

Z to Mu Mu Analysis Project

Barry S. Spurlock

The University of Texas at Arlington

Introduction

The goal of this project was to analyze data from the D0 detector at Fermilab to find events where Z bosons decay into muon pairs and to determine the number of jets produced in association with these Z events. The procedures used in this project were the same as one would use performing actual data analysis; so although this was only a project, this was in effect a real data analysis. Z Bosons are a signature or background in many, if not most, high energy physics analysis. Consequently, this study of Z bosons will be most useful. One distinctive signature of Z bosons is the production of a dimuon pair, and this is the channel I will analyze. Muons also appear in the signatures of many other types of physics processes, and understanding the particles themselves and the detector signature of these particles is very important.

I will review the Fermilab Tevatron and the D0 detector before discussing the analysis process. This process began by selecting and downloading data files and converting them from thumbnail files to root files. Following this, I modified an existing analysis program to apply quality and kinematic cuts to objects detected by the D0 muon system. For those events that passed these cuts, I calculated the invariant mass of the muon pair. The results were plotted as histograms, which were then reviewed for the signatures of Z bosons. Additional cuts were then imposed to further reduce background events. Due to the small size of the surviving data sample, I was then forced to download additional data from Fermilab. Finally, once I was reasonably confident that the events remaining were indeed Z bosons, I then imposed quality and kinematic cuts on the jets produced. The number of jets in each event was then plotted for review.

The Fermilab Tevatron

Fermilab, just outside of Chicago in Batavia, is the home of the Tevatron, which is currently the world's most powerful particle accelerator. It accelerates protons and anti-protons in its 4-mile main ring. The proton and anti-proton beams are brought together at collision points, where the center of mass energy of the colliding particles approaches 2 TeV.

The acceleration process begins with a Cockroft-Walton pre-accelerator [1]. In it, hydrogen atoms are ionized by the addition of an extra electron. These ions are then accelerated to 750 keV. These ions then enter a linear accelerator, reaching energies of 400 MeV. These ions are then fed through a carbon foil, which strips off the electrons, leaving the positively charged protons. These protons enter the booster, a circular accelerator that brings the protons up to an energy of 8 GeV. The protons are then sent to the main injector.

The main injector serves four purposes. First, it accelerates protons to 150 GeV. Second, it generates 120 GeV protons, which are used to create anti-protons. Third, it receives anti-

protons from the anti-proton source and accelerates them to 150 GeV. Finally, it injects the protons and anti-protons into the main ring. The anti-protons are created by colliding 120 GeV protons into a nickel target. Amongst the many secondary particles created in these collisions are anti-protons, which are collected in the accelerator ring, where they collect until sent back into the main injector. The main injector tunnel also holds the anti-proton recycler, where unused anti-protons are taken from the Tevatron to await re-injection.

The Tevatron's main ring accepts 150 GeV protons and anti-protons and accelerates them to nearly 1TeV in counter rotating beams. These beams are crossed at selected collision points in the center of the massive detectors, D0 and CDF. Beams may also be diverted into one of the fixed target experiments.

The D0 Detector

The D0 collaboration includes more than 500 scientists and engineers from 60 institutions in 15 different countries. D0 detected its first interaction on May 12, 1992. Like most high energy particle detectors, it consists of layers of specific purpose. The inner regions are devoted to tracking. Outside of these are layers devoted to measuring energy (calorimeters). Outside of all of this is the muon detection system [2, 3]. This is shown in figure 1.

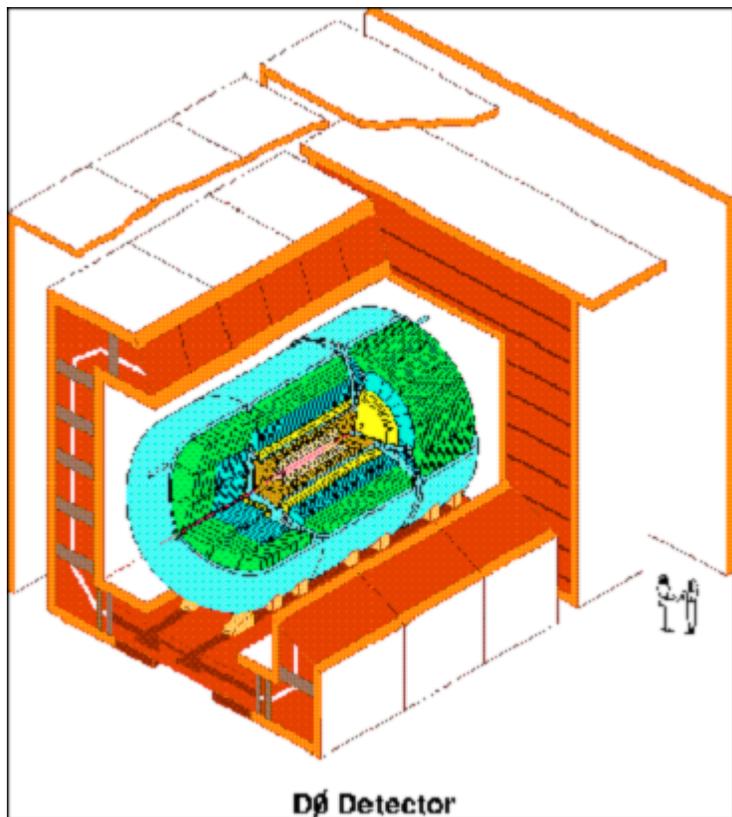


Figure 1. The D0 Detector

The inner tracking system has been upgraded for Run II. The primary upgrade has been the addition of a silicon micro-strip tracker (SMT) for improved track resolution and vertex detection. Charged particles passing through the silicon excite electrons into free states, which are used as a signal. Due to its proximity to the interaction point, this system is radiation hard.

Outside of the silicon tracker is the scintillating fiber tracker (CFT), which serves as the main tracking chamber in D0. Fibers are arranged in 8 concentric cylindrical layers. Each layer has a staggered double layer of fibers to ensure full coverage. Surrounding these detectors is a 2T superconducting solenoid magnet. This causes charged particles to follow curved paths, allowing their momentum to be measured. Surrounding the solenoid are preshower detectors in the central and forward region to provide additional triggers.

The calorimeter is based on detection of ionization in liquid argon produced in electromagnetic or hadronic showers. It consists of a central calorimeter and a pair of end calorimeters. The boundary between the central calorimeter and end calorimeter was chosen to be approximately perpendicular to the beam direction to introduce less degradation in measurement of missing transverse energy. The Inter Cryostat Detector (ICD) was designed and built at UTA to fit within this gap and further improve measurement of missing transverse energy. The calorimeter design has three distinct types of modules: an electromagnetic section with relatively thin depleted uranium absorber plates, a fine hadronic section with thicker uranium-niobium plates, and a coarse hadronic section with thick copper or stainless steel plates. The coarse section allows sampling at the end of hadronic showers while keeping the density high (and hence outer radius small). Most of the energy of electrons and photons is deposited in the electromagnetic calorimeter with very little left over in the hadronic section. The majority of the energy of hadronic jets is deposited in the fine and coarse hadronic calorimeters. In general the only particle that gets past the calorimeter is muons, but on some occasions the tail of a hadronic jet will extend beyond the calorimeter. This is called punch through.

The muon detector uses thick magnetized iron absorbers to provide sufficient momentum measurement and to minimize backgrounds from hadron punch through. It consists of five separate solid-iron toroidal magnets together with layers of detectors. The system consists of three layers called segments A, B, and C. The muon reaches the A segment before the toroid and this provides an entrance point. The muon hits the B and C segments after the toroid and this is used to provide an exit point and the direction of the muon after the toroid. Each of the segments has two layers. One uses scintillator tiles for detection. The other uses mini-drift chambers to detect muon tracks.

Z to Mu Mu Events

The events that are the object of my search are when a quark and anti-quark annihilate each other and produce a Z boson, which in turn decays into a muon/anti-muon pair. This is shown in the Feynman diagram of figure 2.

These events create a unique signature in the detector. Obviously, I should see two muons of opposite sign. In addition, these muons should be nearly back-to-back. In other words, the difference in the two muon's ϕ should be about 180 degrees. Finally, I can reconstruct the invariant mass of the Z boson. For this, I assume that the two muons came from the same source. Summing the energy and momentum of the two muons will give the energy and momentum of that source. I then use the relativistic energy and momentum equation to find the invariant mass:

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

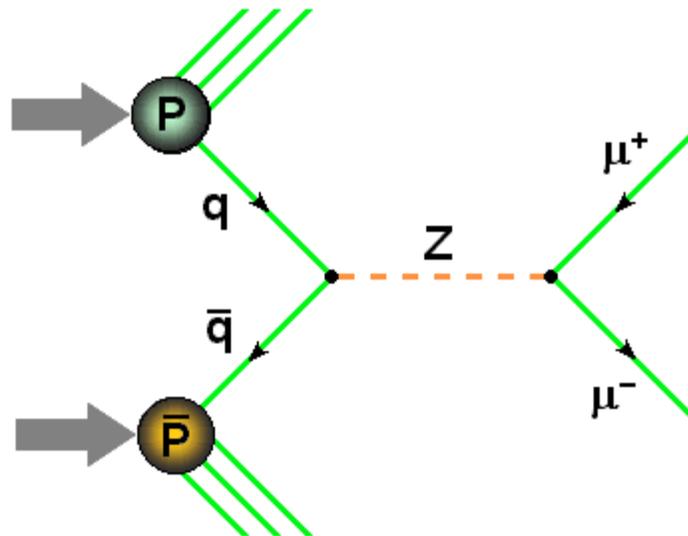


Figure 2. Feynman Diagram of Z to Mu Mu Events.

It is important to note that the relativistic energy momentum equation as shown uses “natural” units where $c = \hbar = 1$. The invariant mass calculated from the two muons should be near the Z-resonance at 92 GeV.

Data Collected for This Analysis

The data used for this analysis had been previously “skimmed” by D0’s WZ group. This data was skimmed from real events (as opposed to Monte Carlo) specifically chosen to have objects detected in the muon system [4]. I originally downloaded two data files, which contained just over 95,000 events. These files are:

WZskim-muStream-20030110-145203.raw_p13.05.00 (“tree1.root”: 47,256 events)
 WZskim-muStream-20030112-200818.raw_p13.05.00 (“tree2.root”: 47,944 events)

In the course of doing this analysis, it became clear that this was an insufficient number of events. More data files were then included in the analysis. These are:

WZskim-muStream-20030112-012201.raw_p13.05.00 (“tree3.root”: 43,987 events)
 WZskim-muStream-20030105-140711.raw_p13.05.00 (“tree4.root”: 44,975 events)
 dimu_030324_030325_p13.06.01_00.tmb (“tree10.root”: 50,000 events)

My data sample now includes 234,162 events. Before use, these files were converted into root files using “TMBAnalyze_x”. This reduced the size of the data by approximately 30%

Muon Identification

My next goal was to search through these candidate events for “high quality” muons. This required some knowledge of the D0 muon detector [5]. The muon detector consists of three concentric layers called “segments,” which are labeled “A”, “B”, and “C” from the inside out. Each of these segments has two layers. One layer consists of mini-drift chambers, and the other is made up of scintillator tiles. Whenever a charged particle, such as a muon, moves through a scintillator tile, it generates light, which is converted to an electronic signal using a

photomultiplier tube (PMT). When a charged particle, such as a muon, moves through a mini-drift chamber, it excites electrons from the gas to a free state. These electrons are collected by high voltage wires running through the chamber. Consequently, detection of a particle in a mini-drift chamber is referred to as a “wire hit”. The electric signals produced are used as indication that a particle has passed through.

Unlike other particles, the muons lose only a fraction of their energy moving through the interior layers of the D0 detector, and they usually don’t have time to decay. Also, muons are the only particles that survive to reach the muon system. There is, however, a small chance that a hadronic jet will reach the muon system. This is called “punch through”.

For P13 a tight muon has to meet the following criteria [5, 6]:

- 1) At least 1 scintillator hit in the A segment
- 2) At least 2 wire hits in the A segment
- 3) At least 1 scintillator hit in the BC layers
- 4) At least 3 wire hits in the BC layers
- 5) χ^2 of the local muon track fit must be positive

The hit information (criteria 1-4 above) is combined into a variable called “muon_idnhit”. The ones place of idnhit holds the number of wire hits in the A segment (2 above). The tens place holds the number of wire hits in the BC segments (4 above). The thousands place holds the number of scintillator hits in the A segment (1 above). The ten thousands place holds the number of scintillator hits in the BC segments (3 above). The χ^2 is associated with the local muon track, the track recreated using only the data from the muon system.

Additional Cuts

In addition to these requirements I wanted a central track matches for both muons and for both muons to have a transverse momentum (pT) greater than 20GeV. By central track match, I mean that the local muon track (as generated solely by hits in the muon system) could be just an extension of a track constructed from data from the central tracker. Muons coming from a Z decay will have relatively high energies, and a pT cut at 20GeV eliminates the background of low energy muons. I also decided to use a cut on eta, namely $|\eta| < 1.5$, which seems pretty standard for muons. This limits the muons to a well understood region of the detector and avoids the seams between the central section and end sections.

After applying these cuts, I saw signs of our signal, but it still had a great deal of noise. Our signal is a peak near 40 GeV in the transverse momentum plots for both muons. Since these two muons are the product of a Z decay, each should have approximately half of the Z’s rest mass of 91 GeV. The background appeared as an exponential decay in these same plots. After careful review of the data, I discovered that for most of my background events the pair of muons were collinear, as opposed to the acollinearity expected in our signal. Consequently, I made a cut removing all events where the tracks of these muons were within 45 degrees (in ϕ) of each other. This seemed to eliminate most of my background, but it was still at significant levels. To eliminate this I increased the pT cuts to 25 GeV. After these cuts I found some anomalous events. In one event I had a muon with pT of 13 TeV, which exceeds the entire energy of the collision. In addition, I still had a handful of events with invariant mass in the vicinity of 50

GeV. To rid myself of these unwanted stragglers, I made cuts on the invariant mass to ensure that it was between 65 GeV and 105 GeV. Plots for the leading muon pT and the second muon pT are shown in figures 3 and 4 respectively. These may be compared with the pT distributions for muons prior to the quality and kinematic cuts as shown in figures 5 and 6. Prior to my cuts I have the exponential decay characteristic of background events.

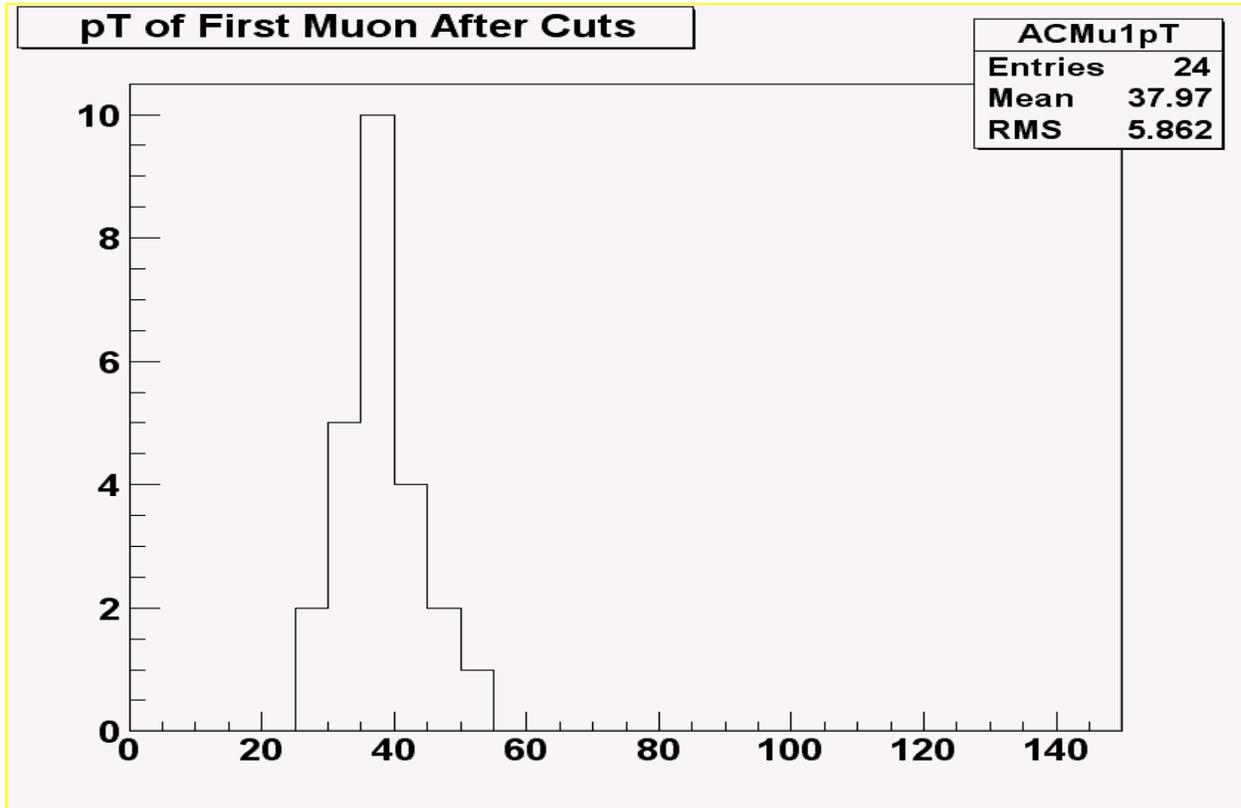


Figure 3. pT of Leading Muon After Cuts.

Verification of the Existence of Z Bosons

To ensure that these events were indeed Z bosons, my next step was to construct the invariant mass of the muon pair. I included a cut to ensure that the Z invariant mass will be less than 105 GeV in order to remove some mismeasured and clearly unphysical events. For example, I showed an event that showed a muon with a pT of 13.1 TeV, which is of course impossible when the machine can only produce 2 TeV. The plot of the invariant mass is shown in figure 7. As expected, this has a peak and average near 91 GeV, clear indication of the presence of Z Bosons.

As a control, I considered the transverse direction of motion (i.e. ϕ) for the two muons. For Z events there should be no preference in direction. The plots of ϕ for the leading muon and second muon are shown in figures 8 and 9, respectively. It is evident from the plots that there is in general no preference in direction, and this confirms the existence of Z Bosons. However, there is an unusual lack of activity near $\phi=5$ on both plots. This can be explained by considering the ϕ plots for the leading and second muon before cuts as shown in figures 10 and 11. These plots show a dramatic decrease in events near $\phi=5$, which has carried over after the cuts were made. As of yet, I do not know how to explain this imbalance.

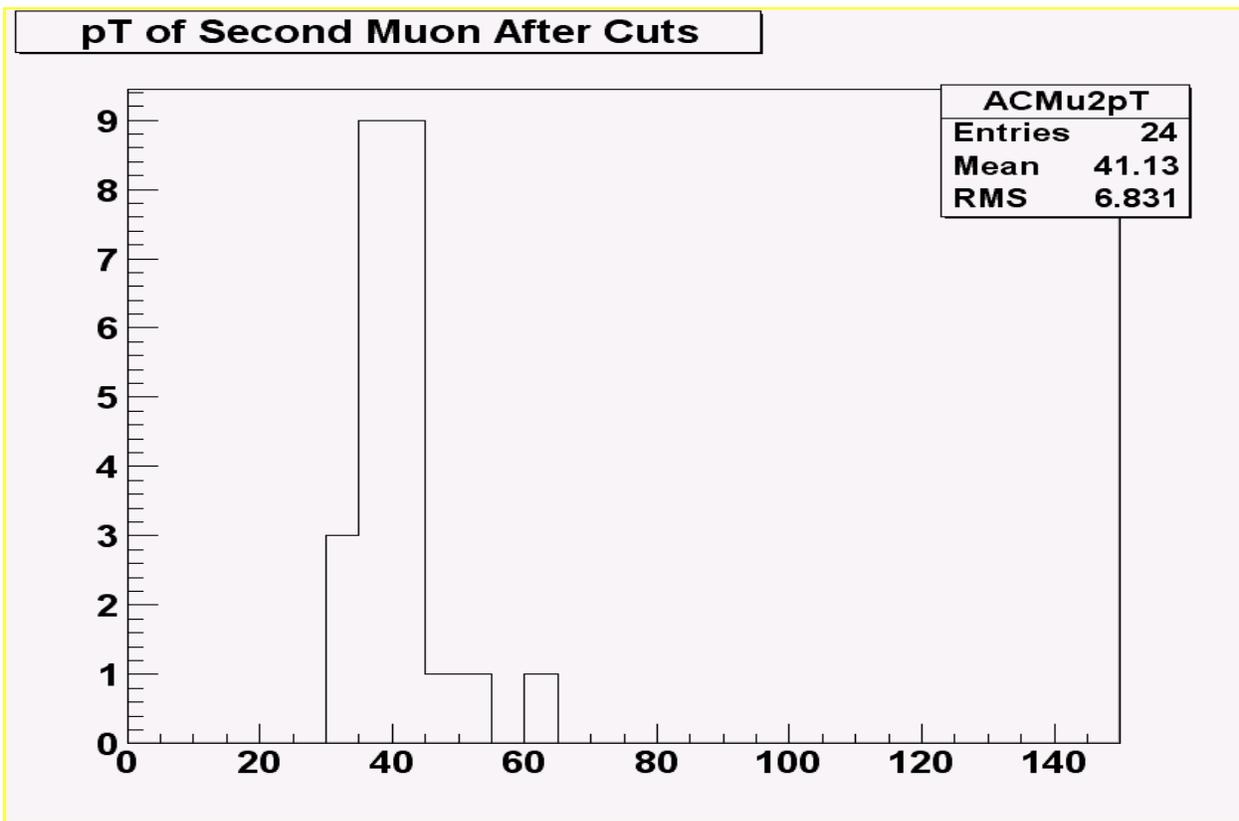


Figure 4. pT of Second Muon After Cuts.

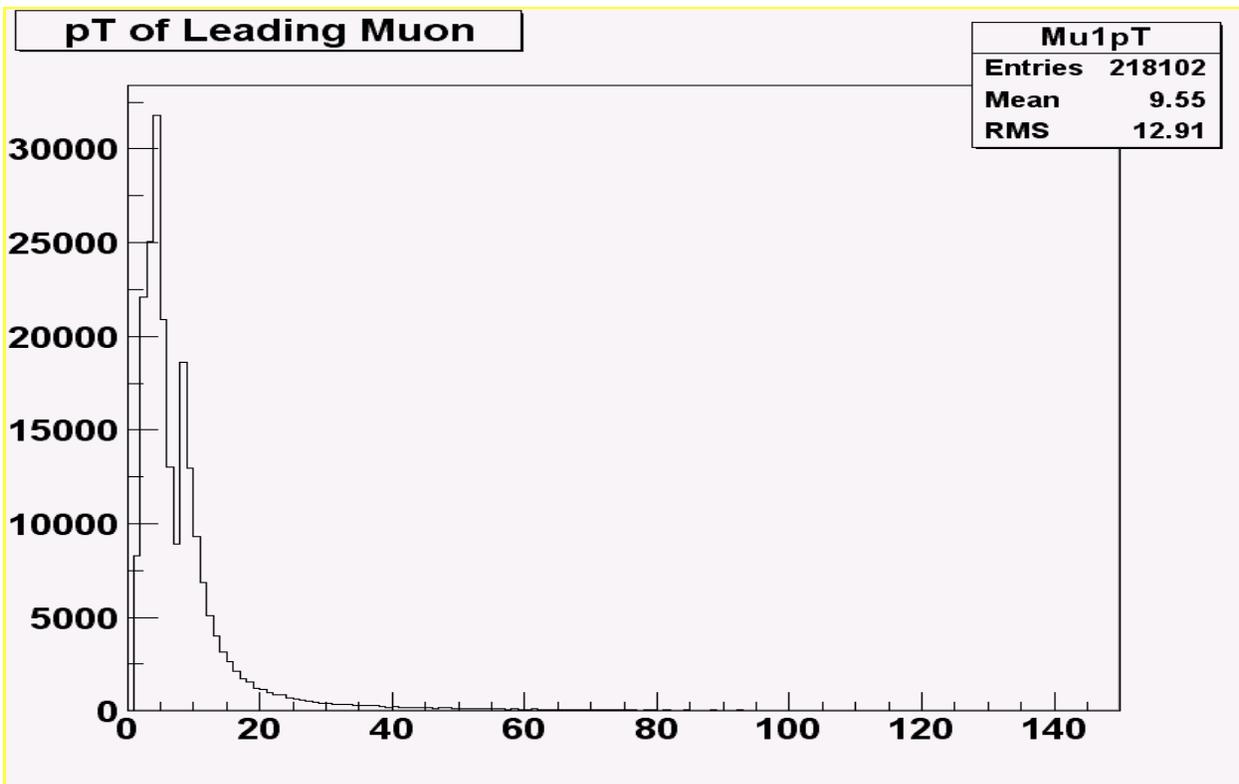


Figure 5. pT of Leading Muon Before Cuts

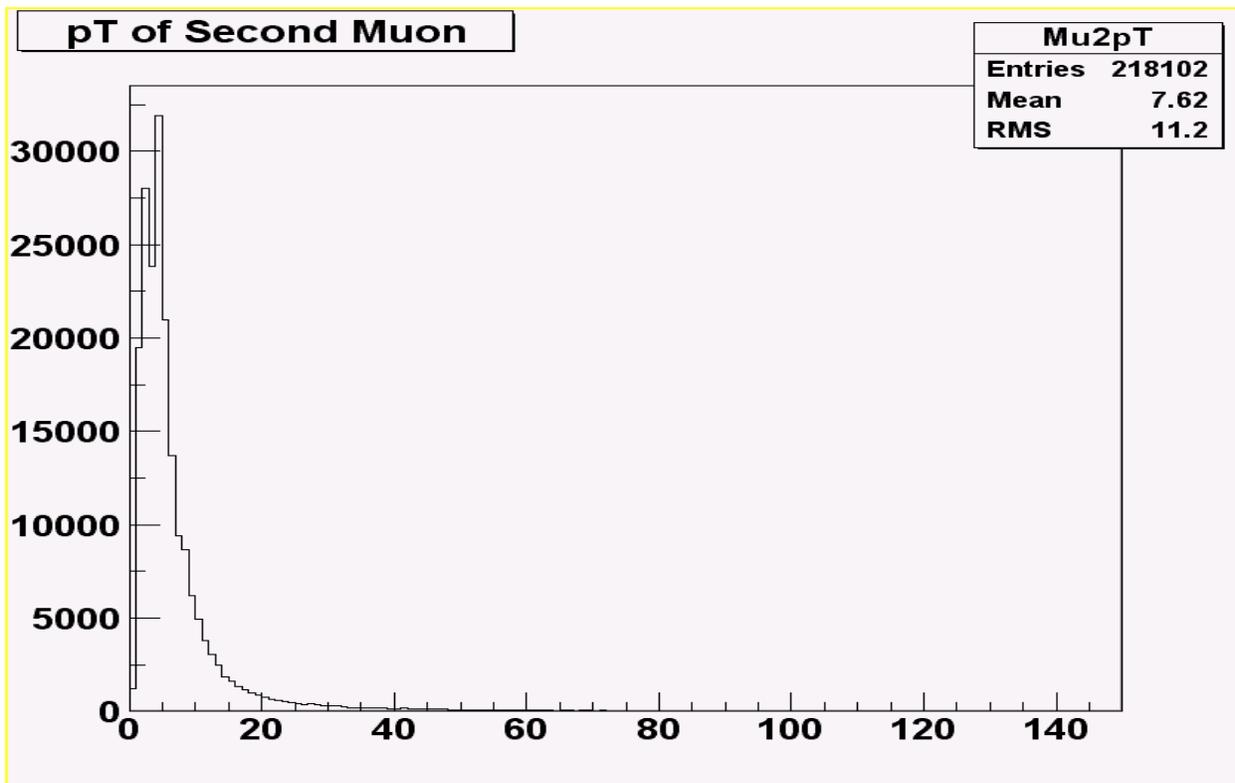


Figure 6. pT of Second Muon Before Cuts

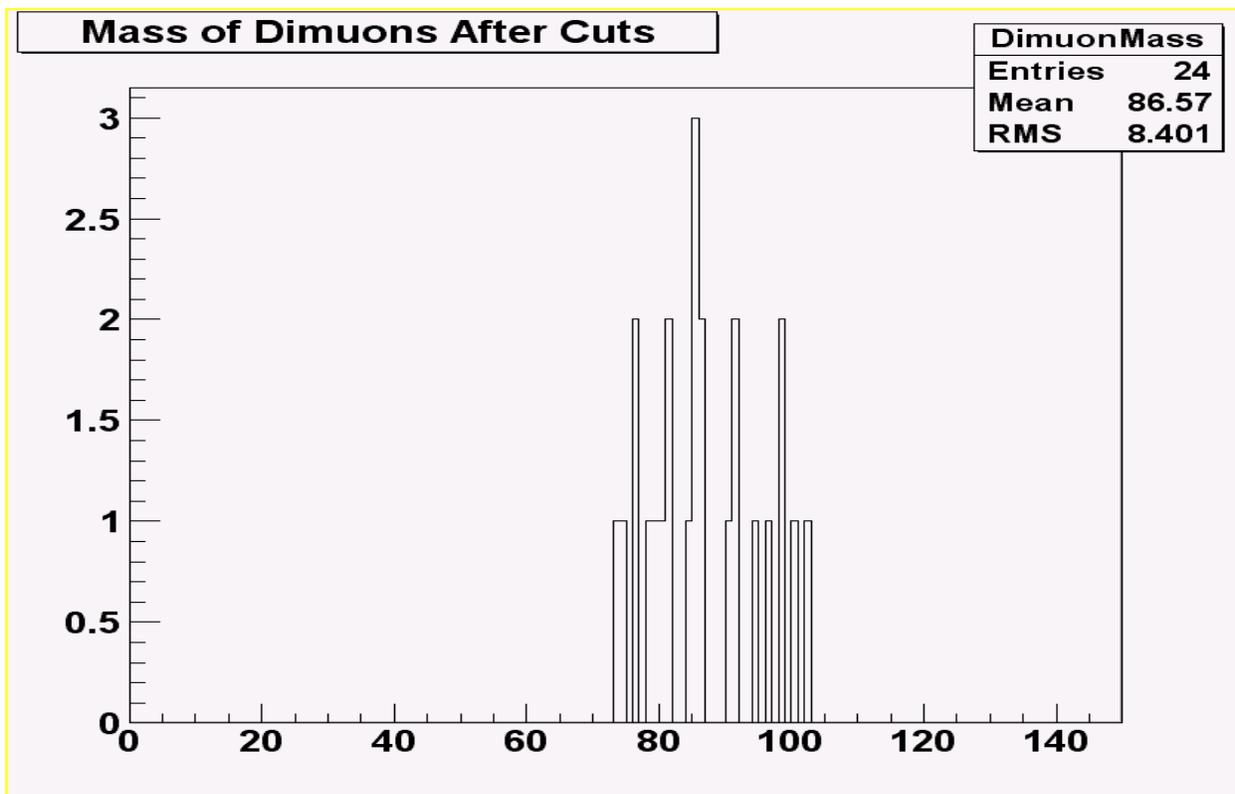


Figure 7. Invariant Mass of the Muon Pair

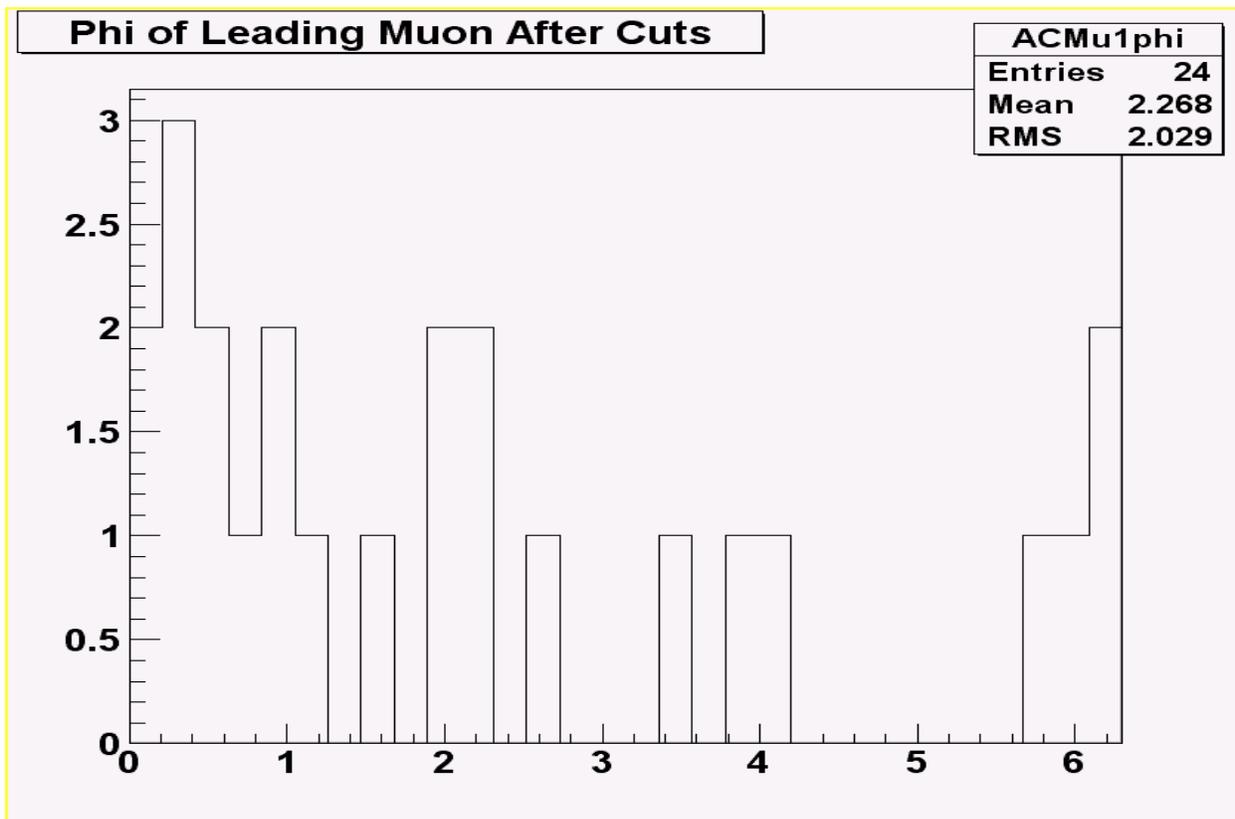


Figure 8. Φ of Leading Muon After Cuts

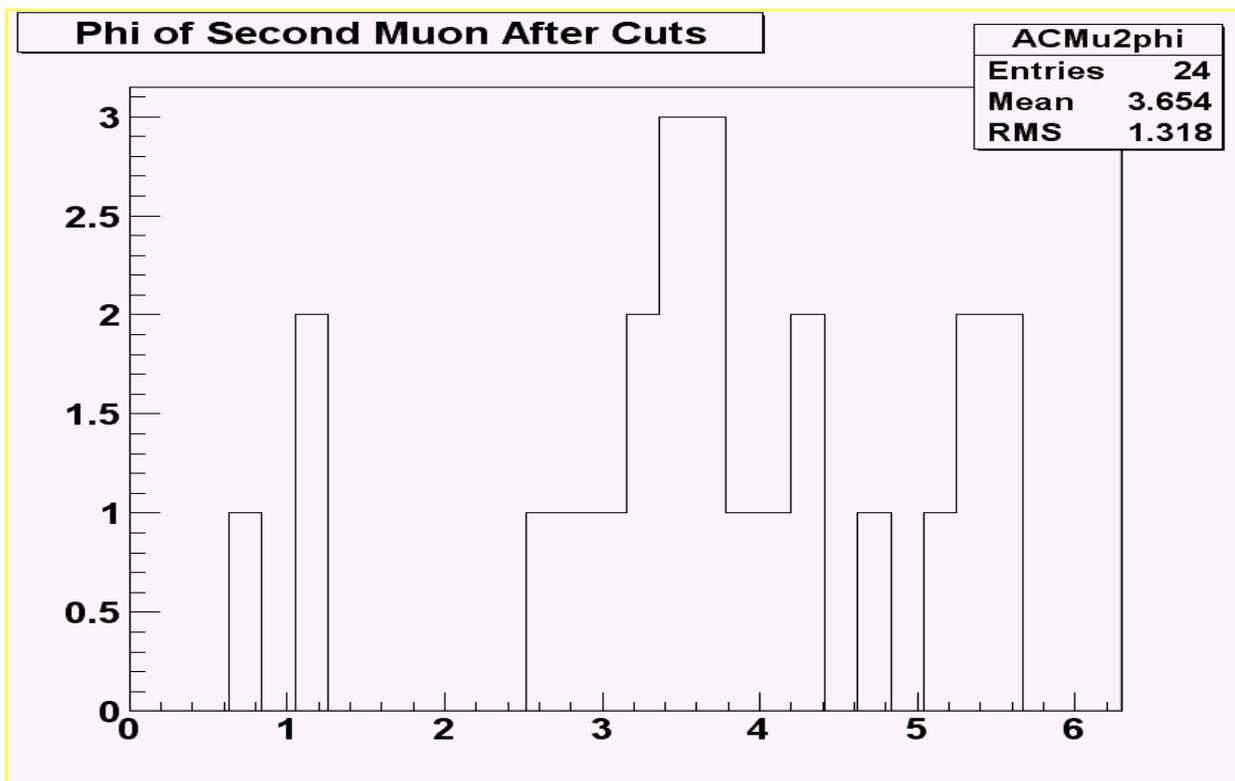


Figure 9. Φ of Second Muon After Cuts

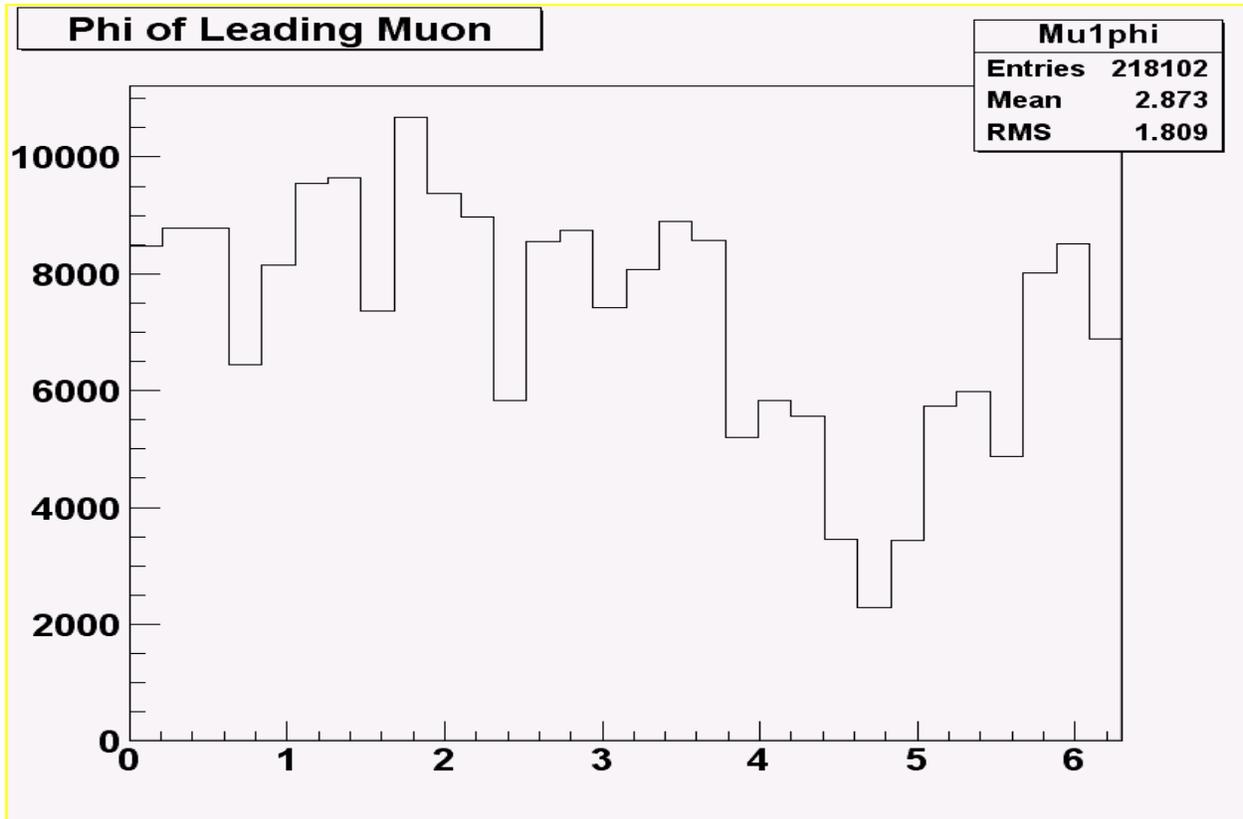


Figure 10. Φ of Leading Muon Before Cuts

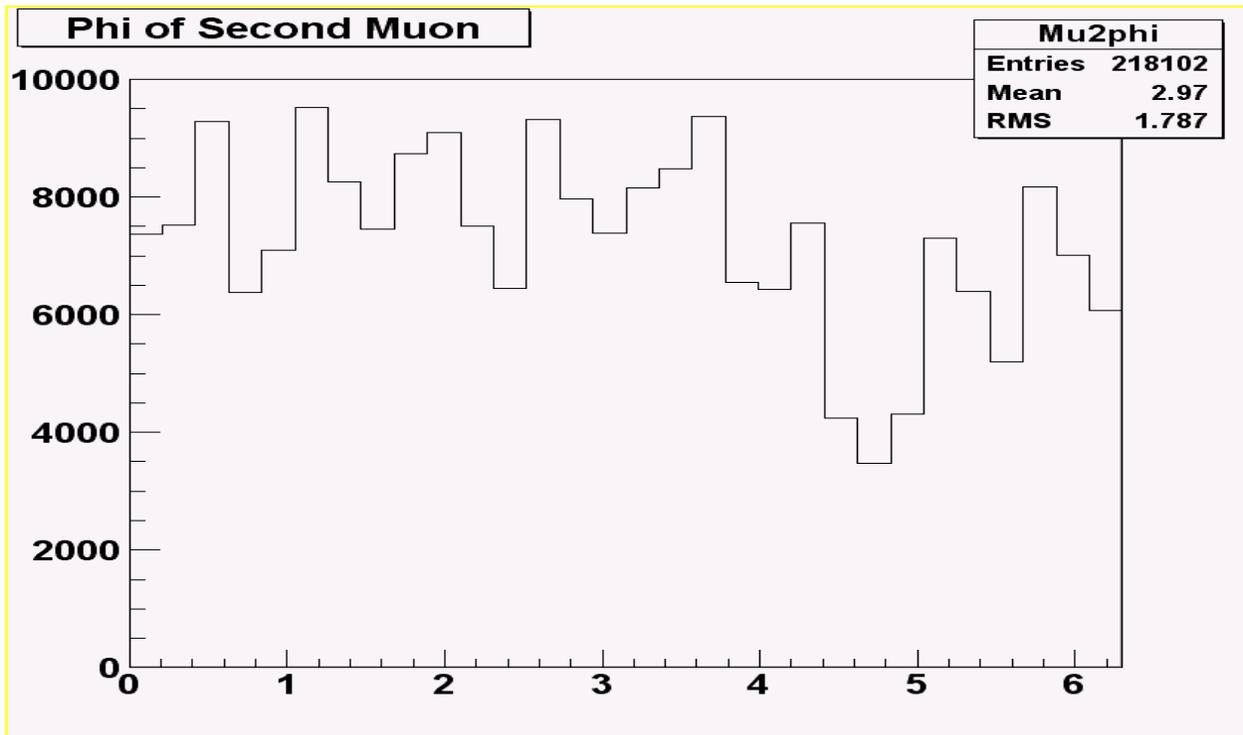


Figure 11. Φ of Second Muon Before Cuts

As another control I examined the difference in the ϕ values of the leading and second muon. Since most of the Z produced should have no momentum in the transverse plane, the muons produced should be back to back in the transverse plane. Consequently the difference in ϕ for these events should be close to π . The difference in ϕ values is shown in figure 12. As expected, the average is near 3. Unfortunately an error in my program took truncated the values when taking the absolute value of delta ϕ .

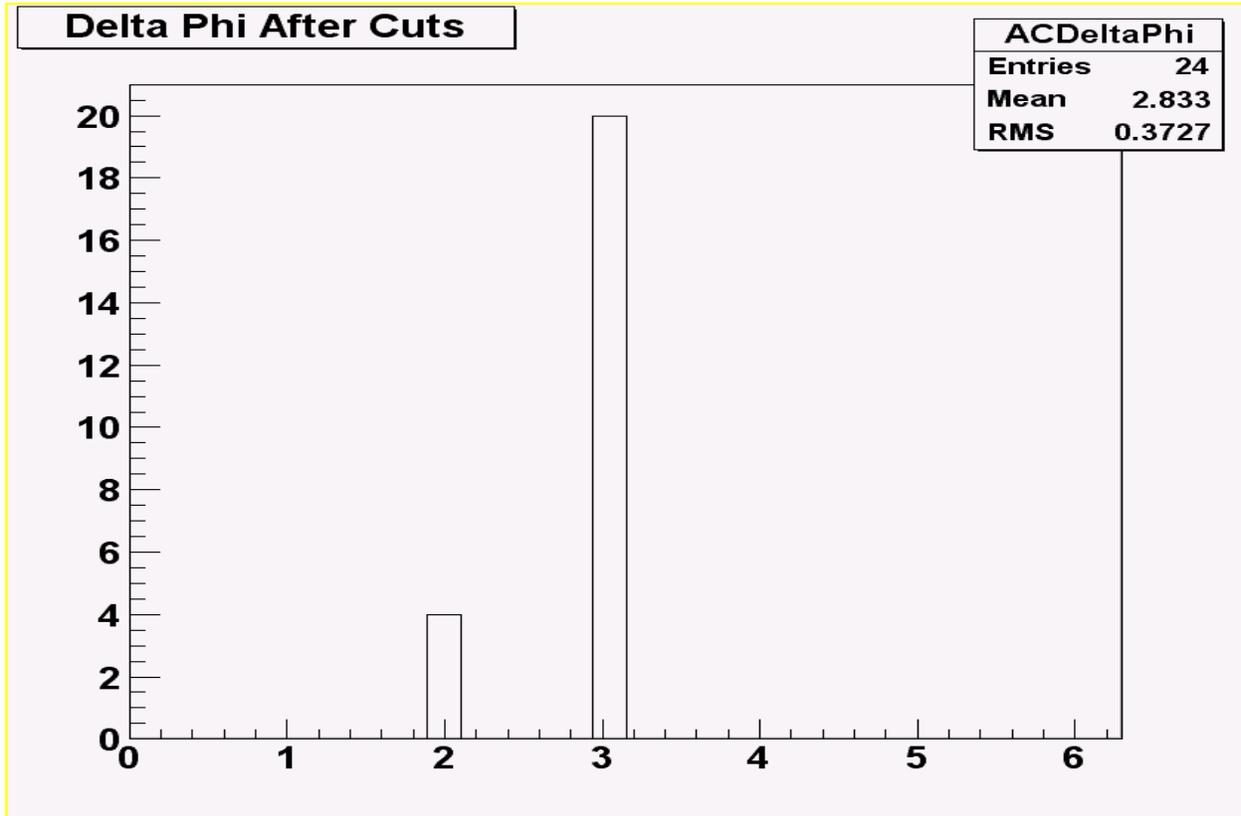


Figure 12. Transverse Angle Between Leading and Second Muons ($\Delta\phi$).

Jets Associated with Z Production

My final task was to find out how many jets were produced in these Z events. We defined a good jet by the following criteria[8,9,10]:

- 1) $0.5 < \text{Electromagnetic Fraction} < 0.95$
- 2) $\text{Coarse Hadronic Fraction} < 0.1$
- 3) $\text{Hot Fraction} < 10.0$
- 4) $n_{90} > 1$
- 5) $|\eta| < 2.5$

The electromagnetic fraction is the percentage of the jets total energy that is found in the electromagnetic calorimeter. A jet should leave some energy in the electromagnetic calorimeter. The lower cut on the electromagnetic fraction helps to eliminate jets due to hot cells or noise in the hadronic calorimeter. If the jet leaves too much energy in the electromagnetic calorimeter, it is likely to be a hot cell in the electromagnetic calorimeter (hence the upper limit). The majority of the jets energy should be absorbed in the inner section of the hadronic calorimeter, the fine

hadronic calorimeter. This shouldn't leave much to be absorbed by the coarse hadronic calorimeter (only the tails). A Jet showering in the CH calorimeter is probably noise. This is the reason for the coarse hadronic fraction cut. The hot fraction is the ratio of the transverse energy of the hottest and second hottest cells. The hot fraction cut will help remove signals caused by a single hot cell being misinterpreted as a jet. Since the jet spreads in the calorimeter, the difference in energy between the hottest and second hottest cells should not be excessive. The n90 cut is also used to eliminate hot cells that are misinterpreted as jets. The value of n90 is the minimum number of cells needed to contain 90% of the jet's energy. The η requirement ensures that the jet is not extremely forward and too close to the beam pipe, losing part of its energy down the beam pipe.

The only other cut we used on the jets was the requirement that the jets have a transverse momentum greater than 10 GeV. This is merely to ensure that the jets pass a minimum energy threshold. Once cuts were made, the number of jets in each Z event was then plotted. This is shown in figure 13.

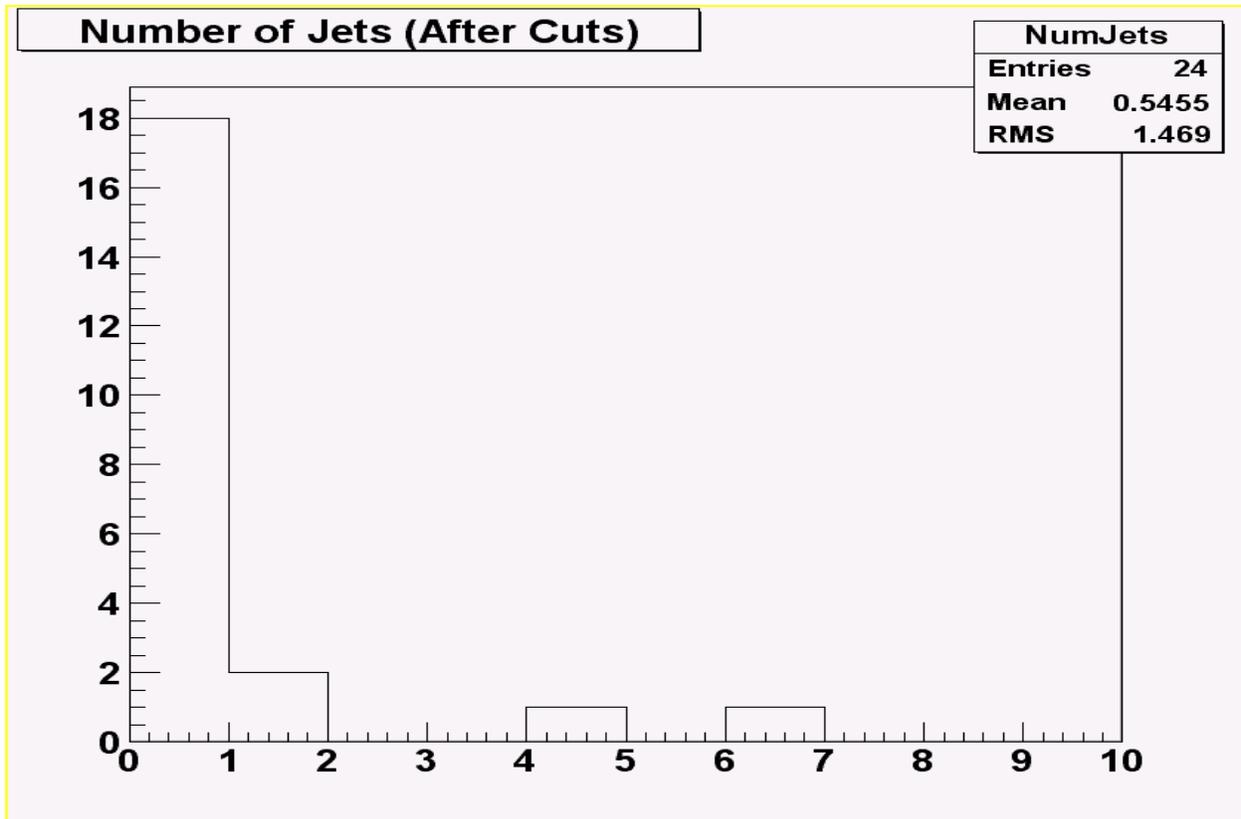


Figure 13. Number of Jets in Each Z Event

Background

The background for these events comes from two sources, physics and detector. The physics background comes from other types of events that produce the same signature. The main sources are:

- 1) Cosmic ray muons
- 2) QCD

- 3) Drell-Yan
- 4) $b \bar{b} \rightarrow \mu \mu + \text{jets}$
- 5) $W \rightarrow \mu \nu$
- 6) $Z \rightarrow \tau \tau$

The muons created in the decay of a b quark pair are of low energy compared to those produced from Z bosons. Consequently, the muon pT cuts should minimize these events. In addition, it is unlikely that the muon pair would create an invariant mass of sufficient size to be mistaken as a Z. The QCD background is most likely associated with punch through, described below. Drell-Yan events ($q \bar{q} \rightarrow \gamma \rightarrow \mu^+ \mu^-$) would also be very unlikely to produce an invariant mass sufficient to be mistaken for a Z. There is, however, a finite probability of Drell-Yan events whose mass is within the window of the Z mass, therefore these are irreducible backgrounds. As far as cosmic rays are concerned, I believe there is a system in place to eliminate most of these events. The W to mu nu events could appear if an associated jet punches through to be misinterpreted as a muon. The experimental background comes from two sources:

- 1) Combinatorics
- 2) Punch through
- 3) Detector and accelerator noise

Punch through deals with events where a hadronic jet is of sufficient strength that its tail extends into the muon system. This will most likely occur with QCD events. There are so many QCD events that even though the chance of punch through is small, it is still a significant number of events. These should be of relatively low energy, and my pT cuts should remove the majority of these. Combinatorics refers to a failure in reconstruction, where muon and tracks might be mismatched.

Conclusions

A sizeable sample of real data was downloaded from Fermilab. These files were converted to root for analysis. Code was then written to make cuts on this data. I extracted those events that included the production of a muon/anti-muon pair as would be expected from the decay of a Z boson. Cuts were used to ensure the quality of the muons and some simple kinematic requirements. Plots, including construction of the invariant mass of the dimuons, were made to verify that the events selected included Z bosons. Once the existence of Z bosons was assured we began to look for jet events associated with Z production. Minimal quality and kinematic cuts were imposed on the jets, and the number of jets in each event was plotted. These plots were consistent with our expectations given the statistics.

Bibliography

- [1] <http://www.fnal.gov/pub/inquiring/physics/accelerators/chainaccel.html>
- [2] "The D0 Detector", D0 Collaboration
- [3] "The D0 Upgrade, where we are and where we're going", H. G. Evans, <http://www.nevis.columbia.edu/~evans/talks/b2k.pdf>

- [4] “WZ group – skimmed data documentation (datasets)”, D0 WZ Physics Group, <http://www-d0.fnal.gov/Run2Physics/wz/d0-private/wzskim-v00-0001/p13.05.00/wzskim1305.mu.html>
- [5] “D0 Muon Identification Primer”, D0 Muon Algorithm and Identification Group, http://www-d0.fnal.gov/phys_id/muon_id/d0_private/muonid_primer.html
- [6] “Content of the p13 Muon Thumbnail”, D0 Muon Algorithm and Identification Group, D0 Note 4091 Version 1.4, Feb 03, 2003
- [7] “D0 Jet and MET ID Properties in p11 and p13”, D0 Jet and MET algorithm and Identification Group, http://www-d0.fnal.gov/~d0upgrad/d0_private/software/jetid/certification/v2_0/jetid_p13.html
- [8] “Study of Jets Produced in Association with W ($\rightarrow\mu\nu$)”, P. Tamburello, D0 Note 4100, March 7, 2003
- [9] “A Search for Squarks and Gluinos Using the Jets and Missing Energy Signature at D0”, N. J. Hadley, Dissertation (1997)
- [10] “The Fit Algorithm in muo_trackreco”, Frédéric Déliot, November 21, 2000
- [11] Mark Sosebee, private communications
- [12] Shahnoor Habib, private communications
- [13] Venkatesh Kaushik, private communications
- [14] Jaehoon Yu, private communications