ABSTRACT

SEARCH FOR CHARGED HIGGS BOSONS IN THE $\tau + \ell$ FINAL STATE WITH 36.1 fb^{-1}OF pp COLLISION DATA AT $\sqrt{s} = 13$ WITH THE ATLAS EXPERIMENT

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This dissertation uses 139 fb^{-1}of ppcollision data collected at a center of mass energy of $\sqrt{s} = 13$ by the ATLAS detector to search for charged Higgs bosons decaying to a tau lepton and a neutrino ($H^{\pm} \to \tau^{\pm}\nu_{\tau}$) in association with a leptonically decaying top quark. No significant excess was found, therefore limits are set at the 95% confidence level on the charged Higgs production cross section times the branching fraction into the $\tau^{\pm}\nu_{\tau}$ranging from XX pb to XX fb. These limits are interpreted in the hMSSM benchmark scenario as an exclusion at 95% confidence on tanas a function of $m_{H^{\pm}}$. In this scenario, for $tan = 60$, the $H^{\pm}$mass range up to $XXXXGeV$ is excluded, with all values of tanexcluded for $m_{H^{\pm}} \leq XXXGeV$

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DEDICATION

To Dr. Dhiman Chakraborty. Thank you for everything.

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CHAPTER 1

INTRODUCTION

CHAPTER 2

THEORY

In this chapter, the theoretical motivation of a search for $H^{\pm} \to \tau^{\pm}\nu_{\tau}$is described. Firstly, a review of the Standard Model of particle physics (SM) is laid out, then a brief overview of Supersymmetry focusing on the Minimal Supersymmetric Standard Model (MSSM). Finally, the Type II 2-Higgs Doublet Model's (2HDM) relation to the $H^{\pm}$production cross section and subsequent branching ratio into SM particles is described as motivation for the choice of studying $H^{\pm} \to \tau^{\pm}\nu_{\tau}$.

2.1 The Standard Model

The Standard Model of particle physics is a quantum field theory that describes all known matter and forces. The Standard Model is built upon a gauge group of type $SU(3)_C \times SU(2)_L \times U(1)_Y$. The $SU(3)_C$ term dictates the strong interaction while the $SU(2)_L \times U(1)_Y$ term describes the electroweak interaction. These interactions occur between fundamental particles called fermions that comprise the known matter of the universe. The interactions, or forces, are mediated by fundamental particles called bosons.

2.1.1 Particles

The particles that make up the Standard Model are separated into two groups according to their intrinsic angular momentum charge, or spin. Fermions are those that carry half-integer spin, and thus obey Fermi-Dirac statistics, while Bosons carry full integer spin values and obey Bose-Einstein statistics.

2.1.1.1 Fermions

The matter we encounter in everyday life is comprised of fermions. Fermions are subdivided into two groups, quarks and leptons. The quarks participate in the strong interaction via their color charge. Quarks cannot exist as a singular particle and thus combine into hadrons in a process called hadronization; the bound states they form are colorless. Leptons carry no color charge and therefore do not participate in strong force interactions. The fermions in the standard model all participate in the electroweak interaction. However, the electromagnetic interaction is limited to those fermions that carry an electromagnetic charge.

Fermions can then be further divided into three generations, each lepton has an electrically neutral weak force partner in the form of a neutrino. Table 2.1 lists all the SM fermions and their properties.

Table 2.1: Standard Model fermions and their properties [1]

	1^{st} Generation	2^{nd} Generation	3^{rd} Generation	Spin	EM Charge	Color	Mass
Quarks	Up (u)	Charm (c)	Top (t)	$\frac{1}{2}$	$+\frac{2}{3}$	✓	$m_u = 2.3^{+0.7}_{-0.5}$ MeV $m_c = 1.275 \pm 0.025$ M $m_t = 173.2 \pm 0.7$ Ge
	Down (d)	Strange (s)	Bottom (b)	$\frac{1}{2}$	$-\frac{1}{3}$	✓	$m_d = 4.8^{+0.5}_{-0.3}$ MeV $m_s = 95 \pm 5$ MeV $m_b = 4.18 \pm 0.03$ Ge
Leptons	Electron (e^-)	Muon (μ^-)	Tau (τ^-)	$\frac{1}{2}$	-1	X	$m_{e^-} = 511$ keV $m_{\mu^-} = 105.7$ MeV $m_{\tau^-} = 1.8$ GeV
	Electron Neutrino (ν_e)	Muon Neutrino (ν_μ)	Tau Neutrino (ν_τ)	$\frac{1}{2}$	0	X	$m_{\nu_e} < 1.1$ eV $m_{\nu_\mu} < 0.19$ MeV $m_{\nu_\tau} < 18.2$ MeV

Check these numbers with current PDG

2.1.1.2 Bosons

Bosons are colloquially referred to as force-carriers in that the fundamental forces act via an exchanging gauge bosons. This means that each force has an associated boson which is described by a field theory. The ElectroWeak quantum field theory (QFT) is more complicated, and is described in detail in section 2.1.2.2. Table 2.2 lists the SM bosons [1], their associated field theory and properties.

Table 2.2: Standard Model bosons and their properties [1]

Field Theory	Boson	Spin	EM Charge	Color	Mass
Quantum Chromodynamics (QCD)	Gluon (g)	1	0	✓	0
Quantum Electrodynamics (QED)	Photon (γ)	1	0	X	$< 1\,\text{x}\,10^{-18}$ eV
ElectroWeak Theory	$W^{\pm}$	1	± 1	X	80.377 ± 0.012 GeV
	Z^0	1	0	X	91.1876 ± 0.0021 GeV

2.1.2 Interactions

At its core, the SM relies upon symmetries. From these symmetries, conservation laws follow. It is these laws of conservation, and the breaking of said symmetries, that dictate the allowed interactions of matter. The first, being a symmetry under charge conjugation, mirror reflection, and time reversal is known as CPT symmetry. The symmetry between charge conjugation and mirror reflection (CP) can be broken in certain circumstances, but holds in strong and electromagnetic interactions. This breaking of CP symmetry occurs in

[1] excluding the Higgs

the weak interaction and implies a non-symmetry between matter and antimatter. Since this symmetry holds for strong and electromagnetic interactions, baryon number ($B = \frac{1}{3}(n_q - n_{\bar{q}})$) and lepton number are conserved in SM interactions. Lepton generation number [2], electric charge, color charge, 4-momentum ($p = (E, \vec{p})$), and angular momentum are all conserved in the SM.

2.1.2.1 Quantum Electrodynamics

The electromagnetic force is governed by the QFT known as Quantum Electrodynamics (QED). This force is mediated by the photon, γ, a massless boson with EM charge 0. The EM force only affects, i.e. the photon only interacts with, charged particles; including all quarks and the e, μ, and τ leptons. Antiparticles are those that carry the opposite EM charge from their normal counterparts and differ in no other way.

2.1.2.2 ElectroWeak Interaction

The weak force is mediated by the $W^{\pm}$ and Z^0 bosons. Due to the relatively large mass of these bosons, the weak force has a very limited range. The W^{pm} affects the third component of isospin (T_3), thus only coupling to so called left-handed fermions. This “handedness”, or chirality, is a property similar to color charge, in that an individual particle can have a number of different values. Table 2.3 contains the allowed values for isospin (T) and hypercharge (Y_W).

The $W^{\pm}$ bosons have a T_3 component of isospin and act as raising or lowering operators on the T_3 component of left handed fermions. The Z does not have a T_3 component, and

[2] Ignoring neutrino oscillations

Table 2.3: Standard Model fermions and their ElectroWeak properties [1]

	1^{st} Generation	2^{nd} Generation	3^{rd} Generation	EM Charge	Y_W		T		T_3	
					LH	RH	LH	RH	LH	RH
Quarks	Up (u)	Charm (c)	Top (t)	$+\frac{2}{3}$	$+\frac{1}{3}$	$+\frac{4}{3}$	$\frac{1}{2}$	0	$\pm\frac{1}{2}$	0
	Down (d)	Strange (s)	Bottom (b)	$-\frac{1}{3}$	$+\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{2}$	0	$\pm\frac{1}{2}$	0
Leptons	Electron (e^-)	Muon (μ^-)	Tau (τ^-)	-1	-1	0	$\frac{1}{2}$	0	$\pm\frac{1}{2}$	0
	Electron Neutrino (ν_e)	Muon Neutrino (ν_μ)	Tau Neutrino (ν_τ)	0	-1	-2	$\frac{1}{2}$	0	$\pm\frac{1}{2}$	0

thus does not act on isospin of fermions. However, the Z boson instead transfers momentum, energy, and spin on all fermions irregardless of their chirality. At energies > 100 GeV the electromagnetic and weak forces combine into the electroweak force. In fact, isospin and hypercharge combine to give electromagnetic charge. $Q_{EM} = T_3 + \frac{1}{2}Y_W$

2.1.2.3 Quantum Chromodynamics

Quantum chromodynamics (QCD) is the QFT that describes the strong force that holds together atomic nuclei and other objects called hadrons. The strong force interacts via the color charge [3] which can have values of either red, green, or blue. Particles that have a color charge cannot exist on their own, they must form colorless bound states called hadrons. Since the strong force grows with distance, if a quark is ejected out from a hadron, the stored energy is such that new particles with color charge will be spontaneously created from the vacuum, binding with the free quark in a process called hadronization. In a particle detector, the hadronization process cascades and creates showers of energy that are reconstructed as so called jets.

[3] This color does is not the visual color we are used to. Merely an convenient analogous naming scheme.

2.1.3 The Higgs Mechanism

The Higgs field was first theorized by Peter Higgs [2], François Englert, and Robert Brout [3] in 1964. The SM itself has four massless Goldstone bosons that do not correspond to the observed bosons. Instead, the Higgs mechanism couples to them via a complex scalar doublet.

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \tag{2.1}$$

The scalar potential that gives rise to this phenomena can be written as

$$V(\phi) = \mu^2|\phi^\dagger\phi| + \lambda(|\phi^\dagger\phi|)^2 \tag{2.2}$$

When $\mu^2 > 0$ and $\lambda > 0$ the minimum of the potential $V(\phi)$ is 0. However, when $\mu^2 < 0$,

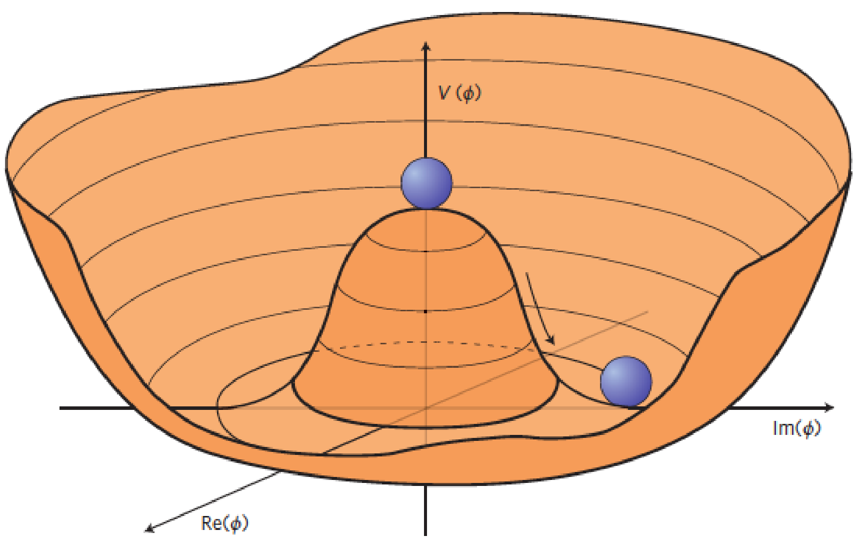

Figure 2.1: The Higgs potential defined in 2.2 with $\mu^2 < 0$ [4]

the scalar potential $V(\phi)$ takes the shape shown in figure 2.1 It follows that the vacuum expectation value (VEV) of ϕ is then

$$\langle\phi\rangle = \sqrt{\frac{-\mu^2}{2\lambda}} = \frac{\nu}{\sqrt{2}} \tag{2.3}$$

From here, convention states that we choose an arbitrary direction of the fluctuation as

$$\phi^0 = \frac{1}{\sqrt{2}}\binom{0}{\nu} \tag{2.4}$$

By choosing these values, $SU(2)$ and $U(1)_Y$ symmetries are broken, the Goldstone bosons are "eaten" and we are left with the remaining degree of freedom being the real scalar field $h(x)$

$$\phi(x) = \phi^0 + h(x) \tag{2.5}$$

Substituting in our definition of ϕ^0, we get

$$\phi = \frac{1}{\sqrt{2}}\binom{0}{\nu + h(x)} \tag{2.6}$$

and our coupling becomes

$$(\frac{1}{2}g\vec{\sigma}\cdot\vec{W} + \frac{1}{2}g'B)\phi^0 \tag{2.7}$$

, where $\vec{\sigma}$ are the Pauli matrices, $\vec{W}$ are $W_{1,2,3}$, g is the weak coupling constant, and $g\prime$ is the hypercharge coupling constant. From this coupling, we get the four eigenstates that correspond to the observed bosons

$$W^{\pm} = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2)$$
$$Z^\mu = \frac{-g\prime B_\mu + gW_\mu^3}{\sqrt{g^2 + g\prime^2}} \tag{2.8}$$
$$A^\mu = \frac{gB_\mu + g\prime W_\mu^3}{\sqrt{g^2 + g\prime^2}}$$

These eigenstates have corresponding mass values of

$$M_W^2 = \frac{1}{4}g^2\nu^2$$
$$M_Z^2 = \frac{1}{4}(g^2 + g\prime^2)\nu \tag{2.9}$$
$$M_A^2 = 0$$

The eigenstate labeled here as A is the photon. The Higgs field is the mass generator of the SM. The Higgs boson was discovered in 2012 by the ATLAS and CMS collaborations at CERN with a mass of 125 GeV [5]. The scalar boson that was found appears to be the SM Higgs Boson.

2.2 Supersymmetry

NEEDS TO BE DONE

2.2.1 MSMM Particles

NEEDS TO BE DONE

2.2.2 R-Parity

NEEDS TO BE DONE

2.2.3 The MSSM Higgs Sector

NEEDS TO BE DONE

2.3 Charged Higgs Bosons

NEEDS TO BE DONE

2.3.1 Previous Result

NEEDS TO BE DONE

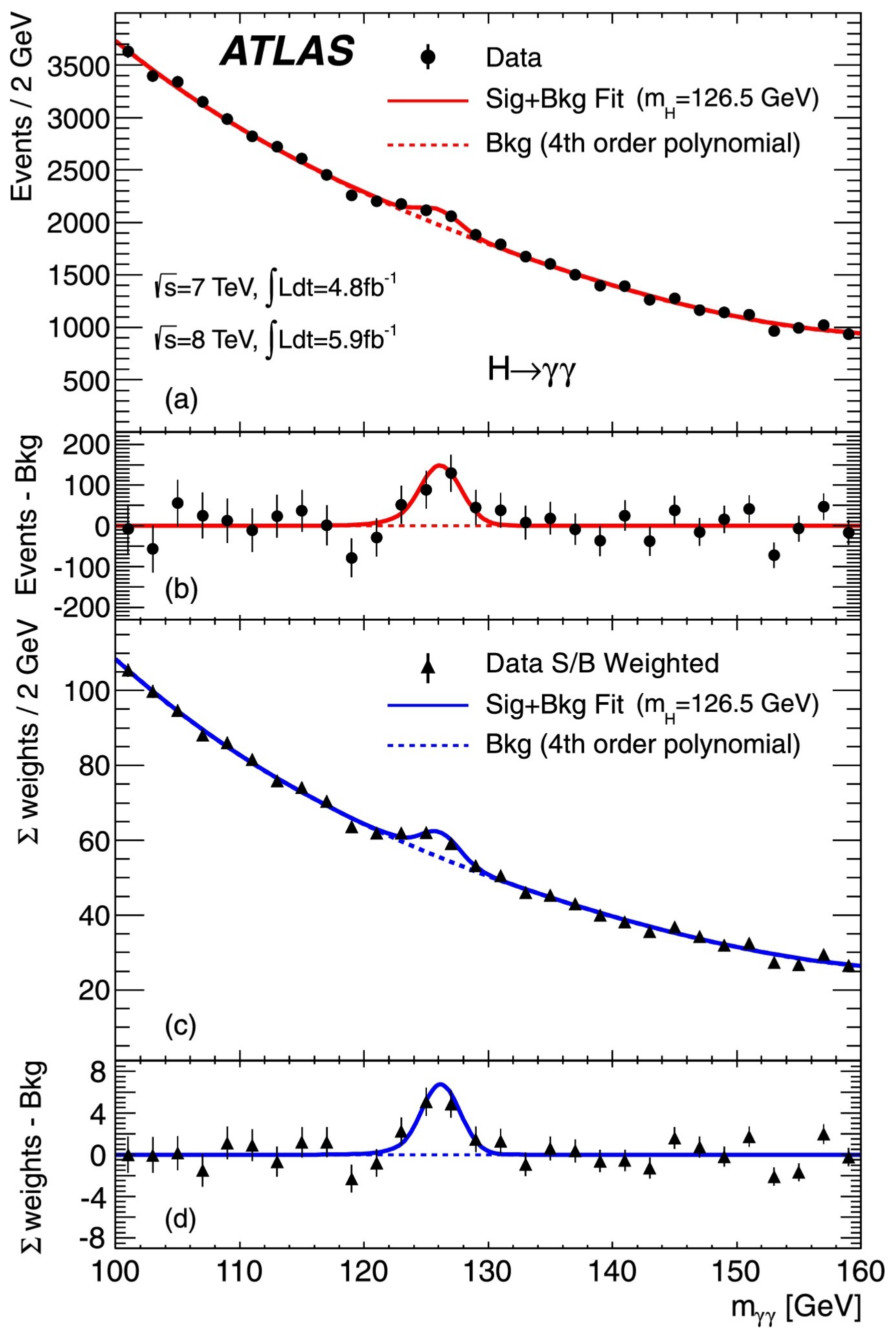

Figure 2.2: The distributions of the invariant mass of diphoton candidates after all selections for the combined 7 TeV and 8 TeV data sample. The inclusive sample is shown in (a) and a weighted version of the same sample in (c); the weights are explained in the text. The result of a fit to the data of the sum of a signal component fixed to $m_H = 126.5$ GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The residuals of the data and weighted data with respect to the respective fitted background component are displayed in (b) and (d).

CHAPTER 3

THE LHC AND ATLAS EXPERIMENT

3.1 The Large Hadron Collider

In order to study the Standard Model,the Higgs boson, and hints of new physics, the Large Hadron Collider (LHC) was built outside of Geneva, Switzerland. At 27 km in circumference with a center of mass energy of 13.6 TeV, the LHC is the largest and highest energy particle accelerator ever built. It consists of NUM SECTORS magnet sectors split between dipole and quadrupole magnets.

3.2 The ATLAS Detector

NEEDS TO BE DONE [6]

3.2.1 Inner Detector

NEEDS TO BE DONE

3.2.1.1 Pixel

NEEDS TO BE DONE

3.2.1.2 Semiconductor Tracker

NEEDS TO BE DONE

3.2.1.3 Transition Radiation Tracker

NEEDS TO BE DONE

3.2.2 Calorimeters

NEEDS TO BE DONE

3.2.2.1 Liquid Argon Electromagnetic Calorimeter

NEEDS TO BE DONE

3.2.2.2 Tile Hadronic Calorimeter

NEEDS TO BE DONE

3.2.3 Muon System

NEEDS TO BE DONE

3.2.3.1 Monitored Drift Tubes

NEEDS TO BE DONE

3.2.3.2 Cathode Strip Chambers

NEEDS TO BE DONE

3.2.3.3 Resistive Plate Chambers

NEEDS TO BE DONE

3.2.3.4 Thin Gap Chambers

NEEDS TO BE DONE

3.2.4 Magnet Systems

NEEDS TO BE DONE

3.2.4.1 Solenoid Magnet

NEEDS TO BE DONE

3.2.4.2 Toroid Magnet

NEEDS TO BE DONE

CHAPTER 4

EVENT RECONSTRUCTION

4.1 Trigger

4.2 Inner Detector

4.3 Calorimeters

4.4 Muon

4.5 e γ

4.6 Jets

4.6.1 Flavor Tagging

4.6.2 τ

4.7 $E_{\mathbf{T}}^{\mathrm{miss}}$

CHAPTER 5

SEARCH FOR CHARGED HIGGS BOSONS

5.1 Signature and Event Selection

NEEDS TO BE DONE

5.1.1 Object Definitions

NEEDS TO BE DONE

5.1.2 Event Selections

NEEDS TO BE DONE

5.2 Datasets

NEEDS TO BE DONE

5.2.1 Signal Modeling

NEEDS TO BE DONE

5.3 Background Modeling

NEEDS TO BE DONE

5.4 Analysis Strategy

NEEDS TO BE DONE

5.4.1 Multivariate Analysis Techniques

NEEDS TO BE DONE

5.4.2 Training

NEEDS TO BE DONE

5.4.3 Feature Selection

NEEDS TO BE DONE

5.4.4 Hyperparameter Optimization

NEEDS TO BE DONE

5.5 Systematic Uncertainties

NEEDS TO BE DONE

5.6 Results

CHAPTER 6

CONCLUSION

Appendices

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