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Course 4C00 full unit project report
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Modelling the highest energy collisions in the world

Top left: The Large Hadron Collider tunnel at CERN. Top right: A two jet collision resulting in Z boson production. Bottom left: Picture showing the proton Synchrotron at CERN in 1959, three weeks before the machine delivered its first beam at full energy. Bottom right is a picture showing the enormity of the 27Km large electron positron collier tunnel. All from the CERN website

Content

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I wish to thank my supervisors Dr Butterworth and Dr Waugh for all their help throughout the duration of the project.

Internet page

The Webpage summary of the report can be found:*www.homepages.ucl.ac.uk/~zcapw75*

Abstract

The new particle accelerator at CERN, a European based project located in Geneva, Switzerland, is due to start its measurement at the end of this year. It is capable of colliding protons and antiprotons together at energies of up to 14 TeV. The high energies of the collisions will provide the probing of matter to scales that have never before been tested. The results from CERN will provide fundamental tests to the current understanding of physics. Events, such as those that will take place at CERN, can be simulated using Monte Carlo simulation, which simulate the events using current physics models and formulae. To optimise the use of the data, many of the current models and simulations need to be refined.

In this report, a subroutine was produced which modelled measurements made from the Tevatron proton collider, from collisions at a centre of mass energy of 1.8 TeV, with the simulated Monte Carlo events using the Herwig simulator. The results show that altering generator parameters for the transverse momentum, and making cuts on the fragmentation of the particles increases the correlation of the simulated results from Herwig to the Tevatron collider results. The parameters which gave the best fit were PTRMS=0.7, VQCUT=0.4, VGCUT=0.2.

Aim

When the experiments commence, the new particle accelerator at CERN will be the world's highest energy particle accelerator. The aim of the high energy apparatus is to test the understanding of the current physics models, in order for them to be enhanced. This will aid the understanding of the world we view today. To optimise the use of the data from CERN, it is vital that a good understanding of the data and models currently available exists. There are other high energy experiments that have taken place, such as the particle collider at Fermilab. The 'real' data from Fermilab can be compared to data from models that are based purely on our physical understanding of how the particles interact, and the results from the collisions. It is the refining of these models to fit the data from colliders, such as the Tevatron, that will prove fundamental in using the data collected from CERN to its full advantage. Hence, it is important that before the new particle accelerator starts its collisions, there is a good correlation between the physical model and the real data.

The fundamental aim of the project is to use the Monte Carlo simulation to produce histograms comparable to the measured data from the Fermilab Tevatron collider in Chicago, USA. By comparing the simulated data with the measured data, the parameters of the simulated data can be altered to better fit the data from the Tevatron. Resulting in the refining of the physics model from which the Monte Carlo data is simulated. This will aid the parameters used when the Large Hadron Collider (LHC) at CERN is run at the end of the year. The LHC will test the standard model and provide new evidence for Quantum ChromoDynamics (QCD), and may even provide evidence for the existence of the Higgs boson which is crucial to proving QCD.

The histograms for the measured and simulated data were produced by using HZTOOL. Therefore, the requirements of the project meant that the initial aim was to learn how to use HZTOOL and the software required to produce the histograms such as PAW and EMACS. Once the basic skills necessary to run and compile the programs that are used to produce histograms had been acquired, the next aim was to write a subroutine. This would be written using the software EMACS in the Fortran code. The final routine would then be applied to produce a set of histograms that compare the Monte Carlo (simulated) data to the actual data from the Tevatron. The final aim of the project was then to alter the simulated data's generation parameters to provide a better fit of the simulated histograms to the histograms compiled from the Tevatron. Thus providing a comparison of our physics understanding of the data to the actual data.

Introduction

1.1 The particle accelerator

Since their conception 100 years ago, particle accelerators have been the source of many major developments and discoveries. The earliest forms of particle accelerators were simple vacuum tubes where electrons were accelerated by a potential difference between a positive anode and a negative cathode. In the early 1920's, Ernest O.Lawrence invented the cyclotron that used magnets to move particles in a spiral path to provide acceleration through electric fields. As the technology advanced the energies that could be achieved increased dramatically until today, where a particle accelerator can obtain many Giga and even Tera electron volts of energy.

Einstein's Special Theory of Relativity describes the motion of particles moving at close to the speed of light (1). From Einstein's famous theory of special relativity

$$E^2 = m^2c^4 + p^2c^2$$

Equation 1: Einstein's Special relativity

Where energy *(E)*, momentum (*p)*, and its rest mass (*m)* (1). This shows that at speeds close to the speed of light, a particle becomes more massive the more energetic it is (1). Particle physicists realised that if particles were accelerated to ever increasing energies, closer to the speed of light, Einstein's equation provided a new way of obtaining information about the constituents of particles by carrying out very powerful high energy collisions. If two very energetic particles are collided together, some energy involved in the collision would be used in creating entirely new particles through the conversion of some of the collision energy into mass. This means the particles that are produced are not necessarily what was inside the original particles, but are particles that are produced though mass conversion. This also means that the 'type' of particles that are produced depends on the energy of the collision. Furthermore, due to equation one, the production of light particles requires less energy and so they are more easily and commonly produced.

The Conseil Européenne pour la Recherche Nucléaire (European Council for Nuclear Research [CERN]), based at Geneva in Switzerland, was founded in 1954 as a European based organisation for particle research. The origins of CERN are traceable to 1949 when the Nobel Laureate, Louis de Broglie, proposed setting up a European based laboratory to halt the movement of talented physicists from Europe to America (4). Since then CERN has been at the forefront of particle physics research. The main collider at CERN was, until recently, the Large Electron Positron collider, capable of colliding electrons and positrons with a centre of mass energy of up to 209 GeV. The project was responsible for making precise measurements of particles, such as the Z^0 and W^+ bosons (2). Currently at CERN, a new accelerator, the Large Hadron Accelerator, is being built. Upon completion, the LHC will be the largest and highest energy particle accelerator in the world. The LHC is capable of providing a centre of mass energy of up to 14 TeV, making the collisions occurring the highest energy collisions yet carried out. The LHC is being built inside the LEP tunnel, which is a tunnel with a circumference of 27 meters

(3). By colliding protons and antiprotons together at such high energies, the LHC will provide an important role into the testing of today's current physics models, as it will enable the probing of matter to scales that have never before been tested

The LHC will use beams of protons and antiprotons, and if everything goes according to plan, the beams will be accelerated and collided up to energies of 14TeV and at luminosities of up to $10^{34}cm^{-2}s^{-1}$(4). The protons used in the collisions are produced by ionising Hydrogen gas. Antiprotons are generated by firing a beam of protons from an accelerator, called the Proton Synchrotron, at a target of iridium (5). The antiprotons are then funnelled through three separate devices to slow them down. They are then fed directly into a storage ring that has a circumference of 90 meters. Once in the ring, the antiprotons are slowed by a technique called stochastic cooling. This relies on sensing the position of bunches of antiprotons, then sending a signal across the ring to apply microwave pulses to control their movement. The antiprotons are then slowed further by running them alongside a beam of low energy (6). The slowing of the antiprotons means that they have a final velocity of one tenth of the speed of light before they enter the actual experiment apparatus (6).

The LHC, like most particle accelerators, is a circular machine where two beams of the desired particles that are to collide are sent travelling in the opposite direction on a circular course. It is built from high-powered magnets that are 14 meters long, these are used to steer and focus the beam. These very powerful magnets, called bending magnets, ensure that the counter rotating beams of protons are held on a steady course around the ring (5). These work on the basic principle that when a charged particle moves in a straight trajectory across a magnetic field, the particle will experience a force perpendicular to the field and to the particles' direction of motion called the Lorentz force (5).

$$F=qv \times B$$

Equation 2: The Lorentz force

By having a magnetic field that operates up and down with particles moving in the forward direction, the particle will turn left or right depending on the charge of the particle. The higher the energy of the particles which are collided together, the stronger the strength of the magnetic field required to bend the higher energy particles. This is a limitation to the energy to which the particles can be accelerated. To overcome this superconducting, magnets are used which operate at a temperature of 1.9 Kelvin, achieved by using superfluid Helium in a large refrigeration system (7). The superconducting effects are then used with powerful electric fields so that the two beams are accelerated to speeds close to the speed of light (7).



Figure 1: The refrigerators for the LHC consists of a compressor station (left) and a cold box (Air Liquid, middle and right).

Tevatron is the collider detector at Fermilab (CDF), situated in Batavia, Illinois; it is currently the world's most powerful particle accelerator, providing collisions of protons and antiprotons at a centre of mass energy of up to 1.8TeV (8). The Tevatron uses an alternating electric current to accelerate the protons to within a small fraction of the speed of light (8). This means that the protons have a mass that is more than 1000 times the mass of a proton at rest.

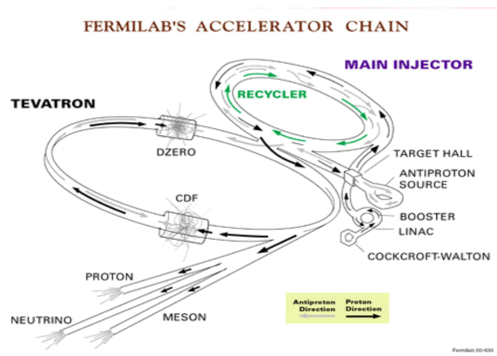
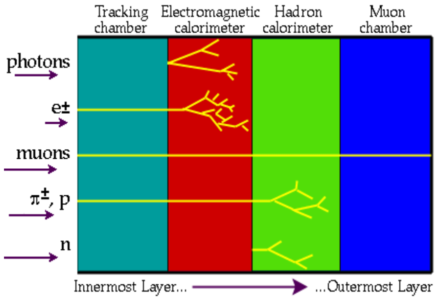


Figure 2: Schematic figure of the Fermilab accelerator chain (8)

The Tevatron has a circumference of 4 miles, and once the protons are in the circular ring, magnets within the ring make the beams collide at approximately 1.8 TeV. This dissipation process may last up to thirty hours (8). Once the particles have collided via the accelerator, it is important that the collision is properly recorded and that the data is used effectively though the detection process. The Tevatron detector is a complex 100-ton detector that measures most of the interesting particles produced by the proton-antiproton collision (8). The CDF detector uses multiple detectors to optimise the detection process. In the centre of the detector there are silicon vertex trackers and central trackers, which show the tracks of any charged particles resulting from the collision. From this, details on the particles momentum can be deduced. Surrounding the tracking chambers there are two types of calorimeters. Each detects ionisation tracks from either electromagnetic or hadronic showers respectively. The EM calorimeter consists of Lead sheets sandwiched with a scintillator to measure the ionisation. This then infers information on the energy of the electrons or photons detected (8). Conversely, the Hadronic calorimeter has two iron plates, again with the scintillator situated in between. The final layer of the detector is a muon chamber, which detects the presence of muons. Figure 3 depicts how the detection process may look.

(a) (b)



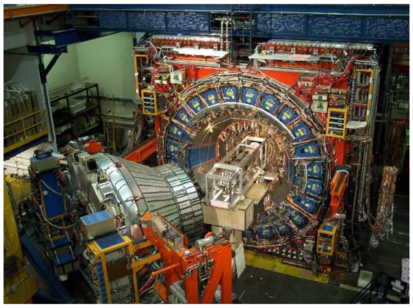


Figure 3: (a) Detection of particles (b) The silicon detector at Fermilab (8)

The detector coverage starts at an angle of between 1-2 degrees from the beam, covering all the "large" angle region from the collision. Coverage from about 30 degrees to 90 degrees (Central region) is the most thorough. This is mainly described above. There is less tracking coverage between 10 and 30 degrees, adequate calorimetry coverage (PLUG region), and muon coverage only down to (20 degrees) (8). When the generator is running there are millions of collisions per second, but the detectors only record about 50 events per second; as only a few collisions gives out energetic particles at large angles into the detector (8). Tevatron has provided fundamental research into the studies of the top quark in and of a lepton known as the tau neutrino (9).

1.2 The Standard Model

The standard model explains all phenomena and interactions of particle physics in terms of elementary point like particles, where the interacting particles are either themselves point like or consist internally of the following point like particles: leptons; quarks and field particles consisting of six quarks and six leptons; four spin 1 gauge bosons and a spin 0 Higgs boson, which all constitute the building blocks of the universe. The quarks and leptons are all interacting particles, each said to have a family of particles. There are three families of Leptons, with each family having four members: two particles and two antiparticles. These generations are named from one to three. For example, the first generation contains two electrons (electron and positron) and two electron neutrinos (neutrino and antineutrino) (10). For further families see table 4 bellow.

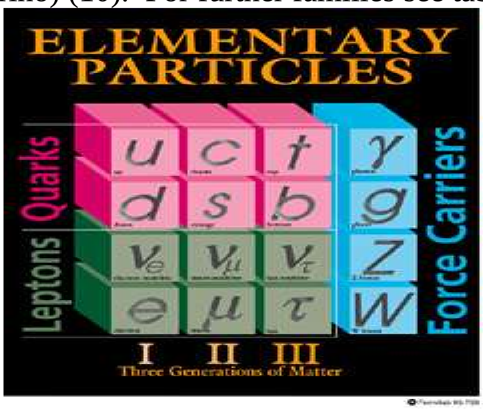


Figure 4: A table of the families of quarks and leptons (10)

Quarks also have three families; it is the members of each family that come together to form observable particles. For example, a neutron in the nucleus has two down quarks and one up quark (10). The bosons are force transmitters. For instance, the transmitter of the electromagnetic force is the photon hence the force transmitters are also called exchange particles. There are another three fields besides the electromagnetic field. These are the strong and weak nuclear forces that have the force mediators of the gluon and W and Z boson respectively. The forth force is gravity, which uses exchange particles of gravitons, although the standard model does not describe the interactions of gravity. All of the particles that the standard model predicts have been observed experimentally, with the exception of the Higgs boson. This is a particle that gives 'heavy' particles, such as the W and Z bosons their mass, and the Higgs particle itself is expected to have a mass of in excess of 110 GeV (9). The strong nuclear force is a force that occurs exclusively between quarks, while the weak nuclear force is the force that occurs between nuclei responsible for certain nuclear reactions and radioactive decays.

The standard model, however, does not describe all of the physics that is observable or postulated today. The standard model does not describe the dichotomy between quarks and leptons; why electrons can convert into their antiparticle, the positron, and the up quark into a down quark. Also it is much debated as to why quarks cannot convert into leptons and vice versa. (11) For questions such as these concerning quarks, Quantum Chromodynamics (QCD) bridges the gap. Particle accelerators provide supporting evidence for QCD. For example, QCD provides good evidence for strong interaction processes at high energy in the production of heavy quarks and jets of particles (11), for which the standard model lacks explanation.

At the most basic level of explanation, QCD is a theory of quark interaction. In this theory each quark is said to carry a colour charge, where the force between the quarks is called the colour force. The colour charge can be thought of as an analogy to electrons, where the interaction between two electric charges is described by the electric force. An obvious difference being that instead of two forces, like with the electric charge, there are three forces named red, green and blue for particles and (anti)red, (anti)green and (anti) blue for antiparticles, also known as cyan, magenta and yellow (10). Therefore, the colours red, green and blue are quantum numbers for the colour of the quark (12). From the exclusion principle each quark inside a nucleon must have different colour (12). This means that the three colours inside a nucleon will cancel each other to be white. Colour also means that there are six different flavours of quark, which come in three different colours, where each flavour of quark can have one of the three possible colour values (12). The fact that each quark has a colour charge associated with it means that the strong force between the quarks also has an added complication in that there are three kinds of strong charge; one for each of the strong force colours (10). Each colour charge can have a positive and a negative value, where a combination of equal amounts of red, green of blue charges results in net zero strong charge as well. Therefore the gluon, which mediates the strong interaction, comes in eight different varieties, one for each of the different quarks and antiquarks combinations.

The quark model has led to extensive investigation into the search for the observation of a free quark. Despite many investigations a free quark, i.e. one that is free and unbound from other quarks, has never been found. This has lead to the conclusion that quarks cannot exist as free particles and are only observable in their bound state. This is because the attractive potential energy between quarks increases linearly with separation (10). Also related to this are the facts that not only do gluons interact with quarks, but also that gluons can self interact. This leads to the phenomena of asymptotic freedom and to the theory of confinement. Asymptotic freedom is where the strength of the force is large at large distances and small at small distances. This has the consequence that the quarks inside a hadron can move around relatively freely, but will attract strongly as the separation increases. This leads to the confinement of the quarks to within the size of hadrons. It is also believed, due to observations, that there is confinement of coloured combinations of quarks. For example, a red quark combined with a green down quark has never been observed. Due to these observations, the only quark combinations where the quarks are colour neutral are observable.

Despite the advances of QCD, in the early stages of the theory it was still thought that the cloud making up the proton could be made up of particles other than quarks. To overcome this lack of understanding at the time, Feynman developed a theory where by he chose to ignore the detailed form of the type of particles that were making up the proton cloud (13). Hence, the parton was a hypothetical fundamental particle considered, in the 'parton model' of strong interactions, to be a constituent of the hadron (14). This consequently lead to the Bjorken-Feynman parton model which views nucleons as being made up of point-like constituents, and provides a very simple framework for calculating scattering cross sections as well as structure functions for the nucleons. This subsequently paved the way for particle physicists to later identify the partons as quarks (12).

Parton distribution functions (pdfs) give the number of partons (quarks and gluons) in a high momentum hadron e.g. the proton (15). Technically the parton distribution is given as

$$f_{a/A}(x, \mu)$$

equation 2: The parton function of a proton

This gives the distribution of partons as a function of the variables *a*, *A*, *x* and *mu* (16). Parton distribution functions precisely defined in terms of matrix elements of operators and are determined by data from particle physics experiments (16). This is done by extracting a set of pdfs from measurements of different quarks combinations. Subsequently, this means that the individual quarks pdf can be inferred from the measurements. The distribution function is necessary to know to calculate the cross sections at ppbar colliders.

We now know that the proton consists of a cloud of quarks and gluons, and there is a probability distribution of these, which are called structure functions. When a proton antiproton collision occurs by the exchange of a single intermediary particle, certain types of events, called two jet events, are observed. In these two jet events bundles of particles are emitted in the opposite direction at large angles, hence with a large momentum transfer, from the colliding beams (17). This indicates that the colliding particles are point like, at least down to the minimum resolution available from today's accelerators (17). From the Bjorken-Feynam parton model of the proton the collision between two highly energetic protons and antiprotons looks like that in figure 5

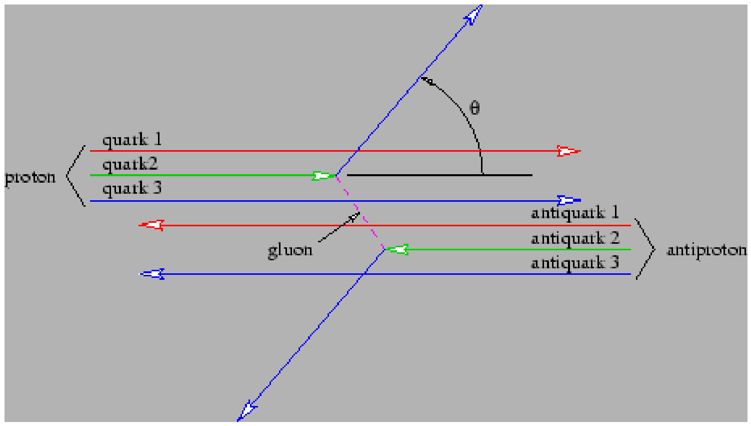


Figure 5: The collision between a proton and antiproton according to the Bjorken-Feynman parton model (17)

Here, the quark and antiquark are from the proton and antiproton respectively. The particles are scattered out of the incident particles in opposite directions due to momentum conservation, and the resultant is the two jet event. When protons and antiprotons collide they annihilate to give an exchange particle. An exchange particle can also be considered as a virtual particle. A virtual particle is called 'virtual' as they never manifest themselves directly outside the scattering region (18). This arises from the uncertainty principle, where by a particle has an uncertainty in its mass for a short period of time

$$\Delta M \times \Delta t \sim \hbar$$

Equation 3: Heisenberg's uncertainty principle

An example of the types of exchange particles in proton and antiproton collisions is Z and W bosons.

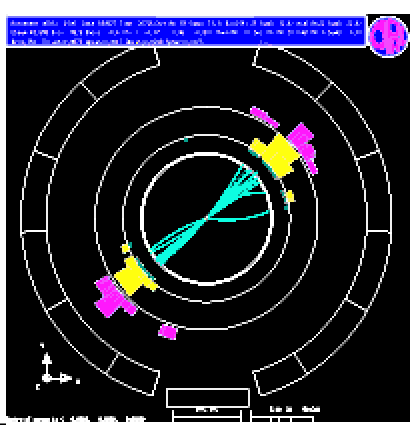


Figure 6: A two jet event of the Z boson decaying to a pair of quarks. As the quarks move apart, the energy in the field between them caused by their colour charge to build up and further quarks and antiquarks are

formed. Finally, the quarks are seen in the detector as two collimated back-to-back "jets". Also seen here is a third jet; sometimes, an energetic gluon may be emitted by one of the quarks creating a gluon jet.

1.3 The Simulation

Results from the collisions at the colliders, such at the Tevatron or the LEP, are recorded and written up into research papers .It is hard at high energies to understand from the published papers the information required to provide detailed and useable analysis so that there is good comparison between data for simulated models and measurement. For example, difficulty occurs when investigating hadronic final state and looking at the kinematic cuts (19). To ease and speed up this process HZTOOL was invented. HZTOOL consists of a set of routines allowing a comparison of published collider data with Monte Carlo generator predictions. It contains most of the data available on the hadronic final state in DIS and photoproduction.

"*HZTOOL is basically a library of subroutines, each of which corresponds to a published paper. If supplied with the final states of a set of simulated collisions, these routines will perform the analysis of the final state exactly as it was performed in the paper, providing simulated data points that may be compared to the measurement. HZTOOL therefore has to provide the relevant jet finders, events shape variables etc. It is, however, independent of the generator used to simulate the collisions*". (20)

There are many different programs and generators that can be used to simulate an event. The generator, Herwig is an example of one that is used. Herwig is a Monte Carlo package for simulating hadron emission reactions with interfering gluons (20). More specifically, it is a

"*General-purpose event generator for high energy processes, with particular emphasis on the detailed simulation of QCD parton showers….the program provides a full simulation of hard hadron-hadron scattering and soft hadron-hadron collisions in a single package*" (21)

The data that Herwig uses is based on a combination of data from research and also on physics theories such as formulae. The program is written in Fortran where the main program can be modified to generate the type and number of events required. This is done by altering the event parameters, in particular the IPROC number. The IPROC number corresponds to a specific process: lepton-lepton scattering to produce combinations of quarks or gluon, boson gluon fusion, or (as what is desired for the subroutine) quark-quark interaction, which produces a Z boson, which subsequently decays to an electron-positron pair. For all these various events there are IPROC numbers that range from between 100 and 1000.

The main program is written by setting up parameters in common blocks. Many of the parameters are set to default values. The main program can be easily called up using HZTOOL: any parameter of interest that can be altered, saved and then the routine can be rerun with the new parameter values. A list of the parameter values is given in table 1 below.

Name	**Description**	**Default**
QCDLAM	ΛQCD	0.18
RMASS(1)	Down quark mass	0.32
RMASS(2)	Up quark mass	0.32
RMASS(3)	Strange quark mass	0.50
RMASS(4)	Charmed quark mass	1.55
RMASS(5)	Bottom quark mass	4.95
RMASS(6)	Top quark mass	174.30
RMASS(13)	Gluon effective mass	0.75
VQCUT	Quark virtuality cutoff (added to quark masses in parton showers)	0.48
VGCUT	Gluon virtuality cutoff (added to effective masses in parton showers)	0.10
VPCUT	Photon virtuality cutoff	0.40
CLMAX	Maximum cluster mass parameter	3.35
CLPOW	Power in maximum cluster mass	2.00
PSPLT(1)	Split cluster spectrum parameter	1.00
PSPLT(2)	1: light cluster, 2: heavy b-cluster	PSPLT(1)
QDIQK	Maximum scale for gluon->diquarks	0.00
PDIQK	Gluon->diquarks rate parameter	5.00
QSPAC	Cutoff for spacelike evolution	2.50
PTRMS	Intrinsic Pt incoming hadrons	0.00

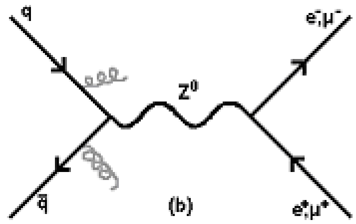
Table 1: *Herwig parameters*

Another extremely useful tool used to compare simulated and measured data is JetWeb. JetWeb contains a database of data and predictions for collisions and allows calculated models and data from observations to be compared. It uses HZTOOL to compare different models with the data from experiments, storing the data from HZTOOL so that it can be easily accessed via the Internet. Hence, making JetWeb an invaluable tool for refining physics models.

1.4 The project

Due to the high energies that will be produced at the LHC, there are many types of reactions occurring that will not have previously been observed. To optimise the use of the data it is necessary to tune the current physics models to fit with the current results. In this project the parameters for Z boson production will be tuned to fit with results from the Tevatron. The paper of interest for the purpose of this report is *'The Transverse Momentum and Total Cross Section of e+ e- Pairs in the Z-boson Region from p anti-p Collisions at s**(1/2) = 1.8 TeV*'. Within which the physical process of interest is the production of Z bosons from quark annihilation resulting in a lepton pair. A copy of this report can be found in Appendix B

The measurements of bosons are inferred from colliding highly energetic beams of protons and anti-protons in particle accelerators. The mass of the Z-boson can then be determined via observations of the leptonic decay products, i.e. from the electron-positron pair.



(22)

Figure 7: A Feynman diagram for the creation of a Z^0 boson. The radiation of gluons prior to collision is also depicted.

The lepton pair resulting from the collision can only be produced via a virtual photon when two protons collide. It has been suggested that one quark in the proton and one quark in the antiproton annihilate into a photon, which then creates a lepton pair. This is called the Drell-Yan process (23). The process is an electromagnetic effect.

As the energy of the collision increases, the quarks become more likely to emit gluons before they collide. This is where our physics knowledge is lacking, as we do not know much about what is occurring with gluon radiation before the quarks collide. By tuning the parameters we can attempt to work out what we think is happening by fitting the parameters to the real data. Then these parameters will be useful to look at once there is data from CERN.

For proton-antiproton collisions the parameters of interest are PTRMS, VQCUT and VGCUT. PTRMS refers to the transverse momentum of the incoming proton and antiproton. The default in the Herwig generator for PTRMS is set to zero. This is an unrealistic default to simulate real physical processes. If the incoming hadrons had no transverse momentum, the mediator and the resulting leptons will also have no transverse momentum. However, the physics results show this to be false, as the detector data from the resulting electron and positron show that they do in fact have transverse momentum. This means that as the hadrons are accelerated along a linear path, with no transverse momentum, there must be processes occurring before the hadrons collide to give them some momentum transversely.

After a particle, like a proton, interacts with a nucleon it enters a state called off-shell, and the final asymptotic state of the proton is called on-shell. It must take time to evolve to the on shell state (24). When a quark is struck by an electoweak boson it can emit partons which gives rise to initial and final state parton showers (25). A parton that is close to the incoming nucleon can initiate a parton shower. For each branching of the shower, one of the parton has space-like virtuality and the other has time-like virtuality, with them being off and on-shell respectively. The initial space-like shower results in a space-like quark that will interact with the boson. This turns it into an outgoing quark. The time-like shower results in the off-shell mass being reduced by further branching. The shower continues until all partons are on-shell (25). The showers are based on the branching process q-> qg, g->gg and g ->qg. (q refers to a quark or antiquark and g to a gluon). VQCUT and VGCUT refer to the virtuality cut off of the quark masses and the effective mass in parton showers respectively.

JIMMY is another parameter that is alterable. It has a default of either zero or one that corresponds to off or on respectively. The Jimmy generator is:

"A library of routines which should be linked with the HERWIG Monte Carlo event generator. JIMMY will allow you to generate multiple parton scattering events in hadron-hadron, photon-photon or photon-hadron events parton-parton scattering". (6)

Therefore, the effects of turning JIMMY on and off will be investigated.

To summarise, the main goal of the project is to model the collision using Monte Carlo methods. By altering simulator parameters, the effect of gluon radiation and transverse momentum of the quarks has upon the kinematics of Z boson production can be better understood. This will be done by firstly writing a subroutine that will form the process. Data will be calculated, looking at data for the electron position pair, inferring a value for the Z boson. From this the collision cross sections will be plotted, and in addition the Z boson mass will also be plotted. The data can then be added into the JetWeb library to be used to compare data when LHC is operating.

2 Method

2.1 Writing the Program

Due to the nature of the report, there was a large computer basis involved with the project. A large element of the project was involved with learning the computer skills required to use the programs and software such as PAW, HZTOOL and EMACS. The software would be used to write and compile the routines and histograms, with the skills I have acquired being combined to write my own routine. For this reason, half of the time spent on the project was dedicated to principally learning how to use the computer software. Once competency with the computer software and commands used had increased, time was then spent looking at example routines. This enabled an understanding of how the basic structure and form of a routine is written.

A routine, which was fundamental in learning how to write a routine, was written from a research paper, *'A Measurement of the Differential Dijet Mass Cross Section in ppbar collisions at a centre of mass energy of 1.8 TeV'*. The paper and the corresponding subroutine are given in appendix A. From this it was possible to see how a routine is written. Hence, much time was spent looking over this routine and also in generating the histograms from the routine: tools that would be fundamental later in the project for writing my own routine.

Initially the routine was written by using the routine from Differential Dijet mass production. This served as a template that was used as the 'skeleton' of the routine. For example it showed, where the measured data from the research paper should be entered in the routine, where the histograms should be booked, and where the calculations should be carried out with the histograms being filled after this. It also showed how the Fortran should be written, for example, the form in which the loops should be written, and other relatively minor additions, like putting a '/' at the end of the data statements.

The start of the routine states any additional files required to read the routine, the status of any arrays; whether it contains double precision, real numbers or integer values and how many values there are in the array. The additional files in the routine are .inc files. These contain data on the number of particles created in a run and data on the types of particles created (see appendix C). Although this is the first part of the routine, the process of stating the status of the arrays was left as the final part to be written. This was as a result of the fact that at the early stages of the routine, during writing, it was impossible to tell which arrays or loops would be written. So, this was left as one of the final things to write for the routine.

To begin, data was added to the routine from the table in the appendix of the research paper (appendix B, table I). The bin width that would be used in the histograms was firstly put in from the values given in the research paper in the column labelled Pt. The values given in the research paper were the bin centres. For plotting the histograms the bin edges would be required so that the histograms could be correctly filled. The bin edges were therefore entered by adapting the bin centre values given in the paper into the array binPt starting at 0 up to energy of 200Gev/c with the bin changing size at

0,12,20,30,50,100 and 150GeV/c with corresponding widths of 0.5,1,2,4,10,25 and 50 GeV/c. The values for the differential cross section of the electron-positron pairs (dP/dPt) were added directly into a data array named 'mass' and correspondingly the error in these mass values were also directly added from the table, into an array called 'error'. The data had to be added with the / sign at the end of each array and the data had to be entered with no spaces and to two decimal places using a d for standard form.

The next stage was to book the space in the computer memory where the histograms would be stored. This was done by using the HZTOOL function, HBOOKB, and the Fortran function CALL. Booking the space for the histogram was written in the form:

Call HBOOKB(histogram number),'title',number of bins,binwidth(binPt),weighting(0))

Four histograms would need to be plotted: the Differential electron-positron cross section of the results directly from the research paper, the unnormailised values of the cross section from the Monte Carlo simulation, the normalisation values, and one for the simulated with normalised values for the cross section.

Then next stage was to add the cuts to the routine that would need to be implicated later. Three cuts would need to be made to the data, a mass cut, a rapidity cut and an energy cut. The mass cut would be used so that only masses in the mass range corresponding to the Z boson mass would be plotted in the final histogram. This range was 66 to 116 GeV/c, with the median of these numbers corresponding to 90GeV/c: this is approximately the measured mass of the Z boson. The second and third cuts apply to the limitations of the detectors; both electrons are required to fall within the fiducial area of the calorimeter. Therefore cuts are made on the central, end plug and forward regions of the calorimeter. The electrons in these regions are each required to possess a minimum transverse energy. Also, the regions must also have a corresponding rapidity that corresponds to the energies and directions of the electrons, photons and jets. All these cuts were entered into the routine from values stated in the research paper to be used later in the calculations.

The next part of the routine involved writing a loop to find the correct electron and positrons from Z boson decay in the generator. Then the correct cuts could be applied so that only electrons and positrons that fit required criteria are plotted into the histogram. To find the mass and the transverse energy of the pairs the four momentum of them was required (E,Px,Py,Pz). Initially, all of the values were put in an array and initialised to zero. A loop was then written which looped over all particles in the event which corresponds to the HBOOK function NHEP. In HBOOK, all particles are given an identifier corresponding to an integer. The ID for an electron is 11 and a positron, –11. To ask the routine to pick out only electrons and positrons from the generator an IF statement was written. If statements have the form:

IF (IDHEP.eq.11)then

In addition, another if statement was necessary to demand that the only particles that are 'picked' out from the generator are final state; only particles which are stable are physically correct to be filled into the histogram. The HBOOK function that looks at the status of a particle is ISTHEP. Again, this uses integer numbers that correspond to different particle status. For particles in final state the corresponding number is IDHEP equal to 1. Two sets of IF statements were used inside the loop; one corresponding to electrons and the other to positrons. So to briefly summarise, electrons and positrons have now been found which are only in final state. From this the energy and momentum could be stored in an array. The arrays were named Eelec or Epos etc, depending on which value and for which particle it corresponded to. The HBOOK function PHEP that corresponds to physical particle values, again with integer identifiers, with numbers 1-4 corresponding to energy, x momentum, y momentum and z momentum respectively.

So that the cuts could be applied correctly, the transverse momentum, rapidity, and the energy of the electron-positron pair needed to be calculated. Transverse energy is the energy carried by a particle in the transverse plane. The equation for this is given in equation 4.

$$Et = \text{Squareroot}\ (Px^2 + Py^2)$$

Equation 4: *Transverse energy*

Where Px and Py are the momentum of the particle in the x and y direction.

The transverse energy of the electron and positron were calculated individually and then the individual components were added together to calculate the transverse energy of the pair.

The rapidity, Y, was calculated from the formula

$$Y=\text{LnCos}\theta$$

Equation 5: Rapidity

Where θ is the scattering angle given by:

$$\theta= E_t/P_z$$

Equation 6: *Scattering angle*

The rapidity for the electron and the positron were calculated individually and separate cuts were made on the electron and positron in the routine. The rapidity cuts were applied by using RETURN. They were written in the form that if the if the transverse energy or the rapidity were outside the limits from the research paper then RETURN, i.e. ignore these values and continue with the loop.

The normalisation values were then calculated so that the measurements of the differential cross section for the simulated data is normalised to allow it to be compared to the measured data. The normalisation were calculated from the formula given in the research paper

$$\text{Normalisation value} = (\text{Bin width}) \times (1/L)$$

Equation 7: Normalisation values

Where L is the luminosity given by:

$$\text{Luminosity (L)} = \frac{\text{Number of events}}{\text{Cross section}}$$

Equation 8: Luminosity

The normalisation values were calculated by writing a small loop which calculated the bin sizes which were then divided by the luminosity.

The final stage was to fill the histograms by using the function HFILL. To call HFILL the HZTOOL command was written in the form:

CALL HFILL(histogram number,data,weigting)

Once the routine had been completed it needed to be compiled so that it was written in the correct Fortran code, and so that there were no errors. The routine was complied using the HZTOOL command 'make'. This read the routine line by line and if there was an error in that it would show an error message highlighting where and what the error was. This was quite time consuming. The errors were to be corrected and then the routine would be recompiled to see if the alteration fixed the error. In total though, it took about half a day to fix the errors and alter the routine so that it would then compile.

Once the routine would compile there were still problems encountered. Half way through the run, the routine would crash with a message aborted, core dumped. This indicated that there were still errors in the routine. After examining the routine, it was realised that there was an error in the loop written to calculate the normalisation values. The loop was written to calculate the bin width by finding the nth value of the bin and subtracting this from the n-1 value, for which there was no value given in the routine. Changing the formula to n subtracted from the n+1 value easily solved this. Once this alteration had been made, the routine was then saved, recompiled and then run. The routine was then run, which took approximately seven minutes, and the data from this was output to be made into the histograms.

2.2 Making the Histograms

The histograms were made using PAW. This enabled an efficient and easy way to look at the histograms, and to superimpose the measured and simulated data so that they could be easily compared. To see the detail of the curves the information needed to be plotted on a logarithmic scale. The initial set of histograms obtained looked like the simulated and measured data both followed a similar shape. The measured data's histogram was correct to the one given in the research paper. The measured data had some zero data bins that were being filled, and the peak of the plot had some extra peaks at lower bins. After looking through the routine it became apparent that there was an error in the loop for finding the electron and the positron. By looking through the data for the run, it was possible to deduce that the loop was not finding the correct positron and electron. The desired pair that the loop needed to find had to be from the decay of a Z boson. It became apparent that the way in which the routine was written meant that simply the last pair being generated was being booked in the arrays. By looking through the data for the run, it was possible to see that the last pair generated was from a Pion interaction. Hence, the histograms being made were not representing the Z bosons properties, but were representative of different particles present. Therefore, the loop was rewritten so that only electron-positron pairs that are from Z bosons are kept and any others that are not are rejected. This was solved by writing a secondary loop for the positron inside the initial loop for the electron, instead of having two individual loops, as was previously done.

The histograms had extremely large error bars. To reduce the size of the error bars, and to produce more data points, the number of events being measured was increased. This could be done by calling up the main program (see appendix C) and changing the default value of MAKEV. It was changed from a value of 1000 events to 100,000 events. This meant that, as there were so many events being generated, the routine now took hours rather than minutes to run. Also, only one run could be ran at a time, as once the program was changed, any additional alterations then made would alter the run. Therefore, the runs were redirected to a set of computers in the HEP department which are set aside for running programs and routines. Therefore, half a dozen alterations could be made and the program saved under a new name for each. Then the routine would run for each individual changed program.

2.3 Altering the parameters

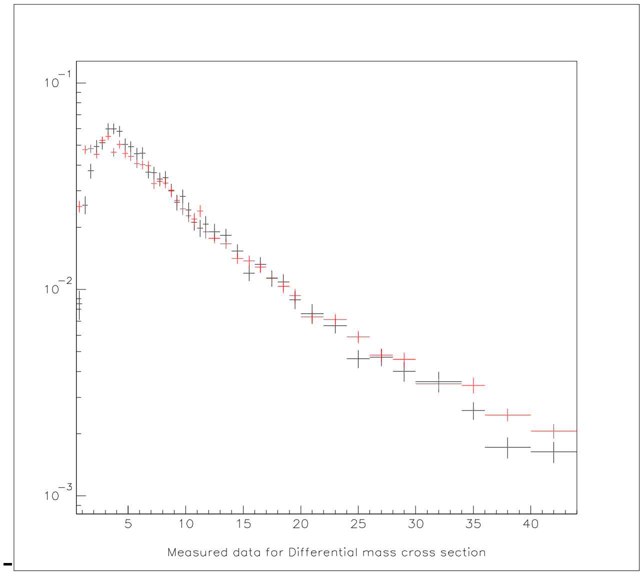
The table 1 showed a list of parameters used in the Herwig generator for an IPROC number of 1531. It was decided that the parameters of interest were PTRMS, VQCUT and VGCUT. The PTRMS default value for the generator is zero, meaning that the generator uses the assumption that the protons have no momentum transversely. Runs were set for values of the PTRMS ranging from 0 to 3 in intervals of 0.5. More detailed results were taken between PTRMS values of between 0-1 by using intervals of 0.25. VQCUT and VGCUT had defaults of 0.48 and 0.1 respectively. These were also run for values from 0-3 at intervals of 0.5, with more concentrated results about the default value.

To investigate the effect of altering the JIMMY parameter, all the runs for PTRMS, VQCUT and VGCUT were each run with JIMMY on and then off (i.e. with values set to 0 and then 1).

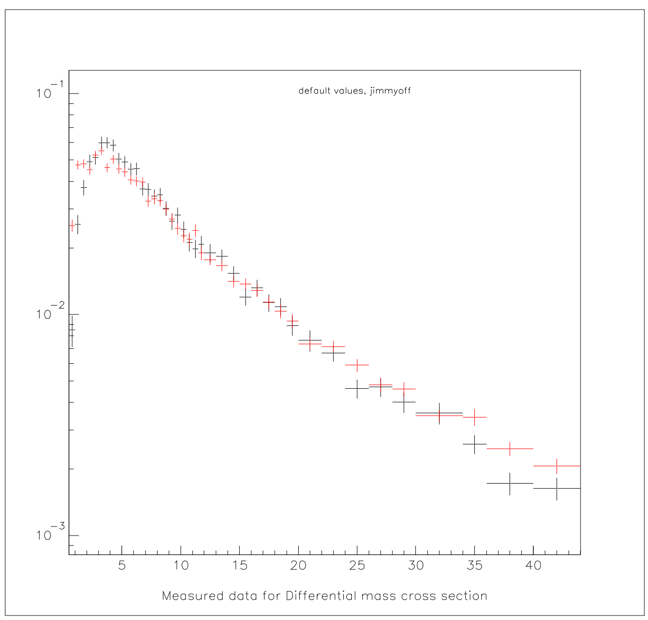
3 Results

The final histograms to be compared were created in PAW. Appendices D-F show a complete set of histograms for all the results.

Graph 1a and 1b are for the default values that the generator is set to; i.e. with the defaults given by table 1. Graph 1a compares the simulated and measured data with the parameter jimmy turned on, and graph 1b is with jimmy turned off.



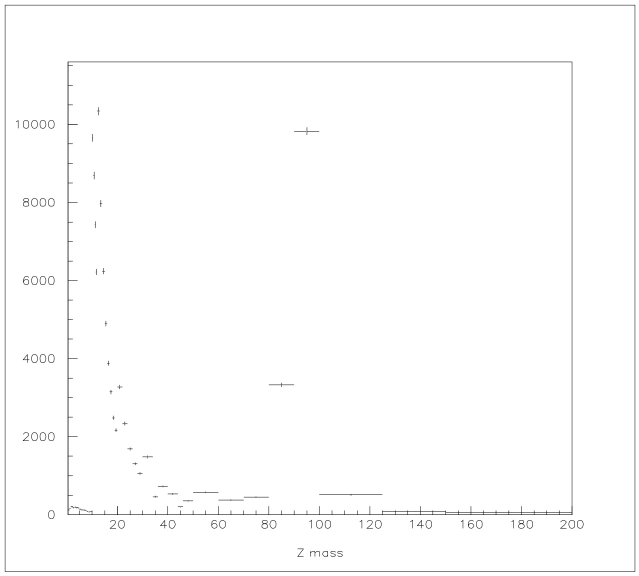
(a)



(b)

Graph 1a: Jimmy on. Graph 1b: Jimmy off. The black curves are for the simulated data and the red is for the measured results.

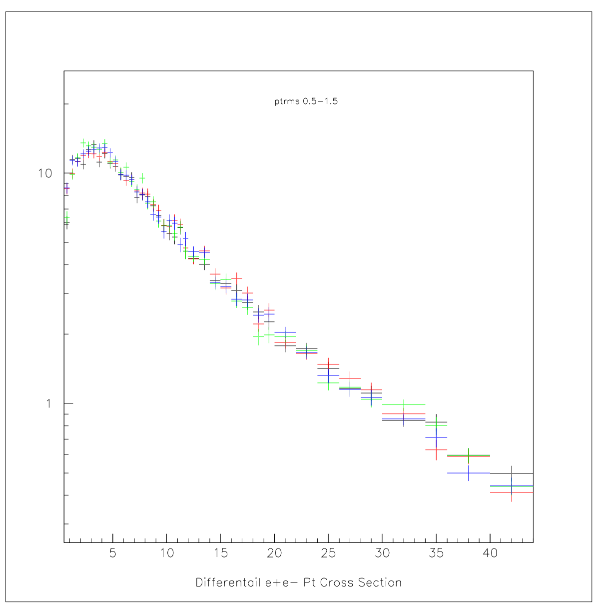
It is possible to see from graphs 1a and 1b that there is a good correlation between the measured and correlated data. However, the detail at the higher energy values is quite difficult to see. The correlation at the lower energy values are good as all the error bars for the data points of the simulated data lie within the measured data's error bars. Therefore, all following plots are plotted using the PAW zoom function to enable better analysis at the lower bins between 0 and 40. Also, the plots are all normalised to an area of one so that they could be better compared.



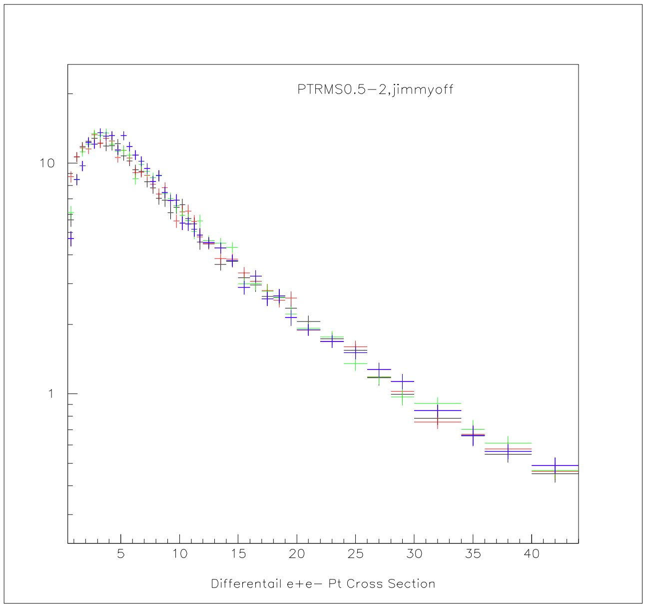
Graph 2: Plot for the Z boson mass from the simulated data.

Graph 2 shows a plot for the Z boson mass. This has a distinct peak at approximately 90GeV. The Z boson mass is measured to be 91.2 GeV.

3.1 PTRMS

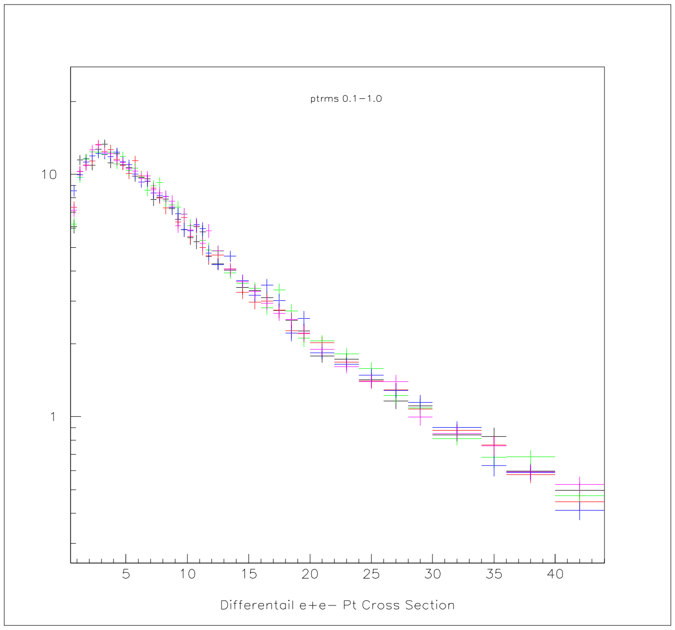


Graph 3: Plot for the effects of altering PTRMS between 0.5-1.5 with jimmy off (black=measured data, red=0.5, green=1, blue=1.5)



Graph 4: Plot for the effects of altering PTRMS between 0.5-2 with jimmy on. (black=measured data, red=0.5, green=1.5, blue=2)

From graphs 3 and 4 it is possible to see that the effect of altering jimmy appears to be minimal. It would appear that the differences of altering jimmy makes some data points above the measured curve, and some below it. Therefore suggesting that the differences are more likely due to random fluctuations in the simulator. The value of PTRMS that best fits the data are the values of PTRMS between 0.5 and 1. To better determine the value of PTRMS that produces a more accurate fit the routine was rerun for more values in this range. Graph 5 shows results for values of PTRMS of 0.1 to 1.

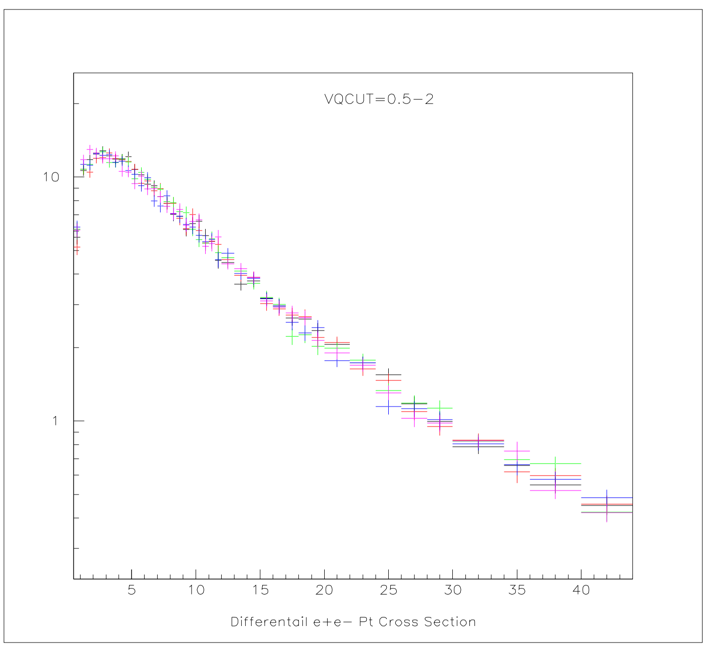


Graph 5: Plot for the effects of altering PTRMS between 0.1-1 with jimmy off. (black=measured data, red=0.1, green=0.25, blue=0.5, purple=0.75)

The graph shows that the higher values of PTRMS, in this range, provide a slightly better fit for the data. The closest fit is for PTRMS equal to 0.7

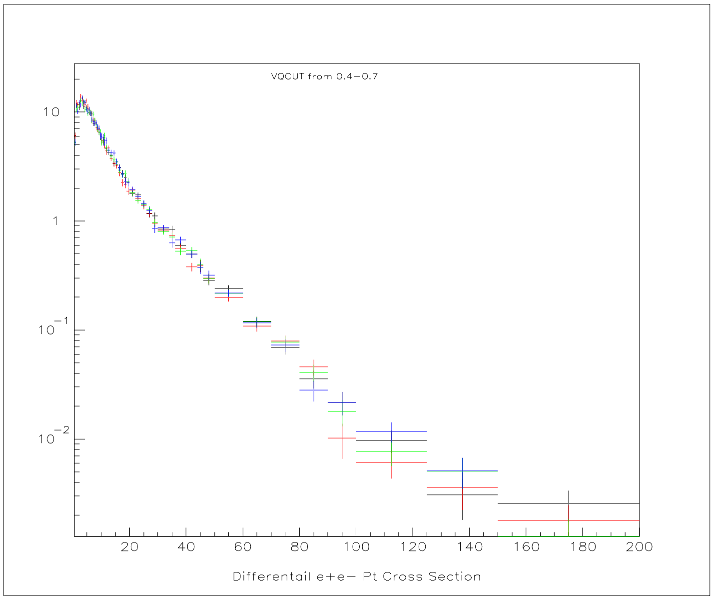
<u>3.2 VQCUT</u>

Graph 6 shows the results of altering the VQCUT parameter between 0.5 to 2.

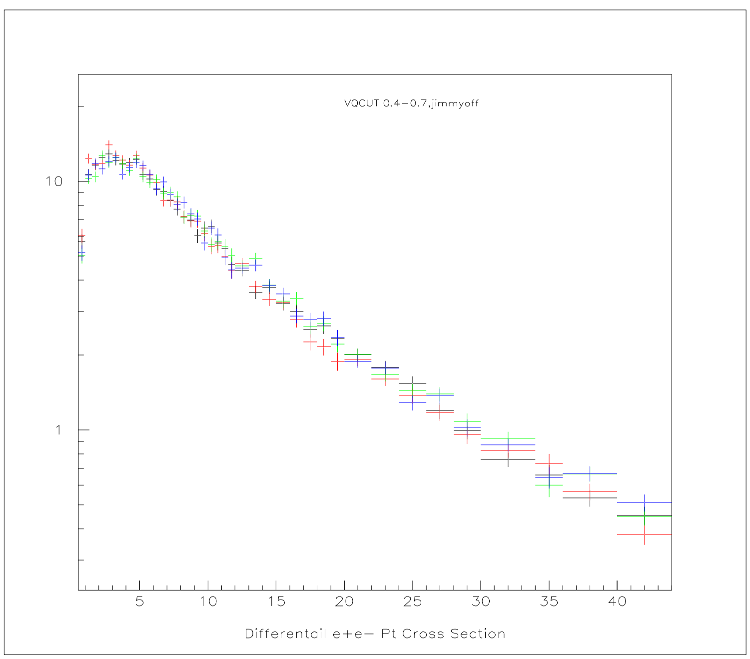


Graph 6: Plot for the effects of altering VQCUT between 0.5-2 with jimmy off. (black=measured data, red=0.5, green=1.0, blue=1.5, purple=2)

Higher values of VQCUT are decreasing the correlation between the data. Graph 6 shows that values of 0.5 and 1 give a better correlation to the measured data. Plots 7 and 8 focuses on this area with jimmy on and off respectively.



Graph 7: Plot for the effects of altering VQCUT between 0.4-0.7 with jimmy on. (black=measured data, red=0.4, green=0.6, blue=0.7)



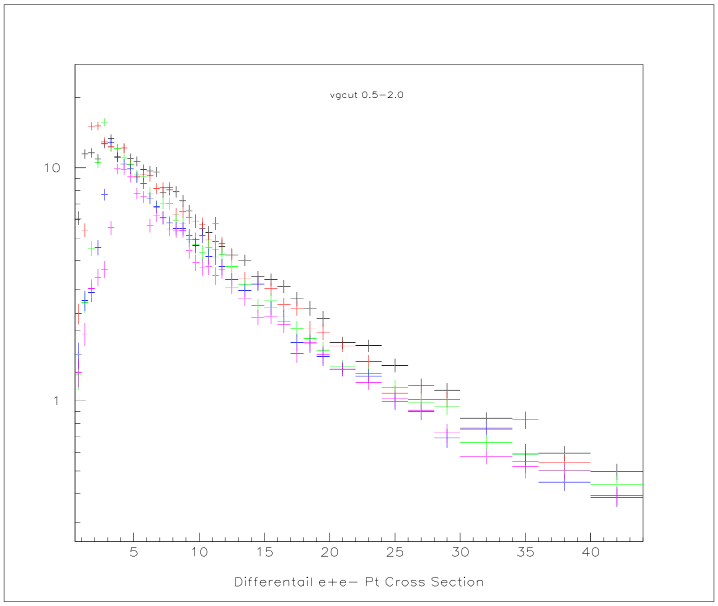
Graph 8: Plot for the effects of altering VQCUT between 0.4-0.7 with jimmy off.

(black=measured data, red=0.4, green=0.6, blue=0.7)

From these results the best fit for the data is a VQCUT equal to 0.6 with jimmy on.

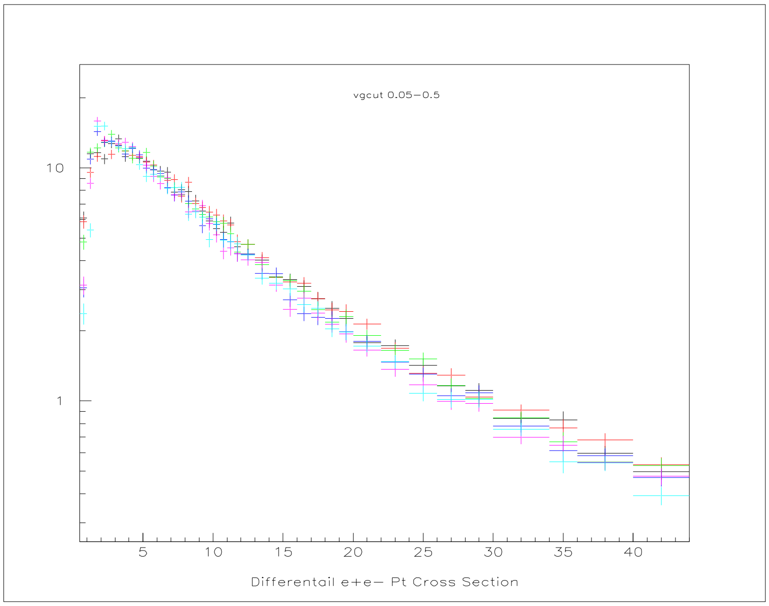
3.3 VGCUT

For the plots where PTRMS and VQCUT were altered, the plots still did not show a precise match of the simulated data to the measured data. After re-examining the parameters and speaking to a PHD student, Emily Nurse, who looked at a similar collision (but for the W boson), it was recommended to observe the effect for VGCUT. This parameter is concerned with the effect of gluon fragmentation; when the quarks collide, there could be some gluon fragmentation and reactions taking place that could alter the properties of the incoming quarks for if there were no gluon interactions. The histograms are shown in graphs 10-12.

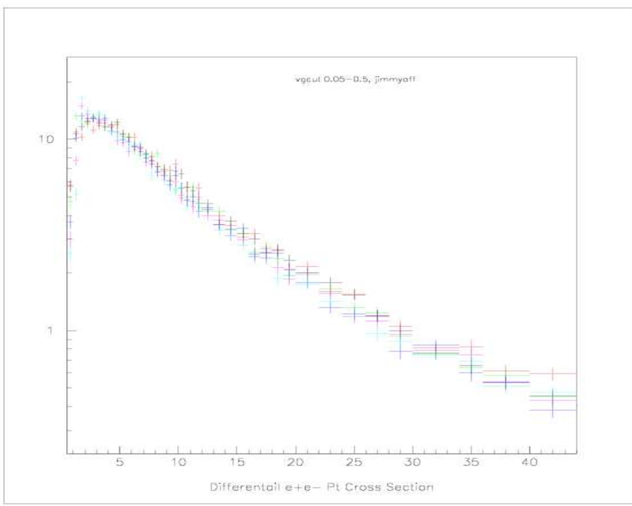


Graph 10: Plot for the effects of altering VGCUT between 0.5-2 with jimmy off. (black=measured data, red=0.5, green=1, blue=1.5, purple=2)

Similarly to VQCUT the higher values of the parameter decrease the correlation. The closest fit of the data is for data values below 0.5; plots 10 and 11 focus of this area.



Graph 11: Plot for the effects of altering VGCUT between 0.05-0.4 with jimmy off. (black=measured data, red=0.05, green=0.2, blue=0.3 purple=0.4, light blue =0.5)



Graph 12: Plot for the effects of altering VGCUT between 0.05-0.4 with jimmy on. (black=measured data, red=0.05, green=0.2, blue=0.3 purple=0.4, light blue =0.5)

4 Conclusions

The results show that altering the generator parameters does provide a better fit to the data from the Tevatron. The best generator parameters that provide the best fit to the measured data is:

Parameter	Best fit value
PTRMS	0.7
VQCUT	0.4
VGCUT	0.2

Table 2*: The parameters for the best fit*.

As the energy of the collision increases, the quarks become more likely to emit gluons before they collide. The assumption that Z boson has no transverse momentum is now invalid, affecting the calculated mass. As the leptons emerge with a nonzero value of transverse momentum (pt), this indicates the presence of gluon emission. In a parton model without gluon emission, all the final state jets are collinear with the colliding beams. This means that the spread of the transverse momentum is only as wide as the spread that is required by the uncertainty principle for confined quarks. Measurements show that the final particles do posses pt, which means that there must be processes occurring before the protons collide to produce this. Hence, in the actual collision there will be extra processes occurring, such as gluon radiation, which will introduce more momentum into the collision.

This is apparent in the results. The results for altering the PTRMS value parameter are given in graphs 3-5. From this, it is possible to see that if the value of PTRMS is too low, and also too high, the measured and simulated graphs do not show good comparison. This is a result of the incoming hadrons in the simulation having less or more pt than the ones that took place in the Tevatron collisions. Therefore, there is an optimum value that the value pt can have. This value appears to lie between PTRMS values of 0.1 and 1. Graph 5 shows the results for these values. The simulated data provides a better match for PTRMS values between 0.5 and 0.7; with 0.7 providing a slightly better fit.

The parameter VQCUT had a similar effect to altering the PTRMS vaules. High or low values pushes the results far from the Tevatron data, but values between 0.5 and 1 proved the closest fits. VQCUT generates values that are added to the quark masses in the parton showers and is set to a default of 0.48 in Herwig. Graphs 7 and 8 shows results for VQCUT for values either side of the default value. VQCUT values of 0.4 and 0.6 produce very similar effects, with neither producing a large noticeable improvement in the correlation, with 0.4 produceing a marginally better correltaion. Therefore, this indicates that the default that Herwig uses is probably a value representive to collider events.

Altering the parameter VGCUT had a very noticeable effect on the distribution. As the value of the parameter is increased, it is possible to see that the peak of the curve narrows and decreases in height, see graph 10. VGCUT are values that are added to the effective masses in the parton showers. Increasing the values of these parameters means that the cut off value for this process is being increased. The higher the value of VGCUT, the less radiation there is in the collision. As it is the radiation processes that introduces pt into the collision, there will also be less pt for the incoming hadrons for increasing this value. The reduction in pt results in creating a sharper peak in the curve. So, it is important to have correct values for the parameter. Given the poor correlation for graph 10 for VGCUT, the results show that having values of the parameter which are above 1 are much too high and not representative to what actually occurs in the collider. Therefore, values closer to the default value must be more physically correct for the collision. By comparing graphs 11 and 12 it is possible to see that values of 0.05 and 0.2 provided the best fit to the measured data, with 0.2 providing a better fit. This also indicated that VGCUT is set to approximately the correct value.

The effect of jimmy on the process is hard to determine. With jimmy on there is an increase in the number of hadrons in the event. This means that there will be extra interactions occurring which can cause more gluons to be radiated. Hence, it may add more pt into the collision process. The results found in the project are hard to see whether or not this has a real effect on the data, but would be an interesting area for further research. It is possible to see a difference when jimmy is off and on, but the effect appears to be rather random for low values of the generator parameters. However, for the high values of VGCUT above 1.5, it is possible to see a slight flattening of the simulated curve where jimmy is on. Jimmy allows the simulator to generate multiple scattering events. With jimmy on for high values of the parameters, too many scatters are being generated. As the curves of these simulated data points show little correlation with the real data points this also indicates that these results are unphysical to the actual processes occurring.

The reason that the simulated and measured data have not provided exact matches could be for several possible reasons. Firstly, there could still be some bugs in the routine; in that when the routine is run though the generator the data being out put is incorrect. This should be an unlikely candidate, as the routine was thoroughly checked, and although there is not an exact match, there is still a very good match between the results. Also, the plot of the Z boson mass peaks at a value of 90GeV (graph 2): this approximately corresponds to the mass that has been measured for it in previous experiments of 91.2GeV. Therefore, as this is correct, it is unlikely that there are errors in the routine.

Secondly, it could mean that the simulation itself has some bugs contained in it. The simulation is based upon physics formulas that are known and that are believed to be correct today. Therefore, the simulation may not contain all the formulae needed to produce data that is close to what is observed. As there may be processes occurring in the reaction that we are currently unaware of, this is therefore not contained within the simulation.

Lastly, the measurements themselves may be inaccurate. When the data is being detected the measurements that are recorded could be lacking. The electronic calorimeters are of a finite length and, therefore, it is possible that they will not detect events where the particles scatter at small angle. So results are measured more accurately if a particle passes into the centre of the detector, instead of to the outer limits of its detection. Also, there is a missing source of transverse energy because the calorimeter is not perfect. There are crack regions due to the support structures and the transition region between components, e.g. from the central region calorimeters to the end cap calorimeters to the forward calorimeters. The probability that all the energy of a particle is undetected is small, but QCD processed have a huge production rate. Some of the jets could have a lot of energy undetected and make a significant missing transverse energy. Therefore, it could be that the simulation provides a better result that what is actually possible to measure.

The main problems encountered were mostly in learning the Fortran and computer skills required to write the routine. Having had no previous experience in Fortran, or in similar packages, was the main constraint in this project. For example, it was not until compiling the histogram that I realised that Fortran could only read a certain number of characters per line. Also, incorrect commands were being used, such as, for the inverse function of tan, INVTAN was being used instead of the Fortran command, ATAN: the software was unable to read this. These were problems that were time consuming to solve rather than difficult. For example, by pressing the keys ‘alt’ and ‘q’, the computer automatically altered and numbered the line lengths, which was simple to do.

As much of high energy physics has such a large computer basis involving a lot of programming, other problems encountered were with bugs in the routine resulting in the routine crashing, or with false results being given. These types of problems are fairly easy to solve, but can be detrimental when working to a deadline. Due to the nature of the project, where the main body of the project is ‘made’ in the last third of the available time, this was a big constraint on the project. This means that if these bugs were not encountered more time would have been available to see the results of different types and combination of cuts.

Other problems encountered were mainly due to random errors due to human inaccuracies. For example, one of the problems why the routine would not compile was due to the array ‘mass’ only containing 49 values instead of the required 50 values. This meant that when the data values were being entered, they had been accidentally missed. After looking through the values given in the research paper the missing value was found. This was easily solved as the missing value was just simply added to the ‘mass’ array, which was then resaved and recompiled. Hence, the main problems encountered were in the writing of the routine: they were easy to solve but also time consuming.

If time had permitted, further research could have been carried out using the PYTHIA generator. This generator is similar to HERWIG, it generates high energy physics events, but is slightly more up to date as it is written in the C++ code, instead of Fortran. So it would have been interesting to see if the PYTHIA would have provided similar, or even a better fit to HERWIG. Another area that would have been interesting to investigate would be in varying more than one parameter at the same time. This would, in theory, provide an even better fit as the investigation carried out so far looked at the individual effect of each parameter in turn. In reality, when the collision takes place it is not just one of the parameters that changes, i.e. the incoming hadrons will not either have nonzero transverse momentum, or just a higher VGCUT. In an actual collision, all three parameters acting collectively will effect how the collision results. Therefore, varying all three parameters together would give a more realistic picture of what is physically occurring. However, due to the nature of the project, there was insufficient time to research this, although it would be a very interesting area to research.

Overall, the project was extremely interesting and has taught me some very valuable research skills. I have thoroughly enjoyed learning every step of all the information and knowledge required to make the final routine and histograms. This was very rewarding, when at the end of the report, all the individual elements leaned were brought together.

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5.2 Additional Reading:

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