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High P_T Muons

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Abstract

We examine high p_t muons from Z decays for both data and Monte Carlo

1 Introduction

For two years the Collider Detector at FermiLab (CDF) has been taking data from proton anti-proton collisions generated by the Tevatron at FermiLab in Batavia, IL. The approximately 500 member international CDF collaboration is studing a variety of high energy physical phemomena such as electro-weak interactions, top quarks, B meson physics, Higgs searches and 'beyond the standard model' searches. One of the particles that the Tevatron produces in relative abundance is the Z boson, the neutral mediator of the weak force. The Z boson is an important probe into electro-weak physics, allowing us to test the universality of electroweak interactions and search for new physics. This note describes the characteristics of muons from Z boson decays. We begin in section 2 with a brief phenomenological overview of the weak force and the Z boson. In section 3 we describe the CDF detector and its response to muons. In section 4 we describe the data and simulation used in the study followed by an overview of the muon variables in section 5. We then calculate the Z boson mass from muon decays and compare the data and monte carlo in section 6.

2 The Electro-Weak Force and the Z boson

As far as we know there are four fundamental forces that govern all interaction of matter: gravity, the strong nuclear interaction, the weak interaction and electro-magnetism. In addition to these four fundamental forces there is a set of fundamental particles which constitute all of matter. Together with the forces, these particles form the standard model of particle physics. At high enough energies in the standard model, two of the four forces, the weak force and electro-magnetism become unified; they are the same force. This happens near TeV energies, close to the masses of the standard model particles. Each of the forces has a set of force mediators, boson (integer spin particles) exchange is a manifestation of the forces. In this note we are interested in the Z boson, the neutral carrier of the weak force.

2.1 The Electo-Weak Force

First postulated to describe nuclear beta decay, the weak force demonstrated remarkable similarity to the electromagnetic and strong forces. It had a universal coupling constant and depended on the weak charge of the particles involved. It also coupled only to left handed particles, manifestations of a vector and axial (V-A) interaction. Glashow, Weinberg and Salam postulated that the weak force was a part of a new gauge theory, the ElectroWeak Unified theory, which described weak and electromagnetic interactions through the unification of two symmetry groups, $SU(2)$ and $U(1)$. At low enough energies, the symmetry breaks because of the coupling of the electroweak force to the Higgs scalar field. This produces 3 massive bosons and 1 massless boson. The massless boson is the photon, from electromagnetism, and two of the massive bosons are the charged $W+$ and $W-$. The third massive boson, the Z was first observed in 1981.

2.2 The Z Boson

This well studied particle has a precisely known mass (91.19 GeV) and decay width (2.495 GeV), which were established thanks to extremely high precision measurements at LEP in 1995. It is a neutral force carrier and hence does not permit any charge exchanges in the interactions it mediates. One possible Z decay channel is two oppositely charged leptons, which occurs in approximately 10% of all decays. Because they are well defined in the detector through their clean signitures, the electron and muon channels are the most studied decay modes at CDF. The Z boson is essentially a heavy photon and to probe its properties is to probe the physics of electro-weak unification. Since the properties of the Z boson are extremely well contained due to the work at LEP, Z bosons acts as a standard candle for electroweak processes. Hence, not only do they serve as an excellent calibration tool for detector energy scale, efficiencies, and luminoisity normalization, any unexplained deviation from standard model predictions are relatively easily detected.

3 FermiLab, The CDF Detector and Muons

3.1 Fermi National Accelerator Laboratory

The Fermi National Accelerator Laboratory (FermiLab) is home to the highest energy particle accelerator in the world. Under the auspices of the Department of Energy, the national research laboratory is home to experiementers, theorists, adminstrative staff and technicians from all over the world. The Tevatron, FermiLab's 4 mile in cirumference particle accelerator, runs with a center of mass energy of 1.96 TeV, producing a 'zoo' of particles for physicists to study.

No less than seven stages of acceleration are used to produce proton anti-proton collisions of TeV energy. First H^- ions are accelerated by a Cockroft-Walton power supply which are then transfered to a linear accelerator, the Linac, which uses alternating radio frequency (RF) cavities to accelerate the hydrogen ions to 400 MeV. At this point the electrons are stripped, leaving only a proton which enters the Booster, a synchotron. 8 GeV protons leave the Booster and enter the main injector, 1 km radius synchotron which ramps the protons up to energies of 150 GeV until they are put into the TeVatron, where they achieve energies of 980 GeV. Anti-protons follow a similar path to high energies. Protons from the main injector are shot at a nickel target, creating anti-protons at a rate of 1 anti-proton per 10^5 protons on target[2]. The resulting 8 GeV anti-protons, after undergoing stocastic cooling and bunching to acculumate sufficient numbers, are injected into the main injector and TeVatron, achieving 980 GeV energies.

The protons and anti-protons traverse the beam line in opposite directions are are brought together at two points along the ring, CDF and D0, the two collider detectors. Also, some protons are diverted earlier on for fixed target experiements and neutrino production. The beams cross every 396 nanoseconds producing on average 3 proton anti-proton inelastic collisions per crossing.[3]

3.2 The CDF Detector

The Collider Detector at FermiLab (CDF) was designed to probe physics at the highest energies possible. With a physics menu ranging from top quark characterization, to constraints on the CKM matrix, to precision electro-weak measuremnts, to direct searches for new phenomena, CDF was designed to investigate a broad range of phenomena. To give an overview of the detector, we will briefly describe each of the major systems. A schematic of the detector is found in figure 1.

1. Silicon Tracking

   Silicon tracking, which forms the inner tracking system of CDF, is comprised of Layer 00, SVX II and ISL, three systems of silicon chips which provide tracking coverage for 96 cm of the detector length and up to an $|\eta|$ of 2.0 ($\eta = -ln(cot\theta/2)$ where θ is measured from the perpendicular to the beam pipe). The silicon provides 3D vertexing information with a resolution of 30 μm in ϕ and 60 μm in z for high momentum tracks.

2. Central Outer Tracker

   The Central Outer Tracker, or COT, is an open cell drift chamber which provides momentum determination and track information for $|\eta| < 1.0$ in a region just outside the silicon system at $44cm < r < 132cm$. There are four axial (wires parallel to beam pipe) and four stereo (wires at a small angle to beam pipe) superlayers, consisiting each of 12 layers of potential and sense wires in an $Ar - Et$ gas, for precise tracking information. The COT is encased in a superconducting solenoid magnet which produces a 1.4 T field along the beam axis, bending charged particles so that the COT can determine their momentum by measuring the curvature of the tracks left in the volume.

3. Calorimeters

   Besides tracking information, CDF also records precise electromagnetic and hadronic calorimetery to measure the energy of incident particles. The calorimeters use 15 degree ϕ wedges of lead and scintillating material backed with photomultiplier tubes.

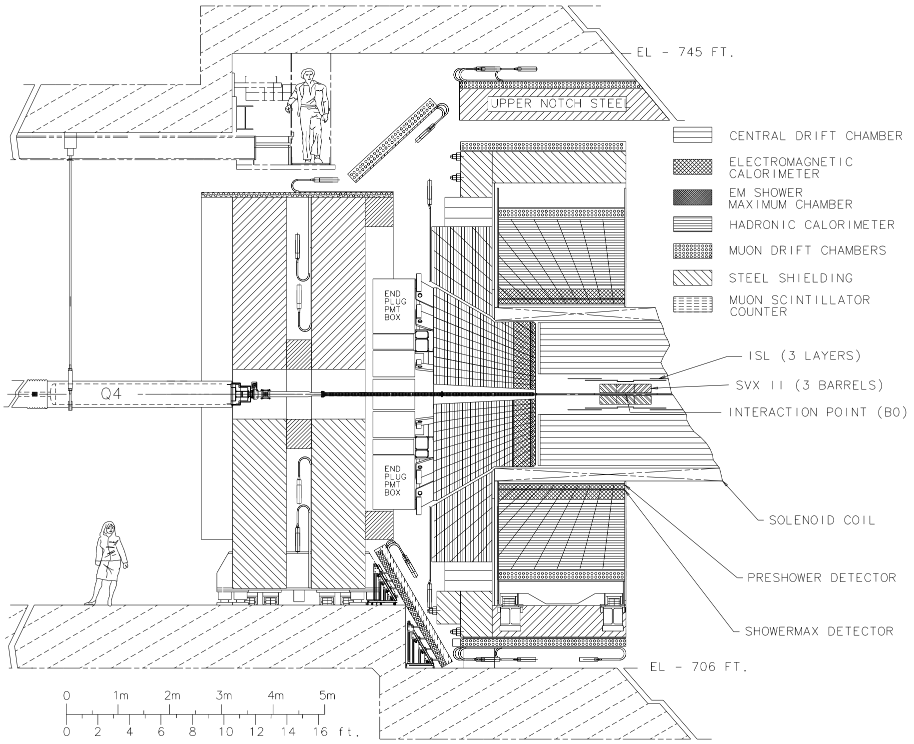

Figure 1: A longitudinal view of the CDF detector. θ is measured from the perpendicular to the bean axis and $r-\phi$ is measured in the plane transverse to the beam axis.

Incident particles shower in the lead and the resulting particles emit Cherenkov radiation proprotional to the energy of the parent particle. This light is read out by the photomultiplier tubes which convert it to an electrical signal which determines the energy of the particle.

4. Muon Systems

   Muons are heavy, penetrating particles that don't shower or lose energy through bremsstrahlung radiation like electrons. In order to separate muons from electrons and hadrons, CDF uses drift chambers, which provide tracking information, separated by dense material to stop particles other than muons. The first set, situated just outside of the calorimeters in the central region of the detector is called the CMU. It is surrounded by 60cm of steel shielding and then the CMUP, another set of drift cells and absorption material.

3.3 CDF and Muons

Muons are a particularly 'nice' physics object to work with because they are easily distinguished from other particles produced in collisions. Since muons are leptons, they interact only through the electroweak force hence they are not associated with jets, sprays of particles that register as large cones of energy associated with multiple tracks in the calorimeter and COT. Electrons are the most similar particle to muons, indeed, muons can most simply be viewed as heavy electrons. However, since the electron is so much less massive (the electron is .5 MeV whereas the muon is approx 100 MeV) it has less momentum and interacts more frequently than muons, depositing more energy in the calorimeter. Muons are the only particles that can penetrate the many layers of steel shielding that surround the muon chambers. The presence of hits in these chambers, combined with a track extrapolated from the COT is how CDF identifies muons. A muon stub is created when the CMU, CMP or CMX matches several hits in their drift chambers. High momentum COT tracks are extrapolated to the muon chambers and if the track matches well enough ("well enough" is defined in the next section) then the track is recorded as a CDF muon.

4 Data Sample and Selection Criteria

Initially we begin with a sample of high P_t muons that have been processed with TopEventModule[1], filtering code which translates the raw data into physics data. The muons in this sample pass two triggers, MUON CMX18 and MUON CMUP18. Triggers are logical paths that event data takes as collisions are occuring which pass only events that have the characteristics of the events defined by the trigger, which in this case are muons. The trigger paths are as follows:

- Level 1 : We require hits in the CMU matched to a XFT track (track constructed from COT hits) of $p_t > 4GeV$ that is further matched to hits in 3 out of 4 layers in the

CMUP.

- Level 2 : Level 2 is auto-accept.
- Level 3 : For the CMUP trigger we require that both CMU and CMP muon stubs (tracks made from matched hits in the muon systems) be matched to a COT track of $p_t > 18GeV$. For the CMX stub we require that the CMX stub be matched to a COT track of $p_t > 18GeV$.

In our sample we require that each event have at least two tight CMUP muons passing standard muon cuts which are described below. We also use simulation of Z decays, called Monte Carlo, which mimic our detectors response to the simulated events. The identification criteria and corresponding data and Monte Carlo sample reductions of the muons are listed in Table 1.

- $P_T > 20GeV$

  We place a minimum 20 GeV cut on muon momentum in order to remove low energy background muons coming from decays other than Zs. Because Z bosons have a rest energy of approximately 90 GeV we expect the average momentum of muons from this decay to be 45 GeV. Of course, the muons from the decays do not need to carry equal momentum because the Z might have some transverse or longitudinal momentum associated with its own motion, however it is unlikely that unless the Z is produced with a large momentum that one muon of the decay muons would have less than 20 GeV.

- Central Muon

  A central muon is one defined as a track with a muon CMU stub matched to the track with in 3 cm in X and 5 cm in Z.

- Good Track

  Good tracks have at least 3 axial and 3 stereo COT superlayers with more than seven hits per superlayer.

- Isolation in R=0.4/P_t < .1

  Isolation in R = 0.4 is a measure of the transverse electromagnetic energy in a radius of $.4 = \sqrt{(\Delta\eta^2 + \Delta\phi^2)}$ about a track, excluding the energy matched to the track itself. It is a measure of how much a particle pair produces and radiates. Muons should have small values for isolation because they are penetrating particles. It is scaled by the p_t of the track to acount for energy dependent radiation and interaction.

- $E_{EM} < 2+max(0, 0.0115*(p-100))GeV$ and $E_{HAD} < 6+max(0, 0.028*(p-100))GeV$

  Since muons do not interact often when passing through materials, they do not deposit much energy in the calorimeters. In fact, muons are considered minimum ionzing

Table 1: Selection criteria of muons.

	Data	Monte Carlo
Total	18641	4573
$P_T > 20GeV$	4958	4175
Central Muon	4776	4154
Good Track	3768	3273
Isolation in R=0.4/P_t < .1	2635	3125
$E_{EM} < 2 + max(0, 0.0115 * (p - 100))GeV$	2516	2564
$E_{HAD} < 6 + max(0, 0.028 * (p - 100))GeV$	2464	2421
$\|Z_{vertex}\| < 60$ cm	2334	2354
$\|d0\| < .2cm$	2331	2218

particles who's electromagnetic calorimeter depositions peak around .7 GeV and who's hadronic deposition peaks around 1.5 GeV. Again, this is an energy dependent phenomenon and for muons with $p_t > 100$ GeV radiation becomes more prominent and hence they deposit more energy.

- $|Z_{vertex}| < 60$ cm

  This requirement helps to insure that the particle passes through a significant portion of the detector so that we can obtain enough information about the event.

- $|d0| < .2cm$

  D0, impact parameter, is a measure of how close a particle track comes to the interaction vertex. A small d0 is required to ensure that the track came from an event. This is used as a way to filter out cosmic rays, which certainly pass all of the muon criterion however are not associated with any event.

5 Muon Variables: Data and Monte Carlo Comparison

As a consistency check between the data and Monte Carlo samples we compare the muon variable distributions for each. There is fairly good agreement with the exception of the electromagnetic and hadronic energy distributions, which is addressed in section 5.1.

5.1 Energy Distribution Studies

There has been some conversation as to the origin of the 0 energy muons seen in both the hadronic and electromagnetic energy distributions for the muons. It occurs in both the data and the monte carlo, with higher significance in the monte carlo. After plotting the phi and

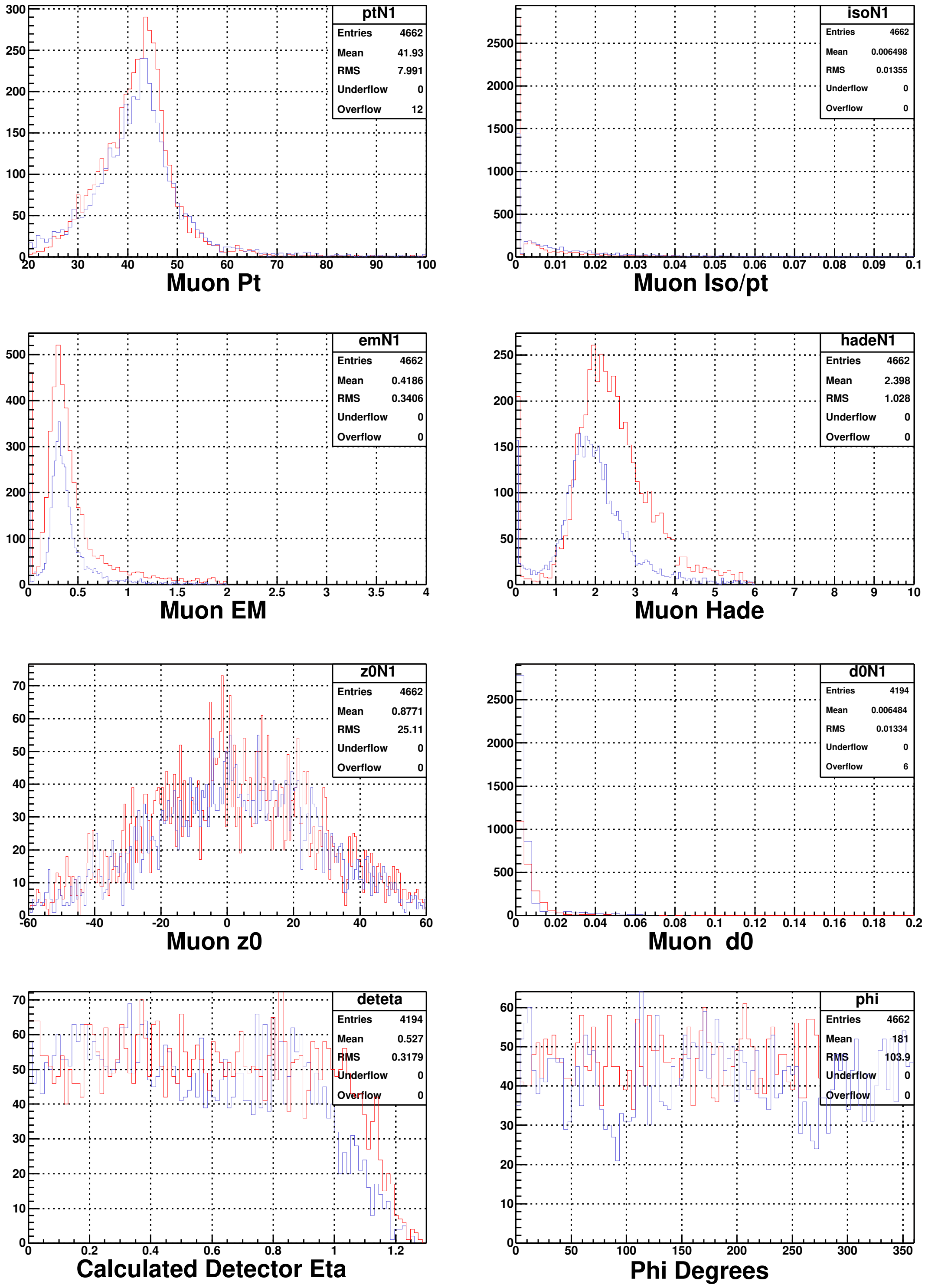

Figure 2: This figure shows variables for data and monte carlo muons passing all of the cuts described above. Monte Carlo is in red, Data in blue. There are a total of 4664 monte carlo muons and 4436 data muons.

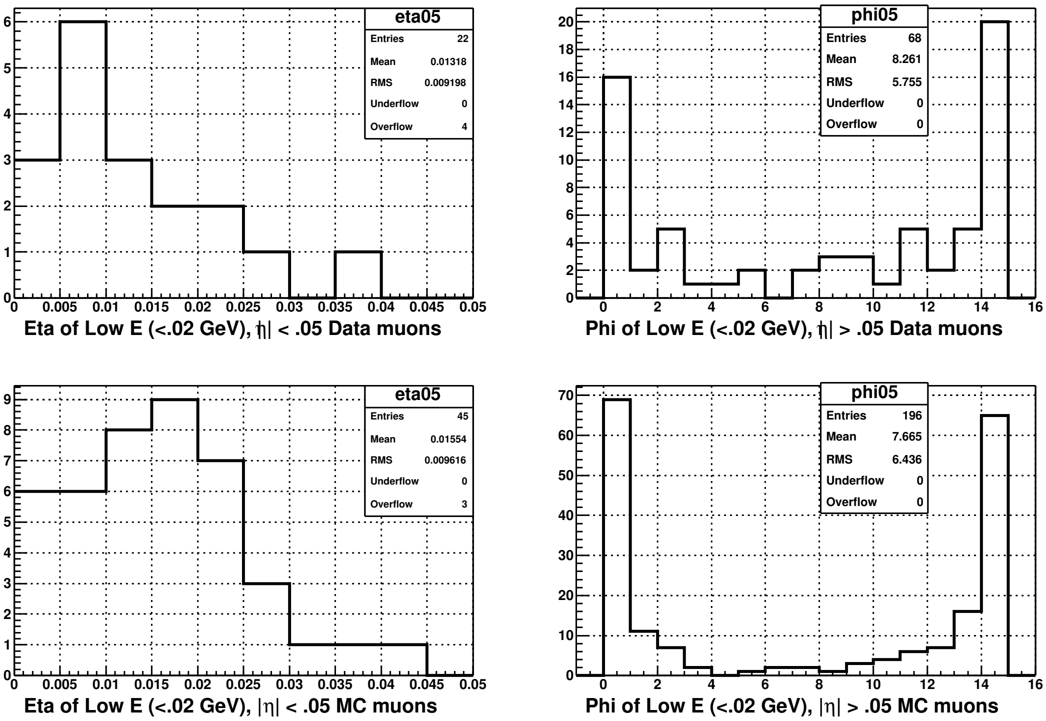

Figure 3: This figure plots the eta distribution of low EM energy muons ($<.05$ GeV) with $|\eta| < 0.05$ on the left and phi distributions, in 15 degree segments, of low EM energy muons with $|\eta| > 0.05$ on the right. Data is shown on the top, Monte Carlo on the bottom.

eta distributions for the low EM energy muons ($E_{EM} < 2GeV$) we have found that those muons are concentrated in the calorimeter cracks at $\eta = 0$ and the 15 degree ϕ cracks. The distributions are shown in figure 3. We expect muons passing through these areas to have almost no energy because muons do not shower, nor do they radiate much, so the majority of the energy that they deposit in the calorimeter ais concentrated tightly along the track of the muon, hence it the muon passes through a crack in the calorimeter, no energy will be recorded.

6 Invariant Mass

The invariant dimuon mass was calculated using beam constrained variables in the data sample and non beam constrained in the COT + SVX tracking varibles of the Monte Carlo.

The resulting distribution was fit with a gaussian and the fit parameters are summarized in table 2 .

In order to determine the momentum correction factor between the data and Monte Carlo to match the two distributions we applied a scale factor ranging from .99 to 1.01 to the p_t of the data. We then calculated the χ^2 of the data and Monte Carlo distributions for

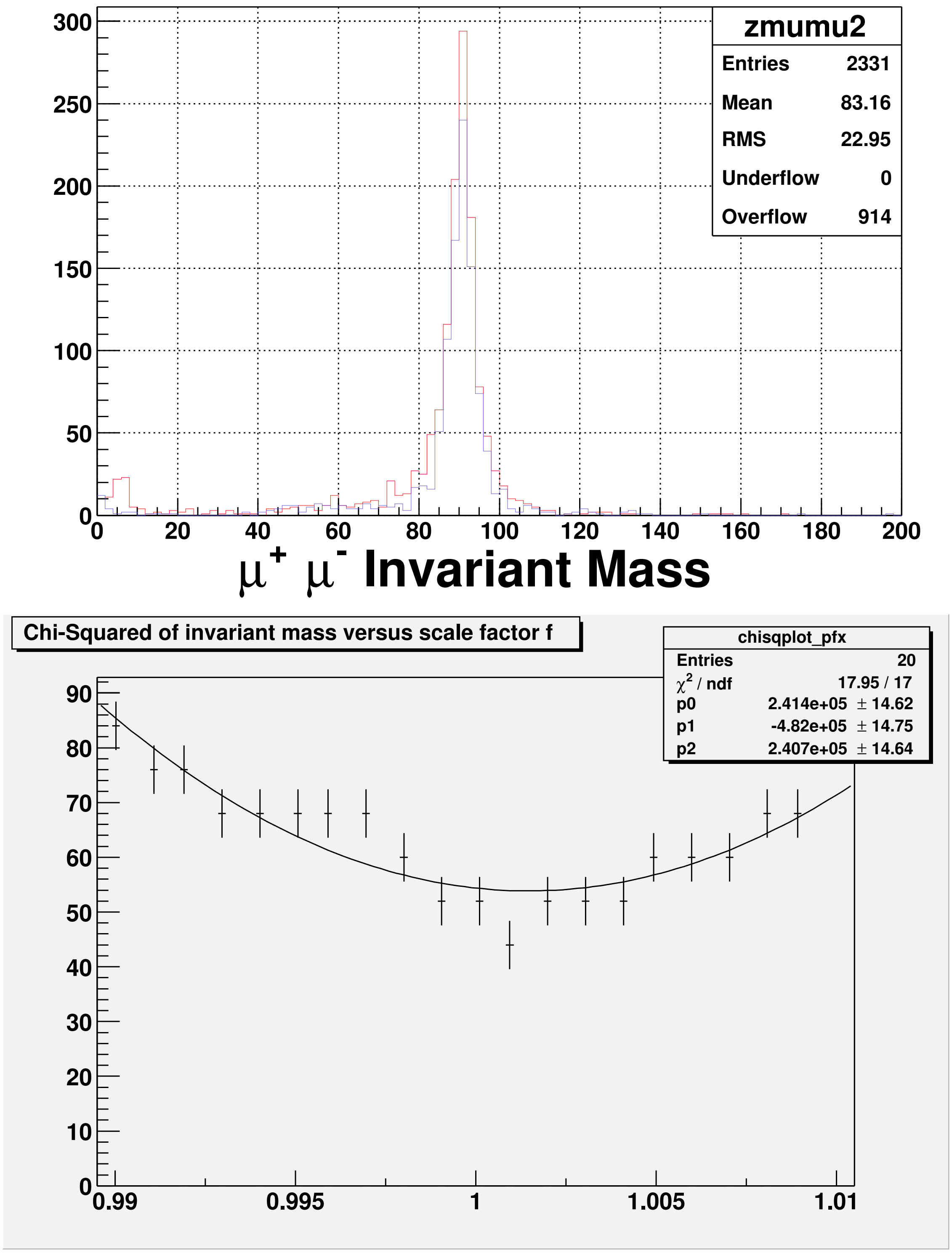

Figure 4: The top figure shows the data and monte carlo invariant mass distribution of muon pairs passing the above cuts. The data (in blue) has been fit to a gaussian and the fit parameters appear in the figure. The bottom figure shows a chi-squared minimization as a function of a scale factor added to the data to match the monte carlo. It is fit with a second degree polynomial and the parameters are show in the figure.

Table 2: Parameters for Invariant Mass Fit

	Data	Monte Carlo
number of events	2097	2331
mean	90.64(12)	90.39(13)
sigma	3.545(121)	4.248(192)
χ^2/dof	207.8/56	369.6/65

each scale factor and then minimized the χ^2 as a function of scale factor. I have found from doing the minimization with a second degree polynomial that the data needs a correction factor of 1.001471 to match the monte carlo.

7 Conclusions

At this stage we are fairly confident that we understand the muon properties. The consistencies we have found between the data and monte carlo ensure that we have a valid way of testing any physics analyses by comparing them to good simulation. A measurement of the forward backward charge asymmetry, a measurement of the relative strengths of the vector and axial couplings of the electro-weak force, is forthcoming.

References

[1] E. J. Thompson, "Description of data samples for the Top and Electroweak Groups for Winter 2003," CDF Note 6265.

[2] Affolder, Anthony. "A Measurement of Bottom Quark-Antiquark Azimuthal Production Correlations". UC Berkeley, 2002.

[3] "CDF Technical Design Report". The CDF Collaboration, Nov. 1996.