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A STUDY OF HIGH TRANSVERSE ENERGY HADRON-HADRON COLLISIONS AT 400 GEV/C USING A QCD MONTE-CARLO INCLUDING INITIAL AND FINAL STATE GLUON BREMSSTRAHLUNG

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HADRON-HADRON COLLISIONS AT 400 GEV/C
USING A QCD MONTE-CARLO INCLUDING
INITIAL AND FINAL STATE GLUON
BREMSSTRAHLUNG

by

KENNETH ARTHUR JOHNS

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ABSTRACT

A STUDY OF HIGH TRANSVERSE ENERGY
HADRON-HADRON COLLISIONS AT 400 GEV/C
USING A QCD MONTE-CARLO INCLUDING
INITIAL AND FINAL STATE GLUON
BREMSSTRAHLUNG

Kenneth Arthur Johns

The production of high transverse energy events in 400 GeV/c pp collisions triggered with a full azimuthal, large solid angle calorimeter is studied. A detailed comparison is made between the experimental data and a QCD Monte-Carlo which includes initial and final state gluon bremsstrahlung. Results on cross sections, energy flows, and event structures are presented for two different types of geometrically unbiased triggers. The characteristics of two and three jet events in the data and Monte-Carlo are also compared. We find that gluon bremsstrahlung effects as implemented in the Field-Fox-Wolfram Monte-Carlo are not sufficient to describe many features of both jetlike and non-jetlike events.
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CHAPTER 1
INTRODUCTION

Jets in large transverse energy hadron-hadron collisions are expected to occur as the result of a hard scattering between the constituents of the hadrons. In the quark-parton model, one parton from the beam hadron and one from the target hadron undergo a hard collision producing two outgoing partons which each fragment into a fountain of hadrons with limited transverse momenta with respect to the parton direction. The remnant partons in the beam and target hadrons hadronize into two additional jets along the beam axis.

Such jets have been observed cleanly, if not spectacularly, at the SPS $\bar{p}p$ collider as shown, for instance, in Figure 1.1 and dominate the event structure above $\sum E_T > 100$ GeV. In lowest order QCD, the inclusive jet cross section is given by:

$$\frac{E d^3 \sigma}{d^3 p} = \sum \int dx_1 dx_2 \ F_a(x_1) \ F_b(x_2) \ \delta(s + t + \mu) \ \sum \frac{d\sigma(ab-cd)}{dt}$$

where $F_a$, $F_b$ are the structure functions (longitudinal momentum distributions) for partons a and b, $s, t, \mu$ are the Mandelstam variables for the ab-cd hard scatter, and $d\sigma(ab-cd)/dt$ is the differential cross section calculated to leading order in QCD for the parton subprocess ab-cd. The observation of a clear two jet signal and the
Figure 1.1 Typical two jet event with $\sum E_T > 100$ GeV in the region $|\eta| < 1.5$ from the UA1 collaboration. The $E_T$ distribution is given as a function of azimuthal angle $\phi$ and pseudo-rapidity $\eta$. 

![Graph showing $E_T$ distribution](image)
agreement of the measured inclusive jet yield with $1.1^{5,7}$ are both successful tests of QCD. Moreover, the measured angular distribution of two jet events is consistent with that expected from vector gluon exchange in the dominant subprocesses.$^9$ Using a differential cross section common to the dominant subprocesses and the measured jet cross section, $1.1$ can be unfolded and an effective structure function extracted from the data which is in agreement with that measured in deep inelastic scattering after scale breaking effects are included.$^9$ This confirms the belief that by measuring high $P_T$ hadron-hadron scattering one is directly observing the strong interaction of the underlying constituents.

Experiments at the ISR have also observed the emergence of a strong two jet signal but only at sufficiently large $E_T$ at the highest ISR energy.$^{10,11,12}$ At the lower ISR energies, and at SPS and FNAL energies, no evidence was found for a dominant, clean two jet structure in events triggered with global ($\Delta$=2π) large solid angle calorimeter triggers.$^{11,13,14,15}$ Instead, these experiments found the majority of large $E_T$ events to have large multiplicities distributed roughly isotropically in phi in the transverse plane. Although subject to many uncertainties and open to interpretation, using various models of high $P_T$ hadron-hadron scattering (including structure
functions and fragmentation schemes), jet cross sections can be extracted from the data at these lower energies. The results are consistent with lowest order QCD calculations and in fact, the nearly thousand-fold increase in inclusive jet yield from ISR to collider energy at fixed jet $P_T$ was a successful prediction of QCD.

Evidence that high $P_T$ hadron-hadron collisions were associated with hard scattering between the pointlike constituents of the colliding hadrons first came at the ISR almost 15 years ago from experiments studying large $P_T$ inclusive pion production. For single $\pi^0$ triggers with $P_T > 1$ GeV, a large and energy dependent cross section was observed which was not expected from extrapolation of the $e^{-6P_T}$ behavior of most of the inelastic cross section. Because the parton model scales, it predicts the inclusive cross section to follow the form

$$\frac{d^3\sigma}{d^3p} \propto P_T^{-N} F(x_T),$$

where $x_T = 2P_T/\sqrt{s}$ and $N=4$ from simple dimensional analysis. Indeed, the data were found to obey this scaling law giving validity to the parton model description of large $P_T$ hadron production, however the power $N$
needed to be 8 indicating the neglect of other effects (intrinsic (primordial) parton transverse momentum, higher twist terms, etc.) in 1.2.

Subsequently, a long series of ISR experiments studying rapidity, phi, and quantum number correlations of the same and away side particles with the high $P_T$ trigger particle confirmed the existence of a two jet structure consistent with the parton model described above. (For reviews covering high $P_T$ hadron-hadron physics see references 23-28.) It was realized by then however that because the parton-parton cross section falls steeply with $P_T$ ($\sim 1/P_T^4$) any mechanism which increases the observed $P_T$ without increasing the $P_T$ of the hard scatter will be preferentially selected upon triggering. Because of this trigger bias, high $P_T$ single particle triggers on average choose those events in which the intrinsic and "effective" (due to gluon bremsstrahlung) transverse momenta of the partons to scatter are directed toward the triggering region and those in which the fragmentation of the scattered parton results in the trigger hadron carrying nearly all the parton's momentum. Because it samples only a small part of the relatively unknown fragmentation function, the assemblage of jets collected by single particle triggers will contain less than a percent of all
possible jets at a given jet $P_T$ and, it follows, these jets will be atypical ones in structure.

To overcome such trigger bias effects, it was proposed\textsuperscript{2} to trigger on and collect the full jet using small solid angle (roughly 1-2sr) hadron calorimeters. Experiments with limited solid angle triggers at FNAL\textsuperscript{30,31} found a roughly $10^2$ increase in the "jet" (hadrons collected by the calorimeter) cross section as compared to the single pion yield at a fixed $P_T$ in good agreement with QCD predictions. A two jet structure consistent with the QCD-parton picture was also observed as evidenced, for example, by the clustered multiparticle composition, coplanarity and approximate $P_T$ balance of jets chosen with single and double arm triggers.\textsuperscript{32,33,34} Skeptics argued however that the trigger geometry itself could easily select events of non-hard scattering origin which appeared jetlike due to statistical fluctuations and that therefore such triggers did not provide an unambiguous test of the existence of jets nor an unbiased jet sample from which to examine their properties. It is hard to understand such objections though when no serious alternative dynamical model existed which could explain the single particle and small solid angle trigger results.

To surmount the difficulties associated with
geometrically biased triggers, experiments were proposed employing large solid angle calorimeters with full azimuthal coverage which would trigger on the total (global) transverse energy deposited within. The NA5 collaboration at the SPS performed the first of these experiments and found no evidence for two jet structure even at values of $E_T$ up to 70% of the kinematic maximum. Rather their experiment, and later E557 and E609 at FNAL, observed most of the events to have large multiplicities distributed fairly isotropically in the transverse plane as shown, for example, in Figure 1.2. Until overshadowed by the dramatic two jet events seen at the CERN collider, the NA5 results fueled heated debates on the existence of jets at FNAL energies and the theoretical interpretation of the globally triggered cross section and event structure.

Experiment E609 at FNAL found itself amid such controversy at the start of its run hence it is easy to understand the motivation to confirm or clarify the conclusions reached by NA5. In addition to the global trigger, E609 employed a large number of additional triggers with both proton and pion beams in an effort to identify jets and study their structure with the hope of gaining information on the strong interaction of the hard scattering constituents.
Figure 1.2 Typical event selected by the E609 global (Δφ=2π) trigger with \( \sum E_T > 17 \) GeV. The \( E_T \) distribution is given versus \( \theta \times \cos \phi \) and \( \theta \times \sin \phi \) where \( \theta \) and \( \phi \) are the polar and azimuthal angles respectively. The border of the plot corresponds roughly to the edges of the E609 calorimeter.
Altarelli has separated tests of QCD into three categories: 1) topological features, 2) order of magnitude estimates of rates and cross sections, and 3) precise quantitative confrontations. One can argue however that with the expectations of QCD showing generally good agreement with an impressive body of data from a number of experimental arenas, we have stopped testing whether QCD is the correct theory of the strong interactions and are now answering questions about the details of what exactly QCD predicts! This thesis will be concerned with tests from the first two groups, e.g. comparisons of energy flows, event shapes, and cross sections for various triggers are made between data and QCD as calculated with the Field-Fox-Wolfram Monte-Carlo for hadron-hadron collisions. Exact numerical predictions of QCD to be confirmed by experiment cannot as yet be made in high $P_T$ hadron-hadron interactions because of the present inability to compute the non-perturbative parts of the scattering picture (e.g. confinement) or even to calculate exactly higher order corrections (because of color combinatorics).

In QCD, the approximate validity of asymptotic freedom at large $Q^2$ allows perturbation theory to be applied to e.g. the calculation of parton subprocess cross sections. The low $Q^2$ processes in the problem, e.g. the
conversion of partons into hadrons or the emission of soft radiation, must be either phenomenologically modeled or approximated to avoid divergences. It is hoped that the approximations used and hadronization schemes adopted will be closely connected to the unknown exact calculation. Because of the probabilistic nature of many parts of the problem, especially structure functions and hadronization, it is usual to use a Monte-Carlo to obtain the details of what QCD predicts for experimental observables.

Since Monte-Carlo calculations represent our best effort in understanding what perturbative QCD predicts, which by definition is an approximation to the exact results of QCD, the questions arise as to how well can Monte-Carlo predictions be trusted to describe QCD and with what weight should they be viewed. Without knowing the full solutions to QCD, one can only be optimistic that those parts of the calculation (e.g. hadronization) which are phenomenologically modeled do not obscure the predictions of perturbative QCD and that by investigating various hadronization schemes a better understanding of hadron formation may be gained.

One objection to the reliability of Monte-Carlo calculations arises because of the number of adjustable parameters and cutoffs contained in the programs which
theoretically allow one to dial any result or outcome desired. That is true; all Monte-Carlos are somewhat tuned, either to $e^+e^-$ annihilation data or inclusive data from lepton-hadron collisions. The test of a given Monte-Carlo model, though, is after adjusting the parameters to give agreement with something, how well does it predict observables for other triggers or at higher energies. The only way to distinguish among various perturbative models is to compare their results against all that is experimentally known.

Another objection begins with the fact that all currently employed Monte-Carlo models for hadron-hadron collisions rely on the Feynman-Field-Fox independent parton parameterization for hadronization\textsuperscript{40,41,42} to a greater or lesser extent. This scheme unfortunately suffers from a number of known maladies\textsuperscript{43} not the least of which is energy and momentum nonconservation due to the generation of massive hadrons from massless partons. This problem is worsened when using any high $E_T$ trigger since those events on the high energy tail of the total energy distribution will be preferentially selected due to a trigger bias similar to those discussed above. Furthermore, it has recently been shown\textsuperscript{44} that how one decides to impose overall energy and momentum conservation, if at all, leads to strikingly different conclusions about
cross sections and event shapes. The objection is that since all methods to impose energy and momentum conservation are arbitrary, all are equally right (or wrong). Yet, each method can change the structure of the of the events one has just generated in entirely different ways. Therefore how can the predictions be taken seriously?

A few comments on this objection are offered. In the fragmentation of a massless parton into massive hadrons one typically has the choice of conserving $E$, $P_Z$, or $E+P_Z$. First, the problem is not that one gets different results depending on which quantity one chooses to conserve here. Any of these methods gives roughly the same results for cross sections, planarity distributions, etc. and so therefore one could choose to conserve $E$ right away and avoid totally the nuisance of having only approximate energy conservation of the final state hadrons. The problem occurs when either of the other two methods are employed and then overall energy and momentum conservation are imposed. Certainly any of the methods used at this point to ensure exact energy conservation which give radically different answers from any of the three choices above should be suspect. Or, one can consider the method used to ensure $E-P$ conservation to be simply another adjustable parameter of the model; one method is chosen based on the agreement of cross sections
and observables for one trigger type and predictions made for other triggers or other energies.

Finally, other than to wait for the implantation of new phenomenologically correct hadronization schemes without the problems of independent parton fragmentation onto parton final states generated according to perturbative QCD, one has no choice but to boldly make use of the current Monte-Carlo models if one's goal is an increased understanding of the details of the mechanism of high $P_T$ interactions.

At present, Monte-Carlo's provide the only proving ground for testing the various models of hadron-hadron collisions and their components. This includes systematically studying the effects of higher order corrections to the perturbative part of the problem, investigating the unknown physics of the spectator partons, and observing the effects of different sets of hadron structure functions and different models of hadron formation. By comparing Monte-Carlo calculations with data one hopes to identify the most important physical features at both the parton and hadron levels in high $P_T$ production picture and to point out the strengths and weaknesses of the present choice of Monte-Carlo models.

This thesis uses a state-of-the-art Monte-Carlo for hadron-hadron collisions developed by
Field-Fox-Wolfram\textsuperscript{37-39} (FFW) which includes both initial and final state gluon bremsstrahlung and makes use of a new hadronization model which is in the spirit of QCD perturbation theory. This Monte-Carlo supercedes the workhorse program originated by Feynman-Field-Fox\textsuperscript{40-42} (FFF) which described many features of high $p_T$ hadron-hadron scattering but contained a number of difficulties and theoretical shortcomings which precluded a detailed understanding of the large $E_T$ production process. As reported by NAS\textsuperscript{35}, the FFP model, which is essentially the quark-parton model described above slightly modified by QCD with primordial parton $k_T$, could not reproduce the large cross section and non-jetlike event structure of the global trigger (although a recent calculation\textsuperscript{44} finds a similar model in good agreement with the data).

The FFW Monte-Carlo is based on the generation of parton showers according to the leading log approximation to perturbative QCD as developed by Fox and Wolfram\textsuperscript{38} and Odorico\textsuperscript{45} for $e^+e^-$ annihilation. In this approach both the initial state partons to scatter and the outgoing final state partons are allowed to radiate gluons according to simple probability factors resulting in a multiparton final state. Once the shower has been produced, color
neutral strings or clusters are formed which subsequently decay into hadrons.

The noteworthy success of this model as reported by its creators is the good agreement between the Monte-Carlo calculations\textsuperscript{29,46,47} with the small and large aperture trigger results from NA5. In the context of this model, the large cross section and non-jetlike nature of globally triggered events are explained naturally in terms of yet another trigger bias. Large solid angle calorimeter triggers are biased towards the production of parton final states with a large amount of noncollinear gluon bremsstrahlung, especially coming from the initial state partons. Because of the rapidly falling parton subprocess cross sections with $p_T$ of the hard scatter, an observed $E_T$ in the calorimeter more likely comes from a low $p_T$ scatter accompanied by large amounts of radiation than from a scatter with $p_T \sim E_T/2$.

We find, however, that gluon bremsstrahlung effects alone, as implemented in the FFW Monte-Carlo, are not sufficient to describe many features of both non-jetlike (global) and jetlike events. This implies that the effects of gluon bremsstrahlung in the high $E_T$ production mechanism are minimal and that the FFW Monte-Carlo does not adequately describe other important effects such as
the hadronization of the beam and target spectator partons (which are not well understood in any case).

In chapter 2, a detailed description of the E609 detector including data acquisition logic and electronics is given. The calorimeter calibration with muons, electrons, and hadrons is also discussed.

The Monte-Carlo method for generating parton showers according to perturbative QCD developed by Fox and Wolfram is described in chapter 3. The hadronization schemes of Field and Wolfram and Feynman, Field, and Fox combined with the parton shower generator are also described. A brief summary of past calculations made with the model is given. The effects of using different kinematic variables in simulating calorimeter triggers and the effects of imposing exact energy and momentum conservation on the final state hadrons are also discussed.

The analysis procedures applied to the E609 data and FFW Monte-Carlo events are described in chapter 4. The E609 results for a number of experimental observables for two types of geometrically unbiased triggers, a global trigger and a relatively efficient jet trigger, are presented and compared with those predicted by the FFW Monte-Carlo. A comparison is also made between the data and Monte-Carlo in the characteristics of two jet events.
as defined by a jet finding algorithm. Evidence for three jet production resulting from hard gluon bremsstrahlung is also given. Finally, the parton substructure of FFW Monte-Carlo events satisfying the global and jet triggers is examined.

Finally, in the last chapter the conclusions of this work are summarized and future directions of effort indicated.
CHAPTER 2

EXPERIMENTAL APPARATUS AND ITS CALIBRATION

2.1 DESCRIPTION OF THE E-609 DETECTOR

The E-609 detector system is located in the M6E beam line at FNAL. This beam line allows proton momenta from 5 to 400 GeV/c with \( \pi/K \) admixtures at momenta < 400 GeV/c. The experimental apparatus (Figure 2.1) consists of a set of beam defining scintillators (not shown), a wall of muon veto counters, twelve planes of drift chambers, three multiwire proportional chambers, a spectrometer magnet with a small \( P_T \) kick, the main hadron calorimeter, and finally a beam hole calorimeter.

The main calorimeter is highly segmented and provides full azimuthal coverage over 8 sr at 400 GeV/c. The beam hole calorimeter is used to absorb the energy of particles traveling down the beam hole (roughly pp center-of-mass (CM) polar angles smaller than 23°) in the main calorimeter. As most of the analysis in latter chapters is primarily based on information from the main and beam calorimeters an abbreviated description of those parts of the detector follows here. A quite detailed and thorough description of the main E-609 calorimeter, its calibration using directed muons, and its response and energy resolution for hadrons and electrons may be found
Figure 2.1 Top view of the E609 detector system.

TOP VIEW OF E-609 APPARATUS
in reference 48. Only the most pertinent parts of that reference are summarized here.

The complete calorimeter is shown in Figures 2.2 and 2.3. It consists of 528 individual modules stacked together to form 132 longitudinal segments or towers. Each segment has 4 layers of modules and all segments point at the hydrogen target. Within a given segment, modules in successive layers grow in cross sectional area so as to subtend roughly equivalent solid angles at the target. This telescoping tower structure minimizes the amount of energy the longitudinal development of the cascade shower spills into adjacent segments.

Each module (Figure 2.4) in the calorimeter array is of sampling construction with alternating layers of passive absorber and scintillator. The "electromagnetic" front layer (called A Prime) of the calorimeter is assembled using modules of 5-8.5 radiation lengths of lead/scintillator sandwich. The remaining three layers (called A, B, and C) form the "hadronic" section of the calorimeter and consist of modules with iron/scintillator sampling giving a total (all layers) of 6.0-8.0 absorption lengths.

We employ modules of 5 types which differ in sampling frequency, material and thickness of absorber, and scintillator choice. The detailed composition of the
Figure 2.2 Front view of the calorimeter array with pp center-of-mass angles shown at $P_{\text{beam}} = 400 \text{ GeV/c}$. 

FRONT VIEW OF CALORIMETER ARRAY AT 400 GeV/c
Figure 2.3 Segmented representation of the calorimeter array.
Figure 2.4 Representation of the 14 gap iron calorimeter module construction.
different module types is listed in Table 2.1. The various sampling thicknesses reflect the fact that at increasing CM angles a particle or cluster of particles which satisfy a high transverse momentum trigger will have decreasingly less energy. Typical particle energies in the outer rings may be only 5-10 GeV. As we wish the energy resolution to be uniform over the whole calorimeter at the trigger level, we must therefore decrease the sampling thickness as we go out in CM angle.

If we imagine the segments in the calorimeter to form 8 concentric rings, then the 5 types of modules and their transverse sizes in the AP and A layers are distributed as follows:

<table>
<thead>
<tr>
<th>AP Layer</th>
<th>Rings 1,2</th>
<th>5 Gap</th>
<th>2x4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring 3</td>
<td>5 Gap</td>
<td>4x4</td>
</tr>
<tr>
<td></td>
<td>Rings 4,5</td>
<td>3 Gap</td>
<td>6x6</td>
</tr>
<tr>
<td></td>
<td>Rings 6,7,8</td>
<td>3 Gap</td>
<td>8x8</td>
</tr>
<tr>
<td>A, B, C Layers</td>
<td>Rings 1,2</td>
<td>14 Gap</td>
<td>2x4</td>
</tr>
<tr>
<td></td>
<td>Ring 3</td>
<td>14 Gap</td>
<td>4x4</td>
</tr>
<tr>
<td></td>
<td>Rings 4,5</td>
<td>16 Gap</td>
<td>6x6</td>
</tr>
<tr>
<td></td>
<td>Rings 6,7,8</td>
<td>20 Gap</td>
<td>8x8</td>
</tr>
</tbody>
</table>

Because of the steeply falling cross section of high $P_T$ events, the collection of output signals from the calorimeter, whether ions or light, must be uniform
<table>
<thead>
<tr>
<th>Sampling Frequency</th>
<th>Fe Plate Thickness</th>
<th>Pb Plate Thickness</th>
<th>Scint Plate Thickness</th>
<th>Scint Type</th>
<th>Labs</th>
<th>Lrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Gap</td>
<td>12.7 mm</td>
<td></td>
<td>12 mm</td>
<td>Roehm 1922</td>
<td>1.93</td>
<td>15.35</td>
</tr>
<tr>
<td>16 Gap</td>
<td>18.8 mm</td>
<td></td>
<td>12 mm</td>
<td>Roehm 1922</td>
<td>2.11</td>
<td>17.89</td>
</tr>
<tr>
<td>14 Gap</td>
<td>26.4 mm</td>
<td></td>
<td>8 mm</td>
<td>Roehm 2003</td>
<td>2.54</td>
<td>25.08</td>
</tr>
<tr>
<td>5 Gap</td>
<td></td>
<td>9.6 mm</td>
<td>8 mm</td>
<td>Roehm 2003</td>
<td>5.37</td>
<td>8.8</td>
</tr>
<tr>
<td>3 Gap</td>
<td></td>
<td>9.6 mm</td>
<td>12 mm</td>
<td>Roehm 1922</td>
<td>9.24</td>
<td>5.57</td>
</tr>
</tbody>
</table>

Table 2.1 Module Types and Composition
everywhere. This means the calorimeter must have no "hot spots" and should have a minimum of lateral and longitudinal dead spaces. The demands for a detector with a large, sensitive area yet which is highly compact and allows efficient and uniform signal collection by the small photocathode area are met by employing light gathering techniques using radiance amplification by fluorescent radiation converters. 49-52

Light from charged particles passing through either of two triangles of scintillator is collected along the 45 degree diagonal by the 3 mm thick BBQ wavelength shifter bar (WSB)(Figure 2.5). Light output is further increased by placing Alzac reflectors on the faces and edges of all scintillator pieces. A portion of the light which is re-emitted isotropically by the fluorescing BBQ is carried by total internal reflection the length of the WSB where it is reflected through 90 degrees by a polished 45 degree cut in the acrylic light guide (Figure 2.6). From here light is carried by total internal reflection to the photocathode.

PM gain stability was monitored daily with an automatic LED calibration system 53 which took ADC data using pulsed LED's glued to each module's light guide approximately 6.3cm from the PM. Subsequently the number of photoelectrons per ADC channel was calculated online
Figure 2.5 Scintillator-BBO bar-light pipe optical system.
Figure 2.6 BBQ wavelength shifter bar.
for each module from its pulse height distribution, compared with values from previous runs, and saved on disk files.

The beam calorimeter (Figure 2.7), positioned directly behind the main calorimeter, consists of 30 iron plates each $61 \times 61 \times 3.81 \, \text{cm}^3$ interleaved between 30 sheets of plastic scintillator giving a total of $6.7\lambda$. On each side of the calorimeter, light from 15 scintillators is transported to the photocathodes of 2 photomultipliers by means of tapered Lucite light pipes and cones.

In the high $P_T$ data analysis, drift chamber (DC) and multiwire proportional chamber (MWPC) data were used only to establish a vertex position hence only an abbreviated description will be presented. The MWPC was located directly downstream of the hydrogen target and consisted of three planes of sense wires, 320 vertical wires and 352 wires each in $u$ and $v$ planes, interleaved between planes high voltage wires. All sense wire planes had 2mm wire spacing and the chamber efficiency was roughly 88%.

The twelve planes of DC's, six planes on either side of the spectrometer magnet, contained a total of 961 vertical sense wires interleaved between two planes of field shaping wires. In the plane of the sense wires, sense wires were alternated with either field shaping
Figure 2.7 Top view of the E509 beam calorimeter.
wires or aluminized mylar strips. Drift cells were thus formed by the two planes of field shaping wires and the field shaping wires or aluminized mylar strips found in the sense plane (Figure 2.8). The position resolution in the x direction averaged over all planes was 730\(\mu\)m and the mean efficiency at 90° in the pp CM was roughly 80%. Details of the drift chamber construction, readout, and performance may be found in reference 55.

2.2 CALORIMETER CALIBRATION WITH MUONS

An accurate and stable intercalibration of calorimeter modules is needed to insure a uniform response across different sections of the calorimeter. All 528 modules were balanced by steering minimum ionizing muons through the center of each module and adjusting individual photomultiplier gains so as to give average pulse heights equal to some calculated response (called the muon balance point). This calculated signal level was determined by the average \(dE/dx\) energy loss for straight through muons, by the saturation limit of the photomultiplier-calamp-summing/weighting module system, by the requirement that all modules should saturate the ADC at approximately the same pulse height per GeV of transverse energy deposited, and by a correction factor for the transition effect.

After all modules had been balanced using an online
Figure 2.8 XZ plane view of large and small drift chamber cells in drift chamber 6.
computer controlled procedure, an additional 1000 muon triggers were taken at the center of all modules in the AP, A, and B layers of rings 3, 4, and 5 and the module responses (ADC channels) written to magnetic tape. The offline analysis for these runs saw the raw ADC data per event have first their pedestal means subtracted and the resulting net channel counts corrected for nonlinear integration of their respective ADC. Cuts were then applied to remove any hadrons or electrons and to minimize effects of the Landau tail of the muon dE/dx and the net average pulse height and standard deviation calculated. In this way the accuracy of the automatic balancing program could be examined and any systematic errors introduced from the calibration procedure could be studied.

For those modules whose responses were written to tape, gain corrections equal to the measured pulse height / muon balance point were compiled for use in the analysis of the hadron calibration as well as of the high $p_T$ data. For those modules whose response to muons could not be rechecked after running the automatic calibration program, gain corrections were taken to be the average measured pulse height for that module type with the mean for the 20 gap modules taken to be that for the 16 gap ones. Finally a low $E_T$ threshold global trigger run was analyzed by histogramming the number of times the $E_T$
deposited in each module exceeded .1 GeV. Groups of geometrically symmetric modules were examined and modules within a group were classified as normal, warm, hot, or cold pendant on the number of hits received. The gain corrections were then adjusted by +.25 or +/- .10 in an attempt to account for any blatant misbalancing. Details of the muon balancing procedure may be found elsewhere. 48

2.3 SELECTED RESULTS FROM HADRON AND ELECTRON CALORIMETER CALIBRATION

The energy resolution and linearity of the calorimeter were measured by centering mixed beams of hadrons and electrons of various momenta on the different segment types and recording the calorimeter response. The calorimeter is effectively comprised of four types of segments differing primarily in sampling thickness:

<table>
<thead>
<tr>
<th>TYPE</th>
<th>COMPOSITION</th>
<th>LOCATION</th>
<th>SAMPLING THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 gap AP, 20A, 20B, 20C</td>
<td>Rings 6,7,8</td>
<td>12.7mm</td>
</tr>
<tr>
<td>2</td>
<td>3 gap AP, 16A, 16B, 20C</td>
<td>Ring 5</td>
<td>18.8mm</td>
</tr>
<tr>
<td>3</td>
<td>3 gap AP, 16A, 16B, 16C</td>
<td>Ring 4</td>
<td>18.8mm</td>
</tr>
<tr>
<td>4</td>
<td>5 gap AP, 14A, 14B, 14C</td>
<td>Rings 1,2,3</td>
<td>28.4mm</td>
</tr>
</tbody>
</table>

where the 20A, etc. refer to the number of samplings in that layer. Approximately 3k triggers were taken at the center of a number of segments in rings 3-8 at momenta of 9.6, 44.2, 87.2, 129.0 GeV/c. Both with these data and
with a horizontal scan of hadrons/electrons at 21.0 GeV/c the uniformity of the calorimeter was checked and the lateral and longitudinal distributions of hadron and electron showers in the calorimeter determined. Only calorimeter properties relevant to the calorimeter simulator are presented here as the analysis and full description of the hadron results may be found in references 48, 56, and 57.

Good discrimination of muons, hadrons, and electrons could be made based on the pulse height information of the calorimeter. For future reference, the electromagnetic sum is defined as the pulse height or energy sum of a module or group of modules over the AP and A layers and the electromagnetic ratio is defined as the electromagnetic sum divided by the energy sum over all four layers. Muons were identified as those events whose total electromagnetic energy deposit was less than 2.1 GeV and whose total energy deposit was less than 4.5 GeV. Separation of hadrons from electrons is based on the differences in spatial development between hadronic and electromagnetic showers. Electrons were tagged by requiring the electromagnetic ratio of the segment on which the beam was centered plus all adjacent segments be greater than .95. Those events not identified as muons or electrons were taken to be hadrons.
Both the hadron and electron pulse height distributions were well fit by Gaussian functions where the high energy tail of the pulse height spectrum extends only to some cutoff (roughly 3σ above the mean) rather than infinity. The energy resolution R defined as $\sigma/E_{\text{peak}}$ was obtained at each momentum from the Gaussian fits to the pulse height spectra for hadrons and electrons for each of the four segment types listed above.

The energy resolution for electromagnetic showers is dominated by the statistical fluctuations in the number and energy of the sampled electrons and positrons which goes approximately as $\sigma/E_{\text{peak}} = 0.04\sqrt{\Delta E/E}$, where $\Delta E$ is the ionization loss in one sampling layer. The energy resolution of electrons was fit as a function of the beam momentum to the parameterization of $R = C_e/\sqrt{P_{\text{beam}}}$ with the resulting values of $C_e$ given in Table 2.2. The measured energy resolution was greater than that predicted solely from sampling fluctuations thus indicating the existence of other important effects limiting calorimeter resolution.

The energy resolution for hadronic showers is dominated by fluctuations associated with the breakup of the iron nuclei and correlated fluctuations in missing energy due to binding energy losses. This contribution to the energy resolution goes approximately as $R =$
Table 2.2 Energy resolution for electromagnetic and hadronic showers for all types of segment sampling. Given are the constants of the parameterizations of $\sigma/E_{\text{peak}} = C_e/\sqrt{P_{\text{beam}}}$ for electrons and $\sigma/E_{\text{peak}} = C_h/\sqrt{P_{\text{beam}}} + C_2\sqrt{P_{\text{beam}}}$ for hadrons.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Type</th>
<th>$C_e$</th>
<th>$C_h$</th>
<th>$C_1$</th>
<th>$C_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.273 + .002</td>
<td>.759 + .013</td>
<td>.595 + .002</td>
<td>.0070 + .0002</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>.349 + .013</td>
<td>.818 + .024</td>
<td>.685 + .023</td>
<td>.0063 + .0009</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>.355 + .011</td>
<td>.821 + .014</td>
<td>.664 + .009</td>
<td>.0060 + .0003</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>.374 + .010</td>
<td>.906 + .020</td>
<td>.869 + .028</td>
<td>.0050 + .0008</td>
<td></td>
</tr>
</tbody>
</table>
0.5/\sqrt{E}. Sampling fluctuations contribute an amount equal to \( R = 0.09 \sqrt{\Delta E/E} \). Fits of the form \( R = C_1/\sqrt{P_{\text{beam}}} \) and of the form \( R = C_1/\sqrt{P_{\text{beam}}} + C_2/\sqrt{P_{\text{beam}}} \) were made to the energy resolution as a function of the beam momentum and the best fit values are tabulated in Table 2.2. Better reduced \( x^2 \) were found using the second form of the fits thus indicating some shower energy noncontainment in the longitudinal direction which served to worsen the energy resolution.

The mean pulse height response of the calorimeter to electrons and hadrons as a function of the beam momentum was found to be linear over all momenta with the slopes of \( E_{\text{electron}}/P_{\text{beam}} \) and \( E_{\text{hadron}}/P_{\text{beam}} \) for the segment types given in Table 2.3.

The energy resolution of the beam calorimeter was measured to be 1.10/\sqrt{E}. The beam calorimeter was calibrated such that \( E_{\text{measured}}/E_{\text{true}} = 1 \) and the calorimeter response was found to be linear over the range from 10 to 400 GeV.

A relatively efficient jet trigger employed by E609 is known as the two high trigger which requires the transverse energy in any two segments to exceed some threshold, typically 1.5 GeV. It is quite important then in simulating hadronic and electromagnetic showers in the calorimeter to input the correct average and distribution
Table 2.3 Mean values of $E_{\text{electron}}/P_{\text{beam}}$ and $E_{\text{hadron}}/P_{\text{beam}}$ for all types of segment sampling.

<table>
<thead>
<tr>
<th>Segment Type</th>
<th>$E_e/P_{\text{Beam}}$</th>
<th>$E_h/P_{\text{Beam}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.789</td>
<td>.578</td>
</tr>
<tr>
<td>2</td>
<td>.748</td>
<td>.589</td>
</tr>
<tr>
<td>3</td>
<td>.756</td>
<td>.593</td>
</tr>
<tr>
<td>4</td>
<td>.627</td>
<td>.561</td>
</tr>
</tbody>
</table>
of energy deposited in a given segment. In Figs. 2.9 and 2.10 the average segment energies divided by the incident beam momentum for both hadrons and electrons is shown for all segment types. The increase with beam momenta of the average segment fraction for hadrons may be due to a slight increase in \( W_0 \) production at the higher energies.

Finally the question of energy leakage from the main calorimeter to the beam calorimeter was answered by examining the total hadron energy as a function of the beam position in a horizontal scan across the calorimeter. Three data sets were used, two from 44 GeV/c calibration runs from the second run of E609 and one from a 21 GeV/c calibration run from the first run. One of later calibration runs showed no decrease in hadron energy as the beam was moved ever closer to the beam hole and was selectively ignored.

All data shown in Figure 2.11 were plotted as the observed hadron energy, \( E_h \), divided by either .56 or .6 times the beam momentum where the factor .56 was used when the beam was targeted on 5,14,14,14 gap segments and .6 elsewhere. Greater than 8 inches away from the edge of the beam hole no decrease in hadron energy was observed. Both data sets were then normalized such that
Figure 2.9 Mean fraction of the beam energy deposited in a segment as a function of $P_{\text{beam}}$ for a hadron beam centered on the segment for all types of segment sampling.
Figure 2.10 Mean fraction of the beam energy deposited in a segment as a function of $P_{\text{beam}}$ for an electron beam centered on the segment for all types of segment sampling.
Figure 2.11 The mean hadron energy divided by $0.56 \ (0.6)$ of $P_{beam}$ as a function of the radial distance from the beam hole edge in inches.
$E_b/(.6 \ P_b) = 1$ at roughly the center of ring 4.

Linear fits were made for both data sets and the average of those fits is shown in Figure 2.11. The parameterization is $Y = .69 + 3.63 \times 10^{-0.2} X$ where $X$ is the radial distance from the beam hole edge and $Y = E_b/(.56$ or $0.6) \ P_b$).

2.4 LOGIC AND ELECTRONICS

A block diagram of the calorimeter electronics used in the acquisition of high $P_T$ data tracing signals from a single segment is shown in Fig. 2.12. Signals from the calorimeter photomultipliers were first fed through low noise dual gain "calibration" amplifiers (referred to as calamps). A dual gain amplifier was needed to allow measurements of both hadron/electron and muon pulse heights. The low gain of the calamps was approximately x10 while the high gain was precisely a factor of 20 higher.

The calamp output signals were next transmitted through twinax cables to the summing/weighting modules. The function of these modules was to perform a weighted sum of the analog signals of the four calorimeter modules (AP, A, B and C) comprising each segment or tower. Each summing/weighting module received as input pulse heights from twelve calorimeter PM's (defining three segments).
Figure 2.12 Block diagram of the data acquisition electronics.
After 200 ns internal delay, signals from the individual calorimeter modules were output directly (gain=1) from the backs of the summing/weighing modules to LeCroy 2285a ADC's. In addition, AP module pulse heights amplified x20 were also sent to the ADC's.

On the front panel of the summing/weighing modules, six of the output signals for each of three segments were used as spares; four outputs were the gain=1 analog signals of the modules in a given segment and two were identically the AP module pulse heights amplified x20. Such spares allowed the measurement and monitoring of individual PM's without the interruption of data acquisition. Two additional outputs for each of the three segments summed the analog signals from a given segment using the algorithm

\[ V(\text{segment}) = (f(.5(2AP) + A) + B + C) \times 3 \]

where AP, A, B, and C are simply the pulse heights from the modules comprising one segment. The PM's of the AP modules were balanced at twice the gain of the A, B, and C modules; hence the factor of 1/2. The coefficient f was used as online compensation for the differences in calorimeter response to electromagnetic and hadronic showers. For most of the running we used a weighting factor of \( f = 0.8 \).

Signals proportional to the transverse energy
deposited in the segments were formed by attenuation via programmable attenuators the 132 segment summed pulse heights from the summing/weighting modules by an amount equal \( \text{dB} = C + 20 \log_{10} \frac{\sin \theta_{\text{max}}}{\sin \theta} \) where \( \theta \) equals the lab angle of the center of the segment with respect to the hydrogen target, \( \theta_{\text{max}} \) is the lab angle of the outermost segment and \( C \) is some arbitrary constant. One set of the 132 transverse energy signals are linearly summed to form a signal proportional to the total \( E_T \) deposited in the calorimeter (which in coincidence with other signals described below becomes the pretrigger) while the other set of 132 signals are input to the trigger matrix.

Figure 2.13 is a simplified diagram of the logic used in the acquisition of high \( P_T \) data. A pretrigger signal was formed by the 3-fold coincidence (BEAM:PILEBAR):GLOBAL:T(GLOBAL). The incident beam was initially defined approximately 36 meters upstream of the hydrogen target by the 3-fold coincidence of B1:B2:B3 where the scintillator sizes may be found in Table 2.4. Directly upstream of the hydrogen target the beam was further defined by the three fold coincidence of B4:B5:B7. The BEAM signal was formed by the 4-fold coincidence of the 2 output signals above along with B8:B6. With its 2.5cm hole, B8 served as a veto counter and the .64cm thick B6 was used as a \( dE/dx \) counter to reject
Figure 2.13 Data acquisition logic for the calorimeter.
<table>
<thead>
<tr>
<th>Beam Scintillator</th>
<th>Size (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1/2 x 1/2 x 1/8</td>
</tr>
<tr>
<td>B2</td>
<td>1 x 1 x 1/8</td>
</tr>
<tr>
<td>B3</td>
<td>4 x 4 x 1/8</td>
</tr>
<tr>
<td>B4</td>
<td>1/2 x 1/2 x 1/8</td>
</tr>
<tr>
<td>B5</td>
<td>1 x 1 x 1/8</td>
</tr>
<tr>
<td>B6</td>
<td>4 x 4 x 1/4</td>
</tr>
<tr>
<td>B7</td>
<td>3/4 x 3/4 x 1/8</td>
</tr>
<tr>
<td>B8</td>
<td>4 x 4 x 1/8</td>
</tr>
</tbody>
</table>

(1 x 1 hole in center)
events with greater than one particle in a single RF bucket.

The BEAM:PILEBAR signal was formed by the coincidence of the BEAM signal and PILEBAR signal which was used to veto an interaction whenever a beam particle as detected within +/- 100 ns of the triggering beam particle. In addition, the BEAM:PILEBAR signal was vetoed by muons detected in any of the counters comprising the approximately 2.1m by 3.7m wall of muon counters lodged between the iron shielding directly upstream of the liquid hydrogen target.

The GLOBAL signal was formed by summing one set of the 132 transverse energy signals from the sine theta attenuators mentioned above. This GLOBAL signal served to reject the low $P_T$ events which dominate the pp cross section by requiring the total $E_T$ deposit in the calorimeter to exceed some threshold $E_T$ (roughly 4 GeV). The $T(\text{GLOBAL})$ was simply a logic level from a toggle switch.

The pretrigger gate fired upon a 3-fold coincidence of the pretrigger signal, RUN gate, and SPILL gate. The SPILL gate signaled beam on and was generated by an external signal from the MCR synchronized with the main ring cycle. Two signals (levels) from the output register of the Bison Box indicated whether the data acquisition subsystem within Multi was "running" or not and were used
as the start and stop input pulses to the RUN gate generator. In addition, the pretrigger gate was vetoed by a pretrigger gate or master gate deadtime signal described below.

The purpose of the pretrigger gate was to serve as an input signal to the master gate, generate the PWC gate and the LRS 4448 coincidence register gate, generate the 110ns wide ADC gate and to generate a fast logic clear to the ADC's in the absence of a master trigger.

In the acquisition of high $P_T$ data a fast logic clear to the ADC's (as well as to TDC's, PWC readout, and latches) is clearly needed for those events which satisfy the pretrigger requirements but fail to exceed any of the 200 or so trigger $E_T$ thresholds. After generation of pretrigger gate and/or a master trigger gate, further gates are inhibited by 7us and 10us respectively to allow time for the ADC analog front ends to settle and scaler and output shift registers to clear once a clear gate has been input to the LRS 2280 System Processor. Additional pretrigger and master gates are also inhibited via the Computer Busy signal output from the Bison Box.

The other set of 132 transverse energy signals from the sine theta attenuators were input to the trigger matrix. The trigger matrix is a fast cross point matrix which simultaneously formed 200 different analog sums
(trigger conditions) from the 132 segment $E_T$ pulse heights. Most of these trigger condition were geometrical and summed the transverse energy in particular regions of the calorimeter; these regions could be as small as one segment (e.g., .06sr single particle triggers) or as large as the entire calorimeter (single arm or global triggers).

Upon leaving the trigger matrix, the 200 different trigger analog signals were amplified x2 and subsequently attenuated by computer controlled attenuators by an amount proportional to the desired $E_T$ threshold associated with each trigger. Output signals from the $P_T$ attenuators were next fed to LRS ECL 4416 discriminators which determined which triggers had exceeded their $E_T$ thresholds. Both ECL outputs from the 4416 discriminators were employed.

One set of output signals was sent to LRS ECL 4448 coincidence registers where all 200 discriminated trigger signals were OR'ed. This OR'ed trigger matrix signal was subsequently fanned-in with the discriminated signals of the other special triggers (e.g., "two high" and global triggers). The master trigger fan-in output signal in coincidence with the pretrigger gate thus formed the master gate (event trigger!) which was input to the Interrupt A port on the Bison Box. The other set of
outputs from the 4416 discriminators were fed to LRS ECL 4432 latching scalers which were readout upon receipt of a master gate thus recording which of the 200 or so triggers had exceeded their thresholds in that event.

Two other input signals into the master trigger fan-in from the two high and global triggers were made as follows. The global trigger signal was taken from an additional output of the GLOBAL signal described above. The $E_T$ threshold for the global trigger was set by attenuating this signal and subsequently discriminating it. The two high signal was formed by sending the 132 feed-through signals (proportional to the segment $E_T$'s) from the trigger matrix into discriminators whose identical levels reflected the segment $E_T$ threshold sought (typically 1 GeV). The output signals from the 132 discriminators were fanned-in and the output signal sent to another discriminator which set the minimum number of segments required to exceed the segment $E_T$ threshold.
CHAPTER 3
DESCRIPTION OF THE FIELD-FOX-WOLFRAM MONTE-CARLO

3.1 INTRODUCTION TO QCD AND ITS APPLICATION TO HADRONE-HADRON SCATTERING

We presently believe Quantum Chromodynamics, or QCD, to be the correct theory of the strong interaction. QCD is a relativistic quantum field theory based on local gauge invariance of the non-Abelian group $SU(3)_{\text{color}}$. This is appealing theoretically since all gauge theories are renormalizable and one can at once exploit that most successful, prototypical gauge theory, QED. On a wider scale, the fact that all the fundamental interactions of quarks and leptons can be generated by imposing local gauge invariance on some Lagrangian certainly inspires hope in attempting to unify the strong, weak, and electromagnetic interactions.

Experimentally, QCD describes many features of $e^+e^-$ annihilation, deep inelastic lepton-hadron scattering, the Drell-Yan process, and the production of large $P_T$ hadrons and jets in hadron-hadron collisions. Such agreement is not yet exact. Although one can write down a QCD Lagrangian which leads to a set of Feynman rules describing the strong couplings of quarks and gluons, the solutions to the equations of motion are not yet known.
The main reason for this is, unlike QED, the basic fields of QCD are not physically observable particles. Rather, because of color confinement, a fact not yet derivable from the QCD Lagrangian, quarks and gluons do not appear as such but rather as hadrons which are the color singlet bound states of these partons. Because the QCD coupling constant becomes large at large parton separations, perturbation theory breaks down and one must add by hand some phenomenological model describing the formation of hadrons. Non-perturbative lattice techniques give only rough estimates of Particle Data properties and do not begin to address the dynamics of say, quark-quark scattering.

Another important difference between QCD and QED, and perhaps the source of confinement, arises because of the non-Abelian nature of SU(3)_c. The locally gauge invariant QCD Lagrangian density is

\[ \mathcal{L} = \bar{q}(i\gamma^\mu \partial_\mu)q - g(\bar{q}T^a_q)G^a_\mu \]

\[ - \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} \]

where

\[ G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g\epsilon^{abc} G^b_\mu G^c_\nu \]
\[ T^a = \frac{1}{2} \lambda^a \] are the generators of SU(3) over 2.

which is to be compared to that from QED,

\[ \mathcal{L} = \bar{\psi}(i\gamma_\mu \partial^\mu - m)\psi + e\bar{\psi} \gamma^\mu A_\mu \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \]

where

\[ F_{\mu\nu} = \partial_\mu A_{\nu} - \partial_\nu A_{\mu} \]

One finds in the QCD Lagrangian not only the propagators for the free fields and a \( q\bar{q}g \) coupling similar to QED but also the existence of three and four gluon couplings.

The fact that the gauge bosons are colored and hence couple to one another has as one of its consequences asymptotic freedom. Summing leading logs, the running coupling constant of QED,

\[ \alpha(Q^2) = \frac{1}{(1/137 - 1/3\pi\log(Q^2/m_e^2))} \]

where \( Q \) is some characteristic momentum, arises as a result of the shielding effect of the vacuum polarization of virtual \( e^+e^- \) pairs around the bare charge. In QCD, an infinite sea of \( q\bar{q} \) pairs similarly shields the bare
color charge; additionally, however, gluon emission and absorption can delocalize the color charge thus decreasing the color charge found at smaller distances (higher \( Q^2 \)). The strong coupling constant is calculated as \(^{60}\)

\[
\alpha_s(Q^2) = \frac{4\pi}{(11-2/3N_f)\log(Q^2/\Lambda^2)}
\]

Thus for \( Q^2 \) high enough, the coupling constant becomes sufficiently weak to permit use of perturbation theory.

Because of color confinement one is still faced with the non-perturbative problem of turning quarks and gluons into hadrons. The present approach is to use some parameterization, e.g. Feynman-Field, or phenomenological model, e.g. QCD cluster models, to describe the fragmentation of partons into hadrons in the hope that the physics of hadronization is sufficiently soft to allow the perturbative part to be compared to experiment. In reality however, nearly all observables are sensitive to the hadronization scheme used thus limiting the degree to which we are truly testing QCD. Though in return, a deeper understanding of the hadronization process may be achieved.

The idea of factorizing the hard and soft parts of physical processes found in the parton model description of large \( P_T \) processes has its origins in the impulse approximation from nuclear physics. Consider the large \( P_T \) process \( A+B \rightarrow C+X \). In the parton model picture this
process is described by the incoherent sum of all possible parton subprocesses \( a+b \rightarrow c+d \), \( d\phi \), convoluted with the probabilities of finding partons \( a \) and \( b \) carrying fractions \( x_1 \) and \( x_2 \) of hadrons \( A \)'s and \( B \)'s initial momentum and the probability that parton \( c \) will fragment into hadron \( C \) carrying fraction \( z \) of \( c \)'s momentum:

\[
\frac{d\sigma}{dz_1} \sim \sum dx_a G(x_a) dx_b G(x_b) d\phi D(z_1) dz_1
\]

In QCD one must correct for the fact that both quarks and gluons can radiate gluons. Fortunately, in the leading log approximation, the radiations can be summed to all orders with the end result of introducing a \( Q^2 \) scale dependence into the structure functions, \( G(x,Q^2) \), and fragmentation functions, \( D(x,Q^2) \). The \( Q^2 \) dependence of these functions is governed by the Altarelli-Parisi equations.

This is the picture of large \( P_T \) physics which existed pre-1980 and served as the basis for the Feynman-Field-Fox (FFF) four jet Monte-Carlo (MC).\(^{40-42}\) The eight possible 2-2 parton subprocesses are calculated to lowest order in QCD at some arbitrary \( Q^2 \). The \( Q^2 \) dependent quark structure functions are taken from those measured in deep inelastic scattering and the gluon structure function is derived by fitting the observed scaling violations of these functions.\(^{61}\) The Feynman-Field independent parton fragmentation functions
are a parameterization of hadronization based on the experimental observations of approximate scaling of the energy distribution of hadrons within a jet and limited transverse momentum of the hadrons with respect to the jet axis. To complete the picture, to account for trigger bias effects of single particle and small aperture triggers, some x independent intrinsic transverse momentum distribution of the partons within the hadrons must be added. The intrinsic transverse momentum distribution is typically taken to be a Gaussian with a mean $k_T^{\text{intrinsic}}$ of approximately 850 MeV.

Despite the Feynman-Field-Fox model's ubiquitous use in describing many aspects of the data from $e^+e^-$ annihilation, the Drell-Yan process, and high $P_T$ hadron-hadron scattering, it remains as a crude approximation to perturbative QCD. Although the corrections to the longitudinal momentum distribution of the initial and final state partons due to collinear parton radiation are made through the $Q^2$ dependence of the G and D functions, both the radiated partons themselves and the $Q^2$ evolution of the transverse momentum distribution of the partons are ignored.

The method of fragmentation used in the FFF model is unsatisfactory also. It is in fact not a phenomenological model at all but rather a
parameterization of hadronization. If multiparton final states are to be incorporated into the 2-2 scattering picture, then clearly, fragmenting nearly parallel partons independently is not sensible. Analysis of the energy and particle flows of three jet events produced in $e^+e^-$ annihilation seems to favor hadronization of strings rather than independent fragmentation. Moreover, the FFF hadronization scheme suffers from an additional number of known problems such as energy nonconservation which is discussed below.

Experimentally, three jet events arising from a hard radiated gluon in addition to the two scattered partons predicted by the FFF model have been observed at Petra, the ISR, and the Collider. There exist other evidence, namely the large cross section and low planarity nature of globally $E_T$ triggered events observed by NA5 and the relatively large $E_T$ flow found in the plateau region outside dijets found by UA1, which support the importance of soft gluon bremsstrahlung effects in understanding the structure of high $E_T$ events.

One might think of incorporating multiparton final states into the above picture by replacing the 2-2 Born cross sections with the perturbative cross sections
calculated exactly to some low order in $\alpha_s$. To date, however, the full $O(\alpha_s^3)$ calculation has been made for quark-quark scattering only.

3.2 DESCRIPTION OF THE FIELD-FOX-WOLFRAM PARTON SHOWER MONTE-CARLO

Alternatively, one can approximate the emission of $N$ gluons by summing to all orders in $\alpha_s$ some subset of perturbative diagrams. Consider as an example the $O(\alpha_s)$ corrections to the Born cross section, $\sigma_0$, in $e^+e^-$ annihilation into hadrons at $E_{CM}^e=Q$. One correction comes from the emission of a real gluon in the process $e^+g(P_1) + q(P_2) + g(P_3)$. Using energy fractions $x_j = 2E_j/Q$ ($j=1,2,3$) the differential cross section can be written as

$$\frac{1}{\sigma_0} \frac{d\sigma}{dx_1 dx_2} = \frac{2\alpha_s}{3\pi} \frac{x_1^2 x_2^2}{(1-x_1)(1-x_2)}.$$  

Integrating this over the physically allowed regions of $x_1$ and $x_2$, $0 \leq x_1 \leq 1$ and $1-x_1 \leq x_2 \leq 1$, one finds the total cross section for gluon emission to be infinite due to both infrared ($E_g \to 0$) and collinear ($\cos(\theta_{eg}) \to 0$) divergences in the integrand. Defining momentum fraction $z_2 = \frac{2z_2}{Q}$ with the $Z$ axis in the direction of $\vec{P}_2 + \vec{P}_3$ and
Mandelstam variable \( t = (P_2 + P_3)^2 \), and working in the collinear (parallel gluon emission) limit, the differential cross section (3.6) can be written as:

\[
\frac{1}{\sigma_0 \, dz_2 \, dt} \approx \frac{2\alpha_s}{3\pi} \frac{1}{t} \frac{(1+z_2^2)}{(1-z_2^2)} = \frac{\alpha_s}{2\pi} \frac{1}{t} P_{q-gq}(z). \tag{3.7}
\]

\( P_{q-gq}(z) \) is one of the Altarelli-Parisi splitting functions and the cross sections for other types of QCD transitions can be found by simply substituting the correct parton splitting function for \( P_{q-gq}(z) \). Keeping only those parts of the perturbative probability singular in the collinear \((t=0)\) limit constitutes the leading logarithm approximation (LLA). All Monte-Carlo parton shower algorithms involve the generation of values of \( t \) and \( z \) for \( q-gq \), \( g-gg \), and \( g-q\bar{q} \) branchings according to the probability (3.7).

The other \( O(\alpha_s) \) corrections to the \( e^+e^-q\bar{q} \) cross section come from the interference terms between the Born amplitude and the amplitudes from virtual gluon emission. This contribution also diverges. However, if one regularizes both real and virtual corrections, e.g. by giving the gluons a fictitious mass, recalculating both contributions, and summing those terms not vanishing as \( m_g \to 0 \), a finite cross section results. In the LLA, these \( O(\alpha_s) \) virtual corrections can be included in the cross
section (3.7) by modifying the splitting function with the "+ prescription", i.e.

\[
P_{q-gg} \to \frac{4(1+z^2)}{3(1-z)} + 26(1-z).
\]

Equation (3.7) with this modification then gives the probability that a quark of invariant mass \(\sqrt{t}\) splits into a quark and gluon carrying \(E+\vec{p}\) fraction \(z\) and \(1-z\) respectively where in the collinear limit \(z\) has been equivalently redefined.

One would next like to calculate the probability for \(N\) gluon emission and in the collinear limit this is best done using an axial gauge for the gluon propagator. The advantage of working in this gauge is that the interference terms between diagrams of real gluon emissions do not contribute to the leading pole result. The probability for \(N\) gluon emission is then just the product of the probabilities (3.7) for each individual emission thus allowing the parton shower to be interpreted as a probabilistic process. The partons produced in these decays may be partons of the final state or may in turn radiate other partons and so on until one has generated a multiparton final state.

Consider the \(q(P) \to q(zP) + g((1-z)P)\) transition above in which the parent quark has maximum off shell invariant
mass$^2 = t_{p}$. The extension to other parton branchings is simply accomplished by substitution of the correct splitting function. Because the probability for emission (3.7) diverges as the emitted gluons become increasingly soft ($z \rightarrow 1$), a resolvability criterion is introduced to have meaningful results. A resolvable gluon (or parton) is defined as one whose $z$ satisfies $z_c \leq z \leq 1 - z_c$. Partons softer than this are considered irrelevant to the parton final state (i.e. would not give rise to individual jets) and are assumed to be described by the non-perturbative part of the model. (Here $1 - z$ is now taken to be the $E + p_T$ fraction of the gluon which provides for radiation from both the quark and antiquark from the $s^*$ as opposed to the $E + p_T$ fraction which associates all gluons with only one of the pair.$^{38,43}$)

This resolvability cut is implemented by enforcing a mass cut $t_c$ on all radiated partons (internal lines) where partons with $t \leq t_c$ are considered final state partons which do not further radiate. This mass cut, $t_c$, and $z_c$ are related by$^{37,43}$

$$z_c = \frac{t_{\min}}{t_{c}} \frac{t}{(E + p_T)^2}.$$  \hspace{1cm} (3.9)

Given a quark with maximum invariant mass, $t_{p}$, we would like to know the probability that it emits only
unresolvable gluons until its invariant mass is degraded to \( t_c \). The probability for a single unresolvable radiation occurring at mass \( \sqrt{t} \) is

\[
dP_1 = \frac{d \alpha_s(t)}{t \frac{2\pi}{2\pi}} \left[ -\int dz P_{q\rightarrow qg}(z) \right]
\]

with \( P_{q\rightarrow qg}(z) \) given by (3.8) and \( \alpha_s \) given by (3.4). Letting

\[
\chi_{q\rightarrow qg}(z_c) = \int dz P_{q\rightarrow qg}(z)
\]

then the probability \( \pi(t_p, t_c, z_c) \) that a quark of initial invariant mass \( t_p \) evolves to some minimum invariant mass \( t_c \) by emitting only unresolvable gluons is just equal to

\[
\sum \left[ \int \frac{dt_1 \alpha_s(t_1)}{2\pi} \int \frac{dt_2 \alpha_s(t_2)}{2\pi} \cdots \int \frac{dt_N \alpha_s(t_N)}{2\pi} \left[ -\chi_{q\rightarrow qg}(z_c) \right]^N \right]
\]

which can be evaluated as \(^70\)

\[
\pi(t_p, t_c, z_c) = \left[ \frac{\alpha_s(t_p)}{\alpha_s(t_c)} \right] \chi_{q\rightarrow qg}(z_c) / \beta_0
\]

where \( \beta_0 = 11 - 2N_F / 3 \).

Knowing the probability that a parton emits only unresolvable radiation in evolving from \( t_p \) to \( t_c \) determines
the probability of a resolvable emission at mass \( \sqrt{t} \),
\( Z(p',t,z_c), \) \( 70,71 \)

\[
Z(t_p', t, z_c) = \frac{a_c(t)}{2\pi t} \hat{g}_{qg}(z_c) \pi(t_p', t, z_c) = -\frac{d\pi}{dt}(t_p', t, z_c)
\]

3.14

The iterative algorithm for generating a parton shower thus proceeds as: \( 70,71 \)

1. Given a \( t_p' \) and \( z_c \), generate a random number \( r \) and solve \( \pi(t_p', t, z_c) = r \) for \( t_1 \). The \( z_c \) used in evaluating \( \hat{g}(z_c) \) in reality depends on \( t \) and so to account for this \( z_c \) is minimized over the \( t \) range as in (3.9).

2. If \( t_1 < t_c \), the parton does not radiate.

3. If \( t_1 > t_c \), a parton emits resolvable radiation and the parton type and \( z \) (\( E+\vec{p}_T \) fraction) of the daughter partons are chosen in accordance with the Alterelli-Parisi splitting functions where \( z_c \leq z \leq 1-z_c \). Exact non-collinear kinematics are maintained at each vertex with \( t_1 \), \( z \), and a randomly generated azimuthal angle specifying the daughter partons' momenta.

4. If the generated \( z \) is outside the kinematically allowed range for the generated \( t_1 \), steps (1)-(3) are repeated with \( t_p' \) replaced by the generated \( t_1 \). This corrects for the fact that \( z_c \) was chosen as the minimum over the \( t \) range in step (1).

The algorithm is repeated for the daughter partons
which have maximum invariant mass equal to $\sqrt{t_1}$ and so on until all the partons have decided to emit no further resolvable radiation i.e. until the invariant mass of all partons has reached $\sqrt{t_c}$.

Further details of the FFW parton shower procedure can be found in refs. 37, 38, 43, 70, 71, and 72.

With the above formalism of generating parton showers according to the leading log approximation using a Monte-Carlo approach behind us, the present phenomenological model for high $P_T$ scattering is depicted in Fig. 3.1. Several Monte-Carlo shower generators and hadronization schemes are currently being used, e.g. Isajet$^{73}$, Cojets$^{74}$, FFW, and Webber-Marchasini$^{75}$, all based on the generic figure differing only in the grimy details of the various parts. A brief summary of the FFW model follows.

One starts by considering the proton to be a bound system of two partons, one parton which will evolve and eventually undergo the hard scatter and the other, a "hole" representing the beam remains. Because the partons are bound they have spacelike invariant mass. The parton type and longitudinal momentum fraction $x$ are determined by the structure functions $G_i(x,Q^2)$ mentioned above.
Figure 3.1 Present picture of high $P_T$ hadron-hadron scattering

\begin{align*}
Q^2 = -4 \, \text{GeV}^2 \\
Q^2 = -4 \hat{s} \, \text{GeV}^2 \\
Q^2 = 3 \, \text{GeV}^2 \\
Q^2 = 4 \hat{t} \, \text{GeV}^2
\end{align*}

$$\decay[Q_a \bar{Q}_a]{hadron}$$

$$\decay[hadron]{hadron} \quad \text{FFFF jet} \quad \text{FFFF jet}$$
In the FFF four jet Monte-Carlo, initial state gluon bremsstrahlung effects were analytically summed by evaluating the $G$ functions at the $Q^2$ at which the hard scattering occurred, taken (arbitrarily) to be $Q^2 = \frac{2ptu}{s^2 + t^2 + u^2}$. In the FFW model, however, initial state gluon bremsstrahlung will appear as explicit final state partons arising from the evolution of the active partons having initial negative invariant mass $Q_0^2$ to some new, smaller (more negative) $Q^2$. The FFW Monte-Carlo reproduces (approximately) the alterations to the longitudinal momentum distribution of the initial partons as from using $G(x,Q^2)_{FFF}$. More importantly however, the FFW Monte-Carlo now estimates the $Q^2$ dependence of the parton transverse momentum associated with the radiations and effects of the hadrons arising from soft radiated quanta, both of which were ignored in the four jet FFF model.

The initial state partons begin with an invariant mass of $-Q_0^2 = TCUTB = -4$ GeV$^2$ and evolve forward in time to some more spacelike invariant mass. With this TCUTB, the partons are given intrinsic (Fermi) transverse momentum $k_T^{intrinsic}$ taken from an $x$ independent Gaussian distribution with a mean of 750 MeV. This choice of $k_T^{intrinsic}$ and TCUTB is determined by fitting the Monte-Carlo results to the $P_T$ distribution of Drell-Yan $\mu^+\mu^-$ pairs at FNAL and ISR energies. Note the total
"intrinsic" transverse momentum now consists of a part arising from the Fermi motion of the active partons and a $Q^2$ dependent part arising from the radiation of gluons.

Because the structure functions diverge as $x\to 0$, a cutoff of $x\sim 0.006$ is introduced in choosing the longitudinal momentum of the active partons. The parton flavor is chosen according to the probability $P_i = \int G_i(x,Q_0^2) / \sum G_j(x,Q_0^2)$ where $G_i(x,Q_0^2)$ is the structure function for parton flavor $i$, e.g. $u(x)$. Only gluons, $u$, $d$, $s$ quarks and their antiquarks are used. Having chosen the flavor, the parton $x$ is chosen according to $dP/dx = G(x,Q_0^2) / \int G(x,Q_0^2)$.

The hole, or spectator, parton type is taken to be the antiquark of the parton to be evolved (or a gluon if a gluon is to be evolved) and its momentum is such that the sum of the momentum of the evolved parton and its hole equals the beam or target momentum. Since the beam remains are nearly on shell and there is no hard scatter to take care of a large invariant mass, the beam (hole) partons do not radiate.

The two active partons with spacelike invariant mass $-Q_0^2$ evolve forward in time radiating timelike partons and leaving partons with a smaller, more negative invariant mass. This branching process continues until the invariant masses of the active initial state partons have
reached some new scale, $-Q^2$, at which point the hard scattering occurs. Because the initial state partons have negative invariant masses which evolve towards more negative invariant masses, the branching kinematics are slightly different and the algorithm used above in generating timelike parton showers must be modified somewhat.\textsuperscript{37,72} The details of the initial state shower formalism are slightly complicated and can be found in references 37 and 72.

The invariant mass scale $Q^2$ below which no further initial state radiations take place and at which the hard scattering occurs is somewhat arbitrary and reflects the age old problem of how far to evolve the initial state partons depends on the $Q^2$ of the hard scatter which depends on how far the initial state partons were evolved. (A newer formulation for initial state parton showers in which partons are evolved backwards in time thus avoiding this problem is given in reference 71.) For event generation convenience, Fox and Kelly\textsuperscript{46} have chosen $Q^2 = 4p_t^2$, where $p_t$ is the transverse momentum of the hard scatter, as the maximum negative invariant mass of the active partons. At the scale $Q^2$ then, the two active partons undergo a 2-2 hard scatter with each parton carrying away $p_t$ of transverse momentum. The cross section for the hard scattering, $d\sigma/dp_t^2$, is just the $O(\alpha_s^2)$ Born
cross section for that particular parton subprocess and each event carries this cross section as weight.

At this point then we have two scattered partons with maximum timelike invariant mass \( 4p_t^2 \) and the timelike initial state radiations. These partons are allowed to radiate other partons according to the final state shower algorithm discussed above until their invariant masses fall below some cutoff \( TCUTA = 3 \text{ GeV}^2 \). Partons whose invariant masses are less than \( TCUTA \) are considered final state partons and are put on the mass shell.

3.3 DESCRIPTION OF THE FIELD-WOLFRAM QCD CLUSTER MODEL AND FIELD-FOX-FEYNMAN MODEL FOR HADRONIZATION

In section 3.2, a multiparton final state was generated by a Monte-Carlo procedure according to the probabilities from the LLA to perturbative QCD. Because QCD confines one needs some phenomenological model to turn these final state partons into hadrons. The method chosen by Field et al. is a combination of two hadronization schemes, the old FFF fragmentation parameterization \(^{41}\), and a newer model, the QCD cluster approach, first introduced by Field and Wolfram \(^{39}\). Both methods are briefly described.

The QCD cluster model is based on the ideas that due
to confinement, color sources must somehow be neutralized before they separate by distances > 1f, and that hadronization depends only on the local spacetime configuration of the final state parton system.43 The radiation of a large number of soft gluons with the subsequent formation of low mass colorless strings is one such example of these ideas. The decay of these strings into hadrons is assumed to depend only on the mass and flavor of the clusters and can e.g. be determined from low energy experiments.

The FW QCD cluster approach consists of three steps:

1. The generation of a parton shower using the Monte-Carlo approach discussed above.

2. The formation of color neutral clusters arising from strings associated with these final state partons.

3. The decay of these clusters into hadrons via two body phase space.

Because the partons shower was generated recursively, it is straightforward to keep of the color indices of the final state partons. Gluons are forcibly split into quark-antiquark pairs with each quark carrying one of the color indices of the gluon. The quark and antiquark carry fractional momentum z and 1-z of the gluons momentum, where z is generated uniformly between 0 and 1 and the quarks' momentum is parallel to the gluon. The
quarks are given flavors $u,d,$ and $s$ with equal probability.

By following the color flow in the event, strings connecting colored quarks to its color conjugate antiquark can thus be formed. These strings have four momenta $= (p_q + p_{\bar{q}})^2$ and are called color singlet (neutral) clusters. The invariant mass of these clusters is strongly damped at large masses $^{39}$

The final step of the QCD cluster approach is to independently decay each cluster into hadrons. If the invariant mass of the cluster is small, say less than $2^*PQMIN=3$ GeV, then the cluster decays into hadrons isotropically in the string CM frame according to one or two body phase space. If the cluster mass is below the threshold for allowed two body decays, it is called a $\pi$ or $K$ even though the cluster mass may be 100 MeV smaller or larger. The hadrons from the two body decay can be any from the $0^-, 0^+, 1^-, 1^+$, and $2^+$ nonet mesons or the $1/2^+$ octet and $3/2^+$ decuplet baryons if the cluster is sufficiently massive. The probability for any given decay is determined by the spin of the product hadrons (weighting each with a factor of $2J_{1}+1$), the phase space available for the decay, and a factor which governs whether a quark-antiquark pair or diquark-antidiquark pair is to be created. Both hadrons are then allowed to
decay according to the Particle Data Book decay modes. The parameters of the FFW model, QCD $\Lambda$ and TCUTA, can be adjusted to give good agreement with $e^+e^-$ annihilation results including hadron multiplicity, transverse and longitudinal momentum distributions, and jet properties and shapes.

If the cluster mass is greater than 3 GeV then its decay into hadrons proceeds by two back-to-back FFF jets in the string CM frame. Because of their large momentum, the beam and target hole partons often form one end of these large mass strings. In the FFF hadronization parameterization, an energetic parton decays into a meson and a leftover parton which subsequently decays into another meson and another leftover parton, and so on. The energy fraction carried by the mesons are distributed according to a scale dependent fragmentation function $f(z,Q^2) \sim (1-z)^2$ and the transverse momentum of the created (from the vacuum) quark-antiquark pair with respect to the momentum of the parent parton is distributed according to the Gaussian distribution

$$\exp(-\frac{P_T}{2(320 \text{ MeV})^2}d^2P_T).$$

Further details may be found elsewhere.

3.4 WEAKNESSES OF THE MODEL
Satz has identified the hadronization of gluons (especially soft ones) by splitting color strings and the fragmentation of the beam and target parton holes to be the weakest phenomenological points of the FFV model. A large invariant mass color string connecting a final state quark and antiquark will typically produce a number of hadrons in its decay. If the string were broken by the emission of an arbitrarily soft gluon, two clusters each with invariant mass $\sim$ TCUTA will be produced and result in only a few hadrons upon their decay because of their small mass. We anticipate then, that the Monte-Carlo may generate events with too low a multiplicity as compared to real data. Also, allowing the production of soft gluons, a low $Q^2$ process not covered by perturbative QCD, to have such a large effect on experimental observables is not phenomenologically correct.

The physics of the evolution and hadronization of the beam and target partons is not well understood. Field has found that the average transverse energy outside, $E_T^{\text{out}}$, of the back to back $\Delta\phi=\pi/2$ triggering region used by NA5 is about 750 MeV out of 2.75 GeV too low in the Monte-Carlo indicating the transverse energy from the hadronization of the beam remnants is too small or possibly the beam and target jets are too narrow.

The choice of using the FFF parameterization for the
hadronization of large mass clusters is an unfortunate one for it carries with it a number of known problems.\textsuperscript{41,43} The most troublesome of these, energy and momentum nonconservation, arises from the decay of a massless parton into a jet of massive hadrons. One may choose to do nothing about this, impose cuts on $E_{\text{TOT}}$ and $\sum p_T$, or use some method of rescaling individual particle momentum components in such a manner so as to restore energy conservation. All methods are completely arbitrary so in some sense no one method is correct. More importantly however, as emphasized by Corcoran\textsuperscript{44}, both event shapes and cross sections can be dramatically different depending upon how one chooses to impose energy and momentum conservation. It is in fact just this point which was ignored in the interpretation of the comparison between the NA5 global trigger data and their 4-jet Monte-Carlo results and led to such comments as "Global triggers cannot be described by simple QCD.". The results from the FFF hadronization of a parton depend also on the frame in which the hadronization takes place.

Finally, it is important to remember that the FFW parton shower Monte-Carlo approach is only an approximation to perturbative QCD. In fact it is an approximation to the leading log approximation which is valid only in the limit $t\to 0$, whereas the generated internal partons
have nonzero masses. Other theoretical uncertainties in the model are discussed in references 72 and 76.

3.5 SUMMARY OF WORK BY THE MODEL'S CREATORS

Previous work$^{47,77,78,72}$ has shown that the FFW parton shower Monte-Carlo gives moderate to good agreement with results from the SPS, ISR, and the $\bar{p}p$ collider. Field and Fox$^{47}$ reproduce well the NA5 cross sections for single arm ($\Delta\phi = \pi/2$) and double arm (each with $\Delta\phi = \pi/2$) triggers and, more importantly, agree within a factor of 1.8 with the NA5 global ($\Delta\phi = 2\pi$) trigger. (The NA5 experiment was performed at $p_B = 300$ GeV and their cross sections were calculated using a fiducial region of $-0.88 < y < 0.67$). Field and Fox also report rough agreement with the mean total ($\Delta\Omega = 4\pi$) charged multiplicity as a function of calorimeter $E_T$ and reproduce the average planarity as a function of $E_T$ though their results extend only to $E_T = 12$ GeV. As mentioned above, the average $E_T^{\text{out}}$ as a function of $E_T^{\text{in}}$ for back-to-back $\Delta\phi = \pi/2$ triggers is found by Field and Fox to be 25% too low compared to data.

Shatz's version$^{72}$ of the FFW Monte-Carlo differs primarily in his treatment of the evolution of the beam and target partons and his use of Gottschalk's improved
QCD cluster model\textsuperscript{79,80} which breaks large mass clusters into smaller ones based on the 1+1 dimensional LUND string model. Shatz shows excellent agreement with the NA5 cross sections but his mean charged multiplicity is slightly too small as Field's. The average planarity as a function of calorimeter $E_T$ agrees reasonably with that of NA5 up to $E_T = 16$ GeV and the average $E_T^{\text{out}}$ agrees better with NA5 results than that found by Field.

In the context of the FFW model, global $E_T$ triggers are biased towards the production of larger amounts of gluon bremsstrahlung, especially from the initial state which both increases the calorimeter $E_T$ and reduces the $p_t$ of the collision. At a given $E_T$ observed in the calorimeter one might have events with $\hat{p}_t \sim E_T/2$, where $\hat{p}_t$ is the transverse momentum of the hard scatter. Alternatively, events can come from much lower $\hat{p}_t$'s in which a large fraction of the $E_T$ arises from other processes, e.g. initial state gluon bremsstrahlung or fluctuations in the hadronization of the final state partons (especially of the beam and target hole partons). Because of the steep $1/\hat{p}_t^4$ fall off of the 2-2 hard scattering cross section $\frac{d\sigma}{d\hat{p}_t^2}$ and an additional suppression of large $\hat{p}_t$ collisions from the structure functions, (the partons must have some minimum $x$ to be able to undergo a
hard scatter with transverse momentum $p_t$, the lower $p_t$ scatters may dominate the higher ones.

Field argues that at FNAL and ISR energies, nature most economically gives the experimenter high $E_T$ by the emission of an anomalously large number of gluons from lower $p_t$ collisions. This results in an enhanced $d\sigma/dE_T$ cross section of high hadron multiplicity events which obscure the underlying 2-2 dijet structure. The clean two jet events with $p_t\sim E_T/2$ hoped for using large $E_T$ global calorimeter triggers are buried beneath the more readily produced lower $p_T$ events having high multiplicities and low planarities. It is only at the highest $E_T$ values of the ISR and at sufficiently high $E_T$ at the $\bar{p}p$ collider that clean and unambiguous two jet events arising from truly hard $p_t$ collisions become favored and dominate the high $E_T$ cross section.

Field and Fox also show good agreement between the FFW Monte-Carlo and large aperture cross section data at $\sqrt{s}=63$ GeV from the AFS and R807 groups. Using the parton shower generator described above but letting each final state parton fragment independently in the $pp$ CM frame according to the FFF parameterization, Field reports agreement with the global $\Delta\phi=2\pi$ cross section from AFS. With this version of the model, the mean multiplicity and circularity ($1 - \text{planarity}$) for the
global trigger as a function of $E_T$ follow the AFS data even out to $E_T \sim 35$ GeV where the event structure begins to be dominated by clean two jet events. Shatz with his modifications can also reproduce the single arm and global cross sections of the AFS however his version does not describe well the mean multiplicity and circularity at the higher $E_T$'s. His Monte-Carlo events become too jetty at too low an $E_T$ when compared with the AFS results.

Hadronizing by independently fragmenting each final state parton according to FFF, Field 78 gets rough agreement with the UA2 global cross section at $\sqrt{s}=540$ GeV in the range $50<E_T<100$ GeV. Using a cluster (jet) analysis similar to UA2 and comparing the fraction of total $E_T$ carried by the highest and highest plus second highest $E_T$ clusters as given by UA2 with the Monte-Carlo model, Field finds the generated events are not jetty enough at the larger $E_T$ values in the region studied.
3.6 GENERATION OF EVENTS IN THIS ANALYSIS

Monte-Carlo events were generated at $\sqrt{s}=27.4$ using the FFW parton shower generator and hadronized by either the FW QCD cluster model or the FFF fragmentation scheme depending on the invariant mass of the color neutral cluster (see Section 3.3 above). Events were generated with $p_T$, the transverse momentum of the hard scatter, between 2 and 6.5 GeV. The total cross section over this $p_T$ range at this energy is approximately 270 $\mu$b and the peak of the E609 calorimeter $E_T$ distribution is roughly 6 GeV. The model is not thought to be reliable below $p_T = 2$ GeV; the collisions are just too soft for perturbative QCD to be applicable. The upper limit of $p_T$ was chosen for computational convenience and was well above the threshold for the triggers subsequently studied except at the highest total $E_T$ values (> 15 GeV) examined. Hence an additional 900 events were generated over the $p_T$ range from 2 to 8 GeV which also passed a calorimeter $E_T$ cut of 15 GeV. For Monte-Carlo aficionados a list of the relevant parameters used along with a few word description of each is given in Table 3.1.

Each event carries along with it a weight equal to the cross section per produced hadron event given by $\frac{d\sigma}{dp_T^2}$/ NEVGEN. NEVGEN is essentially a flux factor
Table 3.1 Relevant parameters used in the Field-Fox-Wolfram Monte-Carlo.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALAM</td>
<td>0.3</td>
<td>QCD $\Lambda$</td>
</tr>
<tr>
<td>TCUTA</td>
<td>3.0</td>
<td>All internal partons with $m^2 &gt; 0$ have $m^2 &gt; -TCUTA$</td>
</tr>
<tr>
<td>TCUTB</td>
<td>4.0</td>
<td>All internal partons with $m^2 &lt; 0$ have $m^2 &lt; -TCUTB$</td>
</tr>
<tr>
<td>TUPB</td>
<td>$4 \hat{p}_t^2$</td>
<td>The $Q^2$ governing evolution</td>
</tr>
<tr>
<td>ECUTB</td>
<td>0.3</td>
<td>All bremsstrahlung partons produced in evolution of $m^2 &lt; 0$ parton have energies &gt; ECUTB</td>
</tr>
<tr>
<td>ECUTOB</td>
<td>0.3</td>
<td>In evolution of $m^2 &lt; 0$ internal $m^2 &lt; 0$ partons have energies &gt; ECUTOB</td>
</tr>
<tr>
<td>SHGAU</td>
<td>0.6</td>
<td>Standard Deviation of Gaussian distribution of primordial $k_T$</td>
</tr>
<tr>
<td>ICUTA</td>
<td>2.0</td>
<td>$m^2 &gt; 0$ evolution controlled by kinematics</td>
</tr>
<tr>
<td>MAXACT</td>
<td>2.0</td>
<td>Conserve $E$ and $\vec{p}$ at all steps of evolution</td>
</tr>
<tr>
<td>QMSFRC</td>
<td>0.5</td>
<td>Mass given to all final state quarks</td>
</tr>
<tr>
<td>GMSFRC</td>
<td>1.0</td>
<td>Mass given to all final state gluons</td>
</tr>
<tr>
<td>PQMIN</td>
<td>1.5</td>
<td>Use FFF fragmentation for cluster masses &gt; 2·PQMIN</td>
</tr>
<tr>
<td>EMIMIN</td>
<td>1.5</td>
<td>In FFF fragmentation, force $m_m$ of lower momentum parton ≥ EMIMIN</td>
</tr>
</tbody>
</table>
and equal to the number of times the program attempted to hard scatter.

Not every pair of evolved initial state partons results in a hard scatter for there may not be sufficient $\mathcal{E}$ (parton-parton CM energy of the collision) to allow a scatter of transverse momentum $p_t$. The factor of $p_t^2$ range (equal to 38.25 GeV$^2$ in this particular generation) arises because we are choosing $p_t^2$ randomly from a flat distribution instead of generating events at discrete $p_t^2$ and integrating over $p_t^2$ by trapezoidal integration at the end. The factor $\frac{d\sigma}{dp_t^2}$ is just the $O(\alpha_s^2)$ QCD cross section for the 2-2 subprocess.

Because local changes are affected in any large, distributed program, 10-15K events were generated (choosing to do nothing about energy nonconservation of the final state hadrons), analyzed and compared with published results at $\sqrt{s} = 60$, 27.4, and 24 GeV. At $\sqrt{s} = 60$ GeV, Monte-Carlo events were generated in the range $4 \leq p_t \leq 8$ GeV with TCUTA=10 GeV, TCUTB=4 GeV, and $\Lambda=3$, and a $4\pi$ detector was assumed. The transverse energy distributions in the pp CM frame for both hadrons and partons from reference 47 and the version of the FFW Monte-Carlo we have used are shown in Figure 3.2. Although the total cross section was found to be 30% below that quoted by Field and Fox$^{47}$, above the $E_T$ threshold, $d\sigma/dE_T$ for both
Figure 3.2 The cross section $d\sigma/dE_T^*$ as a function of $E_T^*$ at the hadron and partons level for a 4n detector at $\sqrt{s} = 60$ GeV from this Monte-Carlo (solid symbols) and from reference 47 (open symbols). Monte-Carlo events were generated in the range $4 \leq p_T \leq 8$ GeV with TCUTA=10 GeV, TCUTB=4 GeV, and $\Lambda = .3$ GeV and $E_T$ in the pp CM frame was used.
hadrons and partons matches well with their results. Comparing other "observables" such as \( n_{\text{parton}} \), \( n_{\text{hadron}} \), \( \langle p_T^{\text{max}} \rangle_{\text{parton}} \), and \( \langle p_T^{\text{max}} \rangle_{\text{hadron}} \) with ref. 47 we find excellent agreement, with the average hadron multiplicity in our version being slightly (20%) too high.

At \( W=27.4 \) GeV, Monte-Carlo events were generated between \( 2 \leq p_t \leq 6.5 \) GeV with now TCUTA=3 GeV. The triggering region was taken to subtend \(-.88 \leq Y \leq .67\) in rapidity and \( \Delta \phi = 2\pi \). The \( E_T \) cross sections in the pp CM frame at the hadron and parton levels were compared with those in ref. 47 and found to be approximately 1.5 times smaller over the \( E_T \) range 8-12 GeV.

At \( W=24 \) GeV, Monte-Carlo events were generated between \( 2 \leq p_t \leq 6.5 \) GeV again with TCUTA=3 GeV. The triggering calorimeter was taken to subtend \(-.88 \leq Y \leq .67\) in rapidity, identical to the fiducial cuts imposed by the NA5 group, and \( \Delta \phi = 2\pi \). The \( E_T \) cross sections in the pp CM frame at the hadron and parton levels were compared with those of Field and Fox\(^{47}\) and found to be approximately a factor of 2.0 smaller over the \( E_T \) range 8-12 GeV.

A comparison of the mean planarity versus \( E_T \) curves (Fig. 3.3) from the version of the FFW Monte-Carlo we have used, from Field and Fox\(^{47}\), and from NA5\(^{35}\), show good agreement out to \( E_T = 12.5 \) GeV where Field and Fox
Figure 3.3 Comparison of the mean planarity as a function of $E_T$ from this Monte-Carlo and from reference 47 with the NA5 global data. The predictions from reference 47 (solid squares) and this Monte-Carlo (solid circles) use a calorimeter trigger with rapidity range $-0.88 \leq y \leq 0.67$ and $E_T^z$ in the pp CM frame. Also shown is the prediction from this Monte-Carlo (open squares) using a calorimeter trigger covering $2.3^\circ \leq \theta_{lab} \leq 10.9^\circ$ with the rapidity cut $-0.88 \leq y \leq 0.67$ and where $E_T$ in the lab system was used.
unfortunately run out of statistics. Above $E_T = 13$ GeV, we find the mean planarity begins to rise with $E_T$ whereas the NA5 result essentially remains constant out to $E_T = 15.5$ GeV with only the hint of an increase in mean planarity above $E_T = 13.5$ GeV.

Comparing the mean total multiplicity in a 4m detector versus pp CM $E_T^*$ deposited in the NA5 calorimeter we find the slopes from the Monte-Carlo version we have used and Field and Fox match well but with the $\langle n_{\text{total}} \rangle$ being 2-3 particles higher in our version. (In comparing with the results from ref. 47 we multiplied their mean charged multiplicity by 1.5.)

On the question of how trustworthy are the cross sections from the Monte-Carlo, Fox feels the parton shower calculations are uncertain to at least a factor of 2.\textsuperscript{46} Other reasonable choices for TCUTA, the parameter which controls the amount of final state gluon bremsstrahlung, give NA5 global cross sections which vary by a factor of 2 also. Varying the width of the transverse momentum distribution of the quark-antiquark pair with respect to the parent quark's momentum in the FFF hadronization scheme, a parameter to which the global cross section is sensitive to in the old four jet Monte-Carlo, has little effect on the NA5 global cross section in this model. Lowering the lower limit of the
\( p_T \) range from 2 to 1.5 GeV increases the total cross section for E609 global triggers with calorimeter \( E_T > 8 \) GeV by approximately a factor of 2. Finally there is an unexplained factor of 1.5-2 between the global cross sections of the Monte-Carlo version we have used and the one employed by Field and Fox. Therefore, the cross sections are probably only reliable within roughly an order of magnitude.

In making cross section comparisons between Monte-Carlo and experiment, it is important to ensure the Monte-Carlo trigger is as similar to the data trigger as possible. In particular, consider the \( E_T \) cross section for global \((\Delta \Omega = 2\pi)\) triggers at \( p_{Beam} = 300 \) GeV with the following angular coverages:

1. \( -.88 \leq Y \leq .67 \), \( E_T^* \) is used
2. \( 54^\circ \leq \phi^* \leq 135^\circ \), \( E_T^* \) is used
3. \( 2.3^\circ \leq \phi_{\text{lab}} \leq 10.9^\circ \), \( E_T^* \) is used
4. \( -.88 \leq Y \leq .67 \), \( E_{lab}^* \) is used

where \( E_T^* \) is the \( E_T \) in the pp CM frame. One might expect these four triggers to give similar results, but in fact, because of the (mostly pion) masses of the hadrons, they do not (see Figs. 3.4a-c). If the hadrons were taken to be massless, all four triggers would give identical cross
Figure 3.4a Comparison of the cross section $d\sigma/dE_T^*$ as a function of $E_T^*$ at $\sqrt{s}=24$ GeV for the rapidity range $-.88 \leq y \leq .67$ (solid circles) and for the CM scattering (polar) angle range $54^\circ \leq \theta^* \leq 135^\circ$ (open circles).
Figure 3.4b Comparison of the cross section $d\sigma/dE_T^*$ as a function of $E_T^*$ at $\sqrt{s}=24$ GeV for the rapidity range $-0.88 \leq y \leq 0.67$ (solid circles) and for the lab scattering (polar) angle range $2.3^\circ \leq \theta_{lab} \leq 10.9^\circ$ (open circles).
Figure 3.4c Comparison of the cross section $d\sigma/dE_T$ as a function of $E_T$ at $\sqrt{s}=24$ GeV for the rapidity range $-0.88<\gamma<0.67$ using $E_T^*$ (solid circles) and $E_T^{lab}$ (open circles).
sections. However, using the true particle masses, one finds \( \frac{d\sigma}{dE_T} \) for both the \( \vartheta^* \) and \( \vartheta^{lab} \) triggers to be about 1.8 times smaller than triggering with the corresponding rapidity range. Furthermore, using the same rapidity range but comparing results using \( E_T^* \) and \( E_T^{lab} \), one finds the \( E_T^{lab} \) cross section to be smaller by a factor of 3.1.

In Fig. 3.5, we again plot \( \frac{d\sigma}{dE_T} \) for the global trigger, this time triggering with the following two coverages:

1. \(-0.88 \leq Y \leq 0.67\), \( E_T^* \) is used
2. \(1.9^o \leq \vartheta^{lab} \leq 10.9^o\), \(-0.88 \leq Y \leq 0.67\), \( E_T^{lab} \) is used

The results of Field and Fox\(^{47}\), who presumably presented their results using triggering method 1, and the NAS data\(^{35}\), which was presumably analyzed with the cuts of triggering method 2, are also shown. Using a rapidity trigger and employing \( E_T^* \) (we presume), Field and Fox find the global cross section to be roughly 1.75 times smaller than that measured by NAS and point to this reasonable agreement as support for the validity of the FFW model and the importance of gluon bremsstrahlung effects in understanding the global trigger. Indeed, the addition of
Figure 3.5 Comparison of the cross section \( \frac{d\sigma}{dE_T} \) as a function of \( E_T \) at \( \sqrt{s}=24 \) GeV for the rapidity range \(-0.88 \leq y \leq 0.67\) using \( E_T^* \) (solid circles) and for the proper NA5 trigger (open circles). Shown also are the predictions from reference 47 (solid squares) and the measured NA5 global cross section (open squares).
gluon bremsstrahlung does give a parton level cross section over the same rapidity range above that is a factor of 10 greater than the usual four jet parton level cross section. 46

With the version of the Monte-Carlo we have used, the global $E_T$ cross section for the triggering conditions of method 1 are approximately a factor of 2 smaller than Field and Fox over the $E_T$ range shown but still in rough agreement with NA5. However, the NA5 detector sat in the lab frame covering polar angles $1.9^\circ \leq \theta_{\text{lab}} \leq 10.9^\circ$. Then after triggering the NA5 group imposed a fiducial cut of $-0.88 \leq Y \leq 0.67$ and $E_T$ in the lab system was used. Applying these cuts (method 2) gives a Monte-Carlo prediction shown in Figure 3.5 which is now a factor of 13 smaller than the NA5 data.

Therefore one, it is important to ensure any Monte-Carlo trigger is as similar to the data trigger as possible and two, the version of the FFW Monte-Carlo we have used does not find that gluon bremsstrahlung with the hadronization scheme detailed above is sufficient to describe the NA5 cross section.

Plotting in Figure 3.3 the average planarity as a function of $E_T$ for both methods 1 and 2, from Field and Fox, and from the NA5 group, one finds slightly different results also. Whereas method 1, also used by Field and
Fox, agrees well with the NA5 data out to \( E_T = 13 \) GeV and increases faster than NA5 thereafter, method 2 gives an average planarity that begins to increase roughly 2 GeV earlier thereby widening the disagreement with the NA5 result. The mean multiplicity as a function of \( E_T \) is approximately the same for both triggering methods.

3.7 EFFECTS OF IMPOSING OVERALL ENERGY CONSERVATION

It is well known that any Monte-Carlo which uses the Feynman-Field-Fox independent parton fragmentation for hadronization, and all Monte-Carlos presently in use do to some greater or lesser extent, only conserves energy approximately. In the FFW Monte-Carlo, for example, which only uses this parameterization for the hadronization of the large mass color singlet clusters (typically those clusters which contain the beam and target holes or spectator partons), the shape of the total energy of the final state hadrons distribution is roughly Gaussian with a mean of approximately 400 GeV (397) but with a width (sigma) of 43 GeV. One can of course choose to do nothing about this as Field and Fox have done however the problem is then worsened due to a trigger bias which will preferentially select events in the high energy tail of
the total energy distribution when using a high $E_T$ trigger.

For Figure 3.6, events have been generated at $P_{\text{Beam}} = 400$ GeV and have been taken as is from the Monte-Carlo. In Figure 3.6 we plot the mean total energy in the lab system as a function of the lab $E_T$ into the E609 calorimeter. As the calorimeter $E_T$ requirement is increased so does the mean total energy of the hadron final state until e.g. for $14 \leq E_T \leq 16$ GeV, the average total energy is 430 GeV. Clearly then this is a trigger bias not found in the physical world and one's results will then depend on the level of energy nonconservation achieved especially at the higher $E_T$ values.

One can of course impose overall energy conservation by some means e.g. rescaling some or all of the momentum components of the final state hadrons but all methods are arbitrary so in some sense no one method is correct. More importantly however, as emphasized by Corcoran, who uses the Feynman-Field-Fox four jet Monte-Carlo, both event shapes and cross sections can be dramatically different depending upon how chooses to impose energy and momentum conservation.

We have chosen to impose energy conservation in the following hopefully gentle manner. We simply reject events and their associated tries if they fail either of
Figure 3.6 Mean total lab energy as a function of calorimeter $E_T$ from the Field-Fox-Wolfram Monte-Carlo.
the following cuts: \( |(E_{\text{total}} - 27.43)/27.43| \leq 0.05 \) or \( \sum P^*_Z \leq 0.5 \) GeV and simply regenerate a new event.

To see what effect, if any, this method of imposing energy conservation had on the structure and cross section of generated events, two samples of Monte-Carlo events were generated with and without the above energy and \( P^*_Z \) cuts. A global \( E_T \) threshold of 8 GeV into the main E609 calorimeter was used and the global \( E_T \) cross section for the two event samples is shown in Figure 3.7. The total cross section for global triggers with \( E_T \geq 8 \) GeV is 1.3 times smaller when the energy conservation cuts are imposed. For \( E_T \geq 11 \) GeV, the global cross section for the sample which conserves energy is roughly 2.3 times lower than for the sample in which the events are taken as is. Recall the result in Figure 3.5 that the FFW Monte-Carlo, when using the correct trigger, underestimates the NA5 global cross section by a factor of about 13. These events were taken as is and therefore if energy conservation were enforced the FFW Monte-Carlo may produce a cross section which is too small by at least a factor of 17.

For \( E_T \geq 8 \) GeV with the E609 calorimeter trigger, there are slight differences between the energy conserved and nonconserved events in the multiplicity and planarity of the events which increase as the trigger \( E_T \) is
Figure 3.7 Comparison of the cross section $d\sigma/dE_T$ as a function of $E_T$ at $\sqrt{s}=27.4$ GeV for the E609 global trigger with (open circles) and without (solid circles) cuts imposing overall energy conservation on the final state hadrons.
increased. For $8 \leq E_T \leq 9$ GeV, good agreement is found in mean total and calorimeter multiplicities and mean planarity between the energy conserved and nonconserved sample. For $16 \leq E_T \leq 17$ GeV though the mean total and calorimeter multiplicities are 8% and 14% smaller respectively in the energy conserved sample while the mean planarity is approximately 13% higher.

In examining the parton substructure of the energy conserved and nonconserved Monte-Carlo events, an interesting and somewhat larger difference is noted between the two samples in the number of underlying partons. In Figure 3.8a mean the total number of partons produced in the event as a function of calorimeter $E_T$ is shown for both the energy conserved and as is case. At the lowest $E_T$ value, the difference in the total number of partons produced is approximately .7 smaller when energy conservation is imposed and this difference increases by 1 parton to 1.7 as the highest $E_T$ values shown here are reached.

We will subdivide the partons generated into initial state, final state, and spectator partons in the following manner. We define an initial state parton to be a radiated parton from either of the incoming spacelike partons which eventually hard scatter and do not include the beam or target holes. Final state partons are taken
Figure 3.8a Mean total number of partons produced as a function of calorimeter $E_T$ for the E609 global trigger for FFW Monte-Carlo events generated with (open circles) and without (solid circles) cuts imposing overall energy conservation on the final state hadrons.

![FFW NOECON-ECON COMPARISON](image)
to be the two scattered outgoing partons and their associated radiations. And the spectator partons are the beam and target holes.

In Figures 3.8b and c are shown the mean number of initial and final state partons produced as a function of calorimeter $E_T$ for the energy conserved and as is samples. A few comments here. First, averaging over both event samples, the global trigger typically chooses a a parton substructure containing 7 partons. There is roughly 1 initial state parton radiated before the hard scatter plus 4 final state partons (the two scattered partons and 2 radiations) plus the 2 spectators. Whether one chooses to call this an anomalously large amount of gluon bremsstrahlung is a matter of preference.

Second, roughly 65% of the difference in the total number of partons produced is due to the difference in initial state bremsstrahlung between the energy conserved and as is samples. By choosing not to conserve energy exactly at the hadron level biases oneself towards the radiation of extra gluons, especially ones radiated from the initial state.

Third, restricting our remarks to $E_T > 12$ GeV, the average $E_T$ carried per initial state parton is roughly 100 MeV higher (1.1 versus 1.0 GeV independent of $E_T$) when exact energy conservation has been imposed. The
Figure 3.8b Mean total number of initial state partons produced as a function of calorimeter $E_T$ for the E609 global trigger for FFW Monte-Carlo events generated with (open circles) and without (solid circles) cuts imposing overall energy conservation on the final state hadrons.
Figure 3.8c Mean total number of final state partons produced as a function of calorimeter $E_T$ for the E609 global trigger for FFW Monte-Carlo events generated with (open circles) and without (solid circles) cuts imposing overall energy conservation on the final state hadrons.
mean $E_T$ carried per final state parton is 200 MeV higher at $E_T = 12.5$ GeV for the energy conserved sample increasing to roughly 700 MeV at $E_T = 16.5$ GeV. The mean $p_T$ of the hard scatter is approximately 100 MeV higher at $E_T = 12.5$ when exact energy conservation has been imposed increasing to more than 370 MeV at $E_T = 16.5$ GeV. Compared to the Monte-Carlo events taken as is, the energy conserved events satisfy a global $E_T$ requirement of $> 12$ GeV by having slightly harder initial state radiation and harder 2-2 parton scatterings which, because of the steeply falling cross sections with $x_L$ (where $x_L$ is the radiated gluon energy fraction) and $p_T$ result in the reduced cross section found in Figure 3.7.

Finally, these effects are not changed if only partons collected by the E609 calorimeter are considered. (Roughly 65% of the initial state partons and 85% of the final state partons hit the calorimeter.)

Summarizing sections 3.6 and 3.7, one explanation for the large cross section and non-jetlike structure of globally triggered events is due to a trigger bias towards the production of final and especially initial state gluon bremsstrahlung. This picture was partly supported by the Monte-Carlo predictions of Field and Fox which gave good agreement with the NA5 global trigger data.
We find however, that the FFW Monte-Carlo underestimates the NA5 global cross section by an order of magnitude if one uses the proper trigger. Also, imposing exact energy conservation on the final state hadrons suppresses initial state gluon radiation thus decreasing the cross section further by roughly a factor of 2. We conclude that the effects of initial state gluon bremsstrahlung on the global cross section and event structure may have been previously overestimated.
CHAPTER 4

ANALYSIS PROCEDURES AND EXPERIMENTAL AND MONTE-CARLO

RESULTS

4.1 PRELIMINARY DATA ANALYSIS PROCEDURES

As discussed in Chapter 2, the 400 GeV/c proton beam was defined by a series of beam counters in coincidence with run, spill, and computer live time conditions and in anticoincidence with beam pileup and muon shield triggers. The number of live beam triggers (LBT's) surviving these conditions and available for interactions was roughly 250k per 1 second spill with four machine spills coming every minute. The total integrated luminosity used in the low and high $E_T$ threshold global trigger analysis was $7.3 \times 10^{31}$ cm$^{-2}$ and $6.1 \times 10^{33}$ cm$^{-2}$ respectively. The total integrated luminosity used in the two high trigger analysis was $3.6 \times 10^{33}$ cm$^{-2}$. An additional set of high $E_T$ threshold two high runs of integrated luminosity $2.5 \times 10^{33}$ cm$^{-2}$ was also employed for a large part of the two high analysis.

To compact a large number of data tapes, a series of first level data summary tapes (DST's) were produced. The following cuts were applied to the raw data tapes:

1. The event was required to have readout from a
given piece of the apparatus (calorimeter, DC's, etc.) in its correct position in the data array.

2. All pedestal subtracted calorimeter ADC's had to be \( \leq 3600 \) counts.

3. A minimum of 3 ADC's had to have fired.

4. The total \( E_T \) was required to be \( \geq 2 \) GeV.

5. The energy in calorimeter was required to be \( \leq 440 \) GeV.

6. The counters DEDX (B6) and B2 were required to have pulse heights less than twice minimum ionizing.

7. The event was required to exceed at least one of the 200 odd trigger thresholds where the threshold for each trigger was defined to be the peak of the \( E_T \) distribution of the triggering region less .5 GeV.

All ADC's had their pedestals subtracted and were corrected for any previously measured nonlinearities. The energy of each nonzero ADC was computed based on the calculated conversion factors used in the muon gain balancing procedure discussed in Chapter 2 and was written to the DST. TDC information from the drift chambers, MWPC readout, trigger latches, and scalers were written to the first level DST also.

The results presented below are concerned with two types of geometrically unbiased triggers, the global trigger and the "two high" trigger. The global trigger
requires the sum of the calorimeter segment $E_T$'s to exceed some threshold which for most of the running was roughly 16 GeV. The two high trigger requires any two segment $E_T$'s to exceed a threshold typically set at 1.3 GeV. The two trigger segments can be any of the calorimeter and are not required to be back to back. Although both triggers are geometrically unbiased they are subject to different physics biases which will be commented on below.

A few remarks on the $E_T$ scale are appropriate here. Because of the steeply falling $E_T$ spectra of high $E_T$ interactions, the observed cross section $\sigma(E_T^{\text{obs}})$ is not the true physics cross section but rather the convolution of the energy response of the calorimeter, $R(E_T^{\text{obs}},E_T^{\text{true}})$, with the true $E_T$ cross section\textsuperscript{81,82}:

$$\sigma(E_T^{\text{obs}}) = \int R(E_T^{\text{obs}},E_T^{\text{true}}) \frac{d\sigma}{dE_T^{\text{true}}} dE_T^{\text{true}}$$

where $R(E_T^{\text{obs}},E_T^{\text{true}}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{1}{2} \frac{(E_T^{\text{obs}} - E_T^{\text{true}})^2}{2\sigma^2}\right)$

and where $\sigma = c \sqrt{E_T^{\text{true}}}$. For a true cross section which falls off exponentially with $E_T$, for example, the above has consequence that a measured $E_T^{\text{obs}}$ will have most probably originated from particles whose $E_T^{\text{true}} < E_T^{\text{obs}}$ thus inflating the measured cross section. The experimenter
measures $\sigma(E_T^{\text{obs}})$ and the calorimeter resolution, $R(E_T^{\text{obs}}, E_T^{\text{true}})$ and must then extract the true cross section from unfolding. In practice, one method of accomplishing this is by searching for an observed $E_T$ scale such that $\frac{d\sigma}{dE_T^{\text{true}}} R(E_T^{\text{obs}}, E_T^{\text{true}})$, the effective calorimeter resolution, is centered about $E_T^{\text{true}}$ for each $E_T^{\text{obs}}$ bin.

A further difficulty in exacting cross sections is the difference in response of the calorimeter to hadrons and $\pi^0$'s, though the usual solution to this problem is to employ an electromagnetic section in front of the hadronic part of the calorimeter and to weight the different sections accordingly. Unfolding the true $E_T$ distribution from the energy resolution is made increasingly difficult if the detector has poor energy resolution or gives a non-Gaussian response (extended high energy tail) to hadrons as a result of errors in the calibration which balances the responses of different sections of the calorimeter. In analysis of the hadron calibration runs, no such high energy tails were observed.\(^48\)

Because analysis of empty target runs indicated that the fraction of events interacting with the mylar walls of the LH$_2$ target was quite high at the higher $E_T$ values, the global and two high hardware triggers in each each run were next tracked to establish a vertex position. Details of the tracking program may be found in reference
83. For each event, for each vertex found, the x and z coordinates of that vertex and the number of tracks forming the vertex were written to a data file. If no vertex was found, the event was identified with one of several possible reasons why the tracking program failed. This data file was subsequently used in the production of the second level DST's.

To further reduce the number of data tapes and to facilitate subsequent analyses, a second level DST consisting primarily of the four momenta of particles striking the calorimeter was written separately for each trigger of interest. Each event had first its online trigger latches checked and was rejected if the trigger of interest had not exceeded its set $E_T$ threshold during running. A gain correction factor was applied to each calorimeter ADC nullifying any difference between the measured response of that module to muons and the calculated response used in the muon balancing procedure. The energy in each calorimeter ADC was then multiplied by 1.25, an preliminary estimate of the overall $E_T$ scale factor discussed above, and the energy in each segment was formed by summing the energy of its member ADC's with layer weights of 1.0 for the AP and A layers and 1.25 for B and C layers.

The transverse energy deposited in each segment is
given by $E_T^i = E^i \sin(\phi^i)$ where $E^i$ is the $i$th segment energy and $\phi^i$ is the polar angle of the $i$th segment with respect to the beam axis, all measured in the laboratory system. Then the total transverse energy of the event is $E_T = \sum E^i \sin(\phi^i)$, where the sum runs over all calorimeter segments. For global triggers, an $E_T$ cut roughly 1 GeV smaller than the peak of the $E_T$ distribution served to reject events below threshold. For two high triggers, an $E_T$ cut at approximately the peak (1.3 GeV) was applied to the highest and second highest segment $E_T$ distributions. In addition, if a hot segment was noticed in the distributions of which segment had the highest and second highest segment $E_T$'s, the run was reanalyzed rejecting those events triggered by culprit segments.

Next the four momenta of particles hitting the calorimeter were crudely reconstructed by applying a clustering algorithm to the segment energy deposits and giving each cluster a pion mass. The clustering algorithm was based on data of the lateral and longitudinal spreading of electromagnetic and hadronic showers in the E609 calorimeter.

Briefly, the clustering algorithm first orders the segments according to their $E_T$ and begins with the one with highest $E_T$. The electromagnetic ratio, equal to the sum of the energy in the AP and A layers of the segment
divided by the segment energy, is calculated and used to classify the shower as hadronic or electromagnetic. An initial shower center is computed by taking the energy weighted sum of the coordinates of the central segment and four nearest neighbors. The fraction of shower energy inside the central segment is calculated using the sum of two Gaussians to describe the lateral spreading of shower energy and an initial estimate of the cluster energy is given by the segment energy divided by the expected fraction. Next the amount of energy expected in all neighboring segments within a 1sr radius is computed, subtracted from those segments up to the maximum energy of the segments, and added to the central segment energy. Finally, the cluster center is recomputed by taking the energy weighted sum of the coordinates of all contributions to the cluster and the three momenta calculated by multiplying the cluster energy times the direction cosines at the cluster center. The segments are reordered according to $E_T$ and the process repeated until no segments with $E_T$'s smaller than 85 MeV remain.

These cluster (particle) four momenta were then written to the second level DST along with the energy in the beam calorimeter, a list of the 10 highest $E_T$ segments and their $E_T$'s, and the online trigger latches. The energy in the beam calorimeter was taken to be the
hardwired sum of pulse heights from its four phototubes times a conversion factor based on steering a 200 GeV/c beam into the beam calorimeter and setting the mean pulse height equal to the beam momentum. The total number of charged tracks found by the DC's and the vertex information for each vertex or the failure identifier if no vertex was found was included on the second level DST also.

4.2 PRELIMINARY MONTE-CARLO ANALYSIS PROCEDURES

A detailed discussion of the generation of events using the Field-Pox-Wolfram Monte-Carlo can be found in Chapter 3. Briefly, events were generated flat in $p_t^2$ over the $p_t$ range from 2 to 6.5 GeV where $p_t$ is the parton-parton hard scattering transverse momentum. The cross section per generated event is given by $\frac{p_t^{range}}{N\text{EVGEN} \frac{d\sigma}{dp_t^2}}$ in $\mu$b where $\frac{d\sigma}{dp_t^2}$ is the $O(\alpha_s^2)$ cross section for the 2-2 parton subprocess and NEVGEN is a flux. The values of the relevant parameters of the model are listed in Table 3.1. Because the FFF parameterization is used for the large mass cluster hadronizations, e.g. those clusters containing a beam or target remnant parton, energy and momentum are not exactly conserved. Energy conservation is imposed by making cuts on the total energy and total
momentum along the beam direction in the pp CM frame. The consequences of these cuts are discussed in Chapter 3. Under these conditions 130k FFW events were generated, though obviously only a fraction of them satisfy the high $E_T$ triggers of interest. To study the effect of the upper limit of the $P_T$ range on the experimental observables, an additional 900 events were generated over the $P_T$ range from 2 to 8 GeV which also passed a calorimeter $E_T$ cut of 15 GeV.

Before having their showers simulated in the calorimeters, all particles were transformed to the lab frame. Those particles traveling down the beam hole had their energies smeared according to the Gaussian beam calorimeter energy resolution function whose mean was just equal to the particle's momentum. Those particles striking the main calorimeter had first their energies degraded according Table 2.3 and then smeared according to the segment type dependent Gaussian main calorimeter energy resolution functions given in Table 2.2. Naturally, $\pi^0$'s, $\eta$'s and $\phi$'s are taken to shower electromagnetically. If the particle strikes within 8" of either the inside or outside edge of the calorimeter, the smeared energy is degraded by a fraction $f = 1-(.69+.0363d)$ where d is the distance from the edge.
The fraction removed is added to the beam calorimeter energy for particles striking near the beam hole.

Next the smeared energy of each particle is deposited in the calorimeter according to the longitudinal shower profile determined from hadron and electron calibration data and the lateral shower profile determined from that data and data taken by stepping a hadron beam across the face of the calorimeter. Briefly, the shower energy is spread in x and y according to a Gaussian function whose width (sigma) is approximately .5" for electrons and between 1.5" and 2." for hadrons depending on segment type. In addition, approximately 10% of the smeared energy of hadronic showers is randomly placed outside the region of the struck segment and all nearest neighboring segments. Also, an energy dependent fraction of the struck segment's energy is removed and randomly placed in some of its nearest neighbor segments.

Finally, the energy in each segment is divided up into an AP+A layer and B+C layer component based on the longitudinal shower profile. This allows for the weighting of different layers as is done in the real data analysis discussed above. At this point then, the energy from particles produced by the Monte-Carlo is in exactly the same form as the real data written to the first level DST's.
From this point on, the showered Monte-Carlo events are treated in exactly the same manner as the real data was processed in producing the second level DST. That is, with the layer weights and overall $E_T$ scale factor used above, two high and global trigger conditions are imposed on the events and rejected if failing to satisfy at least one of the triggers. The clustering algorithm is applied to reconstruct the four momenta of the Monte-Carlo produced events. The multiplicity of cluster four momenta, beam calorimeter energy, and the 10 highest $E_T$ segments and their $E_T$'s were written to a tape similar to the real data second level DST.

In addition, both the underlying parton final state and the hadron state before shower simulation for the Monte-Carlo events were written to the same tape. For the parton level, the four momenta, parton type, and origin of all partons remaining after generation of the parton shower were written, while for the hadron level, the four momenta and string indicies of all generated hadrons were written. By parton type, we refer to $u$, $d$, $s$, or gluon and by origin, we mean the partons were labeled as arising from the initial state evolution, the final state evolution, or as beam or target remnants. By string indices, we mean hadrons were labeled with the two
partons forming the color neutral cluster from whose hadronization they were produced.

4.3 GLOBAL ANALYSIS PROCEDURES

As mentioned in section 4.1 above, a common method for unfolding the true $E_T$ cross section, $d\sigma/dE_T$, from that experimentally observed is to apply an overall, possibly $E_T$ dependent scale factor. In the production of the second level E609 data and FFW Monte-Carlo DST's, an overall $E_T$ scale factor of 1.25 was used based on a earlier Monte-Carlo calculation which generated FFF two jet events (no beam jets) with $dN/dp_T^{jet} \sim e^{-3p_T^{jet}}$, showered their hadrons according to the measured energy resolution of the calorimeter, and recomputed the $p_T^{84}$.

A more accurate scale factor was obtained by comparing the calorimeter $E_T$ of FFW Monte-Carlo events before and after having their showers simulated in the calorimeter as described in section 4.2. For each trigger, the scale factor was found as $\text{SCALE} = \langle E_T^{\text{before}} / E_T^{\text{after}} \rangle$. With an overall scale factor of 1.46 for global triggers and 1.41 for two high triggers, the quantity SCALE for these triggers is shown in Figures 4.1a and 4.1b as a function of the total calorimeter $E_T^{\text{obs}} = E_T^{\text{after}}$. Little $E_T$ dependence on the scale factor needed is noted. (One
Figure 4.1a Mean $E_{\text{true}}/E_{\text{obs}}$ as a function of $E_{\text{obs}}$ for FFW global trigger events with calorimeter $E_T > 9.5$ GeV using an $E_T$ scale factor of 1.46.
Figure 4.1b Mean $E_T^{true}/E_T^{observed}$ as a function of $E_T^{observed}$ for FFW two high trigger events with calorimeter $E_T>7$ GeV using an $E_T$ scale factor of 1.41.
might instead choose to set the total calorimeter energy, ECAL, before and after shower simulation equal. Using the overall $E_T$ scale factors of 1.46 and 1.41, the results for $\text{SCALE} = \frac{\text{before}}{\text{after}}$ as a function of the observed (after showering) calorimeter energy are shown in Figures 4.2a and 4.2b. The scale factor needed in this case would have to be roughly 10% larger and a function of the calorimeter energy.

The distribution of $E_T^{\text{before}} - E_T^{\text{after}}$ for global triggers with total calorimeter $E_T > 9.5$ GeV and for two high triggers with total calorimeter $E_T > 7$ GeV is shown in Figures 4.3a and 4.3b and has widths ($\sigma$) of 694 and 705 MeV respectively. The $E_T$ cross section before showering of those Monte-Carlo events which satisfied the global and two high trigger conditions (using the observed $E_T$) is compared in Figures 4.4a and b respectively with the observed (after showering) $E_T$ cross section. The slopes of the global and two high cross sections are not changed by smearing the $E_T$ in the shower simulation. The scale factors of 1.46 for global triggers and 1.41 for two high triggers were applied to all cluster momentum components in both the E609 data and PPW Monte-Carlo events. The uncertainty in the $E_T$ scale is estimated to be 7%.

Of course the multiplicity as found by the
Figure 4.2a Mean ECAL_{true}/ECAL_{observed} as a function of ECAL_{observed} for FFW global trigger events with calorimeter $E_T > 9.5$ GeV using an $E_T$ scale factor of 1.46.
Figure 4.2b Mean ECAL$^{\text{true}}$/ECAL$^{\text{observed}}$ as a function of ECAL$^{\text{observed}}$ for FFW two high trigger events with calorimeter $E_T>$7 GeV using an $E_T$ scale factor of 1.41.
Figure 4.3a Distribution of $E_T^{\text{true}} - E_T^{\text{observed}}$ for FFW global trigger events with calorimeter $E_T > 9.5$ GeV using an $E_T$ scale factor of 1.46.
Figure 4.3b Distribution of $E_T^{\text{true}} - E_T^{\text{observed}}$ for FFW two high trigger events with calorimeter $E_T > 7$ GeV using an $E_T$ scale factor of 1.41.
Figure 4.4a Cross sections $d\sigma/dE_T^{\text{true}}$ and $d\sigma/dE_T^{\text{observed}}$ for FFW global trigger events with calorimeter $E_T > 9.5$ GeV using an $E_T$ scale factor of 1.46.
Figure 4.4b Cross sections $d\sigma/dE_T^{\text{true}}$ and $d\sigma/dE_T^{\text{observed}}$ for FFW two high trigger events with calorimeter $E_T > 7$ GeV using an $E_T$ scale factor of 1.41.
clustering algorithm is only roughly equal to the true multiplicity. In Figures 4.5a and b, the difference between the mean multiplicity of Monte-Carlo events before and after showering and clustering is shown for global triggers with $E_T > 9.5$ GeV and two high triggers with $E_T > 7$ GeV. Thus the clustering algorithm overestimates the lower true multiplicities and underestimates the higher ones. The multiplicity as given by the clustering algorithm is used instead of the MWPC or DC multiplicity (times 1.5) because we wish to compare the E609 data and Monte-Carlo using as identical analysis procedures as possible.

The analysis of the E609 global data was performed with a series of low $E_T$ threshold runs as well with the high $E_T$ threshold global data collected throughout most of the experiment. Two of the low threshold runs were taken at different times from the rest of the series. Within statistics, these two runs gave similar averages for calorimeter energy ECAL, beam calorimeter energy BCAL, multiplicity, etc. to the other runs of the series, however their $E_T$ cross sections were slightly higher (by a factor of about 2.3) indicating a shift in the $E_T$ scale, likely due to some temperature dependent drift in the calorimeter electronics. Because the other
Figure 4.5a Mean difference between FPW Monte-Carlo multiplicity and the multiplicity from the clustering algorithm as a function of the Monte-Carlo multiplicity for FPW global trigger events with calorimeter $E_T > 9.5$ GeV.
Figure 4.5b Mean difference between FFW Monte-Carlo multiplicity and the multiplicity from the clustering algorithm as a function of the Monte-Carlo multiplicity for FFW two high trigger events with calorimeter $E_T > 7$ GeV.
low threshold runs in the series had sufficient statistics, these two runs were ignored.

Observables such as mean ECAL, BCAL, $E_T$, multiplicity, planarity, and normalized event rate were calculated for each high $E_T$ threshold run after applying the cuts discussed below and plotted as a function of time. Over that time period of the data taking used for this analysis (about 6 weeks), the run to run variations of the means of these observables were quite small. Three runs had less than two events after cuts and were ignored. Also, five runs gave good agreement with the observable averages but had event rates roughly two to three times that for the other runs and for this reason were not used. Typical run by run variations in experimental observables for the high threshold global trigger quoted as $\sigma$/mean were 1% in $E_T$, 2% in ECAL, 19% in BCAL, 4% in cluster multiplicity, 7% in MWPC multiplicity, and 13% in planarity.

The following cuts were applied to the global data:

1. The calorimeter $E_{T\text{lab}}$ was required to be $\geq E_{T\text{threshold}}$ where $E_{T\text{lab}}$ is now defined as the scalar sum of the cluster $E_T$'s. The $E_{T\text{threshold}}$ was typically 1 GeV above the peak of the $E_T$ distribution.

2. The momentum imbalance in the event, $\text{PTT} = (\sum P_x^i)^2 + (\sum P_y^i)^2)^{1/2}$, must be $\leq 4.5$ GeV.
3. The $E_T$ of the highest $E_T$ segment in the calorimeter was required to be $\leq 3$ GeV for the low threshold runs and 4.5 GeV for the high threshold runs. Cuts 2 and 3 served to eliminate knock-on electrons from accidental muons and or any hot segments missed in the production of second level DST's.

4. The total observed energy ECAL + BCAL must be $\leq 550$ GeV. Cut 4 guarded against pileup, i.e. two interactions occurring within the ADC gate width of 110 ns.

5. The event was required to have a vertex within the LH$_2$ target.

Figures 4.6a and b show the vertex (along the beam axis) distribution for LH$_2$ target full and empty runs for global triggers at the highest $E_T$ threshold along with the applied cuts. The mylar walls and windows of the target are clearly visible. Approximately 12% of the empty target events survive using the vertex cuts shown. The empty target vertex distribution and vertex cuts for two high triggers are similar to Figure 4.6b though the fraction of non-hydrogen events outside the vertex cuts is a few percent higher than found in the empty target global runs and the mylar walls cannot be as easily distinguished in the two high full target vertex distribution. The fraction of non-hydrogen events as a function
Figure 4.6a Full LH$_2$ target vertex distribution along the beam direction and vertex cuts for high $E_T$ threshold global trigger events.
Figure 4.6b Empty LH$_2$ target vertex distribution along the beam direction and vertex cuts for high $E_T$ threshold global trigger events.
of total calorimeter $E_T$ for both global and two high triggers is presented in Figures 4.7a and b.

4.4 E609 AND FFW MONTE-CARLO GLOBAL TRIGGER RESULTS

We begin the comparison of E609 and FFW Monte-Carlo globally triggered events with results for some basic experimental observables. Figures 4.8 and 4.9 show the mean main calorimeter energy, ECAL, and the mean beam calorimeter energy, BCAL, as a function of the calorimeter $E_T$ for both the E609 data and FFW Monte-Carlo events. As expected, ECAL (BCAL) rises (falls) with $E_T$, with the rate of increase (decrease) slightly lessening at larger $E_T$'s. The mean ECAL (BCAL) is approximately 25 (35) GeV smaller (larger) in the FFW Monte-Carlo than E609 data. The mean observed energy, ECAL plus BCAL, rises roughly 7% from ~380 GeV at $E_T=8.5$ GeV to ~405 GeV at $E_T=19.5$ GeV. This trend is approximately seen in the Monte-Carlo also. The shapes (Gaussian) and widths (35 and 50 GeV at $E_T=9.5$ GeV) of the ECAL and BCAL distributions agree well between data and Monte-Carlo over the full range of $E_T$'s.

The difference between Monte-Carlo and data in mean ECAL and BCAL can be understood by examining the mean cluster multiplicity, $n$, as a function of $E_T$ as shown in Fig. 4.10. The mean cluster multiplicity as predicted
Figure 4.7a Mean fraction of non-hydrogen events as a function of calorimeter $E_T$ for the global trigger.
Figure 4.7b Mean fraction of non-hydrogen events as a function of calorimeter $E_T$ for the two high trigger.

![Graph showing mean non-hydrogen fraction versus ET lab (GeV)]
Figure 4.8 Mean main calorimeter energy, ECAL, as a function of calorimeter $E_T$ for low and high $E_T$ threshold E609 global data and for the FFW Monte-Carlo global trigger events. The FFW points labeled global $> 16$ GeV (open triangles) use the extended $p_T$ range (2 to 8 GeV).
Figure 4.9 Mean beam calorimeter energy, BCAL, as a function of calorimeter $E_T$ for low and high $E_T$ threshold E609 global data and for the FFW Monte-Carlo global trigger events. The FFW points labeled global > 16 GeV (open triangles) use the extended $E_T$ range (2 to 8 GeV).
Figure 4.10 Mean cluster multiplicity as a function of calorimeter $E_T$ for low and high $E_T$ threshold E609 global data and for the FFW Monte-Carlo global trigger events. The FFW points labeled global $> 16$ GeV (open triangles) use the extended $p_T$ range (2 to 8 GeV). Also shown is the prediction from ISAJET minimum bias events.
by the Monte-Carlo is roughly 16% too low at $E_T = 8.5$ GeV widening to 30% too low at $E_T = 19.5$ GeV compared to the E609 data. A smaller cluster multiplicity means smaller ECAL and hence larger BCAL energies as observed in the previous figures. The requirement of a large $E_T$ to be deposited in the calorimeter is satisfied by the production of higher and higher multiplicities. Both the data and Monte-Carlo events show an increase in mean cluster multiplicity with $E_T$ though the rate of increase flattens out at the higher $E_T$'s. Below $E_T = 16.5$ GeV, the rate of increase of multiplicity with $E_T$ is slightly faster in the data than predicted by the Monte-Carlo and above $E_T = 16.5$ GeV, the Monte-Carlo multiplicity remains essentially constant whereas the multiplicity of the data continues to increase.

As a measure of the event shape in the transverse plane, the planarity variable is typically employed. Consider the matrix

$$M_{\alpha\beta} = \sum P_{i\alpha} P_{i\beta}$$

where $\alpha, \beta$ are X and Y, the transverse directions, and $i$ runs over the multiplicity of the event. Diagonalizing $M$ is equivalent to finding a set of eigenaxes such that $\sum P_{iX}^2$ ($\sum P_{iY}^2$) is maximized (minimized) along the major
(minor) eigenaxis. Let the eigenvalues of $M$ be $\lambda_1, \lambda_2$, then $P = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2}$. Clearly, a pencil-like event will have $P \sim 1$ while an isotropic event will have $P \sim 0$.

The first striking difference between E609 data and the FFW Monte-Carlo is seen in Fig. 4.11 where the average planarity is plotted as a function of calorimeter $E_T$. The Monte-Carlo finds the planarity to be flat at $\sim 0.48$ out to $E_T \sim 11.5$ GeV, increases linearly with $E_T$ reaching $\sim 0.85$ at about 18.5 GeV, and then flattens out with that value. Comparing the planarity means above $E_T = 17.5$ GeV for the nominal ($\sum_{t}^{max} = 6.5$, black triangles) and extended ($\sum_{t}^{max} = 8.5$, white triangles) $P_t$ ranges, one can see that at the larger $E_T$'s it is necessary to include higher $P_t$'s which have increased the mean planarity by $\sim 1$ over that using the nominal $P_t$ range.

The E609 data, on the other hand, give a planarity of $\sim 0.38$ throughout the entire $E_T$ range with only a slight increase to $\sim 0.45$ for $E_T > 18$ GeV. This difference between experimental data and FFW Monte-Carlo in average planarity as a function of $E_T$ was also found by FNAL experiment E557.

Note that even though there is no dramatic rise in the mean planarity as $E_T$ is increased, the fact that the mean planarity remains essentially constant in the data gives information about the structure of the global
Figure 4.11 Mean planarity as a function of calorimeter $E_T$ for low and high $E_T$ threshold E609 global data and for the FFW Monte-Carlo global trigger events. The FFW points labeled global $> 16$ GeV (open triangles) use the extended $p_T$ range (2 to 8 GeV). Also shown is the prediction from ISAJET minimum bias events.
events. Plotting the mean planarity as a function of cluster multiplicity for the lowest and highest $E_T$ thresholds, one finds the mean planarity to decrease by about .2-.3 from $n=19$ to $n=33$, the endpoints of Fig. 4.10. However, at a given multiplicity, the mean planarity increases as the threshold $E_T$ is increased. (For example, for fixed multiplicity, the mean planarity increases by $\sim .2$ roughly independent of multiplicity as the threshold $E_T$ is increased from 9.5 to 17. GeV.) Hence although the calorimeter multiplicity increases with calorimeter $E_T$ (which would tend to decrease the average planarity), the mean planarity remains constant because at any given multiplicity, the additional $E_T$ is put into the high $E_T$ events in such a manner as to increase the planarity (i.e. make them more jetlike). The planarity of the global triggers is not determined simply by the event multiplicity.

Similarly, one can show that the difference in average planarity at large $E_T$ between E609 data and FFW Monte-Carlo is not solely the result of a difference in multiplicity but rather reflects a difference in event topology. From an average planarity versus multiplicity plot, the difference in multiplicity between data and Monte-Carlo at $E_T\sim 17.5$ GeV translates to a difference of .1 in planarity when in fact the observed difference at
$E_T = 17.5$ GeV is $\sim 4$. Therefore, we conclude that the events generated by the FFW Monte-Carlo are simply too jetlike, becoming increasingly so as the $E_T$ is increased, and that this difference is not simply due to the difference in multiplicity.

The planarity distributions for events satisfying the global trigger with calorimeter $E_T > 9.5$ and 17 GeV are shown in Figures 4.12a and b for both the E609 data (solid curve) and FFW Monte-Carlo events (dashed curve). The planarity distribution for the E609 global trigger with $E_T > 9.5$ GeV shows the decidedly non-jetlike shape of events selected with a global trigger first observed by NA5. The planarity distribution for the FFW Monte-Carlo for the same $E_T$ threshold is roughly the same though shifted upwards towards higher planarities by $\sim 1$. The fraction of events with planarity $> .7$ (what by eye could be called "clean" 2 jet events) is approximately 6% in the E609 data and 17% in the Monte-Carlo.

Increasing the global $E_T$ threshold to 17 GeV results in a planarity distribution for the data only slightly shifted towards higher planarity from that for $E_T > 9.5$ GeV. In the FFW Monte-Carlo for $E_T > 17$ GeV though, the planarity distribution changes dramatically from that at the lower $E_T$ threshold and is a relatively narrow distribution peaked around planarity $\sim .8$. The fraction
Figure 4.12a Planarity distribution for the global trigger with calorimeter $E_T > 9.5$ GeV for the E609 data (solid line) and FFW Monte-Carlo (dashed line).
Figure 4.12b Planarity distribution for the global trigger with calorimeter $E_T > 17$ GeV for the E609 data (solid line) and FFW Monte-Carlo (dashed line).
of events with planarity > .7 is only approximately 12% in the data but 61% in the Monte-Carlo. The difference in the planarity distribution between E609 data and FFW Monte-Carlo at high threshold $E_T$'s is a major failure of the hard scattering plus initial and final state gluon bremsstrahlung model.

For comparison, the mean multiplicity and mean planarity as a function of $E_T$ for ISAJET minimum bias events is also shown in Figs. 4.10 and 4.11. For minimum bias ISAJET events, the mean multiplicity is slightly (~10%) too large below $E_T$=12.5 GeV compared to the E609 data. Thereafter though, the minimum bias multiplicity continues to rise linearly with calorimeter $E_T$ while the rate of increase of multiplicity with $E_T$ in the E609 data drops off. For ISAJET minimum bias events, the average planarity decreases as a function of $E_T$ whereas the data remain flat. This argues against the origin of the non-jetlike structure of globally triggered events as being simply the high multiplicity tail of minimum bias events.

As a measure of the event shape in three dimensions we use the sphericity and aplanarity variables familiar from their use in $e^+e^-$ annihilations. One first forms the three dimensional momentum tensor as above only now $\alpha, \beta = X, Y, Z$. Next one orders the the normalized
eigenvalues with $Q_3 > Q_2 > Q_1$ which also satisfy $Q_1 + Q_2 + Q_3 = 1$. These normalized eigenvalues measure the length($Q_3$), width($Q_2$) and flatness($Q_1$) of the event. With only two of the three eigenvalues being independent it is usual to describe the event by its sphericity $S = \frac{3}{2}(Q_1 + Q_2)$ and aplanarity $\lambda = \frac{3}{2}Q_1$. Sphericity~$\lambda$ corresponds to an isotropic event while jetlike events will have sphericity ~0. The quantities $\langle p_{Tout}^2 \rangle$ $\langle p_{Tin}^2 \rangle$ used in the search for three jet structure in $e^+, e^-$ annihilations are also quickly determined as $Q_1 \langle p^2 \rangle$ and $Q_2 \langle p^2 \rangle$ respectively.

Figures 4.13a and b show the average sphericity and aplanarity as a function of $E_T$. Dissimilarities in the average sphericity versus $E_T$ curves from the E609 data and FFW Monte-Carlo lead to the same conclusion as differences in average planarity curves, namely that the events produced by the Monte-Carlo are too jetlike. The mean aplanarity as a function of $E_T$ is constant at ~.21 out to $E_T=16.5$ GeV where it then decreases with $E_T$ falling to ~.15 at $E_T=19.5$ GeV. For the Monte-Carlo events, the mean aplanarity is constant at ~.18 but only out to $E_T=10.5$ GeV after which it decreases linearly with $E_T$ to ~.07 at 19.5 GeV. This indicates that the events produced by the FFW Monte-Carlo are slightly too flat compared to the data (i.e. have too little momentum flow out of the event plane (as defined by the eigenvectors of
Figure 4.13a Mean sphericity as a function of calorimeter $E_T$ for low and high $E_T$ threshold E609 global data and for the FFW Monte-Carlo global trigger events. The FFW points labeled global > 16 GeV (open triangles) use the extended $p_T$ range (2 to 8 GeV).
Figure 4.13b Mean aplanarity as a function of calorimeter $E_T$ for low and high $E_T$ threshold E609 global data and for the FFW Monte-Carlo global trigger events. The FFW points labeled global > 16 GeV (open triangles) use the extended $p_T$ range (2 to 8 GeV).
the two largest eigenvalues)) and become more planar as $E_T$ is increased at too low an $E_T$.

Although they have not found wide use in the analysis of $e^+e^-$-hadrons and high $P_T$ hadron-hadron collisions, another set of observables for describing event shapes are the two and three dimensional Fox-Wolfram moments.\cite{88,89} These observables have the advantage of being independent of the axes chosen to about which to calculate them unlike other observable such as thrust and sphericity. The three dimensional Fox-Wolfram moments are defined by\cite{88}

$$H_1 = \sum \frac{1}{s} \frac{1}{P_i} \frac{1}{P_j} P_1(\cos(\theta_{ij}))$$

while in the two dimensions of the transverse plane one can use

$$C_1 = \sum \frac{1}{s} \frac{1}{P_{Ti}} \frac{1}{P_{Tj}} \cos(1(\phi_i - \phi_j))$$

where $\theta_{ij}$ is the angle between particles $i$ and $j$ and $\phi$ is the azimuthal angle. Usually the ratios $H_1/H_0$ and $C_1/C_0$ are formed since the values of $H_0$ and $C_0$ vary from event to event because not all particles are detected. between particles $i$ and $j$. For idealized two jet events one expects $H_1/H_0$ and $C_1/C_0$ $\sim 1$ for $l$ even and $\sim 0$ for $l$ odd.
Multijet events will give a wide range of $H_1/H_0$ and $C_1/C_0$ values. We have investigated the first three two and three dimensional Fox-Wolfram moments but find they give little information that planarity, sphericity, and aplanarity do not. The distributions of the two and three dimensional first and third F-W moments for the E609 data and Monte-Carlo are similar. The distributions of the two and three dimensional second F-W moments show disagreement between data and Monte-Carlo consistent with the disagreement in planarity distributions observed above.

In Figure 4.14 the global cross section $d\sigma/dE_T$ using the E609 calorimeter is shown for both the E609 data and FFW Monte-Carlo events. As foreshadowed by the Monte-Carlo comparison with the NA5 global data in section 3.6, the FFW Monte-Carlo cannot reproduce the E609 global cross section. At $E_T=10$ GeV, the Monte-Carlo is a factor of $\sim 13$ smaller than the data while at $E_T=18$ GeV, the Monte-Carlo is a factor of $\sim 71$ too small. The global cross section falls off exponentially with $E_T$ going as $\exp(-0.86E_T)$ in the E609 data and slightly steeper as $\exp(-1.09E_T)$ in the Monte-Carlo. Shown also in Figure 4.14 is the Monte-Carlo prediction with the ISAJET minimum bias option. Although the ISAJET minimum bias global cross section shows good agreement with the E609
Figure 4.14 Global cross section $d\sigma/dE_T$ for the E609 calorimeter as a function of calorimeter $E_T$ for low and high $E_T$ threshold E609 global data and for the FFW Monte-Carlo global trigger events. The FFW points labeled global $> 16$ GeV (open triangles) use the extended $P_T$ range (2 to 8 GeV). Also shown is the prediction from ISAJET minimum bias events.
data, small changes in the inclusive $P_T$ distribution for $P_T > 0.75$ GeV or in the shape of the rapidity distribution can change the cross section by two or three orders of magnitude. Nevertheless, some contribution to the global cross section and influence on the average global event structure from purely minimum bias events is not completely ruled out.

An alternate explanation of the large cross section and non-jetlike nature of globally triggered events observed by NA5 as well as this experiment is that global $E_T$ triggers are biased towards collecting a large number of hadrons from the fragmentation of the beam and target spectator partons. In the context of the quark-parton four jet model, the hadronization of the energetic beam and target remnants would result in a high multiplicity of hadrons with limited $P_T$ with respect to the collision axis (which in this case is also the jet axis). A large observed $E_T$ in the calorimeter can be satisfied by a hard scatter of small $P_T$ with the remainder of the calorimeter $E_T$ coming from particles originating from the hadronization of the spectator partons. (Although first historically, this explanation is in fact nearly identical to the bias towards enhancement of initial state gluon bremsstrahlung; a description of beam and target remnants in terms of $Q^2$ dependent fragmentation functions
as in the FFF model or in terms of the fragmentation of the beam parton plus all associated $Q^2$ dependent radiated partons as in the FFW model is nearly one and the same.) Using the FFF Monte-Carlo, Singer et al.\textsuperscript{90} find that with a global $E_T$ threshold of 10 GeV, in 90% of the events at least 50% of the $E_T$ is carried by the beam and target fragments and that this event fraction decreases only slightly (to 83%) as the threshold $E_T$ is increased to 20 GeV.

Motivated by the above discussion, Figures 4.15a and b show the mean energies in calorimeter rings 1 and 2 (see Fig. 2.2) as a function of $E_T$. Ring 1 covers roughly 23° to 34° in the pp center-of-mass while ring 2 extends from 34° to 46°. In the E609 data, the mean energies of rings 1 and 2 increase by roughly 10 GeV from $E_T=8.5$ GeV to $E_T=13.5$ GeV for ring 1 to $E_T=15.5$ GeV for ring 2 and decrease thereafter. In fact, the average energy in ring 1 is smaller at $E_T$'s greater than 20 GeV than it is at $E_T = 8.5$ GeV. The mean energy in ring 1 from the FF$\nu$W Monte-Carlo follows the rise and fall observed in the data but remains approximately 10 GeV smaller. The FF$\nu$W Monte-Carlo agrees with the data for the mean energy in ring 2 out to $E_T$ of 13.5 GeV, but decreases thereafter whereas the data increases out to 15.5 GeV before beginning to decrease. The slope of the
Figure 4.15a Mean ring 1 energy as a function of calorimeter $E_T$ for low and high $E_T$ threshold E609 global data and for the FFW Monte-Carlo global trigger events. The FFW points labeled global > 16 GeV (open triangles) use the extended $p_T$ range (2 to 8 GeV).
Figure 4.15b Mean ring 2 energy as a function of calorimeter $E_T$ for low and high $E_T$ threshold E609 global data and for the FFW Monte-Carlo global trigger events. The FFW points labeled global $> 16$ GeV (open triangles) use the extended $p_T$ range (2 to 8 GeV).
decrease in mean ring 2 energy is the same for both data and Monte-Carlo with the Monte-Carlo value being roughly 5 GeV smaller. Part of the difference in ring energies between data and Monte-Carlo might be attributed to an overestimation of the shower energy spillover into the beam hole used in the hadronic shower simulator which was 10.5 GeV on average for an $E_T$ threshold of 9.5 GeV.

Assuming (in the context of the FFF four jet model) the energy deposited in rings 1 and 2 comes primarily from hadrons resulting from the hadronization of the beam spectators, we can attempt to comment on the conclusion of Singer et al. that a large and constant fraction of the total calorimeter $E_T$ is carried by the beam and target fragments. Let us assume all the energy in rings 1 and 2 is carried by all the beam fragments. Let us also make the reasonable assumptions that, on average, 60% of the calorimeter $E_T$ (or $E$) has its origin as spectator fragments (Singer et al. find in at least 90% of the events, the fraction is at least 50%) and that of that fraction, 60% is carried by the beam fragments. Using Fig. 4.8, we would estimate the sum of energies in rings 1 and 2 to be 57 GeV at $E_T=8.5$ GeV increasing to 103 GeV at $E_T=14.5$ and 126 GeV at $E_T=20.5$ GeV. At the same $E_T$ values, the observed mean sums of ring 1 plus ring 2 energies are 73, 93, and 69 GeV respectively.
Therefore, the data seem to rule out that a constant or increasing fraction of the total $E_T$ comes from the spectator fragments based on the decrease of the mean ring 1 and ring 2 energies with increasing $E_T$ at the larger $E_T$ values.

On the other hand, the assumptions made in the above argument may have been simplified too much. First, there are certainly beam fragments which are produced at polar angles $> 46^\circ$, approximately the maximum polar angle covered by ring 2. Although the fraction of total calorimeter energy contributed by these larger polar angle fragments might be small, the fraction of total calorimeter $E_T$ they carry could be larger. Second, at high $E_T$, kinematic constraints may indeed force those beam spectator fragments which hit the calorimeter to larger polar angles, where not as much energy is wasted in producing the $E_T$. It could still be that the beam fragments contribute a constant fraction of the total calorimeter $E_T$, just that at higher $E_T$, energy conservation requires the beam hadrons to be produced at larger polar angles which would then also give a smaller energy flow in the more forward directions.

In Figures 4.16a and b the polar angle, $\theta$, in the pp CM frame of all clusters (particles) is shown for both data (solid line) and FFW Monte-Carlo (dashed line) for
Figure 4.16a Angular distribution of all particles for the global trigger with calorimeter $E_T > 9.5$ GeV for the E609 data (solid line) and FFW Monte-Carlo (dashed line).
Figure 4.16b Angular distribution of all particles for the global trigger with calorimeter $E_T > 17$ GeV for the E609 data (solid line) and FFW Monte-Carlo (dashed line).
global $E_T$ thresholds $\geq 9.5$ GeV and 17 GeV respectively. The area under each histogram is proportional to the mean multiplicity for that event sample and $E_T$ threshold. The peaks in the histogram correspond to the centers of the rings into which the calorimeter can be divided and are a side effect of the clustering algorithm which tends to place the position of the particles formed from segment energies in the center of segments. The beam hole of the calorimeter as defined by the multiplicity polar angle flow seems to be approximately 3° larger when using the Monte-Carlo sample. This is possibly due to the fact that the shower simulator which is applied to the generated Monte-Carlo events treats the calorimeter as a two dimensional object at a fixed distance from the target. Other than this inner edge difference, the agreement in the angular distribution is quite good. The smaller multiplicity in the Monte-Carlo does not occur in a particular section in the calorimeter but rather is spread roughly equally over the range of CM angles covered by the calorimeter.

In Figures 4.17a and b the polar angle, $\theta$, in the pp CM frame of all clusters (particles) this time weighted with their energy in that frame is shown for both data (solid line) and FFW Monte-Carlo (dashed line) for global $E_T$ thresholds $\geq 9.5$ GeV and 17 GeV respectively. The
Figure 4.17a Angular distribution of all particles weighted with their energy in the pp CM frame for the global trigger with calorimeter $E_T > 9.5$ GeV for the E609 data (solid line) and FFW Monte-Carlo (dashed line).
Figure 4.17b Angular distribution of all particles weighted with their energy in the pp CM frame for the global trigger with calorimeter $E_T > 17$ GeV for the E609 data (solid line) and FFW Monte-Carlo (dashed line).
area under each histogram is proportional to the mean total calorimeter energy in the pp CM frame for that event sample and $E_T$ threshold. When compared to the data, the entire CM energy flow for the Monte-Carlo sample appears to be shifted by about $3^\circ$ towards larger polar angles. Again, this effect is probably due to an inexact matching between the actual position of the calorimeter and its segments and that used by the shower simulator. The agreement between data and Monte-Carlo is reasonably good. However, especially in the global $E_T$ threshold $\geq$ 17 GeV sample, the FFW Monte-Carlo slightly underestimates the energy flow in the forward direction compared to the E609 data (recall the energies in calorimeter rings 1 and 2 from the Monte-Carlo were too low also). This might indicate problems with the manner in which the beam remnants are treated and hadronized. The Monte-Carlo multiplicity fraction in the forward direction approximately agrees with data but the energy carried by the forward fragments is somewhat too low at large $E_T$.

Continuing on the same tack, in Figures 4.18a and b are histogrammed the multiplicity flow and CM energy flow for E609 data for global $E_T$ thresholds of 9.5 (solid line) and 17 GeV (dashed line). The two histograms in each figure are normalized to the same area. Effectively
Figure 4.18a Angular distribution for all particles for E609 data for the global trigger with calorimeter $E_T > 9.5$ GeV (solid line) and $> 17$ GeV (dashed line).
Figure 4.18b Angular distribution for all particles weighted with their energy in the pp CM frame for E609 data for the global trigger with calorimeter $E_T > 9.5$ GeV (solid line) and $> 17$ GeV (dashed line).
then, what is plotted is multiplicity fraction and CM energy fraction polar angle flow. Both the multiplicity fraction and CM energy fraction for \( \theta < 60^\circ \) decrease as the threshold \( E_T \) is nearly doubled. This seems, too, to rule out a constant or increasing fraction of the total calorimeter \( E_T \) coming from the beam fragments as the calorimeter \( E_T \) is increased. However, as pointed out above, a constant fraction of the calorimeter \( E_T \) contribution from the beam fragments does not necessarily contradict a decrease in the forward energy flow at high \( E_T \). Clearly, a better understanding of the details of the hadronization of the beam and target spectators is needed.

4.5 TWO HIGH ANALYSIS PROCEDURES

Recall that the two high trigger demands that any two calorimeter segments each exceed an \( E_T \) threshold of about 1.3 GeV. A discussion of the \( E_T \) scale factor used for the two high analysis and the difference between cluster and true multiplicity for two high events is found in section 4.3. Approximately half of the E609 two high data was collected with no global \( E_T \) requirement (\( E_T^{\text{peak}} \approx 7.8 \) GeV) while the rest of the two high data was taken with an additional global \( E_T \) requirement of
approximately 11.5 GeV ($E_T^{\text{peak}}$). Most of the two high analysis was performed on the data taken with no global $E_T$ requirement to enhance differences between the two high and global triggers.

Observables such as mean ECAL, BCAL, $E_T$, multiplicity, planarity, and normalized event rate were calculated for each run for two high triggers with no global $E_T$ requirement after applying the cuts discussed below and plotted as a function of time. As was observed with the global trigger data, the run to run variations of the means of these observables was quite small. A total of 8 out of 52 runs (without and with the global $E_T$ requirement) were rejected for having a mean calorimeter $E_T$, ECAL, BCAL, total energy, or normalized event rate which deviated significantly from the average taken over all runs. Typical run by run variations in experimental observables for the two high trigger with no global $E_T$ threshold quoted as $\sigma$/mean were 2% in $E_T$, 2% in ECAL, 3% in BCAL, 2% in cluster multiplicity, 2% in MWPC multiplicity, and 2% in planarity.

The following cuts were applied to the two high data:

1. The $E_T$ of the segment with the highest and second highest $E_T$ was required to be greater than 1.7 and 1.3 GeV respectively. These cuts were approximately 170
MeV above the peak of the $E_T$ distributions for the segment with the highest and second highest $E_T$.

2. The calorimeter $E_{T}^{\text{lab}}$ was required to be $\geq 7$ GeV for the data taken with no global $E_T$ requirement and $\geq 12.5$ GeV for the data taken with the global $E_T$ requirement. The $E_T$ cut in the no global $E_T$ requirement data was needed because the $E_T$ distribution of events generated by the FFW Monte-Carlo is peaked at about 6 GeV and we wish to analyze the data in as identical a manner as possible. The $E_T$ cut in the two high data above a global $E_T$ threshold was taken to be 1 GeV above the peak of the $E_T$ distribution.

3. The momentum imbalance in the event, $P_{TT} = (\sum P_X^i)^2 + (\sum P_Y^i)^2)^1/2$, must be $\leq 4.5$ GeV.

4. The $E_T$ of the highest $E_T$ segment in the calorimeter was required to be $\leq 4$ GeV.

5. The total observed energy ECAL + BCAL must be $\leq 600$ GeV.

6. The event was required to have a vertex within the LH$_2$ target.

The target full and empty vertex distributions for the two high trigger are similar to those shown in Figures 4.6a and b. The vertex cuts used in the two high analysis were slightly looser than in the global analysis since at a given $E_T$ the fraction of non-hydrogen events
was smaller in the two high trigger data (see Figure 4.7).

4.6 E609 AND FFW MONTE-CARLO TWO HIGH TRIGGER RESULTS

To begin the analysis of the two high data, we shall make some comparisons of the basic experimental observables between data and Monte-Carlo as was done in the global analysis. In Figure 4.19 the mean energy flow into the main calorimeter, ECAL, is plotted as a function of calorimeter $E_T$ for the two high trigger. At the smaller $E_T$ values the mean ECAL is approximately 15 GeV greater in the data as compared to the FFW Monte-Carlo, increasing to roughly 40 GeV at $E_T=13.5$ GeV and then decreasing to approximately 15 GeV at the largest $E_T$ values. In fact although, as we shall observe later, the two high and global triggers pick up two different types of events, the mean ECAL as a function of calorimeter $E_T$ is approximately the same for both triggers in the E609 data, but somewhat lower for the two high trigger than for the global trigger in the Monte-Carlo sample.

The ECAL distribution is given by a Gaussian with widths of 58 GeV for the E609 data but only 44 GeV for the FFW Monte-Carlo events. Naturally, which two high
Figure 4.19 Mean main calorimeter energy, ECAL, as a function of calorimeter $E_T$ for E609 and FFW Monte-Carlo two high trigger events with calorimeter $E_T > 7$ GeV. The FFW points labeled 2 high $> 16$ (open squares) use the extended $p_T$ range (2 to 8 GeV).
events are chosen from the input Monte-Carlo events depends heavily on the shower simulator which takes the hadron's energy, smears it according to the measured calorimeter energy resolution, and then spreads that energy into some number of calorimeter segments. The smearing according to the calorimeter energy resolution is modeled well however the spreading of energy into some number of segments is handled roughly by average with only moderate fluctuations. For example, the distribution of the ratio of the energy deposited in the struck calorimeter segment from a single hadronic shower to the total energy deposited in the calorimeter is given by a Gaussian with a mean shown in Figure 2.9. The width of this ratio distribution though is roughly three times greater for the actual measured ratios as compared to that given by the shower simulator. This may somewhat account for the greater difference in the width of the ECAL distribution between E609 data and FFW Monte-Carlo for the two high trigger than found for the global trigger.

In Figure 4.20, the mean energy flow into the beam calorimeter, BCAL, is plotted as a function of calorimeter $E_T$ for the two high trigger. For $E_T < 9.5$ GeV, the mean BCAL is slightly (0-15 GeV) larger in the data than Monte-Carlo. For $E_T > 9.5$ GeV, the mean BCAL becomes
Figure 4.20 Mean beam calorimeter energy, BCAL, as a function of calorimeter $E_T$ for E609 and FFW Monte-Carlo two high trigger events with calorimeter $E_T > 7$ GeV. The FFW points labeled 2 high > 16 (open squares) use the extended $p_T$ range (2 to 8 GeV).
larger in the Monte-Carlo by roughly 20 GeV. The BCAL distribution is Gaussian with widths of 78 GeV in the E609 data and 57 GeV for the Monte-Carlo events. This may reflect the larger fluctuations found in the ECAL distribution in the data since ECAL and BCAL are highly correlated. Compared to the global trigger at a given $E_T$, the two high trigger has higher mean BCAL in both the data and FFW Monte-Carlo with the difference between the two triggers decreasing as $E_T$ is increased.

At $E_T=7.5$ GeV, the mean total energy, equal to the sum of ECAL plus BCAL, is approximately 420 GeV in the E609 data, decreases to approximately 400 GeV at $E_T=12.5$ GeV, and remains at this value thereafter. The total energy of the FFW Monte-Carlo events is independent of $E_T$ at 385 GeV. We feel these differences reflect trigger biases from imperfections in the shower simulator. Also we have assumed that the $E_T$ scale factors for both Monte-Carlo and data are identical when in fact because the Monte-Carlo only roughly approximates the physics of high $E_T$ scattering, they may be slightly different.

The mean cluster multiplicity is plotted in Figure 4.21 as a function of calorimeter $E_T$ for both E609 and FFW Monte-Carlo data. The difference in mean multiplicity between E609 data and Monte-Carlo grows progressively larger from $\sim.6$ at $E_T=7.5$ to $\sim8.5$ at
Figure 4.21 Mean cluster multiplicity as a function of calorimeter $E_T$ for E609 and FFW Monte-Carlo two high trigger events with calorimeter $E_T > 7$ GeV. The FFW points labeled 2 high $> 16$ (open squares) use the extended $p_T$ range (2 to 8 GeV).
$E_T = 19.5$ with the E609 data multiplicity being the greater. As observed with the global trigger, the rate of increase of mean multiplicity with $E_T$ is faster in the data than in the Monte-Carlo events.

At a given $E_T$, in both the E609 data and Monte-Carlo events, the mean multiplicity of global triggers (Figure 4.10) is larger than that chosen by the two high trigger. As a general rule, as the experimenter asks for more calorimeter $E_T$, nature responds by increasing the calorimeter multiplicity. The requirement of two particles to have larger than average $E_T$ obviously reduces the remaining multiplicity needed to make up a given calorimeter $E_T$. Also, it is fairly obvious that increasing the calorimeter $E_T$ for the two high trigger will simply give observables increasingly like those for the global trigger since the fraction of total $E_T$ provided by the two highest particles becomes ever smaller.

The mean planarity for the two high trigger is plotted in Figure 4.22 for both the E609 data and FFW Monte-Carlo events. The mean planarity of the data decreases steadily from .73 at $E_T = 7.5$ GeV to approximately .57 at $E_T = 18.5$ GeV and above this $E_T$ show only a hint of an increase in mean planarity. The mean planarity of the FFW Monte-Carlo events generated with the nominal $p_T$ range (closed squares) is essentially
Figure 4.22 Mean planarity as a function of calorimeter $E_T$ for E609 and FFW Monte-Carlo two high trigger events with calorimeter $E_T > 7$ GeV. The FFW points labeled $2$ high $> 16$ (open squares) use the extended $\phi_L$ range (2 to 8 GeV).
independent of $E_T$ at .75 however increasing the upper limit of $p_T$ to 8. GeV (open squares) gives a mean planarity for $E_T>16.5$ GeV that is flat at about .84.

The decrease in mean planarity in the E609 data as the calorimeter $E_T$ is increased is merely a reflection of the increase in multiplicity with $E_T$. From a plot of the mean planarity as a function of multiplicity for E609 two high triggers with calorimeter $E_T>7$. GeV, we find that the mean planarity decreases from .75 to .55 as the multiplicity is increased from n=11 to n=28, the endpoints of Figure 4.21. Note that this decrease in mean planarity is identical to the one observed in Figure 4.22 which implies a very strong correlation between calorimeter $E_T$ and multiplicity. That the mean planarity remains constant with $E_T$ for FFW Monte-Carlo events in spite of the increase in multiplicity with $E_T$ implies that the additional $E_T$ or multiplicity put into higher $E_T$ events is added in such a manner as to increase the planarity i.e. make them more jetlike.

The planarity distribution for the two trigger with calorimeter $E_T > 7$. GeV for both E609 data (solid curve) and FFW Monte-Carlo (dashed curve) is shown in Figure 4.23. The peak of the planarity distribution is roughly .4 planarity units higher in the Monte-Carlo. In addition, there are a substantial number of events
Figure 4.23 Planarity distribution for the two high trigger with calorimeter $E_T > 7$ GeV for the E609 data (solid line) and FFW Monte-Carlo (dashed line).
tailing down to $P=0$ in the data that are not reproduced by the Monte-Carlo. Only 5.3% of the Monte-Carlo produced two high events have planarity $< .5$ compared to 22.2% found in the E609 data. The FPW Monte-Carlo fails to produce enough dirty or non-jetlike events which are present in the E609 data.

Comparing Figures 4.11 and 4.22, the mean planarity versus calorimeter $E_T$ curves for global and two high triggers, it is clear that, at a given $E_T$, the two high trigger in both the data and Monte-Carlo collects higher planarity (more jetlike) events than does the global trigger. This is also readily observed in Figure 4.24, where the planarity distributions for E609 global (solid curve) and two high events (dashed curve) with calorimeter $E_T > 9.5$ GeV are presented. The two high trigger collects a substantially larger number of high planarity events than does the global trigger. From Figure 4.24, with the two high trigger, 47.3% of the triggered events have planarity $> .7$ compared to only 5.8% of the triggered events using the global trigger.

This is not just a consequence of the lower two high multiplicity at a given $E_T$ either, for examination of the mean planarity as a function of multiplicity plot for the E609 data for both global and two high triggers with $E_T > 9.5$ GeV shows that, at a given multiplicity, the mean
Figure 4.24 Planarity distribution for the global (solid line) and two high (dashed line) triggers with calorimeter $E_T > 9.5$ GeV for the E609 data.
planarity is approximately .22 higher with two high triggered events than with globally triggered events. Therefore it must be that the two highest $E_T$ particles are often produced roughly back to back (even though the two high trigger has no such requirement). Also, as mentioned above, at the very highest $E_T$ values, the planarity means of the global and two high triggers begin to approach one another for both the E609 data and FFW Monte-Carlo events.

A comparison of the mean sphericity as a function of $E_T$ between the E609 data and FFW Monte-Carlo gives the nearly identical result of the comparison of mean planarity versus $E_T$. Namely that the Monte-Carlo events satisfying the two high trigger are somewhat too jetlike compared to the E609 data. A comparison of the mean aplanarity as a function of $E_T$ between the E609 data and FFW Monte-Carlo shows that, in addition to having too low a sphericity, the Monte-Carlo events satisfying the two high trigger are flatter (i.e. have too little momentum flow normal to the event plane).

In Figure 4.25, the aplanarity distribution for the E609 data for both the global (solid curve) and two high trigger (dashed curve) with calorimeter $E_T > 9.5$ GeV is shown. Hence the two high trigger collects not only higher planarity (lower sphericity) events than does the
Figure 4.25 Aplanarity distribution for the global (solid line) and two high (dashed line) triggers with calorimeter $E_T > 9.5$ GeV for the E609 data.
global trigger, it also collects events which are flatter or tend more to lie in a plane.

The cross section $d\sigma/dE_T$ for events satisfying the two high trigger is shown in Figure 4.26 for both the E609 data and FFW Monte-Carlo. The FFW Monte-Carlo underestimates the global $E_T$ cross section for the two high trigger by roughly an order of magnitude at the lower $E_T$ values increasing (the difference) by another factor of 2-3 at the higher $E_T$ values.

In the E609 two high data, the mean ring 1 energy is approximately 30 GeV at $E_T=7.5$ GeV, increases to about 44 GeV at $E_T=11.5$ GeV, and then remains constant at 44 GeV out to $E_T=16.5$ GeV above which it begins to decrease. This is same trend observed in the mean ring 1 energy curve for the E609 global trigger data (Figure 4.15a) where the values of the global triggered mean ring 1 energies are about 8 GeV larger. For the two high triggered Monte-Carlo events, the mean ring 1 energy is independent of $E_T$ at approximately 26 GeV. Recall also from Figure 4.15a, that with the global trigger, the mean ring 1 energy for the FFW Monte-Carlo followed the increase, then decrease, trend of the data whereas with the two high trigger the Monte-Carlo gives a flat curve.

The results for the mean ring 2 energy versus calorimeter $E_T$ are nearly identical. In the E609 two
Figure 4.26 The cross section $d\sigma/dE_T$ for the E609 calorimeter for E609 and FFW Monte-Carlo two high trigger events with calorimeter $E_T > 7$ GeV. The FFW points labeled 2 high > 16 (open squares) use the extended $p_t$ range (2 to 8 GeV).

\[ \text{E609–FFW TWO HIGH COMPARISON} \]

- E609 2 HIGH (1.7,1.3)
- E609 2 HIGH > 12.5
- FFW 2 HIGH (1.7,1.3)
- FFW 2 HIGH > 16.
high data, the mean ring 2 energy is initially 20 GeV at $E_T=7.5$ GeV, increases to 39 GeV at $E_T=15.5$ GeV, and then decreases thereafter. For the FFW Monte-Carlo two high events, the mean ring 2 energy increases slowly from 20 GeV at $E_T=7.5$ GeV to 25 GeV at $E_T=19.5$ GeV. These trends can be compared with those from the global trigger (Figure 4.15b).

In Figure 4.27a the polar angle, $\theta$, in the pp CM frame of all clusters (particles) is shown for both data (solid line) and FFW Monte-Carlo (dashed line) for events satisfying the two high trigger with $E_T \geq 7$. GeV. The area under each histogram is proportional to the mean multiplicity for that event sample. We see that the difference in multiplicity between data and Monte-Carlo is spread roughly equally over the region from 20° to 90° in the pp CM frame.

In Figure 4.27b the polar angle, $\theta$, in the pp CM frame of all clusters (particles) this time weighted with their energy in that frame is shown for both data (solid line) and FFW Monte-Carlo (dashed line) for two high triggered events with $E_T \geq 7$. GeV. The area under each histogram is proportional to the mean total calorimeter energy in the pp CM frame for that event sample. As was observed in the angular distribution weighted with CM energy comparison between data and Monte-Carlo for the
Figure 4.27a Angular distribution of all particles for the two high trigger with calorimeter $E_T > 7$ GeV for the E609 data (solid line) and FFW Monte-Carlo (dashed line).
Figure 4.27b Angular distribution of all particles weighted with their energy in the pp CM frame for the two high trigger with calorimeter $E_T > 7$ GeV for the E609 data (solid line) and FFW Monte-Carlo (dashed line).
global trigger (Figures 4.17a and b), when compared to the data, the entire CM energy flow for the Monte-Carlo sample appears to be shifted by about 3° towards larger polar angles. Again, this effect is probably due to an inexact matching between the actual position of the calorimeter and its segments and that used by the shower simulator. The agreement between data and Monte-Carlo is not quite as good as observed with the global trigger, especially in the region 50°<Ø<70° where too little energy flow in the FFW Monte-Carlo is most noticeable.

In Figures 4.28a and b are histogrammed the angular distribution and angular distribution weighted with CM energy for the E609 data for the global (solid line) and two high (dashed line) events with calorimeter E_T>9.5 GeV. The two histograms in each figure are normalized to the same area. Effectively then, what is plotted is multiplicity fraction and CM energy fraction polar angle flow. In Figure 4.28a, we observe that the angular distribution is identical for the global and two high trigger which is somewhat surprising in view of the very different planarity distributions given by each (Figure 4.24). From Figure 4.28b it is seen that the global triggered events put slightly more energy into the forward (Ø<50°) direction and correspondingly less into the region 50°<Ø<90° than do the two high triggered events.
Figure 4.28a Angular distribution of all particles for the global (solid line) and two high (dashed line) triggers with calorimeter $E_T > 9.5$ GeV for the E609 data.
Figure 4.28b Angular distribution of all particles weighted with their energy in the pp CM frame for the global (solid line) and two high (dashed line) triggers with calorimeter $E_T > 9.5$ GeV for the E609 data.
4.7 JET FINDING RESULTS

The existence of jets at Fermilab energies has been the subject of acrimonious debate. No striking, clean jet signal as was observed at the CERN pp collider (see Figure 1.1) is observed with the global trigger at $\sqrt{s} = 27.4$ GeV (see Figures 1.2, 4.11, and 4.12a,b). The planarity distribution of the two high trigger (see Figures 4.23 and 4.24) though is peaked at roughly $P \sim 0.8$ indicating that this trigger may be a relatively efficient jet trigger. Hence we will use those events in the E609 data and FW Monte-Carlo which satisfy the two high trigger as a source in which to find jets and then proceed to compare the properties of two and three jets found in the data with those found in the Monte-Carlo events.

In the QCD-parton model, a hard scattering between the incoming hadron constituents should result in a four jet structure. A beam and target jet directed along the beam axis result from the fragmentation of the spectator partons and two coplanar jets which balance in transverse momentum result from the fragmentation of the scattered partons. The hadrons associated with each jet exhibit limited transverse momentum with respect to the parton's direction (jet axis) and a flat rapidity distribution
relative to the jet axis. In order to prove the existence of QCD jets, one must first find jets, second show that their characteristics are in qualitative agreement with those expected by say, the QCD-parton model, and finally show that their rate of production is consistent with that predicted by QCD.

Naturally, the last step in proving the existence of QCD jets is the hardest for one must be able e.g. to determine the true $P_T$ of the jet, distinguish the true jet signal from "background", and calculate the detection efficiency. For the purposes of comparing the jetlike events found in the data and FFW Monte-Carlo it is enough to ignore step three and to concentrate on finding jets and observing their structure. It should be noted though that a jet cross section has been extracted from the E609 two high data using the FFP four jet Monte-Carlo to estimate background and trigger efficiency and good agreement with a naive parton level calculation was found. 17,92

The above discussion assumes the validity of the QCD-parton model picture of high $E_T$ hadron-hadron scattering. However, in the framework of the FFW parton shower model and the FW QCD cluster model of fragmentation, the final state at the parton level is comprised of a number of partons of complex configuration which subsequently gives rise to "jets" from the hadronization
of a number of strings. Jets in this picture are no longer the fragments of solely one parton hadronizing, and therefore, except possibly with particular triggers and cuts, is it possible to reconstruct the parton-parton scattering kinematics e.g. the $x$ of the initial state partons or the $p_T$ of the scattered partons. We do not attempt do this for the simple reason that with a multi-parton final state this is clearly impossible. At these energies it is in fact quite difficult to do even assuming the validity of the four jet QCD-parton model e.g. FFF. In the context of the FFW model also, a single jet or two jet cross section is somewhat meaningless, at least in the sense that one would like to compare it with some QCD parton model calculation in lowest order.

A jet finding algorithm was applied to both the E609 and Monte-Carlo data in an effort to (somewhat arbitrarily) identify jetlike structures. We define a jet to be that found by the jet finding algorithm described below. This algorithm was employed previously in the analysis of single particle data from the ISR to identify and study properties of the away side jets. The transverse momentum of the jets found in their data ranged from 1.5 to 5 GeV where only charged particles were detected. This range compares favorably with typical jet $P_T$'s observed in the E609 data.
The jet finding algorithm used in this analysis is based on the idea that jets will appear as groups of large $P_T$ particles correlated in rapidity $y$ and azimuthal angle $\phi$. The associated particles of a jet falling within a cone of half-angle $\alpha$ with respect to the jet axis will be found as a cluster of particles within a circle of radius $\alpha$ in $y-\phi$ space. A surface is formed in $y-\phi$ space (see Figure 4.29) with height at any point given by:

$$G(y, \phi) = \sum p_T^i \exp\left(-\frac{(y-y_i)^2}{2\sigma_y^2} - \frac{(\phi-\phi_i)^2}{2\sigma_\phi^2}\right)$$

where the sum is over the event multiplicity and we have used $\sigma_y = .5$ and $\sigma_\phi = 28.6^\circ$ as used in reference 93. Jets are then isolated and defined by the maxima of this function which exceed some threshold $P_T$.

Briefly, the jet finder first orders the particles (clusters from the clustering algorithm) according to their $P_T$ and considers them in decreasing order. All jet candidates must have at least one particle whose $P_T$ is $\geq G_1 = .6$ GeV/c and whose value of $G(y, \phi)$ at that particle’s position is $\geq G_2 = 1.2$ GeV/c. Next, a gradient search for a maximum or peak is carried out in the region of particles passing these cuts and a jet is found if $G(y_{\text{peak}}, \phi_{\text{peak}})$ is $\geq G_0 = 3$ GeV/c. The jet axis
Figure 4.29 The function $G(y, \phi)$ for a two jet event.
is defined by the position of the peak and the $P_T$ of the jet is taken to be the height. If any of the jets found are separated by less than $\Delta Y = 0.5$ units of rapidity and less than $\Delta \phi = 34.4^\circ$, the second jet found is skipped over. All particles located within the contour at half maximum of $G(Y_{\text{peak}}, \phi_{\text{peak}})$ are taken to be members of the jet.

In Figure 4.30, the mean number of jets with $P_T > 3$ GeV is plotted as a function of calorimeter $E_T$. Obviously, increasing the calorimeter $E_T$ increases the probability of finding jets with $P_T$ greater than some threshold $P_T$. Also as obvious, the number of jets found depends on the $P_T$ cut, $G0$, above which we call a peak in $y-\phi$ space a jet. The $P_T$ cut of 3 GeV is somewhat arbitrary balancing the need for a relatively clean jet signal with the need to increase statistics. In the $E_T$ range $8.5 < E_T < 16.5$ GeV, the mean number of jets is larger in the Monte-Carlo than in the E609 data indicating that the events produced by the Monte-Carlo are more often found to be di-jetlike than in the data. This was our conclusion from the comparisons of the planarity means and distributions between data and Monte-Carlo using the two high trigger (Figures 4.22 and 4.23). Above $E_T = 16.5$ GeV, the mean number of jets in the Monte-Carlo is approximately equal to 2 while in the data, the number is
Figure 4.30 Mean number of jets with jet $P_T$ each $> 3$ GeV found in two high trigger events with $E_T > 7$ GeV as a function of calorimeter $E_T$ for the E609 data and FFW Monte-Carlo. The FFW points labeled 2 high $> 16$ (open squares) use the extended $P_T$ range (2 to 8 GeV).
slightly higher indicating a greater three jet fraction (as defined by the jet finding algorithm).

In Figure 4.31, the fractions of one, two, and three jet events are shown as a function of $E_T$ for both the E609 data and FFW Monte-Carlo. The fraction of two jet events found in the E609 two high data increases from approximately 14% at $E_T = 9.5$ GeV to approximately 73% at $E_T = 15.5$ GeV. Above $E_T = 15.5$ GeV, the two jet fraction in the data is roughly constant at 80% though here we begin to be limited by statistics. The fraction of two jet events produced by the FFW Monte-Carlo is roughly 25 percentage points higher, increasing from 31% at $E_T = 9.5$ GeV to a roughly constant value of > 95% for $E_T > 15.5$ GeV. The three jet fraction in the E609 data becomes nonzero at $E_T = 12.5$ GeV, increases to approximately 13% at $E_T = 16.5$ GeV, and remains at this or possibly a slightly higher fraction at higher $E_T$. The three jet fraction in the FFW Monte-Carlo is roughly constant at 1-2% for $E_T > 13.5$ GeV.

Lego plots are traditionally used in convincing large audiences of the existence of jets so in Figures 4.32a and b two typical two jet events from the E609 two high data are shown. In these lego plots, each particle has coordinates $(\theta \cdot \sin(\phi), \theta \cdot \cos(\phi))$ and is plotted with a height proportional to its $P_T$. (One can think of the
Figure 4.31 The percentage of one, two and three jet events with jet $P_T$ each $> 3$ GeV in the E609 (solid symbols) and FFW Monte-Carlo (open symbols) two high events. The lines are drawn to guide to eye.
Figure 4.32a Typical two jet event with jet $P_T$ each $> 4.5$ GeV from the E609 two high data. The $E_T$ distribution is given versus $\theta^* \cos \phi$ and $\theta^* \sin \phi$ where $\theta$ and $\phi$ are the polar and azimuthal angles respectively.
Figure 4.32b Typical two jet event with jet $P_T$ each $> 4.5$ GeV from the E609 two high data. The $E_T$ distribution is given versus $\theta^* \cos \phi$ and $\theta^* \sin \phi$ where $\theta$ and $\phi$ are the polar and azimuthal angles respectively.
border of the plot as roughly corresponding to the border of the E609 calorimeter.)

We next check that the two jets events as found in the E609 data and FFW Monte-Carlo sample have the characteristics predicted by the QCD-parton model. In Figure 4.33, the difference in azimuthal angle between the two jets, Δφ, is shown for both E609 (solid line) and FFW Monte-Carlo (dashed line) two jet samples. Recall that the jet finding algorithm does not constrain the jets to be back-to-back in azimuthal angle and therefore the peak in the Δφ distribution at ~180° is evidence that the jets as defined by our jet finding algorithm are indeed QCD jets. It is also true for both E609 and FFW Monte-Carlo two jet events that as the average p_T of the jet pair is increased, the width of the Δφ distribution decreases which is consistent with QCD-parton model expectations. In Figure 4.33 it is also seen that the width of the Δφ distribution is slightly narrower for the FFW Monte-Carlo two jet events indicating that events produced by the Monte-Carlo are slightly too clean or do not possess enough "background" as found in the real data.

Again, even though the jet finding algorithm does not require it, the two jet events in both the data (solid line) and Monte-Carlo (dashed line) show approximate p_T balance as shown in Figure 4.34 in agreement with
Figure 4.33 Distribution of $|\phi_{\text{jet 1}} - \phi_{\text{jet 2}}|$ for two jet events with jet $P_T$ each $> 3$ GeV from the E609 (solid line) and FFW Monte-Carlo (dashed line) two high events.
Figure 4.34 Distribution of \(|p_T^{\text{jet 1}} - p_T^{\text{jet 2}}|\) for two jet events with jet \(p_T\) each \(> 3\) GeV from the E609 (solid line) and FFW Monte-Carlo (dashed line) two high events.
QCD-parton model predictions. Good agreement in the absolute value of the difference in $P_T$ between the two jets is found between the E609 data and FFW Monte-Carlo two jet samples.

To compare the multiplicity flows of the E609 and FFW Monte-Carlo two jet events, we first define $\Delta R_i = (\phi_{\text{jet}} - \phi_i)^2 + (y_{\text{jet}} - y_i)^2)^{1/2}$ where $\phi_{\text{jet}}$ and $y_{\text{jet}}$ are the azimuthal angle and rapidity of the highest $P_T$ jet. (Recall that a cluster of particles within some cone about the jet axis will appear as a group of particles in $y-\phi$ space with the radius of the group being related to the tightness of the cone angle.) In Figure 4.35, the distance $\Delta R_i$ is histogrammed for each particle in the E609 and FFW Monte-Carlo two jet samples. The area under each histogram is proportional to the mean multiplicity found for that two jet sample (19.0 in the E609 data and 15.5 in the FFW Monte-Carlo). Two clusters of particles corresponding to the highest and away side $P_T$ jets are clearly visible. The mean multiplicity per jet agrees between the E609 data and FFW Monte-Carlo two jet samples (5.1 versus 4.8) and therefore as seen in Figure 4.35, the extra multiplicity found in the E609 (solid line) two jet events compared to those from the Monte-Carlo (dashed line) lie outside the jet 'cones'. So again we have clearly shown that the events produced by the Monte-Carlo
Figure 4.35 Distribution of $\Delta R_i = (\phi_{\text{jet} 1} - \phi_i)^2 + (\gamma_{\text{jet} 1} - \gamma_i)^2)^{1/2}$ for two jet events with jet $P_T$ each $> 3$ GeV from the E609 (solid line) and FFW Monte-Carlo (dashed line) two high events.
are much cleaner than those observed in the E609 data. There is an excess of particles found outside the regions of the two jets that is not mimiced by the Monte-Carlo.

The two jet events produced by the Monte-Carlo are also more coplanar than those found in the E609 data. In Figure 4.36, the $P_{out}$ distributions, where $P_{out}$ is the momentum perpendicular to the plane defined by the beam momentum vector and the vector of the highest $P_T$ jet, are compared for E609 (solid line) and FFW Monte-Carlo (dashed line) two jet events. Following reference 5, we have calculated $P_{out}$ by adding the $|P_{out}|$ of all particles not belonging to the highest $P_T$ jet. The $P_{out}$ distribution from the Monte-Carlo two jet sample has a peak approximately 1.5 GeV lower and a narrower width than the distribution from the data indicating again that the Monte-Carlo events are too clean and too di-jetlike.

One last significant difference between the two jet events found in the E609 data and those produced by the FFW Monte-Carlo is in their angular distribution as shown in Figure 4.37. For Figure 4.37, the polar angle for each jet for all two jet events is histogrammed with the areas under each curve being identical. Clearly at pp CM polar angles $< 70^\circ$ the Monte-Carlo (dashed line) does not match the jet production of the data (solid line). One explanation of this difference in forward jet
Figure 4.36 Distribution of $P_{\text{out}}$ for two jet events with jet $P_T$ each $> 3$ GeV from the E609 (solid line) and FFW Monte-Carlo (dashed line) two high events.
Figure 4.37 Distribution of the polar angle $\theta$ of each jet for two jet events with jet $P_T \geq 3$ GeV from the E609 (solid line) and FFW Monte-Carlo (dashed line) two high events.
production is that the FFW Monte-Carlo does not properly describe the hadronization of the spectator partons. In the data, some fraction of found jets, especially those at forward angles, may not be jets from the hard scattered partons but rather large energy hadrons associated with the fragmentation of the beam remnant parton which hit the calorimeter. If the beam fragmentation in the FFW Monte-Carlo were too soft, for example, then the number of jets found by the jet finding algorithm in the forward direction would be too small.

Three jet events due to hard gluon bremsstrahlung have been clearly observed in hadronic $e^+e^-$ events\textsuperscript{66,67,68} and are a successful prediction of perturbative QCD\textsuperscript{95,96}. Their energy and angular distributions support their origin as resulting from the process $e^+e^-\rightarrow q\bar{q}g$\textsuperscript{66,67,68,97} and the two to three jet ratio has been used to determine $\alpha_s$\textsuperscript{98,99,100}. Three jet events have also been seen at the CERN $\bar{p}p$ collider\textsuperscript{5,7,69} and the three jet angular distributions are in qualitative agreement with leading order QCD predictions\textsuperscript{69}. There is some evidence that three jet events have also been observed at the ISR\textsuperscript{68,101} though the signal is not as clean as at the $e^+e^-$ machines or at the collider.

In applying the jet finding algorithm to those E609 events satisfying the two high trigger, three jets events
with $p_{\text{jet}}^T \geq 3$. GeV are indeed found, with the fraction of three jet events being slightly greater than 10% above $E_T = 16.5$ GeV (Figure 4.31). Lego plots of two events which show a clean three jet topology are shown in Figures 4.38a and b. Of course not all of the three jet events chosen by the jet finder are this clean. Lego plots of all 90 three jet events culled from both the calorimeter $E_T$ cut = 7. and 12.5 GeV two high event samples were scanned by eye by three physicists and roughly 50% showed a clear three jet structure using purely subjective criteria.

In Figure 4.39, the mean planarity for all E609 two high events, for those two high events with two jets of $p_T > 2.75$ GeV, and for those two high events with three jets of $p_T > 2.75$ GeV is plotted as a function of calorimeter $E_T$. The mean planarity for E609 two jet events roughly follows the curve for all two high events but with a higher mean value of planarity, especially at the lowest and highest $E_T$ values. The mean planarity for E609 three jet events is roughly flat at $\sim 0.41$ clearly showing they do not resemble two jet events.

The mean cluster multiplicity as a function of calorimeter $E_T$ for E609 two and three jet events fairly follows that for all two high events (shown in Fig. 4.21) except at the very lowest $E_T$ values where the mean
Figure 4.38a Clean three jet event with jet $P_T$ each $> 3$ GeV from the E609 two high data. The $E_T$ distribution is given versus $\theta^* \cos \phi$ and $\theta^* \sin \phi$ where $\theta$ and $\phi$ are the polar and azimuthal angles respectively.
Figure 4.38b Clean three jet event with jet $P_T$ each $> 3$ GeV from the E609 two high data. The $E_T$ distribution is given versus $\theta \cdot \cos \phi$ and $\theta \cdot \sin \phi$ where $\theta$ and $\phi$ are the polar and azimuthal angles respectively.
Figure 4.39 Mean planarity as a function of calorimeter 
$E_T$ for all two high events and for two and three jet 
events with jet $p_T$ each $> 2.75$ GeV from the E609 data.
two jet multiplicity is slightly lower. The fact that the mean three jet multiplicity is not significantly higher than the mean multiplicity for all two high events or for two jet events argues against the three jet origin as being simply fluctuations in the particle distributions of high multiplicity minimum bias events. The mean beam calorimeter energy as a function of calorimeter $E_T$ for E609 two and three jet events again follows that for all two high events (shown in Fig. 4.20) except at the very lowest $E_T$ where the two jet mean beam calorimeter energy is slightly larger. The fact that the mean three jet beam calorimeter energy is not significantly lower than for all two high events or for two jet events argues against the source of three jet events as being true two jet events in which the third jet arises from energetic beam parton fragments hitting the calorimeter.

In order to find some distribution in which a three jet signal might be distinguished, we return to the three dimensional momentum tensor defined above in equation (4.1) where $\alpha, \beta = X, Y, \text{and} Z$. The eigenvectors $\mathbf{q}_3$, $\mathbf{q}_2$, and $\mathbf{q}_1$ of the momentum tensor are the principal axes of the momentum ellipsoid and if their corresponding normalized eigenvalues are ordered such that $Q_3 > Q_2 > Q_1$ then the event plane defined by $\mathbf{q}_3$ and $\mathbf{q}_2$ has a normal direction in which the sum of the squares of momentum components is
minimized. (In the parton-parton CM frame, the momentum vectors of the three jets are planar.)

We next find for each event the projections of all particle and jet momenta onto this plane. In Figure 4.40a, the difference in angle, $\Delta \phi^i$, between the projected particle momenta and the projection of the highest $P_T$ jet vector weighted with the pp CM energies of the particles is histogrammed (solid line) for all three jet events with jet $P_T$ each $\geq 3$ GeV. Also in Figure 4.40a is shown the same distribution for all two jet events (dashed line). Each histogram has been normalized to the same number of events and in both histograms the first and last bins in $\Delta \phi^i$ have been suppressed. The two jet $\Delta \phi^i$ distribution weighted with $E^*_i$ shows a narrow clustering of particles at $\Delta \phi^i=0^\circ/360^\circ$ and a second broader clustering at $\Delta \phi^i=180^\circ$ in agreement with the QCD-parton model picture of two coplanar jets. The three jet $\Delta \phi^i$ distribution weighted with $E^*_i$ however shows the same narrow clustering of particles at $\Delta \phi^i=0^\circ/360^\circ$ but two broader clusterings at roughly $\Delta \phi^i\sim 120^\circ$ and $260^\circ$ which is consistent with three well separated QCD jets.

The three jet signal is admittedly weak however if the source of the three jet events as chosen by the jet finding algorithm were only fluctuations of particle distributions of true two jet events, then we would
Figure 4.40a Difference in azimuthal angle in the $\vec{q}_3 - \vec{q}_2$ plane, $\Delta \phi^i$, between all particles and the highest $P_T$ jet for three (solid line) and two (dashed line) jet events with jet $P_T$ each $\geq$ 3 GeV from the E609 two high trigger data.
expect the three jet $\Delta \phi^i$ distribution weighted with $E_i^*$ summed over all events to look similar to the distribution for two jets (dashed line in Fig. 4.40a). If, on the other hand, the source of three jet events were only fluctuations of particle distributions of high multiplicity isotropic events, then we would expect the distribution to look roughly flat.

Distributions similar to those in Figure 4.40a are also observed if, working now in the plane transverse to the beam direction, $\Delta \phi^i$ is taken to be the difference in azimuthal angle with respect to the $\phi$ of the highest $P_T$ jet and weighted with the $E_T$ of each particle.

The $\Delta \phi^i$ distribution weighted with $E_i^*$ is shown in 4.40b for FPW Monte-Carlo two (dashed line) and three (solid line) jet events (using jet $P_T = 2.75$ GeV to increase statistics) selected from the two high trigger sample. The distributions are similar to those observed in the data however the small number of three jet events found in the Monte-Carlo (16) does not really allow any conclusions based on the comparison of the two distributions to be drawn.

Unfortunately, the statistics of the Monte-Carlo three jet events also precludes an analysis of their underlying parton structure as a function of calorimeter $E_T$ and comparison to the same for Monte-Carlo two jet
Figure 4.40b Difference in azimuthal angle in the $q_3-q_2$ plane, $\Delta \phi^i$, between all particles and the highest $P_T$ jet for three (solid line) and two (dashed line) jet events with jet $P_T$ each $> 2.75$ GeV from the FFW Monte-Carlo two high trigger events.
events. However, examination of the parton level of all three jet events with jet $P_T > 2.9$ GeV shows that all events do indeed contain at least one hard parton (with $p_{\text{parton}} \sim 3$ GeV), which could be radiated from either an initial or final state parton, in addition to the two hard scattered partons. A typical three jet event produced by the FFW Monte-Carlo and its underlying parton structure are shown in Figures 4.41a and b. It is also interesting that no three jet events as defined by the jet finder are found in those Monte-Carlo events satisfying the two high trigger which have a total of only four underlying partons (two scattered partons plus beam and target holes). This is evidence that the jet finder picks events which truly are the result of a hard bremsstrahlung rather than being fluctuations in the fragmentation of QCD-parton model two jet events.

4.8 PARTON LEVEL RESULTS

To investigate the parton substructure chosen or favored by large solid angle global $E_T$ triggers and two high triggers, it is convenient to label the partons according to their origin in the evolution of the parton shower. As in section 3.7, we define an initial state parton as a radiated parton from either of the incoming
Figure 4.41a Typical three jet event with jet $P_T$ each $\geq 2.9$ GeV at the hadron level from the FFW Monte-Carlo two high trigger events. The $E_T$ distribution is given versus $\theta^* \cos \phi$ and $\theta^* \sin \phi$ where $\theta$ and $\phi$ are the polar and azimuthal angles respectively.
Figure 4.4lb  Typical three jet event with jet $P_T$ each > 2.9 GeV at the parton level from the FFW Monte-Carlo two high trigger events. The $E_T$ distribution is given versus $\theta^* \cos \phi$ and $\theta^* \sin \phi$ where $\theta$ and $\phi$ are the polar and azimuthal angles respectively.
spacelike partons which eventually hard scatter, and do not include the beam or target holes (the spectator partons). Final state partons are the two scattered outgoing partons and their associated radiations. Finally, when we refer to a calorimeter parton we mean a parton which would have struck the E609 calorimeter if hadronization had not occurred.

In Figure 4.42a the mean number of partons (≥4) produced in the shower is shown as a function of calorimeter $E_T$ for both the global and two high triggers. In Figures 4.42b and 4.42c, the mean number of initial state and final state partons generated are shown also as a function of calorimeter $E_T$ for both triggers. In all figures, the points labeled global > 16 GeV and two high > 16 GeV are from the Monte-Carlo sample generated over the larger $P_T$ range (2 to 8 GeV) which required a calorimeter $E_T$ of at least 15 GeV in addition to satisfying either the global or two high trigger conditions.

We see then that the underlying parton substructure of an average FFW Monte-Carlo global event at $E_T$=8.5 GeV is composed of the 2 spectator partons, .9 initial state partons, and 3.1 final state partons for a total of 6. At $E_T$=14.5 GeV, for global events, the mean number of initial state partons increases to 1.1 and the mean number of final state partons increases to 3.6. Above $E_T$~14
Figure 4.42a Mean number of partons produced in FFW Monte-Carlo events satisfying the global and two high triggers as a function of (hadron) calorimeter $E_T$. The points for $E_T \geq 16.5$ GeV use the extended $p_T$ range (2 to 8 GeV).
Figure 4.42b Mean number of initial state partons produced in FFW Monte-Carlo events satisfying the global and two high triggers as a function of (hadron) calorimeter $E_T$. The points for $E_T \geq 16.5$ GeV use the extended $p_T$ range (2 to 8 GeV).
Figure 4.42c Mean number of final state partons produced in FFW Monte-Carlo events satisfying the global and two high triggers as a function of (hadron) calorimeter $E_T$. The points for $E_T \geq 16.5$ GeV use the extended $p_T$ range (2 to 8 GeV).
GeV, the mean number of initial state partons appears to decrease slightly, falling to \(-0.7\) at the highest \(E_T\) values, while the mean number of final state partons continues to increase slowly, reaching \(\sim 3.9\) at the highest \(E_T\) values. (For \(E_T \geq 16.5\) GeV, we take the mean to be the average of all data points above \(E_T = 16.5\) GeV from the Monte-Carlo sample with the larger \(p_T\) range.)

The underlying parton substructure of FFW Monte-Carlo two high events as a function of calorimeter \(E_T\) is approximately the same as for global trigger events although the means are slightly lower. The mean numbers of initial state partons selected with the two high trigger are \(0.8, 1.0\), and \(-0.7\) at \(E_T\)'s of \(8.5, 14.5\), and \(\geq 16.5\) GeV while the mean numbers of final state partons at those \(E_T\)'s are \(2.8, 3.4\), and \(4.0\).

Note that although the event structures chosen by the global and two high triggers are quite different at the lower \(E_T\)'s (see the Monte-Carlo curves in Figures 4.12a and 4.23) the underlying parton levels for each trigger are nearly identical, at least in the number of partons produced. Also, it is a matter of preference whether or not the \(-1\) initial state radiation and \(-1.5\) final state radiations selected with the global (or, for that matter, two high) trigger constitute an "anomalously large amount" of gluon bremsstrahlung.
If one chooses instead to count the number of calorimeter partons, the curves in Figs. 4.42a-c would be displaced downwards with the shapes essentially un-changed. For both triggers and averaged over all $E_T$'s, the mean number of calorimeter partons is approximately 2.8 partons smaller than the mean total number of partons. This number reflects the 2 spectator partons, ~0.3 initial state partons, and ~0.5 final state partons which, on average, miss the E609 calorimeter.

In Figure 4.43, the mean $p_T$ as a function of calorimeter $E_T$ is shown for both the global and two high triggers. The lines in the figure connect the data points from the nominal $p_T$ range sample (2 to 6.5 GeV) ≤ 15.5 GeV with those generated with the extended $p_T$ range (2 to 8 GeV) ≥ 16.5 GeV and are meant to guide the eye. A comparison of the mean $p_T$'s above 16.5 GeV of the samples generated using the nominal and extended $p_T$ ranges shows clearly why the nominal upper limit of 6.5 GeV needed to be increased. At the highest $E_T$ values the upper limit needs perhaps to be as high as 10 or 12 GeV but computer time considerations prevent extension to higher limits. Below $E_T=10.5$ GeV, the mean $p_T$ for the global trigger increases more slowly with $E_T$ that at higher values of $E_T$ which is due to the lower cutoff in
Figure 4.43 Mean $p_t$ of the hard scatter as a function of (hadron) calorimeter $E_T$ for FFW events satisfying the global and two high triggers. The points for $E_T \geq 16.5$ GeV use the extended $p_t$ range (2 to 8 GeV).
\( p_t \) of 2 GeV; at these \( E_T \)'s these is an additional contribution from smaller \( p_t \)'s which is not sampled.

Below \( E_T \sim 14 \) GeV, the mean \( p_t \) selected by the two high trigger is over 1 GeV larger than that selected by the global trigger. Above \( E_T \sim 14 \) GeV, the difference in mean \( p_t \) between two high and global triggers begins to decrease becoming \( \sim 4 \)GeV at the highest \( E_T \) values. The harder parton-parton scattering selected by the two high trigger partially accounts for the smaller cross section of the two high trigger compared to the global trigger.

The mean total calorimeter parton \( E_T \) is plotted in Figure 4.44 as a function of the calorimeter hadron \( E_T \) for both the global and two high triggers. Again, the lines on the figures are simply to guide the eye and above \( E_T = 16.5 \) GeV, the data points from the extended \( p_t \) range are used. For the global trigger, the difference between the mean hadron and parton level calorimeter \( E_T \) is roughly 3.5 GeV independent of the calorimeter \( E_T \); while for the two high trigger, the difference steadily increases from approximately 1.6 GeV at \( E_T = 8.5 \) GeV to roughly 2.6 GeV at the highest \( E_T \) values.

The difference between the mean hadron and parton level \( E_T \) comes from hadronization effects. First, \( E_T \) is not a conserved quantity and therefore hadronizing a single parton into many hadrons can effectively increase
Figure 4.44 Mean total calorimeter parton $E_T$ as a function of (hadron) calorimeter $E_T$ for FFW events satisfying the global and two high triggers. The points for $E_T \geq 16.5$ GeV use the extended $p_T$ range (2 to 8 GeV).
the observed $E_T$. Second, because of the flat rapidity
distribution of the hadrons in a jet with respect to the
jet axis, many fragments of the hadronization can hit the
calorimeter (e.g. fragments of the beam and target par-
tons) even though the partons themselves do not. In a
given $E_T$ range, the distribution of hadron level $E_T$
parton level $E_T$ (called ETDIF) is roughly Gaussian. For
example, for the global trigger in the $E_T$ range $10 \leq E_T \leq 11$
GeV, only roughly 6% of the events have ETDIF $\leq 0.4$ GeV
while the same percentage of events has ETDIF $\geq 7.2$ GeV.

In Figures 4.45a and b, the mean initial state
calorimeter parton $E_T$ and mean final state calorimeter
parton $E_T$ are presented as a function of the total ob-
served (hadron) calorimeter $E_T$ for both the global and
two high triggers. For the global trigger, the mean initial
state calorimeter parton $E_T$ increases from $\sim 0.6$ GeV
at $E_T = 8.5$ GeV to $\sim 1.2$ GeV at $E_T = 14.5$. The mean initial
state calorimeter parton $E_T$ for $E_T \geq 16.5$ GeV is roughly
0.7 GeV where we have taken the average of all points in
this $E_T$ range from the Monte-Carlo sample generated with
the extended $p_T$ range. Similarly for the two high
trigger, the mean initial state calorimeter parton $E_T$ in-
creases from $\sim 0.4$ GeV at $E_T = 8.5$ GeV to $\sim 1.0$ GeV at
$E_T = 14.5$ GeV and then falls to $\sim 0.8$ GeV for $E_T \geq 16.5$ GeV.

We see then that for both the global and two high
Figure 4.45a Mean initial state calorimeter parton $E_T$ as a function of (hadron) calorimeter $E_T$ for FFW events satisfying the global and two high triggers. The points for $E_T \geq 16.5$ GeV use the extended $p_T$ range (2 to 8 GeV).
Figure 4.45b Mean final state calorimeter parton $E_T$ as a function of (hadron) calorimeter $E_T$ for FFW events satisfying the global and two high triggers. The points for $E_T \geq 16.5$ GeV use the extended $p_T$ range (2 to 8 GeV).
triggers, the amount of $E_T$ carried by the initial state calorimeter partons is not very large, being on the order of 0.5-1.0 GeV. It is hard to see how such a small amount of $E_T$ could be important in determining the event structure or cross section of globally triggered events. This conclusion was also reached by Odorico\textsuperscript{102} who used a similar QCD Monte-Carlo which included both initial and final state gluon bremsstrahlung\textsuperscript{74}.

Recall once again that both the FFW Monte-Carlo predictions and the experimental data show that at the lower $E_T$'s (say $E_T<14$ GeV), the global and two high triggers select quite different event structures (see Figures 4.12a and 4.23). Moreover, Field and Fox have stated that global triggers are biased towards the emission of a large number of gluons, especially initial state gluons, and that the non-jetlike structure of the final state hadrons chosen with the global trigger can be understood in terms of this large amount of gluon bremsstrahlung\textsuperscript{47}.

Although the mean fraction of calorimeter parton $E_T$ carried by the initial state calorimeter partons is higher for the global trigger compared to the two high trigger (approximately 12\% versus 7\%, independent of calorimeter $E_T$) the mean number of initial state calorimeter partons and the mean $E_T$ they carry are in fact identical for both triggers. (Roughly independent of $E_T$, the mean number of
initial state calorimeter partons is 0.1 lower and the mean $E_T$ they carry 0.2 GeV lower for the two high trigger compared to the global trigger.) Since the mean number of initial state calorimeter partons and the mean $E_T$ they carry are the same for both global and two high triggers and yet each trigger selects quite different event shapes, we conclude that initial state gluon bremsstrahlung is not responsible for the non-jetlike event structure of globally triggered events.

Because, for a given calorimeter $E_T$, the difference in the mean initial state calorimeter parton $E_T$ between global and two high triggers is small, then clearly the difference in the mean final state calorimeter parton $E_T$ (Figure 4.45b) between the two triggers accounts for nearly all the difference in the mean total calorimeter parton $E_T$ (Figure 4.44) as a function of $E_T$. Furthermore, from the mean $p_T$ versus $E_T$ curves for the global and two high triggers (Figure 4.43) we see that most of the difference in the mean final state calorimeter parton $E_T$ between the two triggers is due to the difference in mean $p_T$. Therefore, although the global and two high triggers select very different event structures at the hadron level, the only real difference in the parton level substructure between the global and two high triggers is that the two high trigger chooses higher $p_T$. 
hard scatters (by roughly 1 GeV) than does the global trigger.

This by itself is not enough to account for the very different event shapes of the final state hadrons chosen by the two triggers. For example, the mean $\bar{p}_t$ chosen with the two high trigger at $E_T = 10.5$ GeV is 3.8 GeV (compared to 2.8 GeV with the global trigger) and the mean planarity of two high events at this $E_T$ is approximately .81. For the global trigger, a mean $\bar{p}_t$ of 3.8 GeV requires a calorimeter $E_T$ of ~13.2 GeV but the mean planarity at this $E_T$ is only ~.57. Therefore, we conclude that because the only real difference in the parton level substructure between global and two high triggers is in the $\bar{p}_t$ of the hard scatter and because the hadron level event structures for a given mean $\bar{p}_t$ can still be quite different, the effects of hadronization are the most important factor in determining the hadron level event structure of any trigger.

In Figure 4.46 the parton $x$ is shown as a function of calorimeter $E_T$ for both the global and two high triggers. As expected from the linear increase with $E_T$ of $\bar{p}_t$ for both triggers, $x$ increases linearly with $E_T$ and, at a given $E_T$, is greater for the two high trigger compared to the global trigger due to the higher $\bar{p}_t$ selected with the two high trigger.
Figure 4.46 Mean parton $x$ as a function of (hadron) calorimeter $E_T$ for FFW events satisfying the global and two high triggers. The points for $E_T \geq 16.5$ GeV use the extended $p_T$ range (2 to 8 GeV).
In Figure 4.47 the parton primordial transverse momentum, $k_T$, is shown as a function of calorimeter $E_T$ for both the global and two high triggers. The primordial transverse momentum chosen by the both triggers is independent of $E_T$ and equals roughly 750 MeV, the mean of the $k_T$ distribution used in the generation of Monte-Carlo events. This shows there are no trigger bias effects associated with $k_T$ with either the global or two high triggers.

Finally, we examine the underlying subprocesses most favored by the global and two high triggers. For the FFW Monte-Carlo events satisfying the global trigger with $E_T \geq 9.5$ GeV, $\sim 50\%$ of the events have as the underlying subprocess $qq$-$gg$ while $\sim 39\%$ of the events originate from $gg$-$gg$. Increasing the global $E_T$ threshold to 17. GeV, we find the $qq$-$gg$ subprocess dominates, being favored $\sim 60\%$ of the time, while the $gg$-$gg$ subprocess is chosen $\sim 13\%$ of the time. For two high triggers with calorimeter $E_T \geq 9.5$ GeV, the subprocess $qq$-$gg$ again dominates, underlying $\sim 60\%$ of the events, while the subprocesses $q_1q_2$-$q_1q_2$, $q_1q_1$-$q_1q_1$, and $gg$-$gg$ are found with fractions $\sim 14\%$, $\sim 13\%$, and $\sim 11\%$ respectively.
Figure 4.47 Mean parton primordial \( k_T \) as a function of (hadron) calorimeter \( E_T \) for FFW events satisfying the global and two high triggers. The points for \( E_T \geq 16.5 \) GeV use the extended \( p_T \) range (2 to 8 GeV).
CHAPTER 5
CONCLUSIONS

We have studied the production of high transverse energy events in 400 GeV/c pp collisions triggered with a full azimuthal, large solid calorimeter. For two different geometrically unbiased triggers, one a global trigger and the other a relatively efficient jet trigger, a detailed comparison was made between the E609 experimental data and the Field-Fox-Wolfram Monte-Carlo which includes both initial and final state gluon bremsstrahlung.

The goal of this work was to see if the addition of gluon bremsstrahlung to the usual four jet picture of the QCD-parton model could reproduce various features of E609 high $E_T$ pp data. Certainly the parton shower method and QCD cluster model for hadronization are theoretically superior to the QCD-parton four jet model a la Feynman-Field-Fox. The question remains, though, are these theoretical improvements as implemented in the Field-Fox Wolfram Monte-Carlo sufficient to describe high $E_T$ hadron-hadron scattering at say, Fermilab energies? Results reported by the NAS collaboration showing that the FFF four jet Monte-Carlo could not reproduce the cross section and event structure of their global data
and published predictions from Field and Fox which found that the addition of initial and final state radiation could indeed give a good description of the NA5 global data provided the motivation for this study.

We have found, however, that the Field-Fox-Wolfram Monte-Carlo does not in fact agree with the NA5 global cross section nor, at large $E_T$, describe the structure of globally triggered events. It should also be noted that a recent calculation with the FFF four jet Monte-Carlo gives good agreement with the NA5 and E609 global trigger data. This seems to imply that the effects of other components of these QCD Monte-Carlos, such as the hadronization of the final state partons, especially the beam and target spectator partons, dominate the Monte-Carlo predictions at these lower energies and overshadow any effects due to gluon bremsstrahlung.

As we have mentioned above, one explanation for the large cross section and non-jetlike structure of globally triggered events is due to trigger biases involving the production of final and especially initial state gluon bremsstrahlung. This picture was partly supported by the Monte-Carlo predictions of Field and Fox which gave good agreement with NA5 data. Our work shows that when the proper NA5 trigger is employed, the FFW Monte-Carlo underestimates the NA5 global cross section by slightly
over an order of magnitude. In addition, imposing energy conservation on the final state hadrons suppresses gluon bremsstrahlung, especially initial state gluon bremsstrahlung, thus decreasing the predicted cross section further by a factor of 2. The effects of requiring overall energy conservation on the final state hadrons are important ones and a phenomenologically correct model of hadronization which inherently conserves energy and momentum would be a welcome addition to the parton shower generator.

The E609 global data confirms the structure of high $E_T$ events selected with large aperture, full azimuthal calorimeter triggers first observed by NA5. The global trigger selects events with large (20-30) calorimeter multiplicity and low (~4) planarity. Increasing the calorimeter $E_T$ picks up events with increasingly higher multiplicity but the same (~4) planarity, even out to $E_T$ values over 20 GeV.

Upon comparing the E609 global trigger data with FFW Monte-Carlo events satisfying identical triggering conditions, we find that Monte-Carlo prediction for the mean calorimeter multiplicity is too low by 20-30% and that for $E_T>$12 GeV, the prediction for planarity is too high, increasingly so as the calorimeter $E_T$ is increased. The global cross section for the E609 calorimeter as given by
the FFW Monte-Carlo is over an order of magnitude too small compared to that observed in the E609 data. At the higher $E_T$ values, the FFW Monte-Carlo slightly underestimates the energy flow in the forward direction.

Comparing the energy flow into the calorimeter at low and high $E_T$ values in the E609 data, we find that the fraction of total energy in the forward direction in the pp CM frame is smaller at the higher $E_T$ values. This possibly rules out that a constant or increasing fraction of the total calorimeter $E_T$ is contributed by the fragments of the beam (spectator) partons, which are thought to be responsible for the non-jetlike structure of globally triggered events\textsuperscript{90,102}. Other work using the FFF four jet Monte-Carlo has in fact shown that the fraction of calorimeter $E_T$ for the E609 global trigger contributed by the target remnant fragments is constant with $E_T$ at $\sim 20\%$ while the fraction of $E_T$ contributed by the beam remnant partons decreases from $\sim 30\%$ at $E_T=8.5$ GeV to $23\%$ at $E_T=18.5$ GeV\textsuperscript{103}.

Even with the inclusion of initial and final state gluon bremsstrahlung to the usual leading order 2–2 subprocesses, the FFW Monte-Carlo does not reproduce either the cross section or non-jetlike structure of globally triggered events. We conclude that at FNAL and the lower ISR energies the importance of gluon bremsstrahlung in
determining the cross section or event structure of the global trigger is minimal. We feel effects from the evolution and hadronization of the beam and target spectator partons are much more important in understanding the high $E_T$ production mechanism and are not adequately described in the FFW Monte-Carlo.

The global trigger has a large $E_T$ cross section and does not exhibit jetlike structures because of a sizable contribution to the total calorimeter $E_T$ from fragments of the beam and target spectator parton hadronizations which are collected by the calorimeter. Global triggers are biased towards collecting these fragments for they increase the calorimeter $E_T$ without increasing the $p_T$ of the hard scatter. The fraction of the total calorimeter $E_T$ carried by the beam and target spectator fragments only slowly decreases with $E_T$ thus obscuring the two jet signal from the hard scattered partons even at the highest $E_T$ values. The fact that at these energies the density in $y-\phi$ space at these energies is roughly the same for the beam and target fragments as for the jets from the hard scattered partons further obscures the two jet signal in global triggers. These ideas are not new, having been put forward by Singer et al. and Odorico previously.

We have shown that the two high trigger is a
geometrically unbiased trigger which for $E_T > 7$ GeV is a relatively efficient trigger in picking up two jet structures (i.e. in selecting high planarity events). Compared to the E609 two high trigger data, the FFW Monte-Carlo predictions again show too low a mean multiplicity and too high a mean planarity, with the differences being accentuated as the calorimeter $E_T$ is increased. The cross section $d\sigma/dE_T$ for events satisfying the two high trigger is roughly an order of magnitude too small in the Monte-Carlo as found in the E609 data. The FFW Monte-Carlo underestimates the energy flow in the forward direction compared to the data even slightly more so than with the global trigger.

Two jet events with jet $P_T$ each $\geq 3$ GeV are clearly observed in the E609 data when using the two high trigger. For $E_T > 7$ GeV, the fraction of two jet events (as defined by a jet finding algorithm) in the two high data increases with $E_T$ until reaching a constant value of $\sim 80\%$ for $E_T > 16$ GeV. These two jet events exhibit the properties one expects from the QCD-parton model for high $P_T$ hadron-hadron scattering; namely, they are coplanar, approximately balance in $P_T$, and are composed of a group of particles correlated in $y$ and $\phi$.

Two jet events are also found in the Monte-Carlo though with a somewhat higher fraction. In addition, the
two jet events produced by the FFW Monte-Carlo are too clean, i.e. they have too few particles outside the region of the two jets as observed in the E609 data. That the FFW Monte-Carlo two jet events are too jetlike compared to those in the data is also seen in the smaller $P_{\text{out}}$ distribution predicted by the Monte-Carlo. Finally, a significant fraction of the jets found in the E609 data are found at forward scattering angles indicating possible contamination from the beam spectator parton fragments. The FFW Monte-Carlo, on the other hand, finds a much smaller number in the forward region. The differences in the structure and angular distribution of two jet events from the FFW Monte-Carlo compared to those found in the E609 data are further evidence that the FFW Monte-Carlo underestimates the effects of the beam and target spectator parton hadronization.

Three jet events are observed in the E609 data. The fraction of clean three jet events in the two high trigger data is roughly 5%. A lower fraction (1-2%) of three jet events is predicted by the FFW Monte-Carlo. In the plane that maximizes the momentum flow, the distribution in azimuthal angle for the three jet events shows evidence for three clusters of particles which is not found when looking at purely two jet events. Also there is some evidence that suggests that the origin of the
three jet events is not due simply to fluctuations in the particle distributions of high multiplicity events.

We find little difference in the number of partons produced with the global and two high triggers in spite of the fact they favor very different event structures. In particular, the number of initial state gluon radiations and the $E_T$ they carry are roughly equal for both triggers. This implies that initial state gluon bremsstrahlung effects are not responsible for the non-jetlike nature of globally triggered events. Furthermore, the fraction of calorimeter parton $E_T$ carried by initial state calorimeter partons is only slightly greater than 10%. Such a small amount of $E_T$ mostly likely has little effect on the global cross section and event structure and leads to the conclusion that gluon bremsstrahlung effects are only minimally important in understanding the production of large $E_T$ in hadron hadron collisions. This conclusion has also been reached by Odorico. At these energies, the underlying parton structure does not greatly influence the event structure observed at the hadron level.

Repeating a point from above, because the older FFF four jet Monte-Carlo gives as good or better agreement with the E609 data as the FFW Monte-Carlo, we conclude that hadronization effects, especially those associated
with the beam and target spectator partons are primarily responsible for the structures chosen with different triggers. Future effort must be put into better understanding the physics of the hadronization process, especially the evolution and fragmentation of the spectator partons. These must be solved or better parameterized before more detailed questions on the dynamics of high $E_T$ and jet production in hadron-hadron collisions at both the hadron and parton levels can be answered.
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