Frame (defined in section 6.1). These plots do not have any acceptance correction.

PROTON HY
ALL CHARGES $E_Q > .5$

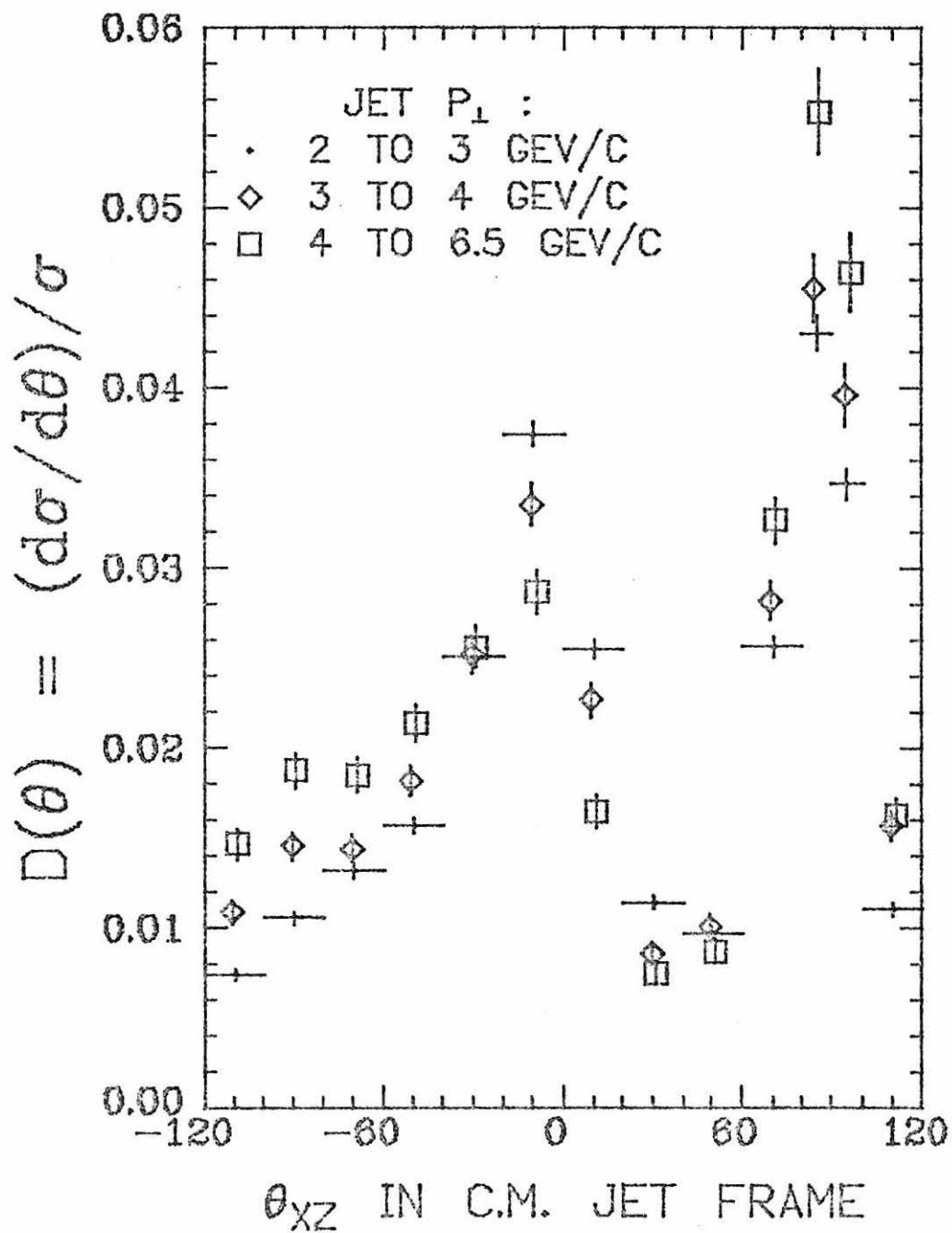


Figure 6.1a Proton beam, hydrogen target.

PROTON AL ALL CHARGES $E_Q > .5$

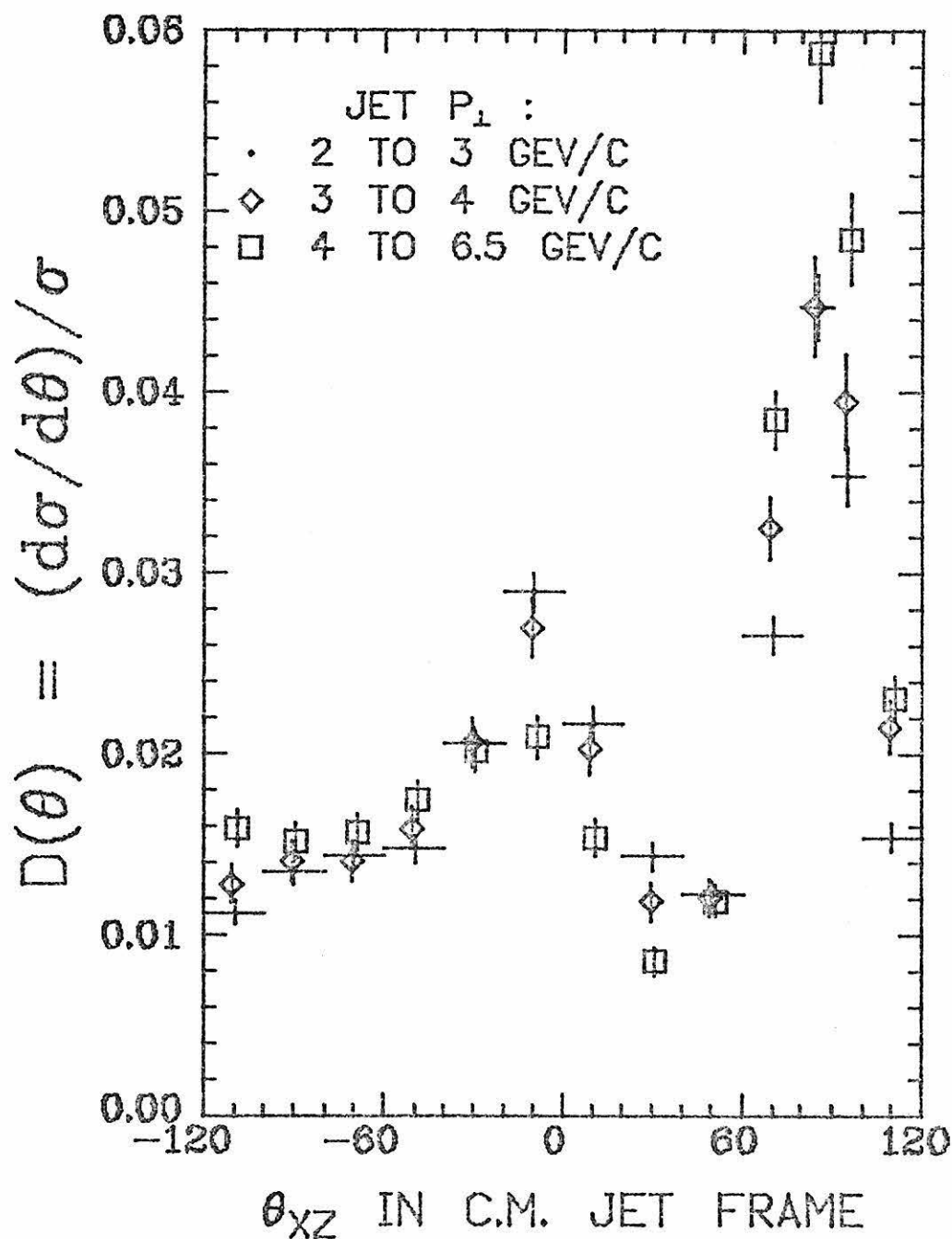


Figure 6.1b Proton beam, aluminium target.

π^+ HY
ALL CHARGES $E_Q > .5$

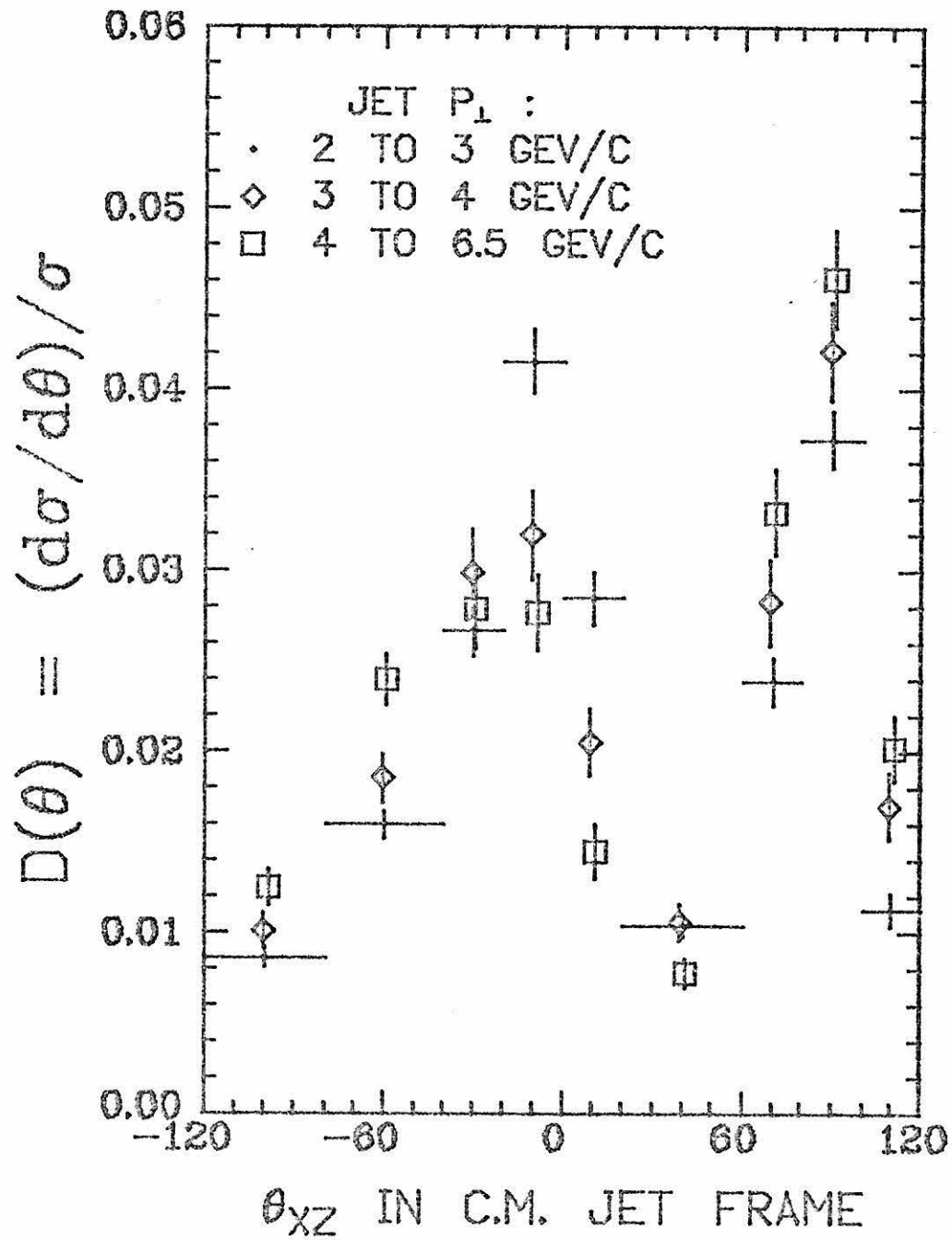


Figure 6.1c π^+ beam, hydrogen target.

π^+ AL
ALL CHARGES $E_Q > .5$

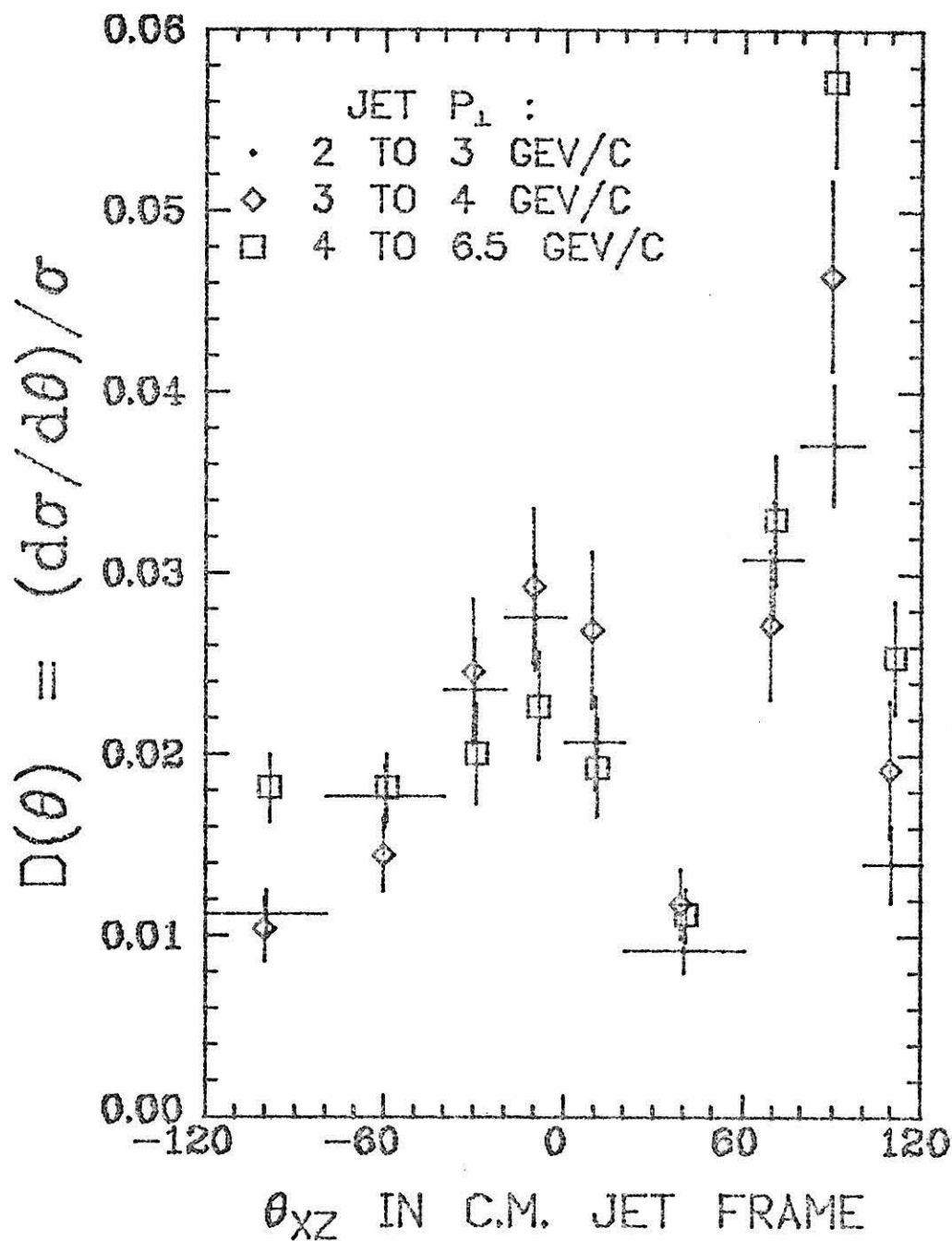


Figure 6.1d π^+ beam, aluminium target.

π^- HY
ALL CHARGES $E_Q > .5$

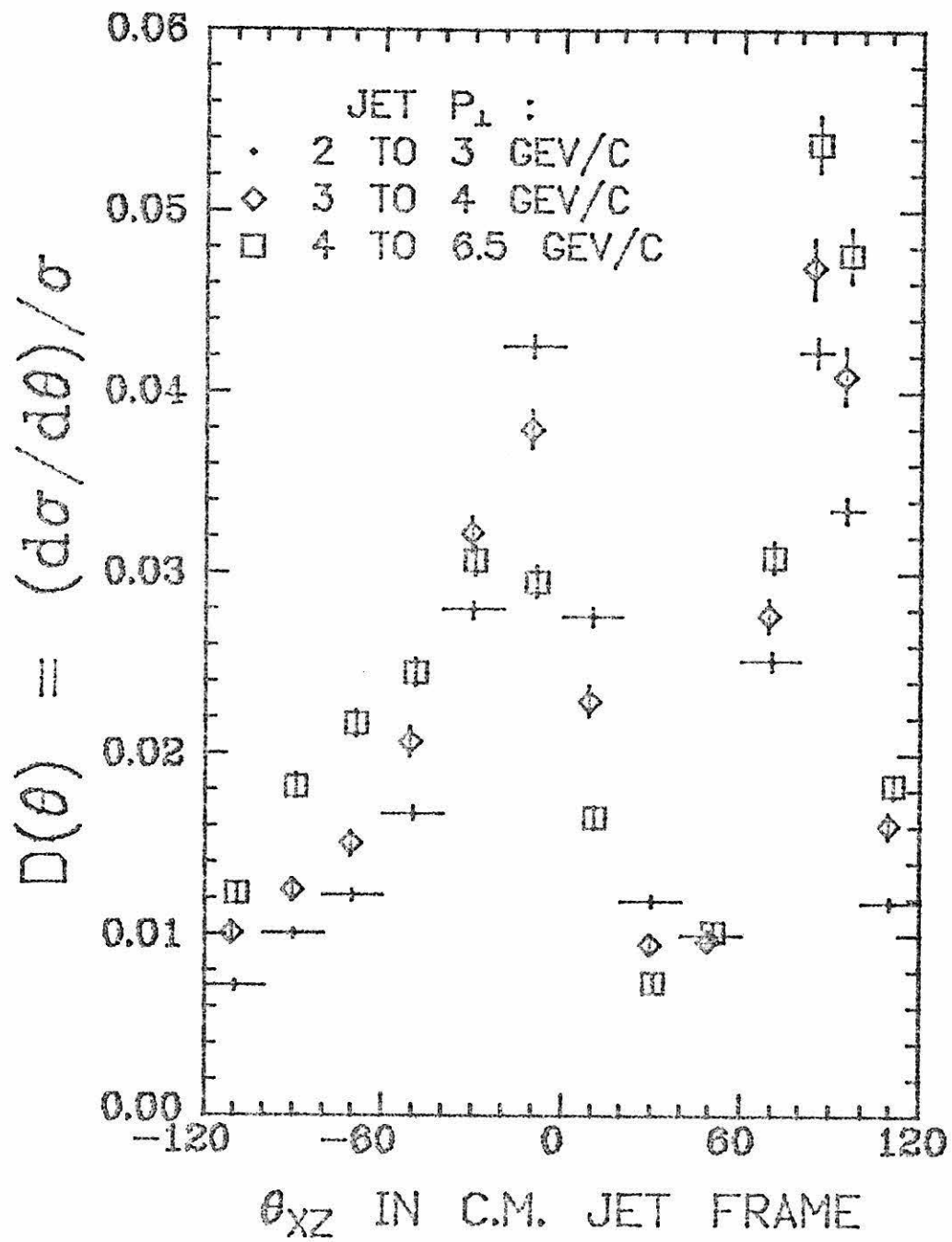


Figure 6.1e π^- beam, hydrogen target.

π^- AL
ALL CHARGES $E_Q > .5$

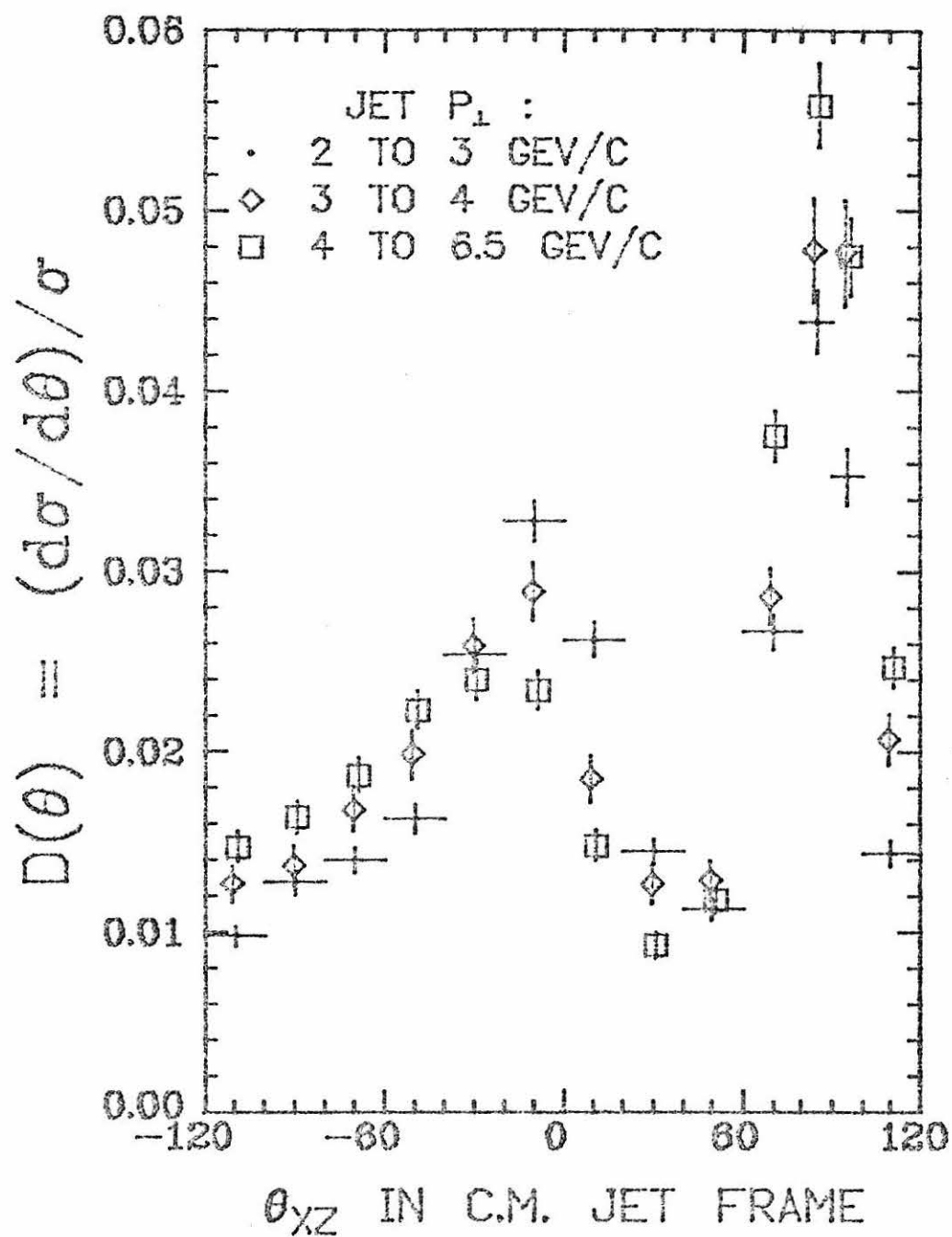


Figure 6.1f π^- beam, aluminium target.

PROTON BEAM

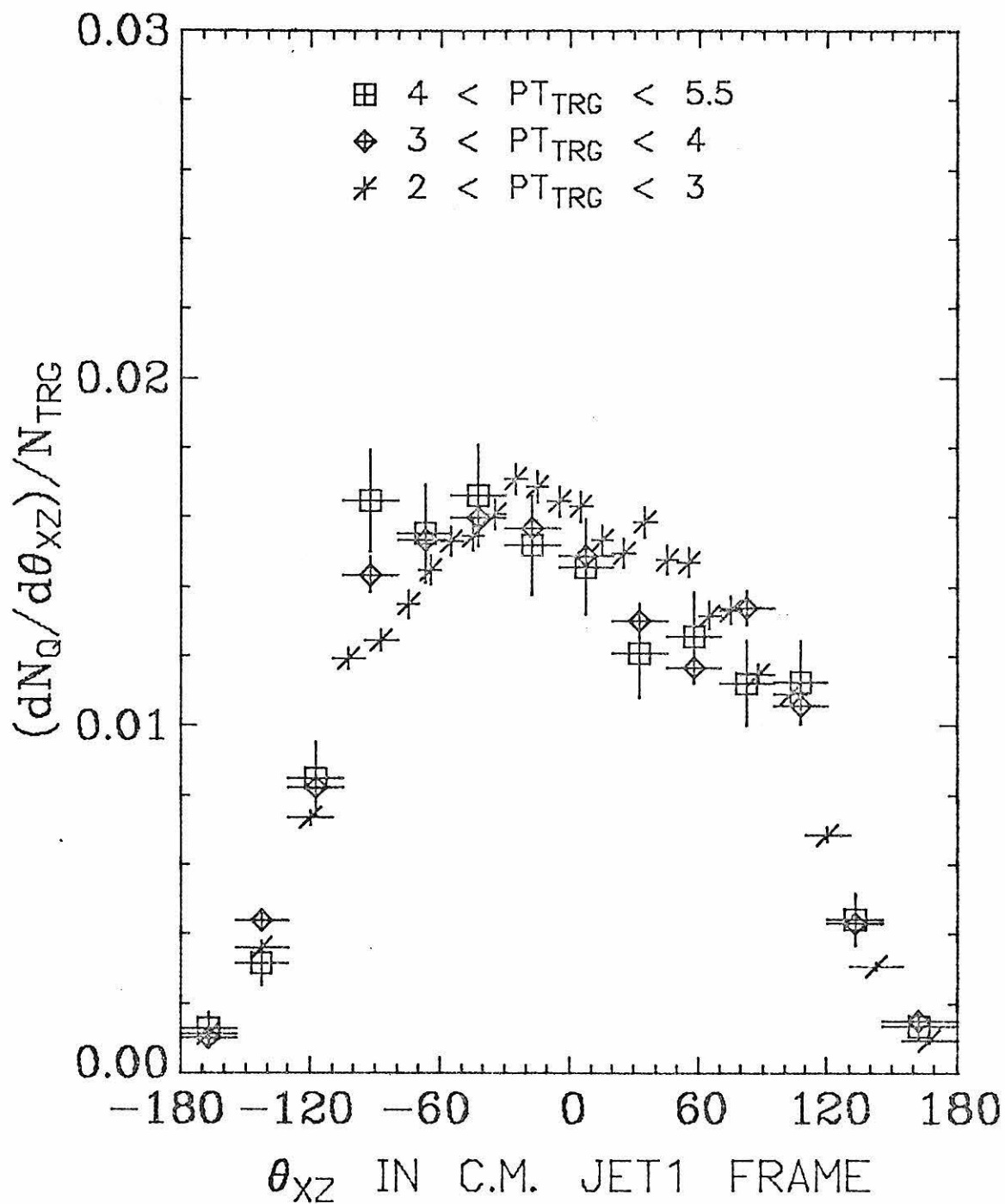
 $0 < E_Q < 0.5$ 

Figure 6.2 $D(\theta_{XZ})$ for lower energy particles ($E < 0.5$).

Figure 6.3 This $D(\theta_{xz})$ plot is similar to those in Figure 6.1, only that the data used here are Monte Carlo simulations. Our M.C. program uses the FFF model [1.6].

MCDATA PROTON ALL CHARGES $E_Q > .5$

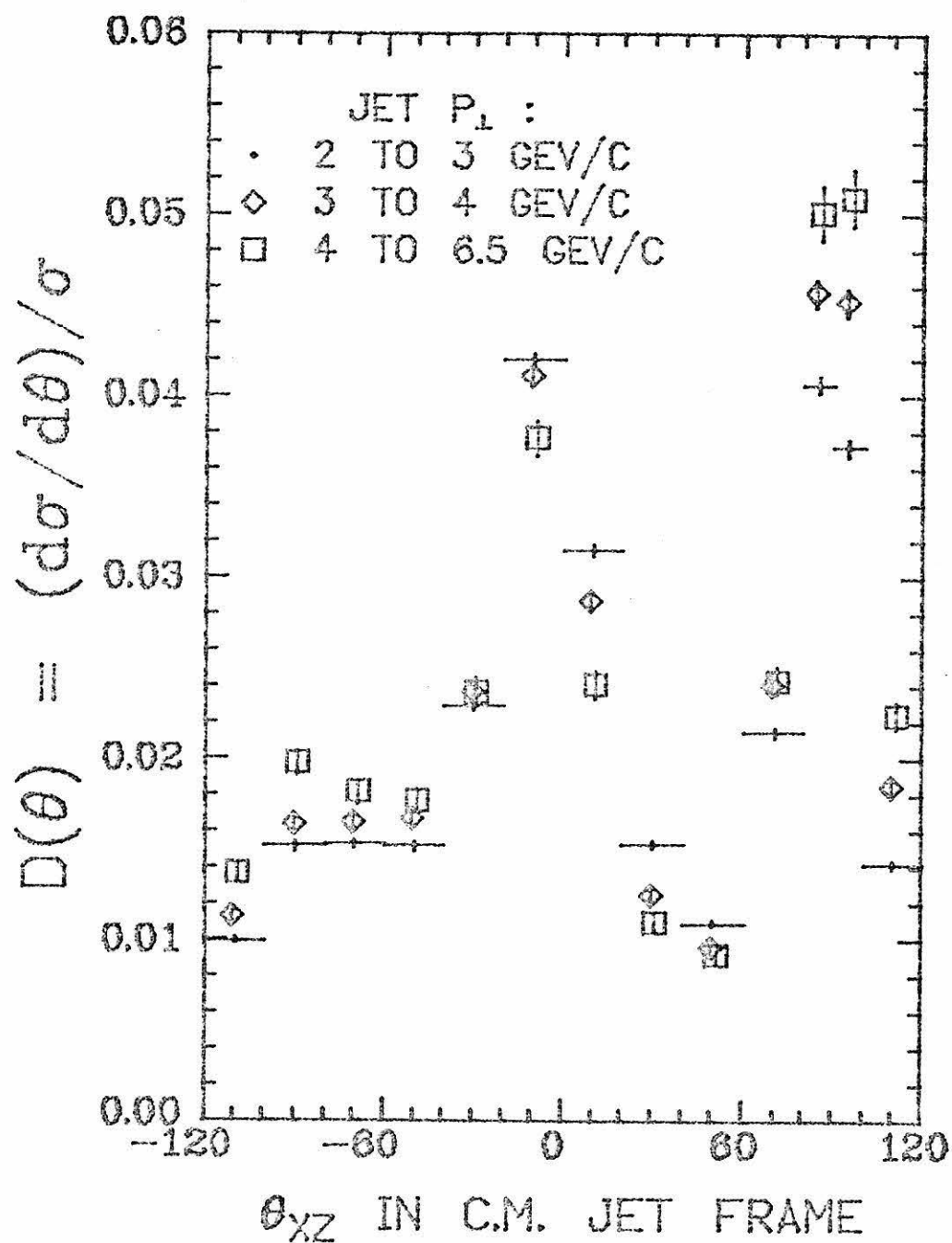


Figure 6.3

Particle density in the spatial X-Y space
(at the $\bar{z}$ position of 2X2) before and after
cuts. The square box shown in the figure
is where the 2 X 2 is.

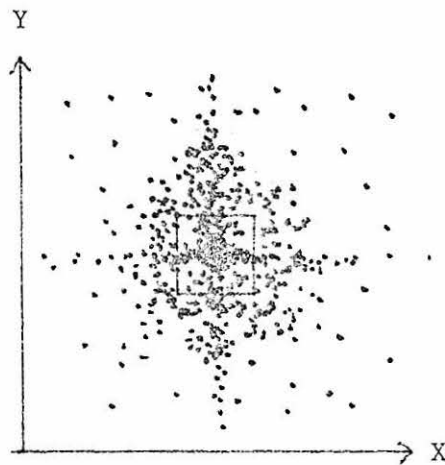


Figure 6.4a Before any cut.

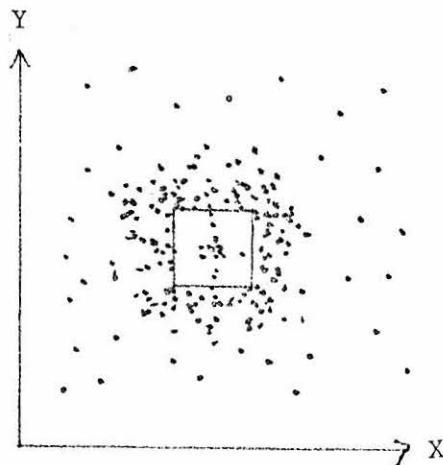


Figure 6.4b After some PWC quality cuts.

Figure 6.4c,d The ratio of the deleted particle over the accepted particle as a function of Θ_{xz} from the Monte Carlo data.

M.C.DATA PP→4JETS
POSITIVELY CHARGED

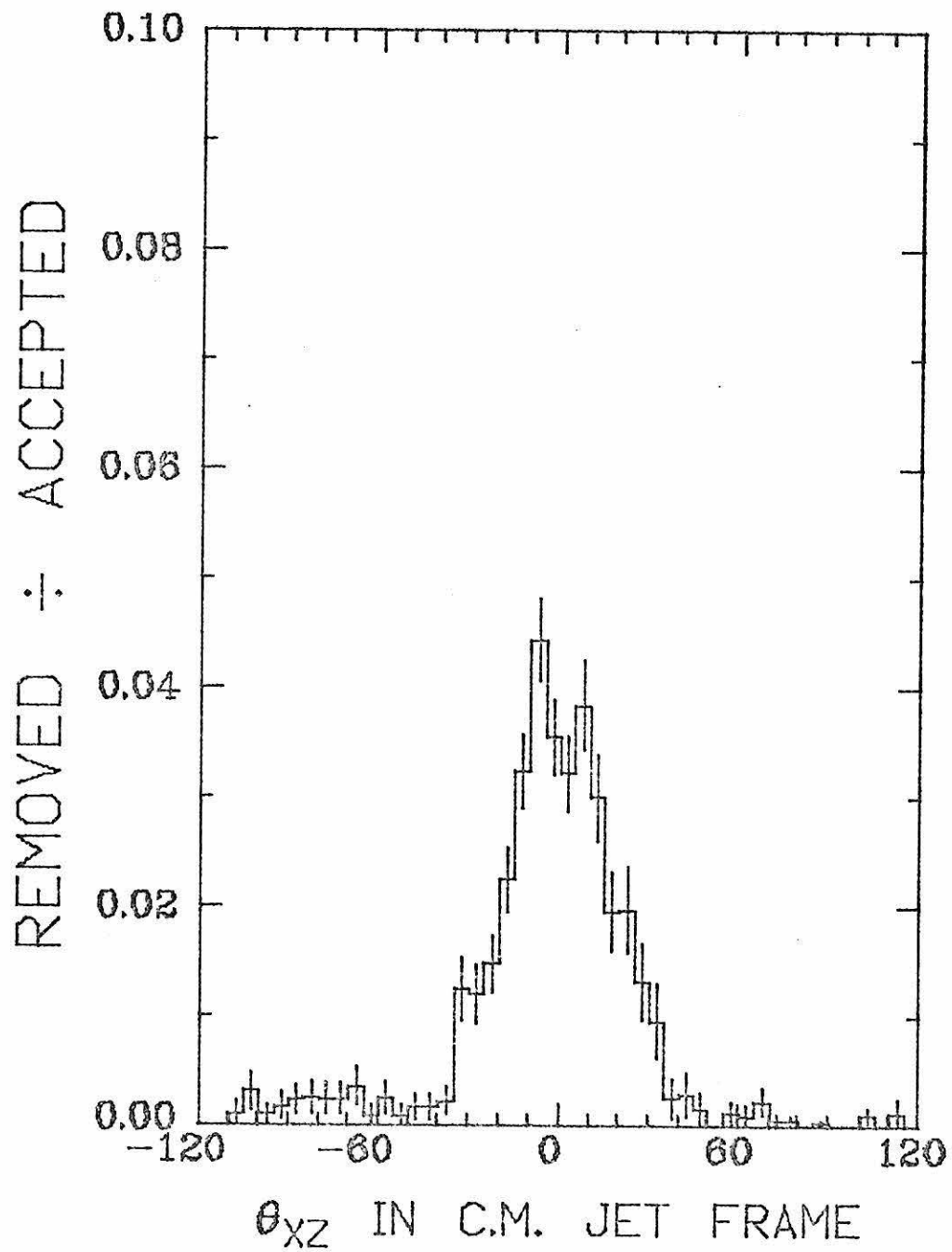


Figure 6.4c

M.C.DATA PP→4JETS
NEGATIVELY CHARGED

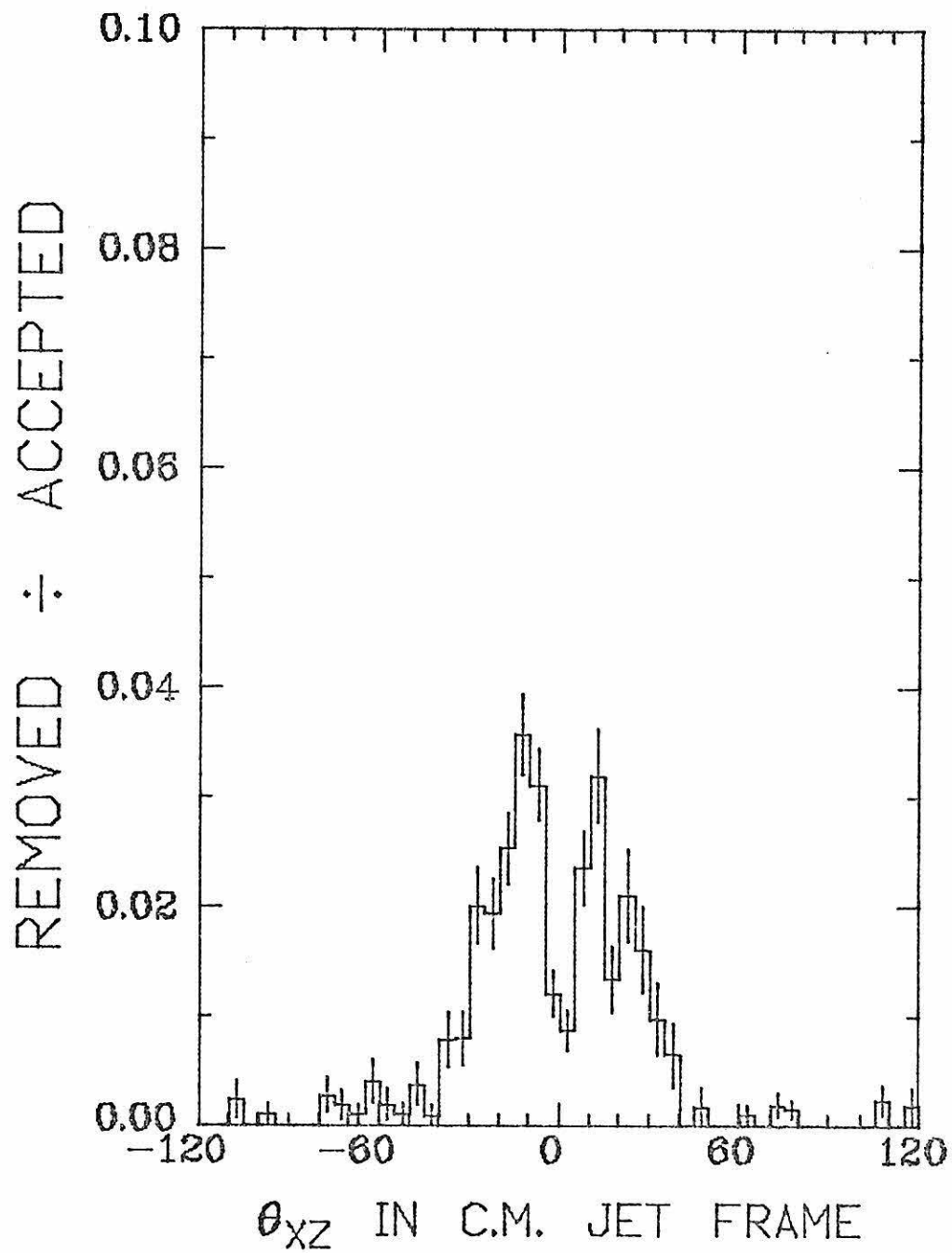


Figure 6.4d

Figure 6.6 The number of positively charged particles over the number of negatively charged particles as a function of θ_{xz} for three values of Q_{JET} . Q_{JET} is defined in the text (section 6.3). Only particles with $E > 0.5$ are included.

PROTON HY $E_p > .5$
HIJT $P_{\perp}^{\text{JET}} 2 \text{ TO } 6.5 \text{ GEV/C}$

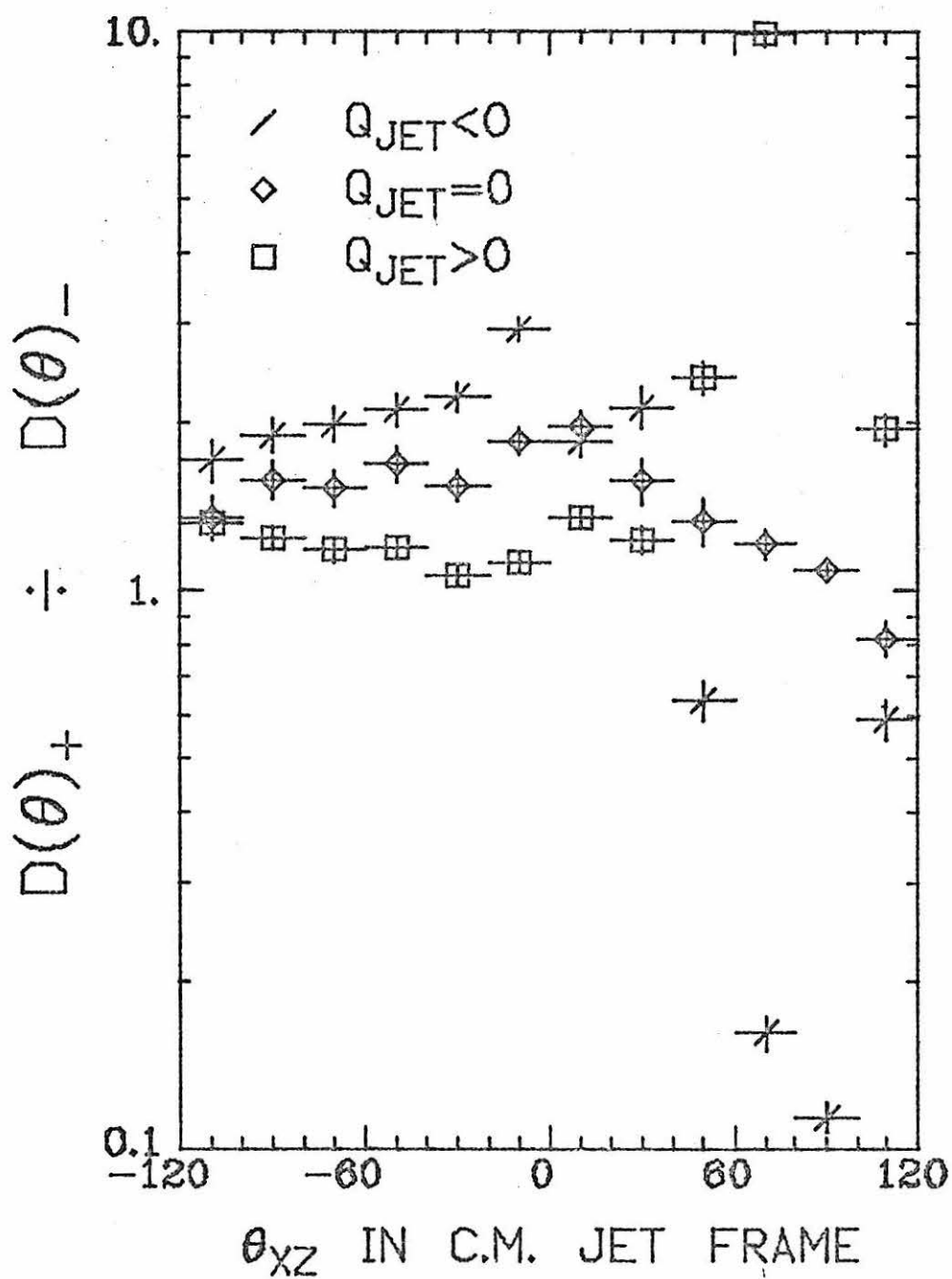


Figure 6.6a Proton beam, hydrogen target.

PROTON AL $E_a > .5$
HIJT P_1^{JET} 2 TO 6.5 GEV/C

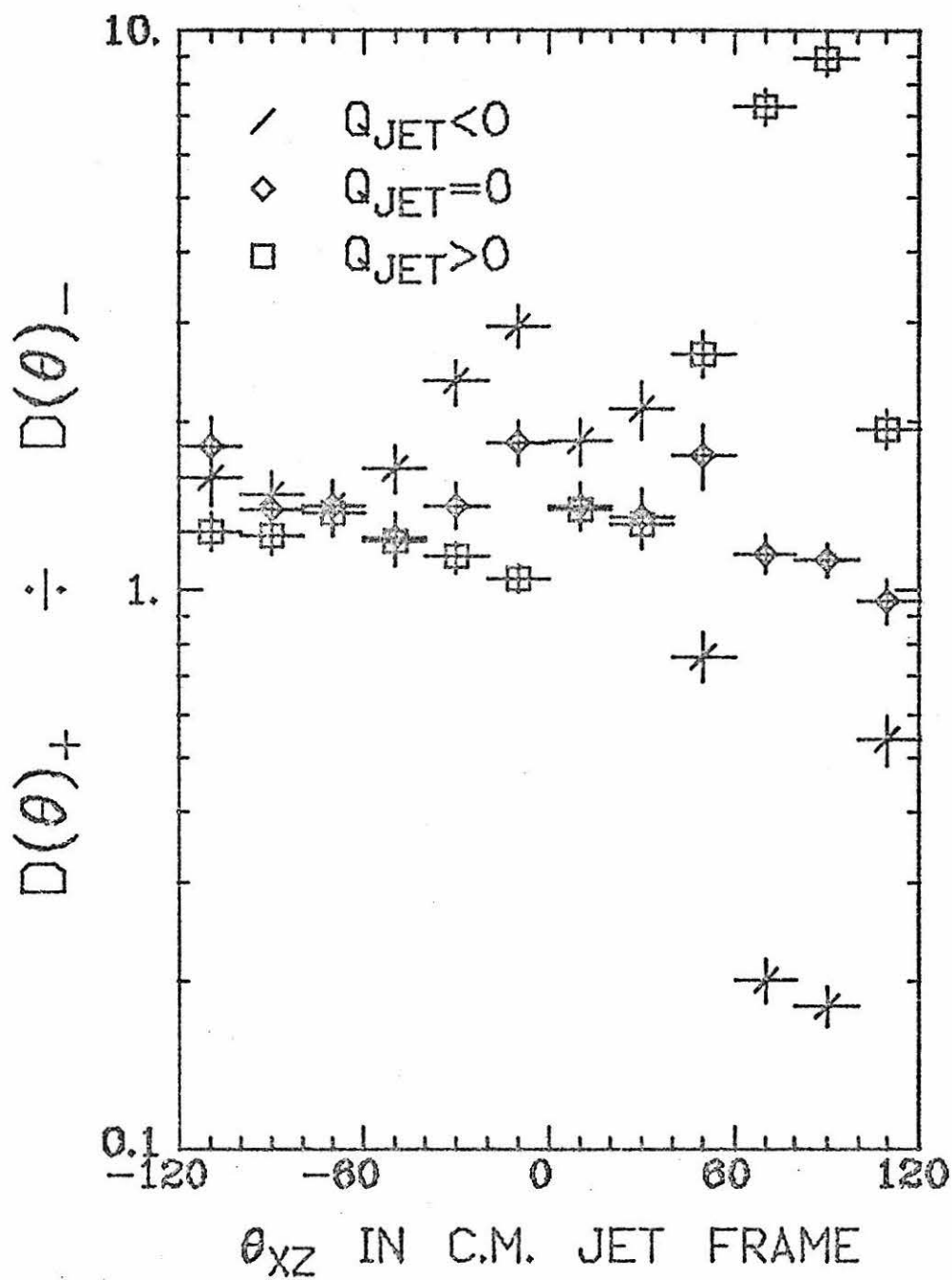


Figure 6.6b Proton beam, aluminium target.

HIJT π^+ HY $E_0 > 5$
 $P_{\perp}^{\text{JET}}$ 2 TO 6.5 GEV/C

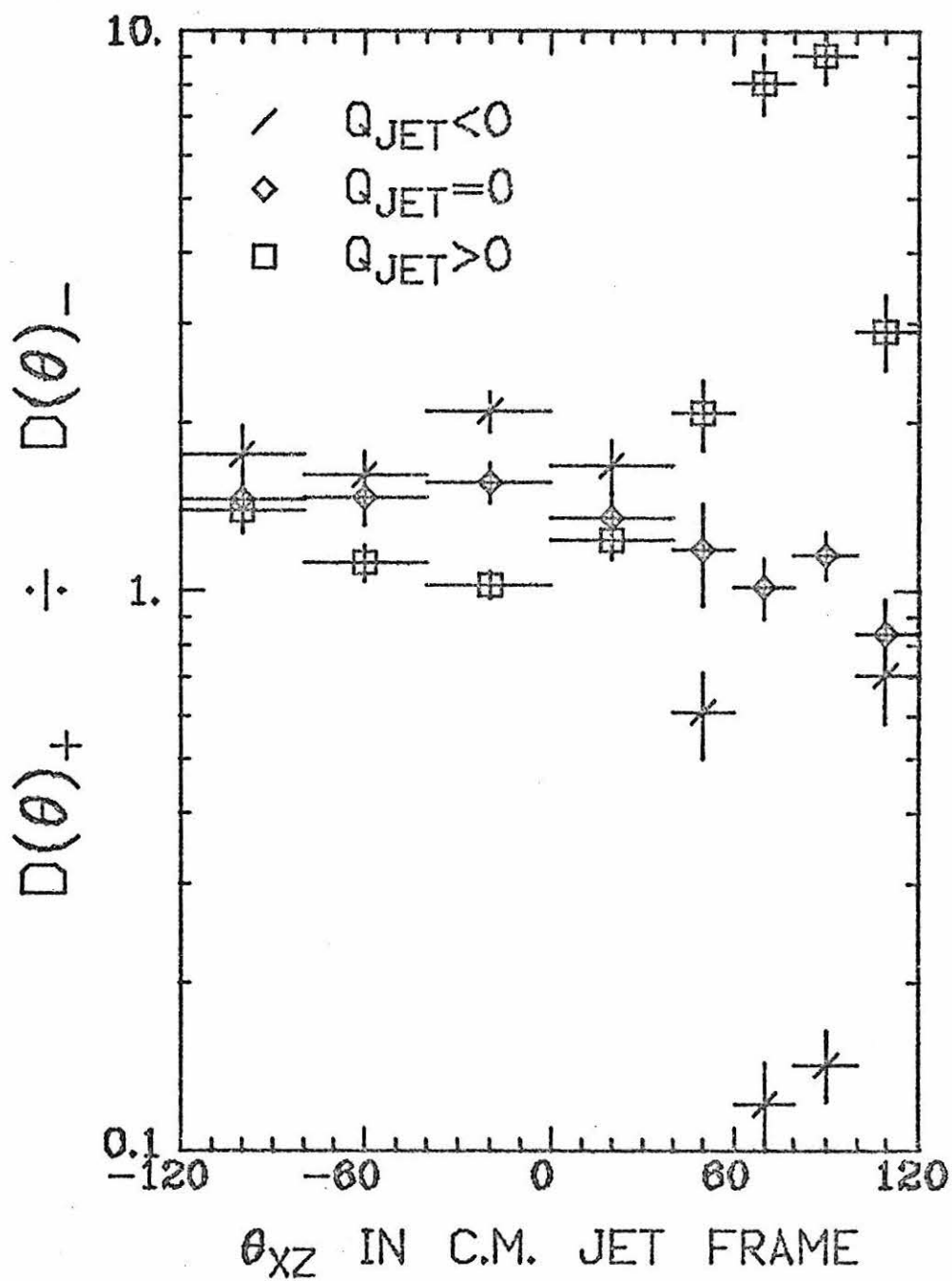


Figure 6.6c π^+ beam, hydrogen target.

HIJT π^+ AL $E_0 > 5$
 $P_{\text{JET}}^{\text{JET}} 2$ TO 6.5 GEV/C

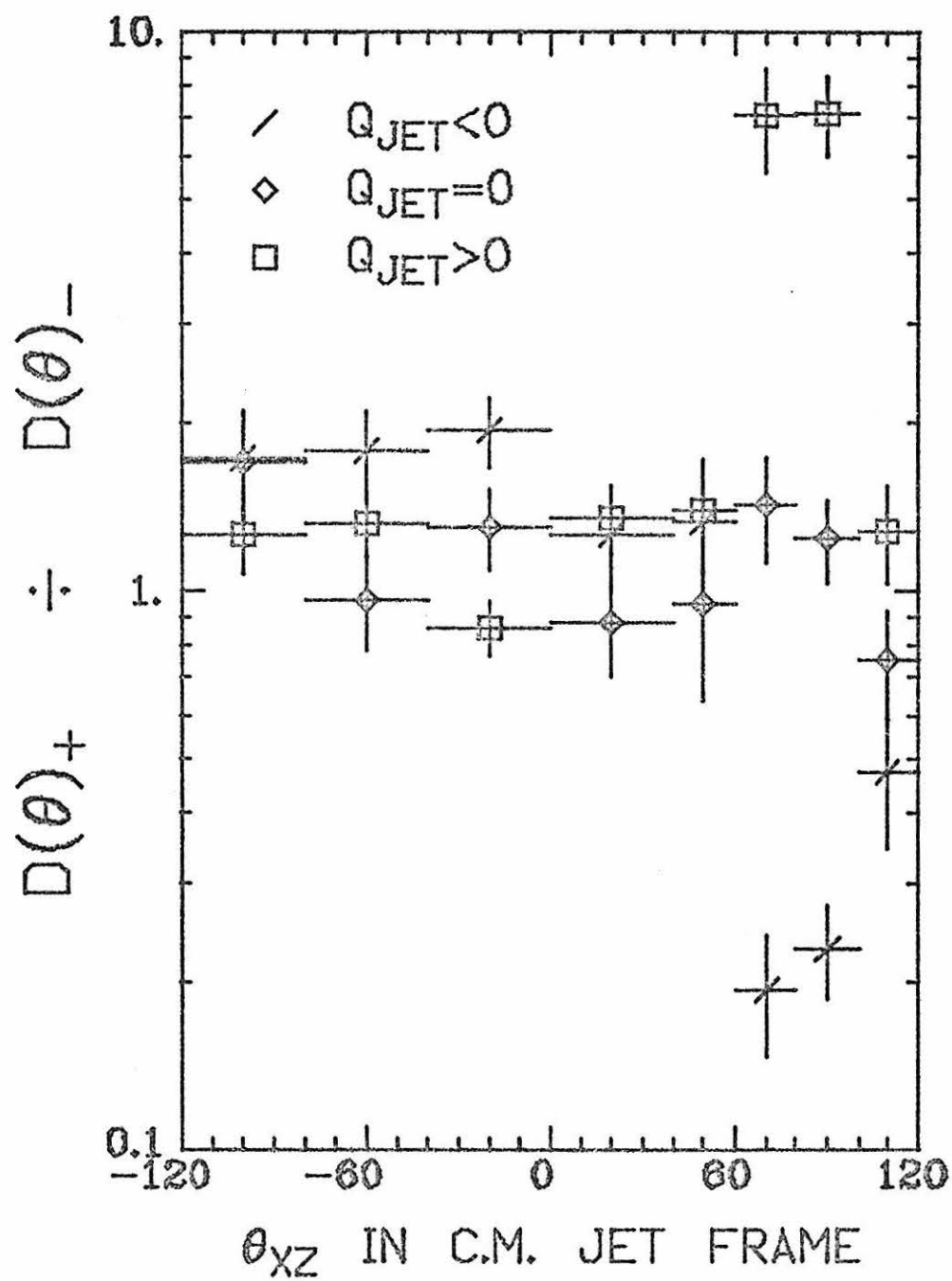


Figure 6.6d π^+ beam, aluminium target.

HIJT π^- HY $E_0 > 5$
 P_{JET}^1 2 TO 6.5 GEV/C

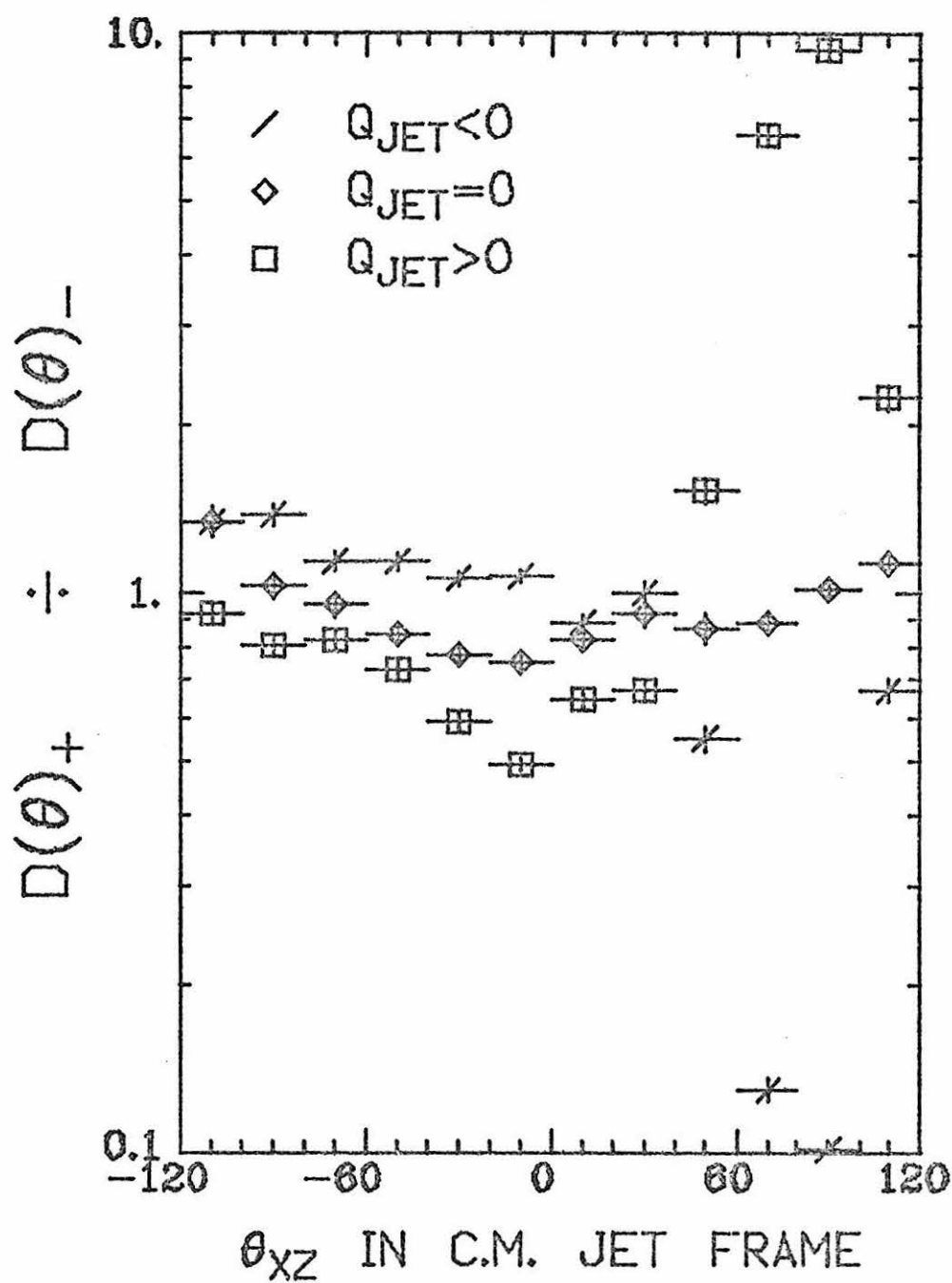


Figure 6.6e π^- beam, hydrogen target.

HIJT π^- AL $E_0 > 5$
 P_{JET}^1 2 TO 6.5 GEV/C

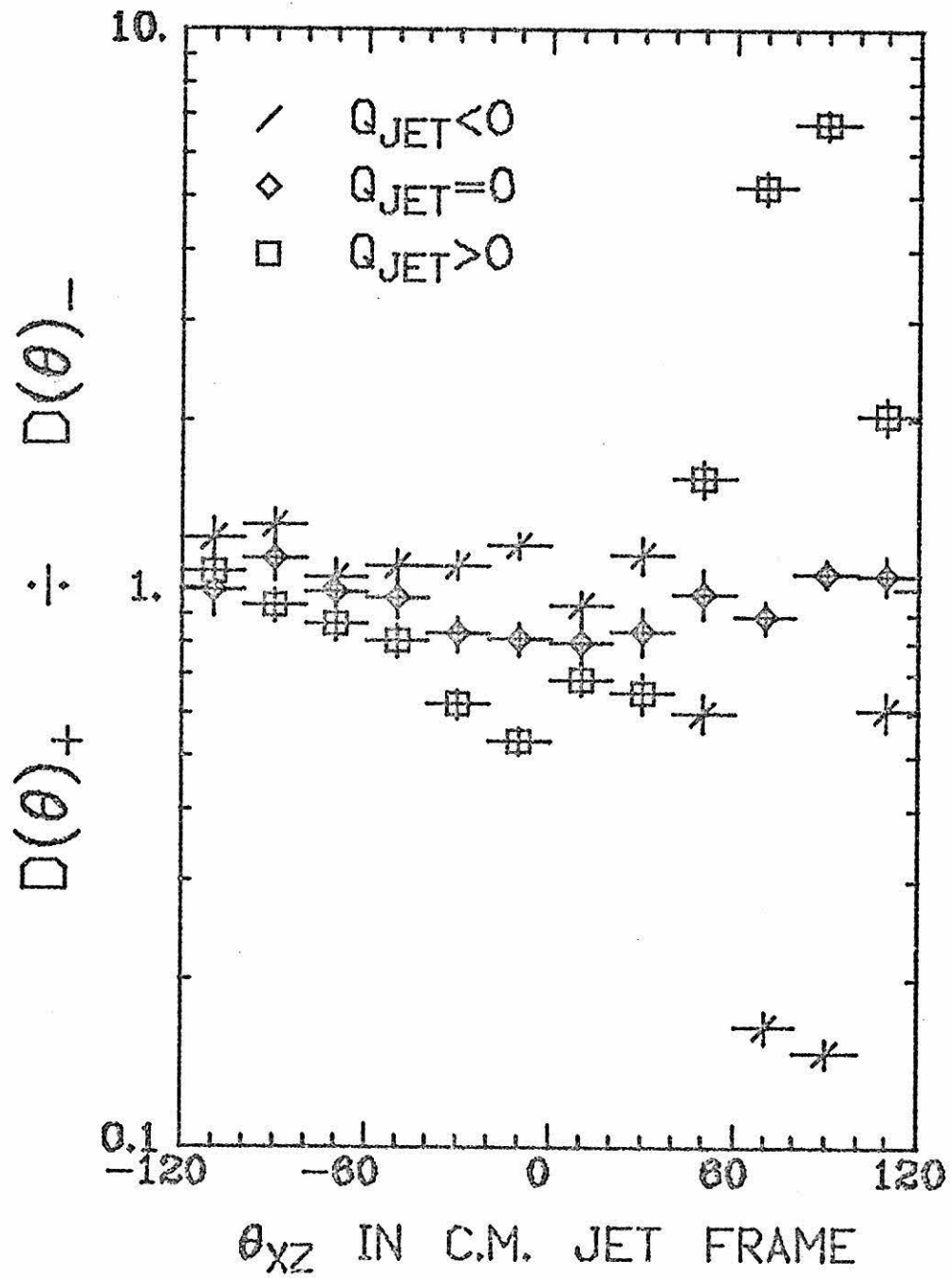


Figure 6.6f π^- beam, aluminium target.

MCDATA PROTON $E_0 > .5$
 HIJT P_1^{JET} 2 TO 6.5 GEV/C

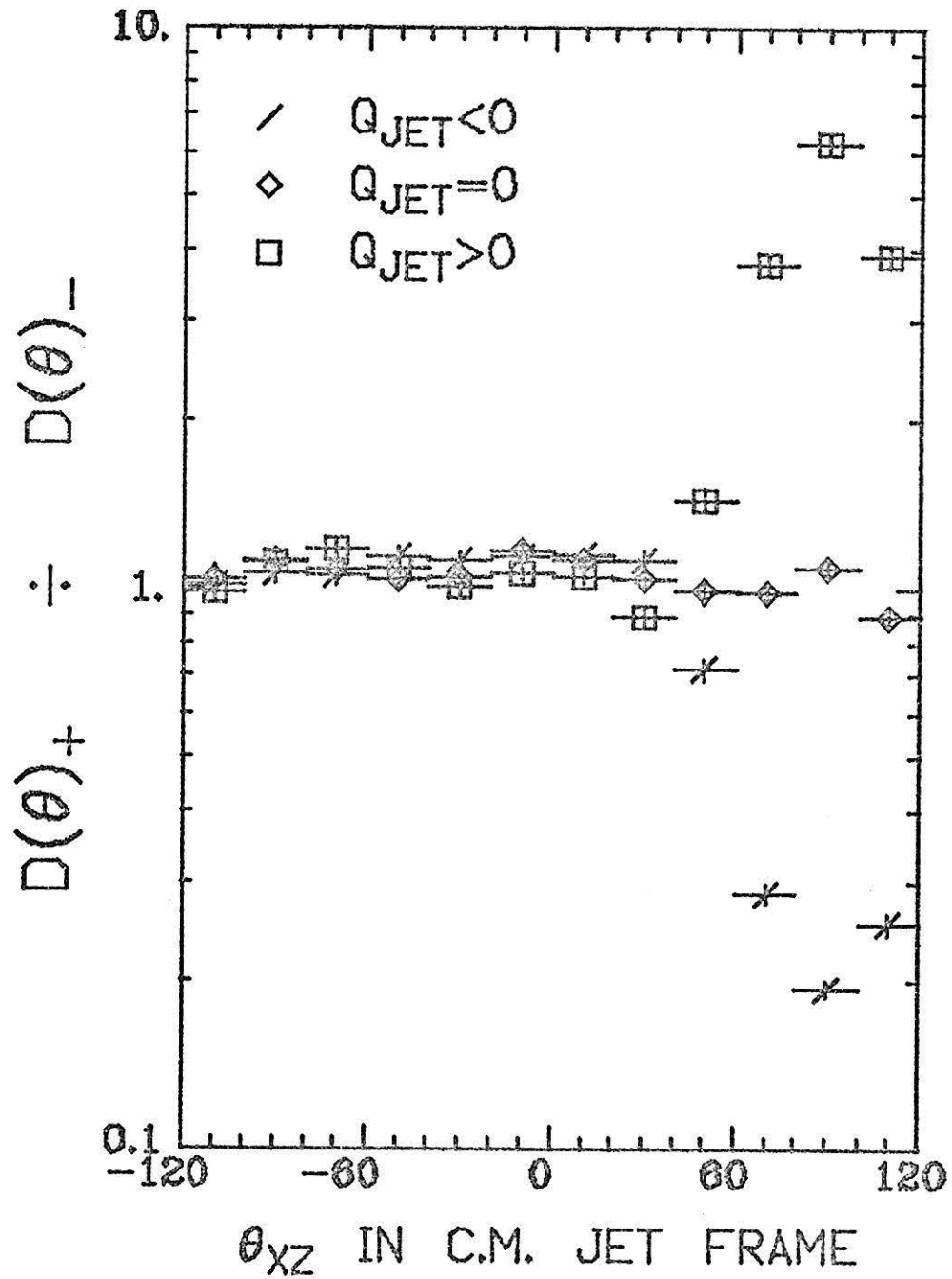


Figure 6.7 $\pm$ ratios for our M.C. data.

Please see figure caption for Figure 6.6.

POS BEAM HIJT $E_Q > .5$

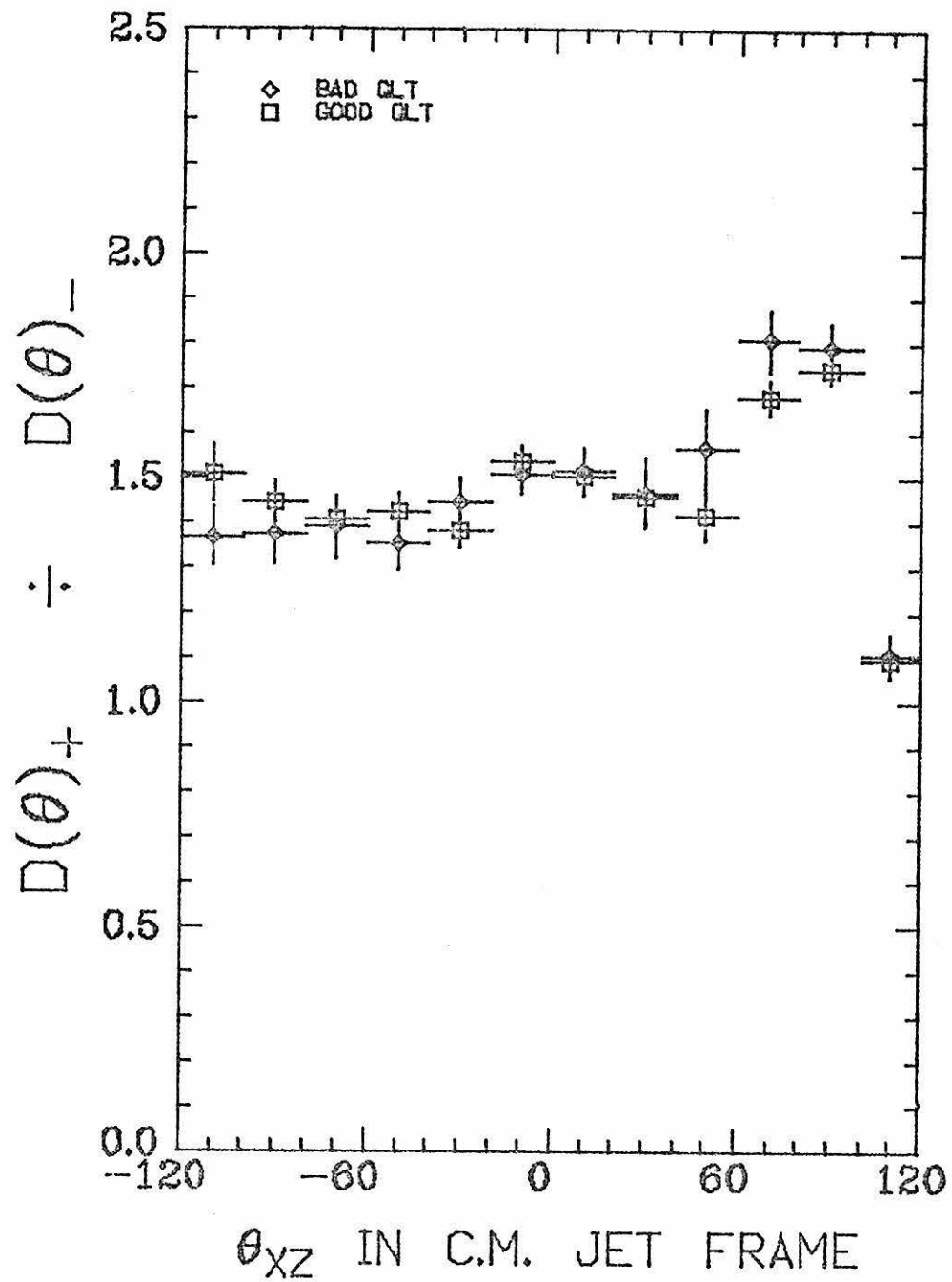


Figure 6.8 $+/-$ ratios for two ranges of PWC quality factors (PWCNCE).

HYDROGEN TARGET ALL CHARGES $E_Q > .5$

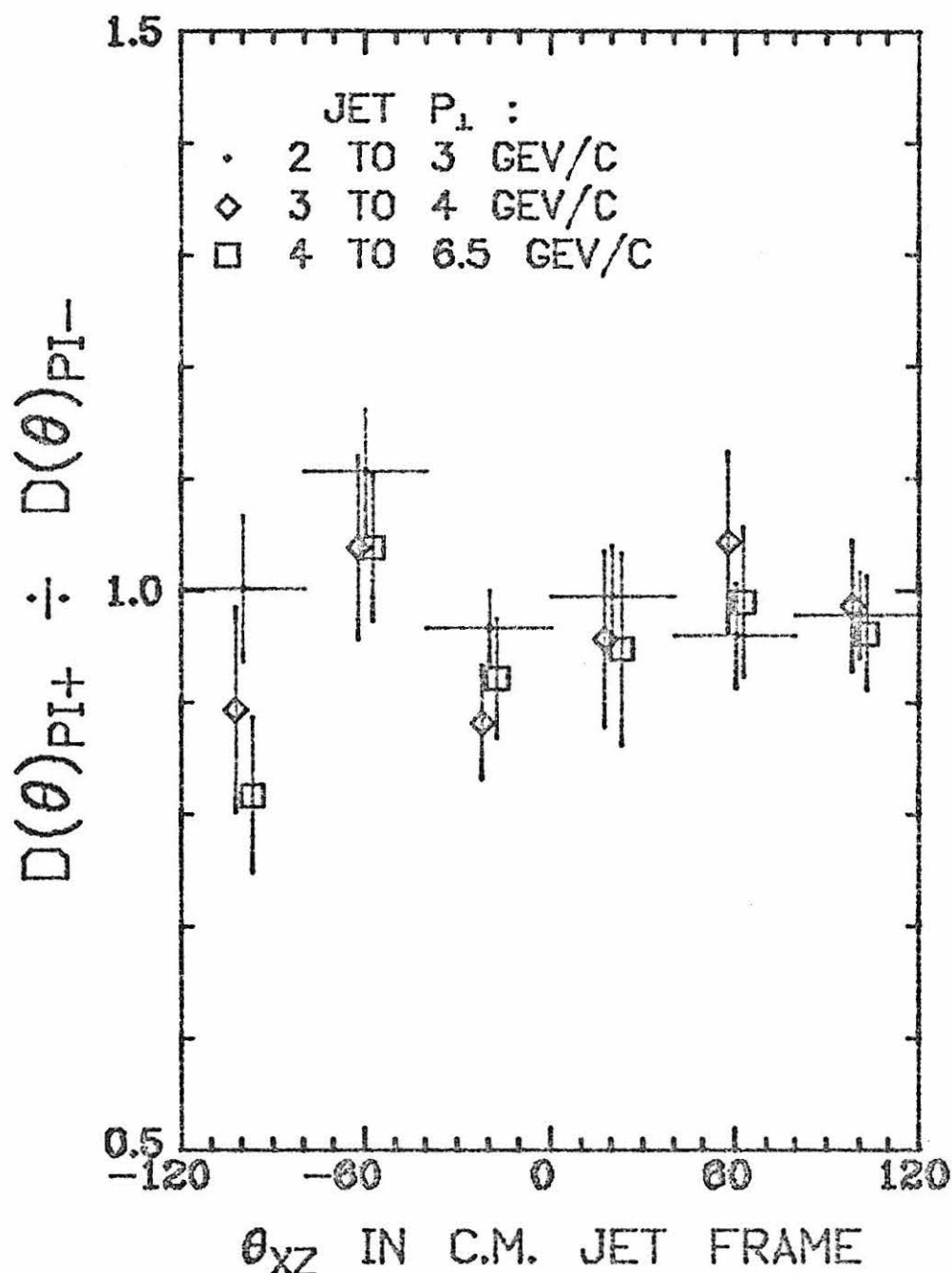


Fig. 6.9a Ratio of the $D(\theta)$ distribution for the π^+ beam over the π^- beam (hydrogen).

ALUMINIUM TARGET ALL CHARGES $E_Q > .5$

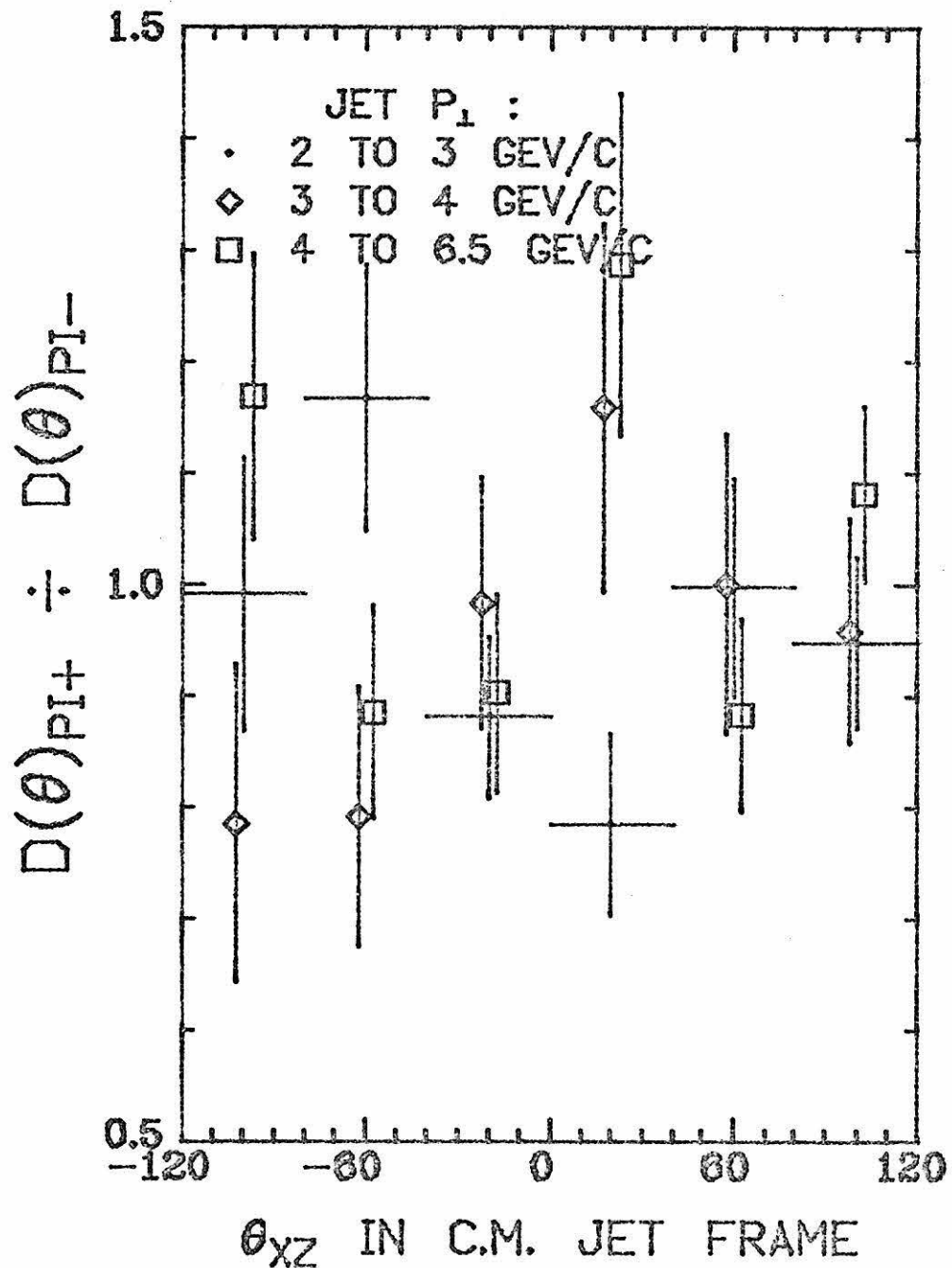


Fig. 6.9b Ratio of the $D(\theta)$ distribution for the π^+ beam over the π^- beam (aluminium).

HYDROGEN TARGET ALL CHARGES $E_Q > .5$

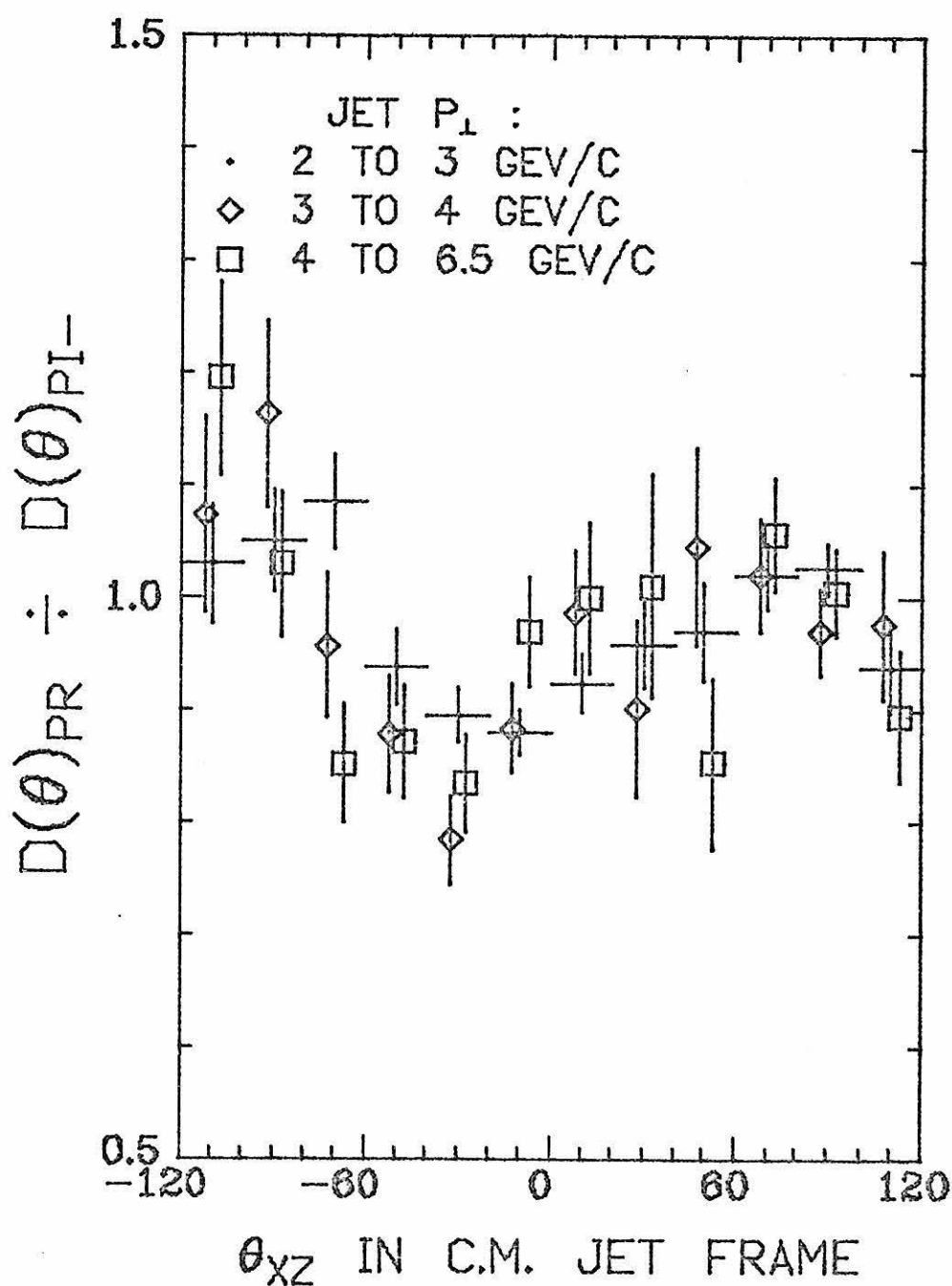


Fig. 6.10a Ratio of $D(\theta)$ for the proton beam over the π^- beam (hydrogen target).

ALUMINIUM TARGET ALL CHARGES $E_Q > .5$

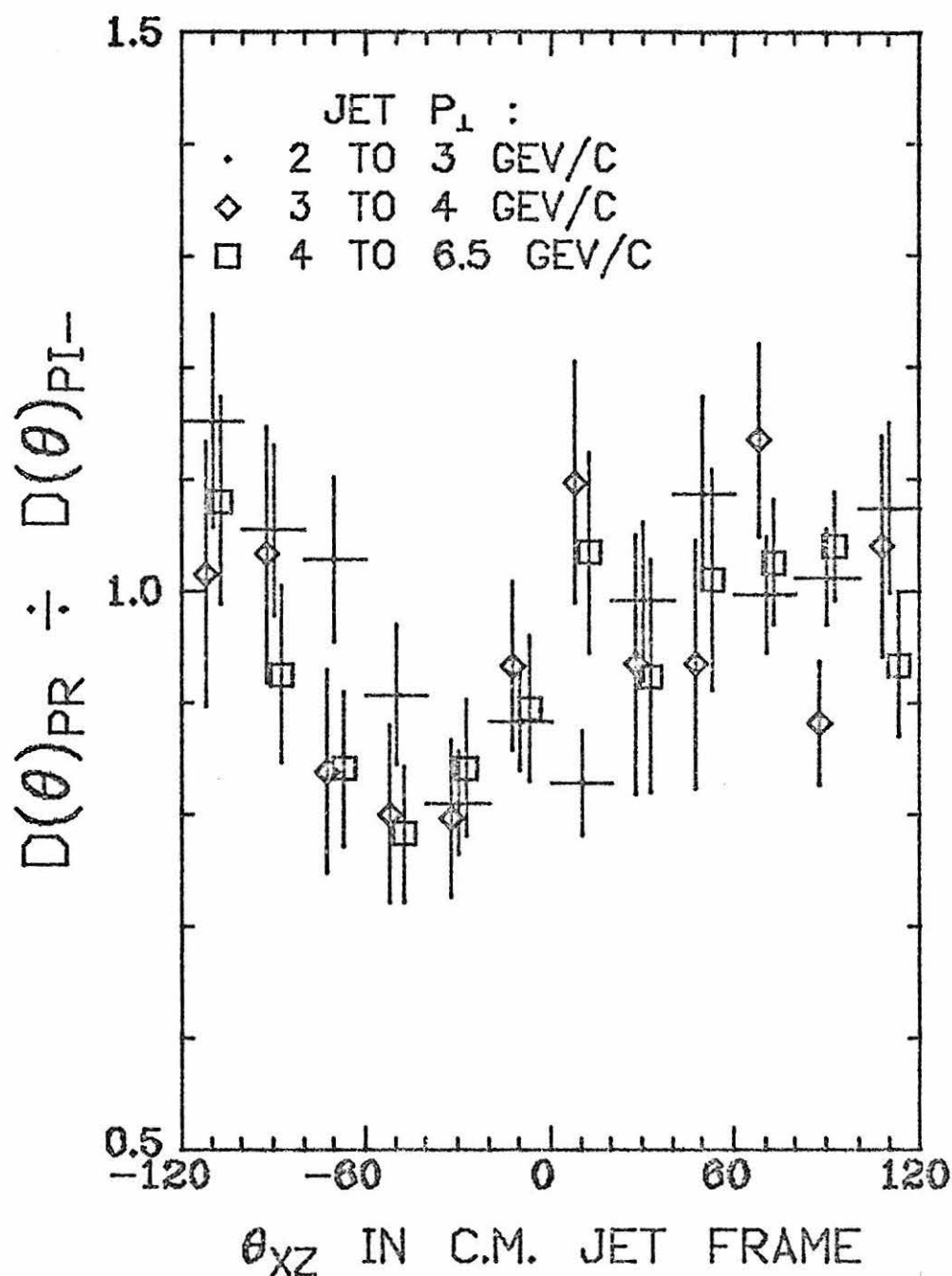


Fig. 6.10b Ratio of $D(\theta)$ for the proton beam over the π^- beam (aluminium target).

HYDROGEN TARGET JET
ALL CHARGES ON THE AWAY SIDE

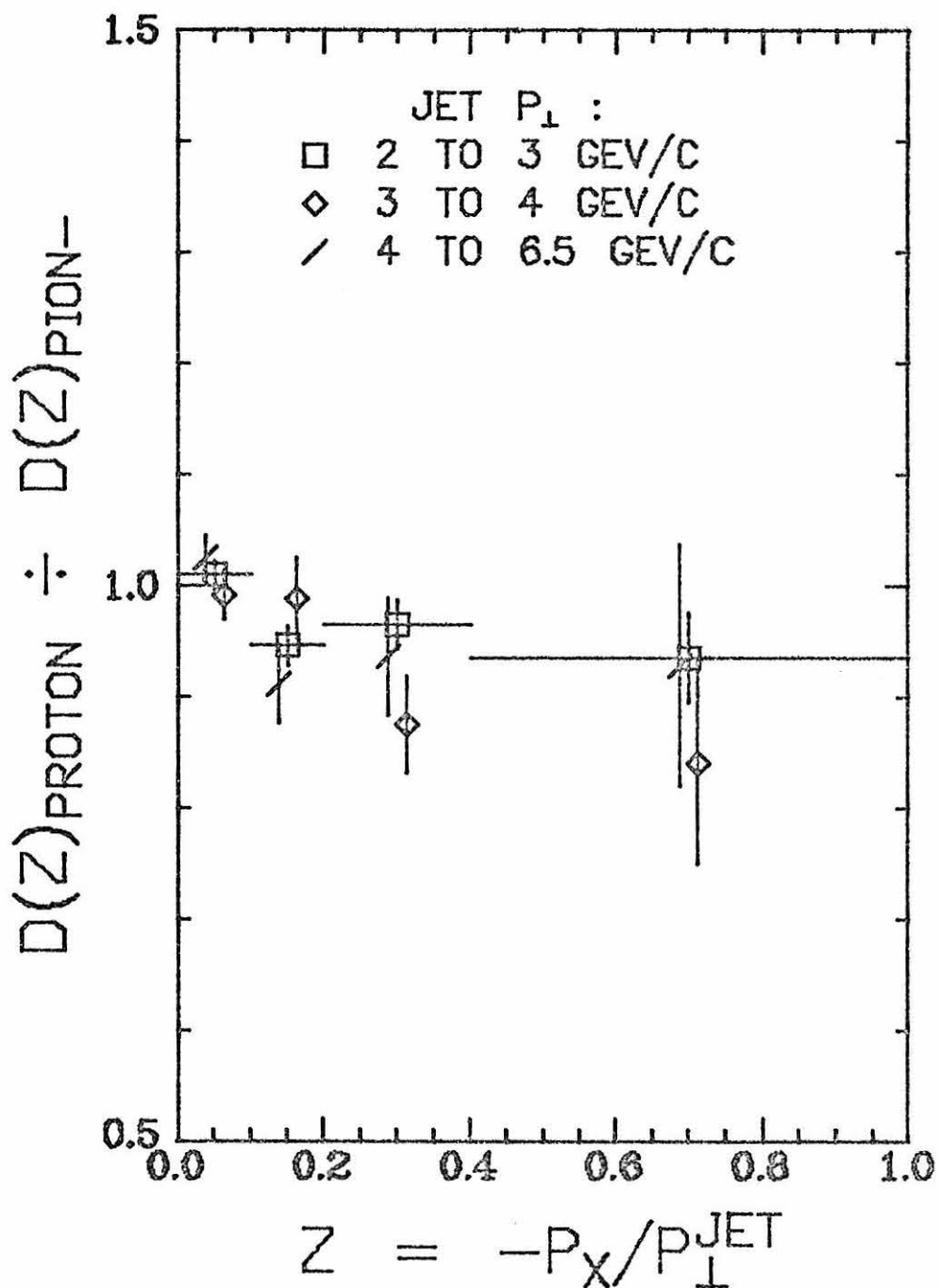


Figure 6.11a Ratio of $D(Z)$ plot for the proton beam over the π^- beam on the away side (hydrogen target).

ALUMINIUM TARGET JET
ALL CHARGES ON THE AWAY SIDE

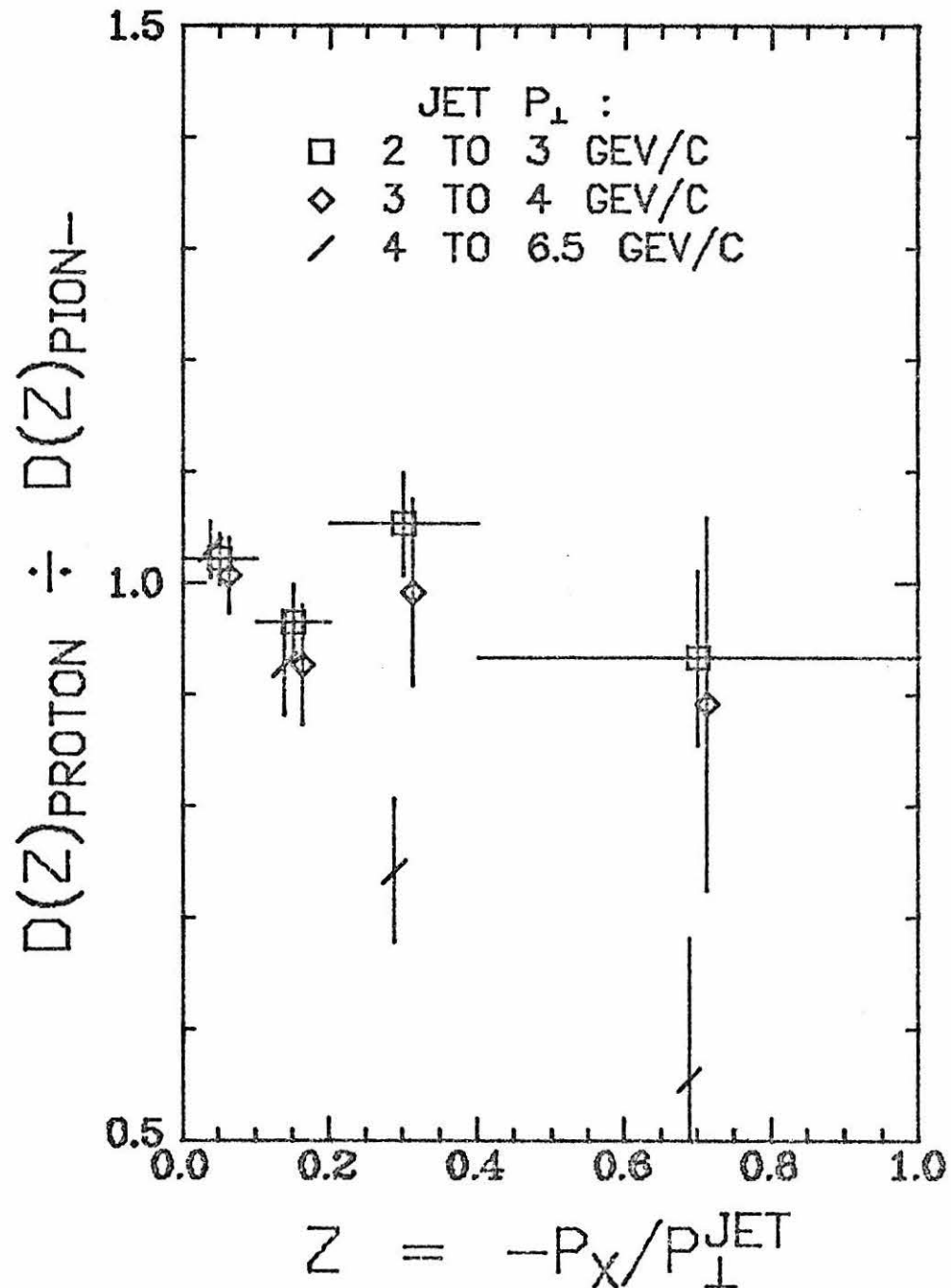


Figure 6.11b Ratio of $D(Z)$ plot for the proton beam over the π^- beam on the away side (aluminium target).

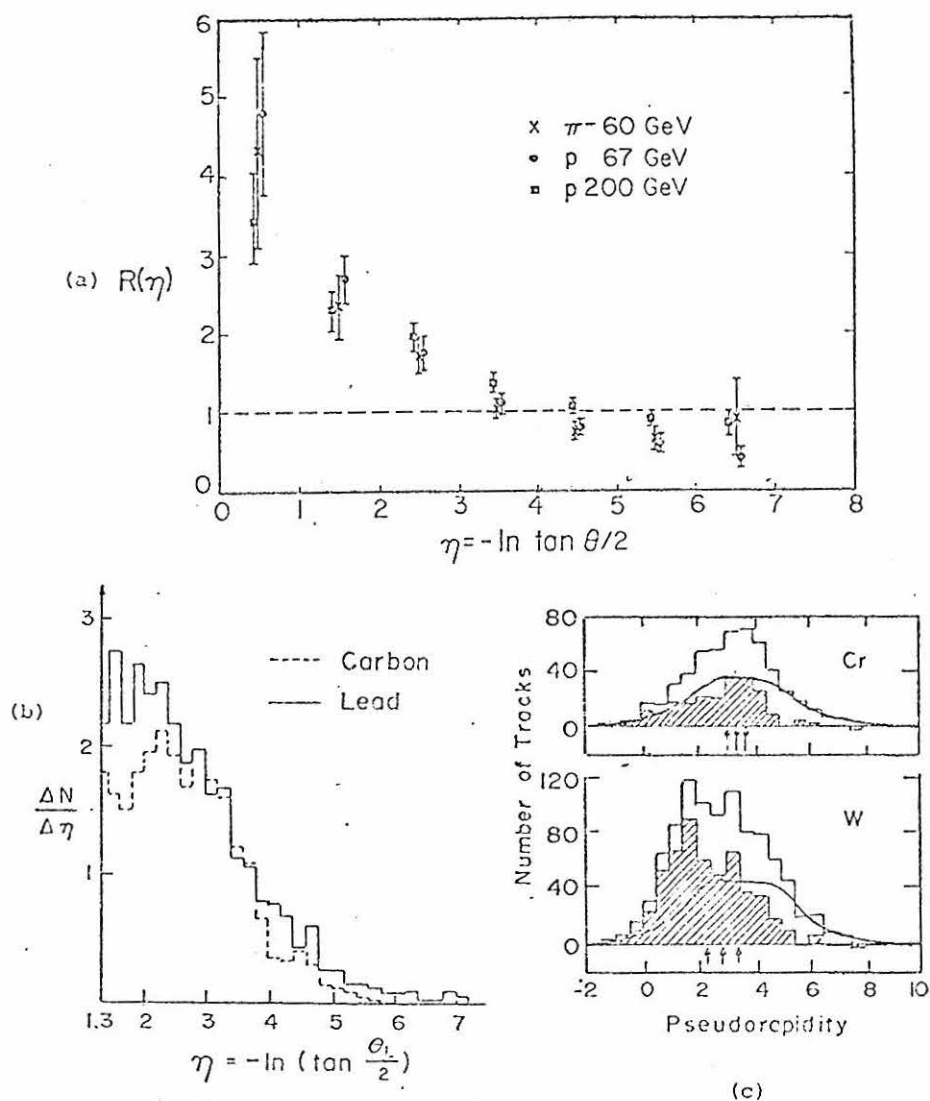


Fig. 11

Data on the A-dependence of leading particle spectrum.
 a) Emulsion data. Ratio $R(\eta)$ of number of particles produced in heavy nuclei to that in hydrogen. Identification of target nucleus through parameter N_h discussed in text. Data compiled by Wolter.⁴¹
 b) Spark chamber data of Abrosimov *et al.*⁴² at 40 GeV.
 c) Data obtained by Florian *et al.*⁴³ using metal pellets in emulsion.

Figure 6.12 Plots taken from page 583 of
 the review paper by Wit Busza [1.18a] .

RAPIDITY DISTRIBUTION OF CHARGED PARTICLES ON BOTH SIDES

○ MINIMUM BIAS

....."UNIVERSAL CURVE"

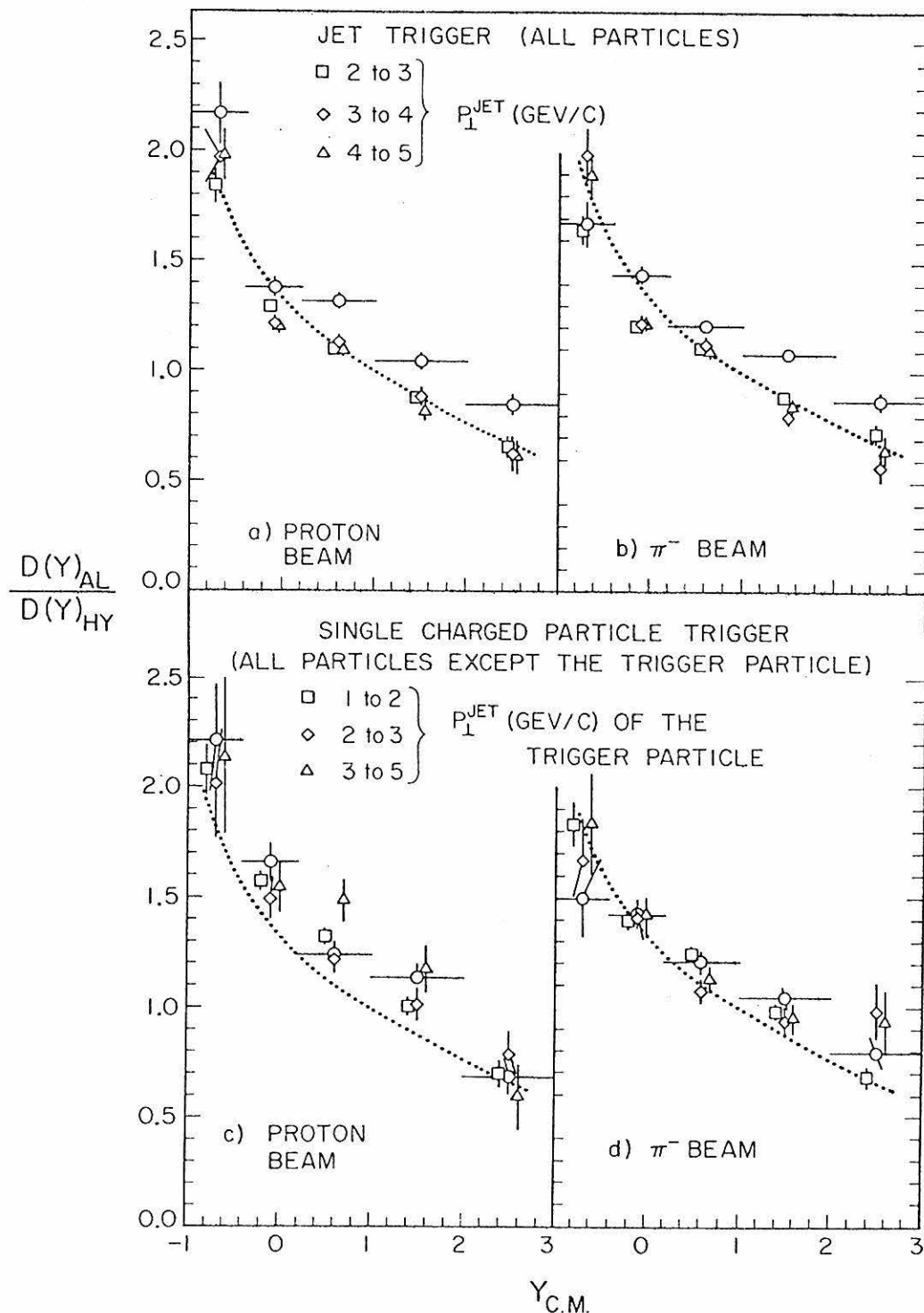


Figure 6.13 Ratio of $D(Y)$ (aluminium over hydrogen) for charged particles on both sides (trigger particle excluded in the single particle trigger).

RAPIDITY DISTRIBUTION OF ALL CHARGED PARTICLES ON THE AWAY SIDE

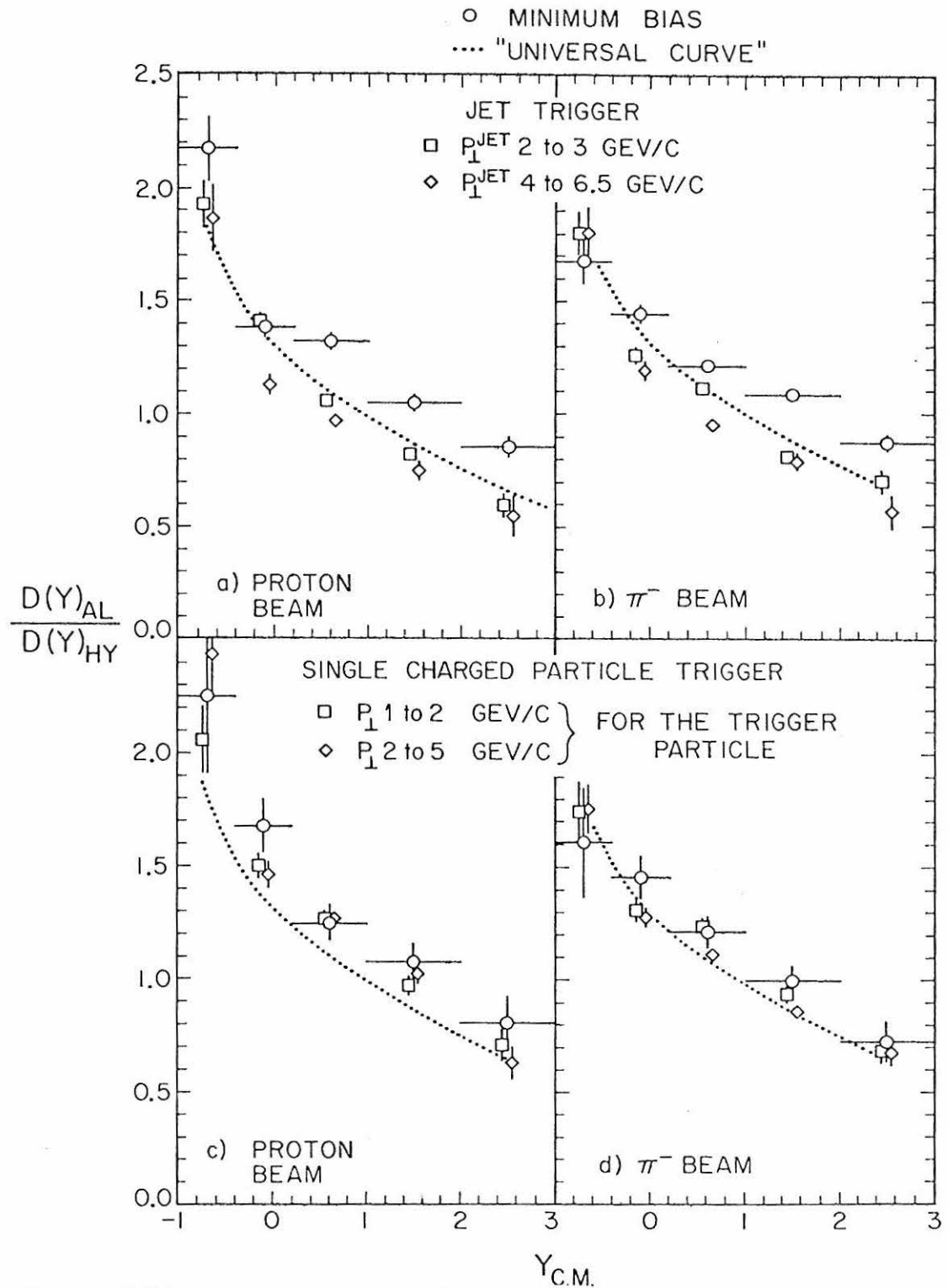


Figure 6.14 Ratio of $D(Y)$ (aluminium over hydrogen) for all charged particles on the away side.

Figure 6.15 $D(Y)$ for the aluminium target
and for three different vertex regions of
the hydrogen target.

PROTON BEAM

$4 > p_{T\text{TRG}} \geq 3$

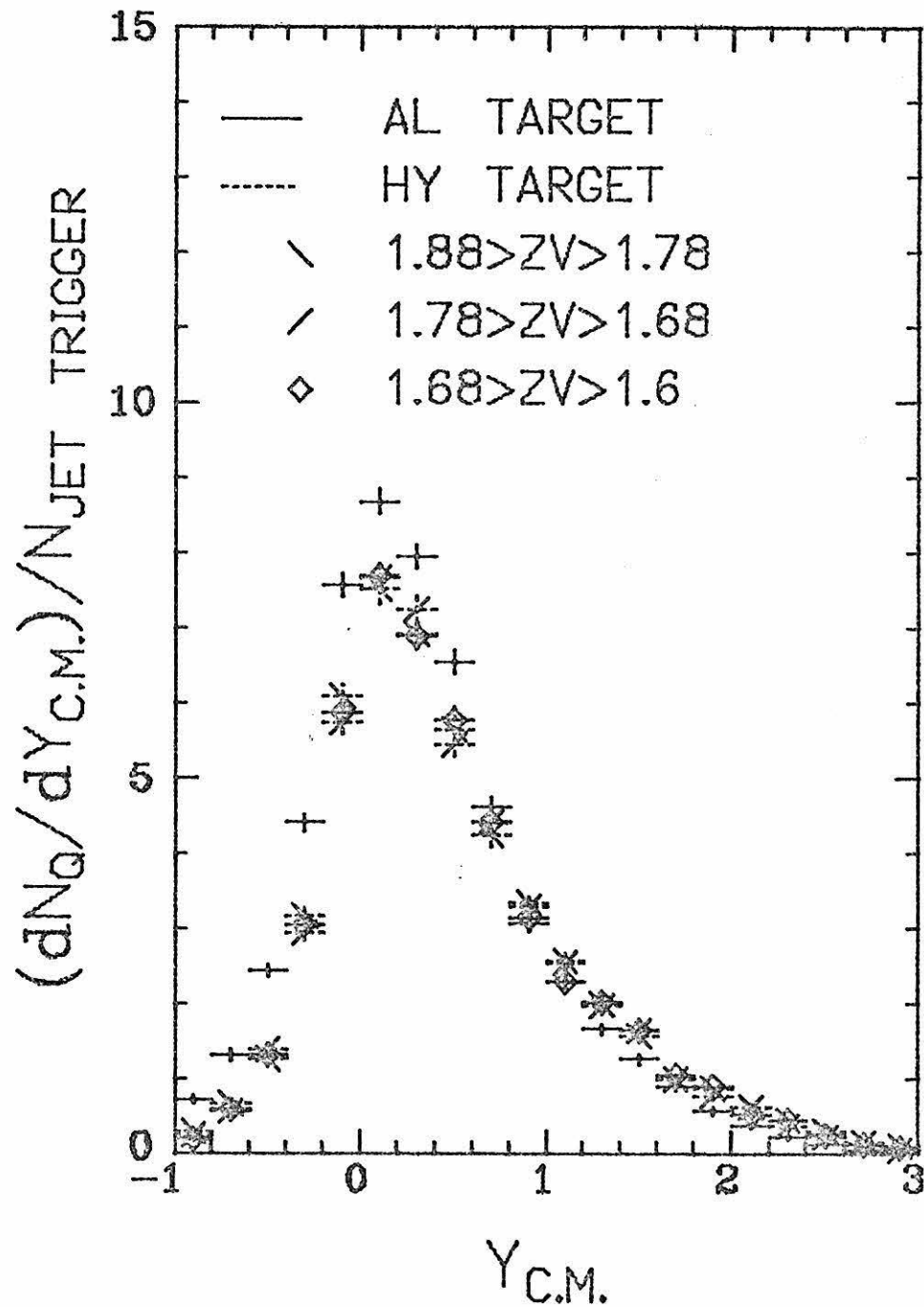


Figure 6.15a Proton beam; trigger jet p_T between 3 and 4 GeV/c.

PROTON BEAM
 $6.5 \geq p_{T\text{TRG}} \geq 4$

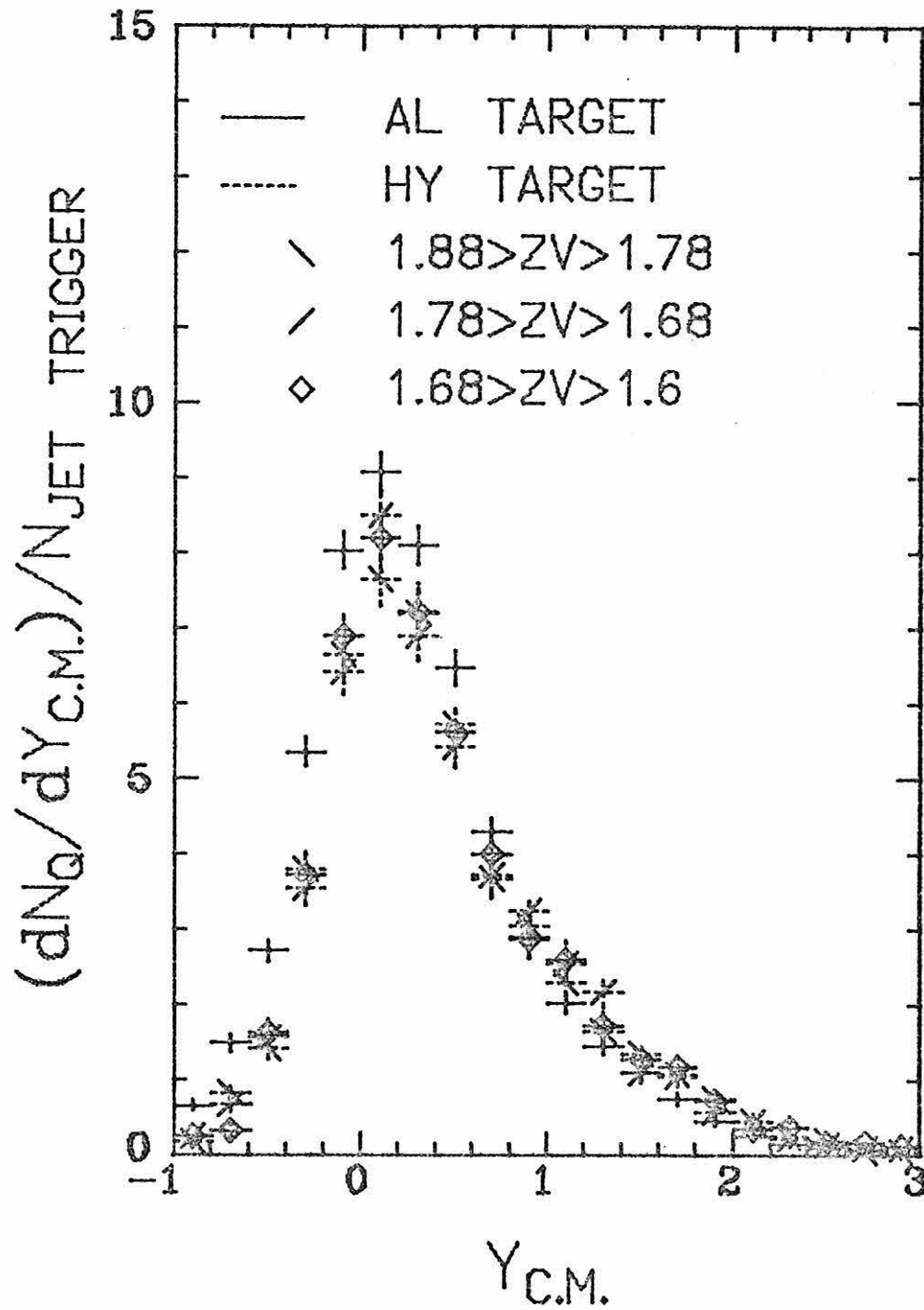


Figure 6.15b Proton beam; trigger jet p_T
 between 4 and 6.5 GeV/c.

π^- BEAM

$$4 > p_{T\text{TRG}} \geq 3$$

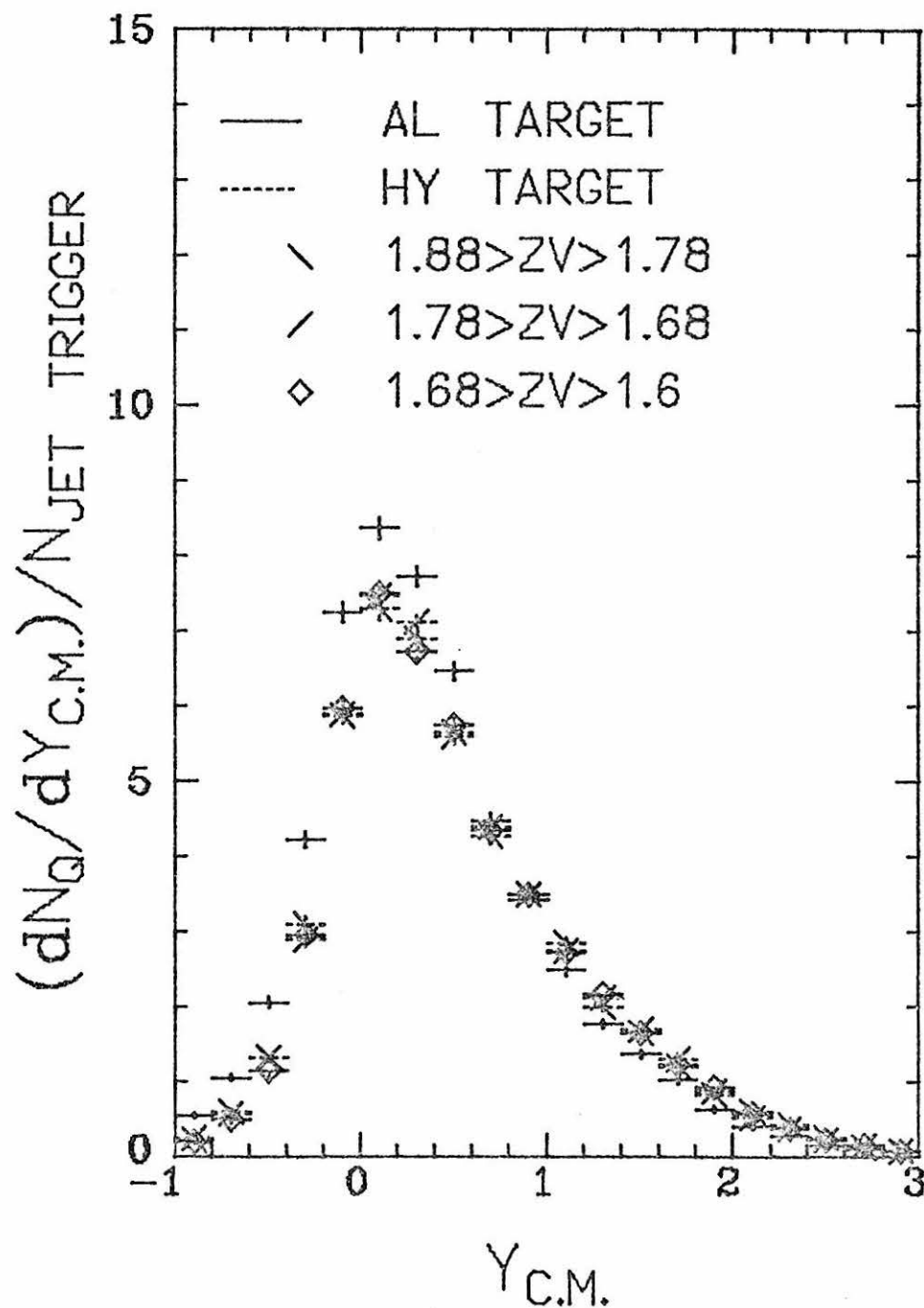


Figure 6.15c π^- beam; trigger jet p_T between 3 and 4 GeV/c.

π^- BEAM

$$6.5 \geq p_{T\text{TRG}} \geq 4$$

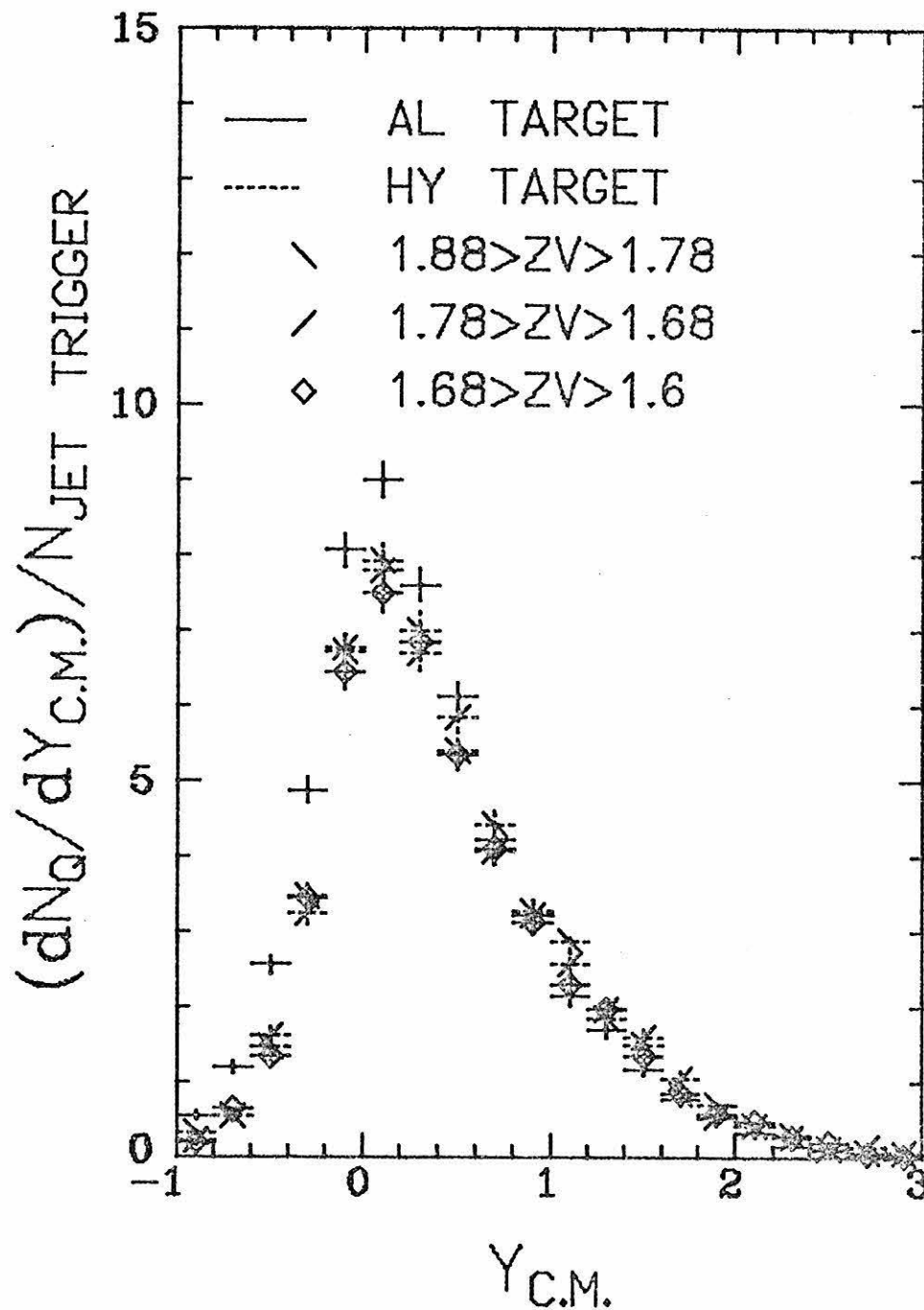


Figure 6.15d π^- beam; trigger jet $p_{\perp}$ between 4 and 6.5 GeV/c.

Figure 6.16 Ratio of $D(Y)$ plots (aluminium over hydrogen) for particles "outside the 2×2 " and "affected by the 2×2 " on the away side for two different jet $p_{\perp}$ regions.

PROTON BEAM LOJET
 $-1.5 < P_x < 0$ ALL CHARGES

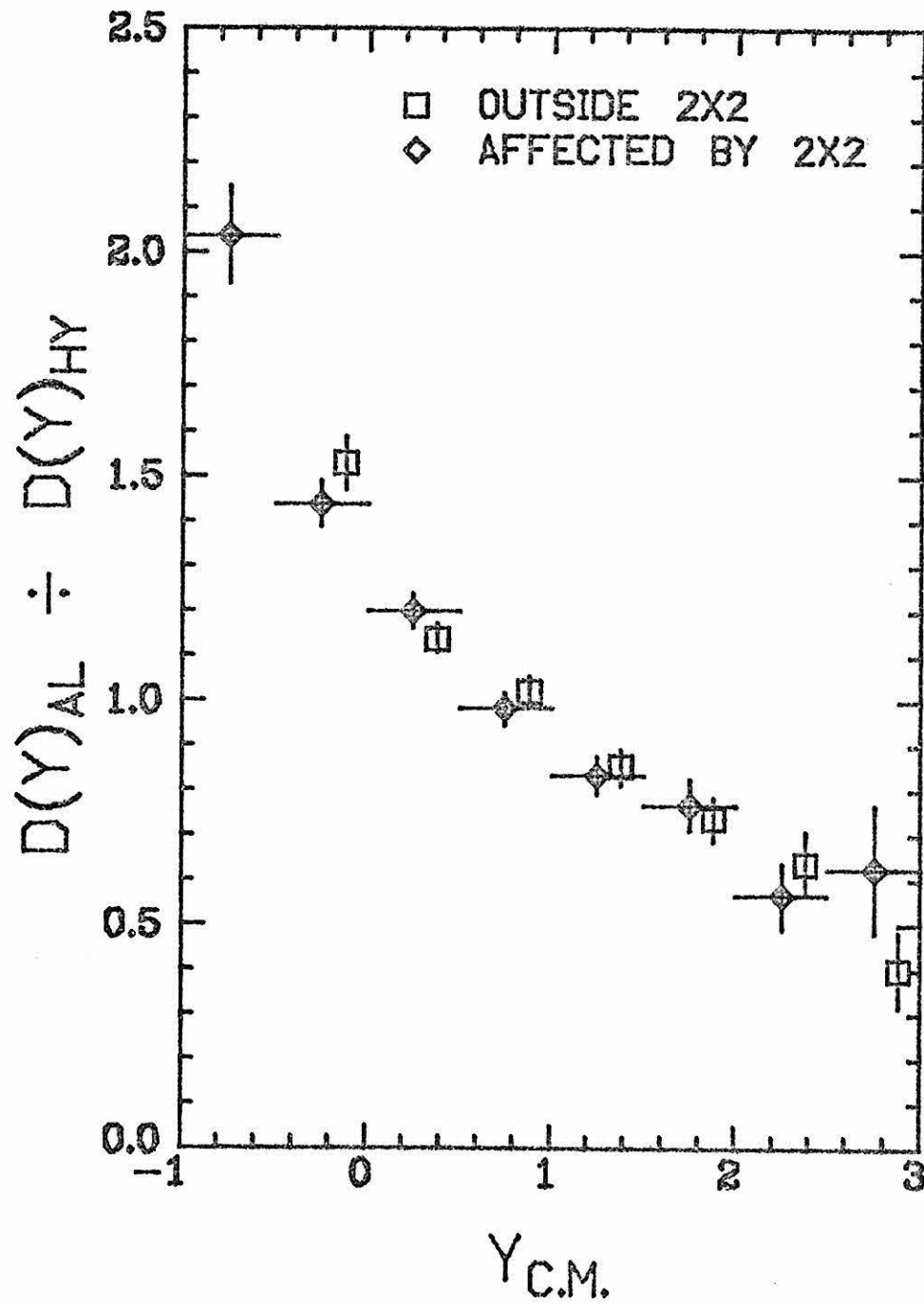


Figure 6.16a.

PROTON BEAM HIJET
 $-1.5 < P_x < 0$ ALL CHARGES

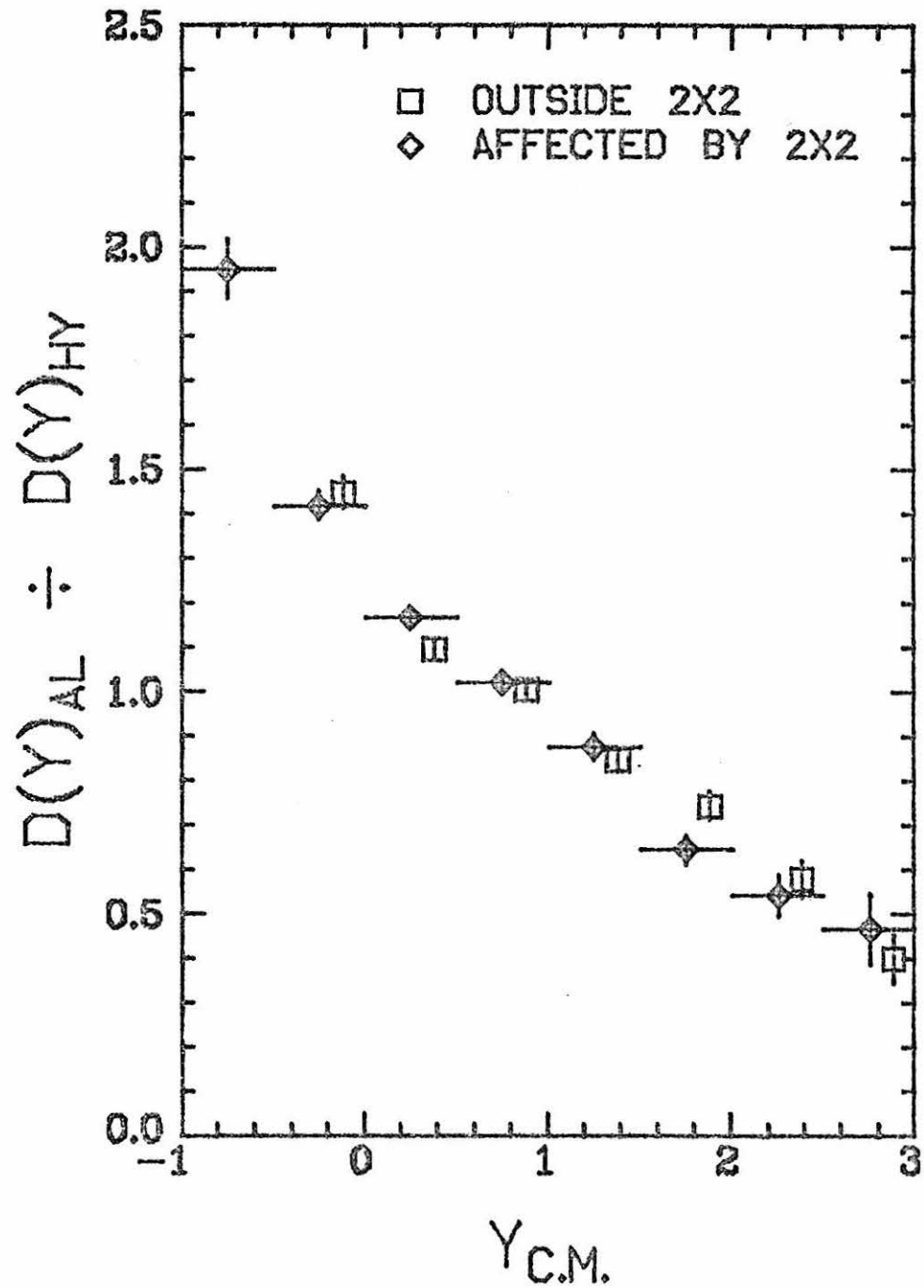


Figure 6.16b.

Z DISTRIBUTION OF ALL CHARGED PARTICLES ON THE AWAY SIDE

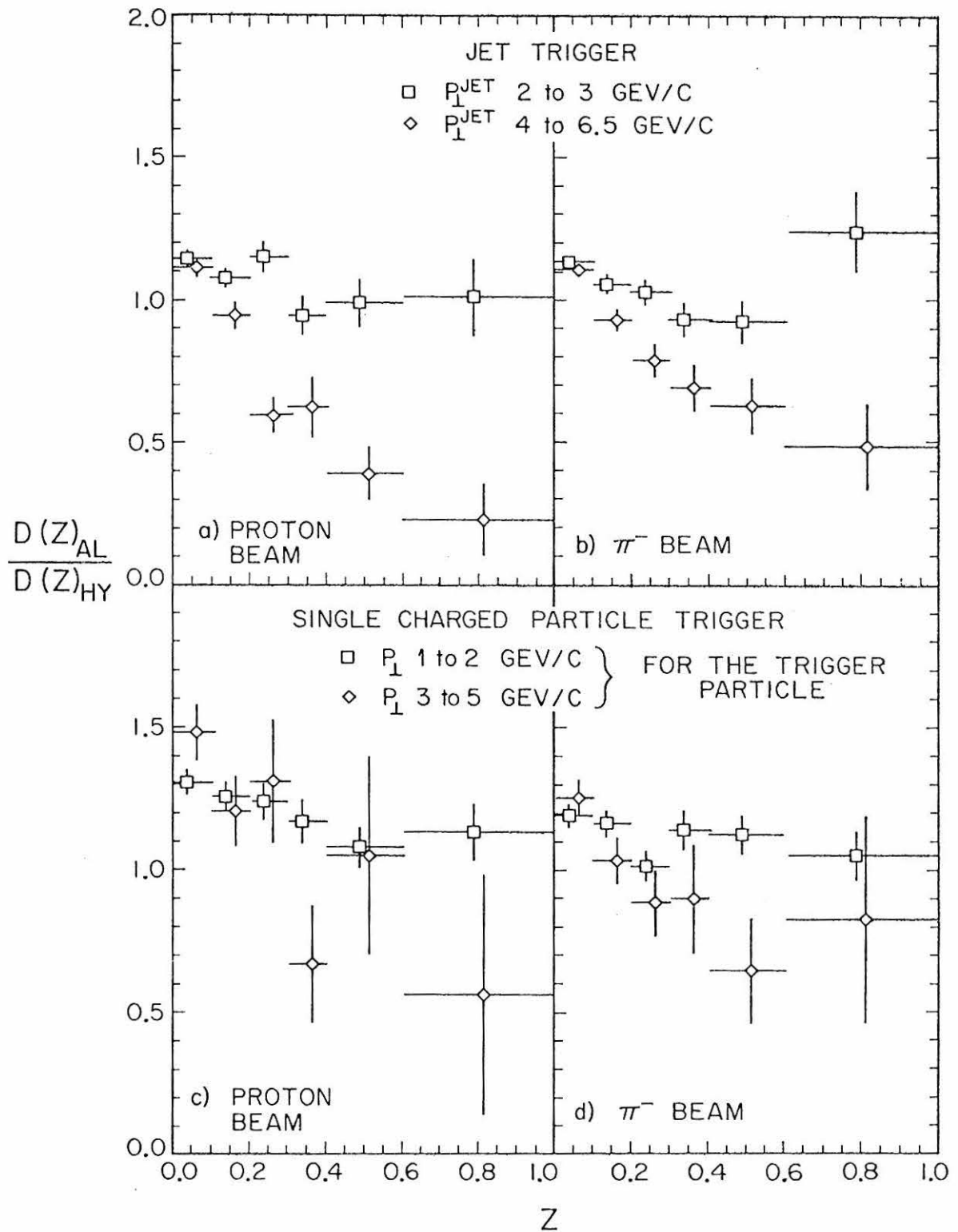


Figure 6.17 $R(Z)$ distribution for particles on the away side.

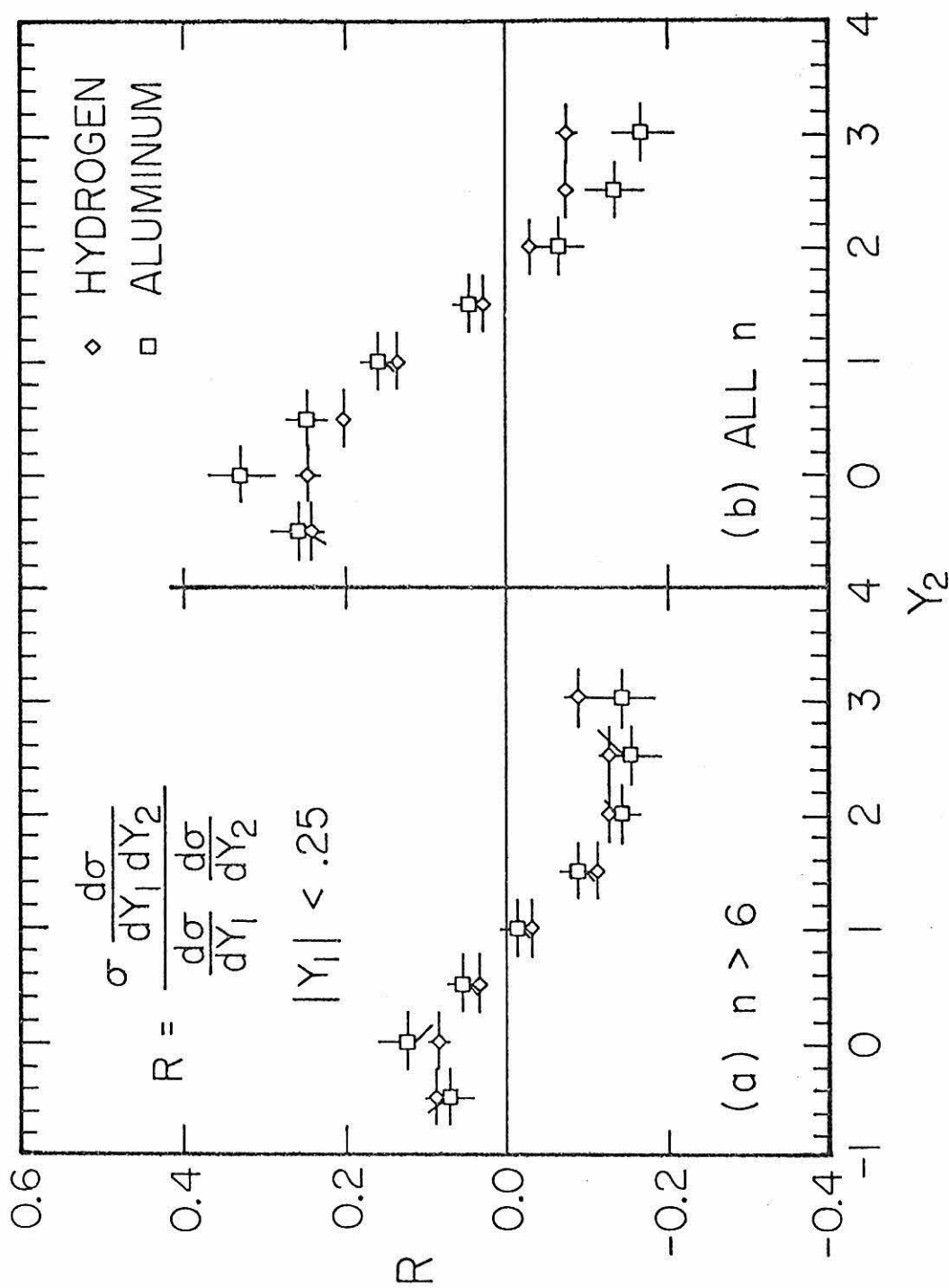


Figure 6.18 Correlation plots by Tse , see [6.17] for detail.

HIJET HYDROGEN CHARGED PARTICLES IN JET

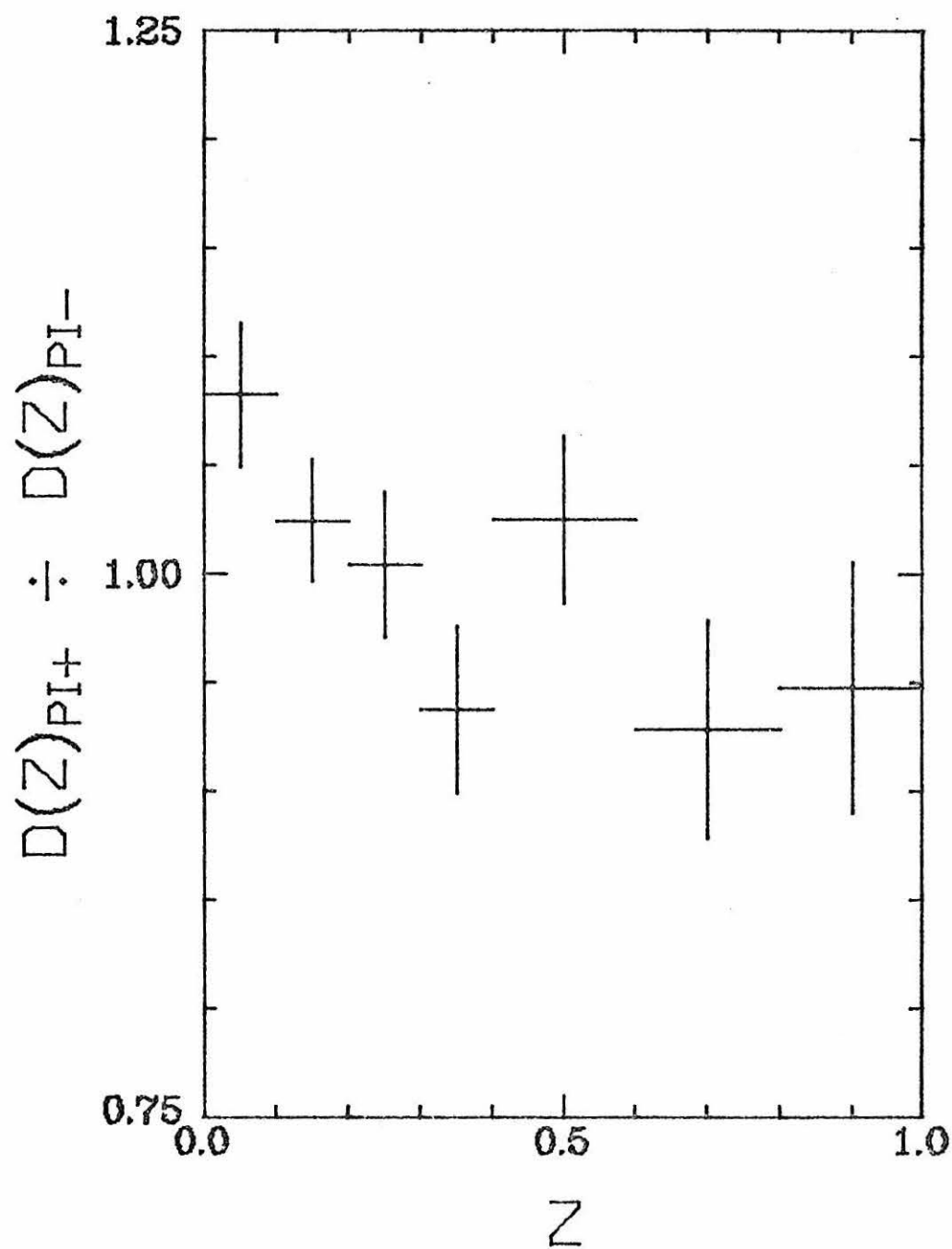


Figure 7.1a Ratio of $D(Z)$ for particles in the jet (π^+/π^- , hydrogen/target).

HIJET ALUMINIUM CHARGED PARTICLES IN JET

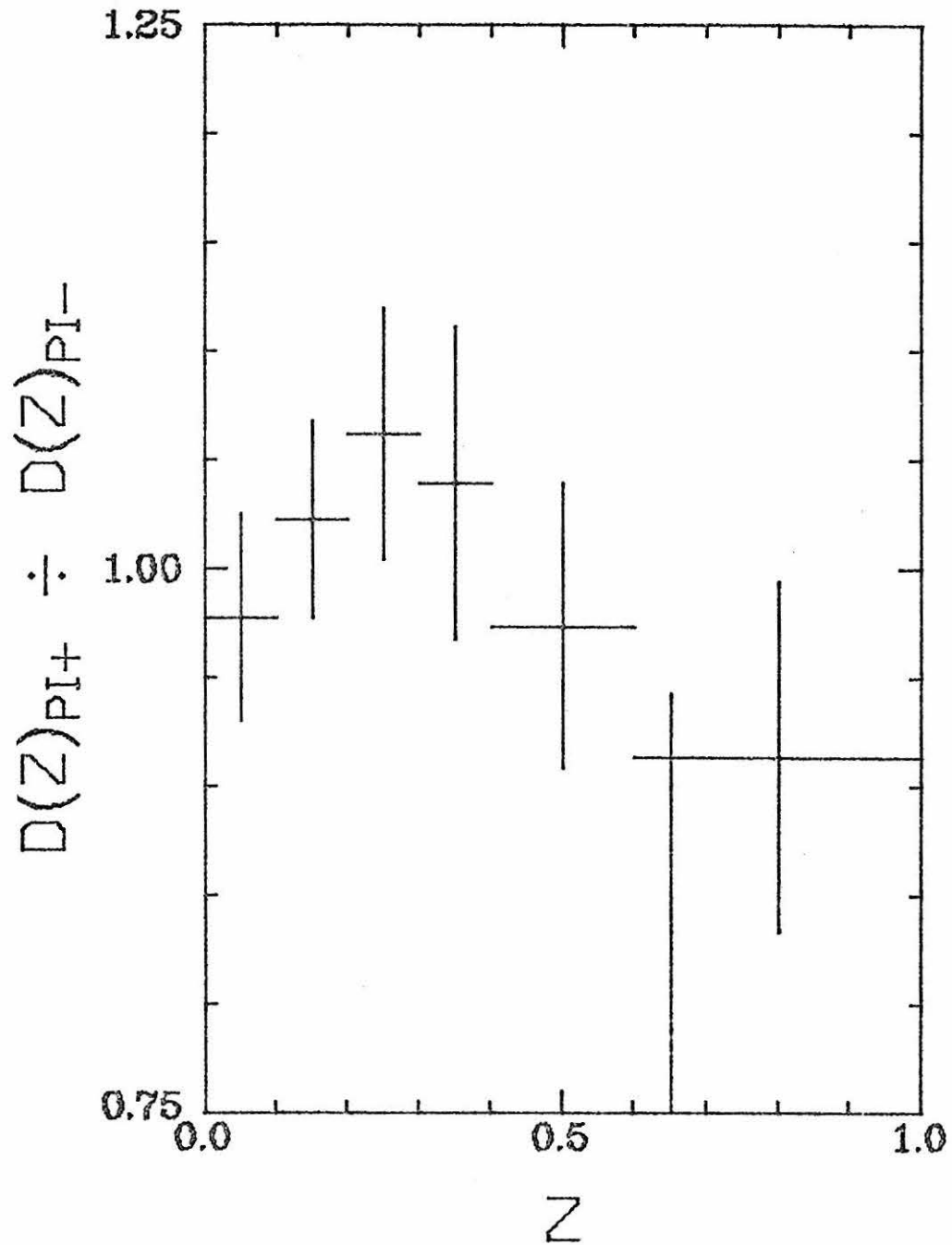


Figure 7.1b Ratio of $D(Z)$ for particles in the jet (π^+/π^- , aluminium target).

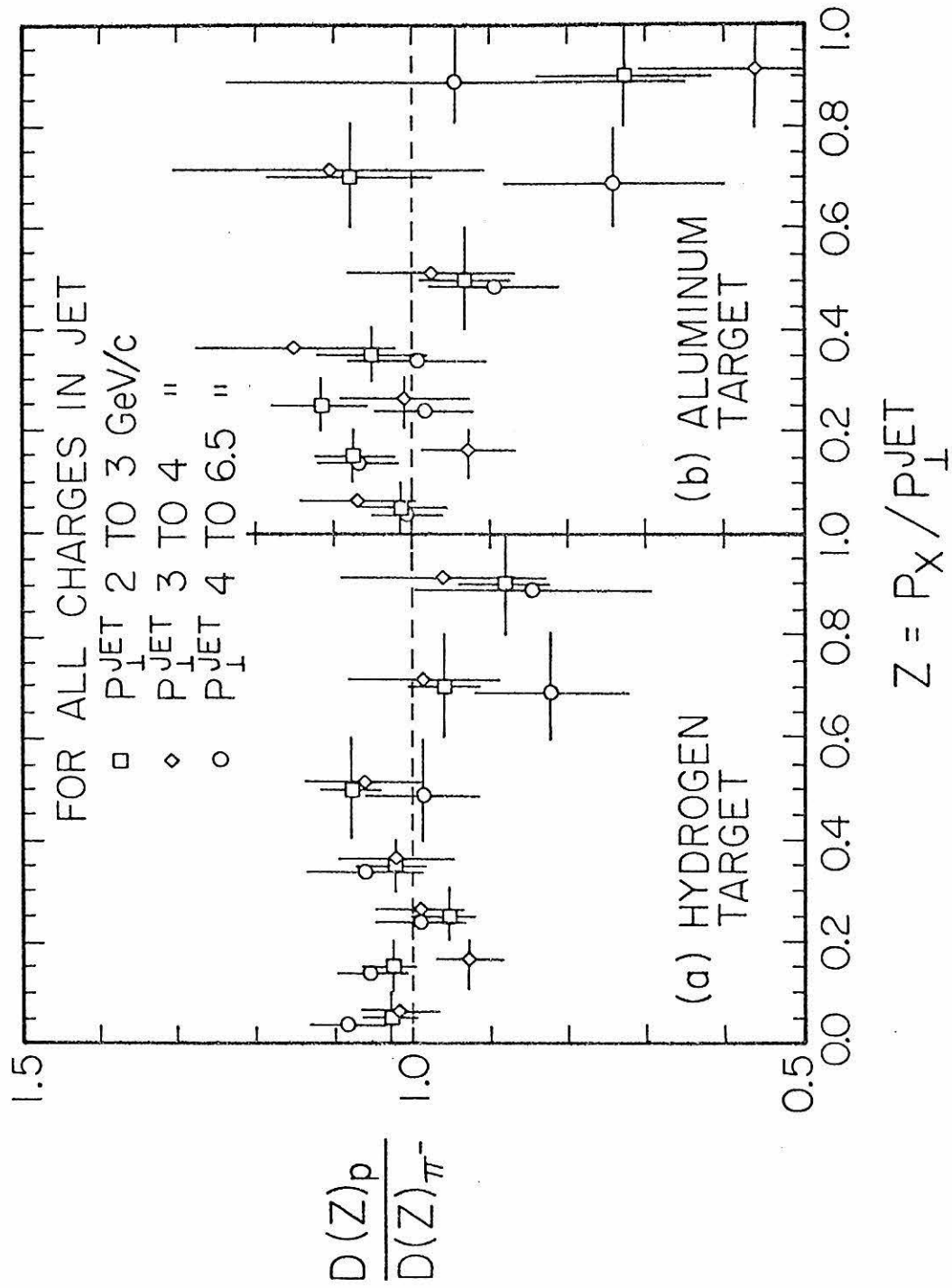


Figure 7.2 Ratio of $D(Z)$ for particles in the jet (proton over π^-).

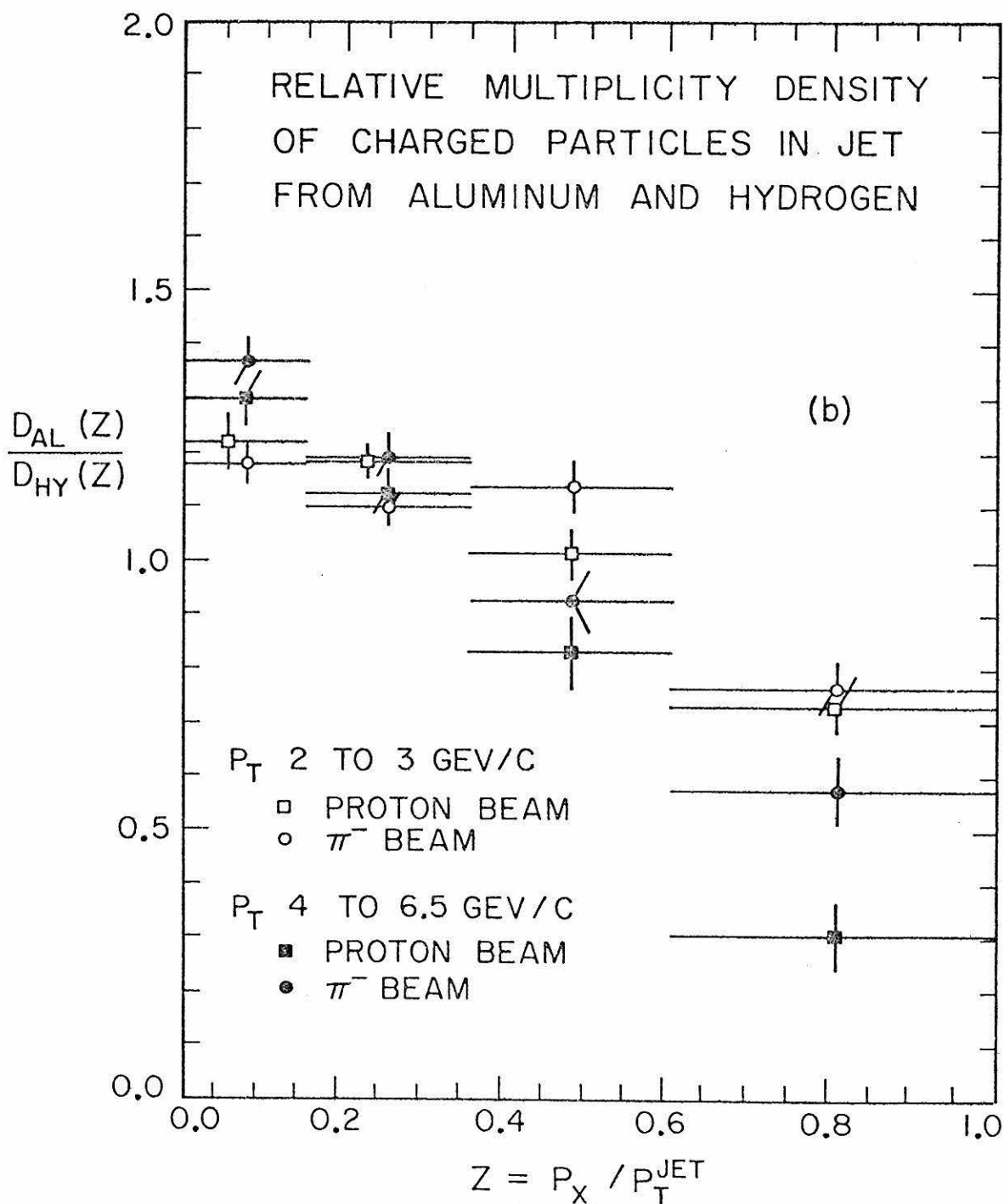


Figure 7.3 Ratio of $D(Z)$ distributions for the aluminium target over the hydrogen target. $D(Z)$ is defined in the text.

Figure 7.4 & 7.5 Ratio of $D(ZQ)$ plots for particles in the jet. The case "NO ZCUT" means $ZQ=Z$. The definition of ZQ is defined in section 7.2. The $\langle \text{jet } P_T \rangle$ for these plots are listed in Table 6.1.

HYDROGEN TARGET HIJET

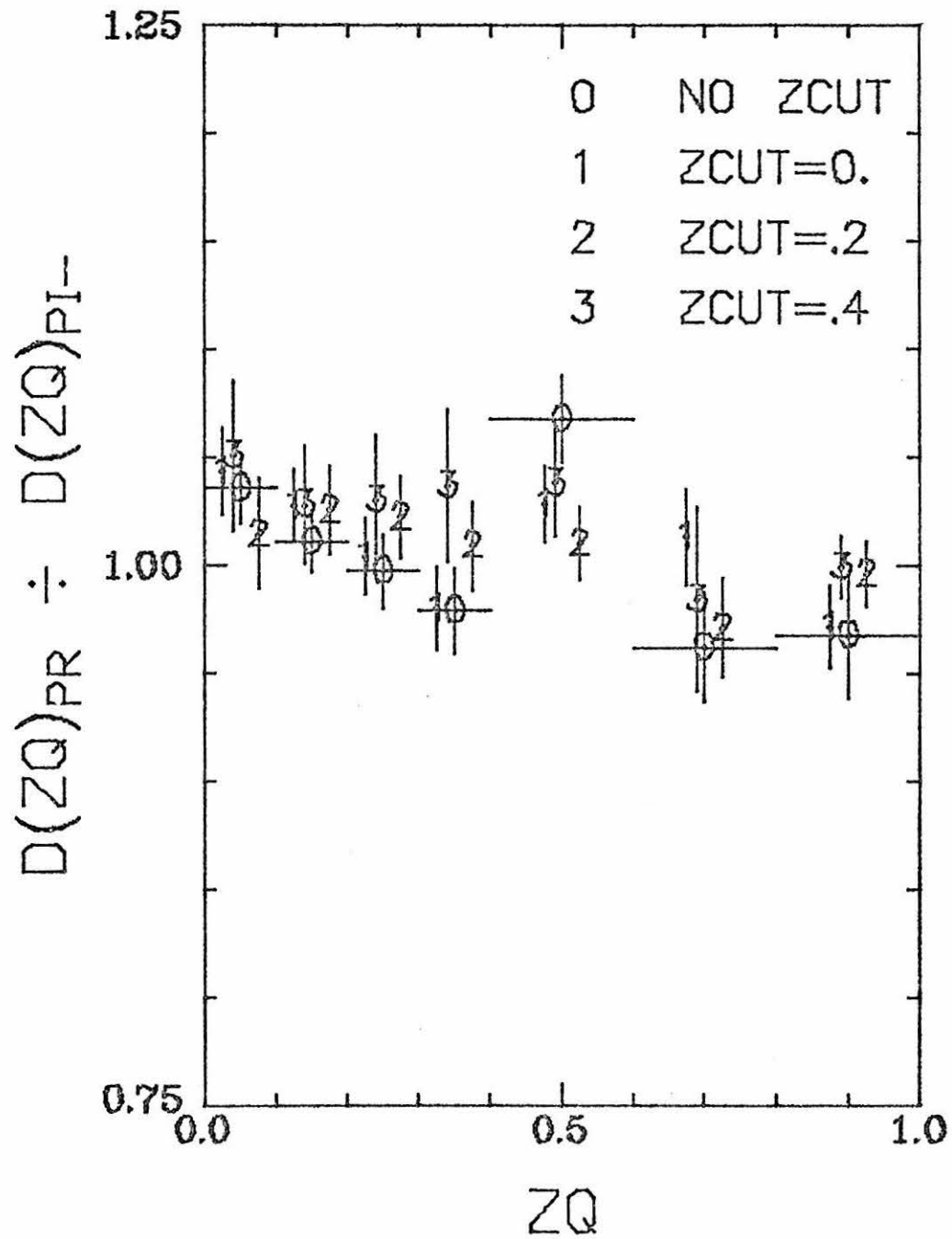


Figure 7.4a Proton over π^- , hydrogen target.

ALUMINIUM TARGET HIJET

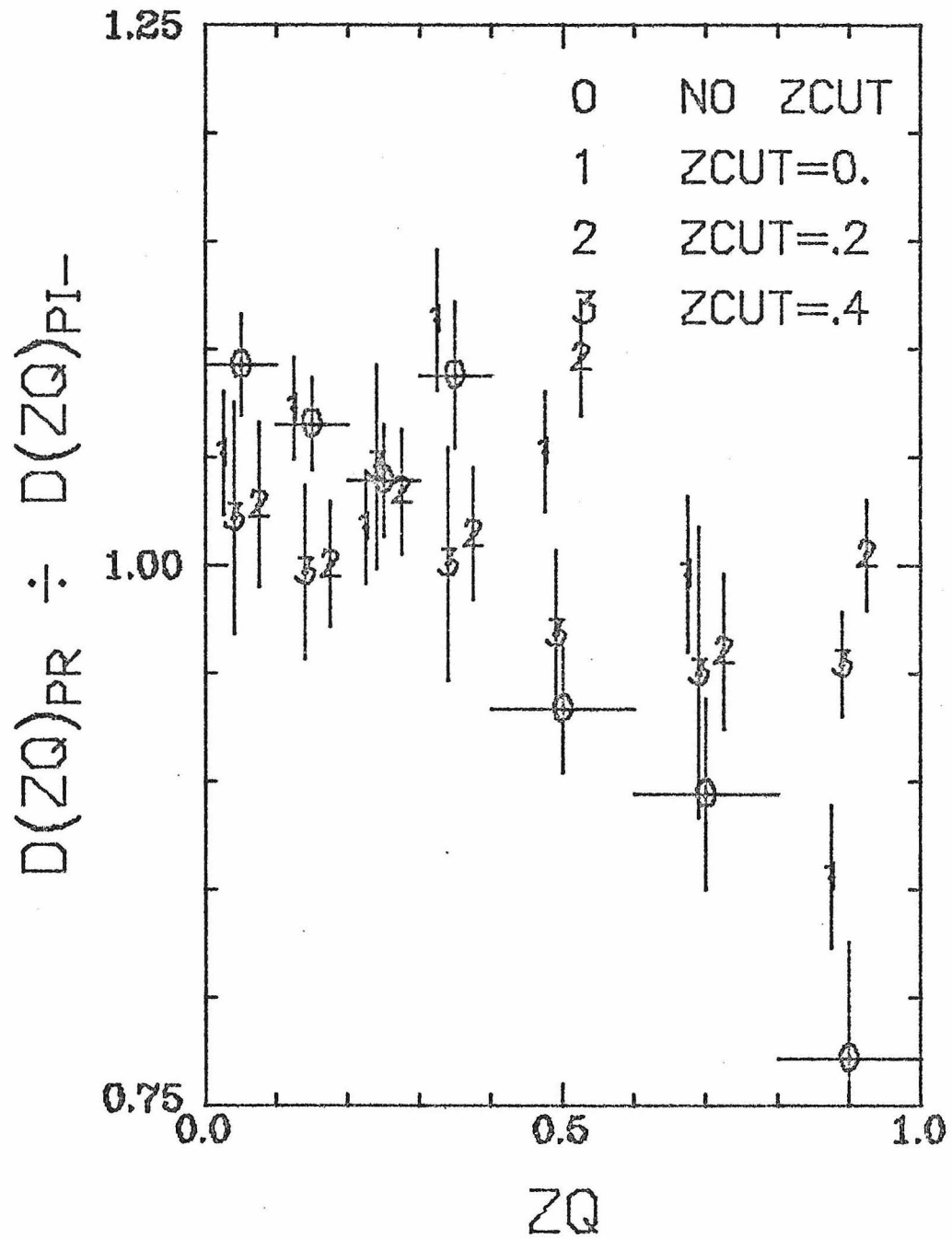


Figure 7.4b Proton over π^- , aluminium target.

PROTON BEAM

HIJET

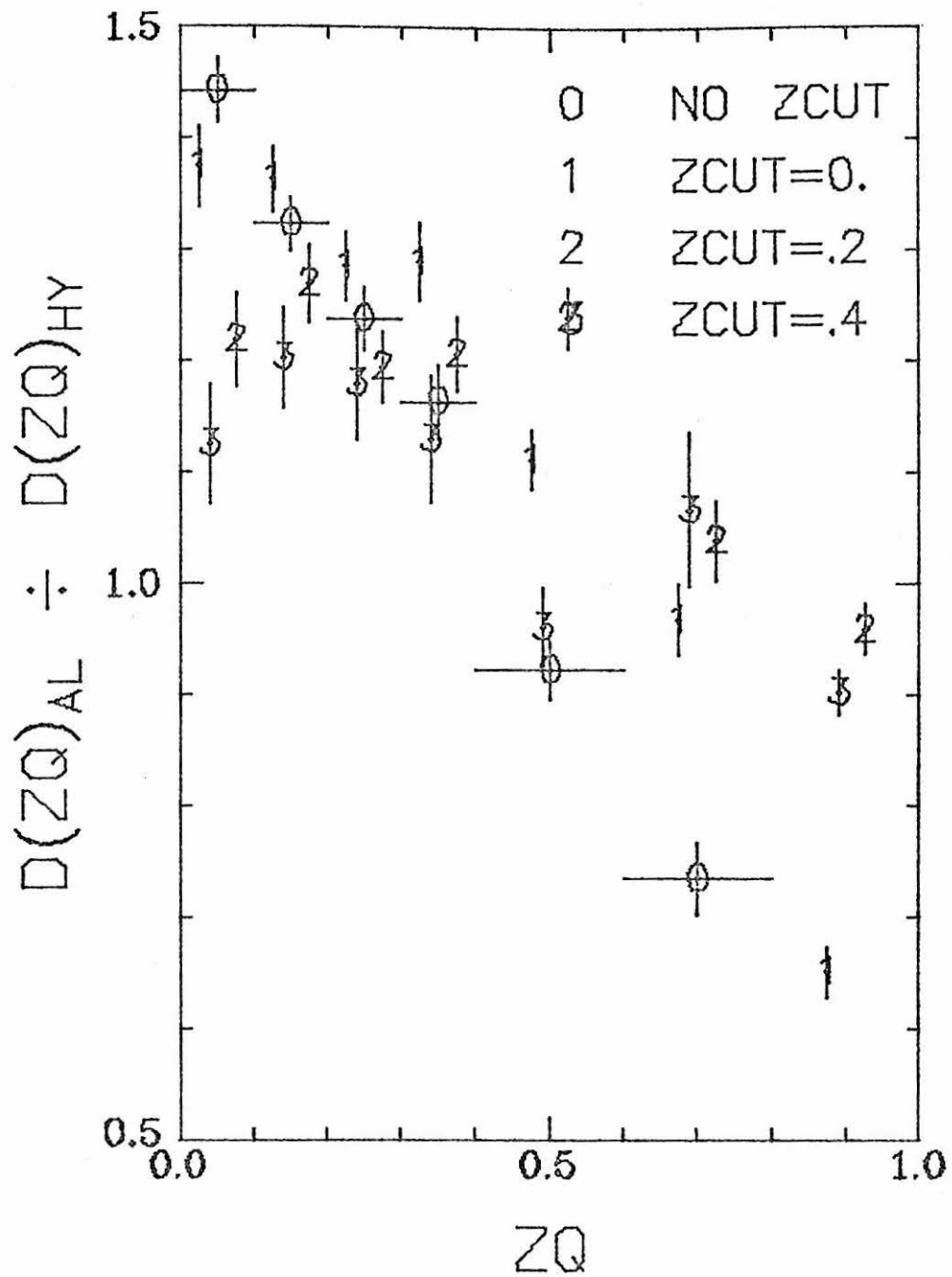
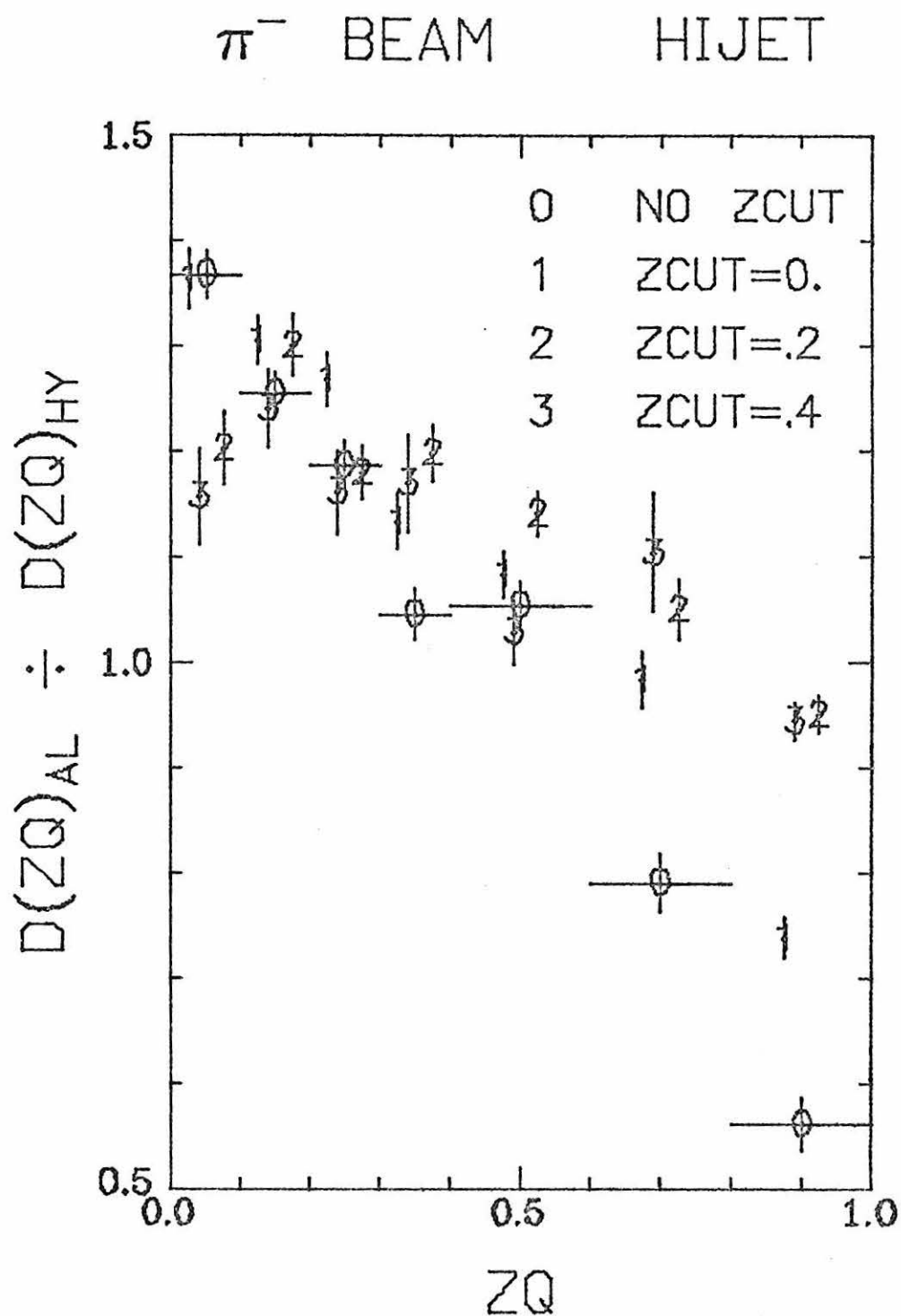


Figure 7.5a Aluminium over hydrogen,
proton beam.

Figure 7.5b Aluminium over hydrogen, π^- beam.