The Search for the h^0 Particle

Elizabeth Goodman
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1 Introduction

In this paper I discuss the search for the Higgs particle (h^0) in a 350 GeV electron-positron accelerator. I will discuss methods for separating the Higgs signal from the Standard Model background and the cuts used to isolate the signal. I measure the mass of the Higgs using two different methods: by measuring the combined mass of the hadron jets that come from the Higgs particle, and by measuring the recoil energy of the Z^0 particle.

1.1 The Method Used

- perform simulations of Point 3 parameters at E_{cm} of 350 GeV, where we can expect to see $e^+ + e^- \to h^0 + Z^0$ events. At 350 GeV, the cross section for an 80% left polarized electron beam is 182 fb, and for 80% right polarization the cross section is 149 fb.[1]
- separate the Supersymmetric signal from the Standard Model background and from other Supersymmetric production modes by applying cuts that reduce the background while leaving as much as possible of the Higgs/Z^0 signal.
- measure the mass of the Higgs by finding the average value of the combined mass of the particles in the hadron jets that survived the cuts.
- measure the mass of the Higgs using the recoil energy of the Z^0.

[1] At 500 GeV, the cross section for $h^0 Z^0$ for 80% left polarization is 72 fb, and for 80% right polarization the cross section is 59 fb.

2 Data Analysis

2.1 Particle Productions and Decay Modes

The cross sections (in fb) for our Standard Model background production modes are shown in Table 1.

Table 1: Cross sections (in fb) for Standard Model background production modes at E_{cm} = 350 GeV.

Mode	Cross Section (fb)	Branching Ratio
W^+W^- (80% left polarized)	17759	0.0443%
$\gamma + \gamma$	13030	0.0325%
$\gamma^* or Z^0$	10490	0.0262%
$\gamma + \gamma^* or Z^0$	10310	0.0257%
$Z^0 + Z^0$	689	0.00172%
$\gamma^*\gamma^*$	3.99 x 10^7	99.9%
W^+W^- (80% right polarized)	4547	0.0114%
$\gamma + \gamma$	13030	0.0325%
$\gamma^* or Z^0$	10490	0.0262%
$\gamma + \gamma^* or Z^0$	10310	0.0258%
$Z^0 + Z^0$	689	0.00172%
$\gamma^*\gamma^*$	3.99 x 10^7	99.9%

It is our goal to determine how to remove, by kinematical cuts, the Standard Model background and the non-Higgs/Z^0 Supersymmetric events while minimally affecting the Higgs/Z^0 signal. In order to determine what cuts to make, we need to understand how the particles in our production modes decay.

The h^0 particle decays as shown in Table 2.[2]

The τ decays as shown in Table 3.

The Z^0 decays as shown in Table 4.[3]

[2]Supersymmetric particle production modes and decay rates were determined using ISAJET.

[3]With the exception of $\gamma^*\gamma^*$ events, Standard Model decay modes were taken from the Particle Data Book (APS Physical Review D Particles and Fields 1994). $\gamma^*\gamma^*$ cross sections were determined using HERWIG.

Table 2: Decay Modes for h^0.

Mode	Branching Ratio
$q\bar{q}$	93.75%
$\rightarrow b\bar{b}$	89.2%
$\tau^+\tau^-$	5.48%
$\mu^+\mu^-$	0.05%
$gluons$	0.72%

Table 3: Decay Modes for τ.

Mode	Branching Ratio
hadrons + ν_τ ($\bar{\nu_\tau}$)	64.2%
e $\nu_e \nu_\tau$	18.0%
μ $\nu_\mu \nu_\tau$	17.6%

Table 4: Decay Modes for Z^0.

Mode	Branching Ratio
$q\bar{q}$	69.90%
$\rightarrow b\bar{b}$	15.5%
neutrinos	20.01%
e^+e^-	3.37%
$\mu^+\mu^-$	3.37%
$\tau^+\tau^-$	3.37%

The W particle decays as shown in Table 5.

The $\gamma^*\gamma^*$ intermediate state produces particles as shown in Table 6.

The type of event we will use to determine the mass of the Higgs is shown in Figure 1.

The mass of the Higgs particle can be determined by measuring the combined mass of the particles in the hadron jets (from the $q\bar{q}$). Alternatively, the mass can be determined by measuring the recoil energy of the Z^0.

Table 5: Decay Modes for W.

Mode	Branching Ratio
hadrons ($q\bar{q}'$)	67.8%
$\rightarrow b\bar{b}$	0.0%
$e^{\pm} + \nu_e(\bar{\nu_e})$	10.8%
$\mu^{\pm} + \nu_\mu(\bar{\nu_\mu})$	10.6%
$\tau^{\pm} + \nu_\tau(\bar{\nu_\tau})$	10.8%

Table 6: Production Modes for $\gamma^*\gamma^*$ at 350 GeV.

Mode	Cross Section (fb)	Branching Ratio
$q\bar{q}$	3.51 x 10^6	8.78%
$e^{\pm} + e^{\mp}$	2.50 x 10^7	62.6%
$\mu^{\pm} + \mu^{\mp}$	1.12 x 10^7	28.0%
$\tau^{\pm} + \tau^{\mp}$	2.67 x 10^5	0.668%

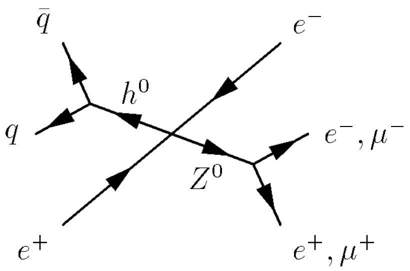

Figure 1: Feynman diagram of h^0 Z^0 event.

2.2 Combined Mass Calculation

We calculate the combined mass as follows:

$$
\begin{aligned}
P^2 &= (\sum Px_i)^2 + (\sum Py_i)^2 + (\sum Pz_i)^2 \\
E^2 &= (\sum E_i)^2 \\
M_{h^0} &= \sqrt{E^2 - P^2},
\end{aligned}
$$

where $\sum Px_i$ is the sum of the x momentum of each particle in the hadron jet, and $\sum E_i$ is the sum of the energy of each particle. P is the magnitude of the momentum of the jet, and E is the jet's total energy.

2.3 Cuts

In order to remove Standard Model background events and supersymmetric events other than h^0 Z^0, we need to apply cuts. To decide what cuts to use, we compare histograms of Supersymmetric signal events with histograms of background events. In order to reduce the size of our files, we begin with histograms that have already had cuts applied to them. In the following histograms, we only include events that have visible hadrons and one electron (or muon) and one positron (or anti-muon), and the combined mass of the electron and positron must be within $\pm$ 5 GeV of the mass of the Z^0 (91 GeV).

These cuts remove all supersymmetric events (i.e., chargino events $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}$, neutralino events $\tilde{\chi}_1^0\tilde{\chi}_1^0$) except Higgs/$Z^0$ events. Because the decay mode $Z^0 \to e^+(\mu^+) + e^-(\mu^-)$ is only 6.7% of the production modes, most of the Higgs/Z^0 events are cut here, leaving only events of the type described in our Feynman diagram.

Our task now is to remove as much of the standard model background as possible, without removing Higgs/Z^0 events. The $\gamma^*\gamma^*$ events are all removed with our first set of cuts because, as shown in Table 6, they never produce both hadrons *and* visible leptons with the required combined mass of $\pm$ 5 GeV of 91 GeV.

The situation for W^+W^- is similar: as shown in Table 5, $W^{\pm}$ either produces hadrons, or it produces a pair of leptons and neutrino, but it almost never produces hadrons and leptons together. (The only way a pair of leptons is produced in the same event as hadrons is via a τ decay.)

The γ/γ^*+ Z^0 events don't have leptons and hadrons, and neither do the $\gamma\gamma$ events, so these events have already been removed.

We are left with mostly h^0 Z^0 events, and Z^0 Z^0 events.

In order to keep particle physics interesting, Z^0 Z^0 events have a signature which is virtually identical to the h^0 Z^0 event's signature, as shown in Figure 2.

The visible decay products from the h^0 Z^0 events are the virtually identical to the decay products from Z^0 Z^0 events. Our task is to find ways that the Z^0 Z^0 events behave differently from the h^0 Z^0 events.

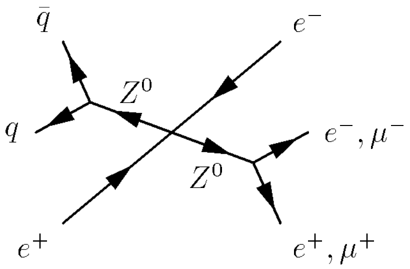

Figure 2: Feynman diagram of Z^0 Z^0 event that survived our first cuts.

2.4 Data Comparisons and Cuts

We begin with the histograms shown in Figure 3[4]. This histogram shows the combined mass of hadrons in both the signal and background for an integrated luminosity of 175 fb^{-1}, following the first set of cuts we made: events have visible hadrons and one electron (or muon) and one positron (or anti-muon), and the combined mass of the electron and positron must be within $\pm$ 5 GeV of the mass of the Z^0 (m = 91.2 GeV). An integrated luminosity of 175 fb^{-1} is the equivalent of 3.5 years of run time. We need an integrated luminosity of this size in order to have a signal large enough to measure after all of our cuts.

There is a peak in the red histogram between 60 - 70 GeV, which is due to the Higgs particle (69.2 Gev). There is a tail going from about 60 GeV down to almost 0, because some of the particles are lost due to detector resolution and inefficiency. There are also a few events with more energy than the Higgs mass, again because of poor resolution (the simulation assigns some jet particles to the wrong jet, as would happen in an actual detector).

In the background, there is a peak just under 90, which is due to the Z^0 (m = 91.2 GeV), and a peak below 80, which is due to $W^{\pm}$ (m = 80.4 GeV). The combined mass peaks are not exactly at the expected values because they represent the combined mass of the hadron jets, and the simulated detector has simulated inefficiencies.

We now apply a series of cuts to remove Standard Model background (blue) events while leaving as many Higgs/Z^0 (red) events as possible.

[4]In the following plots, "pythia" refers to the following processes, which were generated using pythia: $\gamma + \gamma$, $\gamma^* or Z^0$, $\gamma + \gamma^* or Z^0$, $Z^0 + Z^0$.

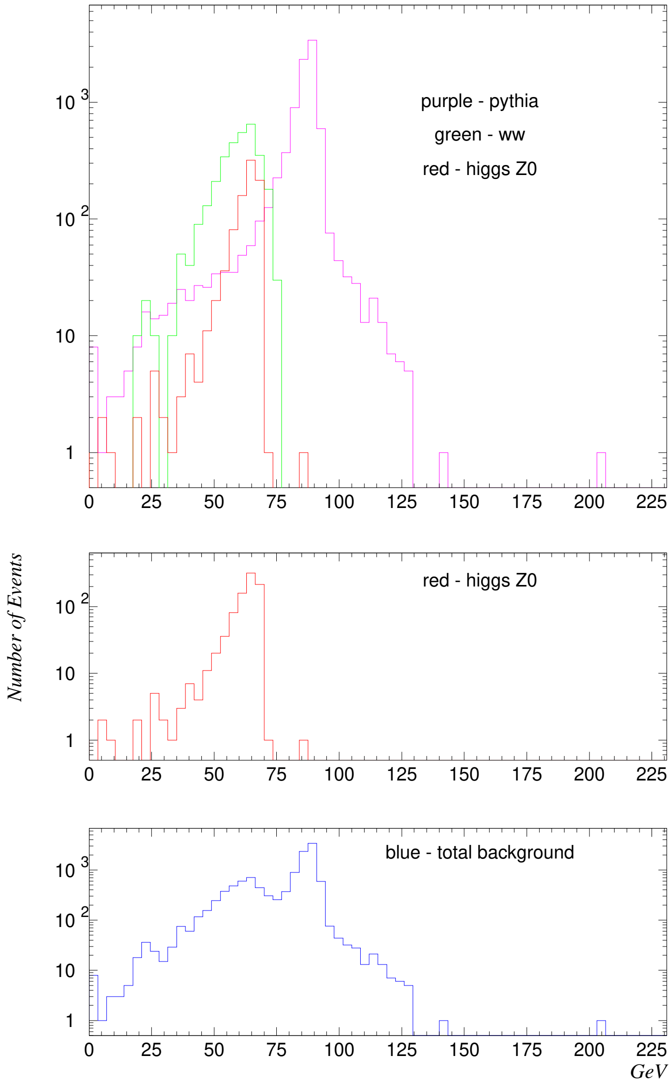

Figure 3: Mass of hadrons from Higgs Z^0 events and Standard Model backgrounds. All events have exactly one visible electron (or muon) and one visible positron (or anti-muon), whose combined mass is within $\pm$ 5 GeV of the mass of the Z^0 (91.2 GeV). Also, all events have deposited energy in the hadron calorimeter. Point 3 parameters, E_{cm} = 350 GeV, integrated luminosity of 175 fb^{-1}.

Cosine of the Angle of Particles with Respect to the Beam Axis Zeta (ζ) is defined as the angle of a particle with respect to the beam axis. We plot $cos(\zeta)$ for signal and background in Figure 4. We can see from

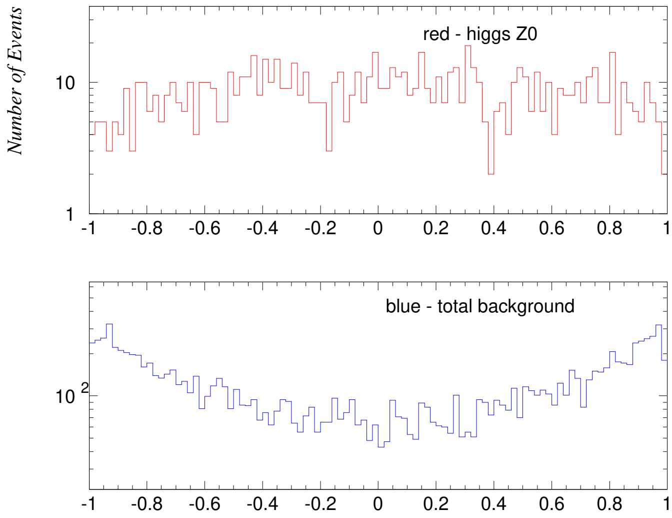

Figure 4: Angle of each visible particle with respect to the beam axis for Point 3 parameters, center of mass energy 350 GeV, 80% left polarized incoming electron (polarization does not affect the shape of $cos(\zeta)$).

Figure 4 that the angular distribution for the Higgs/Z^0 events is peaked around $|cos(\zeta)| = 0$, while the Standard Model background is peaked at $|cos(\zeta)| = 1$. We make a large cut on $cos(\zeta)$, eliminating all events with more than 1 GeV of visible energy between $0.65 \leq |cos(\zeta)| \leq .995$.

The resulting combined mass histogram is shown in Figure 5.

This cut removes most of our background, and a lot of our signal too. We now have a discernable signal between 60 - 70 GeV, and the expected Z^0 peak in the background at about 90 GeV.

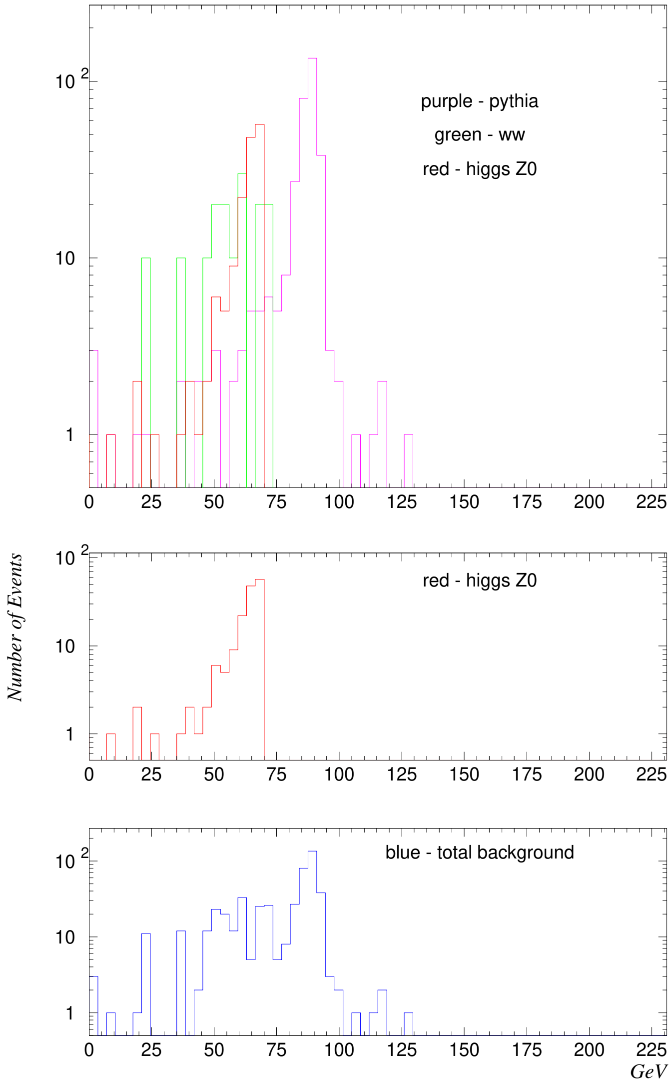

Figure 5: Combined mass of hadrons after removing events with more than 1 GeV of visible energy between $0.65 \leq |cos(\zeta)| \leq .995$. Point 3 parameters, center of mass energy 350 GeV.

Angle between electrons The angle between the visible electron and positron (or muon and anti-muon) is different for the h^0 Z^0 events than it is for the some of the background events. We plot this angle in Figure 6.

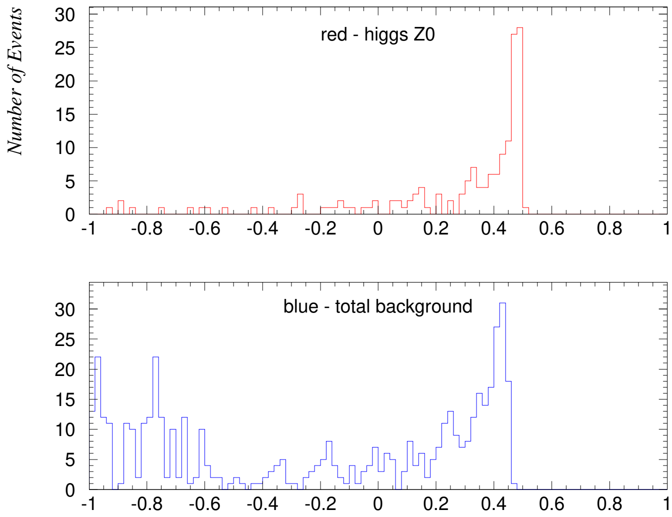

Figure 6: Angle between electron and positron for Point 3 parameters, center of mass energy 350 GeV, 80% left polarized incoming electron.

We can see that the background has some events with the electron and positron going in opposite directions (cos θ = -1), of which the signal has none. We also see that there are many more background events as signal between -1 $<$ cos θ $<$ -0.5. We remove these in the next cut.

Demand that the Magnitude of the Cosine of the Angle Between the Electron and the Positron is Less than 0.5. The next cut, Figure 7, removes events with the magnitude of the angle between the electron and positron greater than 0.5. This cut removes the remaining W^+W^- events, so the background now consists entirely of pythia events.

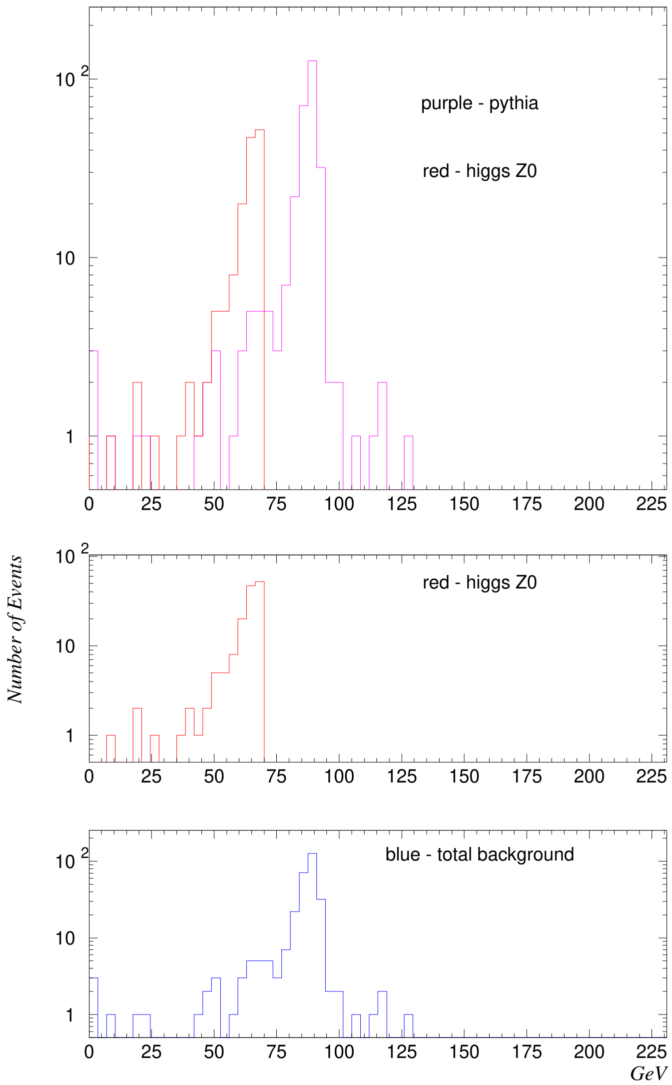

Figure 7: Remove events with $|\cos\,\theta|$ greater than 0.5. Point 3 parameters, center of mass energy 350 GeV, 80% left polarized incoming electron.

Visible energy The visible energy of the signal vs. the background is shown in Figure 8.

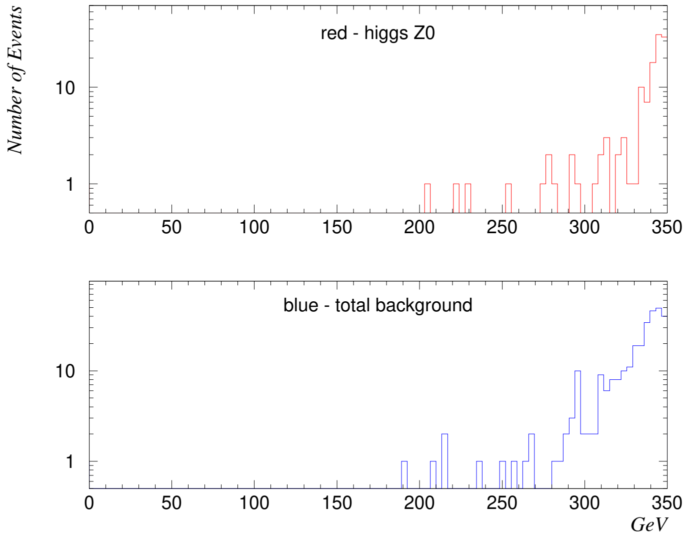

Figure 8: Visible energy for Point 3 parameters, center of mass energy 350 GeV, 80% left polarized incoming electron.

Because the decay products from the $h^0 Z^0$ events are all visible particles (that is, we have excluded events with neutrinos or neutralinos), our visible energy signal is largest at 350 GeV and falls away because of poor resolution and inefficiency. Our Standard Model background visible energy histogram has a similar peak at 350 GeV, again because all particles are detected. The background also has a few straggling events with energy less than 275 GeV, which are due either to neutrino events (which we don't want to keep) or events with missing energy due to ineffiency and poor resolution (which we also don't want to keep).

Demand that all Events have More than 280 GeV of Visible Energy. The next cut, Figure 9, removes events that have less than 280 GeV (E_{cm} - 20% E_{cm} = 280 GeV) of visible energy. This removes most events with neutrinos and events with energy missing due to poor resolution.

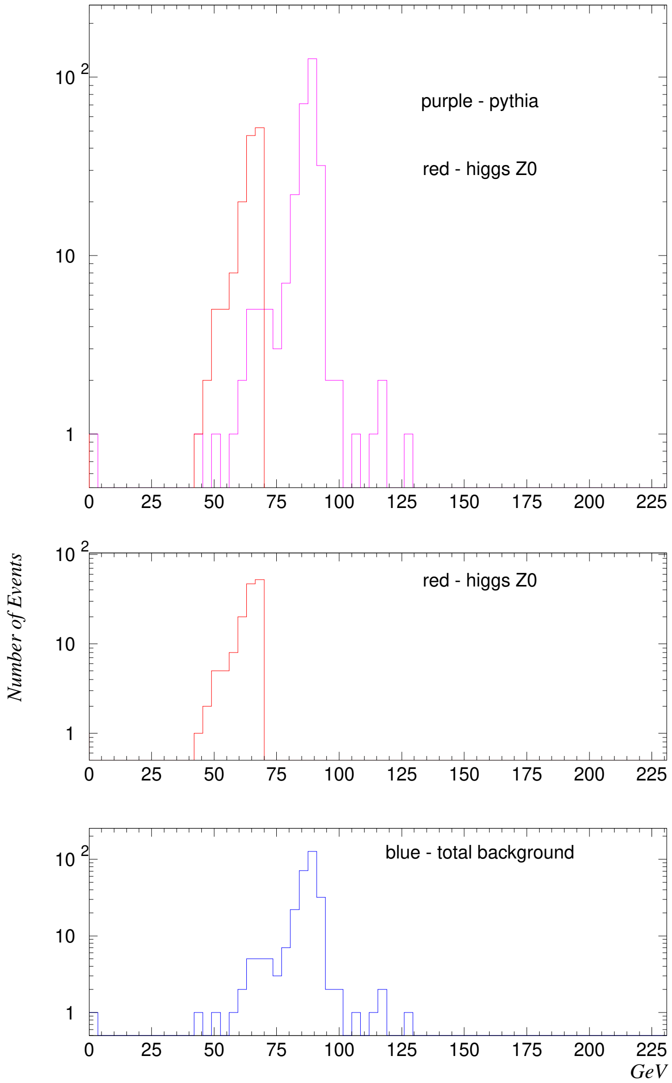

Figure 9: Signal and background after we remove events with less than 280 GeV visible energy. Point 3 parameters, center of mass energy 350 GeV, 80% left polarized incoming electron.

Demand that all events have two b quarks The Z^0 decays into two b quarks only 15.5% of the time and the W particle *never* decays into two b quarks. Since the Higgs is expected to decay into $b\bar{b}$ 89.2% of the time, cutting events that don't have two b quarks removes almost all of the remaining Z^0 and W background and leaves most of the Higgs events. In Figure 10 we show the combined mass after removing events without two b quarks.

Summary of Cuts This set of cuts is the most effective way we found of reducing the backgrounds while leaving enough Higgs/Z^0 events to measure. To summarize, the cuts we used are:

- Only keep events that have visible hadrons, and exactly one visible electron (or muon), one visible positron (or anti-muon) whose combined mass is 91 $\pm$ 5 GeV.
- Eliminate all events with at least 1 GeV of visible energy for 0.65 $\leq |cos(\zeta)| \leq .995$.
- Demand that all events have more than 280 GeV of visible energy.
- Only keep events with magnitude of the cosine of the angle between the electron and positron less than 0.5.
- Include only events that have two b quarks.

A closeup of the area of interest is shown in Figure 11.

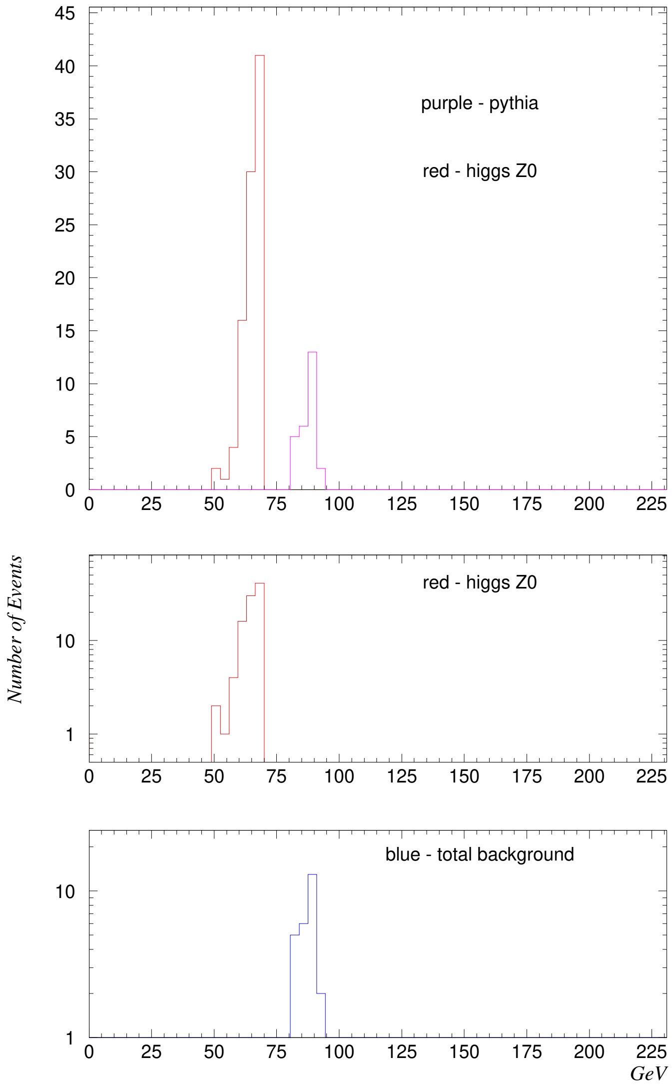

Figure 10: Include only events that have two b quarks.

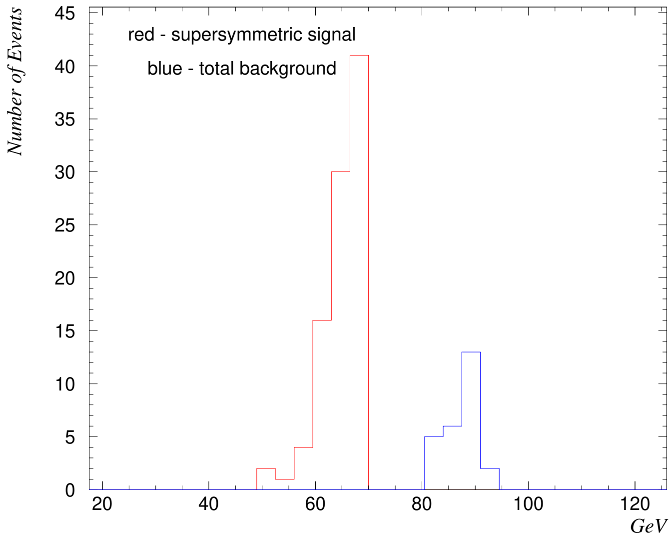

Figure 11: Closeup of mass of particles that come from hadron jets following all cuts.

3 Mass Measurement

3.1 Find mass of Higgs using combined mass of hadron jets.

After all the cuts have been made, we apply a fit function to the left peak in Figure 11[5]. The mean of the fit should be the mass of the h^0 particle.

The mean of the fit is 68.5, with an error of 1.9. The theoretical mass of the h^0 is 69.2 GeV. The discrepancy from the theoretical mass is 1.0%.

3.2 Find mass of Higgs using recoil energy of Z^0

It is possible to measure the recoil energy of the Z^0 particle and use that to measure the mass of the Higgs particle. The energy of the Z^0 is the sum of the energies of the two leptons into which it decays. Figure 12 shows the energy of the leptons in events that survived all of the previous cuts.

The mass of the Higgs is calculated as follows:

$$
\begin{aligned}
E_{cm} &= E_{Z^0} + E_{h^0} \\
E_{h^0} &= E_{cm} - E_{Z^0} \\
E_{h^0}^2 &= E_{cm}^2 - 2E_{cm}E_{Z^0} + E_{Z^0}^2 \\
E^2 &= p^2 + m^2 \\
m_{h^0}^2 + p_{h^0}^2 &= E_{cm}^2 - 2E_{cm}E_{Z^0} + m_{Z^0}^2 + p_{Z^0}^2 \\
p_{h^0}^2 &= p_{Z^0}^2 \\
m_{h^0}^2 &= E_{cm}^2 - 2E_{cm}E_{Z^0} + m_{Z^0}^2
\end{aligned}
$$

We expect that the mean for Z^0Z^0 events will be 1/2 E_{cm}, which is 175 GeV. There is a small peak at about 175 GeV, and a much larger peak at about 180 GeV. This is expected to represent the Higgs particle. We apply a fit function to Figure 12 and determine the mean of the larger peak, which is 180.2. Using this value with $E_{cm} = 350$ GeV and $m_{Z^0} = 91.2$ GeV, we calculate the mass of the Higgs particle. We obtain a mass of 68.3, which differs from the theoretical mass of 69.2 with a discrepancy of 1.3%.

[5] We can assume that the peak on the right represents the Z^0 mass because it is centered around 90 GeV.

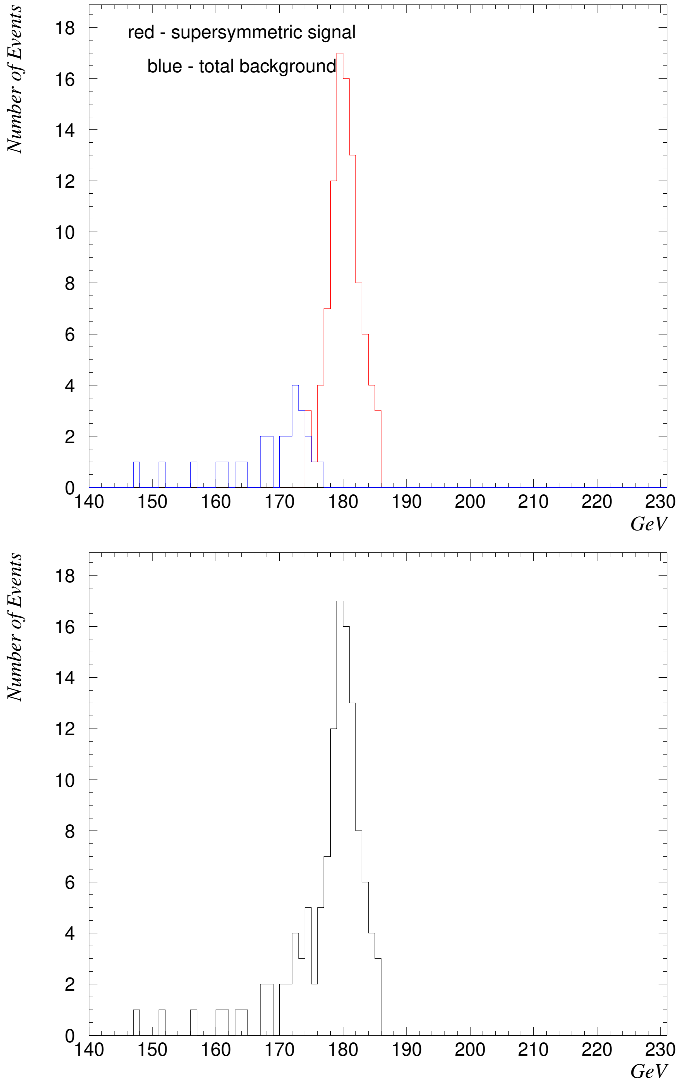

Figure 12: Sum of the energies of the two visible leptons following all cuts.