Searches for invisibly decaying Higgs bosons with the CMS detector

Patrick James Dunne
of Imperial College London

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

1.1 The standard model of particle physics

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 [1]. 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 [2] 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

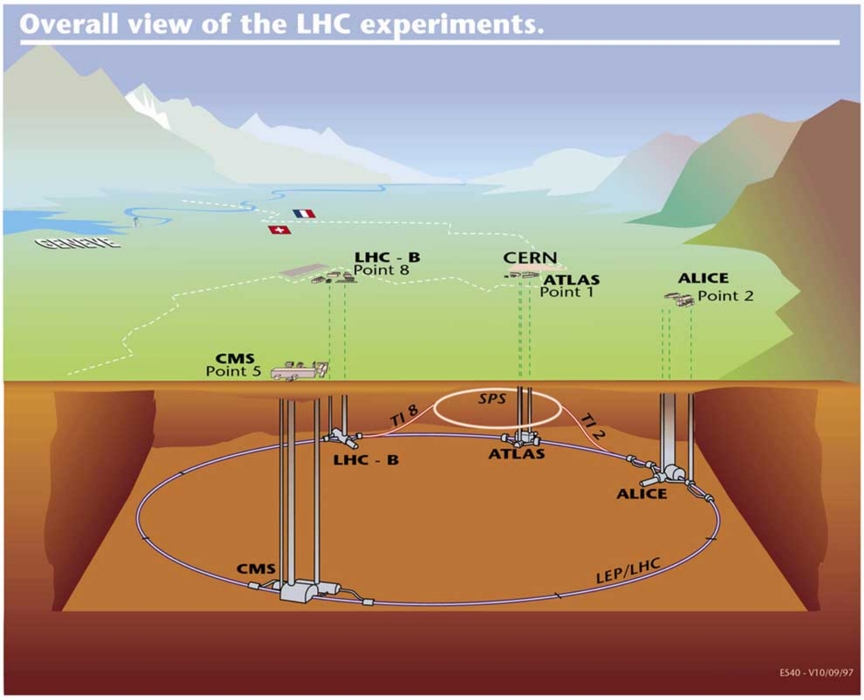

Figure 2.1: The layout of the LHC accelerator chain, showing the position of the four main detectors.

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 [3], ATLAS [4], CMS [5] and LHCb [6]. 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:

$$\mathcal{L} = \frac{k_b N_b^2 f_{rev} \gamma}{4\pi \epsilon_n \beta}, [7] \tag{2.2}$$

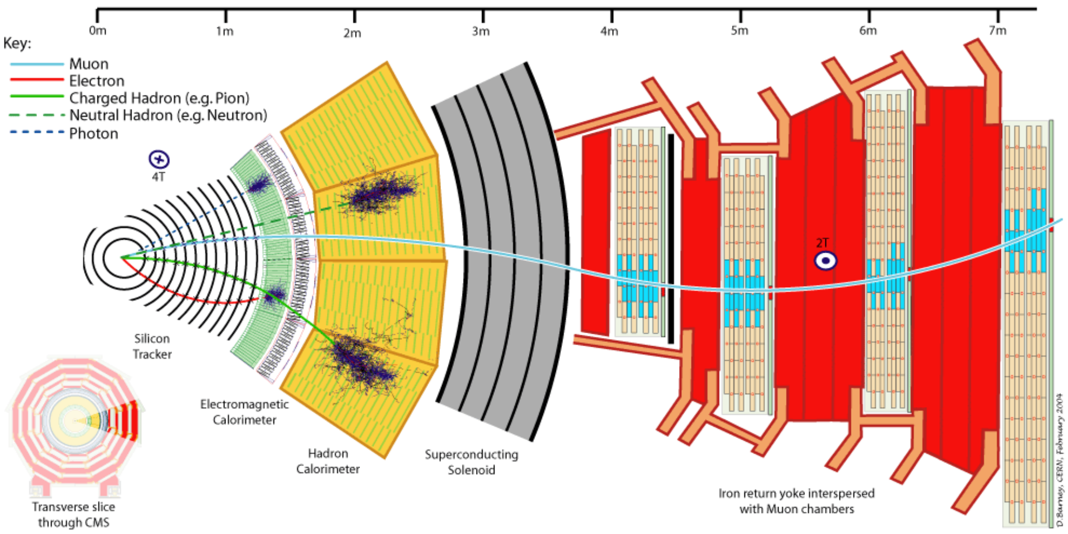

Figure 2.2: A schematic cross-section of the CMS experiment showing the path taken by several types of particles.

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

Bibliography

[1] L. Evans and P. Bryant, "LHC Machine", *JINST* **3** (2008), no. 08, S08001, doi:10.1088/1748-0221/3/08/S08001.

[2] LEP Injector Study Group, "LEP design report, volume I: The LEP injector chain; LEP design report, volume II: The LEP Main Ring". CERN, Geneva, 1983.

[3] A. Collaboration, "The ALICE experiment at the CERN LHC", *JINST* **3** (2008) S08002, doi:10.1088/1748-0221/3/08/S08002.

[4] A. Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider", *JINST* **3** (2008) S08003, doi:10.1088/1748-0221/3/08/S08003.

[5] C. Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[6] LHCb Collaboration, "The LHCb Detector at the LHC", *JINST* **3** (2008) S08005, doi:10.1088/1748-0221/3/08/S08005.

[7] M. Benedikt, P. Collier, V. Mertens et al., "LHC Design Report". CERN, Geneva, 2004.

List of Figures

List of Tables

List of Acronyms