The Search for the W’ and Right-Handed Neutrino

Guy Grubbs
St. Mary’s University,

Nevis Labs
Columbia University
Mentor: Thomas Gadfort

August 10, 2009

Abstract

In this experiment, a search was conducted for the W’ and right-handed neutrino in the W’→llqq channel. A program was created in order to read data, make cuts, and look for interesting data points. After this program was created, signals of different W’ and right-handed neutrino masses were input along with data and cuts were made. In the end, the experiment was able to conclude with a 95% confidence level that a W’ particle does not exist for right-handed neutrino masses of 100 and 300GeV. More signals of different W’ and right-handed neutrino masses should be tested in order to set limits on their existence in this channel.
Contents

1 Introduction .............................................. 2
  1.1 Tevatron ............................................... 2
  1.2 D0 Detector ........................................... 3
    1.2.1 Tracking System .................................. 3
    1.2.2 Calorimeters ..................................... 3
    1.2.3 Muon System ...................................... 4
    1.2.4 Trigger System .................................... 5
  1.3 Particle Detection .................................... 5

2 Motivation for Search ............................... 6
  2.1 Standard Model (SM) ................................. 6
  2.2 Beyond the Standard Model ......................... 6
  2.3 Proposed W' Decay Channel ......................... 6
  2.4 Possible Background Sources ....................... 7

3 Process Used in Search .............................. 7
  3.1 Using Root to Program Data Analysis ............... 7
  3.2 Measurement Explanation .......................... 7
  3.3 Validating Monte Carlo Signals .................... 8
  3.4 Preselection Cuts .................................. 9
  3.5 Looking for Patterns ............................... 9
  3.6 Making Tighter Cuts ............................... 10

4 Results .................................................. 11
  4.1 Collie ............................................... 17
  4.2 Setting Limits ...................................... 17
  4.3 Conclusions ........................................ 17
  4.4 Future Work ........................................ 17

5 Acknowledgments ....................................... 17
1 Introduction

During this experiment, a search was conducted for the $W'$ through a unique channel involving a right-handed neutrino. In this channel, the $W'$ would decay into a lepton and a right-handed neutrino, which would decay into a $W$ and another lepton. The $W$ would then decay into two quarks, causing two jets in the detector. The end results of this decay would be two leptons and two jets, and these products were searched for in the analysis of data from the Tevatron in Fermilab.

1.1 Tevatron

The Tevatron is a high-energy cyclotron, also known as a circular particle accelerator, which collides protons and anti-protons at approximately 1.96 TeV in the center of mass frame. This accelerator is located at Fermi National Accelerator Laboratory in Illinois. The layout and landscape of the Tevatron can be seen in Figure 1.

Currently, the Tevatron is the highest energy particle collider and has already made many discoveries contributing to quantum field theory including the top quark various baryons that were previously undiscovered. The two collaborations that discovered these various particles are the Collider Detector at Fermilab (CDF) and the D0 experiment (D0). The data that was concentrated on for this experiment came from D0.

The Tevatron has run for two periods of time called Run I and Run II. Run I had a center of mass energy of 1.8 TeV, and ran between 1992 and 1996. During this run, the top quark was discovered and approximately $120 \text{ pb}^{-1}$. After five years of down time, repairs, and upgrades, Run II began on March 1st, 2001. Run II has been running almost continuously since that time, and has almost collected $5.3 \text{ fb}^{-1}$ worth of data at present with a new center of mass energy of 1.96 TeV. Many collaborations are looking through this data for new particles or decays that may affect the Standard Model (SM) as it is known today.

Figure 1: The Tevatron Collider
1.2 D0 Detector

The D0 detector provides data for a collaboration of many scientists located throughout the world, and it is named for its location in the Tevatron, called D0. The D0 Detector is approximately thirty feet tall and fifty feet long, and is constructed from four major components which sound the beam crossing.[2]

1.2.1 Tracking System

The tracking system in D0 consists of a Silicon Microstrip Tracker (SMT) surrounded by a Central Fiber Tracker (CFT). The SMT system can be seen in Figure 2. The SMT consists of many silicon wafers in constructed in a disc surrounding the beam pipe. These discs are stacked along the beam line surrounding the collision point. The CFT is composed of scintillating fiber layered parallel to the beam line and connected to many Visible Light Photon Counter (VLPC) photodetectors. The tracking system uses ionization of silicon and scintillation of the CFT in order to precisely determine the location of a particle and its momentum. The momentum is calculated easily because the tracking system lies in a solenoid that creates a 2T magnetic field parallel to the beam-line. Using very basic physics concepts, the transverse momentum of the particle, $P_t$, can be extrapolated from the curvature of the particle path.[1]

![Figure 2: The Silicon Microstrip Tracking System](image)

1.2.2 Calorimeters

The calorimeter system lies outside of the 2T magnetic field, and consists of alternating layers of uranium and liquid argon. In order to keep the argon in its liquid state, the calorimeter must be kept at approximately 78 degrees Kelvin at all times. The particles which enter the calorimeter are very likely to collide with the dense uranium nuclei and cause particle showers which ionize the liquid argon. The ionized liquid argon can then be detected and interpreted. The first four layers are considered the electromagnetic calorimeter and are fine so that readings can be taken more precisely for the lighter charged particles and photons. The rest of the calorimeter consists of fine and coarse hadronic layers. The coarse layers differ from the rest of the calorimeter because they are layered with steel to stop hadrons in order to save money. The layers of the calorimeter can be seen in Figure 3.[1]
1.2.3 Muon System

The muon system is the outermost layer of the D0 Detector. It consists of proportional drift tubes (PDTs) which are tubes filled with a ionizing mixture of gas and wire which can detect the charge and deliver a signal if the gas is ionized. The PDTs are located in 1.66T magnetic field created by toroidal magnet, which is placed between the first and second layers of the muon system. The system is also covered with many scintillating fibers which can either help in calculating the $P_t$ of the incoming muon or detect cosmic muons so that their hits can be thrown out instead of detected as data. This part of the detector is the heaviest part, and can be seen in Figure 4.[1]
1.2.4 Trigger System

The beams cross paths in D0 once every 396ns, and there may or may not be a collision when these beams cross. Even if there is a collision, the data from the collision may be uninteresting and unnecessary. For this reason, a three level triggering system has been introduced to the detector in order to throw out any data that is not useful and only record interesting events. The first level of this triggering system is purely hardware, and checks for any interesting hits in certain areas of the detector. The second level is a global processor which correlates data from different parts of the detector and passes the event onto the third level if certain criteria are met. The third level is purely software, and a processor farm reconstructs the event from the readings to check what likely happened and record the event if it was interesting. This three level triggering system can be viewed in Figure 5.[1]

Figure 5: The Trigger System

1.3 Particle Detection

Once all of these parts of the detector are combined and particles are collided, it is easier to see how certain particles are identified. The identifications are seen in Figure 6, although this isn’t the whole story. There are many particles that decay too quickly and must be reconstructed from their products in order to find out if they were created in the collision.

Figure 6: Detecting Different Particles
2 Motivation for Search

2.1 Standard Model (SM)

The SM predicts electric, weak, and strong interactions very well. It cannot, however, account for why there is more matter in the universe than antimatter. It also didn’t predict that neutrinos have mass. There was no reason that there should be three generations of fermions, according to SM. For this reason, it’s possible that there may be extensions to the standard model which have not been discovered as of yet.

2.2 Beyond the Standard Model

In many of the proposed extensions to the standard model, there exists a $W'$ particle which would help restore symmetry to the SM. As seen in Figure 7, right-handed particles spin in the direction of their momentum, while left-handed particles do the opposite. The $W$ can only interact with particles left-handedly, so the $W'$ would only interact with particles right-handedly. Other than this characteristic, the $W'$ would act in much the same way as the $W$, and interact weakly with a positive or negative charge.

![Figure 7: Right-Handed Particle on Left, Left-Handed Particle on Right](image)

2.3 Proposed $W'$ Decay Channel

As shown in Figure 8, this experiment has chosen to look for the $W'$ in a channel where it decays into a lepton and a right-handed neutrino. The right-handed neutrino is proposed to decay into a $W$ and another lepton. If the $W'$ exists and this were one of its decay channels, it would be observed as two leptons and two jets inside the detector.

![Figure 8: Feynman Diagram of $W'$ Decay](image)
2.4 Possible Background Sources

In looking for this decay, there are many other background sources which also have two jets and two leptons as their products. As seen in Figure 9, two major sources of background are Z plus jets and multijet events (also known as QCD). A Z can decay into a lepton and an antilepton, and if two jets are also present in the event it will look just like the decay products of the proposed W'. The QCD background can have multiple jets, including some jets which are mistagged as lepton events. If two jets and two mistagged lepton events are present, this will also look like the W' products. In searching for W' events, these backgrounds will need to be cut.

3 Process Used in Search

3.1 Using Root to Program Data Analysis

The beginning of this experiment began with using ROOT to create a program which could analyze and display signals, background, and data. This program would also need to be able to reconstruct the W' and right-handed neutrino masses in order to look for data that could be classified as a W' decay. Capability of making cuts would also be necessary, and this program was eventually coded after many weeks of debugging and testing.

3.2 Measurement Explanation

In this data analysis, there were many important variables that needed defined. Missing $E_T$, as shown in Figure 10a, can come from neutrinos which escape the detector unnoticed in a collision, or from mismeasured particle masses and energies. The W had to be reconstructed from the jets in the event, and was easy if there were two jets as shown in Figure 10b. If there was one jet, as shown in Figure 10c, then the W could only be reconstructed using the value of the one jet. This was possible if the W had a high momentum and decayed into two jets which moved very quickly together.

It was also necessary to create new variables for this search in order to make better cuts. For example, in Figure 10d the angle between the lepton coming from the W' decay and the W was measured and called $\cos (l_{W'} - WdPhi)$. The angle between the lepton from the right-handed neutrino and the W was also measured, and called $\cos (l_N - WdPhi)$. This variable can be seen in Figure 10e. The measurements and calculations for...
this search were all conducted in the transverse plane to the beam line, as the conservation of momentum and energy laws would apply and all particle vectors summed together should equal 0.

Figure 10: Assorted variables used in making cuts, and their sources.

3.3 Validating Monte Carlo Signals

After creating the program to process the signals, data, and background, it was important to check if the Monte Carlo (MC) signals for different predicted $W'$ and right-handed neutrino masses were correct. The MC signals were generated using the idea that the decay existed and the cross section could be given by quantum field theory calculations. The signals were of the form $xxx_xxx$, where the first number was the assumed $W'$ mass and the second number was the assumed right-handed neutrino mass. A quick check could be made to see if the products in the signal all summed to the $W'$ mass from which they came from. The signals were first normalized to 1 so that they would all be on the same scale, even though they had different cross sections. As shown in Figure 11a, many of the signals summed to the correct $W'$ Mass. The only exception was the $800,100$ signal, and this was likely due to the fact that there was only one jet used to calculate the $W$ mass. The number of jets for each signal can be seen in Figure 11b.
3.4 Preselection Cuts

Before analysis of the signals, data, and background began it was necessary to make a few cuts to get rid of a considerable amount of the background. All events required at least one jet, and both leptons had a $P_T$ greater than 20GeV. The missing $E_T$ had to be below 50GeV. The reconstructed Z mass, which was the vector sum of the two leptons, had to be above 170GeV. The reconstructed Z $P_T$, also calculated from the vector sum of the leptons, had to be above 75GeV. The reconstructed W $P_T$ in an event had to exceed 50GeV.

3.5 Looking for Patterns

A search for patterns in the way the neutrino could be reconstructed was conducted, and it was found that for low neutrino mass signals, the lepton with the smallest angle from the reconstructed W was more likely to have come from the neutrino. This idea was visible in Figure 12a. The opposite was found to be true when the neutrino had a high mass, as seen in Figure 12b. For this reason, cuts were made both ways on the data and background so that a low or high mass right-handed neutrino could be searched for at the same time.
3.6 Making Tighter Cuts

After correctly matching each lepton with its origin, cuts could be made on the $P_T$ of the corresponding leptons in order to get rid of as much background as possible. Cuts could also be made on the angle between a lepton and the reconstructed W as needed. In order to make cuts that kept as much signal as possible while getting rid of as much background as possible, the integral of the signal was compared to the integral of the background. The equation $$\sqrt{\frac{\text{Signal Yield}}{\text{Signal Yield} + \text{Background Yield}}}$$ was used in each bin, and the yield was obtained by taking the integral to the right or to the left depending on where the most background existed. After the equation was applied at each bin, the value calculated was put into the corresponding bin in a new graph with the same binning. The peak of the optimization graphs would be the optimal cut to keep as much signal as possible. This idea can be seen applied to the angles graphed in Figure 13a and Figure 13b. The corresponding optimization graphs are Figure 13c and Figure 13d, respectively. From these graphs, we can see that a cut on $L_{WP} - WdPhi$ below 2.7 rad and $L_N - WdPhi$ above 1.3 rad would be optimal. This method could be applied to each signal one at a time to optimize cuts after preselection was done.
After the optimization cuts were made to each of the signals, final plots were made of signal versus background and data. Since the search was for the W' and right-handed neutrinos, the plot of their masses were an appropriate area to look for interesting points. The plots for the 200;100 signal can be viewed in Figure 14. This signal was very hard to look for after the basic cuts were made, because the basic cuts eliminated almost all of the points. The 400;100, 400;300, 800;100, and 800;700 signals can be found in Figures 15, 16, 17, and 18, respectively. The cuts made for each signal can also be found below their final plots, in Tables 1, 2, 3, 4, and 5.

4 Results

Figure 13: Optimization of cuts made to the different signals.
Figure 14: Final product of cuts made on the 200,100 signal.

Table 1: Cut off points for 200,100 signal

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low $L_{WP} - W_{p}dPhi$</td>
<td>2.5</td>
</tr>
<tr>
<td>High $L_{N} - W_{p}dPhi$</td>
<td>1.9</td>
</tr>
<tr>
<td>High $L_{N}$ $P_t$</td>
<td>70</td>
</tr>
<tr>
<td>Low $L_{WP}$ $P_t$</td>
<td>100</td>
</tr>
<tr>
<td>High $L_{WP}$ $P_t$</td>
<td>160</td>
</tr>
<tr>
<td>Smaller Angle Chosen</td>
<td>true</td>
</tr>
</tbody>
</table>
Figure 15: Final product of cuts made on the 400,100 signal.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low</strong> $L_{Wp} - WpdPhi$</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>High</strong> $L_N - WpdPhi$</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Smaller Angle Chosen</strong></td>
<td>true</td>
</tr>
</tbody>
</table>

Table 2: Cut off points for 400,100 signal
Figure 16: Final product of cuts made on the 400,300 signal.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $L_{Wp} - WpdPhi$</td>
<td>2</td>
</tr>
<tr>
<td>Low $L_N - WpdPhi$</td>
<td>2</td>
</tr>
<tr>
<td>Low $L_N P_t$</td>
<td>100</td>
</tr>
<tr>
<td>Smaller Angle Chosen</td>
<td>false</td>
</tr>
</tbody>
</table>

Table 3: Cut off points for 400,300 signal
Figure 17: Final product of cuts made on the 800,100 signal.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{WP} - \tilde{W} p d \Phi)</td>
<td>2.2</td>
</tr>
<tr>
<td>(L_N - \tilde{W} p d \Phi)</td>
<td>.9</td>
</tr>
<tr>
<td>(L_N P_t)</td>
<td>75</td>
</tr>
<tr>
<td>(L_{WP} P_t)</td>
<td>250</td>
</tr>
<tr>
<td>Smaller Angle Chosen</td>
<td>true</td>
</tr>
</tbody>
</table>

Table 4: Cut off points for 800,100 signal

(a) 800,100 Neutrino Mass

(b) 800,100 \(W'\) Mass
Figure 18: Final product of cuts made on the 800,700 signal.

Table 5: Cut off points for 800,700 signal

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $L_{WP} - W_{pdPhi}$</td>
<td>2.5</td>
</tr>
<tr>
<td>Low $L_N - W_{pdPhi}$</td>
<td>2.4</td>
</tr>
<tr>
<td>Low $L_N$ $P_t$</td>
<td>180</td>
</tr>
<tr>
<td>Low $L_{WP}$ $P_t$</td>
<td>60</td>
</tr>
<tr>
<td>High $L_{WP}$ $P_t$</td>
<td>110</td>
</tr>
<tr>
<td>Smaller Angle Chosen</td>
<td>false</td>
</tr>
</tbody>
</table>
4.1 Collie

The final plots provided a lot of evidence that there were no events where a W’ or right-handed neutrino was produced. In order to make conclusions, it was necessary to use Collie (Confidence Level Limit Evaluator). This program, when provided with .root files containing graphs of signal versus background and data, would calculate if the proposed signal occurred within the data with a 95% confidence level.

4.2 Setting Limits

The different final plots were converted to .root files and the scaling factor for each signal was calculated. This scaling factor, if below one, would provide evidence that the proposed signal did not exist with a 95% confidence level. The different scaling factors given by Collie can be found in Table 6

<table>
<thead>
<tr>
<th>W’ Mass (GeV)</th>
<th>Neutrino Mass (GeV)</th>
<th>Expected Scaling Factor</th>
<th>Observed Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>700</td>
<td>1.54</td>
<td>1.54</td>
</tr>
<tr>
<td>800</td>
<td>100</td>
<td>4.98</td>
<td>4.01</td>
</tr>
<tr>
<td>400</td>
<td>300</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>400</td>
<td>100</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>200</td>
<td>100</td>
<td>1.01</td>
<td>1.24</td>
</tr>
</tbody>
</table>

Table 6: Collie Scaling Factor Output for Assorted Signals

4.3 Conclusions

From this experiment, it can be concluded with 95% confidence that a 400GeV W’ does not exist at a neutrino mass of 300 and 100GeV. There was also no interesting points for any other signal, but there was too low of a cross section and too little signal yield after cuts for the other signals to be completely sure that the decay cannot occur.

4.4 Future Work

Because the data analysis code has already been written and debugged, it will be very easy to run the analysis and cuts over other signals involving different W’ and right-handed neutrino masses. If enough of these signals are analyzed at different masses and the results entered into Collie, it will be possible to eliminate or find the W’ and right-handed neutrino in this channel.

5 Acknowledgments

I would like to thank Nevis Labs for the opportunity to work in this field and learn more about experimental particle physics. I would also like to thank Thomas Gadfort, my mentor, for helping me throughout the internship when I had trouble debugging my program or when I needed clarification on my work. I would like to thank Gustaaf Brooijmans as well for generating the Monte Carlo signals I used during my analysis.

References
