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Simulation of Z boson Production at D0

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ABSTRACT

This thesis presents the results of some of the author's work in the High Energy Physics Group at Brown University, work done within the framework of the D0 collaboration at the Fermilab National particle accelerator. To allow a broader audience an easier understanding of the experimental data presented, a brief review of the relevant areas of Particle Physics precedes the description of the experimental setup and results. Monte Carlo simulations of Z boson production at the D0 experiment were made to allow for precise predictions of expected data at the accelerator when construction reaches completion. The specific work that was executed is presented in detail, from the point of view of experimental high energy research, followed by comments on the results obtained and on possible future directions.

1. A Brief Introduction to Particle Physics

Scientists have the goal of understanding the world around them, and how they interact with it. Traditionally, this process has involved two different but related research goals: understanding what the constituents of the world are, and understanding how they interact. From the first division of the world into its “air, fire, earth and water” constituents, to the atomic classification of Mendeleev and the nucleonic structure that followed, a trend is consistently present. To better understand Physics, it is necessary to understand the different types of smaller scale constituents as well as what their similarities and differences are, so as to comprehend how they interact to build larger structures. This framework of research has existed for many centuries, and has proven quite productive. In the 1950’s and 1960’s, however, experimental results have provided us with data that did not satisfactorily fit existing theories. Hundreds of so called “elementary” particles had been analyzed, weighed, and named. Such a wide diversity conflicts with a basic assumption that exists throughout scientific research, that “There must be a simple answer.”

This idea of a simple theory that explains complex experimental data appears in many implementations throughout the history of Physics. The concept of total energy being the sum of kinetic and potential energy, special relativity and its unification of the concepts of energy and matter are two such examples. With this concept of a “simple solution” always in mind, theorists have developed mathematical formulations that try to encompass as many of the experimental results as possible. A brief survey of the history of this *unification* process as it has been applied to the forces of the universe follows.

1.1. ELECTROMAGNETISM

The first unified field theory, developed by Maxwell and others, unified two apparently very distinct forces, electricity and magnetism. Electricity acts only between charged particles, which sets it apart from other known forces. Similarly, the magnetic force seemed to act only between matter that was magnetic, a characteristic exclusive to ferromagnetic metals. Electromagnetism provided a well-defined field

theory which encompassed both the electrical and magnetic forces using a simple formulation, composed of a set of four first order linear differential equations. A massless gauge particle, the photon, mediates the force over an infinite distance. The symmetry group for this gauge theory is $U(1)$, or unitary group of dimension 1. The fact that it is of dimension one results from the requirement that the photon be an abelian interaction i.e., that it carry no charge.

1.2. ELECTROWEAK THEORY AND THE QUARK MODEL

The next theory that promised to help unify forces is the electroweak theory. The name reflects the fact that it integrates into one formulation the electromagnetic interaction described above with the weak force. This force, unnoticeable in the everyday world, is responsible for such phenomena as the β^- decay of neutrons into protons in unstable nuclei:

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

To explain this phenomenon, it is necessary to present a small overview of the quark model of particle physics. In this model, nucleons (neutrons, protons) are made up of smaller, point-like constituents—*quarks*. These quarks are labeled u (*up*), d (*down*), b (*bottom*), c (*charm*) and s (*strange*). A sixth quark, the *top* quark (t), which has never been experimentally observed, is being sought at the new high energy accelerators at CERN and Fermilab. These quarks are usually arranged in the following families of six “flavors:”

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

where the mass of the lower element is less than that of the upper one, and less than that of any quark to its right. The up quark has a charge of $+2/3$, while the down has a charge of $-1/3$. All six quarks have antimatter counterparts, which are

called antiquarks. These quarks and antiquarks combine to make hadrons (3 quarks) or mesons (one $q\bar{q}$ pair). For example, a proton is made of 2 ups and 1 down quark (uud), a neutron of 2 downs and one up (udd). In the β^- decay described above, a down quark in the n is changed into a up quark, an antineutrino and an electron. This “flavor changing” process occurs through the action of the weak force, specifically through the exchange of a W boson (see Figure 1).

Just as for electromagnetism, a gauge field theory for the weak force was developed. In this instance, the symmetry group is $SU(2)$. A restriction is placed on the Lagrangian L so that it be invariant under local gauge transformations. This requirement is implemented by the introduction of massless gauge particles, which cancel out the asymmetry in the Lagrangian undergoing a transformation. Given the dimension 2 of the $SU(2)$ symmetry group, there must be three invariants (the number of gauge particles for a symmetry group $SU(n)$ is always $n^2 - 1$). These three particles have been named W^+ , W^- , and Z^0 , and are referred to as the intermediate vector bosons for the weak force. An important characteristic of these bosons is that they are non-abelian, i.e., that they possess a charge, and can therefore interact with one another. Further study of these particles is delayed until a later section, since their study constitutes the basis for the theoretical grounds of this thesis.

These two forces, the weak and the electromagnetic force, constitute the bases for the electroweak theory of particle interactions. According to a unified theory, the weak and electromagnetic forces are different manifestations of the same force different manifestations of the same force. At high energy, however, the forces have comparable strengths. However, the Lagrangian is not at an energy minimum in its vacuum state—a situation often compared to the potential energy of a marble at the bottom of a wine bottle (see Figure 2 for a graphical representation of such a field). At high temperatures, the ground state is above the peak, therefore there is no such asymmetry. When the temperature is lowered, the ground state of the Lagrangian becomes asymmetrical—the marble rolls in the trough of the bottle. This process is known as “spontaneous symmetry breaking.” It has the crucial consequence that the gauge particles become very massive, thus explaining the large masses of W ’s and Z .

However, this simple combination of both groups provides us with an incomplete theory, as it does not fit the data. Indeed, the $SU(2) \times U(1)$ symmetry group cannot lead to the presence of massive gauge particles, but we know from experiment that W 's and Z 's have high mass. The correction factor that can account for that is a scalar field that, when added to the electroweak Lagrangian, provides us with the needed "symmetry breaking." Just as the symmetrical center of the bottom of a wine bottle bottom is not at the energy minimum, so the Lagrangian is asymmetrical when it is at a minimum. This scalar field, the Higgs field, allows for the apparent asymmetry between the massive bosons and the massless photon.

1.3. QCD AND GRAND UNIFIED THEORIES

There are nonetheless more forces in the universe than the electroweak interaction. An example is the *strong force*, the force responsible for the confinement of quarks in matter. The theory of Quantum Chromo Dynamics, or QCD, incorporates the strong force by assigning to quarks a new characteristic called color. By imposing this new quantum number on quarks, one solves the conflict with the Pauli principle inherent in the quark structure of hadrons (a proton would otherwise be symmetric under the exchange of two quarks). Furthermore, one notices that the limited number of existing hadrons can be explained by requiring the color combinations to combine to white, which provides an interesting insight into why some otherwise predicted particles have never been seen. QCD theory, not being wholly relevant to this work, will not be explored in any further detail.

One last force has not been dealt with in this unification process. It is however the force we are most familiar with, as it affects our everyday life: gravity. The most important problem in integrating gravity into the same formulation as the other forces is the lack of a robust gravitational quantum theory. These theories are of considerable interest, however, especially in the field of cosmology, where they can provide insight as to the creation of the Universe, before the symmetry breaking which made the forces as distinct as they seem today.

1.4. W AND Z BOSONS

The intermediate vector boson under its multiple forms (neutral Z^0 and charged $W^\pm$) is considered in the Standard Model to be the vector carrier of the weak force in the interaction between two locally interacting particles, just as the pion carries the strong force between two hadrons. Since the weak force acts at such small distances, the W boson is difficult to detect as such—it decays into two leptons or quarks before it can reach a detector. This is a consequence of the high mass (and therefore short range) of the W boson. However, if one can accurately predict the physical properties of the W boson, one can detect its presence from the products of its decay. This is a fundamental tool throughout particle physics, and it will be used constantly throughout this work.

The W boson can decay in many modes, the leptonic series being as follows:

$$W^+ \rightarrow \mu^+ + \nu$$

$$W^+ \rightarrow e^+ + \nu$$

$$W^- \rightarrow \mu^- + \bar{\nu}$$

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

$$Z^0 \rightarrow e^+ + e^-$$

$$Z^0 \rightarrow \mu^+ + \mu^-$$

The high mass of the W and Z bosons explains why they have only recently been seen, at very high energy accelerators (Fermilab, CERN), and why more powerful accelerators have raised hopes of better results in the production and study of these heavy bosons.

Intermediate vector boson research

In a $p\bar{p}$ collider, such as the Fermilab Tevatron Collider, one can infer the creation of W's and Z's from the results of their decay. These decay modes are known, and can therefore be used as "signatures" for the W and Z bosons. High energy W's and Z's usually decay into either lepton pairs (neutral Z^0), or into lepton-neutrino pairs

(charged W's). From the detection of the charged leptons, their energies and p_T 's, we can derive several characteristics of the bosons we are interested in, such as their mass and "width" (more specifically the width of the mass distribution).

The values for M_Z and M_W are especially useful since they allow for a measure of θ_W and ρ , two key components of the Weinberg-Salaam model, the Standard Model — of Electroweak interactions.

Other physics goals beyond the specific values of the boson masses can be expected from weak boson research. Such research is expected to test the Standard Model in many ways. Moreover, testing for weak interactions at high energies may give experimental evidence supporting or disproving proposed theories, as well as new physical phenomena.

2. The D0 experiment at Fermilab

2.1. THE FERMILAB TEVATRON AND THE D0 DETECTOR

The Fermilab Tevatron accelerator is a large (≈ 6.4 km in circumference) $p\bar{p}$ collider located in Illinois. It has been in operation since 1983, and collides protons and antiprotons against each other at an energy of 1TeV each ($\sqrt{s} = 2\text{TeV}$).

The protons are created and accelerated in a small synchrotron, while antiprotons are created and stored in the antiproton accumulator ring, before both particle beams are sent to the Tevatron, where they are accelerated to 1TeV . After circling around in the beam tunnel in opposite directions, the beams collide at one of six collision points (see Figure 3).

The D0 detector at the Fermilab $p\bar{p}$ collider simulated in this work is scheduled to undergo its first run in middle 1991. It, along with two other experiments at Fermilab, consists of a large underground detector. This detector, consisting of physical and electronic detection devices, has a total mass of 4750 tons, and is set on a rolling platform.

The detector setup around the collision point at D0 was designed to detect hadrons and leptons coming away from the central collision, to measure their energies and momenta as well as to record their trajectories. Also, it is hoped that the leptons produced by the collision will be identified by the detector. This complex device will provide physicists with the data needed to study the physics of the collision.

By examining Figure 4 and Figure 5, we see that the detector is composed of 3 different types of detectors. The central tracking chambers are designed to measure the particle trajectories. This allows among other things for a precise measurement of the vertex position of the collision, that is to say the precise location along the beam where the $p\bar{p}$ collision occurs. This value is especially useful in increasing the accuracy of missing neutrino p_T 's, given the available calorimeter data.

The second type of detector located radially is our main data-collection tool for this thesis, the three liquid argon calorimeters. The first one, of cylindrical shape, is

coaxial to the beam pipe, and provides coverage for the particles leaving at an angle nearly normal to the beam pipe. The other two provide coverage for particles that would escape the central calorimeter, down to a few degrees of the beam direction, so as to provide maximum coverage and resolution over the entire distribution of particle tracks. Evidently, particles created in the collision chamber which follow trajectories along the beams' direction will not be detected by any detectors.

The third detector installed at D0 is the muon detector, located outside of the calorimeter. This calorimeter's main task is to detect the existence of and measure the momenta and direction of the charged muons which have gone through the two previous kinds of detectors.

2.2. THE PHYSICS AT D0

The D0 detector was designed with a specific set of physical processes in mind. Indeed, a high-energy, high-luminosity collider like the Tevatron will be most useful for the study of processes that require these conditions. This effort to best utilize available resources explains many design decisions that were made in the building of the D0 detector, as well as the choice of planned experiments.

The physical processes of *intermediate vector bosons*, namely the Z neutral current and the $W^\pm$ charged currents, given their high rest mass (several tens of GeV 's), and therefore their short lifetimes, need high energy collisions to be created. This explains why the $1TeV$ energy scale of the Fermilab accelerator is a useful tool in vector boson research. Moreover, the high-luminosity (a standard year-long run will have a luminosity of $L = 2.0 \cdot 10^{30} cm^{-2} sec^{-1}$) will provide us with a large enough number of events to do significant statistical analysis. As an example, about 2500 $Z^0 \rightarrow e^+e^-$ events are expected per collider year.

The UA1 and UA2 experiments at CERN, and the CDF data from Fermilab have proven that advanced calorimetry that provides good hadron jet resolution, precise measurements for missing transverse energy, along with detectors that identify and measure the energy of the produced leptons, can produce interesting and accurate physics results.

A list of specific results that are expected to come out of D0 follows:

- The mass difference between the W and Z bosons should be measurable with an accuracy of $\pm 0.8 \text{ GeV}$.
- The result above can allow precise measurements of the Weinberg angle θ_W , since:

$$\sin(\theta_W) = \frac{38.5 \text{ GeV}}{M_W}$$

- the ρ parameter—the relative strength of neutral ($J_\mu^{NC} - Z^0 - J_\mu^{NC}$) current to charged ($J_\mu - W^+ - J_\mu^\dagger$) current (see Figure 6)—can then also be computed using:

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W}$$

- the mass of the Z boson, M_Z , and the width of the Z , Γ_Z can be measured, as will be described further in more detail. The mass and width of the W , M_W and Γ_W , will also be measured at D0, with an expected accuracy of $\pm 0.3 \text{ GeV}$.

Careful measurements of the mass of the intermediate vector bosons and their widths will allow for precision tests of the accelerator design and construction, as well as tests for the Standard Model.

3. The Simulation

3.1. OVERVIEW OF THE SIMULATION

As noted in the introduction to particle physics, as well as in the chapter on D0, precise measurement of the mass of the Z boson, as well as its width, can provide useful insights into the physics of high-energy processes. Indeed, knowing the mass of the gauge bosons gives us a measure of the strength of the force. Such is the motivation for the work presented in this thesis.

Although the first complete run of D0 is not expected until June 1991, computer simulations allow for studies that provide tools for adjusting the final construction details of the detection and measurement devices, as well as the analysis software. With this in mind, a two-part experiment was conducted throughout the year. In the first part of the experiment, simulated data was generated from a precise physical and geometrical description of the D0 detector, specifying the types of events that were to be generated by the simulation. The data that was created should theoretically be equivalent to the data that can be provided by the D0 experiment when it begins operation. In the second phase of the experiment, the data was reconstructed using the analysis tools that will be used in the experiment. This allowed for development, testing and debugging of the software as well as the establishing of preliminary results, resulting from a combination of theory (the standard model) and experiment (the geometry of the detector, the validity of the analysis decisions that were made, etc.).

The procedure that was followed for these two steps will be developed in detail below.

3.2. SIMULATION PHASE: GENERATION OF EVENTS

For this type of analysis, a very specific type of event needs to be chosen and analyzed in depth. A valid question is what event type should be chosen, among all the possible particle productions at such energies. Given the original goal of measuring the mass of Z^0 , two criteria were established. The first criterion, given the test nature of the software packages that were to be used, is that the decay mode

have a very “clean” signature. That condition is met by the decay $Z^0 \rightarrow e^+e^-$, since both electrons deposit nearly all their energy in a small area of the electromagnetic calorimeters. The second requirement is that it be an event with significant statistical value. As was mentioned above, a year-long run of D0 is expected to yield ≈ 2500 such events, therefore giving this simulation a realistic scale.

ISAJET: Generation of a parton and hadron cascade

To simulate the physics of the D0 accelerator and detector, the ISAJET program was used to obtain a physically realistic parton and hadron cascades that would correspond to the laws of physics. In our set of runs, ISAJET input was specified so that a $2\text{TeV } p\bar{p}$ collision be simulated and a Z^0 boson be generated. It was further specified that this Z^0 boson decay into two charged leptons, specifically e^+ and e^- . Running ISAJET then produced both a listing file (see Figure 7), and a data file in the Zebra file format to be read by the GEANT program.

DOGEANT

The DOGEANT program is a version of the GEANT program developed at CERN that was customized to generate data appropriate for the D0 experiment. This program is a Monte-Carlo simulation of the physical behavior of an detector's (in this case Fermilab's) collision chamber detectors (in our case the D0 detector), which requires as input a precise description of the particles generated in the $p\bar{p}$ interaction. For example, the ISAJET data we have described above outputs the energy, mass, and direction of flight of each particle in the event. This data was input to GEANT, at the same time as a “geometry” file describing the detector characteristics. The results of the simulation are a set of data banks (in the case of D0 they follow the Zebra format, so they will be referred to as *Zebra banks*). This set of Zebra banks corresponds to the data that would be obtained from a real accelerator run. From this stage on, the analysis is identical to that done on actual experimental data.

3.3. ANALYSIS PHASE: DETECTION OF Z 'S, MEASUREMENT OF M_Z

If one were given an unknown Zebra bank from an detector, one would have to perform complex analyses to identify exactly what type of event had occurred, using the signature of the particle tracks through the calorimeters, tracking and muon detectors. This phase of "event recognition" was overlooked for this thesis, given that the main objective was a measurement of M_Z , not the filtering of events. This is an important stage in physics analysis, however, and can introduce additional margins of errors that should be taken into consideration when examining the results of this work.*

DOUSER, a general purpose event analysis package, was used in two steps of the analysis: the jet-finding and the calorimeter data reconstruction. Both of these tasks will be described in detail below.

Calorimeter reconstruction

The calorimeter data reconstruction phase corresponds to the extracting from the Zebra banks the energy readings from each of the calorimeters, along with their positioning (η and ϕ). Figure 8 shows a 2-dimensional projection of these readings, which can be interpreted in the following fashion. One should imagine that the calorimeters arranged concentrically around the beam axis are unrolled on a plane, and that each calorimeter cell now corresponds to a square on the 2-dimensional grid it creates. If the corresponding calorimeter energy reading is assigned to each square, and a parallelepiped of the corresponding height is put on that square, we obtain what is referred to as a *lego plot*. It should be noted that the top-right bar is always assigned a standard value (in this case 25 GeV), so as to provide a scale to the drawing. This type of plot is useful in giving a qualitative view of the calorimeter data, but the difficulty of reading static 2-dimensional projections of 3-dimensional

* As with any filtering system, there may be "false-positives" and "false-negatives", viz. some events that we are filtering for may be dropped by the filter program, whereas some other irrelevant events may be considered to be the events we are looking for. These latter events will probably (if they are not detected in further tests) distort the results somewhat, therefore adding uncertainty to the results.

data makes it a poor medium for precise quantitative analysis. Jet finding is an appropriate alternative to this.

Jet finding

The calorimeter data was used most importantly in the jet-finding phase. During this stage of the analysis, one has to recognize groups of neighboring towers that correspond to the emission of jets from the collision. Jets are collections of particles that have similar directions, as a result of quark fragmentation in the $q\bar{q}$ collision. See Figure 9 for a schematic representation of quark generation, Figure 10 for an illustration of a two-jet collision, and Fig. 8 for a lego plot of the calorimeter readings corresponding to such an event.

The specific jet-finding algorithm that was used is usually referred to as *cone algorithm*. In this method, a cone is centered on top of the highest energy towers, and the energy data corresponding to the calorimeter readings under the cone are summed together. This technique reduces the aliasing, or “faking”, due to the discrete sampling inherent in the calorimeter granularity, and allows for a more accurate detection of energy clusters.

The jet finder outputs a list of all the jets it finds, with the corresponding energy sums, their pseudo-polar coordinates η and ϕ (η is the pseudo-rapidity, related to the angle the particle trajectory makes with the beam direction ($\eta = \ln(\cot(\theta/2))$), and ϕ describes the angle about that axis), and the electromagnetic fraction. This last number corresponds to how much of the energy was deposited in the electromagnetic calorimeter, the rest being deposited in the hadron calorimeter. It is crucial in differentiation of various high energy clusters, such as an electron shower (high electromagnetic ratio) or a quark jet (low electromagnetic ratio).

Once the jets for all the events are found, the relevant data are stored into files that can be read by the IDA program. This program, Interactive Data Analysis, allows for a quick graphical output of relevant data depending on user input at interactive speeds, thereby giving the user the possibility of adjusting threshold levels and modifying small analysis programs with great ease.

For this experiment, a total of 670 $p + \bar{p} \rightarrow Z^0 \rightarrow e^+ + e^-$ events were generated on two DEC MicroVaxTM III workstations, and analyzed on a MicroVaxTM II.

Detection of the electron pairs

To infer the existence of a Z boson in a specific event, it is necessary to detect electrons specifically. Given the possible decay modes of $p\bar{p}$ collisions, the most discriminating characteristic of electron tracks is the high electromagnetic ratio. This value (always between 0 and 1) was graphed for all 670 events. The results are shown in Figure 11.

It is clear from this plot that most of the electrons can easily be detected if a cut is made for an electromagnetic ratio $\rho \geq 0.95$. For this reason, three cuts were made, each resulting in a different set of data. These cuts required electromagnetic ratios greater than 0.925, 0.95, and 0.975.

However, one electron is not enough to allow for the inference of a Z^0 . We need two opposing electrons, produced by the $Z^0 \rightarrow e^+ + e^-$ decay. To account for this requirement, a new filter was created. Only events with two electrons were used to build masses. These two cuts (high electromagnetic ratio and presence of two e^- 's) reduced the number of events in the three cases to 307, 387 and 418 respectively.

Building of M_Z from the electron data

When the two e^- jets were identified, the mass of the corresponding Z was computed using the following formula, where E^1 is the energy derived from the first electron jet reading, E^2 that from the second, and the p^n 's are the momenta of the two jets.

$$M_Z = \sqrt{2(E^1 E^2 - \mathbf{p}^1 \cdot \mathbf{p}^2)} \quad (3.1)$$

This value of M_Z was obtained for each event, and graphed for all of the events that met the criteria described above. The resulting histograms are shown in Figure 12, Figure 13, and Figure 14.

MINUIT

The Z^0 mass distribution is given by a relativistic Breit-Wigner. Therefore, the distribution of M_Z should theoretically fit the following curve, shown in Figure 15, where M_0 is the mean value of M_Z , M_Z is a given value of the mass of the Z , and $d(M_Z)$ is the proportion of events with that value for the mass of the Z :

$$d(M_Z) = \frac{\alpha}{(M_0^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \quad (3.2)$$

By fitting this theoretical curve—dependent on the three parameters α , M_0 , and Γ_Z —to our data, we can find the values of these three parameters that best fit our data. The program we used for this, MINUIT, uses several different minimization techniques, including the simplex method outlined by Nelder and Mead and a method based on a variable metric method by Fletcher^[1]. The values that were produced by the MINUIT run for each of the values of the electromagnetic cut ρ are:

Table 1: Summary of Numerical Results

	$\rho = 0.925$	$\rho = 0.95$	$\rho = 0.975$
α	$1.94 \cdot 10^7 \pm 1.84 \cdot 10^5$	$1.77 \cdot 10^7 \pm 1.61 \cdot 10^5$	$1.20 \cdot 10^7 \pm 1.45 \cdot 10^5$
M_0	$89.3 \pm 5.22 \cdot 10^{-2}$	$89.3 \pm 4.99 \cdot 10^{-2}$	$88.9 \pm 5.67 \cdot 10^{-2}$
Γ_Z	$7.48 \pm 4.49 \cdot 10^{-2}$	$7.38 \pm 4.45 \cdot 10^{-2}$	$6.57 \pm 4.77 \cdot 10^{-2}$

These values can be averaged to yield as a final result:

Table 2: Comparison between Original ISAJET values and the results of the simulation

	Brown Simulation	ISAJET input
M_{Z^0}	$89.5 \pm 5.29 \cdot 10^{-2}$	91.0
Γ_Z	$7.17 \pm 4.57 \cdot 10^{-2}$	2.409

4. Comments on the results

The average value of M_Z for all three cuts was $89.5 \pm 5.29 \cdot 10^{-2}$, whereas the value for Γ_Z averaged $7.17 \pm 4.57 \cdot 10^{-2}$. The original values input in the ISAJET program were of 91.0 and 2.043. Our result for M_Z is relatively close to ISAJET's value, but our value for Γ_Z is significantly greater than ISAJET's. The latter can be explained by remarking that the resolution of the detector was not taken into consideration in the building of M_Z . Suggestions for improving this result are presented in the next chapter. A factor that may explain the difference between our value for M_Z and that obtained at other experiments lies at the source of the processing pipeline that was outlined. Indeed, ISAJET requires estimates on the value of the mass of t , as well as M_W . These values were chosen within a range derived from previously published work, but a variation on these initial data may result in slightly different values for M_Z .

Given the simulation nature of this work, the more interesting comments about the experiment are about the technique used, its validity and accuracy. Therefore, a brief comment on each stage of the analysis and its results is presented below.

4.1. DATA GENERATION

Apart from the variations allowed within ISAJET mentioned above, the package provided the author with a reliable, efficient and accurate particle cascade generation tool.

4.2. VALIDITY OF THE M_Z RECONSTRUCTION METHOD

The qualitative fit between the curves shown in Figs. 12, 13, 14, and the theoretical Breit-Wigner curve shown in Fig. 15 proves the correctness of several assumptions made in the analysis:

- that the mass of the Z can be reconstructed using the formula in (3.1),
- that the $Z^0 \rightarrow e^+ + e^-$ decay does follow the relativistic Breit-Wigner model, and that the resultant distribution for M_Z is that outlined in (3.2).

5. Further work

This simulation is not a standalone piece of work. It is tightly connected with the rest of the D0 collaboration effort. Further work within the collaboration that pertains most directly to this thesis is distributed in the following areas:

5.1. TAKING INTO ACCOUNT DETECTOR RESOLUTION

The distribution function for the Z is the convolution of two functions, one resulting from theoretical derivations, one resulting from the specifics of the D0 detector. In the simulation that was presented, this fact was not taken into account. One way to improve the accuracy in Γ_Z would be to simulate a set of events with absolutely no theoretical variations in the mass of the Z , thereby obtaining the detector resolution function, which could then be convoluted with the Breit-Wigner theoretical distribution to produce the expected distribution.

5.2. SOFTWARE ENHANCEMENTS

The data generation and analysis software custom tailored for the D0 project, DOUSER and DOGEANT, need to undergo complete wide-scale testing before they can be entrusted with large amounts of analysis. Instability in test releases, lack of documentation and/or support, and constant upgrades made using the software more difficult than necessary.

5.3. EVENT FILTERING

Throughout this work, ISAJET generated very specific $Z^0 \rightarrow e^+ + e^-$ events. To adequately test the statistics of this analysis setup and technique, it is necessary to generate random events, and perfect the filtering techniques so that when computing M_Z as described above, one can assume a low to very low level of false events (events that in reality do not correspond to those assumed).

5.4. QUANTITATIVE INCREASE IN TEST DATA

Analysis of 670 events of a specific type was presented in this thesis. To ensure the validity of the analysis system in use at D0, it would be helpful to execute a full-scale testing of a large number of event types, with a large number of events per decay type. Hopefully, the microprocessor farm in development at Brown University can provide enough computing power so that the data generation and analysis process can be automated and executed without great delay.

Overall, it can be said that the work presented allowed for initial testing of the analysis tools needed for D0, as well as some preliminary results specific to the determination of M_Z and Γ_Z . However, a more thorough and exhaustive set of tests needs to be undertaken in order to achieve a satisfactory level of confidence in the accuracy of these tools.

REFERENCES

1. MINUIT: a System for Function Minimization and Analysis of the Parameter Errors and Corelations

Francis Halzen and Alan D. Martin (1984) "Quarks & Leptons – An Introductory Course in Modern Particle Physics." *John Wiley & Sons*

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Figures and Illustrations

FIGURE CAPTIONS

- 1) The W boson as a vector in the weak β^- decay
- 2) An example of a field with an off-center minimum energy level
- 3) Aerial view of the Tevatron accelerator, indicating the location of the D0 detector, that simulated in this thesis
- 4) Artist's rendering of the D0 detector
- 5) Photograph of the D0 detector
- 6) The W and Z bosons as vectors for charged and neutral currents respectively
- 7) Sample ISAJET Listing
- 8) Two-jet lego plot
- 9) Schematic representation of quark generation
- 10) Two-jet collision
- 11) Electromagnetic fraction for 670 $Z \rightarrow e^+ + e^-$ events
- 12) Distribution of M_Z for an electromagnetic threshold of 0.925
- 13) Distribution of M_Z for an electromagnetic threshold of 0.95
- 14) Distribution of M_Z for an electromagnetic threshold of 0.975
- 15) Theoretical Breit-Wigner Curve for $M_Z = 90$ and $\Gamma_Z = 10$

1) The W boson as a vector in the weak β^- decay

6) The W and Z bosons as vectors for charged and neutral currents respectively

2) An example of a field with an off-center minimum energy level

3) Aerial view of the Tevatron accelerator, indicating the location of the D0 detector, that simulated in this thesis

D-ZERO DETECTOR

4) Artist's rendering of the D0 detector

5) Photograph of the D0 detector

 * ISAJET V6.25 29-DEC-1989 11:17:02 *

RUN ID 900414 1414 EVENT NO 1 SEED 0.100983988754087E+15

JET PARAMETERS

JET	TYPE	PX	PY	PZ	P0	PT	THETA	PHI	X	Y
1	Z0	0.00	0.00	97.80	133.63	0.00	1.5708	0.0000	0.0978	0.9328
1	E-	-17.25	-18.66	104.34	107.39	25.41	0.2389	3.9662	0.1043	2.1200
2	E+	17.25	18.66	-6.54	26.24	25.41	1.6225	0.8246	-0.0065	-0.2544

W, Z DRELL-YAN PRODUCTION, CORRECTED HIGGS AND TOP MASSES

NUMBER OF JETS TO BE GENERATED PER EVENT 2

P ON AP AT COM ENERGY 0.2000E+04

NUMBER OF DRELLYAN EVENTS TO BE GENERATED 50

PRINT A MAXIMUM OF 10 EVEN'S SKIPPING 10 EVENTS AT A TIME

RUN ID 900414 1414

PARAMETERS FOR Z0

MASS LIMITS	C.8000E+02	0.1200E+03
TRANSVERSE MOMENTUM LIMITS	C.0000E+00	0.0000E+00
THETA LIMITS	C.0000E+00	0.3142E+01
PHI LIMITS	C.0000E+00	0.0000E+00
RAPIDITY (Y) LIMITS	-C.3217E+01	0.3217E+01
FEYNMAN X LIMITS	-C.1000E+01	0.1000E+01

FOLLOWING PARAMETERS HAVE BEEN FIXED QTW PHW

JET NO. 1

MOMENTUM LIMITS	0.1000E+01	0.1000E+04
TRANSVERSE MOMENTUM LIMITS	0.1000E+01	0.1000E+04
THETA LIMITS	0.1000E-02	0.3141E+01
PHI LIMITS	0.0000E+00	0.6283E+01
RAPIDITY (Y) LIMITS	-0.7601E+01	0.7601E+01
FEYNMAN X LIMITS	-0.1000E+01	0.1000E+01
JET TYPE	E+	E-

JET NO. 2

MOMENTUM LIMITS	0.1000E+01	0.1000E+04
TRANSVERSE MOMENTUM LIMITS	0.1000E+01	0.1000E+04
THETA LIMITS	0.1000E-02	0.3141E+01
PHI LIMITS	0.0000E+00	0.6283E+01
RAPIDITY (Y) LIMITS	-0.7601E+01	0.7601E+01
FEYNMAN X LIMITS	-0.1000E+01	0.1000E+01
JET TYPE	E+	E-

EICHTEEN STRUCTURE FUNCTIONS

QCD LAMBDA = 0.2000 JET CUTOFF MASS = 6.000

HEAVY QUARK MASSES = 150.00 -1.00 -1.00

WEINBERG MODEL SIN**2(THETA-W)= 0.2300

MASS OF Z0 = 91.059

D(SIGMA)/D(Q**2)D(YW) = 0.2811E-11

D(SIGMA)/D(Q**2)D(YW)D(OMEGA) = 0.2419E-12

PARTON CASCADE PARAMETERS

I	JET	ORIG	TYPE	DECAY	PX	PY	PZ	P0	MASS
1	11	0	DB	11- 12	-5.49	1.30	142.87	142.20	-15.10
2	12	0	DN	5- 6	15.15	-42.45	-29.03	9.56	-52.78
3	1	0	E-	FINAL	-11.31	-48.30	119.03	129.00	0.00
4	2	0	E+	FINAL	20.96	7.14	-5.27	22.76	0.00
5	12	2	GL	7- 8	-8.06	-0.74	-84.57	82.76	-19.19
6	12	2	DB	FINAL	-23.21	41.71	-55.49	73.20	0.30
7	12	5	GL	15- 16	0.03	-2.18	-250.35	250.18	-9.40
8	12	5	GL	9- 10	8.10	-1.44	-165.78	167.42	21.90
9	12	8	GL	FINAL	-6.90	-3.21	-38.15	38.90	0.00
10	12	8	GL	FINAL	15.00	1.77	-127.63	128.52	0.00
11	11	1	DB	13- 14	-0.32	0.09	194.40	193.98	-12.69
12	11	1	GL	FINAL	5.17	-1.21	51.51	51.78	0.00
13	11	11	DB	INITIAL	0.00	0.00	194.32	194.32	0.30
14	11	11	GL	FINAL	0.32	-0.09	-0.08	0.34	0.00
15	12	7	GL	17- 18	-1.05	0.16	-302.18	302.08	-7.96
16	12	7	GL	FINAL	-1.09	2.34	-51.84	51.90	0.00
17	12	15	GL	INITIAL	0.00	0.00	-307.63	307.63	0.00
18	12	15	GL	FINAL	1.05	-0.16	-5.45	5.55	0.00

NUMBER OF POMERONS = 4

HADRON PARAMETERS

I	JET	ORIG	TYPE	DECAY	PX	PY	PZ	P0	PT	THETA	PHI
1	11	-12	RHO	69- 70	0.03	-1.01	4.24	4.43	1.01	0.2332	4.7385
2	11	-12	P10	71- 72	0.98	0.54	1.20	1.64	1.12	0.7533	0.5018
3	11	-12	RHO	73- 74	-0.22	-0.10	1.15	1.41	0.24	0.2065	3.5692
4	11	-12	ETAP	75- 77	1.15	-0.05	10.98	11.08	1.15	0.1043	6.2356
5	11	-12	ETA	78- 79	0.98	0.10	9.01	9.08	0.99	0.1092	0.1001
6	11	-12	RHO	80- 81	1.56	-0.41	7.20	7.42	1.61	0.2203	6.0280
7	11	-12	K-	STABLE	-0.38	0.53	2.80	2.91	0.65	0.2281	2.1977
8	11	-12	K*0	82- 83	0.39	-0.15	1.44	1.74	0.42	0.2819	5.9070
9	11	-12	RHO-	84- 85	0.57	0.53	6.47	6.56	0.78	0.1199	0.7503
10	11	-12	RHO+	86- 87	-0.67	-0.67	0.32	1.27	0.95	1.2465	3.9309
11	11	-12	P1-	STABLE	1.39	0.52	1.23	1.93	1.48	0.8765	0.3562
12	11	-12	P1+	STABLE	-0.35	-0.24	0.38	0.59	0.43	0.8477	3.7530
13	11	-12	AK0	88- 88	-0.60	-0.43	0.06	0.89	0.73	1.4910	3.7667
14	11	-14	P1+	STABLE	-0.06	-0.37	-0.20	0.45	0.38	2.0661	4.5407
15	12	-6	P1+	STABLE	-3.36	5.11	-6.76	9.12	6.12	2.4063	2.1520
16	12	-6	ETA	89- 91	-1.05	2.98	-3.75	4.93	3.15	2.4418	1.9088

8) Two-jet lego plot

9) Schematic representation of quark generation

3D VIEW PT12. volume MCEN. max. depth 2

26-JAN-88

MASS MEMORY 75 PERCENT FILLED

10) Two-jet collision

Distribution of the Electromagnetic ratio of the jet towers

11) Electromagnetic fraction for 670 $Z \rightarrow c^+ + e^-$ events

12) Distribution of M_Z for an electromagnetic threshold of 0.925

Distribution of M_Z for a cutoff of 0.95

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15) Theoretical Breit-Wigner Curve for $M_Z = 90$ and $\Gamma_Z = 10$