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HIGH TRANSVERSE ENERGY PROTON-NUCLEAR INTERACTIONS

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RICE UNIVERSITY

HIGH TRANSVERSE ENERGY PROTON-NUCLEAR INTERACTIONS

by

JAMES ALLEN RICE

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

DOCTOR OF PHILOSOPHY

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JUNE, 1983

ABSTRACT

High Transverse Energy Proton-Nuclear Interactions

by

James Allen Rice

A study of high transverse energy events resulting from 400 GeV protons scattering from targets of hydrogen, carbon, aluminum, copper, tin, and lead has been performed with the E609 apparatus at Fermilab. Wire chambers and a highly segmented calorimeter detect secondary particles. The use of efficient jet collecting triggers and of a beam jet calorimeter have been originally applied to nuclear target studies in this thesis. A^α scaling with hydrogen deviations is observed for E_T and planarity. The data provide evidence that A^α scaling results from multiple scattering.

Evidence for hadron jets is seen with a large solid angle calorimeter for all the targets when triggers requiring two high E_T single particles are employed. Jet cross-sections for nuclei are approximately determined herein. Jet event angular distributions possibly indicate that low and high transverse energy particles in jets from nuclei may result, in part, from different types of interactions.

ACKNOWLEDGEMENTS

A variety of fine people have helped me to reach this apex of formal education. I thank J. B. Roberts for encouraging me and supporting the subject of p-A scattering. I also thank the faculty and graduate students of Bonner Nuclear Lab who provided insights and questions.

I thank and love my wife, Paula, and daughter, Bobbie. Their patience has been beyond compare. Mom has been my stalwart supporter and source of comfort. I love her, too. I thank God for the opportunity to walk with such people as these.

All of my family, the Rice's, Mason's, Baldridge's, and so on, have been very helpful through the encouragement that they have provided over the years. The sine qua non of this thesis, and my studies in general, is Grandpa, alias J. G. Baldridge. His support has been essential, and joyfully given and accepted. I dedicate this thesis to Grandpa.

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CHAPTER 1

INTRODUCTION

1.1 Why Study Proton-Nuclear Collisions?

The study of hadron-nuclear scattering is receiving increasing attention. The experimental result that many cross-sections scale as a power of target atomic number, and that the power exceeds unity, has not been fully explained. In addition, there are theoretical predictions to be tested. These include effects of length scales in parton hadronization, phase transitions from hadronic matter to a quark-gluon plasma, and gluon enhancement by nuclear targets.

In the remainder of this introduction, the fundamental physics goals of testing the theoretical predictions are delineated. The likeliest explanation of the A^α enhancement is discussed both here and in chapter 2.

1.2 Parton Hadronization Lengths

The mechanism for the hadronization of hard-scattered quarks and gluons is of great interest. It must be understood before Quantum Chromodynamics (QCD) can attempt to account for the detailed structure of high transverse energy (E_T) events in a non-phenomenological way.

Hadron-nucleus collisions may provide insights concerning the space-time development of multiparticle production by scattered partons^{1,2}. The density of nuclear matter is sufficient that the probability of secondary interactions by the scattered partons is significant in large nuclei. This may allow information about the character of the scattered parton to be found (e.g. whether it is a quasi-free parton or is still part of a hadron at a distance of a few Fermi's).

In the string model of parton binding, there is never a "free" parton, i.e. a parton which is not bound directly to other partons in such a way as to form a neutral color field for the hadron required by the parton's existence. A displacement of about³ two Fermi's (1 Fermi = 10^{-13} cm) of a quark from its hadronic companion quark(s) creates sufficient potential energy to create a new hadron through the formation of a new quark and

anti-quark pair. This model implies that a hard collision, i.e. a collision yielding a large E_T , in a heavy nucleus could yield several mesons or other hadrons before the leading particle of the collision exits the nucleus^{4,5}.

In the relativistic view, sufficiently hard scattering of partons temporarily destroys the hadronic character of the initially confined states of the parton. This means that there is a net color charge carried by the parton, which for an estimable time is not neutralized by the color charges of other nearby partons. Hadronic properties are not restored for a time of order²

$$\Delta t = R_h/c = 3 \times 10^{-24} \text{ sec} ,$$

where R_h is the average hadron radius and c is the speed of light. During this time, the leading parton emerging from the scattering traverses a distance

$$d = \gamma \Delta t c ,$$

where γ is the relativistic Lorentz factor for the scattered parton as seen from the center-of-mass frame of the collision. For a 400 GeV proton beam, d is about 80 Fermi's in the nucleon-nucleon center-of-mass reference frame⁶. The largest nuclear diameters are about 15 Fermi's, therefore it would be anticipated that the study

of high transverse energy hadron-nucleus interactions would yield information on the interactions of free partons (non-neutral color fields) with nuclear matter. The data of this experiment may assist in theoretical testing of these models of parton hadronization.

1.3 Quark-Gluon Plasma

Thermodynamic calculations⁷⁻⁹ indicate that a phase transition from hadronic matter to a quark-gluon plasma occurs when the temperature inside a nucleus exceeds about 300 MeV per nucleon. One predicted signature¹⁰ of such an occurrence is that the production cross-section for lepton and anti-lepton pairs would scale with atomic number as A^2 . This scaling occurs if the struck nucleus becomes a "fireball" of quarks and gluons, as should occur if the mean free path in nuclear matter of partons emerging from hard collisions is on the order of one nucleon diameter. Since this implies a rise in the ratio of lepton pairs to all particles from 10^{-5} for hydrogen to 10^{-3} for lead, the effect is not easily detected by this experiment. The lepton pair fraction is overwhelmed by stray muon detection¹¹.

The many collisions implied by the plasma state imply an alternate signature. The production of isotropically shaped events should grow in similar proportion to the lepton pair production, since pair production is proportional to the number of collisions between partons in the plasma. The detectors of this experiment are more sensitive to event shape than particle identity. As will be shown in chapter 5, the cross-section for production of isotropically structured events varies as $A^{1.5}$ in high E_T events. It is not clear whether this could be a plasma signature (without detailed theoretical modeling), but it appears to rule out the A^2 signature hoped for at low planarity.

1.4 Gluon Enhancement by Nuclei

Due to multiple scattering and larger parton-gluon than parton-quark cross-sections, the production of gluon jets is enhanced relative to that of quark jets for larger nuclei¹². A hadron jet is a collimated cone of hadrons presumably resulting from the hadronization of a hard-scattered parton. Lowest order QCD contributions to hard parton-parton scattering are shown in figure 1. The color factor implies that

Figure 1: The first order QCD diagrams for parton-parton scattering are shown. Quarks appear as straight lines and gluons appear as springs. The interactions occur at quark-gluon and gluon-gluon vertices.

$$\sigma(gN) = (9/4) \sigma(qN)$$

for one hard collision, so that for n hard collisions,

$$\Sigma_n \sigma(gN) = (9/4)^n \Sigma_n \sigma(qN).$$

It is possible, therefore, to vary the relative rates of quark-hadron and gluon-hadron interactions. The variation of jet structure with atomic number, A , can thus test techniques for distinguishing quark and gluon jets, e.g. by leading particle flavor.

This experiment could detect the predicted enhancement of gluons by comparing the production of pions to kaons. Leading pions are believed to result from quark jets, while kaons result from gluon jets¹³. The pions decay electromagnetically before reaching the calorimeter, so the calorimeter forward layers could be deprived of energy by a gluon enhancement. This will be detailed in chapter 3.

1.5 A^α from Multiple Collisions

Secondary collisions¹⁴ of hard scattered partons flying through nuclear matter can contribute significantly to the nuclear high transverse energy cross-section. The basic secondary collision diagrams appear in figure 2. It is multiple scattering theory that has best

Figure 2: The lowest order multiple parton scattering diagrams are shown. (a) represents the interactions shown in figure 1 when they occur as a result of a proton-nuclear collision. (b) gives the form of multiple scattering which results when four independent partons, two from the beam particle and two from the target, experience two independent parton-parton scatterings. This is sometimes called a pseudo-jet event. (c) shows another multiple scattering mechanism, whereby the initial parton-parton scattering is followed by one of the initial partons hitting a third parton which can come from either the beam or the target particles.

explained the "anomalous nuclear enhancement" thusfar. The cross-section, σ , of hadron nuclear events can frequently be scaled with atomic number as

$$\sigma(E_T) = \sigma_0(A) A^{\alpha(E_T)},$$

where σ_0 is a constant for each nucleus, and σ and α can be functions of polar scattering angle and other variables, as well as E_T . This cross-section enhancement as a power of A is termed anomalous when the value of α exceeds unity.

The anomalous nuclear enhancement was first noted in the cross-sections for production of high E_T hadrons of a particular species¹⁵. It has also been found for multiplicities of particles produced at wide angles¹⁶ and for large aperture calorimeter detection of high transverse energy events¹⁷. The magnitude of α is found to increase as E_T and scattering angle increase.

This experiment seeks to test the multiple scattering model. Among the predictions of such a model are that multiplicities of secondary particles grow as A increases, the cross-sections for isotropic event production increase with A , and the energy transmitted parallel to the particle beam decreases as A increases.

The experiment described herein should help to clarify the mechanism(s) involved in producing the anomalous nuclear enhancement. The five triggers used comprise a diverse set. They are detailed in chapter 3. Six nuclear targets are employed. These are listed and described in table 1. Wire chambers enable charged particle tracking. A beam calorimeter detecting the energy of the beam jet augments the detector system. This is then a very powerful detector apparatus and the beam energy is the highest available for fixed target studies. This allows the experiment to have the goals of both confirming all existing 400 GeV protons on nuclei data and searching for new phenomena with the new detection capabilities of varied triggers and a beam calorimeter. The data provided form a substantial test for any theory seeking to explain the anomalous nuclear enhancement, the hydrogen deviation from A^α extrapolations, and the beam jet phenomena to be shown in the data presented.

Table 1: The targets employed are listed. The actual thicknesses of the targets and their thicknesses in nuclei/cm² are shown.

TARGET	AT.NO.	THICKNESS(cm)	THICKNESS(N/cm ²)
Hydrogen(H)	1.008	45.72	1.934×10^{24}
Carbon(C)	12.01	1.276	9.916×10^{22}
Aluminum(Al)	26.98	.9677	5.831×10^{22}
Copper(Cu)	63.55	.3602	3.058×10^{22}
Tin(Sn)	118.7	.2985	1.107×10^{22}
Lead(Pb)	207.2	.3653	1.205×10^{22}

CHAPTER 2

THEORY

2.1 Multiple Nucleon Scattering

The theories expounded in attempts to explain hadron-nuclear scattering phenomena are varied in philosophy; however, all contain the idea of multiple scattering of the incident particle by the constituents of the nucleus. Elias et al.¹⁶ wrote a theory for multiple nucleon scattering, which I have generalized for variable event E_T .

Elias et al. present a theory based on multiple nucleon-nucleon scattering. The phrase "thickness of nuclear matter traversed" will refer to the nuclear target density integrated along the beam direction. It is a function of impact parameter. The mean thickness of nuclear matter traversed, L , by a high energy incident proton is

$$L = \int_{-\infty}^{\infty} \rho(b, z) dz ,$$

where the density of nucleons, ρ , expressed as a function of impact parameter, b , and distance parallel to the beam, z , is approximately of the form¹⁸

$$\rho(R) = \rho_0 / (1 + \exp(R/a - c/a))$$

where $R = (b^2 + z^2)^{0.5}$, nucleon radius $a = 0.54F$, nuclear radius $c = (.978A^{1/3} + .0206A^{2/3})F$, and nucleon normalization density

$$\rho_0 = 3A / (4\pi c^3 (1 + \pi^2 a^2 / c^2))$$

in nucleons per cubic Fermi. Then the cross-section for ν collisions for an incident nucleon is

$$\sigma(\nu) = (\pi/\nu!) \int_0^\infty (\sigma_N L)^\nu e^{-\sigma_N L} db^2,$$

and the total cross-section is

$$\sigma_A = \int_0^\infty (1 - e^{-\sigma_N L}) db^2.$$

The probability of ν collisions is then

$$P_A(\nu) = \sigma(\nu) / \sigma_A.$$

Results of this model are indicated in reference 16 and in Table 2 of this thesis.

2.2 Generalization for E_T Variation

I now generalize this formulation to calculate cross-sections as a function of transverse energy. The proton-proton cross-section has been measured for E_T triggers of fixed solid angle at 400 GeV by E557¹⁹ and

Table 2: The results of multiple scattering models for nucleons striking nuclei at high energies are summarized. The mean thickness of nuclear matter presented by a target, L , is given in nucleons per unit area, and the mean number of nucleon-nucleon collisions as the proton traverses the nucleus is shown as ν . The nuclear radius is in Fermi's (10^{-13} cm).

TARGET	RADIUS(F)	ν	$L(F^{-2})$
H	1.0	1.00	0.88
C	2.3	1.38	2.11
Al	3.0	1.62	2.69
Cu	4.0	1.97	3.46
Sn	4.9	2.27	4.11
Pb	5.9	2.62	4.76

E609²⁰ at Fermilab. For E_T in the range of 5 to 15 GeV, the NA5²¹ nucleon-nucleon cross-section can be parameterized as

$$\sigma_N = \sigma_0 e^{-mE_T},$$

where for 8 steradian (sr) global triggers, $m=0.9/\text{GeV}$. Note that E609 differs in that m is a function of E_T for the p-p data in this E_T range. Note that the results shown in figure 4 depend sensitively on the form of the cross-section parameterization in E_T . Double arm (4 sr) and single arm (2 sr) triggers have steeper slopes, yielding $m=1.5/\text{GeV}$ and $2.3/\text{GeV}$, respectively. The cross-section is generalized to vary with E_T by considering all possible combinations of nucleon-nucleon interactions in a given event that will yield the desired total E_T . The generalized cross-section as a function of the number of nucleon-nucleon collisions and resulting event transverse energy then takes the form

$$\begin{aligned} \sigma(\nu, E_T) &= (2\pi/\nu!) \int_0^\infty \left\{ \int_0^{E_T} \int_0^{E_T-X_1} \int_0^{E_T-X_1-X_2} \dots \int_0^{E_T-\sum_{i=1}^{\nu} X_i} \right. \\ &\quad \sigma(X_1) \sigma(X_2) \dots \sigma(X_{\nu-1}) \sigma(E_T - \sum_{i=1}^{\nu-1} X_i) \\ &\quad \left. dX_1 dX_2 \dots dX_{\nu-1} \right\} L^\nu e^{L[-\int_0^\infty \sigma_0 e^{-mE_T} dE_T]} bdb \\ &= (2\pi/\nu!) \sigma_0 e^{-mE_T} ((\sigma_0 E_T)^{\nu-1}/(\nu-1)!) \\ &\quad \times \int_0^\infty L^\nu e^{-L \int_0^\infty \sigma_0 e^{-mE_T} dE_T} bdb. \end{aligned}$$

Therefore,

$$\sigma_A(E_T) = \sigma_A \frac{\sum_{\nu=1}^A (\sigma_0 P_A(\nu) E_T^{\nu-1} e^{-mE_T})}{\left(\int_0^\infty \sigma_0 e^{-mE_T} dE_T (\nu-1)! \right)},$$

where σ_0 is the high energy nucleon-nucleon cross-section, which is²² 38 mb (1 mb = 10^{-27} cm²). The dependence of the nuclear cross-section on the slope of the nucleon E_T cross-section implies that $\sigma_A(E_T)$ is directly proportional to e^{-mE_T} . This model does not require A^α scaling, but does yield such scaling to a reasonable accuracy as shown in figure 3. The behavior of this model for α versus E_T is shown in figure 4.

Figure 3: The atomic number dependence of cross-sections for various event transverse energies is calculated with my multiple scattering model.

Mult. Collision Model (N-N)

- ET=0 GeV
- ET=5 GeV
- △ ET=10 GeV

Figure 4: The α from the A^α fit to the A=12-207 cross-sections calculated as functions of E_T with the multiple collision model for nucleon-nucleon scattering.

CHAPTER 3

DETECTORS AND EXPERIMENTAL PROCEDURE

3.1 The E609 Detector Apparatus

The data presented in subsequent chapters were obtained in May of 1982. The E609 apparatus at the Fermi National Accelerator Laboratory (Fermilab) was employed. It was stationed on the Meson-6-West beam line.

An overview of the E609 detector system appears in figure 5. The proton beam steering magnet string extended from just upstream of the shielding blocks, over a distance of a few hundred yards, to the Meson-6-West beam line scattering target that scattered a fraction of the total Meson Lab beam into this particular beam line. The **M6** magnet string was tuned and controlled by E609 to allow variation of beam energy (by the strength of bending magnetic fields) and intensity (by the aperture size of collimators). Beam Cherenkov detectors tagged beam particle identities. At 400 GeV, only proton beams are

Figure 5: An overview of the E609 detector system is shown. A description is provided in the text.

available in Meson-6-West. For the nuclear target runs that this thesis studies, a standard 400 GeV proton beam tune was used. Three beam line bends filtered the beam for momentum resolution on the order of one percent.

The beam passed along a vacuum pipe through iron and concrete shielding blocks. Stray particles produced at the Meson-6-West target, by beam particle - beam pipe collisions, in interactions at other experimental sites, and from cosmic rays, yielded a high background. The shielding blocks stopped all stray particles except muons and cosmic rays. Muon veto counters in the shielding covered the area of the calorimeter face. These vetoed events in which stray muons from beam line sources would hit the calorimeter. Cosmic ray rates were observed to be negligible as compared to target data rates, the ratio being about 10^{-3} . Between the end of the vacuum pipe and the hydrogen target vessel, a series of scintillator telescopes determined when a 400 GeV beam proton impinged on the target. The number of these so-called "live beam triggers" was recorded on scalars and written to tape with the data. Thus a continuously updated number of potentially interacting beam particles was supplied. The beam particles then went through the target, which was

liquid hydrogen or a solid A>1 target. For the A>1 target runs, the vessel of the three inch diameter liquid hydrogen target was emptied by allowing it to warm up to liquid nitrogen temperatures. A three inch square nuclear target foil was then placed in a mounting frame at a distance of eight and one-half inches upstream of the first wire plane of the Proportional Wire Chamber (PWC). (In this thesis, the term chamber frequently refers to the gas-tight box in which wire planes are contained.) Thus there can be more than one wire plane in a chamber. The beam diameter was tuned to 1.5 centimeters and its centering was monitored by a SWIC wire chamber placed just upstream of the hydrogen target. The PWC also showed the beam to be on axis, so it is known that the beam was centered on the targets. The PWC consisted of three wire planes at plus and minus fifteen degrees and zero degrees relative to the vertical. The wire planes were transverse to the beam axis. The passage of a charged particle near a given wire or between two wires was registered in each plane. The Cherenkov detector, used for flavor identification, was not in place during the nuclear target runs. This device slowed statistical accumulation rates by a factor of five, and the limited

time allowed for this study dictated its removal. Removal of the CID allowed an additional drift chamber with two wire planes to be placed between the PWC and the next drift chamber. Downstream of the PWC, drift chambers (DC) further located and counted charged particles. Four planes of wires in the first two drift chambers yielded horizontal position (x) information. Downstream of these first two drift chambers and upstream of the bending magnet was a drift chamber wire plane and a delay line chamber (DLC). The wire that registers a hit gives a particle's x location, while the time difference for the signals arriving at the top and bottom of the chamber on the delay line gives the y coordinate.

The particles then pass through the field of the bending magnet. The purpose of this magnet is to reveal the sign of the charge of particles passing through it by the direction in which they bend, and to provide their momentum by the magnitude of the bending angle. For the nuclear target runs, the magnet current was reduced to a level where only a 10 MeV kick was given to such particles. The magnetic field was reduced to this level so as not to differently influence the events from targets with large positive charge which might yield many more

positive secondaries relative to negative secondaries. The field was left on at a lowered level, which was too small to influence the E_T of the particles to within the resolution of the calorimeter, in order to sweep the beam line clear of drifting electrons resulting from ionizing interactions of the beam with the targets and chambers. This allowed a check of wire chambers before and after the magnet to insure that multiplicities were not overestimated. No measureable numbers of such electrons were detected.

Downstream of the magnet were four more planes of drift chamber wires in two drift chambers. One more plane of DC wires and one plane of delay line chamber wires were in another chamber. Following the chambers was the highly segmented triggering calorimeter surrounding the beam axis. A four by four inch beam hole through the center of this calorimeter lead to the beam hole calorimeter, which was the most downstream element of the detector system. Both calorimeters represent about eight interaction lengths for incoming hadrons, so that only a very small percentage of the energy of the secondaries leaks out the back. Of course, some energy leakage out of the sides also occurs, although it is thought to be of

lesser magnitude than that lost out the back since segments are telescopically growing to fill the same solid angles at the back of the calorimeter as at its front. This is complicated by the fact that angular distributions grow wider for increasing target atomic number, so that the outer calorimeter rings grow in importance. The beam calorimeter consisted of two modules in the segment comprising the front half of the calorimeter and two modules in the back segment. Only front to back energy loss information is available, and there is no transverse energy information in the beam hole calorimeter. Table 3 gives the polar angle range covered by the primary detectors. All detectors cover the full azimuthal angle about the beam axis.

3.2 The Primary Calorimeter

The triggering calorimeter, hereafter often referred to simply as the calorimeter, is the centerpiece of the E609 detector apparatus. A front view in figure 6 reveals the 132 segment face of the calorimeter. The angles shown are in the nucleon-nucleon center-of-mass reference frame. These are appropriate to the proton beam on the hydrogen target at the hydrogen target position. Each

Table 3: The angular acceptance ranges for the various detectors are given. η is pseudorapidity, which is defined¹⁶ as $\eta = -\ln(\tan(\theta_{\text{lab}}/2))$ for polar scattering angle in the lab frame θ_{lab} . Calorimeter ranges are given in degrees for lab angle θ_{lab} and p-p center-of-mass angle θ^* .

DETECTOR	H TARGET	A>1 TARGETS
Proportional		
Wire Chamber	$1.8 < \eta < 5.1$	$0.6 < \eta < 3.5$
Triggering		
	$.55 < \theta_{\text{lab}} < 8.22$	$.62 < \theta_{\text{lab}} < 9.16$
Calorimeter	$30.1 < \theta^* < 125.2$	$33.3 < \theta^* < 134.4$
Beam-Hole		
	$\theta < .827$	$\theta < .924$
Calorimeter	$\theta^* < 46.7$	$\theta^* < 49.1$

(Note that the Bcal acceptance is limited by the beam hole through the triggering calorimeter.)

Figure 6: The front of the 132 segment triggering calorimeter is shown. The angles given are the azimuthal angles of the nucleon-nucleon center of mass.

segment occupied about 0.06 steradians in this reference frame. The calorimeter is further subdivided into four layers along the beam line. Thus each segment consisted of four modules. The modules increased in size from the front to the back of the calorimeter, so that each calorimeter segment pointed toward the target, and conically increased to fill the same solid angle at the back of the calorimeter as at its face. There are then 528 modules, each of which is individually monitored by a two inch photomultiplier tube. The PMT signal is digitized by an ADC and recorded for each module in each event.

Figure 7 indicates the layered structure of the calorimeter and the target positions relative to the calorimeter. The A' layer consists of lead-scintillator sandwiches which detect the showers of electromagnetic particles, such as electrons, direct photons, and photons resulting from π^0 decay. Most short lived mesons, such as the ρ and the J/ψ , decay predominantly into pions and photons. Excited baryon states also frequently decay with pion emission. It is estimated that about 1/3 of the particles produced may be detected electromagnetically. This estimate results from single particle cross-sections¹⁵ for baryons and for short-lived mesons

Figure 7: An oblique view of the calorimeter showing its position relative to the targets and its layered structure is shown.

with known decay modes. Steel has four times the radiation length of lead ($1.8\text{cm}/.5\text{cm}$). Steel and lead have about the same nuclear collision length ($10.2\text{cm}/9.8\text{cm}$). Therefore, electrons and photons, which lose energy primarily by radiation at energies of several GeV, deposit most of their energy within a few centimeters of lead. The hadrons lose energy primarily through strong interaction collisions. They usually pass through the few centimeters of lead. About fifty centimeters of steel is required to ensure detection of nearly all of the hadron's energy. The lead and steel are in sheets a few millimeters thick in the calorimeter and alternate with thin sheets of plastic scintillator material. The lead forward layer of the calorimeter allows electromagnetically collected energy to be separated to a degree from hadronically collected energy. The electromagnetically detected particles deposit their energy in a statistical distribution that on average deploys equal energies in the A' (lead) and A (steel) layers. The hadronically detected particles deposit little energy in the A' layer, about half in the A layer, and the rest in the B and C (steel) layers. The electromagnetically radiating particles give off energy in the form of radiated photons that

ionize lead-bound electrons or pass into the scintillator. The electrons also radiate photons and ionize other electrons in the scintillator. The hadrons generally collide with a nucleus and induce a multi-particle hadron shower. The shower hadrons are of lower energy than the initial hadron, and thus have a greater cross-section for secondary nuclear collisions and a higher ionization energy loss rate. Eventually, most of the initial hadron's energy is lost in electron ionization by secondary hadrons, and the ionized electrons, photons radiated by the charged hadrons, and directly produced photons are detected in the scintillators interspersed with the steel plates.

The calorimeter's energy scale was calibrated by steering muons of known energies into each segment, then hadrons of known energies, for a range of 10-20 GeV in the outer segments, 10-120 GeV for the inner segments, and 10-40 GeV in central segments. The muons deposit minimum ionizing energy in each module, interacting only electromagnetically. The hadrons deposit only ionizing energy until they experience a strong interaction collision. They then deposit most of their energy in a short distance, usually one or two modules²³. The details of

the calibration are provided in reference 23. Calorimeter module-balancing gain factors have been derived from the muon calibration in reference 23. The stability of the calorimeter modules to the energy calibration was continuously monitored with LED signal inputs to the scintillators of the module. This system is detailed in the literature²⁴. The basic electronics outlay of the calorimeter appears in figure 8. The signals from each segment are summed and multiplied by the sine of the polar angle from the beam axis of that segment. These E_T estimates are then input to the trigger matrix. Event recording is latched when one or more of the triggers are satisfied. All the triggers operate simultaneously to maximize statistics. The event recording system is initialized when a live beam particle trigger occurs. This is called a pretrigger in the diagram. Recording an event required about 1msec to read all wire chamber hits, all calorimeter module energies, and all beam calorimeter module energies. The data is processed by a PDP-11 mini-computer and written to magnetic tape.

3.3 Experimental Procedure and Triggers

Figure 8: The basic electronics used in collecting data with the calorimeter appear. The electronics system is discussed in the text.

A 400 GeV proton beam impinged on a target consisting of liquid hydrogen or a solid foil of carbon, aluminum, copper, tin, or lead. The targets are abbreviated as H, C, Al, Cu, Sn, and Pb, respectively. The target thicknesses were given in Table 1 of Chapter 1. The targets were placed at distances of 6.22 meters upstream of the calorimeter face for hydrogen, and 5.49 meters upstream of the calorimeter face for the solid foil targets. Target positions relative to the triggering calorimeter were shown in figure 7. The angular acceptances were detailed in Table 3. All cross-sections for hydrogen as functions of the energy of all or part of the triggering calorimeter have been increased by 5%. This corrected for the smaller acceptance of the calorimeter for H than $A > 1$ targets. Note that sine module signal attenuators had the same on-line value for all targets, but that corrected sine values were used for each target in the analysis. These values were corrected on a module by module basis since the modules of each segment were aligned differently for the different target positions. The PWC had a 1/2 inch diameter beam hole. Because the nuclear targets were much nearer to the PWC than the H target was, the PWC acceptance was different. An

analysis of the acceptance from table 3 and the angular distributions given in reference 16 yielded a 25% correction factor. All multiplicities for $A > 1$ targets have been increased by 25% to correct for the different acceptance angles of the PWC. This factor was determined by analysis of the particle distributions given in reference 16, and correlations between multiplicities in the PWC and the most downstream DLC. The beam calorimeter energies for hydrogen have been increased by 10% to correct for the reduction in acceptance angle for that detector. This factor resulted from the acceptance differences given in table 3 and an assumption of uniform average energy distributions over the face of the beam calorimeter.

The p-A study employed five calorimeter triggers. Three looked for high E_T signals in specific geometrical regions of the calorimeter, while the other two required both the transverse energy and the multiplicity of segments hit to satisfy selected constraints. The triggers are detailed below, with their abbreviations in parentheses.

(1) A global trigger (G) selected all events depositing E_T greater than or equal to a specified threshold in the entire calorimeter. The calorimeter occupies 8

steradians (sr) in the nucleon-nucleon center of mass frame of the hydrogen target. The threshold is typically about 10 GeV.

(2) A double arm trigger (DA) tagged events for recording when they deposited an E_T above a threshold in a region comprised by two coplanar wedges of segments at azimuthal angles (ϕ) of 0 and 180 degrees. Each wedge filled 2 sr in the nucleon-nucleon center of mass frame, for a total trigger region solid angle of 4 sr. The threshold of required E_T is usually slightly more than half that required by the global trigger.

(3) A single arm trigger (SA) operated just as the double arm trigger, but only uses the ϕ equals 0 degrees wedge. Thus the total trigger solid angle is 2 sr. The threshold E_T required in this region for an event to trigger is a little over half that for the DA threshold, typically.

(4) The two high transverse energy particles trigger (2HI) records those events which fire two or more segments anywhere on the face of the calorimeter with an E_T exceeding a set threshold. The threshold E_T level for each of the two segments is typically one GeV. This trigger is interesting because it yields high planarity

events, but has no geometrical bias.

(5) The low multiplicity global trigger (LMG) rewards events linearly for E_T deposited in the calorimeter, and penalizes them with a different linear coefficient for the multiplicity of segments firing with E_T in excess of about 0.4 GeV. The reward has the penalty subtracted from it, and the result must exceed a threshold value for the event to be recorded. The trigger region requirement can be expressed as

$$E_{T\text{tot}} - 0.4 \times N_{\text{seg}}(>0.4) > 5 \text{ GeV} .$$

The targets were exposed to the proton beam for about one hour of real time each. The order of target exposure was Cu, Pb, C, Al, Sn, empty target holders, then H. Three runs were taken for each target. First the calorimeter module pedestal energies were recorded. The first data run was then a beam trigger run in which 3000 events per target were recorded where the pretrigger of a live beam particle acted as the trigger to record data. These runs enabled an updated calibration of the beam calorimeter for each target. The total scattering cross-section could also have been estimated from these runs, as could very low E_T cross-sections. The former by looking for tracks in the wire chambers (bubble chamber

cross-sections would be more accurate), and the latter by seeking calorimeter signals. Neither of these was performed since the former is well-known and there were low statistics and no QCD motivation to study the latter.

Each trigger had a threshold setting that its summed electrical inputs was required to exceed before it would cause an event to be recorded. The value of the threshold determined the lower limit of the transverse energy region that would be explored by that trigger. The upper limit was a result of the rapid fall of cross-sections with increasing transverse energy and the limited number of events attainable for each trigger and target during the time allotted for p-A data collection. I now summarize the threshold settings for the data to be presented in Chapter 4. The low multiplicity global trigger required that the total E_T (in GeV) in the entire triggering calorimeter, minus a product of 0.4 GeV times the number of segments with E_T in excess of 0.4 GeV, be greater than 5 GeV. The two high E_T trigger threshold required only that at least two segments anywhere in the calorimeter detect E_T values of 1.2 GeV or higher. The global, double arm, and single arm triggers were operated at two levels. The "low threshold" values required E_T to

be at least 9, 5, and 3 GeV, respectively, in the triggering regions that occupied 8 sr, 4 sr, and 2 sr, respectively. The "high threshold" runs required 12, 6, and 4 GeV, in each of the respective triggering regions of the G, DA, and SA triggers. During the data collection, the second run made employed the constant thresholds of the LMG and 2HI triggers, and the low threshold settings for the G, DA, and SA triggers. This run collected about 3000 events per target, with nearly all the events shared among the latter three triggers. The purpose of this run was to extend the E_T range that the data would cover for those triggers. The third run used the constant LMG and 2HI thresholds, and the high threshold settings for the G, DA, and SA triggers. This run collected about 8000 events per target, spread evenly among all five triggers. In addition to the three runs of the types described above that were made for each of the six targets, all three run types were repeated with the hydrogen target vessel drained and with no solid foil target in place. This "empty target" run was made in order to measure the rate of background events due to scatterings in upstream scintillators and air that yielded falsely high E_T events as a result of geometrical

effects, and which in any case did not come from the target of interest. The calorimeter segments detected total energy at various polar and azimuthal angles. The energy signal was then electronically multiplied by the sine of the polar angle of the segment from the beam axis to give E_T . Events occurring upstream of the target region for which the polar angle of the electronic sine multiplication was appropriate, were given falsely high E_T because their actual polar angle was smaller than that accorded in the electronic calculation of E_T . This caused enhanced background levels since all cross-sections increase as actual E_T decreases. The observed background levels relative to events originating in the targets is about one in eight, after stray muon removal. For all data, muons are removed in software by requiring charged multiplicity to exceed two and planarity to be less than 1.000. The empty target runs were normalized to the beam particle flux of each target and run, and were then subtracted from the appropriate target runs. The statistical levels of the empty target and target runs were roughly equal, so that the statistical accuracy of the final cross-sections obtained is reduced only by the loss of events in the subtraction.

3.4 Data Analysis Considerations

The recorded data has been processed on the Fermilab Cyber and the Rice VAX computers into final cross-sections and multiplicities. The charged multiplicities have been obtained by comparing corrected PWC multiplicities, given by total wires hit divided by the number of wire planes times the previously noted factor of 1.25 for $A > 1$, and the multiplicities of the last DLC, given by total wires hit divided by the number of wire planes. These values are consistent with an accuracy of 4% averaged over all triggers. Therefore, an estimated accuracy of 5%, with a possible systematic error of 5% from reference 16, applies to the charged multiplicities given. It is likelier that the multiplicity is underestimated than overestimated due to particles at wider angles, which hit forward planes and miss downstream planes, since double firing by wires near a particle is often detected and can be statistically subtracted. The muon calibration correction factors from reference 23 were applied to the calorimeter modules and all triggers were then reapplied in software.

The particle energies registered by the calorimeter are accurate only to the resolution of the calorimeter,

which depends on its thickness and efficiency of energy loss detection. The beam calorimeter was calibrated with muon and hadron beams over a broad energy range, and its resolution has been found²⁵ as

$$\sigma E^{-1} = 110\%/\sqrt{E} + 3\% ,$$

where 3% is a systematic distribution width and E is the energy of the particle or jet hitting the beam calorimeter in GeV. The resolution of the triggering calorimeter was determined in reference 23 to be

$$\sigma E^{-1} = 90\%/\sqrt{E} + 1\% ,$$

where 1% is a systematic distribution width and E is the energy incident upon the calorimeter. Systematic errors in energy calibrations leave uncertainties in the energy scales for the cross-sections. The triggering calorimeter has only a 1% systematic distribution width error; however, the triggering calorimeter was calibrated by a formula that consistently underestimated the energy deposit required to produce an observed calorimeter response. The final energy scale, agreed upon by the E609 collaborators²⁶, multiplied the calibration energy scale by 5/4. Systematic errors have been estimated to be of 7% in the calorimeter energy scale²⁷. This error of scale does not affect the general results, but must be

considered when comparing E609 data with other experiments or with theoretical computations.

CHAPTER 4

COMPARISONS OF DATA FROM DIFFERENT TARGETS

4.1 Detector Performance

The data of this experiment represent a uniquely large and diverse sample of high transverse energy proton-nuclear collisions. Due to the large number of targets, triggers, and measured parameters, it is not instructive to show all of the raw data curves. As an orientation, I show the effects on various observables of multiple nucleon versus single nucleon targets. In particular, hydrogen and lead are compared in detail for events taken with a 400 GeV proton incident beam. The global and two high E_T triggers are primarily considered. They are effectively large multiplicity and high planarity triggers, respectively, and trigger on much different types of events. Later in this chapter, data for all targets and triggers appears.

As discussed in Chapter 3, the triggering calorimeter consists of 132 segments of about 0.06 sr solid angle each, in the p-p center-of-mass frame. Assuming an isotropic particle distribution, the small solid angle of a given segment implies that it is probabilistically favored for not more than one particle to land in a given segment. Correlations in particle scattering directions increase the probability for particles to land near one another. Energy sharing between segments due to particles landing in or near the seams between segments and shower spreading complicate the picture. Several adjacent segments, if all hit in a given event, can enhance the total energy that some of the segments receive due to cross-leakage of shower particles and photons. A particle landing between segments shares its energy with both, so that either segment alone underestimates the energy of the particle. Nevertheless, the calorimeter must behave in the same way for all of the various nuclear targets. The above difficulties and the effect of the multiplicity of particles produced in a given event on them must be considered when drawing conclusions about signals from individual segments. The multiplicity increases as the atomic number, A , of the target increases, so that more

segment energy enhancement due to cross-leakage could occur for high A targets.

4.2 Comparisons of Hydrogen and Lead

In the following discussion, lead and hydrogen curves for figures 9-16 are normalized so that the area under the hydrogen curve equals that under the lead curve. This is done for convenience in making comparisons. The relative sizes of the actual curves are given in the form of cross-sections in later figures.

In figure 9, the distribution of the transverse energies (E_T) detected by individual calorimeter segments is shown. The lead and hydrogen curves are normalized to subtend the same area underneath, and the data considered are high threshold globally triggered events. The average E_T in a hit segment is 0.125 GeV for hydrogen and 0.123 GeV for lead. The statistical errors in these means are 0.001.

The charged particle multiplicity (N_{ch}) distributions, calculated from PWC and DLC data, are shown in figure 10(a) for the high threshold global trigger. The mean charged multiplicities are 16.5 for H and 32.1 for Pb with statistical errors of 0.8 and 1.0, respectively.

Figure 9: The spectrum of tranverse energy deposited in single calorimeter segments is shown for hydrogen and lead from global trigger data. Errors do not show up on this scale.

Figure 10: The charged particle multiplicity distributions for hydrogen and lead appear for the (a) global and (b) two high E_T triggers.

a. Global; Nch

b. Two High ET; Nch

□ Hydrogen
○ Lead

Thus lead typically has twice as many particles as hydrogen in high E_T global events. In figure 10(b), the two high E_T trigger charged particle multiplicity distribution appears. The mean charged multiplicities are $10.6 \pm .2$ for H and $26.9 \pm .8$ for Pb. Thus the two high E_T trigger serves to reduce the N_{ch} of H and Pb from the global levels by about six particles for each target.

Observations of PWC data imply that angular distributions of particles in high E_T events broaden as target A increases, with roughly equal numbers of particles for all targets in the $\eta > 3$ angular region, but rapidly increasing multiplicity in the $\eta < 2$ region as atomic number, A , increases. This agrees with the results of other high E_T experiments²⁸. Pseudorapidity η equal to 2 means that laboratory frame angle θ is 15.4 degrees, while $\eta=3$ implies that $\theta=5.7$ deg. Large η means small θ and vice versa. Mathematically, $\eta = -\log(\tan(\theta/2))$. The same type of broadening, where nuclear multiplicities are enhanced mainly by production in the $\eta < 2$ region, are observed in hodoscope¹⁶ and bubble chamber^{29,30} studies. This implies that most of the multiplicity enhancement of the nuclear targets misses the triggering calorimeter, which covers η down to about 2.7 only.

In figure 11(a), lead and hydrogen are compared on the basis of the number of segments in a given event which fire with $E_T > 0.2 \text{ GeV}$. The number of such segments is greater for lead than for hydrogen in a typical event. On average, there are 18 ± 5 such segments for hydrogen and 20 ± 5 for lead. In figure 11(b), a similar pair of curves is shown for the two high E_T trigger. This trigger requires two segments with $E_T > 1.2 \text{ GeV}$, and as would be expected by energy conservation, the number of high E_T secondaries is reduced from that in the global case. Interestingly, lead still averages more segments with $E_T > 0.2 \text{ GeV}$ than hydrogen, those averages being 12.3 ± 4 and 8.7 ± 2 , respectively.

The global trigger fires when the total transverse energy in the entire calorimeter exceeds a set threshold. In figure 12, the high threshold runs for hydrogen and lead targets are compared as functions of calorimeter E_T . The curves are normalized to subtend equal areas underneath, but there are actually many more lead events than hydrogen events, so that the two curves meet at 12 GeV in the raw data. Actual cross-sections appear later in this chapter. Even with the same electronic triggering threshold value, the trigger bias affects events of much

Figure 11: The number of events in which a given number of calorimeter segments detected $E_T > 0.2$ GeV is shown as a function of the number of such segments. Part (a) gives global trigger data, while (b) is from two high E_T data.

a. Global; $ET(seg) > .2$

□ Hydrogen
○ Lead

b. Two High ET; $ET(seg) > .2$

□ Hydrogen
○ Lead

Figure 12: The distribution of the E_T detected in the 8 sr calorimeter appears for global trigger hydrogen and lead data.

Global; ET total

□ Hydrogen
○ Lead

higher E_T for lead than for hydrogen. The mean E_T values for H and Pb are $13.3 \pm .4$ and $15.7 \pm .3$ GeV.

The same electronic triggering threshold value is required for both targets. A difference in the effective threshold of about 3 GeV is apparent in figure 12. A 2.0 GeV difference resulted from different target positions. The different calorimeter solid angles have already been corrected for by the 5% E_T factor. The 2.0 GeV gap comes from differences in the actual sine theta values which were not reflected in the electronic sine theta values used by the triggers, which were the same for H and Pb. About 1.0 GeV of the threshold gap results from wider angular distributions of the particles scattered from Pb. This causes the effective solid angle of the triggering regions to be smaller for lead than hydrogen. For events of a given E_T , in the E_T region of trigger bias (where trigger bias is described in reference 31), the trigger efficiency for collecting hydrogen events is greater than its efficiency for collecting lead events. This is the result of the wider angular distributions of secondaries from p-Pb than from p-p collisions.

In figure 13(a), the distribution of the trigger region E_T for the two high E_T trigger ($E_{T\text{trig}}$) is

Figure 13: The E_T distributions of events firing the two high E_T trigger are shown. (a) gives the E_T in the triggering region consisting of the two highest E_T segments, and (b) gives the E_T for the 8 sr calorimeter.

a. Two High E_T ; E_T in trigger

□ Hydrogen
○ Lead

b. Two High ET; ET total

□ Hydrogen
○ Lead

displayed. The trigger region consists only of those two segments of highest E_T , with E_T at least 1.2 GeV in each segment. The idea of trigger bias is similar to the global case. The effects due to target position are the same. Additionally, the shift to higher segment E_T may be enhanced by nearby segment leakage since lead fires more segments than hydrogen. The events that this trigger selects are characterized by E_T clustering so that the highest E_T segments generally have several adjacent segments firing for either target. Lead usually fires more nearby segments than hydrogen, primarily due to the large multiplicities of lead events. Cross-leakage among segments can not be corrected for a given event because it is a statistical process that depends on where particles land relative to a segment's center and the physical size of the segment. The mean E_T values are $3.8 \pm .1$ GeV for hydrogen and $4.7 \pm .1$ for lead.

In figure 13(b), it is shown that regardless of how the two triggering segments have their E_T enhanced for Pb, the events that satisfy this trigger have much higher total E_T ($E_{T\text{tot}}$) for lead than for hydrogen. The mean total E_T in GeV is $7.9 \pm .2$ for hydrogen and $12.1 \pm .4$ for lead. The shift in the peak of the lead distribution to

a higher E_T value than the peak of the hydrogen distribution is not entirely due to trigger bias, but is in part due to the intrinsically higher E_T of the lead events satisfying this trigger. The increase of E_T from the trigger region to the total calorimeter sum is larger for Pb than for H.

The total lab frame energy deposited in the calorimeter, (E_{cal}), is considered in figure 14. The high threshold global trigger distribution of E_{cal} appears in figure 14(a). The total energy of the calorimeter is very similar for hydrogen and lead targets, with mean E_{cal} values of 234 and 227 GeV, equal within statistical errors of 6 GeV for each. This implies that the ratio of total E_T to total E_L is greater for lead than for hydrogen, implying a wider angular distribution of high energy secondaries for lead than for hydrogen. This means that the wide angle particles from lead enhance the E_T of its typical events. The wide angle particles, which result from multiple scattering¹⁶, are the primary contributors to the E_T enhancement for Pb.

In figure 14(b), the E_{cal} distribution is shown for the two high E_T trigger. Areas under the hydrogen and lead curves are equal due to a normalization of event

Figure 14: The total energy deposited in the triggering calorimeter is displayed for hydrogen and lead for events obtained with (a) global triggers, and (b) two high E_T triggers.

a. Global; Ecal

□ Hydrogen
○ Lead

b. Two High ET; Ecal

□ Hydrogen
○ Lead

rates, and the numerical scale of the y-axis is not true. Here we find that the mean E_{cal} is 150 ± 4 GeV for H and 193 ± 6 for Pb. Average total E_T/E is larger for lead than for hydrogen, indicating the importance of wide angle particles in E_T enhancement of lead events for the 2HI trigger.

The beam calorimeter measures the total energy passing through the beam hole of the triggering calorimeter. Its resolution of about $110\%/(E^{1/2}) + 3\%$, as described in chapter 3, should be kept in mind in the present discussion. Figure 15(a) shows the beam calorimeter energy (B_{cal}) distribution for the high threshold global trigger events. The mean B_{cal} values are 133 ± 4 GeV for hydrogen and 103 ± 3 GeV for lead. Therefore, a large portion of the total energy is scattered at angles wider than 30 degrees in the nucleon-nucleon center of mass for globally triggered events.

The B_{cal} distributions for the two high E_T trigger appear in figure 15(b). The mean B_{cal} values are 268 ± 6 and 180 ± 6 GeV for H and Pb. The shift upward in B_{cal} energy for both targets from the global to the two high E_T triggers has the following possible cause: the global trigger accepts any additional E_T anywhere in the

Figure 15: Same as figure 14, but the energy deposited in the beam hole calorimeter is displayed.

a. Global; Bcal

□ Hydrogen
○ Lead

b. Two High ET; Bcal

□ Hydrogen
○ Lead

calorimeter, therefore beam jet broadening into the inner calorimeter rings adds to the triggering E_T and it is favored by the global trigger. The two high E_T trigger requires only two very high E_T segments. Beam jet broadening is not favored by this trigger because it gives low E_T particles.

4.3 Behavior of All Targets

Now we consider the full range of five triggers and six targets. The effects that appear in figures 9-16 are continuous over the range of targets, and systematically vary for the various triggers. In table 4, the mean values of the transverse energies deposited in the trigger region, $E_{T\text{trig}}$, and in the full calorimeter, $E_{T\text{tot}}$, the energies in the calorimeter, E_{cal} , and in the beam calorimeter, B_{cal} , and the total energy missing both calorimeters, $400 - E_{\text{cal}} - B_{\text{cal}}$, are tabulated. For each trigger, $E_{T\text{trig}}$ increases as a function of increasing target atomic number, A . The mean energy in the triggering region also increases as the solid angle of the trigger region increases in the SA, DA, and G triggers for each target for a fixed event rate. The total E_T and E_{cal} in the calorimeter also increase as A increases and seem to

Table 4: Mean values of the energy deposited in the calorimeters are displayed. These pertain to all triggering events for each trigger shown. E_T is shown for only the triggering region and for the entire calorimeter, denoted $E_{T\text{trig}}$ and $E_{T\text{tot}}$. The total energy deposited in the triggering and beam calorimeters is denoted E_{cal} and B_{cal} , respectively. 400-Ecal-Bcal gives the mean energy missing both calorimeters. The negative results are within statistical errors (and calibration error estimates) of positive values. The statistical errors for $E_{T\text{trig}}$, $E_{T\text{tot}}$, E_{cal} , and B_{cal} are about 3% of the values shown. The errors in 400-Ecal-Bcal result from E_{cal} and B_{cal} , and statistical errors are shown below in parentheses.

TRIGGER		$E_{T\text{trig}}$	$E_{T\text{tot}}$	E_{cal}	B_{cal}	400-Ecal-Bcal
+TARGET						
SA	H	4.10	9.76	170	233	-3(12)
	C	4.60	11.2	175	224	1(12)
	Al	4.82	12.5	192	190	18(12)
	Cu	4.78	12.7	191	188	21(12)
	Sn	4.90	12.8	192	182	26(12)
	Pb	5.04	13.2	193	146	61(11)
DA	H	5.87	10.5	180	217	3(12)

	C	6.49	12.0	185	204	11(12)
	Al	6.84	13.1	198	174	28(12)
	Cu	6.81	13.4	198	168	34(12)
	Sn	6.85	13.6	200	163	37(11)
	Pb	6.82	13.7	198	135	67(11)
G	H		13.3	234	146	20(12)
	C		14.1	222	141	37(12)
	Al		15.5	234	118	48(12)
	Cu		15.6	228	122	50(12)
	Sn		15.7	230	115	55(12)
	Pb		15.7	227	93	80(11)
LMG	H	3.48	7.89	150	259	-10(10)
	C	4.01	9.05	157	248	-5(10)
	Al	4.21	10.1	172	225	3(10)
	Cu	4.34	10.7	175	220	5(10)
	Sn	4.50	10.8	176	211	13(10)
	Pb	4.44	10.9	176	183	41(10)
2HI	H	3.80	7.92	150	268	-18(10)
	C	4.31	9.54	168	245	-13(10)
	Al	4.60	10.4	179	233	-12(10)
	Cu	4.46	11.4	185	227	-12(11)
	Sn	4.57	11.5	191	211	-2(11)
	Pb	4.74	12.1	193	180	27(11)

plateau for large A , and the mean values increase for each target as the trigger solid angle increases. This implies that geometrically confined triggers tend to detect events that are geometrically biased to the shape of the triggering region. The energies reaching the beam calorimeter decrease monotonically as the target atomic number increases. This implies that nuclei attenuate or spread the beam jet energy.

The energy missing the calorimeters represents particles flying at angles wider than the calorimeter coverage (which is up to about nine degrees in polar lab angle) and energy leakage through the backs of the calorimeters. The leakage through the back is estimated³² at less than 5% of the energy striking the calorimeters. What we observe is that the energy missing both calorimeters increases monotonically as a function of increasing target A . The amount of missing energy increases as the trigger solid angle increases for the "geometrical" triggers, i.e. SA, DA, and G. This merely reflects the increase in E_{cal} with trigger region solid angle. The amount of missing energy is significantly less for the "multiplicity" triggers, i.e. LMG and 2HI, but they show the same increase in the amount of missing energy as A

increases. Since the geometrical triggers are centered at $\theta^* = 90^\circ$ in the p-p center of mass frame, larger solid angles mean more trigger region segments near the outer edge of the calorimeter. This means significant numbers of wide angle particles are detected, and wider angle particles correlated to these particles can miss the calorimeter. The multiplicity triggers do not preferentially select wide angle particle production in this way, but beam jet secondary scattering could add to wide angle production in a way that increases as target A increases.

Table 5 shows ratios of various calorimeter observables for all triggers and targets. First note that $E_{T\text{trig}}/E_{T\text{tot}}$ decreases and $E_{T\text{tot}}/E_{\text{cal}}$ increases as functions of increasing target atomic number A. Particularly for the geometrical triggers, this implies that events become more isotropically distributed over the face of the calorimeter, and that relatively more wide angle particles are produced as A increases. In addition, the above ratios increase as functions of increasing trigger region solid angle for the geometrical triggers. This shows that wider angle events are increasingly favored as trigger region solid angle increases. As discussed in

Table 5: Important ratios of mean values are computed. The implications of these numbers are discussed in Chapter 3. The variables are defined: $E_{T\text{trig}}$ is the transverse energy deposited in the triggering region, $E_{T\text{tot}}$ is the transverse energy deposited in the entire segmented calorimeter, E_{cal} is the total energy deposited in this calorimeter, E_{em} is the energy deposited in the first two layers of the calorimeter, and B_{cal} is the energy deposited in the beam hole calorimeter. All are means of the values they represent, taken for the triggering events of each trigger. The errors on the ratios in each column are approximately .005, .0005, .010, and .05, which apply to data columns 1, 2, 3, and 4, respectively.

TRIGGER		$\frac{E_{T\text{trig}}}{E_{T\text{tot}}}$	$\frac{E_{T\text{tot}}}{E_{\text{cal}}}$	$\frac{E_{\text{em}}}{E_{\text{cal}}}$	$\frac{B_{\text{cal}}}{E_{\text{cal}}}$
+TARGET		$E_{T\text{tot}}$	E_{cal}	E_{cal}	E_{cal}
SA	H	.420	.0598	.773	1.43
	C	.410	.0640	.788	1.34
	Al	.385	.0653	.775	1.05
	Cu	.376	.0668	.780	1.04
	Sn	.382	.0668	.775	1.00
	Pb	.381	.0685	.776	.81

DA	H	.559	.0610	.778	1.26
	C	.540	.0650	.799	1.16
	Al	.525	.0664	.782	.93
	Sn	.508	.0678	.788	.90
	Pb	.497	.0693	.782	.73
G	H		.0599	.791	.67
	C		.0637	.800	.68
	Al		.0655	.787	.53
	Sn		.0682	.792	.54
	Pb		.0693	.788	.45
LMG	H	.441	.0550	.797	1.79
	C	.443	.0576	.817	1.64
	Al	.418	.0587	.790	1.37
	Cu	.396	.0611	.795	1.31
	Sn	.418	.0610	.789	1.26
	Pb	.407	.0618	.789	1.10
2HI	H	.480	.0552	.812	1.85
	C	.452	.0568	.814	1.52
	Al	.442	.0582	.785	1.36
	Cu	.391	.0615	.799	1.28
	Sn	.398	.0602	.805	1.16
	Pb	.393	.0624	.801	.98

COMPARISONS OF DATA FROM DIFFERENT TARGETS

Chapter 3, an estimate of the relative numbers of electromagnetically interacting particles, such as the short-lived mesons, to the number of hadrons is obtainable. The sum of the A' and A calorimeter layer energies, denoted Eem, gives all the energy deposited by the electromagnetically decaying particles plus half the energy of the hadrons²³. The Ecal sum of all layers gives all the energy of both particle types. The ratio Eem/Ecal is observed to be constant for all triggers to within the statistical errors. This implies that no target or trigger results in much different levels of production of π^0 mesons or direct photons or e^+e^- pairs relative to total hadron production.

The planarity variable has been employed by several authors³³⁻³⁵ as a means of characterizing event structure. When the sum $B = \sum_i (P_T)^2$ of the squared momentum of each particle (i) transverse to a line perpendicular to the beam is minimized and the sum $A = \sum_i (P_L)^2$ of the momentum of each particle parallel to that line is maximized, and this is accomplished by properly orienting the line, then planarity, P, is defined as

$$P = (A - B) / (A + B) .$$

Planarity nears zero for events that are cylindrically

symmetric. Planarity is one for an idealized pencil-like jet pair, where each jet is collimated to a single ray and the jet rays are back-to-back in azimuthal angle ϕ . The planarity distribution of high threshold global events is shown in figure 16(a) for hydrogen and lead. As usual, the areas under the two curves are equal due to normalization. The average planarities are 0.46 ± 0.01 for H and 0.40 ± 0.01 for Pb. The lower planarity of the events from lead reflects the more isotropic character of the particle distributions for the high A target events.

Figure 16(b) shows the planarity distribution for the two high E_T trigger. The mean P is 0.64 ± 0.01 for H and 0.58 ± 0.01 for Pb. The lower mean P of lead relative to hydrogen reflects that the uncorrelated contributions seen in the global events are still present in many of the two high E_T trigger events. The planarity is shifted upward for the two high E_T trigger from that of the global trigger for both targets. That is presumably because the two high trigger does not favor gluon bremsstrahlung or beam jet broadening because it requires only that the leading particles of each of the two hard jets to retain much of the scattering energy. The global trigger favors gluon bremsstrahlung because the gluon jets generally land

Figure 16: The planarity distributions for the (a) global and (b) two high E_T triggers are shown for hydrogen and lead targets.

a. Global; Planarity

□ Hydrogen
○ Lead

b. Two High ET; Planarity

□ Hydrogen
○ Lead

somewhere in the calorimeter and contribute to the total E_T of the event.

The hydrogen through lead trends over the full range of targets employed are shown in table 6. The mean planarity is observed to decrease for all triggers as the atomic number of the targets increases. There is, however, a general tendency to bottom out, so that a mean planarity plateau occurs for Cu, Sn, and Pb targets. The mean planarity decreases as the trigger region solid angle increases for the geometrical triggers. The mean planarity of the triggers which require high E_T but low multiplicity (LMG and 2HI) is higher than that of the high E_T and high multiplicity geometrical triggers.

The mean multiplicity of charged particles increases as target A increases. The geometrical triggers show that larger trigger region solid angle leads to higher multiplicity. The multiplicity triggers show lower multiplicities since the LMG trigger directly restricts the number of segments firing, and the 2HI trigger indirectly restricts it by requiring high leading particle energies.

Figure 17(a) shows the cross-sections obtained for the single arm trigger as a function of trigger region E_T for all the targets. These cross-sections are obtained

Table 6: The variation of average planarity, P , and charged particle multiplicity, N_{ch} , is shown as a function of trigger and target. Statistical errors are approximately 0.010 for P and 5% for N_{ch} .

TRIGGER		P	N_{ch}
+TARGET			
SA	H	.594	14.1
	C	.540	18.0
	Al	.507	20.3
	Cu	.485	23.1
	Sn	.481	25.6
	Pb	.486	31.2
DA	H	.548	15.2
	C	.499	19.0
	Al	.483	20.7
	Cu	.455	24.1
	Sn	.455	26.4
	Pb	.455	31.7
G	H	.455	16.5
	C	.423	20.1
	Al	.405	21.8
	Cu	.396	24.8

	Sn	.393	27.3
	Pb	.395	32.1
LMG	H	.577	11.6
	C	.541	15.8
	Al	.507	17.5
	Cu	.497	20.5
	Sn	.493	23.0
	Pb	.487	28.3
2HI	H	.639	10.6
	C	.620	14.6
	Al	.607	16.1
	Cu	.579	19.6
	Sn	.569	21.3
	Pb	.578	26.9

Figure 17: The cross-sections measured as functions of trigger region E_T are displayed for the (a) single arm, (b) double arm, and (c) global triggers.

a. SINGLE ARM: TRIGGER REGION

□ HYDROGEN
○ CARBON
△ ALUMINUM
+ COPPER
× TIN
◇ LEAD

b. DOUBLE ARM: TRIGGER REGION

□ HYDROGEN
 ○ CARBON
 △ ALUMINUM
 + COPPER
 × TIN
 ◇ LEAD

c. GLOBAL: TOTAL CALORIMETER

by looking at both high threshold and low threshold runs above trigger bias after empty target subtractions. Note that all targets show an approximately exponentially decreasing cross-section as E_T increases over some range of E_T . Note also that the slope is flatter for high A than for low A targets. In figure 17(b), the cross-sections for the double arm trigger as a function of the trigger region E_T are plotted. They decrease exponentially as E_T increases. Note that the slopes also flatten as A increases. Note also that the slopes are less steep than for the single arm trigger for each target. Figure 17(c) shows the cross-section for the global trigger as a function of its trigger region E_T . Again the slopes flatten as A increases. The slopes flatten as trigger region solid angle for the geometrical triggers increases.

The LMG cross-sections as a function of trigger region E_T are shown in figure 18(a). The trigger region consists simply of all segments in an event satisfying the E_T minus multiplicity threshold which have $E_T > 0.4 \text{ GeV}$. A steep exponential decay as E_T increases is noted above about 6 GeV for the various cross-sections, while a less steep slope is seen at slightly lower E_T . The LMG cross-sections as functions of total calorimeter E_T

Figure 18: The cross-sections measured for the low multiplicity global trigger are shown for the E_T detected in (a) the trigger region, consisting of all segments with $E_T > 0.35 \text{ GeV}$, and (b) the total calorimeter.

a. LOW MULT. GLOBAL: TRIGGER REGION

□ HYDROGEN
○ CARBON
△ ALUMINUM
+ COPPER
× TIN
◇ LEAD

b. LOW MULT. GLOBAL: TOTAL CALORIMETER

□ HYDROGEN
 ○ CARBON
 △ ALUMINUM
 + COPPER
 x TIN
 ◇ LEAD

appear in figure 18(b).

Figure 19(a) shows the cross-sections as functions of E_T in the two high E_T trigger's triggering region, which consists of the two highest E_T segments. An exponential decline in E_T is again noted, with slopes flattening as A increases. Figure 19(b) shows the 2HI cross-sections as functions of the total energy in the calorimeter. The cross-sections are lower and the slopes are steeper than in the LMG case. The cross-sections show a consistent ranking of $\sigma(G) > \sigma(LMG) > \sigma(2HI)$ and $\sigma(G) > \sigma(DA) > \sigma(SA)$. Thus it is increasingly less likely to have a given high E_T in a decreasing number of particles. It is also increasingly less likely to have high E_T in a decreasing solid angle region.

These cross-sections are used in the next chapter. Comparisons between target type and cross-section for the different triggers are made and empirical rules are sought there.

Figure 19: Similar to figure 18, but for the two high E_T trigger, which has its two highest E_T segments as the trigger region.

^a. TWO HIGH E_T : TRIGGER REGION

□ HYDROGEN
○ CARBON
△ ALUMINUM
+ COPPER
× TIN
◇ LEAD

b. TWO HIGH ET: TOTAL CALORIMETER

□ HYDROGEN
 ○ CARBON
 △ ALUMINUM
 + COPPER
 × TIN
 ◇ LEAD

CHAPTER 5

OBSERVED ATOMIC NUMBER DEPENDENCE

5.1 Empirical Relationships of Cross-Sections

Two empirical observations in high transverse energy hadron-nuclear scattering events are checked for new triggers. One is the apparent variation of cross-sections as a power of the atomic number of the target. The other observation considered is the approximate variation of cross-sections as exponential functions of E_T , which has been seen for p-p scattering in the E_T range considered here.

The variation of hadron-proton cross-sections for fixed geometrical triggers as functions of transverse energy takes the form

$$\sigma(E_T) = \sigma_0 e^{-mE_T}$$

for a wide range of E_T values^{19,36}. The cross-section for p-A scattering results in part from multiple scattering. On the basis of the model presented in chapter 2,

it is anticipated that

$$\sigma_{pA}(E_T) = A \sigma_0 e^{-mE_T + \sigma_0 L E_T} ,$$

when the attenuation of the beam particle energy by the nuclear target is neglected. The E_T range of the data and the accuracy of the cross-sections are limited. This exponential scaling is tested and applied over the E_T ranges shown in the cross-section versus E_T plots at the end of Chapter 4. Thus the fits only apply for transverse energies near 10 GeV. These cross-section curves are fit with the above functional form as

$$\sigma_{pA}(E_T) = A \sigma_0 e^{-m' E_T} .$$

In table 7, the m' values obtained by fitting these data are given. As in the case of p-p scattering, we observe that as the solid angle of the E_T gathering region decreases, the slope m' of the exponential cross-section fall is seen to increase for each target type. Additionally, the slope becomes less steep as the atomic number of the target increases. This is what the above formula predicts insofar as the magnitude of the slope decreases as A increases because L increases.

The cross-sections of high transverse energy events from hadron-nucleus collisions are frequently parameterized³⁷⁻³⁹ as

Table 7: The slopes, m , obtained by fitting the cross-sections with $\sigma = \sigma_0 e^{-mE_T}$ are given for all triggers and targets. These slopes apply to the E_T ranges shown in figures 17, 18, and 19. Errors in m appear in parentheses. The E_T is binned in the trigger region only for the geometrical triggers, and is binned in either the trigger region or the 8 sr calorimeter for the multiplicity triggers, as indicated below.

TRIGGER	TARGET	$m(\text{GeV}^{-1})$
SA	Pb	1.00(.12)
	Sn	1.22(.12)
	Cu	1.31(.13)
	Al	1.27(.15)
	C	1.24(.18)
	H	1.45(.25)
DA	Pb	.82(.08)
	Sn	.87(.08)
	Cu	.87(.10)
	Al	.81(.12)
	C	.97(.13)
	H	1.15(.16)
G	Pb	.65(.07)
	Sn	.62(.07)

	Cu	.67(.07)
	Al	.74(.07)
	C	.92(.08)
	H	.99(.09)
2HI trigger	Pb	.64(.11)
region ET	Sn	.60(.12)
	Cu	.87(.14)
	Al	1.20(.17)
	C	1.34(.22)
	H	1.50(.30)
2HI total	Pb	.55(.08)
cal. ET	Sn	.55(.08)
	Cu	.51(.10)
	Al	.60(.13)
	C	.76(.16)
	H	.83(.21)
LMG trigger	Pb	.74(.10)
region ET	Sn	.76(.11)
	Cu	.81(.11)
	Al	.85(.14)
	C	.98(.16)
	H	.99(.21)
LMG total	Pb	.35(.05)

cal. ET	Sn	.41(.05)
	Cu	.48(.05)
	Al	.58(.06)
	C	.60(.07)
	H	.64(.07)

$$\sigma_A(E_T) = \sigma_0 A^{\alpha(E_T)},$$

where the parameter α is a function of E_T and A is the number of nucleons in the target nucleus. This notation uses $\sigma_A(E_T)$ to represent the differential cross-section in E_T . Values of $\alpha > 1$ are referred to as^{40,41} the "anomalous nuclear enhancement". To test this scaling, linear regression fits to the logarithms of the cross-sections for a given E_T as functions of logarithmic target atomic number are made. Typically, correlation coefficients greater than or equal to 0.999 are found for fits to the $A > 1$ points, i.e. carbon, aluminum, copper, tin, and lead. Hydrogen cross-sections clearly fail to scale as A^α at high E_T . This has been observed for single particle production^{39,42} and for global trigger events¹⁷. In the latter case, the deviation is in the direction such that hydrogen cross-section points fall below A^α linear extrapolations from $A > 1$ cross-section data. In the former, deviations in this direction are seen for π^- production, and in the opposite direction for π^+ production.

In figure 20(a), the $A > 1$ linear regression fits to cross-sections for the E_T range of 12-15 GeV deposited in the full calorimeter are shown for the G, DA, and SA

Figure 20: The cross-sections for the various nuclear targets to deposit 12-15 GeV in the 8 sr calorimeter for each trigger are shown, along with A^α linear fits. (a) shows the global (G), double arm (DA), and single arm (SA) triggers, while (b) shows the low multiplicity global (LMG) and two high E_T (2HI) triggers.

triggers. The E_T in the entire calorimeter is taken because the hydrogen deviation is less apparent for trigger region E_T binned cross-sections over a similarly small range of transverse energy. We observe that A^α scaling is obeyed by the heavy targets, but that hydrogen target data consistently deviate below the extrapolated lines. The size of the hydrogen deviation grows as the solid angle of the triggering region decreases. Throughout this thesis, the term "hydrogen deviation" refers to the difference between the base 10 logarithm of the A^α extrapolated cross-section for hydrogen, and the base 10 logarithm of the experimentally observed hydrogen cross-section. This figure represents the first observation of trigger region solid angle dependence in the hydrogen deviation. The cross-sections of the multiplicity triggers, LMG and 2HI, are considered in figure 20(b). The E_T in the full calorimeter is required to fall in the 12-15 GeV range. A^α scaling is observed to hold for the multiplicity triggers for the $A > 1$ points binned in this fashion, but it does not apply to data binned by trigger region E_T , unlike the geometrical trigger cases. The hydrogen deviation is larger and of opposite sign for these triggers as compared to the geometrical triggers. There

are indications⁴³ that geometrical trigger cross-sections are enhanced by soft processes, while multiplicity triggers restrict soft processes.

5.2 Variation with Transverse Energy

The $A > 1$ points are fit for cross-sections calculated in 1.2 GeV wide E_T bins. The slopes of the linear fits to the $\log(\sigma)$ versus $\log(A)$ plots give $\alpha(E_T)$. In figure 21(a), $\alpha(E_T)$ for the geometrical triggers is plotted as a function of the E_T deposited in the triggering region. The α for each trigger is observed to rise from a value below unity at low E_T to a value of roughly 1.4 as E_T increases. The value of α for the geometrical triggers then plateaus for high E_T (at the 1.4 value) as was seen in reference 17. Another observation in agreement with the Fermilab experiment E557 data published in reference 17, is that the onset of the $\alpha=1.4$ plateau occurs at about 12 GeV of transverse energy for global trigger data. In addition, E609 agrees with E557 that the E_T at which the onset of the plateau occurs is related to the trigger region solid angle for the geometrical triggers. Thus α reaches 1.4 at lower $E_{T\text{trig}}$ as the trigger region solid angle decreases. The global trigger asymptotic

Figure 21: The α obtained by fitting the $A > 1$ data is shown for the geometrical triggers as a function of the E_T deposited in (a) the trigger region only and (b) the entire calorimeter.

a. ET for Trigger Regions Only

- Single Arm Trigger
- Double Arm Trigger
- △ Global Trigger

b. ET in 8 sr Calorimeter

- Single Arm Trigger
- Double Arm Trigger
- △ Global Trigger

value of α is not the same as E557's 1.2 value. This could be due to different calorimeter acceptance ranges. Our calorimeter covers about 15 degree smaller scattering angles, so we could be more sensitive to beam jet spreading than E557. In figure 21(b), the E_T dependence of α is shown for the geometrical triggers when cross-sections are calculated for events binned according to their E_T deposit in the entire calorimeter. The α values all match the global curve of part (a) of this figure. Note that E_T is now evaluated for 8 sr solid angles in each trigger's set of events. This indicates the isotropy of events gathered by large solid angle fixed geometry triggers.

Figure 22(a) plots α versus E_T for the trigger regions of the multiplicity triggers. A^α scaling is not exact here, but correlation coefficients of .98-.99 are typical. For the LMG trigger, the trigger region consists of all the segments with $E_T > 0.4 \text{ GeV}$, and for the 2HI trigger it is the two highest E_T segments. The value of α monotonically increases as a function of increasing E_T for both triggers, beginning at $\alpha < 1$ and continuing through 1.7, which is where the data E_T range ends, with no plateaus observed through the E_T range shown. In

Figure 22: Same as figure 21, but for the multiplicity triggers, with trigger region E_T in (a) and total calorimeter E_T in (b).

a.
ET for Trigger Regions Only

□ Low Mult. Global Trig.
○ Two High ET Trig.

b. ET in 8 sr Calorimeter

□ Low Mult. Global Trlg.
○ Two High ET Trlg.

22(b), α is plotted as a function of total calorimeter E_T for events from these two triggers. Again a steady rise in α as a function of E_T is observed, with α exceeding 1.8 at high E_T and with no plateau apparent.

The hydrogen deviation is considered in figure 23, where it is plotted as a function of the E_T in the calorimeter for the global and two high E_T triggers. Obviously, the difference between the A^α extrapolation of the hydrogen cross-section from $A > 1$ data and the observed hydrogen cross-section grows as E_T increases for each trigger. This was seen for the global trigger case by E557. Multiple scattering is increasingly important at higher transverse energies. Referring back to figure 3, recall that my multiple scattering model predicts an increasing difference between hydrogen and high A cross-section behavior in A^α scaling as E_T increases. The hydrogen deviation is further discussed later in this chapter.

5.3 Variation with Planarity

The planarity variable, which characterizes event shape, can be used to look at nuclear target dependences of event structure. Planarity is zero for cylindrically

Figure 23: The hydrogen deviation from A^α extrapolations is shown as a function of calorimeter E_T for the global and two high E_T triggers.

symmetric events and one for back-to-back pencil-like jet events. In figure 24(a), the cross-sections for events satisfying the single arm trigger are given in several planarity bins for the nuclear targets as a function of target atomic number. The $E_{T\text{tot}}$ range is 11-16 GeV for this planarity analysis. It is observed that the cross-sections nearly obey A^α scaling, but that there may be a systematic violation. The very heavy targets, tin and lead, have cross-sections that appear to be lower than those extrapolated by an A^α line fitted to carbon, aluminum and copper, when planarity is small. They are higher than the same fitted extrapolation when planarity is large. For the most probable event structure, which falls in the $0.4 < P < 0.7$ range, A^α scaling appears to hold.

The same plot is shown for double arm trigger data in figure 24(b). The planarity bins' cross-sections show a shift toward lower planarities relative to the single arm case, and overall slopes still decrease as planarity increases. A^α scaling is observed in the $0.4 < P < 0.7$ range. In figure 24(c), the planarity binned curves for the global trigger data appear. A^α scaling is obeyed over a somewhat lower planarity range of $0.2 < P < 0.6$, reflecting the lower average planarity of global events.

Figure 24: The cross-sections for $E_{T\text{tot}}$ of 11-16 GeV are binned according to event planarity to give the cross-sections shown below for the (a) single arm, (b) double arm, and (c) global triggers.

a. Single Arm Planarity

$\square$ $P=0-.2$
 $\circ$ $P=.2-.4$
 $\triangle$ $P=.4-.6$
 $+$ $P=.6-.8$
 $\times$ $P=.8-1.0$

b. Double Arm Planarity

- $P=0-.2$
- $P=.2-.4$
- △ $P=.4-.6$
- + $P=.6-.8$
- × $P=.8-1.0$

c. Global Planarity

- P=0-.2
- P=.2-.4
- △ P=.4-.6
- + P=.6-.8
- × P=.8-1.0

The cross-sections for the multiplicity triggers as simultaneous functions of planarity and target atomic number are shown in figure 25. The low multiplicity global trigger is shown in 25(a). The effects observed are quite similar to those seen for the geometrical triggers in figure 24. The cross-sections are shifted toward higher planarities. The overall alpha values decrease as planarity increases. This is consistent with multiple scattering explanations.

In figure 25(b), the planarity binned cross-sections of the two high E_T triggered events are shown for the various atomic numbers. These curves are dissimilar to the data seen thusfar. At high planarity, the cross-sections of copper, tin, and lead all fall below A^α extrapolations from the lighter targets. Additionally, a drop in the lead cross-section of the $0.0 < P < 0.2$ curve is seen.

I can think of no physics reason for the kinks in the planarity curves to be real. They may be the result of a systematic error not yet understood.

It is instructive to view the slopes α of linear fits to these curves. In figure 26(a) is shown this approximate α as a function of planarity for the

Figure 25: Same as figure 24, but for the (a) low multiplicity global, and (b) two high E_T triggers.

a. Low Mult. Global Planarity

- $P=0-.2$
- $P=.2-.4$
- △ $P=.4-.6$
- + $P=.6-.8$
- × $P=.8-1.0$

b. Two High ET Planarity

- P=0-.2
- P=.2-.4
- △ P=.4-.6
- + P=.6-.8
- × P=.8-1.0

Figure 26: α values calculated from the cross-sections shown in figures 24 and 25 are shown as functions of planarity for the (a) geometrical triggers and the (b) multiplicity triggers. The E_T range is 11-16 GeV.

a. Alpha vs. Planarity

□ Single Arm
○ Double Arm
△ Global

b. Alpha vs. Planarity

□ Low Mult. Global
○ Two High ET

geometrical triggers. Clearly, α decreases as planarity increases. This trend is predicted by multiple scattering models in that more secondary scattering means lower planarity. If $\alpha > 1$ enhancements result from multiple scattering, then α should be greatest at low planarity and decrease as planarity increases. In figure 26(b), the multiplicity triggers show the same decline in α as planarity increases. Note that the highest planarity range events tend toward $\alpha=1$ for the G, DA, SA, and LMG triggers.

5.4 Beam Calorimeter Observations

The events satisfying the geometrical triggers are considered on the basis of the energies which they deposit in the beam hole calorimeter in figure 27. Due to the relatively poor energy resolution of this device, large bins of beam calorimeter energy are used to categorize the events. The exception is the 0-20 GeV bin, which according to the resolution formula can contain events with beam calorimeter energies of as much as 25 GeV incident on the beam calorimeter. This bin is considered because there is theoretical interest⁴⁴ in the nature of events with no beam jets. Unfortunately, most of

Figure 27: The cross-sections for the various nuclear targets appear as functions of the energy deposited in the beam calorimeter for the (a) single arm, (b) double arm, and (c) global triggers.

a. Single Arm Trigger

- BC E=0-20 GeV
- BC E=0-100 GeV
- △ BC E=100-200 GeV
- + BC E=200-300 GeV
- x BC E=300-420 GeV

b. Double Arm Trigger

- BC E=0-20 GeV
- BC E=0-100 GeV
- △ BC E=100-200 GeV
- + BC E=200-300 GeV
- × BC E=300-420 GeV

c. Global Trigger

- BC E=0-20 GeV
- BC E=0-100 GeV
- △ BC E=100-200 GeV
- + BC E=200-300 GeV
- x BC E=300-420 GeV

the events in this bin do not show nearly 380 GeV in the triggering calorimeter, so either wide angle particles or calorimeter leakage prevent absolute determination of beam jet absence. In figure 27(a), the cross-sections of the various nuclear targets satisfying both the single arm trigger and the indicated beam calorimeter energy bin are shown. Note that A^α scaling applies to aluminum through tin cross-sections for all beam calorimeter energies. There are systematic kinks in the curves, and in this case there are two kinks in each fixed beam calorimeter energy curve. The kink direction, relative to the aluminum through tin slope, changes sign as Bcal increases. For the carbon to aluminum kink, the C-Al slope is greater than the Al-Cu-Sn slope for low Bcal energies, but it monotonically decreases to a value less than the Al-Cu-Sn slope for high Bcal energy deposits. The same behavior is seen in the tin to lead kink, where the Sn-Pb kink slope is greater at low Bcal and less at high Bcal than the Al-Cu-Sn slope. In fact, for $Bcal > 300 \text{ GeV}$, the cross-section for lead is actually less than the corresponding tin cross-section to satisfy the single arm trigger.

The beam calorimeter energy distribution of the cross-sections of the double arm triggered events is shown as a function of nuclear target atomic number in figure 27(b). The kinks are observed to occur at the same locations, i.e. C-Al and Sn-Pb, as in the single arm trigger case. The behavior of their slopes relative to that of the Al-Cu-Sn slope is similar to that in the SA trigger case. In figure 27(c), the global trigger beam calorimeter energy distribution is shown for the various targets. The kinks again appear at C-Al and Sn-Pb in atomic number and the behavior of the slopes of the kinks relative to the Al-Cu-Sn slope is similar to that for the SA and DA triggers. Note that these event samples are not completely independent. Some events satisfy more than one of the triggers, including some that satisfy, for example, the SA and DA.

The beam calorimeter energy distributions of events satisfying the low multiplicity global trigger appear in figure 28(a) for the various nuclear targets. The kink behavior of the geometrical triggers is emulated, but the relative slope trends are shifted upward in Bcal energy. This is reflective of the higher average Bcal energy of LMG events as compared to geometrically triggered events.

Figure 28: Same as figure 27, but for the (a) low multiplicity global and (b) two high E_T triggers.

a. Low Mult. Global Trig.

- BC E=0-20 GeV
- BC E=0-100 GeV
- △ BC E=100-200 GeV
- + BC E=200-300 GeV
- × BC E=300-420 GeV

b. Two High ET Trigger

- BC E=0-20 GeV
- BC E=0-100 GeV
- △ BC E=100-200 GeV
- + BC E=200-300 GeV
- × BC E=300-420 GeV

The reason is that the multiplicity restrictions of the LMG trigger do not favor multiple scattering as a means of attaining large transverse energies. Thus the beam jet broadening through multiple scattering that is favored by the geometrical triggers is suppressed by the LMG trigger. In figure 28(b), the 0-20 GeV Bcal bin should be neglected for kink observation purposes, since its errors are so large. The 2HI trigger is similar to the LMG trigger in that its beam calorimeter energy is higher than that of the geometrical triggers. However, the 2HI trigger does not restrict multiple scattering induced beam jet broadening. Since it triggers on the leading particles from the primary hard collision, it only requires that there has been one hard collision jet pair that has experienced minimal secondary interaction. Therefore, it should neither enhance nor suppress beam jet broadening.

I have no physics reason for the Bcal kinks to be real. They may result from a systematic error not yet understood.

The beam jet characteristics of the 2HI trigger reflect the attenuation of the energy of the beam fragment as it flies through nuclear matter. For the 2HI trigger,

we find from table 4 that

$$(2/3) \times 400 \text{ GeV} - B_{\text{cal}} (in \text{ GeV}) = 20 \text{ GeV} (L_A - 1) ,$$

where L_A is the mean number of nucleons per square Fermi as seen by an incident proton according to the calculation of table 2. Therefore, the beam jet fragment loses about 20 GeV of energy in each nucleon that it traverses.

Recall from table 6 that the charged multiplicity of two high triggers grows as

$$N_{\text{ch}_A} - N_{\text{ch}_H} = 4(L_A - 1) .$$

A possible connection is that the 20 GeV imparted to a nucleon by the beam fragment could cause that nucleon to hadronize into about six particles. Such low energy particles would often be produced at wide angles relative to the high energy leading particles of the beam jet.

In figure 29, the α obtained by fitting the $A > 1$ data of the preceding figure's cross-section curves via linear regression is shown. The results qualitatively agree with a multiple scattering interpretation. In figure 29(a), the geometrical triggers all indicate large anomalous nuclear enhancements at low B_{cal} energy.

In figure 29(b), the α for the multiplicity triggers as a function of the B_{cal} energy is shown. The LMG trigger curve appears similar to those for the

Figure 29: α from A^α fits to the beam calorimeter cross-sections for the (a) geometrical and (b) multiplicity triggers is shown as a function of beam calorimeter energy deposited by an event.

a. Alpha vs. Beam Cal.

□ Global Trigger
○ Double Arm Trig.
△ Single Arm Trig.

b. Alpha vs. Beam Cal.

- Two High ET Trig.
○ Low Mult. Global Trig.

geometrical triggers, except that α is not as large at low Bcal. The 2HI trigger shows an even lower α .

5.5 Particle Multiplicities

The atomic number dependence of particle multiplicities is complex, but varies systematically. In figures 30 and 31, the cross-sections for each nuclear target to produce events of a given charged particle multiplicity while satisfying each of the triggers are shown as functions of A . Clearly, the slopes of lines fitted to these points are small at low charged multiplicity and large at high charged multiplicity. Low multiplicity events are suppressed in nuclear targets by multiple scattering, while high multiplicity events are enhanced. We observe that the mean values are ordered as

$$Nch(G) > Nch(DA) > Nch(SA) > Nch(LMG) > Nch(2HI) .$$

While the charged multiplicity binned cross-sections do not vary as A^α , we observe that the slopes of lines fitted to the $\log(Nch)$ versus $\log(A)$ data can be approximated using pairs of light and heavy nuclei. For this comparison, α is defined as

$$\alpha = \log(\sigma_1/\sigma_2) / \log(A_1/A_2) .$$

In figure 32, the α values thus obtained appear for the

c. Global N(charged)

- Nch=3-5
- Nch=6-11
- △ Nch=12-18
- + Nch=19-24
- × Nch=25-30
- ◇ Nch=31-36
- ♣ Nch=37-43
- z Nch>43

Figure 31: Same as figure 30, but for the (a) low multiplicity global and (b) two high E_T triggers.

b. Two High ET N(charged)

Figure 32: The α calculated for the charged multiplicity cross-sections by comparing heavy and light targets is shown for the (a) global and (b) two high E_T triggers.

global and two high E_T triggers. The very sharp rise in high multiplicity cross-sections as A increases is indicated by the steep rise in α as N_{ch} increases.

5.6 Data Cuts to Approximate Jets

The implications of this chapter lead us to attempt to isolate those p-A dijet events which have a p-p dijet character. This requires high transverse energy, low multiplicity, and high planarity. Figure 33 shows the resulting cross-sections as a function of A . Vertical error bars are of order 0.1-0.3 for individual points on this scale, but are not shown to allow a clear view of the relative positions for the various triggers. A^1 scaling lines are indicated in the figure, but large error bars in the data prevent an accurate α determination.

Figure 33: The cross-sections for the various triggers and targets to simultaneously have high E_T , high planarity, and low charged multiplicity are shown as a function of A .

CHAPTER 6

HADRON JETS FROM NUCLEI

6.1 Description of Jets

Hadronic jets are studied in the belief that they are the products of hard parton-parton scattering⁴⁵⁻⁵³. The present experiment is designed to preferentially select events which exhibit characteristics of the hardest available parton collisions. A large sample of jet events is sought for a variety of nuclear targets. The definition of a hadron jet is not firmly established, especially in light of Fox et al. Monte Carlo calculations which indicate that all high E_T events may result from parton scatterings with varying degrees of hardness. The lack of clear jet structure in the majority of globally triggered events is attributed to gluon bremsstrahlung. It is expected that clean pairs of well collimated hadron showers at opposite azimuthal angles represent events where gluon bremsstrahlung is minimized, so that the hardness of the parton-parton collision is maximized.

It is this type of event to which the following definition applies:

1. Jets appear as a cluster of high E_T signals.
2. Jet pairs are roughly coplanar (to within the Fermi momenta of the confined partons) in azimuthal angle.
3. The E_T of a jet cluster is largely contained in a small enough solid angle that it can clearly be distinguished above the "background" E_T distribution resulting from beam and target jets and low energy interactions.
4. The E_T values for the two jets in a pair should roughly balance (to within the Fermi momenta of the confined partons, after considering the finite extent of the calorimeter).

These criteria are basically satisfied by requiring high transverse energy events that approximately balance momentum and that have high planarity values. In particular, $E_T > 10\text{GeV}$, $P > 0.75$, and momentum conservation within about one GeV shall suffice as jet definitions for these data.

6.2 Scrambling Analysis

Investigating the jet production cross-section requires making a random event subtraction from the data. In other words, the number of events that have jet-like structure due to random statistical fluctuations in secondary particle directions must be estimated and subtracted.

This thesis uses a scrambling routine developed by M. Arenton of Argonne National Laboratory. First the calorimeter signals are identified as individual particles. This procedure is called "clustering" because it groups calorimeter segment signals into single particle signatures. The technique is to fit the segment signal distributions with Gaussian energy distributions representative of the showering of high energy particles as they interact in a calorimeter. This is done independently for the electromagnetic and hadronic layers of the calorimeter, then cross-correlated. Clustering is limited in its accuracy by the fact that the solid angle resolution of the calorimeter is 0.06sr in the p-p center-of-mass frame. Thus a particle pair landing, on average, within 0.03sr is not resolved into two particles by the clustering technique unless one is electromagnetically interacting with the calorimeter, while the other

is hadronic. The probability of such an occurrence increases with increasing θ and ϕ correlation within an event. The clustering algorithm allows the scrambling routine described below to possess approximately correct multiplicities and particle E_T spectra.

The clustering results in "particles" of specific energy and direction. In the "scrambling" procedure the particles are randomly redistributed in their ϕ orientations with the kinematic constraint of momentum conservation. Momentum is conserved to an accuracy of about one GeV/c, in such a way as to match the conservation accuracy observed in the data. The θ orientations are not scrambled, so that $d^2\sigma/d\theta dE_T$ is not altered.

The accuracy of this random event approximation is limited by the following considerations. Clustering procedures that occasionally combine two actual particles into one cluster introduce extra ϕ correlations into the model. Similarly, jets which are collimated in θ and ϕ in the data are scrambled only in ϕ , so that extra θ correlations remain in the scrambled data. The scrambling routine does not account for resonance exchanges which could contribute to the data. The lack of resonance considerations over-reduces the ϕ correlations in

the scrambled data. The relative importance of these effects is likely to be trigger dependent, so we do not know if this model underestimates or overestimates the number of high planarity random events. An independent phase space model⁵⁴ has found that p-p global trigger events have planarity distributions that are well approximated by phase space events satisfying the trigger. The scrambled and data curves for the global events are very similar, as can be seen in figure 34. This means that there is no evidence for jets in the global trigger data sample considered.

6.3 Indications of Jets

The implication from p-p data²⁷ is that geometrically unbiased triggers which require individual particles possessing high E_T , such as the two high E_T trigger, produce data samples with significant fractions of jet events. The data and scrambled data results for the 2HI trigger appear in figure 35. The software cut for the 2HI trigger required one particle with at least 1.5 GeV of E_T and another particle with at least 1.1 GeV of E_T in each event, but no overall event E_T cut was made. The high planarity region shows a clear indication of hadron

Figure 34: The planarity distributions of the actual data are compared with the approximate phase space distributions obtained by scrambling the data in ϕ . The global trigger data are shown for (a) H, (b) C, (c) Al, (d) Cu, (e) Sn, and (f) Pb.

^a. Hydrogen Global $ET > 10$

□ DATA
○ SCRAMBLED

b. Carbon Global $ET > 10$

□ DATA
○ SCRAMBLED

c. Aluminum Global ET>10

□ DATA
○ SCRAMBLED

d.
Copper Global ET>10

□ DATA
○ SCRAMBLED

e. π In Global $ET > 10$

□ DATA
○ SCRAMBLED

f. Lead Global ET>10

□ DATA
○ SCRAMBLED

Figure 35: The scrambled phase space and the data are compared as functions of planarity for the two high E_T trigger for all targets in (a)-(f). Jet signals are seen in the high planarity region.

a. Hydrogen 2HI (1.5,1.1)

□ DATA
○ SCRAMBLED

b. Carbon 2HI (1.5, 1.1)

□ DATA
○ SCRAMBLED

c. Aluminum 2HI (1.5,1.1)

□ DATA
○ SCRAMBLED

d. Copper 2HI (1.5, 1.1)

□ DATA
○ SCRAMBLED

e. $\text{Ti n 2HI (1.5, 1.1)}$

□ DATA
○ SCRAMBLED

f. Lead 2HI (1.5,1.1)

□ DATA
○ SCRAMBLED

jets for each target. In other words, the number of data events at $P > 0.7$ exceeds the number of scrambled events outside statistical errors (at least when events are summed over $0.7 < P < 1.0$). This implies that the data are correlated in ϕ to a higher degree than would be expected if these events were simply random fluctuations in the phase space background.

A trigger which was not used during data collection, but which is easily applied in software, has proven even more efficient than the 2HI at detecting jet events. It is analogous to the 2HI trigger, but it is a four high E_T particle trigger (4HI). 4HI requires that in addition to the software 2HI trigger requirement of two particles with at least 1.5 and 1.1 GeV of E_T , there be two additional particles with at least 0.8 GeV of E_T each that strike the triggering calorimeter. No overall event E_T cut is made because nuclear target events are generally of much higher total E_T than are hydrogen target events for a given trigger. The scrambled data and data curves appear in figure 36. At high planarity, comparisons of data and scrambled data show statistically significant jet signals. Table 8 shows the mean planarities of data and scrambled data distributions for various triggers and

Figure 36: Similar to figure 39, but for four high E_T trigger data.

a.

Hydrogen 4HI (1.5, 1.1, .8, .8)

□ DATA
○ SCRAMBLED

b.

Carbon 4HI (1.5,1.1,.8,.8)

□ DATA
○ SCRAMBLED

c.

Aluminum 4H1 (1.5, 1.1, .8, .8)

□ DATA
○ SCRAMBLED

d.

Copper 4HI (1.5, 1.1, .8, .8)

□ DATA
○ SCRAMBLED

e.

Tin 4HI (1.5,1.1,.8,.8)

□ DATA
○ SCRAMBLED

f.

Lead 4HI (1.5, 1.1, .8, .8)

□ DATA
○ SCRAMBLED

Table 8: The mean planarity values for data and scrambled data distributions are shown for global, 2HI and 4HI triggers. The statistical errors in the P values shown are generally 0.01 or less.

TRIGGER	TARGET	P(data)	P(scrambled)
Global	H	0.43	0.41
$E_T > 14$ GeV	C	0.39	0.39
	Al	0.37	0.37
	Cu	0.34	0.35
	Sn	0.36	0.36
	Pb	0.36	0.37
2HI	H	0.69	0.62
(1.5,1.1)	C	0.64	0.59
	Al	0.60	0.57
	Cu	0.56	0.54
	Sn	0.57	0.55
	Pb	0.58	0.54
4HI	H	0.65	0.48
(1.5,1.1, 0.8,0.8)	C	0.52	0.44
	Al	0.52	0.46
	Cu	0.49	0.45
	Sn	0.50	0.46
	Pb	0.49	0.46

targets.

An interesting point to investigate is the approximate jet cross-sections which can be obtained by subtracting the scrambled events of planarity above 0.7 from the data events in the same planarity range to yield a net number of jet events. The jet cross-sections are plotted as functions of atomic number for the 2HI and 4HI triggers in figure 37. Note that in both cases, A^α scaling appears to hold, and that α is 1.1 ± 0.2 .

6.4 Particle Angular Distributions for Jets

The character of high E_T events produced on the various targets can be studied through the angular distributions of the collision products. The clustering algorithm uses the calorimeter signals to produce a distribution in position and energy of all the particles, charged and neutral, that strike the calorimeter. We can therefore compare the angular distributions of particles of a given transverse energy range.

In figure 38, the distributions in lab angle of clusters with 0.0-0.3 GeV of E_T and 1.0-2.0 GeV of E_T are shown for H and Pb targets for 2HI trigger data. Clearly, the lead target produces proportionately more wide

Figure 37: The jet cross-sections calculated by subtracting the phase space model from the data for .7-1.0 planarity bins are shown for the 2HI and 4HI triggers.

Jet Cross-Sections

□ Two High ET Trigger
○ Four High ET Trigger

Figure 38: The angular distributions of particles found by clustering that have (a) 0.0 through 0.3 GeV of transverse energy or (b) 1.0 through 2.0 GeV of E_T are shown for 2HI events from hydrogen and lead. The number of counts applies to hydrogen and the H and Pb curves are normalized to have the same area underneath.

a. 2HI 0.0-0.3 GeV ET Particles

□ HYDROGEN
○ LEAD

b. 2HI 1.-2. GeV ET Particles

□ HYDROGEN
○ LEAD

angle particles than the hydrogen target for both bins of single particle E_T . When the data are cut in planarity so that $0.75 < P < 1.0$ as occurs in figure 39, the low E_T particles are still produced at wider angles by the Pb target than by the H target; however, the high E_T particles are now similarly distributed in angle for both H and Pb targets.

Table 9 shows the average scattering angle of the particles for different particle E_T ranges in the global and 2HI triggers for hydrogen, carbon, and lead targets. The angles are larger for lower E_T particles in general. The angles are larger for higher A targets, but become similar for all targets in the high particle E_T , high planarity 2HI events. It is therefore possible that the high E_T particles of jet events are produced similarly for all targets, while the low E_T particles are produced at wider angles by high A targets even in jet events.

Table 10 shows the composition of events in terms of the fractional part of all particles produced that have a given E_T for the global and 2HI triggers. About 77% of all particles produced in the fiducial region of the calorimeter in globally triggered events have $E_T < 0.6 \text{ GeV}$. For two high trigger events the fraction is the same when

Figure 39: Same as figure 38, but after selecting only those events with planarity above 0.75.

a. 2HI 0.0-0.3 GeV ET Particles, $P > .75$

□ HYDROGEN
○ LEAD

b. 2HI 1.-2. GeV ET Particles, $P > .75$

□ HYDROGEN
○ LEAD

Table 9: The mean lab angle theta is shown in degrees for H, C, and Pb targets for global and 2HI triggers with and without high planarity cuts. The mean angle is presented for particles with 0.0-0.3 GeV of E_T , 0.3-0.6, 0.6-1.0, and 1.0-2.0 GeV of E_T . Statistical errors in the angles shown are less than 0.1 degree for all cases.

TARGET	Particle E_T (GeV)			
	.0-.3	.3-.6	.6-1.	1.-2.
Global Trigger; all planarities:				
H	4.1 deg.	3.8	3.6	3.5
C	4.8	4.3	4.1	4.0
Pb	5.0	4.6	4.3	4.2
Global Trigger; $P > 0.75$:				
H	4.1	3.6	3.8	3.7
C	4.6	4.1	3.9	3.8
Pb	4.9	4.4	4.2	4.1
2HI Trigger; all planarities:				
H	3.9	3.5	3.3	3.3
C	4.6	4.1	3.8	3.6
Pb	4.8	4.3	4.0	3.9
2HI Trigger; $P > 0.75$:				
H	3.9	3.4	3.3	3.5
C	4.5	3.9	3.7	3.6
Pb	4.7	4.1	3.7	3.6

Table 10: The fraction of the total multiplicity of particles striking the calorimeter comprised by particles with transverse energies in GeV of 0.0-0.3, 0.3-0.6, 0.6-1.0, and 1.0-2.0, are shown for global and 2HI triggers with and without planarity cuts. The statistical errors for the all P cases are 0.02 for the .0-.3 bin, 0.03 for the .3-.6 bin, 0.02 for the .6-1. bin, and 0.02 for the 1.-2. bin. For 2HI triggers with $P > 0.75$, these errors are ~ 1.5 times larger, and for global triggers with $P > .75$ these errors are ~ 3 times larger.

	Particle E_T (GeV)			
TARGET	.0-.3	.3-.6	.6-1.	1.-2.
Global Trigger; all P:				
H	.35	.42	.16	.07
C	.38	.39	.15	.08
Al	.36	.40	.16	.08
Cu	.33	.42	.17	.08
Sn	.36	.40	.16	.08
Pb	.37	.40	.15	.08
Global Trigger; $P > 0.75$:				
H	.39	.44	.12	.06
C	.38	.42	.15	.06
Al	.37	.43	.14	.07

Cu	.36	.42	.16	.06
Sn	.37	.43	.15	.06
Pb	.37	.43	.12	.07

2HI Trigger; all P:

H	.35	.39	.12	.14
C	.38	.38	.12	.12
Al	.37	.42	.12	.08
Cu	.32	.43	.16	.10
Sn	.36	.40	.13	.11
Pb	.37	.40	.13	.10

2HI Trigger; $P > 0.75$:

H	.37	.37	.11	.15
C	.41	.37	.10	.11
Al	.38	.40	.12	.10
Cu	.33	.42	.16	.10
Sn	.35	.42	.13	.10
Pb	.36	.43	.12	.10

no planarity cut is made. In fact, there is no apparent difference between the results for these two triggers when $P > 0.75$ is required. No strong A dependence is apparent in the percentages of all secondaries produced in a fixed E_T range.

6.5 Parton Transverse Momentum

The intrinsic momentum of the partons inside a nucleon has been measured in p-p scattering⁴⁸. It is measured by using a double arm trigger and seeking left-right imbalances in E_T , reflecting partonic transverse motion prior to hard scattering. The x-component of this motion is measured by taking the difference of the left hemisphere and right hemisphere E_T values. A Gaussian distribution results, and its width is related to the mean intrinsic parton momentum in the x direction, designated as k_{Tx} . Some of the width is due to phase space fluctuations that cause imbalances when more E_T misses the left 4sr of the calorimeter than the right 4sr, or vice versa. To measure k_{Tx} , these fluctuations must be corrected for via Monte Carlo techniques.

The values of k_{Tx} are calculated for 6 and 8 Gev of E_T required in the 4 sr double arm trigger. The results

are plotted in figure 40 as a function of the mean number of collisions made by an incident particle traveling through a nucleus, ν , as calculated in chapter 2. The curves shown are approximately described by

$$k_{Tx} = a + b(\nu-1) \quad ,$$

where "a" is 1.0 GeV and "b" is 0.3 GeV for the 6 GeV DA trigger cut, and $a=1.2\text{GeV}$ and $b=0.4\text{GeV}$ for the 8 GeV cut.

Possibly of related significance, the charged particle multiplicities measured in the wire chambers also scale linearly in ν . Figure 41 shows the dependence of multiplicity on ν for the global and two high E_T triggers. Scaling the charged multiplicity as

$$N_{ch} = a + b\nu \quad ,$$

we find for the global trigger with $E_T > 12\text{GeV}$ that $a=6.9$ and $b=9.6$. For the 2HI trigger with two particles of E_T above 1.5 and 1.1 GeV, we find that $a=0.5$ and $b=10.1$.

Figure 40: The half-width of the PTL-PTR distribution is displayed for the 4 sr double arm trigger as a function of nuclear thickness expressed in mean nucleon-nucleon collisions per event. The data are cut for at least 6 GeV in the trigger region and for at least 8 GeV in the trigger region.

Double Arm kT_x

Figure 41: The charged particle multiplicity is plotted as a function of mean nucleon-nucleon collision number for the global and 2HI triggers.

CHAPTER 7

CONCLUSION

7.1 Empirical Data Trends

Several empirical rules for high transverse energy proton-nuclear scattering have been confirmed or first observed. These include approximate A^α scaling as seen when cross-sections and the parameter α are treated as functions of E_T , planarity, and beam calorimeter energy, i.e.

$$\begin{aligned}\sigma(E_T) &= \sigma_0 A^{\alpha(E_T)} , \\ \sigma(P) &\approx \sigma_0 A^{\alpha(P)} , \text{ and} \\ \sigma(Bcal) &\approx \sigma_0 A^{\alpha(Bcal)} .\end{aligned}$$

We have also tested the parameterization

$$\sigma(E_T) = \sigma_0 e^{-mE_T}$$

for m and σ_0 constant, and found it to hold within statistical errors over a broad range of E_T . In addition, charged multiplicity and approximate intrinsic parton momentum are found to vary as the mean number of nucleon-nucleon collisions in p-A scattering. This means that

$$N_{ch} = a + b\nu \quad , \text{ and}$$

$$k_{Tx} = c + d\nu \quad ,$$

where a , b , c , and d are constants for a given trigger and E_T . We have measured the attenuation in nuclear matter of thickness L of the beam jet energy transmitted into a cone about the beam axis with a half angle of 30 degrees in the p - p center of mass frame. For nuclear target thickness given in nucleons per square Fermi, it is

$$B_{cal} = 270 \text{ GeV} - (20 \text{ GeV})(L-1)F^2 \quad .$$

In addition to finding these empirical rules, their parameters are measured over large ranges in the appropriate variables. We find e.g. that α decreases as B_{cal} increases, as P increases, as E_T decreases, and as N_{ch} decreases. We also find a hydrogen deviation from A^α scaling and find its sign to be opposite for the geometrical and multiplicity triggers, and that its magnitude increases as E_T increases and as B_{cal} decreases.

7.2 Jets from Nuclei

Hadron jets are clearly seen for p - A interactions. We find that the 2HI and 4HI jet cross-sections scale approximately as A^α so that

$$\sigma(2HI \text{ jet}) = \sigma_0 A^{1.1 \pm 0.2} \quad \text{and}$$

$$\sigma(4HI \text{ jet}) = \sigma_0 A^{1.1 \pm 0.2} .$$

The angular distributions of particles of a given E_T imply that in jet events, high E_T particles are similarly produced from all targets, while low E_T particles are generally produced at wider angles by higher A targets (via softer processes?).

7.3 Hadronization Lengths

The mechanism of parton hadronization could occur on the following length scales: an instantaneous explosion of 30 particles, a string model production of one particle per Fermi traversed by a scattered parton, or a hadronization mechanism in which one particle is created per about 80 Fermi's of parton travel. The first is not the case since many nucleons would be seen in the secondaries, and they are not seen in sufficient abundance. This is seen by comparing the ratios of single particle production cross-sections measured in reference 15, and noting that the meson-to-baryon ratio does not appreciably vary with A . This experiment does not provide conclusive evidence for or against either of the latter two suggested hadron formation lengths. Another experiment⁵⁵

has found evidence of a momentum dependent hadron formation length at lower energies. The constant nature of the ratio of the electromagnetically deposited energy to the hadronically deposited energy in the calorimeter indicates that particle production from nuclei does not differ at our sensitivity level.

7.4 The Future of p-A Scattering

Suggestions for future work in this field are that

1. This experiment should be repeated with targets of $1 < A < 12$. The question of whether the A^α enhancement is primarily due to soft or hard collisions should be answered by low A cross-section scaling dependences.

2. This experiment should be repeated with higher statistics over a wide range of E_T so that $\alpha(\text{jet})$ can be mapped.

3. Beam calorimeter effects should be independently checked with this same set of nuclear targets to determine the validity of the kinks in the A^α scaling that we see there.

APPENDIX

SEA QUARK EFFECTS

The anomalous nuclear enhancement effect is not explained by an enhanced number of sea quarks (e.g. mesons in the nuclear strong field) alone. This has been shown by studies of the Drell-Yan process, in which a quark and anti-quark pair annihilates into a photon which decays into a lepton and anti-lepton pair. This effectively measures the relative abundances of quarks and anti-quarks when both meson and baryon beam particles impinge on the same targets. The Drell-Yan cross-section^{56,57}, when scaled as A^α , shows $\alpha=1.0$ for both pions and protons as incident beams. This indicates that the total number of sea quarks scales proportionally to the number of nucleons. It is known from photon-nuclear and lepton-nuclear scattering⁵⁸ that the total number of partons scales as the number of nucleons. There is a dependence on Bjorken x_T . There is evidence of a sea quark enhancement in nuclei at small (and possibly at large) x_T , in references 59, 60, and 61. In the x_T range of this experiment, $\alpha < 1$ is the Drell-Yan result, according to the results of reference 61. Bjorken's

scaling variable, x_T , is defined as

$$x_T = 2 P_T / \sqrt{s} ,$$

where P_T is the transverse momentum of the detected particle in the center of mass of the collision, and s is the square of the center of mass energy of the colliding particles. The nature of the A^α cross-section enhancement is not completely clear since small x_T secondary scattering can add a small amount of transverse energy to an event, and the steep drop of σ with E_T causes a small boost in the E_T of ordinarily lower E_T events to greatly enhance the higher E_T cross-sections.

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