DOE/ER/03130--T24

Received by [signature]
JUL 1 2 1990

Simulation of Top Quark Production at D0

DOE/ER/03130--T24

DE90 013331

Christopher M. Barter

Senior Thesis

Submitted in partial fulfillment of the requirements of the

Degree of Bachelor of Science

in the Department of Physics at Brown University

May 12, 1990

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

1. Introduction	2
1.1 The Standard Model	2
1.2 The Top Quark	6
1.3 Bounds on Top	8
2. The D0 Experiment	9
2.1 The D0 Detector	7
2.2 Physics at D0	11
3. Top Simulation Procedure	15
3.1 Top Processes	15
3.2 Data Generation	16
4. Analysis and Results	18
4.1 JETS Bank Analysis	18
4.2 Electron Finder Analysis	19
4.3 Conclusions	20
5. Figures	21

Acknowledgements

I would like to direct special thanks to my advisor, Professor Richard Partridge, without whose guidance this thesis would not have come to fruition. Thanks as well to David Ascher for his help and patience in all tasks ranging from computing to proofreading. Finally, I am indebted to Niko Waesche and Jeff Humphrey for their friendship and support during the best and worst of times.

ABSTRACT

The production of top at the Fermilab Tevatron D0 detector was investigated using full monte carlo and event reconstruction packages. In total, 480 events were generated for $m_T = 150 \frac{GeV}{c^2}$ in the specific $t\bar{t}$ decay modes $t(\bar{t}) \rightarrow b(\bar{b}) + W^\pm$, with at least one W decaying to leptons. These events were then analyzed in an attempt to find characteristic signals for top production at D0.

1. Introduction

1.1. THE STANDARD MODEL

One of the major goals of modern particle physics is to describe the electromagnetic and weak forces within the confines of a single theory. One such description currently under investigation is the Standard Model of Electro-weak Interactions. At the present time there are many experimental efforts concentrating on this theory. These large scale experiments are being currently conducted at high energy accelerator laboratories such as the CERN *SppS* and Fermilab Tevatron hadron colliders, and at the CERN LEP and SLAC SLC lepton colliders.

The Standard Model describes the electromagnetic and the weak interactions as manifestations of a single force. The unification of the forces in nature within the confines of ever more fundamental theories has historically been a primary motivation of physical thought. The first unified field theory was given by Maxwell's Equations, which describe electricity and magnetism as manifestations of a single electromagnetic force. As physics progressed, the number of fundamental forces has been reduced to four: electromagnetism, gravity, and the strong and weak nuclear forces. While the first two forces are familiar from the macro-universe, the strong and weak interactions exist at the atomic scale. The strong nuclear force, commonly called Quantum Chromodynamics, is responsible for binding together the nucleons of atoms, and, at a deeper level, for the structure of the nucleons themselves. The Weak Nuclear Force is responsible for β^- decay of unstable nuclei. In this case the dynamics are

$$n \rightarrow p + e^- + \bar{\nu}_e$$

At first glance, it would appear that the Weak Force and electromagnetism would have very little in common. In reality the symmetry is hidden, and unveils itself experimentally only at relatively high energies.

As mentioned above, the Standard Model of electroweak interactions is a gauge field theory, also termed Yang-Mills theory. The term gauge means that the dynamics

of the theory originate from the invariance of the field Lagrangian under symmetry transformations. By Noether's Theorem, for every symmetry of the Lagrangian, i. e., for every transformation under which the Lagrangian remains invariant, there exists a conserved quantity. A common example is the invariance of the electromagnetic Lagrangian under redefinition of the electrostatic potential. This in turn implies conservation of charge. The Standard Model is based, in particular, on the symmetry group $SU(2)_L \times U(1)$. Here, the $U(1)$ group represents the invariance of the electroweak Lagrangian under local unitary transformations. Such local invariance requires the existence of the (massless) photon "gauge particle" to restore the symmetry. Thus, the electromagnetic mediating boson arises as a direct consequence of the $U(1)$ symmetry. A Feynman diagram of one such mediated interaction, $e^- + e^- \rightarrow e^- + e^-$ is given in figure 1a. It should be noted that $U(1)$ is an Abelian group, indicating that the photon does not interact with itself, i. e., it is not charged. Analogously, by requiring $SU(2)_L$ local Lagrangian invariance, one generates three massless, in this case non-Abelian gauge bosons, one neutral and two charged. Here, the " L " indicates that the interaction fields mediate between left-handed fermions, i. e., fermions with helicity of $-1/2$. Following the analogy to electromagnetism, these three massless interaction fields could be taken to be the mediating particles of the Weak Force. Furthermore, this force does not couple directly to the nucleons themselves, but rather to the fundamental fermions, quarks and leptons. Thus, for example, the β^- decay description above can be recast into the form

$$d \rightarrow W^- + u \rightarrow e^- + \bar{\nu}_e + u$$

where u and d are the quark constituents of the neutron and the proton. Mathematically, the interaction amplitude for this charge current is expressed at low energies as

$$M^{CC} = \left(\frac{g}{\sqrt{2}}J^\mu\right)\left(\frac{1}{M_W^2}\right)\left(\frac{g}{\sqrt{2}}J_\mu^\dagger\right)$$

where g is a coupling constant analogous to e in electromagnetism, and J^μ and J_μ

are the currents of the left-handed fermions which undergo the “flavor” changes

$$d \rightarrow u, \bar{\nu}_e \rightarrow e^-.$$

The mediative nature of the W^- is more apparent in the corresponding Feynman diagram (fig. 1b).

Left in such a state, however, the model would be incomplete. As mentioned above, the $SU(2)$ Yang Mills’ fields are massless which would imply an infinite interaction distance, as is the case for electromagnetism. But experiment shows that the Weak force is effective only over very small distances, implying the existence of very massive gauge bosons. The mechanism responsible for generating these masses while preserving the gauge symmetries of the interaction Lagrangian is Spontaneous Symmetry Breaking. To produce this, one introduces a self-interacting scalar field to the Lagrangian, the so-called Higgs Field, of the form:

$$L = (\partial_\mu \phi)^* (\partial^\mu \phi) + \mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2$$

where μ and λ are positive constants. As before, one requires $SU(2)$ symmetry for this portion of the Lagrangian. By constructing the Higgs self-interaction terms in this manner, the state of minimum energy for the field lies asymmetrically about the origin (see fig. 2). Upon “breaking the symmetry” of the Higgs field by expanding about the minimum energy state, the interaction Lagrangian gains mass terms for the three $SU(2)$ gauge bosons. One finds

$$M_W = g\mu \frac{1}{2\lambda}$$

The constants λ and μ can be chosen to fit the experimentally determined mass spectrum. An added bonus to the model is that Spontaneous Symmetry Breaking similarly generates masses for the complete set of leptons and fermions in the Lagrangian.

To complete the model, an additional parameter is introduced, θ_W (the Weinberg Angle), which is to be determined by experiment. The Weinberg Angle determines

the mixing of the two neutral $SU(2) \times U(1)$ gauge bosons to produce the desired massless photon field and massive neutral current:

$$A_\mu = \cos \theta_W B_\mu + \sin \theta_W W_\mu^3$$

$$Z_\mu = -\sin \theta_W B_\mu + \cos \theta_W W_\mu^3$$

The masses of the $W^\pm$ and Z^0 are predicted to be

$$M_W = \frac{37.3}{\sin \theta_W} \frac{\text{GeV}}{c^2}$$

$$M_Z = \frac{74.6}{\sin 2\theta_W} \frac{\text{GeV}}{c^2}.$$

Taken as whole, the Standard Model has been a great theoretical success. It reduces a multitude of physical phenomenon to only 18 parameters. In particular, the added element of Spontaneous Symmetry Breaking, first applied to electro-weak interactions by Weinberg and Salam, was shown by 't Hooft to be the necessary ingredient to make the theory "renormalizable". Renormalizable means that the theory is convergent at high energies despite the existence of massive gauge particles. The detection of the theoretically predicted charged and neutral currents by the CERN UA1/UA2 experiments in 1982 is considered to be a great confirmation of the Standard Model. There remain, however, many additional phenomenon in the model yet to be verified. One such task is the experimental detection of the Higgs scalar boson. Although the Standard model can make no exact prediction as to the mass of the Higgs, experimental lower bound estimates indicate that $M_H > 25 \frac{\text{GeV}}{c^2}$. The best prospects for detection are at e^+e^- machines such as LEP (CERN).

1.2. THE TOP QUARK

Another significant experimental task is detection of the theoretically predicted t quark. According to the quark model of particle structure, all hadrons, such as the proton and neutron, among others, are made up of fundamental entities called quarks which are bound together in different way. In particular, baryons are made up of three quarks (qqq) and mesons of quarks and antiquarks ($q\bar{q}$). As mentioned above, quarks interact via a third fundamental force, the Strong Force, or Quantum Chromodynamics (QCD). Like electroweak interactions, QCD is a Yang-Mills theory, this time obeying $SU(3)$ symmetry. The eight non-Abelian, massless gauge particles generated by local gauge invariance are called Gluons. Just as the photon mediates the force between charges $+$ or $-$ carried by particles in electromagnetism, the Gluons mediate between quarks carrying 3 different “color” charges, red, blue and green. One important requirement of QCD is to explain the phenomenon of quark confinement. The word confinement simply expresses the fact that quarks are only found confined in hadronic bound states. The color force describes this mechanism by requiring quark combinations to behave as color singlets. Thus, no net color, such as that of a single quark, can be observed.

Experimental evidence for the quarks was first obtained from inelastic scattering of leptons and baryons. In particular, the structure functions of the nucleons hinted at the existence of point like objects within. The final confirmation of quark theory came with the 1974 discovery of the J/ψ resonance (predicted to consist of a $c\bar{c}$ singlet.) Based on past experiments, five quark types, or “flavours”, have been identified: up, down, charm, strange, and bottom. One can arrange the quark flavors u, d, c, s according to their quantum numbers, (charge and flavor) in order of increasing mass into two “families”:

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

In each family the first entry carries fractional charge $\frac{+2}{3}$, the second entry $\frac{-1}{3}$. The totality of multiplets formed by these quarks can be constructed by the fundamental

quadruplet represented by the symmetry group $SU(4)$ (see fig. 3). One could, naturally, expand the symmetry group to $SU(5)$ to include the heavy b quark. However, the typical mass of the b quark lies well above that of charm, thus indicating a rather awkward symmetry in such a case. In addition, since bottom carries the same charge as strange, it would seem natural to predict the existence of a sixth quark state, top, which would complete the symmetry of three parallel quark families:

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

The standard model makes no prediction as to the mass of t ; one can only reason by symmetry that it must lie above that of bottom, in an interval on the order of magnitude of the mass differences within the other two quark families. Thus, a reasonable estimate might be $M_T \approx 100 GeV$.

Further evidence for the existence of a sixth quark flavor stems from the analogous classification scheme for the known leptons:

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

Symmetric to the hadron family structure, the leptons differ in one unit of charge within families and are ordered in increasing order of mass, each electron heavier than its (presumably) massless neutrino counterpart. It should also be noted that the desire to match the hadronic parton families to their leptonic counterparts is founded in more than pure aesthetics. If the top quark did not exist, the electro-weak coupling scheme within the Standard Model would become rather asymmetrical. The only possible decay for bottom would be into other quark families at small rates via the unitary Kobayashi-Maskawa mixing matrix. The expected dominant decay mode is, however, analogous to the flavour changing mechanism in the lighter quark families. To see this, recall that in the Standard Model, all hadronic and fermionic families can couple. Assuming top exists, it would weakly couple to bottom analogously to

coupling in the β^- decay example. Recall for β^- decay, $d \rightarrow u$ and $\nu_e \rightarrow e^-$. Thus, in a b physics scenario, the following process would be possible:

$$b \rightarrow W^- + t \rightarrow e^- + \bar{\nu}_e + t$$

Clearly, if top were to exist, it would carry the same quantum numbers as all upper members of the quark families. Hence, the evidence supporting the existence of top is indeed compelling.

1.3. BOUNDS ON TOP

Since the Standard Model makes no direct predictions as to the mass of top, all regions of experimentally accessible energies are combed for likely signatures. The most recent search for top has been at the CDF experiment. Based on a detailed analysis of the most recent data run, the current lower bound (unofficial as of May, 1990) for the top mass has been determined to be:

$$m_T \geq 89 \frac{\text{GeV}}{c^2}$$

An upper bound of the top mass can be calculated by considering a combination of experimental and theoretical limitation factors. Most recently, precision Z and W mass measurements from CDF and SLAC have been used in conjunction with new results in $\nu_\mu e$ scattering, theoretical atomic parity violation requirements, and other weak-neutral-current data in calculating the upper bound to be: ^{1*}

$$m_T < 210 \frac{\text{GeV}}{c^2}$$

This calculation is made at a 90 percent confidence level, and is based on the masses $M_W = 80.0 \pm 1.0 \frac{\text{GeV}}{c^2}$, $M_Z = 90.9 \pm 0.5 \frac{\text{GeV}}{c^2}$ (CDF). For our $t\bar{t}$ simulations, we take

$$m_T = 150 \frac{\text{GeV}}{c^2}$$

which lies well within the given bounds.

* 1. P. Langacker, Phys. Rev. Lett., 1920 (1989).

2. The D0 Experiment

2.1. THE D0 DETECTOR

The Fermilab Tevatron Collider is a .28 km long ring which produces proton-antiproton collisions at energies reaching $\sqrt{s} = 2.0 \text{ TeV}$. The D0 experiment (D0 is the name of the interaction region where the detector is installed - see figure 4) was originally planned to complement the CDF (Collider Detector at Fermilab) detector located at the B0 site. Most recently, CDF researchers have obtained very impressive results from their first data run. There are several reasons for the construction of a second major detector at the Tevatron. The foremost justification is to provide an independent verification of the results obtained at CDF. This is particularly necessary since CDF will be the first exploration of physics in this energy range. The design of D0 is intended to complement that of CDF to fully exploit the Tevatron facility. For example, the CDF detector measures charged particle momenta by means of a solenoidal magnet, while D0 employs magnetic-free methods to make such measurements. A detector free of a central magnet means higher resolution energy measurements and improved particle identification. Assuming a four month run at 50 percent efficiency and a planned luminosity of $L = 5 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ (integrated luminosity $\int L dt = 2.5 \times 10^{37} \text{ cm}^{-2} = 5 \text{ pb}^{-1}$), D0 will achieve a beam crossing rate peaking at $\approx 50 \text{ kHz}$. Naturally, the physics contained in such high event rates would remain untapped without a detector capability to match.

The D0 detector is tailored in particular to making excellent energy and angular measurements of hadronic jets, and to enable precise identification and energy resolution of electrons and muons. Meeting these goals entails very fine calorimeter segmentation, few detector cracks (for high resolution measurements of missing p_T , and angular coverage extending to only a few degrees from the beam line. The detector itself is divided into three components (see figure 5): the central tracking detector, calorimeter and muon detector. The central tracking detector is responsible for identifying and determining the direction of charged particles. Cylindrical inner vertex and outer drift chambers track particles in the central region, while forward drift chambers make measurements down to small angles. The vertex and outer

drift chambers lie concentrically about the beam pipe. High spatial resolution and precise dE/dx measurements optimize particle identification. The additional element of three concentric transition radiation detector modules located in the region between the vertex and outer drift chambers compensates in tracking for lack of a central magnetic field in D0. In particular, it is essential for the TRD's to reject the high π^0 background in order to correctly identify electrons in the calorimetry.

Muons generally pass undetected through the calorimeter sections of the detector. To detect these particles, a muon detector is positioned in the outermost regions of D0. It consists of two major components for making p_T measurements: iron toroidal magnets and proportional drift tubes. The magnets located in the central and end regions of the detector utilize the muon's charge by bending the trajectories. These trajectories are tracked in the proportional drift tubes situated before and after the iron regions.

For the D0 experiment, unlike many other high energy experiments, calorimetry is the primary detection tool. The relevant particles to be detected are hadronic jets, leptons and missing p_T (neutrinos). High resolution calorimetry measures these particle energies without the help of a central magnetic field and thereby allows an unobstructed maximal angular coverage and higher resolution energy measurements. At higher energies, calorimetry offers better resolution than magnetic measurements. It is also more suited to record jet production since it equally treats all fragmentation products (photons, charged and neutral hadrons). The calorimeter itself consists of a central and two endcap components (see figure 6). Its interior is divided into individual channels of liquid argon sandwiched by uranium/copper absorber plates. The central region provides full-azimuth coverage of electromagnetic energy for at least 20 interaction lengths in the range $45^\circ < \theta < 135^\circ$, of hadronic energy for at least seven interaction lengths in the range $60^\circ < \theta < 120^\circ$. The end caps extend the coverage down to 1° from the beam line with up to nine radiation lengths of depth which is extremely important for accurate p_T measurements. The central region is divided into three concentric cylindrical layers: an innermost electromagnetic layer (best sampling), a fine hadronic layer (coarser sampling), and an outer coarse

hadronic layer. The granularity of these regions is on the average $\delta\eta = \delta\phi = 0.1$ with $\delta\eta = \delta\phi = 0.05$ for the high resolution electromagnetic layer. Based on test measurements, D0 hopes to achieve the energy resolutions

$$\frac{\sigma_{Had}}{E} \leq \frac{40\%}{\sqrt{E}}$$

$$\frac{\sigma_{EM}}{E} \leq \frac{12\%}{\sqrt{E}}$$

2.2. PHYSICS AT D0

In general, D0 will be examining two classes of physical phenomenon. To the first class belong those measurements which are already understood within the framework of existing theories such as the Standard Model. In these cases, the precision of model parameters are hoped to be improved within predictable bounds. The second class of phenomena include all those measurements which cannot be classified into existing theory. The increased energy and luminosity of D0 over previous detector experiments could reveal an entire range of unexplored physical phenomena. Below is a short overview of some of the physics goals.

Precision Tests

CDF and D0 are the first experiments which enable precise measurements of the intermediate boson sector. With the luminosity quoted above of $L = 5 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$, a typical several month data run period can be expected to produce on the order of 1500 $Z^0 \rightarrow e^+ + e^-$, and 5000 $W^\pm \rightarrow l^\pm + \nu$ events, where l denotes electrons or muons. Figure 7 displays the dependency of the cross section of the gauge bosons on beam energy upon which this calculation is based. Among the most interesting gauge parameters to be measured are $\sin \theta_W$ and

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2(\theta_W)}.$$

For predicted mass measurements of the W , it should be possible to determine the former to within ± 0.0025 of overall uncertainty. The ρ parameter is predicted to be

identically 1 within present formulations of the standard model. The boson mass measurements should improve its precision to ± 0.005 . Deviations from unity would indicate additional ingredients to the Standard Model, such as heavy quark families. Precise measurements of the width of the Z^0 , Γ_Z , are of particular interest. Its upper bound constraint can give an experimental limit on the number of neutrino families. Each additional neutrino family should contribute $181 \frac{MeV}{c^2}$ to Γ_Z . The direct comparison of Γ_Z and Γ_W will also grant the possibility of verifying the accuracy of QCD radiative corrections.

The detailed examination of branching ratios of the decay mode $Z^0 \rightarrow e^+ + e^- + \gamma$ could indicate the existence of narrow states. One such state might be $Z^0 \rightarrow l^+ l^- \gamma$ with the companion state $W \rightarrow e \nu \gamma$. To make these measurements, excellent energy resolution in the calorimeter and the ability to distinguish γ from π^0 are particularly critical. Some other high precision tests of the Standard Model include decay asymmetry in $W^\pm$ production, the search for gauge boson self couplings, and the study of jet production as a result of quark decays of the W and Z . In addition, detailed measurements of W and Z cross sections offer the possibility to examine the structure functions of the u , d and sea quarks.

Some precision tests would directly facilitate our understanding of QCD. The common trademark of high energy hadron colliders is the production of small angle clustering of energetic particles (see figure 8). This phenomenon, commonly called jet production, is predicted by QCD. Jets can be characterized by multiplicity distributions, energy flow, transverse momenta, angular distributions, and cross sections. Jets commonly occur in pairs, but can also be produced in groups of three or more. The D0 detector is tailored to measuring these properties in the energy range $200 \leq p_T^{Jets} \leq 500 \frac{GeV}{c}$. QCD parameters such as the strong coupling constant at high energies and effects of quark compositeness can thereby be examined. As mentioned above, good jet resolution requires very high calorimeter granularity which was one design goal for D0.

Physics Beyond the Standard Model

The most exciting prospects for D0 are the possibility of discovering new particles

and phenomena in the TeV energy range. Despite the overall success of the Standard Model, nature still leaves us with a great number of unsolved questions and hypotheses to be tested. In particular, the search for a Grand Unified Theory which would describe the electroweak and strong forces as manifestations of a single force, (with hopes of eventually including gravity as well,) has heavily occupied theoretical particle physics over the past decade. It would be the next logical step in line with the success in unifying electromagnetic and weak interactions. One example of such a theory utilizes the symmetry group $SU(5)$. Just as the group $SU(2)$ describing weak interactions predicts the existence of $2^2 - 1$ gauge particles, $SU(5)$ analogously predicts the existence of $5^2 - 1 = 24$ such bosons. Of the 24, only the 8 gluons, 3 weak bosons, and the photon have been experimentally verified. As the energy of colliders increase, so too do the prospects of achieving experimental unification of the forces. Thus, D0 opens the possibility of finding additional such heavy bosons. The sensitivity for detecting a heavy boson, Z' , extends to $m_Z \simeq 230 GeV$, for a W' to $m_W \simeq 150 GeV$. The search for these particles would be similar to that which lead to the discovery of the weak bosons, i. e., with emphasis on clean leptonic decay modes for which the background would be small.

Another interesting prospect is the search for heavy leptons. Cosmological considerations place a theoretical upper bound on the number of lepton families (between three and four). If additional leptons were to indeed exist, it could alter not only our understanding of the Standard Model, but also our perceptions of physics in the early universe. D0 offers a unique opportunity to make such discoveries due to the large harvest of weak bosons expected to be produced. In the TeV energy range, processes such as $W^\pm \rightarrow L^\pm \nu_L$ or $Z^0 \rightarrow L^+ L^-$, where L is one such heavy lepton, are inhibited only by larger phase space factors of the common leptons. The decays of heavy leptons into lighter families via the weak force are well understood, subject to the uncertainty of the mass of the top quark. Such a search would thus require good electron and muon identification, good missing p_T measurements for neutrinos, and comparable jet resolution to tag hadronic decay modes of $L^\pm$. Analogous to the possibilities of $L^\pm$ are those of detecting additional heavy neutral leptons. Here, the known decay $\tau \rightarrow \nu_\tau \pi^\pm$ points to $L^0 \rightarrow l^\pm \pi^\mp$ as a likely candidate for detection.

There are many additional phenomena which hopefully could be uncovered by $D0$, but are either not as theoretically well understood as the prospects above, or are not as easily detected. For example, the uncertainty in the number of lepton families is analogous for the number of quark families. Ideally, there would exist an equal number of hadronic and leptonic fermion families. Unfortunately, however, recognizing the signatures of jets produced by any such heavy quarks would push the hadron calorimetry to its limit. Other more theoretically hypothetical models open to test at $D0$ are Technicolor and Supersymmetry, both of which completely lack any past experimental confirmation. Due to the large number of uncertainties in these theories, the physics they would produce at $D0$ is largely unknown. Their exotic signatures would most likely be born out in post-experimental analysis of anomalous events.

Finally, although certainly not considered as physics beyond the Standard Model, the search for the missing top quark will be high on the agenda of exciting phenomena at $D0$. As mentioned above, it is the last undiscovered fermion in the third generation of quark and lepton families. It is the goal of this thesis to investigate the characteristics of a top decay at $D0$ and make predictions as to the feasibility of obtaining a definite signature.

3. Top Simulation Procedure

3.1. TOP PROCESSES

The first step in simulating the signature of a particle is to choose a decay mode which both produces a relatively clean and unique signature and has a statistically reasonable branching ratio for the given collider luminosity. In our simulations of $p + \bar{p} \rightarrow t + \bar{t}$ we concentrated on the decay mode $t \rightarrow b + W^+$, $\bar{t} \rightarrow \bar{b} + W^-$. The $W^\pm$ could then take any of the familiar quark and lepton decay channels. However, if both W 's were to decay into quark channels, it would be exceedingly difficult to recognize the resulting high p_T jets against the multiple jet backgrounds produced by a hadron collider. We therefore specify in the monte carlo that one of the W 's take the decay channel $W^\pm \rightarrow e^\pm + \nu_e$ (see figure 9a). Note, however, that the decay mode of the second W remains unspecified. Let us examine its two decay scenarios:

If it were to decay to quarks (see figure 9b), a suitable jet finding procedure could separate hadronic jets from electron towers to fully reconstruct one W . Since the neutrino escapes the detector, its "missing" transverse momentum, p_T^ν , can be calculated (assuming the absence of other high p_T neutrinos in the event). As mentioned above, the design of the D0 calorimeter is tailored to making high resolution estimates of the missing p_T . Using p_T^ν , the transverse mass m_T^W of the second W could then also be reconstructed. Thus, $t\bar{t}$ would result in the production of at least four mid to high p_T jets accompanied by an isolated high p_T electromagnetic tower.

The second decay scenario is for both W 's to take leptonic decay channels (see figure 9c). In this case two high energy neutrinos are produced. Naturally, it would be impossible to extrapolate their missing p_T 's. Therefore, such events produce a background in our simulation of top. Statistically, since there are two light quark families with three color degeneracies and three leptonic decay modes, the W will decay to quarks 67 percent of the time, to leptons 33 percent. Overall, the cross section for the desired decay scenario was computed by the monte carlo program to be $\sigma \approx 5pb$ which would produce 250 events for a collider year at the luminosity quoted above. While these statistics are far from impressive, it is hoped to increase

the collider luminosity of the Tevatron by additional factors which would offer more promising prospects of recognizing the top signature.

3.2. DATA GENERATION

The monte carlo data generation of $t\bar{t}$ was performed on the DEC MicroVax 2. The first step in the process was to generate detector independent events with the program ISAJET. ISAJET allows the user to specify the physical parameters and decay processes to simulate p on $\bar{p}$ physics. We chose the following: $\sqrt{s} = 2000\text{GeV}$ (beam energy), $71 < M_W < 91\text{GeV}$ (mass width of the W), $M_H = 200\text{GeV}$ (mass of the Higgs boson), $M_T = 150\text{GeV}$ (mass of the top quark). We further specified as stated above that one of the W's decay to quarks. Figure 10 shows a typical ISAJET event output; the first listing gives the parton cascade, the second all the particles produced in the event. The ISAJET physics data is stored in sophisticated data allocation units titled "ZEBRA Banks." The ZEBRA Banks are used in every step of monte carlo event generation as well as for real data gathering and analysis.

The next step in event generation is to produce detector dependent data which uses the physics generated by ISAJET. Currently, several high energy physicists are writing such a program tailored to the D0 detector called D0GEANT. The GEANT qualifier indicates that the program utilizes the so titled CERN framework for constructing detector dependent monte carlos. D0GEANT itself is an extremely complicated program consisting of many thousands of lines of code which simulates both the D0 detector geometry and all detector related physics. While a typical ISAJET event might take 10 to 20 seconds to generate, D0GEANT takes over two hours of CPU time. For this reason we chose to install D0GEANT on a MicroVax 3 which cut the event generation time down to one half hour. Since the program is still in the process of being written, we were forced to use test release versions to generate data. This was possible since D0GEANT is a versatile program allowing user control over various sections of the detector. Since we were interested particularly in the calorimeter data, we could switch off certain problematic sections of the monte carlo. Although we tried in general to retain as much of the D0GEANT data as possible,

we were forced to remove the Transition Radiation Detector modules due to errors in the software. Figure 11 is an example of a typical D0GEANT interactive output displaying active sections of the detector.

Since D0GEANT is intended to be a true to life simulation of physics at D0, its data is output in a completely raw form. It is therefore necessary to piece together the various electronic signals from the detector before any data analysis can be performed. To meet this end, event reconstruction programs are currently being written and tested on D0GEANT by experimental collaborators. We utilized, in particular, the calorimeter test release reconstruction packages. These packages take the calorimeter raw data signals as an input and output summed hadronic and electromagnetic energy towers with their η and ϕ cell indices. This data is then stored in the CATE Zebra bank. Figure 12 gives some lego plots of the CATE bank calorimeter towers for a sample event. In the events, one observes the expected hadronic jet formations and isolated high p_T electromagnetic towers, most likely stemming from a W decay.

Another possibly useful event reconstruction package currently under development by D0 physicists is the jet finder. The jet finder searches the D0 calorimeter for clusters of hadronic and electromagnetic energy. It employs a fixed cone algorithm to sweep the region surrounding high p_T towers and sum the energies of calorimeter cells within a given radius. The jet finder then stores this data in the corresponding JETS ZEBRA bank.

Since it is rather cumbersome to analyze event data stored in the ZEBRA banks, routines were written to extract and pack the data in a more compressed format. This was particularly useful in keeping all the relevant D0GEANT data online for analysis, which otherwise consumed large portions of memory. Ideally, the CATE and JETS event data would be sufficient for performing the search for top decay characteristics. The JETS banks would contain the electron and quark jet information, while a summation over the p_x and p_y components of the CATE bank towers would give the missing p_T belonging to the neutrino. We generated in total 480 D0GEANT events in 10 event blocks which were consecutively processed in this fashion. Figure 13 gives a flow chart summary of the steps in data generation.

4. Analysis and Results

4.1. JETS BANK ANALYSIS

As-discussed above, the D0 reconstruction packages include jet finding routines. The jet finder searches the calorimeter data stored in the CATE banks for the highest p_T towers in a given event. These towers are considered to be the “seeds” of particle jets. The jets are reconstructed by summing the hadronic and electromagnetic energy in the surrounding cells of the seeds within a fixed radius. The summed p_T and $\eta - \phi$ indices are then stored in the corresponding JETS bank. As can be seen in the sample lego plots, a typical $t\bar{t}$ event contains as many as three or four jets accompanied by an isolated high p_T tower of electromagnetic energy produced by the electron. Optimally, each of these would be registered in the JETS banks by the reconstruction routines. Our initial goal was thus to utilize the JETS banks in finding the W 's produced by $t\bar{t}$.

As a first step, the full mass of the W could be reconstructed by permuting over all the entries of the JETS banks and forming quark pairs. One would then recognize the W signature by a peak in the histogrammed mass distribution centered at the mass of the W . The hypothetical mass is given by the relation

$$M_W = \sqrt{(2E^1 E^2 - 2p^1 \cdot p^2)}$$

where E^1, p^1 and E^2, p^2 are the energies and 3 momenta of two given jets respectively. Contrary to expectations, the resulting histogram given in figure 14 exhibits a very wide peak centered at $55 GeV$. The mass distribution extends well beyond the true mass of the W , indicating that many false mass combinations present a large background for such a procedure. Indeed, it is impossible to discern any definite characteristics of the W from this histogram.

More interesting results can be obtained for the W produced by the electron decay. It should be emphasized, however, that only a transverse mass, M_T^W , can be reconstructed from the electromagnetic data in an event. This is due to the fact that

while the neutrino p_T can be calculated by summing over the towers of the calorimeter using the formula:

$$p_T^\nu = \sqrt{[(\Sigma p_x)^2 + (\Sigma p_y)^2]}$$

no information can be extrapolated as to the z component of its momentum. Hence, one can compute

$$M_T^W = \sqrt{(2E_T^1 E_T^2 - 2p_T^1 \cdot p_T^2)}.$$

To compare our results with past experiment, figure 15 presents CERN UA1 transverse energy distributions for $148 W^\pm \rightarrow e^\pm + \nu_e$ events.^{1*} The electron p_T distribution is centered at $\approx 35 GeV$ and drops off sharply at $50 GeV$, well in advance of M_W . The transverse energy of the neutrino from our top decay exhibits a similarly distinguished peak at $\approx 40 GeV$ (figure 16). One notes, however, the long tail of the distribution extending beyond $100 GeV$. This wide spread is most likely due to background events in which the p_T of two energetic neutrinos is necessarily summed together. To find the electron information in the JETS banks, one requires the ratio of electromagnetic to total E_T of a jet to be greater than 95 percent. The histogram of the energy ratios in each event given in figure 17 sharply peaks in the region near 100 percent, indicating that the jet finder registers a large number of purely electromagnetic towers most likely produced by the electrons. However, the entirely flat electron/neutrino transverse mass distribution in figure 18 unexpectedly exhibits no similarities with the UA1 results. Since the neutrino spectrum in figure 16 is well behaved, one concludes that the jet finder is outputting low resolution electron data.

4.2. ELECTRON FINDER ANALYSIS

To correct for the deficiency in the data output by the JETS banks, we applied our own electron finding algorithm to the CATE calorimeter data. The routine cycles through the regions of the calorimeter for $-3.5 \leq \eta \leq 3.5$ and finds the highest p_T towers passing a fixed threshold $p_T^{min} = 10 GeV$. The hadronic and electromagnetic

* Supersymmetry, SLAC Summer Conference

energy is summed for the cells lying within a radius of three in $\eta - \phi$ space of the towers. In addition, the summed cells are flagged so as not to be counted twice in any one event. To distinguish jets and electrons, one again requires 95 percent of the summed energy to be electromagnetic. Figure 19 gives the resulting transverse energy distribution. Although our electron distribution is distinct from the UA1 electron data, the neutrino/electron transverse mass distribution in figure 20 is a far improvement over the mass generated by the JET data. In particular, one notes the distinct peak centered below the total mass of the W . The tail of the distribution extends into unexpectedly high energy regions which is again most likely due to electron combinations with background neutrinos. Our best M_T^W results are obtained by requiring the electrons to lie in the central calorimeter region $-1 \leq \eta \leq 1$ (figure 21).

4.3. CONCLUSIONS

Clearly, both the quark jet reconstructed M_W and the electromagnetic M_W^T distributions leave much room for improvement. To narrow the peak in the former, more sophisticated jet finding techniques need to be developed which would reduce the number of false mass combinations. Simply permuting over every jet in an event produces backgrounds which wash out characteristics of the W . Similarly, algorithms more specialized in finding the electrons should be employed. However, before any such improvements can be undertaken, more regions of the detector need to be reconstructed along with the calorimeter. In particular, since the interaction vertex is different for each event, it is incorrect to take all angles as originating from the center of the detector. This may have been a major source of error in our analysis of the calorimeter data. To correct for it, one needs information from the central tracking detector which has been unavailable to us due to the failure of the TRD modules in D0GEANT. Upon improvement of the jet finding resolution, one could then search for correlations between the electromagnetic M_T^W and the quark M_W which would more concretely reveal the signature for top. Thus, improved results depend on the official release of D0GEANT and the reconstruction packages. It should be noted,

however, that a major goal has been accomplished in successfully generating and reconstructing the 480 events. Only by utilizing the D0 software during test release stages can improvements be made leading to more accurate simulations.

Fig. 1a: Feynman Diagram of QED Exchange

Fig. 1b: Feynman Diagram of Weak Exchange

Fig. 2: (a) The spin- $\frac{1}{2}$ and spin- $\frac{1}{2}$ ground-state baryons made from u, d, s, c quarks, with the $SU(3)$ multiplicities of the $C = 0, 1, 2, 3$ states shown in parentheses. (b) The $C = 1$ spin- $\frac{1}{2}$ baryons ($6 + \bar{3}$) and their quark content with $q = u, d$.

Fig. 3: The potential $V(\phi)$ for a complex scalar field for the case $\mu^2 < 0$ and $\lambda > 0$.

(fig.'s 2, 3 and 8 taken from F. Halzen and D. Martin, Quarks and Leptons; John Wiley and Sons, (New York, 1984).)

Fig. 4: D0 at the Tevatron

Fig. 5: D0 Detector

Fig. 6: Cross Section of D0 Calorimeter

Fig. 7: Vector Boson Cross Sections

Head-on hadron-hadron collisions are described by simple quark and gluon processes, such as one-gluon exchange, which give rise to jets of hadrons emerging from the collisions.

Fig. 8: QCD Jet Production for Two Baryons

a

b

c

Fig. 9: W Decay Modes

Fig. 10: Sample ISAJET Output

R/JN ID 900316 1954 EVENT NO 1 SEED 0.162423316313838E+15									
JET PARAMETERS									
JET	TYPE	PX	PY	PZ	PO	PT	THETA	PHI	X Y
1	TB	-56.51	-115.63	-75.50	211.57	128.70	2.1013	4.2578	-0.0755 -0.5573
2	TP	56.51	115.63	308.52	366.40	128.70	0.3952	1.1162	0.3085 1.6084
D(SIGMA)/D(PT**2)D(Y1)D(Y2) = 0.2412E-14									
PARTON CASCADE PARAMETERS									
I	JET	ORIG	TYPE	DECAY	PX	PY	PZ	PO	MASS
1	11	0	UP	7- 8	17.21	7.75	428.90	438.98	-93.63
2	12	0	UB	5- 6	-47.92	-0.21	-191.16	151.78	-112.54
3	1	0	TB	FINAL	-70.29	-112.47	-73.14	213.17	150.00
4	2	0	TP	FINAL	39.59	120.01	310.88	357.58	150.00
5	12	2	UB	11- 12	4.41	-3.88	-269.23	265.83	-84.06
6	12	2	GL	FINAL	52.33	-3.67	-78.07	94.06	0.00
7	11	1	UP	15- 16	-2.75	5.23	463.53	461.70	-41.57
8	11	1	GL	9- 10	-19.96	-2.51	34.64	-2.73	14.87
9	11	8	GL	FINAL	-3.98	4.01	2.35	6.12	0.00
10	11	8	GL	FINAL	-15.98	-6.52	32.29	36.61	0.00
11	12	5	UB	13- 14	8.48	-5.97	-265.21	261.92	-42.92
12	12	5	GL	FINAL	4.07	-2.08	4.02	6.09	0.00
13	12	11	UB	19- 20	-0.45	-0.70	-281.87	281.54	-13.56
14	12	11	GL	FINAL	-8.93	5.27	-16.66	9.62	0.00
15	11	7	UP	17- 18	-2.80	3.31	467.44	466.06	-36.14
16	11	7	GL	FINAL	-0.05	-1.93	3.90	4.35	0.00
17	11	15	UP	21- 22	0.36	0.34	474.03	473.95	-8.58
18	11	15	GL	FINAL	3.17	-2.97	6.59	7.89	0.00
19	12	13	UB	INITIAL	0.00	0.00	-282.76	282.76	0.30
20	12	13	GL	FINAL	0.45	0.70	-0.89	1.22	0.00
21	11	17	UP	23- 24	0.30	0.33	474.65	474.57	-8.42
22	11	17	GL	FINAL	-0.06	-0.01	0.62	-0.62	0.00
23	11	21	UP	25- 26	0.24	0.08	475.82	475.78	-6.61
24	11	21	GL	FINAL	-0.07	-0.25	1.18	1.21	0.00
25	11	23	UP	INITIAL	0.00	0.00	476.47	476.47	0.30
26	11	23	GL	FINAL	-0.24	-0.08	0.65	0.69	0.00
NUMBER OF POMERONS = 3									
HADRON PARAMETERS									
I	JET	ORIG	TYPE	DECAY	PX	PY	PZ	PO	PT THETA PHI
1	11	-9	ETAP	55- 57	-1.24	1.04	0.84	2.06	1.62 1.0917 2.4454
2	11	-9	N	STABLE	-0.98	-0.25	0.80	1.59	1.01 0.9028 3.3886
3	11	-9	P10	58- 59	-0.21	0.99	-0.03	1.02	1.01 1.5966 1.7832
4	11	-9	ADL--	60- 61	0.25	0.30	0.13	1.30	0.39 1.2611 0.8764
5	11	-10	P1-	STABLE	-0.05	0.34	0.89	0.96	0.35 0.3716 1.7234
6	11	-10	P10	62- 63	-3.21	-1.71	5.55	6.64	3.64 0.5796 3.6310
7	11	-10	OMEG	64- 66	-3.69	-2.55	8.16	9.35	4.48 0.5022 3.7459
8	11	-10	ETAP	67- 69	-3.22	0.02	5.48	6.43	3.22 0.5309 3.1340
9	11	-10	RHO+	70- 71	-2.08	-0.55	2.93	3.72	2.15 0.6326 3.4021
10	11	-10	RHO0	72- 73	-0.28	0.06	0.67	1.06	0.28 0.3995 2.9106
11	11	-10	RHO0	74- 75	0.27	-0.66	0.61	1.22	0.72 0.8658 5.0987
12	11	-10	RHO0	76- 77	-0.66	0.34	0.17	1.09	0.75 1.3471 2.6720
137	12	50	P10	183- 184	-0.17	0.36	-0.09	0.43	0.40 1.7826 2.0257
138	1	53	DT-	185- 186	-72.66	-113.40	-72.92	214.56	134.68 2.0670 4.1425
139	1	53	GM	STABLE	-0.03	-0.07	-0.06	0.09	0.07 2.2226 4.3544
140	2	54	TS-	194- 195	36.20	117.04	310.63	366.25	122.51 0.3757 2.1709
141	2	54	GM	STABLE	-0.03	0.03	0.10	0.11	0.04 0.3869 2.3128
142	11	55	GM	STABLE	0.03	0.24	0.16	0.29	0.24 0.9899 1.4470
143	11	55	GM	STABLE	-0.86	0.54	0.39	1.09	1.02 1.2036 2.5811
144	11	56	GM	STABLE	-0.12	0.23	0.10	0.28	0.26 1.2233 2.0470
145	11	56	GM	STABLE	-0.12	0.05	0.09	0.15	0.13 0.9676 2.7435
146	11	57	GM	STABLE	-0.05	-0.05	0.10	0.12	0.07 0.5936 3.8859
147	11	57	GM	STABLE	-0.12	0.02	0.01	0.13	0.13 1.5066 2.9834
148	11	66	GM	STABLE	-0.07	-0.04	0.11	0.14	0.09 0.6565 3.6402
149	11	66	GM	STABLE	-1.52	-1.37	3.49	4.04	2.05 0.5314 3.8733
150	11	67	GM	STABLE	-1.55	0.22	2.09	2.61	1.56 0.6416 3.0009
151	11	67	GM	STABLE	-0.60	-0.14	1.34	1.47	0.61 0.4274 3.3661
152	11	71	GM	STABLE	-0.11	0.03	0.27	0.29	0.11 0.3901 2.8820
153	11	71	GM	STABLE	-0.84	-0.06	1.47	1.70	0.84 0.5188 3.2077
154	11	79	GM	STABLE	0.05	0.04	-0.08	0.10	0.06 2.5082 0.6355
155	11	79	GM	STABLE	-0.04	0.05	0.02	0.07	0.07 1.2605 2.2648
156	11	80	KL	STABLE	0.32	-0.06	0.18	0.62	0.32 1.0493 6.0945
157	11	84	GM	STABLE	-0.08	0.01	0.21	0.22	0.08 0.3735 3.0525
158	11	84	GM	STABLE	-0.27	-0.24	0.84	0.91	0.36 0.4080 3.8547
159	11	89	KS	STABLE	-0.32	-0.26	0.15	0.67	0.42 1.2171 3.8162
160	11	90	GM	STABLE	0.04	0.06	-0.02	0.07	0.07 1.7825 0.9698
161	11	90	GM	STABLE	0.15	0.05	0.15	0.22	0.16 0.8083 0.3445
162	11	95	KL	STABLE	0.43	-0.58	-0.04	0.88	0.72 1.6225 5.3545
163	11	96	GM	STABLE	0.01	0.09	0.11	0.14	0.09 0.6934 1.4357
164	11	96	GM	STABLE	-0.07	-0.02	0.06	0.09	0.07 0.8766 3.4849
165	11	100	GM	STABLE	-0.01	0.03	0.16	0.16	0.03 0.1749 1.7539
166	11	100	GM	STABLE	0.12	-0.02	0.14	0.19	0.12 0.7388 6.1252
167	12	108	GM	STABLE	0.17	-0.02	-0.24	0.29	0.17 2.5081 6.1799
168	12	108	GM	STABLE	1.91	0.04	-3.30	3.82	1.91 2.6162 0.0209
169	12	110	GM	STABLE	0.09	-0.04	-0.15	0.18	0.10 2.5655 5.9009
170	12	110	GM	STABLE	2.57	-0.32	-4.37	5.08	2.59 2.6074 6.1583
171	12	111	P1+	STABLE	0.88	-0.14	-0.67	1.13	0.90 2.2157 6.1256
172	12	111	P1-	STABLE	0.81	0.26	-1.57	1.79	0.85 2.6427 0.3054
173	12	120	KL	STABLE	1.13	-0.09	-1.44	1.90	1.14 2.4748 6.2020
174	12	121	GM	STABLE	0.19	-0.07	-0.27	0.34	0.20 2.5003 5.9528
175	12	121	GM	STABLE	1.35	-0.24	-2.35	2.72	1.37 2.6140 6.1050
176	12	127	GM	STABLE	0.13	0.05	-0.39	0.41	0.14 2.7841 0.3714
177	12	127	GM	STABLE	0.45	0.36	-1.06	1.21	0.58 2.6393 0.6763
178	12	131	GM	STABLE	-0.05	-0.02	-0.02	0.06	0.05 2.0008 3.4968
179	12	131	GM	STABLE	-0.07	0.01	0.14	0.16	0.07 0.4375 3.0039
180	12	133	GM	STABLE	-0.58	0.24	-1.01	1.18	0.63 2.5850 2.7555
181	12	133	GM	STABLE	-3.36	1.67	-5.72	6.84	3.75 2.5612 2.6792
182	12	134	KL	STABLE	-0.32	0.01	0.03	0.59	0.32 1.4824 3.1224
183	12	137	GM	STABLE	-0.19	0.28	-0.08	0.35	0.34 1.8051 2.1672
184	12	137	GM	STABLE	0.02	0.07	0.00	0.07	0.07 1.6155 1.3194
185	1	138	W-	187- 188	12.75	-48.82	-41.65	102.91	50.46 2.2608 4.9678
186	1	138	BB	191- 193	-85.41	-64.58	-31.27	111.65	107.07 1.8549 3.7890
187	1	185	ANUM	189- 189	37.02	-11.67	-43.75	58.48	38.81 2.4159 5.9778
188	1	185	MU-	190- 190	24.27	-37.16	2.10	44.43	44.38 1.5236 4.1338
189	1	187	ANUM	STABLE	36.78	-11.82	-43.40	58.10	38.63 2.4143 5.9723
190	1	188	MU-	STABLE	24.49	-37.61	2.03	44.93	44.88 1.5255 4.1351
191	1	186	SB+	204- 205	-71.08	-53.91	-26.09	93.11	89.21 1.8553 3.7904
192	1	186	PHI	206- 208	-13.12	-9.67	-4.76	17.01	16.30 1.8549 3.7768
193	1	186	K*0	209- 210	-0.74	-0.39	-0.70	1.41	0.83 2.2705 3.6294
194	2	140	W+	196- 197	75.46	98.39	262.23	301.02	123.99 0.4417 0.9166
195	2	140	BT	200- 203	-39.26	18.65	48.40	65.23	43.47 0.7318 2.6982
196	2	194	E+	198- 198	87.68	59.65	172.02	202.08	106.04 0.5524 0.5974
197	2	194	HUE	199- 199	-12.22	38.74	90.21	98.94	40.62 0.4231 1.8763
198	2	196	E+	STABLE	87.13	59.42	169.85	199.93	105.46 0.5556 0.5985

***** GEANT Version 3.1107 Released on Tuesday 2 June 1987 *****
 ***** Library compiled on 890320 at 2207 *****

***** DOGEANT V3.01 31-JAN-1990 16:56:21.02
 ***** MUON_UTIL V1.14 13-FEB-1990 09:31:19.26
 ***** TRACKING_UTIL V1.06 31-JAN-1990 17:38:11.56
 ***** CALOR_UTIL TEST V1.23_03 27-JAN-1990 12:38:53.07
 ***** GENERAL V1.23 7-MAR-1990 17:47:12.03

**** GEANT FREE FORMAT SWITCH PROCESSOR ****

LBAT F (BATCH IF TRUE)
 SHWG 1 (GHEISHA=0, SHOWER PARAM=1, FROZEN SHOWER=2)
 SSEC 1. (SAVE SECONDARYS=1, DON'T SAVE=0)
 DTRK 0 DHIT 1 DDIG 1 (0=OFF,1=PRINT,2=DRAW)
 RKIN 0 (.GT.0: EVENT FROM ASCII FILE)
 ZBIO 0 0 (ZEBCOM INPUT/OUTPUT UNIT #'S (0=OFF))
 PDO 1 (PRINT LEVEL)
 DLAM 0 (1->BLUE BOOK ABSORPTION LENGTHS)

**** Package Specific Switches ****

DCEN 3 DCAL 3 DMUO 3 DLVO 3 (0=OFF,1=DEAD,2=HITS,3=DIG,4=ANALY)
 PCEN 1 PCAL 1 PMUO 1 PLVO 1

FFICAL ** DECA 3 DUCA 3 DCRY 3 DEAD 3
 LOECUT 0.010000 HIECUT 0.200000 X0STEP 1.000
 SCAL(1:10): 1.0 0.0 0.0 1.0 0.0010 0.0 0.0 0.0 0.0 0.0
 FFICDC ** DCDC 3 PCDC 1
 SCDC 1.0 0.0 0.0 1.0 0.0 -1.0 -1.0 -1.0 -1.0 -1.0
 FFIFDC ** DFDC 3 PFDC 1
 SFDC 1.0 -0.0 0.0 1.0 0.0 -1.0 -1.0 -1.0 -1.0 -1.0
 FFITRD ** DTRD 3 PTRD 1
 STRD 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
 FFIVTX ** DVTX 3 PVTX 1
 SVTX 1.0 0.0 0.0 1.0 0.0 -1.0 -1.0 -1.0 -1.0 -1.0
 FFIMUO ** SMUO 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
 FFILVO ** SLVO 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

==> Enter your Detector switches

Fig. 11: Sample D0GEANT Output

GNTTST EVENT 6

Fig. 12a: Legoplot

CNTTST EVENT 2

Fig. 12b: Legoplot

Fig. 13: Flow Chart of Data Generation

Fig. 14: W Mass Generated by Quark Jets

Electron transverse energy distribution for $W^\pm \rightarrow e^\pm \nu_e$ decays. The curve shows the prediction for the background-subtracted distribution (normalized to the data).

The electron-neutrino transverse mass distribution for $W^\pm \rightarrow e^\pm \nu_e$ decays. The curve shows the prediction for the background-subtracted distribution (normalized to the data).

Fig. 15: UA1 Results

(taken from M. Levi, SLAC Summer Institute on Supersymmetry, 663 (1986).)

ET : NEUTRINOS

Fig. 16: Neutrino Pt

Fig. 17: Energy Ratios in Jets

Fig. 18: Jet Finder Leptonic Mt

Fig. 18

ET : ELECTRONS, FLAGGED, 95% CUT

Fig. 19: Electron Finder electron Et

MT : ELECTRON NEUTRINO MASS

Fig. 20: Electron Finder Leptonic M_t

MT : $\text{ETA} < 1$

Fig. 21: Electron Finder Leptonic M_t for Central Calorimeter