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Search for Dark Matter
(Test, Times New Roman, Bold)

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Search for Dark Matter (Test)

by

Jack Smith

Submitted to the Department of Physics
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Abstract

A search for heavy resonances decaying to a Higgs boson and a Z boson is presented. The analysis is based on the data collected in 2015 with the CMS detector at a center-of-mass energy $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 2.51 fb^{-1}. The Higgs bosons are reconstructed from high momentum $b\bar{b}$ quark pairs that are detected as a single massive jet, while the Z bosons are reconstructed from electron pairs and muon pairs. The analysis is separated in electron and muon channels, with single and double b-tag categories. A 95% upper limit on the production cross section of $\sigma_X \times \mathcal{B}(X \to ZH)$ is derived from the combination of four categories with a limit of 0.063 pb to 0.265 pb for m_X from 800 to 4000 GeV.

Thesis Supervisor: Jones Davies
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摘要

本篇論文呈現了由新理論模型預測之粒子衰變到一個希格斯粒子和一個 *Z* 玻色子的分析。本分析使用了於 2015 年由大強子對撞機中的緊湊渺子線圈偵測器所記錄之質子-質子對撞總能量為 13 TeV，總亮度為 2.5 fb^{-1} 的數據。高動量的希格斯粒子衰變到一個底夸克和一個反底夸克，在偵測器裡被偵測為一個大質量的噴流。*Z*玻色子有兩個衰變通道，分別為正反電子通道以及正反渺子通道。本分析將分別探討電子通道和渺子通道，各通道將再細分為單底夸克標記和雙底夸克標記此二類別。通過合併電子通道和渺子通道，以及它們所有的底夸克標記類別，結果顯示質量由 800 GeV 至 4000 GeV 的新粒子於 95%信置區間的生產截面上限為 0.063 *pb* 至 0.265 *pb*。

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Chapter 1

Introduction and Theory Overview

1.1 Introduction

This thesis presents the search of a heavy resonance decaying into a Z boson and a Higgs boson at center-of-mass energy of 13 TeV using 2.51 fb^{-1} proton-proton collision data collected with the CMS detector at the LHC. The Z boson further decays into two charged leptons (electrons or muons), while the Higgs boson decays into two b quarks. The Feymann diagram of the signal production is presented in Figure 1.1.

In this search, the high-momentum Higgs boson is reconstructed as a massive jet, and is identified by a b-tagging algorithm. The leptonic decay of Z is considered in order to discriminate against the large multijet background. The heavy resonance signal appears as an excess in the spectrum of the invariant mass of the jet and the two leptons. This analysis is a part of the search for heavy resonances decaying into one vector boson plus one Higgs boson (VH) [1].

The organization of this thesis is described as follows. In the next section, a brief overview of Heavy Vector Triplets Model described by a simplified phenomenological Lagrangian is presented. A specific explicit model is then introduced, which is the benchmark model in this analysis. In Chapter 2, an overview of the LHC and the CMS detector with its sub-detectors are presented. Chapter **??** reports the data sets and Monte Carlo samples used in this analysis. The reconstruction of physics objects and their selections are also described, and the

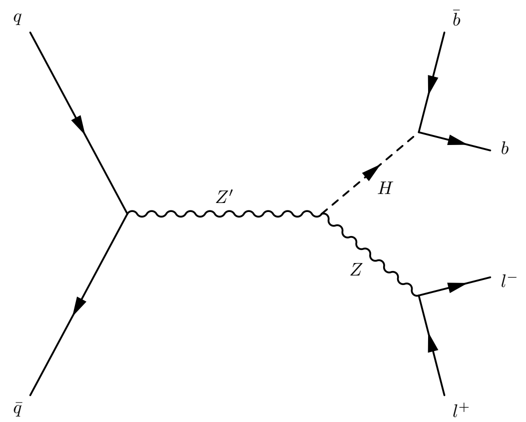

FIGURE 1.1: Feymann diagram of the production of the heavy vector Z', decaying into a Z boson and a Higgs boson. The Z boson further decays into two charged leptons, while the Higgs further decays into two b quarks.

agreement of data sets and Monte Carlo samples are presented. The estimation of backgrounds based on a data driven strategy is presented in Chapter **??**. In Chapter **??**, various systematic uncertainties are described. In Chapter **??**, the results of this analysis are discussed, and a conclusion is summarized.

1.2 Theoretical Motivations

In the Standard Model (SM), the generation of masses for the weak gauge bosons ($W^{\pm}$ and Z) through electroweak symmetry breaking (EWSB) can be explained by the Higgs mechanism [2]. The mechanism was confirmed by the ATLAS and CMS experiments [3–5] at the CERN 50 years after the theory has been proposed.

However, the discovered Higgs boson with mass of 125 GeV is much lighter than the Planck energy, which suggests that the SM may be incomplete. Various theories postulate the existence of new heavy resonances that couple to the SM bosons in an attempt to solve the hierarchy problem or naturalness problem. Some common models include the Little Higgs models [6, 7] and strongly coupled Composite Higgs [8, 9].

Various models can be generalized in the Heavy Vector Triplet (HVT) framework [10], which is a simplified approach based on a phenomenological Lagrangian. In the Simplified Model, only the relevant couplings and mass parameters are retained. The reason for this is that resonant searches are typically not sensitive to all the free parameters of the specific model, but only to those parameters that are related to the resonance mass and the interactions involved in its decay and production.

1.2.1 Heavy Vector Triplet

Consider a heavy vector boson V_μ^a, a = 1,2,3, the simplified Lagrangian is described as

$$\begin{aligned}\mathcal{L}_V =& -\frac{1}{4} D_{[\mu} V_{\nu]}^a D^{[\mu} V^{\nu]a} + \frac{m_V^2}{2} V_\mu^a V^{\mu a} \\ & + i g_V c_H V_\mu^a H^\dagger \tau^a \bar{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a \sum_f \bar{f}_L \gamma^\mu \tau^a f_L \\ & + \text{quadrilinear terms}\end{aligned} \tag{1.1}$$

The first term[1] in Eq. 1.1 describes the interactions of V with the SM weak bosons. The second term in the equation is the interactions of V with itself, where the mass parameter m_V does not coincide with the physical mass of the resonances. The third and fourth terms of the equation contains the interactions of V with the Higgs current[2] and with the SM left-handed fermionic currents[3], respectively. The quadrilinear terms[4] do not contribute directly to V decays and single production processes, therefore these terms can be disregarded.

[1] The term $D_{[\mu} V_{\nu]}^a = D_\mu V_\nu^a - D_\nu V_\mu^a$, where $D_\mu V_\nu^a = \partial_\mu V_\nu^a + g \varepsilon^{abc} W_\mu^b V_\nu^c$.

[2] The Higgs current term $i H^\dagger \tau^a \bar{D}^\mu H = i H^\dagger \tau^a D^\mu H - i D^\mu H^\dagger \tau^a H$.

[3] The fermionic currents $\sum \bar{f}_L \gamma^\mu \tau^a f_L$ involve the interactions of V to leptons, light quarks and the third quarks family.

[4] The quadrilinear terms can be written as

$$\frac{g_V}{2} c_{VVV} \varepsilon_{abc} V_\mu^a V_\nu^b D^{[\mu} V^{\nu]c} + g_V^2 c_{VVHH} V_\mu^a V^{\nu a} H^\dagger H - \frac{g}{2} c_{VVW} \varepsilon_{abc} W^{\mu\nu a} V_\mu^b V_\nu^c.$$

In Eq. 1.1, besides the $SU(2)_L$ coupling constant g, another coupling constant g_V is introduced to represent the strength of V interactions. In addition, the term c_H describes the V interactions with the SM vector bosons and with the Higgs. Similarly, the term c_F describes the V interactions with fermions. They are expected to be of the order of unity in most models.

Masses

After the EWSB, only the photon stays massless due to the unbroken $U(1)_{EM}$, while the weak bosons acquire a mass and a mixing with heavy vector V. The mass matrix of the (Z, V^0) and the $(W^\pm, V^\pm)$ are

$$\mathcal{M}_N^2 = \begin{pmatrix} \hat{m}_Z^2 & c_H \xi \hat{m}_Z \hat{m}_V \\ c_H \xi \hat{m}_Z \hat{m}_V & \hat{m}_V^2 \end{pmatrix} \tag{1.2}$$

and

$$\mathcal{M}_C^2 = \begin{pmatrix} \hat{m}_W^2 & c_H \xi \hat{m}_W \hat{m}_V \\ c_H \xi \hat{m}_W \hat{m}_V & \hat{m}_V^2 \end{pmatrix} \tag{1.3}$$

respectively, where

$$\hat{m}_Z = \frac{e}{2 \sin\theta_W \cos\theta_W} \hat{v}$$

$$\hat{m}_W = \cos\theta_W \hat{m}_Z$$

$$\hat{m}_V^2 = m_V^2 + g_V^2 c_{VVHH} \hat{v}^2$$

$$\xi = \frac{g_V \hat{v}}{2 \hat{m}_V}$$

Note that $e \approx \sqrt{4\pi/137}$, $\hat{v}$ is the Higgs field Vacuum Expectation Value, which has a value of 246 GeV, and θ_W is the weak mixing angle.

By taking the determinant of the mass matrices in Eq. 1.2 and Eq. 1.3, the relation of the physical masses M between charged and neutral heavy vectors are connected by θ_W.

$$m_W^2 M_\pm^2 = \cos^2\theta_W m_Z^2 M_0^2 \tag{1.4}$$

In the experimental searches, the masses of new vectors should be at or above TeV scale, but the masses of SM bosons $m_{W,Z}$ should be preserved at about 100 GeV. A hierarchy in the mass spectrum is required to have

$$\frac{\hat{m}_{W,Z}}{\hat{m}_V} \sim \frac{m_{W,Z}}{M_{\pm,0}} \ll 1 \tag{1.5}$$

Under the limit in Eq. 1.5, by expanding the determinant of the mass matrices in Eq. 1.2 and Eq. 1.3, a simple approximate expressions for m_W and m_Z are given by

$$m_Z^2 \approx \hat{m}_Z^2(1 - c_H^2\xi^2)$$
$$m_W^2 \approx \hat{m}_W^2(1 - c_H^2\xi^2)$$

Since $\hat{m}_W = \cos\theta_W \hat{m}_Z$, the W-Z mass ratio is given by

$$\frac{m_W^2}{m_Z^2} \simeq \cos^2\theta_W \tag{1.6}$$

Experimentally, the value of $\cos^2\theta_W$ is about 0.77. The charged and neutral Vs are degenerated by

$$M_\pm^2 = M_0^2(1 + \mathcal{O}(\%)) \tag{1.7}$$

It is clear that the mass splitting of charged and neutral states of V is small enough to be ignored. This implies that the two states have comparable production rates.

Decay Widths

Given that the mixing angles between weak bosons and V are small due to the hierarchy in the mass spectrum, the couplings of the neutral and charged V to left- and right-handed fermion chiralities can be written as

$$\begin{cases} g_L^N \simeq \frac{g^2}{g_V}\frac{c_F}{2}, & g_R^N \simeq 0 \\ g_L^C \simeq \frac{g^2}{g_V}\frac{c_F}{\sqrt{2}}, & g_R^C = 0 \end{cases} \tag{1.8}$$

The $(g_{L,R}^{W,Z})_{SM}$ in the Eq. 1.8 is the ordinary SM W and Z couplings with a normalization of $g_L^W = g/\sqrt{2}$. The g is electroweak coupling which has a value of 0.65.

The decay width Γ for fermionic channels can be written as

$$\Gamma_{V_\pm \to f\bar{f}'} \simeq 2\Gamma_{V_0 \to f\bar{f}} \simeq N_c[f](\frac{g^2 c_F}{g_V})^2 \frac{M_V}{48\pi} \tag{1.9}$$

where $N_c[f]$ is the number of colors (3 for di-quarks and 1 for di-leptons). The parameters $c_F = c_l, c_q, c_3$ control the relative branching ratios (BR) to leptons, light quarks and the third family quarks.

The decay width for bosonic channels are

$$\Gamma_{V_0 \to W_L^+ W_L^-} \simeq \Gamma_{V_\pm \to W_L^\pm Z_L} \simeq \Gamma_{V_0 \to Z_L h} \simeq \Gamma_{V_\pm \to W_L^\pm h} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi}[1 + \mathcal{O}(\xi^2)] \tag{1.10}$$

The channels that are not reported in the Eq. 1.9 and Eq. 1.10 are either forbidden or suppressed.

Since the M_V is in the order of TeV scale, the ξ should be very small. In this case, for a given resonance mass, the decay widths are fixed by the couplings $g^2 c_F/g_V$ and $g_V c_H$. The BRs and the production rate are controlled by the two parameters $g^2 c_F/g_V$ and $g_V c_H$.

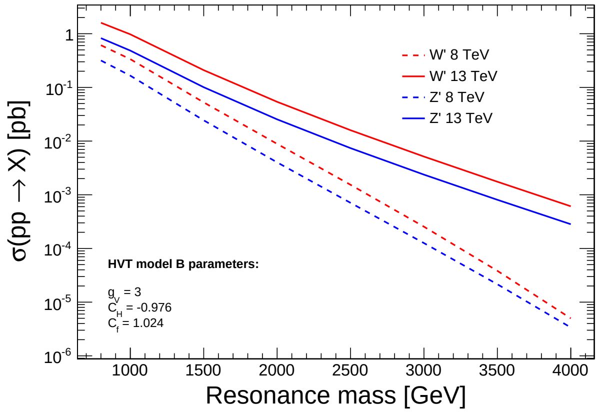

FIGURE 1.2: Theoretical production cross section as a function of resonance mass for HVT Minimal Composite Higgs Model.

1.2.2 Explicit Model

It is now clear that the explicit model can be entirely described in terms of the two couplings $g^2 c_F/g_V$ and $g_V c_H$ and the mass M_V with a good approximation [10].

Consider a strongly coupled scenario, so called Minimal Composite Higgs Model, where the Higgs doublet emerges from the spontaneous symmetry breaking of a global $SO(5)$ symmetry to an $SO(4)$ subgroup. In this scenario, the parameters c_H and c_F are fixed,

$$c_H \sim -1, \quad c_F \sim 1$$

In addition, $g_V \gtrsim 3$ is set to represent the strong coupling. In this case, the dominant BRs are bosonic decays due to $g_V c_H \simeq -g_V$ in Eq. 1.10, while the fermionic decays are extremely suppressed due to $g^2 c_F/g_V \simeq g^2/g_V$ in Eq. 1.9.

The results of this model is particularly interesting for the present search, since it predicts signal cross sections in the order of fb for resonances up to 2∼3 TeV (Figure 1.2), branching ratios to vector bosons close to the unity (Figure 1.3), and thus being accessible at the LHC Run-II.

If the coupling is very large (for example g_V = 8), the total width will be

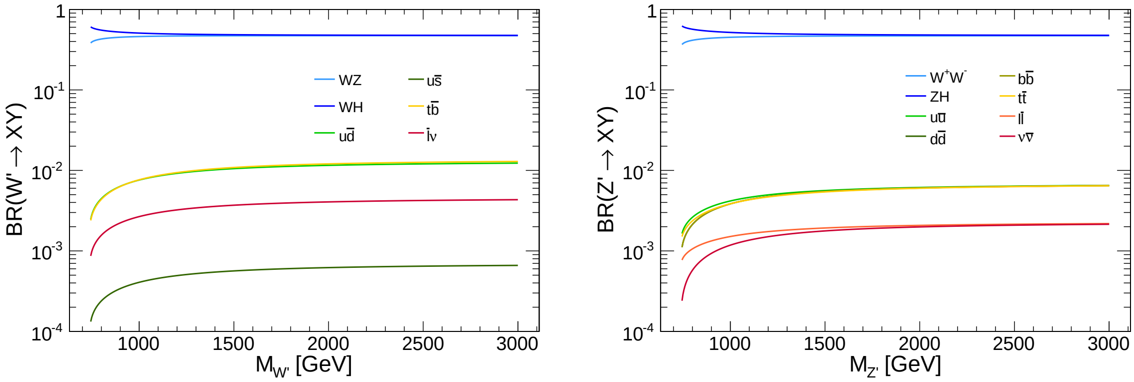

FIGURE 1.3: Branching ratios as a function of the resonance mass for a W′ (left) and Z′ (right) in the HVT Minimal Composite Higgs Model.

increased since the width of decays to dibosons grows with g_V from Eq. 1.10. But a very large coupling leads to an extremely broad resonance, which is not interesting to the experimental searches for a narrow resonance. Therefore, the g_v has been constrained by $g_V \lesssim 4\pi$.

Chapter 2

Analysis Strategy

The purpose of this analysis is to search for a heavy resonance decaying into a Z boson and a Higgs boson. The Z boson is reconstructed from the dielectron or dimuon final state. The $Z \rightarrow l^+l^-$ channel is chosen mainly because it has low QCD and $t\bar{t}$ backgrounds. The Higgs boson is reconstructed via the $b\bar{b}$ channel because the branching ratio of $H \rightarrow b\bar{b}$ is the largest at m_H = 125 GeV. Note that the b quarks are reconstructed as a single jet with large radius in the CMS detector due to the high transverse momentum of Higgs.

In this chapter, the data sets and Monte Carlo (MC) samples used are presented, and the selection criteria of physics objects are introduced. The final selection efficiency is also discussed and reported. The data and MC comparisons of various kinematic variables are presented to show the agreement between them.

2.1 Data Sets and Monte Carlo Samples

2.1.1 Data Sets

In this analysis, the data collected with CMS during 2015 RunD, with integrated luminosity of 2.51 fb^{-1} are used. The muon and electron data sets are collected with a single-muon or a single-electron trigger, which will be explained in detail

TABLE 2.1: Data sets Run2015D used in this analysis.

Samples	**Luminosity** L **[**fb^{-1}**]**
SingleElectron-Run2015D-05Oct2015-v1	0.877
SingleElectron-Run2015D-PromptReco-v4	1.635
SingleMuon-Run2015D-05Oct2015-v1	0.877
SingleMuon-Run2015D-PromptReco-v4	1.635

TABLE 2.2: Filters used in this analysis.

Filters
CSCTightHaloFilter
eeBadScFilter
HBHENoiseFilter
HBHENoiseIsoFilter

in latter section. All data sets used are listed in Table 2.1. Moreover, a list of filters [11] are applied on data in order to remove problematic or noise-dominated events, are reported in Table 2.2.

2.1.2 Monte Carlo Samples

Signal samples

The signal samples are generated with the `MadGraph5` [12] LO generator. The showering and hadronization have been performed with `PYTHIA8` [13]. A full detector simulation and event reconstruction has been performed with `GEANT4` [14] and `CMSSW`. The simulated signal MC samples are listed in Table 2.3. All signal samples belong to the `RunIISpring15MiniAODv2-74X_mcRun2` campaign with the 25 ns asymptotic conditions. Moreover, the samples are produced assuming the narrow-width approximation, with the resonance width set to 1 MeV.

Background samples

All physics processes yielding final states with one or two leptons in association with one or two b quarks are considered as possible sources of background for the analysis. The list of background samples used is reported in Table **??**.

The Z+jets background is produced in several samples binned in H_T (the scalar sum of the p_T of the outgoing partons) starting from 100 GeV with the `MadGraph5` LO generator. The contribution of events with H_T less than 100 GeV is found to be negligible after requiring the Z p_T to be greater than 200 GeV. The inclusive $t\bar{t}$ sample has been produced with `POWHEG` [15] interfaced with `PYTHIA8`, including all the possible decays of the W bosons. For the diboson production processes, the WW, WZ, and ZZ are inclusive processes generated with `PYTHIA8`, while the ZH has decay mode same as the decay mode of signal and is generated with `POWHEG`.

The cross sections listed in the table are used to normalize SM backgrounds. The cross sections of Z+jets samples are computed by `MadGraph5` with an NLO/LO electroweak correction [16] (k-factor) derived from the inclusive Z cross section computed by `FEWZ` [17]. The amount of k-factor as a function of the Z p_T is presented in Figure 2.1. The cross section of $t\bar{t}$ samples are obtained from TTbarNNLO group [18], while the VV samples are computed from `MCFM` [19] calculator.

TABLE 2.3: Signal samples used in this analysis.

Samples	**Number of events**	**Cross section** σ **[**pb**]**
ZprimeToZhToZlephbb_narrow_M-800_13TeV-madgraph-v1	48400	0.0282665
ZprimeToZhToZlephbb_narrow_M-1000_13TeV-madgraph-v1	50000	0.0153743
ZprimeToZhToZlephbb_narrow_M-1200_13TeV-madgraph-v1	50000	0.00790857
ZprimeToZhToZlephbb_narrow_M-1400_13TeV-madgraph-v1	50000	0.00421385
ZprimeToZhToZlephbb_narrow_M-1600_13TeV-madgraph-v1	50000	0.00233319
ZprimeToZhToZlephbb_narrow_M-1800_13TeV-madgraph-v1	50000	0.00133522
ZprimeToZhToZlephbb_narrow_M-2000_13TeV-madgraph-v1	50000	0.000785119
ZprimeToZhToZlephbb_narrow_M-2500_13TeV-madgraph-v1	50000	0.000227178
ZprimeToZhToZlephbb_narrow_M-3000_13TeV-madgraph-v1	50000	0.000071426
ZprimeToZhToZlephbb_narrow_M-3500_13TeV-madgraph-v1	49800	0.0000235715
ZprimeToZhToZlephbb_narrow_M-4000_13TeV-madgraph-v1	49800	0.00000797489

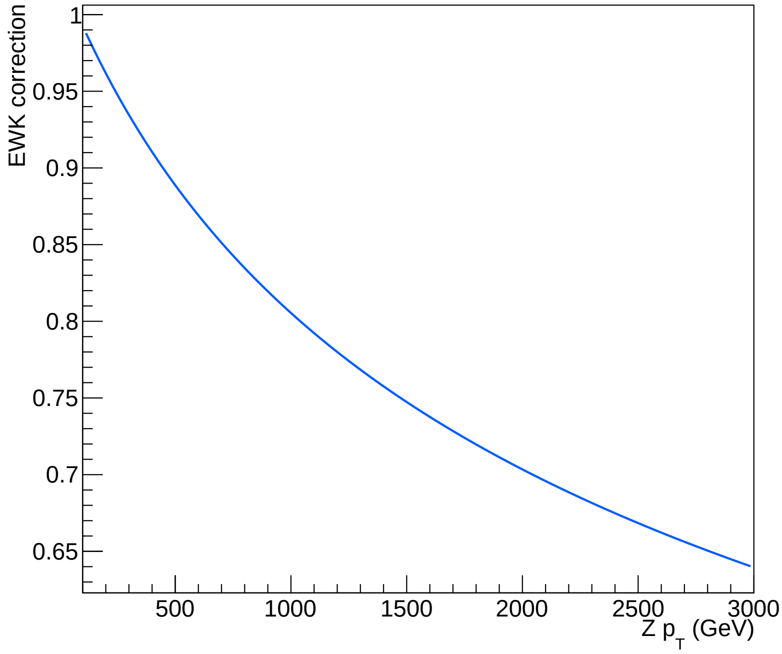

FIGURE 2.1: Electroweak correction for the Z as a function of the transverse momentum.

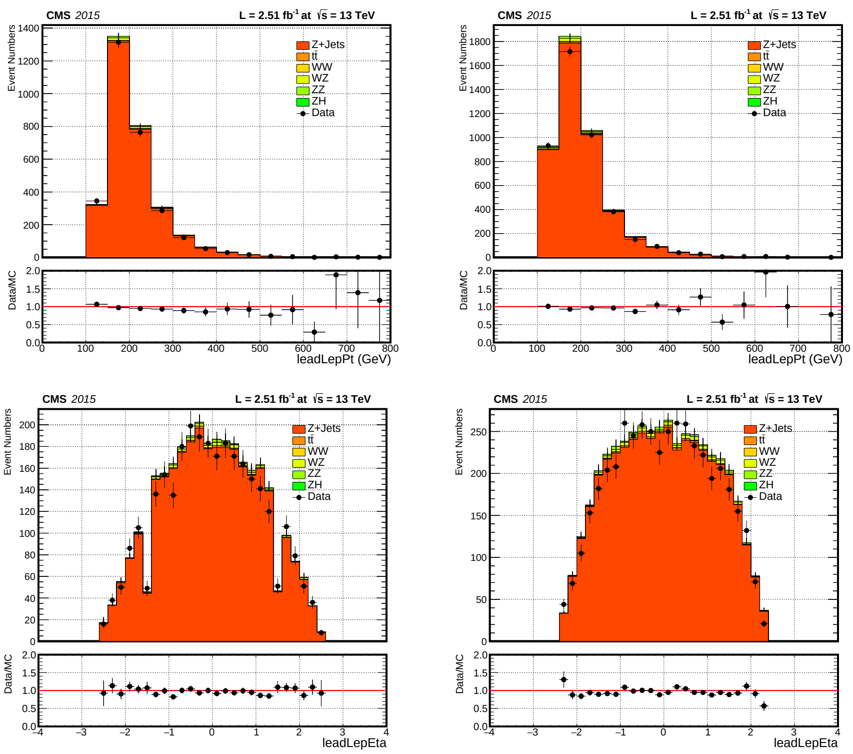

FIGURE 2.2: Distributions of p_T and η variable for the leading leptons of Z candidate in electron channel (left) and in muon channel (right).

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