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INVESTIGATION OF THE DISCOVERY POTENTIAL FOR A NEW NEUTRAL GAUGE BOSON AT THE ATLAS EXPERIMENT

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Abstract

Investigation of the Discovery Potential For a New Neutral Gauge Boson at the ATLAS Experiment

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We begin by giving a brief overview of the Standard Model of Particle Physics and discuss the possible existence of a new neutral gauge boson to be discovered by the ATLAS detector using a center of mass energy of 10 TeV/c^2 and an integrated luminosity of 200 pb^{-1}. Next we derive the statistical significance formula in terms of the number of signal and background events and discuss the discovery threshold. From a series of Monte Carlo simulations using MadGraph/Madevent, PYTHIA, and PGS, we were able to determine the number of signal events for a Z' mass in the range 400-1000 GeV/c^2. We then computed the number of background events from a Drell Yan simulation and produced a plot showing the statistical significance for Z' mass in the given range.

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To my family,

without them this would not have been possible.

Acknowledgements

I want to thank my advisor, Jason Nielsen, for his time and tremendous patience to help me understand a subject that fascinates me more than any other.

1 The Standard Model of Particle Physics

1.1 The Leptons

The leptons are a group of elementary particles which is comprised of the electron, muon, tau and the neutrinos. The neutrinos are electrically neutral, while the others have a charge of -1. All leptons interact with the electromagnetic force and the weak nuclear force but do not interact with strong force. Later we will be looking at processes which decay into two muons and look at possible signals which could arise from this mechanism. Table 1.1 shows the leptons and their properties.

Flavor	Mass (GeV/c^2)	Electric Charge
e	.0005511	-1
ν_e	0.13×10^{-9}	0
μ	0.106	-1
ν_μ	$(0.009 - 0.13) \times 10^{-9}$	0
τ	1.777	-1
ν_τ	$(0.04 - 0.14) \times 10^{-9}$	0

Table 1.1: The leptons and their properties.

1.2 The Quarks

The quarks are another group of elementary particles which, unlike the leptons, do interact with the strong nuclear force. There are a total of six quarks which have the names top, bottom, charm, strange, up, and down. These are the particles that bind together to form particles called

Flavor	Mass (GeV/c^2)	Electric Charge
u	.002	2/3
d	.005	-1/3
c	1.3	2/3
s	.01	-1/3
t	173	2/3
b	4.2	-1/3

Table 1.2: The quarks and their properties.

hadrons. The proton is an example of a hardron which is comprised of a down quark and two up quarks. The Large Hadron Collider (LHC) in Geneva, Switzerland will be colliding high energy protons together and essentially looking at the results of the colliding quarks inside. Table 1.2 shows the six quarks and their properties.

1.3 The Gauge Bosons and the Z^0

The last group of fundamental particles are called the gauge bosons. These are responsible for mediating the force between the particles experiencing the interaction. Therefore, each fundamental interaction has its own gauge bosons. The most familiar boson is the photon, which is responsible for mediating the electromagnetic force. For the weak interaction, there are the massive $W^{\pm}$ and Z^0 bosons, while the strong force has the massless gluon.

The Z^0 boson has a mass of 91.188 GeV/c^2 and a mean lifetime of the order 10^{-25} seconds. The total decay width of the Z^0 is related to the mean lifetime by the equation $\Gamma_{tot} = \frac{\hbar}{\tau}$ where τ is the mean life time of the particle.

Because the Z^0 has such a short lifetime, it is difficult to detect directly, and it is easier to look for the decayed particles. In the case where the Z^0 decays to two leptons, it is best to look at muons specifically since the momentum of the electron is affected more by the radiation given off when it is traveling through a magnetic field. Once the momentum and energy from the muons have been measured in a detector, one can reconstruct the mass of the Z^0 by the invariant mass formula

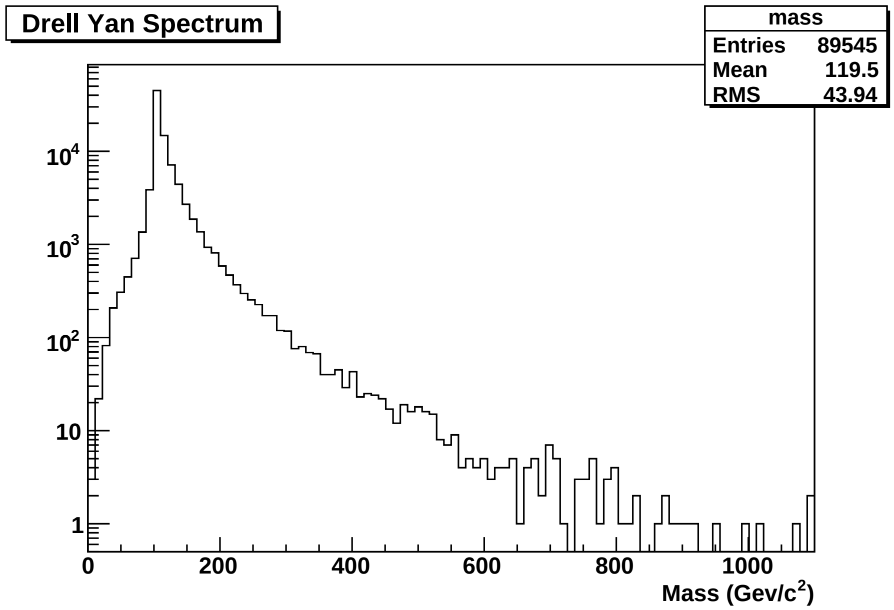

Figure 1.1: A simulation using MadGraph, PYTHIA, and PGS of the Drell-Yan background from muons for mass values of 0 to 1 TeV/c^2

$$M_Z^2 = m_{\mu^+}^2 + m_{\mu^-}^2 + 2E_{\mu^+}E_{\mu^-} - 2\mathbf{p}_{\mu^+} \cdot \mathbf{p}_{\mu^-} \tag{1.1}$$

1.4 The Drell Yan Spectrum

With a large enough number of measurements, one can use equation 1.1 to create a histogram of the possible mass values. Figure 1.1 shows a histogram of generated muon events for a reconstructed mass of 0 to 1 TeV. There is clearly a peak centered just around the 100 GeV point. This peak, or resonant signal, corresponds to the production of a Z^0 with a mass of 91.188 GeV/c^2.

The is called the Drell-Yan spectrum because the muons were produced by what is called the Drell-Yan process, $q\bar{q} \to Z \to \mu\bar{\mu}$. Here, q is a quark from one of the protons and it annaliates with its antiparticle, $\bar{q}$, from the oncoming proton and produces a Z which then decays into two muons.

1.5 A New Neutral Gauge Boson

One of the exciting aspects of the LHC will be its ability to investigate energy levels which have not been reached before. Due to the lack of experimental data in these energy regions, there are a wide range of theoretical models predicting physics above the 1 TeV scale.

It turns out that many models predict the existence of a new heavy neutral gauge boson within the range of detection by the LHC [7]. This particle, called a Z', is similar to the Z^0 execpt with a much higher mass. Later we will be looking at the possibility of detecting a Z' at the LHC by the means of the Drell-Yan process. Identification of a Z' is important since it could be one of the first clues to new physics.

1.6 Theories Predicting a Z′

The Z' gauge boson appears in many models including certain string theories and other grand unified theories. There are Kaluza-Klein models involving a fifth dimension of spacetime that predict a Z', as well as certain Higgs models. For this paper, we will not look at one specific model but rather a generalization of the Z' parameters.

1.7 Previous Experiments Looking for a Z′

Most of the current search for a Z' has been at the Collider Detector II at Fermilab's Tevatron (CDF II). While using $p\bar{p}$ collisons at a center of mass energy $\sqrt{s} = 1.96$ TeV and looking at the dimuon invariant mass spectrum, CDF II was able to exclude the mass of the Z' from the interval of 100 GeV to 982 GeV with a 95% confidence level (CL) [1].

The D0 collaboration at the Tevatron has also done seaches for a Z'. By using an integrated luminosity of 250 pb^{-}, they were able to set a lower limit on the Z' mass at 680 GeV/c^2 with a 95% CL [2]. For our purposes, we will look at the possibility of a Z' having a mass between 400 and 1000 GeV/c^2 and look at the statistical significance behind a Drell Yan background.

2 The ATLAS Experiment

The A Toroidal LHC Apparatus (ATLAS) experiment is one of the major particle detectors at the LHC. It will provide one of the best opportunities to discover a Z'.

2.1 Measured Quantities

It is important to understand the specific quantities that are measured in a particle detector in order to effectively reconstruct mass values. In a detector, the coordinates are set up such that the beam runs along the z-direction and the x-y plane, or transverse plane, lies perpendicular to the beam line. For the LHC, the positive x direction is towards the center of the LHC ring, and the positive y direction is defined to be upwards.

One important parameter which ATLAS will be measuring is the tranverse momentum p_T of an incoming particle. This is done by observing the trajectory of the particle as it travels through the strong magnetic field inside the detector. An electrically charged particle will curve as travels through this magnetic field. The direction of curvature will give information about the identification of the particle. Since high momentum particles will curve less through a magnetic field, the extent to which a particle path deviates from a straight line will tell us p_T.

Also defined are the azimuthal angle ϕ which is measured around the beam line and the polar angle θ which is the angle from the beam line. The polar angle is used to define a quantity called the pseudorapidity and can be calculated by the equation η = -ln[tan(θ/2)].

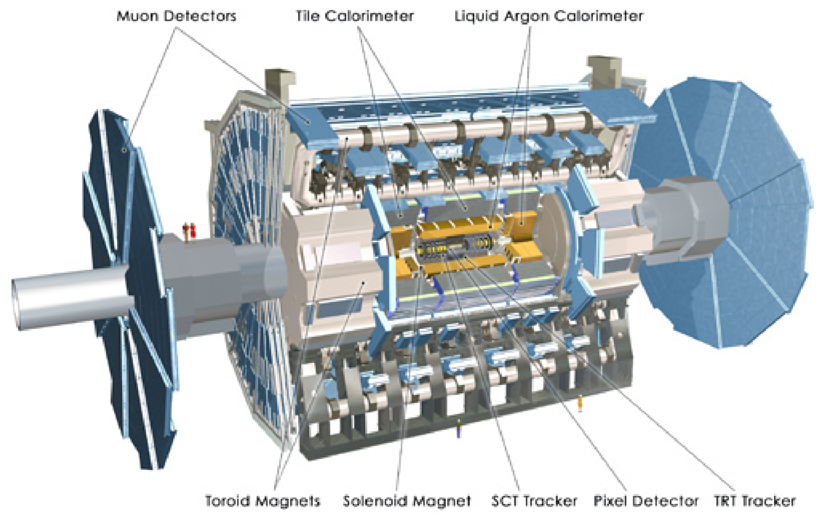

Figure 2.1: A figure of the ATLAS experiment and its major components.

2.2 Major Components

The component of the ATLAS detector which is nearest to the beam line is called the inner detector and is responsible for measuring charged particles produced near the beam line. It will be immersed in a magnetic field of 2 T, which is produced by a solenoidal magnet between the inner detector and the calorimeter. By measuring the the particle at discrete points, it will be able to reconstruct the trajectory of the particle.

Radially outward from the solenoidal magnets are the two calorimeters. The first is the electromagnetic calorimeter which absorbs particles that interact with the electromagnetic force to measure their energy. Lead plates will be used to absorb charged particles and photons, and electrodes will be placed between each plate to take measurements.

The other calorimeter is the hadron calorimeter and it measures energy from particles which pass through the electromagnetic calorimeter but interact with the strong nuclear force. It will use steel plates to absorb the particles along with scintillating tiles to measure the associated energy.

Most importantly, for this paper at least, is the muon spectrometer (MS) which is the outermost component of the detector. It encircles the barrel of the detector and covers both of the endcaps. The main function of the MS is to measure high momentum muons traveling from the center of the detector. This is done by using thousands of Monitored Drift Tubes (MDT) which track the position of the muon to a high degree of accuracy. Figure 2.1 shows the major components of ATLAS including the MS on the outermost layer of the detector.

Each of the MDT are filled with an Ar/CO_2 gas and a central tungsten-rhenium anode wire with a diameter of 50 μm, which will sit at a potential of 3080 V between the tube [3]. High momentum muons will pass through the entire detector before reaching the aluminum MDT where they will ionize the Ar/CO_2 and send a signal to the central anode wire. This will result in a momentum resolution of 10% at about $p_T = 1$ TeV [3].

As mentioned earlier, reconstructing the mass of a Z′ requires accurate measurments of the muon's momentum. With accurate measurements from the the MS, it should be possible that the ATLAS experiment will be able to discover a Z′ from the Drell- Yan process around 1 TeV.

3 Statistics

3.1 Statistical Significance

When there appears to be a resonant signal over some background, there has to be a way of determining statistically that the signal is produced by a new particle and is not just part of the background. For our purposes, it would be best to be able to determine the significance in terms of the number of signal and background events, then all we would have to do is count the events for each and find the significance. To do this, we start with the equation for Poisson distribution

$$f(k;\lambda) = \frac{\lambda^k e^{-\lambda}}{k!} \tag{3.1}$$

where k is the number of observed events, and λ is the expected number of events for the specific interval.

Next, we take expression 3.1 and write it so that the expected events is due to both the signal and background, $\lambda = s + b$. Then we divide this by the same equation but with background expected events, $\lambda = b$, and take the natural log. So what we are left with is the log likelihood ratio (LLR) that we have signal and background events over just the background. Then the equation has the form

$$LLR = \ln \frac{(s+b)^k e^{-s}}{b^k} \tag{3.2}$$

Then by some simplifications and setting the number of events on average to be $k = s + b$, we find that expression 3.2 takes the form

$$LLR = (s + b) \ln(1 + \frac{s}{b}) - s \tag{3.3}$$

For a signal-like sample in which s > b, the LLR is positive and gets larger for s >> b.

Now the significance is determined by how far the events are from the mean. If the majority of the events are within five standard deviations from the mean, then we can unequivocally say that the signal is not caused by random chance. We can then convert this to a significance by using a χ^2 distribution and using $\frac{1}{2}$ unit of log-likelihood is equivalent to one unit of $\Delta\chi^2$. We then find that

$$S = \sqrt{2[(s + b) ln(1 + \frac{s}{b}) - s]} \tag{3.4}$$

where S is the significance level. For a discovery threshold, we require that this corresponds to a value of S$\geq$5.

4 Analysis

4.1 Simulations

Using the programs Madgraph/Madevent, PYTHIA, ROOT, and Pretty Good Simulations (PGS) [4] [5] [6] [8], we created a series of Z' signals with masses from 400 GeV/c^2 to 1 TeV/c^2 using 1000 events and $\frac{\Gamma_{Z'}}{M_{Z'}} = 0.01$, where $\Gamma_{Z'}$ is the associated width [7]. We then used equation 1.1 by making the approximation $E_\mu \approx P_\mu$. Figure 4.1 shows our reconstruction for a Z$'$ mass of 600 GeV/c^2 without any background events. This allowed us to compare the signal generated events with the background from figure 1.1.

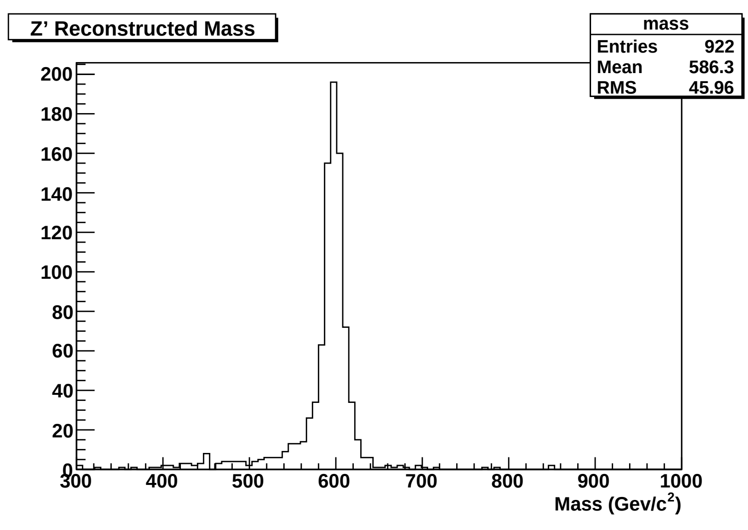

Figure 4.1: Reconstructed Z$'$ mass of 600 GeV/c^2.

Mass of Z′ (GeV/c^2)	σ (pb)	N$_{exp}$
400	17.3274705	3466
500	8.4321639	1687
600	4.60077692	921
700	2.70143526	541
800	1.6794563	336
900	1.07748438	216
1000	0.710724287	143

Table 4.1: The calculated cross sections and expected number of events for a luminosity of 200 pb^{-1}.

4.2 Luminosity

For each generated signal, PYTHIA calculated the cross section for each process. This is important because it allows us to scale our generated events to what an actual signal would look like given a specified luminosity.

The luminosity is a measure of the number of particles per unit area in an accelerator. For the LHC, which will initially be running at 10 TeV, the integrated luminosity int the first year will be 200 pb^{-1}. Therefore, the number of expected events, N_{exp} can be determined by the formula

$$N_{exp} = \sigma \mathcal{L} \tag{4.1}$$

where σ is the cross section and $\mathcal{L}$ is the time-integrated luminosity. Table 4.2 shows a summary of our calculated cross sections and expected events.

4.3 Significance Calculations

By scaling each signal histogram and the Drell-Yan background by N$_{exp}$/N$_{gen}$, where N$_{gen}$ is the number of events generated, we were able to calculate the number of signal and background events to plug into equation 3.4. This was done by integrating the histogram in the region where the signal was present, which turned out to be about $\pm 10 GeV/c^2$ from the mean of the signal. Figure 4.2 shows a plot of our final results of the significance calculations. We also included a plot of the cross section for each process according to PYTHIA.

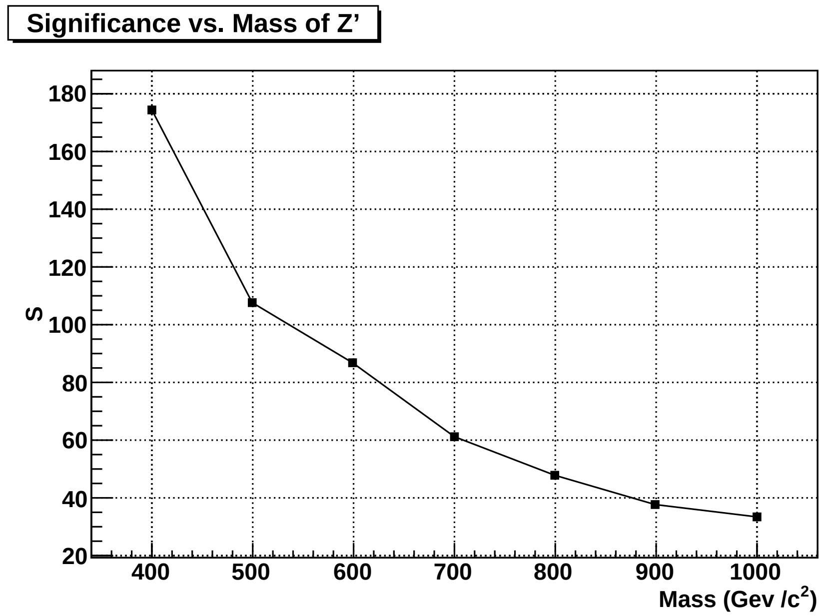

Figure 4.2: Our final results of the significance calculated for each mass value.

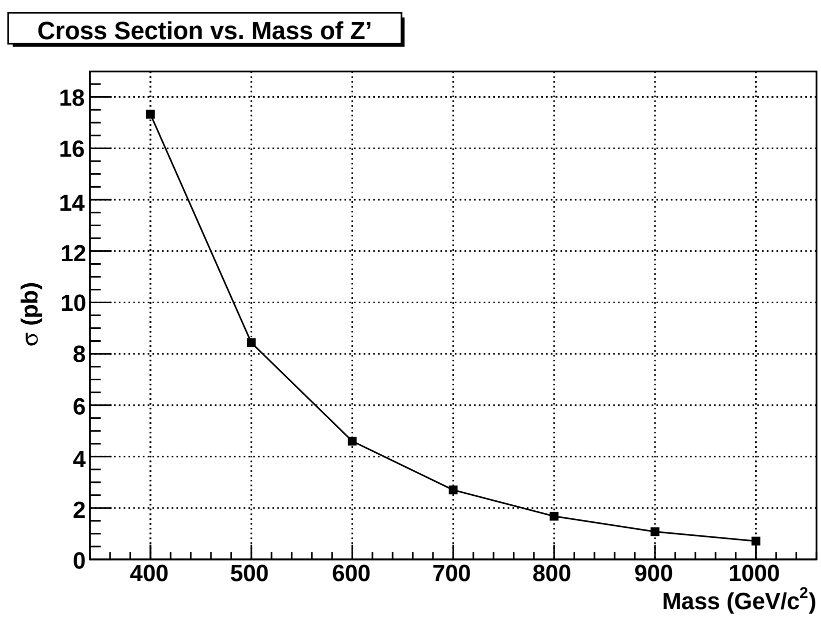

Figure 4.3: Plot of the cross sections as calculated by PYTHIA

5 Conclusion

Using simulations generated by MadGraph/Madevent and PYTHIA, we were able to calculate the number of signal and background events for a $Z^{'}$ with the constraints $\frac{\Gamma_{Z'}}{M_{Z'}} = 0.01$. With this we were then able to calculate the statistical significance and plot it with respect to $M_{Z'}$. We were able to show that for a Z' produced at the ATLAS detector, the statistical significance from 400 GeV/c^2 to 1 TeV/c^2 is well above the discovery threshold of S = 5.

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