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ATLAS detector studies using Z boson leptonic decay

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Abstract

When the ATLAS experiment on the Large Hadron Collider (LHC) at CERN begins taking real data, it is important that the detector be as well-understood as possible. Using well-understood decays, it is possible to calibrate and align the ATLAS detector so that it can achieve its design performance as quickly as possible.

This approach involves the decays $Z^0 \rightarrow \mu^+ \mu^-$ and $Z^0 \rightarrow e^+ e^-$. The transverse momenta of the two decay particles are reconstructed to give the mass of the Z boson. By fitting the mass curve to a Breit-Wigner smeared with a Gaussian, a scale can be determined to show the ratio between the reconstructed Z mass and the known Z mass, which was precisely measured at the Large Electron-Positron (LEP) collider. This can be used to quantify various detector effects, most notably the impact of detector misalignment (for the muons) and EM energy scale (for the electrons).

Introduction

The ATLAS experiment has been designed and planned by high-energy particle physicists over a very long time (over 15 years). The first beam injection will commence in August at a testing energy of about 5 TeV per beam. This energy will be scaled up after the dipole magnets have been trained to hold their full field. With the petabytes of information that ATLAS is expected to produce, it is important to ensure that the data are correctly reconstructed.

There are a number of ways to approach detector calibration; here, well-understood Z boson leptonic decays ($Z^0 \rightarrow \mu^+ \mu^-$ and $Z^0 \rightarrow e^+ e^-$) will be used as a "standard candle." In proton-proton collisions at LHC energies (7 TeV per beam), copious production of Z^0 bosons is expected[1]. The ATLAS detector is built to detect electrons and muons over a wide range of energies, and their presence can reveal a great deal about alignment and equipment status.

Transverse momentum (p_T) analysis will show bugs within the reconstruction software. Both the inner tracker and the muon spectrometer determine a charged particle's momentum and charge from the bend (or sagitta) of its track, due to the magnetic fields. The higher the momentum, the less a charged particle will bend in ATLAS's magnetic field. Detector misalignment combined with a straighter track significantly affects the ability to determine properties of the particles, namely their charge and momentum. In the case of a very high p_T track where the sagitta is smaller than the misalignment, there may even be incorrect charge determination. Figure 1 shows how a track will be incorrectly reconstructed (both misalignment and the sagitta are exaggerated). By studying the probability of charge confusion through a range of momenta, it is possible to determine the effects of misalignment on high energy decays (such as a heavy Z') and on lower energy decays (like Z^0).

Monte Carlo simulated data were used to check the effectiveness of these techniques, allowing for the comparison between simulated data and the true decays. A data set designed to replicate real ATLAS data as accurately as possible will finally be used to show that the techniques still perform as expected when analyzing signal through a realistic background. This particular data set is referred to within the ATLAS group as Full Dress Rehearsal 2 (FDR2) data.

Theory

The accepted model of particle physics is called the Standard Model. This model postulates that all matter is made up of different mixtures of six quarks and six leptons. Three interactions between these quarks and leptons can be described by gauge particles: the Z^0 boson is a carrier of the

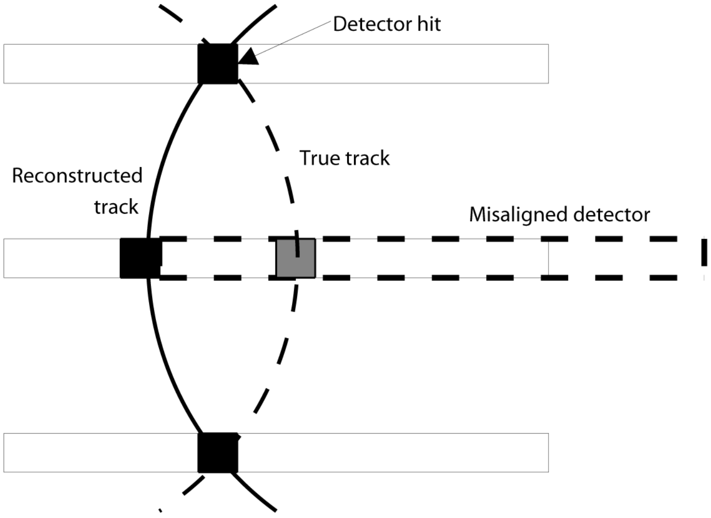

Figure 1 Charge confusion in the detector.

weak force (along with the W^+ and W^- bosons), gluons control the strong force, and electromagnetic interactions are due to the exchange of photons. For further information on the Standard Model, see Halzen's paper[2].

A Z boson has been found to decay to an electron pair or a muon pair about 7% of the time[3]. *Z* boson leptonic decay has been studied quite thoroughly, in particular at LEP[4]. By examining *Z* boson decay at the LHC through ATLAS detector data, it can be determined whether the detector is functioning as designed.

A number of factors are used to determine the effectiveness of the analysis. Here, a misidentification ratio is used, which is the ratio of reconstructed same-charged *Z* events to reconstructed oppositely charged *Z* events.

Methods

The software toolkit used for this analysis includes ROOT[5] (statistical analysis and graphing software) and Athena (for the physics analysis). Data were simulated using Monte Carlo (MC) algorithms in Athena[6].

Electrons and muons are selected by the reconstruction software if they pass all of the software and hardware triggers in the detector, and displaying qualities characteristic of muons. The truth container consists of the simulation input – it contains what would be reconstructed had the detector been perfect. It shows, for example, the number of muons that were requested to be produced. Because no means of detecting a particle is perfect, there will be discrepancies between the actual event (truth) and the reconstruction.

With simulated data, it is possible to access both of these quantities to determine how accurately the particles are reconstructed. In turn, this allows observation of the effects of misalignment of the detector.

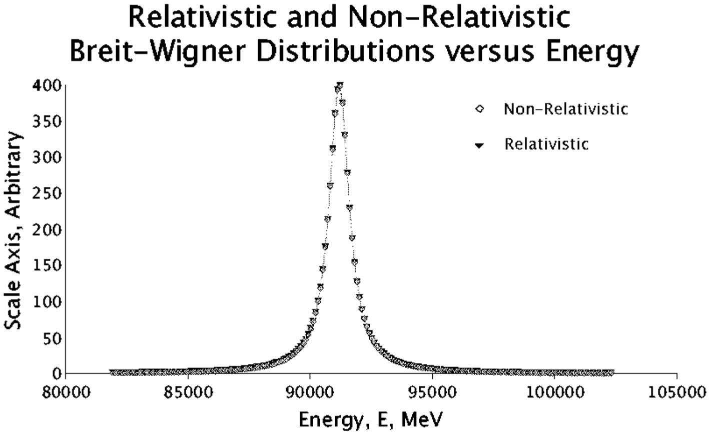

Figure 2 Breit-Wigner comparison plot.

The reconstructed invariant masses of pairs of muons and electrons will be fitted to a curve, and a quantity called the scale of the fit will be measured in each case. The scale is the ratio between the predicted mean of the reconstructed masses and the mean of the fit.

Reconstruction fitting

The electron and muon pair reconstructed masses were fitted to a non-relativistic Breit-Wigner convolved with a Gaussian. This fit function is represented by Equation (1):

$$\frac{\Gamma}{2\pi\left[\left(x-M\right)^2+\Gamma^2/4\right]}\otimes\frac{e^{-x^2/2\sigma^2}}{\sqrt{2\pi}\cdot\sigma}. \tag{1}$$

The Breit-Wigner models the probability of producing a Z^0 particle at a given energy, and the Gaussian represents the resolution of the detector. Here, Γ is the width of the *Z* boson, *M* is the *Z* mass, *x* is the energy at which the Z^0 is produced, and σ is the standard deviation of the Gaussian – a parameter related to the detector's resolution.

Within ROOT, the fitting algorithm selects values for any of these parameters such that the resulting curve best fits the data. Since the width of the *Z* decay has been studied very closely, it will not be chosen as a variable; we substitute the value[3] 2.4952 GeV.

There exists a relativistic Breit-Wigner distribution, but for this application, the non-relativistic Breit-Wigner is a good approximation. Figure 2 shows the Breit-Wigner function compared with the relativistic Breit-Wigner function at an appropriate energy scale, using $\Gamma = 1000$ MeV and $M = 91188.2$ MeV. There is little difference between the plots.

The predicted Z^0 peak[3] is 91.188 GeV. When fitting, a range from 85 GeV to 110 GeV was used. This is required because the fit function does not account for the radiative tail (shown in Figure 4b). The electron plot shows a more distinctive tail because electrons are much lighter than muons and experience "external bremsstrahlung" by interacting with matter.

Using $Z^0 \to \mu^+ \mu^-$ signal (no background), a value of 90.79 GeV was found for the reconstructed mass. The muon fit ratio is therefore 1.0044. For $Z^0 \to e^+ e^-$ signal, the reconstructed and fitted Z^0 mass was 89.52 GeV. Thus, the electron scale value is 1.0186.

The scale is related to the intricacies of the detector. In the calorimeter, there is essentially a sandwich of material, and the electrons produce a nonlinear response, which must eventually be translated into their energy by the analysis software. This is complicated, process-dependent, and a factor

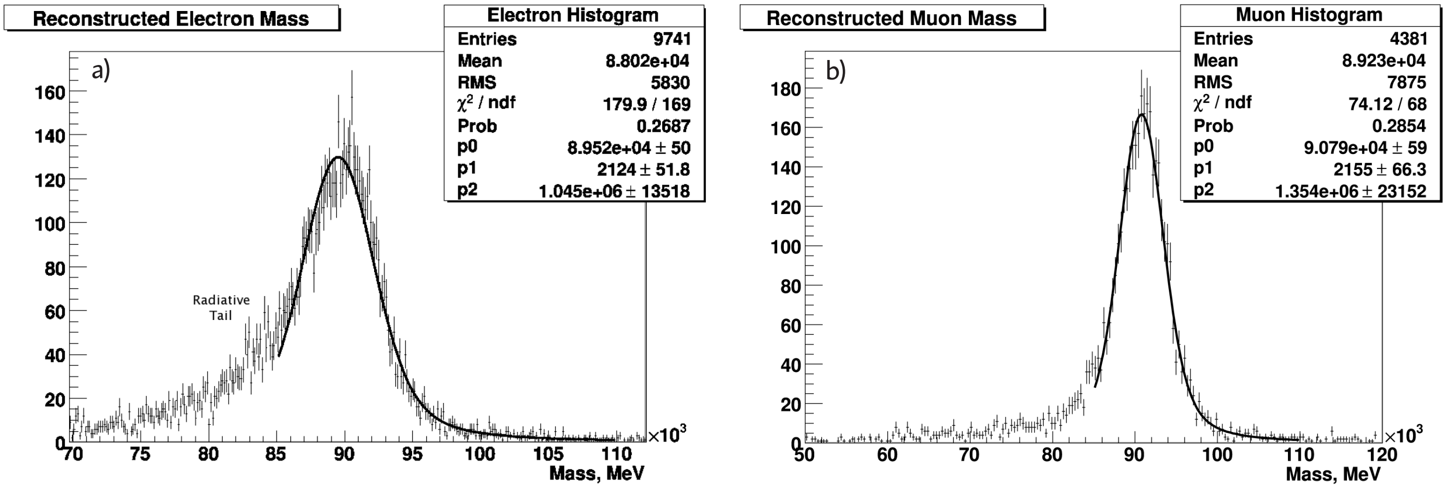

Figure 3 Scale fits for a) electrons and b) muons.

behind the scale. The scale is somewhat global; it affects the entire calorimeter (which is essentially a large chunk of material). Once real data are obtained, determining the scale will be a strong and fast technique for correcting the initial EM calorimeter bias.

The muon spectrometer is different; it has a good chance of local misalignments rather than a single constant bias. Instead of defining a single scale and adjusting all measurements by it to correct error, the muon fit ratio is indicative of a significant bias. The individual misalignments should contribute in a random fashion, giving a scale close to 1, and if the value is far off, the muon spectrometer must be studied much more closely. So, the muon fit ratio will give a quick check to see whether there is something larger than random misalignments in the muon spectrometer.

Also of interest is the width of the detector's Gaussian. This was a floating parameter (p1), so it was optimized for the best fit. Resolution values were 2.124 GeV for the electrons and 2.155 GeV for the muons. This reflects the design of the detector – it makes sense that an intention of the developers is to maintain a similar resolution for decays of interest.

It is expected that the detector resolution will change for the decays of a hypothetical heavy Z'. In Figure 4, it can be seen that the resolution of the detector increases by a factor of ten, but the electrons now have better resolution than the muons. It is most intuitive to represent resolution as a ratio with respect to the mean; that is, Resolution = [Resolution (MeV)][Mean (MeV)] × 100%.

The difference in the resolution parameter shows that the muon decay has worse resolution at high p_T. The momenta of muons are determined from the muon spectrometer, which, for the reasons stated above, is more sensitive to misalignment at higher p_T. Electron energy, on the other hand, is measured using the electromagnetic (EM) calorimeter. The resolution improves between 100 GeV and 1 TeV. It was expected that the percent error in energy in the electron calorimeter is of the form[7] $\sigma(E)/E = a/\sqrt{E} \oplus b$.

Decay	Detector Resolution, %
$Z \rightarrow e^+ e^-$	2.31
$Z \rightarrow \mu^+ \mu^-$	2.35
$Z' \rightarrow e^+ e^-$	1.18
$Z' \rightarrow \mu^+ \mu^-$	8.21

Table 1 Detector resolution expressed as a percentage.

Misidentification analysis

Next, the probability of background misidentification and charge confusion was studied at high and at low momenta. This is highly visible when a reconstruction is performed if the decay particles have the same charge. A $Z^0 \rightarrow e^+ e^+$ or any other same-charge combination is impossible, so it is clear that the event is a fake.

Given the strengths of the magnetic fields within ATLAS, tracks in the momentum ranges of interest are likely to have enough curvature to deter-

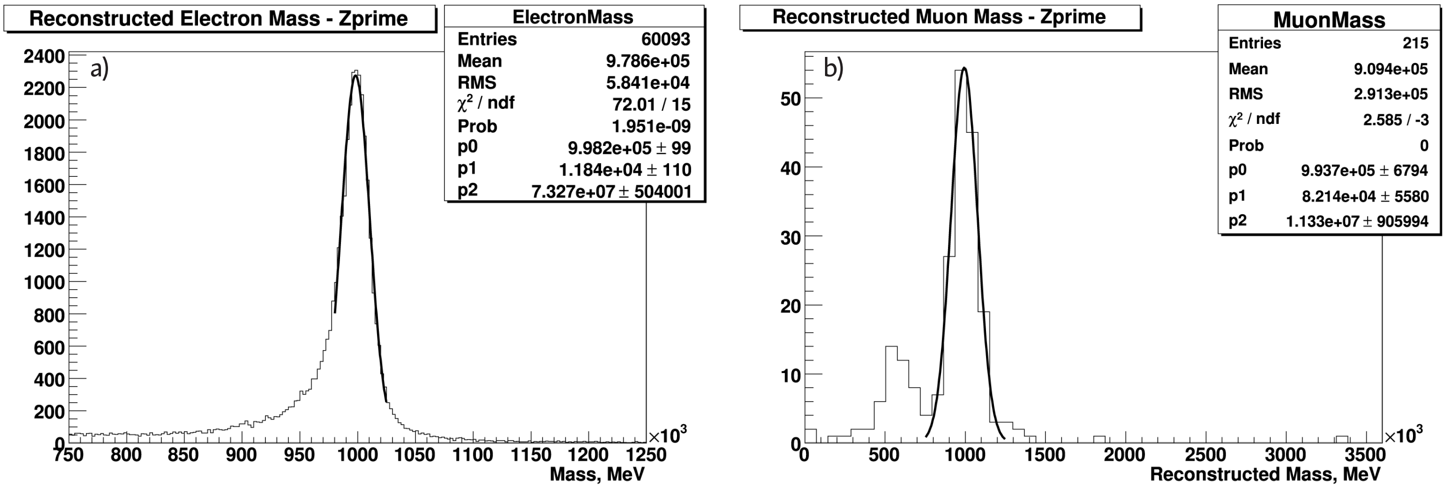

Figure 4 Z' reconstructed mass for a) electrons and b) muons.

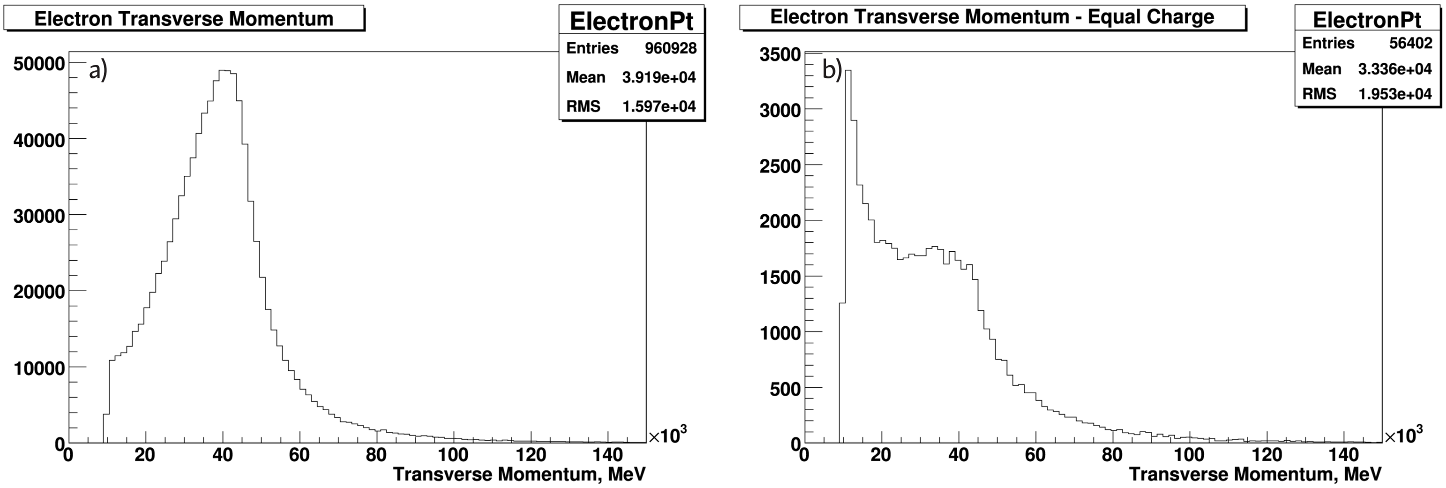

Figure 5 Z^0 decay p_T for a) opposite charge electrons and b) same charge electrons.

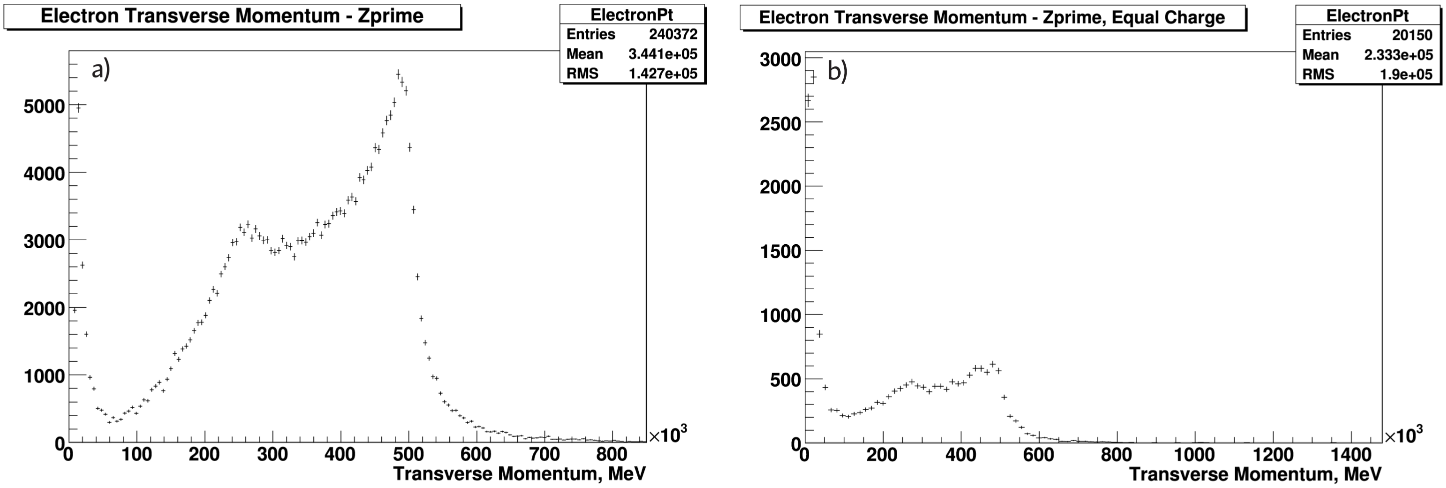

Figure 6 *Z′* decay p_T for a) opposite charge electrons and b) same charge electrons.

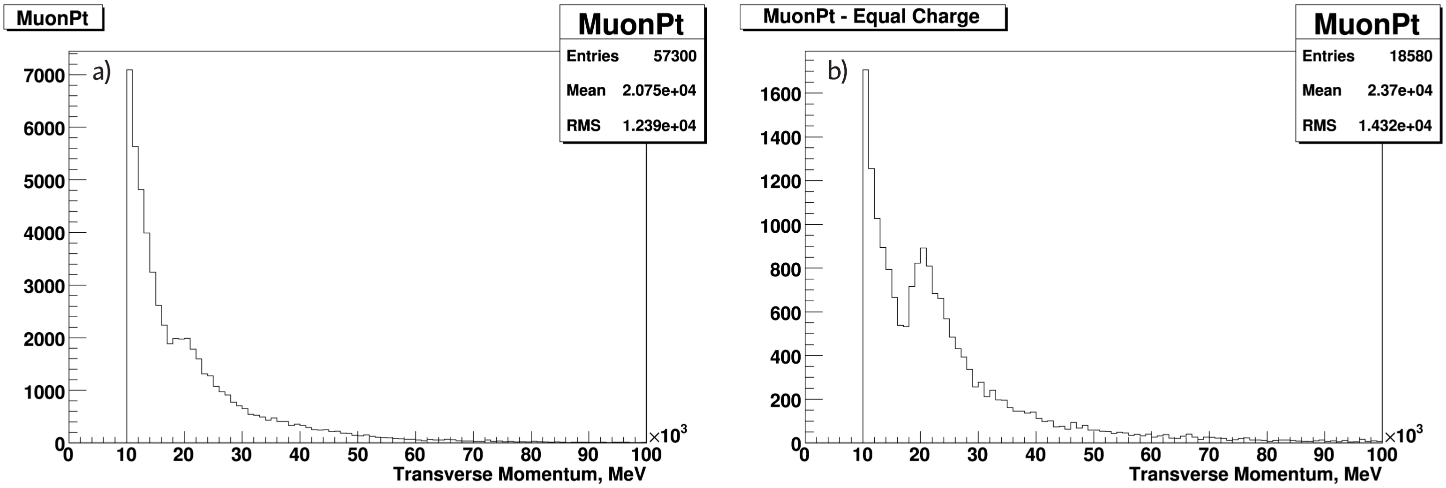

Figure 7 Muon momenta for lower p_T decays (FDR2) for a) opposite charge muons and b) same charge muons.

mine charge correctly. It is therefore predicted that there will be a very small charge confusion ratio for Monte Carlo Z^0 signal. The software contains a 10 GeV cut. Electrons with momenta lower than this value will not be included in the reconstruction. In Figure 5, there is a misidentification ratio of $\varepsilon = (56402)/(1017330) \approx 5.5\%$. It is very easy to see, though, that a cut at 20 GeV would significantly reduce this ratio. Most of the misidentification is seen to occur at the lowest p_T. The lack of misidentification due to charge confusion is evident – there is no trend of high p_T electrons being misidentified.

The *Z′* particle is good for comparison with the Z^0, since the *Z′* has a large mass and thus decays to leptons with very high momenta. The peak around 500 GeV is expected; this likely shows that two such electrons were produced, making up the 1 TeV *Z′*. At rest, a *Z′* boson will decay “back to back,” with the two leptons at equal energy. Since the beams collide at equal and opposite velocities, it is more probable that the particle will be created at rest, but due to the asymmetry of proton collisions (since protons are not elementary particles), the *Z* and *Z′* particles will typically be boosted. Often, however, they are at rest perpendicular to the beam axis, so the decay products will still possess equal p_T.

Figure 6 shows the results for a 1 TeV *Z′*. A cut on p_T at around 250 GeV would reduce background here, as well. The misidentification ratio is $\varepsilon = (20150) / (260522) \approx 7.7\%$. It becomes clear that the electrons are not experiencing charge confusion due to their high p_T. The signature of this occurrence would be a plot of same-charge events that occur mostly at high p_T. In this case, the misidentified events are background.

To observe how the detector functions with a lot of background, the familiar $Z^0 \rightarrow \mu^+ \mu^-$ decay is examined on FDR2 data. A cut is made at 10 GeV, preventing any muons with p_T lower than this from being reconstructed. From Figure 7, the misidentification ratio is $\varepsilon = (18580) / (75880) \approx 24\%$. The fact that there were far more equal-sign events may be attributed to the high portion of background events.

These like-sign events should not form a mass peak and should instead be representative of other events in the background. Still using the FDR2 data, an exponential function can be fitted to the plot of reconstructed data, appropriately scaled, and compared with the correctly reconstructed signal events. The events that may be modelled by the exponential exist due to the actual signal being $q\bar{q} \rightarrow Z / \gamma^* \rightarrow e^+ e^-$. Most importantly, the energetic gamma may also decay: $\gamma^* \rightarrow e^+ e^-$. This occurs in an exponential fashion with respect to the electron momenta.

Figure 8 shows the exponential function used to fit to the portion of the reconstructed events which were misidentified. This fit was found to have the equation shown in Equation (2):

$$e^{5.95-0.0000254\cdot x}. \tag{2}$$

It is shown to fit the correctly reconstructed FDR2 $Z \rightarrow e^+ e^-$ in Figure 8b. This function can be added to the Breit-Wigner convolution of Equation (1), producing a function to fit unmodified FDR2 data (Figure 9). The fourth parameter of the fit (p3) is a normalizing factor.

This analysis has shown that it is possible to obtain an accurate fit using

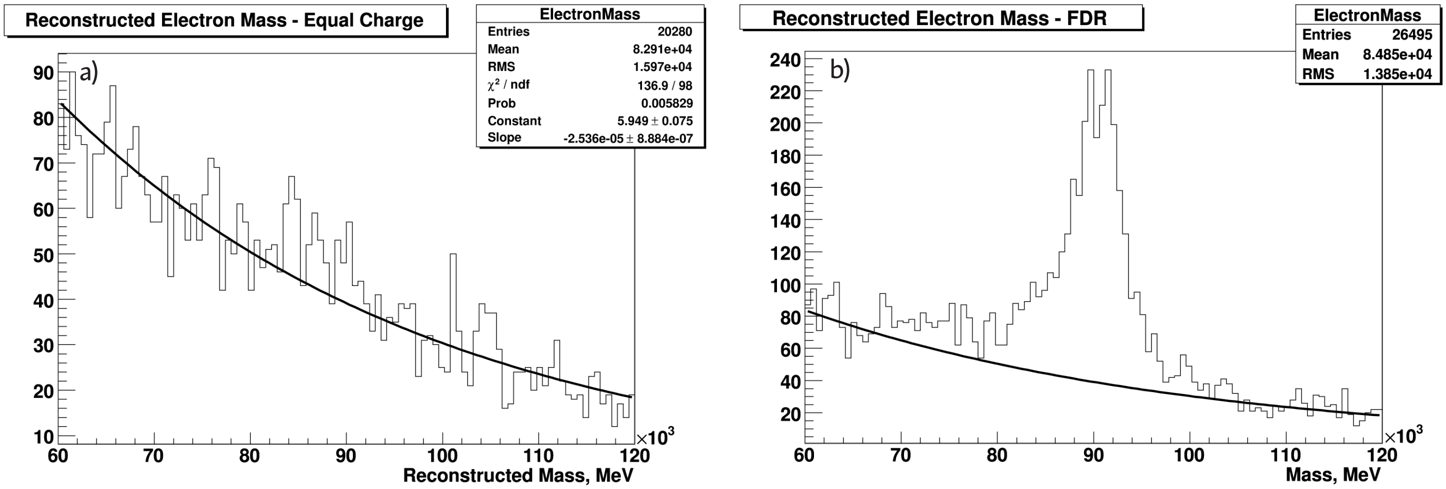

Figure 8 Exponential fit (FDR2) for a) fit to confused charge reconstruction and b) overlay on same charge events.

the misidentified events as an estimate of the background. The chi-squared value divided by the number of degrees of freedom (goodness of fit) of ≈ 2 shows that the fit is indeed quite accurate.

Conclusion

The EM calorimeter scale and a muon fit were both determined from Monte Carlo signal, and it was seen that this technique could be useful at quickly identifying detector misalignment (for the muon calorimeter) and bias (in the EM calorimeter). Monte Carlo showed that the predicted resolution was equal for both $Z^0 \rightarrow \mu^+ \mu^-$ and $Z^0 \rightarrow e^+ e^-$ decays. The corresponding 1 TeV Z' decays showed that relative to the mass of the reconstructed boson, the resolution became better for $e^+ e^-$ and worse for $\mu^+ \mu^-$. This result is expected; if this effect does not appear in real data, detector misalignments could be inferred.

Charge confusion was studied for signal Z decay, Z' decay, and FDR2 Z decay data. It was seen that at higher transverse momenta, there was a higher incidence of misidentification, but this was not charge confusion due to the lack of a high p_T trend; instead, it was representative of background events.

With the FDR2 data, the background was seen to contribute most to the like-sign events. Since the energetic gamma decay is indistinguishable from true data, it is difficult to improve this misidentification rate. A preliminary technique of removing background was covered, and it was shown to be effective at matching the desired signal.

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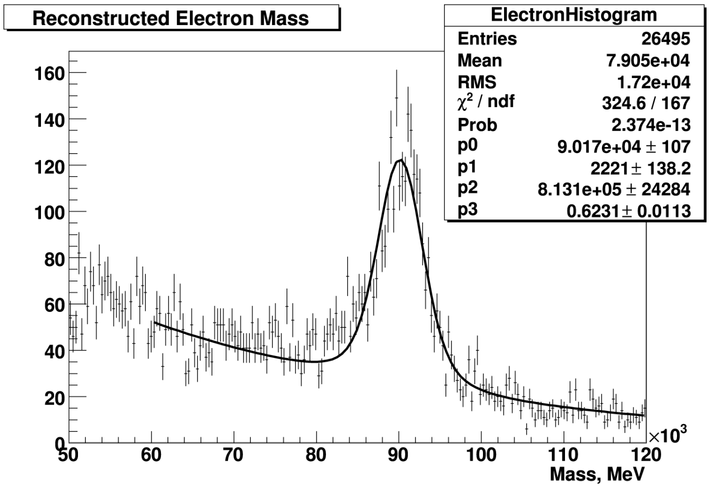

Figure 9 Breit-Wigner fit with exponential background correction.

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