Searches for invisibly decaying Higgs bosons with the CMS detector

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A dissertation submitted to Imperial College London
for the degree of Doctor of Philosophy

Abstract

Declaration

This dissertation is the result of my own work, except where explicit reference is made to the work of others, and has not been submitted for another qualification to this or any other university. This dissertation does not exceed the word limit for the respective Degree Committee.

Patrick Dunne

Acknowledgements

Contents

Chapter 1

Introduction and theory

This chapter will explain the theory of the Higgs boson. It will start with an introduction to the standard model (SM), focussing on the Higgs mechanism, before outlining the motivations behind and some candidates for physics beyond the SM (BSM). Natural units, where $\hbar = c = 1$, Einstein summation convention and Feynman slash notation are used throughout. Four vector indices are labelled using greek letters, SU(2) generators are labelled using i,j and k, and SU(3) generators are labelled using a,b and c.

1.1 The standard model of particle physics

The SM describes the interaction of the particles currently thought to be fundamental with the strong, weak and electromagnetic forces. Its predictions, which come solely from specifying the particles in the theory, the symmetries the theory respects, how they are broken and 18 free parameters have been tested in many different experiments in some cases up to one part in a trillion [1]. However, it does face challenges, described in section Section 1.1.6, one example being that it does not describe gravity.

The SM is a gauge invariant quantum field theory (QFT). In order to construct a QFT the symmetries that are respected by the theory and the fields it describes must be specified. Symmetries are important because of Noether's theorem, which states that for every continuously differentiable symmetry of the Lagrangian of a theory there is a corresponding conservation law [2, 3]. An example of this is that we observe that the laws of physics are invariant under translations and rotations in space and time, this is known as Poincaré invariance. These simple requirements lead through Noether's theorem to the conservation of energy, linear momentum and angular momentum. In addition to giving rise to conservation laws, some types of symmetry lead to additional fields being required to preserve invariance [4].

The particles must be specified, because in a QFT they correspond to the quantised excitations of fields. Specifically, scalar fields correspond to spin zero bosons, spinor fields correspond to spin half fermions, and vector fields correspond to spin 1 bosons. Therefore, the fields that can be present are limited by the particles that are observed. In order to add a new field an explanation for why the corresponding particle has not yet been observed must, therefore, be provided.

1.1.1 Particles and forces in nature

As discussed in Section 1.1, the properties of the universe place powerful constraints on the terms that enter the Lagrangian of any theory describing it. The observed particles in the universe fall into two types, fermions and bosons.

1.1.2 Introduction to gauge symmetries

As the SM is a gauge invariant gauge symmetries will now be introduced. Gauge symmetries are local transformations, i.e. the transformation can be different at different points in space and time, that form a symmetry group. To see the effect of imposing such a symmetry on a theory consider imposing local invariance under U(1) transformations on the Dirac Lagrangian for a masssive fermion:

$$\mathcal{L} = i\bar{\psi}\partial\!\!\!/\psi - m\bar{\psi}\psi. \tag{1.1}$$

This Lagrangian is invariant under a global $U(1)$ transformation $\psi \to e^{iq\theta}\psi$. However, if the $U(1)$ transformation is local i.e. θ is a function of spacetime position the Lagrangian is no longer invariant and transforms as:

$$\mathcal{L} \to \mathcal{L} - q(\partial_\mu\theta)\bar{\psi}\gamma^\mu\psi. \tag{1.2}$$

In order to restore invariance a vector field, A_μ, referred to as a gauge field or gauge boson, which transforms as $A_\mu \to A_\mu + \partial_\mu\theta$ and has an interaction with the fermion field:

$$\mathcal{L}_{int} = q(\bar{\psi}\gamma^\mu\psi)A_\mu, \tag{1.3}$$

can be added to the theory. The interaction term of the new gauge field transforms as:

$$\mathcal{L}_{int} \rightarrow \mathcal{L}_{int} + q(\partial_\mu \theta)\bar{\psi}\gamma^\mu \psi, \tag{1.4}$$

which cancels out the non-gauge invariance seen in equation (1.2).

Ignoring the free term of the new gauge field the Lagrangian is now:

$$\mathcal{L} = i\bar{\psi}\partial\!\!\!/\psi - m\bar{\psi}\psi + q(\bar{\psi}\gamma^\mu\psi)A_\mu. \tag{1.5}$$

This can be rewritten as:

$$\mathcal{L} = i\bar{\psi}\gamma^\mu \mathcal{D}_\mu \psi - m\bar{\psi}\psi, \tag{1.6}$$

where $\mathcal{D}_\mu = \partial_\mu + iqA_\mu$ and is referred to as the covariant derivative. Comparing equation (1.1) and equation (1.6) it can be seen that in order to go from a globally invariant Lagrangian to a locally invariant one we have substituted the normal spacetime derivative for the covariant derivative.

$U(1)$ transformations have one degree of freedom and can be described by one parameter, in the above case θ, and in order to make the Lagrangian locally invariant one interacting gauge boson had to be added. This correspondence between the number of degrees of freedom and the number of gauge bosons holds generally. For each degree of freedom of a group's transformations there exists a generator of the group, and for each generator one interacting gauge boson must be added to achieve local invariance.

1.1.3 Gauge symmetries in the SM

Fermions in the SM are spin half representations of the above symmetry groups.

The vector bosons in the standard model emerge as a result of the gauge invariance described above

1.1.4 Spontaneous symmetry breaking

1.1.5 Higgs boson production and decay at the LHC

The Lagrangian of the SM is globally invariant under Poincaré group transformations and locally gauge invariant under the group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$.

1.1.6 Challenges for the SM

1.2 Dark matter

1.3 Some extensions of the standard model incorporating dark matter

Chapter 2

The LHC and the CMS experiment

The purpose of this chapter is to introduce the CMS experiment and the LHC [5]. Without both of these apparatus the analyses performed for this thesis would, of course, not have been possible. In Section 2.1 an overview of the LHC and the chain of accelerators which feed into it will be given. This will then be followed in section Section **??** by a description of the CMS experiment focussing on the aspects most relevant to the search for invisibly decaying Higgs bosons.

2.1 The LHC

The LHC is situated 100m underground in a tunnel formerly built for the LEP accelerator [6] at CERN near Geneva, Switzerland. It is a 27km storage ring which accelerates both protons and heavy ions and collides them at the highest centre of mass energies of any collider built to date. The work contained in this thesis uses data from proton-proton collisions. These protons are obtained by taking hydrogen gas and stripping its atoms of their electrons with an electric field. The first accelerator in the LHC accelerator sequence, Linac 2, then accelerates the protons to 50 MeV. The protons are then accelerated to 1.4 GeVby the next accelerator, the Proton Synchrotron Booster (PSB), which is followed by the Proton Synchrotron (PS) where they reach 25 GeV. The beam energy is then increased to 450 GeVin the Super Proton Synchrotron (SPS). The protons are then injected into the LHC where, at time of writing, the maximum energy the beams have been accelerated to is 6.5 TeV, close to the design maximum of 7 TeV.

When fully filled the LHC contains two counter-rotating beams which are formed of up to 2808 bunches spaced either 25 or 50 ns apart and each containing $\mathcal{O}(10^{11})$ protons. The

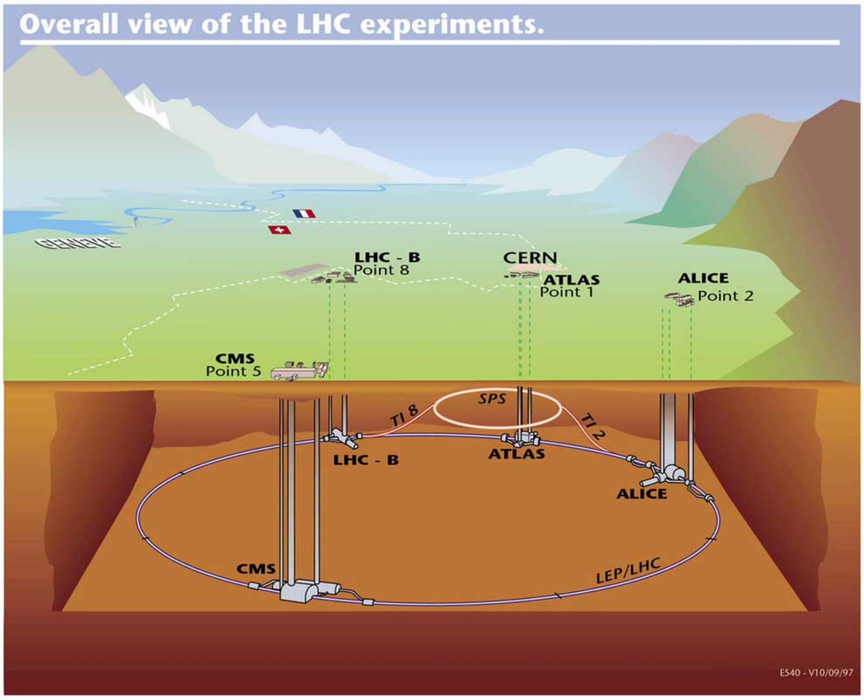

Figure 2.1: The layout of the LHC accelerator chain, showing the position of the four main detectors.

two beams are kept travelling in a cirlce by 1232 superconducting dipole magnets and steered to four collision points around the LHC. Detectors are situated at these collision points to observe the collisions, the main four being: ALICE [7], ATLAS [8], CMS [9] and LHCb [10]. A schematic of the LHC accelerator chain and the detectors can be seen in Figure 2.1

The number of times any physical process will occur in particle collisions can be expressed as:

$$N = \mathcal{L}\sigma, \tag{2.1}$$

where $\mathcal{L}$ is the integrated luminosity and depends only on the parameters of the collisions and σ is the cross-section which depends only on the process. In order to observe rare (i.e. low cross-section) processes it is therefore necessary to use very high luminosity datasets. The integrated luminosity is obtained by integrating the instantaneous luminosity over time. For collisions at the LHC the instantaneous luminosity is given by:

$$\mathcal{L} = \frac{k_b N_b^2 f_{rev} \gamma}{4\pi \epsilon_n \beta}, [11] \tag{2.2}$$

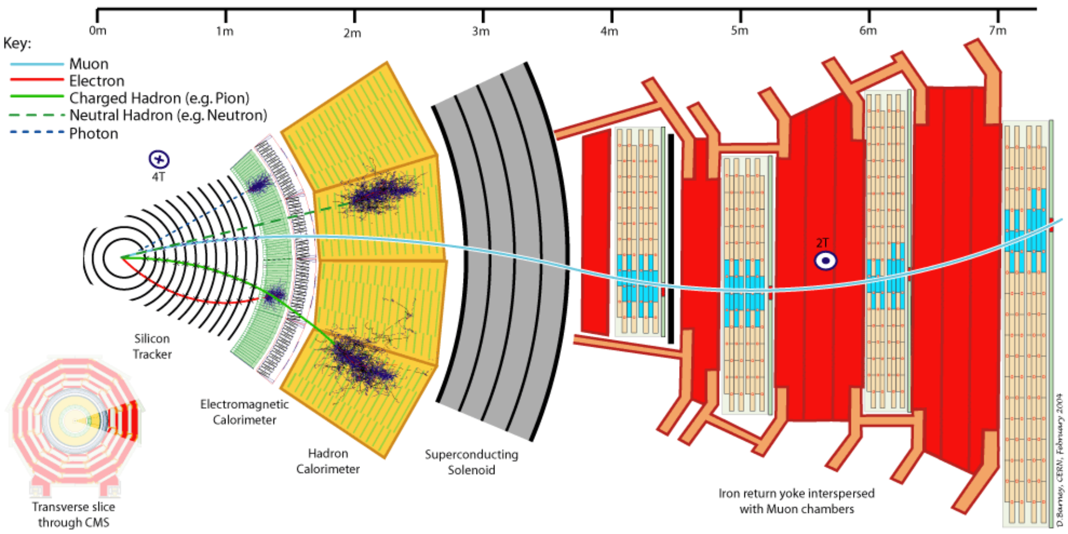

Figure 2.2: A schematic cross-section of the CMS experiment showing the path taken by several types of particles.

where k_b is the number of bunches per beam, N_b the number of protons per bunch, f_{rev} the revolution frequency, ϵ_n the normalised transverse beam emittance, β^* the beta-function at the interaction point and γ the Lorentz factor.

The cross-section for several processes is shown in Figure **??** and it can be seen that the cross-section for VBF Higgs production is approximately 1 pb.

2.2 The CMS experiment

2.2.1 Tracker

2.2.2 Electromagnetic calorimeter

2.2.3 Hadronic calorimeter

2.2.4 Muon system

2.2.5 Trigger system

Chapter 3

Physics objects and event reconstruction

3.1 Primary vertex

3.2 Jets

3.3 Missing transverse energy

3.4 Electrons

3.5 Muons

3.6 Taus

3.7 Photons

Chapter 4

Methods for limit setting

Chapter 5

Search for invisibly decaying Higgs bosons in run I prompt data

5.1 Trigger and event selection

5.2 Background estimation

5.2.1 W→ $e\nu$+jets

5.2.2 W→ $\mu\nu$+jets

5.2.3 W→ $\tau\nu$+jets

5.2.4 Z→ $\nu\nu$+jets

5.2.5 QCD

5.2.6 Minor backgrounds

5.3 Systematic uncertainties

5.4 Results

Chapter 6

Search for invisibly decaying Higgs bosons in run I parked data

6.1 Trigger

6.2 Event selection

6.3 Background estimation

6.3.1 W→ $e\nu$+jets

6.3.2 W→ $\mu\nu$+jets

6.3.3 W→ $\tau\nu$+jets

6.3.4 Z→ $\nu\nu$+jets

6.3.5 QCD

6.3.6 Minor backgrounds

6.4 Systematic uncertainties

6.5 Results

Chapter 7

Combinations and interpretations of run I searches for invisibly decaying Higgs bosons

7.1 Searches in other channels

7.2 Combination with prompt VBF search

7.3 Combination with the parked VBF search

7.4 Dark matter interpretations

Chapter 8

Search for invisibly decaying Higgs bosons in run II data

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List of Figures

List of Tables

List of Acronyms