Investigation of Higgs Portal Dark Matter Models

From Collider, Indirect and Direct Searches to Electroweak Baryogenesis

Ankit Beniwal

PRINCIPAL SUPERVISOR: Dr. Martin J. White
CO-SUPERVISOR: Prof. Anthony G. Williams

A dissertation submitted towards the degree in
Doctor of Philosophy

Department of Physics
School of Physical Sciences
University of Adelaide

July 2018

To my loving parents and sister.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Signature

Date 06/07/2018

Acknowledgements

First and foremost, I would like to thank my principal supervisor, Dr. Martin J. White, for his support, encouragement and dedication towards my research. You have taught me a lot about the challenges and benefits of undertaking research in physics. I also thank you for getting me into Formula 1. I look forward to a competitive F1 championship fight this year. I also thank my co-supervisor, Prof. Anthony G. Williams, for sharing his experience in the field and providing guidance during my PhD candidature. More importantly, I have learned to make clear plans and present my ideas in a pedagogical manner.

I acknowledge the support received from the Centre of Excellence in Particle Physics (CoEPP) at the University of Adelaide. In particular, I would like to thank S. Johnson and S. Santucci for their help in sorting out countless administrative tasks such as arranging my weekly meetings, booking flights, transport and accommodation for interstate as well as international workshops/conferences. I also thank S. Crosby and L. Boland from the Research Computing Team at CoEPP for answering my queries and allocating computer resources for my project. Some of the results presented in this thesis would not have been possible without their support.

During the course of my PhD candidature, I had the privilege of working with some of the world-renowned experts in my area of research. In particular, I enjoyed my collaboration with P. Scott, C. Weniger, C. Savage, J. D. Wells and M. Lewicki. I also had the pleasure of meeting other members of the GAMBIT collaboration during my international trip.

I would also like to thank my fellow PhD and master students. It was a great experience to engage in conversations with all of you from time-to-time and share interesting ideas around the office. In particular, our weekly symmetry for students (S4S) meeting is a great way to broaden our horizons and learn new concepts beside our own field of research.

Last but not least, I would like to thank my mum, dad, sister and Timmy for their unconditional love and support. None of this work would have possible without their support.

Abstract

This thesis addresses two limitations of the Standard Model (SM) of particle physics, namely dark matter (DM) and the origin of matter-antimatter asymmetry. Specifically, we study the Higgs portal DM models where the DM-SM interaction proceeds via a SM Higgs boson. Such models lead to a rich DM phenomenology that can be tested at collider, indirect and direct search experiments.

This thesis is composed of three parts. In the first part, we provide a brief background on the SM and follow the road that led to the Higgs boson discovery. We also present evidence for the existence of DM and motivate the observed baryon asymmetry in our universe.

In the second part of this thesis, we present results from a combined analysis of effective scalar, vector, Majorana and Dirac fermion Higgs portal DM models. For the fermion models, we include both CP-even and CP-odd terms. The parameter space of all models is constrained using the DM relic density, limits on the Higgs invisible branching ratio from the Large Hadron Collider (LHC) as well as indirect and direct DM detection experiments. In line with previous studies, we find that direct detection experiments will continue to exclude much of the model parameter space. For the CP-odd case, indirect searches are the only probe for accessing the high mass range of the theory.

We also study the scalar singlet model in light of electroweak baryogenesis (EWBG). By requiring a large scalar-SM Higgs coupling, the model can explain the observed matter-antimatter asymmetry via a strong first-order electroweak phase transition. This has important implications for EWBG that can be tested using collider, gravitational wave (GW) and direct detection signals. We find that the new scalar *cannot* simultaneously account for the observed DM abundance and matter-antimatter asymmetry. However, a large portion of the model parameter space can lead to a sizeable GW signal.

In the third part of this thesis, we focus on global fits. In particular, we perform a global fit of the extended scalar singlet model with a fermionic DM candidate. In this model, the new scalar mixes with the SM Higgs boson, leading to two scalar mediators. By coupling to the new scalar, a Dirac fermion field can play the role of a DM candidate. From our 7-dimensional scans of the model using *only* the EWBG constraint, we find that EWBG is viable in all parts of the model parameter space provided the scalar-fermion DM coupling $g_S \lesssim 5.62$. On the other hand, the combined constraints from the DM relic density, direct detection limit from the PandaX-II experiment, EWBG, electroweak precision observables and Higgs searches at colliders place an upper limit on some of the model parameters. We also compute the GW spectra of viable points and check their detection prospects at current or future GW experiments.

Lastly, we present preliminary results from global fits of the vector and Dirac fermion Higgs portal DM models using the GAMBIT software. After motivating and outlining the benefits of using GAMBIT for global fits, we perform scans of the model parameter space using the same set of constraints, model parameter ranges, nuclear and astrophysical parameter values as our previous study. For the Dirac fermion model, we allow the scalar-pseudoscalar mixing parameter ξ to vary in our scans. We find that our preliminary results using GAMBIT are in good agreement with those obtained in our previous study. This is used to motivate a future study of these models using the GAMBIT software.

Table of Contents

List of Figures xii

List of Tables xviii

List of Abbreviations xix

1 Introduction 1

I Background 3

2 The Standard Model of Particle Physics 5
- 2.1 Introduction 5
- 2.2 Gauge Invariance 7
- 2.3 Quantum Electrodynamics (QED) 7
- 2.4 Quantum Chromodynamics (QCD) 10
- 2.5 The Electroweak (EW) theory 11
  - 2.5.1 The Fermi theory of weak interactions 12
  - 2.5.2 Parity violation and $V - A$ currents 14
  - 2.5.3 Weak isospin and hypercharge 16
  - 2.5.4 The Electroweak Lagrangian 17
- 2.6 The Higgs mechanism 18
  - 2.6.1 Gauge boson masses 20
  - 2.6.2 The Weinberg angle 22
  - 2.6.3 Interactions in mass eigenstate basis 23
- 2.7 Fermion masses 25
  - 2.7.1 Lepton masses 26
  - 2.7.2 Quark masses 27
- 2.8 Origin of the quark mixing 27
  - 2.8.1 The Cabibbo-Kobayashi-Maskawa (CKM) matrix 29

3 Road to the Higgs boson discovery **35**
3.1 Introduction 35
3.2 Theoretical constraints on the Higgs boson mass 35
  3.2.1 Unitarity 36
  3.2.2 Triviality 38
  3.2.3 Vacuum stability 39
  3.2.4 Electroweak precision measurements 39
  3.2.5 Fine-tuning 40
3.3 Higgs decay branching ratios 42
  3.3.1 Higgs decay into gauge bosons 45
  3.3.2 Higgs decay into fermions 45
  3.3.3 Loop-induced Higgs decays 46
3.4 Higgs searches at colliders 47
  3.4.1 Direct bounds from LEP 48
  3.4.2 Higgs production at hadron colliders 48

4 Dark Matter **61**
4.1 Introduction 61
4.2 Evidence 62
  4.2.1 Galactic rotation curves 62
  4.2.2 Microlensing 64
  4.2.3 Big Bang Nucleosynthesis 66
  4.2.4 Cosmic Microwave Background 67
  4.2.5 Large-scale structures 70
  4.2.6 N-body simulations 71
  4.2.7 Collision of galaxy clusters 71
4.3 Candidates 73
  4.3.1 Weakly Interacting Massive Particles (WIMPs) 73
  4.3.2 Axions 79
4.4 Relic density of WIMPs 80
4.5 Detection methods 83
  4.5.1 Collider searches 83
  4.5.2 Direct detection 87
  4.5.3 Indirect detection 94

5 Electroweak Baryogenesis **101**
5.1 Introduction 101
5.2 Baryon asymmetry 101
5.3 Sakharov conditions 104
  5.3.1 B violation 104

5.3.2 Departure from thermal equilibrium 105
5.3.3 C and CP violation 105
5.4 B and CP violation in the SM 107
5.4.1 B violation 107
5.4.2 CP violation 109
5.5 Electroweak baryogenesis 111
5.6 Electroweak phase transition 113
5.6.1 Perturbative methods 114
5.6.2 Non-perturbative methods 120
5.7 Extended scalar sector 120
5.8 Tests for electroweak baryogenesis 122
5.8.1 The high-energy frontier 123
5.8.2 The intensity frontier 124
5.8.3 The cosmological frontier 125

II Phenomenology of Higgs portal dark matter models 127

6 Higgs portal dark matter models 129
6.1 Introduction 129
6.2 Models 130
6.3 Constraints 132
6.3.1 Thermal relic density 133
6.3.2 Higgs invisible width 135
6.3.3 Indirect detection 135
6.3.4 Direct detection 141
6.3.5 Validity of the fermion EFTs 145
6.4 Results 147
6.4.1 Scalar model 147
6.4.2 Vector model 149
6.4.3 Majorana fermion model 151
6.4.4 Dirac fermion model 155
6.5 Summary 160

7 Scalar singlet electroweak baryogenesis 163
7.1 Introduction 163
7.2 Scalar singlet model 164
7.3 Electroweak baryogenesis 165
7.3.1 Vacuum structure 165
7.3.2 Dynamics of the phase transition 166

7.4 Experimental probes . . . 169
  7.4.1 Collider signals . . . 169
  7.4.2 Gravitational wave signals . . . 171
  7.4.3 Dark Matter signals . . . 174
7.5 Cosmological modification . . . 177
  7.5.1 The sphaleron bound . . . 178
  7.5.2 Implications for dark matter . . . 179
7.6 Summary . . . 179

III Global fits **183**

8 Global fit of the extended scalar singlet model **185**
8.1 Introduction . . . 185
8.2 Model . . . 186
8.3 Constraints . . . 188
  8.3.1 Thermal relic density . . . 189
  8.3.2 Direct detection . . . 191
  8.3.3 Electroweak baryogenesis (EWBG) . . . 191
  8.3.4 Electroweak precision observables (EWPO) . . . 192
  8.3.5 Higgs searches at colliders . . . 193
8.4 Likelihoods . . . 194
  8.4.1 Relic density likelihood . . . 194
  8.4.2 Direct detection likelihood . . . 195
  8.4.3 EWBG likelihood . . . 195
  8.4.4 EWPO likelihood . . . 196
  8.4.5 Higgs search likelihood . . . 197
8.5 Preliminary results . . . 197
  8.5.1 EWBG only . . . 198
  8.5.2 Global fit . . . 200
  8.5.3 Gravitational wave signals . . . 204
8.6 Summary . . . 207

9 Global fits with GAMBIT **209**
9.1 Introduction . . . 209
9.2 GAMBIT . . . 210
9.3 Models . . . 211
9.4 Constraints . . . 213
  9.4.1 Thermal relic density . . . 213
  9.4.2 Higgs invisible decays . . . 215

9.4.3 Indirect detection via gamma rays 215
9.4.4 Direct detection 216
9.4.5 Nuisance likelihoods 217
9.4.6 EFT validity 218
9.5 Preliminary results 219
9.5.1 Vector model 220
9.5.2 Dirac fermion model 221
9.6 Summary and future work 222

10 Conclusions **225**

A List of Papers **229**

B Spontaneous Symmetry Breaking **231**
B.1 Global symmetry breaking 231
B.2 Local symmetry breaking 233

C Big Bang Cosmology **237**
C.1 Friedmann equations 237
C.2 Matter and Radiation 240
C.3 The ΛCDM model 243

D Chiral rotation of fermion fields **245**
D.1 Dirac fermion model 245
D.2 Majorana fermion model 248

E Scalar singlet effective potential **251**

F Supplementary details **253**
F.1 Tree-level scalar potential 253
F.2 Mass eigenstate basis 256
F.3 DM-nucleon coupling 257
F.4 Effective potential 259

G Annihilation cross sections **261**

References **263**

List of Figures

2.1 Elementary particles of the Standard Model (SM). Figure from Ref. [1]. 6

2.2 Feynman diagram for an interaction between a photon and two fermion fields. 9

2.3 Feynman diagram for an interaction between a gluon and two quark fields. 11

2.4 Feynman diagrams for the self-interaction of three (*left*) and four (*right*) gluon fields. 11

2.5 Fermi's analogy of the neutron β-decay (*right*) with the photon-proton interaction (*left*). 12

2.6 Feynman diagram for the process $\overline{\nu}_\mu + \mu^- \longrightarrow \overline{\nu}_e + e^-$ in the Fermi (*left*) and electroweak (*right*) theory. 13

2.7 Effect of parity transformation on the β-decay of ^{60}Co atoms. Figure from Ref. [2]. . 15

2.8 Cubic and quartic self-interactions between the Higgs bosons. 20

2.9 Cubic and quartic interactions between the Higgs and gauge bosons. 22

2.10 Feynman diagrams for an interaction between the Higgs boson and two leptons. . . . 26

2.11 The unitary triangle in the Wolfenstein parameterisation. Figure from Ref. [3]. . . . 32

2.12 Constraints on the $(\overline{\rho}, \overline{\eta})$ plane from various measurements and a global fit. The shaded regions are at 95% C.L. Figure from Ref. [3]. 33

3.1 Feynman diagrams for the scattering of $W^\pm$ bosons at high energies. 37

3.2 1-loop contributions to the running of the Higgs quartic self-coupling λ. Figure from Ref. [4]. 38

3.3 Dependence of the Higgs potential on the sign of the Higgs quartic coupling λ. . . . 39

3.4 Comparison between the indirect (LEP1, SLD; dotted red contour) and direct (LEP2, Tevatron; solid blue contour) measurements of m_W and m_t. 40

3.5 The 68% C.L. contours in the (m_h, m_t) (*left*) and (m_h, m_W) (*right*) plane. The precision fit includes all data except the direct measurement of m_t as indicated by the shaded horizontal band of $\pm 1\sigma$ width. 41

3.6 The SM Higgs boson mass as a function of the scale of new physics Λ. Constraints from triviality (dark shaded region at the top), vacuum stability (dark shaded region at the bottom) and electroweak precision fits (hatched blue region) are also shown. . 43

3.7 Branching ratios (*left*) and total decay width (*right*) of a SM Higgs boson as a function of its mass m_H. Figure from Ref. [5]. 44

3.8 Branching ratios with theoretical uncertainties of a SM Higgs boson in the low (*left*) and high (*right*) mass range. Figure from Ref. [6]. 44

3.9 Feynman diagrams for the Higgs decay into two photons via a quark (*left*) and $W^\pm$ boson (*right*) loop. 46

3.10 Dominant production modes for a SM-like Higgs boson at the LEP experiment. Figure from Ref. [7]. 48

3.11 Leading production modes for a SM-like Higgs boson at the hadron colliders such as gluon fusion ($gg \to h$) (*left*), vector boson fusion ($q\bar{q} \to q\bar{q}h$) (*center*) and Higgs-stralung ($q\bar{q} \to Wh/Zh$) (*right*). Figure from Ref. [7]. 49

3.12 SM Higgs production at hadron colliders with heavy quarks. Figure from Ref. [7]. . 49

3.13 *Left panel*: SM Higgs production cross-section at the Tevatron, Run II ($\sqrt{s}$ = 1.96 TeV). *Right panel*: SM Higgs production cross-section at the LHC ($\sqrt{s}$ = 14 TeV). Figure from Ref. [8]. 50

3.14 *Left panel*: Distribution of the log-likelihood ratio (LLR) as a function of the Higgs boson mass for the combined CDF and DØ analyses. *Right panel*: Same as in the left panel except the solid black corresponds to an artificially injected signal for a SM-like Higgs boson with m_h = 125 GeV. Figures from Ref. [9]. 52

3.15 Expected and observed upper limits on the ratio of the SM Higgs production cross-section and SM expectation at the 95% C.L. from the combined CDF and DØ analysis. Figure from Ref. [9]. 53

3.16 Distributions of the reconstructed invariant mass for the selected candidate events along with the total background and signal expected in the $h \to \gamma\gamma$ (*left*) and $h \to ZZ^{(*)} \to 4l$ (*right*) channels. The datasets used correspond to integrated luminosities of roughly 4.8 fb^{-1} collected at $\sqrt{s}$ = 7 TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s}$ = 8 TeV in 2012. Figure from Ref. [10]. 54

3.17 95% C.L. upper limits on the signal strength $\mu \equiv \sigma/\sigma_{\rm SM}$ for light (*right*) and heavy (*left*) Higgs boson masses from the ATLAS (*top row*) and CMS (*bottom row*) experiments. 55

3.18 Best fit values of $\sigma_i \cdot {\rm B}^f$ for each channel $i \to h \to f$ used in the combined ATLAS and CMS measurements. The dataset used corresponds to integrated luminosities per experiment of roughly 5 fb^{-1} at $\sqrt{s}$ = 7 TeV (2011) and 20 fb^{-1} at $\sqrt{s}$ = 8 TeV (2012). Figure from Ref. [11]. 57

3.19 Best fit results for the production signal strengths μ_i from the combined ATLAS and CMS data. 58

3.20 Best fit results for the decay signal strengths from the combined ATLAS and CMS data. 59

4.1 Rotation curve of the Andromeda (M31) galaxy. 64

4.2 A schematic diagram of the gravitational lensing effect. 65
4.3 *Left panel*: Gravitational lensing of the background galaxy (shown as blue arcs) by the galaxy cluster CL0024+1654. *Right panel*: Projected density plot of the galaxy cluster CL0024+1654. 66
4.4 Abundance of light elements vs the baryon matter density $\Omega_b = \rho_b/\rho_c$. 67
4.5 The cosmic microwave background (CMB) power spectrum for various values of $\Omega_b = \rho_b/\rho_c$ along with the 7-year WMAP data. Figure from Ref. [12]. 69
4.6 Temperature fluctuations in the CMB as measured by the COBE, WMAP and *Planck* satellite. Figure from Ref. [13]. 70
4.7 *Left panel*: Optical image of the Bullet cluster from the Magellan telescope. *Right panel*: Same as the left panel but in X-rays as measured by the Chandra X-ray telescope. 72
4.8 Feynman diagram for a contact interaction between a fermion DM χ and SM quark q. 76
4.9 Artistic view of the DM theory space. Figure from Ref. [14]. 78
4.10 Feynman diagram for an interaction between a fermion DM χ and a SM quark q via a Z' portal. 79
4.11 Evolution of the WIMP χ abundance as a function of $x \equiv m_\chi/T$. 82
4.12 Detection methods for dark matter (DM). Figure from Ref. [15]. 84
4.13 Mono-X searches for DM f in the case of a Z' portal model. Figure from Ref. [16]. . 86
4.14 A sketch of the mediator-DM mass plane used to present experimental results for simplified DM models. Figure from Ref. [17]. 87
4.15 Detection techniques used by various direct DM detection experiments. Figure from Ref. [18]. 89
4.16 Upper limits on the WIMP-nucleon cross-section vs WIMP mass at 90% C.L. from the PandaX-II 2017 (red), PandaX-II 2016 (blue), XENON1T 2017 (black) and LUX 2017 (magenta) experiments. Figure from Ref. [19]. 91
4.17 Upper limits on the spin-dependent WIMP-proton (*left*) and WIMP-neutron (*right*) cross-section vs WIMP mass. Figure from Ref. [20]. 92
4.18 A simplified picture of the WIMP velocities as seen from the Sun and Earth. 93
4.19 Results from the DAMA/NaI and DAMA/LIBRA experiment which shows a 9σ detection of annual modulation. Figure from Ref. [21]. 93
4.20 Upper limits on the SI WIMP-nucleon cross-section (solid lines) and hints of WIMP signals (closed contours) from current DM detection experiments, and projections (dashed) limits for planned direct detection experiments. 94
4.21 Energy spectrum of photons for the $\gamma\gamma$ final state without (blue) and with (red) virtual bremsstrahlung. 96
4.22 Comparison between the IceCube limits and latest constraints from Super-Kamiokande [22] and PICO [23, 24]. 99

5.1 Primordial abundance of light elements vs the baryon-to-photon ratio η. 102

5.2 Dependence of the CMB Doppler peaks on η. Figure from Ref. [25]. 103
5.3 The non-perturbative sphaleron process which violates B and L by 3 units. Figure from Ref. [25]. 105
5.4 Energy of the gauge field configurations vs the Chern-Simons number N_{CS}. Figure from Ref. [25]. 108
5.5 Sphaleron transition and Hubble rates vs time. The sharp drop in the sphaleron transition rate occurs at the electroweak phase transition (EWPT) when $T \simeq 100$ GeV. Figure from Ref. [25]. 110
5.6 Expanding bubbles of the broken phase within the surrounding plasma in the symmetric phase. Figure from Ref. [26]. 112
5.7 Production of baryons in front of the expanding bubble walls. Figure from Ref. [26]. 112
5.8 Schematic illustration of the evolution of $V_{\text{eff}}(\phi)$ with temperature T for a first- (*left*) and second- (*right*) order phase transition. Figure from Ref. [25]. 116
5.9 Phase diagram for EWPT in the SM. Figure from Ref. [25]. 121
5.10 Higgs production rates via gluon fusion relative to the SM (red dotted lines) and contours of ϕ_c/T_c (black solid lines) for one new color-triplet scalar for given values of the parameter $-\text{sgn}(M_X^2)\sqrt{|M_X^2|}$ and Q. 124

6.1 Feynman diagrams for an interaction between the SM Higgs boson and DM X where $X \in (S, V_\mu, \chi, \psi)$. 132
6.2 A flow chart of `micrOMEGAs`. Figure based on Ref. [27]. 133
6.3 *Left panel*: The signal and background regions of interest (RoIs) as used in the ring method of Ref. [28]. *Right panel*: Separation of the signal and background RoIs into 28 sub-RoIs for the morphological analysis of Ref. [29]. Figure from Ref. [29]. . . . 141
6.4 Contours of fixed scalar relic density for $f_{\text{rel}} = 1$ (black solid), 0.1 (red dashed) and 0.01 (blue dotted). 147
6.5 Indirect search limits on the scalar model parameter space. 148
6.6 Direct search limits on the scalar model parameter space. 149
6.7 Same as Fig. 6.4 but for the vector DM model. 150
6.8 Same as Fig. 6.5 but for the vector DM model. 150
6.9 Same as Fig. 6.6 but for the vector DM model. 151
6.10 Same as Fig. 6.4 but for the Majorana fermion DM model. 152
6.11 Same as Fig. 6.5 but for the Majorana fermion DM model. 153
6.12 Breakdown of the current 1σ C.L. (blue solid) indirect search limit in the Majorana fermion model parameter space when $\cos\xi = 0$. 154
6.13 Same as Fig. 6.12 but for the future 90% C.L. (NFW, $\gamma = 1.3$). 154
6.14 Same as Fig. 6.6 but for the Majorana fermion DM model. 156
6.15 Same as Fig. 6.10 but for the Dirac fermion DM model. 157
6.16 Same as Fig. 6.11 but for the Dirac fermion DM model. 158

6.17 Same as Fig. 6.14 but for the Dirac fermion DM model. 159

7.1 Parameter space of the scalar singlet model relevant for electroweak baryogenesis (EWBG). 166
7.2 Parameter space of the scalar singlet model relevant for EWBG along with the reach of various collider experiments. 170
7.3 Parameter space of the scalar singlet model relevant for EWBG along with the gravitational wave (GW) signals. 173
7.4 Spectra of GWs from EWPT for the example points marked in Fig. 7.3. 173
7.5 Parameter space of the scalar singlet model relevant for EWBG along with the DM abundance and LUX (2016) limits. 176
7.6 *Left panel*: Maximal modification of the Hubble rate H that is not in conflict with any experimental bounds. *Right panel*: Values of v_*/T_* needed to avoid the washout of the baryon asymmetry after the EWPT vs the modification of the Hubble rate. . . 179
7.7 Parameter space of the scalar singlet model relevant for EWBG along with the DM abundance and LUX (2016) limits from a modified cosmological history. 180

8.1 Feynman diagrams for the fermion DM annihilation into SM and h/H particles. . . . 190
8.2 2D profile likelihood plots from a 7D scan of the model parameter space using *only* the electroweak baryogenesis (EWBG) constraint. 199
8.3 2D profile likelihood plots from a global fit of our model. 203
8.4 1D profile likelihood plots for the free model parameters from our global fit. 205
8.5 Gravitational wave (GW) spectra of viable points and their dependence on the transition temperature T_*. 206
8.6 GW spectra of viable points and their dependence on v_*/T_*. The current sensitivity bands and detection prospects of GW experiments are same as in Fig. 8.5. 206

9.1 *Left panel*: Profile likelihood in the (m_V, λ_{hV}) plane for low vector DM masses. Contour lines mark out the 1σ and 2σ C.L. regions. *Right panel*: Vector DM model results from Ref. [30]. 220
9.2 *Left panel*: Profile likelihood in the (m_V, λ_{hV}) plane for high vector DM masses. Contour lines mark out the 1σ and 2σ C.L. regions. *Right panel*: Vector DM model results from Ref. [30]. 220
9.3 *Left panel*: Profile likelihood in the $(m_\psi, \lambda_{h\psi}/\Lambda_\psi)$ plane for low Dirac fermion masses. Contour lines mark out the 1σ and 2σ C.L. regions. *Right panel*: Dirac fermion model results from Ref. [30] for the case $\xi = \pi/2$. 221
9.4 *Left panel*: Profile likelihood in the $(m_\psi, \lambda_{h\psi}/\Lambda_\psi)$ plane for high Dirac fermion masses. Contour lines mark out the 1σ and 2σ C.L. regions. *Right panel*: Dirac fermion model results from Ref. [30] for the case $\xi = \pi/2$. 222

B.1 The Mexican-hat potential for a complex scalar field ϕ with $\mu^2 < 0$. Figure from Ref. [31]. 233

B.2 Three- and four-point interaction between the Higgs boson and photon field. 235

C.1 Composition of the universe as a function of the scale factor $a(t)$. Figure from Ref. [32]. 241

C.2 Effective number of degrees of freedom $g_{\mathrm{eff}}(T)$ vs temperature T. Figure from Ref. [32]. 242

List of Tables

2.1 Weak quantum numbers of quarks and leptons. 17
2.2 Weak quantum numbers for the components of the Higgs doublet. 19
2.3 Coupling strength between the first generation of quarks/leptons and neutral Z boson. 25
2.4 Spinor fields for the three fermion generations in five interaction representations. . . 29

3.1 SM predictions for the decay branching ratios of a Higgs boson with $m_h = 125.09$ GeV together with their uncertainties. Table from Ref. [33]. 56

5.1 Maximum value of the Higgs boson mass m_h^c allowed for a first-order EWPT in the SM as obtained from lattice studies. Table from Ref. [25]. 120

8.1 Ranges and priors for the free parameters of our model. 195
8.2 Best-fit point from a global fit of our model. 201

9.1 Likelihoods and corresponding GAMBIT modules/backends that provide the relevant routines. 213
9.2 Ranges and priors for the vector DM model, and the SM nuisance parameter m_h. . . . 219
9.3 Ranges and priors for the Dirac fermion DM model, and the SM nuisance parameter m_h. 219

List of Abbreviations

ATLAS	A Toroidal LHC ApparatuS
BBN	Big Bang Nucleosynthesis
BBO	Big Bang Observer
BSM	Beyond the Standard Model
CMB	Cosmic Microwave Background
CMS	Compact Muon Solenoid
CP	Charge Parity
CPV	Charge Parity Violation
DM	Dark Matter
dSphs	Dwarf Spheroidals
EW	ElectroWeak
EWBG	ElectroWeak BaryoGenesis
EWPO	ElectroWeak Precision Observables
EWPT	ElectroWeak Phase Transition
EWSB	ElectroWeak Symmetry Breaking
Fermi-LAT	Fermi Large Area Telescope
GAMBIT	Global And Modular BSM Inference Tool
GW	Gravitational Waves
LEP	Large Electron-Positron

LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
NFW	Navarro-Frenk-White profile
PT	Phase Transition
SD	Spin-Dependent
SI	Spin-Independent
SM	Standard Model
SSB	Spontaneous Symmetry Breaking
UV	UltraViolet
VEV	Vacuum Expectation Value
WIMPs	Weakly Interacting Massive Particles
WMAP	Wilkinson Microwave Anisotropy Probe