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Abstract
Vectorlike leptons are a simple extension of the standard model, akin to a fourth family of leptons. This paper describes aspects of the preparation for a search for VLLs at an ATLAS particle collider. During this research, signal and control regions were determined with use of a Monte Carlo simulation in order to best estimate where to measure different kinds of background and where to search for a potential signal. These signal and control regions were optimized with respect to MET, LT, and number of light and heavy leptons with a goal of a 95\% confidence limit.

Keywords
vectorlike leptons, high energy particle physics, cern

SEARCHING FOR DOUBLET VECTORLIKE LEPTONS USING THE ATLAS PARTICLE DETECTOR

A PREPRINT

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ABSTRACT

Vectorlike leptons are a simple extension of the standard model, akin to a fourth family of leptons. This paper describes aspects of the preparation for a search for VLLs at an ATLAS particle collider. During this research, signal and control regions were determined with use of a Monte Carlo simulation in order to best estimate where to measure different kinds of background and where to search for a potential signal. These signal and control regions were optimized with respect to E_T^{miss}, L_T, and number of light and heavy leptons with a goal of a 95% confidence limit.

1 Introduction

The standard model (SM) is the most universally agreed upon and used model of fundamental particle physics. With the increased functionality of experimental methods for studying particles and their behaviors, it has become more and more apparent that the standard model is an incomplete model of fundamental particles. There are several observations that remain unexplained by the SM such as the composition and properties of dark matter or the existence of baryon asymmetry. Research beyond the SM combines theoretical and experimental physics to discover new particles that may provide insight into these unexplained observations. These particles are first predicted in theory and then searched for using detectors or particle colliders.

This paper discusses the search for vectorlike leptons (VLLs) occurring at ATLAS (A Toroidal LHC Apparatus). Vectorlike leptons are part of a proposed new class of particles: singlet fermions that couple to SM leptons. Because they appear in a number of theoretical models, models of supersymmetry and extra dimensions, VLLs are a prime candidate for the subject of a large search at ATLAS.

The research presented in this paper uses a SU (2) doublet particle model of VLLs represented by τ'^-, its neutrino ν', and their antiparticles τ'^+ and $\bar{\nu}'$. The τ symbol is used because in this model, the VLL is seen as a kind of "fourth lepton," coupling to third generation leptons or heavy leptons[1] and Z, W, and H bosons. Fig. 1 is a Feynman diagram that shows an example of one possible decay from a doublet VLL. In this example, the τ'^- decays to Z τ (its other option in this specific model is H τ) and $\bar{\nu_\tau}'$ decays to W τ [1].

[1] The convention in high energy particle physics is to describe electrons and muons as light leptons and taus as heavy leptons.

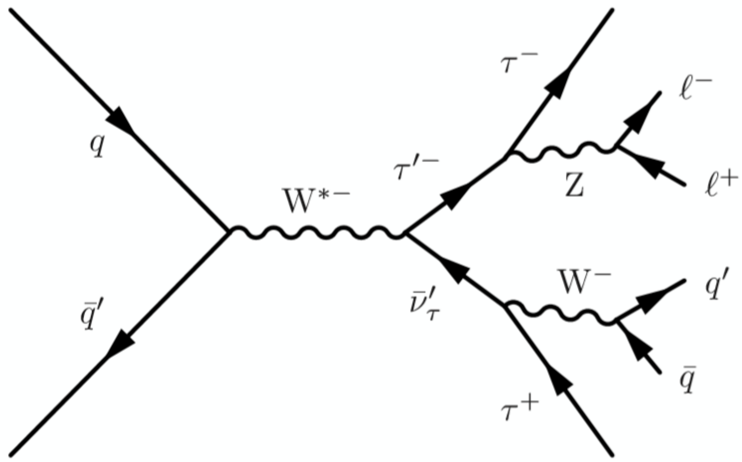

Figure 1: This is a Feynman diagram showing one possible decay path from a double VLL. Note the quark and antiquark interaction that stems from the proton-proton (pp) collision which is used at ATLAS [1].

2 The Detector

The detector at ATLAS is constructed from a series of apparatuses that are tailored to measure the momenta and trajectories of particle products of the pp collision. A solenoid magnet causes charged particles to curve in their path which can be measured by the detector. Then there is an electromagnetic calorimeter, followed by a hadronic calorimeter, and finally a muon spectrometer. Depending on the amount of energy given off by a specific particle at a certain distance from the initial collision, we are able to set parameters that assign labels, such as photon, muon, or electron for example, to different particle signals detected [3]. An example of a few particles moving through the detector is found in Fig. 2.

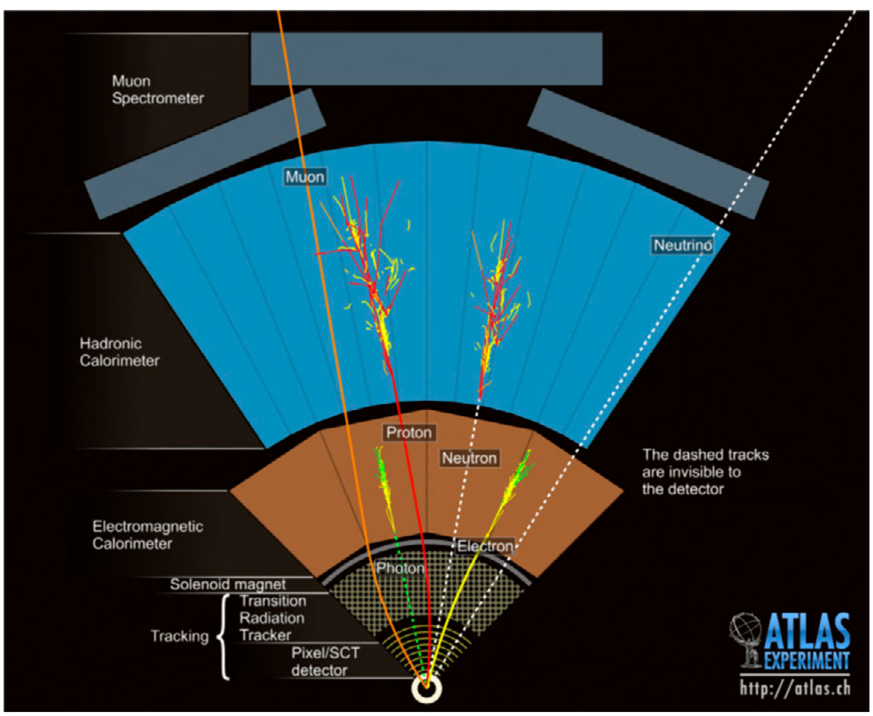

Figure 2: This graphic from the CERN website shows a few examples of particles moving through the detector. Note that the dashed lines indicate particles invisible to the detector, such as neutrinos or, for some time, neutrons [2].

2.1 Coordinates and Measurements

The system of coordinates used to describe measurements made by the detector is most similar to cylindrical coordinates, given that the detector is a solenoid. A pp collision is considered "large" when it has a greater magnitude of momentum in the transverse, or radial, direction. The momentum in the transverse direction is notated as p_T. The sum of lepton p_T is known as L_T. Another parameter used to distinguish and measure particles is pseudorapidity, η, as defined by

$$\eta = -ln(tan\frac{\phi}{2}) \tag{1}$$

where ϕ is the angle around the axis of collision. Because η depends on ϕ, it is used as a measure of the angle from the horizontal collision axis. η is an important variable and constraint on events because it is invariant under a Lorentz boost [1].

3 Making Cuts

It is important to choose the optimal parameters to set signal and control regions. In general, signal regions are categories of events that would be sensitive to a VLL signal. Then, control regions complement these regions by providing examples of categories that are predominantly representative of background signal. Control regions give accurate estimations of the amount of background to expect with either simulated or real data so that we can compare and weight both cases.

Before choosing signal and control regions, I had to choose parameters to define the very regions themselves. To start, the regions are split according to how many light leptons and heavy leptons are found in an event: 2, 3, or 4 `emu` (electrons and muons), and 0, 1, or 2 `ta` (taus). Then, for the regions with just a pair of light leptons, we specify whether the particles have an opposite sign and the same flavor (OSSF) or not (NOOSSF).

Missing Energy in the Transverse Direction Having sorted the categories this way, the next step is to separate categories according to their amount of missing energy in the transverse direction, E_T^{miss}. The standard procedure for this separation is to use three groupings: E_T^{miss} > 150 MeV, 50 MeV < E_T^{miss} < 150 MeV, and E_T^{miss} < 50 MeV. These categories are referred to as `highmet`, `medmet`, and `lowmet`, respectively. Fig. 3 helpfully visualizes why these different categories are necessary - the background obscures the signal for E_T^{miss} < 50 MeV, so those cuts will generally serve as control regions. Likewise, when E_T^{miss} > 150 MeV the signal is stronger than the background so that region will be used for signal regions.

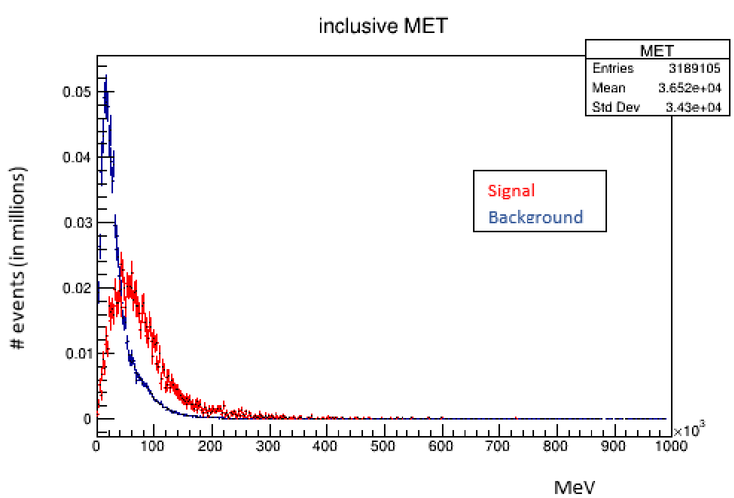

Figure 3: A figure comparing the signal and background signal strength as a function of E_T^{miss}. Note that the strength of the signal (red) is greater than the strength of the background (navy) at around 100-200 MeV.

Sum of Momentum in the Transverse Direction More generally, when the detectors are looking for possible decays of VLLs, there are many particles and thousands of events to sort through. One cut that helps to reduce the number of viable signal events is a cut on the L_T. When L_T is too low then the detected lepton is unlikely to have come from a VLL decay. We make cuts on L_T so that the particles considered for signal regions are viable. Fig. 4 demonstrates that for signal regions, the ideal cut excludes L_T < 150 MeV.

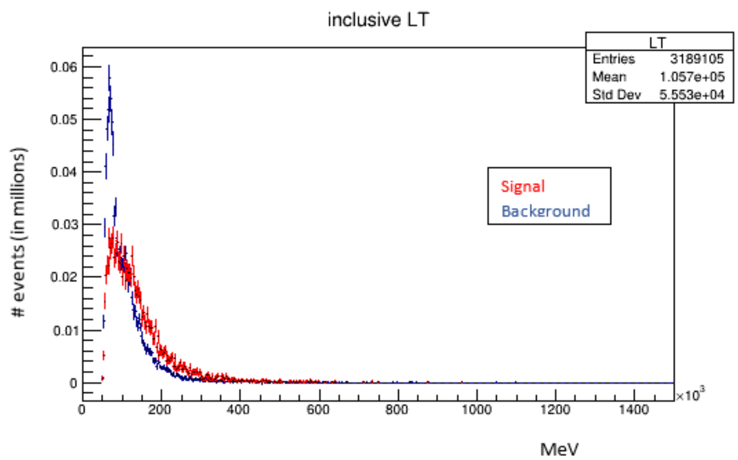

Figure 4: A figure comparing the signal and background signal strength as a function of L_T. Note that the strength of the signal (red) is greater than the strength of the background (navy) at around 150-250 MeV.

Additional Cuts There are kinds of additional cuts that can be made when identifying possible signal events: leading lepton p_T, ΔR, and η. Leading leptons are the lepton candidates that have the greatest p_T. In order to make sure lepton candidates have enough energy to have decayed from a VLL, all lepton candidates must exceed a certain p_T, with an additional minimum p_T for leading leptons [1]. In order to distinguish between particles that are close together, the variable ΔR is used such that

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}. \tag{2}$$

ΔR is thought of as the "distance" between two leptons, $\Delta R_{l,l'}$, or between a lepton and a jet, $\Delta R_{l,j}$. Another essential, standard cut to make is on η so that the lepton candidates had a steep transverse angle, which typically indicates an energetic collision (one more likely to produce VLLs). Keeping these explanations in mind, lepton candidates (e, μ, τ_h) must satisfy:

$$p_T > 15 \text{ GeV for all candidates}, \tag{3a}$$
$$p_T > 28 \text{ GeV for leading leptons}, \tag{3b}$$
$$|\eta| < 2.4, \tag{3c}$$
$$\Delta R_{l,l'} > 0.1, \tag{3d}$$
$$\Delta R_{l,j} > 0.3. \tag{3e}$$

4 Optimization of Regions

It is important to choose the optimal parameters to set signal and control regions. In general, signal regions are categories of events that would be sensitive to a VLL signal. Then, control regions complement these regions by providing examples of categories that are predominantly representative of background signal. Control regions give accurate estimations of the amount of background to expect with either simulated or real data so that we can compare and weight both cases.

Before choosing signal and control regions, I had to choose the categories themselves that would define these regions. To start, the regions are split according to how many light leptons and heavy leptons are found in an event: 2, 3, or 4 `emu` (electrons and muons), and 0, 1, or 2 `ta` (taus). Then, for the regions with just a pair of light leptons, we specify whether the particles have an opposite sign and the same flavor (OSSF) or not (NOOSSF). Once these parameters for

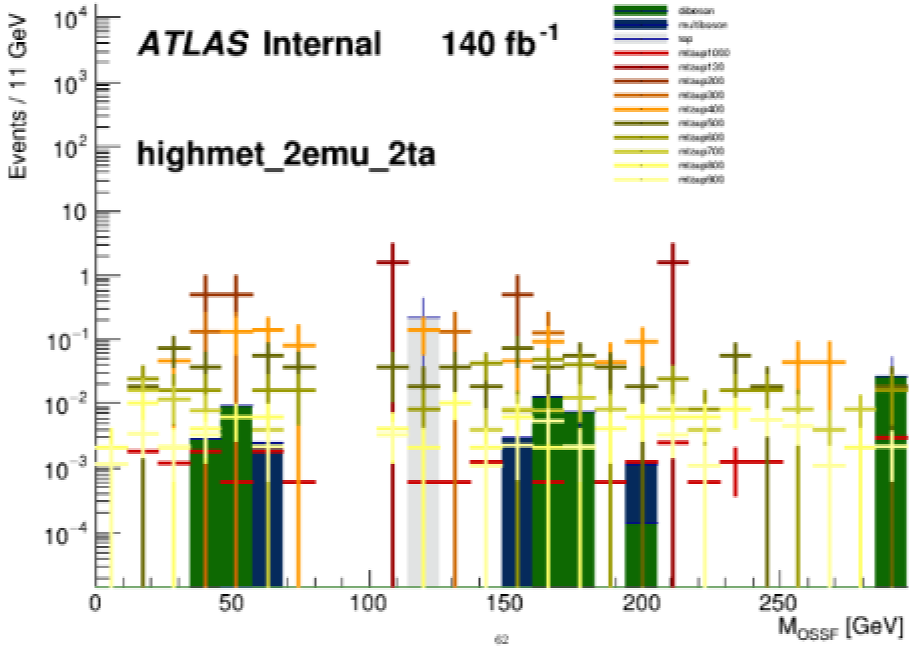

Figure 5: The histogram of simulated data for the signal region at high E_T^{miss} with 2 each of light and heavy leptons. There is very small background in this region which allows for the potential VLL signal to be visible to our detector.

Table 1: The signal regions chosen. Note that they are all in the "highmet" range.

N leptons	E_T^{miss} (GeV)	Name
$2e/\mu$ OSSF, 1τ	>150	highmet_2emuOSSF_1ta
$2e/\mu, 2\tau$	>150	highmet_2emu_2ta
$3e/\mu, 0\tau$	>150	highmet_3emu_0ta
$3e/\mu, 1\tau$	>150	highmet_3emu_1ta
$4e/\mu$	>150	highmet_4emu

the search have been optimized to at least a 95 % confidence limit, it is possible to begin choosing signal regions based on the significance of the signal in each designated region [3].

4.1 Signal Regions

By running over the regions we have created, we are able to measure which regions are best suited to show a VLL signal. The best signal regions have little background, leaving room for a signal to appear at high energies. Fig. 5 is a histogram of the region with high E_T^{miss}, 2 light leptons, and 2 heavy leptons. It is an excellent example of a signal region: there is just small contributions from diboson, multiboson, and top backgrounds but the majority of the signal is visible. Another aspect of the this histogram to note is that the signal visibility varies depending on the possible mass of the actual vector like lepton. The ATLAS detector is sensitive to masses up to about 900 MeV, but in our simulation we still have possibilities for higher masses just to see what the data looks like at the very limit of the accelerator's capacity.

Table 1 shows the 5 regions that were chosen to be signal regions. Notice that they are all at high E_T^{miss}, where the signal is more prevalent (see Fig. 3). The histograms for the other four signal regions can be found in Fig. 6. One might observe that each histogram is cutting all signal, background or otherwise, from the mass region 75-105 MeV. This is the approximate mass of the Z boson ± 15 MeV .

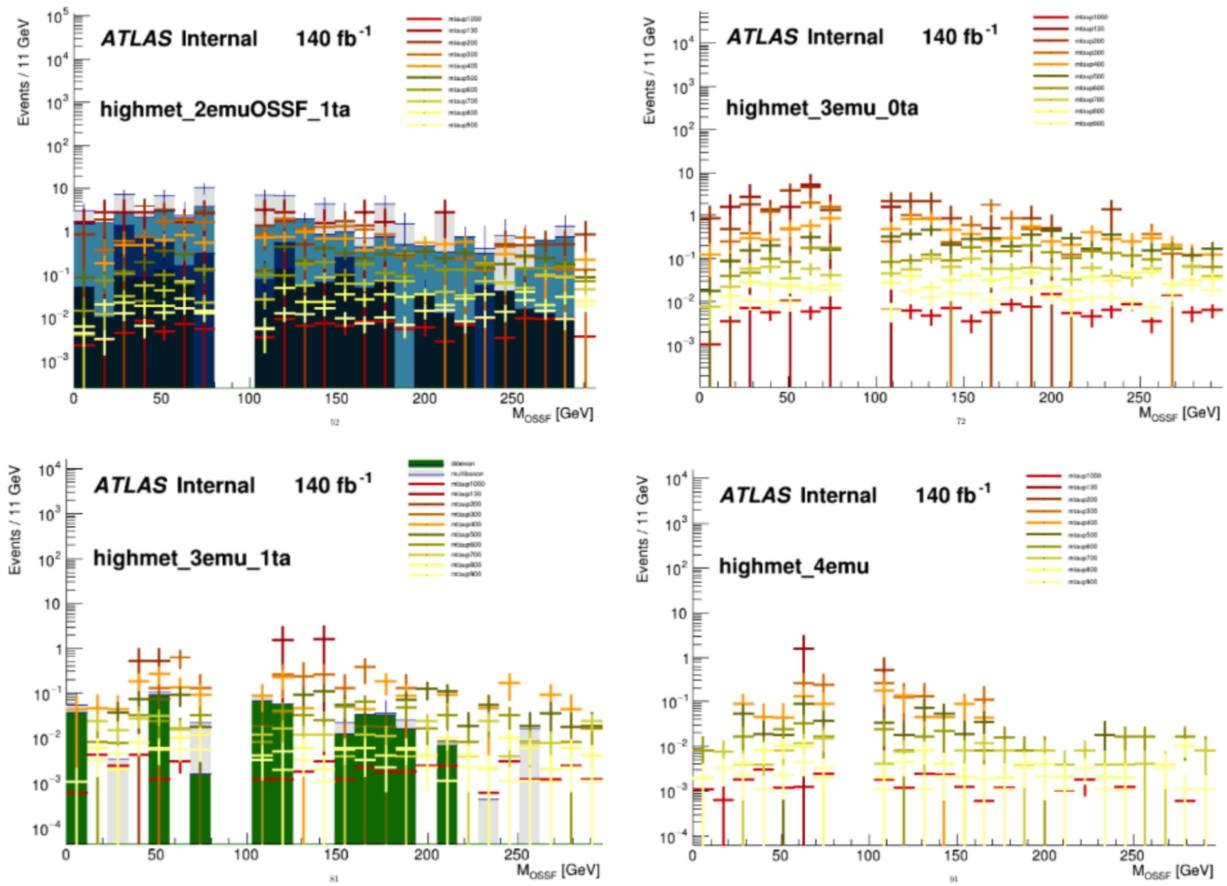

Figure 6: These are the histograms for the four remaining signal regions (with the fifth signal region being shown in Fig. 5). Note that the signal "rising above" the background is the characteristic that makes these regions optimal for viewing VLL signal.

Table 2: The control regions for top and Z-jet backgrounds.

N leptons	E_T^{miss} (GeV)	Name
$2e/\mu$ OSSF, 0τ	50<x<150	medmet_2emuOSSF_0ta for top
$2e/\mu$ OSSF, 0τ	<50	lowmet_2emuOSSF_0ta for z-jet

4.2 Control Regions

With the signal regions chosen, it becomes more clear which backgrounds need control regions. There are five backgrounds that we currently measure from the data: Z-jet, W-jet, top, diboson, and multiboson, but not all of these backgrounds necessarily require an individual control region. There are a few reasons that lead to this conclusion. One is that due to the cuts that we make for all of the regions (described in Eq. 3a-3e), some backgrounds are weak in all the possible regions, meaning it is less important to have an accurate reference for them with which to compare our simulation. Secondly, we prefer to more closely monitor the backgrounds that most prominently appear in the already chosen signal regions.

The number of events with a particular background within a specific region over thousands of runs was compiled into Fig. 7-11. Referring to both these figures and the histograms of chosen signal regions, two backgrounds were significant enough to have a control region: top and Z-jet. Fig. 7 shows that the low E_T^{miss} region with 2 light leptons OSSF and 0 heavy leptons has a high amount of Z-jet background, making it the choice for the z-jet reference region. Fig. 9 shows that the medium E_T^{miss} region with 2 OSSF light leptons and 0 heavy leptons is the best choice for the top control region. These results are also summarized in Table 2.

Z JETS	high MET	medium MET	low MET
2emuNOOSSF_0ta	146.222	2683.5	44518.5
2emuOSSF_0ta	117.43	16757.5	403478
2emuNOOSSF_1ta	4.39926	0	353.127
2emuOSSF_1ta	8.292	204.937	9963.64
2emu_2ta	0	-1.04805	73.8493
3emu_0ta	0	10.13	-48.5216
3emu_1ta	0	0.0794135	22.989
4emu	0	-3.64904	0.0923023

Figure 7: Number of events for Z-jet background in the various regions.

W JETS	high MET	medium MET	low MET
2emuNOOSSF_0ta	58.3845	384.872	1209.14
2emuOSSF_0ta	8.43478	125.018	539.347
2emuNOOSSF_1ta	0.0739937	0	215.49
2emuOSSF_1ta	0.0599846	12.7884	-2.36168
2emu_2ta	0	0	0
3emu_0ta	0	0.0415823	12.9001
3emu_1ta	0	0	0
4emu	0	0	0

Figure 8: Number of events for W-jet background in the various regions.

TOP	high MET	medium MET	low MET
2emuNOOSSF_0ta	4590.06	71635.9	43523.3
2emuOSSF_0ta	2607.58	34876.1	20507.7
2emuNOOSSF_1ta	79.7376	0	548.867
2emuOSSF_1ta	35.1284	669.206	410.858
2emu_2ta	-0.551325	3.29017	-0.799518
3emu_0ta	0	383.664	261.454
3emu_1ta	0.189831	5.53882	0.442716
4emu	0	2.68985	0.17014

Figure 9: Number of events for top background in the various regions.

DIBOSON	high MET	medium MET	low MET
2emuNOOSSF_0ta	817.246	8532.09	9426.92
2emuOSSF_0ta	427.088	3902.98	5583.83
2emuNOOSSF_1ta	21.5281	0	289.637
2emuOSSF_1ta	26.3392	185.342	300.636
2emu_2ta	-0.0612969	2.4567	6.69356
3emu_0ta	0	152.403	258.162
3emu_1ta	0.305229	4.5326	7.26567
4emu	0	0.661643	4.82217

Figure 10: Number of events for diboson background in the various regions.

MULTIBOSON	high MET	medium MET	low MET
2emuNOOSSF_0ta	7.75663	29.9929	14.6389
2emuOSSF_0ta	2.44936	11.7922	5.49061
2emuNOOSSF_1ta	2.0783	0	7.67195
2emuOSSF_1ta	1.20159	5.26173	3.01283
2emu_2ta	0.0387016	0.272301	0.205653
3emu_0ta	0	8.02283	3.90454
3emu_1ta	0.192997	0.433106	0.288168
4emu	0	0.180133	0.0448032

Figure 11: Number of events for multiboson background in the various regions.

The histograms in Fig. 12 best demonstrate visually why the two control regions were chosen for top and Z-jet backgrounds.

5 Conclusion

Current experiments and research teams across the world are working on developing a responsible and accurate simulation of the creation of vectorlike leptons through pp collisions at the ATLAS accelerator. Once these programs are unbiased and can compare expected background results to control region references and magnify specific regions where a VLL signal is likely to be found, the programs can be run with real data from ATLAS. After my work specifying our signal and control regions and optimizing our cuts on lepton candidates, our group has moved forward with the authorization process to use real-world data. We look forward to seeing the results from the data and hope exciting new high energy physics can be done with these extensions to the Standard Model [4].

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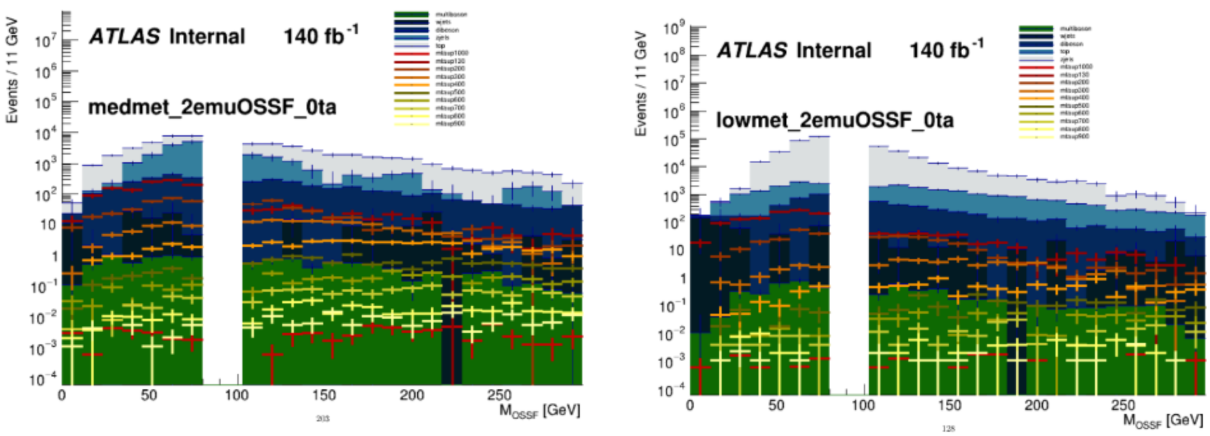

Figure 12: These are the histograms for the two control regions. The medium E_T^{miss} histogram on the left is the control region for Z-jet background (represented by the lightest blue color). The low E_T^{miss} histogram on the right is the control region for top background (represented by the medium blue color second from the "top").