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Phenomenological Study of Heavy Neutrinos at the LHC, through high mass resonances, using the vector boson fusion technique

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Chapter 1

Introduction

The standard model (SM) gathers the entire understanding about fundamental particles and their interactions. Although the model has successfully explained various physical phenomena observed experimentally, there are still multiple unanswered questions concerning particle physics. For example, experiments [1] have shown that accelerator and reactor, solar, and atmospheric neutrinos have mass by proving the existence of neutrino oscillations. The fact that there are neutrino oscillations contradicts the SM, because the neutrinos are massless in the Standard Model. Some specific experiments for each neutrino category are: Super-Kamiokande [2] for solar and atmospheric neutrino oscillations, KamLAND [3] for reactor neutrinos, and K2K [4] for accelerator neutrino oscillations [5]. An additional open question about neutrinos is the fact that only neutrinos with left helicity have been observed. Helicity is defined as the projection of the particle's momentum vector over its spin direction. Only neutrinos with spin anti-parallel to its linear momentum have been observed.

In order to provide neutrinos with mass, several models that extend the predictions of the Standard Model have been proposed. One of the most known model is the "see-saw" or balance mechanism [6]. The see-saw mechanism includes three models that provide mass to neutrinos. For this model, ϕ is the doublet associated with the SM Higgs Boson and L_l the representation of a doublet field associated with the lepton number +1. In the type I see-saw mechanism the product between L_l and ϕ results in a fermionic singlet state. In the type II see-saw mechanism, the product between the two elements forms a scalar triplet. Finally, the product between L_l and ϕ results in a fermionic singlet state. Besides the see-saw mechanism, other models propose the existence of neutrinos with high mass and right helicity. If this kind of neutrinos are observed, the left and right symmetry in the SM would be restored and the mechanism by which the neutrinos acquire mass would be explained.

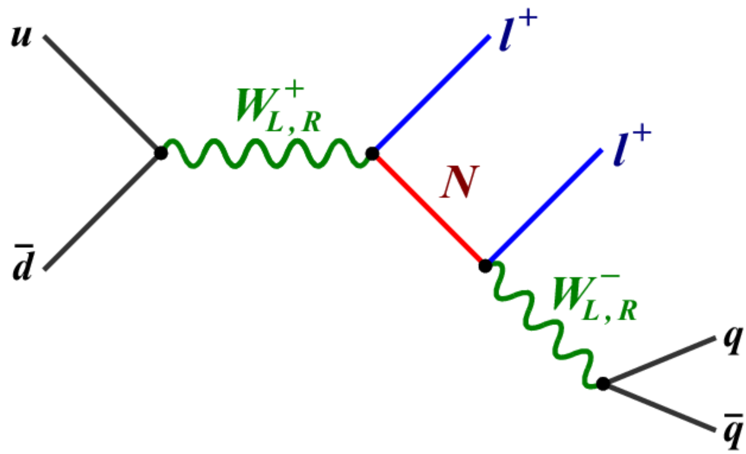

Figure 1.1: Feynman diagram of heavy neutrino production. (Taken from [8])

Heavy neutrinos searches have been conducted in experiments LEP [7], CMS y ATLAS [8], but none of these collaborations has proved that heavy neutrinos exist. In order to understand heavy neutrino searches it is necessary to define the concept of jet. A jet at phenomenological level is defined as a quark or a gluon. In high energies experimental physics, a jet is defined as a collection of particles resulting from the fragmentation of quarks or gluons. Searches at CMS and ATLAS have focused in final states with associated leptons and jets. Figure 1.1 shows a Feynman diagram of the production of a heavy neutrino mediated by a W boson with left or right helicity. The final state for this process has two leptons (μ or τ) and two jets.

The main objective of this monograph is to perform a phenomenological study about the feasibility of conducting an experimental analysis for the detection of heavy neutrinos in the Large Hadron Collider (LHC) using a technique known as vector boson fusion (VBF). The search of new physics using VBF, has been used recently in the LHC [9]. In high energy physics, the bosons $W^{\pm}$, Z^0 and γ are known as vector bosons. The process of vector boson fusion occurs through an electroweak interaction of associated quarks with the LHC proton beams. In the analysis, the production of heavy neutrinos is considered through the decay of a high mass hypothetical resonance known as Z' (shown in the Feynman diagram of Figure 1.2). This high mass resonance comes from the vector boson fusion process.

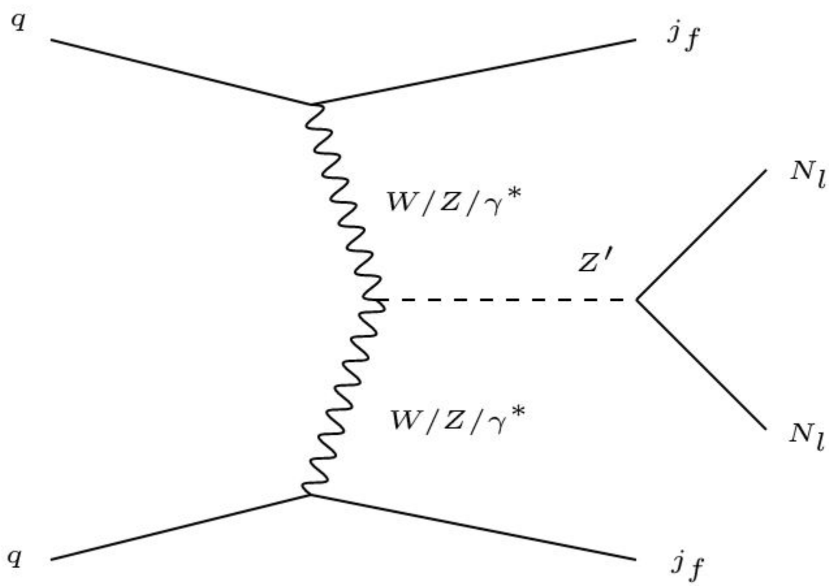

Figure 1.2: Feynman diagram of VBF process.

The production of the heavy neutrino consists in the interaction of two quarks associated to the protons colliding in the beam. The protons emit vector bosons that produce a heavy resonance when they fuse. The heavy resonance decays afterwards producing the heavy neutrinos (N_l): $pp \to jjZ^{'} \to jjN_lN_l$.

The VBF topology consists in requiring two highly energetic jets in the longitundinal region of the detector and in opposite hemispheres thereof. It has been shown that by requiring this type of event, the noise level (background) is reduced considerably in regions of difficult study in searches of new physics.

$$S = \frac{N(s)}{\sqrt{N(s) + N(B)}} \tag{1.1}$$

In order to conduct the analysis, it is important to simulate signal and background processes and to perform a detailed physical study of the variables that allow to distinguish signal for experimental noise. It is necessary to use a cuantitative estimator commonly known as figure of merit to determine optimal cuts in the mentioned variables. The latter with the objective of reducing the amount of experimental noise. Using this procedure the optimal cut in the variables is achieved, always looking to optimize the significance for each relevant variable in the analysis. For this particular analysis, the significance formula that will be used is the one shown in Equation 1, where S is the significance, $N(s)$ is the number of signal events, and $N(B)$ is the number of background events.

Furthermore, it is important to establish the expected experimental sensitivity using maximum likelihood limits or the calculation of the final significance for different hypothetical signal points.

Chapter 2

Objectives

2.1 General Objectives

Conduct a phenomenological study to determine the possible experimental sensitivity of heavy neutrino searches in the LHC, using the VBF topology, in channels with high-mass resonance production.

2.2 Specific Objectives

- Develop the signal events and experimental noise simulations using MadGraph, Pythia, and Delphes software.
- Write an analysis code using ROOT software to analyze the simulated data.
- Conduct a physical study of the appropiate cinematic and topological variables that show strong separation between signal and background.
- Find the optimal cut points of the relevant physical variables using a significance figure.
- Conduct a statical analysis of the results.

Chapter 3

Computational Resources

The project requires computational work, because simulations of events from the different processes are needed. Also, an analysis of the samples using the analysis code is required. The background and signal samples will be simulated using the software MadGraph [10], Pythia [11] and Delphes [12]. The data analysis and all the subsequent cinematic variables and optimal cuts analyses will be performed using ROOT software [13].

Pythia is a software that allows the simulation of various strong processes models that evolve from a few bodies to final states with high particle multiplicity. Particularly, in this case Pythia will be used for the simulation of quark and gluon fragmentation processes. This fragmentation process occurs when, due to and intrinsic characteristic of the strong interaction, there is an energy increase caused by the increase of the distance of two bound quarks. If the separation is enough to reach a critical energy, a pair quark-antiquark is created. The Pythia is simulation is necessary, because processes like the ones mentioned above occur during a proton collision at the LHC.

MadGraph software is an event generator that allows the simulation of collision between two particle beams. For this analysis in particular, the simulations will consist in proton collision at 13 TeV in order to reproduce the actual conditions of the LHC. MadGraph includes the physical parameters that determine the production probability of a given process, as well as the possible decays that the initial simulated particles suffer. Besides providing the necessary matrices to calculate the cross sections of the processes, MadGraph also creates the pictorial representations of the Feynman Diagrams from the generated processes. To this end, the software uses perturbation theory in the calculations of production and generation of physical processes.

Delphes is a software used to add the effects that a multipurpose, like ATLAS or CMS, may have on the particles to the Monte Carlo simulations performed for different processes. In this pareticular case, Delphes is necessary to simulate the interaction of the particles coming from the generated processes in MadGraph and Pythia with the CMS components. Namely, reproducing the conditions of the detector and the uncertainties coming from the measuring process are achieved by using Delphes. The changes in the cinematic variables due to their interaction with matter, errors caused by the electronics of the detector, and the additional particles generated because of the interaction between the particles and the detector components can be accounted for using Delphes. Other functionalities included in Delphes are: simulation of the detector geometry, the effect of the magnetic field over the particles, and the particle identification and reconstruction efficiencies, among others.

ROOT is a software library developed by CERN to perform data analyses related eith particle physics. On the main characteristics of this library is the possibility of handling large volumes of data efficiently. The latter is achieved using a tree structure in which the information related with the particles is stored and can be accessed easily using ROOT functionalities. Other features included in the library are the creation of histograms from data trees, multivariate analysis, four-vector calculations, among others. Using ROOT functionalities, it is also possible to estimate optimal cuts in variables to reduce experimental noise to its minimum. This is why the entire final analysis will involve using tools provided by ROOT.

Chapter 4

Signal Simulation

The MadGraph signal simulation was performed assuming the mass of the heavy neutrino was 1.5 TeV. Also, taking into the account that the analysis was going to be performed using Vector Boson Fusion, the paramater of minimum pseudorapidity (η) separation between two jets for WBF process was set to 3.5.

The commands used to generate the desired signal were the ones shown in Figure 4.1.

- import model SM_HeavyN_NLO
- generate p p > n3 ta+ j j QCD=0, n3 > ta+ j j
- add process p p > n3 ta- j j QCD=0, n3 > ta- j j
- add process p p > n3 ta+ j j QCD=0, n3 > ta- j j
- add process p p > n3 ta- j j QCD=0, n3 > ta- j j

Figure 4.1: MadGraph commands used to generate signal

The first command imports the theoretical model that includes the interactions of the heavy neutrino. The next command specifies the processes that are going to be simulated. pp > n3 ta+ jj stands por the proton-proton collision that decays into a heavy neutrino, a τ with positive charge, and two jets. The flag QCD=0 is used to exclude all strong interactions that can be involved in the process. Finally, n3 > ta+ jj is used to force the decay of the heavy neutrino into a τ charge positively and two jets. The subsequent commands are used to take into account all the possible combinations of the electrical charge that the τ may have.

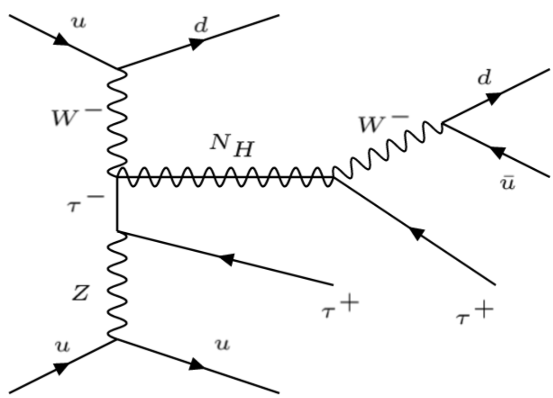

Figure 4.2: Feynman diagram of simulated process involving Z boson

Figures 4.2 and 4.3 show two of the main possible diagrams generated by MadGraph for the processes simulated. This two diagrams present a complete picture involving the processes shown in the diagrams of Figures 1.2 and 1.1. Figure 1.2 shows the diagram of the vector boson fusion process, ocurring in Figures 4.2 and 4.3 in the fusion of the W boson with the Z boson and the photon (γ) respectively. In these last two diagrams, the decay of the of the W boson coincides with the one shown in Figure 1.1 for the decay of the W boson resulting in a heavy neutrino and a lepton, which in this case is a τ.

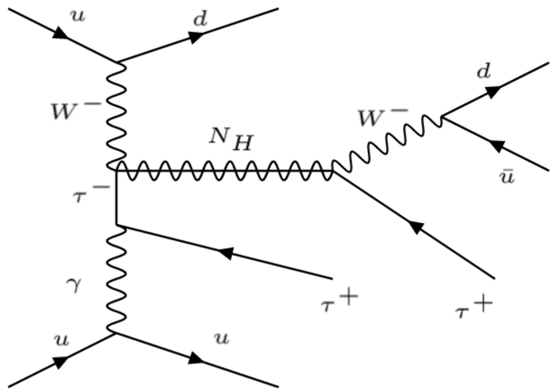

Figure 4.3: Feynman diagram of simulated process involving photon

The simulation was performed in 10 different simulation of batches of 10,000 events each. Each batch was generated with a different random seed to guarantee the independence of the events between each the generated batches. This independance was necessary because the 10,000 event files were merged to form a single file with 100,000 events. As explained earlier, after the events were simulated in MadGraph they were passed to Pythia and then to Delphes so the signal resembled one that could be found at CMS.

Chapter 5

Definitions

5.1 Variable Definitions

The transverse momentum or p_T, is defined as the momentum component that a particle has in the plane perpendicular to the beam line. In the coordinate system of the LHC, this plane corresponds to the $x - y$ plane.

The variable related with the polar angle in the LHC is called pseudorapidity, or η, defined as in Equation 5.1. The use of this variable is justified for mainly two reasons. The first one is that $\Delta\eta$, contrary to $\Delta\theta$, is a Lorentz invariant. This makes $\Delta\eta$ a more natural variable than $\Delta\theta$ for relativistic calculations. The second reason is that the distribution of the values of η in barrel region, where the multiplicity of particle is less than in the end-caps, is wider allowing the η particle distribution to be aproximately constant.

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \tag{5.1}$$

In each event, the two jets that resulted in the greatest mass combination was stored and defined as the Di-Jet Pair. The jet with greater momentum in the Di-Jet Pair is the leading jet and the other one in the pair is the sub-leading jet. Another variable defined regarding the Di-Jet Pair was the Di-Jet mass and corresponds to the sum of the masses from the jets in the Di-Jet Pair.

With the idea of exploiting the possible difference between signal and background in the p_T varibles, two new variables shown in Equations 5.2 and 5.3 were defined to check for possible further separation between signal and background. As shown in equation 5.2, the H_T variable is defined as the scalar sum of the jets with p_T greater than 30 GeV and $|\eta| < 5$ that are not B-jets. S_T is defined as the scalar sum of jets that fullfilll the same conditions of H_T, added to the p_T of the τ's in the event.

Since the τ selection is important for this analysis, it is relevant to provide a further description of the selection criteria for the τ's in the simulated events. For starters, a jet identified as a tau is considered a valid τ if it has minimum a transverse momentum of 10 GeV. Also, it was required that a valid τ should not overlap with an electron or a muon. That is, the ΔR, defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ should not be less than 0.3. This condition guarantees that the jet identified as a τ does not overlap with other leptons. Other condition required for a valid τ is that the jet has a minimum transverse momentum of 20 GeV. Since the final state for this analysis includes two tau's, the two taus with greater p_T are selected among a maximum of three taus stored for each event. The leading τ is the one with highest p_T and the sub-leading τ is the one with second highest p_T.

$$H_T = \sum_{i=1}^{n} p_T(jet_i) \tag{5.2}$$

$$S_T = \sum_{i=1}^{n} p_T(jet_i) + \sum_{j=1}^{m} p_T(\tau_j) \tag{5.3}$$

5.2 Cut Definitions

In order to achieve a separation between background and signal, several successive cuts in variables were made. A total of eight cuts were made to the histograms storing in each cut the resulting distributions to analyze them later. The first four cuts were related with jets and τ's and the subsequent four were related with the VBF topology. In the next paragraphs of this section a description of each one of the cuts is given as well as the order in which they were performed.

The first cuts that were made to the histograms were that the leading and sub-leading τ's should have a minimum transverse momentum of 20 GeV and a maximum of 2.1 for the absolute value of η. The second cut guarantees that the τ's left are detected by the barrel and not the end-caps of the detector. That is and important fact, because the detection components in the barrel section are more accurate than the ones in the end-caps. As a result, a signal detected in the barrel is most certain to be accurate than one detected in an end-cap.

The next cut requires that the event does noot have any B-jet. This cut is justified by the fact that one of the man backgrounds for the signal is the top anti-top ($t\bar{t}$) process.The interaction bewteen the top and anti-top quark results is related with the prodcution with jets associated with the b quark. That is why, much of the $t\bar{t}$ should be eliminated by requiering no B-jets in the event. This fact will be later analized further in chapter 6.

Chapter 6

Distribution Analysis

6.1 Normalized Distributions

As mentioned in section 5, the variables H_T and S_T were defined to achieve a greater separation between background and signal. Figures 6.1 and 6.2 show normalized to the unity plots with no additional cuts in the variables. The plots in both figures show that a separation between signal and background is achieved for values greater than 500 GeV for both H_T and S_T.

The plot shown in Figure 6.3 shows the distribution for the transverse momentum of the main τ. It can be seen that the shape of the signal distribution separates from the backgrounds at around 150 GeV.

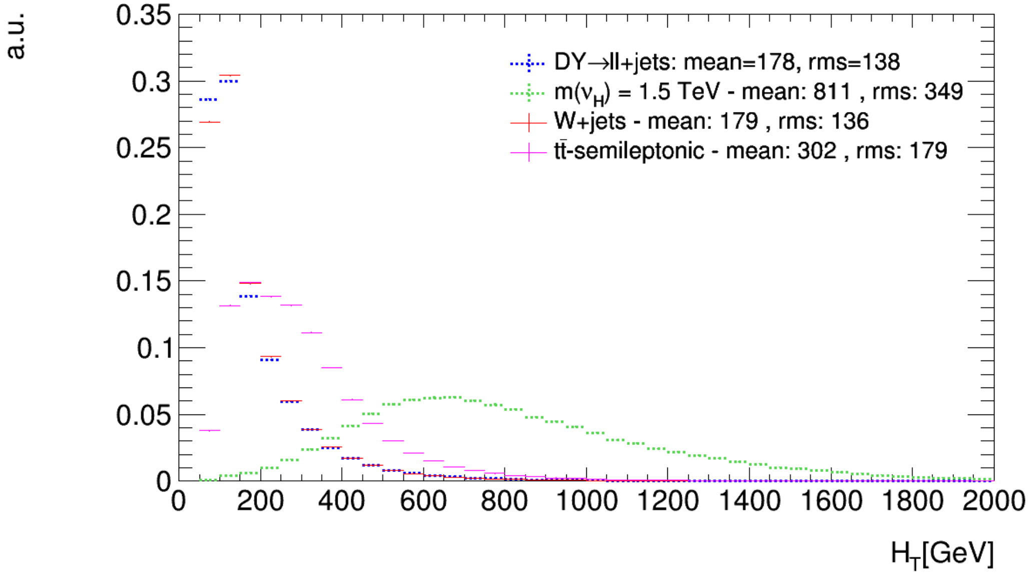

Figure 6.1: Unit plot of H_T with no cuts

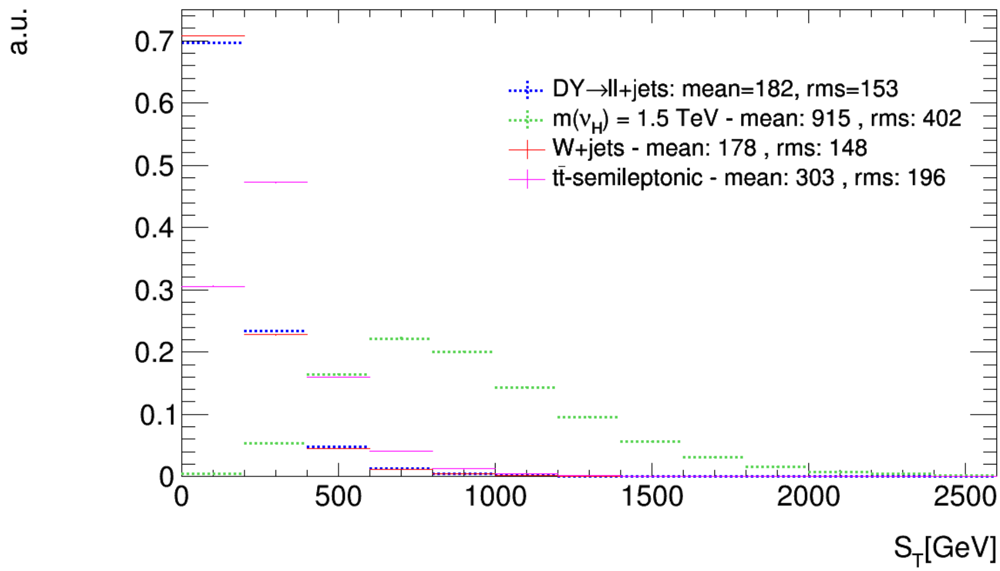

Figure 6.2: Unit plot of S_T with no cuts

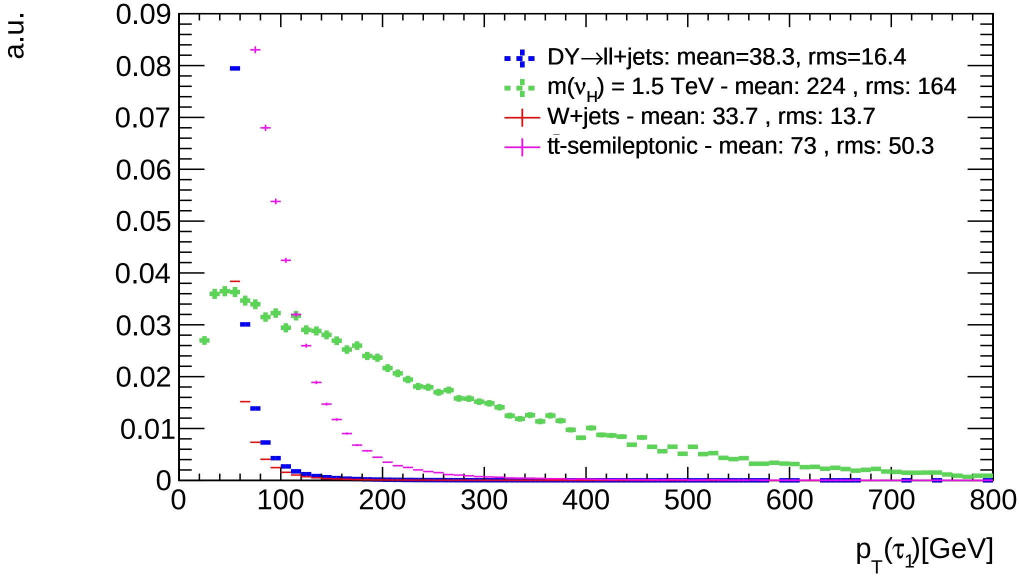

Figure 6.3: Unit plot of p_T from the leading τ with no cuts

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