INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI
A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700  800/521-0600
RICE UNIVERSITY

EXPERIMENTAL OBSERVATION OF THE PHOTON STRUCTURE FUNCTION AT $\sqrt{s}$ 21 GeV

by

GREGORY P. MORROW

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

DOCTOR OF PHILOSOPHY

APPROVED, THESIS COMMITTEE:

[Signature]
Marjorie D. Corcoran
Professor of Physics, Director

[Signature]
Gordon Mutchler
Professor of Physics

[Signature]
Curt Michel
Professor of Space Physics and Astronomy

Houston, Texas
April, 1998
Experimental Observation of the Photon

Structure Function at $\sqrt{s}$ 21 GeV

by

Gregory P. Morrow

Abstract

The triggered photon structure function at center-of-mass energy 21 GeV is measured from the interaction $\gamma p \rightarrow \text{jets}$. Descriptions of the experimental apparatuses are given and the physics goals of the experiment are discussed.

The methods used to calculate the photon structure function $x_\gamma$, are discussed in detail, with particular attention given to Monte Carlo simulation. The energy of the photon beam is carefully analyzed and methods of understanding and compensating for multiple bremsstrahlung photons, among other beam effects, are determined.

Results from experimental data are compared with theoretical predictions from both leading-order and next-to-leading-order calculations and with the results of another experiment. Some examination of other targets and other beam energies is made. We observe substantial disagreement between data and lowest order Monte Carlo. Experimental results are more consistent with NLO calculations. No experimental separation of direct and resolved photons is observed or predicted by calculation.
Acknowledgements

My thanks go out to everyone who contributed to this dissertation, and my plea for forgiveness to anyone I leave out, but I want to keep this short and sweet. This document could not have been started were it not for the tremendous amount of work done by my predecessors and colleagues.

My greatest thanks are to my advisor, Marj Corcoran, who is tremendously inspirational in her drive, her knowledge, and most importantly, her leadership. Marj works twice as hard with four times the results. The most self-evident fact I know is that E683 would be nothing without her.

The rest of E683 was no less influential, both the senior physicists from all the institutions and the graduate students who labored so hard to make everything make sense so that my work would be simple. I won’t waste your time with a list of names we’ve all seen on transparencies at a dozen conferences, but you all mattered a great deal and what I’ve accomplished is a miniscule part of a greater whole.

My thanks also go out to Gordon Mutchler, an expert at asking questions that force me to understand what I do. I got the ranges right on the graphs this time, Gordon.

I am greatly indebted to Jeff Owens for the material in Section 4.3. He and his students did the work and I just turned the crank.

I could not have accomplished anything were it not for the love and support of my family and the divertissements of my friends.
# Contents

1 Introduction .................................................. 1
   1.1 An Overview of the Physics of Experiment 683 ............... 1
   1.2 The Components of Experiment 683 .......................... 4
      1.2.1 The Beamline ......................................... 4
      1.2.2 Experimental Apparatus ............................... 7
      1.2.3 The Main Calorimeter ................................ 9
   1.3 Triggering ................................................ 10

2 Jet Physics and $x_\gamma$ .................................... 13
   2.1 The Definition of $x_\gamma$ ................................. 15
   2.2 Expectations for $x_\gamma$ ................................ 17
   2.3 Other Measurements of $x_\gamma$ ............................ 17
      2.3.1 Zeus .................................................. 17
      2.3.2 Next-to-Leading Order Theory .......................... 19

3 Methods of Analysis ......................................... 20
   3.1 The Data .................................................. 20
3.2 The $\theta - \phi$ Jetfinder ........................................ 22
3.3 Data Selection Criteria ........................................... 27
3.4 Monte Carlo Simulation ............................................ 30
   3.4.1 Lund Monte Carlos Used ....................................... 30
   3.4.2 Adding the Beam Monte Carlo .................................. 35
3.5 Measuring Photon Energy .......................................... 39
   3.5.1 Resolution of Measured Photon Energy ........................ 39
   3.5.2 The Missing Energy Cut ....................................... 46
   3.5.3 The BCAL EM Correction ...................................... 48
   3.5.4 Revisiting Photon Energy Resolution .......................... 51
3.6 Comparison of Full Monte Carlo and Data ........................ 53

4 Results and Conclusion ............................................. 64
   4.1 Monte Carlo Prediction of $x_\gamma$ ............................. 64
      4.1.1 Resolution of $x_\gamma$ .................................... 72
   4.2 Experimental Measurement of $x_\gamma$ .......................... 75
   4.3 NLO Monte Carlo .................................................... 77
   4.4 Other Targets ....................................................... 83
   4.5 Dependence of $x_\gamma$ at higher energies ...................... 91
   4.6 Conclusions ......................................................... 91

A Tracking ............................................................. 98
   A.1 Algorithm ............................................................ 101
      A.1.1 Hit Resolution ................................................. 101
A.1.2 Track Candidate Identification ......................... 103
A.1.3 Arbitration among Track Candidates ..................... 105
A.2 Results .................................................. 108

B Smearing Matrix .............................................. 114
## List of Figures

1.1 Lowest-order Feynmann diagrams for direct coupling .................................. 2  
1.2 Lowest-order Feynmann diagrams for resolved coupling ............................ 3  
1.3 Next-to-lowest order Feynmann diagrams .................................................. 3  
1.4 Primary beam conversion ............................................................................ 6  
1.5 Electron beam creation ............................................................................... 6  
1.6 Electron and photon beam tagging .............................................................. 6  
1.7 E683 experimental setup. ............................................................................ 8  
1.8 Front face of the calorimeter ...................................................................... 11  
2.1 Cartoon of $\gamma p \rightarrow$ jets ..................................................................... 16  
3.1 A typical high-$E_\perp$ dijet event ................................................................. 23  
3.2 $\Delta E$ for jets perpendicular to the beam axis. ........................................ 24  
3.3 $\Delta E$ for forward jets. .............................................................................. 25  
3.4 $x_\gamma$ for two jetfinders ........................................................................... 26  
3.5 BCAL EM energy with and without pileup ................................................ 28  
3.6 Monte Carlo cross-section .......................................................................... 31  
3.7 The effect of the parton matching cut .......................................................... 34
4.6 $x_{\gamma}$ at the jet level plotted versus $x_{\gamma}$ at the parton level ......................... 71
4.7 Resolution of $x_{\gamma}$ relative to parton level .................................................. 73
4.8 Resolution of $x_{\gamma}$ relative to parton level for monochromatic beam ............ 74
4.9 Resolution of $x_{\gamma}$ relative to parton level without beam correction .......... 75
4.10 $x_{\gamma}$ as observed in data. ................................................................. 76
4.11 NLO sensitivity to $Q^2$ scale factor ......................................................... 78
4.12 NLO sensitivity to coalescence radius ...................................................... 79
4.13 LO and NLO predictions for parton-level $x_{\gamma}$ ........................................... 81
4.14 $x_{\gamma}$ from data compared with smeared NLO prediction ............................. 82
4.15 Comparison of lowest order predictions from two models. .......................... 84
4.16 Comparison of smeared lowest order and NLO predictions. .......................... 85
4.17 $x_{\gamma}$ as observed in data on nuclear targets. .......................................... 86
4.18 $x_{\gamma}$ as observed in data on nuclear targets. .......................................... 87
4.19 $E_\perp$ flow for different targets ............................................................. 89
4.20 $x_{\gamma}$ results from hydrogen, deuterium, and empty targets ..................... 90
4.21 $x_{\gamma}$ variation with increasing beam energy ......................................... 92
4.22 $x_{\gamma}$ variation with increasing beam energy in Monte Carlo ................... 93
4.23 $E_\perp$ spectra with increasing beam energy ............................................. 94

A.1 A typical tracked event ................................................................. 109
A.2 Number of tracks in vertex ................................................................. 110
A.3 $d^2$ of vertices ............................................................... 110
A.4 X position of vertex ................................................................. 111
A.5 Z vertex, hydrogen and nuclear targets ........................................... 111
List of Tables

3.1 Targets ........................................ 21
3.2 Data statistics ................................. 21
3.3 Monte Carlo cross-sections ................. 32
A.1 PWC Characteristics .......................... 99
A.2 Upstream DC Characteristics ............... 99
A.3 Downstream DC Characteristics ............. 100
A.4 Chamber resolutions .......................... 113
B.1 Raw smearing matrix, part 1 .................. 115
B.2 Raw smearing matrix, part 2 ................. 116
B.3 Normalized smearing matrix, part 1 ......... 117
B.4 Normalized smearing matrix, part 2 ......... 118
B.5 Normalized smearing matrix, part 3 ......... 119
Chapter 1

Introduction

This document will demonstrate the measurement of a triggered photon structure function at several values of $\sqrt{s}$.

1.1 An Overview of the Physics of Experiment 683

Fermilab experiment 683 was a fixed-target experiment studying $\gamma p \rightarrow$ jets. The advantage in using a photon beam over conventional hadronic beams in high-$P_T$ jet production is the direct coupling of the photon in lowest order. In hadron beam experiments, one valence or sea parton of the beam particle interacts with one valence or sea parton of the target particle. The momentum of the interacting parton from the beam is determined by the structure function of the beam particle, and is a fraction of the momentum of the beam particle. The non-interacting “spectator” partons of both the beam and target form soft jets, the so-called “underlying event” which accompanies the high-$P_T$ jets. In photon beam experiments, however, the entire photon can couple directly to the target quarks, with two great benefits: the entire four-momentum of the beam is absorbed in the event, and there
are no spectator partons from the beam to contribute to the underlying event. In fixed target experiments, the target jet is backwards in the center of momentum frame, creating very soft background in the lab frame. Photoproduction of jets is thus expected to produce a clean jet signal from direct coupling.

Figure 1.1 shows lowest-order ($\alpha\alpha_s$) diagrams at the parton level for direct coupling. These diagrams have been fully calculated to second order for E683.[17] Both of them produce one soft target jet and two high-$P_T$ jets in the final state at the lowest order. QCD Compton scattering, $\gamma q \rightarrow q g$, is the QCD analog to the familiar $\gamma e \rightarrow \gamma e$ with a gluon jet in the final state instead of a reradiated photon. Photon-gluon fusion, $\gamma g \rightarrow q \bar{q}$, is an interaction with the gluons of the target particle. QCD Compton is calculated to dominate all other processes in the cross-section at $P_T > 5$ GeV at $\sqrt{s} = 19.4$ GeV [1].

Four-jet processes (order $\alpha\alpha_s^2$) also occur due to the parton structure function of the photon. In these resolved coupling processes, the photon virtually produces a $q\bar{q}$ pair. Partons from this vector meson-like object can couple to partons from the target particle via...
Figure 1.2: Typical lowest-order Feynmann diagrams for resolved coupling processes. Crosses and s-channels are not shown. Color flow on quark lines is arbitrary.

Figure 1.3: (a) One of the lowest-order resolved diagrams. (b) A typical next-to-lowest order direct process diagram. "Hard" indicates high-$p_T$ partons.

typical QCD interactions, e.g. $\gamma q \rightarrow q\bar{q}q\rightarrow$ jets, with two of the quarks in the intermediate state exchanging a high-$P_T$ gluon. Figure 1.2 shows typical diagrams of this sort.

However, the distinction between these two general classes of processes disappears at higher order, where the diagrams share topologies whose kinematics smoothly converge. Figure 1.3 demonstrates this by showing a lowest-order resolved diagram and a higher-order direct diagram, both of which have a soft target jet, two high-$p_T$ jets, and a fourth soft jet. Both diagrams are order $\alpha\alpha_s^2$.

E683 offers many opportunities to do interesting physics, beyond the simple photoproduction of jets. The beamline can be configured to transport pions instead of photons, so
that $\gamma p$ can be compared to $p p$ with the exact same systematics. A variety of targets can be used to study nuclear effects, e.g. the Cronin effect:

$$\frac{\sigma(pA)}{\sigma(pp)} \propto A^\alpha$$

with $\alpha > 1$, where one would naively expect $\alpha = 1$ for hard parton-parton interactions in the absence of multiple scattering in the nucleus [2].

The particular physics objectives of E683 include:

- Demonstration of photoproduction of jets.
- Measurement of $\gamma p$ cross-sections as a function of various kinematic variables.
- Measurement of the photon structure function, with resolution of direct and resolved coupling.
- Observation of higher-twist processes $\gamma q \rightarrow Mq$, where $M$ is an isolated meson[3].
- Study of $A$-dependence, such as the Cronin effect.
- Comparison of $\gamma p$ and $p p$ interactions.

1.2 The Components of Experiment 683

1.2.1 The Beamline

E683 was performed at Fermi National Accelerator Laboratory, near Batavia, Illinois. E683 was the successor to a previous experiment in jet production, E609, also at Fermilab, which used proton and pion beams incident upon a fixed target.

E683, however, was located upon Fermilab’s Wide Band Photon beamline, the highest energy tagged photon beam in the world. Figures 1.4–1.6 sketch some elements of the
beamline. The Fermilab Tevatron primary beam, which is set to 800 GeV protons during fixed target running, was incident upon a liquid deuterium target, producing a variety of hadronic debris. The charged debris was swept into beam dumps, while the neutral particles continued forward. At this point, the beam consisted mainly of photons from the decay of $\pi^0$s with a significant contamination of neutrons and neutral kaons.

The neutral beam was then incident upon a lead radiator. The photons pair-produced, and a tuneable spectrum of electrons was swept into the beam transport system. Most of the hadronic neutral particles of the beam did not interact in the lead target, and were directed into a neutral dump. There was, however, a small hadronic content, mostly $\pi^-$, in the electron beam. While the Wide Band beam had the capacity to transport the positron component of the beam, this capacity was not used; the positron beam had too much hadronic contamination. During photon running, the beam transport system was set to accept 350 GeV electrons, with an RMS acceptance of 15% around that value.

The high-energy electrons then passed through a tagging system comprised of five planes of silicon microstrips and two dipole magnets. With the strength of the magnets known, a track fitted to hits in the silicon strips can have its momentum calculated from the bending angle with an uncertainty of 2%.

The electrons were then incident upon a radiator, generally 20% of a radiation length of lead. Bremsstrahlung photons produced in the radiator continued forward while another set of dipole magnets swept the electrons and any other charged debris into a Recoil Electron Shower Hodoscope (the RESH), which measured the energy of the recoil electrons. Simple subtraction would then give the energy lost by an electron, and thus the energy of any
Figure 1.4: Diagram of beam elements in conversion of Fermilab primary beam to a beam of neutral particles in the Wide Band Photon beamline.

Figure 1.5: Diagram of beam elements in conversion of neutral beam to electrons in the Wide Band Photon beamline.

Figure 1.6: Diagram of beam elements in tagging of electrons and photon production in the Wide Band Photon beamline.
photons\textsuperscript{1} radiated by that electron.

The $\pi^-$ contamination in the electron beam can be used as a productive beam for studying $\pi p \rightarrow$ jets. In order to do this, the electron beam must be eliminated by putting in a thick lead radiator upstream of the tagging system. The pions pass through the radiator largely unscathed and are tagged by the tagging system. Then the final lead radiator is taken out of the beamline and the sweeper magnets are turned off.

One additional beamline device of particular interest to experimenters was the pileup monitor, which determined when electrons were present in RF buckets near the one of interest. This device consisted of two layers of five scintillator paddles, whose output was fed into TDCs and latches.

1.2.2 Experimental Apparatus

Figure 1.7 shows the experimental setup of E683. Wide Band Experimental Hall contained two experiments. E687 occupied the upstream position. Beam particles reaching E683 had to pass through E687 material amounting to approximately 23\% of a radiation length. The upstream boundary of E683 is set by the hadron shield, three meters' thick of reclaimed battleship armor, with an 8'' square hole along the beam line. The hadron shield was used to remove any hadronic debris from the upstream experiment.

On the upstream side of the hadron shield, counter C1, a 9''\times9'' scintillator paddle, was mounted over the beam hole. On the downstream side of the wall, a muon hodoscope was mounted, consisting of an X and a Y layer of scintillator paddles, with an area which projected over more than the entire face of the main calorimeter, excluding the beam hole.

\textsuperscript{1}Note that the experimental setup is unable to differentiate multiple-photon radiation from single-photon radiation, leading to possible uncertainties in the energy of the photon which actually interacts in the E683 target. This will be elaborated on later.
Figure 1.7: E683 experimental setup.
The purpose of the hodoscope is to act as a muon veto in data acquisition, since muons can mimic high-$P_T$ triggers by producing energetic delta rays in the calorimeter [4]. Also mounted on the downstream side of the muon wall, over the beam hole, were counters B1 and B2, 1" and 9" square respectively.

Downstream of the hodoscope was the target tent. During data acquisition, a rotating wheel of solid targets was alternated with a cryogenic target filled with either liquid hydrogen or liquid deuterium. Downstream of the target was counter C2. In the E683 main trigger, the combination ($\overline{C1} + \overline{B2}$). C2 was used to veto charge going into the target and require charge coming out. Next downstream were sets of proportional wire chambers (PWCs) and drift chambers (DCs), using for tracking purposes. A spectroscopic magnet separated the DCs into upstream and downstream sets. Appendix A has more detail about the tracking that could be done with E683 wire chambers.

The two final devices in E683 were the calorimeters. The main calorimeter (MCAL) will be described more fully below. Details of its construction and initial testing can be found in [5,6]. The beam calorimeter (BCAL) is a four-layer, dual-readout sampling iron calorimeter, with coverage from $0^\circ$ to $20^\circ$ in the CM frame. Details of its design and construction can be found in [7].

### 1.2.3 The Main Calorimeter

The calorimeter is divided into 528 modules, in four layers and 132 towers. The whole structure is contained within six “supermodules”. The calorimeter is divided into right and left halves, each half containing 66 towers. The layers are named from front to back: AP, $A'$, or A-Prime; A; B; and C. The AP and A layers of one group of 66 towers are located in
one supermodule, while the B and C layers each occupy their own supermodules, for three
on a side and six total.

In this geometry, with a beam momentum of 250 GeV/c, the MCAL had complete
coverage in the CM frame from 20° to 100°, with partial coverage out to 120°.

The 132 MCAL towers come in four sizes. In the front layers, modules are 2x4, 4x4, 6x6,
or 8x8, measured in inches. Towers are numbered as seen in Figure 1.8. Modules get larger
in the back layers. This is done so that each module in a tower will cover approximately
the same solid angle with respect to the fixed target used in the experiment. In this way,
the shower resulting from an incident particle will be contained in as few towers as possible.

The calorimeter has been extensively calibrated[8]. Its resolution has been measured to
be 35%/√E for electromagnetic showers and 80%/√E for hadronic showers.

1.3 Triggering

E683's data acquisition system was operated by the E683 μVax utilizing a CAMAC driver
for the electronics. The μVax waited for a master gate signal from the electronics, at which
point it collected information from all reporting electronic devices. When processing, a
busy signal was issued which inhibited the production of further master gates. When free
to process, the μVax reset the busy signal. Events, consisting of this collected information,
were stored, using the Fermilab standard storage format, on 9-track magnetic tape. Some
events were also passed to the cluster partner of the μVax, a Vax 3200, and were used for
online monitoring. The software used to control the data acquisition system was developed
and maintained by the Fermilab Computer Division and E683 personnel Don Lincoln and
John Marraffino.
Figure 1.8: Front face of the calorimeter, with tower numbering convention.
Generating the master gate, or triggering, consisted of two different stages. The pretrigger was the combination of counters mentioned above, $(\overline{C1} + \overline{B2}) \cdot C2$. Once the pretrigger was established, the analog signals from the MCAL towers were summed and weighted by $\sin \theta$ by custom electronics to produce an analog measure of $E_\perp$.

Trigger logic electronics were configured to look for various forms of high-$E_\perp$ signals. The simplest was the global trigger. If the scalar sum of transverse energy exceeded $\sim 6$ GeV, the full trigger was fired. Offline software cuts require global $E_\perp$ of 8 GeV in order to avoid hardware threshold effects. The two-high trigger could be satisfied if two individual towers had $E_\perp \geq \sim .6$ GeV. As with the global trigger, offline software cuts push this to .75 GeV to avoid threshold effects. The two kinds of trigger are largely redundant; most events pass both, particularly after software cuts.

In addition to high-$E_\perp$ physics events, a variety of other events were also recorded. Triggers based on signals from C2, the RESH, and the BCAL, which were heavily prescaled, were used to help monitor flux. A separate trigger was used to monitor MCAL gain using flashing LEDs within individual modules.
Chapter 2

Jet Physics and $x_\gamma$

Much as Rutherford’s scattering of alpha particles off gold atoms revealed the existence of the nucleus, deep inelastic scattering has demonstrated the existence of quarks and gluons, collectively known as partons, within hadrons. However, the fragmentation of a hadron does not proceed as one might naively expect, due to the peculiar self-attractive nature of the color field. In a scattering which transfers a large four-momentum to a constituent parton, the parton escaping the hadron trails behind it a color tube, which binds more and more energy until the tube fragments into quark-anti-quark pairs. The products of this fragmentation hadronize into color-neutral objects, mostly light mesons, which are nearly collinear.

A jet is comprised, in theoretical terms, of the resulting stream of particles. Jet four-momentum is taken to be the sum of the four-momenta of its components and construed to closely reflect the kinematics of the parent parton. Thus, jets are used as the real-world expression of parton interactions which are directly unobservable due to color confinement.

Jets were first observed by Hanson et al.[9] working with the $e^+e^-$ collider at SLAC,
using topological variables to demonstrate an abrupt shift in event structure with increasing center-of-mass energy. Similar results focusing on the production of high-$p_T$ particles followed at ISR[10]. By the time of the Cern $p\bar{p}$ collider, the UA1 and UA2 collaborations were able to confirm jets produced by purely hadronic processes.[11,12]

The use of jets to do experimental parton physics is not as clean as one would hope. At the lowest level, hadronization disrupts the correspondence between jet momenta and parton momenta, with jets accreting an invariant mass from the sum of their constituents that is at best ill-defined for the original parton, for example. The jet formation model described above also does not allow for color tube interactions with both the color field of the remnant partons and the color tubes of other deconfined partons. Cross-talk here further muddles the identification of the jet with its parent parton.

Of even more importance is the difference between the theoretical and experimental definitions of jets. In the real world, there are no tags on particles identifying which parton they came from (indeed, as above, there may not be a unique definition of their parent). Although collinearity of particle and parent momenta improves as parton $p_T$ increases, nonetheless, particles may be produced at a considerable angle from the originating axis. When the softer products of remnant partons are added to the mix, it becomes increasingly difficult to unambiguously assign particles to jets. This lead to an experimental (and recursive) definition of a jet as the set of all particles within a cone around the jet axis, with the result that an experimenter is forced to accept that jets will include some inappropriate particles and exclude appropriate ones.

The experimenter is also forced to expend considerable effort tuning the algorithm for finding jets to limit the effects outlined above and maximize the correspondence of jets to
parent partons. This itself demands a thorough understanding of how partons form jets, which requires a thorough study of jet production, ad ourobourus.

2.1 The Definition of $x_\gamma$

Keeping in mind these limitations, it is still possible to do physics using jets. As mentioned earlier, the study of high-$p_T$ photon-hadron interaction is traditionally, and somewhat arbitrarily, taken to come in two forms, direct and resolved.¹ A signature difference between these two types of processes is the four-momentum contribution of the photon to a hard scatter. In direct events, the photon is expected to contribute all of its four-momentum to the event, while in resolved events, there is some structure function determining the distribution of four-momenta found among the hadronic content of the photon.

Figure 2.1 illustrates the $2 \rightarrow 2$ scatter between parton constituents of photon and proton. Fractions of their four-momenta (1 and 2) collide, producing partons (3 and 4) which hadronize into jets. In such a kinematically simple situation, it is trivial to reconstruct the initial state from the final state, e.g.,

$$E_1 = \frac{E_3(1 + \cos \theta_3) + E_4(1 + \cos \theta_4)}{2},$$

$$E_2 = \frac{E_3(1 - \cos \theta_3) + E_4(1 - \cos \theta_4)}{2}.$$

Naturally, this formulation assumes that the contributions of the photon and proton are anticollinear, which is not strictly true. The extra transverse momentum is called $K_\perp$. Sources of $K_\perp$ include uncertainty-scale fluctuations of the momenta of the partons in the beam and target particles as well as initial and final state gluon radiation. Primordial $K_\perp$ is

¹The bulk of the photon-hadron cross-section is low-$p_T$ interactions, well-described by the vector dominance model, which treats the photon as if its interactions mimicked a vector meson.
typically small compared to the magnitude of the $E_\perp$ of jets and is comparable in size to the error in measuring jet $E_\perp$, so this complication is considered part of the systematic error. However, gluon radiation can have a significant contribution. Generally, $K_\perp$ is a difficult issue, especially for theoretical predictions. The amount of $K_\perp$ in a reaction affects the cross-section significantly as well as the ability of an event to pass high-$E_\perp$ thresholds. As will be discussed later, our data show evidence of considerable $K_\perp$.

It is therefore trivial to define $x_\gamma = 2E_1/E_{CM}$ and $x_p = 2E_2/E_{CM}$.

We use the two highest $p_\perp$ jets to determine $x_\gamma$. As discussed later, jetfinding usually only reconstructs two jets, so there is no ambiguity. Because of $K_\perp$ in the Monte Carlo simulation of the interaction, the jets may not correspond to what the Monte Carlo considers the “scattered” partons. This is an artifact of how the Monte Carlo assembles the event and does not introduce a bias into the simulation.
2.2 Expectations for $x_\gamma$

The structure functions of the proton are well-understood and, in general, favor small values of $x_p$.

In general, the direct photon will couple completely to an event with an effective $x_\gamma$ of 1.0. Higher order effects such as soft gluon radiation will tend to decrease this. Since $x_p$ is typically small, kinematic considerations alone suggest that direct photon events will be forward in the CM frame.

The quasi-hadronic resolved photon will distribute its four-momenta among its constituent hadrons in a manner similar to any meson. However, since the hadronic nature of the photon is virtual, the expectation is that the photon will not be completely “dressed”, i.e., that there will not be a full complement of gluons and sea quarks around the virtual valence quarks, and therefore that the structure function will be generally harder than that found for mesons[13]. Relatively smaller $x_\gamma$ suggests that events will be situated further backward in the CM frame relative to direct photon events.

2.3 Other Measurements of $x_\gamma$

2.3.1 Zeus

The Zeus detector, at the Hera $e^+p$ collider, is the only other major experiment to make measurements of this variable. References [15,16] give more detail, but, essentially, the Hera collider is midway between fixed-target and collider experiments, operating at $\sqrt{s} \approx 300$ GeV but in a reference frame displaced from the lab and from the center-of-mass. Zeus is a polar-asymmetric detector otherwise of the familiar collider type.
E683 has several advantages over Zeus. Our major advantage is that our beamline delivers real photons, whereas Zeus can only look at quasi-real photons by putting a cut on the $Q^2$ exchanged between the positron and proton. Similarly, E683 can measure the photon energy directly and accurately, whereas Zeus is forced to reconstruct the CM of the photon-proton system by identifying the scattered beam particle and interpreting the rest of the calorimeter signal as energy from the photon-proton interaction. This requires the energy scale of the calorimeter to be very well known (often the major source of systematic error in precision measurements at collider experiments), and the assumption that minimal energy escapes the calorimeter up or down the beam pipes.

However, Zeus has compensating advantages over E683. Primarily, high CM energy allows Zeus to probe low $z_\gamma$, while the high-$E_\perp$ jets associated with high CM energy are better collimated than low-$E_\perp$ jets. In addition, the nearly complete coverage of the $4\pi$ calorimeter improves the accuracy of reconstruction. (This latter point is expanded on in a later section.)

Zeus reports measurements of $z_\gamma$ consistent with the lowest order interpretation of direct and resolved coupling. The earlier citation ([15]) reports experimental observation of both a resolved peak and a direct peak. However, the later citation ([16]), using more rigorous cuts that have the effect of suppressing low-$z_\gamma$, does not observe two separate peaks, although the results are still completely consistent with Monte Carlo; the contributions from direct and resolved processes overlap in part of their range.
2.3.2 Next-to-Leading Order Theory

Jeff Owens of Florida State University was the first to note the useful properties of photon interaction with hadronic matter[1] and still continues to investigate the phenomenon. In collaboration with others, he has performed calculations out to the full order $\alpha\alpha_s^2$ for both resolved and direct contributions and applied them to Monte Carlos designed to simulate E683 and Zeus kinematics.

Preliminary results for E683 kinematics can be found in [17]. We have been able to recreate these results using Owens' Monte Carlo. They conform to expectations in having the largest difference being the smearing out of the direct peak by higher-order effects. This topic is discussed in greater detail in a later section.

Brian Harris, who is Owens' student, and Owens have issued a preprint in which they apply next-to-leading order calculations to Zeus kinematics.[18] Although this paper does not contain a prediction for $x_{\gamma}$, it does agree quite well with various cross-section measurements.
Chapter 3

Methods of Analysis

3.1 The Data

Approximately one million triggered events with minimal jetfinding\(^1\) were taken with photon beam. Of these, some 25% were on a liquid hydrogen target and 45% were on liquid deuterium. 2.5% were on the target vessel when it was empty of liquid and contained only cold gas. The rest were on nuclear targets. The target wheel was set to rotate one-eighth turn a minute so that each target would spend a spill in the beam in turn. One position on the wheel was empty for purposes of controlling systematics. Information about the targets is specified in 3.1. Table 3.2 gives statistics for data from each target.\(^2\)

Slightly more than 75,000 triggered events with minimal jetfinding were taken using a pion beam incident on the various targets. See [20]–[22] for more on the pion beam.

\(^1\)One jet of only 2 GeV \(E_\perp\).

\(^2\)I would be remiss in not noting at this point that certain difficulties in early analysis of data from target 2 have caused it to be colloquially known as “the evil tin target”.

20
<table>
<thead>
<tr>
<th>Target</th>
<th>Target Number</th>
<th>A (g/mol)</th>
<th>z (cm)</th>
<th>$X_0$ (cm)</th>
<th>$\rho$ (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH$_2$</td>
<td>-</td>
<td>1.01</td>
<td>50.8</td>
<td>865</td>
<td>0.0708</td>
</tr>
<tr>
<td>LD$_2$</td>
<td>-</td>
<td>2.01</td>
<td>50.8</td>
<td>757</td>
<td>0.162</td>
</tr>
<tr>
<td>Be</td>
<td>5</td>
<td>9.01</td>
<td>2.54</td>
<td>35.3</td>
<td>1.848</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>12.01</td>
<td>2.54</td>
<td>18.8</td>
<td>1.72</td>
</tr>
<tr>
<td>Al</td>
<td>3</td>
<td>26.98</td>
<td>2.07</td>
<td>8.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Cu</td>
<td>4</td>
<td>63.55</td>
<td>0.612</td>
<td>1.43</td>
<td>8.96</td>
</tr>
<tr>
<td>Sn</td>
<td>2</td>
<td>118.69</td>
<td>0.504</td>
<td>1.21</td>
<td>7.31</td>
</tr>
<tr>
<td>Pb I</td>
<td>0</td>
<td>207.19</td>
<td>0.368</td>
<td>0.56</td>
<td>11.35</td>
</tr>
<tr>
<td>Pb II</td>
<td>7</td>
<td>207.19</td>
<td>0.127</td>
<td>0.56</td>
<td>11.35</td>
</tr>
<tr>
<td>Empty</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.1: Targets used in E683, with position on the target wheel (for nuclear targets), atomic mass $A$, thickness $z$, radiation length $X_0$, and density $\rho$. Adapted from [3].

<table>
<thead>
<tr>
<th>Target</th>
<th>Triggered Events</th>
<th>Dijet Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH$_2$</td>
<td>264835</td>
<td>6489</td>
</tr>
<tr>
<td>LD$_2$</td>
<td>449643</td>
<td>12202</td>
</tr>
<tr>
<td>Empty (vessel)</td>
<td>36898</td>
<td>865</td>
</tr>
<tr>
<td>Be</td>
<td>34299</td>
<td>935</td>
</tr>
<tr>
<td>C</td>
<td>59068</td>
<td>1627</td>
</tr>
<tr>
<td>Al</td>
<td>49899</td>
<td>1387</td>
</tr>
<tr>
<td>Cu</td>
<td>57452</td>
<td>1551</td>
</tr>
<tr>
<td>Sn</td>
<td>56053</td>
<td>1449</td>
</tr>
<tr>
<td>Pb I</td>
<td>18185</td>
<td>500</td>
</tr>
<tr>
<td>Pb II</td>
<td>29262</td>
<td>844</td>
</tr>
<tr>
<td>Empty (nuclear)</td>
<td>7959</td>
<td>224</td>
</tr>
<tr>
<td>Total</td>
<td>1062570</td>
<td>28073</td>
</tr>
</tbody>
</table>

Table 3.2: Number of events from each kind of target. "Triggered" events include minimal jetfinding. "Dijet" events include all standard cuts described below, of which the most important is the fiducial cut.
3.2 The $\theta - \phi$ Jetfinder

During this analysis, a jetfinder operating in the center-of-mass was used. The jetfinder could operate on either Monte Carlo particles or calorimeter towers, which were boosted to the CM frame as massless pseudoparticles. A high-$E_\perp$ particle was used as a seed. A cone with a half-opening angle of 45° used the momentum vector of the seed particle as its axis. All particles falling within the cone were considered part of the jet, and the jet momentum was defined as the vector sum of the momenta of its constituent particles (discounting the effect of jet mass). This provided a new axis for the jet cone, which led to an iterative process, since changing the direction of the cone could in principal change the particles included within the cone, which would change the jet momentum. This process was iterated three times and was not checked for convergence. A jet was required to have a minimum of $2 \text{ GeV}$ of $E_\perp$. Jet momentum was scaled to the jet energy in order to make the jet massless.

Although jet cones could overlap, particles in the overlap region between two jets were assigned to the first jet found (usually the one with higher $E_\perp$). For calorimeter-based jetfinding, the BCAL was not used, as it exerted a discontinuous systematic effect on the angle of found jets. Even though the BCAL has zero $E_\perp$ by definition, its energy can pull the jet axis forward, changing the MCAL towers that contribute to the jet and thereby changing both the energy and the $E_\perp$ of the jet.

A typical Monte Carlo high-$E_\perp$ dijet event is shown in Figure 3.1 superimposed on the face of the calorimeter. Since each jet occupies a significant fraction of the calorimeter, it is geometrically difficult to fit three jets on the calorimeter, particularly given the obvious difficulty in resolving overlapping jets. 40.2% of events with beam energy between 225–275
Figure 3.1: A typical high-$E_\perp$ dijet event superimposed on the face of the calorimeter. Shaded towers are included in one of the jets. Numbers indicate the amount of $E_\perp$ in a given tower in GeV, rounded to the nearest tenth.

GeV had exactly two jets, while only 2.9% had three jets. Less than a tenth of a percent had four jets.

In jet physics, particularly at collider experiments, the jetfinder is typically based in $\eta-\phi$ space rather than in CM $\theta-\phi$ space. This is because of the generally known principle that the number of particles is relatively constant in a given interval of $\eta$. As $\theta$ approaches $0^\circ$ or $180^\circ$, $\eta$ approaches positive or negative infinity, so a cone of fixed angle covers a much larger range of $\eta$ when the cone axis is near the beam axis than when the cone axis is perpendicular to the beam axis.

We have chosen to use the $\theta-\phi$ jetfinder over the $\eta-\phi$ jetfinder because it is more robust in our kinematic range. Figure 3.2 compares the two jetfinders for jets found near $\theta$
Figure 3.2: $E_{\text{jet}} - E_{\text{parton}}$ for jets satisfying $80 \leq \theta \leq 100$ in the center-of-mass. (a) Using the $\eta - \phi$ jetfinder. (b) Using the $\theta - \phi$ jetfinder.

$90^\circ$. Here, the cone of $45^\circ$ in $\theta - \phi$ space closely matches a cone with 0.8 radius in $\eta - \phi$ space. What is plotted is the difference between the energy of the found jet and the energy of the corresponding parton. As expected, the two jetfinders give similar results, and both do a good job reconstructing kinematic variables of the initial parton.

Figure 3.3 is the same as Figure 3.2 except that now we're comparing forward jets with
Figure 3.3: $E_{\text{jet}} - E_{\text{parton}}$ for jets satisfying $25^\circ \leq \theta \leq 60^\circ$ in the center-of-mass. (a) Using the $\eta - \phi$ jetfinder. (b) Using the $\theta - \phi$ jetfinder.

$25^\circ \leq \theta \leq 60^\circ$. In the forward direction, the $\eta - \phi$ cone is closing down and getting smaller, and it can plainly be seen that this is missing energy. The $\eta - \phi$ cone simply underestimates parton energy in the forward direction, while the $\theta - \phi$ cone does not.

Finally, Figure 3.4 compares $x_\gamma$ reconstructed from dijets with average $E_\perp$ of at least 3.0 GeV found by the two jetfinders to $x_\gamma$ reconstructed from the original partons. Although
Figure 3.4: $x_\gamma$ at the jet level compared to $x_\gamma$ at the parton level. A line of $y = x$ is superimposed to indicate ideal correspondence between jet and parton level. (a) Using the $\eta - \phi$ jetfinder. (b) Using the $\theta - \phi$ jetfinder.

Both jetfinders underestimate $x_\gamma$ near 1, the $\eta - \phi$ jetfinder reconstructs an $x_\gamma$ typically 0.10 lower than the $\theta - \phi$ jetfinder in this region. The discussion of Monte Carlo predictions for $x_\gamma$ is greatly elaborated on later, but the prediction is show here to demonstrate that the $\eta - \phi$ jetfinder is not as good at reconstructing $x_\gamma$ as the $\theta - \phi$ jetfinder.

It is important to note that these figures (3.2-3.4) all use jetfinders operating on Monte
Carlo particles. Neither calorimeter acceptance, fiducial volume, nor calorimeter response are included, making this a robust test of the two jetfinders.

Both jetfinders get many kinematic variables, such as jet $\theta$, equally right.

3.3 Data Selection Criteria

- Both data and Monte Carlo were required to pass a software trigger with two tests, either of which was sufficient. The first test, the global trigger, required a minimum of 8 GeV $E_{\perp}$ in the MCAL. The second test, the two-high trigger, required at least two towers in the MCAL to have at least 0.75 GeV $E_{\perp}$ each. There is a high degree of redundancy, since most events that passed one trigger also passed the other.

- In data, a pileup cut was used to isolate the event in time. Recall that the beam comes in bunches (or buckets) separated by about 19 ns. The pileup monitor measured which buckets were occupied. The requirement was that an electron be in the bucket of interest (which is simply a cut on the efficiency of the pileup monitor), that there be no electron in the preceding five buckets, and no electron in the following three buckets. A typical untriggered event had bremsstrahlung energy from an electron that did not interact in E687 or at the E683 target and was therefore deposited in the BCAL. Since the BCAL gate covered several buckets, the BCAL could see energy from several buckets either forward or backward in time, and the pileup cut was necessary to eliminate mismeasuring the BCAL energy due to contributions from other buckets. Figure 3.5 plots BCAL EM energy with and without pileup. Events with pileup see an increase in BCAL EM energy which is attributed to bremsstrahlung energy from electrons in neighboring buckets.
Figure 3.5: BCAL EM energy plotted with and without pileup. (a) Events without pileup (i.e., that pass the pileup cut). (b) With pileup. These events are normally discarded.
• Unless otherwise mentioned, a cut was used to require $225 \text{ GeV} < E_{\text{beam}} < 275 \text{ GeV}$ after correction to $E_{\text{beam}}$ for multiple bremsstrahlung.

• In order to reconstruct $x_\gamma$, it is necessary to reconstruct at least two jets in the final state. However, because of the possibility of reconstructing a third jet, a strict requirement of two and only two reconstructed jets is imposed. As discussed elsewhere, the limited fiducial volume of the calorimeter limits the practical significance of this limit, since a third jet is reconstructed in less than 3% of events. However, in general, the target jet is too far backward and the beam jet is too far forward to reconstruct, so a third jet is typically either spurious or a product of higher order effects or primordial fluctuations producing a third high-$p_T$ parton in the final state. Therefore, a strict requirement of dijets concentrates the analysis on pure $2 \rightarrow 2$ events.

• The threshold for a jet to be found was $2 \text{ GeV} E_{\perp}$. However, there are significant threshold effects in the jetfinder, both on the likelihood of finding a jet and the likelihood of getting its kinematics right. For dijets, therefore, a cut was used to require an average jet $E_{\perp}$ of at least 3 GeV.

• Unless otherwise mentioned, $40^\circ < \theta_{\text{jet}} < 100^\circ$. The higher limit defines the calorimeter limit of full $\phi$ coverage; the lower limit is intended to enhance low-$x_\gamma$ signal, since high-$x_\gamma$ events are preferentially forward. The lower limit also improves jet reconstruction. This cut is applied individually to both jets in dijet events.

• The difference between the beam energy (i.e., the bremsstrahlung energy lost by the beam electron) and energy seen in the calorimeters was required to be less than 60 GeV. This cut improves the accuracy of the measurement of beam energy and is
discussed more fully below in Section 3.5.2.

- For Monte Carlo, jets must uniquely match to partons with at least 1 GeV $E_\perp$. How the matching is done is discussed below.

3.4 Monte Carlo Simulation

3.4.1 Lund Monte Carlos Used

The LUND Monte Carlos LUCIFER (direct) and TWISTER (resolved) were used to simulate the physics of the hard scatter.[19] The EHLQ set 1 structure function was used for nucleons and the Duke-Owens set was used for the photon. Detector effects were modeled by custom E683 software.

In the final analysis, slightly more than one million events with $Q_\perp$-min \(^3\) of 2.0 GeV were thrown for both Lucifer and Twister, using a beam spectrum generated by the beam Monte Carlo. Of those, approximately 100,000 Lucifer events and 160,000 Twister events passed the software trigger cut and a minimal jetfinding cut and were written to ntuples for use in more complex analysis.

Although $K_\perp$ in the proton is well-known to be quite small, $K_\perp$ in the photon in resolved and higher-order direct processes is almost entirely unknown. The LUND Monte Carlo Twister uses a hard, non-Gaussian distribution falling as $1/K_\perp$ with a minimum of 0.5 GeV for photon $K_\perp$.

---

\(^3\) $Q_\perp$-min is a LUND Monte Carlo parameter indicating the minimum transverse momentum exchange. Although $K_\perp$ fluctuations can push events with lower $Q_\perp$ over threshold, these events are less likely to pass jetfinding and other cuts and do not affect the $x_\gamma$ distribution much.
Figure 3.6: Monte Carlo cross-section predictions for two runs each of Lucifer and Twister (simulating direct and resolved processes, respectively).

Cross-sections

Although the ntuples built with the Monte Carlos include the beam spectrum and the trigger efficiency, analysis must also take into account the cross-sections. A 100 GeV photon has a lower cross-section to produce two high-$p_T$ jets than a 400 GeV photon does. Fortunately, the Lund Monte Carlos calculate cross-section automatically in the process of generating events. The cross-sections reported for both Lucifer and Twister as a function of energy are shown in Figure 3.6. Average cross-sections are given in tabular form in Table 3.3.

The cross-sections look reasonable to our prejudices. We expect that the resolved processes should be suppressed kinematically at low energies and the direct processes should
<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Lucifer $\sigma$ (nb)</th>
<th>Twister $\sigma$ (nb)</th>
<th>Energy (GeV)</th>
<th>Lucifer $\sigma$ (nb)</th>
<th>Twister $\sigma$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>608.35</td>
<td>198.55</td>
<td>250</td>
<td>1045.00</td>
<td>948.20</td>
</tr>
<tr>
<td>110</td>
<td>652.10</td>
<td>241.90</td>
<td>260</td>
<td>1059.50</td>
<td>1002.00</td>
</tr>
<tr>
<td>120</td>
<td>699.00</td>
<td>285.75</td>
<td>270</td>
<td>1071.50</td>
<td>1053.00</td>
</tr>
<tr>
<td>130</td>
<td>727.35</td>
<td>335.40</td>
<td>280</td>
<td>1089.50</td>
<td>1113.00</td>
</tr>
<tr>
<td>140</td>
<td>774.30</td>
<td>382.25</td>
<td>290</td>
<td>1111.00</td>
<td>1169.50</td>
</tr>
<tr>
<td>150</td>
<td>805.60</td>
<td>427.25</td>
<td>300</td>
<td>1121.00</td>
<td>1221.50</td>
</tr>
<tr>
<td>160</td>
<td>834.30</td>
<td>477.05</td>
<td>310</td>
<td>1142.00</td>
<td>1277.00</td>
</tr>
<tr>
<td>170</td>
<td>865.25</td>
<td>523.50</td>
<td>320</td>
<td>1148.00</td>
<td>1320.50</td>
</tr>
<tr>
<td>180</td>
<td>896.15</td>
<td>579.95</td>
<td>330</td>
<td>1155.50</td>
<td>1406.50</td>
</tr>
<tr>
<td>190</td>
<td>915.65</td>
<td>631.50</td>
<td>340</td>
<td>1188.00</td>
<td>1443.00</td>
</tr>
<tr>
<td>200</td>
<td>937.80</td>
<td>678.65</td>
<td>350</td>
<td>1186.50</td>
<td>1476.50</td>
</tr>
<tr>
<td>210</td>
<td>963.00</td>
<td>729.60</td>
<td>360</td>
<td>1205.00</td>
<td>1513.00</td>
</tr>
<tr>
<td>220</td>
<td>985.65</td>
<td>788.60</td>
<td>370</td>
<td>1245.00</td>
<td>1596.50</td>
</tr>
<tr>
<td>230</td>
<td>1001.95</td>
<td>844.45</td>
<td>380</td>
<td>1230.50</td>
<td>1674.50</td>
</tr>
<tr>
<td>240</td>
<td>1025.50</td>
<td>891.50</td>
<td>390</td>
<td>1251.50</td>
<td>1755.00</td>
</tr>
</tbody>
</table>

Table 3.3: Average cross-section tabulated by energy for Lucifer and Twister.

increase slowly across a wide energy range. Note that the two cross-sections are equal near the center of our kinematic region, a feature which was considered during the original design of the experiment.

The cross-sections shown here are determined with a $Q_\perp$-min of 2.0. With a $Q_\perp$-min of 1.5, Lucifer cross-sections are typically two times as high and Twister cross-sections are four-five times as high, although almost all of this increase comes in events that do not pass our trigger.

The cross-sections are used as event weights during analysis. With Monte Carlo data, we know the exact energy of the photon and can use the correct cross-section. The contribution of an event to a histogram or other measurement is enhanced or suppressed by a multiplicative factor determined by the appropriate cross-section relative to 1000 nb, e.g. Twister events with high-energy beam photons were enhanced by up to 1.8 while both
Lucifer and Twister events near a beam energy of 250 GeV had weights near 1.0.

In data, of course, nature handles the cross-sections without our intervention.

Manipulations

Because our jet cone is 45°, it is impossible to resolve phenomena that are separated by angles smaller than 45°. Because of this, the Monte Carlo output is put through parton coalescence, or the merging of partons. To avoid merging with beam or target debris, a requirement that partons being considered have $10^\circ < \theta_{\text{parton}} < 170^\circ$, and that the greater of the two have $E_\perp > 1.0$ GeV and the lesser of the two have $E_\perp > 0.8$ GeV. The angle between partons is calculated via the dot product of their momentum vectors. If the angle is less than 45°, the two partons' 4-vectors are added. (In addition, the lists of their daughter particles are merged.) Two partons are coalesced in approximately 1 of every 3 events.

The other significant manipulation involved in analyzing the Monte Carlo output is the matching of partons to jets. Matching a parton to a jet requires that the parton have a minimum $E_\perp$ of 1.0 and be within a space cone defined by $\cos \theta_{\text{parton-jet}} \geq 0.85$, or $\theta_{\text{parton-jet}} < \sim 32^\circ$. It is required that both jets in a dijet event match to separate partons. 83.9% of events which pass all other cuts have good matches to two partons. This requirement is included so that the parton-level event can be reconstructed. This cut preferentially excludes events with lower $x_\gamma$ and has about a 3% effect on the mean of $x_\gamma$. Figure 3.7 illustrates this effect, although the actual parton matching algorithm used in this figure is somewhat looser than that described above.
Figure 3.7: The effect of the parton matching cut on $x_\gamma$. Solid has no matching requirement. Dashed has a requirement that both jets match to partons.
3.4.2 Adding the Beam Monte Carlo

The Lund Monte Carlos require the user to specify the energy of the beam particle. Early analyses of the data used monochromatic beam particles and trusted that this would adequately mimic data with reasonable restrictions on the energy of the beam particle. With the expectation of relatively weak dependence of kinematic variables on energy, this should be a reasonable approximation. However, there is one strongly invalid assumption in this method. As I shall go into in more detail below, the data cannot directly measure the energy of the beam particle. Because of the effects of multiple bremsstrahlung, an event that appears to fall in a bin of given beam energy may actually have a beam particle of much lower energy. A Monte Carlo with a monochromatic beam is not a good approximation to even a narrow bin of data.

Enter the beam Monte Carlo. Written by Michael M. Traynor and Peter Kasper, with later modification by Phillip Birmingham and Chafiq Halii, for the purposes of understanding E683's flux measurements, it takes as input the measured spectrum and beam profile of the electron beam as it enters our section of the beamline, and propagates it through all of the magnets, devices, and apertures, with simulation of bremsstrahlung, pair production, and other processes, and outputs an event-by-event tally of both experimental observables like the electron energy in the silicon and the RESH and unobservables like the number and energy of photons at the E683 target. (The latter unobservable is a quantification of the problem of multiple bremsstrahlung and leads to an improved understanding of our ability to accurately measure photon energy, as detailed below.) Extensive testing of the program has demonstrated an ability to reproduce experimentally observed spectra and counter ratios, indicating significant reliability. See Figure 3.25, for example.
It immediately becomes clear that this is the appropriate front end for any physics Monte Carlo. The beam Monte Carlo was used to create a database containing four pieces of information for each event: electron energy at the silicon and at the RESH, energy of the highest energy photon in the event, and energy of all lower energy particles4 smeared by BCAL EM resolution. It is worth pointing out that we made the approximation that only the highest energy photon could interact in the target.

Because the Lund Monte Carlos require initialization for beam energy, it was necessary to bin up beam Monte Carlo events in bins of lead photon energy. Bins were 10 GeV wide. The number of events in each bin dictated the proportion of events from that bin that should be generated by the physics Monte Carlos. Specific events from each bin were used to provide data to each event generated by the Monte Carlo. The silicon and RESH energies gave the apparent energy of the event, just as they do in the data. The multi-brem energy was included in the BCAL EM energy.

**Ad Hoc Correction to BCAL EM**

Even with the addition of multiple bremsstrahlung photon energy, there is still a qualitative difference between data and Monte Carlo in BCAL EM at the low end, as seen in Figure 3.8a-b. This may be linked to synchrotron radiation emitted by electrons being bent through the sweeper magnets.

A phenomenological simulation of this has been added to the full Monte Carlo simulation. A Gaussian function, centered at 2 GeV with a width of 1 GeV, and zero-suppressed, is added to BCAL EM energy. (No adjustment is made to actual or perceived beam energy

4 i.e. photons. Electrons and positrons generated by pair production of bremsstrahlung photons would either be swept out by E887 magnets or would trigger charge veto counters.
Figure 3.8: BCAL EM energy at the low end of the spectrum. (a) Data. (b) Monte Carlo. (c) Monte Carlo with the ad hoc addition described in the text.
Figure 3.9: BCAL EM energy plotted with and without pileup for low values only. (a) Events without pileup. (b) With pileup.

for this additional energy.) The effect of this addition may be seen to qualitatively improve the reproduction of the data in Figure 3.8c.

Although the synchrotron radiation hypothesis is speculative, there is evidence that the minimum BCAL EM energy seen in data is linked to the beam. Figure 3.9 compares the low end of the BCAL EM spectrum for events with and without pileup. In Figure 3.9b, it can be seen that the minimum energy has increased and broadened. One would expect that synchrotron radiation, or any other beam-related phenomenon, would increase in events with pileup, as we see here. As Figure 3.5 showed, the amount of energy typically added by bremsstrahlung energy from neighboring buckets is large, so the change in the structure of the low end of the spectrum is probably not attributable to the same phenomenon.
3.5 Measuring Photon Energy

Knowing the energy of the photon that interacted in the target is, of course, of paramount importance to the measurement of $x_\gamma$, since photon energy feeds directly into the denominator of the definition of $x_\gamma$.

3.5.1 Resolution of Measured Photon Energy

Prior to this analysis, the experimental measure of photon energy was the difference between the pre-bremsstrahlung energy of a beam electron as measured by the silicon strips and the post-bremsstrahlung energy of the beam electron as measured in the RESH. In fact, this does not measure photon energy directly; it measures energy loss,

$$E_{\text{loss}} = E_{\text{silicon}} - E_{\text{RESH}},$$

which is equivalent to photon energy only in the limit of single-photon bremsstrahlung, i.e., not equivalent at all. Below, a method is described to correct the measured electron energy loss to better correspond to the energy of the highest energy bremsstrahlung photon.

The resolution of the silicon strips is well-known to be $2\%$.[14]. We have heretofore been using the assumption that the contribution of the RESH to the resolution of $E_{\text{loss}}$ is negligible (e.g., [20]). However, the beam Monte Carlo offers a way to measure the resolution more directly, at least in simulation.

The beam Monte Carlo simulates the silicon strips indirectly, by smearing the electron energy at the silicon by the measured silicon strip resolution. This fails to reproduce the observed granularity in the energy distribution measured in the silicon strips, but this is not an important concern. Since the RESH primarily uses geometry to measure recoil electron
energy, and only secondarily uses shower properties, it is much simpler to simulate directly, which the beam Monte Carlo does. Since it gets the parts right, the beam Monte Carlo therefore simulates the measurement of $E_{\text{loss}}$ quite well.

The beam Monte Carlo also keeps track of the photons radiated during bremsstrahlung. It is possible, therefore, to construct the quantity

$$E_{\text{brem}} = E_{\text{loss}} - E_{\text{leadphoton}},$$

where $E_{\text{leadphoton}}$ is the energy of the highest energy (lead) photon. The lead photon is taken to be the interacting photon. $E_{\text{loss}}$ is a measurable quantity that includes all known instrumental resolutions, whereas $E_{\text{leadphoton}}$ is exact within the Monte Carlo. Accordingly, the resolution of $E_{\text{brem}}$ is identically the resolution of $E_{\text{loss}}$. Positive fluctuations in $E_{\text{brem}}$ simply reflect the presence of multiple photons of non-trivial energy produced by bremsstrahlung, convoluted with the resolution of $E_{\text{loss}}$. However, negative fluctuations can only represent fluctuations due to the resolution of $E_{\text{loss}}$. Therefore, a fit to the negative edge of the distribution of $E_{\text{brem}}$ will directly measure the resolution of $E_{\text{loss}}$.

Such a fit has been performed over the entire range of $E_{\text{loss}}$. Figure 3.10 shows several example fits. In the middle of our range of beam energies, the negative edge is Gaussian in shape, with fits to Gaussian functions having $\chi^2$ per degree of freedom of about 1.0. The mean of the Gaussian function is consistent with zero, which suggests that we are successfully picking out the events in which only a single photon of significant energy was emitted during bremsstrahlung. The fit may be extended indefinitely in the negative direction, and may be extended several points beyond the peak of the Gaussian in the positive direction. The parameters of the fit are robust with regards to the limits imposed on the fit. However, at higher values of $E_{\text{loss}}$, especially above 300 GeV, multiple bremsstrahlung reduces the
Figure 3.10: Sample Gaussian fits to $E_{brem}$ to determine $E_{loss}$ resolution. (a) $E_{loss}$ from 85–95 GeV. (b) $E_{loss}$ from 125–135 GeV. (c) $E_{loss}$ from 165–175 GeV. (d) $E_{loss}$ from 205–215 GeV. (e) $E_{loss}$ from 245–255 GeV. (f) $E_{loss}$ from 295–320 GeV.

ability to push the limits of the fit in the positive direction. At lower values of $E_{loss}$, there is a qualitative problem with the fit, as evidenced by the non-zero means of the fit. This may be seen as a smooth trend in Figure 3.11, which shows the Gaussian $\sigma$ for all bins of $E_{loss}$. As $E_{loss}$ decreases, the $\sigma$ steadily increases.

This behavior has been traced to the use of RESH element 1. The RESH is a bank of
Figure 3.11: $E_{\text{loss}}$ resolution (i.e. the width of fitted Gaussians) plotted versus $E_{\text{loss}}$ across the entire range of $E_{\text{loss}}$. 


shower hodoscopes. Understanding the geometric relationship of each RESH element with respect to the sweeper magnet allows one to measure the recoil energy of an electron that hits a particular element. In fact, given the finite size of electron showers, it is possible to further refine the measurement of recoil energy by differentiating between showers that produce a signal in only one element and showers that produce signals in two adjacent elements. There are twenty configurations of RESH elements that correspond to recoil energies between 229.7 and 30.1 GeV.

The largest recoil energy corresponds to a signal only in RESH 1. Since large recoil energy naturally correlates with small $E_{\text{loss}}$, the configuration RESH 1 only is predominant at small $E_{\text{loss}}$ and is significant ($\approx 10\%$) up to $E_{\text{loss}} \approx 150\text{–}160$ GeV. RESH 1 is problematic for several reasons. First, this is the region of small recoil angles, and a small change in angle corresponds to a large change in recoil energy. The next highest energy configuration, RESH 1 + RESH 2, is 187.7 GeV, more than 40 GeV below RESH 1 by itself. RESH 1 intrinsically has the largest variation in true recoil energy across its face. Since recoil energy is calculated as for an electron that hits the center of the element, RESH 1 therefore has the largest error of any element. Second, the distribution of electrons across the face of RESH 1 is manifestly non-uniform and strongly peaked to the near side of the element, which is a further error in the assignment of RESH 1 energy to the center of the element. Finally, there is no “RESH 0” element, and, therefore, no “RESH 0” + RESH 1 configuration. Electrons that hit the far side of RESH 1 will mostly likely have a shower that extends into RESH 2, providing better geometric location for the recoil electron and better resolution of its energy. Electrons that hit the near side of RESH 1, however, do not have an adjacent element for their shower to extend into, and hence use the energy corresponding to RESH 1 alone,
which also increases the error in measuring recoil energy. This consideration represents a systematic underestimate of recoil energy. Figure 3.12 demonstrates the effect of RESH 1 by comparing $E_{brem}$ in a bin of $E_{loss}$ for different RESH elements. Note that the most probable peak in Figure 3.12a is $\approx 35$ GeV. The positive skew is consistent with an undermeasurement of recoil energy.

It is beyond the scope of this investigation to suggest a fix for the problem of RESH 1. However, to demonstrate the effect of RESH 1 on overall resolution, it is possible to remove events with RESH 1 and refit the leading edge of $E_{brem}$ to obtain a new resolution curve. This is shown in Figure 3.13. As expected, bins of high $E_{loss}$ are unaffected, while the resolution improves drastically for low $E_{loss}$. There is an as-yet unexplained cusp in the
Figure 3.13: $E_{\text{loss}}$ resolution (i.e. the width of fitted Gaussians) plotted versus $E_{\text{loss}}$ across the entire range of $E_{\text{loss}}$ but with RESH 1 excluded.

resolution curve at $E_{\text{loss}} = 120$ GeV. This may be attributable to behavior in RESH 2, particularly the non-uniform distribution of electrons across the face, that is similar to but not as dominant as that of RESH 1, although this is conjectural.

To sum up, the resolution of $E_{\text{loss}}$ across the most interesting region, $E_{\text{loss}}$ from 200–300 GeV, is roughly constant at 10 GeV. Previously quoted resolutions of 2% in photon energy are inaccurate. Resolution in $E_{\text{loss}}$ in other bands is less well defined.
3.5.2 The Missing Energy Cut

We expect a difference in energy between $E_{\text{loss}}$ and the energy measured by our calorimeters. Hereafter, this difference is labeled $E_{\text{missing}}$. $E_{\text{missing}}$ has many sources, in particular the resolution of both $E_{\text{loss}}$ and the calorimeters (which fluctuates both up and down) and the limited solid angle of the calorimeter (which can only represent an energy loss). However, one source of energy loss is particularly problematical. Extra photons produced during bremsstrahlung have the possibility of pair-producing in upstream beamline material, where their products are generally subject to being swept out of the beamline by the E687 magnets. The loss of this energy is of some concern because it represents energy that causes a mismeasurement of the energy of the photon that interacted at our target and this mismeasurement cannot be corrected for.

However, we find a strong correlation between energy lost upstream of our target ($E_{\text{lost}}$), as determined by the beam Monte Carlo, and $E_{\text{missing}}$ above $E_{\text{missing}} \approx 60$ GeV for dijet events, as seen in Figure 3.14. This correlation is not strong without a requirement of jets; jetfinding preferentially excludes events with large $E_{\text{missing}}$ and small $E_{\text{lost}}$, i.e. events whose $E_{\text{missing}}$ corresponds to energy missing the calorimeter.\(^5\) Because we do not and cannot know the energy of the interacting photon well when there is significant energy loss, a requirement that $E_{\text{missing}} < 60$ GeV is indicated and has been included herein. This cut is not tuned, but is expected to be robust with respect to small changes in the cut value.

\(^5\)This is good, as it suggests greater reliability for the jetfinder. Jets found even when lots of energy missed the calorimeter would be bogus jets.
Figure 3.14: $E_{\text{missing}}$ (Y axis) plotted against $E_{\text{lost}}$ (X axis) (quantities defined in the text) for dijet events.
3.5.3 The BCAL EM Correction

As mentioned above, one of the tremendous strengths of the beam Monte Carlo/physics Monte Carlo combination is the ability to attack the multiple bremsstrahlung problem. Simply put, some amount of $E_{\text{loss}}$ is the energy of the interacting photon and some amount of energy in the EM section of the BCAL ($E_{\text{BCAL-EM}}$) is extra energy from non-interacting photons. How much is "some" is a critical question whose answer both sets the energy scale for the event and affects our knowledge of the physically significant quantity of far-forward energy. We expect, of course, that the amount of multiple bremsstrahlung photon energy is closely related to the amount of extra energy in $E_{\text{BCAL-EM}}$, but the exact quantization requires trustworthy simulation.

Figure 3.15 plots bremsstrahlung energy (i.e. $E_{\text{loss}} - E_{\text{leadphoton}}$ as in 3.5.1 above) against $E_{\text{BCAL-EM}}$. As expected, there is a strong correlation present, suggesting that a correction to $E_{\text{loss}}$ is possible. There is a distinct population of events with small $E_{\text{brem}}$ and large $E_{\text{BCAL-EM}}$, however, representing events with $\pi^0$s of significant energy or early-showering hadronic particles in the BCAL. A correction to $E_{\text{loss}}$ based on this energy would, of course, be wrong and, if possible, this population should be isolated. However, after some investigation, there is no signature for this population that would enable it to be experimentally separated. In particular, when both $E_{\text{BCAL-EM}}$ and $E_{\text{BCAL-hadronic}}$ are large, there is equal probability of $E_{\text{BCAL-EM}}$ being a result of multiple bremsstrahlung or physics processes.

We do expect, however, that multiple bremsstrahlung particles will produce showers in the exact center of the BCAL while particles from the hard scatter will be spread throughout the solid angle of the BCAL. This suggests that it may be possible to use the BCAL
Figure 3.15: $E_{brem}$ (Y axis) plotted against $E_{BCAL-EM}$ (X axis).
wire chambers to detect the approximate location of showers in the BCAL and thereby
differentiate between multiple bremsstrahlung energy and hard scatter energy. However,
the BCAL PWCs are essentially unanalyzed and the effort required to undertake such an
analysis from a cold start was deemed impractical.

Without a practical method of differentiating the low-$E_{brem}/$high-$E_{BCAL-EM}$ population,
we are forced to damn the torpedos and accept a systematic error in any correction to
$E_{loss}$ for multiple bremsstrahlung. A simple linear fit of $E_{brem}$ as a function of $E_{BCAL-EM}$ for
$E_{BCAL-EM} > 25$ GeV was performed in several bins of $E_{loss}$. In the middle energy region,
the slope of the fit was relatively constant and somewhat smaller than unity. The constant
term, however, showed some dependence on $E_{loss}$, ranging from -7.5 GeV to -15.9 GeV
with $E_{loss}$ from 140 GeV to 260 GeV. The dependence was linear, although the errors in
the coefficient were large enough that a linear fit was underdetermined with $\chi^2$ per degree
of freedom significantly less than unity. Nonetheless, a linear dependence for the constant
term was included in the final form of the correction.

During this part of the investigation, the RESH 1 effect described above was seen again,
this time as a skew in $\Delta E_{\gamma}$ at low values of $E_{loss}$, representing a systematic undermea-
surement of $E_{\gamma}$. Although an ad hoc correction to low $E_{loss}$ was considered and seen to be
relatively effective, a true understanding of this problem should be possible by undertaking
a close study of the effect of RESH 1, a study which was beyond the scope of this investiga-
tion at that time. Accordingly, events with low $E_{loss}$, below 135 GeV, are simply discarded
as unreliable even when looking at the complete photon energy spectrum. (Naturally, this
exclusion does not affect the standard energy cut of 225–275 GeV.)

The fit parameters were convincing enough that the fit was taken as the correction
$E_{\text{corr}}$ to $E_{\text{loss}}$. Some exploration of parameter space showed that resolution was only weakly dependent on the parameters near the minimum. To avoid discontinuity in the correction, the value of $E_{\text{corr}}$ at 25 GeV was propagated linearly to connect to $E_{\text{corr}} = 0$ at $E_{BCAL-EM} \neq 0$.

As mentioned, the constant term $b$ in the fit was dependent on energy, such that

$$b = -6.552 \text{GeV}, E_{\text{loss}} < 140 \text{ GeV},$$

$$b = 3.304 \text{GeV} - 0.0704 \cdot E_{\text{loss}}, E_{\text{loss}} < 260 \text{ GeV},$$

$$b = -15.0 \text{GeV}, E_{\text{loss}} \geq 260 \text{ GeV}.$$

Given $b$, then, for $E_{BCAL-EM} > 25$ GeV,

$$E_{\text{corr}} = 0.97 \cdot E_{BCAL-EM} + b,$$

and for $E_{BCAL-EM} < 25$ GeV,

$$E_{\text{corr}} = (0.97 + \frac{b}{25.0 \text{GeV}}) \cdot E_{BCAL-EM}.$$

### 3.5.4 Revisiting Photon Energy Resolution

Although we have shown that resolution of $E_{\text{loss}}$ is approximately 10 GeV, that is not the final photon energy resolution. Our ability to correct $E_{\text{loss}}$ for multiple bremsstrahlung contributes to the resolution. After correction, $E_{\text{loss}}$ becomes the measured photon energy $E_{\text{meas}}$. The difference between $E_{\text{meas}}$ and the actual photon energy $E_{\text{true}}$ is shown in Figure 3.16 for the energy bin of greatest interest. For comparison, the same quantity without any correction on $E_{\text{loss}}$ is also shown in the figure.
Figure 3.16: Final photon energy resolution for $225 < E_{\text{meas}} < 275$ GeV. The quantity plotted is $E_{\text{meas}} - E_{\text{true}}$. (a) Without the correction described in the text. (b) With the correction. A Gaussian has been fitted to the center of the peak.
3.6 Comparison of Full Monte Carlo and Data

In general, the Monte Carlo does a good job reproducing the gross structure of the data, with the exception that the $E_\perp$ spectrum is too hard and that there is more underlying event in the data. Figure 3.17 shows the average $E_\perp$ spectrum of dijets for data and Monte Carlo with no cut on the angular distribution. The Monte Carlo has a considerably harder spectrum. It is possible to cause the Monte Carlo to have a steeper falloff in $E_\perp$ by turning off primordial $K_\perp$ in the photon and proton, but that fails to reproduce the data spectrum and reduces the underlying event even further.

Figure 3.18 shows the average $E_\perp$ spectrum of dijets again, but after the fiducial volume cut on $\theta_{jet}$. For both data and Monte Carlo, the spectra have stiffened up and the difference is smaller. However, of particular note is the rollover at low $E_\perp$ in the Monte Carlo. This indicates that the angle cut preferentially selects low $E_\perp$ dijets in the Monte Carlo, but not in the data, above and beyond the phenomenon which stiffens the $E_\perp$ spectra. It is probably the forward angle limit doing the work here, as it is the more draconian.

Indeed, as Figures 3.19–3.20 show, the Monte Carlo jets tend to be further forward and do not populate the higher angles as thoroughly as do the data. The difference between $\theta_1$ and $\theta_2$ is an artifact of the jetfinder and does not reflect any significant physics.

Planarity, which is defined more fully in, e.g., [22], is a measurement of the jet-like nature of an event and is derived from the eigenvalues of the moment of momentum tensor, having a value of zero for events which are symmetric in $\phi$ and one for events which are completely planar. By inspection, dijet events tend to have high planarity. Indeed, high planarity, or, rather, low sphericity (a related variable) was taken to indicate the first observed jet signal.
Figure 3.17: The dijet average $E_\perp$ spectrum for data and Monte Carlo. Both (a) and (b) have had exponentials fitted. (a) Data. (b) Monte Carlo.
Figure 3.18: As Figure 3.17 but with both jets required to have $40^\circ < \theta_{jet} < 100^\circ$. Note the limited range of fit in (b).
Figure 3.19: Comparison of the angular distribution of jet 1 in data and Monte Carlo. (a) Data. (b) Monte Carlo.
Figure 3.20: As Figure 3.19, but for jet 2.
Figure 3.21: Comparison of the planarity of dijet events in data and Monte Carlo. (a) Data. (b) Monte Carlo.

in [9]. Figure 3.21 compares planarity for dijet events (average jet $E_\perp > 3$ GeV) for data and Monte Carlo. As expected, dijet events are strongly planar. The Monte Carlo has higher planarity because it has less underlying event and a broader jet $\Delta\phi$ than we see in the data.

Underlying event may be seen more directly in Figure 3.22, which shows $E_\perp$ flow in the
MCAL. $E_\perp$ flow plots are generated by taking the $\phi$ direction of the largest $E_\perp$ jet as an axis, and for each tower in the MCAL plotting $\Delta \phi$ from the tower to the jet axis, weighting the plot by the amount of $E_\perp$ in the tower. As one would expect, there is a peak both at $0^\circ$ and $180^\circ$, indicating the two jets. The $180^\circ$ peak is broadened because jets are not exactly back-to-back, largely due to $K_\perp$ effects.

The amount of underlying event, which should be roughly isotropic, is given by the $E_\perp$ flow in the direction perpendicular to the jet axis, where there is no overlying jet $E_\perp$. It is clear that the Monte Carlo has less underlying event (which is equivalent to saying that it is more jet-like) than is seen in the data.

Figure 3.23 shows a $E_\perp$ flow plot similar to Figure 3.22. However, an average jet $E_\perp$ cut of 4.0 GeV has been imposed. At this higher $E_\perp$, data and Monte Carlo agree much more closely.

Figure 3.24 shows a comparison between photons and pions. $E_\perp$ flow is plotted as in Figure 3.22. It can be seen that pions produce jets with greater $\Delta \phi$ and have more underlying event than photons. Because the pion cross-section falls more steeply with $E_\perp$ than the photon cross-section, there is also less total $E_\perp$ in pion data than in photon data.

Figure 3.25 compares data and Monte Carlo final triggered and jet-found gamma spectra. All standard cuts from 3.3 have been applied, with the exception of the beam energy cut. The only energy cut included is for photons below 135 GeV. As discussed earlier, RESH 1 is a source of error in the photon energy determination, and it dominates low values of $E_{\text{loss}}$. Monte Carlo studies indicate that the RESH 1 problem becomes significant below approximately 135 GeV. Monte Carlo clearly does an excellent job reproducing the
Figure 3.22: Comparison of the $E_\perp$ flow of dijet events in data and Monte Carlo for average jet $E_\perp \geq 3.0$ GeV. Data is solid and Monte Carlo is dashed. Each bin has been divided by the number of events.
Figure 3.23: Comparison of the $E_\perp$ flow of dijet events in data and Monte Carlo for average jet $E_\perp \geq 4.0$ GeV. Data is solid and Monte Carlo is dashed. Each bin has been divided by the number of events.
Figure 3.24: $E_\perp$ flow for photons and pions for average jet $E_\perp \geq 3.0$ GeV. Photons are solid, pions are dashed. Each bin has been divided by the number of events.
Figure 3.25: The photon beam spectrum, after all standard cuts described in 3.3 are applied with the exception of the beam energy cut. See text for more details. (a) Data. (b) Monte Carlo.

experimental spectrum.
Chapter 4

Results and Conclusion

4.1 Monte Carlo Prediction of $x_\gamma$

True $x_\gamma$ describes what happens at the parton level. Experimentally, however, what we observe are jets. The use of Monte Carlos lets us link jet-level phenomena to the hidden parton level. As described above, our event selection requires two jets with an average $p_\perp > 3.0$ in the fiducial volume. In the Monte Carlo, these are matched to two partons, which are used to calculate $x_\gamma$ and any other desired quantities. For Lucifer, of course, there are only two high-$p_\perp$ partons in an event; for Twister, other high-$p_\perp$ partons are disregarded.

Figure 4.1 shows the parton-level prediction for the two Monte Carlos. There are two features of interest not naively expected. The Lucifer plot, which we expect to be identically 1.0, can be less than 1.0 due to $K_\perp$ (predominantly from the proton). Similarly, the Twister plot shows an unexpected peak at very high $x_\gamma$, which we attribute to the large amount of $K_\perp$ in the resolved photon.

The effect of $K_\perp$ is quite profound. Turning off $K_\perp$ reduces the resolved cross section
Figure 4.1: $x_\gamma$ at the parton level. (a) Lucifer (direct photons). (b) Twister (resolved photons).
Figure 4.2: $x_\gamma$ at the parton level for Twister with and without $K_\perp$. (a) No $K_\perp$. (b) With $K_\perp$. Systematics are slightly different than for Figure 4.1b.

dramatically, changing the mix of Lucifer and Twister, and altering the entire shape of the Twister parton-level distribution. Figure 4.2 illustrates this. We know from our data that substantial $K_\perp$ is required.

The fact that there is a significant overlap in value of parton $x_\gamma$ between the two processes suggests that they will be difficult to distinguish at less fundamental levels and calls further
into question the entire dichotomy of "resolved" versus "direct" photons. This is born out in Figure 4.3. In the best case, Figure 4.3a, all particles are considered for inclusion in jets and jets are required only to be backwards of 40°. However, it is already evident that hadronization alone destroys our ability to reconstruct \( x_\gamma = 1.0 \) at any level except the parton level, nor is there a distinct signature for either direct or resolved processes. Restricting the backwards angle of particle jets to fit within the calorimeter solid angle, as in Figure 4.3b-c, limits our ability to probe low \( x_\gamma \). The only difference between Figure 4.3c and Figure 4.4 is calorimeter smearing, and that can be seen to be very little difference at all.

The number of entries in each of the sub-figures of Figure 4.3 may seem to be unusual—more entries in the sub-figure with the most restricted fiducial volume is odd. However, this can be explained fairly simply. The first two sub-figures, which have full acceptance for particle contribution to jets, have jets pulled forward by beam jet particles or pulled backwards by target jet particles. Jets in the third sub-figure, with particles restricted to the solid angle of the MCAL, unsurprisingly cannot be pulled outside the solid angle of the MCAL by spurious constituents. Though the effect appears large based on the statistics printed on the histograms of the figure, it is an effect of only a few percent when compared to the total number of dijet events (here, approximately 40,000 before the angle cut is performed).

Finally, Figure 4.4 shows the Monte Carlo prediction with all calorimeter smearing, using the calorimeter-based jetfinder. As expected, the contributions from Lucifer and Twister overlap broadly, so there is no ability to resolve the two processes. There is also no signal at \( x_\gamma = 1.0 \), due largely to mismeasurement of jet energy.
Figure 4.3: $x_\gamma$ at the particle level. Lucifer and Twister have been combined according to their relative cross-sections folded with triggering and jet-finding efficiencies. (a) $4\pi$ acceptance for particles, dijets required between 40° and 180°. (b) $4\pi$ acceptance for particles, dijets required between 40° and 100°. (c) MCAL solid angle acceptance for particles, dijets required between 40° and 100°.
Figure 4.4: $x_{\gamma}$ at the calorimeter level. Lucifer and Twister have been combined according to their relative cross-sections folded with triggering and jet-finding efficiencies. The dotted line is Twister, the dashed line is Lucifer, and the solid line is the sum. Statistics are the values associated with the solid histogram.
Figure 4.5: $x_\gamma$ at the calorimeter level with and without $K_\perp$. Lucifer and Twister have been combined according to their relative cross-sections folded with triggering and jet-finding efficiencies. (a) With no $K_\perp$. (b) With $K_\perp$. Systematics are slightly different than in Figure 4.4 above.

Revisiting the question of $K_\perp$, Figure 4.5 shows the difference at the jet level for $x_\gamma$ for Lucifer and Twister combined appropriately, with and without $K_\perp$. There are two competing effects. One is that the Twister cross-section is greatly reduced without $K_\perp$. The other is that the parton-level high-$x_\gamma$ contribution from Twister vanishes without $K_\perp$. Remarkably, the greater contribution from Lucifer to the combined Monte Carlo appears to exactly compensate for the missing high-$x_\gamma$ contribution from Twister, resulting in a jet-level distribution that is almost unchanged. (Note that, as mentioned elsewhere, that $K_\perp$ is required in order to get other kinematic variables correct.)

Figure 4.6 compares $x_\gamma$ calculated at the parton level and $x_\gamma$ calculated at the jet level. There is good correspondence between the two values throughout the resolved region of
Figure 4.6: $x_\gamma$ at the jet level plotted versus $x_\gamma$ at the parton level. The highest bins near unit parton $x_\gamma$ are suppressed to enhance the other bins. The function $y=x$ is superimposed as a reference line.

Low $x_\gamma$, but the jet level is unable to resolve unit $x_\gamma$, and there is a distinct turnover as parton $x_\gamma$ goes to unity. More sophisticated jetfinders are in development that may be able to improve the reconstruction of $x_\gamma$ at high $x_\gamma$. 

71
4.1.1 Resolution of $x_\gamma$

Clearly, one of the first concerns that must be answered for any experimental measurement is the size of the error made in the measurement. For $x_\gamma$, the parton level $x_\gamma$ is the true measurement and the jet level $x_\gamma$ is the experimental measurement. The event-by-event difference is the error.

Figure 4.7 shows the resolution for two different bands of true (parton) $x_\gamma$, which approximately represent the "resolved" and the "direct" contributions. In the resolved region, shown in Figure 4.7a, the mean is near zero and the RMS is small; our measurement is good. However, in the direct region, shown in Figure 4.7b, there is unsurprisingly a large offset from zero, although the RMS is still very good. As shown above, we are almost unable to reconstruct $x_\gamma \approx 1$ at the jet level, so the direct region of $x_\gamma$ is systematically undermeasured at the jet level. Nonetheless, our resolution is quite competitive with the Zeus resolution quoted in [15].

As a comparison of the means of analysis, Figures 4.8-4.9 are the same as Figure 4.7 for different simulations. Figure 4.8 uses a monochromatic beam ($E_\gamma = 250 GeV$). One would expect the monochromatic beam to have the best $x_\gamma$ resolution, a full spectrum beam to have worse resolution, and the full spectrum beam with beam energy correction to improve the resolution, perhaps even back to the monochromatic resolution. In fact, this is exactly what is seen. The monochromatic resolution 4.8 is slightly better than the resolution of the full beam with correction seen in Figure 4.7.

Figure 4.9 is the same as Figure 4.7 with the full beam spectrum but without any correction to the beam energy (i.e., using $E_{\text{loss}}$ as $E_\gamma$). Again, as expected, the resolution is significantly degraded, particularly in the direct band, compared to either the monochro-
Figure 4.7: Resolution of \( x_\gamma \) relative to the parton level. The quantity plotted is parton level \( x_\gamma \) - jet level \( x_\gamma \). (a) For parton level \( x_\gamma \) between 0.4 and 0.7 (resolved region). (b) For parton level \( x_\gamma \geq 0.95 \) (direct region).
Figure 4.8: As Figure 4.7, but with a monochromatic beam $E_\gamma = 250$ GeV. (a) For parton level $x_\gamma$ between 0.4 and 0.7 (resolved region). (b) For parton level $x_\gamma \geq 0.95$ (direct region).
Figure 4.9: As Figure 4.7, but without any correction to the beam energy. (a) For parton level $x_\gamma$ between 0.4 and 0.7 (resolved region). (b) For parton level $x_\gamma \geq 0.95$ (direct region).

mation beam or the full spectrum beam with correction.

4.2 Experimental Measurement of $x_\gamma$

Figure 4.10 shows the final result of this analysis. (The Monte Carlo result is repeated for ease of direct comparison.) As predicted by the Monte Carlo, there are no separate signatures for direct and resolved processes. The data lies significantly below Monte Carlo, which is consistent with a significant contribution from higher-order processes, such as soft gluon radiation, which can only reduce apparent $x_\gamma$. The disagreement with Monte Carlo leads to the strong conclusion that leading-order Monte Carlo is inadequate to predict our results in this regime.
Figure 4.10: $x_\gamma$ results. (a) Data. (b) Monte Carlo, repeated from Figure 4.4 above.
4.3 NLO Monte Carlo

Having concluded that leading order is inadequate, the obvious course of action is to search for a next-to-leading order program. Theorist Jeff Owens (e.g. [1]) has worked with E683 to produce a prediction for E683 kinematics and fiducial coverage in the next-to-leading log, encompassing full NLO for direct processes and partial NLO for resolved processes. The prediction is based on a program which does not generate events per se and only operates at the parton level and therefore can not be rigorously considered a true Monte Carlo. Each event thrown by the program is given a weight calculated from the event process and kinematics. This weight can be negative.

The program used a monochromatic photon beam of 250 GeV.

The program uses the CTEQ 3M distribution set for parton calculations and was robust to other sets. However, the results of the model were not robust with respect to other parameters and therefore the results quoted here cannot be considered rigorous. The variation was seen most strongly in the highest bin of $x_\gamma$. The $Q^2$ scale of the QCD calculations was set equal to a scale factor times $p_{\perp}^2$. Small scale factors could drive the highest bin of $x_\gamma$ to negative values, i.e. to unphysical values, but instabilities near the edge of phase space are unsurprising. For our purposes, the scale factor was set to 1, which is considered a reasonable value. Figure 4.11 demonstrates the sensitivity of the calculation to this parameter.

In the program, the final parton state can undergo coalescence, and the results in the highest bin of $x_\gamma$ are sensitive to how this coalescence is performed. Partons are coalesced if they lie within an rapidity–$\phi$ cone of a particular radius. Small or zero radius cones, i.e. little or no coalescence, can produce nonphysical distributions of $x_\gamma$. For results reported
Figure 4.11: Parton-level $x_f$ prediction for the NLO calculation with different $Q^2$ scale factors showing the sensitivity to this scale. The coalescence radius used is 0.8. The scale factor is (a) 0.25, (b) 1.00, (c) 1.50, (d) 2.00.
Figure 4.12: Parton-level $x_\gamma$ prediction for the NLO calculation with different radii in rapidity-$\phi$ space for coalescence showing the sensitivity to this scale. The $Q^2$ scale is 1.0. The radius is (a) 0.00, (b) 0.50, (c) 0.80, (d) 1.00.

Here, the coalescence radius was set to 0.8, which is similar to the coalescence radius used in the LO Monte Carlo above. Figure 4.12 demonstrates the sensitivity of the calculation to this parameter.

After coalescence, the model used fiducial and kinematic cuts that required that there be two and only two partons of at least 3 GeV $p_{\perp}$ each in the rapidity range $-0.2 < Y < 1.0$. 
The LO and NLO predictions for parton-level $z_\gamma$ are given in Figure 4.13. The NLO prediction fits our expectations well. The resolved portion of the distribution is little changed, while the direct-like portion has been smeared into lower bins. Note the large error bars on the largest bin—this bin is populated by events with large positive or large negative weights and is therefore highly sensitive to small changes in the parameters that feed the calculation of the weights.

There is some significant concern that the NLO model is qualitatively different from the LO Monte Carlo at the lowest order. Compare Figure 4.13a with Figure 4.1. The resolved model of the LO Monte Carlo has a large population at very high $z_\gamma$ (i.e., a direct-like population). Together with the direct model Monte Carlo, the bulk of the parton-level distribution is direct or direct-like. The difference of shape may be attributed to the different amount of $K_\perp$ in both models. The Owens model has little $K_\perp$ while the Twister Monte Carlo has a considerable amount. Our data supports significant $K_\perp$ according to various kinematic quantities such as $\Delta \phi$ between jets and $E_\perp$ flow. However, our data also supports a softer $x_\gamma$ spectrum than the LO Monte Carlo, so this issue is not yet resolved.

Since Figure 4.13 is a parton-level result, it cannot be directly compared to jet-level observations. However, Figure 4.6 links parton-level and jet-level. If we construe the figure as a matrix, normalized to unity in the parton-level rows, we can consider it a transformation that acts upon a parton-level distribution and produces a jet-level distribution. Such a smearing matrix takes into account the effects of hadronization and calorimeter response. The smearing matrix produced from the LO Monte Carlo is shown in Appendix B.

The NLO parton-level prediction was smeared according to this procedure. Events at $z_\gamma = 1.0$, at the edge of phase space, were given negative weights by the model and
Figure 4.13: Lowest order and next-to-lowest order prediction for $x_\gamma$ at the parton level for E683 kinematics. (a) Lowest order. (b) Next-to-lowest order.
Figure 4.14: $x_\gamma$ from data compared with LO Monte Carlo and the smeared NLO prediction. Solid: data. Dotted: LO Monte Carlo (same as Figure 4.10b above). Dashed: NLO smeared from the parton-level to the jet-level as described in the text.

were combined with the next lower bin to create a physical distribution. The results of the smearing are compared to data in Figure 4.14. The NLO prediction is much closer to agreement with data. It is important to emphasize again that this result cannot be considered rigorous because of the instability to parameters of the NLO model as well as the unresolved question of $K_{\perp}$. 

82
Figure 4.15 compares the LO Monte Carlo jet-level $x_\gamma$ distribution with the NLO model's lowest order parton-level $x_\gamma$ distribution transformed by the smearing matrix. Coming from such different parton-level distributions, the jet-level distributions are, unsurprisingly, very different. In fact, the NLO model's smeared lowest order prediction is not very different from the smeared NLO prediction, as shown in Figure 4.16. In going from LO to NLO, events have been moved around, but the smearing tends to swamp this effect by moving them around even more.

4.4 Other Targets

As mentioned earlier, in addition to liquid hydrogen and deuterium targets, E683 also had a wheel of nuclear targets. See Table 3.1. Figures 4.17–4.18 give experimental measurements of $x_\gamma$ on the various nuclear targets.

The results are somewhat unexpected. Although individual statistics are not large, all of the nuclear targets have smaller average $x_\gamma$ than the hydrogen/deuterium target, which is indicative of a real systematic difference. There are several possible sources for this effect. The most obvious source is geometric. The nuclear targets are single-valued in $Z$, while the LH2 vessel was a full 20" long. Events that occur upstream in the LH2 vessel will produce particles that measure anomalously large $E_\perp$ because they will appear to hit the MCAL at higher angles than they truly do. They will thus satisfy the high-$E_\perp$ triggers more readily. The effect on $x_\gamma$ should be to decrease $x_\gamma$, however. A quick look at the definition of $x_\gamma$ reminds us that $z_\gamma$ decreases as longitudinal energy ($cos\theta$) decreases. If the shift in nuclear $x_\gamma$ is due to geometry, some other phenomenon must be operating.

Although one would expect scattering in heavy nuclei to decrease "jettiness", and thus
Figure 4.15: $x_\gamma$ at the jet level for lowest order Monte Carlo and lowest order in the NLO model. Solid: lowest order Monte Carlo. Dashed: NLO model lowest order parton-level $x_\gamma$ smeared to jet-level as described in the text.
Figure 4.16: NLO model lowest order parton-level $x_\gamma$ compared to NLO parton-level $x_\gamma$, both smeared to jet-level as described in the text. Solid: NLO smeared $x_\gamma$. Dashed: LO smeared $x_\gamma$. 
Figure 4.17: $x$, results for nuclear targets. (a) Lead I target. (b) Empty nuclear target. (c) Tin target. (d) Aluminum target.
Figure 4.18: $x_\gamma$ results for nuclear targets. (e) Copper target (f) Beryllium target. (g) Carbon target. (h) Lead II target.
decrease $z_\gamma$, E683 has demonstrated that there is no A-dependence in the amount of underlying event in dijets.[21] However, this only rules out gross scattering effects. A small increase in the angular size of a jet due to passage through nuclear matter would result in the jet cone missing energy, in the found jet therefore having lower energy, and $z_\gamma$ being smaller. Moreover, [21] used a significantly larger jet cone, which would presumably swamp this effect. However, the size of the jet can be seen in some general fashion in $E_\perp$ flow plots, and the $E_\perp$ flow plots for various nuclei do not show significant shape variation, as seen in Figure 4.19. There is some small increase in underlying event evident, but that is all.

Hydrogen and deuterium targets are combined for most of the data results presented here. Figure 4.20 separates out the two and includes empty (gas-filled) target results. As Appendix A shows, empty target events mostly come from the vessel windows and the scintillation counter C2.

The important result here is that the empty target does not introduce a bias in the data and, hence, empty target subtraction is not necessary. In addition, there is a small difference between hydrogen and deuterium targets, and the deuterium target is lower, which is consistent with the generally lower results of the nuclear targets. The presence of neutrons in higher-Z nuclei, or, rather, the lower average charge of partons, will tend to suppress direct processes, which would be seen as a reduction in $z_\gamma$. However, the agreement of the empty vessel with the full vessel and the agreement of the empty nuclear target with the various nuclear targets (see Figure 4.17b) points to a purely systematic difference.
Figure 4.19: $E_\perp$ flow. Solid is hydrogen+deuterium targets; dashed is copper+tin+lead II target.
Figure 4.20: $x_\gamma$ results from the target vessel. (a) Liquid hydrogen. (b) Liquid deuterium. (c) Empty (gas-filled) vessel.
4.5 Dependence of $x_\gamma$ at higher energies

The results that have been quoted so far lie in the most populated bin of beam energy in E683 data. It is possible to go to higher beam energies, although one quickly runs out of statistics. The expectation is that $x_\gamma$ will decrease as energy increases because the region of lower $x_\gamma$ becomes capable of generating triggers. This is born out in Figure 4.21.

The relatively greater contribution of resolved processes at higher energies predicted by Monte Carlo (recall Figure 3.6) also supports a decrease in $x_\gamma$, since the resolved processes are naturally lower in $x_\gamma$. However, Monte Carlo studies at higher energy show only small decrease in $x_\gamma$, as shown in Figure 4.22. Note that this actually increases the discrepancy between Monte Carlo and data in $x_\gamma$ as energy increases.

We attribute the relative independence of Monte Carlo $x_\gamma$ on energy to the $E_\perp$ spectrum of the Monte Carlo, which we have already demonstrated is far too hard. This pathology intensifies at higher beam energies, as illustrated in Figure 4.23.

4.6 Conclusions

- It is critical to understand the multiple bremsstrahlung phenomenon in order to understand and properly treat the data. We have demonstrated that the beam Monte Carlo gives experimenters the power to handle multiple bremsstrahlung.

- We observe significant disagreement between leading-order Monte Carlo and data. This is attributed to higher-order effects not treated by the Monte Carlo, but also to an $E_\perp$ spectrum which is too hard and in part to a jet structure which is too clean. The data is more resolved-like than the Monte Carlo suggests.
Figure 4.21: Experimental data for $x$, for four different regions of energy. (a) Beam energy 175–225 GeV. (b) Beam energy 225–275 GeV (repeated from Figure 4.10a above). (c) Beam energy 275–325 GeV. (d) Beam energy 325–500 GeV.
Figure 4.22: Monte Carlo prediction for $x_\gamma$ for four different regions of energy. (a) Beam energy 175–225 GeV. (b) Beam energy 225–275 GeV (repeated from Figure 4.4 above). (c) Beam energy 275–325 GeV. (d) Beam energy 325–500 GeV.
Figure 4.23: $E_\perp$ spectra with increasing beam energy. (a) and (c) are experimental data and (b) and (d) are Monte Carlo. (a),(b) Beam energy 275–325 GeV. (c),(d) Beam energy 325–500 GeV.
• A next-to-leading-order model shows much better agreement with data, as expected, since NLO phenomena tend to lower $x_{\gamma}$, especially for the direct processes. However, the results of the model are not rigorous. Moreover, the NLO model at the lowest order exhibits qualitative discrepancies with the Lund LO Monte Carlo, which are attributed to fundamental differences in the amount of $K_\perp$ in the two models.

Finally, at $\sqrt{s} = 21$ GeV, due to kinematics and the contributions from higher-order processes, we neither observe nor expect to observe separation between resolved and direct coupling.
Bibliography


Appendix A

Tracking

This appendix will discuss tracking routines written for use with E683 data. Tables A.1–A.3 record some characteristics of the wire chambers. Note that the three PWC boxes were given the names “Erin”, “Colleen”, and “Molly” from upstream to downstream, containing 1, 1, and 3 planes respectively. The three upstream drift chamber boxes, containing two planes each, are the “Zhu” chambers, after Qian Zhu, who was responsible for their maintenance. The three boxes immediately downstream of the magnet, which contained two planes each, are called the “Iowa” chambers for the University of Iowa personnel who rebuilt and maintained them. The two boxes upstream of the MCAL are the “monster” chambers, so-called for their great size.

Both the Zhu chambers and the Iowa chambers had cells of different size. Near the beam, where the number of passing particles is expected to be high, cells are narrow. Away from the beam, on the wings of the chambers, the particle flux is expected to be low and cells are wider.

Chamber planes which measure X have wires running in the Y direction and vice versa.
<table>
<thead>
<tr>
<th>Box</th>
<th>Plane</th>
<th>Direction of Measurement</th>
<th>Active Area</th>
<th>Number of Wires</th>
<th>Cell Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erin</td>
<td>PWC 1</td>
<td>Y</td>
<td>18&quot; × 15&quot;</td>
<td>192</td>
<td>1.9538</td>
</tr>
<tr>
<td>Colleen</td>
<td>PWC 2</td>
<td>Y</td>
<td>18&quot; × 15&quot;</td>
<td>192</td>
<td>1.9538</td>
</tr>
<tr>
<td>Molly</td>
<td>PWC 3</td>
<td>X</td>
<td>26.25&quot; × 13&quot;</td>
<td>320</td>
<td>1.9538</td>
</tr>
<tr>
<td>Molly</td>
<td>PWC 4</td>
<td>U</td>
<td>26.25&quot; × 13&quot;</td>
<td>352</td>
<td>1.9538</td>
</tr>
<tr>
<td>Molly</td>
<td>PWC 5</td>
<td>V</td>
<td>26.25&quot; × 13&quot;</td>
<td>352</td>
<td>1.9538</td>
</tr>
</tbody>
</table>

Table A.1: Some characteristics of E683 proportional wire chambers. U and V planes have wires running at an angle with the vertical. The cant of the wires in PWC 4 and 5 is ±15°.

<table>
<thead>
<tr>
<th>Box</th>
<th>Plane</th>
<th>Direction of Measurement</th>
<th>Active Area</th>
<th>Number of Wires</th>
<th>Cell Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhu 1</td>
<td>DC 1</td>
<td>X</td>
<td>38.5&quot; × 17.5&quot;</td>
<td>40</td>
<td>12 and 24</td>
</tr>
<tr>
<td>Zhu 1</td>
<td>DC 2</td>
<td>X and Y</td>
<td>38.5&quot; × 17.5&quot;</td>
<td>40</td>
<td>12 and 24</td>
</tr>
<tr>
<td>Zhu 2</td>
<td>DC 3</td>
<td>X</td>
<td>53.5&quot; × 30.5&quot;</td>
<td>46</td>
<td>12 and 24</td>
</tr>
<tr>
<td>Zhu 2</td>
<td>DC 4</td>
<td>X</td>
<td>53.5&quot; × 30.5&quot;</td>
<td>48</td>
<td>12 and 24</td>
</tr>
<tr>
<td>Zhu 3</td>
<td>DC 5</td>
<td>X</td>
<td>63.5&quot; × 38.5&quot;</td>
<td>44</td>
<td>12 and 24</td>
</tr>
<tr>
<td>Zhu 3</td>
<td>DC 6</td>
<td>X and Y</td>
<td>63.5&quot; × 38.5&quot;</td>
<td>44</td>
<td>12 and 24</td>
</tr>
</tbody>
</table>

Table A.2: Some characteristics of E683 upstream drift chambers. All upstream DC planes had small inactive areas centered on the beam line. Narrower cells are proximal and wider cells are distal to the beam center. DC 2 and 6 are delay line planes with wires that measure x directly and measure y by measuring the time difference between readouts at the top and bottom of the plane.
<table>
<thead>
<tr>
<th>Box</th>
<th>Plane</th>
<th>Direction of Measurement</th>
<th>Active Area</th>
<th>Number of Wires</th>
<th>Cell Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iowa 1</td>
<td>DC 7</td>
<td>X</td>
<td>104&quot; × 76&quot;</td>
<td>84</td>
<td>24 and 32</td>
</tr>
<tr>
<td>Iowa 1</td>
<td>DC 8</td>
<td>X</td>
<td>104&quot; × 76&quot;</td>
<td>85</td>
<td>24 and 32</td>
</tr>
<tr>
<td>Iowa 2</td>
<td>DC 9</td>
<td>X</td>
<td>104&quot; × 76&quot;</td>
<td>85</td>
<td>24 and 32</td>
</tr>
<tr>
<td>Iowa 2</td>
<td>DC 10</td>
<td>X</td>
<td>104&quot; × 76&quot;</td>
<td>84</td>
<td>24 and 32</td>
</tr>
<tr>
<td>Iowa 3</td>
<td>DC 11</td>
<td>X</td>
<td>104&quot; × 76&quot;</td>
<td>85</td>
<td>24 and 32</td>
</tr>
<tr>
<td>Iowa 3</td>
<td>DC 12</td>
<td>X and Y</td>
<td>104&quot; × 76&quot;</td>
<td>84</td>
<td>24 and 32</td>
</tr>
<tr>
<td>Monster 1</td>
<td>DC 13</td>
<td>X</td>
<td>132&quot; × 68&quot;</td>
<td>144</td>
<td>19.05</td>
</tr>
<tr>
<td>Monster 1</td>
<td>DC 14</td>
<td>U</td>
<td>132&quot; × 68&quot;</td>
<td>192</td>
<td>19.05</td>
</tr>
<tr>
<td>Monster 1</td>
<td>DC 15</td>
<td>V</td>
<td>132&quot; × 68&quot;</td>
<td>192</td>
<td>19.05</td>
</tr>
<tr>
<td>Monster 2</td>
<td>DC 16</td>
<td>X</td>
<td>132&quot; × 68&quot;</td>
<td>144</td>
<td>19.05</td>
</tr>
<tr>
<td>Monster 2</td>
<td>DC 17</td>
<td>X</td>
<td>132&quot; × 68&quot;</td>
<td>144</td>
<td>19.05</td>
</tr>
<tr>
<td>Monster 2</td>
<td>DC 18</td>
<td>U</td>
<td>132&quot; × 68&quot;</td>
<td>144</td>
<td>19.05</td>
</tr>
<tr>
<td>Monster 2</td>
<td>DC 19</td>
<td>V</td>
<td>132&quot; × 68&quot;</td>
<td>144</td>
<td>19.05</td>
</tr>
</tbody>
</table>

Table A.3: Some characteristics of E683 downstream drift chambers. Narrower cells are proximal and wider cells are distal to the beam center. DC 12 is a delay line plane. In the monster chambers, the cant in the U and V planes is ±16.7°. One X plane in Monster 1 was uninstrumented.
U and V planes have wires running in a direction at an angle to the vertical. The E683 convention defines U planes as those with wires running from lower left to upper right looking along the beam (or Z) axis. V planes are those with wires running from lower right to upper left. It is often difficult to design chambers with both X and Y planes, and U and V planes in conjunction with X planes are a compromise design permitting hit location in both directions.

A.1 Algorithm

Tracking was divided into three sections: first was the resolution of hits into coordinate space; second was the identification of possible tracks; and third was the arbitration among track candidates, carried out synchronously with vertexing. Because data in Y was very limited and, for DCs 2, 6, and 12, unreliable, tracking only proceeded in the X-Z plane. This was, however, more than sufficient to provide good vertexing, as will be demonstrated.

A.1.1 Hit Resolution

The most important part of tracking is the resolution of hits into coordinate space. This was done by Jim Waters and Med Webster of Vanderbilt University, without whose contributions the tracking could not have proceeded. For the PWCs, hit resolution was relatively trivial since it was purely a geometric exercise. To first order, the location of PWC planes was known from survey data and the location of individual wires was simply a function of wire spacing.

For the drift chambers, wire location could be obtained in the same fashion, but exact hit location required more work. When a charged particle passes through a drift chamber, it
leaves behind a trail of ionization in the gas. The chambers are under high field, under whose influence the ionization electrons move toward high potential sense wires. The electrons are, of course, accelerated by the field and thereby develop enough energy to ionize more gas atoms by collision. In this way, the gas and field act to amplify the charge that reaches the sense wire. For typical drift chamber topologies, the drift time is up to several hundred nanoseconds, a number easily resolvable by standard TDCs. Drift chambers thus record not only wire hit, like the PWCs, but also distance from the wire in the form of drift time. Reconverti ng that drift time into a distance is the difficult part of drift chamber hit resolution, as it requires careful fitting of the time spectrum of hits. In addition, ambiguities crop up because the time recorded cannot distinguish between charge approaching the sense wire from the left and charge approaching from the right. Each wire hit thus represents two possible hit locations.

The time-to-distance conversion was made more difficult when it was discovered that for unknown reasons, the common stop (a reference point for drift times) was several nanoseconds wide. Several nanoseconds uncertainty in drift time is hundreds of microns uncertainty in position.

For both PWCs and DCs, hit resolution was refined by use of single muon tracks by comparing hit location to the position of the track at the location of the plane. By adjusting the Z and X offsets of a given plane, the deviation between hit and track can be minimized; this procedure was be performed iteratively over all planes for maximum consistency.
A.1.2 Track Candidate Identification

Once the hit resolution has been accomplished, all that’s left is brute force computer work. At this stage, the tracking procedure forks. If the spectroscopic magnet is off, straight-through tracking is performed. Regardless of the state of the spectroscopic magnet, tracking is then divided into upstream and downstream segments, although there are additional requirements imposed if straight-through tracking has been done. For all three straight-through, downstream, and upstream types of tracking, the procedure is substantially similar.

Downstream tracking used DC planes 7–13, 16, and 17, and upstream tracking used DCs 1–6 and PWC plane 3. Straight-through tracking used both sets of planes simultaneously. In addition, upstream tracking used a virtual magnet plane (VMP), which is the set of “hits” made by extending downstream tracks to the Z position of the magnet. This will be more fully explicated below.

Two anchor planes are chosen, one each from a set of low Z planes and a set of high Z planes. For downstream tracking, anchors were DCs 8 and 11 (low Z), and 13 and 17 (high Z). For upstream tracking, anchors were the VMP and PWC 3 and DCs 1 and 2, and DCs 3–6 respectively. For straight-through tracking, anchors were PWC 3 and DCs 3 and 4, and DCs 8, 11, 13, and 17 respectively. On each plane, wires were divided into two or three overlapping regions. Each possible pair of hits from each possible pair of anchor planes was considered. Both hits had to come from similar regions. This requirement reduced the amount of computing required by not working on prima facie pathological tracks—tracks neither pointing near the target nor parallel to the beamline, for example.

Pairs of hits define a line. Other planes were inspected to see if they had any hits near the line. “Near” was defined as being within 14% of a cellwidth for the DCs, within
one cellwidth for the PWC, and within seven mm for the VMP. If at least two additional
hits were located near the line (three in the case of straight-through tracks), the set of hits
including the two anchor plane hits plus all near hits was made a provisional track candidate.
A line was fit through the set of hits. Several cuts were then applied. Straight-through and
upstream candidates had to pass within 300 mm of X=0 when projected to Z=0 (the target
location). Straight-through and downstream candidates had to pass through the magnet
aperture. Downstream candidates were projected to the magnet center and the MCAL
face and could not simultaneously have $z_{magnet} > \pm 100$ mm and $z_{MCAL} > \pm 100$ mm, i.e.
tracks could not cross zero by large amounts, in order to eliminate false or very low energy
"clutter" tracks in the highly-populated central regions of the chambers. Finally, the $\chi^2$ per
degree of freedom of the line fitted to the hits had to be less than 8.0 for downstream and
straight-through candidates and less than 10.0 for upstream candidates. The errors on hits
which go into the calculation of $\chi^2$ are not rigorously determined, so the significance of
the value of $\chi^2$ is only relative; the value at which to cut was determined empirically. (In
addition, track candidate duplication culling was implemented, since multiple sets of anchor
planes could produce the same candidate.)

Once straight-through track candidate determination was complete, both downstream
and upstream track candidates were also sought. Here, a downstream or upstream track
candidate that matched the appropriate portion of a straight-through track candidate was
discarded. In addition, no VMP was used for upstream tracking. Otherwise, the procedure
was as outlined above.

If the spectroscopic magnet is on, then downstream tracking is independent of upstream
tracking. Following the identification of downstream track candidates, the candidates go
through arbitration as defined below. On the theory that downstream tracks came from upstream, final downstream tracks are then projected to the center of the magnet. Their position then becomes a hit in the virtual magnet plane (VMP) and is used as a possible additional hit in upstream tracking.

A.1.3 Arbitration among Track Candidates

Typically, large numbers of track candidates are found for each type of tracking. These candidates often differ only slightly in the sets of hits that compose them—a pair of candidates might differ only in a single pair of hits representing the left and right ambiguities of drift time. Obviously, some way of distinguishing among these candidates must be found. E683 has chosen to value both goodness of track as measured by $\chi^2$ per degree of freedom and tracks which have as many hits as possible. Given that our chambers are not particularly good, having many hits is seen as a way of distinguishing genuine tracks from spurious ones. Both valuable measures of track quality have been combined by looking at the single number $\chi^2$ per degree of freedom per degree of freedom ($\chi^2/(df)^2$).

Downstream candidates are arbited in the simplest manner. Given that each hit comes from a wire, and that each wire can give rise to up to two hits via left-right drift ambiguity, candidates are sorted into sets in which every member of the set shares a wire with at least one other member of the set. In each set, then, the track with the lowest $\chi^2/(df)^2$ is accepted into the final set of found tracks. All candidates which share a wire with that track are purged. If there are candidates remaining in the set, the process is repeated. Thus, after arbitration, the set of found tracks consists of tracks which do not share wires and which have the lowest $\chi^2/(df)^2$ when compared to any track candidate with which they do
share a wire.

For all arbitration, candidates with only four hits are considered marginal and are only accepted if there are no possible alternate candidates with at least five hits. Although this represents a considerable complication at the software level, it has the virtue of being easy to explain.

For both straight-through and upstream tracking, the arbitration process is convoluted with vertex-finding. A vertex is defined as the point which has the minimum $d^2$, where

$$d^2 = \frac{\sum_{i=1}^{n}(\text{perpendicular distance from track } i \text{ to vertex})^2}{n - 2},$$

for $n \geq 3$, where $n$ is the number of tracks contributing to the vertex. $d^2$ is defined as zero for $n = 2$ and is undefined for $n = 1$. The division by $(n-2)$ is equivalent to a division by number of degrees of freedom. For a line $A$ with $(\text{slope,intercept})=(m,b)$, there is a line $A'$ with $(-1/m,y_0+x_0/m)$ that is perpendicular to the first line and passes through a point $(x_0,y_0)$. The perpendicular distance between the first line and the point $(x_0,y_0)$ is then the distance between the intersection of $A$ and $A'$ and the point $(x_0,y_0)$. By inspection, $d^2$ is positive definite and second order in $x_0$ and $y_0$ and is thus analytically minimizable for variable $x_0$ and $y_0$. With $(m_i,b_i)$ for the $(\text{slope,intercept})$ of the $i$th track and using the definitions:

$$A = \sum_{i=1}^{n} \frac{m_i^2}{m_i^2 + 1},$$

$$B = \sum_{i=1}^{n} \frac{-m_i}{m_i^2 + 1},$$

$$C = \sum_{i=1}^{n} \frac{1}{m_i^2 + 1},$$

106
\[ D = \sum_{i=1}^{n} \frac{-m_i b_i}{m_i^2 + 1}, \]

\[ E = \sum_{i=1}^{n} \frac{b_i}{m_i^2 + 1}, \]

then:

\[ x_v = \frac{DC - BE}{AC - B^2}, \]

\[ y_v = \frac{AE - BD}{AC - B^2}. \]

From the set of (remaining) upstream or straight-through track candidates, the candidate with the lowest \( \chi^2/(df) \) is accepted as a found track. If at least three tracks have been accepted, their vertex is found with an associated \( d^2 \). The vertex is considered sufficiently point-like if \( d^2 \leq 200 \text{ mm}^2 \). If the vertex is acceptable, the remaining track candidates are purged of all candidates sharing a wire with the most recently accepted track. If the vertex is not point-like, the vertex is tested to determine if any possible subset of \( n-1 \) or \( n-2 \) contributing tracks forms an acceptable vertex. If so, found tracks not within the best acceptable subset are purged from the set of found tracks. Candidates that conflict with the purged found track are returned to the set of candidates being arbitrated. Loop to the beginning of this paragraph until there are no remaining candidates that could contribute to an acceptable vertex. In this way, the best possible vertex is found, using the best possible tracks.

There may be candidates remaining which do not conflict with tracks that contribute to the vertex, but which cannot contribute to an acceptable vertex. These candidates may
also be arbitrated among in the usual fashion. The candidate with the lowest $\chi^2/(df)^2$ is accepted and all candidates that share a wire with it are eliminated; this is repeated until there are no remaining candidates.

A.2 Results

Figure A.1 shows a typical fully-tracked event\(^1\). There are six upstream tracks, all contributing to the vertex. Five of those tracks use VMP hits generated by downstream tracks. The vertex is located nearly on-center within the target vessel. The event comes from run 2917, which is a photon beam incident upon the hydrogen target with the spectroscopic magnet on.

As shown in Figure A.2, a typical vertex had about five tracks contributing to its formation.

Figure A.4 shows a width of $\pm 16$ mm, which is consistent with the size of the pion beam. Thus, the resolution of the vertexing algorithm in X is less than $\pm 16$ mm and cannot be determined more accurately. This figure also shows that the beam was off-center in the tracking coordinate system by about 4 mm. While the beam may be off-center, of course, the tracking coordinate system is consistent only with itself, so small offsets from the nominal coordinate system may be expected.

In Figure A.5a, with no specific biases, the vertexing algorithm reconstructs the hydrogen target vessel with the correct length of 50 cm (at full width half max). Figure A.5b shows a width of $\pm 47$ mm with an offset of 15 mm. Nuclear targets are of smaller thickness than this. Thus, the resolution of the vertexing algorithm in Z is approximately $\pm 47$ mm,

\(^1\)The "X" marks denote out-of-time hits, hits whose drift times are nonsensical, probably leftover from an earlier event.
Figure A.1: A typical event shown with full tracking.
Figure A.2: The number of tracks contributing to acceptable vertices for pion beam incident on hydrogen target, spectroscopic magnet on.

Figure A.3: $d^2$ as defined in the text for vertices, with a cutoff at 200 mm$^2$, for pion beam incident on hydrogen target, spectroscopic magnet on.

which is no more than a few percent of the length of the experiment. A positive offset in $Z$ for nuclear targets is expected, since nuclear targets were mounted on the downstream side of a support positioned at $Z=0$, although this offset is expected to be on the order of a few mm.

The empty target $Z$ vertex shown in Figure A.6 does an excellent job of showing matter in the beam line. The target vessel windows are visible at ±250 mm. The target tent windows
Figure A.4: X position of vertex, with a cutoff at ±40 mm, for pion beam incident on hydrogen target, spectroscopic magnet on.

Figure A.5: (a) The position of the vertex in Z for pion beam incident on hydrogen target, spectroscopic magnet on. (b) The position of the vertex in Z for photon beam incident on nuclear target 3, spectroscopic magnet on.
Figure A.6: The position of the vertex in Z for pion beam incident on empty target vessel, spectroscopic magnet on.

are visible at ±600 mm. The bulk of the material in the beam line is the counter C2, visible at +1000 mm. The slight bump at ≈+1300 mm may be the first of the PWCs. The tracking was tuned to be most accurate over a Z range near the target, so it is impractical to look for other matter in the beam.

Finally, it is possible to determine the resolution of each plane. For a track with a hit on a given plane, the hit is eliminated and the track refitted; the distance from the track to the hit on the given plane is the deviation. The RMS deviation, which is taken to be the resolution, is given in Table A.4. Resolution is on the order of a millimeter, while drift chambers typically have resolutions in the very low hundreds of microns. The bulk of this problem is attributed to the common stop error described above.
<table>
<thead>
<tr>
<th>Plane</th>
<th>RMS Deviation (mm)</th>
<th>Plane</th>
<th>RMS Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWC 3</td>
<td>1.253</td>
<td>DC 7</td>
<td>0.926</td>
</tr>
<tr>
<td>DC 1</td>
<td>1.231</td>
<td>DC 8</td>
<td>0.928</td>
</tr>
<tr>
<td>DC 2</td>
<td>1.222</td>
<td>DC 9</td>
<td>0.902</td>
</tr>
<tr>
<td>DC 3</td>
<td>0.850</td>
<td>DC 10</td>
<td>0.855</td>
</tr>
<tr>
<td>DC 4</td>
<td>1.067</td>
<td>DC 11</td>
<td>0.816</td>
</tr>
<tr>
<td>DC 5</td>
<td>1.202</td>
<td>DC 12</td>
<td>0.924</td>
</tr>
<tr>
<td>DC 6</td>
<td>1.377</td>
<td>DC 13</td>
<td>0.754</td>
</tr>
<tr>
<td>VMP</td>
<td>1.682</td>
<td>DC 16</td>
<td>0.766</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DC 17</td>
<td>0.890</td>
</tr>
</tbody>
</table>

Table A.4: RMS deviations for each plane used in the tracking.
Appendix B

Smearing Matrix

This appendix sets forth the smearing matrix that resulted from the lowest-order Monte Carlo simulation. This matrix transforms $x_\gamma$ at the parton level to $x_\gamma$ at the jet level by incorporating the effects of hadronization, calorimeter acceptance, and jet-finding. This matrix was used to transform the NLO parton-level prediction into a jet-level-like prediction that could be compared to experimental data.

The matrix is given in two forms. The first is raw (weighted) counts. The second row-wise normalizes the matrix, making it independent of parton-level distribution and suitable for use as a transformation matrix.

Note that the matrix is not square. This is because parton-level $x_\gamma$ has a strict maximum of 1.0, which can be smeared to a jet-level $x_\gamma$ larger than 1.0. I.e., the parton-level $x_\gamma$ distribution is represented by a vector of length 16 covering a range from 0.2 to 1.0, the smearing matrix is 16x18, and the jet-level $x_\gamma$ distribution is an vector of length 18 covering a range from 0.2 to 1.1.
<table>
<thead>
<tr>
<th>$x_\gamma$ (parton-level)</th>
<th>$0.20-0.25$</th>
<th>$0.25-0.30$</th>
<th>$0.30-0.35$</th>
<th>$0.35-0.40$</th>
<th>$0.40-0.45$</th>
<th>$0.45-0.50$</th>
<th>$0.50-0.55$</th>
<th>$0.55-0.60$</th>
<th>$0.60-0.65$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.20-0.25$</td>
<td>0.0</td>
<td>3.7</td>
<td>3.7</td>
<td>4.2</td>
<td>5.5</td>
<td>0.0</td>
<td>1.2</td>
<td>0.9</td>
<td>0.0</td>
</tr>
<tr>
<td>$0.25-0.30$</td>
<td>0.0</td>
<td>2.8</td>
<td>8.5</td>
<td>5.2</td>
<td>5.6</td>
<td>4.3</td>
<td>5.1</td>
<td>1.8</td>
<td>1.0</td>
</tr>
<tr>
<td>$0.30-0.35$</td>
<td>0.0</td>
<td>3.3</td>
<td>8.0</td>
<td>14.3</td>
<td>16.2</td>
<td>14.8</td>
<td>14.4</td>
<td>7.9</td>
<td>3.8</td>
</tr>
<tr>
<td>$0.35-0.40$</td>
<td>0.0</td>
<td>2.8</td>
<td>9.4</td>
<td>9.6</td>
<td>18.5</td>
<td>14.2</td>
<td>27.1</td>
<td>15.5</td>
<td>10.4</td>
</tr>
<tr>
<td>$0.40-0.45$</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>7.9</td>
<td>27.6</td>
<td>19.5</td>
<td>23.4</td>
<td>21.1</td>
<td>16.1</td>
</tr>
<tr>
<td>$0.45-0.50$</td>
<td>0.0</td>
<td>0.9</td>
<td>0.0</td>
<td>7.4</td>
<td>19.7</td>
<td>29.0</td>
<td>35.8</td>
<td>35.6</td>
<td>24.4</td>
</tr>
<tr>
<td>$0.50-0.55$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.8</td>
<td>1.0</td>
<td>16.0</td>
<td>20.9</td>
<td>35.4</td>
<td>34.8</td>
<td>27.6</td>
</tr>
<tr>
<td>$0.55-0.60$</td>
<td>0.0</td>
<td>0.0</td>
<td>1.8</td>
<td>1.9</td>
<td>8.7</td>
<td>19.0</td>
<td>42.2</td>
<td>38.0</td>
<td>44.8</td>
</tr>
<tr>
<td>$0.60-0.65$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>10.8</td>
<td>17.8</td>
<td>29.5</td>
<td>40.4</td>
<td>36.5</td>
</tr>
<tr>
<td>$0.65-0.70$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.9</td>
<td>2.6</td>
<td>9.9</td>
<td>20.1</td>
<td>47.3</td>
<td>57.3</td>
</tr>
<tr>
<td>$0.70-0.75$</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.9</td>
<td>2.5</td>
<td>8.0</td>
<td>24.8</td>
<td>32.7</td>
<td>53.9</td>
</tr>
<tr>
<td>$0.75-0.80$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.2</td>
<td>2.4</td>
<td>9.8</td>
<td>17.4</td>
<td>35.2</td>
</tr>
<tr>
<td>$0.80-0.85$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>3.5</td>
<td>13.2</td>
<td>28.4</td>
<td>32.4</td>
</tr>
<tr>
<td>$0.85-0.90$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>5.7</td>
<td>10.7</td>
<td>26.6</td>
</tr>
<tr>
<td>$0.90-0.95$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.9</td>
<td>15.6</td>
<td>35.5</td>
</tr>
<tr>
<td>$0.95-1.00$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>6.8</td>
<td>30.0</td>
<td>102.5</td>
<td>242.2</td>
<td>446.8</td>
</tr>
</tbody>
</table>

Table B.1: The first half of the raw smearing matrix. Each entry in the table is the weighted number of events with $x_\gamma$ at the particle level corresponding to the row and $x_\gamma$ at the jet level corresponding to the column.
<table>
<thead>
<tr>
<th>$x_\gamma$ (parton-level)</th>
<th>0.65-0.70</th>
<th>0.70-0.75</th>
<th>0.75-0.80</th>
<th>0.80-0.85</th>
<th>0.85-0.90</th>
<th>0.90-0.95</th>
<th>0.95-1.00</th>
<th>1.00-1.05</th>
<th>1.05-1.10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20-0.25</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.25-0.30</td>
<td>1.3</td>
<td>1.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.30-0.35</td>
<td>3.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.35-0.40</td>
<td>4.3</td>
<td>4.3</td>
<td>2.6</td>
<td>2.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.40-0.45</td>
<td>15.3</td>
<td>8.0</td>
<td>1.9</td>
<td>0.0</td>
<td>0.0</td>
<td>1.1</td>
<td>1.9</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.45-0.50</td>
<td>30.5</td>
<td>14.0</td>
<td>8.4</td>
<td>3.9</td>
<td>2.0</td>
<td>0.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.50-0.55</td>
<td>31.6</td>
<td>13.6</td>
<td>11.8</td>
<td>6.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.55-0.60</td>
<td>38.0</td>
<td>26.8</td>
<td>16.5</td>
<td>8.0</td>
<td>0.9</td>
<td>3.1</td>
<td>1.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.60-0.65</td>
<td>36.9</td>
<td>22.3</td>
<td>27.7</td>
<td>5.6</td>
<td>4.1</td>
<td>1.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.65-0.70</td>
<td>48.2</td>
<td>34.7</td>
<td>21.9</td>
<td>16.9</td>
<td>8.3</td>
<td>2.9</td>
<td>2.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.70-0.75</td>
<td>48.5</td>
<td>38.6</td>
<td>27.9</td>
<td>29.9</td>
<td>8.5</td>
<td>2.8</td>
<td>2.9</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.75-0.80</td>
<td>48.9</td>
<td>39.9</td>
<td>42.6</td>
<td>24.1</td>
<td>6.4</td>
<td>6.7</td>
<td>2.7</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.80-0.85</td>
<td>43.4</td>
<td>58.3</td>
<td>34.0</td>
<td>22.5</td>
<td>9.3</td>
<td>2.1</td>
<td>1.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.85-0.90</td>
<td>67.0</td>
<td>76.0</td>
<td>63.0</td>
<td>54.3</td>
<td>28.9</td>
<td>10.9</td>
<td>4.9</td>
<td>0.0</td>
<td>1.1</td>
</tr>
<tr>
<td>0.90-0.95</td>
<td>108.0</td>
<td>135.2</td>
<td>115.0</td>
<td>98.7</td>
<td>65.1</td>
<td>34.0</td>
<td>13.2</td>
<td>10.6</td>
<td>1.1</td>
</tr>
<tr>
<td>0.95-1.00</td>
<td>684.4</td>
<td>843.0</td>
<td>786.6</td>
<td>686.9</td>
<td>476.6</td>
<td>305.5</td>
<td>172.1</td>
<td>63.8</td>
<td>19.9</td>
</tr>
</tbody>
</table>

Table B.2: The last half of the raw smearing matrix. Each entry in the table is the weighted number of events with $x_\gamma$ at the particle level corresponding to the row and $x_\gamma$ at the jet level corresponding to the column.
<table>
<thead>
<tr>
<th>$x_\gamma$ (parton-level)</th>
<th>$x_\gamma$ (jet-level)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.20-0.25</td>
</tr>
<tr>
<td>0.20-0.25</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.25-0.30</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.30-0.35</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.35-0.40</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.40-0.45</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.45-0.50</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.50-0.55</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.55-0.60</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.60-0.65</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.65-0.70</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.70-0.75</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.75-0.80</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.80-0.85</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.85-0.90</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.90-0.95</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.95-1.00</td>
<td>0.00000</td>
</tr>
</tbody>
</table>

Table B.3: The first third of the normalized smearing matrix. The matrix is row-normalized to a sum of 1.00 with an entry being the probability of an event with parton-level $x_\gamma$ corresponding to the row having a jet-level $x_\gamma$ corresponding to the column.
<table>
<thead>
<tr>
<th>$x_\gamma$ (parton-level)</th>
<th>0.50-0.55</th>
<th>0.55-0.60</th>
<th>0.60-0.65</th>
<th>0.65-0.70</th>
<th>0.70-0.75</th>
<th>0.75-0.80</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20-0.25</td>
<td>0.06083</td>
<td>0.04637</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.25-0.30</td>
<td>0.13889</td>
<td>0.04838</td>
<td>0.02719</td>
<td>0.03583</td>
<td>0.03465</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.30-0.35</td>
<td>0.16706</td>
<td>0.09236</td>
<td>0.04463</td>
<td>0.03880</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.35-0.40</td>
<td>0.22357</td>
<td>0.12803</td>
<td>0.08556</td>
<td>0.03587</td>
<td>0.03578</td>
<td>0.02132</td>
</tr>
<tr>
<td>0.40-0.45</td>
<td>0.16171</td>
<td>0.14548</td>
<td>0.11157</td>
<td>0.10601</td>
<td>0.05506</td>
<td>0.01310</td>
</tr>
<tr>
<td>0.45-0.50</td>
<td>0.16854</td>
<td>0.16733</td>
<td>0.11460</td>
<td>0.14374</td>
<td>0.06566</td>
<td>0.03976</td>
</tr>
<tr>
<td>0.50-0.55</td>
<td>0.17627</td>
<td>0.17336</td>
<td>0.13721</td>
<td>0.15748</td>
<td>0.06761</td>
<td>0.05850</td>
</tr>
<tr>
<td>0.55-0.60</td>
<td>0.16811</td>
<td>0.15138</td>
<td>0.17846</td>
<td>0.15139</td>
<td>0.10697</td>
<td>0.06576</td>
</tr>
<tr>
<td>0.60-0.65</td>
<td>0.12657</td>
<td>0.17350</td>
<td>0.15670</td>
<td>0.15845</td>
<td>0.09572</td>
<td>0.11886</td>
</tr>
<tr>
<td>0.65-0.70</td>
<td>0.07344</td>
<td>0.17288</td>
<td>0.20943</td>
<td>0.17627</td>
<td>0.12697</td>
<td>0.08022</td>
</tr>
<tr>
<td>0.70-0.75</td>
<td>0.08776</td>
<td>0.11548</td>
<td>0.19048</td>
<td>0.17121</td>
<td>0.13651</td>
<td>0.09858</td>
</tr>
<tr>
<td>0.75-0.80</td>
<td>0.04133</td>
<td>0.07288</td>
<td>0.14797</td>
<td>0.20544</td>
<td>0.16742</td>
<td>0.17874</td>
</tr>
<tr>
<td>0.80-0.85</td>
<td>0.05312</td>
<td>0.11417</td>
<td>0.13012</td>
<td>0.17467</td>
<td>0.23437</td>
<td>0.13653</td>
</tr>
<tr>
<td>0.85-0.90</td>
<td>0.02679</td>
<td>0.06686</td>
<td>0.12228</td>
<td>0.16853</td>
<td>0.19123</td>
<td>0.15853</td>
</tr>
<tr>
<td>0.90-0.95</td>
<td>0.02227</td>
<td>0.05066</td>
<td>0.09442</td>
<td>0.15429</td>
<td>0.19312</td>
<td>0.16439</td>
</tr>
<tr>
<td>0.95-1.00</td>
<td>0.02107</td>
<td>0.04976</td>
<td>0.09179</td>
<td>0.14061</td>
<td>0.17322</td>
<td>0.16162</td>
</tr>
</tbody>
</table>

Table B.4: The second third of the normalized smearing matrix. The matrix is row-normalized to a sum of 1.00 with an entry being the probability of an event with parton-level $x_\gamma$, corresponding to the row having a jet-level $x_\gamma$, corresponding to the column.
<table>
<thead>
<tr>
<th>$x_\gamma$ (parton-level)</th>
<th>$0.80-0.85$</th>
<th>$0.85-0.90$</th>
<th>$0.90-0.95$</th>
<th>$0.95-1.00$</th>
<th>$1.00-1.05$</th>
<th>$1.05-1.10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20-0.25</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.25-0.30</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.30-0.35</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.35-0.40</td>
<td>0.01961</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.40-0.45</td>
<td>0.00000</td>
<td>0.00728</td>
<td>0.01344</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.45-0.50</td>
<td>0.01839</td>
<td>0.00942</td>
<td>0.00446</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.50-0.55</td>
<td>0.03186</td>
<td>0.00000</td>
<td>0.00472</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.55-0.60</td>
<td>0.03176</td>
<td>0.00355</td>
<td>0.01241</td>
<td>0.00487</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.60-0.65</td>
<td>0.02425</td>
<td>0.01746</td>
<td>0.00549</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.65-0.70</td>
<td>0.06197</td>
<td>0.03049</td>
<td>0.01059</td>
<td>0.00854</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.70-0.75</td>
<td>0.10573</td>
<td>0.02995</td>
<td>0.00985</td>
<td>0.01042</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.75-0.80</td>
<td>0.10113</td>
<td>0.02695</td>
<td>0.02812</td>
<td>0.01147</td>
<td>0.00000</td>
<td>0.00374</td>
</tr>
<tr>
<td>0.80-0.85</td>
<td>0.09059</td>
<td>0.03726</td>
<td>0.00847</td>
<td>0.00652</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>0.85-0.90</td>
<td>0.13660</td>
<td>0.07260</td>
<td>0.02729</td>
<td>0.01233</td>
<td>0.00000</td>
<td>0.00265</td>
</tr>
<tr>
<td>0.90-0.95</td>
<td>0.14100</td>
<td>0.09307</td>
<td>0.04853</td>
<td>0.01886</td>
<td>0.01510</td>
<td>0.00156</td>
</tr>
<tr>
<td>0.95-1.00</td>
<td>0.14112</td>
<td>0.09792</td>
<td>0.06278</td>
<td>0.03536</td>
<td>0.01310</td>
<td>0.00408</td>
</tr>
</tbody>
</table>

Table B.5: The last third of the normalized smearing matrix. The matrix is row-normalized to a sum of 1.00 with an entry being the probability of an event with parton-level $x_\gamma$ corresponding to the row having a jet-level $x_\gamma$ corresponding to the column.